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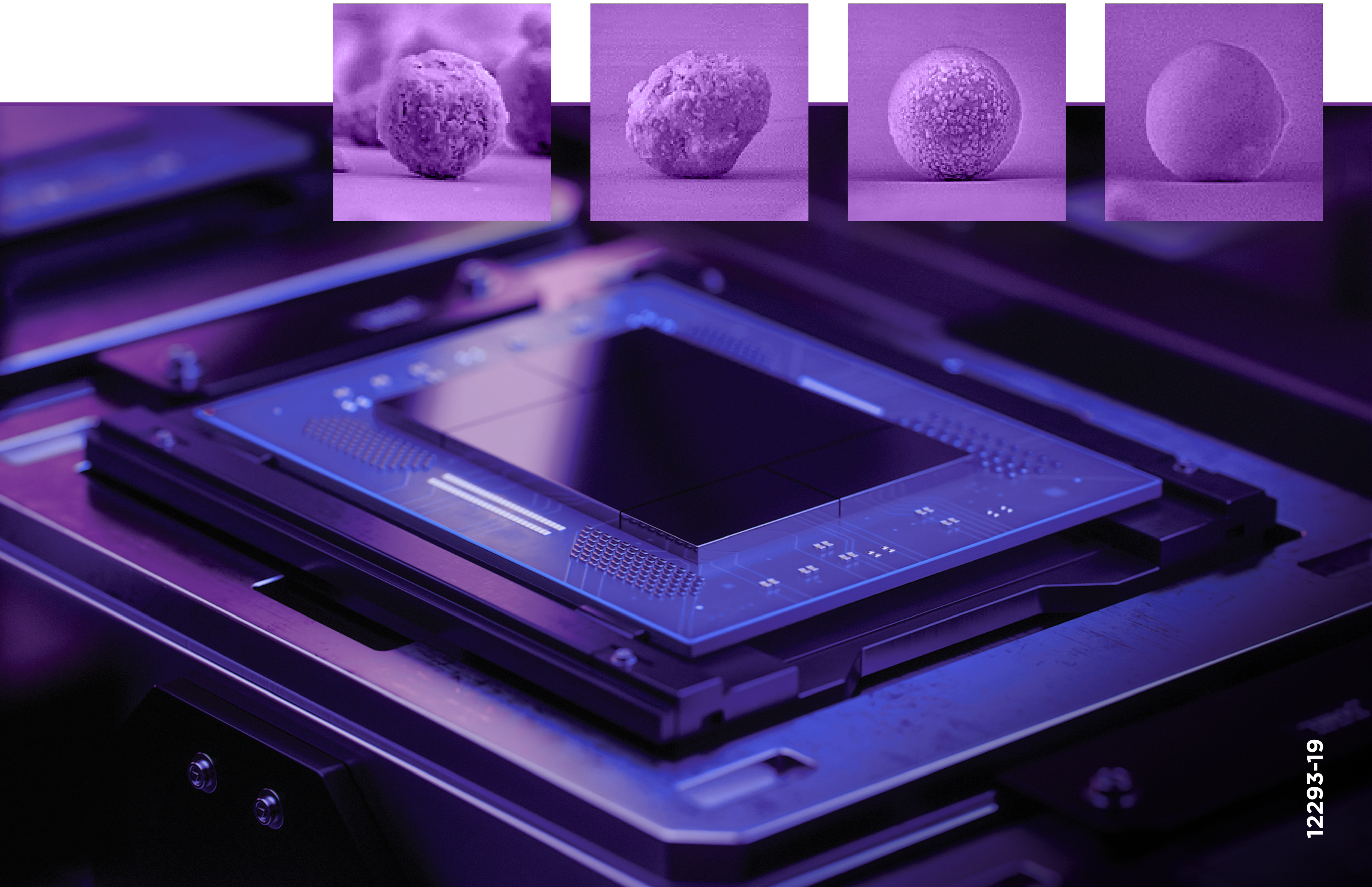
PHOTOMASK TECHNOLOGY GROUP

A Whole New World for Photomasks



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EDITORIAL

A whole new world for photomasks

Kent H. Nakagawa, Toppan Photomasks Round Rock, Inc.

