

# PHOTOMASK

BACUS—The international technical group of SPIE dedicated to the advancement of photomask technology.

PUV20

## High-end EUV photomask repairs for 5nm technology and beyond

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### ABSTRACT

Scaling trends in the semiconductor industry towards smaller technology nodes and feature sizes are continuing and first consumer products manufactured with the help of EUV technology are already on the market. Major industrial players have introduced EUV lithography into their production at the 7nm technology node and with the 5nm node being on its way<sup>[1]</sup>, the amount of EUV lithographic layers is expected to rise significantly and implementation of EUV double patterning is anticipated.

These developments lead to more strict technological requirements especially for the corresponding EUV but also for the used high-end DUV photomasks in terms of minimum feature sizes and acceptable Edge Placement Errors (EPE). Moreover, photomask defectivity increases dramatically with shrinking feature sizes. This creates significant challenges to the industry, as in particular the most cost intensive EUV photomasks possess the highest numbers of defects.

The current industry standard for high-end photomask repair tools is the MeRiT® neXT<sup>[2]</sup>. To face the upcoming challenges an efficient and reliable way to repair future high-end photomasks is inevitable. A corresponding repair tool must address decreased minimum feature sizes and increased pattern complexity on high-end photomasks.

In this paper we present our latest results of high-end EUV repairs carried out on the next generation photomask repair tool MeRiT® LE. The tool shows improved system dynamics, makes use of a new electron beam column, which operates at a low electron beam voltage down to 400V and enables the repair of next generation ultra-small defects.

### 1. Introduction

EUV high volume manufacturing is becoming more and more important and major industrial players of the semiconductor industry have introduced EUV technology to their production for memory as well as for logic

#### Mask making process

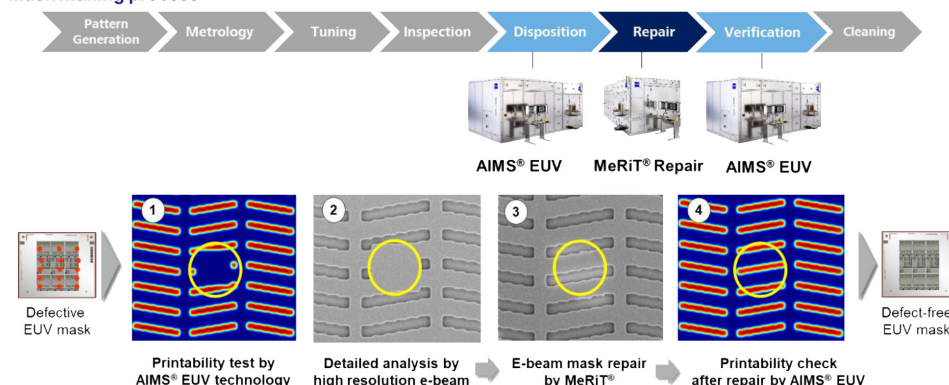


Figure 1. Overview of the measurement setup and fit to mask shop ecosystem.

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SPIE.

# EDITORIAL

## Onwards and upwards

**Michael Watt**, Shin-Etsu MicroSi Inc.

I never thought I would say "I miss traveling." I remember sitting in Schiphol airport in Amsterdam checking my phone in early 2020, when the news came in that the US had stopped travel from Europe to non-US citizens into the country. I sat up and looked around at everyone looking at their laptops and phones with worried looks on their faces. Little did we all know what was to come.

As everyone tries to navigate their way back to a life that they remember, there will be many changes to be negotiated. More especially in the semiconductor industry or as I call it, life's roller coaster – one minute you are enjoying the ride and the next hanging on for dear life!

One of the slightly unexpected repercussions of the pandemic was for car makers being forced to shut down plants last year and well into this year. Automobiles have become increasingly dependent on chips from computer management of engines to better fuel economy, driver assistance, and safety.

These supply chain problems began in the early days of the pandemic, when lockdowns around the world in Asia, Europe, then the US started to close manufacturing plants. Many automotive companies sensing a slowdown in demand scaled back their demand for chips allowing the ever-growing consumer electronics industry to swoop in and fill the void. There was a surge of demand for laptops and all kinds of electronic devices to allow working from home and to keep yourself and your family occupied.

The supply chain is being thoroughly tested and is creaking. Raw material shortages are starting to play a part and can be seen in all industries including housing. With chip shortages, rumors about buyouts, new fabs being promised in the US, and new fabs coming to life in Europe, we are back on the roller coaster.

