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TAKE A LOOK INSIDE

KEY DATES

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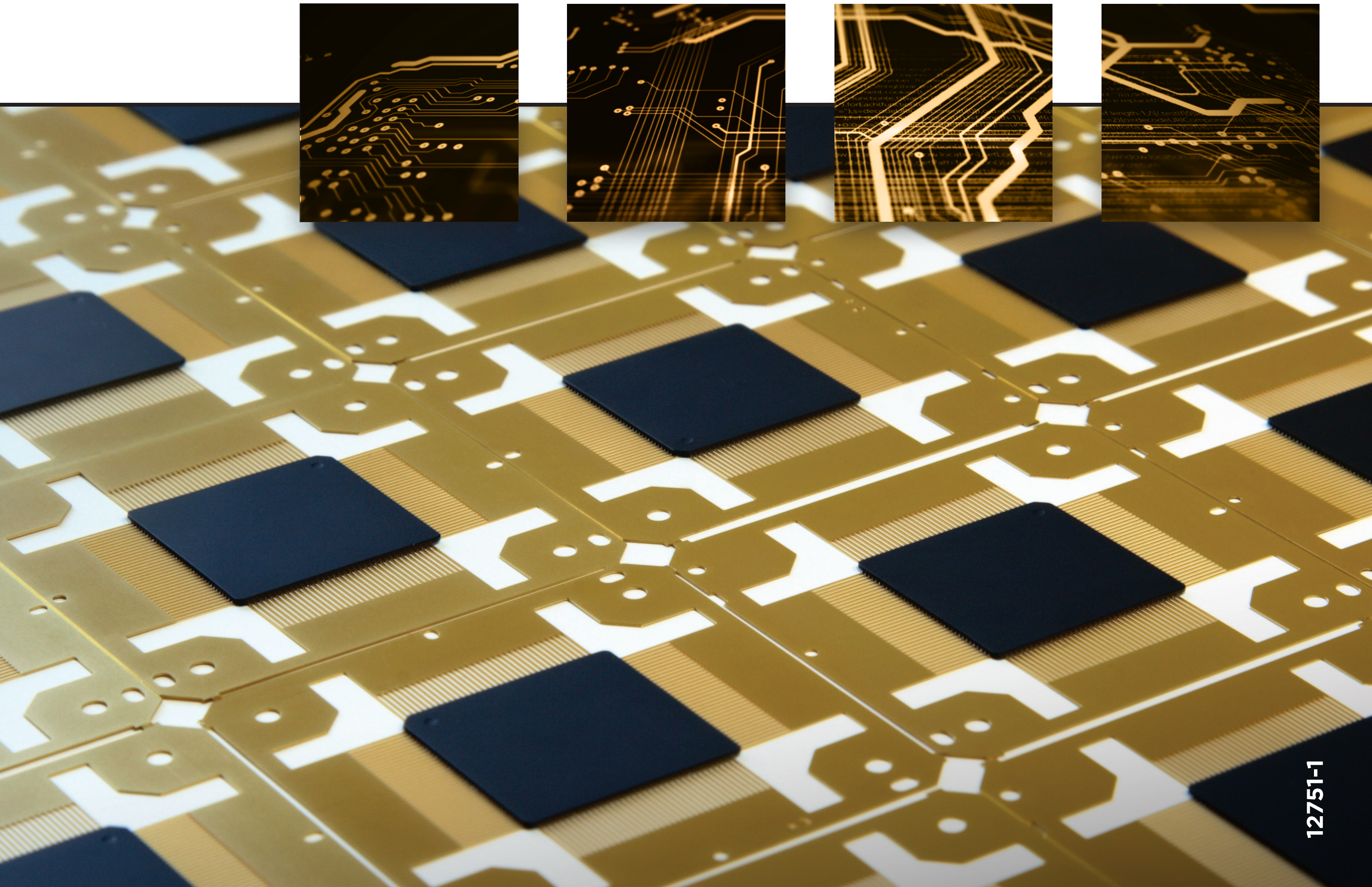
Yesterday's impossible creates tomorrow's possibilities



EDITORIAL

Yesterday's impossible creates tomorrow's possibilities

Jed Rankin, *BACUS President*

We are fortunate to live in a time of dizzying technological progress. I am sure that I'm not alone in remembering my awe the first time I saw a mobile phone (actually, just a giant radio in a bag), played a pixelated game on my TV, downloaded a fuzzy digital picture from my camera, sent an email, or did a thousand other "firsts" with technology.

This technology awe extends into my professional experience, when I first saw a photomask, first saw the stage movement on a scanner, or even read the promised specifications approaching atomic-length scales. This awe was born of the fact that all these feats and all these technologies seemed impossible!

In October, I attended my 14th photomask conference — the BACUS and EUVL symposium in Monterey, CA hosted by SPIE. This year was one of the biggest in recent history — more presentations, more attendees, and more companies represented. Whether it was in the packed conference rooms, navigating the rows of posters, in discussions over coffee during a break, or in line at the bar at the gala, the new ideas and awe over the new solutions was palpable. From the Sunday discussion on large form factor photomasks, to curvilinear data preparation, to resist optimization, and even the seemingly unthinkable hyper-NA EUV scanner, new and amazing concepts were everywhere!

When I look back at past conferences, it doesn't seem so long ago that we were discussing other seemingly impossible technologies — the feasibility of high-transmission optical phase-shift masks, imprint lithography masks, or even immersion lithography. Even more recently, we celebrated VSB mask writers, EUV blank defect avoidance, nanomachining for mask repair, and dozens of other firsts.

It has been observed many times before, but one of the quirky things about humans is how quickly seemingly impossible things become ordinary. I've always felt that the short memory of our awe seems disrespectful for the invention, and the inventors and scientists who put so much of themselves into their creations.

Just like the forgotten bag-phones, the Atari-2600 packed away in the attic, or worrying about making a long-distance phone call, many of the recent photomask innovation miracles have been accepted as "everyday." Why wouldn't you be able to print a photomask with billions of e-beam shots? Why would you think sub-wavelength lithography is impossible? Who could doubt that EUV would reach HVM?

In reflecting on all those everyday lithography and photomask miracles, I've come to realize that the process of normalization of the extraordinary is not only natural, but essential to drive tomorrow's innovation. In many cases, only by taking these technological miracles for granted enables us to dream of what's next. Would curvilinear have been possible without the Multibeam? Would hyper-NA have been possible without EUV blank defect reduction? Would pellicles happen without clean sources?

