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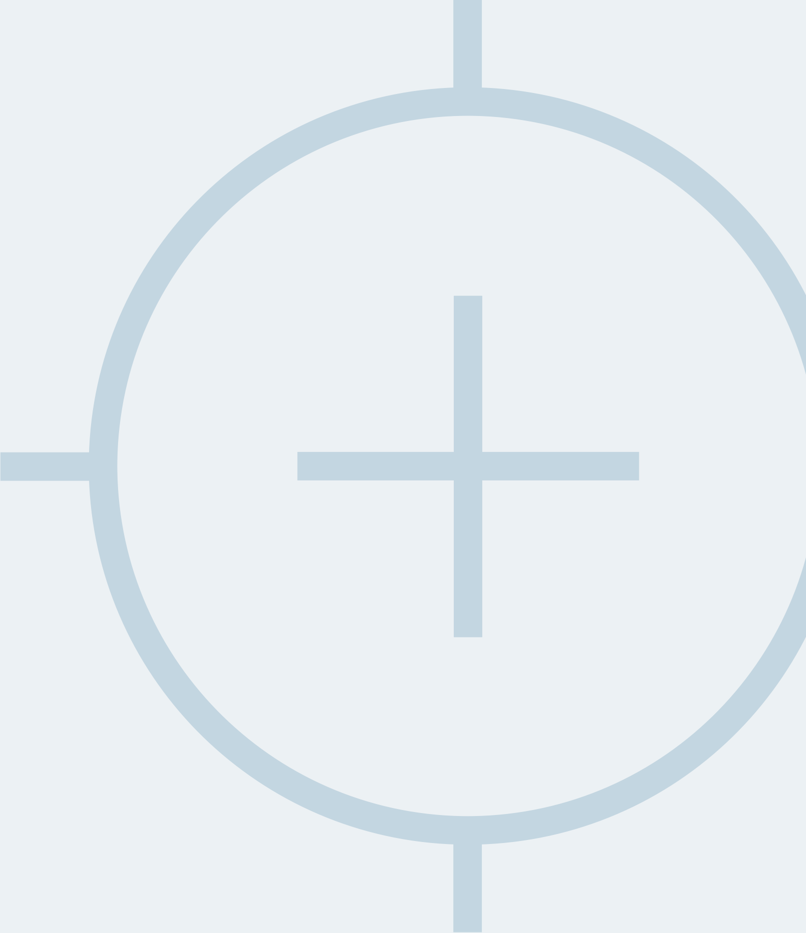

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ABSTRACT

Starting in the early 1960s, mask aligners were the dominating lithography tool for the first 20 years of the semiconductor industry. In the early 1980s industry changed over to projection lithography. However, mask aligners were never sorted out. Still today hundreds of new mask aligners are sold each year. This continuing success of mask aligner lithography is related to two basic trends in lithography: (a) Costs for leading-edge lithography tools double approximately every 4.4 years; and (b) the number of lithography steps per wafer was increasing from a few litho-layers to more than 35 layers now. This explains why mask aligner lithography, a very robust and cost-effective solution for uncritical litho-layers, is still widely used today. Mask aligner systems have much evolved, from manual 1“ aligner to fully automatic 300 mm cluster systems of today. Interestingly, the shadow-printing lithography process itself was never improved. Illumination systems of most commercially available mask aligners are still based on technology developed in the 1970s.

SUSS MicroTec has now introduced a novel mask aligner illumination system, referred as MO Exposure Optics (MOEO)[1,2]. The MO Exposure Optics system is based on high-quality microlens arrays in Fused Silica. MO Exposure Optics stabilizes the illumination against misalignment of the lamp, provides improved light uniformity, telecentric illumination and allows freely shaping the angular spectrum of the illumination light. Full control and light shaping are the key to optimize mask aligner lithography beyond today’s limits.