Going back to my first point about missing traveling, it's the getting there that is the toughest part. The face-to-face time and interactions with customers and friends are a huge part of who we all are, and I certainly miss that. We have all been virtual for over a year, and it is hard to put into words how important face-to-face time is – going to meetings, conferences, and building relationships that are all key to how we do business.

In the last year it seems as though the large jigsaw puzzle that we have been putting together for years has been scattered. Now we are trying to put it all back together bit by bit. Hopefully there are not many pieces missing, hiding under the couch to be found another year later.



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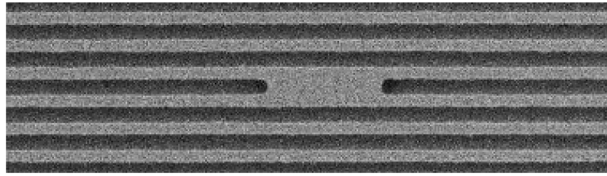


Figure 2a. SEM Pre-Repair image of bridge type defect with 60nm half-pitch on mask.

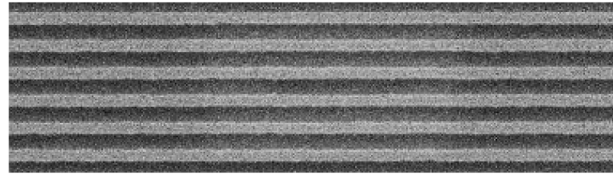


Figure 2b. SEM Post-Repair image of bridge type defect with 60nm half-pitch on mask.

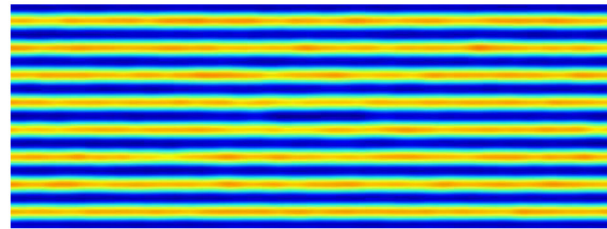


Figure 2c. Post-repair aerial image by AIMS® EUV of bridge type defect with 60nm half-pitch on mask.

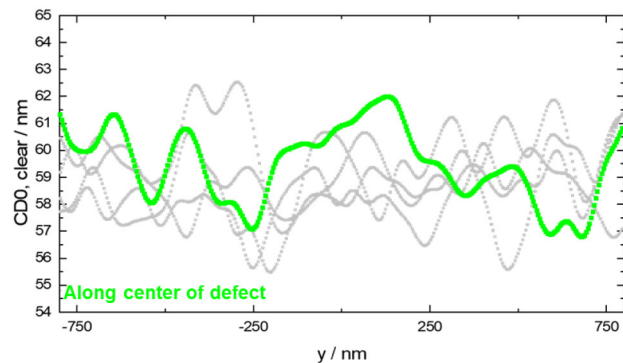


Figure 2d. Post-repair aerial image analysis of the CD with AIMS® Auto Analysis (AAA).

devices. Moreover, first consumer products based on EUV technology are already on the market and the amount of EUV lithographic layers per design is constantly rising<sup>[4]</sup>.

On the other hand, EUV photomasks, which are essential for EUV manufacturing, possess currently the highest numbers of defects. This generates the need for an efficient and reliable method to repair current and future high-end EUV masks. The current industry-standard for high-end photomask repair is the MeRiT® neXT system. It enables the repair of smallest defects on today's photomasks and is based on exposure with a focused electron beam, which interacts with precursor molecules on the mask to perform the repair.

Main factors, which limit the achievable repair process resolution of an electron beam-based repair tool are the amount of scattered secondary electrons and the electron beam spot size. As the number of secondary electrons, which limit the repair resolution, increases with increasing voltages a next generation repair tool, which need to address smaller feature sizes, need to operate at a lower voltage. Otherwise, as the electron beam spot size increases with decreasing voltages a next generation mask repair tool needs to employ an electron beam column, which shows a high-resolution even at low voltages. The new photomask repair tool MeRiT® LE makes use of a new electron beam column, which operates at a low electron beam voltage of 400V and shows improved system dynamics. This enables the repair of photomasks for future technology nodes with shrinking feature sizes.

## 2. Measurement Setup

In the following section the measurement setup and its fit to the mask shop ecosystem is presented. In Figure 1 the typical workflow of the mask making process, starting from 'Pattern Generation' until 'Mask Cleaning', is illustrated. The work presented in this paper focuses on the in blue highlighted sections of 'Repair' and 'Verification'.

