PHOTOMASK

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

N • E • W • S

JANUARY 2013
VOLUME 29, ISSUE 1

2nd Place Best Paper Award - PM12

Interactions of 3D mask effects and NA in EUV lithography

Jens Timo Neumann, Paul Gräupner, Winfried Kaiser, and Reiner Garreis, Carl Zeiss SMT GmbH, Rudolf-Eber-Str. 2, 73447 Oberkochen, Germany

Bernd Geh, Carl Zeiss S.M.T. Inc/ASML-TDC, Tempe, AZ, USA

ABSTRACT

With high NA (>0.33), and the associated higher angles of incidence on the reflective EUV mask, mask induced effects will significantly impact the overall scanner-performance. We discuss the expected effects in detail, in particular paying attention to the interaction between reflective coating and absorber on the mask, and show that there is a trade-off between image quality and mask efficiency. We show that by adjusting the demagnification of the lithography system one can recover both image quality and mask efficiency.

1. Introduction

The ITRS roadmap requires a continuous shrink of pattern layouts. Lithography scanner optics followed this demand for improved resolution mostly by a growth of numerical aperture (NA), and from time to time by decreasing the exposure wave length (allowing for a somewhat reduced NA), see Figure 1. The last step in wave length, the step from ArF with a wave length λ = 193nm to EUV light with λ = 13.5nm, allowed to reduce the NA from 1.35 (ArF immersion) to 0.25 (EUV), still improving the resolution capability from ~40nm to below 30nm. Examples for successfully printing high resolution patterns with the NXE:3100 can be seen in Figure 2. Further improving the resolution of

Continues on page 3.

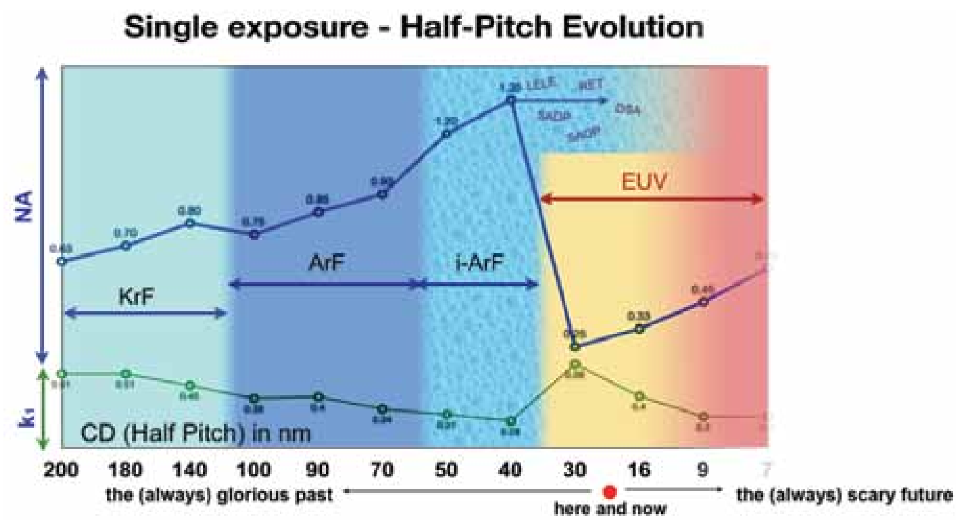


Figure 1. Lithography optics follow the demand for increasingly fine resolution by increasing the NA and from time to time by decreasing the wave length. The step from ArF immersion to EUV allowed for a significant reduction in NA; this NA, however, will again have to grow in order to support future resolution requirements.

TAKE A LOOK INSIDE:

INDUSTRY BRIEFS
—see page 12

CALENDAR
For a list of meetings
—see page 13

SPIE

8522-107

Editorial

We come to the end of another year: successful for some and with challenges for others.

Paul W. Ackmann, GLOBALFOUNDARIES Inc.

During this year (2012), we have witnessed additional consolidation in the logic IDM's, the bankruptcy of another memory supplier, and more focus on foundry space with these changes. There is a continued growth of design companies who ply their trade only in the foundry space. Some refer to these companies as "fabless," but I prefer the designation Design Innovation for a better name and function. The changing nature of the silicon Industry continues to affect the mask industry as control continues to tighten severely at the high-end driven by the high cost of investment. While the mask market shows growth in the Total Available Market (TAM), mask shops trend up, yet the conference attendance is down. We are still a growing industry but not growing with many new mask people. The numbers who have direct interactions with masks continues to drop with consolidation and more on just knowing they are needed but worried about cost. "They cost too much" or "I want my masks for free" are often quote phrases.

In looking at opportunities for people in the mask industry to share ideas with colleagues, customers, suppliers, and yes, sometimes competitors, presentations may be given various technical forums. Some are I.E.D.M., various I.E.E.E. conferences, EUV Symposium, and SPIE Advanced Lithography. Presentations at these forums are usually focused on the interactions of reticles with the chips built and not focused on the reticle build part. With all these other outlets for papers, some of the reduction in attendance can be explained. So how did we get to three conferences specifically focused on masks?

The American mask wing of the mask-centric conferences began with the Bay Area Chrome Users Society (BACUS). The BACUS photomask conference reflects more than 30 years of experience since its 1980 inception and is reflecting the industry changes. We have gone from many small (commercial and captive) mask shops through the commercial consolidation to a few big mask builders plus captives to higher mix of high-end controlled by fewer shops. There is still a strong core group comprising this conferences leadership that has morphed over time, but still supports all aspects of the mask business. The humor and skits are still part of mask lore. Attendance at BACUS went from a high of ~1100 for three years 2004 – 2006 and now down to around 500 for the last three years. We returned BACUS to single track in 2012 and will continue that in 2013. This is the best approach for the short term and long term.

Siemens Mask Shop and Fraunhofer-Gesellschaft started and developed (EMLC) the European wing. It moved to English in the 90's and has added multiple reticle and wafer interactions. I can remember many discussions on the conference in Dresden, when I was there. From a single focus to a wider audience, EMLC flourished in the first 10 years of this century, but t has seen the same trend as BACUS. The attendance was about 250 for the mid years and has dropped to around 200 the last few years. The winter in Dresden can be formidable. The conference in 2013 has moved to June. That is a perfect time of year but now closer to BACUS and just after Photomask Japan, representing the Asian wing.

Japan will celebrate its 20th Symposium this year. It has been attended like BACUS from all around the world. It has done well and started to add video humor to the mask community it is back after a very difficult year for Japan with the tsunami. We have had a good run with all three conferences with a mask focus, but we are losing ground on mask-only attendance and continuing all three may be very difficult to support in the future.

There has been a gradual but an ongoing march to the new paradigm. With tight money and industry changes, the number of people who can travel is reduced even more. I want to raise the idea of consolidation of conferences. This is not the first time nor the last time will we discuss this. We have many options and one is to do nothing at all. We can consolidate or modify or morph into something else. What options do we have for declining attendance at the three major mask conferences held annually?