So maybe the awe is not forgotten, but it just becomes the seed of tomorrow's innovations. I'm looking forward to seeing what miracles we forget next, and the impossibilities that forgetfulness brings with it!

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FEATURED ARTICLE BEST POSTER PRESENTATION AWARD WINNER

Actinic patterned mask inspection for high-NA EUV lithography

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ABSTRACT

Lasertec released the actinic patterned mask inspection (APMI) system ACTIS in 2019 and has since been providing it as an actinic inspection solution for EUV mask inspection. ACTIS performs high-resolution, high-throughput inspection of EUV photomasks. It detects all types of mask defects making lithographic impact because it uses the wavelength of light used in EUV lithography as its light source. While actinic inspection is typically known for its capability to detect phase defects, it is also indispensable for detecting phase shift defects on EUV PSM. ACTIS performs both die-to-die (D2D) and die-to-database (DDB) inspection and can inspect all types of EUV masks including multi-die masks and single-die masks.

High-NA lithography is expected to be used for the EUV process at the technology nodes of N2 and beyond. The next-generation ACTIS has an objective mirror with a higher NA. This makes it possible to have different resolution characteristics in the X and Y directions, enabling it to meet the sensitivity required to detect defects in the anamorphic patterns used for high-NA EUV lithography. In addition, as design nodes become smaller, curvilinear masks will be adopted to improve resolution characteristics on wafers, which will require handling a large amount of design data per mask.

For DDB inspection, which generates reference images using sophisticated, high-speed computer processing, the inspection of curvilinear masks is a major challenge. In DDB inspection, curvilinear masks generate large amounts of data because complex curve shapes are approximated using polygons with a large number of vertices. It needs more computing resources and leads to a longer processing time. The reference images generated for inspection must be more intricate.

APMI is necessary for pattern mask qualification of EUV masks with pellicles. However, the high-sensitivity inspection of masks with EUV pellicles was prevented by the incident power restriction caused by the heat load limitation of the pellicles. Therefore, we have developed a new EUV light source that can minimize the thermal load.

This paper will discuss the next-generation ACTIS for high-NA EUV lithography, the DDB inspection capability of ACTIS for curvilinear masks, the requirements for APMI light sources, and Lasertec's EUV light source "URASHIMA".

INTRODUCTION

Semiconductor device performance enhancement has been achieved through node shrinking. High-resolution EUV lithography is applied in the wafer printing process. Suitable mask metrology and inspection tools operating at EUV exposure wavelength are required at each process during mask manufacturing. Optical inspection systems and EUV actinic inspection systems are used for detecting the defects on the substrate, reflective multilayer, and absorber. After patterning a mask, D2D or DDB inspection is necessary for mask qualification before exposure.

EUV mask inspection conducted with actinic light has the characteristic of more accurately predicting the impact of defects at exposure than inspection with any other wavelength. ACTIS A1XX is an actinic patterned mask inspection tool designed to detect defects that make a lithographic impact at EUV exposure.[1,2] The development of this actinic patterned mask inspection tool operating at 13.5 nm wavelength has been supported by various kinds of technology accumulated through years of experience with other inspection tools such as optical mask blanks inspection, actinic mask blank inspection, and optical pattern mask inspection. Lasertec has developed several different inspection tools applicable to the inspection of EUV masks (Fig. 1) and has accumulated mask inspection technologies through years of experience with these tools.[3,4,5,6,7,8]

(a) (b) (c) (D)

Figure 1. *Inspection technologies for actinic mask inspection. (a) MAGICS M6640/9650: mask blank inspection, (b) ABICS E120 actinic mask blank inspection (ABI) system, (c) MATRICS X9ULTRA: DUV pattern mask inspection system, and (d) ACTIS A1XX: actinic pattern mask inspection (APMI) system.*

APMI is expected to provide the ultimate capability for EUV patterned mask inspection by detecting all types of printable defects.[9] The capabilities of DUV and e-beam inspection tools have been evaluated and discussed.[10] The only candidate to catch all types of defects is APMI. In addition, only APMI can reliably detect lithographic impact defects when inspecting masks with EUV pellicles, which have high transmittance for EUV light.[11,12] ACTIS utilizes both D2D and DDB algorithms for defect detection on EUV masks. The DDB algorithm is essential for inspecting highly sensitive single-die masks. There are several ACTIS units operating in the field, and the field data reported shows that the DDB inspection function of ACTIS provides excellent inspection sensitivity, captures all printable defects on masks with or without a pellicle attached, and prevents yield impact by detecting defects at an earlier stage.[13]

APMI FOR HIGH-NA EUV LITHOGRAPHY

Mask inspection for high-NA EUV lithography

EUV lithography made good progress since ASML's introduction of a 13.5nm EUV scanner with 0.33 NA. It is currently used in production for the latest technology nodes. For future technology nodes of N2 and beyond, a higher NA value has been proposed for EUV lithography exposure.[14] The concept of anamorphic high-NA EUV exposure was proposed in 2015. The high-NA system introduces different magnification scales for the X direction and for the Y direction on the mask. While it is possible to increase the NA value up to 0.55 on the wafer, it is fundamentally impossible to increase the NA value on the mask in the same manner because reflectivity loss becomes significant for a large incident angle on the mask. The introduction of different magnification scales for the X and Y directions is necessary to address this challenge. The magnification of the high-NA mask in the X direction remains 1/4, but the magnification in the Y direction will be changed to 1/8. The area of wafer printing is 16.5 mm x 26 mm, whereas the mask field is 132 mm x 104 mm. It is therefore necessary to meet different sensitivity requirements for the X and Y directions to enable high-NA mask inspection.

Lasertec has developed a new ACTIS model, the A3XX, for high-NA EUV lithography.[15] It has the sensitivity to detect defects that are large enough to have a printable impact, even if the required sensitivity differs between vertical and horizontal directions. In terms of throughput, the A3XX is designed to have a higher throughput than the current A1XX. This is because the projected area covered by each mask is smaller, so more masks are required.

