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PHOTOMASK TECHNOLOGY.

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Technical Conference

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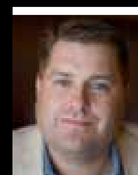

Bryan S. Kasprowicz
Photronics, Inc.

9635-1, Session 1

Lithography and Mask Challenges at the Leading Edge *(Keynote Presentation)*

Harry J Levinson, GLOBALFOUNDRIES Inc. (United States)

Continued scaling using multiple patterning is resulting in large increases in mask counts. Mask defect inspection times are increasing much faster than write times. Pushing optical lithography to its limits necessitates exceedingly tight mask-making process control. The use of EUV lithography introduces many new technical challenges associated with a mask architecture very different from optical masks. Because of higher resolution, smaller defects and LER at higher spatial frequencies print with EUV lithography than with optical lithography.

9635-2, Session 2

EUV lithography scanner and mask optimization for sub-8nm resolution *(Invited Paper)*

Jan van Schoot, Koen van Ingen Schenau, Kars Troost, ASML Netherlands B.V. (Netherlands); John D. Zimmerman, ASML (United States); Sascha Migura, Jens Timo Neumann, Bernhard Kneer, Winfried Kaiser, Carl Zeiss SMT GmbH (Germany)

EUV lithography for resolutions at 8 nm half pitch and below requires the numerical aperture (NA) of the projection lens to be significantly larger than the current state-of-the-art 0.33NA. In order to be economically viable, a throughput above 100 wafers per hour is needed.

As a result of the increased NA, the incidence angles of the light rays at the reticle increase significantly. Consequently the shadowing deteriorates the aerial image contrast to unacceptably low values.

As shown before [1], the only solution to reduce the angular range at the reticle is to increase the magnification in the scanning direction. Simulations show that we have to double the magnification to 8x in order to overcome the shadowing effects. This results into an anamorphic step and scan system, with which we can print fields that are half the size of the current full field, where the main assumption is that we keep the current 6" mask size. By increasing the transmission of the optics and by increasing the acceleration of the wafer- and reticle stage we can enable a throughput in excess of 150 wafers per hour, making this an economically viable lithography solution.

In this paper we will show how we can further optimize throughput, CDU and overlay by optimizing the main system and mask design parameters.

[1] J.B.P van Schoot, K. van Ingen Schenau, C. Valentin and S. Migura, "EUV lithography scanner for sub-8nm resolution," Proc. SPIE 9422, (2015).

9635-3, Session 2

How to make EUV work! *(Invited Paper)*

Hermann Gerlinger, Carl Zeiss SMT GmbH (Germany)

EUV lithography has passed a threshold for introduction of HVM wafer production since the announcement from ASML, a major US-semiconductor manufacturing company to buy a considerable number of EUV scanners. While lithography optics production for the current generation of scanners is well understood and source performance has the required attention of the relevant companies, the wider EUV mask manufacturing ecosystem needs now to be placed into focus. Due to the limited number of participants new ways of cooperation are required to meet the challenges.

In this talk the current and future EUV optics development will be described and its impact on the mask manufacturing infrastructure. The required elements of this eco-system will be discussed. The latest status and test results of the AIMS™ EUV as one of key elements of the mask infrastructure will be presented.

9635-4, Session 3

Expanded view of characterization and mitigation of edge placement errors in full-chip computational lithography *(Invited Paper)*

John L. Sturtevant, Rachit Gupta, Shumay Shang, Vladislav Liubich, James Word, Ahmed Seoud, Mentor Graphics Corp. (United States)

Edge placement error (EPE) was a term initially introduced to describe the difference between predicted pattern contour edge and the design target. Strictly speaking this quantity is not directly measurable in the fab, and further it is not ultimately the most important metric for chip yield. What is of vital importance is the relative epe between different design layers, and in the era of multi-patterning, the different constituent mask sublayers for a single design layer. There has always been a strong emphasis on measurement and control of misalignment between design layers, and the progress in this realm has been remarkable, spurned in part at least by the proliferation of multi-patterning which reduces the available overlay budget by introducing a coupling of alignment and CD errors for the target layer.

In-line CD and overlay metrology specifications are typically established by starting with design rules and making certain assumptions about error distributions which might be encountered in manufacturing. Lot disposition criteria in photo metrology (rework or pass to etch) are set assuming worst case assumptions for CD and overlay respectively. For example poly to active overlay specs start with poly endcap design rules and make assumptions about active and poly lot average and across lot CDs, and incorporate general knowledge about poly line end rounding to ensure that leakage current is maintained within specification. This worst case guard banding does not consider specific chip designs, however and as we have previously shown full-chip simulation can elucidate the most critical "hot spots" for interlayer process variability comprehending two layer CD and misalignment process window. It was shown that there can be differences in X versus Y misalignment process windows as well as positive versus negative directional misalignment process windows and that such design specific information might be leveraged for manufacturing disposition and control schemes.

This paper will investigate an example of via-metal model-based analysis of CD and overlay errors. Both via and metal layers utilize double patterning, so the interaction of 4 layer CD and misalignment errors is very complex. But we illustrate that not only can full-chip verification identify potential edge placement hotspots, the OPC engine can act to mitigate such hotspots and enlarge the overall combined CD-overlay epe process window.

9635-5, Session 3

Accurate mask registration on tilted lines for 6F2 DRAM manufacturing

K.D. Roeth, KLA Tencor MIE GmbH (Germany); Youngmo Lee, Sangpyo Kim, Donggyu Yim, Wonseok Choi, SK Hynix, Inc. (Korea, Republic of); Frank Laske, Michael Ferber, KLA Tencor MIE GmbH (Germany); Mehdi Daneshpanah, KLA Tencor Inc (United States); Eric Kwon, KLA Tencor Korea (Korea, Republic of)

No Abstract Available

9635-6, Session 3

Higher order feed-forward control of reticle writing error fingerprints

Richard J. F. van Haren, ASML Netherlands B.V. (Netherlands)

The understanding and control of the intra-field overlay budget becomes crucial particularly after the introduction of multi-patterning applications. The intra-field overlay budget is built-up out of many contributors, each having their own characteristic. Some of them are (semi-)static like the reticle writing error (RWE) fingerprint, the scanner lens fingerprint, or the intra-field processing signature. Others are more dynamic. Examples are reticle heating and lens heating due to the absorption of a small portion of the exposure light. Ideally, all overlay contributors that are understood and known could be taken out of the feed-back control loop and send as feed-forward corrections to the scanner. As a consequence, only non-correctable overlay residuals are measured.

In the current work, we have studied the possibility to characterize the reticle writing error fingerprint by an off-line position measurement tool and use this information to send feed-forward corrections to the ASML TWINSCAN exposure tool. The current work is an extension of the work we published earlier. To this end, we have selected a reticle pair out of 50 production reticles that are used to manufacture a 28-nm technology device. These two reticles are special in the sense that the delta fingerprint contains a significant higher order RWE signature. While previously only the linear parameters were sent as feed-forward corrections to the ASML TWINSCAN exposure tool, this time we additionally demonstrate the capability to correct for the non-linear terms as well. Since the concept heavily relies on the quality of the off-line mask registration measurements, a state-of-the-art reticle registration tool was chosen. Special care was taken to eliminate any effects of the tool induced shifts that may affect the quality of the measurements. The on-wafer overlay verification measurements were performed on an ASML Yieldstar metrology tool as well as on a different vendor tool.

In conclusion, we have extended and proven the concept of using off-line reticle registration measurements to enable higher order feed-forward corrections the ASML TWINSCAN scanner. This capability has been verified by on-wafer overlay measurements. It is demonstrated that the RWE contribution in the overlay budget can be taken out of the feed-back control loop and send as feed-forward corrections instead. This concept can easily be extended when more scanner corrections become available.

9635-7, Session 3

Exploring the origin of pattern positioning errors induced by the charging effect in mask making using e-beam writers

Chien-Cheng Chen, Tzu-Ling Liu, Shao-Wen Chang, Chia-Jen Chen, Chih-Cheng Lin, Hsin-Chang Lee, Anthony Yen, Taiwan Semiconductor Manufacturing Co. Ltd. (Taiwan)

Mask overlay is becoming more and more critical due to the application of multiple-patterning optical lithography for the 10-nm generation and beyond. Among the error sources of pattern positioning in mask making using e-beam writers, resist charging effect has been recognized as a major factor. To remove the charge-induced pattern positioning errors (CIPPEs), two promising approaches including charge dissipating layer (CDL) and model-based correction have been developed. Although CDL, a conducting polymer layer coated atop the resist, can efficiently prevent the CIPPEs, its application has been limited due to processing cost, degradation of resist performance, and added defects. For the latter approach, there is still no physical model that can perfectly predict and then correct the CIPPEs. Here the authors present a detailed observation on the behavior of CIPPEs and aim to provide an important insight into the origin of the charging effect.

The CIPPE of on an opaque-MoSi-over-glass (OMOG) mask with negative chemically-amplified resist (NCAR) exposed by a 50 keV variable-shape e-beam writer is directly measured by a commercial mask registration tool with less-than-1-nm accuracy. To isolate the CIPPEs, the registration mark with the typical box-in-box structure has been adopted to exclude other systematic errors such as stress induced pattern shifts. Moreover, multiple registration marks were made as an array in the field of view of the registration tool to average out the random positioning errors of the e-beam writer without increasing the measurement time. A specific layout was designed to study the dependence of CIPPEs on the writing order, pattern density (PD), and distance between patterns. More interestingly, the difference between the behavior of CIPPEs with and without a CDL was also carefully analyzed. To further understand the observed phenomenon, Monte Carlo simulation was performed to explore the origin of the CIPPEs.

We found, for the first time, that the CIPPE can be decomposed in to two components, one on the cm-scale and the other on the mm-scale. The long-range effect results from positive charges and becomes stronger as PD increases. In contrast, the short-range charging is also positive at the low PD regime but gradually changes to negative as PD increases. In addition, the time dependence of CIPPEs shows that the long-range effect quickly diminishes in time but the short-range effect decays slowly. Most strikingly, only the short-range effect can be eliminated by the CDL whereas the long-range positive charging cannot. The result implies that the long-range effect, unlike the short-range one, is not from charges in the resist but in the substrate. According to Monte Carlo simulation, the long-range charging effect was speculated to be the image charges of the diffused electrons trapped in the substrate. Based on these findings, a charging-effect correction method was developed to minimize the registration errors of masks.

9635-8, Session 4

EUV mask infrastructure readiness and gaps for TD and HVM *(Invited Paper)*

Ted Liang, Brittany McClinton, John Magana, Guojing Zhang, Kishore Chakravorty, Eric Panning, Rajesh Nagpal, Intel Corp. (United States)

The lithography community has gained confidence recently in the viability of EUVL for manufacturing. Significant progress has been made in EUV mask making and quality control that allowed the demonstration of wafer yield printed with defect free masks. However, EUV mask infrastructure readiness has been identified as the top risk in enabling the technology implementation in a high volume production line. The challenges in reducing the risk lie in the stringent requirement in defect control and fundamental divergence of EUV mask materials and tool sets from current 193nm optical establishment and technical know-hows. Additionally, the immaturity of the EUV scanner system put forth increased burden on reticle protection for particle and contamination control during use. One of the major infrastructure gaps is through-pellicle pattern inspection.

In this paper, we will review current EUV mask status and highlight the capability requirements for both TD stage and eventual HVM. We focus on the assessment of infrastructure readiness and gaps in key modules of mask fabrication and usage from Intel's pilotline development: blank inspection, mask cleaning, defect disposition and repair, pattern inspection, pellicle integration and through-pellicle pattern inspection and post-pellicilization reticle movement. The goal of this paper is to raise the awareness and hopefully the urgency for tool makers, materials suppliers and end users to work concertedly in closing the key technology gaps.

9635-9, Session 4

Fabrication of a full-size EUV pellicle based on silicon nitride

Dario L. Goldfarb, IBM Thomas J. Watson Research Ctr. (United States)

In this paper, the fabrication and initial characterization of an unsupported membrane composed of a single ultrathin silicon nitride (SiNx) layer with potential application as a EUV pellicle is described in detail. Free-standing pellicles with inner film areas arbitrarily ranging from 10x10mm to 113x145mm (full size) and champion EUV transparency equal to 90% (single pass) have been demonstrated utilizing the methodology presented in this study. The high EUV transparency of the disclosed pellicle was achieved by limiting the membrane thickness to less than 15nm, while the intrinsic mechanical stability for the silicon nitride film was realized by adjusting the Si:N ratio to provide a non-stoichiometric layer featuring a low tensile stress. The pellicle thickness and elemental composition were used to calculate the expected EUV transparency, which was found to be in good agreement with experimental EUV transmission measurements. Additionally, careful consideration was given to process-induced mechanical instabilities exerted on the ultrathin pellicle during the wet etch, rinsing and drying fabrication steps, and a unique yet simple set of ancillary hardware, materials and processing techniques were introduced to minimize such disturbances and yield large-area pellicles that are free of visible defects and wrinkles. Once fabricated, the membranes were protected with a novel packaging system that stabilizes the pellicle enabling transport of the fabricated product using a standard mailing service. Last, in the absence of commercially available actinic inspection tools, a distinctive advantage of the SiNx membrane versus a Silicon-based EUV pellicle solution is the demonstrated ArF transmission (25% vs. 0%, single pass), making it attractive for through-pellicle mask defect inspection and advanced metrology work utilizing available 193nm excimer lasers and detection systems.