It was the beginning of 2019, and I had just been installed as BACUS Secretary. I barely had time to get familiar with the role when I was due to give my first BACUS newsletter editorial. After the initial panic attack, I decided to write about a topic that I would spend the next four years addressing: "What is the Modern BACUS." That thought came to mind as I felt a paradigm shift was starting to take place in the semiconductor market that would have a direct ripple effect on the photomask market. I couldn't describe it at the time, but I still felt that a profound change was coming.

Fast forward to now. A chip boom created by a pandemic that disrupted business as we knew it. A chip shortage, particularly on the mature products, as new devices in photonics, automotive electrification, sensors, power control, and medical applications compete for limited capacity from the unglamorous "legacy" manufacturing fabs.

These new products have fueled a growth in photomask unit demand in a segment that is different than what I think anyone had ever forecast — sustainable growth in the mature photomask market. And as with the chip manufacturing sector, there has been fixed capacity in the photomask manufacturing sector due to the perception of "stagnant unit growth" and annual diminishing ROI in that space.

Market forecasts now consistently point to not only revenue growth in the leading-edge photomask market, but also revenue and unit growth in the mature photomask market, as a result of these new semiconductor markets and their growth potential. At the same time, the retirement of obsolete, unsupported mask tools which are still required for the "conventional" markets has created the need and opportunity to rebuild and sustain the mask tooling market, a critical component to the sustainability of the entire semiconductor ecosystem.

At the upcoming SPIE Photomask + EUVL Conference (Oct 2023), we will be having a special session on Mature Mask Technology and Market. Six speakers from mask manufacturing and tooling will speak about the changing market and the technological challenges and opportunities to meet this new photomask demand.

The "new world" that I refer to in my title is a mask industry that is no longer "just about leading-edge devices." It is an industry with a broadening and growing portfolio of device technologies. It's still a very interesting and rewarding time to be a mask maker, and I continue to look forward to the evolution that is sure to continue.

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Managing Editor/Graphics
Ty Binschus, *SPIE*

Exhibition and Sponsorship Coordinator:
Melissa Valum, *SPIE Sales Representative, Exhibitions and Sponsorships*

BACUS Technical Group Manager
Tim Lamkins, *SPIE*

SPIE.
P.O. Box 10, Bellingham, WA 98227-0010 USA
Tel: +1 360 676 3290
SPIE.org
help@spie.org

FEATURED ARTICLE

Removal behavior of Sn and Pb contaminants on EUV mask after EUV exposure

Dong-Hyeon Kwon, *Department of Materials Science and Chemical Engineering, Hanyang University, Republic of Korea;* **Hyun-Gyu Kang,** *Department of Materials Science and Chemical Engineering, Hanyang University, Republic of Korea;* **Tae-Gon Kim,** *Department of Smart Convergence Engineering, Hanyang University, Republic of Korea;* **Jin-Ho Ahn,** *Division of Materials Science and Engineering, Hanyang University, Republic of Korea;* **Sang-Sul Lee,** *Pohang Accelerator Laboratory, Pohang University of Science and Technology, Republic of Korea;* **Jin-Goo Park,** *Department of Materials Science and Chemical Engineering, Hanyang University, Republic of Korea*

Abstract

Tin (Sn) and Lead (Pb) particles released from the EUV scanner can contaminate the EUV mask causing serious yield and throughput problems. These contaminants can worsen during EUV exposure and become difficult to remove, leading to damaging the EUV mask in the process. To effectively remove contaminants without substrate damage, it is necessary to understand the removal behavior of the contaminants. In this study, the removal behavior of Sn and Pb particles was studied by simulating the EUV exposure heated by rapid thermal annealing. The removal forces between the thermally aged Sn and Pb particles and EUV substrate surfaces were quantitatively measured using atomic force microscopy (AFM). With the thermal aging time, the contact area of the deformed particle increases which requires a high removal force. After particle removal, the footprint of the contaminants was investigated to understand the surface quality of where the particles sat under the various exposure conditions. This study helps to better understand the adhesion mechanism and removal behavior of thermally deformed Sn and Pb particles on different EUV substrates.