SUSS MicroTec and GenISys now provide Layout LAB, a lithography simulation software designed for full 3D simulation of proximity lithography in mask aligners[3]. Layout LAB allows the optimization of critical lithography steps, to improve resist pattern fidelity and helps to save costs in process development and to significantly improve the yield in production. Illumination control also opens the door to a new era of Advanced Mask Aligner Lithography (AMALITH), comprising Front-End-of-Line (FEOL) lithography techniques like Customized Illumination (CI), Optical Proximity Correction (OPC), Phase Shift Masks (AAPSM), Source Mask Optimization (SMO) as well as unconventional approaches like Talbot, Pinhole-Talbot, Grey-Level Lithography and more sophisticated wave front shaping techniques[4].

MASK ALIGNER, A SUCCESS STORY FOR 50 YEARS

Jean Hoerni’s revolutionary “planar process”, invented in 1957 and transferred to mass production at Fairchild Semiconductor in 1959, set out the technology path that semiconductor industry still uses today. Hoerni’s planar process used optical lithographic techniques to partially protect a silicon substrate, to diffuse the base of a transistor into the collector and then diffuse the emitter into the base. Hoerni’s planar process allowed for the manufacture of many transistors side-by-side on a planar Silicon substrate or “wafer”. These wafers were micro-structured by using photosensitive resist, light exposure through photographic “mask” and chemical development. Hoerni’s 3 to 4 masking steps required an alignment of a mask versus a previously structured pattern, a “mask alignment”. The planar process was soon licensed to other companies and revolutionized the semiconductor industry. In the early days of the „integrated circuit explosion“, the chip makers had to develop their manufacturing equipment on their own. But soon, the rapidly growing industry triggered a large request for manufacturing and testing equipment. The first semiconductor equipment manufacturer appeared on the scene and started to build mask aligners for 1” wafers.

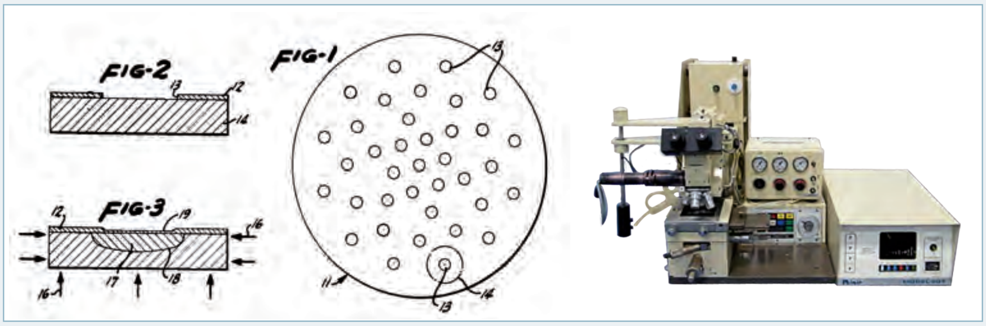

Figure 1. (left) Schematic drawing of a wafer having removed the masking layer within circles, taken from Jean A. Hoerni's famous patent US 3,064,167, filed in 1957; (right) Karl Süss MJB3 manual contact mask aligner.

In 1962 Karl Süss, local sales representative for Leitz Microscopes in Southern Germany since 1949, was approached by Hans Rebstock from Siemens Munich to build equipment for their IC development department. Beside microscopes, Leitz also offered precise translation stages, large substrate illumination systems and other useful parts which were used by Karl Süss and his technician Hans Fieser to build first prototypes of a mask aligner, a wirebonder and a prober for Siemens. Traveling frequently to the US, Ekkehard Süss, the elder son of Karl Süss, got in contact with Fred Kulicke from Kulicke & Soffa (K&S). Ekkehard Süss negotiated an agreement with K&S to distribute their mask aligners in Europe and quickly stopped the mask aligner development. A few years later, when K&S phased out their manufacturing of mask aligners, the Karl Süss KG had to re-start building mask aligners. Winfried Süss, the younger son of Karl Süss, joined the company and conducted the development of the MJB3 mask aligner. More than 2000 systems of the manual MJB3 mask aligner have been sold since then, until the MJB3 was finally replaced by the MJB4 in 2004.