High-NA projection optics of the next-generation ACTIS A3XX

One of the important aspects of the current ACTIS design is that it uses projection optics with asymmetric NA and resolution in the X and Y directions to maximize sensitivity and resolution. This feature is highly compatible with the inspection of anamorphic patterns, which have different sensitivity requirements in the X and Y directions. As shown in Figure 2, the next-generation ACTIS will follow the same design concept but with a higher NA, mainly to meet the high sensitivity requirements in the X direction for anamorphic patterns. This will provide optimal inspection for anamorphic patterns while allowing for further pattern width reduction in future technology nodes.

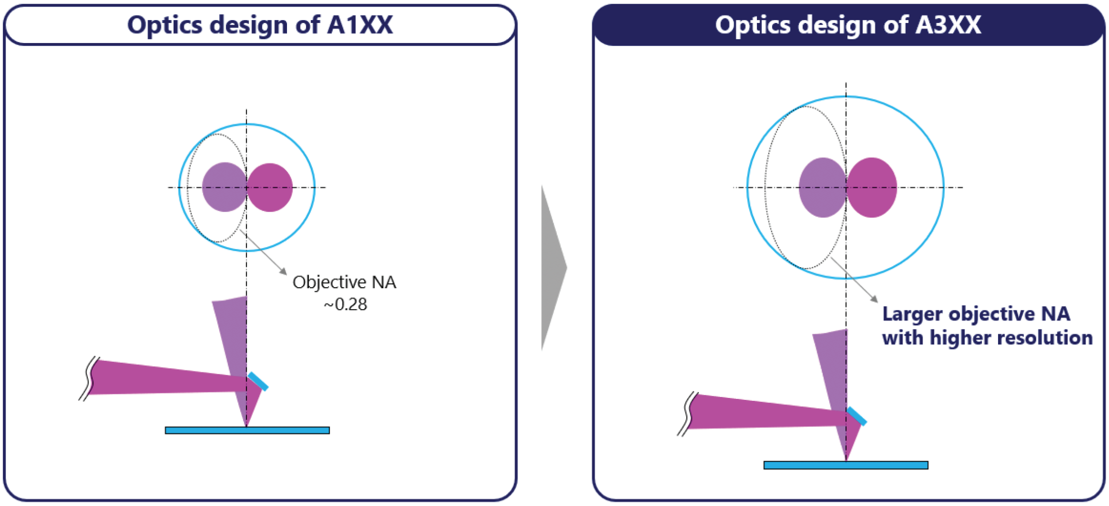


__Figure 2.__ Projection optics design of the current ACTIS A1XX (left) and the next generation ACTIS A3XX (right).

Resolution simulation of high-NA ACTIS A3XX

To assess the inspection capability of the High-NA ACTIS A3XX, we performed imaging simulations using a rigorous optical simulator with electromagnetic calculations with conditions of circular illumination and a standard TaBn-based absorber with a thickness of 70 nm.[16] Figure 3 shows the pattern contrast simulation of ACTIS A3XX with the high-NA objective mirror compared to the current ACTIS A1XX. In this simulation, A3XX shows a significant improvement in contrast, with more than 30 percent improvement for 30 nm half-pitch line-and-space and 64 nm contact holes.

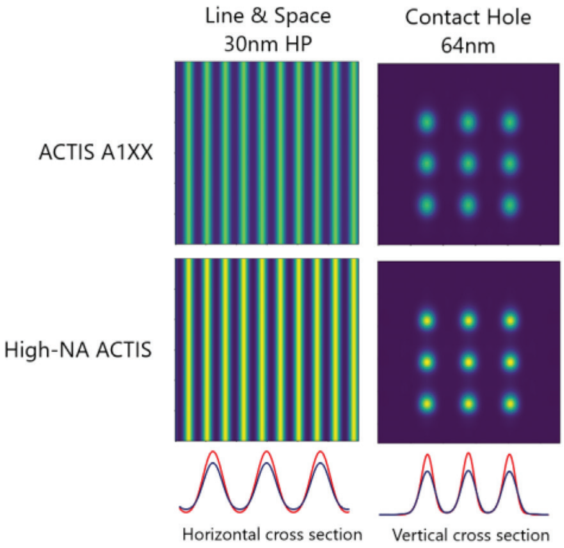


__Figure 3.__ Simulation results of imaging capability of current ACTIS A1XX and high-NA ACTIS A3XX.

Pattern resolution comparison between high-NA ACTIS prototype and ACTIS current model

The results of evaluating pattern contrast from images captured by the actual prototype tool with the aforementioned optical system are shown below. Figure 4 shows a comparison of the pattern contrast between the A3XX and the current ACTIS A1XX. The patterns used were a 30 nm half-pitch line-and-space and 64 nm contact holes. Pattern contrast is defined here as the gray scale difference between the maximum and minimum values of a pattern when it is observed using the same illumination conditions. The results show that the A3XX prototype achieved an average contrast improvement of 32 percent for 30 nm half-pitch line-and-space and 36

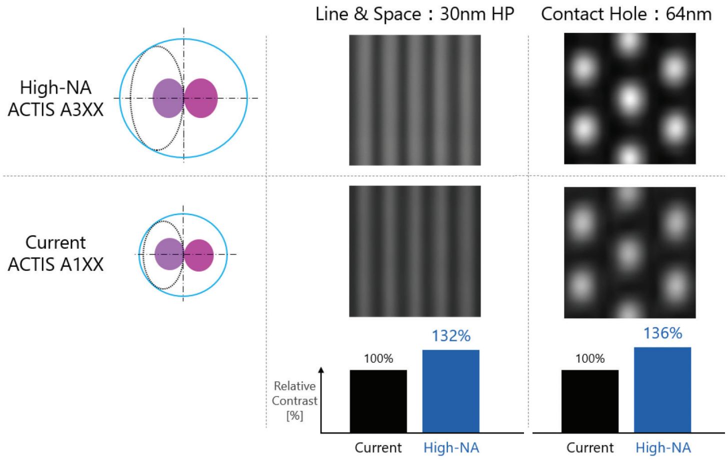


__Figure 4.__ Pattern contrast comparison between current ACTIS A1XX and high-NA ACTIS A3XX prototype.

percent for 64 nm contact holes compared to the current system. This result is consistent with the simulation and shows the greatly improved contrast in fine patterns.