9635-10, Session 4

Detection capability enhancement with a learning system for PEM mask inspection tool

Ryoichi Hirano, EUVL Infrastructure Development Ctr., Inc. (Japan); Masahiro Hatakeyama, Kenji Terao, EBARA Corp. (Japan); Hidehiro Watanabe, EUVL Infrastructure Development Ctr., Inc. (Japan)

A learning system has been exploited for the mask inspection tool with the Projection Electron Microscope (PEM). The system adjusts the image process for defect detection. The detection capability for hp11nm EUV masks is demonstrated.

EIDEC and EBARA CORPORATION have been developing the mask inspection system using PEM technology [1]. The PEM inspection system enables to inspect the (EUV) masks by the highly resolved electron image with the higher throughput obtained by aerial image acquisition. The detection capability to meet the requirement for hp16nm EUV masks has been demonstrated [2]. The defect is identified by the PEM system using the “defectivity” defined as a calculated number in the direct product space of the characteristics of the acquired image. An appropriate adjustment for the contribution of each characteristic determines the value of the defectivity, the latitude of detection capability. The process to optimize the each contribution for the newly defined defect, for a new product series of masks, requires the great labor, often it requires the system refinement by the tool supplier. The learning system has been developed to reduce the labor and the cost to adjust the detection capability to cope the newly defined mask defect.

The learning system for PEM consists of the library of the registered defects, the image processing unit exactly equivalent to the image processing in the inspection system, and an engine for the optimization. We register a newly defined defect image, whether the defect has been captured or not. The learning system totally optimizes detection capability reconciling the previously registered defects and the newly registered defect. The enhancement of the detection capability for the PEM system is easily obtained at the operation site.

We have verified the effectiveness of the learning system. We registered the captured image of the defect on hp11nm mask in the learning system previously optimized for hp16nm, and obtained the enhanced detection capability for hp11nm. We demonstrate the detection capability for hp11nm installed on the PEM inspection system.

We can provide a user-friendly mask inspection system with the higher throughput by PEM and with the smaller cost of ownership by the development.

This study is supported by New Energy and Industrial Technology Development Organization (NEDO) and Ministry of Economy, Trade and Industry (METI).

[1] R. Hirano, S Iida, T. Amano, T. Terasawa, H. Watanabe, M. Hatakeyama, T. Murakami, and K. Terao, “Patterned mask inspection technology with projection electron microscope technique on extreme ultraviolet masks”, J. Micro/Nanolith. MEMS MOEMS 13, 013009 (2014).

[2] R. Hirano, S. Iida, T. Amano, T. Terasawa, H. Watanabe, M. Hatakeyama, T. Murakami, and K. Terao, “EUV patterned mask inspection performance of an advanced projection electron microscope (PEM) system for hp 16 nm and beyond”, Proc. SPIE 9256, 92560M-4 (2014).

9635-11, Session 4

Film loss-free cleaning chemicals for EUV mask lifetime elongation developed through combinatorial chemical screening

Jaehyuck Choi, SAMSUNG Electronics Co., Ltd. (Korea, Republic of)

EUV masks include many different layers of various materials rarely used in optical masks, and each layer of material has a particular role in enhancing the performance of EUV lithography. Therefore, it is crucial to understand how the mask quality and patterning performance can change during mask fabrication, EUV exposure, maintenance cleaning, shipping, or storage.

SPM (Sulfuric acid peroxide mixture) which has been extensively used for acid cleaning of photomask and wafer has serious drawback for EUV mask cleaning. It shows severe film loss of tantalum-based absorber layers and limited removal efficiency of EUV-generated carbon contaminants on EUV mask surface.

Here, we introduce such novel cleaning chemicals developed for EUV mask as almost film loss free for various layers of the mask and superior carbon removal performance. Combinatorial chemical screening methods allowed us to screen several hundred combinations of various chemistries and additives under several different process conditions of temperature and time, eventually leading to development of the best chemistry selections for EUV mask cleaning.

Recently, there have been many activities for the development of EUV pellicle, driven by ASML and core EUV scanner customer companies. It is still important to obtain film-loss free cleaning chemicals because cleaning cycle of EUV mask should be much faster than that of optic mask mainly due to EUV pellicle lifetime. More frequent cleaning, combined with the adoption of new materials for EUV masks, necessitates that mask manufacturers closely examine the performance change of EUV masks during cleaning process.

We have investigated EUV mask quality changes and film losses during 50 cleaning cycles using new chemicals as well as particle and carbon contaminant removal characteristics. We have observed that the performance of new chemicals developed is superior to current SPM or relevant cleaning chemicals for EUV mask cleaning and EUV mask lifetime elongation.

9635-12, Session 5

The study of mask shadowing induced phase on absorber defect to improve EUV actinic pattern inspection

Yow-Gwo Wang, Univ. of California, Berkeley (United States) and Lawrence Berkeley National Lab. (United States); Andrew R. Neureuther, Univ. of California, Berkeley (United States); Patrick

P. Naulleau, Lawrence Berkeley National Lab. (United States)

The impact of the phase associated with the edge due to the EUV mask topography on the absorber defects, and the potential of new pupil engineering technique to improve the absorber defect sensitivity for EUV pattern mask inspection are investigated. In order to enhance the sensitivity of detecting absorber defects, we explore the nature of the defect in relation to the mask topography effects using a 3D EUV mask modeling.

Due to the nature of the EUV lithography, the 6 degree incident angle introduces an edge effect on reflective EUV mask pattern compare to the conventional transmissive projection lithography. Moreover, the mask edge effect changes the defect behavior while printing. Recent research results based on the Bossung plot shows that absorber defect possess a phase behavior. This indicates that absorber defects on the EUV mask have mixed amplitude and phase behavior when we consider the 3D effect of the mask. Therefore, we first study the impact of shadowing effect towards the edge of the absorber defects including comparing the difference between normal and oblique incident angle.

Based on the understanding of the edge effect, we will then study the 3D absorber defect behavior, including phase and the amplitude on the EUV patterned mask. By near-field simulation, we can retrieve the defect behavior due to mask shadowing. With 0° and 6° incident angle on the EUV mask, a phase shift is observed at the edge of the absorber defect which depends on the incident electric field polarization and also an enhancement on its amplitude under oblique illumination. Therefore, there might be a possibility to utilize the induced phase on the absorber defect to improve the sensitivity for pattern mask inspection.

In our previous study of blank inspection, a Zernike phase contrast microscopy with 90° phase shift in the pupil plane demonstrate the ability to detect phase defects at focus with high sensitivity. However, for defect possessing amplitude and phase behaviors, an optimum phase shift less than 90° is needed to bring the peak defect signal at best focus. For an absorber defect on the pattern mask, that is known to have a significant phase component due to mask 3D effect, there is a possibility to improve the defect sensitivity by optimizing the pupil design (phase shift, apodization) and the illumination conditions (illumination type, polarization). Our study will focus on both 1D and 2D mask patterns with a variety of 2D defects.

This research is sponsored by IMPACT+ (Integrated Modeling Process and Computation for Technology). Member companies – ARM, ASML, Global Foundries, IBM, Intel, KLA-Tencor, Marvell Technology, Mentor Graphics, Panoramic Tech, Photronics, Qualcomm, Samsung, SanDisk and Tokyo Electron.

This work was performed in part at Berkeley Lab which is operated under the auspices of the Director, Office of Science, of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231.

9635-13, Session 5

ILP-based co-optimization of cut-mask layout, dummy fill, and timing for sub-14nm BEOL technology

Kwangsoo Han, Andrew B. Kahng, Hyein Lee, Lutong Wang, Univ. of California, San Diego (United States)

Self-aligned multiple patterning, due to its low overlay error, has emerged as the leading option for 1D gridded BEOL in sub-14nm nodes. To form actual routing patterns from a uniform “sea of wires”, a cut mask is needed for line-end cutting or realization of space between routing segments. Constraints on cut mask shapes and colorability result in line-end extensions beyond what is originally seen in the layout tool; the resulting capacitance and timing changes must be consistent with signoff performance analyses. Furthermore, cut mask shapes determine the amount of non-functional (i.e., dummy fill) pattern that remains from the original “sea of wires”; this must be consistent with area density bounds as well as timing constraints.

In this work, we address the co-optimization of cut mask layout, dummy fill, and design timing for sub-14nm BEOL design. Our central contribution is an Integer Linear Programming (ILP) based optimizer that considers cut mask layout rules (minimum width, minimum area, minimum spacing, etc.) arising in sub-14nm process nodes. We formulate as an ILP the minimization of timing violations (equivalently, the maximization of timing slack) subject to complex ground rules that include (i) end-of-line extension (i.e. timing criticality), (ii) cut mask shape, (iii) cut mask coloring and (iv) local metal density. Our framework is based on set covering, where a set corresponds to all possible cut shapes that separate two co-linear (i.e., consecutive on the same track) wire segments. A feasible set of cut mask shapes must cover every such set – that is, separate every wire segment from its co-linear neighbor segments. Only printable shapes are considered for the cut mask layout. Further, as minimum spacing rules on the cut mask may become highly constraining at sub-14nm nodes, we optionally enforce cut mask colorability with two or more colors. Our method also considers local metal density in the sea-of-wires unidirectional metal layer to maintain uniform local metal density for mask write, CMP or etch process steps.

Our experimental framework is based on a prototype 7nm PDK from a leading IP provider. We extract layouts from timing-optimized place-and-route solutions for open-source (encryption, media processing, embedded processor) cores and use ILOG CPLEX v12.5.1 to solve the corresponding ILP instances. Post-cut mask design layouts are extracted and timing impacts (relative to original design signoff) are assessed using a commercial golden timer. We perform several basic studies of how mask complexity and design timing changes trade off against constraints on the cut mask design or on layout density.

These studies encompass (1) mask and layout density constraints, and density balance / density smoothness constraints; (2) number of colors, and separation (resolution) distance, available to the cut mask patterning solution; and (3) cut mask shape constraints. Our studies of optimized cut mask solutions in these varying contexts give new insight into the tradeoff of performance, area density and cost that is afforded by cut mask patterning technology options.

9635-14, Session 5

Phase retrieval algorithms for patterned mask metrology in EUV

Rene A. Claus, Yow-Gwo Wang, Univ. of California, Berkeley (United States); Antoine J. Wojdyla, Markus P. Benk, Kenneth A. Goldberg, Lawrence Berkeley National Lab. (United States); Andrew R. Neureuther, Univ. of California, Berkeley (United States); Patrick P. Naulleau, Lawrence Berkeley National Lab. (United States); Laura Waller, Univ. of California, Berkeley (United States)

We evaluate the performance of several phase retrieval algorithms applied to aerial image measurements of patterned EUV masks. Patterns present a challenge for these algorithms due to the higher contrast images and stronger diffraction. For this study we looked at the ability to correctly recover phase when a multilayer defect was in the presence of line-space patterns. We also applied the algorithm to aerial image measurements of an etched EUV phase shift mask. Measurements were taken on the SHARP EUV microscope at Lawrence Berkeley National Laboratory [1].

The algorithms considered are the iterative algorithm from [2], the algorithm from [3], and the algorithm from [4]. For the etched phase shifting mask a checkerboard pattern of pitch 115nm and a larger checkerboard of pitch 3um were tested. For the multilayer defect a pitch of _ was used. We were able to successfully recover the phase of the etched phase shift mask using algorithm [2]. The phase results show the shadowing effects at the edges.

[1] K. A. Goldberg, I. Mochi, M. Benk, A. P. Allezy, et al. “Commissioning an EUV mask microscope for lithography generations reaching 8 nm,” SPIE Advanced Lithography 8679, (2013).

[2] Seldin, J. H., & Fienup, J. R. Iterative blind deconvolution algorithm applied to phase retrieval. Journal of the Optical Society of America, (1990), 7(3), 428–433.

[3] R. A. Claus, et al. “Phase measurements of EUV mask defects,” SPIE Advanced Lithography (2015).

[4] G. SZhen, et al. “Wide-field, high resolution Fourier ptychographic microscopy,” Nature Photonics (2013).