SPIE Advanced Lithography (SAL) conference has focused on patterning and all aspects of lithography. Advanced Lithography has always had a mask component but not

(continues on page 7)

BACUS N • E • W • S

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

Managing Editor/Graphics Linda DeLano
Advertising Lara Miles
BACUS Technical Group Manager Pat Wight

SPIE

P.O. Box 10, Bellingham, WA 98227-0010 USA
Tel: +1 360 676 3290
Fax: +1 360 647 1445
www.SPIE.org
help@spie.org

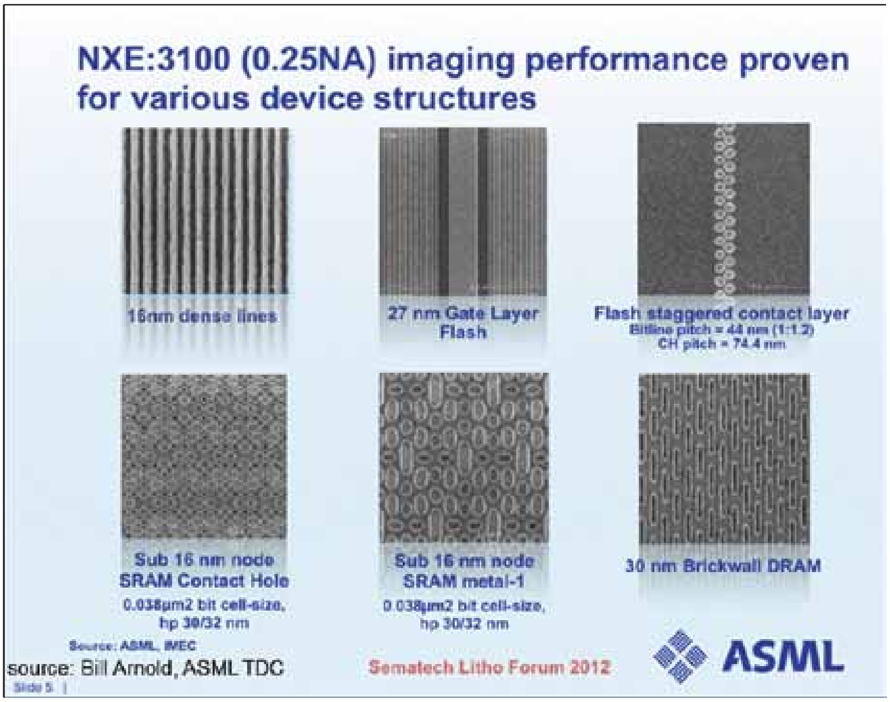


Figure 2. Example of printing half-pitches 30nm and below with the NXE:3100 (NA 0.25).

EUV scanners, however, will again require to increase the NA. Design solutions for scanner optics enabling 11nm half-pitch and below have been announced in Ref.,[1] and also (inorganic) resists have been shown with a resolution of 10nm and below.[2]

From a mask point-of-view, these high-NA options have one peculiarity which needs a careful consideration: Since EUV works with reflective masks, the reticle is exposed under oblique incidence in order to separate incident and reflected light. For increased NA, the angles of incidence get larger, and in particular a larger chief-ray-angle is required; these increased angles will have significant impact on image quality and mask efficiency. Adjusting the demagnification of the projection optics helps to keep incidence angles under control and hence to mitigate or even avoid these mask induced effects. A better understanding of this interaction between incidence angles, mask effects, and demagnification for high-NA EUV lithography is the aim of this paper. A discussion of the interaction between NA, chief-ray-angle, and demagnification can be found in Section 2 of this paper. Section 3 gives an account on the relevant mask effects, in particular the interaction between reflective multi-layer and absorber, and discusses the trade-off between image quality and mask efficiency which is found for large angles of incidence at the reticle. This section further shows the benefit of adjusted demagnification for a high-NA EUV optics. Various options for high-NA EUV optics are then outlined in Section 4. Section 5 finally summarizes the main findings of this paper.

2. NA, Chief-Ray Angle, and Demagnification

As is well known, EUV lithography uses reflective masks as no transparent materials are available to facilitate a transmission mask. Consequently, the mask has to be exposed with oblique incidence in order to allow for a separation between incident and reflected light, or in other words, between the light cones of illuminator and projection optics, see Figure 3(a). The NXE:3100 with NA = 0.25 and also the NXE:3300 with NA = 0.33 use illumination incident on the mask under a chief-ray-angle (CRAO, chief-ray-angle at object) of 6°. Now consider the case that the NA, more precisely: the NA at wafer, is increased in order to enhance the resolution capability. For an optics with demagnification $\beta = 4$, as is common for today's high-volume lithography, the opening angle β of the light cone at the reticle is given by

$$\sin(\alpha) = NA/\beta = NA/4, \qquad (1)$$

i.e., the opening angle of the light cone at reticle is growing proportional to the NA at wafer. Consequently, a CRAO of 6° will not be sufficient any more – the light cones of illuminator and PO would intersect, see Figure 3(b).

There are two possibilities to separate the light cones again. First, and very obvious, one can just increase the CRAO (Figure 3(c)). Choosing this option, and taking volume constraints into account, one would end up with a CRAO of 9° if aiming at an NA of 0.45. Second, looking at Equation (1), one can increase the demagnification β (Figure 3(d)): if, e.g., the NA at wafer is increased from 0.33 to 0.5 (i.e., by a factor of 1.5) and the demagnification is increased from $\beta = 4$ to $\beta = 6$ (i.e., also by a factor of 1.5), all angles at the reticle remain unchanged.