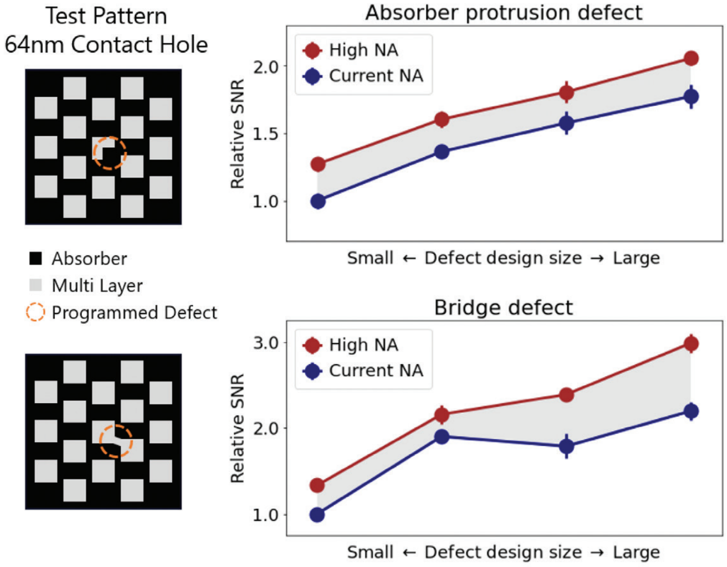


Figure 5. *Comparison of program defect SNR between current ACTIS A1XX and high-NA ACTIS A3XX prototype.*

Defect SNR comparison between high-NA ACTIS prototype and current ACTIS model

Figure 5 compares the signal-to-noise ratios (SNR) for programmed defects of absorber protrusion and multilayer bridge of various sizes formed on 64 nm contact holes on the A3XX prototype system and the current ACTIS. The results confirm that the SNR of the A3XX prototype has been improved by an average of about 30 percent, even for defect sizes that were unable to be detected with the A1XX, and that the detectable defect size can be extended to even smaller scales.

DIE TO DATABASE INSPECTION FOR CURVILINEAR MASKS

Die to database inspection support of ACTIS

ACTIS performs both D2D and DDB inspection of EUV photomasks. D2D inspection compares images of two dies with the same pattern, whereas DDB inspection compares images of the actual mask with a reference image generated by the system's algorithm using design data, and the differences between the two images

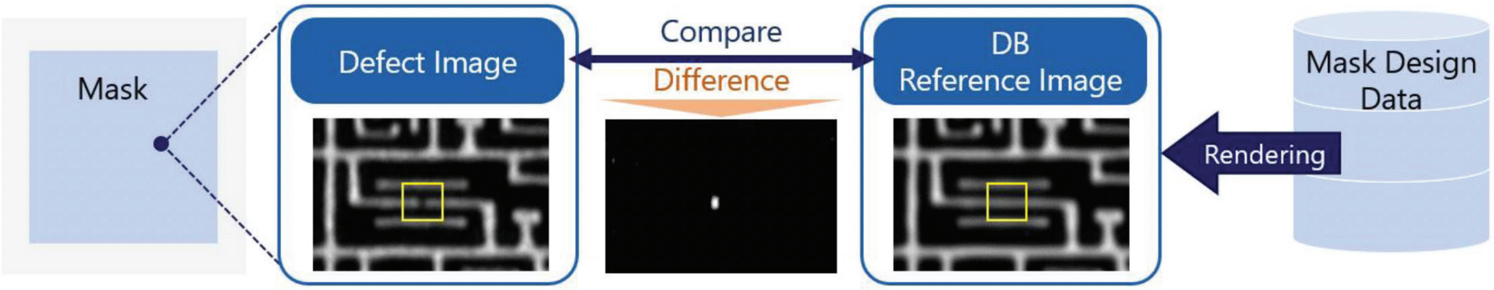


Figure 6. *Overview of DDB inspection method.*

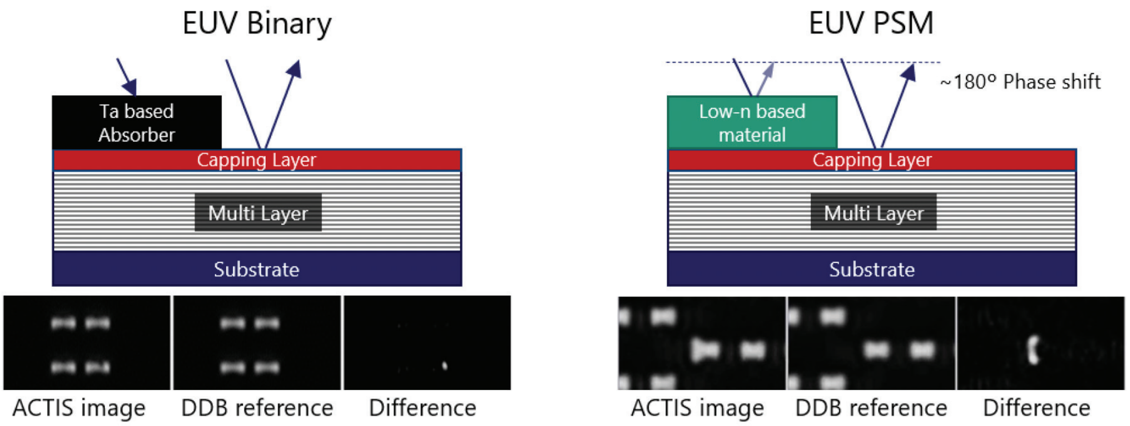


Figure 7. *Cross-sectional view of EUV binary mask and PSM, and example of DDB inspection images.*

represent defects detected (Fig.6). Compared to D2D inspection, DDB inspection is more sensitive. This is because the reference image used in DDB inspection does not contain the roughness information present in the actual mask pattern image, and a high signal-to-noise ratio can be achieved.

The DDB inspection mode of ACTIS supports EUV PSM in addition to binary masks. EUV PSM improves the contrast of printed patterns by using a low-n material that provides a phase shift close to 180 degrees while greatly attenuating the amount of EUV light reflected, thereby improving NILS. Figure 7 shows a cross-sectional view of an EUV binary mask and PSM, the ACTIS images, rendered reference images, and differential images for EUV binary and PSM masks. Note that the DDB reference image is faithfully rendered, although modeling the EUV PSM reference image for DDB inspection is usually difficult due to more complex light interference effects than binary masks.

