PHOTOMASK

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

BACUS N • E • W • S

NOVEMBER 2013
VOLUME 29, ISSUE 11

Best Oral Paper - PM13

The SEMATECH high-NA actinic reticle review project (SHARP) EUV mask-imaging microscope

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ABSTRACT

The SEMATECH High Numerical Aperture Actinic Reticle Review Project (SHARP) is a newly commissioned, synchrotron-based extreme ultraviolet (EUV) microscope dedicated to photomask research. SHARP offers several major advances including objective lenses with 4xNA values from 0.25 to 0.625, flexible, lossless coherence control through a Fourier-synthesis illuminator, a rotating azimuthal plane of incidence up to ±25°, illumination central ray angles from 6 to 10°, and a continuously tunable, EUV illumination wavelength. SHARP is now being used to study programmed and native mask defects, defect repairs, mask architecture, optical proximity correction, and the influence of mask substrate roughness on imaging. SHARP has the ability to emulate a variety of current and future lithography tool numerical apertures, and illumination properties. Here, we present various performance studies and examples where SHARP's unique capabilities are used in EUV mask research.

1. Introduction

The SEMATECH High-NA Actinic Reticle review Project (SHARP) microscope is a new, synchrotron-based extreme ultraviolet (EUV, 13.5-nm wavelength) microscope created to support advanced photomask research for the semiconductor industry. The microscope serves photolithography generations to the year 2020 and beyond, when printed feature sizes are expected to fall below 10 nm. SHARP is designed to emulate the optical properties of current and future EUV lithography tools, enabling the study of mask defects, pattern architectures, optical proximity correction, phaseshifting patterns, and more.[1,2,3] SHARP, which was commissioned in Spring 2013 is the successor to the SEMATECH Berkeley Actinic Inspection Tool (AIT) which was decommissioned in September, 2012 after eight years of operation.

Owing to their highly wavelength-specific optical properties, the creation of production-quality EUV masks may come to rely upon dedicated EUV-wavelength mask-blank inspection and/or pattern-imaging tools. With commercial tools still months to years years from deployment, SHARP was created by an industry/government partnership to provide advanced research and development capabilities.

SHARP utilizes several advanced short-wavelength optical elements and systems, including an array of user-selectable Fresnel zoneplate lenses to achieve high spatial resolution imaging, and a lossless, Fourier synthesis illuminator[4] to provide customizable coherence

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EDITORIAL

Be there or be ■

Wolf Staud, *Consultant*

I remember it like it was yesterday. Jim Reynolds called my boss, to let me know that I was invited to the BACUS Steering Committee. At the time we met at the SEMI building in Sunnyvale. The only other person that was there that day was Jim Wiley. He had just started his “Son of Printability” franchise.

I was at LSI LOGIC. Doug Anberg [still at Ultratech – who I never thanked enough for the opportunities he provided for me] had just put me in charge of Reticle Engineering.

We bought from shops like Micro Mask, Tau Labs, Diamon Images, Master Images, even HP and Align Rite. The business was 90% UT1X, with some 5X Nikon for advanced work. KLA221 for incoming inspections, with a long working distance objective – so we could inspect through the pellicle.

I had just come over from Fairchild Gate Array, where we used a Gray Computer linked with a Cambridge E-Beam writer to do our prototyping. Very unsuccessful. Next thing you know, we are meeting with ATEQ, twisting their arms to build a laser direct write system for us. John Stirnemann offered 1 wafer/hr, we wanted 10 wph. Life was good then – even as a Mask or Reticle Engineer. Lots of vendors competing for your business, lots of lunches, lots of golf, lots of baseball games.

BACUS ran a Monthly Meeting then. Always 2, even 3 talks, lots of good direct interfaces on a very frequent basis. The Steering Committee met afterwards at Reynold’s office in Sunnyvale. One morning Dr. Kueck from FhG Dresden came in. What a shock when he showed us the old GDR chip facilities, and all of their advanced E-Beams. Who knew the East had that kind of advanced technology?

The annual Symposium drew 60 people at the Red Lion Inn. Parties were being held at the Winchester Mystery House, and Villa Montalvo. People in Saratoga did not appreciate our kind.

Then came the years of ‘consolidation’. DuPont and Photronics gobbled up every mask house and captive shop in sight, and BACUS aligned itself with SPIE. We moved the Symposium to Monterey because of MUGS – only to see ETEC fall in the hands of AMAT.

I just left the BACUS Steering Committee. After 25 years, only Larry Zurbrick has been with it longer. Not because ‘masks’ isn’t fun anymore – on the contrary. But the Steering Committee is not. Gone are the heydays of DFM with Bob Naber and Tracy Weed pulling in close to 200 papers. The conference has shrunk to half that size. Darwin said ‘only those who adapt, survive’. BACUS has not learned to adapt. After we battled thru all the NGLs, and only one is left, the technology today is actually more fun than ever, with many many mask questions looming wide and large in EUV. The very recent BACUS Panel on ‘Big Glass’ is a perfect example. Paul Ackmann and team delivered a great debate. A clear sign that consolidation – of the conferences – is needed here too. Wally Rhines, in his keynote a couple of years back, joked that at some point the keynote will be the only attendant at DAC – or any conference for that matter. With the vision that Brian Grenon gave us, of the Merchants becoming irrelevant, and the Captives down to 5 or 6, we are nearing that vision as well. The challenges are bigger than ever, but the players are also fewer and fewer.

Let me close by thanking all of you – the attendees, presenters, authors and chairs of all the conferences past. And the SPIE Staff. What a great job you have done. Because of your commitment BACUS remains a key element of our annual conference cycle. And hopefully it will have many more highlights like that last panel.

Paul, and then Hayashi-san have their work cut out. Let’s support them to the best of our capability.

P.S: as for the title: I support 12” round.