BACUS
N • E • W • S
Volume 29, Issue 1

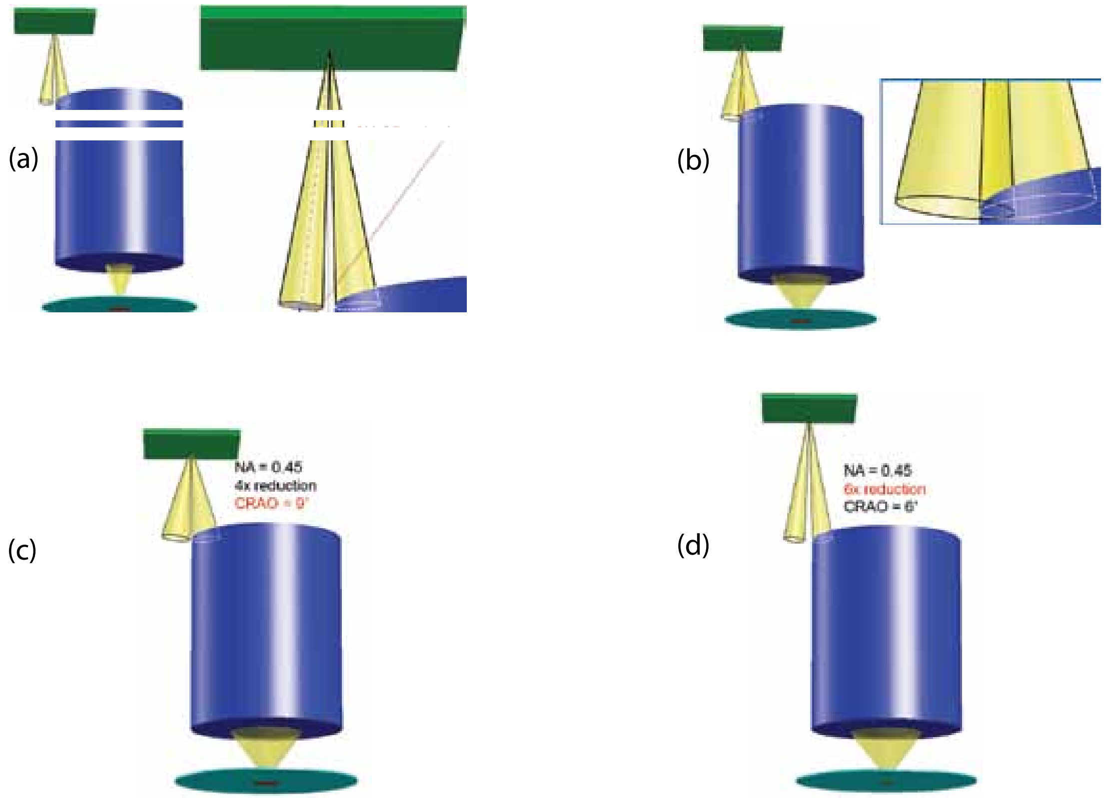


Figure 3. Using a reticle in reflective mode requires oblique illumination in order to separate the light cones coming from the illuminator (from the left, not sketched here) and going to the projection optics (indicated by the blue body) (a). If the NA would be increased without any accompanying measures, these light cones would intersect (b). There are two ways to accommodate for the increased NA and to separate the light cones at the reticle again: One can either increase the chief-ray-angle (c), or adjust the demagnification and hence reduce the opening angle of the light cones at the reticle while the NA at wafer , depicted by the wide light cone below the projection optics, remains large (d).

3. Mask-Induced Effects

We start with an investigation of the first possibility outlined in Section 2: Accommodate for the larger NA by an increased chief-ray-angle. The resulting mask effects will be described in Section 3.1, and the impact on image quality and mask efficiency will be assessed in Section 3.2. The results will then be compared to the imaging behavior if a larger demagnification is used to accommodate for the larger NA.

Note that the data presented in this paper is based on simulation studies. In parallel, experiments are ongoing to check and enhance the validity of these simulations. Results of these experimental studies will be published elsewhere, see References.[3, 4]

3.1 General mechanism: absorber shadowing and multilayer tuning

In order to understand the mask effects on high-NA imaging, it is important to note that there is not only the chief-rayangle, but there is a whole range of angles incident on the mask. It is well known among opticians working with EUV that a wide angular range puts a tough challenge on every mirror. This is even more true for such a complicated kind of mirror as the reticle is, which is not only supposed to reflect light but also carries a topographic absorber pattern. Further, it is important to note that – as an immediate consequence of the non-zero chief-ray-angle – these angles are not distributed symmetrically around zero. As can be seen from the sketch in Figure 4, one pole of a dipole belongs to small angles of incidence, while the other pole – located at the opposite side of the illuminator NA – belongs to large angles of incidence. Due to this asymmetry, these two poles will experience totally different imaging conditions.

It is well known that the pattern on the reticle is formed by an absorber which is located on top of the reflective multilayer; it is also well known that this absorber casts a shadow, due to its thickness and the oblique incidence of light. It is important to note now that this "shadowing" depends on the angle of the incident light as seen in the sketches in Figure 5: Light with a rather shallow angle (left) sees rather strong shadowing and hence sees a relatively wide "effective line width", whereas light with a steeper angle sees a much less severe shadowing and consequently sees a much smaller effective line width. Since we have one side of the illumination pupil – in the example depicted here, one pole of the dipole – at small angles and the other one at large angles, this means that the two poles – more general, the two sides of the illumination pupil – see different absorber shadowing and consequently different effective line widths.

Note that this geometric sketch is a simplification as it

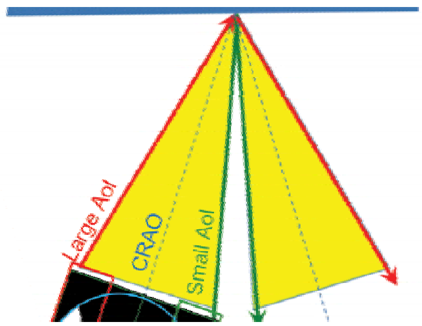


Figure 4. There is not just the chief-ray-angle, but a full range of angles incident on the reticle (sketched by the blue bar). Due to the oblique illumination, the angles of incidence are not distributed symmetrically around zero but around the non-zero chief-ray-angle. Consequently, the two poles of the dipole depicted here correspond to different angles of incidence and hence will see quite different imaging conditions on the reticle.

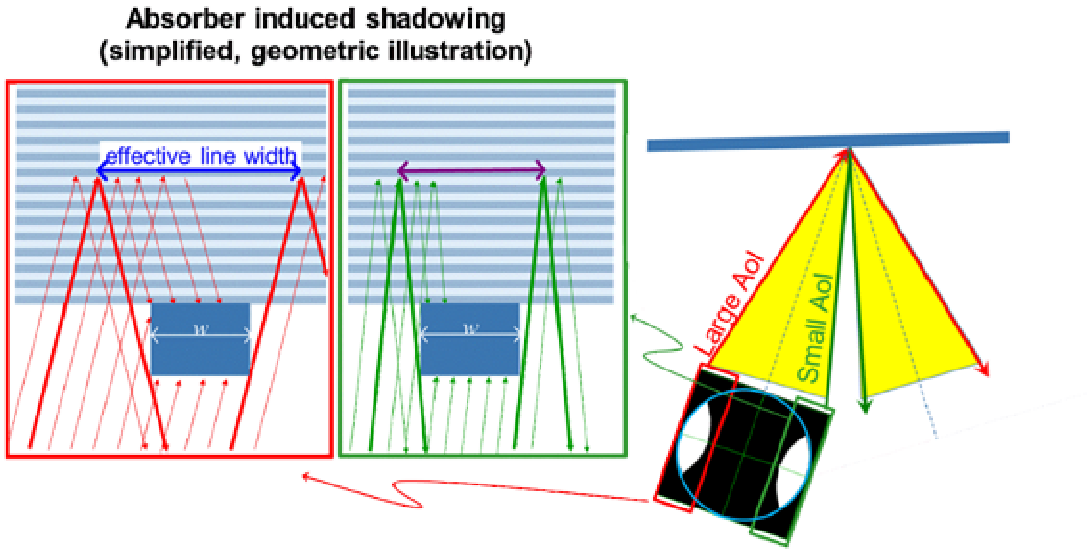


Figure 5. Simplified, geometric sketch of absorber shadowing. Due to the oblique illumination, one pole of the dipole belongs to large angles of incidence and sees a significant shadowing effect while the other pole belongs to small angles and sees a much less pronounced shadowing. In consequence, the two poles see different "effective line widths".

neglects, e.g., diffraction effects. Also, the light is not reflected from one clearly defined plane within the multilayer but, due to constructive interference, from within the bulk of the multilayer. However, even this geometric simplification shows one thing which is worth noticing: Since light is not reflected from the top of the multilayer but from within it, making the absorber thinner will reduce, but not eliminate the shadowing effect. Even an absorber with zero thickness will cast a shadow to within the multilayer.