Projection lithography pushed mask aligner lithography out of semiconductor front-end in the early 1980s. However, mask aligner lithography was never phased-out. The installed mask aligners remained in operation for less critical layers. The semiconductor Back-End-of-Line (BEOL), Advanced Packaging, MEMS, TSV for 3D-IC, and - most recently the very cost-sensitive LED manufacturing - maintained a continuous demand for some hundreds of new mask aligners installed every year in industry. Mature and robust technology, high throughput, ease of operation, low maintenance, moderate capital costs, attractive cost-of-ownership (COO) and low Cost-per-Litho-Layer are the key factors.

MO EXPOSURE OPTICS®

Over 50 years, the mask aligner systems have changed tremendously. Semiconductor manufacturing moved from 1” wafer size to 2” in 1969, to 3” in 1972, to 4” in 1976, to 6” in 1983, to 200 mm in 1993 and finally to 300 mm in 1998. Starting from a manual table-top exposure tool equipped with a single alignment microscope; the mask aligners have evolved to fully automatic cluster systems, providing a throughput of more than 150 wafers per hour. However, only little effort was undertaken to improve the shadow printing process itself. The illumination optics of modern mask aligners still looks very similar to the optics developed for first proximity aligners in the 1970s. Just recently, SUSS MicroTec has introduced a novel illumination system, the MO Exposure Optics. The new optics is based on two Köhler integrators consisting of double-sided microlens arrays. These high-quality microlens arrays are manufactured by SUSS MicroOptics exclusively for SUSS Mask Aligners and have been well optimized for mask aligner illumination. The two-stage homogenization of MO Exposure Optics is a novel illumination concept (patent pending). MO Exposure

Optics improves the light uniformity, provides telecentric illumination and the freedom of freely shaping the angular spectrum of the illumination light. For more details about the optical concept behind the MO Exposure Optics illumination system please review related publications[1,2,4] and the SUSS report from Dec 2010.

The most important benefits of the new MO Exposure Optics are

- stabilization of the illumination against misalignment of the lamp,
- improved light uniformity and telecentric illumination;
- optimization of the angular spectrum of the illumination light to reduce diffraction effects;
- and the possibility to use lithography enhancement techniques like Customized Illumination (CI), Optical Proximity Correction (OPC), Talbot-Lithography, Phase Shift Masks (AAPSM) and Source Mask Optimization (SMO) in mask aligners.

Since the market introduction more than 70 MO Exposure Optics systems have been installed in SUSS Mask Aligners worldwide. Yield improvement and cost savings have been so significant, that beta-customers have already completely upgraded production fabs to the new technology. Advanced Mask Aligner Lithography (AMALITH) research teams have been formed at universities and research centers.

PROXIMITY LITHOGRAPHY IS LIMITED BY DIFFRACTION EFFECTS AT THE PHOTOMASK

The performance of mask aligner lithography is determined by two parameters: Resolution also referred to as minimum critical dimension (CD), and overlay. Resolution is defined to be the minimum feature size that can be transferred with high fidelity to a resist layer on a wafer. Overlay is a measure of how accurately patterns on successive masks can be aligned or overlaid with respect to previously defined patterns on the same wafer. The resolution in shadow printing lithography is limited by diffraction effects. Submicron resolution is achieved for vacuum contact, where the air in-between mask and wafer is evacuated. For vacuum contact lithography, very tight requirements regarding flatness and cleanliness apply. Any remaining particle will increase the mask-to-wafer distance and will deteriorate the printing results. In production environment, with the demand for low costs and high throughput, proximity lithography is used. Here wafer and mask are separated by some 30 to 200 microns proximity gap. The achievable resolution decreases with increasing proximity gap due to diffraction[5]. As already proposed by Abbe, diffraction effects like side lobes, higher orders and interference effects could be altered by spatial filtering of the illumination light, changing both the angular spectrum and the spatial coherence properties of the illumination light. In projection lithography, a spatial filtering of the illumination light is referred as “customized illumination” and a well-established resolution enhancement technology (RET). MO Exposure Optics now offers a quick and easy change of the angular spectrum of the illumination light. Exchangeable illumination filter plates (IFP) allow altering the angular spectrum and the coherence properties of the mask illuminating light in the mask aligner[6].