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BACUS News is published monthly by SPIE for BACUS, the international technical group of SPIE dedicated to the advancement of photomask technology.

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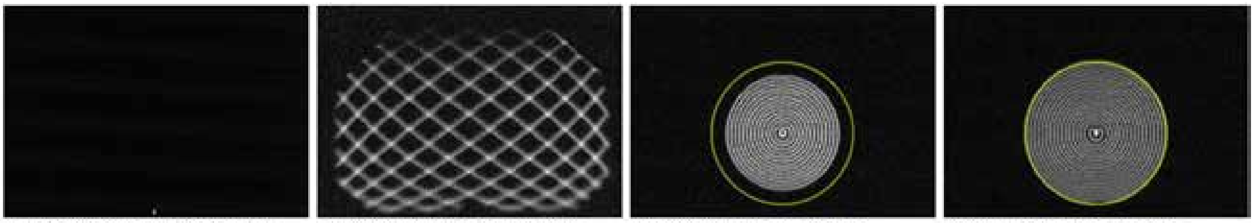
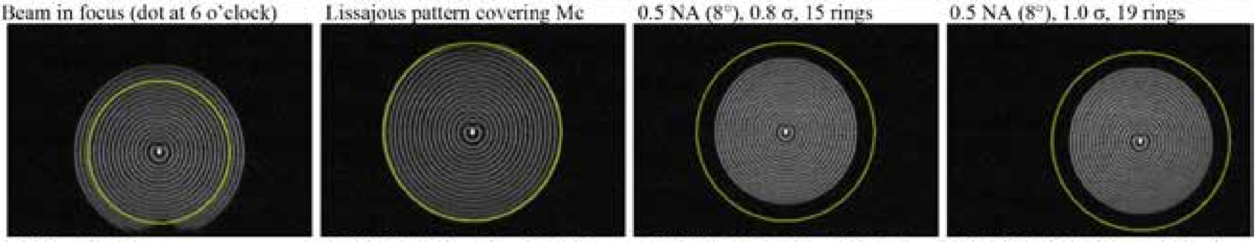
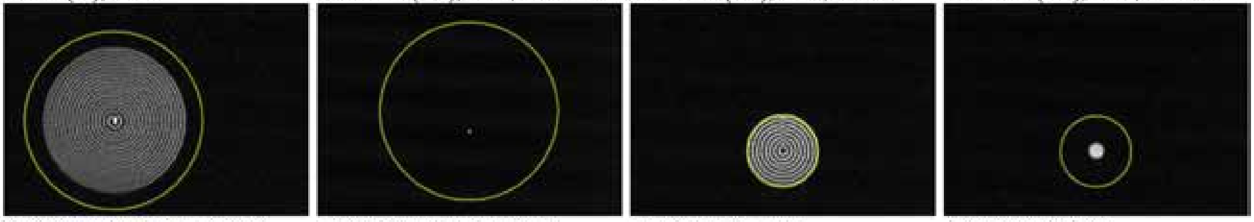


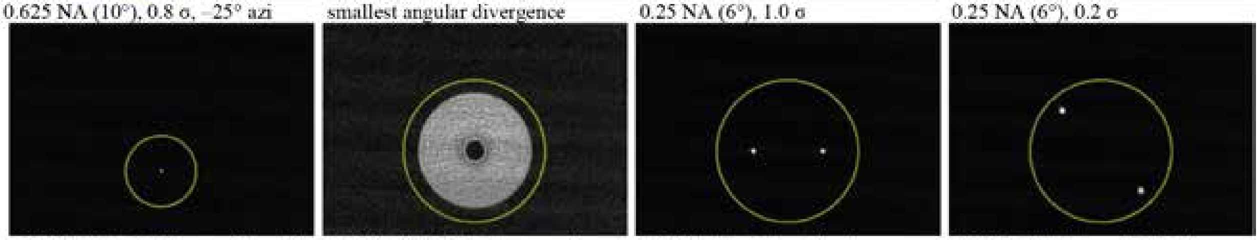
Beam in focus (dot at 6 o'clock)
Lissajous pattern covering Mc
0.5 NA (8°), 0.8 σ, 15 rings
0.5 NA (8°), 1.0 σ, 19 rings



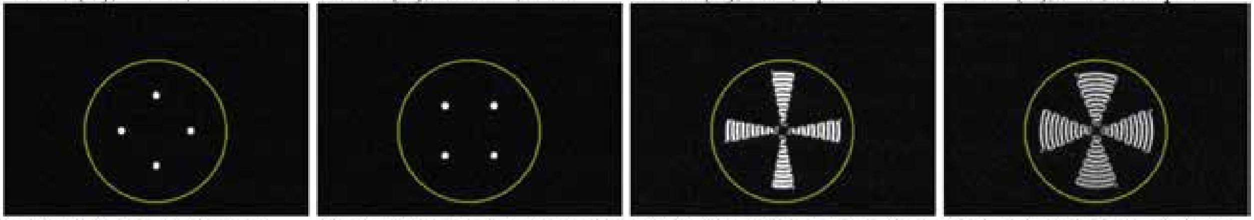
0.5 NA (8°), 1.2 σ
0.625 NA (10°), 1.0 σ, 10° CRA
0.625 NA (10°), 0.8 σ, 10° CRA
0.625 NA (10°), 0.8 σ, +25° azi



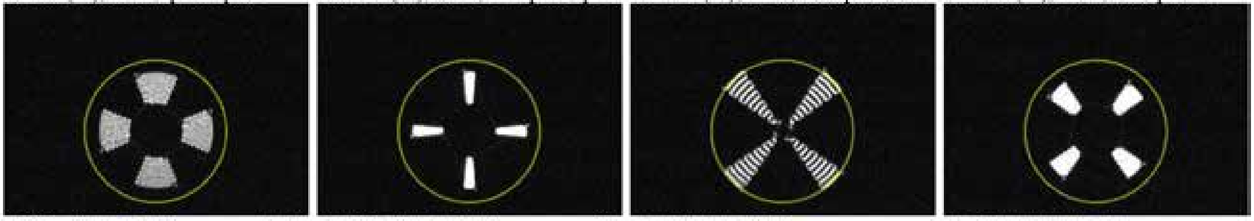
0.625 NA (10°), 0.8 σ, −25° azi
smallest angular divergence
0.25 NA (6°), 1.0 σ
0.25 NA (6°), 0.2 σ



