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Conference 9517A: Smart Sensors, Actuators, and MEMS VII

Monday - Wednesday 4 -6 May 2015

Part of Proceedings of SPIE Vol. 9517 Smart Sensors, Actuators, and MEMS VII; and Cyber Physical Systems

9517-501, Session PLMon

Microsystems: from smart sensors to cyberphysical systems

Robert Plana, Alstom S.A. (France)

It is understood today that data represent the next industrial revolution and this motivates research and innovation in the field of sensors, actuators, but also in the way the data are conveyed and processed. During the last twenty years, we have seen a dramatic evolution from centralized sensors systems featuring more and more functionalities to fleet of sensors distributed generating massive amount of data locally or centrally processed to form relevant information for almost all the industrial sectors. This is sometimes called Internet of Things revolution (IoT).

The communication will present the technologies that are under discussion today and more precisely how the nanotechnologies and the surface states understanding allow the development of new types of sensors featuring high resolution and sensitivity. It will be also outline the architectures that are envisioned to handle fleet of sensors all connected simultaneously. Some important issues will be assessed as miniaturization, high density of integration, power consumption and autonomy and cybersecurity. In a second part, it will be shown the applications targeted by advanced microsystems in almost all the industrial sectors. Finally in a third part, it will be shown that beside the hardware architectures, data processing, storing, visualization will play a major role in the emerging Internet of Things defining a new category of systems called "Cyberphysical systems".

9517-1, Session 1

Vibration energy harvesting: fabrication, miniaturisation and applications (*Invited Paper*)

Stephen P. Beeby, Dibin Zhu, Univ. of Southampton (United Kingdom)

Vibration energy harvesting (VEH) is an applied technology and the nature of the application places important constraints on harvesters that can be overlooked in the laboratory. For vibration energy harvesters to become a practical solution, the characteristics of real world applications should be considered at the outset. This talk will provide a brief overview of VEH research at the University of Southampton and will focus on the practical applications that have been explored. The design of vibration energy harvesters is fundamentally linked to the characteristics of the vibration source i.e. frequency spectrum, amplitude and any variation in these. The application also imposes physical constraints (space limitations and form factor), reliability requirements and cost constraints on the entire system (harvester, power conditioning electronics, energy storage and load electronics). The talk will cover fixed frequency industrial applications utilising miniature and macro scale electromagnetic vibration energy harvesters. Screen printed piezoelectric harvesters designed for use in helicopter health and usage monitoring systems (HUMS) will also be presented. A wireless condition monitoring system for the rail industry powered by PMG Perpetuum's vibration energy will also be discussed. The lessons learnt in each case will be reviewed for both the harvester and the associated system as a whole. Finally, the suitability of different types of energy harvester (linear, bistable and Duffing type non-linear) for use in real applications will also be explored. In summary VEH should be considered as an enabling technology suitable for applications that have to be wireless, cannot accept batteries and offer a suitable vibration energy source. Appreciation of the physical and economic constraints will highlight the research challenges that will ultimately enable the technology to become a widespread practical solution for autonomous wireless systems.

9517-2, Session 1

Influence of process parameters on properties of piezoelectric AlN and AlScN thin films for sensor and energy harvesting applications

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Aluminum nitride (AlN) is a piezoelectric material often used as thin film in SAW/BAW devices. Furthermore, there is an increasing interest in its use as basis for energy harvesting applications. While it has a relative low piezoelectric coefficient, it is a suitable choice for energy harvesting applications due to (for example) its low dielectric constant and good mechanical properties.

The films were deposited by reactive pulsed magnetron sputtering using the Double Ring Magnetron DRM 400. By using this sputter source, as well as suitable powering and process control, it is possible to deposit highly piezoelectric AlN very homogeneous on a deposition area with a diameter of 200 mm with deposition rates up to 200 nm/min, resulting in film thicknesses of several (ten) microns being technically and economically feasible. Moreover, by adjusting process parameters accordingly, it is possible to adjust properties, like film stress, to application specific requirements.

Additionally, it is known that the doping of AlN with Scandium results in significantly increased piezoelectric properties [2]. This is mainly attributed to a softening of the C33 elastic constant as well as increase of piezoelectric constant e_{33} [1]. With this, it is possible to raise the generated power in the case of energy harvesting or increase the signal level when used in sensor applications by several times compared to pure AlN. The influence of process parameters and Sc concentration on film properties were determined by e.g. piezometer-, pulse echo-, SEM-, XRD-, EDS- and nanoindentation-measurements.

Energy harvesting measurements were done using an electromechanical shaker system for the excitation of defined vibrations and a laservibrometer for determination of displacement of the samples. The generated power was measured as function of electric load at resonance.

References:

[1] M. Akiyama, T. Kamohara, K. Kano, A. Teshigahara, Y. Takeuchi, and N. Kawahara, "Enhancement of piezoelectric response in scandium aluminum nitride alloy thin films prepared by dual reactive cosputtering," *Adv. Mater.*, vol. 21, no. 5, pp. 593-596, 2009.

[2] F. Tasnádi et al, "Origin of the anomalous piezoelectric response in wurtzite ScXAl_{1-X}N alloys," *Phys. Rev. Lett.*, Vol. 104, 137601, 2010

9517-3, Session 1

From MEMS to macro-world: a micro-milling-machined wideband vibration piezoelectric energy harvester

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Extracting energy from sources scattered in the surrounding environment, like mechanical vibrations, and converting it into electricity, is a topic that has been investigated for a long time. The emerging paradigm of the Internet of Things (IoT) is a very interesting field of exploitation for vibration Energy Harvesters (EHs), ranging from Microsystem (MEMS) based realizations, rising up to energy macro converters.

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EHS typically exhibit narrow vibration frequency range of operability. We recently presented a novel EH design realized in MEMS technology with a particular structure, named Four-Leaf Clover (FLC), meant to increase the number of mechanical resonant modes in the vibration frequency range up to a few kHz.

In this work we propose to bring the FLC EH concept from the MEMS to the macro-world, in order to realize wide-band, multi-modal vibration EHS able to address higher levels of power (in the mW range) for vibrations spanning from 40-50 Hz up to 12 kHz. We realized the FLC mechanical macro resonator (8 cm diameter) by micro-milling a 700 μm thick Aluminium layer. In parallel, we realized simple cantilevers (2 cm by 10 cm) in order to test the conversion performance of a PVDF-based piezoelectric film glued and wired on the Aluminium mechanical support. Such test structures present good performance in terms of open-circuit voltage, when the cantilever structure is stimulated with a mechanical pulse.

Further steps of this work will consist in: 1) Patterning, gluing and wiring PVDF piezo material on the FLC surface; 2) Providing the FLC macro-converter with proof masses at the tip of petals to tune the resonant frequencies; 3) Mounting the device on a suitable support for testing purposes; 4) Providing the FLC with circuitry for energy extraction, storage and management. In the full paper we will demonstrate the multi modal behaviour of the FLC macro-EH.

9517-4, Session 1
Low-profile and wearable energy harvester based on plucked piezoelectric cantilevers

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The Energy Harvester (EH) presented is designed to be worn by a person on the lateral side of a knee. A central aluminium hub holds 16 cantilevered piezoelectric bimorphs, whereas a set of 80 plectra is fixed to an underlying plate. As hub and plate rotate relative to each other during walking, the bimorphs are plucked by the plectra and generate electrical energy. A set of 16 full bridges rectifies the current produced and outputs it onto a common bus. Laboratory controlled experiments were carried out using a servomotor reproducing different gaits, such as walking, running and stairs climbing. Besides the traditional resistive load directly attached to the EH, tests were performed also with a circuit offering a stabilised 3.3 V supply. Based on a commercially available IC, the circuit produced a 0.1 mA supply during running gait with kapton plectra. Kapton and steel plectra were tested on the simulator, with the latter showing potential for much larger energy generation. Kapton plectra were cut from a 125- μm -thick film using a cutting plotter. The steel plectra were formed by Photochemical Machining from a 100- μm -thick sheet and electrically passivated by sputtering a layer of zirconium oxide. After cutting or machining, the 2x3 mm² plectra were lifted to be normal to the original sheet, remaining attached to it by one of the short sides. The bimorphs were obtained by diamond-cutting commercially available 13x25 mm² series bimorphs made with PZT-5H. As the resulting bimorphs have a trapezoidal shape, a sleek profile is possible for the overall EH. Custom braces were developed and used to allow a person to wear the device while walking on flat ground and climbing stairs.

9517-5, Session 2
High temperature performance of sputter-deposited piezoelectric aluminium nitride thin films

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High temperature stable piezoelectric materials for high operating temperatures are desired for new sensor applications as for process monitoring in harsh environments. The operation temperature of piezoelectric materials is limited by increase of the leakage current, diffusion effects or phase transformation in the material leading all to reduction or even cancellation of the piezoelectric properties. An appropriate material seems aluminium nitride (AlN), which is chemically stable up to 1000°C in vacuum.

In this study, AlN was reactively sputtered in a pure nitrogen plasma at high DC power (800 W), low pressure (2 μbar), and nominal unheated substrates. First, the impact of layer thickness on the intrinsic biaxial film stress was analyzed. Samples were annealed in oxygen or nitrogen atmosphere for 2 hours with a constant flow rate of 50 sccm. The samples were annealed at 250°C, 500°C and afterwards up to 1000°C in 100°C steps. Finally, intrinsic film stress, XRD and electrical leakage current measurements were performed.

AlN grows c-axis oriented on sapphire, which can be seen in Figure 1. The thickness of AlN layers has a major impact on the intrinsic stress level when deposited at equal deposition conditions. The layers grow compact and columnar. Furthermore, the layers are highly c-axis orientated and hence piezoelectric [1]. Stress and further film properties are changing by thermal annealing. For 100 nm layers a XRD measurement is shown in Figure 2. In oxygen atmosphere at 1000°C the (002)-peak disappears, indicating a complete oxidation of the AlN film. However, the degradation process starts already at lower temperatures, monitored also in a change in leakage current mechanism. Below 700°C, the layers are stable and show Poole-Frenkel behavior, which is shown in Figure 3 (a) and (b). Above, the mechanism changes to a mixture of different mechanisms, due to the effusion of gaseous constituents and the oxidation of the layers. The leakage current can not be fitted with Poole-Frenkel behaviour anymore, also the electron barrier height decreases after high temperature loading in oxygen atmosphere, see Figure 3 (c) and (d).

References

[1] M. Schneider, T. Strunz, A. Bittner, and U. Schmid, Impact of Sputter Deposition Parameters on the Leakage Current Behavior of Aluminium Nitride Thin Film, *Advances in Science and Technology*, Vol. 77, pp. 29-34, 2013.

9517-6, Session 2
Wafer bonding technology for new generation vacuum MEMS: challenges and promises

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During the past decade consumer electronics has emerged as the main driving force in technology development for Micro Electro Mechanical Systems (MEMS) manufacturing. The demands of these new applications resulted in development of new processes and techniques, particularly addressing the compatibility with CMOS technology processes for achievement of high levels of integration as well as with respect to the use of wafer bonding for high vacuum levels sealing (pressure < 10-2mbar).

From the broad range of wafer bonding processes only few are compatible with vacuum applications: fusion bonding, anodic bonding, glass frit bonding and metal-based bonding. The permeability of the bond interface as well as any outgassing during the formation of this bond are very important; also any outgassing from the enclosed surfaces after bonding will affect the vacuum level in the cavity. In some cases, a getter material is used inside the device cavity to compensate for this outgassing. Additionally the bonding process selected must be compatible with the devices on the wafers being bonded.

This work reviews the principles of vacuum encapsulation using wafer bonding. Examples showing the suitability of each process for specific applications types will be presented.

A significant challenge in vacuum MEMS fabrication is the lack of analytical methods needed for process characterization or reliability testing. A short overview of the most used methods and their limitations will be presented. Specific needs to be addressed will be introduced with examples.

9517-7, Session 2

3D integration approaches for MEMS and CMOS sensors based on a Cu through-silicon-via technology and wafer level bonding

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3D integration represents a decisive technology for realizing miniaturized, heterogeneous smart systems. In contrast to microelectronic devices, specific constraints have to be considered for MEMS with fragile structures or CMOS sensors with high-pattern densities. Here, the wafer thickness is usually higher (~400 µm) due to the MEMS fragility and for reasons of avoiding thin wafer technologies. This requires through-silicon vias (TSVs) with large dimensions and high aspect ratios (HAR). For MEMS, the realization of a protective, hermetically sealed capping is crucial, and could be realized by wafer level bonding. In this paper, both Cu-TSV as well as a glass frit bonding technology, and their application to MEMS and CMOS sensors, will be described.

Two TSV approaches were investigated, in which the TSVs were fabricated either before or after wafer thinning. Both approaches will be compared and related critical issues discussed. One distinctive feature is an incomplete TSV Cu-filling, which avoids long processing and complex process control, while minimizing the thermomechanical stress between Cu and Si and related adverse effects in the device. However, the incomplete filling also includes various challenges regarding process integration. A method based on pattern plating using spin-on negative resist will be described where the TSVs are metalized at the same time as the redistribution layer. This eliminates the need for additional planarization and patterning steps. Presented electrical data will include TSV resistance measurements with TSV-chains (4-200 TSVs), and single TSVs yielding 11 mOhm.

In addition, glass frit wafer bonding will be discussed for hermetic sealing of MEMS inertial sensors. With respect to the desired system miniaturization, the width and spacing of the bonding frames is critical. A major challenge in glass frit bonding is the realization of glass paste patterns with dimensions in the range of 50 µm. Related investigation results will be presented.

9517-8, Session 2

Design and fabrication of indium phosphide air-bridge waveguides with MEMS functionality

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We present the design and fabrication of a dual air-bridge waveguide structure integrated with MEMS functionality. The structure is designed to function as a tunable optical buffer for telecommunication application.

The optical buffer structure is based on two parallel waveguides made of high refractive index material with sub-wavelength dimensions. They are suspended in air, and are separated by a sub-micron air gap. Due to the fact that the size of the waveguides is much smaller than the wavelength of light that propagates in the structure, a significant fraction of the

optical mode is in the air gap between the waveguides. By changing the size of the air gap using MEMS techniques, we can vary this fraction and hence the effective refractive index of the waveguide structure, thus generating tunable optical delay.

The optical buffer structure was grown on an InP substrate by molecular beam epitaxy, and the device layer was made of InGaP. An InGaAs layer was sandwiched between the device layer and the substrate to serve as a sacrificial layer. We characterised the surfaces of the epitaxially grown InGaP and InGaAs layers by atomic force microscopy, and our analysis showed that the rms values of surface roughness for both layers were less than 1nm. The sub-micron waveguides, their supports in the form of side pillars with tapered shapes in order to minimise optical losses, and the MEMS structures were patterned using electron beam lithography and plasma etching. Electrodes were integrated into the structure to provide electrostatic actuation. After the sample patterning, the waveguide structure was released using HF etch. In our simulation, we estimated that by varying the waveguide separation from 50nm to 500nm, we could achieve a change in propagation delay by a factor of two.

9517-9, Session 3

Electrothermal piezoresistive cantilever resonators for personal measurements of nanoparticles in workplace exposure

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Low-cost and low-power piezoresistive cantilever resonators with integrated electrothermal heaters are developed to support the sensing module enhancement of the second generation of handheld cantilever-based airborne nanoparticle (NP) detector (CANTOR-2). Resonant cantilevers with different shapes of free ends have been fabricated using silicon bulk micromachining technologies (i.e. rectangle, hammer-head, triangle, and U-shaped cantilevers). Built-in heating resistor and full Wheatstone bridge are set close to the cantilever clamp end for effective excitation and sensing, respectively, of beam deflection. Moreover, the cantilever sampling area was enlarged to collect more engineered NPs (ENPs). To design the resonator and investigate the excitation mode, COMSOL Multiphysics 4.3b was used in the device simulation. Before being mounted in the NP sampler head of CANTOR-2, the employed resonator is first characterized in an offline resonance measurement. Subsequently, the joining of the silicon cantilever resonator was carried out with spring-loaded contacts for fast and easy replacement in case of overload. During exposure assessment in a test chamber under typical workplace conditions ($V = 1 \text{ m}^3$, $T = 23^\circ\text{C}$, $\text{rH} = 30\%$, and $p = 1 \text{ atm}$) using carbon aerosols (6–523 nm), a uniform distribution of deposited carbon ENPs and their agglomerates on the sampling area was obviously observed. After calibration, the detected ENP mass concentrations of CANTOR-2 show a standard deviation from a fast mobility particle sizer (FMPS, TSI 3091) of 8 – 14%. By having a total device volume of 540 cm³, weight of 375 g, and power consumption of 1.25 W in the current version, this developed CANTOR-2 provides a sufficient precision and a very good portability for being used as a personal airborne NP monitoring device, which can be easily held or worn by workers during their activities.

9517-10, Session 3

Out-of-plane piezoelectric microresonator and oscillator circuit for monitoring engine oil contamination with diesel

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Real time monitoring of the physical properties of liquids is an important subject in the automotive industry. Contamination of lubricating oil by diesel soot has a significant impact on engine wear, especially with most engine manufacturers opting for Exhaust Gas Recirculation (EGR) technology to curb oxides of nitrogen (NOx) emissions [1, 2]. Returning exhaust product to the diesel engine combustion chamber may accelerate the degradation of the lubricant oil affecting the rheological properties [3].

Resonant microstructures may be a precise and compact solution for tracking the viscosity (μ) and density (ρ) of liquids. Since pure shear losses do not allow an independent determination of the density and viscosity [4], two out-of-plane modes for the monitoring of oil dilution with diesel have been selected. The first one (12-mode) is working at 51 kHz and the second mode (14-mode) at 340 kHz. We have obtained better resolution values for the 14-mode, due to the higher quality factor and conductivity peak (see table 1).

An oscillator circuit was implemented based on each resonator. A commercial PLL circuit was utilized for setting the phase at resonance [5]. Two parameters were measured: the quality factor and the resonance frequency from which the viscosity and density of the fluids under test can be determined, requiring only a small amount of test liquid. A calibration of the microresonator was performed using various test liquids, a commercial viscometer and theoretical models reported in the literature [6]. Our results demonstrate the performance of the resonator in oils up to 90 cP. The quality factor measured in SAE OW30 lubricant at 25°C was 7 for the 12-mode and 19 for the 14-mode, obtaining a better resolution in density and viscosity for the 14-mode. In the final paper, results demonstrating real time oil density and viscosity monitoring will be presented.

9517-11, Session 3
FBAR-on-diaphragm type electro-acoustic resonant micro-accelerometer

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A novel FBAR-on-Diaphragm sensor-head structure for the FBAR-based electro-acoustic resonant micro-accelerometer is presented. It overcomes disadvantages in the FBAR-beam structure for its limited cantilever beam thickness, and those in the embedded-FBAR structure for its complex micro-fabrication process. Its elastic diaphragm is made of silicon dioxide (SiO₂) / silicon nitride (Si₃N₄) bilayer film, which is not only more susceptible to the IC compatible integration process for the Si-based microstructure and the FBAR, but also benefits improving sensitivity and temperature stability of the FBAR accelerometer. By preliminary performance analysis on the FBAR-on-Diaphragm type FBAR accelerometer that integrates the acceleration sensing structure, i.e. the SiO₂/Si₃N₄ bilayer diaphragm and the Si proof-mass, with the AlN FBAR electro-acoustic transducer, the feasibility of the FBAR-on-Diaphragm structure is verified. Through the finite element modal analysis and static simulation, modal frequencies of the FBAR-on-Diaphragm structure and stress distribution of the diaphragm under 0-100g acceleration loads are obtained. Then the calculated maximum stress is applied to the piezoelectric film in FBAR for qualitative analysis, and combined with the dependency of elastic coefficient on stress in the Wurtzite AlN film calculated with the first-principle method, the maximum elastic coefficient variation in the Wurtzite AlN film under different acceleration load can be roughly predicted. With the help of the RF simulation software ADS, by changing the longitudinal wave velocity corresponding to the elastic constants with variant acceleration loads, and comparing the resulted resonant frequencies of the sensor head without and with different acceleration loads, its frequency shift and sensitivity can be qualitatively characterized. Further analysis of the simulation results also reveals that: the first-order modal frequency of the SiO₂/Si₃N₄ circular

diaphragm is quite far away from the higher ones, which means less cross modal coupling; under the acceleration load, its resonant frequency will up-shift with the sensitivity of several KHz/g, and with a quite linear acceleration - frequency shift characteristic.

9517-12, Session 3
Complexity in multimode dynamics of self-excited optomechanical resonators

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Self-excited oscillations of thermo-visco-elastic resonators that are subject to continuous wave (CW) laser irradiation, have been studied experimentally for macro, micro, and nano configurations for over two decades, and have been identified in multiple-length scale applications, including quantum information sensors and atomic force microscopy. Furthermore, periodic multimode interactions between the first and second modes of an irradiated cantilever have been documented in the recent decade. However, the experimentally documented modal energy transfer has not been explained analytically or numerically. Moreover, unlike similar cantilever structures which exhibit modal energy transfer between the second and third modes due to an externally excited 3:1 internal resonance, there have been no measurements of third mode interactions in any of the experiments reported to-date. Thus, the motivation of this research is to identify the mechanism that governs the onset of self-excited multimode dynamics and to analyze the complexity of the resulting bifurcation structure.

In order to resolve the spatio-temporal complexity of the thermo-elastic system response near primary, secondary and internal resonances, we formulate an initial-boundary-value problem for the optomechanical cavity that consistently includes both nonlinear elastic and thermal fields influenced by a highly nonlinear heat generation function. We determine the coupled thermo-elastic field basis functions and construct a ninth-order nonlinear modal dynamical system for experimental conditions defined by Hane and Suzuki in 1995. Stability analysis of the thermo-elastic dynamical system equilibrium reveals existence of a complex bifurcation structure which includes coexisting bi-stable solutions and flutter thresholds that correspond to saddle-node and Hopf bifurcations, respectively. A numerical analysis reveals coupled modal interactions culminating with both periodic and quasiperiodic energy transfers. We note that regions of coexisting equilibrium solutions exhibit chaotic-like dynamics reminiscent of a global homoclinic bifurcation.

9517-13, Session 3
Influence of electrode materials and thicknesses on AlN Lamb wave resonator characteristics

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Aluminum Nitride (AlN) Lamb wave resonators utilizing the lowest-order symmetric (S₀) mode have drawn intensive attention recently, since they can simultaneously solve the high motional resistance (R_m) issue faced by the electrostatic resonators, the low frequency limitation faced by the surface acoustic wave (SAW) resonators, and the multiple frequency capability problem faced by the film bulk acoustic resonators (FBARs). While the effect of the electrode material and design has been widely studied for the SAWs and FBARs, few research have been done for the Lamb wave resonators. This study adopts the Alder's matrix approach and finite element analysis (FEA) to investigate the influence of electrodes on the dispersive characteristics of the S₀ mode propagating in the multi-membranes. The effects of electrodes configurations, AlN film thicknesses, electrode materials and electrodes thicknesses on the performance of Lamb wave resonators are also explored.

The results obtained in this study show that thicker AlN film is preferred when single interdigital transducer (IDT) configuration is adopted and thinner AlN is favorable when a bottom electrode is applied for a large

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electromechanical coupling coefficient (k_2). The effect of electrode materials on the k_2 is different for these two electrode configurations. For example, Aluminum (Al) offers a relatively low v for the single-IDT configuration but a high k_2 when there is a bottom electrode. On the contrary, Platinum (Pt) enlarges the k_2 for the single-IDT topology but not with a bottom electrode. The characteristics of Lamb wave resonators also depend on the thickness of the top. Specifically, an increase in electrode thickness reduces k_2 for Al, but for Pt the optimized thickness is around 0.02λ . The effects of the type of top-electrode material and AlN film thickness on the k_{2eff} and quality factor (Q) of the fabricated Lamb wave resonators are also discussed.

9517-29, Session 3

Experimental investigation of creep in gold RF-MEMS microstructures

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The study of creep in MEMS is crucial for their lifetime prediction and reliability evaluation. The experimental approaches used in macromechanics can be extended to the microscale if their effectiveness is proved by dedicated experiments. This goal may provide more general validity of creep effects prediction in MEMS, instead of spotted experiments on single devices like those ones reported in most of the work presented in literature. The demonstration of the validity of some established creep models and experimental methodologies also in the micromechanics is the goal of this paper.

Novelty / Progress Claim(s)

Many applications, as RF, involve material heating and reliability issues related to permanent plastic deformations. This paper reports the results of experimental investigation of creep behavior in gold thin films based microbridge specimens, resembling the typical configuration of the microbridge RF-MEMS switch. Differently from earlier experiments in literature, this study is not limited to single specific devices but aims to characterize the effect of creep in gold metal MEMS with general validity, as function of temperature and time.

Background / State of the Art

Highly conductive metal thin films of Al, Ni, Au and Pt have been widely used in RF MEMS for better electrical performance. However, decreased thin film thickness and fabrication techniques including sputter deposition, electrodeposition and evaporation result in the considerable difference of the electrical (conductivity, resistivity), mechanical (intrinsic stress, elasticity, ductility, adhesion) and thermal (expansion coefficient, thermal conductivity, melting point) properties from that of bulk sample of the same material. The performance and the life of the metal structure layer based RF MEMS is significantly affected by the temperature induced plastic deformation. The effect of the creep was originally observed in digital micromirror devices (DMD) made of Al [1]. Some of the significant initial experimental investigations of the creep phenomenon in MEMS are presented in [2-6].

Experimental setup and test specimens

The specimens used for the experimental investigation of the creep phenomenon in gold thin films were fabricated through the gold electrodeposition process, referred as RF Switch Surface Micromachining (RFS) process. The schematic of the electrostatically actuated microbridge specimen, used in this study, will be shown along the paper the optical image and the 3D profile of one of the specimen. This particular shape with the lateral supports allows an out-of-plane deflection when a bias voltage is applied between the central plate and the bottom polysilicon electrode. The specimen dimensions were designed to be reasonably close to some of the RF-MEMS devices developed using the same fabrication process. The actual dimensions of the specimen are measured optically by the interferometer microscope ZoomSurf3D Fogale profiling system. The temperature of samples is increased by means of a Peltier cell; a temperature sensor is used to provide the temperature feedback signal. The vertical displacement of the central plate and supporting beams with respect to the initial position is monitored, at fixed time intervals using the optical profilometer, to measure the creep strain in the specimens at the specific testing conditions.

Experimental results

The behavior of different specimens snapped down after several hours will be shown. The plausible reason for this difference is sequential heating of different specimens on the same die. To avoid the size and sequential heating effect on the creep results, a repeatability tests is carried out. The creep behavior is studied for the three specimens with the same dimensions and test conditions but on the separate dies. The comparison of the pull-in voltage and resonance frequency for the three specimens before and after the creep tests.

References

- [1] M.R. Douglass, proc. of 36th IEEE Int. Reliab. Physics Symp., Reno, USA, 1998.
- [2] A. Somà et al., proc. Symp. on Design, Test, Integration and Packaging of MEMS/MOEMS, DTIP 2014, pp. 13-16, Cannes, France, 2-4 April 2014.
- [3] R. Modlinski et al., Microelectron. Eng., vol. 76, pp. 272-278, 2004.
- [4] K. Tuck et al., Journal of engineering materials and technology 127,vol. 1 pp. 90-96, 2005.
- [5] M. Van Gils et al., EuroSime Int. Conf. on Thermal, Mechanical and Multi-Physics Simul. Experiments in Microelectronics and Micro-Systems, 2007.
- [6] X. Yan, et al., Journal of Microelectromechanical Systems, vol. 18(3), pp. 570-576, 2009.

9517-14, Session 4

The next generation of MEMS-based optical microspectrometers (Invited Paper)

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Presently available MEMS-based microspectrometers are typically composed of MEMS devices for operation as dispersive element or as tunable resonator within an optical system that also includes collimating optics, detector and, in some applications, an excitation light source. The potential for functional integration of the MEMS part with the detector is not yet fully exploited and remains limited to systems that operate in the visible part of the spectrum, due to the preferred use of the mature technology for fabrication of CMOS photon detectors. Applications are usually in general-purpose spectroscopy in the visible spectral range with limited spectral resolution (several nm over a band of several hundred nm), but the highly interesting application for gas absorption spectroscopy in the mid-IR spectral range is also at the point of commercialization. Another, very promising, class of microspectrometers is based on waveguide optics and has the dispersive element and some of the optics integrated in the waveguide.

The next generation of microspectrometers is expected to fully exploit the benefits of functional integration of MEMS structure, optics and detector (array). Applications will be increasingly demand operation outside the visible spectral range and is likely to include two main categories: the first in which moderate optical specifications are required, while low-costs are paramount. The second category of upcoming applications is more demanding with respect to the optical specifications. The medical application of the microspectrometer as a point-of-care diagnostic instrument is very promising.

The actual exploitation of the functional integration of the entire microspectrometer with all its core components within one functional unit (the IC-compatible package or –even more challenging – the chip) imposes several challenges. The state-of-the-art and some of the technology challenges will be outlined, followed by an introduction to some of the upcoming application of high potential.

9517-15, Session 4

Input-shaped actuation of electromagnetic MEMS mirrors

Jörg Reitterer, Franz Fidler, Gerhard Schmid, TriLite

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For many applications of micro-electro-mechanical system (MEMS) actuators a well-defined trajectory of the movable device component is crucial. In general these structures are actuated using an open-loop control to either statically drive the devices to a desired position or to achieve a prescribed dynamic movement. The implementation of closed-loop control techniques for MEMS devices is usually difficult and prohibitively expensive. A driving application for the MEMS technology are laser scanners, e.g. laser light modules with integrated MEMS mirrors for autostereoscopic outdoor displays, where a high linearity of the optical scanning angle as a function of time is required.

For the design of an open-loop controller for the static or quasi-static actuation of MEMS structures it is important to carefully choose the electrical actuation signals in order not to induce any vibrations in the movement due to the undesired excitation of resonant modes. A widely used open-loop control technique is "input-shaping", which has been adopted to a large number of systems at the macro-scale. In this paper we apply this technique to quasi-statically actuated electromagnetic MEMS mirrors.

We derive the impulse response of the input-shaping filter and present simulation and measurement results of the vibration-free linear MEMS mirror movement. We compare different input-shaping filter types in terms of the input-shaped MEMS mirror actuation signals and the resulting mechanical movement of the structure. Employing the zero vibration (ZV) filter, the residual vibrations can be completely suppressed if the system parameters (i.e. resonance frequency and quality factor) are known. The zero vibration derivative (ZVD) and extra insensitive (EI) filters increase the robustness with respect to errors in the estimation of the system parameters. The robustness of these filter types is analyzed while taking into account modeling errors of the structure-related resonance frequency.

9517-16, Session 4
2D stepping microdrive for hyperspectral imaging

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The analysis of hyperspectral information, i.e. means a space-resolved spectral information, has a wide range of applications, e.g. from astronomy to medical analysis methods. Based on the concept of confocal microscopy a hyperspectral imaging system for the visible spectral range [1] was developed for acquiring a full spatial image. The spectral bands are filtered with a combination of an actuated pinhole filter (a matrix of circular apertures), a tunable hyperchromatic lens and a monochrome CCD. The pinhole filter is scanned across an intermediate image plane to capture the full object plane. In this paper a two-axis stepping microdrive is presented for the pinhole filter positioning, featuring a 10 μm step size and a 200 μm displacement range in each direction. The fabricated device is integrated in the confocal chromatic hyperspectral imaging system. With the two-axis stepwise actuation of the pinhole filter, the imaged area of the object plane is increased from 7% (fixed pinhole array) up to 89% with actuated array. The two-axis positioning is implemented with a three-axis inchworm motion driven by electrostatic forces. A combination of horizontal and vertical electrostatic actuators are arranged to achieve a precise in-plane actuation of the pinhole filter. The microdrive is fabricated with established MEMS technologies and features a size about 1 cm^2 with 1 mm thickness. The microdrive is capable of discrete positioning of the 20 mg, 6x7.5x0.2 mm^2 pinhole filter over the displacement range. The filter size enables a 1:1 optical imaging on a Sony ICX415AL CCD. The presented stepping microdrive outperforms existing microsystem solutions such as [2] with a combination of high payload, large step size, displacement range, and the large optical aperture. Furthermore, the device concept enables the positioning of milligram weights with a highly integrated microsystem of other optical elements e.g. of angular band-pass filters [3].

[1] A. Grewe, C. Endrödy, R. Fütterer, P.-H. Cu-Nguyen, S. Steiner, M. Hillenbrand, M. Correns, M. Hoffmann, G. Linß, H.Zappe, A.Seifert, E. B. Kley, S. Sinzinger, Microsystems Technology in Germany, ISSN 21917183, 52-53, 2014.

[2] K. Laszczyk, S. Bargiel, C. Gorecki, J. Krežel, P. Dziuban, M. Kujawińska, D. Callet, S. Frank, Sensors and Actuators A: Physical, vol. 163 (1), 255-265, 2010, DOI: 10.1016/j.sna.2010.06.020

[3] S. Steiner, S. Kroker, T. Käsebier, E.-B. Kley, A. Tünnermann, Opt. Express, vol. 20 (20), 22555-22562, 2012.

9517-17, Session 4
Design and fabrication of an endomicroscopic imaging module for minimally invasive medical devices

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The performance of minimally invasive devices for medical inspection (used in ophthalmology and endoscopy) could be significantly improved by an endomicroscopic imaging module (ENIM), which can be considered a highly miniaturized digital microscope used to in-vivo tissue microscopy in real-time. A classic example is the magnification provided by the (large) conventional endoscope that allows the recognition of the affected mucosa with higher precision as compared to normal endoscopic inspection and enables the differentiation of affected tissue from healthy surroundings. Therefore, an ENIM that can be integrated in very small medical devices as optical tools for ophthalmologic diagnostic and endoscopic capsules will be a tremendous breakthrough.

The ENIM is composed of three commercially available microlenses plus an especially microfabricated 200 μm thick PDMS lens, limiting the total length of the optical system to about 11 mm plus 4 mm for the lateral lens assembly (suitable to include in a 30 mm x 11 mm cylindrical medical device). A side-view arrangement, perpendicular to the object, was designed for allowing close proximity to the tissue. This configuration was assembled with a mirror placed after the lens to fold the light beam onto the imaging sensor. The height, radius of curvature and focal length of the PDMS lens can be changed by design and were selected to meet the specified system performance, which is set by the imaging requirements. The material was chosen for its optical properties, especially its optical transparency in the visible spectral range. The fabrication process was based in a hanging droplet approach, which is a very low-cost and effective method for obtaining lens with the desired properties. Several analyses were performed showing good performance of the lens system: a paraxial magnification of 14 times was achieved with a Modulation Transfer Function (MTF) around 37% at 50 lp/mm and maximum distortion about 1.83%.

9517-18, Session 5
Acoustic high-frequency effects inside the package of capacitive silicon microphones and their impact on the device performance

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We present investigations on acoustic effects occurring inside the sound port of capacitive silicon microphones exerting additional frequency-dependent damping forces on the sensing membrane and, finally, affecting the overall performance of the microphone. Extensive FE simulations have been carried out in order to investigate the airflow inside the package, to identify relevant impact factors and to optimize an existing acoustic network model intended for implementation in a fully coupled, multi-energy domain system-level model of the device.

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An on-purpose developed mounting allows for the emulation and characterization of varying sound port dimensions and, thus, for the evaluation of the proposed models.

The geometrical shape of the sound port suggests the use of a simple analytical Helmholtz resonator model as a first approximation. However, comparisons to detailed fluidic FE simulations revealed that this approach cannot properly describe the real situation, since the geometrical dimensions deviate substantially from the assumptions made in the analytical approximation. Furthermore, the results indicate the presence of high-frequency effects for the considered device geometries within the relevant frequency range: the so-called annular effect shifts the maximum of the velocity distribution to the walls of the sound port (similar to the skin effect in electromagnetic wave propagation), which increases the friction. Thermal and fluidic relaxation effects cause additional losses at higher acoustic frequencies, which cannot be predicted by the simple Helmholtz resonator model alone.

Instead, we propose an alternative model, which includes these effects by introducing additional elements (frequency-dependent impedances) in the acoustic network. The transfer characteristics obtained with this model show a significant improvement compared to the simple Helmholtz model. The implementation in the system-level model of the microphone is focus of ongoing work; detailed results and comparison to measurements will be presented at the conference and in the extended version of this abstract.

9517-20, Session 5

Optimization method for designing multimodal piezoelectric MEMS energy harvesters

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Piezoelectric Energy Harvesters (EH) extract energy from mechanical vibrations using a piezoelectric material, typically placed onto a mechanical resonator. The intrinsic drawback of this solution is the narrow bandwidth of the device. To overcome this limitation it is possible to tune the mechanical resonance of the device, to introduce non-linear elements (e.g. magnets) or to design the mechanical resonator with a multimodal behavior. In Ultra Low Power (ULP) applications the aspect of integration is of paramount importance and so MEMS-based (micro electro-mechanical systems) EH are preferable. Within this scenario the multimodal solution is the more suitable considering the technological constrains implicit into the micro machined fabrication process.

A multimodal energy harvester can be approximated with multiple couple spring-mass. Depending on how those elements are connected together, the mechanical response of the whole device presents several resonant frequencies, at least one for each mass-spring couple. In order to optimize the device, more resonant peaks should lie in the desired frequency bandwidth. Furthermore, in order to achieve the best performances also the geometry of the piezoelectric material has to be designed according to the shape of the exploited resonant mode. In a multimodal device where more than one mode is exploited, a trade-off between geometrical complexity and performance has to be found.

In this paper we face both problems of designing the multimodal mechanical resonator and the piezoelectric electrodes, aiming to the optimization of a multimodal EH design. The presented optimization procedure is divided in two steps. The first one is a FEM-based mechanical optimization, while the second step focuses on the geometry optimization of the piezoelectric transducer element, starting from the desired resonant mode configuration defined in the first stage.

Initial results show clearly how an optimization of the geometry could significantly boost the performance of such devices.

9517-21, Session 5

Scaling effects for piezoelectric energy harvesters

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This paper presents a fundamental investigation into the scaling effects of the mechanical properties (natural frequency and frequency tunability) and the electrical output power of piezoelectric vibration energy harvesters. The energy harvester structure analysed is based upon a cantilever, which is typical of most vibration energy harvesters. Assuming that the energy harvester is scaled by a factor a (the structure is scaled up when $a > 1$ and the structure is scaled down when $0 < a < 1$), its resonant frequency becomes $1/a$ of the original harvester. Resonant frequency of a cantilever structure can be achieved by applying an axial force. The compressive force required to buckle the cantilever reduces and the tuning range under a tensile force increases as the structure is scaled down. If the scaled harvester is excited by the same vibration acceleration as the unscaled harvester and assuming the same substrate and piezoelectric materials are used, the output power of the scaled harvester at resonance becomes a^5 times that of the original energy harvester. If the scaled harvester is excited under the same vibration displacement as the unscaled harvester, the output power of the scaled piezoelectric energy harvester at resonance is a times that of the original energy harvester. In addition to the scaling effect caused by the physical size of the energy harvesters, the properties of the piezoelectric materials, such as Young's modulus, piezoelectric coefficients and dielectric constants, also affects performance of the piezoelectric energy harvesters. It is found that the energy harvester with PZT Type 5A has the highest output power among all and the harvester with ZnO has the highest output power among all MEMS scaled harvester. The simulation results also show that ZnO has the highest coupling factor among all piezoelectric materials.

9517-50, Session 5

Assessment of MEMS energy harvester for medical applications

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Energy harvesting as a way of obtaining usable electrical energy from ambient sources represents a promising opportunity for development of an autonomous power supply for the new generation of low-power medical devices. Micro-electro-mechanical harvesters could be used for gathering the ambient energy from human body movement to provide electrical power for small electronic and electrical devices, making them self-sufficient and battery-independent.