Die to database inspection of EUV curvilinear masks

The use of curvilinear masks in advanced technology nodes is expected to increase. This is because they offer various improvements, including better process windows, by increasing mask fidelity and flexibility in OPC solutions.[17,18] However, efficiently rasterizing curvilinear masks for DDB inspection requires using polygons with a large number of vertices to approximate the curve shape, which imposes a very large data processing load compared to conventional EUV masks. Faithfully modeling complex OPC reference images without sacrificing throughput is a major challenge in the DDB inspection of curvilinear masks.

To cope with the increased data processing load, ACTIS's rasterization engine has been improved. Previously, rasterization was performed only by CPUs, but the newly developed hybrid rendering engine uses both CPUs and GPUs. The engine performs design data processing and vertex extraction on the CPUs and rendering on the GPUs at ultra-high speed by taking advantage of the high-speed rasterization capability of GPUs, which is their primary role. In addition, a newly developed modeling algorithm using machine learning has improved the fidelity of the reference image. Figure 8 shows an example of a DDB reference image using Lasertec's curvilinear test mask design data. Currently, ACTIS supports high-sensitivity inspection of curvilinear masks in both D2D and DDB inspection modes and has already inspected many masks in the field.

Figure 8. *Example of DDB inspection reference images with Curvilinear test mask design data.*

SEMI P49 curvilinear MULTIGON extension support for die to database inspection

SEMI P49 OASIS MULTIGON extension for curvilinear masks is a design data format that uses cubic Bezier and B-spline curves for curve representation to significantly reduce design data volume.[19,20] Standardization as an extension of SEMI P39 is in progress as of October 2023. A larger design data file size is one of the challenges in DDB inspection, and we have developed and demonstrated support for the SEMI P49 OASIS MULTIGON extension. Figure 9 shows the rasterization results of MULTIGON records by the SEMI P49 OASIS support engine we developed. Sample data was provided by Synopsys. In the engine, MULTIGON objects are automatically converted to polygon objects within a specified error tolerance, as shown in Figure 10. This enables accurate processing of curve objects while maintaining compatibility with other existing applications. The MULTIGON-enabled application will be tested in the field for DDB inspection of masks manufactured with SEMI P49 design data.

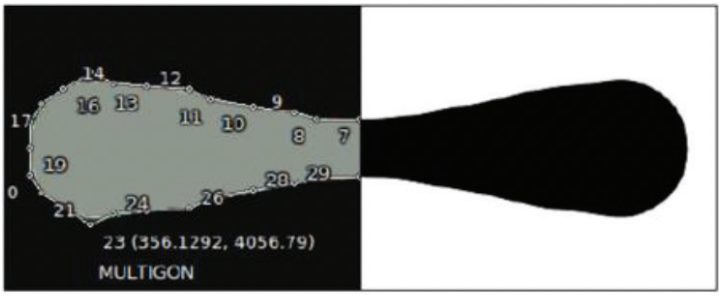


Figure 9. *Symmetrical MULTIGON record displayed by design data viewer (left) and rasterized image by ACTIS with the developed SEMI P49 OASIS-compliant engine (right).*

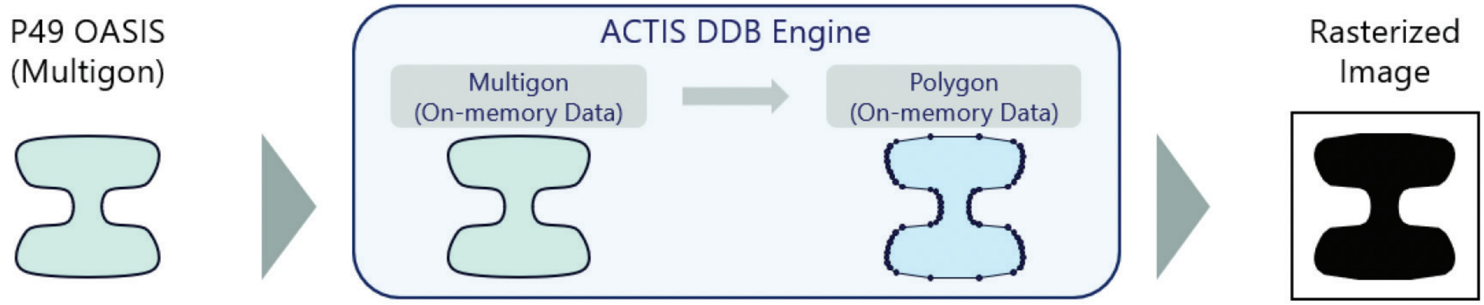


Figure 10. *Conversion process of a MULTIGON object to a polygon object.*

NEW EUV LIGHT SOURCE FOR INSPECTION "URASHIMA"

Light source requirement for APMI

The issue of heat load on EUV pellicles is unavoidable when we consider a suitable light source for APMI. Although the transmittance of EUV pellicles is steadily improving, the heat absorption cannot be ignored, and there is input power limitation at present. High-brightness illumination contributes to high-sensitivity, high-throughput defect inspection, but there is a limit to the brightness of illumination you can use because excessive heat load would damage the pellicles. Therefore, there is a limit to inspection performance.

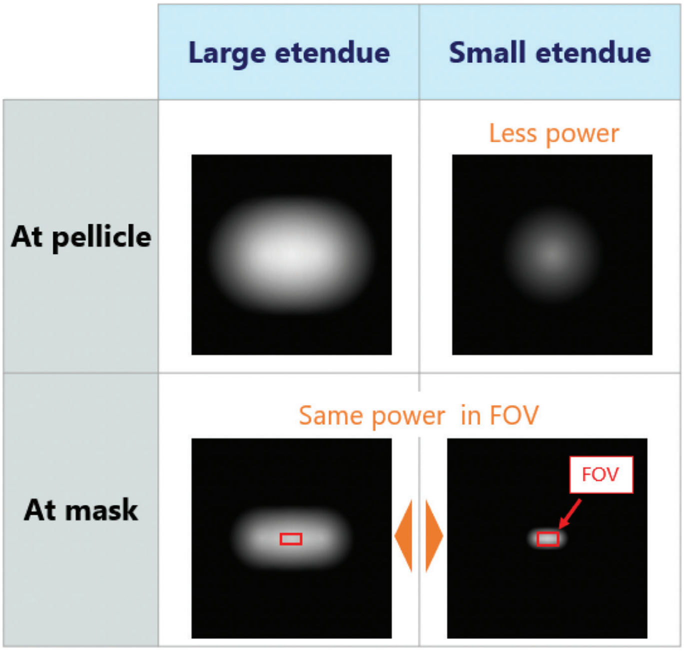


Figure 11. *Illumination power distribution with a large etendue and a size larger than the inspection FOV and lighting with a small etendue and a size close to the FOVobject.*