0.25 NA (6°), 0.047 σ, smallest fill
0.5 NA (8°), 0.2–0.8 σ, annular
0.5 NA (8°), 0.8 σ, dipole
0.5 NA (8°), 0.8 σ, 45° dipole

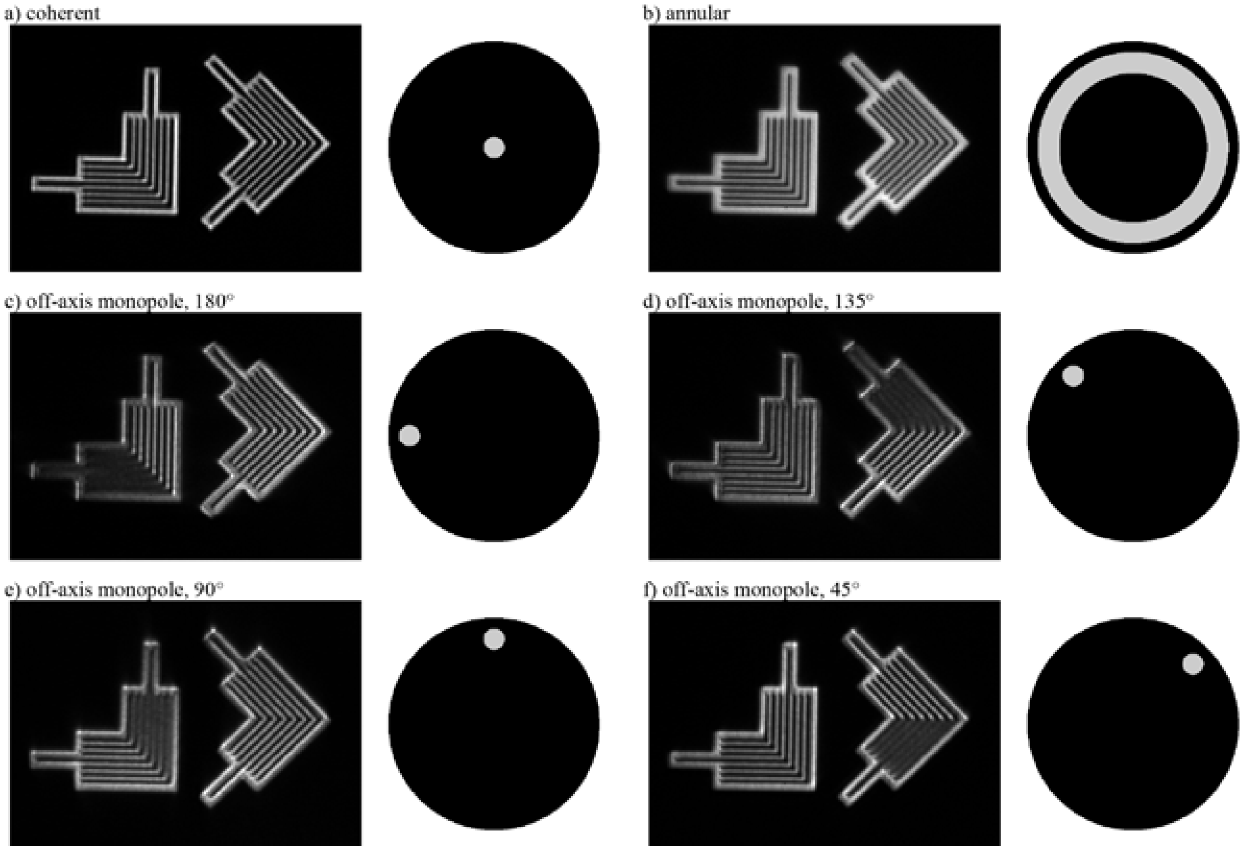


0.5 NA (8°), 0.5 σ, quadrupole
0.5 NA (8°), 0.5 σ, 45° quadrupole
0.5 NA (8°), 0.8 σ, crosspole 22.5°
0.5 NA (8°), 0.8 σ, crosspole 45°



0.5 NA (8°), 0.4–0.8 σ, crosspole 45°
0.5 NA (8°), 0.4–0.8 σ, crossp. 10°
0.5 NA (8°), 0.1–1 σ, 45° crosspole, 22.5°
0.5 NA (8°), 0.4–0.8 σ 45° crosspole, 22.5°

Figure 1. Demonstration of (angular) pupil fill patterns, recorded with EUV light on the pupil-fill monitor. Patterns are drawn during each exposure.



a) coherent

b) annular

c) off-axis monopole, 180°

d) off-axis monopole, 135°

e) off-axis monopole, 90°

f) off-axis monopole, 45°

Figure 2. Demonstrations of coherent on-axis and off-axis monopole illumination of an elbow test-pattern. The black circles represent the full pupil, and the white dot the illumination angle and size within it. The patterns have 100-nm half-pitch, and were imaged using 0.33 4xNA. (b) Annular illumination with the same offset angle.

control. The zoneplate lenses are fabricated with electron-beam lithography in a freestanding nickel absorber membrane featuring a stenciled design for mechanical strength. A number of lenses are available with 4xNA values ranging from 0.25 to 0.625 and five separate azimuthal angles between –25° and +25° to reproduce a rotating plane of incidence across the aperture of a ring-field system. SHARP's mechanical design and vibration isolation strategy have been described previously.[2] SHARP's monochromator enables illumination with a tunable wavelength and a $\Delta E/E$ bandwidth that is typically below 1/1450. Multilayer mirrors limit the usable range to approximately 13.2–13.7 nm.