CUSTOMIZED ILLUMINATION

Figure 2 a) shows schematically a simple lithography model for the use of MO Exposure Optics for proximity lithography[4]. The photomask is assumed to have a single square opening similar to a pinhole. Thus, the lithography system is reduced to three planes: The illumination filter plane, defining the angular spectrum, the mask plane and the wafer plane, where the resulting aerial image is recorded in photoresist. In this simple model, the opening of the photomask acts like a pinhole camera and images the illumination filter pattern onto the photoresist. As shown schematically in Figure 2 b) the illumination

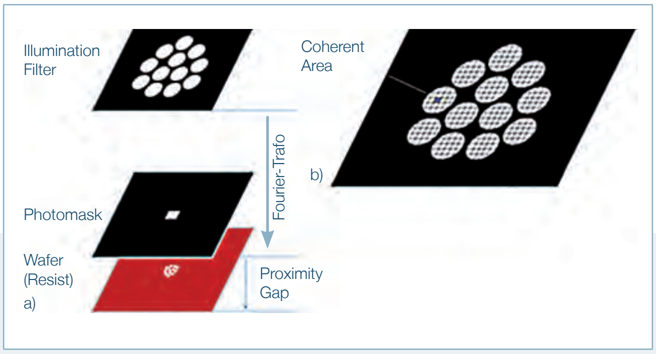

Figure 2. Simplified lithography model for the use of MO Exposure Optics in proximity lithography introduced by Stürzebecher[4]. (a) For a single opening in the mask the illumination filter pattern is imaged to the wafer plane. (b) The illumination filter plane is assumed to be subdivided in a multitude of coherent areas, where each is considered to be an ideal coherent source, but no coherence between different areas is assumed. The geometry of the illumination filter plate defines which of the coherent areas are transmitted and can contribute to the mask illumination.

filter plane is assumed to be subdivided in a multitude of coherent areas, where each is considered to be an ideal coherent source, but no coherence between different areas is assumed.

The geometry of the illumination filter plate defines which of the coherent areas are transmitted and which areas contribute to the mask illumination. In this simplified model, the optical system performs a Fourier transformation from the illumination filter to the mask. Thus, every coherent area in the illumination filter plane is creating a tilted plane wave while the tilt corresponds to the position of the considered area in the filter plane. Each of these plane waves is coherent, but different waves are incoherent to each other. The mask aligner is considered to be a device which is creating a set of non-interacting plane waves in which the composition of angular components is selected by choice of the illumination filter plate. This simple model is useful to predict the resulting aerial image and to optimize the illumination to improve resolution and fidelity of the resist prints[4].

OPTICAL PROXIMITY CORRECTION (OPC) AND SOURCE-MASK OPTIMIZATION (SMO)

Optical proximity correction (OPC) is a resolution enhancement technology (RET) commonly used to compensate for errors and irregularities like corner rounding, line width narrowing and edge shortening. Optical proximity correction corrects these errors by moving edges or adding extra polygons to the photomask pattern. If both customized illumination and optical proximity correction are used this is referred as source-mask optimization (SMO). Primary goals are enhanced CD control, increased resolution and depth of focus, improvement of the manufacturability for critical lithography steps and enlargement of the process window. Source-mask optimization allows pre-compensating print errors due to diffraction and process effects. MO Exposure Optics and source-mask optimization technology have a strong impact on process window enlargement and yield improvement in production environment.

LAYOUT LAB - SIMULATION TOOL FOR ADVANCED MASK ALIGNER LITHOGRAPHY (AMALITH)

Layout LAB from GenISys[3] provides full 3D simulation for proximity lithography processes. Simulation shortens the development cycle, enables Design For Manufacturing (DFM) to save costs on process development and allows for pushing mask aligner lithography beyond its current limits. This “ease-of-use” software, geared towards casual users as well as power users is capable of modeling the illumination of a broadband source and the different illumination types of SUSS Mask Aligners, including the capability to model the new MO Exposure Optics with arbitrary illumination filter plate (IFP) designs. It rapidly calculates the intensity image for arbitrary mask layouts (including grey-tone and phase-shift) at any proximity gap. The reflections and absorption of the light in the wafer stack is accurately modeled, resulting in a 3D intensity image in the resist. The calculated intensity image allows the optimization of IFP design and mask layout in combination, without high expenses for photomasks and experimental wafer exposure series.

