

Photomask Repair Technology by using Gas Field Ion Source

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ABSTRACT

Recently, most of defects on high-end masks are repaired with electron beam (EB). The minimum repairable dimension of the current state-of-the-art repair systems is about 20-30 nm, but that dimension is not small enough to repair the next generation masks. Meanwhile, new molybdenum silicide (MoSi) films with high cleaning durability are going to be provided for an alternative technology, but the etching selectivity between new MoSi and quartz under EB repair process is not high enough to control etching depth. We developed the focused ion beam (FIB) technology that uses light ions emitted from a gas field ion source (GFIS). In this study, the performance of our developed GFIS mask repair system was investigated by using new MoSi (HOYA-A6L2). Specifically, the minimum repairable dimension, image resolution, imaging damage, etching material selectivity and through-focus behavior on AIMS were evaluated. The minimum repairable dimension was only 11 nm that is nearly half of that with EB. That result suggests that GFIS technology is a promising candidate for repairing the next generation masks. Meanwhile, the etching selectivity between A6L2 and quartz was 6:1. Additionally, the other evaluations on AIMS showed good results. Those results demonstrate that GFIS technology is a reliable solution of repairing new MoSi masks with high cleaning durability.

1. Introduction

1.1 Background

The photomask repair technology has been evolved to achieve more precise process with the shrinkage of design rules. Recently, most of defects on high-end masks are repaired with EB. In regard to the next generation masks, it was reported that EB repaired defects on EUV masks.^{1,2} However, since EUV masks will be applied to hp15

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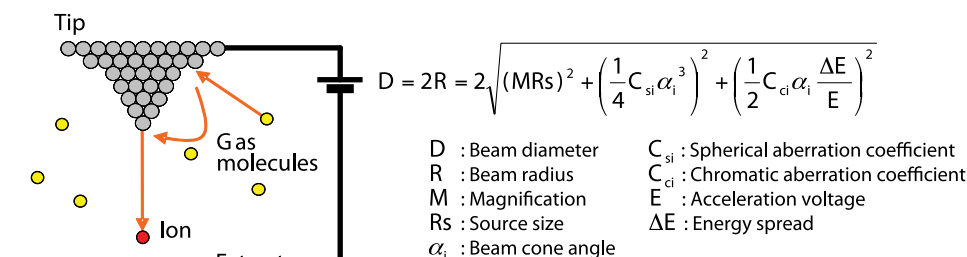


Figure 1. Structure of GFIS.

TAKE A LOOK INSIDE:

INDUSTRY BRIEFS
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CALENDAR
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EDITORIAL

We're Still Here . . .

Michael D. Archuletta, RAVE LLC

We're still here and (when you think about it) stronger than ever. And by "we," I mean the worldwide society of Photomask makers and Photomask equipment suppliers. And by "stronger than ever" I mean those us still standing after the last ten years. We've shown the strength and tenacity to be a real force in our industry, especially when we come together. But in recent years, we seem to have lost our way as a community.

In the past thirty years, the count of global mask shops has dropped from over 150 to less than 50. Only about 30 of those can be considered "advanced" technology mask shops. There have been numerous drop-outs, buy-outs, consolidations and mergers, leaving an ever dwindling number of mask companies. I suppose all this can be considered normal for a maturing industry, especially where technology is everything and competitiveness requires an investment that sometimes outweighs the reward. But the fact remains; there are fewer companies in the game with more casualties expected. So we should consider these circumstances as some of contributors to the diminishing sense of communal enthusiasm in our industry.

When you review the conference statistics over the last decade, you'd think the Photomask Industry was inexorably fading out of existence. For example, Figure 1. shows the attendance records from 2002 through 2012 at two of the world's premier advanced lithography symposia. The decline in attendance is obvious and dramatic. Furthermore, technical submissions to these conferences decreased in equal proportion. Presentations at BACUS in 2007 numbered almost 200 papers and posters. By 2012 presentations dropped to less than 100.

We've heard plenty of excuses for these trends. Fewer papers and attendees at conferences could reflect an increase in the overall number of events; or a serious decline in budgets available to participate in events; or a greater need to protect the IP and secrecy



Figure 1.



Figure 2.

of competitive research; or a worsening opinion of the value of the events; or simply a pervasive lack of interest by the members at large; or some combination of all the above.