Figure 11 shows images of illumination with a size larger than the field of view (FOV) and illumination with a size close to the FOV. The top row shows the intensity on the pellicle and the bottom row shows the intensity on the mask. The red square indicates the FOV. The size of the illumination spot is determined by the etendue and solid angle of illumination. With a smaller etendue, a smaller illumination spot can be obtained with the same solid angle condition. If we assume that the brightness in the FOV of both is equal, then it is clearly preferable to efficiently illuminate only the area necessary for inspection in APMI because a higher output from the light source will put a larger heat load on the pellicle.

New EUV light source: URASHIMA

This section describes our EUV light source, "URASHIMA", which is shown in Figure 12. URASHIMA is a high-brightness EUV light source system designed for actinic mask inspection systems. We use the principle of EUV generation with a high-speed rotation liquid target

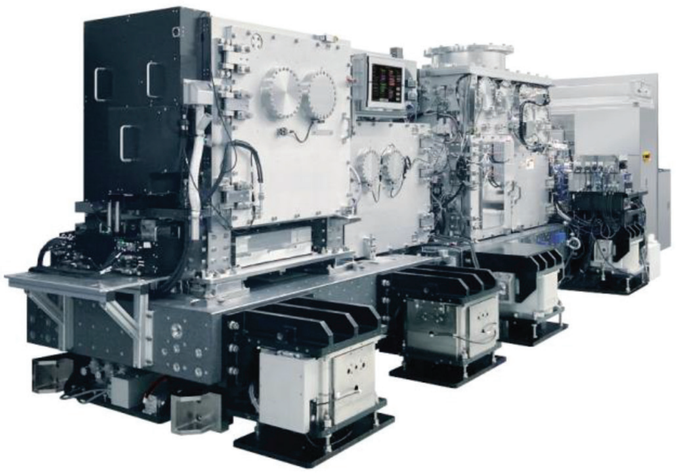


Figure 12. *URASHIMA light source in ACTIS system.*

developed by ISTEQ.[21] Its key features include the use of a laser-produced plasma (LPP) system, which provides stable output, and optimized illumination to minimize the heat load on the pellicle. Many ACTIS units have been fitted with URASHIMA and are operating stably at our customers' sites.

Figure 13 is a schematic of EUV light generation by URASHIMA light source. URASHIMA is an LPP light source that generates EUV light by hitting liquid tin with laser pulses. It uses two infrared laser beams to generate EUV light of optimal size for the inspection FOV. A high-speed rotating tin container constantly supplies fresh tin to the laser irradiation position to maintain stable EUV emission. It also reduces tin consumption by recycling scattered tin back to the side walls using centrifugal force.

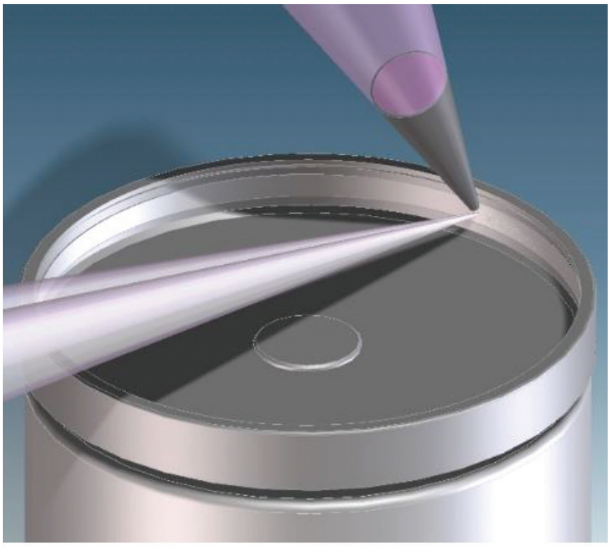


Figure 13. Schematic of EUV light generation by URASHIMA light source.

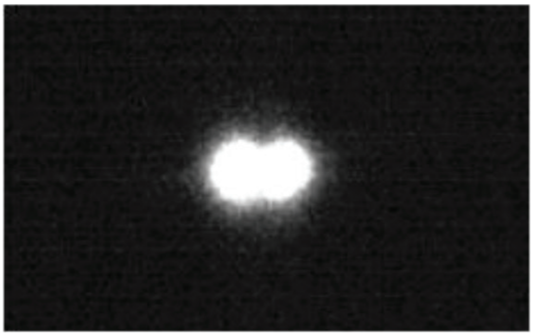


Figure 14. Plasma shape of the EUV emission area. Size is 90 micrometers by 45 micrometers.