Introduction

One of the major issues in the EUV scanner is that the flow of hydrogen plasmas may carry defect particles directed from optics toward the reticle contaminating the EUV mask and causing serious yield and throughput problems[1]. The adhesion between nano and microparticles with the substrate under vacuum conditions is dominated by the Van der Waals force which is proportional to the particle radius[2]. With the advancement of the EUV patterning technology, the use of EUV source power above 400 W causes the contaminants to adhere more strongly on various surfaces which are difficult to clean and damage the EUV mask surfaces[3].

Fig. 1 illustrates the deformed particle on the EUV mask under exposure to EUV light. The metallic contaminants with low melting points are difficult to remove from the surface due to thermal aging which results in the deformation of the contaminants during EUV exposure[4,5]. Therefore, we focused on the removal behavior of Sn and Pb contaminants observed on the EUV mask and analyzed the adhesion mechanism.

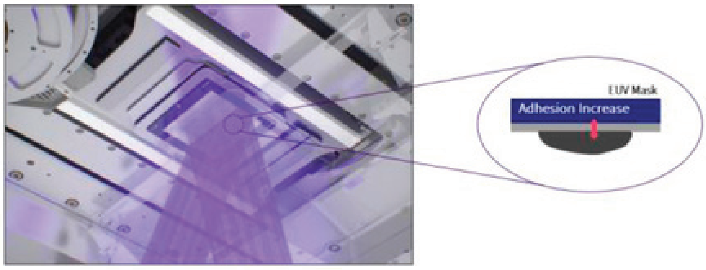


Figure 1. *Schematic for particle contamination on EUV mask after EUV exposure*

A quantitative method for measuring the particle removal force by using an AFM cantilever has been reported and the calibration of the torsional spring constant, the lateral sensitivity, and the force conversion factor of the AFM cantilever have been carefully characterized[6,7]. In another study, the effect of thermal aging on particle cleaning efficiency was reported earlier[8-10]. However, studies have not yet been reported on the footprint of thermally aged particles. The residue after the removal of contaminants is hard to detect by measurement tools such as SEM and AFM due to their small size. In this paper, reveals the quantitative removal force of Sn and Pb particles above Ru and TaN EUV mask substrates under various exposure conditions and introduced a reliable method to investigate the footprint after particle removal which helps to understand the adhesion mechanism.

Experimental procedure

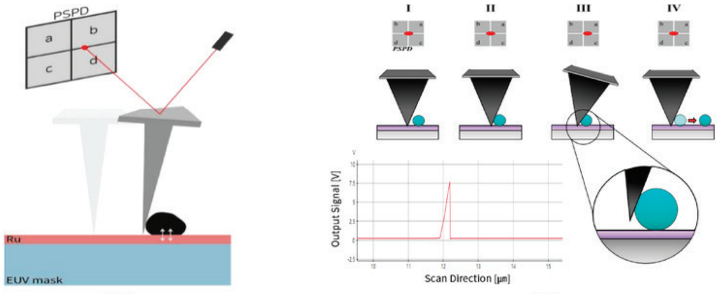
Sample preparation and footprint measurement

The Sn and Pb particles were deposited on Si, TaN, and Ru wafers. The thickness of TaN and Ru are 60 and 3 nm, respectively. The particles of Sn and Pb were purchased from the company Sigma-Aldrich with purities of 99.9 %.

To mimic the situation of particle contamination during the EUV exposure, Sn and Pb particles with diameter between 5 to 10 μm were thermally aged at temperatures of 200, 300, and 400°C. The contaminated samples were heated on rapid thermal annealing (RTA) under a vacuum pressure of 10-5 Torr for 5, 10, and 30 minutes[11-13]. The contaminated samples were then imaged by Field Emission Scanning Electron Microscopy (FE-SEM, S4700, Hitachi) before and after the thermal aging process to investigate their deformation[11-13].