This paper assesses use of an energy harvesting principle for developing an autonomous power supply unit for a new generation of biomedical devices, e.g. artificial cochlear implant. Proposed system must be small and lightweight enough to be fully implantable in the head area of the user, yet it has to provide adequate energy levels to ensure powering-up the implant without the need for additional batteries.

Requirements for the harvester are set based on research of power supply demands of state-of-art medical devices. Acceleration is then measured in the area of human head to help assessing the feasibility of a device exploiting the ambient kinetic energy for energy harvesting. In the next step, possible methods of energy conversion are reviewed. Mathematical model of generic energy harvesting device is developed in Matlab environment to evaluate the theoretical obtainable power output of proposed MEMS sized harvester. Since placing the harvester in the human tissues could considerably change the mechanical properties of the body, an influence of implanting the device into the user's head on the mechanical response of the human body, and therefore on the output of the device itself is discussed. Optimization process based on modelling is proposed to tune the device's parameters for maximizing its power output. Lastly, the feasibility of developing an actual power supply unit is evaluated and possible course of follow-up research is outlined based on simulation and measurement results.

9517-41, Session PSTue

An active reference spring array for in-situ calibration of the normal spring constant of AFM cantilevers

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Atomic force microscopes (AFM) have long been one of the indispensable tools in the field of nano-technology, due to their outstanding spatial resolution, especially in lateral direction. Besides their tremendous applications for the determination of the topography of an object, in the past more than twenty years AFM have found more and more applications in the field of nanomechanical characterization of micro- and nanomaterials, including ultra-thin metallic films, polymer coatings, micro-organisms and living cells. All these applications depend, to a great extent, on the mechanical performance of the used cantilevers.

The calibration of the mechanical properties of an AFM cantilever has therefore gained more and more interest in the past years, leading to several new calibration methods for the normal stiffness. On basis of a newly developed MEMS nano-force transducer with a force resolution down to \sim nN and a displacement resolution better than 20 pm/Hz^{1/2}, recently an "active reference spring (ARS)" [1] approach has been developed in PTB to quantitatively determine the normal spring constant of AFM cantilevers. In the approach, the nano-force transducer is located underneath the cantilever tip and then driven to quasi-statically bend the cantilever to be calibrated. The driving voltage of the MEMS actuator and the MEMS deflection signal are measured simultaneously. The cantilever stiffness can then be determined directly from the measured force-deflection curve of the MEMS and from the known stiffness of the MEMS.

The ARS approach is only applicable for cantilevers which have similar stiffness than the MEMS. To further extend the capability of the cantilever calibration approach, in this manuscript, the concept of an "active reference spring array (ARSA)" for the AFM cantilever normal spring constant calibration is proposed. MEMS with stiffnesses varying from 0.5 N/m to 100 N/m will be available on these arrays. The realization of this concept is presented in this paper.

The experimental investigation of the MEMS ARSA on basis of the Bonding-DRIE technology developed at TU Chemnitz [2], is reported, including interferometric characterization of the in-plane displacement sensing system of the MEMS and traceable determination of the stiffness of the MEMS suspending system. Preliminary experimental results coincide well with the Finite Element (FE) simulation of the numerical design, and prove the feasibility of the proposed concept.

Reference

[1] S. Gao, et al, "Towards quantitative determination of the spring constant of a scanning force microscope cantilever with a microelectromechanical nano-force actuator", 2010 Meas. Sci. Technol. 21, 015103

[2] Hiller K et al, "Bonding and deep RIE—a powerful combination of high aspect ratio sensors and actuators" Proc. SPIE 5715, 80–9, 2005

9517-42, Session PSTue

Noise spectroscopy of nano- and microscopic periodic material structures

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The authors discuss the application of a broadband noise signal in the research of periodic structures and present the basic testing related to the described problem. Generally, noise spectroscopy tests are carried out to verify the behaviour of the response of periodic structures, and the related objective consists in recording the properties of microscopic structures in natural and artificial materials. The aim is to find a

metrological method utilizable for the investigation of structures and materials in the frequency range between 100 MHz and 10 GHz; this paper therefore characterizes the design of a suitable measuring technique based on noise spectroscopy and introduces the first tests conducted on a periodic structure. In this context, the applied equipment is also shown to complement the underlying theoretical analysis.

9517-43, Session PSTue

Novel Ge nanowire-based gas sensor fabricated by localized growth on microhotplates

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Nanowires are interesting candidates for their incorporation into future low power sensing devices thanks to their large surface-to-volume ratio and to the possibility of growing them monocrystalline and almost defect-free, which gives rise to controlled and reproducible properties. This can be seen as the result of the very extensive research which has been carried out in the field of metal oxide gas sensors of the last 20 years.

In this work we will present the results of our research in developing gas detection systems based on individual nanowires using the self-heating methodology. For this we have fabricated nanosensors using single metal oxide nanowires by employing advanced nanofabrication tools and ad-hoc designed suspended microhotplates, containing both interdigitated electrodes and integrated heater. We have designed an electronic board that allows the control of the heating power and, simultaneously, the readout of the sensors resistance, which varies in the presence of different gases. The results show that few microwatt are required for the whole process, from which the sensor itself consumes below 1 microWatt. This has allowed the use of energy harvesting techniques to power the whole system.

The behaviour of the gas sensing system will be reported and critical discussion on the further improvements will be provided.

9517-44, Session PSTue

High temperature stability of Sc_xAl_{1-x}N (x=0.27) thin films

Patrick M. Mayrhofer, Achim Bittner, Ulrich Schmid, Technische Univ. Wien (Austria)

Piezoelectric thin films based on aluminum nitride (AlN) are implemented into a large variety of Si-based micro- electromechanical systems (MEMS) for actuation or sensing purposes. Recently, it was found that doping of AlN with scandium results in a significant increase of the piezoelectric constants. A scandium concentration of x=42% was reported earlier to yield an increase of the piezoelectric modulus d₃₃ of 400% from its initial value of about 5 pm/V for pure AlN up to 27.6 pm/V.

For this work Sc_xAl_{1-x}N thin films with a Sc concentration of x=27% have been deposited by DC reactive magnetron sputtering with a thickness of 500 nm. Corresponding to the Ar/N₂ ratio used in the sputtering gas, films with a high degree or with a lower degree of c-axis orientation are prepared. This is demonstrated by X-ray diffraction (XRD) analyses, depicted in Figure 1. The full width half maximum of the AlScN(002) peak indicates the best orientation of thin films prepared at a given Ar/N₂ ratio of 25%, as shown in Figure 2. Even without the admixture of Ar the AlScN(100) peak is present.

The crystalline quality of samples with initially poor c-axis orientation improves after thermal annealing, as demonstrated by the XRD analyses (see Figures 1 and 2). This is supported by measurements of the piezoelectric constant d₃₃, depicted in Figure 4. The piezoelectric constant of both thin films deposited under non-ideal deposition conditions increased drastically close to the value that corresponds to the

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thin film with highest crystalline quality, i.e. $d_{33}=13.2$ pm/V.

Furthermore, the thermal stability of ScxAl_{1-x}N thin films with mixed crystalline quality was investigated up to 1000°C under vacuum conditions in a thermal effusion measurement setup where a mass spectrometer continuously records the partial pressure of elements. Figure 5 shows the N₂-partial pressure during the annealing processes of three ScxAl_{1-x}N samples in comparison to a pure silicon substrate. No decomposition of ScxAl_{1-x}N up to 1000°C was observed indicated by a substantial increase of the N₂ partial pressure.

9517-45, Session PSTue
Nanopatterning of titanium oxide thin films using inductively coupled plasma for gas detection

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Titanium oxide thin films were deposited at room temperature by reactive magnetron sputtering in a mixture of oxygen and argon on oxidized silicon substrates. First, TiO₂ nanostructured surfaces were defined by direct write EB lithography. EB exposures have been done using the scanning electron microscope Inspect F50 (FEI) equipped with a control system for nanolithography (Elphy Quantum, Raith). The layers of SU-8 2002 resist with a thickness of 500 nm were deposited on a TiO₂ thin film by spin coating. Dry etching through both of the nanomasks was performed in a Vacutec 310/320 reactor utilizing a planar inductively coupled plasma source operated at 2.4 MHz and separate RF (13.56 MHz) biasing of the sample electrode. TiO₂ thin films were etched in CF₄/Ar plasma with variable process parameters. The optimal etching characteristics of TiO₂ films by an inductively coupled plasma system were investigated. The maximum etch rate of TiO₂ was 104 nm/min at fixed 200 W of ICP power and the highest investigated value of RF chuck power of 150 W. Experimental results showed that the exposure dose optimization was a significant parameter for controlling the tip size and its shape. It was found that our developed ICP etching process was able to fabricate TiO₂ tip arrays with a minimal diameter less than 100 nm, when the etching time about 3 min. Nanopatterned TiO₂ thin films were examined for gas detection.

9517-46, Session PSTue
Impact of titanium layer and silicon substrate properties on the microstructure of c-axis oriented AlN thin films

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Aluminium nitride (AlN) is widely used as active piezoelectric layer in a large variety of MEMS sensors and actuators [1]. Most recently, MEMS based resonators are proposed using AlN for self-actuation and self-sensing purposes [2]. The deposition and patterning of the AlN is highly challenging to achieve structured highly c-axis orientated AlN thin films.

In this work we investigate the wet chemical etching performance of highly c-axis oriented AlN layers deposited on titanium (Ti) sub-layers and on pure silicon (Si) substrates. A significant higher surface roughness of AlN layers deposited onto Ti ($R_{rms,Ti}=4.45$ nm) compared to Si ($R_{rms,Si}=0.473$ nm) is observed, as shown in Fig. 1 recorded with an AFM in tapping mode. XRD analyses indicate in all layers a high c-axis orientated wurtzite structure with no other crystallographic orientations than the (002) peak with low values for the FWHM (full width half maximum) comparable to those reported in [3] (see Fig. 2). To evaluate the piezoelectric response of the AlN layers on different substrates, measurements with a commercially available Piezometer are performed. The absolute piezoelectric coefficients $|d_{33,eff}|$ are in the range of 5.2 - 6.0 pC/N and 0.4 - 0.7 pC/N (for depicted samples) when

using monocrystalline Si or sputtered Ti as underlying materials. Prior to the etching process in an 80 °C hot aluminium etch mixture, SEM characterisation of the AlN layers is done. Whereas cross sections of the AlN thin films show a columnar film structure in both cases (see Fig. 3), the surface morphology appears different. While AlN on Si shows a fine grained, almost featureless microstructure, AlN thin films deposited onto Ti sub-layers consist of coarser grains embedded in a matrix of finer grains, as shown in Fig 4.

After wet chemically etching, a porous, but homogeneous AlN microstructure is observed at these samples synthesized on Ti layers (see Fig. 5 a-c), whereas on Si the film is either etched very inhomogeneous (see Fig. 5 d-e) or nearly completely besides some pyramidal residues (see Fig. 5 f). In the final paper we will correlate piezoelectric properties with the microstructure of the different films.

(1. Tadigadapa, S. and K. Mateti, Piezoelectric MEMS sensors: state-of-the-art and perspectives. Measurement Science and Technology, 2009. 20(9): p. 092001.

2. Kucera, M., et al., Q-factor enhancement for self-actuated self-sensing piezoelectric MEMS resonators applying a lock-in driven feedback loop. Journal of Micromechanics and Microengineering, 2013. 23(8): p. 085009.

3. Ababneh, A., et al., c-axis orientation and piezoelectric coefficients of AlN thin films sputter-deposited on titanium bottom electrodes. Applied Surface Science, 2012. 259(October 2012): p. 59-65.)

9517-47, Session PSTue
Nonlinear numerical modelling and experimental validation of multilayer piezoelectric vibration energy scavengers

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Scavenging of low-level ambient vibrations i.e. the conversion of kinetic into electric energy, has been proven as effective means of powering low consumption electronic devices such as wireless sensor nodes. Cantilever based scavengers are thoroughly investigated since they are characterised by low eigenfrequencies tunable by the selection of the dimensions and of the tip mass, high energy densities per device volume, simple MEMS integration and linear coupling of mechanical and electrical domains. Analytical models which employ a distributed parameter approach, Euler-Bernoulli beam theory and eigenvalue analysis have been developed and experimentally verified. Finite element models (FEM) have also been proposed employing different modelling approaches and commercial software with coupled analysis capabilities.

A conventional approach of using a FEM analysis of a simple piezoelectric cantilever bimorph under harmonic base excitation is used first in this work. Modal, harmonic and nonlinear transient analyses are thus performed. Different dynamic effects are observed and then compared to the results obtained by using a distributed parameter model implemented in MATLAB®. A comparison of the influence of two different types of finite elements and three different mesh densities types is also investigated. In the second part of the work, a complex bimorph cantilever, based on commercially available energy scavengers, is considered. These scavengers are characterised by an intricate multilayer structure not investigated so far in literature. In fact, instead of the three layers found in conventional piezoelectric bimorphs, these devices consist of 7 layers.

An experimental set-up is developed next to evaluate the behaviour of the considered class of devices. The results of the modal and the harmonic FEM analyses of the behaviour of the multilayer scavengers are verified experimentally for three different tip mass values and 12 different electrical resistances. A satisfying agreement between the numerical and the experimental results is achieved.

9517-48, Session PSTue

Relaxation phenomena in nematic liquid crystals with multiwall carbon nanotubes adding

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Relaxation phenomena in nematic liquid crystals with multiwalled carbon nanotubes additions can be very useful for the evaluation of the relaxation times of any type of CL-microparticles mixtures or the anchoring energy of the nematic molecules to these nanoparticles.

A theoretical and experimental study about the effects of a magnetic field in a nematic liquid crystal doped with carbon nanotubes is presented. Planar oriented cells filled with 5CB nematic and multi-walled carbon nanotubes mixtures (various mass concentrations) were subjected to a magnetic field higher than the critical one for the magnetic Freedericksz transition. A laser beam was used to observe the molecular director oscillations. Dynamical measurements of the transmitted light intensity were performed when the magnetic field was switched on and off. The results were used to evaluate the relaxation times (ton and toff). We have also developed a theoretical model to explain these mixtures behavior in magnetic field and the results are in good agreement with experimental data.

9517-49, Session PSTue

Efficiency of electromagnetic vibration energy harvesting system

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This paper deals with the efficiency calculation of an electromagnetic vibration energy harvesting system. This system uses ambient energy of mechanical vibrations for harvesting of energy and the efficiency of this system will be defined, measured, calculated in this paper. The energy harvester is usually a key element of the whole energy harvesting system. Nowadays energy harvesting technologies are used in varied engineering's applications and the efficiency of energy harvesting systems is still improved. It can be used as power supply for ultra- low power electronics.

The impact of vibration energy harvesting systems has limitations in a resonance operation and level of used mechanical vibrations. However the efficiency improvement could be useful for the wider using vibration energy harvesting systems in applications with lower level of vibrations.

The fundamental part of the vibration energy harvester is a resonance mechanism. This mechanism is based on spring suspension of a moving seismic mass. This resonance mechanism is excited by ambient mechanical vibrations and it provides relative movement of mass a magnetic circuit against a fixed coil. This movement induced voltage due to Faraday's law and the output power is observed on an electrical load.

The harvested output power depends on a level and frequency of excited vibration, moving seismic mass and connected electrical load. The harvested output power is observed on the electrical load. The input mechanical power is defined as product of the mechanical force in a harvester mounting place and velocity of vibrations.

A developed electromagnetic vibration energy harvester is used for efficiency measurement and the simulation model is verified on the base of the measured results. The effect of individual harvester parameters will be observed and described in this paper with aim to improving design for higher harvested output power with the same volume and weight.

9517-51, Session PSTue

Finite element analysis of AlGaIn/GaN micro-diaphragms with diamond coating

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The III-Nitrides are very attractive for pressure sensing applications due to their excellent piezoelectric properties. Compared to the other common piezoelectric materials, they offer important advantages such as high mechanical and chemical stability, biocompatibility, and possibility to be operated at elevated temperatures. Previously we introduced the AlGaIn/GaN MEMS pressure sensor with integrated circular high electron mobility transistor (C HEMT). This concept used the C HEMT as a vertical ring gate capacitor to sense the changes in the piezoelectric charge induced by the external loading of the diaphragm. The sensor function was evaluated at small static pressure. For the purpose of extreme conditions (e.g. high pressure, elevated temperature), the sensing diaphragm needs to be modified. The deep reactive ion etching (DRIE) process was used to create the suspended AlGaIn/GaN diaphragms on silicon (Si) substrate. The diamond coating might be the solution for the high temperature device and can be deposited onto the bottom surface of the diaphragm after the last manufacturing step. Thanks to the unique mechanical properties of the diamond, the behavior of the diaphragm is improved. The total thickness of the diaphragm is increased what results in the strengthening of such a structure. Modified sensor better prevents the effect known as thermal buckling of the diaphragm. In this work, we present the modified finite element model provided the extended operation temperature range compared to our previously used AlGaIn/GaN diaphragm-based sensors. Further, the finite element analysis of several types of our MEMS pressure sensor is performed. Various material compositions (AlGaIn/GaN with/without Si or diamond) of the sensor diaphragm are investigated and the effect of used material on the behavior of diaphragm is examined.

9517-52, Session PSTue

In-liquid characterization of high order out-of-plane modes in piezoelectric square plates

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Nowadays there is an increasing interest in the use of vibrating MEMS structures in many different fields, such as automotive industry, biology or blood analysis[1]. In all these applications, the device might be immersed in high viscous fluids and its vibration is hindered mainly by the hydrodynamic loading. The use of in-plane modes of vibration, for efficient performance in such applications, is already well established[2]. Despite that, high order out-of-plane modes have recently revealed their suitability for liquid media applications, due to a high quality factor and low resonant frequency[3].

In this work, different square plates, anchored at the four corners, were designed, fabricated and characterized in order to study the in-liquid behaviour of high order out-of-plane modes. The structures integrated an AlN piezoelectric film, which allowed an all-electrical actuating/sensing scheme and a specially designed top electrode layout, which maximized the response of the target mode[4] (fig. 1). The use of an optimal electrode configuration is crucial for the detection of these very

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complex modes, where a fully covering electrode might fail due to charge distribution symmetries.

Among all the studied modes, the degenerate out-of-plane modes, which come from the superposition of two orthogonal modes in rectangular plates[5] (fig. 2), showed the best quality factor in the experimental characterization, reaching quality factors as high as 155 in isopropanol for the case of a (8,0)-(0,8) mode at 3.63 MHz. Moreover, by grouping these modes into positive and negative (phase and antiphase, as in fig. 2), from the superposition point of view, a trend in the quality factor was observed: modes from the negative group showed much higher quality factors than their positive counterparts, despite being very close in terms of resonant frequency. A finite element method model was developed to explain this behaviour and compared against other analytical models for high order out-of-plane modes from the literature.

References

- [1] Jakoby, B., Vellekoop, M. J., "Physical Sensors for Liquid Properties," *IEEE Sens. J.* 11(12), 3076–3085 (2011).
- [2] Waggoner, P. S., Tan, C. P., Bellan, L., Craighead, H. G., "High-Q, in-plane modes of nanomechanical resonators operated in air," *J. Appl. Phys.* 105(9), 094315 (2009).
- [3] Kucera, M., Wistrela, E., Pfusterschmied, G., Ruiz-Díez, V., Manzaneque, T., Sánchez-Rojas, J. L., Schalko, J., Bittner, A., Schmid, U., "Characterization of a roof tile-shaped out-of-plane vibrational mode in aluminum-nitride-actuated self-sensing micro-resonators for liquid monitoring purposes," *Appl. Phys. Lett.* 104(23), 233501 (2014).
- [4] Sanchez-Rojas, J. L., Hernando, J., Donoso, A., Bellido, J. C., Manzaneque, T., Ababneh, A., Seidel, H., Schmid, U., "Modal optimization and filtering in piezoelectric microplate resonators," *J. Micromechanics Microengineering* 20(5), 055027 (2010).
- [5] Rossing, T. D., Fletcher, N. H., *Principles of Vibration and Sound*, 330, Springer Science & Business Media (2004).

9517-53, Session PSTue
Numerical Model a Graphene Component for the Sensing of Weak Electromagnetic Signals

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The paper discusses the design and analysis of a graphene coaxial line suitable for sub-micron sensors of magnetic fields. In relation to the presented concept, the target areas and disciplines include biology, medicine, prosthetics, and microscopic solutions for modern actuators or SMART elements. The proposed numerical model is based on an analysis of a periodic structure with high repeatability, and it is built upon a graphene polymer having a basic dimension in nanometers. The model simulates the actual random motion in the structure as the source of spurious signals and considers the pulse propagation along the structure; furthermore, the model also examines whether and how the pulse will be distorted at the beginning of the line, given the various ending versions. The results of the analysis are necessary for further use of the designed sensing devices based on graphene structures.

9517-54, Session PSTue
Modeling distributed electrostatic effects in silicon microphones and their impact on the performance

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Silicon microphones have conquered the market benefiting from low cost mass production and their compatibility with reflow soldering. However,

the application range of silicon microphones is still limited by the low signal quality. It turned out that electrostatic effects play an important role in their operational behavior. The detailed understanding and accurate modeling of the governing electrostatic effects, like the highly perforated backplate with its thousands of holes and the distributed effects caused by the position-dependent deflection of the membrane, is a prerequisite for the optimization of microphone characteristics and inevitably needed for predictive simulations.

To this end, we discretize the microphone geometry in form of an electrical network using a differential plate capacitor approximation. The fringing fields occurring beneath perforation holes are taken into account by adding parameterized compact models for basic structural elements, which contain only local geometry parameters and are valid over a wide range of geometry variations. Finally, the basic models are linked to form a generalized Kirchhoffian network, which allows for the simulation with a standard circuit simulator. Detailed electrostatic finite element simulations have been carried out to calibrate the models, which are then implemented into a multi-energy domain model on system level. This modularly composed model of the microphone shows good agreement between simulation and measurement, which is an immediate consequence of the dedicated calibration procedure carried out for the submodels. Our model enables a detailed analysis of the spring softening effect caused by electrostatic forces as well as the total harmonic distortion of the microphone's output signal caused by the non-linearity in the capacitive read-out. Thus, the model combines the detailed analysis of distributed effects with the efficiency of compact models to obtain important microphone characteristics, which highlights its potential for fast and efficient design and optimization studies.

9517-55, Session PSTue
Optical characterization of MEMS-based multiple air-dielectric blue-spectrum distributed Bragg reflectors

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The optical performance of a distributed Bragg reflector (DBR) is typically the determining factor in many optical MEMS devices. For instance in the case of a Fabry-Perot-based microspectrometer, the spectral resolution and operating bandwidth directly relates to the reflectance of its mirrors. The performance of a dielectric-based CMOS-compatible DBR is limited by the optical contrast of the materials used. Implementing a large number of layer pairs also increases the process complexity. Air is a superior low-index material candidate ($n \approx 1$, $k \approx 0$), improving refractive index contrast by about 50% compared with most conventional layer combinations. The combination of air and silicon-dioxide gives an optical contrast of 1.5 which is already close to the highest contrast conventionally achievable in DBRs.

Design, fabrication, and optical characterization of multiple air-dielectric Bragg reflectors with 2 or more air layers centered around 400 nm is presented in this work. Compared to all-dielectric DBRs with a similar layer complexity, the air-dielectric structure gives a superior optical performance, both in terms of reflectivity peak and bandwidth. Alternate polysilicon deposition and silicon-dioxide growth on the wafers followed by the selective etching of polysilicon layers in a TMAH-based solution results a layer stack according to the optical design. However, unlike the conventional MEMS processes, fabrication of a blue-band air-dielectric DBR demands several sacrificial layers in the range of 100 nm. Therefore, a successful release and drying of the membrane after the etching is critical to the successful performance of the device. DBRs with 2 and 3 layer pairs has been fabricated and successfully released using CO₂ supercritical drying process. The wide-area reflection measurements showed a peak reflectance of 65% and an FWHM of about 100 nm. This paper presents preliminary optical characterization results and discusses the challenges for a reflector design in the visible range.

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9517-56, Session PSTue

Optical design and characterization of a gas filled MEMS Fabry-Perot filter

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Analyzing natural gas is very important for safe and clean combustion. This should preferably be implemented at each burner, which requires small, robust and low-cost gas sensors. Optical absorption spectroscopy is a self-referencing and non-destructive method that allows ultimate miniaturization, while maintaining a sufficient performance. Among all the components in a spectrometer, the gas cell is the only part that remains not miniaturized due to the minimum optical path length required for detectable absorption. In this paper a Fabry-Perot type optical filter is presented in which the resonator cavity is designed to be suitable for use as a gas cell as well, because the multiple reflections from highly reflective Bragg mirrors and high-order operation result in an elongated absorption path.

The light beam must travel a reasonably long path for a detectable absorption, which is provided by the combined effect of a long cavity and highly reflective mirrors. For a long resonator cavity, the filter must be operated at high orders, which results in high resolution in a limited bandwidth. Therefore, we designed a linear-variable optical filter that operates at the 15th order in 3.2-3.4 μm wavelength range with a FWHM resolution of less than a nanometer.

To prove the concept, a fixed filter that is tuned to the strongest absorption peak of methane at 3319 nm is fabricated. This filter is composed of two flat 6-layer mirrors, one sputtered on a bare Si wafer and the other sputtered in a 24900 nm deep cavity. The FTIR measurements show that this peak is suppressed due to the cone angle of the light beam. By changing the incident angle, the response of the filter at 3319 nm will be measured with a laser at 3.39 μm . The combination of these results with FTIR measurements makes it possible to characterize these filters.

9517-57, Session PSTue

Low loss optomechanical cavities based on silicon oscillator

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In an optomechanical cavity the optical and mechanical degree of freedom are strongly coupled by the radiation pressure of the light. This field of research has been gathering a lot of momentum during the last couple of years, driven by the technological advances in microfabrication and the first observation of quantum phenomena. These results open new perspectives in a wide range of applications, including high sensitivity measurements of position, acceleration, force, mass, and for fundamental research. We are working on low frequency ponderomotive light squeezing as a tool for improving the sensitivity of audio frequency measuring devices such as magnetic resonance force microscopes and gravitational-wave detectors.

It is well known that experiments aiming to produce and manipulate non-classical (squeezed) light by effect of optomechanical interaction need a mechanical oscillator with low optical and mechanical losses. These technological requirements permit to maximize the force per incoming photon exerted by the cavity field on the mechanical element and to improve the element's response to the radiation pressure force and, at the

same time, to decrease the influence of the thermal bath.

In this contribution we propose a class of mechanical devices for which we measured a mechanical quality factor up to 1.2×10^6 and with which it was possible to build a Fabry-Perot cavity with optical finesse up to 9×10^4 . From our estimations, these characteristics meet the requirements for the generation of radiation squeezing and quantum correlations in the ~ 100 kHz region. Moreover our devices are characterized by high reproducibility to allow inclusion in integrated systems.

We show the results of the characterization realized with a Michelson interferometer down to 4.2 K. Measurements in optical cavities are performed at low temperature with input optical powers up to a few mW. We also report on the dynamical stability and the thermal response of the system.

9517-58, Session PSTue

Optoelectronic sensor device for monitoring ethanol concentration in winemaking applications

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The supervision of key variables such as sugar, alcohol, released CO₂, microbiological evolution and density of fermenting grape must is of great importance in the winemaking process. The fermentation kinetics is assessed by monitoring the evolution of the density as a fermentation progresses [1,2], since density is an indicator of the total amount of sugars, ethanol and glycerol.

This work aims at the design of a fast, portable and reliable optoelectronic sensor for measuring ethanol concentration in fermenting must samples, based on absorbance measurements in selected wavelengths of the near-infrared region. There are previous works based on spectroscopic techniques to determine the presence of ethanol in alcoholic beverages. They use different wavelengths of the spectrum: either 1.7 μm [3] or 0.98, 1.30 and 1.45 μm [4], or the range between 1.17 and 1.20 μm [5]. All of them were reported on finished alcoholic beverages, but they were not tested in fermenting grape must samples.

Samples containing ethanol, water, fructose, glucose, and glycerol, in the appropriate concentrations to emulate the fermenting must composition at different stages of the fermentation, were prepared (A1 to A15). The absorption characteristics were measured with a commercial spectrophotometer in the spectral range of interest (fig.1). The optimum set of discrete wavelengths to be used in a LED-photodetector scheme was identified through analysis of the sample spectra (fig. 2). Design issues regarding the spectral width of the LED sources and its effect on the ethanol sensor resolution will be discussed. An example of ethanol concentration estimated with our proposed measurement scheme, compared with the real concentration, is shown in fig. 3. The potential of this solution for the deployment of cost-effective and portable sensors in all tanks of a wine cellar will be described.

9517-59, Session PSTue

Force monitoring transducers with more than 100,000 scale intervals

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This paper represents the results obtained at characterization of new high performing force transducers to be employed into monitoring systems that are applicable in various domains. The transducers are ready for plug-and-play use and include coherently designed mechanical transducer and bulk micromachined MEMS sensor. The key application advantages of the transducers – ppm-accuracy and robust performance –

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are due to availability of more than 100,000 scale intervals and extremely low temperature dependence. Thus, the performance of the entire force monitoring systems, such as high class electronic scales, will be strongly improved by replacing the currently employed force transducers.

Every MEMS sensor comprises two rigid elements: an anchored and a moveable one connected via monolithic flexures. Every flexure comprises strain detecting cantilevers having embedded piezoresistors connected in Wheatstone bridge, thus multiple voltage sensor signals in the range of up to 200mV/V prior amplification are provided.

Since the MEMS sensors provide simultaneously all six independent signals responding to the relative position of the both parts (six DoF), there's no need for unidirectional constrain of the displacement. Respectively, novel compliant mechanisms having features for mounting the both MEMS parts and providing a relative displacement in the range of from 50 μ m to 1.5mm have been developed. They are made of different materials and have been used for transducing of various in range forces.

Based on experimentally measured results a method of force monitoring with ppm-accuracy independently on ambient conditions has been proposed.

The present work is a part of development of a common approach for precise measurement of various physical values when they are pre-transduced in a multi-D displacement. Due to the demonstrated record high accuracy, the force transducers with piezoresistive MEMS sensors remove most of constrains in force monitoring with ppm-accuracy. Alternatively, up-to six physical values can be simultaneously monitored in applications in other domains.

9517-60, Session PSTue
Passive microsensor for binary counting of numerous threshold events

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The Mean Time Between Maintenance (MTBM) of technical equipment is often based on empirical data. Microsystems for passive detection of threshold violation events can be used for triggering maintenance, and thus help to maximize the MTBM and reduce costs. Examples are known from acceleration sensors [1-3].

In our approach, a passive microsystem consists of a transducer, a powerless counter value storage and a read-out by radio-frequency identification (RFID). The transducer converts the energy supplied by the threshold event into mechanical energy which is stored as the counter value.

This contribution focuses on the mechanical powerless counter storage. Adapting the idea of an electronic shift register, a fully integrated passive microsystem for mechanical binary counting of threshold events was designed. We present the mechanical design and first mechanical measurements of the system fabricated using a standard SOI technology. Energy of threshold events, e.g. temperature, acceleration or pressure changes causes a mechanical switching of structural elements – referred to as bit elements – between two stable positions. A binary counting mechanism is realized by utilizing mechanical coupling elements between the bit elements. The mechanical energy needed for switching the first bit element to the state high was measured to be 0.61 μ J by moving the transducer element about 90 μ m wide and applying a maximal force of up to 20.9 mN. 0.76 μ J was measured for switching it back to the state low by applying the same 90 μ m distance and a force of up to 22.0 mN. Expanding the design to up to ten bit elements would offer a passive microsensor able to measure 1023 threshold events. For the first time a microsensor is presented suitable for monitoring of numerous critical threshold events without the need of any energy supply during measurement time.

[1] L. J. Currano, S. Baumann, W. Churaman, M. Peckerar, J. Wienke, S. Kim, M. Yu, B. Balachandran, *Sensors and Actuators: a-physical*, Vol. 147, 490-97, 2008.

[2] D. R. Ciarlo, *J. of Micromech. And Microeng.*, Vol. 2., 10-3, 1992.

[3] X.-Q. Sun, S. Zhou, W.-N. Carr, *Proc. Transducers 97*, Vol. 2, 1189-92, 1997.

9517-61, Session PSTue
Soft magnetic properties of permalloy thin films on polyimide-based substrates

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A novel approach to meet the increasing demands towards precision and efficiency of machine tools is pursued within the Collaborative Research Center (CRC) 653. This novel approach is based on collecting information during the whole lifetime of a system. To achieve this task, as much information as possible has to be gathered to obtain a comprehensive image of the observed component. Thus, various types of highly integrable micro sensors, namely strain gauges, eddy current sensors and anisotropic magneto-resistive (AMR) sensors, have been successfully implemented by applying a modular thin film fabrication technology on flexible polymer substrates.

It has to be considered that various factors such as homogeneity, morphology and surface roughness of the substrate material, do have an impact on the properties of deposited thin films, specifically in the case of soft magnetic material. These factors determine physical properties such as surface anisotropy, domain structure or stress anisotropy.

Surface anisotropy attributes the deviant behavior of thin films from bulk samples to the reduced symmetry of the atomic environment of surface atoms and applies for magnetic thin films on any substrate. The domain structure correlates with the homogeneity of the used substrate and on an inhomogeneous substrate complex domain changes during magnetization that cause a dispersion of anisotropy have to be expected. Stress anisotropy may occur when large discrepancies between the physical properties of a polymeric substrate and a metallic thin film are present and the appearance of elevated stress in the thin film is very likely.

The objective of this study was to investigate the impact of polymeric substrates on the soft magnetic properties of sputter deposited permalloy thin films. And to evaluate the performance of AMR sensors based on these substrates. As substrate, different polyimide-based materials were examined. Sputtered permalloy (NiFe 81/19), was used as soft magnetic thin film layer.

9517-62, Session PSTue
Technology towards a SAW based phononic crystal sensor

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Phononic crystals (PnC) with a specifically designed defect have been recently introduced as novel sensor platform. Those sensors feature a band gap covering the typical input span of the measurand as well as a narrow transmission peak within the band gap where the frequency of maximum transmission is governed by the measurand. This innovative approach has been applied for determination of compounds in liquids [1].

Improvement of sensitivity requires higher probing frequencies around 100 MHz and above. In this range surface acoustic wave devices (SAW) provide a promising basis for PnC based microsensors [2]. The respective feature size of the PnC SAW sensor has dimensions in the range of 100 μ m and below. Whereas those dimensions are state of the art for common MEMS materials, etching of holes and cavities in piezoelectric materials having an aspect ratio diameter/depth is challenging. In this contribution we describe an improved technological process to manufacture considerably deep and uniform phononic crystal structures inside of SAW substrates.

9517-63, Session PSTue

Parameters influencing focalization spot in time reversal of acoustic waves

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Time reversal of acoustic waves permits the creation of a multitouch tactile feedback by focusing acoustic wave on a surface with which the user interacts. Those waves are generated by piezoelectric actuators spread on the surface's perimeter, allowing the whole system to be transparent and easily fitted to a touchscreen interface. In order to increase tactile perception, the contrast ratio between focus spot and surrounding noise has to be maximized.

In order to achieve this we investigated the main parameters influencing the size of the focus spot, which are the plate's thickness and the frequencies used. We compared the results with a model based on Lamb waves theory. Acoustic waves were focused through the time reversal method in the 0-25kHz range split into 1kHz intervals. 2mm and 3mm thick glass plates (330x254mm²) were equipped with 16 piezoelectric discs driven in pair by a 30Vcc signal. 12mm and 35mm sizes of discs were used. At full frequency range (0-25kHz) the spot was approximately 23mm wide. The different frequency intervals produced a spot varying from 70mm (0-1kHz) to 15mm (24-25kHz) complying with the Lamb waves calculations for A0 mode. An increase in the plate's thickness from 2mm to 3mm decreased the spot's magnitude by 20%. Specifically, 35mm piezoelectric discs generated a 3.6µm high spot on a 2mm thick plate, respectively 2.8µm on a 3mm thick plate and 12mm discs generated a 0.6µm high spot on a 2mm thick plate, respectively 0.5µm on a 3mm thick plate.

The frequency range influences the width of the focus spot and the plate's thickness influences its magnitude. Different sizes of piezoelectric discs actuators did not yield significant differences on the focus spot dimensions. Resonant behavior of the plate and its implication on focus spot dimensions, focalization contrast and transfer function of the electronics were also investigated.

9517-64, Session PSTue

Experimental verification of a novel MEMS multi-modal vibration energy harvester for ultra-low power remote sensing nodes

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Nowadays the paradigm of the Internet of Things (IoT) assumed the worth of being the common denominator between emerging technology solutions and applications, like smart sensors and objects, pervasive computing, distributed sensing, Wireless Sensor Networks (WSNs), and so on. In fact, evolution of the IoT poses a critical concern related to power requirements of distributed nodes, as traditional batteries are difficult to miniaturize and replace. To this regard, MEMS Energy Harvesters (i.e. EH MEMS) are able to address power demand of Ultra-Low Power (ULP) electronics and wireless circuits, and enable, on the other hand, miniaturization of integrated hybrid systems.

In this work, we discuss the experimental characterization of novel vibration EH-MEMS device. The structure consists in four petal like double cascaded spring-mass elements, kept suspended by four triangular tapered suspensions. Because of this particular shape, the device is named Four-Leaf Clover (FLC). A piezoelectric thin-film of aluminium nitride (AlN) is applied as transduction element. Gold layers are patterned on top and bottom of AlN in order to collect charges generated by piezoelectric effect. The mechanical elements are realized using a Silicon-On-Insulator (SOI) wafer patterned by a Deep Reaction Ion Etching (DRIE) process. The particular FLC EH MEMS shape is meant to increase the number of mechanical resonant modes in the vibration frequency range up to a few kHz (i.e. multi modal concept), thus increasing the device environmental power conversion capability (i.e. wideband EH).

Preliminary experimental results show the presence of several resonant frequencies in the observed range (up to 15 kHz), proving the concept of multi-modality of FLC EH-MEMS.

In the full paper, we will discuss more comprehensively the experimental characterization of the manufactured EH MEMS also including indications related to the FLC mechanical-into-electric power conversion characteristics. Furthermore, device multiphysics modelling performed by means of Finite Element Method (FEM) tools will be reported and evaluated.

9517-65, Session PSTue

A comparative study between SMF-MMF-SMF interferometers and LMR optical fiber devices for sensing

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In this work, a thin-film consisting of 15 bilayers of TiO₂ and poly(sodium 4-styrenesulfonate) (PSS) has been simultaneously deposited onto two optical fiber structures: an SMS (SMF-MMF-SMF) device and a lossy mode resonance (LMR)-based device. The performance of both structures when they are used as refractometers and relative humidity sensors has been studied and compared. In both cases, the sensitivity of the LMR-based device (955 nm/RIU and 3.54 nm/RH%, respectively) highly improves the one of the SMS (142 nm/RIU and 0.3 nm/RH%). This is the first time that a comparative study between SMS and LMR-based sensors is performed.

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High-sensitive lossy mode resonance-based optical fiber refractometers by means of sputtered indium oxide thin-films

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In the last few years, optical fiber refractometers have attracted the attention of many authors as a promising label-free sensing platform. This work, describes the fabrication of optical fiber refractometers based on Lossy Mode Resonances (LMRs).

Indium oxide (In₂O₃), with a high refractive index (n=2), has been utilized as the resonance supporting coating. In₂O₃ coatings have been fabricated onto the core of 4 cm. long plastic-cladding multi-mode fibers (200/225 µm core/cladding diameter). The fabrication of In₂O₃ films was performed using the DC-sputtering technique in order to obtain thin homogeneous coatings around the core.

In order to characterize the response of the refractometers as a function of the In₂O₃ coating thickness three different devices with thickness of 70 nm (device A), 300 nm (device B) and 690 (nm) were fabricated.