Of course, downturns, consolidations, increased R&D and equipment costs, unit volume reductions, margin losses and budget cuts are not helping. But the fact remains, our best technology information exchange events are losing traction and could end-up being cancelled altogether.

This downward trend also extends to the vendor companies who supply equipment to the Photomask Industry. Figure 2. illustrates the diminishing number of equipment vendors exhibiting over the same ten year time frame. The average number of exhibitors at BACUS has dropped from over 50 in the early 2000's to less than half that in the last few years. During this time, there has been a moderate decline in the number of equipment companies who serve the Photomask Industry, but nowhere near enough to explain the significant loss of exhibitor participation.

Have the vendors stopped attending because the audience is shrinking? Or is the audience shrinking because the vendors have stopped going? It's a downward spiraling cycle. One could theorize that because the number of mask companies has decreased so dramatically, the equipment vendors have decided it's a waste of time and money to advertise in a small market where everybody already knows everybody.

But I have a message for the equipment vendors. Some companies have always found it hard to calculate a suitable return on investment for the cost of displaying their wares at trade expositions, large or small. They've never understood that being there on display is not about instant sales gratification. It's about presence, corporate dominance, the real-time communication of your most important messages, a show of community commitment and the long-term perception members hold about your organization. These subjective accomplishments create a community mindset that can often be a deciding factor in the

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BACUS N • E • W • S

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Table 1. Specifications of our developed GFIS system.

Acceleration voltage	15 - 30 keV
Probe current	0.1 - 1.0 pA
Field of view	1 - 300 μm
Sample interface	SMIF
Defect recognition	Automatic

and beyond, the pattern sizes on masks will be narrower than 60 nm. The minimum reaction area of the current state-of-the-art EB repair systems is usually about 20–30 nm. From the viewpoints of the pattern sizes and the reaction area, it is difficult for EB to repair EUV masks beyond hp15. Thus a new repair technology is expected. Meanwhile, a microscope of helium ion (He^+) beam from GFIS is well known.^{3,4} He^+ FIB is theoretically estimated to have much smaller reaction area than EB. We also developed GFIS system and repaired opaque defect on EUV masks with hydrogen ions (H^+),⁵ but had not evaluated its minimum repairable dimension yet.

On the other hand, high-end masks are very expensive, but its lifetime is not so long due to reduction of MoSi film thickness by cleaning processes. Blanks manufactures developed new MoSi films to improve cleaning durability. One of those films is “HOYA-A6L2”. Those blanks have not been introduced to actual mask production yet, because the etching selectivity between new MoSi and quartz under EB repair process is not high enough to control etching depth.

1.2 Objective of this study

This study has two objects. One is to evaluate the minimum repairable dimension of GFIS technology. The other is to verify the feasibility of GFIS technology for repairing new MoSi masks with high cleaning durability. In the concrete, we evaluated the minimum repairable dimension, image resolution, imaging damage, etching material selectivity and through-focus behavior on AIMS.

2. Theory and Materials

2.1 Overview of GFIS

Fig.1 shows a typical structure of GFIS. GFIS emits ions through field ionization process at the apex of the sharpened needle which is refrigerated to very low temperature between 40 and 60 degrees Kelvin. The beam diameter of focused ion beam is generally expressed by the following equation. Since ions of GFIS are generated in a field of a few atoms, the source size (R_s) of GFIS is much smaller than that of liquid metal ion source (LMIS). Since gas molecules are ionized in an electric field of particular intensity, the energy spread (ΔE) of GFIS is much smaller than that of LMIS. Thus the beam diameter (D) of GFIS is much smaller than that of LMIS.

2.2 Our developed GFIS repair system

We developed the new mask repair system by using GFIS. Fig.2 shows the appearance of that system. The GFIS of that system can emit a few species of light ions. The design of



Figure 2. Appearance of our developed GFIS system.

the other functions except the GFIS is greatly modified from our conventional FIB systems. The main specifications are shown in Table 1.

3. Results

3.1 Image resolution

We observed holes with optical proximity correction (OPC) on an A6L2 mask by using our developed system. Fig.3 shows a scanning ion microscopy (SIM) image of secondary electrons generated by GFIS beam. The beam conditions were 25 kV acceleration voltage (ACC), 0.1 pA probe current (Ip) and 1.5 μm field of view (FOV). A 4-nm-intrusive feature was recognized at the edge of a hole.