Quantitative analysis of removal force

The removal forces of thermally aged Sn and Pb particles were quantitatively measured by using AFM (NX-20, Parks Systems, Korea) and to collect deflection signals of bending and twisting of the cantilever by the signal access module. To measure the particle removal force, a silicon AFM probe with a spring constant of 2 N/m (240AC-NA, Mikromasch) was used. Before the measurement, the normal spring constants of cantilevers were calibrated by Sader's method and the torsional spring constant was calculated by numerical mechanical calculation[14,15]. To convert the lateral signal to the lateral force which is the removal force, the angle conversion and force conversion factors were achieved by the lateral force calibration method based on the angle conversion factor[6,7]. Fig. 2 shows the schematic representation showing the evaluation of particle removal force particle by AFM probe.



(a) (b)

Figure 2. ***(a)*** *Schematic illustration of the removal force analysis by AFM cantilever and* ***(b)*** *schematic diagram of probe motion and corresponding signal gains*

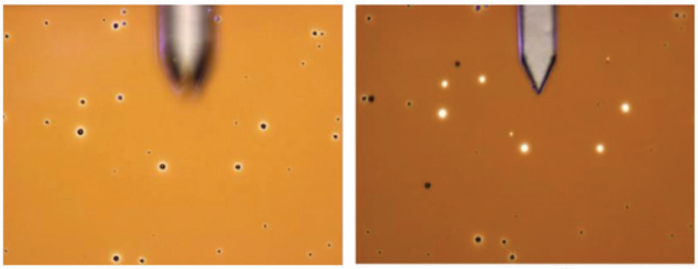
AFM tip was scanned at a tip velocity of 0.1 μm/s during the measurement of removal force, and it provides a precise record of signal changes. Figure 2b shows that when the AFM tip starts to push the particle, the probe twist until the particle is removed. Once the particle is removed from the surface or location, then the AFM tip comes back to its normal position. The bending of the AFM tip and lateral deflection signals from the position-sensitive photo detector (PSPD) were recorded instantaneously (Fig. 2a). The removal force was calculated from the AFM signal by using Eqn. 1.

$$F_t = \frac{k_t}{H} \cdot \eta \cdot V_{Signal} = \kappa \cdot V_{Signal}$$

were *K* is the force conversion factor, V_{Signal} is the deflection of lateral signal from the PSPD where the AFM tip was twisted while pushing the particle and released back to its place, η is the angle conversion factor, k_t is the torsional spring constant, and H is the distance between the AFM tip where it pushes the particle and the center of the cantilever.

Footprint investigation by Pt coating

After the removal of particles by AFM probe, the footprint of Sn and Pb was hard to locate due to the nano-sized residues on the surface which are difficult to identify by using SEM or AFM. To locate the exact position of the residues after the particle removal, the contaminated surface was coated by Pt sputtering before the removal by AFM (Fig. 3a). The Pt sputtering was performed for 180 seconds (40 nm thickness) to obtain a uniform coating over the surface. After the removal of particles, the spots where particles were located lit up brightly and it was easy to find the spots where the particles were as shown in Fig. 3b. Then, the AFM topographic images were taken at the spots. The remaining residues of Pb and Sn particles were investigated from the AFM topographic images (Fig. 4).



(a) (b)

Figure 3. *Footprint investigation by platinum sputtered coating. The images of,* ***(a)*** *Pt sputter coated surface with contaminants particles and* ***(b)*** *the surface after removal of particles*