Figure 5 merely shows a geometric illustration of the angular-dependent shadowing effect; now we show this effect in terms of diffraction patterns obtained by rigorous calculations. As setting we chose a dipole-setting at NA 0.45, CRAO = 9°. We use here not the standard NXE:3300 reticle multilayer but a coating which has been optimized for this NA and CRAO. To set a reference, we start with simulating an open-frame exposure, so without any absorber present on the reticle. Consequently, the diffraction pattern as it would appear in the pupil plane of the PO contains only 0th order, namely just the dipole which we used for illumination. As can be seen in the upper part of Figure 6, this coating has a uniform reflectivity over the whole relevant range of incidence angles, and hence both poles – the "large angle pole" in the red box and the "small angle pole" in the green box – are reflected with the same intensity.

Next, we put an absorber pattern on the mask: 11nm dense lines and spaces (i.e., 44nm at mask). With this absorber pattern present, we of course get a "real" diffraction pattern with 0th and 1st orders, and this diffraction patterns shows quite some asymmetry, as can be seen in the lower part of Figure 6. First of all, we find a significant asymmetry in the 0th orders. We have seen before that the

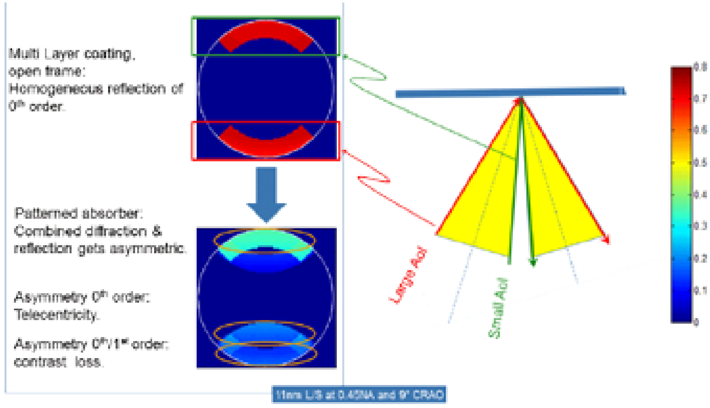


Figure 6. Assuming a multilayer with sufficient broadband reflectivity spectrum, both poles of a dipole are reflected with same intensity in an open frame exposure, i.e., without any absorber pattern on the mask (upper diffraction pattern). Adding now an absorber pattern, the diffraction pattern becomes highly asymmetric (lower diffraction pattern). Since the multilayer was proven to have a uniform reflectivity, this asymmetry must be due to absorber induced effects. It is indeed a consequence of the angular dependent absorber shadowing which was sketched in Figure 4: The large angles (lower pole) see more shadowing and hence see a wider effective line width than the small angles (upper pole).

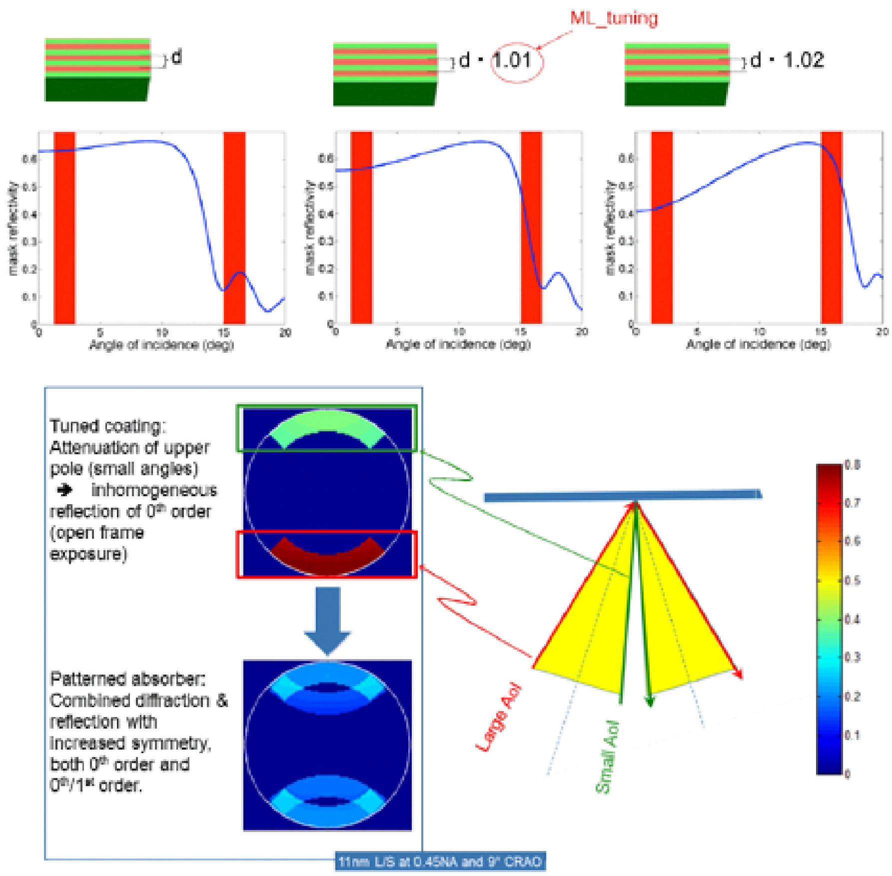


Figure 7. Tuning the layer thicknesses, i.e., the periodicity of the multilayer, one can modify the reflectivity behavior of the multilayer, inducing some apodization and in particular an attenuation of small angles of incidence (upper part of the figure). Repeating the exercise depicted in Figure a broadband multilayer as above, we find a strong imbalance of the reflected poles in the simulation of the open frame exposure: the upper pole (small angles) is now significantly attenuated (upper diffraction pattern). Adding an absorber pattern, though, we now find a nicely symmetric diffraction pattern (lower diffraction pattern): The effects of absorber (attenuating large angles) and multilayer (attenuating small angles) mutually compensate. Note, however, that this compensation comes at the cost of significant reflectivity loss at the reticle.

multilayer reflects both poles with identical intensity, so this asymmetry must be due to the absorber. This is indeed the angular-dependent shadowing which we discussed before: The lower pole – which belongs to larger angles – sees significantly more shadowing and hence a broader effective line width than the upper pole, which belongs to small angles. Consequently, the lower pole is significantly more attenuated than the upper pole. This asymmetry of 0th order will lead to noticeable telecentricity effects as has been noted, e.g., in References.[3, 5] Further, we also see an intensity imbalance between 0th and 1st order of the upper pole which will lead to inconvenient contrast loss in the aerial image. This effect has been noted in Reference [6], but generally it appears to be far less well known than the telecentricity effect; as this contrast loss effect, however, clearly is of great importance we will focus on this effect in the subsequent subsection; some remarks on telecentricity can be found in the appendix.