3.2 Minimum repairable dimension

We cut a narrow groove into A6L2 film with 1-line scan. Fig.4 shows a SEM image that was observed in the direction A. The etched sidewall of that groove is perpendicular on that image. The graph is the intensity profile of secondary electron generated at the side of that film. The width of that groove is 11.2 nm on that graph.

3.3 Imaging damage

We observed holes on an A6L2 mask once, 5 times, 10 times and 20 times with usual imaging conditions that are 15/25 kV ACC, 0.1 pA Ip and 5 μm FOV. After cleaning, those holes were measured with AIMS. The critical dimension (CD) of those holes is 60 nm (wafer dimension). CD change by imaging is defined as the difference between CD at the scan area and CD at non-scan area on AIMS. Fig.5 shows the correlation between number of imaging times and CD change. The CD change by 20-time imaging with 25 kV ACC was less than 1.5%.

3.4 Etching rate and material selectivity

We etched 6 areas on A6L2 film with 25 kV and various FIB doses, and then measured those etching depth with AFM. Fig.6 shows the correlation between FIB doses and etching depths. The etching rate of A6L2 is 0.0762 nm^3/ion . The etching rate of quartz is 0.0124 nm^3/ion . Thus the etching

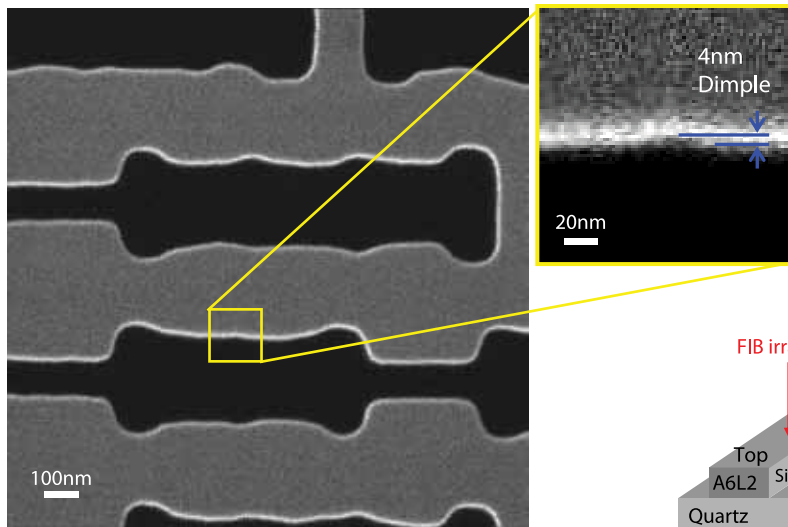


Figure 3. SIM image of A6L2 mask (ACC=25kV, $I_p=0.10\text{pA}$).

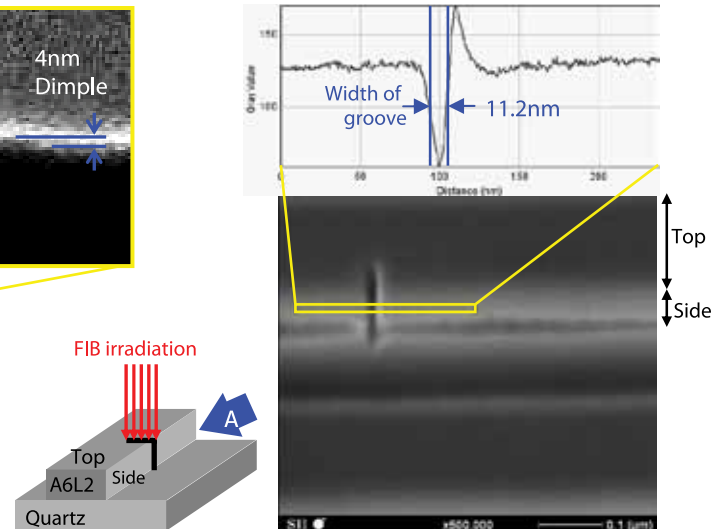


Figure 4. SEM image and secondary electrons intensity profile of a groove etched with 1-line FIB irradiation on A6L2 film.