In its first four months of operation, SHARP has been used to study patterned and native defects, repairs, mask architecture, multilayer surface roughness, line-edge roughness, and the dependence of imaging on illumination properties. This last subject is particularly well aligned with SHARP's measurement capabilities.

Illumination coherence is central to imaging in photolithography. Coherence has a strong effect on the appearance of defect repairs and printability, multilayer and line-edge roughness, optical proximity corrections, and the basic properties of contrast and image slope for patterns, especially at small sizes. Data from SHARP is used to calibrate modeling and to provide aerial image information for comparison with wafer printing.

In addition to now-routine operations in support of SEMATECH member company users, we are conducting experiments to characterize and improve the performance of the various sub-systems over time. Here we present several experiemntal demonstrations of the capabilities of SHARP, and a small sampling of data collected with the tool.

2. Fourier-Synthesis Illuminator

SHARP's Fourier-synthesis illuminator[4] uses three multilayer-coated mirrors to convert the synchrotron beamline's inherent low-divergence beam into arbitrary off-axis angular patterns ranging from 1 to 20° supporting central ray angles up to 10° (mask side). The first mirror, M_A, is a 1-mm-diameter MEMS mirror mounted on a two-axis actuator that is capable of scannnig an angular range of ±4° at frequencies up to 2 kHz.[3] Within each exposure, we scan an illumination pattern to create customized partial coherence 'fill patterns.' The beamline is focused onto M_A, with a beam size of approximately 250 µm that can be reduced using a pair of *xy* slits, close to the mirror. The second mirror, M_B, is a flat folding mirror that steers the beam upward into a condenser. Its purpose is to minimize

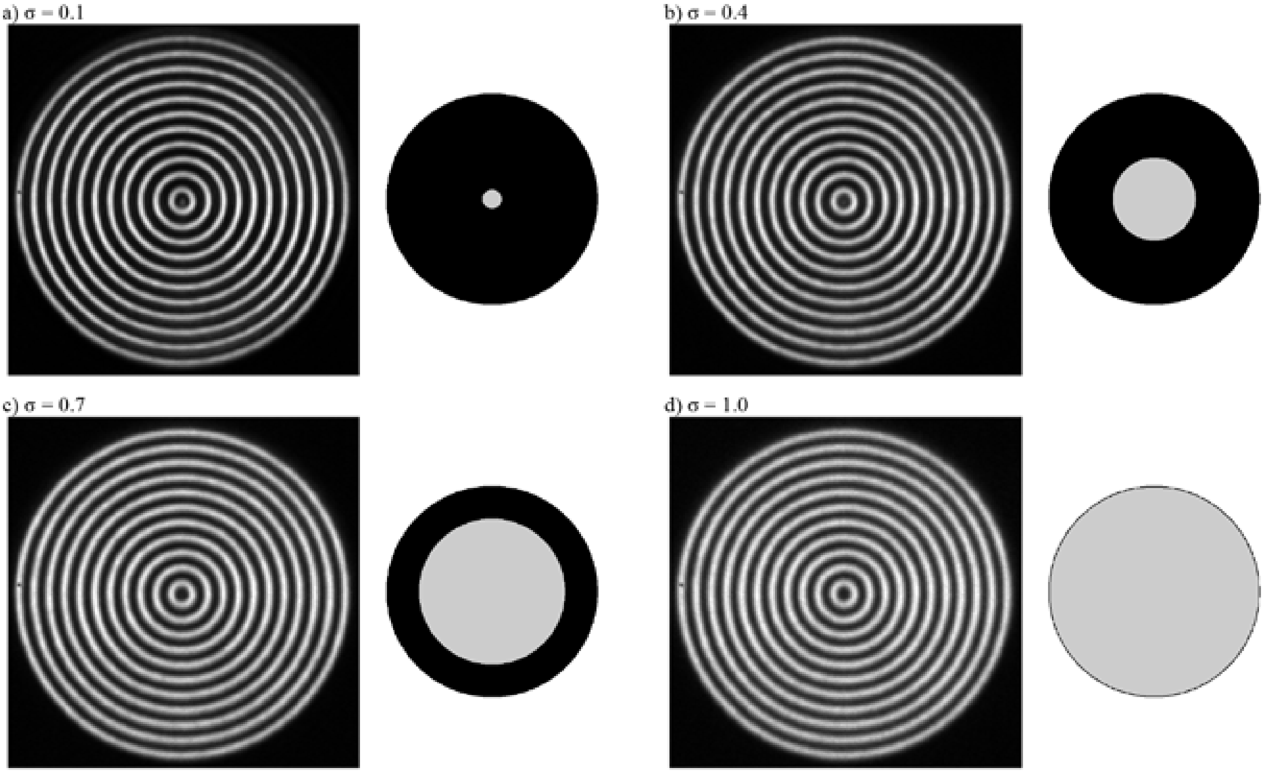


Figure 3. Circle grating images recorded with varying disk fill patterns. The gratings have 110-nm half-pitch, and are imaged by a 0.33-4xNA lens

the angles of incidence on the condenser, M_C. The condenser is an off-axis ellipsoid with a graded multilayer coating. The condenser provides a 10x demagnification, reimaging the beam spot from M_A onto the mask. In other words, M_C focuses every ray that leaves M_A, to a demagnified beam spot on the mask surface.

To visualize and calibrate the illumination, SHARP has a low-magnification (1.7x), in-vacuum, YAG microscope mounted to the mask stage, called the *pupil-fill monitor*. The YAG crystal converts the incident EUV beam into visible light, which is reimaged by the microscope. The mask stage allows the YAG to be placed into the focal plane of the illuminator, where the rays converge to a single point. Beam angles are calculated by measuring the light in two longitudinal planes: the focal plane, and a plane 5 mm lower.