9635-15, Session 5

Absorption dependence of phase edge effects in OMOG masks

Aamod Shanker, Univ. of California, Berkeley (United States); Martin Sczyrba, Falk Lange, Advanced Mask Technology Ctr. GmbH Co. KG (Germany); Brid Connolly, Toppan Photomasks, Inc. (Germany); Laura Waller, Andrew R. Neureuther, Univ. of California, Berkeley (United States)

Rigorous EM simulation is used to determine the underlying physical phenomena that cause unexpectedly high TM polarization EM edge effect in OMOG masks. Experiments have shown that OMOG masks can have up to half the topographic phase edge effects as ATT-PSM masks [1], despite a thinner absorber and stronger attenuation. However, the stronger attenuation likely relies on using materials for which the imaginary part of the refractive index (α) is larger than the real part of the refractive index (n). This will lead to significant phase changes in transmission coefficients, increased polarization differences with incident angle, and even the excitation of plasmons at corners when the electric field is not parallel to the mask edge. The corresponding impact on aerial image quality is known to depend on absorber topography, complex refractive index and optical polarization. Refractive index of mask material is important in the design of polarization elements on mask, studied by Lam et al. 2002 [2], while Miller et al [3] showed that TM polarization has stronger phase at edges than the TE counterpart in thick masks. This paper explores the even more challenging complexities in mask performance that arise in the anomalous dispersion region where α is larger than n.

The significance of the polarization dependence of the EM edge effects is demonstrated by comparing AIMS images above and below focus (Fig. 1 in supplement). Asymmetries about focus, which depend on the phase of the fields leaving the mask, are about three times larger for the TM polarization. To determine underlying physical causes we start from fundamental boundary conditions at mask sidewalls. Where the sidewall meets the top surface of the OMOG, Gauss’ law predicts abrupt discontinuities in the near field for the TM case, normal to the sidewall (Fig. 3). Since the AIMS measurements were made at a sigma of 0.3 corresponding to about 6 degrees incidence on the mask, we explore the extent to which the mask performance changes with off-axis angles.

Surface plasmons are source free solution of Maxwell’s equations that can only occur on planar surfaces for certain $\alpha > n$. To explore the existence and impact of plasmon effects we begin by using the plasmon dispersion condition to determine the propagation /attenuation constants along the surface and the exponential decay of the fields away from it. Rigorous EM simulation automatically includes these effects and their generation at topography turning points where planar faces of the mask meet. In looking at near fields (Fig. 2) the challenge is, however, to recognize these surface waves in the presence of more conventional diffraction.

The main concern is the impact of these effects on imaging after low pass filtering by the lens. As a metric we compare deviations from ideal imaging and look for generalized thin-mask models based on edge boundary layers. Observations in focus give the real component of boundary layers, while asymmetries through-focus determine the imaginary part. We automate the extraction of mask effects using phase recovery algorithms on the images in the same manner as we treated AIMS data in diagnosing EM edge effects [1].

[1] Shanker et al.,SPIE Vol. 9052, 90521D (2014)

[2] Lam et al Proc. SPIE 4889, BACUS 2002, 530

[3] Miller, PhD Thesis Ch. 5, UC Berkeley 2010

9635-16, Session 5

PMJ Best Student Paper: Extreme ultraviolet mask observations using a coherent extreme ultraviolet scatterometry microscope with a high-harmonic-generation source

Takahiro Fujino, Yusuke Tanaka, Tetsuo Harada, Univ. of Hyogo (Japan); Yutaka Nagata, RIKEN (Japan); Takeo Watanabe, Hiroo Kinoshita, Univ. of Hyogo (Japan)

The three-dimensional (3D) structure of the EUV mask, which has an absorber layer and a Mo/Si multilayer on a glass substrate, strongly affects the EUV phase. EUV actinic metrology is required to evaluate the feature of defect printability and the critical dimension (CD) value. The 3D structure strongly modulates the EUV phase, causing the pattern position and focus shift. A microscope that observes phase images is necessary.

We have developed a coherent EUV scatterometry microscope (CSM), which observes EUV patterns with quantitative phase contrast. The exposure light is coherent EUV light. For the industrial use, we have developed a laboratory coherent source of high-harmonic-generation (HHG) EUV light. Figure 1 schematically depicts the HHG-CSM. High harmonics is pumped by a laboratory scale of a Ti:Sapphire laser. In the previous study, the fluctuation of source position was not negligible. The throughput of the EUV power was quite low because the relay optics had an intermediate pinhole to fix the beam position on a mask. In this study, we report a new feedback system for the beam position and upgraded relay optics. The detection performance of an absorber defect using the new relay optics is evaluated.

Figure 2 shows the relation between the defect area and the defect signal intensity for three defect shapes. The detection limit is a 24-nm line-end-oversize defect, which has area of 2688 nm2. This area is equivalent to a 52 x 52 nm2 square defect. This result shows high performance capability of HHG-CSM for detecting small defect. We will observe the patterns with quantitative phase contrast.

9635-46, Session PS1

Automatic defect review for EUV photomask reticles by atomic force microscope

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Defects on a reticle are inspected, reviewed, and repaired by different tools. They are located by automated optical inspection (AOI); however, if the characteristic size of defects is similar to that of light and electron beam wavelengths, they are often unclassified or misclassified by AOI. Atomic force microscopes (AFM) as well as electron microscopes are used for investigating defects located by AOI to distinguish false defects from real defects and effectively classify them. Both AFM and electron microscopes provide high resolution two-dimensional images. However, electron microscopy is known to be destructive and have less accuracy in 3rd dimension measurement compared to AFM. [1] On the other hand, AFM is known to have low throughput and limited tip life in addition to laborious effort to find the defects. These limitations emanate from having to perform multiple large scans to find the defect locations, to compensate for stage coordinate inaccuracies, and to correct the mismatch between the AFM and the AOI tools.

In this work we introduce automatic defect review (ADR) AFM for defect study and classification of EUV mask reticles that overcomes the aforementioned limitations of traditional AFM. This metrology solution is based on an AFM configuration with decoupled Z and XY scanners that makes it possible to collect large survey images with minimum out of plane motion. To minimize the stage errors and mismatch between the AFM and the AOI coordinates, the coordinates of fiducial markers are used for coarse alignment. In addition, fine alignment of the coordinates is performed using enhanced optical vision on marks on the reticle. The ADR AFM is used to study a series of phase defects identified by an AOI tool on a reticle. Locating the defects, imaging, and defect classification are performed using the ADR automation software and with the throughput of several defects per hour. In order to preserve tip life and data consistency, AFM imaging is performed in non-contact mode. The ADR AFM provides high throughput, high resolution, and non-destructive means for obtaining 3D information for defect review and classification. Therefore this technology can be used for in-line defect review and classification for mask repair.

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9635-47, Session PS1

Ruthenium capping layer preservation for 100X clean through pH driven effects

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In the absence of pellicle a EUVL reticle is expected to withstand up to 100x cleaning cycles. Surface damage upon wet and dry cleaning methods has been investigated and reported in recent years.1 Thermal stress, direct photochemical oxidation and underlying Silicon layer oxidation are reported as the most relevant root-causes for metal damage and peeling off.2,3 An investigation of final clean performance is here reported as a function of media chemistry; the results show increased Ruthenium durability upon modification of the media chemistry. Possible explanations behind surface integrity will be presented.

The study shows how optimization of the cleaning media can lead to stable Ruthenium oxides formation without further oxidation or dissolution (etching into the metal layer); ruthenium peeling off is also avoided by means of this new chemistry media.

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9635-48, Session PS1

Process capability of etched multilayer EUV mask

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With shrinking pattern size at 0.33 NA EUV lithography system, mask 3D effects are expected to become stronger, such as horizontal/vertical shadowing, best focus shifts through pitch and pattern shift through focus. [1] Also at high-NA (>0.4) EUV lithography whose chief-ray-angle (CRA) is 8 degree and whose mask magnification is 4x, conventional absorber stacked EUV mask 3D effects impact the lithographic performance. Therefore, high-NA system is currently proposed that CRA should be lower than 8 degree and mask magnification should be larger than 4x instead, which leads to half-field exposure system. [2] On the other hand, etched multilayer type mask structures have been proposed in order to reduce mask 3D effects at high-NA under the condition that CRA is 8 degree and that mask magnification is 4x. [3], [4] And it is estimated that etched multilayer type mask is also effective in reducing mask 3D effects at 0.33NA with lithographic simulation. [1] Recently, we have demonstrated that etched multilayer dense, isolated trench of 40nm (10nm on wafer) and isolated line of 56nm (14nm on wafer) were achieved still after mask cleaning process by SEM observation. [5]

In this paper, we present process integration results of etched multilayer mask such as resist patterning process, etch process, and cleaning durability, including etched multilayer pattern collapse by mask pattern inspection tool. And we will show outlook for etched multilayer mask targeting 0.33NA EUV extension.

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9635-75, Session PS1

Actinic review of EUV masks: status and recent results of the AIMS EUV System

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Key enabler of the successful introduction of EUV lithography into volume production is the EUV mask infrastructure. For the production of defect free masks, actinic review of potential defect sites to decide on the need for repair or compensation is required. Also, the repair or compensation with the MeRiT™ electron beam repair tool needs actinic verification in a closed loop mask repair solution. For the realization of actinic mask review, ZEISS and the SUNY Poly SEMATECH EUVL Mask Infrastructure consortium started a development program for an EUV aerial image metrology system, the AIMS™ EUV, with realization of a prototype tool.

The development and prototype realization of the AIMS™ EUV has entered the tool calibration and qualification phase utilizing the achieved capabilities of EUV aerial image acquisition and EUV mask handling. In this paper, we discuss the current status of the prototype qualification and show recent measurement results.

9635-76, Session PS1

Phase imaging results of phase defect using the lensless EUV microscope

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For imaging a phase defect in quantitative phase contrast, we have developed the lensless EUV microscope. This microscope records diffraction from a phase defect, which is illuminated with focused coherent EUV light of 140-nm diameter. The intensity and the phase distribution were reconstructed with the iterative calculation of ptychography. We observed phase defects with 30-nm spatial resolution in intensity and phase contrast. The phase image will be very helpful to estimate the printability of the defect on the exposure tool.

9635-49, Session PS2

Optical proximity correction for extreme-ultraviolet mask with pellicle

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Extreme ultraviolet lithography (EUVL) is indispensable for the next generation technology to make the pattern size small on the wafer. As EUV lithography is being close to high volume manufacturing for the next generation device, the impact of defect becomes more critical on the patterns. Therefore a pellicle is essential to implement the defect free mask for EUV lithography. The optical proximity correction (OPC) for EUV that includes the image effect with a pellicle might be needed for better critical dimension control. The main effect of a EUV pellicle is a transmission loss.

We investigated the impact of image blurring induced by the mask pellicle. In order to check the imaging error by transmission loss of a pellicle, we considered image difference caused by using a pellicle for the different pattern shape, pattern position and pattern density on the wafer. The positions on 2D logic patterns such as inner corner and outer corner of the logic patterns. The outer corner shrink with a pellicle will be larger than that without a pellicle since the lack of light will be amplified at the outer corner. Because of this difference in intensity with/without a pellicle, an edge placement error (EPE) with a pellicle will be different. First, we considered the 2D logic patterns with 16 nm half pitch (line width = 16 nm, line length = 100 nm) with and without pellicle. The pattern with a pellicle is simulated by increasing the amount of dose in order to correct with target pattern contour. By increasing the dose only, the inner corner and the outer corner is not corrected to the target contour, while the line width of the line center is corrected.

By using the pellicle we can protect the mask from the defect, but we cannot avoid the patterning error caused by a transmission loss. Therefore this error should be corrected by OPC. In order to correct the difference of the EPE by pellicle at the mask, we corrected the position and the size of the pattern with sub-resolution assist features, serif, hammerhead and so on.

9635-50, Session PS2

Mask process simulation for mask quality improvement

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Demand for mask process correction (MPC) is growing facing 14nm era. We have developed model based MPC and can generate mask contour by this mask process model. This mask process model consists of EB (development) and etch, which employs threshold (level set) model and variable bias model respectively. Model calibration tool accepts both CD measurement result and SEM image. The simulation can generate mask image (contour) and runs with distributed computing resources and its performance is scaleable.

Contour simulation shows of MPC correction visually and provides comprehensive information of hot spot in mask fabrication. Additionally, it will be possible to improve lithography simulation quality by providing simulated mask contour.

In this paper, accuracy and computational performance of mask process simulation is shown. Contribution to accuracy of lithography simulation by providing simulated mask contour will also be shown.

9635-52, Session PS2

Rule-based OPC and MPC interaction for implant layers

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Implant layers must cover both logic and SRAM devices with good fidelity even if feature density and pitch differ very much. Additionally, the active area coverage design rules of implant layers for SRAM and logic can vary. Lithography targeting for implants between these two regions, therefore, can be problematic since it may cause issues of either over exposure in logic area or under exposure in SRAM area. Typical rule-based (RB) re-targeting in the SRAM region for implants is to compensate the under exposure in SRAM area. However, a global sizing in SRAM may introduce some bridging issues. Therefore, selective targeting with awareness of the active layer is necessary. Another compensation method is to achieve different mean-to-nominal (MTN) in some special areas during the reticle process. Such implant wafer issues can also be resolved during the lithography and mask optimized data preparing flow or named as lithography tolerance mask process correction (MPC).

In this manuscript, this systematic CD offsets between logic and SRAM areas on implant layers will be demonstrated. The selective rule-based re-targeting with respect to active layer will also be discussed, together with the improved wafer CDSEM data. The alternative correction method is to achieve different mean-to-nominal in different reticle areas which can be realized by lithography tolerance MPC during reticle process. The investigation of alternative methods will be presented, as well as the trade-off between them to improve the wafer uniformity and process margin of implant layers.