The transmission spectra were obtained using a typical transmission setup. This setup was used to characterize the device when it is subjected to changes in the surrounding medium refractive index (SMRI) from 1.332 to 1.471.

Devices A, B and C revealed 1, 2 and 5 LMRs respectively positioned at different wavelengths. All the LMRs shift to larger wavelengths when the SMRI is increased but the average wavelength shift and full-width at half maximum varies. Device A shows an average sensitivity of 5680 nm/RIU in the studied range. However, FWHM is not easily measurable. The first and second LMRs of device B show sensitivities of 1620 and 354 nm/RIU respectively and narrower resonances than Device A. Device C shows five LMRs with decreasing sensitivities from 1790 nm/RIU to 191 nm/RIU. In this case, the FWHM is in the order of tens of nanometers.

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From previous results it can be assumed that thin-film In₂O₃ coatings enable to obtain high sensitive refractometers. However, thicker coatings are preferred when it is required a good FWHM value.

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Optical fiber pH sensor based on gold nanoparticles into polymeric coatings

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In the last decades, the design of hybrid nanocoatings combined with optical fiber devices can be used to enhance the sensing properties as well as adding novel functionalities. Among the techniques to fabricate hybrid thin-films, the Layer-by-Layer assembly is one of the most used methods to obtain nanostructured coatings based on the incorporation of metallic nanoparticles (gold, silver, copper) into polymeric films. A great control of the thickness coating can be obtained as a function of the pH, number of bilayers, concentration or ionic strength of the polyelectrolytes. The control of the resultant thickness is the key to observe different resonant bands which appear in the optical transmission spectrum of the devices. The first absorption band observed is the Localized Surface Plasmon Resonance (LSPR) which is inherent to the metal nanoparticles and appears for thinner coatings. This LSPR phenomenon consists in a resonant coupling between an incident electromagnetic wave and the surface of a metallic-thin film, where some of the energy of the light is transferred to the surface free electrons of the metal, causing an electronic wave at the metal-dielectric interface. This results in the apparition of a sharp absorption peak in the transmitted light at a fixed wavelength position. The second absorption band is the Lossy Mode Resonance (LMR) and appears for thicker coatings. This LMR phenomenon occurs when the real part of the thin-film permittivity is negative and higher in magnitude than both its own imaginary part and the real part of the permittivity of the material surrounding the thin film. This new phenomenon presents several advantages in comparison with the LSPR phenomenon because the LMR condition can be generated for a broader range of supporting materials, showing a better sensitivity to physical, chemical or biological parameters. In this work, it is presented a wavelength-based sensor with a high robustness and immunity to undesired optical power fluctuations. The device shows a high sensitivity, a fast response time and a large dynamic range to pH changes.

9517-68, Session PSTue

Development of silicon microforce sensors integrated with double meander springs for standard hardness test instruments

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Silicon microforce sensors, which are used as a standard for force and depth scale calibrations of hardness testing instruments, are developed using silicon bulk micromachining technologies. Instead of wet chemical etching, inductively coupled plasma (ICP) cryogenic deep reactive ion etching (DRIE) is employed in the sensor fabrication process. Double meander springs are designed flanking to the boss replacing the conventional rectangular springs and thereby improving the system

linearity. Two full p-SOI piezoresistive Wheatstone bridges are added on both clamped ends of the active sensors. In the SOI-based fabrications, the passive and active microforce sensors require 2 and 6 chromium masks for their photolithography processes, respectively. Differentiating from the passive sensors, which needed only DRIE technology, the active sensor development was started with p+-diffusion (Borofilm 100, Emulstone) for its ohmic contact line extensions of the etched piezoresistors. For both sensors, the most challenging step was the backside etching of the meander springs because of their deep structures (300 μm) and small gaps (50 μm). However, by optimizing the main dry etching parameters (e.g., SF₆/O₂ plasma and temperature), sensor chips (20 x 2.2 mm²) with smooth meander sidewalls and surfaces could be obtained. Moreover, 3 μm thick etched piezoresistors were realized acting as a read-out element. From the previous measurements, the bridge offset was down to 0.1 mV/V, thus ensuring small noises. Nevertheless, the oxide areas surrounding the bridge need to be enlarged to avoid unwanted nanoparticles shorting the active silicon regions. To combine two passive sensors into a stack device, glue and photoresist were used as joining materials. Correspondingly, although plastic deformation seemed to occur when the second spring was contacted, the kink effect (i.e., abrupt increase of stiffness) was obviously observed from the first test of the passive stack sensor.

9517-69, Session PSTue

Optimal design of piezoelectric microtransducers for static response

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A systematic procedure to simultaneously design the shape of the structure and the electrode layout, in a piezoelectric sensor or actuator moving in-plane, is described. The technique allows maximizing any electromechanical coupling or output efficiency of the transducer. Either the output current collected at the electrodes when a mechanical force is applied (sensors), or the in-plane displacement when a given voltage is applied to the electrodes (actuators) can be optimized. The method can be applied to both static and dynamic responses. Besides force and displacement sensors, due to the reciprocal relationship between piezoelectric sensors and actuators, many MEMS-based actuators like micro-grippers, surface probes, or micro-optical devices can be optimized following this procedure [1,2]. A similar approach has been demonstrated previously in modal sensors/actuators, although restricted to the design of the electrode layout for a given structure [3]. The novel method shown here allows the simultaneous optimization of both shapes, for electrode and structure in the static case so far [4].

Finally, it is important to point out that the situation treated to date can be considered as the previous case of a more general and interesting problem in the context of modal filtering to be dealt with in the near future.

References

- [1] D. J. Bell, T. J. Lu, N. A. Fleck and S. M. Spearing, "MEMS Actuators and Sensors: Observation on their Performance and Selection for Purpose", *J. Micromech. Microeng.*, vol. 15, pp. 153-154, 2005.
- [2] Q.M. Wang, X.H. Du, B. Xu and L.E. Cross, "Electromechanical Coupling and Output Efficiency of Piezoelectric Bending Actuators", *IEEE Transactions on ultrasonics, ferroelectrics, and frequency control*, vol. 46, pp 638-646, 1999.
- [3] J. L. Sánchez Rojas, J. Hernando, A. Donoso, J. Bellido, T. Manzanque, A. Ababneh, H. Seidel and U. Schmid, "Modal Optimization and Filtering in Piezoelectric microplate resonators", *Journal of Micromechanics and Microengineering*, vol. 20, pp 1-7, 2010.
- [4] D. Ruiz, J.C. Bellido, A. Donoso, J.L. Sánchez Rojas. "Design of in-plane

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piezoelectric sensors for static response by simultaneously optimizing the host structure and the electrode profile". Struct. Multidisc. Optim., vol. 48, pp 1023-1026, 2013.

9517-70, Session PSTue

Features design and manufacturing technology in microelectromechanical encapsulated devices

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MEMS devices have both general and specific features, but they all have sealed execution. This complicates the task of development and makes it necessary to solve complex technological problems of sealing, control and stabilization gas medium parameters inside device housing.

Research methodology for measuring the natural frequency of inner and outer frames of micromechanical oscillating system with an electrostatic actuator in filling spaces inside corps with nitrogen, and verification methodology of micromechanical sensor element (SE) on the basis of rotation angle measurement has been developed. Settlements of size elements of SE moving part required ensuring specified parameters for micromechanical systems such as steering angle; bandwidth, control voltage value and angle sensor capacitance, and moment sensor have been performed. Developed new technical solution was consisted in that for correcting errors in the form of etched shapes compensator topology with special configuration has been used. It was possible to obtain the moving parts of MEMS with etched rectangular shape figures and with large etching depth about 400 microns.

Hydrogenated silicon surface layers were investigated by IR - spectroscopy. It was shown that substrate temperature plays a primary role in the formation of hydrogen-defect layer in silicon. The behavior of the low-frequency band in the region of Si-H stretching vibrations during annealing has been analyzed. Dependence character of resonance frequency of the movable (SE) part of MEMS torsion type vs temperature has been investigated. It was found that when the temperature changes from 25 to 80 °C, so natural SE frequency does not change more than 1%. The dependence of the quality factor and the natural frequency of moving SE part from the inside corps pressure on the various modes of oscillation was investigated. It was shown that getter usage was the most efficient means of increasing the sensors Q factor with such system and to maintain it during the operation. The effect of gas damping on the oscillatory circuit parameters has been studied. Empirical dependence of the oscillating system Q factor and natural oscillation frequency vs pressure within the casing has been found on the basis of experimental data.

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Fabrication of microfluidic chips using lithographic patterning and adhesive bonding of the thick negative photoresist AZ 125 nXT

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Fabrication of microfluidic devices on the basis of silicon or glass substrates is frequently done by using the epoxy-based negative photoresist SU-8. The suitability of this material for various microfluidic applications has been shown in the fields of bioanalytic devices, lab-on-chip systems or microreaction technology. However, processing of SU-8 is always a very challenging task with regard to the adaptation of process parameters to the individual design and required functionality. Especially

the sealing of structured SU-8 layers to obtain permanently closed microchannels has been investigated extensively, yet without establishing a simple and reproducible standard method.

Besides SU-8, different groups are using other thick negative liquid or dry film photoresists to realize microfluidic and other permanent structures.

In this work, for the first time the negative photoresist AZ 125 nXT was used for the fabrication of a microfluidic chip. This material was originally developed for the use in electroplating applications, where a chemically stable but removable photoresist is required. The AZ 125 nXT allows for the fabrication of structures in a wide thickness range with only one type of viscosity. In contrast to SU-8, the AZ 125 nXT is fully cross-linked during UV exposure and does not require a time-consuming post-exposure bake. 90 µm deep microfluidic channels were defined by lithographic patterning of AZ 125 nXT. The sealing of the open microfluidic channels was performed by a manual adhesive bonding process at a temperature of 100 °C. For this bonding step an unstructured layer of AZ 125 nXT was used as an intermediate layer. The fluidic function was successfully tested with flow rates up to 20 ml/min by means of a microfluidic edge connector. Long term stability and chemical resistance of the fabricated microfluidic channels will be investigated in the near future. The presented work shows the potential of AZ 125 nXT as a possible alternative to SU-8 for the fabrication of microfluidic chips.

9517-72, Session PSTue

Laser ablation for membrane processing of AlGaIn/GaN- and micro structured ferroelectric thin film SiC based MEMS and pressure sensors for extreme conditions

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AlGaIn/GaN based high electron mobility transistors (HEMTs), Schottky diodes and/or resistors have been effectively presented as sensing devices for mechanical or chemical sensors operating in extreme conditions. Additionally we investigate microstructured ferroelectric thin films for integration into micro-electro-mechanical-systems (MEMS). Creation of appropriate diaphragms and/or cantilevers out of SiC is necessary for further improvement of sensing properties of such MEMS sensors. For example sensitivity of the AlGaIn/GaN based MEMS pressure sensor can be modified by membrane thickness. We demonstrated that SiC diaphragms can be fabricated much faster with laser ablation than by electrochemical, photochemical or reactive ion etching (RIE). We verified the feasibility to fabricate micromechanic structures in bulk SiC substrates with epitaxial AlGaIn/GaN heterostructures by femtosecond laser ablation at 520nm wavelength in combination with RIE for pressure sensor applications. On a 4H-SiC substrate we produced an array of 250µm deep and 500µm diameter blind holes without damaging the AlGaIn/GaN heterostructures. We now also investigate ferroelectric thin films as they can be deposited and micro-patterned by a direct UV-lithography method after the ablation process for a specific membrane design. The risk to harm or damage the function of thin films can be eliminated by that means. However, to create thin membranes without RIE leaking of laser radiation from the ablation area has to be minimized by maintaining a smooth pattern surface during the entire ablation process in order to suppress back side damage. Some defects are also affected by the polarisation of the laser light. The ripple structure is oriented perpendicular to the laser polarisation and we believe they do to some extent promote creation of pin holes which would perforate a thin membrane. We developed an ablation technique strongly inhibiting formation of ripples and pin poles for membranes of higher quality entirely produced by laser ablation.

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9517-73, Session PSTue

Microstructures replication using high frequency excitation

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Micro and nanotechnologies employ interdisciplinary methods allowing to cope with many essential problems in various fields, like: medical industry, mechanics, information technologies, ecology, production and reservation of energy, material science, manufacturing, measurement and control technologies, food, water and environmental researches. The aim of the paper is to research and develop of micromechanical periodical systems for replication. The new replication technology based on mechanical hot imprint process, using high frequency vibration are developed. It enables to improve the quality of the complex microstructure replicas. Thus, novel nanocomposite thin films with periodical microstructure will be created, investigated and applied, in order to further design perspective novel active optical elements. All these new technologies will be used to develop concept of micromechanical periodical systems.

Diffraction efficiency of grating, created by hot imprint process on the surface of polycarbonate is one of the parameters, which determines the quality of microstructure. Microstructures are replicated by using hot imprint process with and without high frequency excitation and during the quality investigation, diffraction efficiencies were measured on purpose to find microstructure of best possible optical quality, as well determine whether high frequency excitation and other process parameters during the process affect this parameter. Process parameters include: temperature, excitation frequency, force of mechanical load and duration of hot imprint process, the purpose is to determine the collection of parameters, which influences the diffraction efficiency most positively. The novel vibro active pad is proposed for microstructures replication. The main dynamical characteristics of the vibropad are presented in the paper.

9517-74, Session PSTue

Fabrication of wear-resistant silicon microprobe tips for high-speed surface roughness scanning devices

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Silicon microprobe tips are fabricated and integrated with piezoresistive cantilever sensors for high-speed surface roughness scanning systems. The fabrication steps of the high-aspect-ratio silicon microprobe tips were started with photolithography and wet etching of potassium hydroxide (KOH) resulting in crystal-dependent micropylamids. Subsequently, thin conformal wear-resistant layer coating of aluminum oxide (Al₂O₃) was demonstrated on the backside of the piezoresistive cantilever free end using atomic layer deposition (ALD) method in a binary reaction sequence with a low thermal process and precursors of trimethyl aluminum and water. The deposited Al₂O₃ layer had a thickness of 14 nm. The captured atomic force microscopy (AFM) image exhibits a root mean square deviation of 0.65 nm confirming the deposited Al₂O₃ surface quality. Furthermore, vacuum-evaporated 30-nm/200-nm-thick Au/Cr layers were patterned by lift-off and served as an etch mask for Al₂O₃ wet etching and in ICP cryogenic dry etching. By using SF₆/O₂ plasma during inductively coupled plasma (ICP) cryogenic dry etching, micropillar tips could be obtained. From the preliminary friction and wear

data, the developed silicon cantilever sensor has been successfully used in 100 fast measurements of 5-mm-long standard artifact surface with a speed of 15 mm/s and forces of 60–100 μN. Moreover, the results yielded by the fabricated silicon cantilever sensor are in very good agreement with those of calibrated profilometer. These tactile sensors are targeted for use in high-aspect-ratio microform metrology.

9517-75, Session PSTue

Wafer edge protection kit for MEMS and TSV Si-etching

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A new process kit for a SPTS Pegasus DRIE Si-Etch tool has been developed and tested for several different process regimes, i.e. bulk-Si cavity etching and TSV (through-Silicon-Via) etching with high aspect ratios >10:1, using the so-called Bosch process. Additionally, Si-etch back (recess etching) with a single step process has been tested as well.

The especially developed „edge protection kit“, consisting of Al₂O₃ material and optionally of PEEK material, covers the edge of a wafer, preventing it from being etched or even being etched away. However, placing such a part on top of the cathode, results in changes of the electric field distribution and the gas flow behavior compared to the standard process kit supplied by SPTS.

The consequences may be altered Si-etch rates combined with changes of the different tilt and side wall taper of the etched structures, mainly near the outside regions of the wafer. To this end, extensive investigations on the mask and bulk-Si etch rates, the tilt and taper angle of various MEMS test structures and their respective uniformity over the wafer surface had been performed. Tilt and taper angle data were calculated based on SEM-micrographs of etched Si-bulk profiles. Additionally, simulations applying Comsol Multiphysics have been carried out to visualize the potential impact of the new process kit on the electrical field distribution. A simplex-optimization was carried out, varying the platen power and source power, in order to improve the tilt and to maintain the proper taper angle. One major advantage of the new process kit design compared to the original one is the reduction of parts.

Additionally, a polymer-based material for the lower part of the process kit, the so-called “cathode ring”, was tried. Since this part of the kit is never exposed to plasma, it could well serve as a low cost alternative to the standard material Al₂O₃.

Figures 1 – 4 show details of the process kit components, Si etch rates and the electrical field distribution for different configurations obtained by FE simulation.

9517-76, Session PSTue

Research and development of capacitive transducer with linear acceleration

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Entire infrastructure for production of many MEMS classes, which allows their use in mobile and stationary devices systematically and single-use for many applications have been already created. Sensors of physical quantities, which include linear acceleration transducers (LAT) occupied important place among the MEMS. We present the study results and modeling of functional characteristics of the linear acceleration transducers, enabling sensors creation with the specified parameters. Sensing element made for linear acceleration transducer with torsion cruciform section has been proposed on the basis of design and technological principles. It allows you to minimize the impact of cross-acceleration and gives the maximum of center mass displacement

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for high sensors sensitivity in the given dimensions. The range of measured acceleration from $\pm 0.2g$ to $\pm 50g$ was provided by changing the torsion bar thickness $n = 34 \div 56$ microns. The transducers frequency range of linear acceleration 100-150 Hz depends on the gas pressure $P = 700-800Pa$ in which the sensor element was located. Methods converting displacement of sensing element in the sensor output have been provided. On their basis the linear acceleration transducers with analog output signal having a predetermined frequency range and high linearity of the transformation (nonlinearity 0.2-1.5%) was developed. Also the linear acceleration transducers with digital signal consuming little (no more than 850 μA), low noisy (standard deviation to 0.1mg/rt-Hz) and high sensitivity (up to 0.1mg) to the accelerations was made. Errors in manufacturing process of sensitive elements and operating environment temperature affect the changes in the characteristics of the linear acceleration transducers. It has been established that different plate thickness up to 3.6% leads to the scale factor error to 4.7%. Irreproducibility of depth anisotropic etching of silicon up to 6.6% introduces an error in the output signal of 2.9 ... 13.8mg. Error splicing process leads to changes in the sensor zero signals. Change in functioning environmental temperature leads to scale factor errors. Obtained dependences can reasonably generate requirements for parameters of manufacture technological process for linear acceleration transducers.

9517-77, Session PSTue

Characterization of down-state capacitance degradation in capacitive RF MEMS switch with rough dielectric layer

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In order to obtain the high-fidelity model of latching failure threshold power of the capacitive RF MEMS switch, it is necessary to find out the rough dielectric layer effect on its down-state capacitance degradation. The comparative modeling method between the 3-D electromagnetic simulation and the equivalent circuit simulation is proposed. First, the simulation curve of the switch isolation (S21) is attained at different surface roughness levels with the HFSS 3-D electromagnetic model. And then the simulation curve of the S21 of the ADS equivalent circuit model is consistent with the simulation result of the 3-D electromagnetic as far as possible by tuning the down-state capacitance in the equivalent circuit. Hence, the relationship between the dielectric layer surface roughness and the down-state capacitance is identified. By changing the surface roughness level of dielectric layer and repeating the above steps, the relationship between the dielectric layer surface roughness and the down-state capacitance degradation is identified. Rationality and feasibility of the method is verified by comparing the calculated values of the down-state capacitance with the measured values in a relevant literature. And analytical formula of the latching failure threshold power of the capacitive RF MEMS switch with perfect smooth dielectric layer is modified, according to the relationship between the dielectric layer surface roughness and the down-state capacitance degradation, which is also suitable for predicting the power handling capacity of the switch with rough dielectric layer.

9517-78, Session PSTue

Characterization of cross-spring pivots for micropositioning applications

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Compliant mechanisms gain at least part of their mobility from the deflection of flexible member. They are characterised by high precision, possibility of monolithic manufacturing ('design for no-assembly') and of parallel kinematics, as well as no backlash and wear. Several analytical and numerical methods are used in this work to characterise the behaviour of compliant rotational mechanisms, known as cross-spring pivots, aimed

at micropositioning applications. In a typical design configuration, a cross-spring pivot allows a movable block to rotate, via the deflection of leaf springs, with respect to the fixed block. In general, the pivot is loaded with a pure bending moment.

When ultra-high precision is required, the limits of applicability of approximated calculation algorithms have to be determined. The results obtained by employing these methods are thus compared with results obtained via the generalized nonlinear Elastica-type approach, results obtained by using nonlinear finite element calculations as well as the experimental data reported in literature.

The finite element model, tuned to the results of the exact Elastica approach, allows also to consider the influence of lateral loads and of non-symmetrical pivot configurations where the angle or point of intersection of the leaf springs, or even the initial curvature of the springs, can be varied. The aim of this part of the work is to determine the influence of the cited design parameters on the minimisation of the parasitic shift of the geometric centre of the pivot as well as on the minimisation of the variability of the rotational stiffness of the pivot so as to ensure its stability and avoid the possible occurrence of buckling.

The obtained results allow therefore determining design solutions applicable in ultra-high precision micropositioning applications, e.g. in the field of production or of handling and assembly of MEMS.

9517-79, Session PSTue

Modeling and simulation of the multiphase flow involving magnetophoresis-based microfluidic systems

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The selective separation of target biomaterials such as cells, proteins, genes and pathogens from a multiphase and heterogeneous sample flowing through a microfluidic device is increasingly becoming central to many biotechnology fields such as medical diagnostics and sensing. In particular, magnetic separation of magnetically labeled biological entities has recently grown rapidly due to the advances in device fabrication.

In this study, we use the Lagrangian-Eulerian model, usually termed as Discrete Particle Model (DPM), and the Eulerian mixture model to numerically simulate the magnetophoresis-based separation of magnetic beads in a microfluidic system. The appropriate multiphase modeling and simulation approach must depict the interaction between the carrier liquid and the dispersed particles. However, a direct numerical simulation of interfacial dynamics for problems involving millions of dispersed solid particles is prohibitively expensive with the available computational resources. In this study, interfacial dynamics have been resolved by using proper modeling. The selection of an appropriate model depends on the Stokes number, which scales the mobility response time of particles suspended in a fluid relative to a characteristic time of the flow. If the system involves a dilute dispersion of particles (volume fractions less than ~5%) with small Stokes numbers and there is a need to track typical trajectories to follow physical processes, then the particles motion can be solved discretely (i.e. on particle basis) using a Lagrangian tracking approach. Under the same flow conditions, the Mixture model, as an alternative to DPM, presented a viable compromise between accuracy and computational cost. Mixture model greatly reduced computational time as it only solves a single momentum equation for the continuous mixture. However, the slip velocity of magnetized particles relative to the host liquid must be appropriately modeled. For both of DPM and mixture approaches, the appropriate constitutive models for drag, lift and slip were resolved.

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9517-81, Session PSTue

Electrospray ionization deposition of BSA under vacuum conditions

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In this paper, the Electrospray ionization (ESI) process, known from mass spectroscopy, was used to transfer the organic molecules into the vacuum. During ESI the material will not be thermal evaporated, but ionized and sprayed through a capillary into the vacuum. The usually powdery functional material has to be solved in a suitable liquid. This dispersion is pumped through a needle on electrical potential. Because of the electrical field between spray needle and capillary, the liquid builds a Taylor cone at the needle tip. From this very small tip, droplets are emerged and accelerated in the direction of the capillary. During transfer into the vacuum, the solvent in the droplets is evaporated. Thus, the charge carriers trapped in the droplet are getting closer together. As soon as the Rayleigh limit is reached, the repulsive forces of the charges are so high that Coulomb explosions will take place and the droplets burst into much smaller droplets. This process continues until the whole solvent is evaporated, so that only the organic material without any solvent remains and is deposited on the substrate. The deposition area is approximately 2 cm².

9517-82, Session PSTue

Numerical analysis of a smart composite material mechanical component using an embedded long period grating fiber sensor

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Results obtained by FEM analysis of a smart mechanical part manufactured of reinforced composite materials with embedded long period grating (LPG) fiber sensors used for operation monitoring are presented. Fiber smart reinforced composite materials because of their fundamental importance across a broad range of industrial applications, as aerospace industry. The main purpose of the performed numerical analysis consists in final improved design of composite mechanical components providing a feedback. The performed numerical analysis is pointing to a correlation of composite material internal mechanical loads applied to LPG fiber sensor with the NIR peak wavelength shifts of the characteristic transmission spectra.

9517-83, Session PSTue

Design of a smart superstructure FBG torsion sensor

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The paper presents the results obtained in FEM analysis of a Superstructure Fiber Bragg Grating (SFBG) torsion sensor. SFBG sensor simulation points to an improved smart composite or metallic parts design to be operated under torsion loads in various applications. SFBG sensor simulation consists in correlating the fiber deformation under applied mechanical loads with the modified FBG characteristic reflection spectrum considering the polarization mode variations. The analyzed SFBG is developed by the selective deposition of on-fiber periodic metal

thin films on regular FBGs. Bragg wavelength induced shifts and side bands in the characteristic reflection spectrum are analyzed.

9517-22, Session 6

Thermal cycling reliability of RF-MEMS switches

Viviana Mulloni, Guido Sordo, Benno Margesin, Fondazione Bruno Kessler (Italy)

In satellite networks applications, RF-MEMS switch reliability performances are rather demanding, and include mechanical, thermal and long-term functioning performances. Recently, mechanical issues have been considered in greater detail, being recognized as one of the important source of failure in RF-switches. For space application purposes, the mechanical stability to thermal cycling is an important parameter, because this is normally requested in space qualification procedures. Different mechanical structures were studied, including one cantilever switch, four clamped-clamped structures and two circular, four-anchored switches. The switching structures are made by a suspended gold membrane over the transmission line. When electrostatically actuated, the membrane collapses connecting the input with the output ports or the input port to ground in the series and shunt configurations, respectively. In order to test their mechanical stability, the investigated structures underwent to 10 rapid thermal cycles of five minutes each in the temperature range from 25 to 200 °C, and their mechanical deformations were studied in detail by means of an optical profiler. The purpose of this test is to discriminate and select the most resistant typologies and to find out what are the design parameters that most influence the thermal cycling stability.

Optical profilometric analysis performed before and after the thermal cycles allowed a precise evaluation of the mechanical deformations, evidencing important quantitative differences among the different switch structures studied. Simulations of the membrane shape in the range 25-200 °C were also performed, in order to related the effect of the maximum temperature with the cycling degradation. The mechanical modifications can be understood in terms of thermal induced stress variation in the switch mobile membrane. Criteria to predict thermal cycling resistance are given, and guidelines to design a thermal cycling resistant switch are derived.

9517-23, Session 6

Microsystem integration from RF to millimeter wave applications

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Radio frequency systems have been applied successfully to consumer products. Typically these radios operate up to 6 GHz. During recent years, interest towards microwave (up to 30 GHz) and millimeter wave frequencies (30 ... 300 GHz) has increased significantly. Technologies have been developed to have high performance microwave and millimeter wave components. On the other hand, integration and packaging technologies have not developed as fast while their importance is crucial especially in consumer applications. This presentation focuses to latest trends in wireless microsystem component integration and packaging trends backed up with demonstrators and measured results.

We at VTT Technical Research of Finland have been developing microwave and millimeter wave integration and packaging platforms based on low temperature co-fired ceramics (LTCC), printed circuit board and silicon based technologies. The LTCC is suitable for packaging providing capability for hermetic sealing. It can also be used for multi-chip modules as an integration platform as well as integrating microwave and millimeter wave passive components such as filters and antenna arrays. This presentations shows examples of millimeter wave antennas and antenna arrays realized on LTCC, component packaging and multi chip module integration. Other integration platform is based on integrated passive devices silicon based integration platform technology. Compared to LTCC, it can have accurate and small size passive components as well as it supports fine pitch flip chip. On the

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other hand, it doesn't provide hermetic packaging which is the case of LTCC. Silicon based technologies support volume production mainly because of high investments done to develop low cost Complementary Metal Oxide Semiconductor (CMOS) technologies. Integrated passive devices integration platform uses similar processes used in semiconductor industry while not having lossy substrates needed for transistors. This presentation shows integration concepts for silicon based integration platforms and experimental results up to 110 GHz.

9517-24, Session 6

Tailoring design and fabrication of capacitive RF MEMS switch for K-band applications

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RF MEMS switches are very promising for K-band wireless terrestrial and space-oriented applications, taking advantage from the high wide-band linearity, low insertion loss, negligible power consumption, small volume and low batch fabrication cost, being the last characteristics peculiar of the micromachined devices. In particular, RF MEMS switches in capacitive configuration exhibit a higher isolation at resonance, with potential tunability of the frequency.

In this work, capacitive RF MEMS switches of different size were modelled, fabricated, and characterized in the RF domain. The modelling is aimed to tune the RF behavior of the switches by varying the bridge and the actuator size, obtaining an increase of the resonance frequency up to 30 GHz. The switches were fabricated on silicon substrate, with a process which is fully compatible with integrated circuits fabrication. Moreover, innovative solutions were adopted in some technological steps, which are of crucial importance for the device operation, such as the deposition and removal of the dielectric layer. A study as a function of the deposition parameters was also performed for the electro-deposition of the moveable bridge gold. A morphological and structural analysis of the different material layers were performed by scanning electron microscopy (SEM) and focused ion beam (FIB) techniques, allowing to infer important information on the adhesion and quality of the electroplated gold and on the removal of the sacrificial layer under the bridge. The RF performance of the switches were characterized, observing the effect on the S parameters of the size variation, the deposition and removal of the sacrificial layer, and the covering of the actuator with a floating metal layer. Finally, the reliability of the different switches was tested to estimate their lifetime and to evaluate the failure causes under different cycling conditions.

9517-25, Session 6

Investigation of diaphragm deflection of an absolute MEMS capacitive polysilicon pressure sensor

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Circular shaped hermetically vacuum sealed, deflectable diaphragms made of polycrystalline silicon for absolute pressure measurements are utilized as capacitive sensor elements in an integrated CMOS pressure sensor process suitable for medical implants.

An accurate description of the deflection line of real pressure sensor diaphragms is a prerequisite e.g. for models for the electrical simulation of integrated capacitive pressure sensors.

The pressure sensor diaphragms were investigated in a pressure range of

about 700 -1300 hPa. The diaphragm touched the underlying substrate at a contact pressure point of about 1600 hPa. In pressure ranges smaller than 1600 hPa a diaphragm sensitivity of $-19 \text{ nm} \pm 1$ per 100 hPa was found. The deflection line is measured as a function of the applied pressure with the aid of phase shift interferometer.

Significant deviations in deflection with respect to the "standard" theoretical model of clamped plates are observed. These are primarily attributed to the internal tensile stress. An analytical formula was established that describes the deflection including initial deflection due to intrinsic stress and the process variations.

Furthermore, fabrication process fluctuations influence the main characteristics of the diaphragms such as sensitivity, cavity height and initial deflection. The height of the PECVD oxide layer that defines the cavity varied about $\pm 5 \%$ on an 8-inch wafer. Considering the diaphragm sensitivity a variation in contact pressure up to 300 hPa is expected. In addition, the high temperature deposition of the diaphragm - polycrystalline silicon is expected to show wafer to wafer deviations.

Process parameters included the impact of the variation of the oxide layer defining the diaphragm cavity height on the contact pressure point and were found to be about $3.5 \pm 0.5 \text{ hPa/nm}$. Further, differences in sensitivity and vertical as well as lateral displacement of the fit functions were identified. These impacts originate from diaphragm processing.

9517-503, Session PLWed

Miniaturized dielectric elastomer actuators: towards intelligent soft machines

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Dielectric Elastomer Actuators (DEAs), often referred to as artificial muscles, are stretchable soft transducers consisting of an elastomer membrane sandwiched between two compliant electrodes. DEAs can be used as actuators with strains of over 200%, but also for energy harvesting, as sensors, switches and as lightweight structural elements. These attributes make them particularly well suited for intelligent deformable machines.

Our research centers on μm - to cm-scale miniaturized DEAs. We present the microfabrication, design and operation of a wide range of DEA devices, based on soft silicone elastomers and printed silicone-based conductive inks. Our devices cover a wide range of applications, including compliant grippers for grabbing small space debris, foldable control surfaces for small drones, arrays of $100 \times 100 \mu\text{m}^2$ actuators to apply mechanical strain to biological cells, and fast ($150 \mu\text{s}$) tunable polymer lenses.

Our research goal is fully flexible smart machines that are reliable, self-powered, incorporating high strain, high energy-density silicone elastomers actuators, with integrated sensing and flexible printed control circuitry.

9517-26, Session 7

Smart sensors and calibration standards for high precision metrology (*Invited Paper*)

Uwe Brand, Sai Gao, Zhi Li, Lutz Doering, Min Xu, Sebastian Bueteffisch, Physikalisch-Technische Bundesanstalt (Germany); Erwin Peiner, Technical University Carolo-Wilhelmina at Braunschweig, Institute for Semiconductor Technology (Germany); Joachim Fruehauf, SiMETRICS GmbH (Germany); Karla Hiller, Chemnitz University of Technology, Center for Microtechnologies (Germany)

The surface metrology group of PTB is developing together with partners different types of tactile sensors and calibration artefacts using silicon

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micro-machining.

The first sensor developed together with Carl Zeiss and the Institute for Microtechnology of Braunschweig Technical University was a high precision 3D-microprobe for coordinate measurements of micro-parts. The second sensor developed together with the Institute of Semiconductor Technology (IHT) was a piezoresistive 2D-microprobe with integrated silicon tip for roughness measurements inside of modern diesel injection nozzles. The smallest version of this sensor is only 30 μm wide but 1.5 mm long and allows to measure roughness in bore holes with diameters below 100 μm . The third sensor is a micro-electro-mechanical system (MEMS) based on a lateral comb drive with electrostatic actuation and capacitive displacement measurement. Applications are tensile testing of nanometre thin free standing films, nanoindentation, scanning-probe microscopy (AFM) and the calibration of AFM cantilever normal spring constant.

Silicon is due to its excellent linear elastic behaviour also the material of choice when designing calibration standards for dimensional metrology. Not only depth setting standards were fabricated in cooperation with the Technical University of Chemnitz and the SiMetrics GmbH, but also silicon beam and bridge type stiffness standards for the calibration of probing forces of stylus instruments, nanoindenters, coordinate measuring machines and AFMs. A new type of meander shaped bridge type standard developed together with the IHT and the CiS GmbH reduces the dependence of the stiffness from the probing location. First results of a new concept which allows to calibrate probing force and displacement directly based on two springs in series are also presented.

9517-27, Session 7
Characterization of a dispersion-controlled approach to surface profilometry on wafers using a white-light interferometer

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The manufacturing of structures on wafers demands high quality materials and production processes. Geometric deviations of structures can lead to systematic errors during all steps of manufacturing and therefore to high running expenses for calibration. Some requirements for the characterization of the wafer topography are high measurement resolution, fast data acquisition and the capability to perform measurements in-line.

In this paper an alternative approach to surface profilometry based on a combined time-frequency domain white-light interferometer is shown. Within the setup a reference interferometer arm contains of a fixed mirror and a material with known dispersion while a second arm is aligned to a sample e.g. a wafer surface. Contrary to established dispersion characterization methods the used approach utilizes the surface profile of the sample as the translational interferometer arm. The corresponding difference of the optical path length can be measured as a change of the equalization wavelength on a spectrometer. Due to the known dispersion of the reference material an equivalent change in height can be calculated from the equalization wavelength.

In order to show the basic working principle and to evaluate the characteristics in terms of accuracy and repeatability experiments were carried out in the range of 400 to 1000 nm. First of all data on the thermal and vibrational stability of the setup were recorded over a period of 20 hours. In a second step height profiles ranging from 1 μm to 100 nm were emulated by using nm-precision translation stage. By using the described approach it was possible to measure the given height profiles with reasonable deviation. As a third step measurements on wafers could

be performed and compared with reference measurements in order to prove the usability of the measurement approach.

It has been found that a reliable acquisition of profile differences in the given range was possible.

9517-28, Session 7
Piezoresistive position microsensors with a ppm-accuracy

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The results found at characterization of novel contact MEMS sensors for position detection with ppm- (part per million) accuracy are reported in the present work. The devices comprise two rigid members: a single anchored and a single actuated part, connected via monolithic flexures. Every monolithic flexure comprises two strain detecting cantilevers, each having two embedded piezoresistors connected in a voltage divider. Further, the dividers are connected in a Wheatstone bridge, additionally enhancing usability of the sensor signal. Sensing piezoresistors are located either in the sidewalls or on the top-surface of the fixed end of the flexures in the areas of highest strain, thus high displacement sensitivity has been achieved.

The MEMS sensors provide multiple independent signals, each responding to the relative position of the actuated and the anchored parts. Exploiting different flexure layouts, a travel range between 50 μm and 1.8 mm and sensors' sensitivity in the range between 20 $\mu\text{V}/\mu\text{m.V}$ and 2 mV/ $\mu\text{m.V}$, have been demonstrated.

Based on experimentally measured results at characterization of 1D, 2D and 3D position sensors a method of calculation of the above mentioned relative position with ppm-accuracy has been proposed. For example, all three translational degrees of freedom (DoF) of the actuated part can be simultaneously defined when three independent flexures are monitored. Due to the close distance between the flexures' contact points to the actuated part, its position can be accurately calculated though neglecting the relative displacements between the mentioned contact points.

The present work is a part of a common approach to develop a novel sensor platform for precise measurement of various physical values when they are transduced in a change of the relative position. Due to the demonstrated record high accuracy, the proposed piezoresistive MEMS devices remove most of the application constraints of contact position sensors. Alternatively, up-to six physical values can be simultaneously monitored.

9517-30, Session 8
Multifunctional thin film sensor system as monitoring system in production

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The two most important measurement categories in production are temperature and load. Therefore commercial sensors are applied in machinery as near as possible to the working parts. For a cost efficient production the integration of sensor elements directly on top of the surface in the heavily loaded regions is important to get the real temperature and load distributions during the production process. Therefore a new multifunctional thin film sensor system is in development.

This multilayer system starts with the piezoresistive hydrogenated carbon film, deposited homogeneously directly on the steel component of machinery. It is deposited in a PACVD process in a thickness of 6 μm . This layer has a hardness of 20 GPa, so it can be integrated in harsh environments. In the second step a structured deposition of an insulating layer is realized also in a PACVD process. This layer with a thickness of 1 μm is a carbon based layer modified with silicon and oxygen with a hardness of about 8 GPa. In the third step a homogeneous chromium

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layer is deposited in a PVD process in a thickness of just 200 nm. This metal layer gets structured by a combined process of photolithography and wet etching. The results are chromium meander structures only on the insulating layer for temperature detection and electrode structures. They start in direct contact with the piezoresistive ground layer where load measurement is relevant. The contact areas of these structures are lying on the insulating layer and they are connected by a conductive path. These structures have to be protected against wear with the insulating silicon and oxygen modified carbon layer, which is also used as intermediate layer. The thickness of the top layer is about 3 μm .

The first applications of this thin film sensor system are in strip drawing machines, where the metal sheet moves over the layer system and in injection molding machines. There the sensory layer gets in direct touch with the polymer melt.

9517-32, Session 8

Car glass microphones using piezoelectric transducers for external alarm detection and localization

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This work describes the potential use of car windows as a long range sensing device for external alarm signals. The goal is to detect and localize siren signals (e.g. ambulances and police cars) and to alert presbycusis drivers of its presence by visual and acoustic feedback in order to improve individual mobility and increase the sense of security. The car's glass panes are equipped with 50 mm piezoelectric rings able to detect bending waves collected in the 4 mm thick tempered glass window operating as an acoustic antenna.