Examples of vaious pupil-fill patterns are shown in Fig. 1. Positions in the images correspond to off-axis angles. Here, angles in the central plane of incidence would be along the y-axis in the center of the image. The smallest static angle is 2.96 mrad, which corresponds to 0.047 σ at 0.25 4xNA, or 0.019 σ at 0.625 4xNA.

3. Demonstration of Partial Coherence Effects in Imaging

In SHARP images, the effects of illumination partial coherence are readily observable, giving insight into the nature of image formation. All illumination patterns may be understood as an additive synthesis of off-axis monopoles, a point that underlies the operation of the Fourier-synthesis illuminator.[5] Here we first study the pattern imaging from a coherent, off-axis monopole illumination. We then consider line imaging under varying partial coherence. Finally, we observe the effect of increasing the NA while preserving constant illumination conditions.

3.1 On-axis and off-axis monopole illumination

Figure 2 contains a series of images of the same elbow-pattern test object recorded with different illumination settings. For these experiments a 100-nm half-pitch elbow pattern was used with a 4xNA value of 0.33. With coherent illumination (Fig. 2a) the features are clear and well resolved. However, off-axis monopole illumination, with 0.1 σ, and a relative offset magnitude of 0.8, causes significant changes. Readily observable is the loss of resolution of features parallel to the off-axis direction. This behavior is readily understood from the perspective of Fourier optics, wherein the lens pupil behaves as an angle-space filter on the imaging. For dense, line pattern features to be resolved by a lens, the diffraction orders must pass into the pupil. Those diffraction orders follow the angle offset of the central ray. So, when the central ray is close to the edge of the pupil's solid angle, diffraction orders falling in the direction perpendicular to the offset angle can be clipped by the pupil. The images in Fig. 2c, d, e, and f show how the rotation of the illumination selectively filters different line orientations in the pattern. For comparison, Fig. 2b shows imaging annular illumination, which may be considered as the synthesis of a

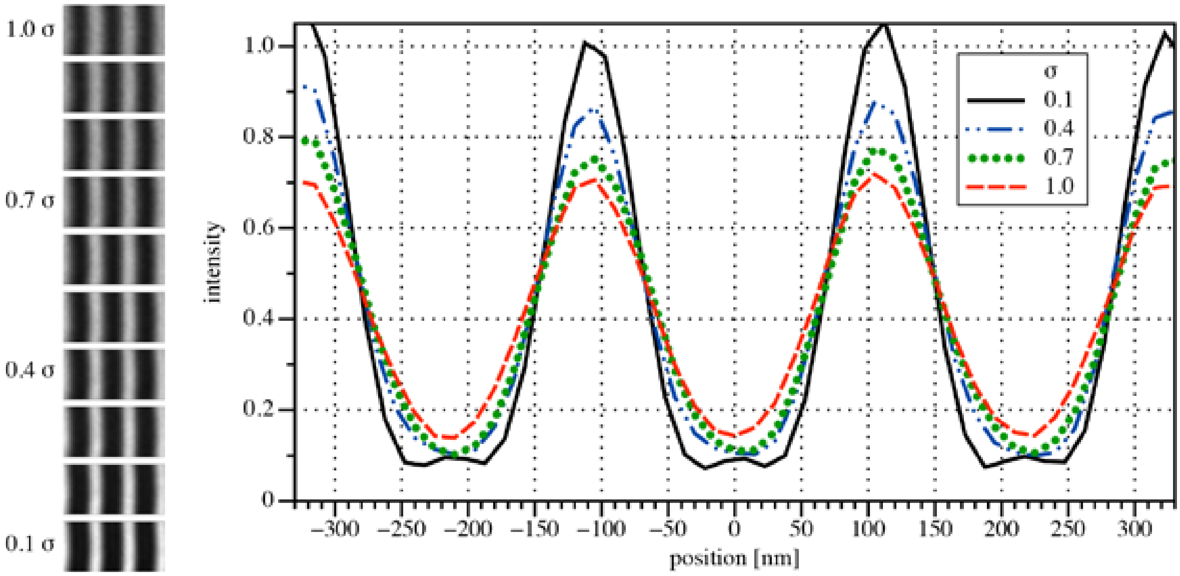


Figure 4. Line intensity profiles extracted from the circle grating pattern in the 3 o'clock position. The profiles share a common intensity normalization, showing that the coherent light ($\sigma = 0.1$) has the globally highest peaks. At this line size and NA, higher σ values are associated with reduced contrast, and lower image intensity slope. (Color online.)

continuous ring of off-axis angles. With annular illumination, the contrast in these small features is reduced, but the depth of focus (not shown) can be enhanced.

3.2 Varying partial coherence

Figures 3 and 4 provide a demonstration of varying line intensity profiles as a function of the partial coherence, with disk illumination ranging from $\sigma = 0.1$ to 1.0. The intensity profiles in Fig. 4 are normalized to the brightest portions of the $\sigma = 0.1$ case, showing that larger sigma values lead to a redistribution of the intensity within the pattern. In addition to the contrast differences, the reduction of the image intensity slope in the high σ cases is apparent.

3.3 Varying numerical aperture

Imaging of fine patterns depends strongly on the ways in which the various diffraction orders are transmitted or are filtered by the lens. A series of measurements conducted on SHARP reveals how the lens numerical aperture affects line imaging behavior with a fixed illumination pattern, and a constant mask pattern. Figure 5 contains SHARP image details of 110-nm half-pitch vertical lines imaged with five different numerical aperture values: {0.25, 0.33, 0.35, 0.42, and 0.50 (4x)}. The illumination is on-axis disk fill with $\sigma = 0.5$ at 0.25 4xNA. Keeping this fixed, the effective σ values for all of the NAs are {0.5, 0.379, 0.357, 0.298, and 0.25} respectively, as shown in Fig. 5. Figure 5 also contains a representation of the position of zero order and the first diffracted orders within the pupil in each case. In the lowest-NA cases, the diffraction angle is large enough that the pupil cuts a fraction of the light, leading to a loss of contrast in the image. The line intensity profiles are normalized in the plot. We can observe that as the numerical aperture increases, the line profiles show an increase in contrast and slope.