In order to compensate for the pupil dependent absorber shadowing, we now tune the multilayer reflectivity. In particular, we tune the thicknesses of the individual layers, i.e., change the periodicity of the multilayer, and hence tune the angular dependent reflectivity, as sketched in upper part of Figure 7; the tuned multilayer now shows a significant dependency of the reflectivity on the angle of incidence, or, in other words, a significant apodization. Starting again with an open-frame exposure, i.e., without absorber pattern, we now see a significant asymmetry (lower part of Figure 7): The upper pole (small angles of incidence) is significantly attenuated as the multilayer reflectivity now drops towards small angles. Putting 11nm dense lines and spaces on the reticle as before, we now find a diffraction pattern which is nicely symmetric: the absorber still attenuates large incidence angles, and our tuned multilayer now attenuates small incidence angles, and in consequence the effects of absorber shadowing and multilayer apodization mutually compensate. Note that the mechanism sketched here is based on taking away light twice – once by absorber shadowing and once by multilayer apodization, and these two effects are balanced. However, combining two light-consuming effects will, of course, lead to a reduced reflectivity of the reticle and hence to light loss.

3.2 Image quality and mask efficiency

Having outlined the general mechanism of mask effects and their potential compensation by multilayer tuning, we now have a look at image quality and mask efficiency in example use cases.

To set a reference, we start with 13nm dense lines & spaces at NA 0.33, CRAO 6°. Using a standard reticle stack, we obtain a contrast of ~80% in the aerial image (without any resist blur), which is a good value: Experience shows

Editorial *(continued from page 2)*

a “BACUS” like session. BACUS focused on masks, mask making, and mask tool support and less on use. SAL focused on use of the mask. OPC was first pushed there and many of us have done presentations there. In fact, I focused on Advanced Lithography for many years, presenting on mask results until I moved to the reticle side of business, then I realized the value of a standalone mask focused conference, like BACUS.

The stand alone options require more thought and integration. In any version that impacts all three, much effort and timing to effect a change is more problematic. All suggestions are version on the same theme. To be the most effective we must consolidate and reduce.

Version one (1) rotates around the world and uses the current conference sites. Each year is in a different site. BACUS - Year 1, EMLC- Year 2, Photomask Japan - Year 3 and then the rotation starts again. If we do not have a conference every year but on a three year cadence, the support and cost each of the conferences may be higher and the attendance may be very inconsistent. Therefore the conference organizers may reject this strategy. Another option is just to hold BACUS every other year and a second mask conference alternates between continents. However hotel and facility commitments may not allow for this, and long term synergy every three years may not provide the linkage and continuity needed.

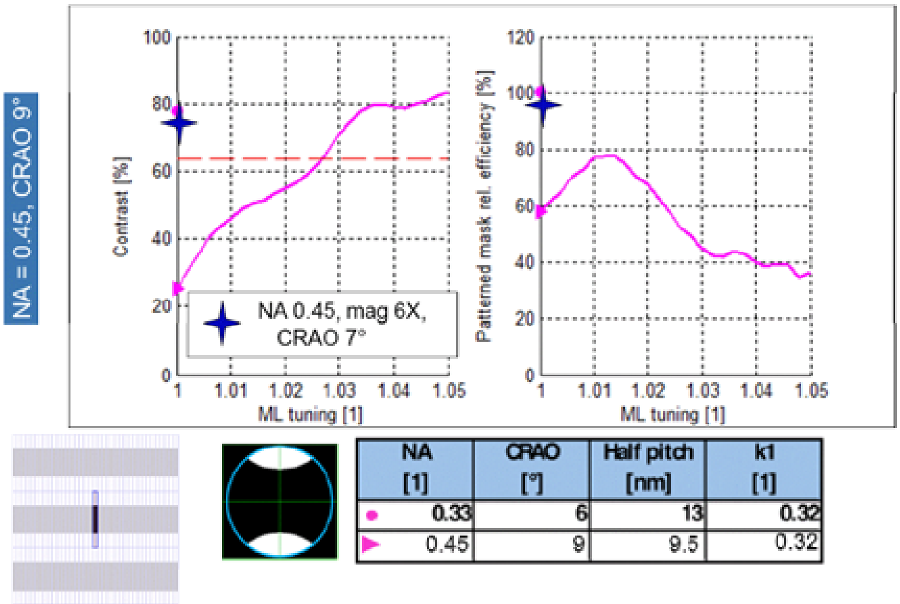
Version two (2) is simple and BACUS Centric. The EMLC and Photomask Japan add one session each to the BACUS agenda. The conference focuses all mask activity in one place. It would be the simplest to see and the hardest to implement. Having to sell on moving everything to BACUS may be a tall order for the steering committees of all three organizations.

Version three (3) has a hybrid from BACUS every year and the other conferences alternate years so that no conference is forgotten. Each year, we would have two conferences: Bacus and EMLC, Bacus and PMJ and so on. This also means that travel expenses can be reduced and still be local sessions in America, Asia, and Europe.

Version four (4) is food for thought of multiple options from other sources. We are sure there are other possibilities out there including but not limited to these and we’d be happy to pick an alternate should it prove economically viable to us and to the community. In the meantime we can continue on with “survival of the fittest”. That’s how the industry works!

The final outcomes are yet to be written. Doing nothing is not an option. If we wait the attendance will continue to drop and make it harder to keep all three running. This is a simple extrapolation but unless we change, the industry dynamics will drive us out of the BACUS, EMLC and Photomask Japan business. We need the conferences to drive new blood and interest in a very critical technology. The three continent approaches have been very helpful for the industry.

We will continue to work to enhance the conferences involving reticles and infrastructure to support the reticle industry. The linkage to all who make masks and the suppliers who build the tools must have an annual meeting. It is critical to discuss where we have been and where we will go. The relationships built, the humor shown, and video stories show why we must keep the fire lit. The conversation has begun.



	NA [1]	CRAO [°]	Half pitch [nm]	k1 [1]
●	0.33	6	13	0.32
▶	0.45	9	9.5	0.32

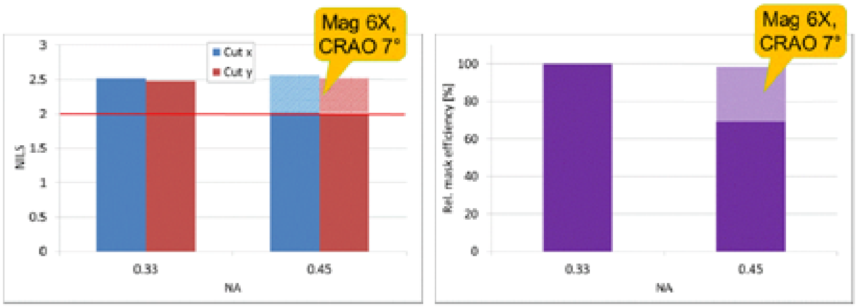
Figure 8. Image contrast and relative mask efficiency for lines and spaces. NA 0.33, chief-ray-angle (CRAO) 6° gives a good performance for 13nm half pitch (large pink dots), with the standard multilayer (tuning = 1; absorber thickness 71nm). NA 0.45, CRAO 9° gives poor contrast for 9.5nm half pitch with this multilayer, although k1 is the same as before (triangles). Applying multilayer tuning, reasonable image contrast is recovered at a tuning factor ~ 1.026 (solid line in the left plot). The relative mask efficiency, however, then drops to ~50% of the efficiency in the NA 0.33 case (right plot). Adjusting the demagnification (here: NA 0.45 with demagnification 6X and CRAO 7°) helps to recover both good image contrast and mask efficiency with the standard multilayer (blue "stars").