9635-53, Session PS3

Attenuated phase-shift mask (PSM) blanks for flat panel display

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The fine pattern exposure techniques are required for Flat Panel display applications as smart phone, tablet PC recently. The attenuated phase shift mask (PSM) are being used for ArF and KrF photomask lithography technique for high end pattern Semiconductor applications. We developed CrOx based large size PSM blank that has good uniformity on optical characteristics for FPD applications. We report the basic optical characteristics and uniformity, stability data of large sized CrOx PSM blanks.

9635-54, Session PS3

Advanced repair solution of clear defects on HTPSM by using nanomachining tool

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As the mask specifications become tighter for low k1 lithography, more aggressive repair accuracy is required below sub 20nm tech. node. To meet tight defect specifications, many maskshops select effective repair tools according to defect types. Normally, pattern defects are repaired

by the e-beam repair tool and soft defects such as particles are repaired by the nanomachining tool. It is difficult for an e-beam repair tool to remove particle defects because it uses chemical reaction between gas and electron, and a nanomachining tool, which uses physical reaction between a nano-tip and defects, cannot be applied for repairing clear defects.

Generally, film deposition process is widely used for repairing clear defects. However, the deposited film has weak cleaning durability, so it is easily removed by accumulated cleaning process. Although the deposited film is strongly attached on MoSiN(or Qz) film, the adhesive strength between deposited Cr film and MoSiN(or Qz) film becomes weaker and weaker by the accumulated energy when masks are exposed in a scanner tool due to the different coefficient of thermal expansion of each materials. Therefore, whenever a re-pellicle process is needed to a mask, all deposition repair points have to be confirmed whether those deposition film are damaged or not. And if a deposition point is damaged, repair process is needed again. This process causes longer and more complex process.

In this paper, the basic theory and the principle are introduced to recover clear defects using nanomachining tool, and evaluated results are reviewed at L/S and C/H patterns. Also, the results using a nanomachining were compared with those using an e-beam repair tool and the cleaning durability was evaluated by the accumulated cleaning process. Besides, we discuss the phase shift issue and solution about pattern shift.

9635-55, Session PS3

Exposure characterizations of polymer type electron beam resists with various molecular weights for next-generation photomask

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A polymer resists are expected as a high-resolution electron beam resist for next-generation photo-mask production as well as a chemically amplified resist and a molecular resist. The performance of the polymer resist is mainly characterized by the chemical structure and the molecular weight. It is generally known for the positive tone polymer resist that the solubility of unexposed portion decreases with increasing molecular weight, which enables to obtain high contrast patterns, while the sensitivity becomes lower. In contrast, the sensitivity is improved as the molecular weight decreases, but the edge shape of the resist pattern becomes broader due to the thickness loss in the unexposed portions. In this study, we synthesize the polymer resists having various molecular weights and evaluate the exposure characteristics from the viewpoint of the next-generation photo-mask production.

Considering the production of the next-generation photo-mask, not only the high-resolution but also the high-sensitivity is desirable. Therefore, the exposure dose was set to be bellow 200°C/cm2 at an acceleration voltage of 50 kV. Designed values of line and space (L/S) patterns were from 20 to 40 nm. The developing conditions were examined to be optimal for each resists. Acrylic-styrene copolymers having the molecular weight ranging from 10k to 500k were synthesized by radical polymerization. The measurement of the molecular weight was done by using Size Exclusion Chromatography. The copolymers were dissolved in anisole. 50-nm-thick resists were spin-coated on Si wafers and backed on a hot plate at 180°C for 2 min. After pre-backing, exposure experiments were carried out using an electron beam writing system, ELS-7500EX (ELIONIX). Exposed samples were developed at room temperature. Formed patterns were examined with a scanning electron microscope, S-4700 (Hitachi).

The cross-section profile of the 20 nm L/S resist patterns with molecular weight of 500k and 300k were roughly rectangular. The exposure doses were 180°C/cm2 for 500k and 160°C/cm2 for 300k, respectively. For 50k, although the 20 nm L/S patterns were also formed with the exposure dose of 140°C/cm2, the cross-section profile of the resist pattern became rounder and the disconnections were observed. The formed L/S patterns for the resist with the molecular weight of 10k were up to 25 nm due to the large amount of thickness loss in the unexposed portions. From the viewpoint of pattern shape, the resist having the larger molecular weight was more advantageous to the miniaturization. The resist with the molecular weight of 50k was the most sensitive in the 20 nm L/S pattern formation. Comparing the exposure does for 500k with that for 50k, it was found that the sensitivity decrease was approximately 20% by optimizing the development process although the molecular weight was ten times larger. The resist thickness tends to become thinner which is advantageous to both the resolution and sensitivity. However, the improvement of dry etching resistance is required at the same time. The dry etching resistance of the resists is also presented.

9635-56, Session PS3

New grade of 9-inch size mask blanks for 450mm wafer process (2015)

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6-inch size (known as 6025QZ) binary Cr mask is widely used in the semiconductor lithography for over 20years. Recently for the 450mm wafer process, high grade 9-inch size mask is expected. For this application, we have studied and developed new grade 9-inch size mask blanks for recent 450mm wafer process requirement. This time we will explain these further studies.

9635-57, Session PS3

Printability evaluation of programmed defects on OMOG masks

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Opaque MoSi on Glass (OMOG) photomask, significantly less prone to mask degradation, has been applied in leading-edge photolithographic flows on 20 nm and 14 nm node. Mask defect problem occurs at any time, rooted in various causes; therefore, defect printability disposition and verification need to be evaluated for new developing process. A series of programmed defects with typical sizes and shapes have been established for different mask patterns on OMOG masks and investigated for the defect printability influences through the CDSEM, AIMS and inspection tools. The results are compiled to produce the defect specifications that can be implemented on OMOG mask fabrication.

9635-58, Session PS3

Mask repair and verification for the next generation

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No Abstract Available

9635-59, Session PS3

Investigation of scum type growing defects on attenuated PSM and its prevention

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The abnormal growing defects(we called this defect 'scum haze defects') in the photomask which occur during the wafer lithography process is very important issue on semiconductor industry. Because wafer yield loss could be caused by the mask CD variation and the transmittance loss

due to the growing defects on the photomask. Many studies have been done about the mechanism and the solution of the general type growing defects such as haze and Cr migration so far, however it still remains the solution for the control of abnormal haze defects such as scum haze defects. In this paper, we investigated the occurrence mechanism and prevention techniques for the scum haze defects on the attenuated phase shift mask. These defects are gradually caused by the increase of the accumulated exposure energy on photomask which consist of CrOx at isolated space patterns. This phenomenon shows a remarkably similar to shape the Cr migration on binary mask besides, it occurred on the attenuated PSM which mainly consist of MoSiON film. The scum haze defects was too difficult to control because of its irregular occurrence. Additionally, it was very hard to remove the scum haze defects through the conventional wet cleaning process, it only could be removed by a kind of plasma treatment. In this study, the difference of generation mechanism between the scum haze defects and the general haze was discussed, and the optimal process for controlling these scum haze defects in the mask manufacturing was described.

9635-77, Session PS3

Photomask repair using low-energetic electrons

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Mask repair is an essential step in the mask manufacturing process as the extension of 193nm technology and the insertion of EUV are drivers for mask complexity and cost. The ability to repair all types of defects on all mask blank materials is crucial for the economic success of a mask shop operation. In the future mask repair is facing several challenges. The mask minimum features sizes are shrinking and require a higher resolution repair tool. At the same time mask blanks with different new mask materials are introduced to optimize optical performance and long term durability. For EUV masks new classes of defects like multilayer and phase defects are entering the stage. In order to achieve a high yield, mask repair has to cover etch and deposition capabilities and must not damage the mask. We will present in this paper that low energetic ebeam based mask repair is a commercially viable solution. Therefore we developed a new repair platform called MeRiT® neXT to address the technical challenges of this new technology. We will analyze the limits of the existing and low energetic induced repair technologies theoretically and experimentally and show performance data on photomask reticles. Based on this data, we will give an outlook to future mask repair technology.

9635-38, Session PS4

Accurate defect die placement and nuisance defect reduction for reticle die-to-die inspections

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Die-to-die reticle inspections are among the simplest and most sensitive reticle inspections because of the use of an identical-design neighboring-die for the reference image. However, this inspection mode can have three key disadvantages: (1) The location of the defect is indeterminate because it is unclear to the inspector whether the test or reference image is defective; (2) nuisance and false defects from mask manufacturing noise and tool optical variation can limit the usable sensitivity; and (3) It is time-consuming to validate the impact of the defect being reported in the wrong die. The use of a new sequencing approach for a die-to-die inspection can resolve these issues without any additional scan time, without a sacrifice in sensitivity, and with a manageable increase in computation load.

In this paper we explore another approach for die-to-die inspections using a new method of defect processing and sequencing. The use of this die-to-die double-arbitration method maintains the reqiured inspection sensitivity for mask quality as verified with programmed-defect-mask qualification and then further validated with production masks comparing the current inspection approach to the new method. Under that condition, it has also been proven through extensive testing to generate accurate placement of the defect in the correct die to ensure efficient defect position at the AIMS step. Furthermore, this approach can significantly reduce the total number of defects that need to be reviewed by essentially eliminating the nuisance and false defects that can result from a die-to-die inspection. This “double-win” will significantly reduce the effort in classifying a die-to-die inspection result and will lead to improved cycle times

9635-60, Session PS4

In die mask overlay control for 14nm double-patterning lithography

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According to the ITRS roadmap, semiconductor industry drives the 193nm lithography to its limits, using techniques like double exposure, double patterning, mask-source optimization and inverse lithography. In terms of considering the photomask metrology, full in-die measurement capability is required for registration and overlay control with challenging specifications for repeatability and accuracy.

Double patterning using 193 nm immersion lithography has been adapted as the solution to enable 14 nm technology nodes. The overlay control is one of the key figures for the successful realization of this technology.

In addition to the various error contributions from the wafer scanner, the reticles played an important role in teams of considering lithographic process contribute errors. Accurate pattern placement of the features on reticles with a registration error below 4nm is mandatory to keep overall photomask contributions to overlay of sub 20nm logic within the allowed error budget.

In this paper, we show a more comprehensive characterization of in-die mask overlay by using a 14nm DPT product mask, by measuring in-die overlay pattern and regular mask registration mark . The mask measurements will be used to obtain an accurate model to predict mask contribution to wafer overlay of double patterning technology.

9635-61, Session PS4

Reduction of in-lot overlay variation with integrated metrology, and a holistic control strategy

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As DRAM semiconductor manufacturing approaches high volume for

1x nm nodes with immersion lithography, an increased emphasis is being placed on reducing the influence of the systematic wafer-level contribution to the on-product overlay budget. The cost of the needed metrology has hitherto been challenging. However, it will be shown that the availability of fast, accurate diffraction based metrology integrated within the Lithography cluster can enable cost-effective solutions. Together with applications software we will use any relevant context information to optimize control of all exposure-tool actuators during lot processing, to deliver the needed on-product performance.

Current process corrections typically are done based on feedback per lot and per exposure chuck. Wafers exposed on the same chuck, belonging to the same lot get exactly the same process corrections. In current HVM processing however, a main contribution to the wafer variation is the differences in processing of the different wafers. These differences can be related to different usage of the processing tools (e.g. different etch chambers). An extension of the process corrections from chuck-based to process-context based can help reducing the wafer variation. With Integrated Metrology the sampling of wafers through the lot can be adjusted to make sure all different processing-contexts are covered in the measurements.

Finally, the impact on Litho process cycle time of the total metrology effort required to enable these performance improvements, will be evaluated, and a proposal will be made on the optimum strategy to enable high-volume manufacturing.

9635-62, Session PS4

Novel CD control of HTPSM by advanced process for sub-20nm tech

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As the design rule of the semiconductor shrinks, the CD MTT (Critical Dimension Mean-to-Target) specification for photomask becomes tighter. So, more precise control of CD MTT is required. We have investigated the CD MTT control and applied it to the attenuated PSM (Phase Shift Mask) successfully for several years. We can control the CD MTT of MoSi pattern by measuring Cr/MoSi pattern to estimate MoSi pattern CD and additional etch to shrink MoSi pattern as reported in previous study. At first, the MoSi pattern CD can be estimated with the Cr/MoSi pattern CD because the CD gap between MoSi pattern and Cr/MoSi pattern is relatively constant. Additional MoSi etch is performed to shrink the MoSi pattern CD after then. The CD gap alwasys exists and the variation of the CD gap is enough small to be not considered in conventional photomask production until now. However, the variation of the CD gap is not ignorable in case of sub-20 nm tech.

In this study, we investigated new method to measure MoSi pattern CD before Cr strip process to eliminate the CD gap between MoSi pattern and Cr/MoSi pattern. To eliminate the CD gap, we attempt three solutions – 1) Optimize etch process to perform perfect Cr/MoSi pattern profile without the CD gap, 2) Improve CD measurement accuracy by developing new SEM measuring mechanism, 3) Develop of new process to modify Cr/MoSi pattern profile to be measured without the CD gap. It was found that the CD gap can be eliminated and MoSi pattern CD can be measured perfectly. Finally, MoSi pattern CD control was improved because of CD gap elimination.