In the framework of our work we used a programmed defect mask (PDM) based on industry standard EUV blank material for our investigations. Transparent and opaque defects on this PDM have been repaired with the next generation photomask repair tool MeRiT® LE. Resulting repairs have been verified by using AIMS® EUV actinic measurements, which provide a full emulation of the scanner imaging conditions, in combination with AIMS™ Auto Analysis<sup>[3]</sup>.

## 3. High-End EUV Repairs

In this section the results of the carried out high-end EUV defect repairs are summarized. Investigated defect types included bridge, broken-line and compact extrusion repairs. Defects reflecting future technology nodes of 5nm node and beyond with feature sizes down to 60nm half-pitch on mask and tiny extrusion of smaller than 10nm in size have been successfully repaired. In the subsequently presented figures SEM Pre-Repair, SEM Post-Repair and corresponding AIMS® EUV Post-Repair aerial images are illustrated for the afore mentioned defect types.

### 3.1 Bridge repair

First investigated defect type on the EUV PDM represents a bridge type defect with 500nm in length and a half-pitch size of 60nm on mask. Figure 2a and 2b show the scanning electron microscope (SEM) image of the defect before the repair and corresponding SEM image of the defect site after the repair with the MeRiT® LE system.

In Figure 2c and 2d the post repair aerial image, taken by AIMS® EUV and corresponding detailed analysis of the critical dimensions (CD) after the repair carried out with the software AIMS® Auto Analysis (AAA) are shown<sup>[5]</sup>. The green line in Figure 2d represents the CD along the center of the defect site, i.e. in 'horizontal' direction indicated by the coordinate 'y'. The grey lines represent the corresponding CDs along the 'unrepaired' neighboring reference 'spaces', i.e. along the clear regions. From Figure 2d it becomes clear that the CD variations along the center of the defect (green lines) are below the CD variations of the reference regions (grey lines). For the repair a maximum CD deviation of  $\Delta CD = 2.6\text{nm}$  has been extracted.

### 3.2 Broken line repair

Next investigated defect type on the EUV PDM represents a broken-line type defect with 500nm in length and a half-pitch size of 60nm on mask. Figure 3a and 3b show again the scanning electron microscope (SEM) image of the defect before the repair and corresponding SEM image of the defect site after the repair with the MeRiT® LE system. In Figure 3c and 3d the post repair aerial image, taken by AIMS® EUV and corresponding detailed analysis of the critical dimensions (CD) after the repair carried out with the software AIMS® Auto Analysis (AAA) are shown. The green



line in Figure 3d represents the CD along the center of the defect site, i.e. in 'horizontal' direction indicated by the coordinate 'y'. The grey lines represent the corresponding CDs along the 'unrepaired' neighboring reference 'lines', i.e. along the opaque regions.

In Figure 3d the CD variations along the center of the defect (green lines) are about the CD variations of the reference regions (grey lines). In fact, it can be seen that at the edges of the repair site (around  $y=\pm 250\text{nm}$ ) slightly higher CD deviations for the repair occur. Consequently, the maximum extracted CD deviation is here a bit higher compared to the previous section and has a value of  $\Delta\text{CD}=3.4\text{nm}$ . It is worth mentioning that this CD deviation still represents a significant improvement compared to state-of-the-art repair tools.

### 3.3 Extrusion repair

Last investigated defect type on the EUV PDM represents a small extrusion type defect with  $500\text{nm}$  in length,  $<10\text{nm}$  in size and a half-pitch size of  $88\text{nm}$  on mask. Figure 4a and 4b show the scanning electron microscope (SEM) image of the defect before the repair and corresponding SEM image of the defect site after the repair with the MeRiT® LE system.

In Figure 4c and 4d the post repair aerial image, taken by AIMS® EUV and corresponding detailed analysis of the critical dimensions (CD) after the repair carried out with the software AIMS® Auto Analysis (AAA) are shown. The green line in Figure 4d represents the CD along the center of the defect site, i.e. in 'horizontal' direction indicated by the coordinate 'y'. The grey lines represent the corresponding CDs along the 'unrepaired' neighboring reference 'spaces', i.e. along the clear regions. From Figure 4d it becomes clear that the CD variations along the center of the defect (green lines) are below the CD variations of the reference regions (grey lines). For the repair a maximum CD deviation of  $\Delta\text{CD}=3.3\text{nm}$  has been extracted.