4. Defect Imaging

Among SHARP's primary roles is the study of mask defects, and repairs. Avoiding the limitations of photoresist resolution and roughness, SHARP's measurements directly reveal continuous aerial image variations that can be used as feedback in modeling, sensitivity analysis, and repair recipes. This section presents a few recent examples of defect studies to show the kinds of work SHARP is routinely used for.

4.1 Native amplitude and phase defects under patterns

IBM and partners prepared a mask to study the interaction of native defects and line patterns. Defects were identified during various stages of mask fabrication, and small patterns were created on top of them. Figure 6 shows two such defects, with one behaving more like a so-called amplitude defects, and the other with characteristic phase defect properties.[6] In the amplitude defect case, "defect A," a portion of the bright pattern is dimmed, and that appears on both sides of focus. While in the second case, "defect B," the central intensity is bright on one side of focus and dark on the other, as expected from a bump-type defect.

4.2 Defect Repair

Native defect repair research conducted by GlobalFoundries and partners included imaging on SHARP. Figure 7 shows images of two defects recorded with various tools, including SHARP, a KLA Teron 617[7], and a mask scanning electron microscope (SEM). The SHARP images were recorded following defect repair attempts, and with various illumination conditions. The sensitivity of the imaging to the illumination conditions can be subtle, and difficult to detect in focus without detailed analysis, as is the case here. In many cases we observe the greatest differences in the through-focus behavior

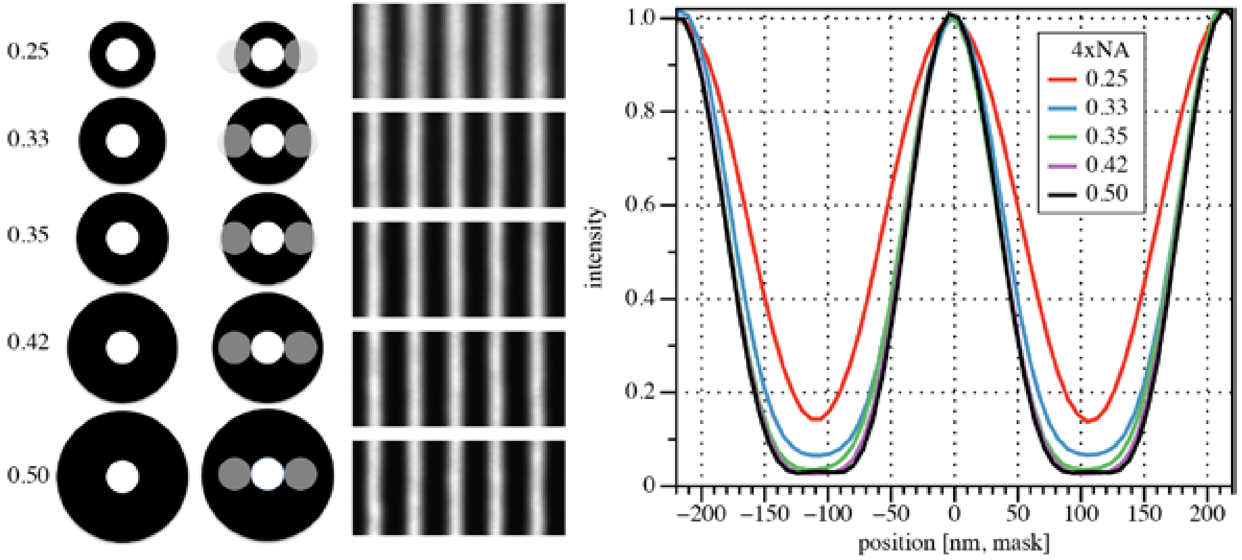


Figure 5. Keeping the mask and illumination conditions fixed, the imaging NA value is increased from 0.25 to 0.50 in five steps to demonstrate the effects of increased resolution. The vertical line pattern has 110-nm half-pitch. The two left columns show a representation of the illumination angles, and the pupil, including the first diffracted orders. Vertical line image details are shown. The plots extract the intensity profiles from two dark lines. The curve with the lowest NA has the lowest contrast. (Color online.)

of the different illumination conditions. In particular, the apparent depth of focus, and the manner in which the defects blur in the out-of-focus images can be observably different.

4.3 Substrate roughness

Mask roughness has been identified as a significant concern for EUV lithography,[8] for its potential impact on pattern edge roughness. SHARP imaging was performed on a mask with a substrate roughness gradient created by the deposition of a thin, non-uniform layer of chromium on the mask surface, below the multilayer and patterned absorber. Figure 8 shows two, similar images of 132-nm half-pitch vertical lines recorded on different regions of this mask. Measurement of the best-focus LWR 3σ values for 2-μm line segments were (a) 16.6-nm and (b) 3.2-nm. The throughfocus behavior of the patterns shows a characteristic behavior of phase-defects, consistent with underlying bumps and pits. Here, the lines that appear to shift to one side below focus, shift to the other side above focus.

5. Conclusion

The SHARP EUV mask-imaging microscope is a substantially improved successor to the SEMATECH Berkeley Actinic Inspection Tool, which it replaced. SHARP's most significant features include variable NA, customizable coherence control and stable through-focus imaging. With its narrow-band illumination, SHARP can also perform wavelengthtuning over a narrow range near 13.5-nm wavelength (approximately 13.2–13.7 nm). SHARP can inspect all positions of the mask surface, and the tool operates at a rate of 8–9 through-focus series per hour, with 19 points per series. Experiments have been conducted to investigate the dependence of imaging on the illumination, and demonstrate the real-world capabilities of the tool.