9635-63, Session PS4

A study of reticle CD behavior for inter-area pattern loading difference

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To find a solution on mask production problem, it was proceeded to confirming the CD suitability on each mask in a stock (including manufactured but already disuse processed), these masks were observed some tendencies of the MTT movement along with the CA change. This evaluation was done and made a Test Masks to verify its accurate relationship between. I had changed on the MTT regardless of the area density difference then a Spider Mask was produced. By producing PWQ wafer at which was targeted the CD through the exposure time on the Split process, the core pattern and the CD movement were observed into the MTT movement. As a result, when the MTT of dense area as the center became larger, a Pattern CD of Sparse area was increased, so it was confirmed that the increase range would become more increased when the MTT was larger.

9635-64, Session PS4

Wafer weak point detection based on aerial images or WLCD

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Aerial image measurement is a key technique for model based optical proximity correction (OPC) verification. Actual aerial images obtained by AMIS (aerial image measurement system) or wafer level critical dimension (WLCD) can detect the printed wafer weak point structures in advance of wafer exposure and defect inspection. Normally, the wafer weak points are determined based on optical rule check (ORC) simulation in advance. However, the correlation to real wafer weak points is often not perfect due to the contribution of mask three dimensions (M3D) effects, actual mask errors, and scanner lens effects. If the design weak points can accurately be detected in advance, it will reduce the wafer fab cost and improve cycle time. WLCD or AIMS tools are able to measure the aerial images CD and bossing curve through focus window. However, it is difficult to detect the wafer weak point in advance without defining selection criteria.

In this study, wafer weak points sensitive to mask mean to nominal values are characterized for a process with very high MEEF (normally more than 4). Aerial image CD uses fixed threshold to detect the wafer weak points. By using WLCD though threshold and focus window, the efficiency of wafer weak point detection is also demonstrated. A novel method using contrast range evaluation is shown in the paper. Use of the slope of aerial images for more accurate detection of the wafer weak points using WLCD is also discussed. The contrast range can also be used to detect the wafer weak points in advance. Further, since the mean to nominal of the reticle contributes to the effective contrast range in a high MEEF area this work shows that control of the mask error is critical for high MEEF layers such as poly or first 1X metal layers.

9635-66, Session PS4

Automatic classification and defect verification based on inspection technology with lithography simulation

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Even small defects on the main patterns can create killer defects on the wafer whereas the same defect on or near the decorative patterns may be completely benign to the wafer functionality. This ambiguity often causes operators and engineers to put a mask “on hold” to be analyzed by an AIMS™ tool which slows the manufacturing time and

increases mask cost. In order to streamline the process, mask shops need a reliable way to quickly identify the wafer impact of defects during mask inspection review reducing the number of defects requiring AIMS analysis.

Source Mask Optimization (SMO) techniques are now common on sub 20nm node critical reticle patterns These techniques create very complex reticle patterns which often makes it difficult for inspection tool operators to identify the desired wafer pattern from the surrounding nonprinting SMO, ILT, NTD and other complex patterns.

In this study, we have tested a system that generates aerial simulation images directly from the inspection tool images. The resulting defect dispositions from a program defect test mask along with numerous production mask defects have been compared to the dispositions attained from AIMS analysis. The results of our comparisons will be presented as well as the impact to mask shop productivity.

9635-67, Session PS4

The capability of lithography simulation based on MVM-SEM system

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SMO-ILT, NTD or more complex pattern are adopted for the 1Xnm technology node lithography. Therefore, in mask defect inspection, defect verification becomes more difficult because many nuisance defects are detected on aggressive mask features. Defect verification is one of key technologies in mask manufacturing, Aerial simulation or the tool which can simulate wafer printability is generally adopted for the verification. For example, AIMS™ Technology shows excellent correlation for the wafer, and it is currently standard tool for defect verification. However, it may be difficult to verify hundreds of defects on such aggressive mask pattern on the tool.

We reported capability of defect verification based on lithography simulation with a SEM system. We showed that the architecture and the software of the system were well developed for simple line and space. Thus, the simulation results showed excellent correlation for wafer result.

In this paper, we will evaluate the new simulation system with next generation SEM system. The target of evaluate is to achieve the good matching for SMO-ILT, NTD and other complex patterns. Furthermore, we will evaluate three dimension (3D) lithography simulation based on Multi Vision Metrology SEM system. Finally, we will confirm the performance of the 2-D and 3-D lithography simulation based on the new SEM system for a defect verification.

9635-68, Session PS4

A study on the factors that affect the advanced mask defect verification

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Defect verification has become significantly difficult to higher technology nodes over the years. Traditional primary method of defect (include repair point) control consists of inspection, AIMS and repair steps. Among them, AIMS process needs various wafer lithography conditions, such as NA, inner/outer sigma, illumination shape and etc. It has a limit to analyze for every layer accurately because AIMS tool uses the physical aperture system. And it needs feedback manually exposure conditions and CD target value which change frequently in advanced mask.

We report on the influence of several AIMS parameters on the defect analysis including repair point. Under various illumination conditions with different patterns, it showed the significant correlation in defect analysis results. It is able to freely measure under certain error budget based on the management specification required for each layer. In addition, it provided us with one of the clues in the analysis of wafer repeating defect. Finally, we will present 'optimal specification' for defect management with common AIMS recipe and suggest advanced mask process flow.

9635-69, Session PS4

Contour-based two-dimension mask pattern metrology

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Mask pattern measurement becomes one of the main challenges for the quality evaluation of the mask which is applied with complicated lithography optical effect correction. Traditional straight edge mask pattern is evaluated with 1-dimension Critical Dimension (CD) method. But for 2-dimension pattern especially the mask full filled with complex shapes OPC pattern, many special approaches are studied attempt to characterize 2D pattern from different points of view. A simple CD's information and the traditional mask performance evaluation parameters, such as CD mean-to-target and CD uniformity, are no longer suitable to such 2D pattern due to lacking of the pattern's character descriptions. Therefore the CD performances may not represent the actual wafer printing result in many cases. In addition, non-straight pattern edge induces significant CD measure error which makes it difficult to clarify the real mask pattern making quality.

This paper investigates a pattern contour based solution for 2D structure performance evaluation which can obtain its performance parameters equivalent to the 1D pattern CD. The basic contours of GDS and CD-SEM image are extracted, overlapped and processed by HOLON's techniques. The edge roughness of SEM contour and the bias between the above two kinds of contour are adopted on 2D individual pattern performance's statistics. By utilizing this solution, the 2D pattern quality can be described quantificational as two main aspects, shape and size with the results of edge roughness and bias. Generalize this solution, the 2D pattern's uniformity, mean size, and other performances, which are equivalent to the parameters of 1D pattern, can be evaluated in the similar way as well. This solution calculation bases on pattern contour, therefore the measure pattern is not limited to 1D or 2D patterns, even any shape curve is suitable as well.

9635-70, Session PS4

Improvement accuracy of defect size measurement by automatic defect classification

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The blank mask defect review process involves detailed analysis of defects observed across a substrate's multiple preparation stages, such as cleaning and resist-coating. The detailed knowledge of these defects plays an important role in the eventual yield obtained by using the blank. Defect knowledge predominantly comprises of details such as the number of defects observed, and their accurate sizes. Mask usability assessment at the start of the preparation process, is crudely based on number of defects. Similarly, defect size gives an idea of eventual wafer defect printability. Furthermore, monitoring defect characteristics, specifically size and shape, aids in obtaining process related information such as cleaning or coating process efficiencies.

Blank mask defect review process is largely manual in nature. However, the large number of defects, observed for latest technology nodes with reducing half-pitch sizes; and the associated amount of information, together make the process increasingly inefficient in terms of review time, accuracy and consistency. The usage of additional tools such as CD SEM may be required to further aid the review process resulting in increasing costs.

Calibre® MDPAutoClassify™ provides an automated software alternative, in the form of a powerful analysis tool for fast, accurate, consistent and automatic classification of blank defects. Elaborate post-processing algorithms are applied on defect images generated by inspection machines, to extract and report significant defect information such as defect size, affecting defect printability and mask usability. The algorithm's capabilities are challenged by the variety and complexity of defects encountered, in terms of defect nature, size, shape and composition; and the optical phenomena occurring around the defect.

This paper mainly focuses on the results from the evaluation of Calibre® MDPAutoClassify™ product. The main objective of this evaluation is to assess the capability of accurately estimating the size of the defect from the inspection images automatically. The sensitivity to weak defect signals, filtering out noise to identify the defect signals and locating the defect in the images are key success factors. The performance of the tool is assessed on programmable defect masks and production masks from HVM production flow. Implementation of Calibre® MDPAutoClassify™ is projected to improve the accuracy of defect size as compared to what is reported by inspection machine, which is very critical for production, and the classification of defects will aid in arriving at appropriate dispositions like SEM review, repair and scrap.

9635-79, Session PS4

Best practices for leveling, vibration, particle, and humidity measurements in reticle mask environments

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The importance of particle, leveling, vibration and relative humidity control has rarely been considered in reticle environment. However, the need to maximize both yields and tool uptimes in reticle mask environments requires best-in-class practices.

Whether for diagnostics, qualification or preventative maintenance, equipment engineers need to efficiently and effectively make measurements and adjustments to the tools. Legacy particle, vibration, leveling and RH measurement methods are typically cumbersome, non-representative, not real time, compromise the production environment and are costly with downtime required to take the tool offline for these tasks.

This discussion will review the advantages of using a wireless, real-time, reticle-like device (AMSR/APSRQ) for key measurement applications in reticle mask environments that delivers on three compelling bottom lines – saving time, saving expense and improving yields.

9635-73, Session PS5

Model-based multiple patterning layout decomposition

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As one of the most promising Next Generation Lithography technologies, multiple patterning lithography (MPL) plays an important role in the attempts to keep in pace with 10 nm technology node and beyond. With feature size keeps shrinking, it has become impossible to print dense layouts within one single exposure. As a result, MPL such as double patterning lithography (DPL) and triple patterning lithography (TPL) has been widely adopted. There is a large volume of literature on DPL/TPL layout decomposition, and the current approach is to formulate the problem as a classical graph-coloring problem: Layout features (polygons) are represented by vertices in a graph G and there is an edge between two vertices if and only if the distance between the two corresponding features are less than a minimum distance threshold value dmin. The problem is to color the vertices of G using k colors (k = 2 for DPL, k = 3 for TPL) such that no two vertices connected by an edge are given the same color. This is a rule-based approach, which impose a geometric distance as a minimum constraint to simply decompose polygons within the distance into different masks. It is not desired in practice because this criteria cannot completely capture the behavior of the optics. For example, it lacks of sufficient information such as the optical source characteristics and the effects between the polygons outside the minimum distance. To remedy the deficiency, a model-based layout decomposition approach to make the decomposition criteria base on simulation results was first introduced at SPIE 2013 [1]. However, the algorithm [1] is based on simplified assumption on the optical simulation model and therefore its usage on real layouts is limited. Recently in [2], AMSL also proposed a model-based approach to layout decomposition by iteratively simulating the layout, which requires excessive computational resource and may lead to sub-optimal solutions. The approach in [2] also potentially generates too many stiches. In this paper, we propose a model-based MPL layout decomposition method using a pre-simulated library of frequent layout patterns. Instead of using the graph G in the standard graph-coloring formulation, we build an expanded graph H where each vertex represents a group of adjacent features together with a coloring solution. By utilizing the library and running sophisticated graph algorithms on H, our approach can obtain optimal decomposition results efficiently. Our model-based solution can achieve a practical mask design which significantly improves the lithography quality on the wafer compared to the rule based decomposition.

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9635-74, Session PS5

Experimental verification of SWHL physical concept and mask size optimization methods

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The main challenges of the common projection photolithography are due to the principle of imaging:

- one-to-one correspondence between mask and image elements results in extremely high sensitivity to any local mask defects;

- masks require regular costly inspection and repaire and have severely limited lifetime;

- light diffraction on mask elements is an inherent trouble, requires additional sophisticated solutions such as OPC and SMO.

To overcome the problems, we develop new Sub-Wavelength Holographic Lithography (SWHL), where:

• there is no one-to-one correspondence between mask and image elements thus the effect of local mask defects almost completely eliminated;

• holographic mask may consist of single-tipe elements with typical size many times bigger than projection mask elements;

• technological methods of image quality optimization can be replaced by virtual routines in the process of the holographic mask calculating, that simplifies mask manufacturing and dramatically reduces the mask cost;

• imaging via holographic mask does not need the projection lens, that significantly simplifies photolithographic tool and reduces ones cost.

SWHL is based on computer synthesis of holographic mathematical models of diffraction and interference in Lensless Fourier Transform holographic layout. Essential issue is the method of the mask binarization and manufacturing, providing the desired modulation of reconstructing wave. We develop three classes of mask design:

1) amplitude modulating,

2) amplitude modulating with binary phase-shifting,

3) amplitude and phase modulating.