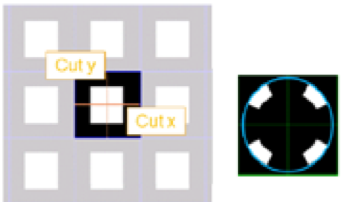
that at least somewhat above 60%, indicated by the dashed line, is needed to have a reasonable process at the end of the day. The reflectivity of this patterned mask will be our reference from now on, and we call this reflectivity, or mask efficiency, "100%". Both results, contrast and efficiency, are given by the large dots in Figure 8. They are located on the y-axis in these graphs as a multilayer tuning factor of 1 belongs to the standard reticle stack which we used as input for this simulation.

Now, we go for NA 0.45 with CRAO 9°. We decrease the half-pitch to 9.5nm, so k1 remains the same as in the reference case and naively one would expect a similar imaging performance. It turns out, however, that the image contrast drops down to below 30% as indicated by the triangles in Figure 8; this is in no way sufficient for a reasonable process. We can now play the trick which was introduced in the previous subsection: We tune the multilayer, that is, we increase the thickness of the layers, or the periodicity of the multilayer; image contrast and mask efficiency as a function of multilayer tuning are shown by the straight lines in Figure 8. And if we tune the multilayer by somewhat more than 2.5%, we indeed get back the minimum contrast indicated by the dashed line (for a similar analysis of multilayer periodicity vs. image contrast, see Reference[6]). However, if we look at the right figure, we see that the mask efficiency at a multilayer tuning of 2.5% drops down to ~50% of the efficiency we had in our reference case. We conclude that we have either good image quality or reasonable efficiency, but not both. This is a direct consequence of the compensation mechanism discussed on the previous slide: The absorber attenuates the large angles of incidence, deteriorating the image quality; in order to compensate this effect and get a good image quality, we use the multilayer to attenuate the small angles of incidence. Now, attenuating large angles by the absorber and small angles by the multilayer, we suppress a huge share of the available light. We conclude from these results that it is not an attractive option to increase the chief-ray-angle in order to accommodate for the high NA. In fact, the chief-ray-angle should not exceed ~7°.

We can solve this issue, however, by coming back to the second option outlined in Section 2: Instead of changing the chief-ray-angle, we adjust the demagnification of the projection optics in order to accommodate for the large NA: Going from 4X to 6X allows to reduce the chief-ray-angle at the mask, and also reduce the range of incidence angles, while keeping the large NA 0.45 at the wafer. Consequently, we get rid of the shadowing effects, do not have to tune the multilayer, and recover those image contrast and mask efficiency we had in our reference case, but now at a resolution of 9.5nm half-pitch for lines & spaces; image contrast and mask efficiency are given by the "stars" in Figure 8.

As a further example, we look at dense contact holes; the results are summarized in Figure 9. Again, we start by simulating a reference case, 19nm dense contact holes at NA 0.33, CRAO 6°. We find a NILS ("normalized image log slope") of 2.5; as a rule of thumb, NILS should be above 2 for a reasonable process, so we are well above this requirement. As before, we set the mask reflectivity, or mask efficiency, obtained in this reference case to 100%. Then we look at 14nm dense contact holes at NA 0.45 and CRAO





NA [1]	CRAO [°]	Half pitch [nm]	k1 [1]	ML tuning f [1]
0.33	6	19	0.46	1.00
0.45	9	14	0.46	1.03

Figure 9. NILS (normalized image log slope) and relative mask efficiency for dense contact holes. NA 0.33, chief-rayangle (CRAO) 6° gives a good performance for 19nm half pitch (left group of bars), with the standard multilayer (tuning = 1). NA 0.45, CRAO 9° achieves a NILS of 2 (required for reasonable process latitude) for 14nm half pitch with a tuning factor of 1.03 (right group of bars in the left plot). The relative mask efficiency, however, then drops to ~70% of the efficiency in the NA 0.33 case (right plot). Adjusting the demagnification (here: NA 0.45 with demagnification 6X and CRAO 7°) helps to recover both good image contrast and mask efficiency with the standard multilayer (shaded areas on top of the right bars).

9°; as in the previous example, the k1 is identical for the NA 0.33 and the NA 0.45 case. For the NA 0.45 case, we show the results obtained with a multilayer tuning of 3%, and we find that this is sufficient to get a NILS of 2 (right group of bars in the left plot of Figure 9), but we have a loss of mask efficiency of ~30% as compared to the reference case (right bar in the right plot). Changing the demagnification helps also in this case: With NA 0.45, mag 6X, and CRAO 7° (and the standard multilayer stack, i.e., without multilayer tuning) we find back the image quality as well as the mask efficiency we had in our reference case (indicated by the shaded areas in the graphs of Figure 9), but now at a resolution of 14nm dense contact holes.

3.3 Further benefits of increased demagnification

The previous subsection showed how an increased demagnification helps to simultaneously get good image quality and good mask efficiency for high-NA EUV. The root cause is, of course, that an increased demagnification helps to keep incidence angles at the reticle on a similar level as in NXE:3300, and hence keep mask induced effects under control. Note that the good performance shown in the preceding subsection was obtained with a standard reticle stack as expected to be used on NXE:3300. This is a huge benefit compared to the option "mag 4X, CRAO 9°, tuned multilayer" which was also discussed: In addition to the trade-off between image quality and mask efficiency which was the topic of the previous subsection, the multilayer tuning depends on the details of mask pattern and illumination setting, and hence this approach would require a library of tuned multilayers for different use cases which would be disadvantageous from a logistics point of view and would also require stable manufacturing processes for various, maybe even setting dependent multilayer stacks.

There is yet another benefit of the increased demagnification for high-NA EUV which was not part of the discussion in the preceding subsection but can hardly be overestimated: Looking at the requirements for mask manufacturing (linearity, CD control, placement, …) as listed in the ITRS roadmap, no solutions are visible for masks to be used on lithography tools with NA beyond 0.33, see Reference.[7] This issue will be significantly relaxed if the high- NA comes with increased demagnification. Indeed, we conclude from the results presented in the previous subsection (and further results which were not discussed there but point into the same direction) that with a 4X demagnification there will be no imaging of features below ~13nm half-pitch at wafer, due to fundamental mask effects and even when all accuracy requirements are met. On mask level this means that there is no reason to get to features with half-pitches below 52nm at reticle. Features below 13nm half-pitch can be printed on the wafer nonetheless; the required high NA then comes with an increased demagnification, so incidence angles at the reticle remain comparable to NXE:3300, and so do feature sizes and hence the mask accuracy requirements.