SHARP is now being used by SEMATECH member companies, in routine operations, to perform research on critical issues in mask development, including (1) native defect inspection and repair, (2) pattern defect sensitivity and detectability in various illumination conditions, (3) native blank defects, (4) absorber defects, (5) mask substrate roughness, and more. In the coming months, SHARP is anticipated to contribute to a number of outstanding issues in mask research. These include the decision to push EUV lithography toward higher magnification, or higher mask-side NA values as feature sizes shrink; optical proximity correction requirements; shadowing at higher angles of incidence; mask absorber architectures; and various defect repair studies, including phase defects near absorber patterns.

6. Acknowledgment

This work is funded by SEMATECH, and performed by University of California Lawrence Berkeley National Laboratory under the auspices of the U.S. Department of Energy, Contract No. DE-AC02-05CH11231. The authors gratefully acknowledge the support of SEMATECH project leaders and managers, David Chan, Andy Ma, Bryan Rice, Frank Goodwin, and Stefan Wurm.

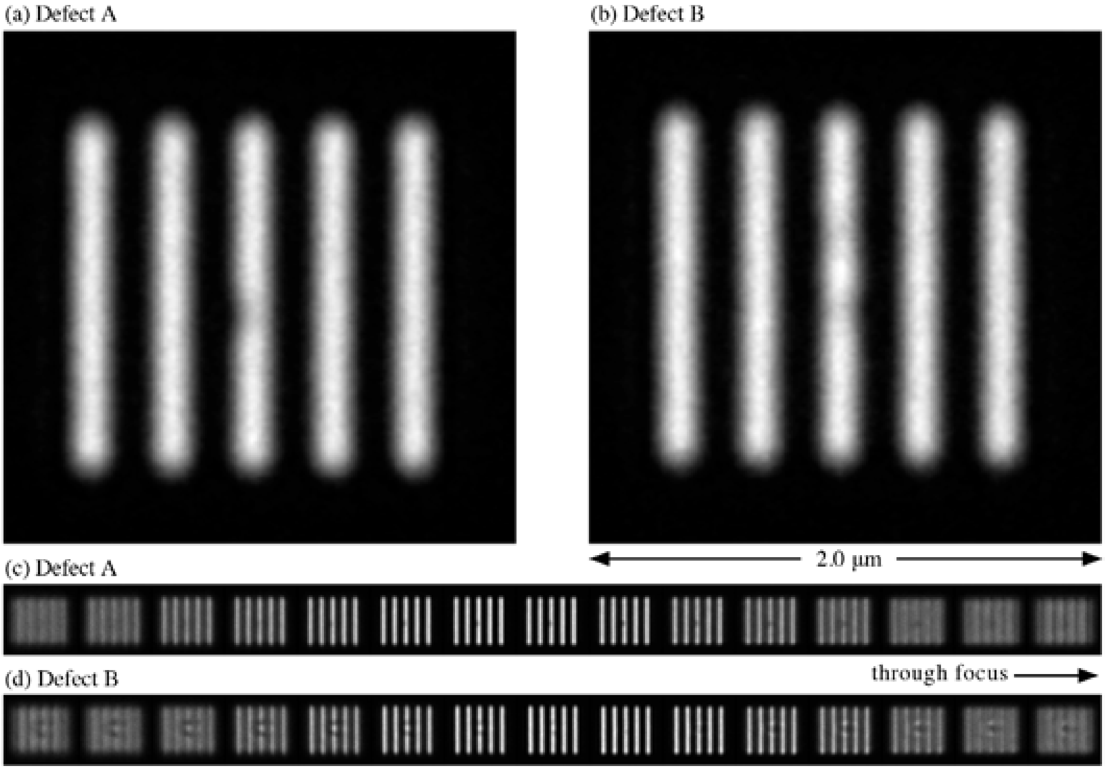


Figure 6. Native defect imaging through focus, created by patterning 160-nm half-pitch lines above known defects. (a) Defect A shows characteristic behaviors of an amplitude defect. (b) Defect B shows behavior associated with bump-type phase defects, with a reversal of the apparent intensity on either side of best focus. Lines were imaged with a 4xNA value of 0.33, and 0.5-µm steps through focus.

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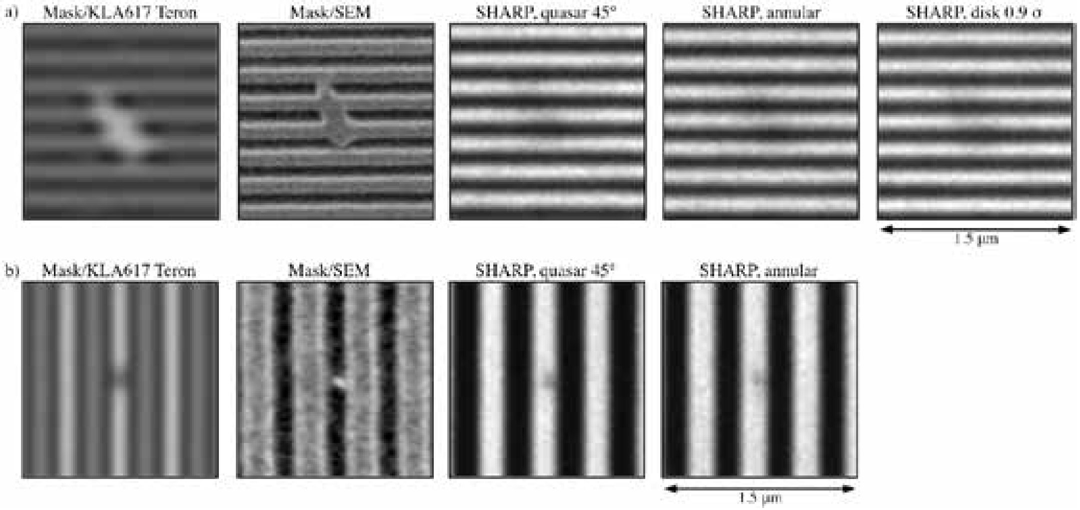

Figure 7. Two native mask defects imaged with various tools, including the KLA617 Teron tool, mask SEM, and SHARP with multiple illumination conditions. (a) Defect in 110-nm half-pitch lines, repaired prior to imaging in SHARP. Images recorded with various illumination conditions show subtle differences. (b) Defect in 200-nm half-pitch lines, repaired before SHARP measurement. Lines were imaged with a 4Å~NA of 0.33, and various illumination conditions indicated in the figure.