For the acoustic car glass, first, a test bench is set up with a Renault Zoé front left window. The door window can be partially opened and closed with the standard door 12V DC motor. An average sensitivity after 60 dB amplification on a 4 kHz bandwidth is estimated at 27 mV/Pa. Then, the car glass transfer function is measured as the glass is mounted in its surrounding and sealing rubber. In general, the glass pane is acting as a high pass filter due to its inherent stiffness and provides only little damping. Thus, there is only a small output signal for low frequencies up to about 300 Hz. Then, the signal is amplified up to about 1 kHz and remains stable at higher frequencies apart from some holes. In the frequency range required for alarm detection enough signal should be provided. Finally, six windows are used to detect and localize an external alarm signal.

9517-33, Session 8

The micro unmanned air vehicles (micro UAVs) In ISR missions In the operation area

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In terms of the optimization of the planning process, the formation of situational awareness which is the first step in planning is very important. To know and determine what the required data is, to what extent it will be used, from where it is obtained, when and in which format it is needed by the planners and decision makers will both provide standardization and minimize the time spent for planning process. In today's operation area, Unmanned Air Vehicles (UAVs), satellites, aircrafts and other many platforms are used to obtain required data accurately and quickly in the Intelligence Surveillance Reconnaissance (ISR) missions. Meteorological constraints, being detected by enemy air defense systems, insufficient range, command and control failures, communication hitches and not having stealth feature prevent to obtain correct and on-time intelligence data. Several studies are worked on to solve these problems. In addition to these efforts some new kinds of platforms are being tried to use and to adapt in operation area. One of these platforms is the Micro UAV which has already used in the other field of life.

In today's operation area, ISR activities are executed to prevent lose of civilians, to reach the desired end of the operation in optimum conditions. Especially optical systems which are very important for the continuously changing operation conditions are affected adversely from concealing and hiding activities of wheather. Micro UAVs have an inherited stealth feature because of their small dimensions. With this feature, they are evaluated as important ISR platforms which can be effective in depth of the operation area.

In near future, considering that Micro UAVs will provide several advantages in accordance with technological developments by using with other platforms in ISR activities, It is expected that air operation will be more effective. The adverse conditions which are affecting the missions and encountered by the other ISR platforms are thought to be solved with Micro UAVs. So, It is planned to execute more flexible ISR operations. In this work, firstly, the difficulties in the operation area are identified. It is studied which difficulties can be answered by the Micro UAVs. This work is held in the context of technical features and capabilities of platforms, components of air operation area and requirements of ISR activities. In an analysis of scenario which occurs in a low density air operation, it is evaluated that using Micro UAVs in the air operation area is effective.

9517-34, Session 8

Autonomous solutions for powering wireless sensor nodes in rivers

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A need for enabling autonomous powering of wireless sensor network nodes is evident today. Sensor nodes may be placed in locations hard to access and powered via batteries of limited lifetime. Different energy harvesting principles allow to overcome these limitations.

Energy harvesting concepts designed for sensor nodes to be placed in watercourses, are explored in this work: a miniaturized underwater turbine, a 'piezoelectric eel' and a hybrid turbine solution coupled with a rigid piezoelectric beam. The foreseen autonomous sensor nodes are to be placed 0.5 m from the bottom of the river and used for measuring pollutants' concentration in the river flow.

The miniaturized underwater hydro-generator, designed in a 3D modelling software, is based on a DC generator enclosed in a watertight enclosure. The electronics used to adapt the voltage levels to the employed sensors is designed and manufactured. Laboratory and river experiments are conducted showing that the achieved power levels are compatible with the foreseen application.

The piezoelectric eel is a composite flag-like compliant device made of two layers of piezoelectric polymer PVDF, a substrate layer and electrodes placed on PVDF's surface layer. A bluff body induces Karman vortexes coercing the eel to move in a flapped motion. A custom software, where fluid flow is modelled using Navier-Stokes equations, while the eel is modelled as a massless beam interacting with the fluid, and a second massive beam, which is connected to the first one via stiff springs, is developed in C++. The eel is prototyped and its performances are experimentally assessed.

The third proposed harvesting configuration is a solution based on 'plucking' a rigid piezoelectric cantilever by means of fulcrums protruding from propeller's shaft and then allowing it to vibrate freely thus generating electrical charge. The concept is modelled via a finite element model in a transient analysis routine.

9517-40, Session 8

Real-time synchronization of wireless sensor network by 1-PPS signal

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The use of wireless sensor networks with different nodes is desirable in a smart environment, because the network setups can be done without fixed infrastructure. The flexibility of the monitoring system is fundamental where the use of a considerable quantity of cables could compromise the normal exercise, could affect the quality of acquired signal and finally the cost of the materials.

The synchronization of data acquisition is the core of the real-time wireless sensor network (WSN). In this paper, we present a comparison between different methods proposed by literature for the real-time acquisition in a WSN and finally we present our solution based on 1-Pulse-Per-Second (1-PPS) signal generated by GPS systems.

The sensor node developed is a small-embedded system based on ARM microcontroller that manages the acquisition, the timing and the post-processing of the data. The communications between the sensors and the master based on 802.15.4 protocol and managed by dedicated software.

Finally, we present the preliminary results obtained with a wireless sensors system for structural health monitoring of civil structures placed in seismic zones.

9517-35, Session 9

The effect of sensor temperature and MOx layer thickness on the sensitivity of SnO₂- and WO₃-based chemiresistive sensors to ethylene gas

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Detection and identification of different gases and volatile organic compounds (VOCs) is an important field of research. The integration of sensitive chemiresistive gas sensors in different industrial sectors is critically important for improving human health, safety and quality of life [1,2]. Ethylene, a well-known VOC, is important for the development of plants and is a good indicator of fruit-ripening [3]. The on-site detection of ethylene in fruit-storage facilities and transportation units will improve the freshness, flavor and shelf-life of fruits and fruit-based products.

In our study, the effect of sensor temperature and metal oxide layer-thickness on the sensor response (sensitivity, saturation and desaturation times) for quantitative ethylene detection were thoroughly investigated using 7 different sensor structures (3 WO₃ and 4 SnO₂). The sensitivities of both sensing layers increased with the temperature of the sensor; the SnO₂ layer (R/R_g = 5.2) was approximately 3.5-times more sensitive than WO₃ layer (R/R_g = 1.5) at 350 °C, and difference was even more pronounced at 450 °C. The ethylene saturation times were similar for both sensing layers at temperatures higher than 400 °C (~ 70 s). The WO₃ layer saturated faster than SnO₂ at lower temperatures. A similar trend was observed in the measurements of the desaturation time. Reducing the layer-thickness increased sensitivity and the speed of saturation and desaturation.

Literature:

1. A.D. Wilson, M. Baietto, *Sensors*. 2009, 9, 5099-5148.
2. K.A. Mirica, J. M. Azzarelli, J.G. Weis, J.M. Schnorr, T.M. Swager, *P. Natl. Acad. Sci. USA*. 2013.
3. B. Esser, J.M. Schnorr, T.M. Swager, *Angew. Chem. Int. Edit.* 2012, 51, 1-6.

9517-36, Session 9

MEMS-based platform optimized for inkjet printing of nano-sized, gas sensitive functional metal oxides to enable the measurement of gas induced changes of the heating power

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Metal oxide (MOX) based gas sensors are usually read-out by determining the electrical resistivity of the gas sensitive layer. However, chemisorption of gas species not only changes the amount of available charge carriers but also affects the heating power necessary to maintain the layer's temperature. While in standard bulk sensor chips the change in heating power is difficult to detect due to their large power consumption, micromachined Si based hot plate devices offer the possibility to measure these changes. Here we present results that have been obtained utilizing a novel hotplate platform optimized for low-power consumption and inkjet printing of gas sensitive, nano sized functional metal oxide particles. The temperature of the gas sensitive layer is controlled via the heaters resistance and the heating power is recorded using a fully automated gas measurement apparatus. To account for effects resulting from changes in the heat conductivity of the gas composition, the measurements have been performed in parallel using hotplates with and without a metal oxide layer deposited onto them. The measurement of the heating power allows for determining signal changes as low as to 10⁻³. The metal oxide layers investigated within this report are zinc oxide (ZnO) and copper (II) oxide (CuO). The MOX particles are derived from commercially available powders and are deposited onto the hotplate platform using a DIMAX ink jet printing system. Combining the described approach with measurements of the gas dependent resistivity yields two independent sensing quantities from one single device and might be an important cornerstone on the way towards selective metal oxide based gas sensors.

9517-37, Session 9

Photoacoustic CO₂ sensor system with potential for further miniaturization and integration in silicon

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The CO₂ concentration is next to humidity and temperature the main indicator for indoor air quality and correlates with the number of persons inside a room. Carbon dioxide at high levels may cause occupants to feel tired, to grow drowsy, or to get headaches. However, Europeans spend more than 90% of their time indoors. To ensure the human health, the indoor carbon dioxide level should be less than 1000 ppm. Due to these facts there is a high demand for miniaturized, low cost and energy efficient CO₂ sensors for the consumer market.

To realize small and energy-efficient mass-market sensors, we develop novel miniaturized photoacoustic sensor systems with optimized design for real-time, selective CO₂ measurements.

The photoacoustic effect describes the formation of an acoustic wave in a gas sample due to the absorption of photons. The acoustic wave is a pressure signal which is periodically generated by a modulated IR-source. The sensor system consists of two chambers, a measurement and a reference chamber. The reference chamber consists of an integrated pressure sensor in a target gas atmosphere. As pressure sensor we use a commercially available cell phone microphone.

We describe the miniaturization process of our developed system by scaling down volume and size of all components. The miniaturization process is approved by comparing measurement results with detailed simulations. The system is manufactured in precision mechanics with IR-optical sapphire windows as optical connections. During the

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miniaturization process the sapphire windows are replaced by silicon windows with special IR anti-reflection coating. The results of the experiments show the possibility for the realization of the system in silicon micromechanics in the ongoing miniaturization process. The developed systems are characterized in detail by gas and optical transmission measurements. The photoacoustic sensor system shows a high capability for mass-market for indoor CO₂ sensors.

9517-38, Session 9

Novel SH-SAW gas sensor based on Graphene

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The general perspective of this work is to obtain a gas sensor on a stable detection platform, which is able to prevent critical concentration levels, dedicated to the equivalent compound. Gas sensors have been studied extensively, because of their ability to detect combustible, hazardous and toxic gases. Particularly the detection of gases could be realized by introducing the principle of acoustic wave sensors based on graphene. The graphene oxide, used as a sensitive layer on the SH-SAW platform, is the key of the sensor sensitivity to target Volatile Organic Compounds. This novel conception allows high sensitivity of the resulting sensor. Innovative methods of graphene solutions have been prepared in order to explore gas sensing applications. The real time detection measurement of the coated sensor reports that the Graphene Oxide is very promising for gas sensing applications. For vapor detection, a constant stream of nitrogen gas with several ethanol and humidity concentrations flown past the sensitive part of the sensor, placed in a hermetic chamber. The adsorption of vapors on the sensitive layer (Graphene Oxide) leads to a frequency shift of 10.5 - 83.2 kHz and 22.7 - 193.3 kHz, at exposure of 100 -750 ppm of ethanol and 6.22 - 41.92% of Relative Humidity, respectively. The experiments have been realized at room temperature; rapid response and recovery time were observed. Further work will focus on realizing graphene-loaded SH-SAW gas sensors with even higher sensitivity to a specific target gas, thus paving the way towards hypersensitive and selective gas sensors.

9517-39, Session 9

Nearly zero-power consuming gas sensor devices based on individual metal oxide nanowires

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Nanowires are interesting candidates for their incorporation into future low power sensing devices thanks to their large surface-to-volume ratio and to the possibility of growing them monocrystalline and almost defect-free, which gives rise to controlled and reproducible properties. This can be seen as the result of the very extensive research which has been carried out in the field of metal oxide gas sensors of the last 20 years.

In this work we will present the results of our research in developing gas detection systems based on individual nanowires using the self-heating methodology. For this we have fabricated nanosensors using single metal oxide nanowires by employing advanced nanofabrication tools and ad-hoc designed suspended microhotplates, containing both interdigitated electrodes and integrated heater. We have designed an electronic board that allows the control of the heating power and, simultaneously, the

readout of the sensors resistance, which varies in the presence of different gases. The results show that few microwatt are required for the whole process, from which the sensor itself consumes below 1 microWatt. This has allowed the use of energy harvesting techniques to power the whole system.

The behaviour of the gas sensing system will be reported and critical discussion on the further improvements will be provided.

and tad-. For this purpose we have been using single crystalline, dislocation free metal oxide nanowires (diameter 40-400 nm), synthesized by chemical vapor deposition (CVD) of molecular precursors [2] grown on ceramic substrates. The grown nanowires have been transferred onto suspended microhotplates with integrated heater and interdigitated microelectrodes. Advanced metallization techniques based on Focused Electron Beam Induced Assisted Deposition (FEBID) inside an SEM instrument have been used to fabricate the contacts to the individual nanowires [3].

Two different low-power operation modes are identified according to the heating method used to achieve the high temperature operation required for these devices. On the one hand, the independent use of the microhotplate's integrated heater to reach the operation temperature and of the interdigitated electrodes to allow the measurement of the resistance change in the presence of different gases. Typical power values to achieve the adequate operating temperature can be as low as 8mW. This has allowed us the development of a portable gas detection system based on these devices and that can be operated with batteries.

On the other hand, the self-heating of the nanowires when a measuring current flows through them allows the simultaneous the heating and measuring the nanowire, dramatically reducing the power consumption by 2-3 orders of magnitude and simplifying the practical operation of the devices. However, the required control electronics that assures the correct and stable current flow through the device becomes much more complex. Based on this approach we have developed a portable detection system that uses a thermoelectric generator to provide the required operating power to both heat and read-out the gas sensing results [4].

In this work we will show the degree of maturity of both approaches in the path towards almost zero-power gas detection systems based on individual nanowires and we will critically discuss the steps required to further improve the sensing properties and to transfer the approach for mass production.

Conference 9517B: Cyber Physical Systems

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9517-101, Session 10

Interdigitated design of a thermoelectric microgenerator based on silicon nanowire arrays

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Micro and nanotechnologies have already made possible the fabrication of small, low cost and good performance sensors. Energy autonomy keeps being one of the most desired enabling functionalities in the context of off-grid applications, such as wireless sensor networks. In many such applications, wired power is not feasible and batteries are normally used. However, battery replacement will eventually become impractical (economically, environmentally, and logistically) not only for sensor networks in remote places or harsh environments, but also for more standard applications if the number of nodes explodes exponentially. Harvesting energy, tapping into environmentally available sources such as heat and vibrations, may be a good solution in man-made scenarios applications.

Thermoelectric harvesting based on silicon nanowires is a promising SINERGY is a recently EU project which focuses on silicon and silicon friendly materials and technologies to explore energy harvesting and storage concepts for powering microsensors nodes. Silicon technologies provide an enabling path to miniaturization, 3D architectures (improved energy densities), mass production with economy of scale, and the ability of power intelligence integration. Being silicon technologies the ones used for the fabrication of the sensors themselves, they are the prime candidate for building microenergy solutions of similar robustness able to power such sensors during their whole lifetime.

The device under test [1], shown in figure 1, consists of a suspended microstructure (S1) bridged to a bulk silicon structure (S2) through an array of silicon nanowires filling the trench (10µm) between the two silicon masses. Different designs with multiple trenches interconnected by transversal silicon spacers are also considered to further increase the thermal gradient between the two silicon masses (figure 1 shows a 3 trench case). In addition, an electrically isolated tungsten heater is integrated on the suspended microstructure for test and characterization purposes.

The measured Seebeck coefficient S and thermal conductivity k , together with an estimate of electrical conductivity σ , achieved from literature data reported for similar boron doped silicon nanowires, allow us to deduce limits for the power factor and the ZT figure of merit for the meta-material under test, resulting in ZT values between 0.30 and 0.93 [2].

In this work the thermoelectric generator includes interdigitated structures which increases significantly the total number of silicon nanowires able to produce energy in the presence of a thermal gradient, while the device area is maintained. Therefore the total power density from the thermoelectric generator might increase.

References

- [1] D. Dávila et al., "Planar Thermoelectric Microgenerators Based on Silicon Nanowires", *Journal of Electronic Materials* 40, pp. 851-855 (2011).
 [2] C. Calaza, M. Salleras, D. Dávila, A. Tarancón, A. Morata, J.D. Santos, G. Gadea, L. Fonseca, "Bottom-Up Silicon Nanowire Arrays

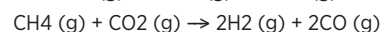
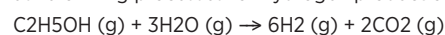
for Thermoelectric Harvesting", 12th European Conference on Thermoelectrics, Madrid (2014).

9517-102, Session 10

Fabrication and characterization of a fuel flexible micro-reformer fully integrated in silicon for micro-solid oxide fuel cell applications

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One of the most promising applications of miniaturized fuel cells is powering portable devices, taking advantage of their high specific energy and grid independence (only fuel refilling is needed once finished).¹ In particular, the development of micro-solid oxide fuel cells (micro-SOFCs) is gaining interest because they combine high fuel flexibility with a high efficiency (five times higher than common Li-ion-batteries).² However, several technological challenges have to be overcome before being able to introduce the technology into the real market. One of the most relevant issues is to safely produce a continuous hydrogen flow for directly fuelling the micro-SOFCs from fuels easy to handle and store. Catalytic fuel reformers using organics have become a realistic alternative as they can provide high energy density, low cost, safety, and easy transportation³. Among them, ethanol and methane are currently considered as some of the most feasible candidates because both present a clear regulation and can be produced from renewable sources (bio-methane and bio-ethanol) and, particularly the ethanol, yield high hydrogen content on a molar basis⁴. Since ethanol is a liquid (at atmospheric temperature and pressure) and methane is a gas, ethanol steam reforming (ESR) and methane dry reforming (MDR) (eq. 1 and eq. 2, respectively) are preferred as reforming processes for hydrogen production⁵.



This work reports the design, manufacturing and experimental results of a novel silicon-based micro-reformer capable to produce acceptable hydrogen production rates from ethanol by steam reforming and methane by dry reforming to supply a micro-SOFC system.

As represented in Figure 1, the current design is based on micro-structured vertical channels crossing a 500-µm silicon platform. The projected area of the micro-reactor is 15 mm x 15 mm while the reactive area is more than 36 cm². This huge active surface per projected area (16 cm²/cm²) is achieved by more than 4.5x10⁴ vertical micro-channels (50µm in diameter) perfectly aligned and loaded with Rh-Pd/CeO₂ catalyst system through which the fuel flows. This high surface-to-volume ratio of micro-channels (8x10⁴ m²/m³) leads to higher performances of both reforming reactions by achieving a larger specific contact area and a shorter diffusion length. An integrated serpentine tungsten heater is embedded in the active area to reach the operation temperature autonomously. In addition, to improve the thermal efficiency of the device, the micro-reformer has been encapsulated with an insulating glass cover by anodic bonding. A two-step glass wet-etching process has been developed for the glass cover fabrication in such a way that a well-defined deep cavity for the fluid flow and well-defined pathways for the external pads of the heater are achieved.

The suitability of the catalytic micro-reformer for ESR and MDR has been tested under operation conditions compatible with those of micro-SOFC systems. Preliminary experiments are conducted by using an external

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source to study the effect of temperature in both reforming reactions. Figure 2 shows the fuel conversion and volumetric hydrogen production obtained over the micro-reformer for the ESR (Fig. 2a) and MDR (Fig. 2b) reactions depending on the operation temperature. The selectivity towards ESR products is shown in Fig. 2c and the composition of the outlet gas of MDR is represented in Fig. 2d.

As observed in Fig. 2a and Fig. 2b, the conversion rate of both fuels increases with temperature, but the production of hydrogen is not meaningful until 700°C (5.1 mL/min for ESR and 4.7 mL/min for MDR). Ethanol is completely converted at 750°C yielding higher amounts of hydrogen (7.7 mL/min at 750°C and 10 mL/min at 800°C), whereas the maximum methane conversion achieved is ca. 36% at 800°C leading to a hydrogen production of 6.9 mL/min. As is represented in Fig. 2c and Fig. 2d, the reforming rates have no significant extent at lower temperatures compared to decomposition of fuels. In the case of ESR (Fig. 2c), only at high temperatures (from 700°C onwards) the ethanol is reformed to a high extent, increasing the amount of hydrogen produced. In contrast, for MDR (Fig. 2d), methane decomposition is the main reaction producing hydrogen, since no detectable amounts of carbon monoxide were measured from 600°C to 700°C. Methane dry reforming appears from 750°C, leading to higher syngas productions and carbon dioxide consumption.

This functional fuel-flexible micro-reformer is the basis for a complete gas processing unit as a subsystem of an entire micro-SOFC system.

REFERENCES

- 1A. Bieberle-Hütter et al, A micro-solid oxide fuel cell system as battery replacement, *J. Power Sources*, 177, 123-130 (2008).
- 2I. Garbayo et al, Full ceramic micro solid oxide fuel cells: towards more reliable MEMS power generators operating at high temperatures, *Energy Environ. Sci.*, 7, 3617-3629 (2014).
- 3L.F. Brown, A comparative study of fuels on-board hydrogen production for fuel-cell-powered automobiles, *I. J. Hydrogen Energy*, 26, 381-397 (2001).
- 4J. Llorca et al, First use of macroporous silicon loaded with catalyst film for a chemical reaction: A microreformer for producing hydrogen from ethanol steam reforming, *J. Catal.*, 255, 228-233 (2008).
- 5D. Pla et al, Fabrication and characterization of a micro-reformer unit fully integrated in silicon for ethanol conversion. 38th International Conference and Exposition on Advanced Ceramics and Composites (ICACC), Daytona Beach (2014).

9517-103, Session 10
An efficient start-up circuitry for de-energized ultra-low power energy harvesting systems

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Cyber-physical systems often include small wireless devices to measure physical quantities or control a technical process. These devices may be placed at specific locations for a direct access to the measurement quantity or best impact of the actuator. These locations are often characterized by a poor accessibility of wired infrastructure. So they need an autarkic power supply which can be achieved with by batteries or energy harvesting systems (EHSs). The use of batteries has the drawback that the maximum operation time is limited. This time can be enhanced by EHSs which convert environmental energy into electrical energy. However, the convertible power is often limited and discontinuous which cause the need of an energy storage unit, e.g. a supercapacitor. If this unit (and thus the whole system) is de-energized, the start-up process may take a significant amount of time, because of an inefficient energy harvesting process during this process. The energy harvesting device is not operated near its maximum power point, because an active control is not available. Another problem during a cold start-up may be caused by the supplied device which includes typically a microcontroller. The microcontroller can draw more power than available at low voltages (below the minimal supply voltage), although it consumes on average less

power after a correct initialization. This is the reason why it is possible that the system will not start. Therefore, this paper presents an EHS which deals with these two problems. First, the system includes a cold start-up charging circuitry which enables an efficient charging of the de-energized energy storage unit. Second, it includes an undervoltage load disconnecter which supplies the device only if enough energy can be provided by the energy storage unit to initialize it correctly.

9517-104, Session 10
Opportunities for energy harvesting in automobile factories

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This paper investigates the opportunities of energy harvesting at a large scale automobile plant for the purpose of powering wireless sensors. While wireless sensors are used for equipment health monitoring as well as asset tracking in the plant, the drawback experienced by facility and plant managers is the associated cost in replacing the batteries. In order to alleviate this financial burden, energy harvesting techniques can be used to either replace battery power and thus create an autonomous robust system. Amongst the diverse use cases for energy harvesting techniques, this paper focuses on characterizing how much power is available within the environment of a car factory. In determining the energy harvesting system to adopt, it is essential that the environment where the device would be placed is evaluated, i.e. if the survey results show that the irradiance from the combined lightning (indoor and outdoor) is sufficient for photovoltaic cells, then this might be a better harvesting option than harvesting machine thermal gradients. The measurement campaign at the plant will measure radio frequency energy in terms of power spectral density (dB/Hz), measure machine vibration in terms of acceleration (ms⁻²) and frequency, measure indoor lightning in terms of irradiance (W/m²) and thermal gradients between machines and the room temperature in terms of degree Celsius. The survey will allow an energy harvesting prototype to be developed that is capable of combining two separate ambient energy contributors.

9517-105, Session 10
Scaling of dynamic thermoelectric harvesting devices in the 1-100 cm³ range

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Energy harvesting as an electrical energy source for autonomous wireless sensors has the potential to reduce cabling in aircraft, thus reducing design complexity and overall weight. Thermoelectric energy harvesters can exploit the fuselage as a heat source, and through the use of phase change materials (PCMs) as thermal mass, convert the ensuing temperature difference to electricity. This type of thermoelectric harvesting, coined dynamic thermoelectric harvesting [1] or heat storage thermoelectric harvesting [2], was initially proposed and experimentally demonstrated in 2008 and 2009 [3], and further analysis on the subject has been reported in [1, 2]. Since then, a variety of its aspects have been studied using analytical and numerical modelling [2, 4], flight testing [5, 6] and integration into wireless sensor nodes [7].

In this work, two new heat storage thermoelectric harvesting devices are presented: one smaller and one larger than the typical size of devices already reported in the literature. The change of PCM volume was approximately an order of magnitude for both devices. In this way, a first

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assessment of scalability of this device concept was obtained. The small prototype contains 1.4 ml of water as a PCM, and was able to deliver 5.8 J of electrical energy over a 40 degC temperature cycle (from +20 degC to -20 degC and back). This corresponds to an energy density of 4.1 J per gram of PCM, close to the corresponding 4.6 J/g reported in [2]. The large prototype contains 80 ml of water as a PCM and was able to deliver 254 J (3.2 J/g) of electrical energy over the same temperature. The increased energy density obtained by the smaller implementations can be attributed to better temperature uniformity in the PCM. These results demonstrate the scalability of heat storage thermoelectric harvesters in the range of 1-100 cm³.

9517-106, Session 11

Computationally efficient models enabling behaviour exploration of large scale cyber physical systems by simulations

Peter Waegli, Dr. P. Waegli-Research (Switzerland)

Cyber physical systems (CPS) are a rapidly emerging new class of systems containing tightly connected physical and computational (cyber) sub-systems, which interact to form intelligent, networked systems enabling functions and/or applications not previously possible. However, due to the tight interaction of the physical and the cyber components such systems can exhibit complex and even emergent behaviours, often difficult to predict. Designing robust and efficient cyber physical systems is hence a demanding task, especially since the early use of prototypes is often not feasible due to time and/or financial constraints. In such situations, systems simulations are the only possibility to cope with the task at hand.

In this paper we propose a new method for building computationally efficient models, which mimic the behaviour of cyber physical components as well as of the behaviour of the environment and eventually the users interacting with them. We combine analytical models for the physical part with neural network models for the cyber part to obtain behavioural models of cyber physical system components. Such models can be easily configured as well as upgraded and refined as development progresses. They are computationally efficient and can be networked to simulate even large scale cyber physical systems.

We used a Modelica based system simulation framework, to develop simulations for a variety of Cyber Physical Energy Systems. Applications include the simulation of semi-autonomous mini-grids and of autonomous systems like mobile devices and distributed sensing and actuating nodes using energy harvesting technology. It will be demonstrated how the versatility of the models makes it possible to quickly build models of large scale heterogeneous systems. Results from the simulation based analysis of various energy systems will be discussed. It will be shown, how such simulations are of high benefit to study architectural issues, overall reliability and also commercial aspects.

9517-107, Session 11

On improving low-cost IMU Performance for Online Trajectory Estimation

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Commercial low-cost Inertial Measurement Units (IMUs) consisting of MEMS (Micro Electro-Mechanical Systems) accelerometers and gyroscopes have become more and more used in different applications thanks mainly to their very cheap prices. IMUs are typically used in a trajectory tracking for estimating the states of a system such as acceleration, velocity and position. However these estimates suffer from high inaccuracies resulting mainly from the random variations of the sensitivity and offset of the used MEMS accelerometers and gyroscopes. These random variations originate from the design and the integration (assembly) imperfections of such MEMS sensors, thus making them unstable and very noisy.

The objective of this work is to develop an automatic mitigation strategy to compensate for the offset and sensitivity values of such MEMS sensors

by automatically recalibrating the sensor parameters online. For online trajectory estimation applications, an automatic event detection derived from the IMU signals could be used to activate the automatic recalibration process.

9517-108, Session 11

Ultra-low power sensor for autonomous non-invasive voltage measurement in IoT solutions for energy efficiency

Clemente Villani, Domenico Balsamo, Univ. degli Studi di Bologna (Italy); Davide Brunelli, Univ. degli Studi di Trento (Italy); Luca Benini, ETHz (Switzerland)

The recent research efforts in the field of smart grid and Internet of Things dedicated to energy efficiency is of increasingly importance. Future energy systems require a pervasive monitoring of the consumption of loads in industrial, residential and public service buildings. The continuous analysis of voltage waveforms and current consumption is fundamental for estimating power consumption, harmonic distortions and to elaborate diagnostics about the power quality and wastage in the grid. We propose a non-invasive approach for measuring the voltage waveform of electrical cables which does not require any electrical contact to the mains. This facilitates the installation, because it does not need any breaking of the wire and can be installed on-the-fly without any load shutdown. The proposed solution is equipped with an ultralow power processor and an energy harvesting circuits which permits the sensor to be completely energy autonomous and smart. Voltage is measured by exploiting coupling capacitance elements with an innovative and noise-free method. Together with non-invasive current transformers, this device demonstrates a low-cost and reliable solution for distributed power quality assessment.

9517-109, Session 11

Use of a prototype pulse oximeter for time series analysis

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Nowadays, telemedicine devices are developed for the acquisition and utilization of biological signals such as cardiac rhythm, temperature, arterial pressure in real time. However, most of commercial solutions do not allow access to measured raw data and this limits posterior analysis using large databases. In this work, we present the development of a wireless pulse oximeter (WPO) prototype developed for cardiac rhythm and oxygen saturation (SpO₂) acquisition and processing during large periods of time for time series analysis. For real life activity monitoring, an ergonomic design using 3G or Wifi platform was designed. The prototype was implemented using an Arduino programmable microcontroller and designed for real-time data acquisition and processing. The device electronics was designed de novo and consists of two pulsed red and infrared commercial LEDs facing a broad spectral photodetector with the patient finger or earlobe in between. The sampling rate and light intensity are adaptable to different patient's absorption levels and the photodetector signal is sent to a graphical user interface (GUI) visible on a computer or a mobile phone for real time analysis or diagnostics evaluation. The WPO is indeed linked to a custom-made, automatic algorithm that successfully calculates and displays the power spectrum of the patient's heart rate variability (HRV) in real life activities and may trigger user-specific alarms or reports as suggested by the preliminary results. Thanks to its connectivity, the device also allows for rich patients databases construction; and saves raw data if different data analysis is required. Accessing this kind of information at a low cost and with ease of use is indeed critical nowadays in personal medicine tools, and our device responds to this need as it enables its massification.

9517-110, Session 12

Abstraction of communication resources in model-based design frameworks for CPS

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The Model Based approach is an effective way to allow designers to develop their own CPSs, as it frees them to learn the low-level technicalities usually involved in such systems, such as code generation, Interrupt handling, scheduling of parallel tasks, protocol handling, and so on.

While the existing formalisms (i.e. Function Blocks or GRAFCET) are well suited to model the behavior of systems in terms of interaction with their physical periphery, none of them are natively well suited to abstract the interaction with the ICT world through the packet communication resources that equip most of today's CPSs, such as serial or network ports.

The present paper discusses an extension to fill this gap: the basic idea is to abstract the communications interfaces and, possibly, the message exchange taking place through them according to with high level protocols (i.e. ModBUS, HTTP,...) as interactions with a kind of logical periphery through a set of ad hoc high level primitives.

A variety of communications media and devices physical are available in embedded boards that encapsulate the communication at different layers of the OSI model, from RS-232 or RS-485, working at Data Link layer to Ethernet networks working at Transport layer.

Two basic primitives are detailed.

1- The Packet Communicator abstracts serial links such as RS-232, RS-485 or SPI; 2 functions are defined, Send and Receive

2- The Network Communicator abstracts interactions over the Ethernet providing a http interface; 4 functions are defined, four functions are provided: WsGet, WsResp, WcGet, WcResp; they work in pairs, each one dealing with one direction of the transmission, on the same channel,

The above primitives are complemented by a set of Protocol Co/Decoding functions; for the case of ModBUS RTU, four functions have been introduced, MBusSIGet, MBusSIRsp, MBusMsGet, MBusMsRsp.

An industry grade IDE, TaskScript, where such functions have been implemented, has been used to design a number of test applications, each of which was completed in a few hours.

9517-111, Session 12

Gbps wireless transceiver for high bandwidth interconnections in distributed cyber physical systems

Sergio Saponara, Bruno Neri, Univ. di Pisa (Italy)

A key issue in emerging Cyber Physical Systems is the networking at high speed of all the nodes belonging to the network of distributed sensing, processing and actuation units. The growing use of high speed sensors like camera, radar, lidar, photo detectors etc. to increase the knowledge of the operating environment in several application fields (transports, surveillance, domotic, health at home systems, aerospace, defense,...) increases the interest in high speed communications, with wireless connections to avoid wiring harness, beyond 1 Gbps [1-3]. The relevant transceivers have to be integrated at low cost and low area/weight in the devices. To this aim the paper proposes the design of integrated transceivers, designed using the same CMOS technology of the digital part, able to reach a transfer data rate above 1 Gbps at a distance of 10 meters. This can enable the diffusion of local area network of high speed sensing and processing nodes in home and office scenarios, or on-board vehicles such as cars, trains, satellites, ships, airplanes, ... The selected target frequency is 60 GHz around which there is a worldwide available free spectrum of several GHz, e.g. 7 GHz from 59 to 66 GHz in Europe. Hence adopting a simple modulation scheme like OOK (On-Off Keying) or in-coherent ASK (Amplitude Shift Keying) with a spectrum efficiency of 1 bit/s/Hz a bandwidth of several Gbps can be achieved while the complexity of transceiver is kept small. Indeed as reported in Fig. 1 for an

in-coherent ASK receiver just an envelope detector is needed at receiver side. Avoiding complex PLL for local oscillators and synchronizations and avoiding high-Q LC filter the transceiver can be integrated with a small area. We integrated the ASK incoherent transceiver whose architecture is reported in Fig. 1 in a 65 nm 1.2V digital CMOS SOI technology. The receiver is characterized by a noise figure of 4 dB with an LNA gain (2 stage cascode) higher than 20 dB. The transmitter has a maximum power transmitted of 12 mW. The power consumption of the whole transceiver is around 180 mW. Note that at such high frequency the lambda amounts to few mm and hence also the antenna can be integrated on chip further reducing area and complexity. To this aim a double slot antenna has been integrated with a S11 bandwidth of 8 GHz and a gain of roughly 3 dBi. The achieved data rate from 59 to 66 GHz is smaller than the theoretical 7 Gbps (7 GHz x 1 bit/s/Hz) since a channel coding scheme is used at baseband (coding gain of 8 dB with a redundancy of 40%) to increase communication robustness. Using the designed transceiver we have set up a simulation environment for a network of ten nodes placed at distances from 1 cm to 10m. Fig. 2 reports the achieved SNR as a function of distance. Fig.1 Architecture of the transceiver. As a conclusion the integration of our transceiver can enable at physical layer the implementation of low cost nodes with data rates of several Gbps up to 10m. This can be the success of CPS where high speed sensor nodes are used such as radars, cameras, array of detectors and so on. At higher layers of the networking protocol stack our solution can be made compliant with upcoming IEEE 802.11ad wireless networking standard [4,5] (WiFi/WiGig Alliance) that foresees 3 physical layer frequencies at 2.4 GHz, 5 GHz and 60 GHz.

9517-112, Session 12

Embedded system for supervision analysis and control of photovoltaic power plants

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In recent years the oil price increase, the need to reduce the environment pollution due to fossil combustible exploitation and the need to have low-cost energy sources due to the global economic crisis, have raised the interest in renewable energy sources.

The most efficient system to harvest energy from alternative sources is the injection into the grid; this produces a new grid model where the energy is provided from a distributed network of sources. In these conditions is becoming increasingly important to have the appropriate tools for the control and monitoring of production plants, in order to manage production, according to consumer requirements and costs for each source. The monitoring system integrates in one single tool several functionalities, among them: data logger storing data in a xml database, alarm states handling, communication through wired and wireless channel, to guarantee the message delivery, data analysis, control of the energy production, and video surveillance management. The supervision system is built by several processes running on pc based on a Linux embedded operating system. The communication with devices of the photovoltaic implant supports multiple protocols in TCP/IP and RTU versions. The connection can be established via wired or wireless network.

Could not be possible tests the supervision systems on a production solar power plant handling an onerous number of alarm states. Due this reason we have tested our system with a photovoltaic power plant simulator. From our test the supervision system is able to handle correctly one alarm event each five seconds. The first aim of this supervision system is not to handle very fast events that could damage single device of the implant, but mostly global malfunctions that have low evolution in the time. Events that should be detected in very short time are often provided with dedicated control inside the single devices.

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9518-502, Session PLTue

Measuring life: sensors and analytics for precision medicine (*Plenary Presentation*)

Stefan Harrer, IBM Research (Australia)

The first industrial revolution was about machines, the second one was about life – the third one has just started and connects the life sciences to novel sensor devices through the power of big data analytics and biomedical engineering. Its foundation are the two codependent core tasks of generating and analysing big data. Thereby novel sensing technologies from wearable biometric devices to lab-on-a-chip platforms for exploratory fundamental research on single-molecule characterization and design occupy a key role in the data generation realm. The groundbreaking potential of these novel nano- and microsensor technologies is leveraged through recent advances in analytical techniques for life sciences, healthcare and genomics applications: DNA-sequencing is approaching the 1000-Dollar-Genome milestone allowing for decoding a complete human genome with unmatched speed and at low cost. Increased sequencing efficiency yields massive amounts of sequencing data. Analysis of such data eventually enables understanding the roles of genes and their correlation with an individual's risk of developing a certain disease. Access to this information triggers fundamental questions for doctors and patients alike: What are the chances of an outbreak? Which drugs are available and how should they be applied? In order to provide answers, technologies for discovering novel drugs, for improving existing drugs, and for their intelligent use in an increasingly complex and customized environment will have to be revolutionized. The path from fast and cheap personalized sequencing via smart genomics towards personal prevention and treatment is reshaping medicine as we know it. Integrated sensing technologies closely linked to big data generation and analytics thereby constitute the backbone of personalized medicine, the Next Big Thing emerging from marrying nano- and microtechnology, biotechnology, and big data. In this talk I will describe IBM's involvement in personalized medicine research with a special focus on two bionanosensor projects in the next-generation DNA-sequencing and drug discovery space.

9518-1, Session 1

A SU-8 based flexible microprobe for close and distal recordings from the cortical network

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In the last decades, system neuroscientists have tried to understand how neuronal networks work and how they malfunction in various diseases. Recording and stimulation with large numbers of electrodes either in the whole brain or in vitro preparations (cell cultured neurons or brain slices), has given rise to a great success in the field of neural interfaces.

To ensure good measurements, besides the good contact between the electrodes and the tissue, which is accomplished by using flexible

materials, it is mandatory to maintain the flow of oxygenated solution under the cortical slice in order to ensure its healthy state.

Here, we have focused on the relative activity of infra versus supragranular layers within the same cortical column (vertical propagation), as well as the horizontal propagation along cortical columns in order to study the detailed properties of synchronization and wave travelling within the cortical network in vitro.

A 16-electrode microprobe was fabricated using SU-8 negative photoresist. The design of the microprobe consisted on six groups of 2-3 electrodes (50 μm in diameter and separated by 200 μm) placed in-between an array of holes. Distances between each group were appropriated for recording from a ferret slice, allowing us to evaluate the close versus the distant network activity.