4. Exposure Tools: Options for High-NA EUV

It is evident that a modified demagnification will have impact on the relation between reticle size and field size at wafer. The current die size at wafer, 26x33mm^2, translates on a system with demagnification 4X into 104x132mm^2 at the reticle, and this fits well into a 6" reticle (6" = 152.4mm, i.e., there remain 20.4mm margin for manufacturing (edge) effects, markers, etc.). To get this 26x33mm^2 wafer field on a system with demagnification 6X, one would need a 9" reticle instead. There are, however, also options available with a 6" reticle: One could, e.g., choose a magnification of

Table 1. Options for high-NA EUV optics with adjusted demagnification.

	unit	6M Full Field	6M Half Field	6M Quarter Field	8M Quarter Field
System specifications					
NA		0.45	> 0.45	0.50	0.60
magnification		6x	5x	8x	8x
CRAO		6° - 7°	7°	6°	6° - 7°
relative transmission	3300=100%	100%	80%	100%	< 40%
mask size	inch	9	6	6	6
min. pupil fill ratio (etendue limit)		9%	12%	15%	10%
scan field	mm x mm	26 x 33	16.5 x 26	13 x 16.5	13 x 16.5
scan direction		↕	↔ ↔	↕ ↕ ↕ ↕	↕ ↕ ↕ ↕
Resolution (NILS=2 - Aerial Image)					
resolution limit L&S (PFR=16%)	nm	8.9	8.5	8.0	7.2
resolution limit CH (PFR=20%)	nm	11.8	11.2	10.7	9.1

5X and go for a half-field on the wafer: The die size would then be 16.5x26mm (so two of these dies would add up to the current 26x33mm^2 die), and the long side of this half-field would again fit well into a 6” reticle (26mm @ wafer → 130mm @ reticle, so there are >20mm margin). Both these options (full field with demagnification 6X, 9” reticle; half field with demagnification 5X, 6” reticle) would work for an NA of up to ~0.45 as the NA at reticle (NA divided by demagnification) would be $NA_{reticle}$ = 0.075 in the first case, $NA_{reticle}$ = 0.09 in the latter case (for comparison: NXE:3300 has $NA_{reticle}$ = 0.33/4 = 0.0825). The first option would be advantageous from a mask-effects point of view as $NA_{reticle}$ and hence incidence angles on the reticle are smaller; the second option has the charm of working with a 6” reticle as is currently available. Increasing the NA beyond 0.45 will then require higher demagnifications: a demagnification of 8X would allow an NA 0.5 ($NA_{reticle}$ = 0.0625) or even NA 0.6 ($NA_{reticle}$ = 0.075). Given a 6” reticle, a demagnification of 8X would correspond to a quarter-field, i.e., to a die size of 13x16.5mm^2 at the wafer. The options described in this paragraph are summarized in Table 1.

Design options for the projection optics are available for all these NA / demagnification / field size combinations outlined here; all these options will have a central obscuration which helps to limit the angular spread on the mirrors of the projection optics. These options differ not only in NA (and hence resolution) and demagnification (and hence field or reticle size) but also in transmission (and hence throughput): Based on current design studies, the options with NA $\leq$ 0.5 come with a transmission comparable to NXE:3300; pushing the NA to 0.6 would require two additional mirrors which would reduce the transmission to ~40% of NXE:3300. To make a proper trade-off between field size, NA, and transmission, is work in progress.

Summarizing these briefly sketched considerations, there are various options available to extend the NA beyond the NA 0.33 of the NXE:3300. The question is not if there can be a high-NA tool at all, but to carefully consider, evaluate, and discuss the advantages and possible drawbacks of the numerous available options and then make the right choice.

5. Conclusion

We evaluated mask effects for high-NA EUV imaging. We found that the chief-ray-angle should not exceed ~7°, and this limits the NA of a projection system with demagnification 4X. However, the mask and chief-ray-angle related issues outlined in this paper can be solved by choosing a demagnification larger than 4X; since in addition optics designs are available (with central obscuration to limit the angular spread on the mirrors in the projection optics), we consider high- NA EUV imaging to be feasible.

The fact that high-NA imaging requires an increased demagnification has an important consequence for mask making: Based on current mask technology (i.e., topographic absorber on a reflective multilayer coating), we don’t see an imaging solution with demagnification 4X below a resolution of ~13nm lines and spaces on the wafer, i.e. below 52nm on the reticle. For further shrink on the wafer, the demagnification of the projection optics must be adjusted in such a way that incidence angles on the reticle don’t grow any more, and this means that we don’t see a need for a resolution below these ~52nm half-pitch at reticle. Accordingly, the requirements for mask making (CDU, registration, defects, surface flatness, …) will correspond to this resolution and will not scale down the way they would do if the shrink would continue on the mask.

It is evident that a modified demagnification will have impact on the relation between reticle size and field size at wafer. Keeping the field size on wafer at the current 26x33mm^2 with a system with demagnification 6X, e.g., would require a 9” reticle. Given the whole-industry effort such a change in reticle size would require, however, our

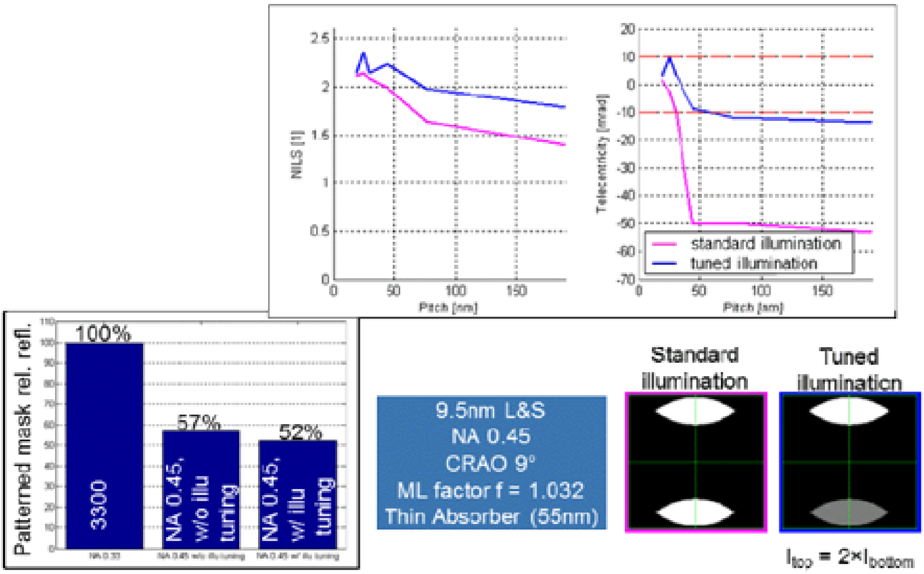


Figure A. Even with the tuned multilayer which showed good imaging performance for the dense pitch, additional pitches which are assumed to be exposed simultaneously with the dense pitch show reduced NILS and significant telecentricity errors (pink lines). Tuning the illumination helps to increase NILS and reduce telecentricity errors (blue lines). Note that this simple example of illumination tuning is shown here just as a mere proof of principle; a more elaborate illumination tuning is expected to show even much better improvement. Although we assume the illumination tuning to be possible without any light-loss, we have to pay for this improvement by another small efficiency reduction as the tuning forced us to move light from the "better reflected" pole to the "worse reflected" pole.

current baseline is to expect 6" reticles and hence a reduced field size. This still leaves various options how to define a high-NA EUV optics; possible options are: NA 0.45, 5X, 6 mirrors, half field; NA 0.5, 8X, 6 mirrors, quarter field; NA 0.6, 8X, 8 mirrors, quarter field. A careful consideration, evaluation, and discussion of the advantages and possible drawbacks of the numerous available options, in terms of resolution, field size, and transmission, is required to make the right choice.