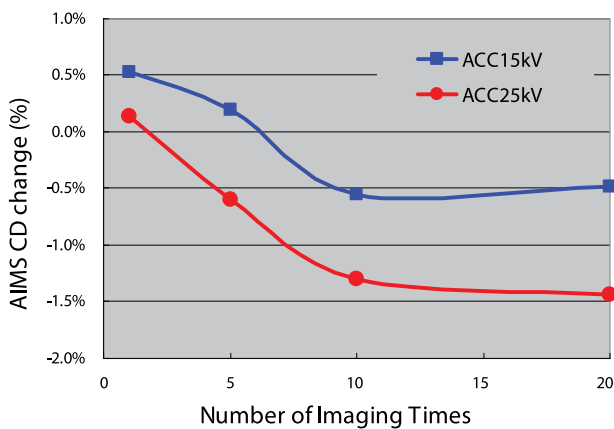


Figure 5. Correlation between number of imaging times and AIMS CD change of holes on A6L2 (Imaging damage).

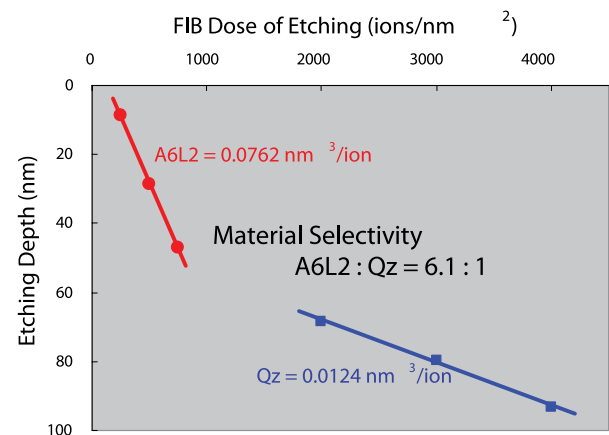


Figure 6. Correlation between FIB doses and etching depths (Etching material selectivity between A6L2 and quartz).

selectivity between A6L2 and quartz is 6.1:1.

3.5 Repair shape on SIM and AFM images

We repaired an extrusion defect and a missing one of holes on an A6L2 mask. The CD of those holes is 60nm (wafer dimension). Fig.7 shows SIM images of those holes before and after repairs. Fig.8 shows AFM images of those holes before and after repair. As shown by Fig.14 and 15, there is no significant difference between the repaired holes and original ones.

3.6 CD controllability and cleaning impact

Our system can bias repair edge positions to expand or shrink an actual repair area from the area where is recognized as a defect. We repaired 3 missing defects of 60-nm-CD holes on an A6L2 mask with various biases. Those holes were measured with AIMS before and after clean. CD error on AIMS is defined as the difference between CD of the repaired hole and CD of an original one. Fig.8 shows the correlation between bias and CD error. A straight line

is fitted to the data after clean. That line shows that CD error is strongly correlated with bias. The standard deviation (3sigma) of the difference between that fit line and the actual data is about 0.1 nm (wafer dimension, 0.4 nm on mask). Meanwhile, each CD change by clean was less than 3 nm that is 5% of the CD.

3.7 Etching depth and through-focus behavior on AIMS

We repaired 4 missing defects of 60-nm-CD holes on an A6L2 mask with various FIB doses, and then measured those etching depth with AFM. Those depths were -16, -14, -5 and +7 nm. Furthermore, we measured those CD with various focus on AIMS. Fig.10 shows the correlation between focus of AIMS and AIMS CD error. CD fluctuation by focus change is defined as the difference between CD with under-focus and CD with over-focus on AIMS. Fig.11 shows the correlation between etching depth and CD fluctuation by focus change. A straight line is fitted to those data. CD fluctuation is strongly correlated with etching depth. That line passes through the origin of the coordinates.