Improving proximity lithography is of much interest for all production-related mask aligner processes. For large wafer sizes like 200 mm and 300 mm and high volume production a proximity gap of ≥30 µm is needed to avoid any contact of mask and wafer. This proximity gap of 30 µm

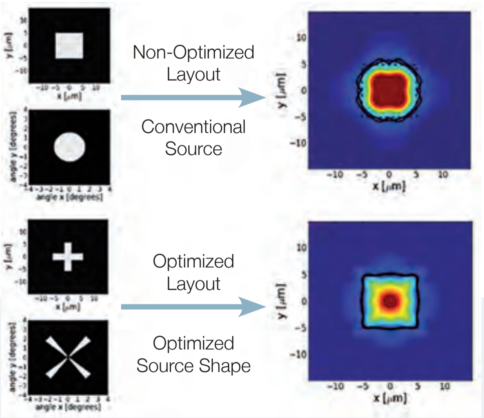

Figure 3. Simulation of a 10µm square exposed at a gap of 50µm. The simulation of the non-optimized mask layout with a conventional source shape shows that the intensity image at 40-50µm gap is distorted. Optimization of mask layout (cross) and the source shape results in a better figure fidelity to the square shape over the gap range.

limits the obtainable resolution to some 3µm, a severe limitation which had driven mask aligner lithography out of the semiconductor front-end in the early 1980s.

Figure 3 shows that the fidelity of a square-type mask pattern with 10 µm features to be printed at a proximity gap of 50 µm could be improved by optimizing the mask layout and the illumination shape (IFP design) in combination.

Without simulation it would not be intuitive that the cross mask layout combined with a 45° rotated cross-like IFP design results in a perfect square.

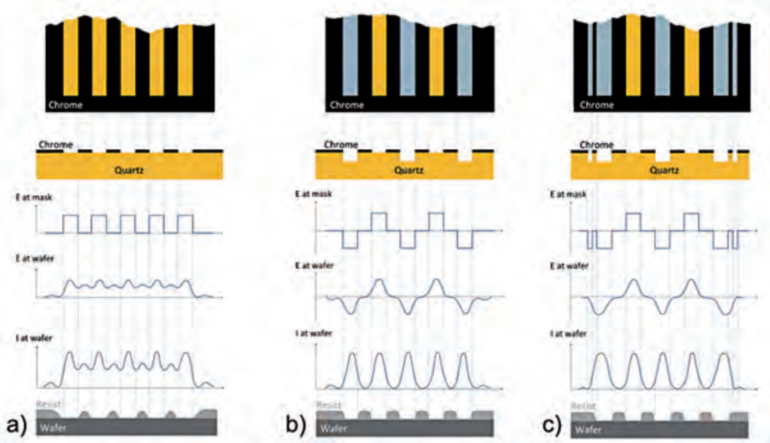

Figure 4. Three different types of photomasks: a) binary photomask, b) alternating aperture phase-shift mask (blue: additional phase step), and c) alternating aperture phase-shift mask (AAPSM) with additional OPC scattering bar.

Layout LAB also includes the 3D modeling of the resist development process. Please see the article "Simulation for Advanced Mask Aligner Lithography" in this SUSS report for more details on the simulation software Layout LAB and its application.

ALTERNATING APERTURE PHASE SHIFT MASKS (AAPSM)

In a next step phase shift masks (PSM) were examined for resolution enhancement. Figure 4 a) shows a binary photomask, where light is either reflected and just partially absorbed by the chromium layer (black) or passes openings (yellow). The shadow pattern at a certain distance behind the mask is affected by diffraction and interference effects. Light also propagates in the dark areas and bright areas are darkened partially.

For alternating aperture phase shift masks (AAPSM), shown in 4 b) and c), a phase step (blue) is added to the binary mask structure. Light passing the glass and phase step openings are shifted in phase by 180° versus each other. As shown in 4 b), this phase shift improves the contrast for proximity lithography significantly. 4 c) shows an alternating aperture phase-shift mask (AAPSM) with additional OPC scattering bars. The additional OPC scattering bar corrects the intensity, width and position of the outer lines. OPC correction of line-end shortening is also possible, but was not applied for this evaluation.