We explored SWHL physical concept by implementing the experimental set-up with amplitude holographic mask, calculated specially. The main components of the set-up were the mirror collimator, illumination lens, holographic mask and registration system. He-Cd laser with wavelength of 441.6 nm was used as light source. Illuminator generated a converging spherical wave with a numerical aperture of 0.53.

The chromium-on-quartz mask pattern comprised a set of square transparent windows with sizes ranging from 0.75 microns to 14 microns. In holographic mask computer synthesis, virtual HoloPhaseShift [2] was used to provide sub-wavelength image resolution. Aerial image was recorded with a CCD camera via special microscope system.

Moreover, aerial images was used to expose Si-wafers coated with photoresist. Exposed plate was processed by common techniques and inspected by SEM.

So, experimentally generated aerial images were topologically identical to the test pattern. Image resolution (half pitch) of about 0.55 wavelength was achieved at NA = 0,53. Thus SWHL physical concept was experimentally proved.

We also develope a set of measures for the mask size (mask to image size ratio) optimization. Main limiting factors are the effect of zero and higher orders of diffraction, physical limitations on the mask elements sizes and the requirement to use the adequate aperture.

Phase-shifting layer on holographic mask, designed with the developed technique, allows to minimize collateral diffraction orders intensity. The use of renormalization of elements sizes of the mask and implementation of additional obscuring layers in mask design allow to achieve acceptable mask to image size ratio keeping feasible the sizes of the mask topological elements.

9635-19, Session 6

The reparability of various pattern and material for 10nm lithography mask and beyond

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In a photomask manufacturing process, Defect repair technology is an exceedingly important topic for 193 immersion lithography, EUV lithography and Nano-imprint Lithography. The several repair tool based on SEM or FIB system improved repair process for any kind of Material, Defect type etc, there tool supplier reported status of Repair tool Development [1],[2] .

However, for 193 immersion optical lithography requires SMO-ILT, NTD, or more complex patterns and it is more tighter MEEF, therefore the repair accuracy requirement is especially difficult. For EUV Lithography, Tool supplier reported excellent repair tool capability for Absorber and Multilayer defect[1], Now ready for detail verification by EUV-AIMS™ or Scanner exposure. For Nano-imprint Lithography, Mask supplier reported development status of Nano-imprint Lithography mask[3]. Nano-imprint Lithography mask using Cr less mask (Qz/Qz mask) and mask pattern width is especially narrow, it require more high image resolution and repair resolution

This paper focuses on capability, possibility and productivity of repair technology for 193 immersion optical extend like ILT-SMO, NTD or tighter MEEF patterns repair and Nano-imprint Lithography mask defect repair.

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9635-72, Session 6

Quantitative analysis of CD error induced by the fogging effect in e-beam lithography

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As semiconductor technology progresses toward the 10-nm generation and beyond, the requirement of the mask critical dimension (CD) uniformity becomes very stringent. Tracking the sources of CD error and minimizing the error are very important tasks in state-of-the-art mask production. Generally, the mask CD error can be decomposed into location-dependent and pattern-dependent components. Among the sources of pattern-dependent CD error, that caused by the fogging effect(FE) is the dominant factor in mask making process with chemically amplified resist(CAR) and 50 kV e-beam writing tool. In this paper, a quantitative method to analyze the effective range of FE from massive data is presented. According to the calculated effective range, we use two approaches to correct the pattern-dependent CD error that come from e-beam writing. One is the fogging effect correction(FEC), which uses a Gaussian distributed model to describe FE. Second, we implement dosage modulation based on the assumption that the error caused by FE is linearly proportional to the pattern density of a mask. In summary, we are able to successfully predict the map of CD error for various layouts, and correct the error caused by FE in mask-making.

9635-20, Session 7

Imaging enhancement by reduction of mask topography induced phase aberrations for horizontal 1D spaces under D90Y illumination

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EUVL is in the qualification phase as next-generation lithography technique for manufacturing integrated circuits at high volumes. EUV reticles are a key enabler for good quality imaging and need to be considered as active optical elements in the scanner. Reticle challenges need to be addressed and solutions evaluated.

For example, the dark field N-bar structures (trenches), which are common in logic design in advanced technology nodes, are aberration-sensitive and suffer from large relative best focus shifts. This behavior can limit the process window and result in full wafer CDU and intra-field pattern shift being larger than required. Most of these (undesired) properties can be related to the so-called mask 3D effects.

In this paper we present a novel way to achieve EUV imaging enhancement by evaluation of reticle-induced phase aberrations. The approach enables us to discuss improved EUV reticle embodiments and absorber stacks to mitigate the effect.

In case of DUV the imaging-impact of the phases induced by the topography of the mask is understood and applied to improve CDU, as will briefly be discussed. This is the motivation to extend this understanding to EUV and to use this to optimize the imaging. Included in the discussion will be the differences with DUV.

Extensive simulations and physical modeling has been used to understand that as in DUV, for EUV the phase of the diffracted waves is a

key factor in the aerial image formation. When the phases are expressed as aberrations, it will be clear that the 3D-mask induced aberrations are orders of magnitude larger than the phases assigned by other active elements of the scanner and depend strongly on the angles of incidence. Originating from this, large impact on fading and best focus shifts are found for e.g. two-bar structures.

The mask-induced phases are explained by using a double-diffraction model and compared/quantified with simulations. The simulations serve as guide to mitigate adverse phase-effects. The impact of the following strategies will be discussed: (i) Absorber height, (ii) different absorber material, (iii) etched ML, (iv) illumination, and (v) the application of assist features. In general, we find that an optimal absorber stack should exhibit a minimal zeroth order phase, minimal tilt of the linear and a wide curvature of the parabolic aberration contribution. For instance, it will be shown that reducing the thickness will help in improving the two-bar contrast because the fading - caused by different phase-shifts for the different illumination-poles - will be reduced.

9635-21, Session 7

EUV photomask defects: What prints, what doesn't, and what is required for HVM

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As Extreme Ultraviolet (EUV) lithography has matured, numerous imposing technical challenges have been the focus of intense scrutiny, including the EUV radiation source, reflective optics, and fundamental mask fabrication, however there has been a lurking question on the state of mask defectivity that has been unanswerable until the recent relative maturation of entire patterning technology. Without readily available actinic blank or patterned inspection systems, EUV blank and mask manufacturers must continue to rely on relatively low resolution optical systems for blank characterization.

Despite best efforts, detectable blank defects still exist; these can be classified into three types: large defects that can be avoided through pattern-shift, medium defects that can be repaired, and small defects which must be suppressed during manufacture. To successfully intercept high-volume-manufacturing (HVM) for the 7nm node, aggressive continued industry focus is required to ensure that these three defect types are addressed.

Without actinic mask inspection, an unknown element with EUV lithography continues to be the presence of non-detected printable defects – defects that print on wafer despite being undetected during mask or blank fabrication. Another risk is that until recently, focus has been on developing techniques to identify catastrophic defects, while past manufacturing experience tells us that much more subtle defects (<10% CD variation) can have significant impact on yield and performance.

Using information from many characterization sources, including blank inspections, patterned inspection, atomic-force microscopy (AFM), scanning-electron microscopy (SEM), as well as 36nm and 32nm pitch wafer printing results, we will try to address what the real current state of mask defectivity is. We will discuss techniques to answer the key questions of: "What defects prints, what defects do not, and what might our inspections methods be missing?" From this vantage point, we will analyze the current mask defectivity capabilities and sources, and assess the gap in capability to support full HVM support.

9635-22, Session 7

New method of detection and classification of yield-impacting EUV mask defects

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Extreme ultraviolet lithography (EUV) advances printability of small size features for both memory and logic. It promises to bring relief to the semiconductor manufacturing industry, removing the need for multiple masks in rendering a single design layer on wafer. However, EUV also brings new challenges, one of which is of mask defectivity. For this purpose, much of the focus in recent years has been in finding ways to adequately detect, characterize, and reduce defects on both EUV blanks and patterned masks.

In this paper we will present an efficient way to classify and disposition EUV mask defects through a new algorithm developed to classify defects located on EUV photomasks. By processing electron-microscopy images (SEM) of small regions of a photomask, we extract high-dimensional descriptors - Histograms of Oriented Gradients (HOG). Using these HOGs, a supervised classification method is applied which allows differentiating between descriptors of non-defective and defective images. In the new approach we have developed a superior method of detection and classification of defects, using mask and supporting wafer printed data from several metallization masks. We will demonstrate that use of the HOG method allows real-time identification of defects on EUV masks regardless of geometry or construct.

The defects identified by this classifier are further divided into subclasses for mask defect disposition: absorber defects, particle defects, and multilayer defects. The goal of disposition is to categorize on the images into subcategories and provide recommendation of prescriptive actions to avoid impact on the wafer yield.

9635-23, Session 7

Viability of pattern shift for defect-free EUV photomasks at the 7nm node

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Several challenges hinder EUV photomask fabrication and its readiness for high volume manufacturing (HVM). The lack in availability of pristine defect-free blanks as well as the absence of a robust mask repair technique mandates defect mitigation through pattern shift for the production of defect-free photomasks. By using known defect locations on a blank, the mask design can be intentionally shifted to avoid patterning directly over a defect. The work presented here provides a comprehensive look at pattern shift implementation to intersect EUV HVM for the 7 nm node. An empirical error budget to compensate for various measurement errors, based on the latest HVM inspection and write tool capabilities, is first established and then verified post-patterning by SEM. The validated error budget is applied to 20 representative EUV blanks and pattern shift is performed using OPC'd 7 nm node fully functional chip designs that were also recently used to fabricate IBM's working 7 nm node silicon-germanium FinFET chips. Probability of defect-free masks are explored for various 7 nm mask levels, including metal, contact, and gate cut layers. From these results, an assessment is made on the current viability of defect-free EUV masks for the 7 nm node.

9635-24, Session 8

Device fabrication using nanoimprint lithography and challenges for template process technologies *(Invited Paper)*

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Continuous shrinkage of design rule (DR) in semiconductor devices is considered by many people to be stopped in near future. However according to such ITRS roadmap 20131), DR shrinkage is still required increasingly large in DRAM, NAND flash, 3D Memory, ReRAM and SOC devices. In the market of memory device, along with the information explosion, which is symbolized by the BigData, demand of the total amount of memory will be increased exponentially. The cost reduction of memory device should be continued. However, investment costs in pattern shrinking technologies, such as multi-patterning and EUVL become enormous. The framework in these pattern shrinking technologies has not been able to provide lower-cost semiconductor devices.

Therefore, in order to significantly provide the low cost investment in lithography, nanoimprint lithography technology has been developing2). One of the most significant challenges of nanoimprint technology is a nano-defect management (NDM) technology in which defect inspection of templates and also imprinted wafer, and the defect mitigation are implemented. These problems have been overcome through building intensive collaboration with a template, nanoimprint lithography equipment, resist, metrology and inspection equipment and cleaning equipment providers. Nano-imprint specific problem has been predicted and corrected with computational lithography technology development3).

In this paper, status of the nanoimprint lithography application to the semiconductor devices, and progress of nanoimprint related technology will be shown.

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9635-25, Session 8

Nanoimprint system development and status for high-volume semiconductor manufacturing

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Imprint lithography has been shown to be an effective technique for replication of nano-scale features. Jet and Flash Imprint Lithography (J-FIL) involves the field-by-field deposition and exposure of a low viscosity resist deposited by jetting technology onto the substrate. The patterned mask is lowered into the fluid which then quickly flows into the relief patterns in the mask by capillary action. Following this filling step, the resist is crosslinked under UV radiation, and then the mask is removed, leaving a patterned resist on the substrate.

Criteria specific to any lithographic process for the semiconductor industry include overlay, throughput and defectivity. The purpose of this paper is to describe the technology advancements made and introduce the new imprint systems that will be applied for the fabrication of advanced devices such as NAND Flash memory and DRAM.

Overlay of better than 5nm (mean + 3sigma) has been demonstrated, and throughputs of 10 wafers per imprint station are now routinely achieved. Defectivity has been reduced by more than two orders of magnitude and particle adders within the tool have come down by approximately four orders of magnitude. A pilot line tool, the FPA-1100 NZ2, was used to generate most of the results in this work and conceptual plans are in place to address the requirements necessary for high volume manufacturing with an attractive cost of ownership relative to other HVM solutions for the semiconductor industry.

9635-26, Session 8

Nanoimprint lithography template readiness for HVM

Naoya Hayashi, Koji Ichimura, Masaaki Kurihara, Dai Nippon Printing Co., Ltd. (Japan)

Nanoimprint lithography is gathering much attention as one of the most potential candidates for the next generation lithography for semiconductor. This technology needs almost no additional mask data preparation from design, simpler exposure system, and just single patterning process without any coat/develop truck, and has potential of cost effective patterning rather than very complex optical lithography and/or EUV lithography.

Replication of the EB written high quality master templates is proposed for the use of nanoimprint for the semiconductor lithography. Maintaining the quality of the master templates in replication process is very important. Nanoimprint technique is also used for the replication of the templates, and optimization of the nanoimprint process is very important as well as pattern transfer etching process after imprint.