With this SU-8 microprobe it has been possible to register spontaneous slow oscillations and also induced activity in all 16 channels. The holes, which were mainly designed to improve the oxygenation of the slice, were also useful to position puffers that allowed us to locally delivered drugs (glutamate) and to register its response. In addition, they were also used for sticking electrodes to simultaneously record single units that allowed us the synchronous recording of population activity (local field potential) with the electrodes of the probe and single unit activity (with glass or tungsten electrodes).

9518-2, Session 1

A remotely operated drug delivery system with an electrolytic pump and magnetically triggered thermoresponsive valve

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A drug delivery device is presented, combining an electrolytic pump and a thermoresponsive valve, which are both remotely controlled by an electromagnetic field. A solid drug in reservoir approach is used, which can form a long term drug delivery solution by repeatedly dissolving in small amounts of body liquid. The device is capable of periodically releasing drug and prevents uncontrolled drug diffusion. The device is remotely operated by an AC magnetic field (40.5-58.5 mT, 450 kHz) that provides the power for the pump and the thermoresponsive valve. Fig.1 illustrates the working principle of the device. Fig.2 shows the measurement setup with the assembled prototype (a) including platinum and titanium (Pt/Ti) interdigitated electrodes (b) and the proposed catalytic reformer (c). The Litz wire coil (Fig. 2 d) is used to induce AC current that is rectified by a diode. Fig. 3 shows the control over the flow rate with the magnetic field amplitude. It can also be seen that the pump with a Pt coated carbon fiber mesh has a slightly reduced flow rate, caused by competitive recombination of bubbles into water during the electrolytic reaction. The size of inductive coil can be further reduced if a lower flow rate is preferred. Fig. 4 verifies that a Pt coated carbon fiber mesh distinctly improves the bubble recombination rate. A higher recombination rate allows more fresh fluid to refill the drug reservoir before the valve seals the outlet. The thermoresponsive valve consists of a serpentine PMMA bonded micro-channel, which is sealed by a polymerized PNIPAm and mixed with iron powder. The valve's working time and correlated temperature under a magnetic field of 40.5 mT is shown in Fig.5. Fig. 6 shows cyclic operation of the device, which responds with a repeatable and stable behavior.

9518-3, Session 1
A low power on-chip class-E power amplifier for remotely powered implantable sensor systems

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Recent developments on implanted medical devices promise to equip human being with sensor nodes for healthcare monitoring. These implanted devices collect biological and chemical vital parameters in the body and transmit the data wirelessly to a base-station. The small and light-weight implants with remote powering and communication eliminate the wires and increase the comfort of the patients thanks to the advances in nanotechnology and microelectronics.

This study presents an implementation of remote powering and communication system in 180 nm CMOS technology for remotely powered sensor interfaces. An inductively coupled remote powering link is implemented at 13.56 MHz to transfer the power to the implanted system. The induced AC voltage on the implant coil is converted into a DC voltage by a passive full-wave rectifier and DC voltage is charged into a large storage capacitor to sustain the energy. The full-wave rectifier is followed by a start-up control and bias generation unit which generates bias currents for the low drop-out voltage regulator and free-running LC tank oscillator. A voltage regulator is used to suppress the ripples and create a clean and stable 1.8 V supply voltage for the sensor and communication blocks. The data collected from the sensors is transmitted by on-off keying modulated low-power transmitter at 1.2 GHz frequency. The transmitter is composed of a LC tank oscillator with an off-chip inductor and a fully on-chip class-E power amplifier (PA). An additional output network for harmonic rejection is used. This network also helps to reduce the value of the inductances and hence allows to integrate the power amplifier fully on-chip. The integrated PA with 0.2 V supply voltage has a drain efficiency of 31.5% at -10 dBm output power for 50 Ω load. As a verification of the system functionality, the remote powering and data transfer are measured. The data communication is verified by using a commercial 50 Ω chip antenna and the remotely powered system supports 600 kbps data communication at 1 m communication distance.

9518-4, Session 1
A 64-channel ultra-low power system-on-chip for local field and action potentials recording

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Besides fostering advances in neuroscience, wireless neural prostheses for the measurement of intracranial neural activity are expected to play a significant role in the development of novel treatments for some neurological diseases and in the implementation of untethered brain-machine interfaces. As long as these prostheses are implanted, they have to achieve and maintain stable long-term recordings so that the need for re-surgery is essentially eliminated. This poses important challenges on the hardware implementation of the prostheses as they have to exhibit ultra-low power consumption, not only to prevent from harmful effects in the brain but also to minimize energy requirements; low form factor; versatility, to prove useful in different scenarios as determined by neurologists; and adaptability to deal not only with the intrinsic statistical deviations of the fabrication process but also with the non-stationary nature of the electrode-tissue interface.

In this scenario, we present an integrated 64-channel neural recording sensor suitable for acquiring Local Field Potentials (LFPs) and Action Potentials (APs). An on-chip dedicated processor defines the operation mode of the channels and implements a full-duplex communication protocol for data transmission through a wireless link. In one operation mode, the recording system can be configured to detect and compress

neural spikes so that feature vectors instead of raw signal samples are transferred. In another mode, the system runs a self-calibration mechanism which automatically adapts the filter bandwidth and the gain setting of the channels. The sensor also offers different alternatives for raw data transmission in which the number of active channels and the effective sampling rate are traded off. In all cases, the total throughput rate of the sensor keeps below 4Mbps as imposed by the wireless link. The sensor has been fabricated in a 0.13 μ m standard CMOS process and consumes 330 μ W from 1.2V voltage supply in the spike compression mode

9518-5, Session 2
Building better organ chips using microtechnologies (Invited Paper)

Sabeth Verpoorte, Univ. of Groningen (Netherlands)

No Abstract Available

9518-6, Session 2
Biological implications of Lab-on-a-Chip devices fabricated using multi-jet modelling and stereolithography processes

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Current microfabrication methods are often restricted to two dimensional (2D) or two and a half dimensional (2.5D) structures. Those fabrication issues can be potentially addressed by emerging additive manufacturing technologies. Despite rapid growth of additive manufacturing technologies in tissue engineering, microfluidics has seen relatively little developments with regards to adopting 3D printing for rapid fabrication of complex chip-based devices. This has been due to two major factors: lack of sufficient resolution of current rapid-prototyping methods (usually >100 μ m) and optical transparency of polymers to allow in vitro imaging of specimens. We postulate, however, that adopting innovative fabrication processes can provide effective solutions for prototyping and manufacturing of chip-based devices with high-aspect ratios (above 20:1). This work provides a comprehensive investigation of commercially available additive manufacturing technologies as an alternative for rapid prototyping of complex, monolithic Lab-on-a-Chip devices with high-aspect ratios. We explored both multi-jet modeling (MJM) and several stereolithography (SLA) processes with five different 3D printing resins. Compared with other rapid prototyping technologies such as PDMS soft lithography and infrared laser micro-machining, we demonstrated that all of the 3D printing technologies and systems had better resolution when manufacturing features of high-aspect ratios (above 20:1). We also for the first time optimized the post-processing protocols and demonstrated polymer features under scanning electronic microscope (SEM). Finally we demonstrate both optical properties of polymers for high-resolution biological imaging and also polymer biocompatibility during on-chip culture of developing zebrafish embryos on innovative 3D printed living embryo microarrays.

9518-7, Session 2
Magnetic microfluidic system for isolation of single cells

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This paper presents the design and realization of a compact, portable and cost effective microfluidic system for isolation and detection of single rare circulating tumor cells (CTCs) in suspension. The innovative

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aspect of the proposed isolation and detection method is that it utilizes magnetic particles (MPs) to label CTCs and then isolate those using microtraps with integrated current carrying microconductors. The magnetically labeled and trapped CTCs can then be detected by integrated magnetic microsensors e.g. giant magnetoresistive (GMR) or giant magnetoimpedance (GMI) sensors. The channel and trap dimensions are optimized to protect the cells from shear stress and achieve high trapping efficiency. These intact single CTCs can then be used for additional analysis, testing and patient specific drug screening. The proposed magnetic microfluidic system consists of microfluidic channels and trapping microchambers (microtraps) fabricated using a dry photoresist thin film (Ordyl) and a standard photolithography process. Commercially available functionalized MPs with selective affinity to CTCs are used to label the CTCs in the liquid sample under investigation. The isolation and capturing of the magnetically labeled CTCs is achieved through current carrying microconductors; they are fabricated underneath the microtraps using evaporation deposition technique and photolithography. Simulations using COMSOL Multiphysics were carried out in order to determine the optimum magnetic flux density and velocity magnitude of the liquid in the microfluidic channel. Moreover, the trapping procedure was also simulated using the same software in order to optimize the design of the microtraps. Experiments were successfully carried out with magnetically labeled Jurkat cells (human T-lymphocyte cells). "M-450 Dynabeads" functionalized with Anti-CD3-antibodies were used as the magnetic labels (diameter of 4.5 μm and susceptibility of 1.6). The microconductors were sequentially switched on and off using a programmable microprocessor.

9518-9, Session PSTue

Design of the charge push-through electronics for fully implantable artificial cochlea

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The artificial cochlea implant is only one way how to get lost hearing back in some cases. Existing artificial cochlear devices use two separated parts for this purpose; a signal processing unit with transmitter, and an implantable receiver with electrodes. This approach is applicable but not fully implantable. The fully implantable artificial cochlea design is one of the most discussed top topics in today's world. It is partially investigated by many worlds' research teams but there are only minimum teams which solve the problem from the complex point of view. The fully implantable device has specific construction demands. One of the demands is ultra-low power consumption which is necessary due to the absence of easy-accessible battery power source in such device. A combination of the methods for power consumption minimization has to be used in this case. Modern energy harvesting technologies are suitable for battery life prolongation or complete battery replacement in the ideal environment.

A new complex approach to design of artificial cochlea implant is described in this article. A combination of MEMS membranes filter bank, possible energy harvesting power source and especially ultra-low power processing electronics is proposed. A unique technique for nerve stimulatory output signal generation is discussed. This technique minimizes energy loss by useful charge transfer from the source to the output with minimal leakage and usages of bias currents.

The new circuits are simulated in relation to the results of complex electro mechanical MEMS membrane and energy harvesting power source simulation. These results are obtained from ANSYS simulations and MATLAB Simulink models. The models are based on experiments in real conditions used for determination of temperature, skin behavior and head motion analysis. The detected acoustic pressure is transformed to the output bipolar current pulses with dependent pulse frequency. These defined pulses are generated by simulated electronics and outputted directly to the implanted cochlear electrodes.

In addition, measurement workplace setup for developed cochlear implant electronics is also partially described. The workplace has to be specially adapted for measurement of this type of device due to specific device demands.

9518-24, Session PSTue

System of polarization correlometry of polycrystalline layers of bile in the differentiation of systemic pathologies

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Among diverse optical-physical methods of diagnosing the structure and properties of the optical-anisotropic component of various biological objects a specific trend has separated – multidimensional laser polarimetry

Our research is aimed at designing the experimental method of Fourier's laser polarimetry of human bile layers for the sake of diagnosing and differentiating cholelithiasis with underlying chronic cholecystitis and diabetes mellitus of degree II by means of the statistical analysis of the polarization filtered out scattered coherent radiation in a distant (Fourier) zone of diffraction with due regard for linear and circular birefringence of biological crystals.

A model of generalized optical anisotropy of human bile is suggested and a method of polarimetric of the module and phase Fourier of the image of the field of laser radiation is analytically substantiated, that is generated by the mechanisms of linear (a phase shift between the orthogonal components of the amplitude of a laser wave) and circular (the angle of rotation of the polarization plane) birefringence of polycrystalline networks with a wavelet - diagnosis and differentiation of cholelithiasis against a background of chronic cholecystitis.

A set of diagnostic criteria and diagnosis and differentiation of cholelithiasis against a background of chronic cholecystitis is identified and substantiated:

- statistical moments of the 3rd and 4th orders, which characterize the distributions of wavelet coefficients of Fourier phase of the image of a polarization inhomogeneous laser image of polycrystalline network of bile.

9518-25, Session PSTue

Rapid prototyping of integrated biochips for on-demand 3D cell culture

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The future of research in biology and medicine depends on modular tridimensional cell culture platforms with suitable on-demand geometries that can imitate any cell-specific environment with micron-size features. It is also important to guarantee a high level of control on several physico-chemical properties of these substrates and scaffolds, as mechanotransduction signals are passed through the cells under study that sense their environment. Finally, the possibility to pattern nanoscale geometries on chip are also leading to better culture results. All these biomimicry parameters that seem to influence the cells phenotype, structure and behavior are now opening new perspectives in 3D cell culturing for basic biology, medicine and drug testing applications. However, this growing need for on-demand 3D platforms is currently limited by two factors: the specificity of the commercial biochips is not suitable for many cell types and the high cost and level of technicality required by the technologies used to design and fabricate custom-made desired substrates restrains the massification of 3D cell culture.

In this work, we present the application of a simple, low-cost alternative enabling the rapid fabrication of on-demand, custom-made biochips for

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3D cell culture with micron-scale resolution. We developed a custom-made process that enables the use of low-power, low-cost lasers to etch on-demand micropatterns in transparent biopolymers and other materials of interest, circumventing the need for high power lasers or photolithography. We also report the integration of embedded electronics for in situ monitoring or actuation and microchannels on chip. We also succeeded in producing localized carbon nanodomains that are enhancing cell cultures and allowing regionalization in 3D cell culture platforms. Different designs successfully tested with hepatocytes for proof of principle purposes will be presented, as well as preliminary results on the comparison between the presence and absence of micropatterns on our platforms to validate our process.

9518-26, Session PSTue

Experimental studies of an ablation plasma for laser micromachining of the MEMS elements

Mateusz Tański, Robert Barbuca, Marek Kocik, The Szwalski Institute of Fluid-Flow Machinery (Poland)

Laser micromachining is an efficient technique for manufacturing microelements of many MEMS systems, like: microchannels, microgears, microelectrodes, etc. However, the ablation plasma generated during laser micromachining process can affect machined material in both thermal and mechanical way, reducing the quality of these elements. Thermal interaction is mainly caused by the electronic heat transfer from plasma to machined material resulting in its thermal degradation. Mechanical interaction is related to the plasma expansion process. Expanding plasma exert force on the machined material what can cause its cracking. By studying thermal and spatial properties of the ablation plasma we can determine the optimal parameters for laser micromachining for which undesirable plasma effect are minimized.

9518-27, Session PSTue

Impedance spectroscopy for detection of mold in archives with an integrated reference measurement

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In this work, we present a new miniaturized culture medium based sensor system where we apply an optical reference in an impedance measurement approach for detection of mold in archives. Mold infestation of documents is a major problem in archives. In addition to the spoilage of documents and books, the growth of mold in indoor environment can produce microbial volatile organic compounds that pose a risk to human health [1]. Thus early detection of mold in the archives not only prevents the loss of valuable documents but also reduces the potential threat to humans. Currently there exists no cost effective autonomous system to monitor the mold infestation in an archive environment [2].

The designed sensor comprises a chamber with pre-loaded culture medium which promotes the growth of archive mold species. Mold detection is carried out by measuring impedance changes in the culture medium caused due to increase in the pH (from 5.5 to 8) during mold growth because of their metabolic activity. In [3] we showed that an integrated approach of colorimetric and impedance principles can be used for the detection of pH changes in agar-gels. Now, we apply this approach for the detection of mold in archives. Integration of a colorimetric reference measurement allows in determining the sensitivity of the sensor to the pH change. As the measured impedance of the medium is dependent on the volume inside the reaction chamber the addition of an independent reference measurement increases the performance of the sensor. In this context, we present a feasibility study aiming at the detection of most prominent archive molds Eurotium

amstelodami, *Aspergillus penicillioides* and *Aspergillus restrictus*. Growth of Eurotium amstelodami shows a proportional impedance change of 10 % (12 chips tested) per day, with a sensitivity of 0.6 k Ω /pH.

9518-28, Session PSTue

Simulation and characterization of hollow microbridge resonators for label-free biosensing

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Micro and nanomechanical resonators have quantified the mass of single particles attaining detection limits down to individual atoms due to its high sensitivity. In this work we describe the use of microscale arrays of polysilicon double-clamped beams, based on the approach of embedding microfluidic channels inside the resonators, as an innovative platform for multiplexed biosensors. Finite element methods in COMSOL were employed to simulate the structural mechanical behaviour and to know the conditions in order to achieve optimal resonator sensitivities and quality factors. Particularly, we studied the effect of microchannel cross-section area, length and sidewalls thickness respect to the stress-strain deformation of sidewalls along the microchannel with the objective of injecting solutions of different densities. By integrating additional multiphysics models we analysed the governing microfluidics, and we estimated that a maximum pressure difference of 10 MPa along the microchannels is required to establish an optimum flow rate of 0.1 μ l/min, which is adequate for biosensor applications. To validate the simulations we characterized the thermal noise response of fabricated arrays of microbridges, in air and in vacuum, by means of a path-stabilized Michelson interferometer. By transversally scanning the microbridge arrays of lengths about 270 μ m and heights about 4 μ m, we obtained resonant frequencies between 700 KHz and 1 MHz, in good agreement with our simulated results but with downward frequency shifts due to the effect of tensile stress after fabrication. Furthermore, quality factors of up to 280 were exhibited in thinner microchannels of 10 μ m width.

9518-29, Session PSTue

Fiber optics, label-free biophotonic diagnostic tool for cardio vascular disease

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The prototype consists on a miniaturized optical bench (20x10 cm) comprising two sets of triaxial micro-positioners, two custom-made magnetic fiber optics clamps and a centered micro-chuck. An artery is located on a glass slide located on the chuck, with the adequate supply of phosphate buffer so as to avoid drying. Then, two multimode fiber optics (with a diameter of 230 μ m) are located at both sides of the artery (orthogonal to its main axis). The output fiber optics is connected to a QE65000Pro spectrometer. To enhance the response of the prototype at lower wavelengths (i.e. below 470 nm) the input fiber optics is connected, via a 1x2 fiber optics coupler, to two light sources (broadband and a 470 nm SLED). We have used this prototype to analyze freshly dissected arteries from "healthy" wild-type mice and atherosclerosis-prone apolipoprotein E knock-out mice (apoE-KO) fed high-fat diet for at least 2 months, therefore allowing the comparison of non-atherosclerotic

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versus atherosclerotic tissue. Results obtained reveal specific photonic fingerprint (PIN) in healthy compared with diseased arteries. Concretely, whereas the former present a main band located at a wavelength of 407 nm and a secondary at 398 nm, the latter presents two main bands (at 398 nm and 436 nm) as well as a decrease in absorbance at 414 nm. Additionally, the presence of clots in the artery were also label-free visualized, with the presence of not only haemoglobin bands (539 nm and 575 nm), but also with a strong band at 439 nm and two elbows (398 nm and 896 nm). The same arterial segments have been stained with Oil Red O, a specific stain for lipids in tissues, to quantify the atherosclerosis burden and benchmark the results. Our prototype has application in biomedical research laboratories and for the early diagnosis of cardiovascular diseases.

9518-30, Session PSTue

GMR microfluidic biosensor for low concentration detection of Nanomag-D beads

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This paper presents a novel microfluidic biosensor for in-vitro detection of biomolecules labeled by magnetic biomarkers (Nanomag-D beads) suspended in a static fluid in combination with giant magnetoresistance (GMR) sensors. While previous studies were focused mainly on exploring the MR change for biosensing of bacteria labeled with magnetic microparticles, we show that our biosensor can be used for the detection of much smaller pathogens in the range of a few hundred nanometers e.g., viruses labeled with Nanomag-D beads. The innovative aspect of the proposed method is that the induced velocity on reference magnetic nanoparticles (bare MNPs – not functionalized with bioligands) and on MNPs (biomarkers) bound to pathogens, while imposed to the same magnetic field gradient in a static fluid, is inversely proportional to their overall, non-magnetic volume. In order to prove the concept of manipulating and detecting Nanomag-D beads inside microfluidic channels we fabricated two GMR sensors and on top of them we fabricated silver microconductors (10 μm width, distance between each of them of 8 μm). Finally, two microfluidic channels, a reference and a measurement channel, were fabricated on top of the conducting microstructures using standard photolithography process and a dry photoresist thin film (OrdyI SY355) of 55 μm thickness. The movement of the biomarkers and the reference MNPs from the inlet to the outlet of the microfluidic channels is achieved through the sequentially actuated microconductors. Their velocity is measured utilizing the GMR sensor pairs. Functionalized Nanomag-D beads, with a diameter of 250 nm were used for the preliminary experiments. These beads are NH₂-coated composites of iron oxide nanoparticles and dextran and are used as the magnetic biomarkers. Results of the average relative change at the voltage output of the sensor for a concentration of 300 ng/ μl Nanomag-D beads suspended in a static liquid are presented and discussed.

9518-31, Session PSTue

Trajectory of microscale entities in a microdevice for field-flow fractionation based on dielectrophoresis

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This article deals with the development of a model for tracking the

trajectory of microscale entities in a continuous flow microfluidic device for field flow fractionation based on dielectrophoresis. The model is subsequently used for parametric analysis of the microdevice. The non-uniform electric field is generated using electrodes placed on the top and bottom surface of the microchannel. The top electrode runs over the entire length of the microchannel while multiple finite sized electrodes are placed on the bottom surface. The governing equation for electric potential inside the microchannel is a Laplace equation with the electric potential as the variable. The boundary conditions include the electric potential on the electrodes as well as the insulated boundary condition elsewhere. The equation governing the trajectory of microscale entity in every direction is based on the Newton's 2nd law. The flow is assumed to be two dimensional due to the high aspect ratio of the microchannel and thus the only governing equations are associated with the trajectory of the microscale entity. The forces considered in compiling the governing equations of the microscale entities include that due to inertia, dielectrophoresis, gravity, buoyancy and drag. The initial conditions include the initial displacements and velocities. The governing equations associated with the electric potential and the trajectory of microscale entities are solved using finite difference method. Biological cells are used as the representative of microscale entities in this work. The calculations are carried out using water as the medium. The developed model is used for parametric analysis. Based on the calculations it is found that the final location of the cell in the transverse direction is independent of its diameter, initial displacement in the transverse direction and volumetric flow rate. Additionally, it is found that increase in voltage leads to increase in the final position of the cell in the transverse direction; increase in microchannel height brings the cell closer to the bottom electrode. This model is beneficial in designing microfluidic devices for field flow fractionation based on dielectrophoresis.

9518-32, Session PSTue

Merging of droplets in micro-channel independent of the droplets size and inter-droplet separation

Mahmuda Akhtar, Mohammad T. Rabbani, Michael J. Vellekoop, Univ. Bremen (Germany)

We present a microfluidic chip where droplets of different liquids and sizes can be generated and merged independent of the droplets size and inter-droplet separation. Moreover, any number of generated droplets can be merged at any time.

In recent years, droplet-based microfluidics has drawn attention from biological and chemical communities because of its potential advantages such as small volume, fast analytical performance, and high-throughput capabilities. Precise merging and mixing is of crucial importance in droplet-based systems where biological and chemical processes are to take place. Under normal operating conditions the mixing of fluids in micro-channels is difficult due to the laminar flow regime. Mixing is mostly determined by diffusion parameters. For merging and mixing of liquids in droplets different structures in microfluidic channels have been discussed in literature, where droplets merging is dependent on inter-droplet separation or droplet size [1,2,3].

In this work a microfluidic chip has been designed and realized utilizing an extra outlet which yields control over the travel time and the hitting speed of the droplets. In addition, the merging location of the droplets can be determined freely.

The microfluidic chip consist of a molded PDMS channel (realized by using standard soft lithography), bonded to a second PDMS layer supported by a glass slide.

A schematic diagram of the chip is depicted in Fig. 1. The merging of two droplets at different merging conditions is shown in Fig. 2. A biological application where *Escherichia coli* bacteria are merged and mixed with a nutrient droplet is demonstrated in Fig. 3.

We have realized a simple system where merging of different sized droplets containing different liquids can be performed with high precision. The proposed method serves the basic needs for biological and chemical processing and has great potential, therefore.

9518-33, Session PSTue

Small-volume multiparametric electrochemical detection at low cost polymeric devices featuring nanoelectrodes

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In this study, a low-cost disposable device is proposed for electrochemical sensing based on polymeric materials and paper. Our target is towards the fabrication of a miniaturized prototype that can work with small sample volumes in the range of 10-20 μ L without the need for external pumps for sample loading and handling. This device can be used for the simultaneous detection of metabolites such as glucose and cholesterol.

An interdisciplinary approach is proposed that combines standard microfabrication processes and rapid prototyping techniques. Specifically, we present a technology to fabricate nanometric interdigitated electrodes (IDEs) on flexible polymeric substrates. Although the fabrication of nano-IDEs is well documented on silicon and glass substrates, their fabrication in polymeric substrates is rather challenging. We selected two polymeric materials for this purpose: cyclo-olefin polymers (COP), and Kapton. One of the most critical parts of this approach is patterning the electrode passivation layer, which defines the biosensors active area, without affecting the polymeric substrate underneath. The detection of different analytes is enabled by pre-immobilized enzymes in a specially patterned paper pad.

In summary, low-cost rapid prototyping techniques have been used for processing polymeric films and paper shaping, while standard microfabrication processes are used for the IDEs fabrication. The next step is the characterization of the device for enzymatic sensing using volumes as small as 10-20 μ L.

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9518-35, Session PSTue

Characterization of small particles in liquid suspension by fiber-optofluidic platform

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Optofluidics is an emerging field, which integrates of different disciplines such as photonics, microfluidics, life science, biomedicine, chemical- and bio-chemical microreactors, etc. Synergism of microfluidics and optics allows a number of advantages such as direct contactless detection, miniaturization, multiplexing, etc. However, a demand still exists for technologies that provide both high specificity and sensitivity of detection of targeted particles and high throughput, e.g. in downstream blood analysis. This paper is our contribution to the aforementioned demand. It is aimed to the characterization of some physical parameters,

like overall size and index of refraction, of small particles in liquid suspension. Our sensing set up is composed of microfluidic platform and fiber-optic sensing configuration making, so called, fiber-optofluidic platform (FOP). The FOP is of sandwich structure consisting of bottom and upper glass plates and middle part made of UV curable polymer. The "cross" shape microchannels are 125 μ m in diameter. Central channel has been supplied with glass-ball suspension. Orthogonal channels were equipped with two single-mode sensing fibers (SMF), sensing and dummy separated for about 125 μ m. Fiber-optic configuration is low-coherence interferometry performed by Michelson interferometer. Principle of operation is measurement of optical path difference (OPD) as a result of change of index of refraction of flowing media in front of the sensing fiber. At the beginning of measurement the interferometer is in balance, i.e. the optical path length (OPL) of both sensing- and reference arms are equal and starting OPD is zero. As long as we have water in the microchannel the OPD remains zero. When a glass-ball appears in front of the sensing fiber the OPD changes since the optical path length in the sensing arm is increased. This technology can be used for determination of index of refraction of the unknown particles hidden in the liquid suspension, such as blood samples.

9518-36, Session PSTue

Fabrication of parylene channels embedded in silicon using a single parylene deposition step

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Neural interfaces rely on microelectrode arrays to acquire and conduct neurophysiological signals. We have already fabricated needle-like microelectrode arrays from silicon. As such microdevices are fabricated by using silicon wafers and micromachining tools, an in-situ integration of microfluidic channels during the microfabrication process flow would be advantageous, for example to enable drug delivery.

Here we propose an efficient method to fabricate microfluidic channels from parylene C onto silicon. Parylene C is a biocompatible, inert material, best suitable to be used in implantable microsystems; its inert nature favors water flow. At first, 100 μ m-deep grooves were realized in a silicon wafer. A 130 μ m-thick PVC foil was fixed onto the wafer top-side and served as a top-cover for the grooves; together they defined the form of the future channels. The wafers were coated with an adhesion promoter (AdProPoly by SCS) and a 15 μ m-thick film of parylene C was deposited conformally into the grooves-foil enclosed space. The characteristics of the foil let it be removed easily from the wafers, resulting in fully-sealed parylene channels embedded in the silicon wafer. We verified the functionality and integrity of the channels by injecting DI water with dispersed polystyrene beads (diameter 6 μ m) at flow rates in the range of 0.1 - 40 μ L/min; the parylene channels remained leak-tight throughout these flow-rate measurements and the polystyrene beads were successfully transported along the channel. A hydrostatic test is in preparation.

Our parylene channels are: (1) suitable for miniaturized medical applications such as implantable microsystems; (2) in-situ enclosed hollow spaces, realized with a single parylene deposition; (3) embedded in the silicon substrate and in plane with the silicon top-surface (free-access to silicon surface e.g. for contact pads). One example of application for such a device is drug-delivery on needle-like microelectrode arrays.

9518-37, Session PSTue

GammarusChip: innovative lab-on-a-chip technology for ecotoxicological testing using marine amphipod Allorchestes compressa

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Traditional marine ecotoxicity testing is inherently labor intensive, requiring extensive manual procedures to be performed both to set up the tests and more importantly to collect experimental readouts. Moreover, static test procedures offer poor control of water parameters such as toxicant concentration and dissolved oxygen, which affect toxicity and are important considerations in evaluating environmental impacts of aquatic pollution. So far only minimal levels of automation have been adopted in ecotoxicology. Our current work attempts to address the current limitations by capitalizing on latest advances in microfluidics, 3D printing and laser micromachining technologies to develop highly customized, low cost and high-throughput devices. These will for the first time enable automation of ecotoxicity biotests performed on marine test organisms.

Here we for the first time introduce a proof-of-concept laboratory automation system to perform ecotoxicity tests on a native marine amphipod *Allorchestes compressa*. Our innovative system incorporates a flow through design that enables the biotests to be run in a closed or open loop circuits. Automated fluidic control technology allows for concentrations of toxicants to be spiked and diluted using computerized manifold of miniaturized pumps and valves. Miniaturized video cameras monitor the amphipods during the experiment and innovative video analysis algorithms provide us with real time sub-lethal endpoints such as changes in swimming activity that would otherwise go unnoticed. A key advantage of this flow through system as compared to conventional approach is the automation of analysis and emphasis on sub-lethal behavioral parameters. We present preliminary data validating the technology, compared to standard methods (US EPA) for testing organisms from the family Gammaridae. The data presented is from a customized biotest for *A.compressa* developed to study the toxic effects of petroleum hydrocarbons.

9518-38, Session PSTue

Lab-on-a-chip technology for a non-invasive and real-time visualisation of metabolic activities in larval vertebrates

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Non-invasive and real-time visualization of metabolic activities in living small organisms such as zebrafish embryo and larvae has not yet been attempted due to profound analytical limitations of existing technologies. Significant progress in the development of physico-optical oxygen sensors using luminescence quenching by molecular oxygen has recently been made. Sensing using such microsensors is, however, still performed in small glass chambers that hold single specimens and thus not amenable for high-throughput data acquisition. In this work, we present a proof-of-concept approach by using microfluidic Lab-on-a-Chip (LOC) technologies combined with sophisticated optoelectronic sensors. The LOC device is capable of immobilizing live zebrafish embryos with continuous flow perfusion, while the sensor uses innovative Fluorescence Ratiometric Imaging (FRIM) technology that can kinetically quantify the temporal patterns of aqueous oxygen gradients at a very fine scale based on signals coming from an optical sensor referred to as a sensor foil. By embedding the sensor foil onto the microfluidic living embryo array system, we demonstrated in situ FRIM on developing zebrafish embryos. Future integration of microfluidic chip-based technologies with FRIM technology represents a noteworthy direction to miniaturize and revolutionize research on metabolism and physiology in vivo.

9518-39, Session PSTue

An integrated, micromechanical large particle in-flow sorter (MILPIS)

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At present, the major hurdle to widespread deployment of zebrafish embryo and larvae in large-scale drug development projects is the lack of enabling high-throughput analytical platforms. In order to spearhead drug discovery with the use of zebrafish as a model, platforms need to integrate automated pre-test sorting of organisms (to ensure quality control and standardization) and their in-test positioning (suitable for high-content imaging) with modules for flexible drug delivery. The major obstacle hampering sorting of millimetre sized particles such as zebrafish embryos on chip-based devices is their substantial diameter (above one millimetre), mass (above one milligram), which both lead to rapid gravitational-induced sedimentation and high inertial forces.

In this work, we present an innovative design of a micromechanical large particle in-flow sorter (MILPIS) capable of analysing, sorting and dispensing living zebrafish embryos for drug discovery applications. The system consisted of a microfluidic network, revolving micromechanical receptacle actuated by robotic servomotor and opto-electronic sensing module. The prototypes were fabricated in poly(methyl methacrylate) (PMMA) transparent thermoplastic using infrared laser micromachining. Elements of MILPIS were also fabricated in an optically transparent VisiJet resin using 3D stereolithography (SLA) processes (ProJet 7000HD, 3D Systems). The device operation was based on a rapidly revolving miniaturized mechanical receptacle. The latter function was to hold and position individual fish embryos for (i) interrogation, (ii) sorting decision-making and (iii) physical sorting. The actuation of the revolving receptacle was performed using a Dynamixel AX12A and RX24F (Robotis Inc, Korea) robotic actuators. The system was designed to separate fertilized (LIVE) and non-fertilized (DEAD) eggs, based on optical transparency differences using infrared (IR) emitters/receivers embossed in the microfluidic chip-based system. Digital storage oscilloscope (DSO) signals were used to distinguish the diffraction characteristics of LIVE vs. DEAD embryos and a voltage threshold was set trigger the actuation of the revolving receptacle.

9518-8, Session 3

A biopsymeter to support the diagnostic procedure of skin samples

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CH₂ vibrations in the lipid chains of cell membrane exhibits alteration in the infrared light absorbance when cancer occurs. In our previous works it was shown that the CH₂-stretch ratio (symmetric/antisymmetric) in lipid membranes is a promising label-free biomarker. The value of the ratio increases due to the presence of malignant melanocytic lesions [1].

A biopsymeter to be used complementary to standard histopathology is presented here. Equipped with a small camera, the pathologists can examine the biopsies for pathologic assessment and simultaneously target specific areas of the specimen where infrared investigation needs to be performed.

Fig. 1 shows the realized biopsymeter. The infrared light source, filtering method and data acquisition system lead to fast data processing, a small light spot size down to 0.5 mm diameter and the possibility to scan the spectral wavelength range between 3.3 μm and 3.6 μm with 12 nm resolution in less than 1 minute. The CH₂ symmetric and asymmetric absorbance peaks occur at 3505 nm and 3415 nm, respectively, and measurements at 3335 nm and 3555 nm are used for baseline correction.

The stained tissues displayed in Fig. 2 are classified by a histopathologist as healthy skin (a), nodular melanomas (b, c) and subcutaneous metastasis (d, e) biopsies. CH₂-stretch ratio measurements performed with our biopsymeter over the aforementioned biopsies revealed a mean CH₂-ratio value of 0.27 for the reference sample (healthy skin) and values between 0.46 and 0.60 for malignant melanomas and metastasized melanomas (Fig. 3). The plotted CH₂-stretch ratios are averaged recordings of three spectral scans on the same spot.

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In conclusion, healthy and tumorous areas of biopsies exhibit significant changes in the CH₂-stretch ratio. The fully automated operation of the biopsymeter, its easiness and fastness (about 1 min) in obtaining biopsy information makes it highly attractive for diagnostic and therapeutic procedures.

9518-10, Session 3

Multifunctional biosensing with three-dimensional plasmonic nanoantennas

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The study of biological systems is performed mainly by optical, chemical or electrical methods. In most cases each of these methods gives only partial information about the system, while combined investigations could reveal new insights into complex systems such as in-vitro neuronal networks for example. With the aim of combining optical and electrical investigations of biological samples, we introduce three-dimensional plasmonic nanoantennas for enhanced infrared-visible spectroscopy integrated on a metal surface, which can be easily used as electrode on electronic devices, thus merging infrared spectroscopy and electrical acquisitions with the same tool.

The nanoantennas are fabricated using a novel ion beam based technique, and their SERS performance in the visible range have been already proven [1]. Here we show, numerically and experimentally, that the three-dimensional nature of the nanoantennas leads to extremely high plasmonic responses also in the infrared region, paving the way to efficient infrared-visible spectroscopy; in particular we measured high near field enhancement as high as 200 and low dumping coefficients (7 times lower than bulk in the case of silver) in the range from 4 to 14 microns. Such performances are desirable for bio-sensing as they allow for high sensitivity and short acquisition times, especially if combined with concentrators such as super-hydrophobic surfaces [2]. Moreover here we show that the nanoantennas not only can be integrated on electronic biosensors (multielectrode-arrays) without performance degradation, but they can also improve the quality of the electrical signals acquired from in-vitro neuronal networks.

At last, in addition to the spectroscopic and electrical functions of the nanoantennas, we show that these three-dimensional tools are also able to guide neurons development along prearranged geometries without any chemical functionalization of the metal surface. Such feature is interesting for patterning neuronal cultures in a non-invasive way.

References:

[1] De Angelis, F., Malerba, M., Patrini, M., Miele, E., Das, G., Toma, A., Zaccaria, R. P. and Di Fabrizio, E., *Nano Lett.* 13, 3553-3558 (2013).

[2] Miele, E., Malerba, M., Dipalo, M., Rondanina, E., Toma, A. and De Angelis, F.; *Advanced Materials* 26(24), 4179-4183 (2014).

9518-11, Session 3

Out-of-plane stainless steel microneedle array for drug delivery application

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In this paper, we report the fabrication of out-of-plane solid Stainless Steel (SS) microneedles and formation of microcup structure within them suitable region for drug delivery application. Array of out-of-plane solid SS microneedles were fabricated using Electric Discharge Machining (EDM) method. Subsequently, the microcup structures on the solid SS microneedles were made using Focused Ion Beam (FIB) technique. The microcup structure on the microneedles forms a dedicated region to fill the drug, so that the possible drug leakage while inserting the microneedles into the skin can be avoided. The drug filling into the microcup structures was performed using drop coating method. This coating method in combination with cup shaped microneedle array enables to deliver multiple drugs simultaneously in desired proportion.

Due to skin shear force, the coated drug might get wiped off while inserting the microneedles. Also it is difficult to measure the volume of the drug coated on the outer walls of the needles. In our present work, we propose the fabrication process for the realization of out-of-plane solid microneedles in a single step and formation of microcup structures within them. Also, in order to easily control the volume of drug to be dispensed within each of the microcups, we have developed a simple drug filling mechanism.

9518-12, Session 4

Creation of hydrophilic microfluidic devices for bio-medical application through stereo-lithography

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We present a method to graft a layer of poly-ethylene-glycol (PEG) to the surface of stereo-lithography fabricated or 3d-printed microfluidic devices rendering it hydrophilic and repellent to the adhesion of proteins.

Rapid prototyping with stereo-lithography enables the realization of prototypes in a shorter time than with conventional fabrication methods. In microfluidic applications, channels, chambers and connectors can be created in one step. A problem, as with many polymer based devices is hydrophobicity, as it makes filling the device without bubbles more difficult and promotes the adhesion of proteins [1]. This is a problem especially in fluorescent or luminescent detection of proteins, as for example in Enzyme-Linked-Immunoassay (ELISA) where non-specific adsorption of proteins drastically reduces the sensitivity.

By grafting [2] a PEG layer to the surface of the device during post-development UV-curing, a durable and long term stable surface modification can be achieved.

It is more stable than oxygen plasma treatment for hydrophilisation, since the PEG-macromolecules bond permanently with the device material.

Through exposure of normal stereo-lithographic resin and subsequent development, a soft chip is created, which needs additional UV-curing to create a rigid, usable device. To form the hydrophilic surface, the device is submerged in the UV-sensitive PEG-diacrylate-solution before UV-curing and exposed in the liquid. After full polymerization the device is rinsed in hot water to remove any loosely attached PEG from the surface.

Boiling the chip for 6 hours in water did only slightly reduce the hydrophilicity, proving further that a rigid bond between the chip and device is present. Even washing in boiling acetone for 10 minutes did not diminish the results.