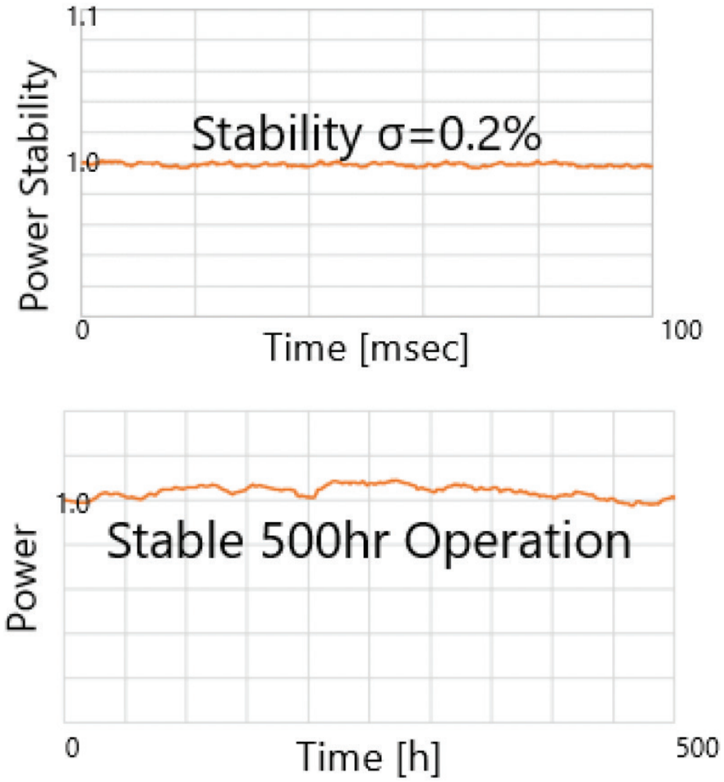
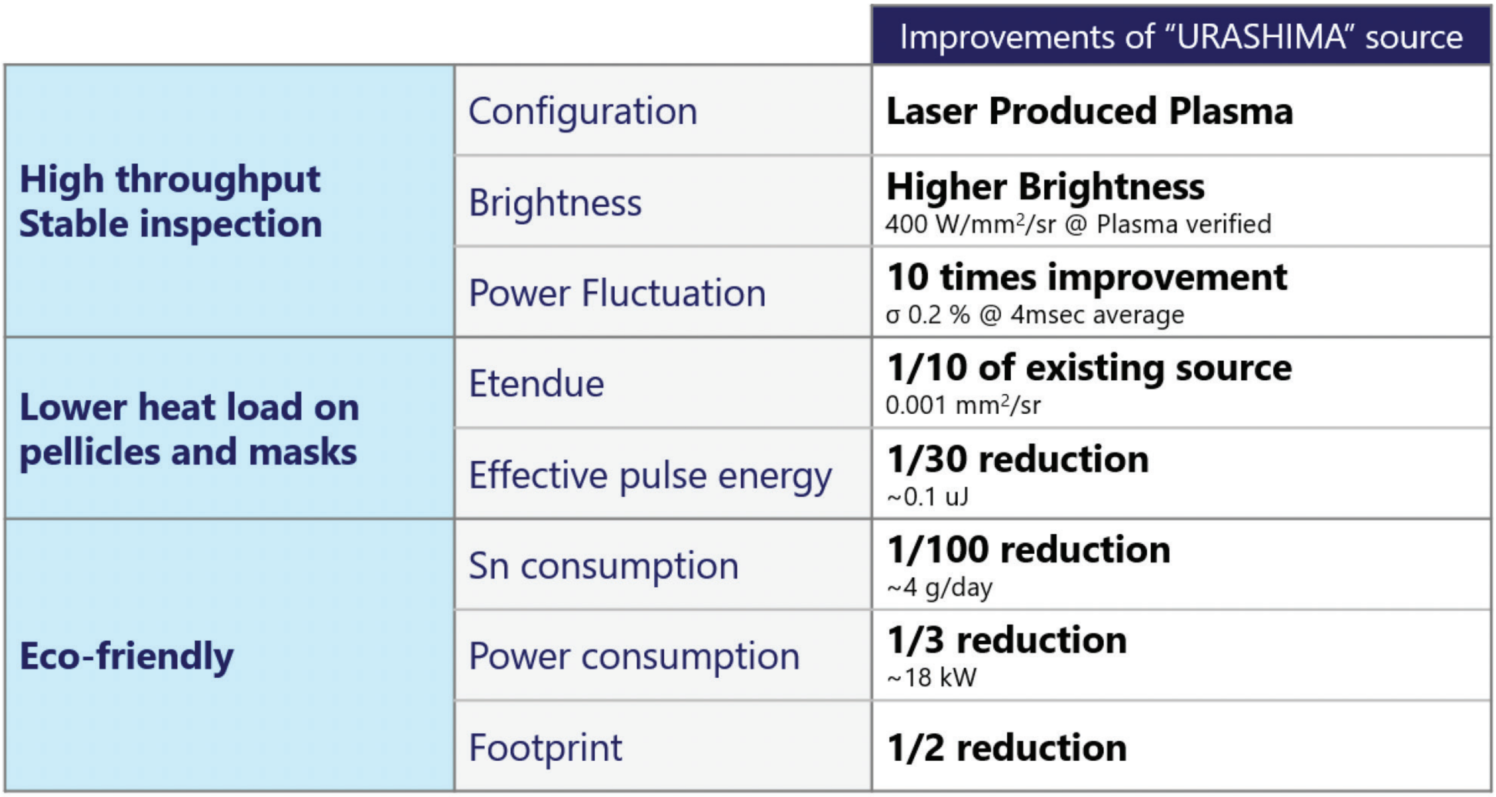


Figure 15. Normalized output power over a 100 ms span. Stability was at 0.2% sigma. (left) and long-term normalized output power over 500 hours (right).

Figure 14 shows the plasma geometry of the EUV emission area, which is approximately 90 micrometers by 45 micrometers. The graph on the left of Figure 15 shows the output power stability of URASHIMA over a span of 100 ms, achieving a power stability of 0.2 percent sigma. The graph on the right is the output power of URASHIMA over a span of 500 hours, or 20 days. This shows it operates stably over a long period of time.

Major performance improvements

The table below (Fig.16) shows the improvements of the URASHIMA light source from existing light sources. URASHIMA is an LPP system and achieves a high brightness of 400 watts per square millimeter steradian at the plasma point. URASHIMA achieves ten times better power fluctuation performance (σ 0.2 percent per 4 ms), ten times smaller etendue size (approximately 0.001 mm^2/sr), 30 times smaller pulse energy per beam spot (approximately 0.1 uJ), and 100 times lower tin consumption (approximately 4 g/day). The power consumption has been reduced to 1/3 (18 kW), and the footprint has also been reduced to half. With these



		Improvements of "URASHIMA" source
High throughput Stable inspection	Configuration	**Laser Produced Plasma**
	Brightness	**Higher Brightness** 400 W/mm^2/sr @ Plasma verified
	Power Fluctuation	**10 times improvement** σ 0.2 % @ 4msec average
Lower heat load on pellicles and masks	Etendue	**1/10 of existing source** 0.001 mm^2/sr
	Effective pulse energy	**1/30 reduction** ~0.1 uJ
Eco-friendly	Sn consumption	**1/100 reduction** ~4 g/day
	Power consumption	**1/3 reduction** ~18 kW
	Footprint	**1/2 reduction**

significant performance improvements, URASHIMA is an environmentally friendly system that achieves higher throughput and more stable inspection than existing light sources while minimizing the heat load on the pellicle and the mask.