A five-bar pattern was printed in 1 µm thick AZ1512 resist at 30 µm proximity gap (365 nm wavelength) for verification of the simulation results. Figure 5 a) - c) shows a similar 2 µm (half-pitch) five-bar pattern printed at 30 µm proximity distance. For Figure 5 a) using a standard binary photomasks, only 4 instead of 5 lines are observed (reversal of image contrast), the pattern is not resolved. For the AAPSM shown in Figure 5 b) the pattern is resolved, however, the outer lines are not exposed with a similar dose and remain

Figure 5. Prints in photoresist for a 2 µm (half-pitch) five-bar pattern printed at 30 µm proximity gap using three different types of photomasks as defined in Figure 4: a) the pattern is not resolved with a binary mask, b) a phase-shift mask (AAPSM) allows to resolve the pattern, c) additional OPC scattering bars allow to correct intensity, width and position of the outer lines. No correction of line-end shortening had been applied.

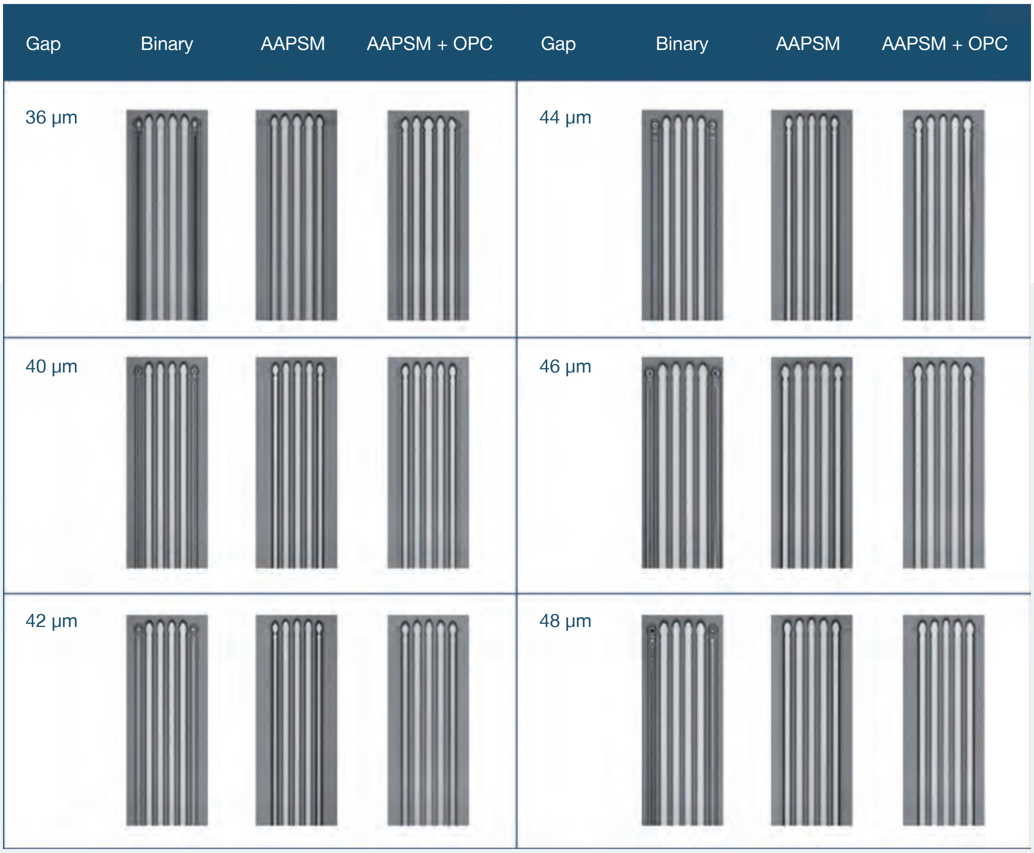

Figure 6. Prints in photoresist for 2 µm openings (lines & space pattern) similar to , but at different proximity gaps. The prints from the alternating aperture phase shift mask (AAPSM) with OPC scattering bars demonstrates a resolution of 2 µm for a proximity range of operation from 30 µm (see f) to 48 µm.

smaller. This remaining error is solved by adding OPC scattering bars shown in Figure 5 c).