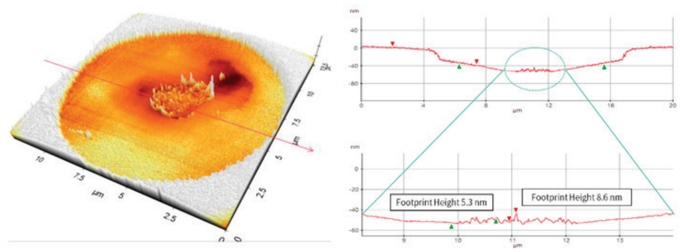


Figure 4. AFM topography image and line analyses of the contaminant footprints

Results and discussion

Quantitative analysis of removal force for Pb and Sn contaminants

Fig. 5 shows the removal force of the Pb and Sn particles from Si, Ru, and TaN substrates aged at 300 to 400°Cfor 5, 10, 30 mins. Due to the strong adhesion of Sn on the Ru treated at 300°C for 30 min, most particles remain on the surfaces and the removal force was hard to obtain. In most cases, thermal aging increases the force required to remove the contaminants. However, the removal force for Sn from TaN remains low irrespective of the aging period and treatment temperature. On the other hand, Pb particles on TaN exhibits high removal force indicating that the Pb adheres to TaN strongly but not as high as Sn on Ru. The strong interaction of Sn on Ru surfaces as reported in the literature makes the removal of Sn contaminants difficult from the Ru substrate[16].

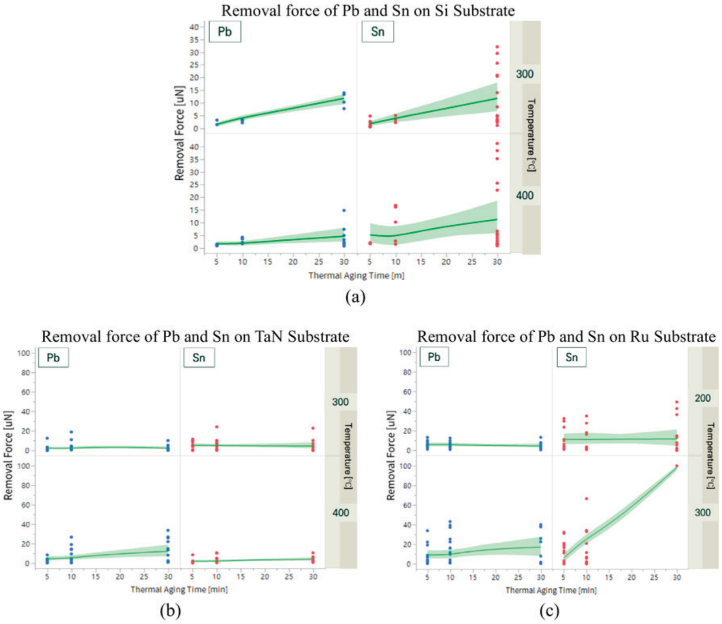


***Figure 5.** Removal force of Pb and Sn contaminants above **(a)** Si, **(b)** TaN, **(c)** Ru substrates at various temperatures and heat treatment periods*

Contact images of Pb and Sn particles

Fig. 6 shows that the contact area of Pb and Sn particles change over the Si, TaN, and Ru surfaces under various thermal aging treatments. This indicates that the particle deformation due to heat treatment increases the contact area between the contaminant and the substrate, especially for Sn over the Ru surface. The large contact area makes the removal of particles difficult and thus it showed a significantly high removal force (Fig. 5).