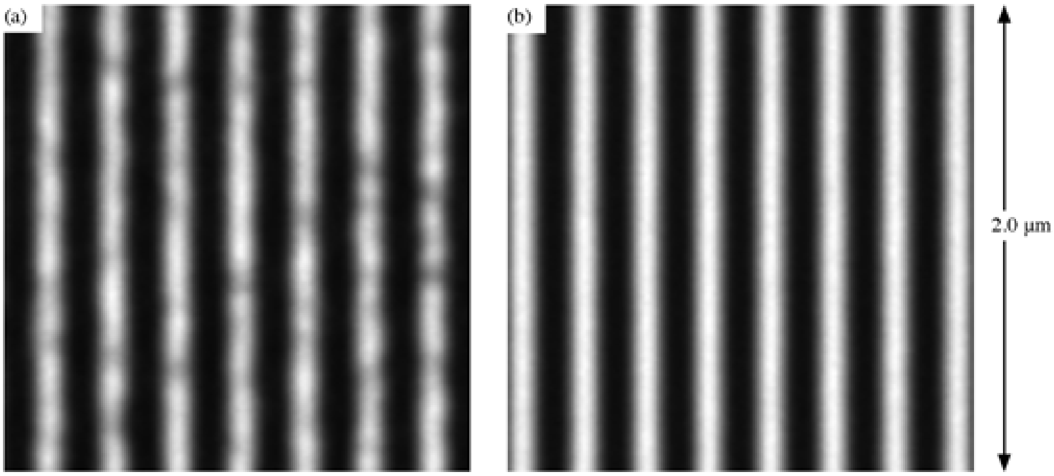

Figure 8. Two similar regions of an experimental mask that has been prepared to contain varying levels of substrate roughness. The measured LWR 3? values for 2-?m line segments were (a) 16.6-nm and (b) 3.2-nm.

Industry Briefs

TSMC Shows Path to 16nm, Beyond: Gains Come as Costs, Complexity Rise

By **Rick Merritt**

SAN JOSE, Calif. -- Taiwan Semiconductor Manufacturing Co. is making steady progress on its next two nodes, bringing advances in performance and low power. The bad news is it's widely expected the latest nodes add less transistor density and more cost than in the past. TSMC has taped out several 20nm chips and expects to let customers start designing 16nm FinFET chips before the end of the year. By the end of 2014 it expects it will have taped out 25 20nm designs and be far along in work on 30 16nm chips.

Company execs gave a frank and detailed rundown of their progress, especially on the 16nm node. TSMC is seen as a bellwether of the chip sector and electronics generally because it is one of the world's largest and most advanced makers of semiconductors. It puts out a whopping 1.3 million eight-inch equivalent wafers each month, some of them now down to 20nm geometries.

GlobalFoundries Rumored to Get a Bite of Apple Chip Business

By **Tam Harbert,** Technology Journalist

Last year GlobalFoundries surpassed United Microelectronics Corp. in revenue, becoming the second largest foundry in the world, behind Taiwan Semiconductor Manufacturing Corp. While unlikely to catch up to TSMC anytime soon (TSMC's $17 billion in 2012 revenue is four times GF's $4 billion), GlobalFoundries has been quite successful.

In midsummer, analytics provider IHS speculated that Apple was considering moving some of its chip business to GF's $6 billion fab in New York State. Apple is one of the largest purchasers of chips in the world. In 2012, it bought more than $21 billion worth of semiconductors, according to Gartner. As it moves chip production for its iPhone and iPad away from Samsung and to pure-play foundries, Apple will "single-handedly boost the growth of the chip contract manufacturing market this year," says IHS. The market research firm forecasts pure-play semiconductor foundry revenue will rise 21 percent in 2013, compared to only 5 percent for the semi industry.

Apple May See Weaker MacBook Shipments in 2013

By **Aaron Lee,** Taipei; Joseph Tsai, DIGITIMES

Apple's overall MacBook shipments in 2013 may decrease on year despite the fact that the vendor has been increasing its orders to the upstream supply chain for new MacBook models, according to sources from the upstream supply chain.

The sources pointed out that their shipments for the new MacBook devices have been increasing since June and the volumes in the third quarter grew 10-20% growth sequentially. The shipment growth is expected to continue in October, the sources added.

SIA: Semiconductor Sales Up for Sixth Months on the Trot

Sales in the Americas showed a 23 percent increase compared to August 2012 - the largest increase in all of the regions. The Semiconductor Industry Association (SIA) has announced that worldwide sales of semiconductors reached $25.87 billion for August 2013, an increase of 6.4 percent. This marks the industry's largest year-over-year growth since March 2011. Sales in the Americas increased by 23.3 percent compared to August 2012, while global sales in August were 1.3 percent higher than the previous month's total of $25.53 billion.

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Calendar

2014

SPIE Advanced Lithography

23-27 February 2014
San Jose Convention Center
and San Jose Marriott
San Jose, California, USA

Website is open for abstract submissions at
www.spie.org/al

SPIE Photomask Technology

16-18 September 2014
Monterey Marriott and
Monterey Conference Center
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