Figure 6 shows photoresist prints (1 µm thick AZ1512 resist, 365 nm) for the three different photomask (similar to Figure 4 and 5), but at different proximity distances behind the mask. The prints from the alternating aperture phase shift mask (AAPSM) with OPC scattering bars show a resolution of 2 µm (half-pitch) for a proximity distance from 30 µm up to 48 µm. Simulation and experiment proofed that AAPSM and OPC allow enhancing the resolution at proximity lithography. In practice, special care has to be taken in OPC algorithms for mask aligners to generate layouts with manageable manufacturing and inspection costs.

COSTS PER LITHOGRAPHY LAYER

Although semiconductor industry changed over from mask aligners to projection steppers/scanners in the early 1980s, mask aligners were never sorted out. Still today some hundreds of new mask aligners are sold each year. This continuing success of mask aligner lithography is due to two basic trends in lithography:

(a) Costs for leading-edge lithography tools double approximately every 4.4 years; and (b) the number of lithography steps per wafer was increasing from a few litho-layers to more than 35 layers now. This explains why the mask aligner, a mature, very cost-effective and robust solution for uncritical litho-layers, is still widely used today.

As shown schematically in Figure 7, the costs for mask aligner lithography for uncritical layers (>5 µm resolution) are typically 3x lower than in a low-cost stepper and about 5x lower than in a wafer stepper from front-end. Mask aligner lithography achieves high yield in production, similar to a front-end lithography processes and typically CD uniformity (CDU) is not even monitored for cost reasons. In practice, the situation is often less favorable. Scientists and engineers always test the limits. The constant demand for higher resolution for a next generation of a device forces process engineers to constantly improve resolution and overlay. As shown schematically in Figure 7, already a resolution of 4 µm is related to higher costs, usually provoked by the lower yield. For 200 mm or 300 mm wafers in a production environment it is not trivial to maintain a constant and accurate gap over the full wafer, and a gap mismatch is getting more critical if the structures are close to the resolution

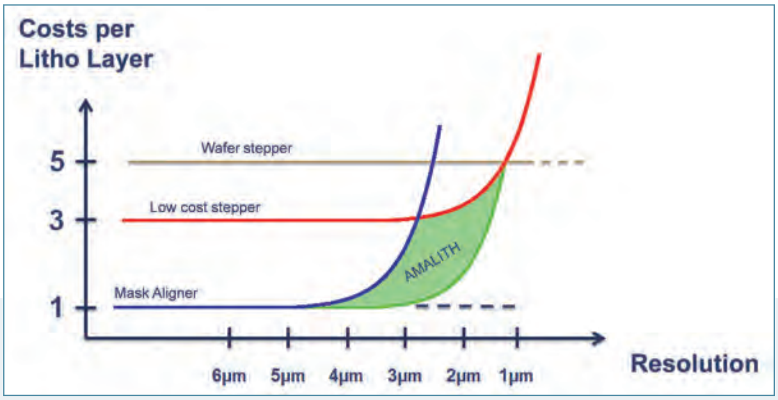

Figure 7. Scheme for the costs per lithography layer for mask aligners (proximity lithography), low-cost steppers and high-resolution wafer steppers related to the required resolution. Costs per layer increase if the technology is reaching its resolution limits due to yield problems. Advanced Mask Aligner Lithography (AMALITH) allows to push the resolution limits, to increase yield of established but critical processes and to compete with low-costs wafer steppers.

limit of 3 µm at 30 µm proximity gap. If mask aligners can't handle it anymore, a painful and cost intensive switch to higher-resolution projection lithography is required. High investment costs, new process development, and higher costs per litho-layer are the price. Often, a switch to projection lithography is not possible at all. Especially for very thick resist layers, the limited depth-of-focus (DoF) of a projection system is not sufficient. As a consequence, the process engineers try to optimize mask aligner lithography to the very limit. The process window is narrowing and the lithography steps become critical and relevant for the overall yield.