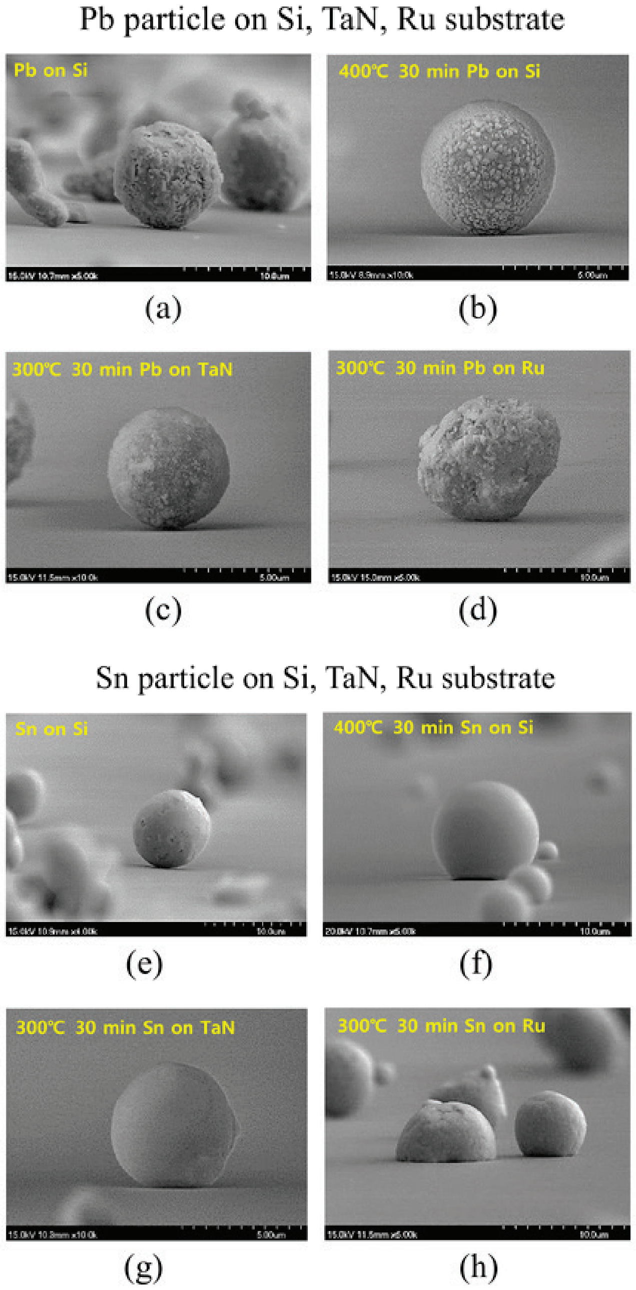


***Figure 6.** SEM images of thermally treated contaminants on various substrates. Pb particles on substrate **(a)** Si at 25°C for 30 min, **(b)** Si at 400 °C for 30 min, **(c)** TaN at 300 °C for 30 min, **(d)** Ru at 300 °C for 30 min, and Sn particles on substrate **(e)** Si at 25°C for 30 min, **(f)** Si at 400 °C for 30 min, **(g)** TaN at 300 °C for 30 min, **(h)** Ru at 300 °C for 30 min*

AFM topography images of Sn and Pb footprints

The AFM topography images show the residues after the removal of thermally treated Pb and Sn particles on Si substrates as shown in Fig. 7. No footprints were observed after the removal of Pb particles from the Si substrate, thermally treated at 400°C for 30 min (Fig. 7b). However, specific footprints were observed after the removal of Sn particles from the Si substrate, thermally treated at 400°C for 30 min (Fig. 7d). The flat surfaces around the spikes confirm that particles contacted above the substrate and the spikes observed in the AFM images are the footprints of the particles. The spikes of 3-10 nm height observed near the center of the AFM images indicate the residues on the substrate.

Fig. 8 shows the footprints of thermally treated Pb and Sn particles on TaN and Ru substrates, thermally treated at 300°C for 30 min. The small amount of footprint was observed after the removal of Pb and Sn particles from the TaN substrate, thermally treated at 300°C for 30 min (Fig. 8 a, b). On the other hand, the large amount of footprint was observed after the removal of Pb and Sn particles from the Ru substrate, thermally treated at 300°C for 30 min (Fig. 8 c, d). Especially, the footprints of Sn particles are significant on the Ru substrate where the 5 ~ 10 nm footprints spreads over a large area (Fig. 8d)

Conclusion

In this study, the removal forces were quantitatively measured by AFM to explore the removal behavior of thermally aged Sn and Pb particles from Si, TaN, Ru EUV mask substrates. Furthermore, the topography of sub-10 nm size footprints after particle removal were investigated by AFM. The extension of this methodology for the evaluation of removal behavior and footprint mechanism is currently in progress to meet the future EUV mask. These future results will give a clear understanding of Sn and Pb particles removal behavior in real EUV scanners.