Contact angle measurements for "Formlabs Clear Resin" [3] are shown below in Figure 1. Measurements with "EnvisionTEC HTM140"[4] have been undertaken, proving that the technique can be applied to different formulations of stereo lithographic resin.

9518-13, Session 4

High-throughput microfluidic device for circulating tumor cell isolation from whole blood

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Circulating tumor cells (CTCs), cells that have been shed from a primary solid tumor and entered in the vasculature, can determine patient prognosis and track disease progression. The rarity of these cells in cancer patients is a great challenge for isolation and enumeration: only 1-10 CTCs are present in a 7.5mL sample of patient blood. We have optimized a novel system to isolate CTC populations: passive, high-throughput, inertial-based microfluidic device that consists of two fractionation devices, each composed of a single contracting and expanding microchannel, connected in series. A balance of inertial and dean drag forces directs cells of different size to their respective transverse equilibrium positions within the microchannel prior to separation. By

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adjusting inlet flow rates, one can isolate cancer cells of different size ranges. A chamber functionalized with anti-CD45 antibody positioned just prior to the desired output removes those leukocytes whose size overlap with that of CTCs. With our device, we have been able to achieve 98% recovery and high purity of MCF-7 GFP breast cancer cells that had been spiked in human donor blood. Serial fractionation is advantageous among existing technologies in its robustness to isolate different sized particles and its ease of use. The absence of time consuming and potentially contaminating sample preparation is particularly attractive not only to physicians and patients who need to track cancer progression, but also to biomedical researchers who desire a deeper understanding of CTCs and their role in metastasis.

9518-14, Session 4

Integrated microfluidic technology for sub-lethal and behavioral marine ecotoxicity biotests

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In this work, we present development of a miniaturized Lab-on-a-Chip (LOC) platform for automation of acute ecotoxicity test based on a marine crustacean *Artemia franciscana* (Artoxkit M™). We for the first time demonstrate development of a proof-of-concept technology for rapid assessment of sub-lethal, behavioral ecotoxic effects. The system working principles incorporated a time-resolved video data analysis to dynamically assess impact of the reference toxicant on swimming behavior of marine crustacean *Artemia franciscana*. Our system design combined: (i) innovative LOC flow-through device for on-chip keeping of *Artemia* sp.; (ii) automated mechatronic hardware for LOC fluidic system actuation and data acquisition; and (iii) innovative video analysis algorithms for the segmentation, tracking, visualization and movement analysis. The algorithm are written in Matlab and released open-source at the website www.phagosight.org. The chip-based device supported rapid loading and keeping of free swimming crustacean larvae suspended in a continuous microfluidic perfusion as a mean of toxin delivery in both open-loop and closed-loop modalities. This system was also capable of performing fully programmable time-lapse and video-microscopy of multiple samples for rapid ecotoxicity analysis. Custom video algorithms were then developed for scoring dynamic features of video frames, capturing detailed statistical information on test specimen movements. This enabled development of a new test protocol to dynamically detect sub-lethal behavioral end-points based on a swimming behavior of *Artemia franciscana*.

9518-15, Session 4

Miniaturized devices towards an Integrated Lab-on-a-chip Platform for DNA diagnostics

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Microfluidics is an emerging technology enabling the development of Lab-on-a-chip (LOC) systems for clinical diagnosis, drug discovery and screening, food safety and environmental analysis. LOC systems

integrate and scale down one or several laboratory functions on a single chip of a few mm² to cm² in size, and account for many advantages on biochemical analyses, such as low sample and reagent consumption, low cost, reduced analysis time, portability and point-of-need compatibility. Currently available nucleic acid diagnostic tests take advantage of Polymerase Chain Reaction (PCR) that allows exponential amplification of portions of nucleic acid sequences that can be used as indicators for the identification of various diseases. In this work, we present a lab-on-a-chip concept that involves the development of a novel DNA bioanalysis platform readily applicable to clinical diagnostics. In particular, we develop low-cost μ PCR devices for fast DNA amplification and we implement them in the detection of mutations related to breast cancer. The devices are fabricated by mass production amenable technologies on PCB or FPC substrates, where copper facilitates the incorporation of on-chip microheaters, defining the thermal zones necessary for PCR as well serving as temperature sensors. The latter is particularly crucial in stationary μ PCR devices, where thermal cycling of the devices between three different temperatures is necessary. Stationary and continuous flow devices are simulated and the pros and cons of each configuration regarding power consumption, time needed, and amplification yield are compared and discussed. The predictions are qualitatively verified in devices realized according to the proposed designs that are also employed for the detection of mutations in the BRCA1 tumor suppressor gene associated with breast cancer.

9518-16, Session 4

Hydrodynamic stretching for prostate cancer detection

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Prostate cancer is one of the most common male cancers in the world. In the UK only, over 250,000 men are currently affected and more than 40,000 are diagnosed each year [1]. Early-stage diagnosis is not effective and this makes treatments extremely invasive. New reliable methods are necessary to improve the existing clinical setting.

Although the common diagnostic techniques are mainly based on measuring biochemical markers (e.g. Prostate-Specific Antigen), intrinsic biophysical properties might be used to assess the presence and the state of the disease. In recent years a few techniques have emerged with the aim of looking at cellular mechanical properties [3 - 5], but their translation into clinical practice has been limited due to their low throughput and poor robustness.

Based on previous work by Di Carlo et al. [2], we developed a microfluidic device able to perform single-cell analysis with a throughput of approximately 2,000 cells/s. Inertial effects deliver cells to centre of a stretching area where they are deformed by large stresses, which are due to the high flow rates imposed by a computer-controlled syringe pump. High-speed imaging and ad hoc automated detection algorithms allow us to measure the cell deformation in fast flowing cell solutions. Using this method we assess, for the first time, the cellular compliance of large populations of cancerous and healthy prostate cells. The deformability, i.e. the ratio between the major and minor axes of an ellipsoidal stretched cell, is plotted against the initial radius of an unperturbed cell and flow cytometry-like density plots are generated. Each individual cellular population shows a density plot with a distinctive pattern, making it possible to identify difference between healthy and cancerous cells. This technique opens up the possibility to perform analyses without specific labelling, leading to reduced costs and simplified sample preparation [2].

[1] Data provided by the Office for National Statistics on request, July 2013: <http://www.ons.gov.uk/ons/rel/vsob1/cancer-statistics-registrations--england--series-mb1-/index.html>.

[2] Gossett, D.R. Henry, T.K. Lee, S.A. Ying, Y. Lindgren, A.G. Yang, O.O. Rao, J. Clark, A.T. Di Carlo, D. (2012). Hydrodynamic stretching of single cells for large population mechanical phenotyping. *Proceedings of the National Academy of Sciences*, 109(20), 7630-5.

[3] Pajerowski, J. D., Dahl, K. N., Zhong, F. L., Sammak, P. J., & Discher, D. E. (2007). Physical plasticity of the nucleus in stem cell differentiation, *PNAS*, 1, 0-5.

[4] Guck, J., Schinkinger, S., Lincoln, B., & Wottawah, F. (2005).

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Optical deformability as an inherent cell marker for testing malignant transformation and metastatic competence. *Biophysical Journal*, 88(5), 3689-98.

[5] Cross, S. E., Jin, Y.-S., Rao, J., & Gimzewski, J. K. (2007). Nanomechanical analysis of cells from cancer patients. *Nature Nanotechnology*, 2(12), 780-3.

9518-17, Session 5

Monitoring dynamic cell-to-cell interactions of tumor, tissue and stem cells in multifunctional lab-on-a-chip systems *(Invited Paper)*

Peter Ertl, AIT Austrian Institute of Technology GmbH (Austria)

Although studying in vitro cell cultures is an essential aspect of cell biology, monitoring dynamic cell-to-cell interaction still remains a challenge using standard in vitro cell-based assays. It is, however, widely accepted that the next generation in vitro diagnostic systems will be based on the creation of microdevices that feature in vivo characteristics. Consequently, three microfluidic 2D and 3D co-culture systems to directly assess the dynamic interactions of adherent and non-adherent co-cultures under physiologically relevant conditions will be presented including (1) a complementary cell analysis method capable of assessing the dynamic interactions of tumor cells with resident tissue and immune cells using optical light scattering and impedance spectroscopy; (2) a fully automated cell chip system containing integrated luminescent-based oxygen sensors to study MSC differentiation capacity under changing environmental conditions; and (3) a microfluidic 3D hydrogel co-culture consisting of adipose derived stem cells (ASCs) and human umbilical vein cells (HUVEC) to study the effects of secretome accumulation and depletion on vascular tube formation. Overall, the reliability and reproducibility of microfluidic cell culture systems has the potential to advance in vitro models for biomedical research.

9518-18, Session 5

Monolithic silicon optical microchips for broad-band Mach-Zehnder interferometry and highly sensitive label free immunosensing

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Photonic probing of adlayers in developing biomolecular reactions is preferable to other types of biosensing (potentiometric, impedance spectroscopy, quartz microbalance, SAW, etc.) because of the galvanic isolation of the transducer from the excitation and detection components and the optical frequency regime of operation. Guided optics interferometry is way more sensitive compared to the free space one. In a sensing waveguide of exposed length L the photons probe the biomolecular adlayer by a number of the same order as L/λ , compared to two times in white light reflectance spectroscopy or standard ellipsometry. Here, interferometric silicon chips are presented with monolithically integrated light emitting devices (LEDs) and silicon nitride waveguides. The LEDs are silicon avalanche diodes that emit white light when biased beyond their breakdown voltage and are coupled to co-integrated monomodal waveguides. The monolithic interferometers are of the Mach-Zehnder type and are made through mainstream silicon technology. The detection is provided by a portable spectrometer that monitors the spectra emitted by the cleaved edge of the chip. The observable here is the spectral shifts of the interference fringes upon effective medium changes. The Mach-Zehnder configuration greatly

enhances the spectral changes so that portable spectrometers with nm range resolution can be employed to monitor the blue shifts. The broad-band nature of the device also allows simultaneous monitoring of the TE and the TM polarization through spectral demultiplexing in the Fourier transform domain. The device is completed by applying the fluidic compartment on top of the spotted waveguides. Each chip consists of 10 interferometers that are multiplexed and monitored by a single portable spectrometer so that multianalyte label free sensing is possible. The potential of the chip as a label free multianalyte biosensor is demonstrated by a model assay.

9518-19, Session 5

Imaging label-free biosensor with microfluidic system

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Guided-mode resonance biosensors based on periodically nanostructured dielectric surfaces (photonic crystal slabs) are promising for label-free biosensing and thus for point-of-care applications. We investigate a microfluidic system suitable for parallel label-free detection of several biomarkers utilizing a compact imaging measurement system. The microfluidic system contains a filter unit to separate the serum from human blood and a functionalized, nanostructured sensor chip. The nanostructured sensor chip is fabricated by nanoimprint lithography of a 350 nm period grating structure into a photoresist spincoated on a glass substrate and subsequent deposition of a 70 nm thick TiO₂ layer. This photonic crystal slab supports quasi-guided modes coupling to far-field radiation. Because of the evanescent fraction of the quasi-guided modes the sensor is sensitive to refractive index changes due to biomarker binding at the surface. In our imaging read-out system the resulting shift of resonances in the transmission spectrum is converted into an intensity change in the specific color channel of a simple CMOS camera aligned to the resonance wavelength. For testing the sensor chip, biotin with a concentration of 500 nM was immobilized in drops via covalent coupling to the surface. A binding experiment is performed with 250 nM streptavidin dissolved in phosphate buffer. By continuously taking photographs of the sensor surface local intensity changes are observed revealing the binding kinetics of the specific target. Two separate measurement fields are evaluated. In the next test series, we bonded a functionalized sensor chip onto a 15 mm x 15 mm opening of the 75 mm x 25 mm x 2 mm microfluidic system. We demonstrate the functionality of the microfluidic system for filtering human blood such that only blood serum is transported to the sensor chip. The results of first binding experiments will be presented.

9518-20, Session 5

Hybrid microneedles devices for diagnostic and therapeutic applications: fabrication and preliminary results

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Applications of microneedles in biomedicine wide range from diagnostics to therapeutics. This crucial and versatile tool is the interface between the human body and often a complicated device. We present two sensing device based on hybrid microneedles array for diagnostic and therapeutic applications. The hybrid microneedles was fabricated by using a commercial photocatalyzer to solidify a liquid PolyEthylene Glycol (PEG) hydrogel. In both case, the solution was casted in to a silicone vessel and

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directly exposed to UV light through a mask (direct photolithography). After PEG polymerization, the MNs have a porous structure, which can include a variety of biological molecules, as bioprobes or drugs. The first device presented is an electro-chemical sensor where microneedles include enzymes in their matrix that interact with lactose or glucose. It is fabricated by plating with gold the MNs and etching their tips. The redox reaction with glucose, mediated by ferrocene, creates a charge transfer resulting in a current proportional to the glucose concentration. The second device is a therapeutic tool with an optically controlled release of drugs. In this case the device includes a porous silicon membrane with a Bragg's mirror, whose reflection wavelength is related to the drugs concentration in the MN. For both devices the fabrication process and preliminary results will be presented.

9518-21, Session 6

Living photonics: monitoring light propagation through cells (LIPHOS)

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The LiPhos project (EU FP7 Grant Agreement No.: 317916) aims to develop three different of biophotonic diagnosis tools (BDTs), namely single layer living photonics (SLLP), single cell analysis (SCA) and multi-layer living photonics (MLLP). Measurement of the Photonic Fingerprint (PIN) of the cells in such BDTs should allow to differentiate between healthy and non-healthy states as well as the effect of specific drugs. This concept is currently being applied to the diagnosis of cardiovascular diseases (CVD).

9518-22, Session 6

A novel strategy to monitor microfluidic in-vitro blood brain barrier models using impedance spectroscopy

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In recent years there has been an increasing interest in developing models to mimic the blood-brain barrier (BBB). In these models, a common technique for quantitatively evaluate the cell barrier integrity without affecting cell physiology is based on the study of the passive electrical properties of cells. This can be performed by means of electrical impedance spectroscopy (EIS) or transendothelial/epithelial electrical

resistance (TEER). Implementation of these measurements in microfluidic systems which better reproduce the in vivo conditions of cell barriers requires new approaches to place the electrodes.

In this work, we present the use of interdigitated electrodes for performing EIS measurements as an optimal electrode configuration that allows a similar sensitivity along a defined cell culture area without impairing the optical visualization of the cell culture. Numerical studies have been performed to evaluate the sensitivity along the cell barrier in a given microfluidic channel geometry and compared to three other common used configurations.

To validate the simulation results, a home-made PMMA bioreactor with three individual cell-culture chambers (5 x 25 mm) was fabricated using the interdigitated electrode geometry given from the simulation data results. Gold microelectrodes covered with platinum black were defined on COP sheets and bonded to the bioreactor plates by means of double-sided PSA. To simulate different cell barrier impedances, perforated silicone sheets with different pore densities were placed between both bioreactor plates. TEER measurements were performed by filling the bioreactor with phosphate buffered saline solution. Decreasing pore density of the silicone sheet resulted in an increase of impedance due to a reduction in the conduction area.

The experimental results show a good sensibility and are comparable with the ideal case confirms the possibilities of the presented measurement method. In addition, measurements using real cell cultures on disposable porous membranes are ongoing.

9518-23, Session 6

Microfabrication of multi-Layered electrodes for dielectrophoresis based field flow fractionation

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This article details a novel microfabrication process for realizing a PDMS device with multi-layered electrodes for field flow fractionation based on dielectrophoresis. Dielectrophoresis based field flow fractionation utilizes negative dielectrophoresis so as to levitate microscale entities to an equilibrium position. Traditionally interdigitated transducer electrodes are used for realizing the negative dielectrophoresis needed for field flow fractionation. The drawback with this configuration is the exponential decay in the associated electric field along the depth of the microchannel. A novel electrode configuration is envisioned and developed in this article to overcome this issue. Multiple electrodes are vertically aligned, through the microchannel, in a step-configuration. For the microdevice developed for this article three electrodes are used to create the step-configuration. The electrodes consist of thin gauge metallic wires. The microdevice is a two-layered device made using PDMS. One of the PDMS layer carries the microchannel and the three slots for holding the electrodes. The slots are aligned perpendicular to the microchannel and these slots are of varying depth in order to achieve the step-configuration. A SU-8 mold is developed using standard microfabrication processes for casting this particular PDMS layer. The SU-8 pattern on the silicon wafer contains the structures corresponding to the microchannel and the slots. The entire microfabrication is a multi-layer process with each layer dedicated to one of the three electrodes. The metallic wires are manually fitted into the slots after the PDMS layer is cast. Finally this PDMS layer is bonded onto another PDMS layer to realize the desired microfluidic device during which the slots and wires become embedded inside device thereby eliminating occurrences of leakage.

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9519-1, Session 1

Tubular nanomembranes: 3D architectures for photonics, electronics, energy storage and micro-biorobotics (Invited Paper)

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Nanomembranes are thin, flexible, transferable and can be shaped into 3D micro- and nanoarchitectures. If differentially strained, nanomembranes roll up into tubular structures upon release from their mother substrate. Tubular nanomembranes can be exploited to rigorously compact electronic and photonic sensing devices and energy storage units. If appropriate materials are chosen, they act as tiny catalytic jet engines which in the ultimate limit may drive compact multifunctional autonomous systems for medical and environmental applications. Hybrid tubular micro-biorobots offer new perspectives towards artificial reproduction technologies.

9519-2, Session 1

ALD tuned titanium dioxide nanophotonics

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Atomic layer deposition (ALD) technology has recently gained a lot of interest in nano-photonics applications, because of its many benefits compared to other thin film deposition technologies, e.g., high quality films and accurate film thickness control. Thus, ALD is a promising technology for fabricating and tuning nano-photonics elements. We use ALD grown titanium dioxide (TiO₂), which is a promising material due to its high refractive index and its transparency at visible and near-infrared regions.

In this work, we focused on an experimental demonstration of the application of ALD through finely tuning the geometrical parameters of nano- and micro-structure at a scale far below the wavelength. This facility offered by the conformal and homogeneous coating provided by the ALD technique is shown through different structures and applications. The devices are fabricated by e-beam lithography (EBL), reactive ion etching (RIE) and ALD. The feature size reduction method, which is one of the main benefits of ALD, is utilized to reach the ideal parameters.

We introduce, at first, a novel approach to reduce propagation losses in amorphous TiO₂ strip waveguides. The principle is based on re-coating the fabricated strip waveguides with an additional layer of TiO₂ by using ALD.

As a second application, we present a TiO₂ ring resonator operating at around $\lambda=650$ nm and based on slot waveguides. The 30 nm-width slot has been obtained by adjusting the width of the rails with the aid of ALD with a precision close to the range of a few nanometers. Moreover, this is the first time such a structure is fabricated in this material and characterized at visible wavelengths.

The third application is a one-dimensional photonic crystal nanobeam cavity operating in the visible region. The parameters of such a structure are crucial, and even slight variations may drastically change the response of the device.

9519-3, Session 1

Fabrication of photonic crystal circuits based on GaN ultrathin membranes by maskless lithography

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We report on maskless fabrication of photonic crystal (PhC) circuits based on ultrathin ($d \sim 15$ nm) nanoperforated GaN membranes exhibiting a triangular lattice arrangement of holes with diameters of 150 nm. In recent years, we have proposed and developed a cost-effective technology for GaN micro- and nano-structuring, the so-called surface charge lithography (SCL), which opened wide possibilities for a controlled fabrication of GaN ultrathin membranes. SCL is a maskless approach based on direct writing of negative charges on the surface of a semiconductor by a focused ion beam (FIB). These charges shield the material against photo-electrochemical (PEC) etching. Ultrathin GaN membranes suspended on specially designed GaN microstructures have been fabricated using a technological route based on SCL with two selected doses of ion beam treatment. Calculation of the dispersion law in the approximation of scalar waves is indicative of the occurrence of surface and bulk modes, and there is a range of frequencies where only surface modes can exist. Advantages of the occurrence of two types of modes in ultrathin nanoperforated GaN membranes from the point of view of their incorporation in photonic and optoelectronic integrated circuits are discussed. Along with this, we present the results of a comparative analysis of persistent photoconductivity (PPC) and optical quenching (OQ) effects occurring in continuous and nanoperforated ultrathin GaN suspended membranes, and assess the mechanisms behind these phenomena.

9519-5, Session 1

Self-organized nano-voids in strained SiGe/Si hetero-structures for plasmonic application

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The formation of new Si-based materials with enhanced light absorption is of great importance for the development of high efficient photovoltaic devices. A possible approach for enhanced light absorption is connected to excitation of localized surface plasmons after interaction of photons with nano-cavities, metallic nano-shells and nano-particles. The plasmonic excitations are then transferred to the semiconductor to generate electron-hole pairs.

The concept of this study is based on self-organized formation of voids in strained Si/SiGe hetero-structures. We will briefly review the effects of strain-driven self-assembly of nano-voids in irradiated Si/SiGeSn/Si layers, gettering and segregation of impurities and formation of buried nano-shells and nano-dots of Ge, Sn and Au in Si layers located nearby of a p-n-junction. Structural transformation in the Si/SiGe layers during self-assembling of nano-voids, optical and electronic properties of the layers, and resulting effects of nanostructures on the spectral dependence of the photocurrent in the Si/SiGe structures will be reported. Finally, special attention will be devoted to possible plasmonic structures for the enhancement of the efficiency of Si-based photovoltaic devices.

9519-6, Session 2

Defect luminescence in oxides nanocrystals

Teresa Monteiro, Joana Rodrigues, Maria Rosa Soares, Nuno F. Santos, Tiago Holz, Nabiha Ben Sedrine, Claudio Nico, António José S. Fernandes, Armando J. Neves, Florinda M. Costa, Univ. de Aveiro (Portugal)

Wide band gap oxides, such as ZnO, SnO₂ and ZrO₂, are functional crystalline materials with a wide range of applications in several important technological areas such as those including lighting, transparent electronics, sensors, catalysis and biolabeling. Recently, doping and co-doping of oxides with lanthanides have attracted a strong interest for lighting purposes, especially among them nanophosphors for bioassays. Tailoring the crystalline materials physical properties for such applications often requires a well-controlled incorporation of dopants in the material lattice and a comprehensive understanding of their role in the oxides matrices. These undoped or intentionally doped wide band gap oxides are known to exhibit optically active centers that span from the ultraviolet to the near infrared region. Recognizing and understanding the role of the dopant-related defects when deliberately introduced in the oxide hosts, as well as their influence on the samples luminescence properties, constitutes a matter of exploitation by the scientific community worldwide.

In this work, we investigate the luminescence properties of undoped and lanthanide doped oxide materials grown by laser assisted techniques. Laser assisted flow deposition (LAFD) and pulse laser ablation in liquids (PLAL) were used for the growth of ZnO, SnO₂ and ZrO₂ micro and nanocrystals with different morphologies, respectively. Regarding SnO₂ and ZrO₂ hosts, the trivalent lanthanide ions were optically activated by in-situ doping and co-doping. The influence of the defect energy states on the optical properties of the different undoped and doped metal oxide hosts is investigated under ultraviolet excitation by means of temperature dependent photoluminescence, photoluminescence excitation and lifetime measurements.

9519-7, Session 2

Self-assembly of semiconductor nanocrystals for optoelectronic applications

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CdSe/CdS nanocrystals are a promising material for light-emitting applications. Devices based on colloidal nanocrystals are typically fabricated via conventional solution based methods as spin coating or drop casting. Nevertheless, three-dimensional self-assembled nanocrystals solids with non-conventional shapes can be designed exploiting substrate functionalization and nanocrystals surface chemistry.

Here, we show how CdSe/CdS quantum dot-in-rods (QDRs) can be stabilized in water, avoiding detrimental effects on their light-emission properties, using a ligand exchange method employing mercaptopropionic acid.¹ 2 Water-soluble QDRs can be used for the fabrication of efficient micro-lasers on glass substrates exploiting the coffee-stain effect.³ The dense packing facilitated by the short-chain surface ligands leads to a very low lasing threshold (11 nJ/cm²).⁴ On the other hand, evaporation of a water solution of CdSe/CdS nanocrystals on a super-hydrophobic substrate leads to the formation of a hollow dome-shaped solid.⁵ These domes are loosely bound to the super-hydrophobic substrate, and therefore can be easily detached, handled and positioned. Such substrate-free three dimensional assemblies of highly luminescent colloidal nanocrystals can be freely positioned in an excitation beam of choice, without detrimental effects from an underlying substrate, which makes them interesting, for example, as a color converters in photonic circuits. Since the domes are obtained from the same nanocrystals solution as the coffee-ring micro-lasers, we can expect also here a dense

packing that should favor optical gain. Furthermore, the shell thickness of the hollow domes is similar to the coffee ring width, i.e. some tens of microns, opening the possibility for these three-dimensional structures to also function as self-assembled micro-lasers

These two micron size light emitting and lasing self-assemblies of colloidal nanorods demonstrate how the interplay of substrate functionalization and surface chemistry can lead to the fabrication of novel nanocrystal structures, that can be of interest for optoelectronic applications.

(1) F. Di Stasio, J. Q. Grim, V. Lesnyak, P. Rastogi, L. Manna, I. Moreels, R. Krahné, *Small* 2014, 10.1002/sml.201402527

(2) S. F. Wuister, I. Swart, F. van Driel, S. G. Hickey, C. de Mello Donega, *Nano Letters* 2003, 3, 503

(3) R. D. Deegan, O. Bakajin, T. F. Dupont, G. Huber, S. R. Nagel, T. A. Witten, *Nature* 1997, 389, 827

(4) M. Zavelani-Rossi, R. Krahné, G. Della Valle, S. Longhi, I. R. Franchini, S. Girardo, F. Scotognella, D. Pisignano, L. Manna, G. Lanzani, F. Tassone, *Laser Photon. Rev.* 2012, 6, 678

(5) A. Accardo, F. Di Stasio, M. Burghammer, C. Riekel, R. Krahné, submitted

9519-8, Session 2

Hybrid core-shell SnO₂/GaN@Ga₂O₃ nanoheterostructures for photodetectors

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Core-shell heterostructures based on semiconducting oxides nanocrystals are in the focus of wide scientific research community due to versatile applications. In this context, core-shell SnO₂/GaN@Ga₂O₃ nano- and microbelts have been assembled into hybrid networks via an efficient two-step technique. The tin oxide nano- and microbelt networks were grown by flame transport synthesis and shell layers composed of GaN@Ga₂O₃ nanocrystallites were deposited by magnetron sputtering. The developed technological route allows rapid synthesis of large amounts of material and it can be easily scaled up for various applications. The SEM and TEM results reveal that the GaN@Ga₂O₃ shells are deposited uniformly on SnO₂ networks with a tailored thickness depending on RF magnetron sputtering regime. The corresponding energy disperse X-ray elemental analysis shows excessive nitrogen and oxygen elements in the core-shell nanocomposite along with those incorporated in GaN and Ga₂O₃. The thickness of the shell is slightly bigger on one side than on the other due to the effect of sputtering. The structural investigations on heterostructures confirmed an excellent agreement with the standard data for rutile SnO₂, hexagonal GaN and monoclinic β-Ga₂O₃. The single crystallinity of the SnO₂ core is evidenced in select area electron diffraction (SAED) pattern. The SAED shows a projection along the [001] zone axis of SnO₂ (space group: P42/mnm) single crystal. These nano- and microstructures have been transferred to different substrates and photodetectors have been integrated on a chip. The nanosensor structures based on SnO₂/GaN@Ga₂O₃ core-shell microbelts on chip are stable and exhibit an UV response with faster switching and reversible performances. Annealing of the heterostructures leads to an enhancement in the UV response. The developed nanocoating approach presents a great interest for further studies of different hybrid metal oxides as promising candidates for fabricating nano- and micro-sensors/photodetectors.

1. L. J. Lauhon, M. S. Gudiksen, D. Wang, C. M. Lieber, *Nature* 2002, 420, 57-61.

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2. O. Lupan, L. Chow, G. Chai, H. Heinrich, Fabrication and characterization of Zn-ZnO core-shell microspheres from nanorods, *Chemical Physics Letters*, Volume 465, Issues 4-6, 13 November 2008, Pages 249-253.

9519-9, Session 2

Ultranarrow luminescence linewidth of silicon nanocrystals and influence of matrix

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The luminescence linewidth of individual silicon nanocrystals was characterized by single-dot spectroscopy, and an ultranarrow linewidth of ~ 200 μeV at 10 K was found.

This value is, in fact, limited by system resolution and represents only the upper limit of the homogeneous linewidth. In addition, the effect of the matrix was investigated for nanocrystals coated with organic ligands, embedded in silicon dioxide, as well as for nanocrystals with only a thin passivating layer. It was found that, depending on the matrix, the room-temperature bandwidth may vary by an order of magnitude, where values as small as ~ 12 meV (~ 5 nm) at 300 K were detected for nanocrystals with a thin passivation. The observed values for silicon nanocrystals are similar and even surpass some of those for direct-band-gap quantum dots.

The narrow linewidth at room temperature enables the use of silicon nanocrystals for nontoxic narrow-band labeling of biomolecules and for application as phosphors in white-light-emitting devices.

9519-32, Session 2

Electrochemical characterization of different carbon additives in silicon microwire anodes

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Silicon with its high gravimetric capacity of 4200 mAh/g is the material of choice for high-voltage applications of Li-ion batteries. Silicon microwire arrays exhibit a high long term cycling stability with a stable capacity of around 3050 mAh/g, if they are charged to 75 % of their capacity and in the right voltage ranges. Infiltration of conductive additives among the wires enhances the conductivity of the wires and the cycling performance. To enhance the understanding of the influence of conductive additives on the performance of electrodes, different carbon additives were investigated with Si microwires as active materials via cyclic voltammetry. Paste electrodes were prepared for the study. The tested carbon additives were CNTs, CNT foam, carbon black and aerographite. All paste electrodes contain the same (volume) amount of conductive additive in a 1:1 ratio to the Si wires. The contacting of the wires with the carbon derivatives is a crucial factor for the battery performance. During cycling, the anodes suffer from volume expansion which influences the contact between the Si wires. The wires start expanding laterally, shifting the carbon to other sides and producing cracks around the wires. This contact loss could be reflected in a rapid capacity fading.

Anodes containing CNTs mixed with an additional amount of binder exhibit easier lithiation and delithiation behavior compared to the ones containing carbon black. A wire length dependency of the lithiation/delithiation behavior has been found in recent studies; contact losses from the conducting matrix could appear depending on the wire length. This study should also prove that the way of contacting short and long wires influence the lithiation behavior when changing the conductive additives.

9519-11, Session 3

Mechanical resonators based on nanotubes and graphene

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Carbon nanotubes and graphene offer unique scientific and technological opportunities as nanoelectromechanical systems (NEMS). Namely, they have allowed the fabrication of mechanical resonators that can be operable at ultra-high frequencies and that can feature high quality factors. In addition, nanotubes and graphene have exceptional electron transport properties, including ballistic conduction over long distances. Coupling the mechanical motion to electron transport in these remarkable materials is thus highly appealing. Here, I will review some of our recent results on nanotube and graphene resonators, including mass sensing at the proton mass level, force sensing with ~ 10 zN/Hz^{1/2} noise, and the measurement of quality factors up to 5 million.

9519-12, Session 3

Potentials of 3D interconnected networks synthesized by flame transport synthesis approach: from ultra-light Aerographite material to multifunctional hybrid networks

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Fabrication of 3D interconnected networks with desired properties is going to play key role in future nanotechnology based applications. However simple and desired synthesis of these networks is an equally challenging task as it can not be simply achieved by conventional bottom-up or top-down recipes. Here we demonstrate the potential of newly introduced flame transport synthesis (FTS) approach which enables simple and versatile fabrication of different types of 3D interconnected networks of metal oxides (e.g., ZnO) [1]. Fabricated 3D networks with tunable porosity and Young's modulus are of high interest for potential applications [2]. These highly porous networks can be used as backbones for growth of composite networks or as sacrificial templates for the synthesis of a completely new 3D network. As an example, these ZnO networks have been converted into a carbon based Aerographite (AG) material using chemical vapour deposition process [3]. This AG material is entirely built from porous carbon microtubes (wall thickness ~ 15 nm) and is one of the least dense materials in the world [3]. Because of epitaxial requirements, versatile growth of GaN nano- and microstructures on different substrates has always been a challenging task and here in an attempt we have successfully grown the GaN nanocrystals on the surface of Aerographite tubes using hydride vapour phase epitaxy process (HVPE) in form of hybrid 3D networks [4]. It is observed that GaN nanostructures grow freely on the surface of Aerographite and the final hybrid material is equipped with features from AG network as well as GaN nanostructures.

[1] Y. K. Mishra et al., *Part. & Part. Syst. Charact.* 30, 775-783 (2012).

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[2] Y. K. Mishra et al., *KONA Powder and Particle J.* 31, 92-110 (2014).

[3] M. Mecklenburg et al., *Adv. Mater.* 24, 3486-3490 (2012).

[4] A. Schuchardt et al., *Scientific Reports* 2014, (Under Review).

9519-13, Session 3
Morphology and cathodoluminescence characterization of ZnO nanostructured layers deposited on Aerographite

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We demonstrate the feasibility of using Aerographite (AG) as three-dimensional flexible template for the growth of ZnO nanostructured layers, and report on their morphology and cathodoluminescence (CL) characterizations. Aerographite has been recently introduced as robust, extremely porous and ultra lightweight 3D network material in the family of carbon based nanostructures [1]. It consists of a network of porous carbon microtubes with average wall thickness of the tubes - 15 nm. The zinc oxide nanostructured layers were grown by using RF magnetron sputtering technique, as described elsewhere [2]. We observed that short time deposition results in the formation of ZnO nanocrystallites on the surface of AG tubes. The density of the deposited ZnO crystallites increases with time, leading to complete coverage of the open Aerographite surface by ZnO structures. In relatively thick layers (thicker than a few hundreds of nanometers) formation of ZnO tetrapods and multipods prevails which makes the deposited layer highly porous. UV and yellow luminescence bands have been revealed in deposited ZnO structures at room temperature. We present and discuss both spectral and spatial distribution of CL as a function of the technological conditions of ZnO depositions. Note that the architecture of the developed ZnO-Aerographite composite material allows one to avoid aggregation of ZnO nanostructures in cluster form which is a very important aspect for many applications, in particular in biomedicine [3, 4].

[1] M. Mecklenburg, A. Schuchardt, Y. K. Mishra, S. Kaps, R. Adelung, A. Lotnyk, L. Kienle, K. Schulte, *Adv. Mater.* 24, 3486-3490 (2012).

[2] L. Ghimpu, T. Potlog, I. Tiginyanu, A. Farcas, *Chem. Phys. Lett.* (submitted, 2014).

[3] Y.K. Mishra, R. Adelung, C. Röhl, D. Shukla, F. Spors, V. Tiwari, *Antiviral Res.* 92, 305-312 (2011).

[4] T. Antoine, Y. K. Mishra, J. Triglio, V. Tiwari, R. Adelung, D. Shukla: *Antiviral Res.* 96(3), 363-375 (2012).

9519-14, Session 3
Photoinduced conductivity enhancement in quantum dot/graphene nanostructures

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Hybrid structures based on nanocarbons and semiconductor nanocrystals is fast growing area in modern nanoscale science [1-4]. These structures combine effective light absorption of nanocrystals and high charge mobility in nanocarbons - properties are attractive for photovoltaic and optoelectronic devices.

Photoinduced increasing of graphene conductivity was shown in presence of quantum dots (spherical shaped nanocrystals) compare with graphene alone [1-3]. Charge transfer from quantum dots to graphene is regarded as the major mechanism of photoinduced conductivity increasing [6]. On the other hand, unlike molecules and quantum dots - point dipoles in the most of approximation - graphene is two-dimensional nanostructure. Therefore effective long-range energy transfer implements in molecule/graphene or quantum dot/graphene hybrid structures increasing photoconductivity of graphene [4]. The first or the second mechanism will prevail depends on hybrid structures appearance.

The purpose of our work is investigation of conductivity amplification in hybrid structures based on graphene and colloidal quantum dots. Structures were formed by successive graphene and QD film deposition on substrate by Langmuir-Blodgett technique. Dependence of photoelectrical and luminescent properties of structures on QD film thickness and energy band width was investigated.

[1] Zhao J. et al. Improving the photovoltaic performance of cadmium sulfide quantum dots-sensitized solar cell by graphene/titania photoanode // *Electrochimica Acta.* - 2013. - T. 96. - C. 110-116.

[2] Guo C. X. et al. Layered graphene/quantum dots for photovoltaic devices // *Angewandte Chemie International Edition.* - 2010. - T. 49. - No. 17. - C. 3014-3017.

[3] Lin Y. et al. Dramatically enhanced photoresponse of reduced graphene oxide with linker-free anchored CdSe nanoparticles // *ACS nano.* - 2010. - T. 4. - No. 6. - C. 3033-3038.

[4] Dai L. Layered graphene/quantum dots: nanoassemblies for highly efficient solar cells // *ChemSusChem.* - 2010. - T. 3. - No. 7. - C. 797-799.

9519-15, Session 4
Nanobiosensors for diagnostics (Invited Paper)

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Nanomaterials (NM) with electrical and optical properties are playing a key role in the design of cutting edge biosensing technologies. Electrocatalytic, plasmonic and quantum properties of NMs such as gold nanoparticles, quantum dots or graphene while operating in simple plastic or paper matrix in diagnostic and safety/security applications will be shown. The effect of the platform architecture and other chemical and physical parameters upon biosensing and actuation including nano/micromotors pick-up or mixing operations will be discussed. The developed smart nanobiosystems are with interest for integration of diagnostic with therapies (nanotheranostics) or sensing and destruction/removal (sensoremoval) for health and environment industries. Examples related to protein (ex. neurodegenerative disease biomarkers), DNA (pathogen related) or cells (cancer cells) with interest for point of care applications will be shown. The developed devices and strategies are intended to be of low cost while offering high analytical performance in screening scenarios beside other applications. Special emphasis will be given to lab-on-a-chip platforms with integrated electrochemical detection with interest for either clinical or environmental monitoring (including sensoremoval). In addition simple paper-based platforms that operate in lateral flow formats with interest for heavy metals or protein detection will be shown. Various enhancement technologies ranging from microfluidics architectures changes, in-chip re-circulations as well as actuation via nano/micromotors able to either pick-up analytes or

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improve reaction medium in solid-liquid phase sensing technologies will be discussed.

9519-16, Session 4

Optical detection of two-color-fluorophore barcode for nanopore DNA sensing

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Solid-state membranes with nanometer-sized pores (nanopores) have drawn great attention because of its promising application potential, such as high throughput protein sensing, DNA or RNA sensing or sequencing with single-molecule resolution. Nowadays, an individual nanopore is routinely fabricated by TEM-drilling and a bio-molecule is detected by changes in the ionic current when a molecule passes through the pore. However, this approach is difficult to scale up to enable parallel sensing with high throughput. In our group, we have an alternative approach from both fabrication and detection perspectives. We have developed two methods namely, electrochemical etching and self-limiting pore shrinkage, to fabricate nanopores in a large array in silicon membranes with controlled pitch distance and relatively small pore size distribution. Sub-10 nm pores were obtained by both methods [1, 2]. From detection side, wide-field optical microscopy is employed to realize parallel detection of labeled molecules passing through an array of pores simultaneously. At this stage, single dsDNA fragments with a length of 450 base pairs, labeled by a fluorophore (ATTO-532), were detected simultaneously when passing through an array of pores. It is shown by the statistics of the translocation events that the translocation duration and recorded event rate are highly dependent on the pore size and its geometry.