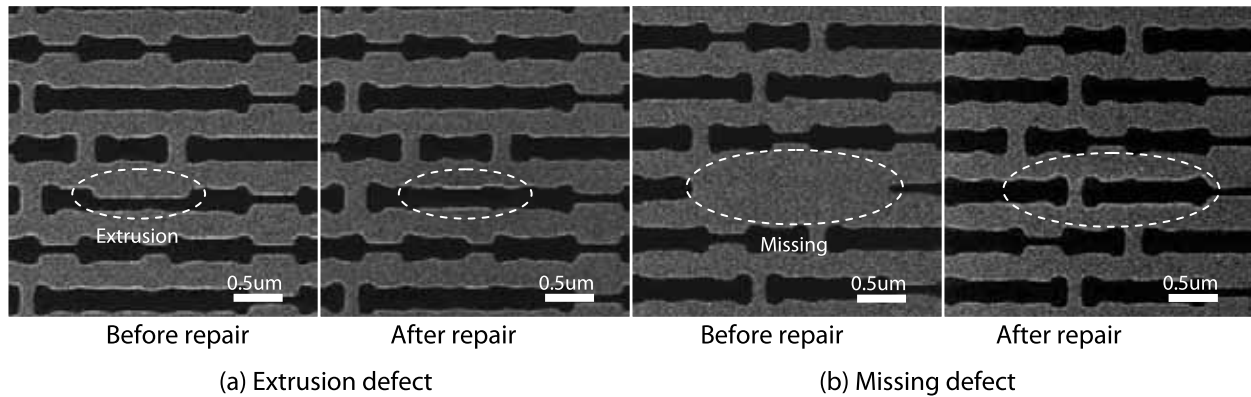


Figure 7. SIM Images of holes on A6L2 mask before and after repair.

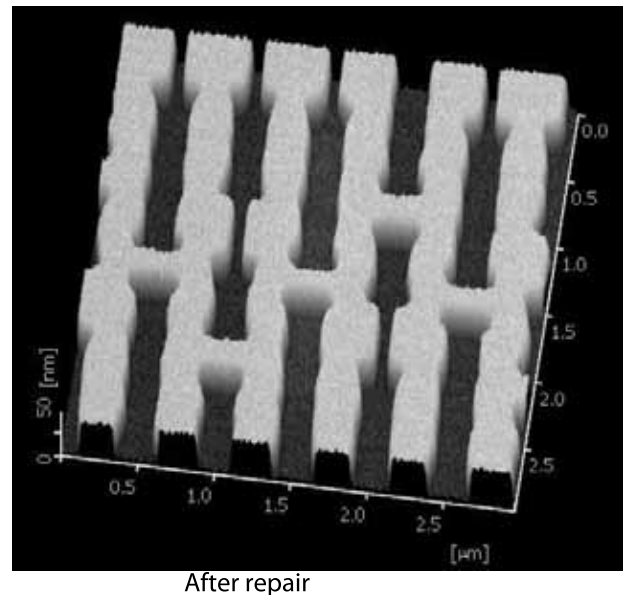
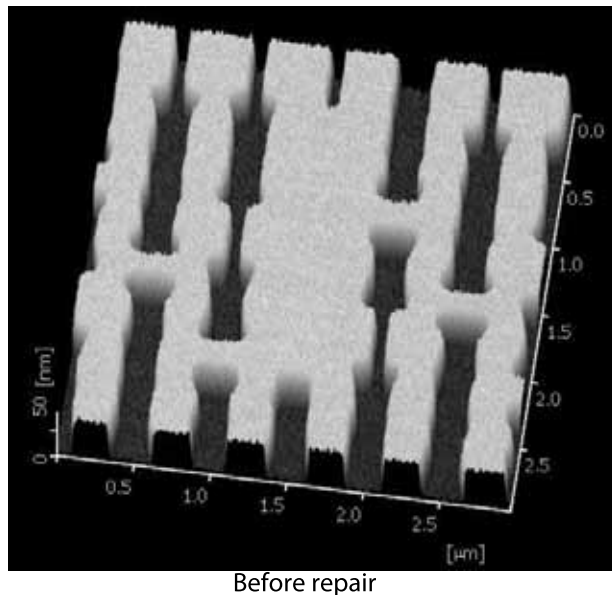


Figure 8. AFM Images of holes on A6L2 mask before and after repair.

4. Conclusions

We developed the new FIB mask repair system with GFIS and evaluated its performance. The main results obtained are listed on the next page. The most important result is that the minimum etching dimension was only 11 nm that is nearly half of that with the current state-of-the-art systems. That result suggests that GFIS technology is a promising candidate for repairing the next generation masks. The second important result is that the etching material selectivity between A6L2 and quartz was 6:1. Basically, it's difficult for EB systems to realize such high selectivity. Additionally, GFIS technology demonstrated good results on AIMS evaluations. Those results demonstrate that GFIS technology is a reliable solution of repairing A6L2 masks.

- The minimum etching dimension was 11 nm.
- SIM image has enough resolution to recognize 4-nm feature.
- AIMS CD change of A6L2 by 20-time imaging was 1.5%. (A repair requires 2 or 3-time imaging.)