Astonishingly, this unfortunate situation is tolerated, at least as long as the costs for a technology switch are higher than the costs introduced by a lower yield. MO Exposure Optics and Advanced Mask Aligner Lithography (AMALITH) now offer a unique chance to significantly improve resolution and yield for established but critical processes in production. After 30 years of standstill with no roadmap for resolution and quality improvement, it is possible to push mask aligner lithography beyond today's limits. MO Exposure Optics is available for all generations of SUSS MicroTec mask aligners.

CONCLUSION AND OUTLOOK

The shadow printing lithography process in a mask aligner has not improved since mask aligners were moved out of front-end lithography in the early 1980s. Still today, contact-less proximity lithography in a mask aligner is limited to some 3 µm resolution for 30 µm proximity gap. Recently, a novel illumination system for mask aligners, referred as MO Exposure Optics, has been introduced. The MO Exposure Optics consists of two microlens based Köhler integrators, providing excellent uniformity of both intensity and angular spectrum of the illumination light. MO Exposure Optics uncouples the light from misalignment and lateral instabilities of the lamp. MO Exposure Optics allows implementing resolution enhancement technology (RET) known from front-end projection lithography, like, customized illumination, optical proximity correction (OPC) and source-mask optimization (SMO) in mask aligner lithography. Layout LAB proved to be a powerful simulation tool for mask aligner lithography. Resolution enhancement by using AAPSM and OPC scattering bars was demonstrated. The results show the high potential to improve mask aligner lithography beyond today's limits. The presented approach for lithography and resolution enhancement in mask aligners will have much impact on yield and costs in production. This new era of mask aligner lithography is referred as Advanced Mask Aligner Lithography (AMALITH).

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After studying mechanical engineering at the Technical University Ilmenau, Germany, Uwe Vogler joined SUSS MicroOptics in 2009 as optical engineer. He has specialized on illumination systems and as Junior Product Manager has been responsible for the product line MO Exposure Optics since 2010.

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Ulrich Hofmann has more than 20 years experience in the semiconductor industry. Before founding GenISys, Ulrich worked working in various technical and management positions on E-beam technologies as well as optical lithography technologies.

Ulrich Hofmann received his Diploma in Physics at the Technical University Munich in 1987. For the thesis in theoretical nuclear physics, he developed a new model on how to compute magnetic moments for nuclei. His first contact with the Semiconductor world was with Sigma-C in 1989, developing the first working hierarchy engine for E-beam lithography, data preparation and proximity effect correction, enabling full chip proximity effect correction on a single desktop computer. After joining Etec Systems in Hayward, CA in 1996, Ulrich pioneered technologies such as real-time proximity effect correction, hierarchical data processing, and ultra-high bandwidth datapath for massive parallel E-Beam direct write, and later became responsible for the commercial development and factory integration of the RSB next generation mask lithography tool. In 2005, he founded GenISys GmbH, a software house providing solutions for the optimization of microstructure fabrication processes for R&D, semiconductor manufacturers and equipment suppliers throughout the world.

As Vice President Marketing & Sales at GenISys GmbH in Munich, Germany, Nezih Unal is one of the company's key figures in creating unique solutions that make a difference. With over 25 years experience in various engineering and management positions in the semiconductor industry, Nezih worked on diverse technologies such as MEMS devices, optical lithography simulation software, and e-Beam lithography software.

Nezih Unal received his Diploma in Electronics Engineering at the University of Wuppertal in Germany in 1988, with a focus area on semiconductor technology. After his thesis on plasma and ion sources for micro-patterning processes he has started to work on the development of Reactive Ion Etching (RIE) processes for sub-micron IC manufacturing at Motorola. In 1992 he joined the new start-up microParts GmbH to develop and manufacture 3D MEMS devices using X-ray lithography (LIGA technology). Nezih joined SIGMA-C GmbH as director of Sales in 2003, and positioned the optical lithography simulation software SOLID as a strong #2 in the market. Early 2006, Nezih joined GenISys GmbH in his current role

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