[1] Zhang M, Schmidt T, Sangghaleh F, Roxhed N, Sychugov I and Linnros J, Oxidation of nanopores in a silicon membrane: self-limiting formation of sub-10 nm circular openings, *Nanotechnology* 2014, 25(35):355302

[2] Schmidt T, Zhang M, Yu S and Linnros J, Fabrication of ultra-high aspect ratio silicon nanopores by electrochemical etching, *App. Phys. Lett.* 2014, 105:12311

9519-18, Session 4

Oxide-bioceramic coatings obtained on titanium items by the induction heat treatment and modified with hydroxyapatite nanoparticles

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The study focuses on the influence of heat treatment with high frequency eddy currents on the micro- nad nanostructure and properties of biocompatible materials, in particular commercially pure titanium VT1-00 and titanium alloy VT16. These materials are widely used in the manufacture of endoprostheses and implants. Particular attention was paid to obtaining on their surface of biofunctional layer, which stimulates osseointegration. The metal substrate of the implant provides resistance to mechanical distributed loads. However, when the implant is installed in the bone bed significant shear stresses occur in the surface layer and abrasion with scratching by hard cortical bone takes place. Induction heat treatment ensures growth of the titania coating represented by rutile. The experiment studied the influence of technological regimes on the surface morphology parameters of the obtained coatings, their physico-mechanical properties, in vitro and in vivo biocompatibility. The temperature range of 600 to 1200 °C during the heat treatment within 300 seconds was considered. Titania coating formation stages included the formation of dotted, needle-like, plate and prismatic crystals. Diffusion of oxygen occurring in the surface layer of cp-titanium and its alloy VT16 was studied. Titania coatings with high hardness of 4.23...9.86

GPa and elasticity modulus of 200...750 GPa were studied using nanoindentation. Scratch resistance was determined by scratch testing and equalled from 1.38 to 8.76 GPa and the friction coefficient – from 0.1 to 0.8. Oxide coatings were modified with hydroxyapatite colloidal nanoparticles. The next stage comprised final heat treatment in order to fix the composite structure of oxide/bioceramic coating. Increased cellular activity (adhesion and proliferation) and accelerated osseointegration on the surface of implants with nanocrystalline coatings were observed. The recommended temperature range from 800 to 1000 °C heat treated during or more than 30 seconds was determined.

9519-39, Session 4

Complexation of porphyrins with nanoparticles of zeolite

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Currently, photodynamic inactivation (PDI) of microorganisms using photosensitizers (PS) is one of the most promising areas for the destruction of antibiotic resistant microorganisms. Photosensitizers (porphyrins) under the action of light promote the generation of molecules of singlet oxygen, which effectively inhibit the growth and kill microorganisms. In order to improve efficiency and increase the selectivity of accumulation of photosensitizers in microorganisms actively used nanocontainers. Among the many types of nanoparticles-nanocontainers, nanoparticles of zeolites occupy a special position due to the high biological activity, as well as unique adsorption capacity of microorganisms and porphyrin-ligands. The aim of this work was to study of processes sorption of porphyrins on nanoparticles of zeolite.

The interaction of cationic porphyrins with nanoparticles of zeolite in the range of visible spectrum, at 350-800 nm was studied. For investigation of sorption on/in nanoparticles of zeolite the following five cationic porphyrins and metalloporphyrins we used: i) meso-tetra (4-N-oxyethyl pyridyl) porphyrin (TOEt4PyP), ii) Zn-TOEt4PyP, iii) meso-tetra (3-N-oxyethyl pyridyl) porphyrin (TOEt3PyP), iv) Zn-meso-tetra (4-N-butyl pyridyl) porphyrin (Zn-TBut4PyP) and v) Ag-TBut4PyP, as well as of photosensitizers chlorin e6 and Al-phthalocyanine. Analysis of the dynamics of change in the absorption spectra for porphyrins and metalloporphyrins (10⁻⁵ M) by adding of nanoparticles in two concentrations (0.024 mg/ml and 0.091 mg/ml) leads to the conclusions: i) that the binding of porphyrins occurs very quickly - less than 3 minutes, ii) that the percentage of adsorption on nanoparticles is for all porphyrins more than 90 %, iii) that the predominant mechanism of binding is the electrostatic binding of cationic porphyrins and metalloporphyrins (charge +4) on/in the negatively charged surface of the zeolite nanoparticles.

It was shown that damage of microorganisms by such nanocomposites (nanoparticles of zeolite + cationic porphyrins) is the promising method for the destruction of both Gram (+), and Gram (-) microorganisms.

9519-19, Session 5

Novel micro-column using a multi-gated field emitter

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Recently, our group has developed four- and five-gated field emitter arrays (FEAs) with an electrostatic lens (einzellens). The five-gated FEA has successfully realized a crossover of the electron beam without any external optical system. However, these multi-gated FEAs have

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large aberrations. We did not apply them to a micro-column for SEM or electron beam lithography.

In this presentation, we have designed and fabricated a novel micro-column using a multi-gated field emitter. The micro-column consists of an objective lens and an electron gun. An acceleration lens was used as an objective lens. The electron gun was designed to produce a parallel electron beam. The electron gun has three gates and a field emitter tip. The key components are the second (focusing) and third (waist) electrodes. The focusing electrode can focus and align the electron beam like a condenser lens without reducing the electric field at the top of the emitter tip. The waist electrode with a small aperture can electrically isolate the condenser from the acceleration lens just above the electron gun. By applying a lower voltage to the waist electrode than to the first electrode, which acts as an electron extractor from the tip, the electron beam can be decelerated before being injected into the objective lens. The slow electron beam enables us to use an acceleration lens as an objective lens. We measured current-voltage characteristics of each electrode for the micro-column. The current variation of each electrode indicates that each structure controls the electron beam and the objective lens focuses the electron beam of about 40 μm at working distance 2 mm and a magnification of 400 times without applying an electric field from the micro-column to the anode.

9519-20, Session 5

Metal silicide/Si thin-film Schottky-diode bolometers

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This research was inspired by the recent successful development of a series of SOI diode uncooled bolometer LWIR FPAs and FLIR cameras which gave a new direction of thought in the IR imaging technology. This success has stimulated our own search for simple CMOS-compatible technological solutions based on diode bolometers which would be suitable for mass production of IR FPAs with low cost and NETD figures sufficient for many civil-medical and industrial-and tactical applications. In our recent article, thin film nickel silicide Schottky diodes formed on poly-Si:P films were demonstrated to be a promising alternative to SOI-diodes in monolithic uncooled microbolometer FPAs. Absolute values of their temperature coefficients of voltage and current were found to reach 0.6 %/°C for the forward bias and be around 2.5 %/°C for the reverse bias of the diodes despite that the studied diodes were far from perfectness. However, the possibility of cascade connection of the Schottky diodes increasing the temperature sensitivity of bolometer elements and the use of layers of the diode structures of bolometer cells as additional absorbers of the incident radiation may be obvious practical advantages of the Ni₂Si/poly-Si structures. Recently, we have proposed a solution even more appropriate for the industry. We have developed PtSi/poly-Si:P Schottky diodes for temperature sensing in microbolometers. Apart from the above mentioned advantages of the Ni₂Si/poly-Si diodes, ease of integration of technological process of the PtSi/poly-Si diode formation into the standard CMOS technology of VLSI manufacturing, in analogy with the technology of the monolithic PtSi/Si IR FPAs well developed in the industry, is the important merit of this approach. In the current paper, we demonstrate a novel type of IR sensors. We have developed and tested PtSi/poly-Si:P thin-film Schottky-diode bolometers and found them to be a promising solution for prospective uncooled diode FPAs.

9519-21, Session 5

Bio-inspired Nanofur for oil spill cleanup and underwater drag reduction

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Disasters like the Deepwater Horizon Blowout or tanker accidents and industry generate oil spills and industrial wastewater which cause long

lasting environmental problems. Conventional methods for oil spill cleanup (like burning, chemical dispersion or collecting with sorbents like sawdust) are harmful to the environment or require complex reprocessing steps.

A bio-inspired nanostructured surface, covered with dense nanohair, paves the way out of this dilemma. The leaves of the floating water fern *Salvinia minima* are superhydrophobic, which occurs from the nano- and microhair-like structure covering the leaf surface. We transferred this effect to polymers and fabricated polymeric nanofur, which is both superhydrophobic (reached contact angle: up to 172°) and superoleophilic and therefore selectively adsorbs oil while repelling water.

Besides the superhydrophobicity, the floating fern shows impressive underwater air retaining properties. Used as ship coatings, this can both increase their speed and significantly reduce fuel consumption.

We present the highly scalable fabrication process which enables the low-cost fabrication of nanofur. A steel plate, roughened by sandblasting, is heated and pressed into a polymer foil, which makes the surface of the polymer melt. Retracting the hot steel plate, nanohair is pulled from the polymer surface. Adjusting the fabrication process enables the application-oriented property tuning: Superoleophilic surfaces with high oil capacities as well as air retaining foils can be produced at low costs. Besides that, we present recent developments concerning the nanofur, ensuring optimal environmental compliance and the expansion of the application range.

9519-22, Session 5

A 2D nanoparticle sorter: towards an 'on-chip' quantification and full characterization of nanoparticles

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In the context of the extensive use of engineered nanomaterials (ENMs) in consumer products, industrial applications and nanomedicine, there is a important need of new methods for an exhaustive characterization of their physico-chemical properties. Among them, surface hydrophobicity is considered as an important property since it has a critical role in various processes such as protein adsorption, interaction with biological membranes or cellular uptake potentially related to an increase in toxicity, immune response, or haemolytic effect. Hence, it has been demonstrated that the ENMs hydrophobicity is a key factor to be controlled, in particular for nanomedicine applications. Furthermore, the few existing processes dedicated to the full characterization of ENMs involve different techniques, which make it expensive and highly time-consuming. The proposed study demonstrates the proof-of-concept of an inexpensive characterization process thanks to a disposable chip connected to an optical reader. The device proposed here would enable the sorting of ENMs according to their hydrophobicity and surface charge, together with the classical characterization of size and shape. The detection platform is based on the use of an arrayed surface with tuned surface properties to bind ENMs selectively by hydrophobic forces and electrostatic interactions. Moreover, thanks to the use of a microfluidic chamber enabling experiment in flow condition and to a microscope-coupled camera for imaging in real-time, it would give information on the kinetics of adsorption, related to the affinity of the ENMs for the different surfaces. The key advantages of such a device would then be a decrease of time and costs thanks to the all-in-one characterization process and the multiplexing that could replace the use of different methods and expensive equipment to give equivalent results. In this way, the full characterization of NP could be expanded in all the areas covering NP-related applications.

9519-23, Session 5

C-IOP/NiO/Ni7S6 composite with the inverse opal lattice as an electrode for supercapacitors

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Nanostructured carbon materials find wide applications in many areas of engineering. The most actively developed areas are connected with portable power sources in microelectronics, energy accumulators, components of pulsed power devices, and other devices requiring high-speed energy sources. Electrodes based on carbon structures modified of metal oxides (MnO₂, RuO₂, NiO, etc.) possess so-called "pseudocapacity". Pseudocapacitive materials let achieve energy density of batteries combined with a long cycle life and a power density of electrical double-layer capacitors.

A template synthesis method is one of the most powerful methods for producing materials with precisely controlled structures at the nanometer level. Opal-like materials are convenient as a matrix to create nanostructures and have great abilities for monitoring and managing of the porous structure. The system of interrelated micro-, meso- and macropores within inverted opal combined with high specific surface area increases sorption, catalytic and electrochemical properties of the material. An important advantage of nanostructures with inverted opal lattice is their three-dimensional regular arrangement.

In this work, we demonstrate the results of studies on the synthesis, structure and properties of carbon inverted opal (C-IOP) nanostructures, the surface of which is modified by oxide and sulfide of nickel. It is shown that the treatment temperature of opal matrices filled with carbon compounds with subsequent dissolving of silicon dioxide and the sizes of silicon dioxide particles in the initial opal matrix exert the decisive influence on the formation and development of the porous structure. The phase compound of the composites with different content of oxide and sulfide nickel has been established. The electrochemical properties of the samples have been measured.

9519-17, Session PSTue

Novel Nanoplasmonic Biosensor Integrated in a Microfluidic Channel

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An important motivation of biosensor research is to develop a multiplexed sensing platform of large-scale, low-cost, and high sensitivity for applications such as the diagnosis and monitoring of diseases, drug discovery and the environmental control. Biosensors based on localized plasmon resonance (LSPR) have demonstrated to be a novel and effective platform for quantitative detection of biological and chemical analytes. Here, we describe the low-cost fabrication of a novel label-free nanobiosensor, consisting of an array of closely spaced, vertical, elastomeric nanopillars capped with plasmonic gold nanodisks in a SU-8 channel. The principle is based on the refractive index sensing using the LSPR of gold nanodisks. The fabrication process of the biosensor was divided into four steps: i) fabrication of silicon nanopillars in a SU-8 channel to be employed as a master mold, ii) fabrication of the negative polydimethylsiloxane mold, iii) replication of the Si master mold, and iv) evaporation of gold nanodisks on the polymer nanopillars by e-beam evaporation. The resulting biosensor consists of an array of polymer nanopillars capped with gold nanodisks of 25 nm of thickness, whose diameter can range from ~150 nm to 200 nm, and whose height can range from ~250 nm to 1000 nm, separated 400 nm from the center to center, integrated in a microfluidic channel of 35 μm of thickness.

9519-29, Session PSTue

The development of double polarity GaN growth for fabrication of the GaN QPM crystal

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In this study, we have tried to fabricate the double polarities GaN (DP-GaN), and we optimized the fabrication process of double polarities GaN by MOVPE growth using the carbon mask formation of the selected region. We considered the interface abruptness of the double polarities selective area growth (DP-SAG) process by examining the optical characteristic of DP-GaN fabricated by DP-SAG process.

DP-GaN is grown by MOVPE on the c-sapphire substrate patterned carbon mask. After the substrate was nitrided by NH₃, the selective area nitridation of the substrate was carried out by etching the carbon mask using high temperature H₂ cleaning. By growing GaN on the selective nitrided substrate, DP-SAG process was obtained. The fabricated DP-GaN was evaluated by PL measurement, and CL mapping measurement. From these results, we considered the emission property of each polar plane in DP-GaN.

In the case of fabricated DP-GaN, Ga polarity surface is the flat circular region and N polarity surface is the region with hexagonal facets surrounding Ga polarity. In addition, we evaluated the DP-GaN by CL mapping measurement result in each emission wavelength. In the result of CL mapping, we confirmed that the region of high emission intensity is the N polarity surface region near the both polarity interface. Then, we fabricated the DP-GaN, which has a region without GaN growth, and evaluated optical characteristic by CL mapping measurement. The CL mapping results indicated that the strong emission region is the N polarity region and facet part of Ga polarity region. These results indicate that the strong emission is caused by the facet of Ga polarity GaN part covered with N polarity GaN.

In conclusion, we considered that it is important to fabricate the DP-GaN with abrupt interface by control the each polarity GaN growth rate and lateral growth.

9519-34, Session PSTue

Angular ellipsometry of indium tin oxide films

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Indium tin oxide (ITO, or tin-doped indium oxide) is a solid solution of indium (III) oxide (In₂O₃) and tin(IV) oxide (SnO₂). ITO is the urgent problem of modern physics. It used in the production of transparent electrodes of liquid crystal screens, touch screens.

We using angular ellipsometry for investigation optical properties of indium oxide films. It produced by reactive magnetron sputtering in DC mode with different deposition times. The total pressure of reactive mixture (1/3 of oxygen and 2/3 of argon) was 7*10⁻³ millimeters of mercury. Samples heated to a temperature of about 140-150 °C during 20-30min. Unoxidized silicon used as substrates. Time of deposition of films was 10, 15 and 40 seconds.

Ellipsometric parameters (Δ phase shift between p- and s- polarization components and azimuth of the restored linear polarization ψ) samples were determined in a wide range of incidence angles φ on standard laser ellipsometer ηEφ -3M -1 with the working wavelength helium-neon laser λ = 632.8 nm. The model not absorbing homogeneous layer (ITO) on the absorption padding (Si) were applied to calculate the refractive index n and thickness d ITO films.

The optical properties of the ITO films (refractive index and thickness) were calculated from the ellipsometry measurements using the model of non-absorbing homogeneous layer (ITO) on the absorbing substrate (Si). Also we tested isotropic films using azimuthal ellipsometry.

9519-36, Session PSTue

Generation-recombination processes in InGaAs/GaAs heterostructures with one-dimensional nanostructures

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Materials with one-dimensional quantum structures are promising for their application in solar cells. The presence of nano-objects in the i-region of p-i-n-diode accelerates the kinetics and widens the spectrum of sensitivity, because the InGaAs are additional recombination centers and photogeneration of nonequilibrium charge carriers, respectively.

9519-37, Session PSTue

Reduced QCSE in InGaN-based LEDs by patterned sapphire substrates with enlarging the diameter of hexagonal hole

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This paper reports the InGaN-based light-emitting diodes grown on patterned sapphire substrates can reduce the related quantum-confined stark effect within multiple-quantum wells with enlarging the diameter of hexagonal hole, which results in that the PL relative intensity is enhanced by up to 95% as compared to the conventional one.

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Recombination of charge carriers in heterostructures Si/Ge with Ge nanoislands

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In nanosize semiconductor heterostructures quantum size effects can result in changes of the electron spectrum. Silicon-germanium nanostructures refer to the second type, when holes are localized in the quantum states in the valence band of Ge nanoisland. In such structures occurs the spatial separation of nonequilibrium charge carriers. Consequently, Ge islands can accumulate positive charge at low temperature which will affect on the redistribution charge density along the epitaxial layers. The investigation of SiGe/Si nanostructures bears good prospects for the development of novel nanoelectronic devices.

During the investigation of the kinetics of photoconductivity in Si/Ge nanoheterostructures at $T < 120$ K we observed the long-term relaxation of the photocurrent. When only $\text{Si}_{1-x}\text{Ge}_x$ nanoislands were excited, the relaxation occurred faster, which proves more effective recombination involving quantum-size states of nanoislands in comparison with the rate of recombination of electron-hole pairs photogenerated in the Si substrate.

We showed that SiGe nanoislands, built-in into the multi-layer structures based on silicon, become the centers of recombination of electron-hole pairs photogenerated in Si and, in general, determine the rate of surface recombination in this heterostructures. It was found that during the selective photoexcitation of nanoislands the recombination of electron-hole pairs in SiGe is defined by the spatial separation of nonequilibrium charge carriers, when holes are trapped in the valence band states of SiGe, and electrons are in their silicon surroundings.

The recombination efficiency of the electron-hole pairs involving quantum confinement states in nanoislands is higher in comparison with the rate of recombination of the carriers photogenerated in Si substrate. We found that when we have selective photoexcitation, recombination of electron-hole pairs in SiGe nanoislands is defined by spatial separation of nonequilibrium charge carriers, when the holes are captured in the valence band states of SiGe nanoislands and electrons are in silicon environment.

9519-40, Session PSTue

Spectral and dielectric properties of nematic liquid crystal doped semiconductor quantum dots CdSe/ZnS

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Doping of liquid crystals with semiconductor quantum dots allows varying the optical and dielectric properties. In this paper, we investigated the absorption and luminescence spectra and low-frequency spectra of dielectric losses of nematic liquid crystal suspensions with the semiconductor quantum dots (QDs) CdSe/ZnS.

Investigations were carried out with a nematic liquid crystal based cyanobiphenyls LC-1289 (NIOPIK, Moscow) and hydrophobic semiconductor QDs CdSe/ZnS with a core diameter 3.5 nm (QD570) and 5.0 nm (QD630), coated TOPO. The suspension was prepared from powders of QD and LC in the nematic phase by mixing them with ultrasound. The concentration of the quantum dots was varied from 0.05 to 0.3 wt. % for QD630 and from 0.014 to 0.23 wt. % for QD570.

We determined that a gradual increase of concentration as QD570 and QD630 in suspension reduces the intensity of the liquid crystal photoluminescence (PL) in its characteristic band 414 nm. The NLC luminescence dropped exponentially. Doping of the QDs with 5.0 nm core diameter facilitated a more rapid luminescence quenching of the NLC compared to the quantum dots with

3.5 nm core diameter. Changing PL of the liquid crystal doped with the semiconductor CdSe/ZnS QDs may relate to the transfer of an electron or hole and exciton from donor to acceptor, where a donor may be the NLC molecules and acceptor is QDs.

We observed that the dielectric spectra deviations for the suspensions of the pure NLC spectrum in the region below 103 Hz with increasing QDs concentration. Significant increase in dielectric losses in the range up to 5 kHz of the suspensions dielectric spectra were due to increase in the conductivity of the medium. We observed the increasing of charge carriers in the suspension NLC with QDs.

9519-41, Session PSTue

Mathematical modeling of sustainability of porous Al₂O₃ growth during two stage anodization process

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Currently, due to the development of nanotechnology and metamaterials, it is important to obtain regular nanopore structures with different parameters. Porous anodic alumina films represent a hexagonal packing of cylindrical pores and is used for synthesis of various nanocomposites.

In the process of anodization electrolyte moderately dissolves alumina. With varying anodization parameters such as voltage, pH of the electrolyte, temperature of anodization, aluminum impurities it is possible to vary pore diameter.

In this work we consider the motion of the interfaces between electrolyte

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and alumina layers (dissolution process), and between alumina and aluminum layers (oxidation). We also took into account the dynamics of moving boundaries and the change of small perturbations of these boundaries. Each area under Laplace's equation is solved for the potential of the electric field. The growth of porous alumina is described with the theory of small perturbations. Small perturbations of the interface are considered, which lead to small changes in potential and current in the boundaries.

As a result of the developed model we obtained the minimum distance between centers of aluminum oxide pores in the beginning of anodizing process and the wavelength of porous structure irregularities.

9519-42, Session PSTue

An analytical model of multi-particle electric double-layer interaction between identical spherical colloid nanoparticles

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This work is devoted to the theoretical study of the colloid nanoparticle interaction driving the coagulation process. A simple analytical model for the multi-particle interaction between the amphoteric oxide nanoparticles with low surface potential was developed.

The model utilizes the framework of the DLVO (Derjaguin, Landau, Verwey, Overbeek) theory and uses an original modification to the traditional approach based on the linear superposition approximation of the Poisson-Boltzmann problem. This modification combines the truncated multipole expansion of the screened nanoparticle potential in electrolyte and a phenomenological linear charge regulation model to account for the nanoparticle surface charge redistribution during their interaction. The phenomenological approach allows to successfully describe the surface charge transformations for nanoparticles with a rather high density of surface features without the need for the explicit description of all the chemical processes involved.

The presented study focuses on the simplest case of considering only the monopole term of the screened nanoparticle potential. The results of this study provide a good qualitative agreement with the experimental data for the initial stage of nanoparticle coagulation. For the interaction between a nanoparticle and an agglomerate of increasing size it demonstrates a limited decrease in attachment probability arriving at a constant value dependent on the system parameters. Within its limits of applicability the model doesn't impose restrictions on the number of interacting particles and allows for the theoretical study of the nanoagglomerate formation. The latter revealed the presence of the orientation effects during nanoparticle aggregation which may cause the formation of aggregates with different morphologies.

9519-43, Session PSTue

Polymers embedded with ZnO tetrapods: Fabrication of 3D-Lightscattering composite materials for lighting applications

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Since semiconductor based light sources are typically only able to emit focused light, light scattering has become an important topic nowadays. Semiconducting nano- and microstructures seem to be very potential candidates in this regard due to their unique size and shape dependent light scattering features. Being a direct and wide band gap semiconductor with high refractive index, ZnO structures are very promising materials as highly effective light scattering elements for LED- and LASER-applications and the present work discusses the fabrication of 3D

lightscattering composites using anisotropic ZnO structures embedded in a solvent free low adsorbing polymer. The recently introduced flame transport synthesis (FTS) technique allows versatile fabrication of ZnO structures with different shapes, e.g., nanorods, tetrapods, multipods, belts etc [1]. Because of three dimensional spatial geometry and submicron size range, ZnO tetrapods are of special interest as they exhibit interesting light scattering properties and can be easily utilized as filler materials. The desired amount of micro- and nanostructured ZnO tetrapods has been synthesized by the FTS approach in form of free-standing powder and 3D ZnO tetrapods. Composites are prepared by blending polymer components with the filler tetrapods and later curing. The fabricated 3D composites have been characterized in detail using scanning electron microscopy and UV-VIS spectroscopy. SEM micrographs demonstrated the shape and structural integrity of ZnO tetrapods in the composites along with homogeneous distribution. Light scattering studies suggest that the fabricated 3D composite materials exhibit low distortion of colors and homogeneous distribution of monochromatic light which could be useful for different focused light source applications. Fabrication of 3D light scattering composites with various other possible arrangements, e.g., using different filler shapes or multilayered geometries will be presented and discussed.

[1] Y. K. Mishra et al., Part. & Part. Syst. Charact. 30, 775-783 (2012).

9519-44, Session PSTue

Infrared absorption properties of sodium nitrate on silver/diamond powder (Ag/DP) composites

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As one of the major marine nutrient salts, the abnormal changes of its concentration usually could indicate the change of oceanic ecological environment. However, for the low nitrate anion concentration such as in seawater (around 10⁻⁶ mol/L), the measurement becomes very challenging with the prohibitively weak absorption signals. Surface-enhanced infrared absorption (SEIRA) by nanomaterials and/or optical antennas would be able to the in-situ monitoring of the marine nutrient at high sensitivity in real time.

In this paper, the pyrolysis method was used to synthesize the Ag/DP composites and use it to detect nitrate ion. It is also examine that the effect of electric field on the IR properties of Ag/DP composites to nitrate ion by Fourier Transform Infrared (FTIR) Spectroscopy. It is found that the obvious enhancement of absorption and the significant difference between the two individual antisymmetric stretching modes of NO₃⁻.

9519-45, Session PSTue

Nanotechnology and discovery new factor that influences on permeability erythrocytes and eryptosis

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This paper presents original research studying the effects of biocompatible nanoparticles standardized (ICNB) on the permeability of erythrocytes and eryptosis. The presented evidence demonstrates that changing orientation and mobility protons of the hydrogen atoms in the pericellular fluid significantly modify the permeability and physiological activity of erythrocytes. The leading role of the state of cell membrane and transport activity enzymes (ATPase) in ensuring its permeability and functional activity is exaggerated. Magnetite nanoparticles (ICNB) act on the fluid of pericellular structure by changing the orientation and mobility of hydrogen protons that ultimately determines the permeability, and physiological activity of cells. These studies support the G. Ling's theory of an "association-induction" and "multi-layered organization polarized water".

9519-46, Session PSTue

Atomic layer deposition of Al₂O₃ on NF₃-pre-treated graphene

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Graphene has been considered for a variety of applications including novel nanoelectronics device concepts such as the recently reported Graphene Base Transistor (GBT).[1] However, the deposition of ultra-thin films on top of graphene is still challenging: On the one hand, the deposition process must not damage or alter the pristine graphene monolayer; on the other hand, the finally deposited films have to provide appropriate functional properties regarding a specific application. In case of the GBT, a dielectric coating is desired which is both pin-hole free to prevent any short circuits and still thin enough (around 3-5 nm) to enable hot electron tunneling. Hence, the dielectric film closure on graphene needs to occur at an early stage of the deposition process.

Atomic Layer Deposition (ALD) has been established as a physicochemical coating technique with excellent thickness control as well as unique conformality over complex three-dimensional-shaped substrates for the last decade.[2] Especially the ALD of oxides has been extensively researched. Accordingly, an ALD process for Al₂O₃ yet exists that alternates the exposure of trimethylaluminum (TMA) and water (H₂O) as the organometallic precursor and co-reactant of two corresponding self-terminating surface reactions, respectively. [3] However, the ALD of Al₂O₃ has been reported to barely initiate on pristine graphene due to graphene's lack of dangling bonds.[4] A fluorine functionalization, using XeF₂, has been found to provide additional nucleation sites resulting in conformal films without pinholes.[4]

Based on this literature finding, we studied the impact of pre-treatments by nitrogen trifluoride (NF₃) on exfoliated as well as epitaxial graphene monolayers prior to the ALD of Al₂O₃. All experiments were conducted in vacuo; i. e. the pristine graphene samples were exposed to NF₃ for 180 s in the same reactor immediately before applying 30 ALD cycles and the samples were transferred between the reactor and a surface analysis unit under high vacuum conditions. The ALD growth initiation was observed by in-situ real-time Spectroscopic Ellipsometry (irtSE) with a sampling rate of 1 Hz. The chemical surface composition before and after the ALD as well as the presence of graphene after the coating procedure were revealed by in-vacuo X ray Photoelectron Spectroscopy (XPS). The morphology of the films was determined by Atomic Force Microscopy (AFM) and Scanning Electron Microscopy (SEM). The defect status was examined by Raman Spectroscopy before and after the coating procedure.

[1] S. Vaziri et al.: Nano Letters 13 (2013), 1435

[2] M. Leskelä, M. Ritala, O. Nilsen: MRS Bulletin 36 (2011), 877

[3] R. Puurunen: Journal of Applied Physics 97 (2005), 121301

[4] V. Wheeler et al.: Carbon 50 (2012), 2307

9519-47, Session PSTue

HRTEM observation of interface states between ZnO epitaxial film and Si(111) substrate

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ZnO epitaxial thin films could be formed by oxidation of ZnS epitaxial thin films deposited on Si substrates by electron beam evaporation. The orientation relation of the ZnO film was (0002)_{ZnO}//(111)_{Si}, [1-10]_{ZnO}//[1-10]_{Si}. ZnS films were oxidized from its surface toward the surface of the Si substrate gradually. The ZnS film with a thickness of about 100 nm was completely changed to ZnO by annealing at 720°C for 10 min. in O₂ atmosphere. By excess annealing longer than 30 min, an intermediate

layer was formed at the interface between the ZnO layer and Si(111) substrate. Exciton emission with a peak at 3.27 eV from ZnO became dominant and visible emission due to oxygen vacancy in ZnO disappeared by the annealing of the film at 800°C for 5 h in O₂ flow.

9519-48, Session PSTue

Production of porous oxide coatings with ultrafine crystalline structure on medical implants fabricated from alloy 12Cr18Ni9Ti

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The structural state of metal-ceramic oxide coatings produced on steel 12Cr18Ni9Ti by thermal modification in the air was studied using scanning electron microscopy. The influence of technological regimes of heat treatment of steel medical implants for osteosynthesis on the changes in the morphological parameters of coatings, their dimensional structural characteristics was determined. In the course of electron microscopy studies it was determined that during thermal modification of the surface of steel substrates in the air polycrystalline metal oxide films with ultrafine structure and different geometries of oxide particles are formed.

Dimensional effects in the resulting films have been analyzed and the influence of oxidation regimes on the characteristics of structural elements in oxide systems has been established. It has been revealed that the resulting thermal oxide layer consists of densely packed ultrafine grains that form the structure of highly homogeneous agglomerates, the spatial arrangement of which in the coating creates a high open porosity. Under the studied conditions at the temperatures of 350 and 400 °C and oxidation duration of 1.5 hours the formation of both bulk and surface structure of coatings was characterized by the formation of numerous nucleations and growth of oxide particles from them with different size effect. Coatings acquired mainly fine structure, the specific feature of which is increased porosity and microheterogeneity.

Based on the experimental studies of the characteristics of surface heterogeneous oxide coatings produced on substrates of medical stainless steel 12Cr18Ni9Ti by gas-thermal oxidation it was found that the resulting thin coatings have the ability to ingrow into the bone tissue. The application of the developed coatings under osseointegration of steel orthopedic implants into different bone segments is explained.

9519-49, Session PSTue

Electrodynamical properties of the nanocarbon/polymer composites with aligned by magnetic field secondary non-conductive component

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In recent years, there is an emergence of electromagnetic interference (EMI). An EMI shielding is required to protect the electronic circuits as well as the health of human beings. In this regard, different composite systems with addition of barium hexaferrite are very promising.

The aim of this paper was to investigate the electrical conductivity, shielding efficiency, transmission of composite materials (CMs) with aligned by magnetic field binary filler.

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Carbon nanotubes (CNTs)/epoxy and graphite nanoplatelets (GNPs)/epoxy CMs (2-5 wt%) as well as the CMs with binary filler were prepared by the method of ultrasonication of the CMs mixture in acetone. Barium hexaferrite (30wt%) was added as the secondary filler. To obtain CMs with aligned barium hexaferrite, the composite mixture was placed to the 0,64Tl magnetic field till the end of the polymerization process.

The Electrical conductivity of the single- and binary filler CMs was measured in 77-290K ranges by the standard 2- and 4-probe methods. Electrodynamical properties were investigated in a frequency range of 36-55,5 GHz.

The secondary non-conductive filler addition results in increase of the conductivity and percolation threshold shifting to the lower filler concentration. But the placing of CMs in the static magnetic field leads to the magnetic nanoparticles alignment and the indirect redistribution effect on the nanocarbon particles. Namely, it is expressed in 2-6 times conductivity increase for the magnetic field influenced binary CNTs/epoxy CMs versus non-influenced and this effect is 6-12 times for GNPs/epoxy CMs. Herewith, the CMs conductivity increases but the conductive mechanism has not been changed, which is confirmed by temperature dependences of the conductivity.

It has been found that for high nanocarbon content CMs (5wt%) reflection loss is weakly dependent from the incident wave frequency. Magnetically treated and untreated samples have the same EMI shielding properties for high-content CNTs and GNPs CMs. But, despite the same BaFe12O19 containment (30wt%), the effect of the magnetic field at CNTs containing CMs properties is less than on GNPs containing CMs. This may be due to the different mobility of the particles in the composite mixture because of the shape and mass otherness of the nanoparticles. However, the 30wt% BaFe12O19+GNPs+epoxy samples unlike the 30wt% BaFe12O19+CNs+epoxy samples are characterized by a slight anisotropy of EM radiation and CMs interaction at the frequency of incident EM wave of 45÷55GGz.

9519-50, Session PSTue
Light absorption of cylindrical quantum dot with Morse potential in the presence of parallel electrical and magnetic fields

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The electronic states and direct interband light absorption are studied in the cylindrical quantum dot with Morse confining potential made of GaAs in the presence of parallel electrical and magnetic fields. Expressions for the particle energy spectrum are obtained within the framework of perturbation theory and variation method for the regime of strong size quantization. In the regime of strong size quantization the energy of Coulomb interaction between an electron and a hole is much smaller than the energy caused by the walls of the quantum dot. In this approximation, the Coulomb interaction between particles can be neglected. Then problem reduces to finding the energy states of electrons and holes separately. It is shown that with increasing of width of the Morse potential the particle energy decreases, and with decreasing of depth of potential the particle energy increases due to size quantization contribution. The case of heavy hole is considered, when the effective mass of hole is much more than the effective mass of electron. The effect of the external fields on the direct interband light absorption of cylindrical quantum dot is investigated. Selection rules are obtained at presence of parallel electrical and magnetic fields. The dependence of the absorption threshold on geometrical parameters of quantum dots and intensities of external fields is obtained. Red shift of absorption threshold has been observed depending on electrical field and blue shift of absorption threshold has been observed depending on the magnetic field.

9519-24, Session 6
Focus on GaN electronics nanostructures: thermal management and reliability (Invited Paper)

Andrei Sarua, Athikom Manoi, Roland Baranyai, Gernot Riedel, Nikole Killat, Huarui Sun, James W. Pomeroy, Michael J. Uren, Martin Kuball, Univ. of Bristol (United Kingdom)

GaN-based electronics technology are capable of delivering and handling high levels of current and power densities giving it advantage over conventional semiconductor technologies. These novel electronics materials employ often elaborate nanostructures, which are required to accommodate different compositions of device and substrate layers, contacts and surface passivations. This leads to the need of a power characterisation technique, which can provide information about different device layers in the operating device, without being destructive. In this work we concentrate on using laser micro-Raman thermography to characterise GaN based nanostructures used in high electron mobility transistors (HEMTs) for radio frequency (RF) and power applications. We have implemented several novel methods to improve spatial and temporal resolution of this method, which make it an ultimate tool in assessing degradation mechanisms in electronic device nanostructure with sub- μm spatial and ns temporal resolutions. In particular we demonstrate measurements of surface temperature in AlGaIn/GaN HEMTs using novel diamond particle thermography method and comparison of these models with results of 3D finite element modelling. Using depth temperature profiling we show significant impact of interface quality in the nanostructured layers on the thermal boundary resistance in AlGaIn/GaN HEMTs on traditional GaN-on-SiC and novel GaN-on-diamond devices.

9519-25, Session 6
Template-assisted synthesis of III-nitride and metal-oxide nano-heterostructures using low-temperature atomic layer deposition

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We report on the template-assisted fabrication of III-nitride and metal-oxide nano-heterostructures via low-temperature atomic layer deposition (ALD). Electrospun polymeric nanofiber mats as well as self-assembled peptide nanofiber networks were utilized as nano-scale templates. Polymeric templates possessed average fiber diameters in the order of 100 nm whereas peptide nanofibers exhibited diameters smaller than 10 nm. Hollow, core-shell, and bi-shell metal-oxide and III-nitride nanostructures were fabricated using thermal ALD and plasma-assisted ALD (PA-ALD), respectively. Hollow ZnO, TiO₂, HfO₂, AlN, core-shell ZnO, TiO₂, ZnO/TiO₂, TiO₂/ZnO, GaN, Ga₂O₃, In₂O₃, and bi-shell AlN/BN nanofiber structures were synthesized successfully. Detailed materials characterization studies were carried out to analyze the structural, morphological, chemical, and optical properties of the fabricated nano-heterostructures. Due to the ultimate conformality of both ALD processes, nano-templates were coated uniformly with highly-precision control of the coating thicknesses.

These functional nanomaterials were used in several applications including photocatalysis, dye synthesized solar cell (DSSC), and chemical sensing. Due to the very high surface area, the photocatalysis efficiency was improved significantly when compared to thin-film counterparts. Furthermore, with respect to single-layer core-shell or hollow ZnO and TiO₂, multi-layered ZnO/TiO₂ and TiO₂/ZnO samples showed higher photocatalysis performance. For DSSC application, the same material combinations are used on peptide-based nano-templates and demonstrated significantly improved quantum efficiencies when compared to thin-film counterparts. Highly sensitive gas (CO) sensing performance was observed using the metal-oxide nanostructures fabricated on polymeric nano-templates. Our early results show that such

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hybrid electrospinning/ALD and self-assembly/ALD synthesis techniques provide versatile precisely-controlled conformal hollow/core-shell/bi-shell functional nanofibrous materials with ultrahigh surface area which can be used in various applications including photocatalysis, renewable energy, and gas sensing.

9519-26, Session 6
Surface modification of CdTe by nano-second laser for radiation detector

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The surface modification in high-resistance CdTe crystals under nanosecond irradiation have been studied and analyzed for making pure-surface and In atom doping by In transportation. The surface modification was measured by time-resolve-reflectance (TRR) in-situ measurement. Surface roughness was taken into account and the surface layer was considered as an equivalent film with flat boundaries and effective optical parameters. In atom transportation is assumed that the concentration diffusion of indium in CdTe and the transfer of impurity atoms by the front of the laser-induced shock wave are not dominant mechanisms of mass transfer under dynamic doping.

9519-27, Session 6
Optical properties of heavy noble gas ion irradiated nanoporous InP membranes

Julian A. Steele, K. Radhanpura, Roger A. Lewis, Univ. of Wollongong (Australia)

In previous work, InP membranes have been demonstrated to exhibit an enhanced nonlinear response and an enhanced terahertz emission. Likewise, the conductivity has been investigated by terahertz spectroscopy and optical excitation has been found to modify the surface states. It is now well established that both bulk and surface-field induced effects play a role in optical rectification from zinc blende crystals in both transmission and reflection geometries. Our experiments reveal that heavy noble gas ion irradiation of bulk and nanoporous samples affects the optical properties further. There is an intriguing interplay between the ion irradiation, nanoporosity, and crystal facet. The ion irradiation has been found to enhance terahertz emission from (111) InP nanoporous membranes but to suppress it from (100) surfaces. We discuss possible origins of this difference. Optical anisotropy has also been recently reported for near-infrared, visible and ultra-violet frequencies and metallic behaviour under above-bandgap illumination confirmed.