- The etching material selectivity between A6L2 and Qz is 6:1.
- AIMS CD can be controlled in the order of nanometers.
- AIMS CD change by cleaning was less than 5% of the CD.
- Through focus behavior of AIMS CD was strongly correlated with etching depth.

5. Acknowledgments

This work was supported by Department of the New Energy and Industrial Technology Development Organization (NEDO).

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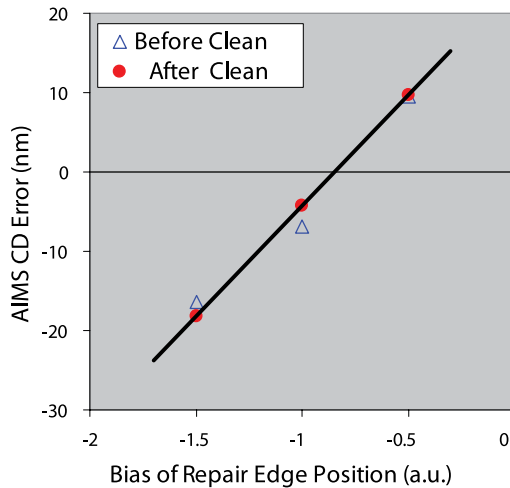


Figure 9. Correlation between bias of repair edge position and AIMS CD error.

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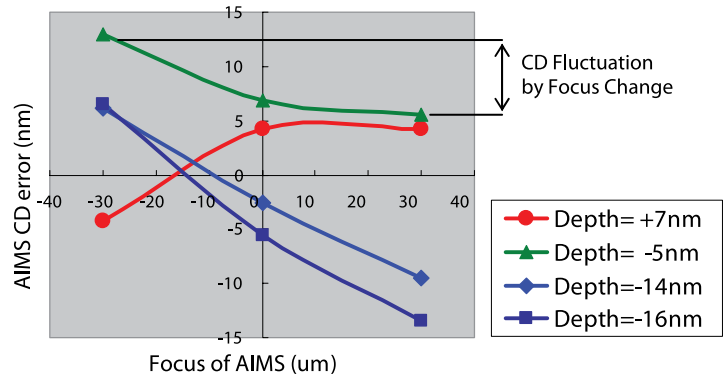


Figure 10. Correlation between focus of AIMS and AIMS CD error.

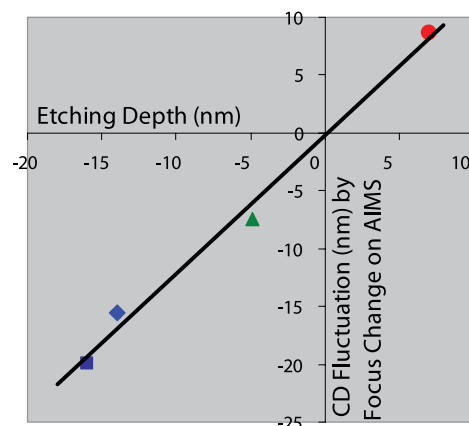


Figure 11. Correlation between etching depth and CD fluctuation by focus change on AIMS.

EDITORIAL (continued from page 2)

long-term equipment selling process. Whether you like it or not, the industry's opinion of you matters and it can never be measured in near-term dollars.

We are grateful that some equipment vendors have continued to sponsor our symposiums. But, if sponsorships begin to drop at the rate of the exhibitor participation, we will definitely lose some of our more important conferences. None of this will bode well for our industry as we move into an ever uncertain future.

Mask makers have suffered right along with the device manufacturers through all the same downturns and escalating technology demands. But, the chip makers still expect us to provide advanced mask technology at their fever pace and oh, by the way, always several years in advance of their new device introduction deadlines. Meanwhile, mask R&D costs have sky-rocketed and the price of advanced mask equipment has soared. It's a wonder we've been able to keep up and mask making is not getting any easier.

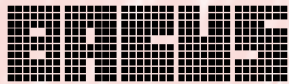
How has the Photomask community done it and how will we manage to keep doing it? We must do what we've always done. We share the load. We share ideas. We share information. We share research endeavors, successes and failures. We collaborate on materials and standards. We work together!