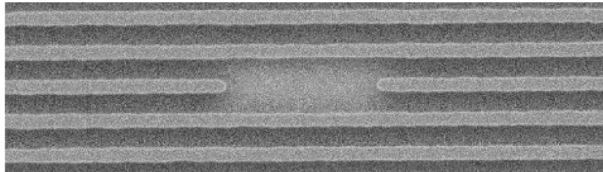


Figure 3a. SEM Pre-Repair image of broken-line type defect with  $60\text{nm}$  half-pitch on mask.

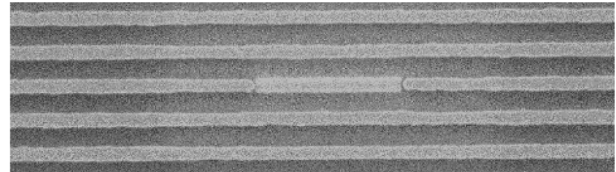


Figure 3b. SEM Post-Repair image of broken-line type defect with  $60\text{nm}$  half-pitch on mask.

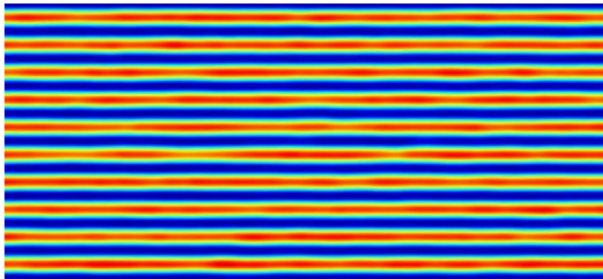


Figure 3c. Post-repair aerial image by AIMS® EUV of brokenline type defect with  $60\text{nm}$  half-pitch on mask.

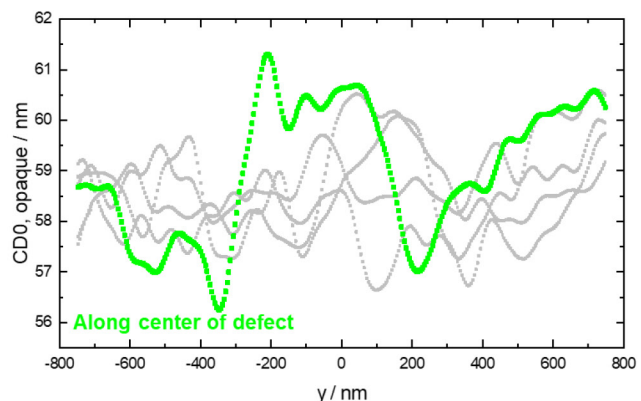


Figure 3d. Post-repair aerial image analysis of the CD with AIMS® Auto Analysis (AAA).

## 4. Summary

In this work we demonstrated high-end EUV photomask repairs with unprecedented precision applicable for the repair of photomasks of  $5\text{nm}$  technology node and beyond. Clear and opaque defects with  $60\text{nm}$  half-pitch on mask and tiny extrusions of smaller than  $10\text{nm}$  in size have been successfully repaired and results have been verified by AIMS® EUV actinic measurements. High-resolution repairs have been facilitated by the use of the next generation photomask repair tool MeRiT® LE.

## 5. Acknowledgements

The authors would like to thank Johannes Schoeneberg and Tilmann Heil for many fruitful discussions and Marcus Serwazi, Matthias Stecher, and Klaus Edinger for their support of the project.

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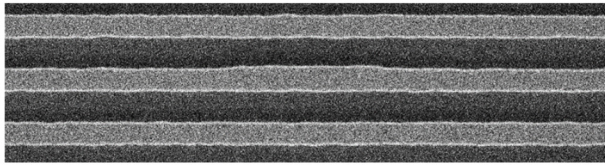


Figure 4a. SEM Pre-Repair image of a small extrusion (9nm width, 500nm length) type defect with 88nm half-pitch on mask.

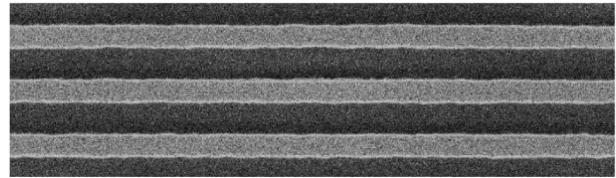


Figure 4b. SEM Post-Repair image of a small extrusion (9nm width, 500nm length) type defect with 88nm half-pitch on mask.