CONCLUSION

ACTIS is an APMI tool that has been proven to provide high-sensitivity inspection with its high-resolution imaging capability. It is widely used in production by several end-users. APMI is the only inspection that can detect all types of lithographic impact defects on EUV masks with or without pellicles.

The newly developed high-NA ACTIS A3XX HVM tool for high-NA EUV lithography is in the final stage of preparation and will be delivered to customers in 2024. The prototype tool is operational and has demonstrated significant improvements in pattern contrast and defect SNR compared to the current system.

ACTIS DDB inspection supports EUV binary masks, PSM, and curvilinear masks as well. Many curvilinear mask inspections have already been performed in the field. Support for the SEMI P49 MULTIGON extension format for curvilinear masks has also been added.

We have developed a high-brightness EUV light source, URASHIMA, for actinic pattern mask inspection. A suitable plasma shape reduces the heat load on pellicles, and laser-produced tin plasma realizes high brightness and stable illumination. URASHIMA light sources have been installed on many ACTIS units at customer sites.

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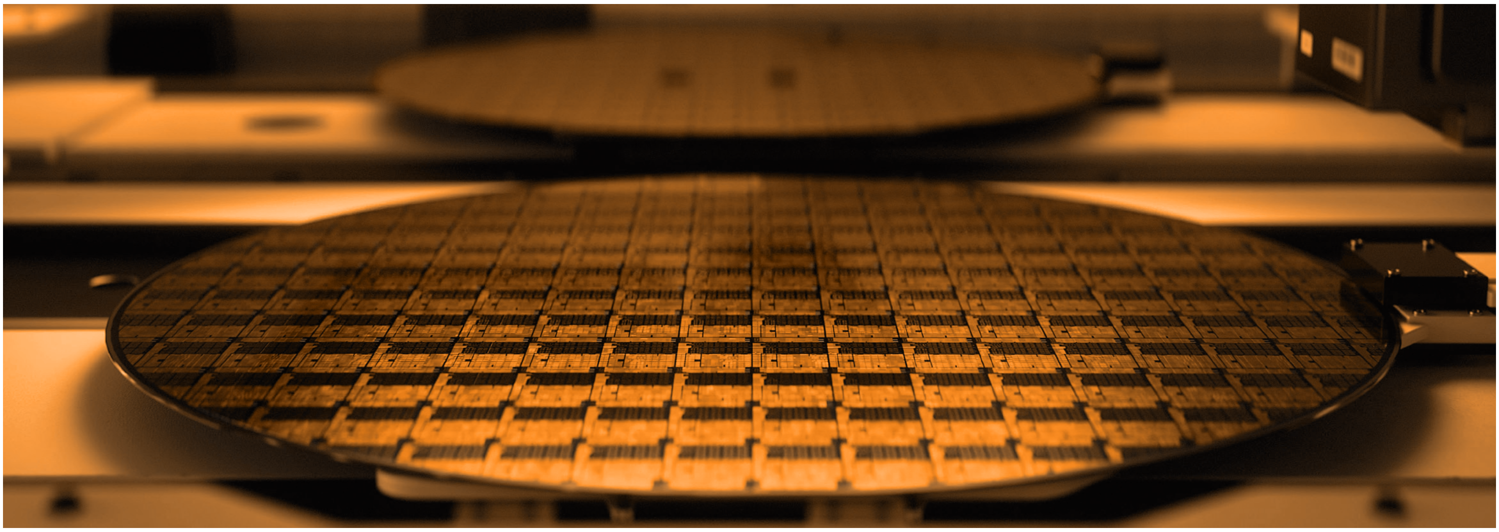

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INDUSTRY BRIEFS

eBeam initiative survey reports semiconductor industry luminaries are confident in high-NA EUV and curvilinear photomasks

Shannon Davis

The eBeam Initiative, a forum dedicated to the education and promotion of new semiconductor manufacturing approaches based on electron beam (eBeam) technologies, announced the completion of its 12th annual eBeam Initiative Luminaries survey. 80 percent of survey respondents believe that broad adoption of high-NA EUV lithography in high-volume manufacturing (HVM) by more than one company will occur by 2028, the same percentage as reported in last year's survey. In addition, confidence that leading-edge mask shops can handle curvilinear mask demand doubled compared to last year's survey, while 87 percent predict that leading-edge mask shops can handle at least a limited number of curvilinear masks.

Semiconductor Digest

Big changes ahead for photomask technology

Gregory Haley

Curvilinear technology could boost yield and improve scalability, but it requires full industry support and a lot of work. Curvilinear shapes are a more accurate representation of features that will be printed on a mask and ultimately etched onto a wafer, allowing tighter spacing between those features. If the whole industry backs this approach, the impact could be significant. But there are challenges associated with any moves of this scale, particularly as it applies to high-volume manufacturing, and the transition is non-trivial.

Semiconductor Engineering

How the worlds of chiplets and packaging intertwine

Majeed Ahmad

Chiplets mark a new era of semiconductor innovation, and packaging is an intrinsic part of this ambitious design undertaking. However, while chiplet and packaging technologies work hand in hand to redefine the possibilities of chip integration, this technological tie-up isn't that simple and straightforward.

EE Times

Understanding the big spend on advanced packaging facilities

Anton Shilov

Leading chipmakers in recent years spent tens of billions of dollars on advanced-chip-packaging facilities—to prepare for building processors in multi-chiplet packages that will offer consistent performance increases and ensure continuity of Moore's law. Advanced-chip-packaging revenue is expected to grow from $44.3 billion last year to $78.6 billion by 2028, according to Yole Intelligence. Meanwhile, the traditional chip packaging market was valued at around $47.5 billion last year and is projected to grow to $57.5 billion by 2028. The whole chip packaging market is expected to reach $136 billion by 2028.

EE Times

Chip industry talent shortage drives academic partnerships

Liz Allan

Universities, companies, and governments are forming broad partnerships to update skills and foster innovation in chips, security, AI, and related fields. Talent shortages repeatedly have been cited as the number one challenge for the chip industry. Behind those concerns are several key drivers, and many more domain-specific requirements.

EE Times

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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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spie.org/membership/bacus-technical-group

Key Dates

2024

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

SPIE Photomask Technology + EUV Lithography
29 September–3 October 2024
Monterey, California, USA
spie.org/puv

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

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