Where do we do all this? Technical conferences! And more than ever, we need to recognize the extraordinary value these venues bring to our communal industry. Yeah, yeah I know, what about trade secrets and IP, blah, blah, blah. No single mask shop, even the biggest captive, has ever been able to solve all the mask manufacturing problems we've

had to overcome. No matter how big the company, no one has ever done it alone. More than one mask maker has fallen behind because they thought they knew it all or could invent everything themselves. Eventually you find out the rest of the industry has passed you by while you were cloistered behind your own ego. Not everything needs to be a secret. You have to give a little to get a lot. There is always more to be gained by taking advantage of shared research. As an industry, we've got to find more ways to do it.

So, what do I mean when I say "We're still here and . . . stronger than ever"? We should never forget, the Photomask Industry remains the literal backbone of the Semiconductor Industry. There is no mass production of micro chips without advanced mask sets. We keep this industry moving forward, sometimes by sheer force of will. Consider this editorial a warning and a "call to arms." As a community of mask suppliers and equipment vendors we are going to be expected to lead the Semiconductor Industry into the next ten years. We must revitalize our commitment to each other and support for our information venues if we hope to be successful. History shows we are a stronger force and achieve more when we work together.

You marketing directors, start planning that sponsorship and maybe even an exhibitor booth this year. You science guys, start lobbying your managers to share the incredible developments you're achieving; send in those abstracts. All you members, start downloading those fantastic technical programs and find a budget to get yourself to the SPIE Photomask (BACUS) conference this year! Can't wait to see you there!



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Industry Briefs

■ Progress in EUV Lithography Reported in SPIE Advanced Lithography Conference

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New results indicating 40 watts of EUV light in continuous operation using MOPA Prepulse technology—a key achievement in EUV lithography—was reported by David Brandt, Cymer's Senior Director of EUV Marketing. "In addition to the good news of EUV source power achievements, there were first signs of considerations for EUV adoption in high volume, coming from infrastructure development such as EUV mask actinic inspection, EUV mask OPC, and EUV lithography integration in a full CMOS flow with yield-defectivity investigations," said symposium co-chair Mircea Dusa (ASML US). A new solution for free standing pellicles for EUV masks, considered to be important progress for improving defectivity of EUV masks during their use in exposure tools, was presented by ASML's Luigi Scaccabarozzi.

■ GLOBALFOUNDRIES to Build R&D Facility Including EUV Masks in New York

Business Wire

GLOBALFOUNDRIES announced plans to build a new global R&D facility at its Fab 8 campus in Saratoga County, New York. The new Technology Development Center (TDC) is expected to play a key role in the company's strategy to develop innovative semiconductor solutions allowing customers to compete at the leading edge technology. The TDC will house a variety of semiconductor development and manufacturing spaces to support the transition to new technology nodes, as well as the development of innovative capabilities to deliver value to customers beyond the traditional approach of shrinking transistors. The overarching goal of the TDC is to provide a collaborative space for GLOBALFOUNDRIES to develop end-to-end solutions covering the full spectrum of silicon technology, from new interconnect and packaging technologies that enable three-dimensional (3D) stacking of chips to leading-edge photomasks for EUV lithography and everything in between. "The new TDC will help us bridge between the lab and the fab by taking research conducted with partners and further developing the technologies to make them ready for volume manufacturing" said GLOBALFOUNDRIES CEO Ajit Manocha.

■ DNP and Luminescent Technologies Achieve Milestone in Development of Metrology and Inspection Program

Solid State Technology

Luminescent Technologies Inc., a provider of computational metrology and inspection solutions for the global semiconductor manufacturing industry, and Dai Nippon Printing Company, Ltd. announced today the successful completion of the first phase of a three-year joint development program for computational metrology and inspection using Luminescent's Automated Image Processing Hub (LAIPH) platform. The goals of the collaboration are to dramatically reduce photomask defect review and analysis cycle time while simultaneously improving overall mask quality. The first phase resulted in the successful implementation of LAIPH Aerial Image Analyzer (AIA) software in DNP's Kami-Fukuoka photomask production plant. Aerial Image Analyzer (AIA) is one of the applications on Luminescent's LAIPH platform to address the growing challenges of inspection in advanced mask shops and wafer fabs. The LAIPH platform provides precise quantitative analysis of defect images captured by Carl Zeiss SMT's Aerial Image Measurement System (AIMSTM) and Applied Materials AeraTM series mask inspection systems.

Join the premier professional organization for mask makers and mask users!

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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