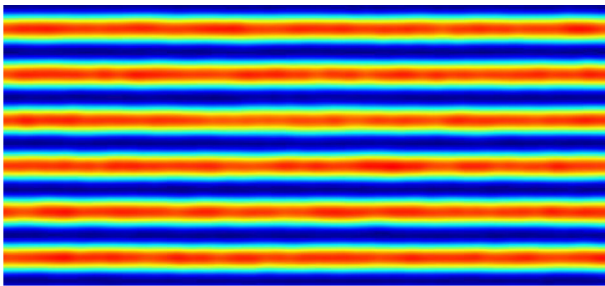


Figure 4c. Post-repair aerial image by AIMS® EUV of a small extrusion (9nm width, 500nm length) type defect with 88nm half-pitch on mask.

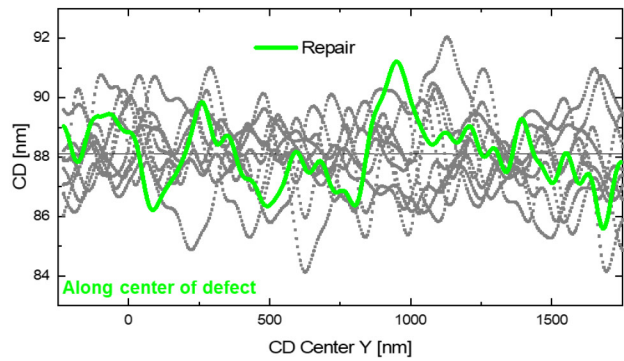


Figure 4d. Post-repair aerial image analysis of the CD with AIMS® Auto Analysis (AAA).



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# Industry Briefs

## ■ The Quest For Curvilinear Photomasks

By **Mark Lapedus**

The semiconductor industry is making noticeable progress on the development of advanced curvilinear photomasks, a technology that has broad implications for chip designs at the most advanced nodes and the ability to manufacture those chips faster and cheaper.

The question now is when will this technology move beyond its niche-oriented status and ramp up into high-volume manufacturing. For years, the industry has been working on the development of complex curvilinear shapes on advanced [photomasks](#) using inverse lithography technology (ILT). These complex mask shapes can be incorporated on both [optical](#) and [EUV](#) photomasks, but bringing these technologies into mass production has been difficult. Optical and EUV masks based on more traditional rectangular shapes have been production for years.

[The Quest For Curvilinear Photomasks \(semiengineering.com\)](#)

## ■ GlobalFoundries Building New Malta Fab And Expanding Current Capacity

By **Patrick Moorhead**

Global Foundries (GF) has made many strategic changes over the past few years, many of which I have written about. The biggest of those was its strategic reset in 2018 to focus on 5G RF, IoT, automotive, and silicon photonics. GF is a big player in the semiconductor manufacturing market that is going through really tough growing pains related to availability, to put it nicely. There has been a massive acceleration in demand for semiconductors, and GF is one of the many industry leaders driving the conversation on how to solve the problem strategically.

Today at an event in Malta, New York, GF announced many ways in how it will do its part to address the chip shortage in the longer and shorter term. The event was attended by U.S. Senate Majority Leader Chuck Schumer and U.S. Secretary of Commerce Gina M. Raimondo.

[GlobalFoundries Building New Malta Fab And Expanding Current Capacity \(forbes.com\)](#)

## ■ ON Semiconductor Affirms Commitment as a United Nations Global Compact Signatory

On April 22, ON Semiconductor marked two years as a Signatory to the United Nations (UN) Global Compact. As a UN Global Compact Signatory, ON Semiconductor participates alongside other global companies to make a difference in the communities where it operates. The company recently published its 2021 [Communication on Progress](#) (COP) report, reaffirming ON Semiconductor's commitment to the UN Global Compact.

[ON Semiconductor Affirms Commitment as a United Nations Global Compact Signatory \(yahoo.com\)](#)

## ■ China Wants a Chip Machine From the Dutch. The U.S. Said No.

Some of the tech industry's most important machines are made next to corn fields in the Netherlands. The U.S. government is trying to make sure they don't end up in China.

Beijing has been pressuring the Dutch government to allow its companies to buy ASML Holding NV's marquee product: a machine called an extreme ultraviolet lithography system that is essential to [making advanced microprocessors](#).

[China Wants a Chip Machine From the Dutch. The U.S. Said No. - WSJ](#)

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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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