Defect control is one of the concerns of template replication. Careful optimization of the nanoimprint process can reduce the defect density on the replicated templates. Critical dimension uniformity can be improved by improving the imprint uniformity. Overlay is of the interest for the next generation semiconductor lithography. Uncorrectable distortion of the nanoimprint template is needed to be as low as possible. Since the nanoimprint process is a kind of the physical contact process and may produce undesirable substrate distortion. Imprint process need to be carefully considered to reduce such distortions.

In this presentation, our recent improvement of the replicated template quality will be reported from the nanoimprint point of view.

9635-27, Session 8

DUV inspection tool application for beyond optical resolution limit pattern

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As Photo-lithography has been faced theoretical resolution limit, several kinds of next generation lithography (NGL) technology such as EUVL, Nano-imprint lithography (NIL), and Inverse Lithography Technology(ILT) have been developed. EUVL has been a strong candidate, but the EUVL timing for high volume production (HVP) has been delayed several times due to the significant concern of light source power.

Recently, attention for NIL has been increased because of its promising capability for fabricating hp1xnm pattern without using double patterning therefore reduces lithography investment. As NIL template pattern size is the same size of wafer pattern and NIL template needs to be replaced after certain period, NIL template pattern inspection requires 1x pattern inspection capability and high throughput.

On the other hand, mask inspection tool with DUV laser source which has been used for Photo-mask production and EUVL mask development has the resolution limit determined by inspection wavelength and optics NA, therefore the pattern inspection for the minute pattern which hp is smaller than optical resolution has sensitivity constrain. In the case of 19x nm wavelength laser is used for inspection, the resolution limit is about hp5x nm. To improve the resolution, the development of the inspection tool which uses further short wavelength laser source, EUV light source, or EB source is needed, but there are many issues such as poor throughput needed to be solved.

We have tested new optical imaging property using DUV mask inspection tool NPI-7000 developed by NuFlare Technology for minute pattern smaller than hp5x. We confirmed the excellent result for defect detection capability and the expendability of DUV optics inspection tool. Here, basic experimental results for NIL template and EUVL mask pattern are described.

9635-28, Session 8

Optical simulations for fractional fluorine terminated coatings on nanoimprint lithography masks

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Simulations of the optical intensity within Nano Imprint Mask features have been made for patterned quartz masks having ultrathin molecular coatings.# Fractionally F-terminated surfaces were recently proposed for improving the yield of Nano Imprint Lithography (NIL) processes by reducing plug and release defects of sub 10nm size features.[1] Practical chemistries for implementation were also proposed [2] and these concepts will be reviewed by way of introduction to the optical intensity simulations presented here.

The basic structure for the optical intensity simulations is a 5nm feature size with an aspect ratio of 1 in a NIL quartz mask, having a 0.2nm Al_2O_3 surface coating and a fractional fluorine terminated hydrocarbon (FHC) monomolecular layer of 0.6nm thickness. The wavelength for the centered calculation is 200nm. The index of refractions for quartz, Al_2O_3 and FHC are assumed to be 1.73, 3 and 1.3, respectively. Extinction coefficients are assumed to be 0, 0.001 and 0.001 for quartz Al_2O_3 and FHC layers, respectively. The optical parameters are ad-hoc assumed for the ultra thin layers. Interestingly, the optical intensity may be increased within the feature for the Al_2O_3/FHC coating relative to the uncoated quartz mask for a 5nm feature size where the interior spacing is a physical size of 3.6nm. As available, a “Design of Simulations” to explore the range of parameters providing different intensities within the feature will be reported for variances of the optical constants, aspect ratio, feature size and wavelength.

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9635-29, Session 9

Mask process matching using a model-based data preparation solution

Brian Dillon, Christopher J. Progler, Photronics, Inc. (United States); Thiago Figueiro, Mohamed Saib, Paolo Petroni, Patrick Schiavone, Aselta Nanographics (France)

Process matching is the ability to precisely reproduce the signature of a given fabrication process while using a different one. A process signature is typically described as systematic CD variation driven by feature geometry as a function of feature size, local density or distance to neighboring structures. The interest of performing process matching is usually to address differences in the mask fabrication process without altering the signature match of the mask, which is already validated by OPC models and already used in production. Observe that the two processes being matched may be very similar (just a slight change in a given step, such as PEB time or use of extra write tool of the same family) or completely different (a different set of tools, using different fabrication strategies and parameters, installed in different locations around the globe). The need for such process matching typically arises from expansion of production capacity within the same or different mask fabrication facilities, introduction of new, perhaps more advanced equipment to deliver same process of record masks and/or re-alignment of processes which have altered over time. For state of the art logic and memory mask processes, such matching requirements can be well below 2nm and are expected to reduce below 1nm in near future.

Traditionally, matching two different processes is performed by adapting some of the new (source) process characteristics to meet the results from the original (target) process. This is done by adjusting the exposure dose, PEC parameters, etch recipe, equipment parameters, etc. While generally a successful methodology, this can be a very complex exercise requiring many months and high process costs to complete. Here, we demonstrate a process matching technique which attacks the problem from an advanced data preparation side. As a supplement to or even instead of adapting the physical process itself, one applies a calibrated model to modify the data to be exposed by the source process in order to induce the result to match the one obtained while running the target process.

In this paper we present a process matching strategy based on a single differential model focused on 1D metrics. The proposed strategy consists of using the differences between measurements from processes to be matched and then performing the calibration of a single differential model. In this approach, no information other than the metrology results is required from the target process. The scheme in Figure 1 presents the flowchart of this strategy.

The proposed method has been developed and then evaluated using two processes with different resists at Photronics. Figure 2 shows the signature of process 1 (source) and process 2 (target) before matching and the signature of process 1 now matching the results form process 2 for a given pattern. The RMS difference between both processes was of 2.8nm. The standard deviation of such difference was of 2.4nm. After the process matching procedure the average absolute difference between the processes was reduced to 1.0nm with a standard deviation of 1.3nm. The methods used to achieve the result will be described along with implementation considerations, including mask validation, to help assess viability for model driven data solutions to play a role in future, critical mask matching efforts.

9635-30, Session 9

A fully model-based MPC solution including VSB shot dose assignment and shape correction

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The value of using multiple dose levels for individual shots on VSB (Variable Shaped Beam) mask writers has been demonstrated earlier [1] [2]. The main advantage of modulating dose on a per shot basis is the fact that higher dose levels can be used selectively for critical features while other areas of the mask with non-critical feature types can be exposed at lower dose levels. This reduces the amount of backscattering and mask write time penalty compared to a global overdose-undersize approach.

While dose assignment to certain polygons or parts of polygons (VSB shots) can easily be accomplished via DRC rules on layers with limited shape variations like contact or VIA layers, it can be challenging coming up with consistent rules for layers consisting of a very broad range of shapes, generally found on metal layers.

On the other side, when using a model for modulating dose of VSB shots, the objectives have to be clearly defined, even more so, when dose and shape of VSB shots are corrected at the same time. For example, in the simple case of a rectangular sub-resolution assist feature (SRAF), either a dose increase or a shape correction would be sufficient for correcting the mask CD error and from a CD error point of view, both corrections are equivalent. However, from a CD uniformity point of view, the dose increase is the better solution since it reduces the CD variability induced by poor dose edge slope. As a result, a new objective in our algorithm is the optimization of edge slope when modulating VSB shot dose in addition to the original objective of optimizing edge position

In summary, this work reports results using a fully model-based modulation of shot dose for VSB machines supporting between two and eight dose levels. Since dose modulation is combined with model-based shape correction, the small number of dose levels used here proves to be sufficient for increasing contrast of small features while minimizing the impact on write time and backscattering as mentioned above.

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9635-32, Session 9

MPC model validation using reverse analysis method

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It became more challenging to guarantee the overall mask Critical Dimension (CD) quality according to the increase of hot spots and assist features at leading edge devices. Therefore, mask CD correction methodology has been changing from the rule-based (and/or selective) correction to model-based MPC (Mask Process Correction) to compensate for the through-pitch linearity and hot spot CD errors.

In order to improve mask quality, it is required to have accurate MPC model which properly describes current mask fabrication process. There are limits on making and defining accurate MPC model because it is hard to know the actual CD trend such as CD linearity and through-pitch owing to the process dispersion and measurement error. To mitigate such noises, we normally measure several sites of each pattern types and then utilize the mean value of each measurement for MPC modeling. Through those procedures, the noise level of mask data will be reduced but it does not always guarantee improvement of model accuracy, even though measurement burdens are increasing. Root mean square (RMS) values which is usually used for accuracy indicator after modeling actually does not give any information on accuracy of MPC model since it is only related with data noise dispersion.

In this paper, we reversely approached to identify the model accuracy. We create virtual perfect data regarded as actual CD trend and then create scattered data by adding controlled dispersion of denoting the process and measurement error to the perfect data. Then we make MPC model based on the scattered data to examine how much the model is deviated from the actual CD trend, from which model accuracy can be investigated. It is believed that we can come up with appropriate method to define the reliability of MPC model developed for optimized process corrections.

9635-33, Session 9

Accurate mask model implementation in OPC model for 14nm node and beyond

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In a previous work [1] we demonstrated that current OPC model assuming the mask pattern to be analogous to the designed data is no longer valid. Indeed as depicted in figure 1, an extreme case of line-end shortening shows a gap up to 10 nm difference (at mask level). For that reason an accurate mask model, for a 14nm logic gate level has been calibrated. A model with a total RMS of 1.38nm at mask level was obtained. 2D structures such as line-end shortening and corner rounding were well predicted using SEM pictures overlaid with simulated contours. The first part of this paper is dedicated to the implementation of our improved model in current flow. The improved model consists of a mask model capturing mask process and writing and a standard optical and resist model addressing the litho exposure and development at wafer level. The second part will focus on results from the comparison of two models, the improved one and the current one.

9635-34, Session 10

Properties and performance of EUVL pellicle membranes *(Invited Paper)*

Emily E. Gallagher, Johannes Vanpaemel, Ivan Pollentier, Houman Zahedmanesh, Cedric Huyghebaert, Christoph Adelmann, Rik Jonckheere, IMEC (Belgium)

EUV mask protection during handling and exposure remains a challenge for high volume manufacturing using EUV scanners. A thin, transparent membrane can be mounted above the mask pattern so that any particle that falls onto the front of the mask is held out of focus and does not image. The fluoropolymer membranes that are compatible with 193nm lithography absorb too strongly at the 13.5nm EUV exposure wavelength to be considered. Initially, the industry planned to expose EUV masks without any pellicle; however, the time and cost of fabricating and qualifying an EUV mask is simply too high to risk decimating wafer yield each time a particle falls onto the mask pattern. Despite the challenges of identifying a membrane for EUV, the industry has returned to the pellicle concept for protection. EUVL pellicles have been in development for more than a decade and reasonable options exist. The danger is that high volume manufacturing conditions have not yet been tested, so establishing alternative membrane options is an important risk mitigation effort. This paper first reviews the desired membrane properties for EUVL pellicles. Next, candidate materials are introduced based on reported properties and compatibility with fabrication. Finally a set of candidate membranes are fabricated. These membranes are screened using a simplified set of tests to assess their suitability as an EUV pellicle. EUV transmission, film stress, and film durability data are included. The results are presented along with general guidelines for pellicle membrane properties for EUV manufacturing.

9635-35, Session 10

PMJ Best Paper: Pattern inspection of etched multilayer EUV masks

Susumu Iida, EUVL Infrastructure Development Ctr., Inc. (Japan)

No Abstract Available

9635-36, Session 10

Experimental validation of novel mask technology to reduce mask 3D effects

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Miyazaki, ASML Japan Co., Ltd. (Japan); Timon F. Fliervoet, Jan van Schoot, ASML Netherlands B.V. (Netherlands); Jens Timo Neumann, Carl Zeiss SMT GmbH (Germany)

No Abstract Available

9635-78, Session 10

PMJ 2015 Panel Discussion Overview: EUV or 193i: Who wins the center stage for 7nm-node HVM in 2018?

Yoshinori Nagaoka, KLA-Tencor Japan (Japan)

No Abstract Available

9635-37, Session 11

From nightmares to sweet dreams: inspection of aggressive OPC on 14nm reticles (and beyond) using a novel high-NA and low-NA dual method

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To prevent catastrophic failures in wafer manufacturing lines from repeating reticle defects, reticle manufacturers employ sophisticated reticle inspection systems to examine every geometry on every reticle for defects. The predominant inspection systems in use today compare the reticle directly with the design database using high-NA optics (typically 3x higher resolution at the reticle plane than advanced wafer scanners).

High-NA optical inspection with its high SNR can readily detect small defects before they have lithographic impact, thus ensuring reticle quality. However, when inspecting certain aggressive OPC, high-NA inspection can overload on small OPC defects which do not have lithographic impact and thus should generally be ignored.

Whereas, inspecting a reticle as imaged in the wafer plane (low-NA in the reticle plane) will generally ignore such small OPC defects, the SNR is often too low for certain defect types to provide the needed defect detection sensitivity to ensure reticle quality.