Acknowledgments

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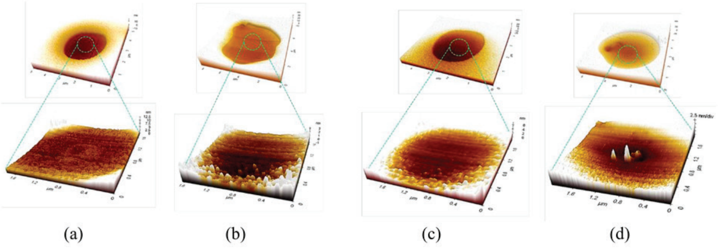

Figure 7. *AFM topography images of the footprint of Pb particle on Si substrate at* ***(a)*** *25 °C and* ***(b)*** *400 °C for 30 min, and Sn particle on Si at* ***(c)*** *25 °C and* ***(d)*** *400 °C for 30 min*

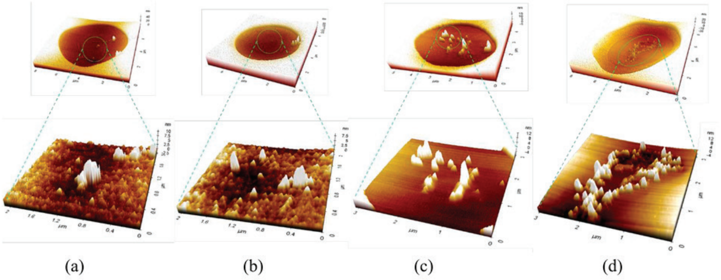

Figure 8. *AFM topography images of the footprint of Pb and Sn particles on TaN substrate at* ***(a)****,* ***(b)*** *300 °C for 30 min, and Pb and Sn particles on Ru substrate* ***(c)****,* ***(d)*** *300 °C for 30 min*

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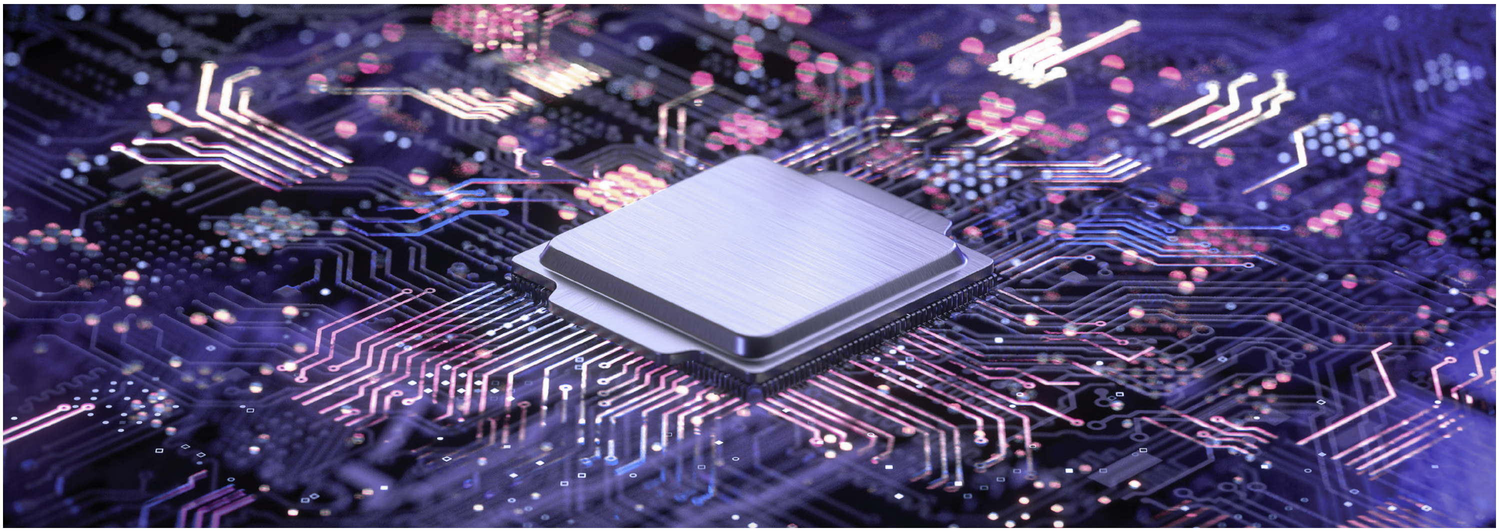