9519-28, Session 6
GaN grown by MOCVD and HVPE: morphology of porous layers fabricated by electrochemical etching techniques

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In this work, we carried out a systematic study of porosification of single crystalline GaN grown by metal-organic chemical vapour deposition

(MOCVD) and hydride vapour phase epitaxy (HVPE). MOCVD samples represented epitaxial layers grown on sapphire substrates, while HVPE specimens were in the form of bulk 300- μm thick wafers. All the investigated samples were of n-type conductivity with epi-ready top surfaces. Porosification was achieved by using electrochemical and photoelectrochemical (PEC) etching techniques, in the latter case the samples were excited by UV radiation from Xe or Hg lamps. We found that MOCVD-grown samples can be uniformly porosified, the transverse dimensions of pores depending upon the applied voltage and electrolyte concentration. The pores, parallel to each other, are oriented perpendicular to the top surface in contact with the electrolyte. At the same time the HVPE-grown samples exhibited non-uniformly distributed pores along the top surface, sometimes patterns of alternating porosified and non-porosified areas were observed. PEC etching of HVPE-grown GaN evidenced the formation of ring-like or hexagon-like structures, reflecting etching non-uniformity. Interestingly, similar patterns were observed in images taken from as-grown single crystals of HVPE GaN by Scanning Kelvin Probe Microscopy. The results evidenced pronounced modulation of the band bending along the initial surface of HVPE-grown GaN crystals. The influence of the networks of threading dislocations and V-defects upon the morphology of electrochemically nanostructured samples was explored in details. We propose a model of electrochemical etching of gallium nitride single crystals that takes into account the non-uniform spatial distribution of impurities and host lattice defects. The research was supported financially by SNF (Switzerland) under the SCOPES Grant no. IZ73ZO_152273/1, STCU (Kiev) and Academy of Sciences of Moldova under the Grant no. 5933.

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9520-1, Session 1

Silicon integrated quantum circuits (Invited Paper)

Mark G. Thompson, Univ. of Bristol (United Kingdom)

No Abstract Available

9520-2, Session 1

Study of Pockels effect in strained silicon waveguides

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Silicon photonics is being considered as the future photonic platform, mainly for the reduction of photonic system costs and the increase of the number of functionalities on the same integrated chip by combining photonics and electronics. Moreover, silicon is also a promising platform for a wide range of nonlinear optical processes due to its strong optical confinement and high optical susceptibilities.

However, silicon is a centrosymmetric crystal which inhibits all second-order nonlinear optical effects. Nevertheless, this limitation can be overcome by straining the crystal lattice to break its symmetry, which is achieved by depositing a stress overlayer (typically SiN) on silicon. Unlike bulk silicon, these strained structures can accommodate Pockels effect, which enables light modulation in silicon at speeds that are not limited by carriers and driven at much lower power consumption.

In the present work we experimentally demonstrate Pockels effect in a silicon waveguide strained by a SiN overlayer deposited by PECVD. We analyse the second order nonlinear effects for three different waveguide widths and for a wide range of the NIR spectra wavelengths, from 1.3µm to 1.64µm. This information is relevant to understand the effects of wavelength in the efficiency of Pockels phenomena in strained silicon waveguides.

From that study, we were able to show that the studied effective nonlinearities are stronger for higher wavelengths and narrower wavelengths. The maximum second order nonlinear susceptibility achieved was 336 pm/V, obtained for the longest wavelength (1.64µm) and lowest width (385 nm). This is, to our knowledge, the highest reported value in the literature for such kind of structures, which proves to be a relevant step towards efficient optical modulation in strained silicon.

9520-3, Session 1

Quantum random number generator based on silicon nanocrystals LED

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In this work we present a post-processing free quantum random number generator (QRNG) based on silicon nanocrystals (Si-NC) LEDs. Generation of random numbers is of high significance in many applications particularly cryptographic applications. The security of cryptographic protocols deeply depends on the characteristics of RNG utilized to obtain cryptographic keys. Such characteristics are unpredictability, uncorrelated bits of a single sequence, and uncorrelated sequences. Pseudo RNGs (PRNGs) are deterministic algorithms able to output long sequences of

bits at high bit-rates. However, their unpredictability is not totally assured since when the initial value is revealed, all the bits in the sequence will be constructed. Truly random numbers essentially need to be generated through physical nondeterministic processes. Our QRNG exploits inherent randomness and indeterminacy of spontaneous emission of photons to generate bit sequences. The Si-NC LED is driven by a current/voltage source and the emitted light is transmitted through a bunch of optical fibers to a single photon avalanche photodiode (SPAD). This photodiode is connected to a multichannel scaler (MCS) by which photon arrivals are registered in bins with no dead time between them. We associate the bit value "1" with the event 'at least one photon is detected in the corresponding bin' and "0" to 'no photons are detected whatsoever'. The bit sequences obtained this way are then analyzed to evaluate their randomness using the NIST test suite. One advantage of our setup is the negligible bias measured from datasets which allows the production of bit sequences that pass NIST frequency test without any deterministic post-processing. The only test in NIST test suite that fails with our setup is the Runs test. Simulating an artificial dead time we removed the correlation between consecutive bits. The main drawback of such simulation is a reduced bit-rate which is overcome by LEDs and detectors parallelization.

9520-4, Session 2

Advances in label-free biosensing using CMOS photonic technologies (Invited Paper)

Dan-Xia Xu, Siegfried Janz, Martin Vachon, Shurui Wang, Nicaulas Sabourin, Pavel Cheben, Jens Schmid, Jean Lapointe, National Research Council Canada (Canada); Robert Halir, Gonzalo Wangüemert Pérez, Carlos Alonso-Ramos, Alejandro Ortega Moñux, Inigo Molina-Fernandez, University of Malaga, Spain (Spain); Jean-Marc Fedeli, CEA-LETI (France)

Complex photonic circuits with high density and multiple functionalities can now be readily integrated on a CMOS photonic chip. These advances enabled new developments in biosensing applications. Label-free sensors made of silicon photonic wire and subwavelength engineered waveguides can be made highly sensitive to surface adsorptions or to bulk index changes. High channel count sensor arrays increase the detection throughput and improve the detection reliability. By integrating other photonic components, improved tolerance to the operating environment and simplified instrumentation are also achieved. These progresses are reviewed and a fully integrated pathogen detection system based on silicon photonic components is described.

9520-6, Session 2

Off-diagonal photonic Lamb shift in reactively coupled waveguide-resonator system

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The coupling between a physical system and its environment is known to activate new channels through which the system may dissipate energy.

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Along this, the coupling may induce a shift of energy levels of the system. In atomic context, the manifestation of these phenomena are described through well known examples of the Coherent Population Trapping for decay channels and the electronic Lamb shift of electronic states of the Hydrogen atom.

Here we report on a joint theoretical and experimental study of such coupling for an integrated microresonator device which is vertically coupled to the waveguide. The developed theory predicts that the presence of a neighboring waveguide induces a reactive indirect coupling between the resonator modes, which are intrinsically orthogonal and, therefore, should not couple directly in the absence of the waveguide. Such a coupling, analogous to an off-diagonal Lamb shift known from atomic physics, alters the bare optical frequencies of the modes and manifests as peculiar Fano lineshapes in the transmission spectra of the waveguide. These theoretical predictions are both validated by 3D numerical simulations and confirmed in the experiments. Moreover, we demonstrate experimentally the possibility to induce thermo-optically clear features of Electromagnetically Induced Transparency by tuning the Fano lineshape of coupled resonator modes.

Our study provides an important insight on the phenomenon of inter-mode dissipative and reactive couplings due to the neighboring waveguide. This phenomenon may find applications in designing resonator devices with nonlinear and quantum functionalities. From a broader perspective, our work provides a generic model which may be useful to study a fundamental feature of the theory of open systems, namely, the environment-mediated couplings – the off-diagonal photonic Lamb shift – between different modes of a system.

9520-7, Session 3
Calibration method for synchronizing the viewing zones of a large-scale autostereoscopic multi-view laser display

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We have developed a concept for a modular autostereoscopic multi-view laser display with sunlight readable luminance. Each picture element—a so-called “trixel” —contains three laser diodes, a cylindrical microlens, as well as a micro-electro-mechanical systems (MEMS) mirror, which deflects the collimated light beams to the left and right eyes of multiple viewers in a time-multiplexed manner.

In this paper we present a calibration method for synchronizing the autostereoscopic viewing zones of individual trixels in the spatial domain by a nonlinear pre-distortion of the laser diode driving signals in the time domain. This calibration method allows for a compensation of sample variances of individual trixel components, nonlinear micromirror movements, objectionable angular tilts of individual trixels due to manufacturing imperfections, as well as inherent effects like the individual trixel’s position on the screen.

A predefined calibration signal consisting of equidistant impulses is applied to the laser diodes of a single trixel. The deflection of the laser beams by the MEMS mirror transforms this impulse train from the time domain into a calibration pattern in the spatial domain, which consists of multiple—generally non-equidistant—vertical stripes with Gaussian intensity distribution. The pattern is recorded by a camera subsequently for all trixels.

The calibration function, i.e. the mapping of the laser diode driver signals from the time domain to the intensity distributions in the spatial domain, is extracted from the recorded image. Unlike conventional autostereoscopic displays, e.g. with parallax barriers or lenticular lenses, the optimal 3D viewing distance, i.e. the distance at which the viewing zones of all trixels overlap perfectly, can be adapted by transforming the calibration functions using linear operations.

We present examples of the calibration patterns recorded by the camera as well as the extracted corresponding calibration functions.

We demonstrate the effectiveness of the calibration method employing

a prototype of the 3D laser display consisting of an array of 5 x 3 trixels, with different test patterns in adjacent 3D viewing zones.

9520-8, Session 3
Precise micromachining of materials using femtosecond laser pulses

Katarzyna Garasz, Mateusz Tański, Marek Kocik, Robert Barbucha, The Szewalski Institute of Fluid-Flow Machinery (Poland)

We present the results of the parametric study on femtosecond laser micromachining of different materials. The micromachining process was performed with a Yb:KYW laser, which generates 500 fs pulses of three different wavelengths and output power up to 50 W. This allows to perform a complex research for a wide range of parameters and materials. It has been established, that the quality of laser ablation process using femtosecond pulses is much higher than while using the long pulsed lasers. The use of femtosecond pulses creates therefore an attractive opportunity for high quality micro and nanomachining of many groups of materials.

9520-9, Session 3
Solderjet bumping technique used to manufacture a compact and robust green solid-state laser

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A compact and miniaturized adhesive-free green laser for extreme application has been achieved for the first time by applying laser induced Solderjet bumping technology to fix the optical components in order to improve robustness and repeatability.

New goals for laser manufacturing demand high output power, with high thermal, wavelength and beam stability, by minimizing size and weight via replacement of optical clamping methods with different types of adhesives. Nevertheless organic adhesives used in extreme applications could suffer slow and constant deterioration resulting in optical component displacement, laser spectrum degeneration, efficiency losses or even failure.

Solderjet bumping technology offers a local and minimized input of thermal energy allowing the joining of components with very high positioning accuracy (in the sub-micron region) even for fragile and sensitive optical components and for different and complex 3D-integrated geometries.

Using the Solderjet bumping technology the assembly of a green diode-pumped solid-state laser has been achieved by soldering the components onto a 24x15x1 mm³ AlN ceramic substrate with copper for the heat dissipative elements and Kovar pads used to reduce the CTE mismatch between the AlN substrate and the rest of the components. Some of the lasers components had a special half sphere shape submount to allow for

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a highly precise tip/tilt alignment.

The specified laser requirements have been accomplished and maintained throughout and following the various vibration, vacuum, radiation, shock and thermal tests performed on the devices. The resulting green miniaturized diode-pumped solid-state laser will be part of the future Raman Laser Spectrometer, designed for the Exomars ESA space mission 2018.

9520-10, Session 4

IR spectroscopy sensing with nanoplasmonic enhancement (*Invited Paper*)

Hatice Altug, Ecole Polytechnique Fédérale de Lausanne (Switzerland)

No Abstract Available

9520-11, Session 4

Microfluidic generation and optical manipulation of ultra-low interfacial tension droplets

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In this work we present a microfluidic platform for the generation and optical manipulation of monodisperse oil droplets in water with equilibrium surface tensions on the order of 1 μ N/m. Such emulsions support an growing number of exciting applications. For instance, optical fields can be used to sculpt oil droplets into more complex shapes, possibly leading to new approaches for the synthesis of geometrically complex solid microparticles. Moreover, those droplets can be used as building blocks for the creation of nanofluidic networks controlled by light. The microfluidic formation of monodisperse droplets with ultra-low interfacial tensions (ULIFT) is still a very challenging task.

We use an oil-brine-surfactant system whose equilibrium surface tension depends on temperature and salinity and it can be varied over a range of 3 orders of magnitudes. We have designed and tested a microfluidic platform capable of controlling the emulsion interfacial tension in the range of 1 μ N/m to a few mN/m. A flow focusing junction device was used to produce droplets with a typical diameter ranging from 10 μ m to 40 μ m. After generation droplets are transferred to an observation chamber (ObC) chip, designed for droplet manipulation and characterization purposes. Through active control of the emulsion salinity and temperature in separate areas of the device, our microfluidic platform offers the unique capability of tuning the surface tension of droplets according to the operation required.

To prove that the generated droplets were in the ULIFT regime, we monitored the thermally-driven capillary waves at the droplet interfaces through bright-field microscopy. We also used lasers to manipulate the ULIFT droplets and to construct nanofluidic networks consisting of several droplets connected by stable oil threads a few nanometer across. Those networks have great potential to be used as nanofluidic laboratory for carrying out chemical reactions at the femtolitre scale.

9520-13, Session 5

Waveguide germanium avalanche photodiode on silicon

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Significant advances in silicon photonics has been made in recent year into realizing on-chip communications and for sensing applications. At the receiver stage, the challenge is to reduce the sensitivity in order to reduce the signal at the maximum. In this context, waveguide avalanche Germanium photodiodes (APD) have been developed. The first approach was based on the use of Separate Absorption, Charge and Multiplication (SACM) APD structures. A Very high gain - bandwidth product was obtained under low input optical power. The second approach was based on a lateral pin diode. Despite being straightforward to fabricate, such diode exhibit a good avalanche behavior under low reverse bias. A gain higher than 20 was demonstrated under a bias voltage as low as -7V. 10Gbit/s operation was demonstrated without the use of a trans-impedance amplifier (TIA) for an input optical power lower than -26dBm. thanks to an aggressive shrinkage of the Ge multiplication region. A maximum gain over 140 was also obtained for optical powers below -35dBm. These results pave the way for the low power consumption on-chip communication applications.

9520-14, Session 5

Integrated silicon photodetector for lab-on-chip sensor platforms

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Within this study we report on the development of an integrated thin film silicon photodetector. The detector was designed to fulfill the needs for a label-free biosensor platform based on silicon oxynitride waveguides and microring resonators for an operation wavelength of ~850 nm for which low cost VCSEL laser diodes are available as light sources. While the response time of silicon photodetectors, typically in the range of some milliseconds, is far too slow for telecom applications, it is more than fast enough for label-free biosensing, where the response time of the resonator, limited by analyte diffusion and bonding kinetics, is in the range of seconds to minutes. The coupling between waveguide and thin film photodetector was studied using FEM/FDTD simulation methods, with special emphasis on the optimization of the coupling efficiency and detector dimensions. During the device fabrication special care was put on achieving geometrical parameters, which are close to the optimum ones obtained in simulations. Thin film photodetectors with different electrode geometries, detector length and thickness both in amorphous and polycrystalline silicon were realized on top of the photonic integrated circuits. The integrated detectors were characterized for different illumination intensities. In addition, the light-wave circuit was characterized at 850 nm by coupling light from a VCSEL diode to the chip. These experiments show that the mode spectrum of the resonator can be monitored with the integrated photodetector.

9520-15, Session 5

SiN-assisted, polarization-insensitive multicore fiber to silicon photonics interface

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Space-division-multiplexing in multi-core fiber (MCF) is gathering

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momentum due to its potential for scaling capacity and front-panel density. Currently an outstanding technical hurdle to reap the benefits of MCF remains coupling to photonic integrated circuits (PICs). Silicon PICs present particular interest owing to their low-cost and high-functionality. Silicon chip-to-MCF coupling has been demonstrated with a 2D grating coupler arrangement matching the MCF core distribution. However, this approach involves a number of challenges and tradeoffs towards combining broad optical bandwidth, high efficiency and simple implementation insensitive to fabrication tolerances. Dual-polarization operation further exacerbates these challenges, necessitating 2D grating designs with polarization diversity that doubles chip real-estate. In this paper we present a polarization-insensitive chip-to-MCF coupler for interfacing MCF cores to 340x400nm Si waveguides. The coupler exhibits theoretical Si-to-fiber loss below 1dB.

The chip-to-MCF coupler comprises a 3D glass fanout transforming the circular MCF core arrangement to linear and performing initial tapering, followed by a Spot-Size-Converter (SSC) on the Si chip. Glass waveguides are formed of multiple overlapped modification elements. Horizontal tapering is performed by introducing a linear increase in pitch between the individual modification elements. In the vertical dimension, a positive vertical offset is applied to the tapered region and a second tapered region is overwritten with a negative vertical offset, producing a symmetric cross-section. The SSC consists of an inversely tapered silicon waveguide with a tapered polymer (SU8) overcladding. Light is initially coupled in the overcladding but as the silicon waveguide widens, phase matching gradually shifts the propagating light towards the Si core. A co-design was followed for the glass fanout and SSC to optimize overall chip-to-MCF efficiency. First, the overlap between the two sections was maximized, respecting fabrication capabilities. Subsequently, adiabatic coupling theory was applied to investigate mode conversion from the optimum SU8 cross-section to the Si waveguide.

9520-16, Session 5
A PEDA approach for monolithic photonic BiCMOS technologies

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Silicon photonics is a key technology for the future development of high-speed data communication systems. It is a major step for the improvement of monolithically integrated electronic-photonic devices on a single chip.

However, the design of such systems is unnecessarily complicated by the separated design flow of the photonic and electronic circuit parts. This paper describes a photonic electronic design automation (PEDA) approach with the commercial design suite Laytools 1 for circuit and physical layout design and simulation.

The goal of the PEDA approach is to integrate an electronic-photonic design flow into an existing EDA tool. Contrary to other solutions, with this approach, it is possible to minimize the required interfaces to other third party tools. In addition to the existing electronic device models, photonic components are described with behavioral models. The mask layout has been extended to the needs of the electronic photonic IC designer and verification flow was adapted to the photonic structures.

The PEDA approach is demonstrated by an application example. A trans-impedance amplifier connected to a photodiode was realized and an eye diagram was measured. This circuit was manufactured in IHP's 0.25µm electronic-photonic BiCMOS technology SG25HIEPIC. 2,3

REFERENCES

1. TexEDA Design GmbH [Online]. Available: www.texeda.de (2014).
2. Sedighi, B. and Christoph Scheytt, J., "Low-power SiGe BiCMOS transimpedance amplifier for 25-GBaud optical links," *Circuits and Systems II: Express Briefs, IEEE Transactions on* 59(8), 461-465 (2012).
3. Knoll, D., Lischke, S., Zimmermann, L., Heinemann, B., Micusik, D., Ostrovskyy, P., Winzer, G., Kroh, M., Barth, R., Grabolla, T., et al., "Monolithically Integrated 25Gbit/sec Receiver for 1.55 µm in Photonic BiCMOS Technology," in [Optical Fiber Communication Conference], Th4C-4, Optical Society of America (2014)

9520-26, Session PSTue
Multi-diode laser system for UV exposure of the photoresists

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PCB (Printed Circuit Board) industry is a global business for many years. PCB can be found in every electronic devices and since it becomes smaller, lighter and more efficient, new sophisticated machines need to be developed to meet this demands. The main part of such machines is exposure head utilized UV light to generate pattern on a substrate. Nowadays, the most advanced units uses UV lasers and scan optics to produce patterns on PCB covered by phototool. Lastly, a new idea showed up to use DMD (Digital Micromirror Device) chips. The DMD is basically an array of digitally controlled switching mirrors that can be used to control or direct light into one of two directions in an addressable pattern at very high speeds. There are many applications of DMD, such as: switching light in a fiber optic network, beam direction and patterning for a biomedical or machine vision. In this paper a new design of laser head is presented where the UV light comes from a great number of UV (Blue-Ray) 405nm lasers. Due to its commonness over the world, their price is lower respectively to LED and mercury lamps sources. This research deals with investigations of innovative method for manufacturing soldermask patterns on PCB where high energy density are required (up to 500mJ/cm²). In comparison to conventional lithography manufacturing method, there is no need to use phototool anymore. It means that production steps as: exposure, development, curing, conditioning, positioning of the phototool are no longer in use. New method saves time, increases yield and secure environment cause a great number of chemicals were used in conventional method. As the result of the research, a technology demonstrator is presented to show possibilities of new technology in high speed and mass production of advanced printed circuits board.

9520-27, Session PSTue
Measurement of nonlinear refractive index based on multiple configuration of FBG in generating multi wavelength

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A reliable method for measurement of the nonlinear refractive index through application of multi wavelength phenomenon. Multi wavelength realisation based on Erbium doped fibre laser (EDFL) is proposed and experimentally demonstrated. A combination of 15 m high efficiency Erbium doped fibre (EDF) and a 20 m Photonic Crystal Fibre (PCF) as main catalyst to suppress the homogenous broadening of EDF and to obtain highly stability of multi wavelength through insertion of a set of fibre Bragg gratings (FBGs) in the cavity. This PCF has zero dispersion of 1040 nm which mismatch from transmission window of 1550 nm. A reliable repeatability of multi wavelength based on multiple configuration of FBGs less than 0.2% obtained. This consistent results influence in determination of nonlinear refractive index by relation of four wave mixing (FWM).

9520-28, Session PSTue
Comparison of femtosecond laser induced micro/nano structures on silicon fabricated at room temperature and 400°C

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We experimentally compare the structures on silicon surface fabricated by multi linear polarized femtosecond laser pulses (pulse duration $\tau=35$

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fs, wavelength $\lambda=800$ nm) irradiation at room temperature (25 °C) and 400 °C for the first time. Scanning electron microscopy(SEM) is used for imaging the structured area and analyze the properties of the surface structures. The results show that the surface structures fabricated at these two temperatures have distinct temperature dependence. At room temperature, random structures, low spatial frequency laser induced periodic ripples structures (LSFL), micrometer size grooves and beads are fabricated consecutively as pulses number increasing while the grooves, which are parallel to the polarization of the laser light, dominates the structures formation at 400 °C. The periodicity of the micro-meter size grooves is sensitive to the fluence, especially when the temperature of the substrate is 400 °C. These results indicate that temperature is an important parameter to be tuned to tailor the micro/nano-structure fabrication.

9520-29, Session PSTue

Modeling of HgCdTe focal plane array spectral inhomogeneities

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Infrared focal plane arrays (IR FPAs) are needed to perform high quality measurements such as high spectrum acquisition rate, ballistic missile defense, gas detection, and hyperspectral imaging. For these applications, the fixed pattern noise represents one of the major limiting factors of the array performance. This sensor imperfection refers to the non-uniformity between pixels, and is partially caused by disparities of the cut-off wavenumbers.

In this work, we focus particularly on mercury cadmium telluride (HgCdTe)-based IR FPAs, which is the most important material of IR detector applications.

Among the many advantages of this ternary alloy is the tunability of the bandgap energy with Cadmium composition, as well as the high quantum efficiency. In order to predict and understand spectral inhomogeneities of HgCdTe-based IR FPAs, we propose a modelling approach based on the description of the optical phenomenon inside the pixels. The model considers the p-n junctions as a unique absorbent bulk layer, and derives the sensitivity of the global structure to both Cadmium composition and HgCdTe layer thickness.

For this purpose, HgCdTe optical and material properties were necessary to be known in low temperature operating conditions. However, to our knowledge, there were no published measurements of the refractive index dispersion over the spectral range above the bandgap energy. Consequently we achieved the calculation of the real part of the refractive index using subtractive Kramers Kronig relations, for several alloy compositions, combined with published experimental points.

The results led to a comparative analysis determining the influence of macroscopic parameters on the spectral nonuniformities. This approach is complementary to other approaches based on semiconductor physics. It can be generalised to any detector technology provided that the optical properties of FPA layers are sufficiently known. It allows an accurate understanding of the FPA nonuniformities, thus enabling appropriate improvements in the technological process and post-process corrections.

9520-30, Session PSTue

Calculation of accurate channel spacing of an AWG optical demultiplexer applying proportional method

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When designing an AWG optical demultiplexer a set of transmission parameters have to be settled. One of them is the channel spacing parameter. It is defined as the separation between the channel center wavelengths (or frequencies) of two adjacent transmitting channels. According to ITU-Grid this channel spacing is constant over the all channels in the frequency domain; it means it is not constant in the wavelength domain. This is due to the nonlinear dependency between wavelength and frequency. The problem is that the channel spacings

between the demultiplexed optical signals of AWG are, in opposite to this, constant in wavelength range but not in the frequency domain as shown in Fig. 1 (it means they do not fit to recommended ITU-Grid transmitting channels). Figure 1 shows the evaluation of 64-channel 50 GHz AWG with its simulated transmission characteristics and calculated transmission parameters. As can be seen the channel spacing parameter, df in red rectangle is changing over the whole channel range even it was designed for the constant value of 50 GHz as presented in the green rectangle.

The graphical representation of this frequency channel spacing tendency, df is shown in Figure 2-left. Figure 2-right shows the wavelength channel spacing tendency, $d\lambda$ that is nearly constant having the value of $0.4 \mu\text{m}$.

In order to solve this problem we developed a proportional method to correct this transmission parameter. This method was applied on the AWG design. The achieved results confirm very good correlation between required channel spacing (50 GHz) and the channel spacing calculated from simulated AWG transmission characteristics. This was also technologically verified. The channel spacing calculated from measured transmission characteristics confirms the accuracy of the applied method as presented in Figure 3. In comparison to Figure 2 the corrected channel spacing parameter df is nearly constant with the values alternating around the required 50 GHz. The $d\lambda$ channel spacing parameter is no more constant but accordingly increases.

9520-31, Session PSTue

A new equalizer for 2 Gb/s short-reach SI-POF links

Cecilia Gimeno Gazca, Erick Guerrero Rodriguez, Carlos Sánchez-Azqueta, Guillermo Royo, Concepcion Aldea, Santiago Celma Pueyo, Univ. de Zaragoza (Spain)

We present a new CMOS analog continuous-time equalizer that overcomes the limitations of the most widely used continuous-time equalizer, the degenerated differential pair. The equalizer has been proved for multi-gigabit short-range applications targeting up to 2 Gb/s through a 50-m SI-POF. The prototype consumes 2.7 mW for a 1-V supply voltage.

9520-32, Session PSTue

CMOS front-end for duobinary data over 50-m SI-POF links

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This paper presents a front end for short-reach high-speed optical communications that compensates the limited bandwidth of 1-mm 50-m step-index plastic optical fiber (SI-POF). For that purpose, it combines two techniques: continuous-time equalization and duobinary modulation. An addition of both enables the receiver to operate at 3.125 Gbps. The prototype contains a transimpedance amplifier, a continuous-time equalizer and a duobinary decoder. The prototype has been implemented in a cost-effective 0.18- μm CMOS process and is fed with 1.8 V.

9520-33, Session PSTue

A multi-rate continuous-time adaptive equalizer for high-speed serial links

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A multi-rate low-voltage continuous-time adaptive equalizer is presented in this paper. It was designed to compensate the high-frequency attenuation of a 50-m length 1-mm core step-index plastic optical fiber (SI-POF) for input data ranges from 400 Mbps up to 1.25 Gbps. The

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equalization is based on the powerspectrum technique and the circuit operates with a single supply voltage of 1 V. The structure is formed by two loops which do not interact with each other; one loop adapts to changes in the channel length and the other in the data rates.

9520-34, Session PSTue

A CMOS merged CDR and continuous-time adaptive equalizer

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We present a low-voltage merged CDR and continuous-time adaptive equalizer capable to compensate the attenuation of a SI-POF channel while at the same time synchronizing and regenerating the incoming signal in a single stage. The system operates at 1.25 Gbps for NRZ modulation through a 50-m SI-POF channel and it is designed in standard 0.18-um CMOS fed at 1 V with a power consumption of 43.4 mW.

9520-17, Session 6

Ge/GeSn direct band gap laser on silicon (Invited Paper)

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Integrated Si-technologies are rapidly changing the landscape of photonics by offering powerful solutions for data links and sensing. Employed light-sources nowadays are made from group III-V materials operated off- or on-chip using heterogeneous integration, contact printing or bonding.

Here, we present an alternative laser solution based on monolithically integrated direct band gap group IV materials. We will show lasing at low temperature of optically pumped GeSn layers directly grown on Ge virtual substrate on silicon and will discuss the forthcoming challenges on the way to empower Si-CMOS with an integrated optical platform for data communication networks and IR to mid-IR sensing.

9520-18, Session 6

Organosilicate thin films: a new candidate for lighting and photonic applications

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The continuous trend for reducing characteristic dimensions of silicon-based devices requires the scientific community to find new materials to solve the problems of low dimension structure and keep a high level of performance. In this context, organosilicate thin films, which are used in microelectronic as low or even ultra-low dielectric constant materials, were developed to replace the conventional silicon dioxidedielectricinterlayers. Although, SiOC:H have been widely investigated for this purpose, their intrinsic optical properties, and in particular their light emission properties after an annealing process at high temperature, stay up to now less studied despite their potential applications for photonics or lighting.

In this work we studythe light emission properties of SiOC:Hthin films deposited by Plasma Enhanced Chemical Vapor Deposition (PECVD) on 200 mm Si wafers using trimethylsilane (3MSsamples) or dietoxyethylsilane (DEMS samples) as precursors. The deposition parameters(e.g. precursors, O2 flow ...) are shown to have an impact on the films stoichiometry and on their photoluminescence(PL) properties after an annealing in the 400-1200°C temperature range. The strong, wide, visible with naked eyes PL around 500 nm for all 3MS samplesreaches a maximum intensity after an annealingtemperature of 700°C. The origin of this PL could be attributed to structuralO radiative defects induced by C in the films.At higher temperatures the PLis quenched due to the structural evolution of the films. On the other hand, in case of DEMS a strong , white PLis detected with an optimum after annealing at 500°C.In order to investigate the origin of the radiative recombination centers in such films, the evolution of their structural and optical properties have been investigatedby mean of Fourier Transformed InfraRedspectroscopy , spectroscopic ellipsometry, X-ray Photoelectronspectroscopy and Raman spectroscopy. As a result, all these investigations will give clues in order to control and optimize these optical emission properties in the perspective of lighting or photonics

9520-19, Session 6

Light emission from carbon nanotubes integrated in silicon ring resonator

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Carbon nanotubes have generated a growing interest for photonic applications thanks to its remarkable optical properties to emit, modulate and detect light in a broad wavelength range. To study these properties, a hybrid integration of carbon nanotube's properties with silicon photonic structures has been developed.

In this presentation, the light emission from carbon nanotubes coupled into silicon ring resonators was then studied. A thin layer of semiconducting carbon nanotubes embedded in polymer was deposited on the top of silicon ring resonators. Under optical pumping, periodic emission peaks, characteristic of both nanotube's emission and resonant peaks of the silicon ring resonator were observed and studied. Q-factors up to 4000 were obtained at the wavelength around 1.3µm.

9520-20, Session 6

Towards AlN optical cladding layers for thermal management in hybrid lasers

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Aluminium Nitride (AlN) is proposed as a dual function optical cladding and thermal spreading layer for hybrid ridge lasers, replacing current benzocyclobutene (BCB) encapsulation. A high thermal conductivity material placed in intimate contact with the Multi-Quantum Well active region of the laser allows rapid heat removal at source but places a number of constraints on material selection. AlN is considered the most suitable due to its high thermal conductivity when deposited at low deposition temperatures, similar co-efficient of thermal expansion to InP, its low refractive index and its dielectric nature. We have previously simulated the possible reduction in the thermal resistance of a hybrid ridge laser by replacing the BCB cladding material with a material of higher thermal conductivity of up to 319 W/mK. Towards this goal, we demonstrate AlN thin-films deposited by reactive DC magnetron sputtering on InP.

9520-21, Session 7

Luminescence yield in Al and Tb³⁺ delta-doped oxide thin films fabricated by electron beam evaporation

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For the last years, rare earth (RE)-doped oxides have attracted great attention due to the intense and narrow luminescence yield, motivating the investigation of novel light-emitting devices for several photonic applications. Different methods have been used to dope semiconductors with RE materials, being ion implantation or thermal evaporation in effusion cells the most widely used.

In this work, we combine the electron beam evaporation (EBE) with a delta-doping approach to demonstrate the feasibility of this methodology to fabricate RE-doped samples with high luminescence yield. The delta-doping approach permits a good control of the inter-ion distance in the growth direction, allowing for a comprehensive study of the role of inter-RE distance in the optical properties of deposited layers. It consists in the sequential deposition of alternated sub-nanometer RE or metallic layers and insulating (or semiconductor) layers to form a multilayer (ML) structure. After the sample deposition, a high-temperature thermal treatment is performed to induce the optical activation of RE ions.

Tb³⁺ delta-doped oxide thin films have been investigated. Films will be deposited onto a silicon substrate (100)-oriented. A set of samples with different oxide thicknesses (d) were deposited to investigate the role of this parameter in the RE luminescence. In addition, the influence of annealing temperature on the RE diffusion in such thin oxide layers is discussed. The annealing process was carried out at different temperatures spanning from 700 to 1100 °C (a reference as-deposited sample was grown for the sake of comparison). Finally, the incorporation of Al dopants in Tb-doped oxides has provided remarkable improvement of the luminescence yield, of about one order of magnitude with respect to Al-undoped samples. This work demonstrates the feasibility of designing ad-hoc thin films with complex multilayer morphologies to enhance the optical properties of conventional single layers.

9520-22, Session 7

Ridge channel waveguides in NLO (Yb,Nb):RbTiOPO₄/RbTiOPO₄(001)

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Ytterbium codoped (Yb,Nb):RbTiOPO₄ ((Yb,Nb):RTP) is a potential self-frequency doubling material, with high nonlinear optical coefficients as KTiOPO₄ and already demonstrated laser emission at 1 micron in bulk crystal configuration. Besides, RTP has also other interesting properties such as large electro-optical coefficients and high laser damage threshold. In the last years, in our group we have been exploring this material, as a new platform for integrated photonics.

In this work we report the fabrication process for obtaining ridge channel waveguides in a single crystalline system based on RTP single crystal substrate (001)-crystallographically oriented grown by Top Seeded Solution Growth, (Yb,Nb): RTP active epitaxial layer grown by Liquid phase epitaxy (LPE) and finally a RTP cladding also grown by LPE. Between each step of growth, it is necessary to cut and polish till optical grade quality the crystals and epitaxies. Dry etching by the Inductive Coupled Plasma-Reactive Ion Etching (ICP-RIE) technique is used to create the channel structures by structuring on the cladding layer to distance the rough etched surface from the guiding region.

The refractive index difference between the active layer and the substrate and the cladding at 1.5 microns, is $\Delta n_z = 0.005$ and allows only

waveguiding with the light polarized in c-crystallographic direction, TM mode configuration. The lattice mismatch between the undoped RTP and (Yb,Nb) doped RTP is low enough to permit to obtain single crystal layers without any visible defect in both interfaces, between the substrate and the active layer, and between the active layer and the cladding.

RIE etching on RTP(001) surface has been done using Argon and SF₆ gas, achieving an etch rate around 150 nm/min with very low roughness (around 4 nm). The dimensions of straight waveguides were optimized by simulation with Rsoft beamPro software to obtain guiding with a single optical mode at 1.5 μm.

9520-23, Session 7

Colour performance and stack optimisation in phase change material based nano-displays

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We recently demonstrated a new breed of optoelectronic devices based on ultra-thin Phase Change materials with a new range of exciting applications now within reach. Non-volatile, ultra-fast, ultra-thin displays based on such PCM devices are of particular interest. In this paper we describe colour performance modelling of such displays by applying well known optical simulation techniques in an effort to refine the design of future high contrast colour PCM displays.

9520-24, Session 7

A study of physical vapor deposition silicon nitride for dense wavelength division multiplexing on silicon wafer

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We present a study of silicon nitride (SiN_x) films deposited at room temperature by a physical vapor deposition (PVD) techniques for reliable implementations of on-chip dense wavelength division multiplexing (DWDM). A mid-refractive index contrast (MiDex) [1] between SiN_x and SiO₂ is favorable in terms of temperature dependence and fabrication tolerance of DWDM than the high refractive index contrast (HiDex) of Si on SiO₂, and has no need for SOI wafer. We demonstrate that the filtering performance of MiDex SiN_x with channel frequency of 100GHz can withstand temperature fluctuation of up to 70 °C without thermal managements. Thanks to a low thermo-optic coefficient, the measured resonance peak shift of MiDex ring resonator is five times as less as that of the HiDex one. The PVD-SiN_x film is used without high temperature annealing thanks to the lack of N-H bonds with room temperature deposition. Moreover, we discussed the design and realization of a compact array waveguide grating (AWG) for DWDM based on our PVD-SiN_x. From beam propagation method (BPM) simulations, the system can ensure compact passive waveguide and AWG. The expected DWDM performance of AWG based on PVD-SiN_x with varied temperature will be discussed. Last but not least to realize an active integrated optical circuitry, efficient optical coupling between PVD-SiN_x waveguide and active Ge-based devices is not a trivial task due to their very large index difference. We study two coupling mechanisms of adiabatic tapering and butt coupling to enable practical coupling designs. We find that adiabatic tapering of Ge-based component could allow effective index matching with the PVD-SiN_x waveguide albeit a very tight fabrication tolerance. Nevertheless, we show that an efficient optical coupling with less than 1dB loss could be obtained via a simple butt coupling between Ge-based

component and PVD-SiNx waveguide using 3D FDTD calculations.

[1] MRS Bulletin 39, 687-695 (2014).

9520-25, Session 7

Self-assembly 'micro-origami' photon cages as hollow micro-resonators

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Micro-optics and micro-photonics technologies are ubiquitous since they are responsible for the displays on smart phones and computing devices, optical fiber that carries the information in the internet, advanced precision manufacturing, enhanced defense capabilities, and a plethora of environmental and medical diagnostics tools. The opportunities arising from these wavelength-scale technologies offer the potential of more integrated multi-functional devices for even greater societal impact in the next few decades. In this large context the advent of high-quality-factor (high-Q) micrometre-scale optical resonators has led to the demonstration of high-fidelity optical sensors. Recent advance in micro/nano fabrication technology allows for miniaturization and cost-effective manufacturing of such optical resonant sensor devices with retained sensing sensitivity. However one of the key points for these optical sensors is to achieve a 3D light control in air, or in a low index media, like fluids. For this, hollow 3D resonator addresses ideal nanoparticles (bio, chemical, gas...) sensor. In this work, we address the challenge of controlling photons in 3D, at the scale of the wavelength and in air or, more generally, in low-index materials like liquids or gas. To this end, we propose to generate a new family of 3D hollow micro-photon resonators based on "Origami" fabrication process combining mechanical and photonic concepts. . The mechanical elastic relaxation of patterned pre-stressed multilayers gives rise to 3D-micro-objects whose final shapes are determined by the initial stress distribution. The 3D photonic design exploits surface addressable Bloch modes (SABM) in a very thin and highly reflective membrane based on a 1D or 2D photonic crystal.

We develop an experimental approach by controlling material composition, mask design and etching process in order to obtain prescribed macroscopic 3D hollow optical micro-cavities.