This paper discusses the design and performance of a novel reticle inspection method using high-NA and low-NA dual optical imaging and processing. This method offers the high defect sensitivity of high-NA inspection with the OPC tolerance of low-NA inspection. These two imaging methods are blended together into a seamless inspection mode suitable for aggressive OPC of the 14nm generation and beyond. The test reticles include 14nm logic designs containing aggressive OPC and native defects, as well as 14 nm test reticles containing relevant programmed defects. Defect lithographic significance is judged using a Zeiss AIMSTM system.

9635-39, Session 11

Variations in programmed phase defect size and its impact on defect detection signal intensity using at-wavelength inspection system

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The influence of phase defects embedded in Extreme ultraviolet (EUV) mask blanks on wafer printing has always been a center of attention because the phase defects as small as 1.0 nm in height or depth are most likely to be printed on wafer at half-pitch 16 nm lines-and-spaces pattern [1]. To detect printable phase defect on the EUV mask blanks, several inspection techniques that employ EUV light or deep ultraviolet light have been developed [2, 3]. Among these techniques, an at wavelength dark-field inspection technique, also known as an actinic blank inspection (ABI) high-volume manufacturing (HVM) model (Lasertec Corporation), is a prime candidate for the EUV mask blank inspection method for 16 nm technology node [4]. The imaging optics of the ABI HVM consists of a concave and a convex mirror so-called a Schwarzschild optics. The optics has a magnification of 26X with its inner and outer numerical aperture of 0.1 and 0.27.

In this study, to investigate the influence of the variations of the phase defect sizes on the defect detection signal intensities of the ABI HVM we prepared programmed phase defect EUV mask blanks. The defect type was pit and the designed lateral sizes were from 30 to 100 nm with various defect depths. The defect sizes were measured, before and after coating the multilayer, using scanning prove microscope (SPM). The calculated defect volumes on the quartz substrate and the multilayer were varied about 20 and 30 percent, respectively, even if the designed lateral sizes were same. These phase defects were measured their defect detection signal intensities using the ABI HVM. As a result, the defect detection signal intensities were strongly associated with the defect sizes on the quartz substrate. And also, the ABI HVM can predict the small variations of the defect volumes.

This work was supported by New Energy and Industrial Technology Development Organization (NEDO) and Ministry of Economy, Trade and Industry (METI).

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9635-40, Session 11

EUV actinic brightfield mask microscopy for predicting defect aerial images

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Mask defects remain one of the most important challenges holding back the wide-scale adoption of extreme ultraviolet (EUV) lithography. Preventing, finding, assessing, mitigating and repairing defects, now and at future technology nodes, are dominant research activities that could determine the ultimate success or failure of the technology. Despite years of work on EUV photomasks and defects, scant published data exists showing detailed, high-resolution comparisons between actinic mask imaging and defect printing in photoresist. In this work, we show numerous, side-by-side, mask and wafer images extracted from studies that were originally designed to generate stastics on the relative capture rates of different mask and wafer inspection and imaging technologies. [1]

Our research with the SHARP EUV mask-imaging microscope at Lawrence Berkeley National Laboratory shows that actinic (EUV-wavelength) mask images of defects are highly predictive of the fine features and details observed in wafer prints, including both strong, bridging defects and subtle, non-bridging defects. Many of the defects selected for this study were first identified on the mask blanks using Lasertec M1350 and Siemens DFX40 tools. Many defects on the patterned mask were further analyzed by a KLA Tencor 6xx and a Reticle SEM. The masks were exposed on ASML NXE3100/3300 tools. Wafer

SEM review was performed with a KLA Tencor EDR-7100 on bright-field repeater defects detected with a KLA Tencor 2835, and blank defect locations detected before patterning. Investigation of the SHARP images through focus reveals some "amplitude defects" and others that show the signature of a phase-shifting nature.

Probing masks with the operational wavelength provides the highest possible accuracy and relevance for mask research, due to the substantially different physical mechanisms involved in non-actinic inspections. Actinic bright field mask imaging is now used in nearly every aspect of EUV mask research and development. Research microscopes have been operational and collecting data for a number of years, and new commercial microscopes are now being commissioned. Tools like SHARP, which can emulate printing conditions, including wavelength and the angular spectrum of the illumination, are used to study mask materials and architecture, pattern and aerial image properties, pattern and surface roughness, illumination dependence, and perhaps most importantly, defects.

We believe that the accurate, high-resolution information and relatively rapid feedback gained from actinic bright-field imaging could improve the success mask-repair workflows, or provide quantitative feedback for improvement. Furthermore, because actinic microscopes can be run with forward-looking optical specifications, defect mitigation and repair strategies for future nodes could be investigated years ahead of the availability of commercial printing tools.

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9635-65, Session 11

Study of various pattern impact for registration and overlay

Shingo Yoshikawa, Nobuaki Fujii, Takashi Yamada, Issei Sakai, Katsuya Hayano, Hidemichi Imai, Hiroyuki Miyashita, Dai Nippon Printing Co., Ltd. (Japan); Takashi Sayano, Carl Zeiss Co., Ltd. (Japan); Sven Heisig, Dirk Beyer, Carl Zeiss SMT GmbH (Germany)

Optical lithography stays with 193nm illumination wavelength for a foreseeable future until it is complemented by other technologies e.g EUV lithography. The 1Xnm technology node lithography is using multiple patterning or even more complex technologies that meet the required tighter overlay specifications. State-of-the-art metrology tools do support the qualification of on-device patterns using In-die measurement schemes. However, as of today, Mask registration and overlay, on the other hand, Pedominantly using conventional patterns (Crosses, Boxes etc.) are rather space-consuming due to their size (>1µm). Those patterns cannot be placed densely enough to reflect placement errors that occur in real device patterns. Moreover, the validation of in-die mask registration at wafer level needs specific in-die strategies as well.

In this paper, we will determine the impact of conventional patterns in comparison to on-device patterns at mask-level registration using in-die mask registration metrology. For verification we will compare the results of both registration measurement methods by wafer prints. Finally, we will evaluate the feasibility of on-device pattern measurements for registration and overlay on wafer-level.

9635-41, Session 12

Sensitivity analysis for high-accuracy proximity effect correction

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The requirements of accuracy on proximity effect correction (PEC) in electron beam (e-beam) lithography, both in the mask and direct writing, are getting higher and becoming critical as the semiconductor technology node is shrinking down towards sub-14nm. The needs of a more precise and robust point spread function (PSF) and its determination within the minute fluctuation of process or exposure conditions are rising. The PSF is able to obtain through simulation, which commonly is done by Monte Carlo method, or can be determined using complementary approach, which is defined by a certain fitting algorithm using the results of a test exposure. Having a stable process, it is considered that the PSF extracted from the latter has a higher precision than that from the fore. However, the complementary method consumes more time and resources to figure out the PSF and it is not clear the correlations between the test exposure, especially the applied test pattern sets, processes and each parameters of characterized PSF.

A sensitivity analysis algorithm was developed and tested to comprehend the influences of different test pattern sets on the calibration of PSF model with complementary approach. The selected algorithm was the variance-based sensitivity analysis which allows attributing the variance of output of a model to the sum of variance of each input of the model and their correlated factors. The objective of this development is heightening the fineness of determined PSF model in the complementary technique through the optimization of test pattern sets.

Inscale® from Aselta Nanographics is used to prep the data and to check the consequences of development. Fraunhofer IPMS-CNT exposed the prepared data using a variable shape beam Vistec SB3050DW exposure tool and observed it with an Applied Materials Verity 4i CD-SEM and SEMVision G3 review SEM. To visualize the link of sensitivities between the PSF parameters and the test pattern, various pattern sets were corrected with each varied parameters from the PSF of process of record (PoR).The results suggest that certain test pattern has unique sensitivity to specific PSF parameter and this should be considered in the PSF extraction with complementary technique.

This paper reveals how much the different sets of test pattern are sensitive for the determination of PSF, particularly to each parameter in the PSF, in the complementary method. These findings followed by the development of sensitivity analysis algorithm to enhance the precision of PSF through the optimizations of test patterns. Furthermore, the suggested sensitivity analysis will be able to assess which parameter in the PSF might be influential and critical for the correction of real application pattern in e-beam lithography.

9635-42, Session 12

Photomask etch process for 10nm technology node and beyond

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While the industry is making progress to offer EUV lithography schemes to attain ultimate critical dimensions down to 20 nm half pitch, an interim optical lithography solution to address an immediate need for resolution is offered by various integration schemes using advanced PSM (Phase Shift Mask) materials including thin e-beam resist and hard mask. Using

the 193nm wavelength to produce 10nm or 7nm patterns requires a range of optimization techniques, including immersion and multiple patterning, which place a heavy demand on photomask technologies. Mask schemes with hard mask certainly help attain better selectivity and hence better resolution but pose integration challenges and defectivity issues. This paper presents a new photomask etch solution for attenuated phase shift masks that offers high selectivity (Cr:Resist > 1.5), tighter control on the CD uniformity with a 3sigma value approaching 1 nm and controllable CD bias (5-20 nm) with excellent CD linearity performance (<5 nm) down to the finer resolution. The new system has successfully demonstrated capability to meet the 10 nm node photomask CD requirements without the use of more complicated hard mask phase shift blanks. Examples of CD uniformity, linearity, minimum feature size, and etch bias performance on 10 nm test site and production mask designs will be shown.

9635-43, Session 12

High-durability phase-shift film with variable transmittance

Osamu Nozawa, Hiroaki Shishido, Takenori Kajiwara, HOYA Corporation (Japan)

In order to maintain the lithographic margin and to have sufficient image resolution, attenuated phase shift masks are widely used as a resolution enhancement technique. To improve the radiation durability of the phase shift film, we have developed a new approach eliminating the molybdenum from the phase shift film and introduced a Silicon-Nitride (Si-N) based attenuated phase shift film. In this presentation, the properties of Si-N based phase shift films with various transmittances will be reported

9635-44, Session 12

Evaluation of multilayer defect repair viability and protection techniques for EUV masks

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Mask defectivity is one of the major concerns for EUV masks. In the mask fabrication process, total mask defects represent a combination of intrinsic blank defects, and defects introduced during the mask patterning process. Intrinsic blank defects are particularly challenging because their elimination is outside of conventional repair methodologies. Past repair methodologies have utilized nanomachining of the multilayer mirror as a potential solution [1]. Without actinic inspection, and because these phase defects are buried below the multilayer surface, the optimal nature of the repair is not obvious. Previous work shows viability of both compensational absorber-only repairs, as well as multilayer nanomachining.

Nanomachining repairs involve excavating the multilayer to mitigate any coherent disruptions which come from intrinsic blank defects. However, this creates a concern by exposing the sidewall of the multilayer, which may experience structural and reflectivity degradation through mask cleaning lifetime and wafer exposure [2].

In order to prevent the degradation of these multilayer repairs, we introduce a methodology which protects the repaired sites by means of surface treatment with oxidation or material deposition with minimal impact to Bragg reflectivity. Simulations will be compared to on-wafer lithographic results of repairs both with and without surface treatment. Wafer results will be used to help to establish optimal repair techniques; cross-sectional TEM view will characterize the lithographic structural impact between pre- and post-process repair in order to evaluate the feasibility of nanomachining and protection for mitigating degradation mechanisms.

[1] Lawliss, M., et al., “Repairing native defects on EUV mask blanks”, Proc. SPIE 9235, 923516 (2014).

[2] Turley, C., et al., “EUV mask black border evolution”, Proc. SPIE 9235, 923513 (2014).

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Relationship between mask surface wettability and cleaning effectiveness

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As semiconductor manufacturing advances to 10-nm generation and beyond, the requirement on shrinking the size of killing defects gets more and more stringent. In this paper, we report our findings on the relationship between surface wettability on photomasks and cleaning effectiveness. Surface wettability is determined by measuring the contact angle between a water droplet and the mask surface, and cleaning effectiveness is determined by quantifying the added soft defects after the cleaning process. Wettability of common films on the mask decrease in the following order: SiO_2 > MoSi > Cr > Ta-based absorber > Ru, and an opposite trend in added soft defect counts was observed after the cleaning process. To reduce the added soft defect counts, different methods are adopted to enhance the surface wettability of these films. For example, the method combining ultraviolet light (?< 300 nm) and ozone water enhances wettability on SiO_2 and MoSi efficiently. However, Cr requires a relatively long time to become hydrophilic using the UV light and ozone water treatment. Ozone water rinse and oxygen plasma are two alternative approaches that can enhance surface wettability of the Cr surface efficiently and can reduce about 90 % of added soft defects. However, the former causes Cr film loss because of the formation of a soluble compound. In contrast, the latter passivates the Cr surface and minimizes the film loss. For EUV mask cleaning, above-mentioned methods can enhance the surface wettability of Ru and Ta-based absorber and therefore reduce added soft defects, but they may also cause Ru oxidation and damage. A unique plasma treatment to enhance surface wettability on EUV mask that minimizes Ru damage will be discussed in the paper. In conclusion, wettability can serve as an important index for cleaning capability on different materials.

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