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INDUSTRY BRIEFS

Chiplet planning kicks into high gear

The chip industry recognizes that the slowing of Moore's Law and fixed reticle sizes require changes in chip design, manufacturing, and packaging. While the concept of combining multiple chips in a package has been around for some time, chiplet and heterogeneous integration (HI) is kicking into high gear thanks to the promise of enabling Moore's law but still face many challenges.

semiengineering.com/chiplet-planning-kicks-into-high-gear/

Nvidia briefly joins $1 trillion valuation club

Nvidia briefly joined the $1 trillion market value club, propelled by its success in the AI sector and the surge of interest in generative AI. The stock's value has tripled in less than eight months, outperforming its peers in the S&P 500 index. Analysts view Nvidia as a crucial company in the rapidly changing AI era, with room for growth as the adoption of its AI chips and generative AI technology is still in the early stages.

reuters.com/technology/nvidia-sets-eye-1-trillion-market-value-2023-05-30/

IBM wants to build a 100,000-qubit quantum computer

IBM plans to build a quantum computer with 100,000 qubits within the next 10 years, partnering with universities in a $100 million initiative. The goal is to achieve quantum-centric supercomputing, where quantum computers work alongside classical supercomputers to solve complex problems. Despite the current limitations, the company aims to overcome these challenges through technological advancements, academic collaborations, and the development of quantum computational scientists and software.

technologyreview.com/2023/05/25/1073606/ibm-wants-to-build-a-100000-qubit-quantum-computer/

China bans Micron chips in key infrastructure over ‘national security’ risks

China has banned the sale of certain Micron products due to cybersecurity risks, following an investigation launched in April. The move is believed to be part of the ongoing economic competition between the US and China, which is impacting the global tech supply chain. The Cyberspace Administration of China cited serious cybersecurity concerns and risks to the country's key information supply chains as the reason for the ban, affecting Micron's operations in China.

techcrunch.com/2023/05/21/china-bans-micron/

France to provide 2.9 bln euros in aid for new STMicro/GlobalFoundries factory.

France will provide 2.9 billion euros in state aid to support STMicroelectronics and GlobalFoundries in building a semiconductor factory in Crolles, southeastern France. The investment is part of France's larger 5.5 billion euro package for the microchip sector by 2030. The move aligns with efforts by the United States and the European Union to reduce reliance on Asian suppliers and boost domestic chip production.

reuters.com/markets/europe/france-provide-29-bln-euros-aid-new-stmicroglobalfoundries-factory-2023-06-05/

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About the BACUS Group

Founded in 1980 by a group of chrome blank users wanting a single voice to interact with suppliers, BACUS has grown to become the largest and most widely known forum for the exchange of technical information of interest to photomask and reticle makers. BACUS joined SPIE in January of 1991 to expand the exchange of information with mask makers around the world.

The group sponsors an informative monthly meeting and newsletter, BACUS News. The BACUS annual Photomask Technology Symposium covers photomask technology, photomask processes, lithography, materials and resists, phase shift masks, inspection and repair, metrology, and quality and manufacturing management.

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Key Dates

2023

SPIE Photomask Technology + EUV Lithography
1–5 October 2023
Monterey, California, USA
spie.org/puv

2024

SPIE Advanced Lithography + Patterning
25–29 February 2024
San Jose, California, USA
spie.org/al

Photomask Japan
16–18 April 2024
Yokohama Japan
smartconf.jp

You are invited to submit events of interest for this calendar. Please send to tyb@spie.org.

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