6. Acknowledgments

The authors thank Johannes Ruoff (Carl Zeiss SMT), Vicky Philipsen, Eric Hendrickx, and Rik Jonkheere (IMEC), Patrick Naulleau (LBNL), and Steve Hansen and Bill Arnold (ASML TDC) for fruitful discussions and support.

7. Appendix

As mentioned in Section 3.1, the mask effects induced for chief-ray-angles larger than 7° will not only lead to contrast loss but also to telecentricity errors. As an example we go back to the example considered in Section 3.2, i.e., 9.5nm lines and spaces exposed at NA 0.45, chief-ray-angle 9°. Since the illumination setting chosen in this examples minimized the telecentricity error for the dense pitch we include further pitches into our analysis. Results with a tuned multilayer (tuning factor 1.032) are shown in Figure A. While this multilayer tuning factor was found to provide good imaging performance for the dense pitch, it turns out that the NILS of the additional pitches considered here is significantly lower (pink line in the left graph). Further, these pitches see large telecentricity errors (pink line in the right graph). NILS and telecentricity for these pitches can both be improved again by tuning the illumination, as is also shown in Figure A: We intentionally imply an imbalance to the poles of this dipole-like illumination setting which again helps to compensate mask induced effects. In consequence, we find increased NILS and reduced telecentricity error for the additional pitches, without harming the performance of the dense pitch. Note that this is just a prove of principle with a very simple illumination tuning. With more advanced optimization, and more degrees of freedom than simply inducing an imbalance to the illumination pupil, even much better improvement appears to be feasible. We further note that the actual illumination tuning was assumed to be lossless, i.e., we assume here that the illuminator will be capable of shifting intensity from one pole into the other one without negative impact on the illuminator transmission. However, the illumination tuning which we applied here forced us to shift light from the "better reflected pole" to the "worse reflected pole" (taking both absorber and multilayer effects into account), so in the end we have to pay with an additional small efficiency loss as can be seen in the bar chart inserted into Figure A.

8. References

[1] W. Kaiser, SEMATECH Litho-Forum, Vancouver 2012.

[2] Y. Ekinci et al., "Evaluation of resist performance with EUV interference lithography for sub-22-nm patterning", **Proc. SPIE 8322,** 83220W (2012).

[3] V. Philipsen et al., "Impact of mask stack on high-NA EUV imaging", International Symposium on Extreme Ultraviolet Lithography, Brussels 2012.

[4] R. Chao et al., "Experimental verification of EUV mask limitations at high numerical apertures", abstract submitted for SPIE Advanced Lithography 2013.

[5] J. Ruoff, "Impact of mask topography and multilayer stack on high NA imaging of EUV masks", **Proc. SPIE 7823,** 7823-41 (2010).

[6] Han-Ku Cho, "EUV readiness and EUV PPT performance", International Symposia on Extreme Ultraviolet Lithography and Lithography Extensions, Miami, 2011.

[7] ITRS Roadmap, http://www.itrs.net/.

BACUS NEWS

BACUS Corporate Members

Acuphase Inc.
American Coating Technologies LLC
AMETEK Precitech, Inc.
Berliner Glas KGaA Herbert Kubatz GmbH & Co.
FUJIFILM Electronic Materials U.S.A., Inc.
Gudeng Precision Industrial Co., Ltd.
Halocarbon Products
HamaTech APE GmbH & Co. KG
Hitachi High Technologies America, Inc.
JEOL USA Inc.
Mentor Graphics Corp.
Molecular Imprints, Inc.
Panavision Federal Systems, LLC
Profilocolore Srl
Raytheon ELCAN Optical Technologies
XYALIS

Industry Briefs

Is Quad Patterning a Possibility for the 10 nm HP Node?

EE Times and Solid State Technology

In September, Intel announced it had found a cost-effective way to make 10 nm chips using quad patterning. Intel anticipates producing chips with this process in as little as two years.

In a brief interview after his keynote address at the ARM TechCon on October 30, Jack Sun, chief technologist at TSMC, predicted that quad patterning may be needed for 10 nm process technology if extreme ultraviolet (EUV) lithography is not ready in 2015 when TSMC expects to start early production of the technology. As for 10-nm, TSMC "is in serious pathfinding development of it," he said. "In the next five years, we can see down to 5 nm easily, but of course there are some pathfinding challenges yet to come." Sun also reported TSMC has successfully made prototypes of both FPGAs and graphics processors using its chip on wafer on substrate (CoWoS) process. The technique, also known as 2.5-D packaging, links multiple die laid side-by-side on a common substrate. TSMC and its partners spent an estimated $11,9 billion on their chip design and manufacturing ecosystem, Sun said. "That's bigger than any single company, and its open--it is one of the biggest innovation forces in the industry."

According to Solid State Technology earlier this year, TSMC joined IMS Nanofabrication AG's multibeam mask writer collaboration to develop an electron multibeam mask writer for advanced mask lithography applications at the sub-10 nm HP node, joining founding members Dai Nippon Printing Co., Ltd. (DNP), Intel Corporation, and Photronics Inc. The program aims to develop a lithographic process that meets <10 nm patterning requirements at high throughput for leading-edge semiconductor manufacturing. The team is finishing up its proof-of-concept phase; the next phase will focus on the design and construction of an alpha and beta version of the multi-beam mask writer.

D2S Tips Model-Based Mask Data Prep Tool

Dylan McGrath - EE Times

Claiming an industry first, computational design tool vendor D2S rolled out a model-based mask data preparation (MB-MDP) tool said to offer fully automated, full-chip mask data preparation for complex photomasks at 20 nm and below process nodes.

According to D2S (San Jose, Calif.), the TrueMask MDP e-beam solution can handle complex masks with Manhattanized, curvilinear, and ideal inverse lithography technology (ILT) shapes in practical, cost-effective write times. TrueMask MDP reduces e-beam shot count to cut the mask write time by 20 to 30 percent or more, while improving the quality of the wafer produced through built-in mask process correction, D2S said. At 20 nm and below process nodes, both the main photomask features and sub-resolution assist features—which help preserve the depth of focus and critical dimension uniformity of the main mask feature they support, but which do not print themselves—must become increasingly more complex to ensure optimal patterning, D2S said. However, the number of e-beam shots required to create these complex features has caused mask write times—and mask costs—to skyrocket.

ASML to Buy Lithography Source Vendor Cymer

Dylan McGrath - EE Times

ASML is acquiring Cymer, a longtime supplier of lithography light sources. This acquisition is expected to accelerate the development of extreme ultraviolet (EUV) lithography, which the semiconductor industry is counting on for building chips at the 10 nm node and beyond. "We expect the merger to make EUV technology development significantly more efficient and simplify the supply chain and integration flow of the EUV modules," said Eric Meurice, ASML's president and CEO. ASML will also acquire Cymer's deep ultraviolet lithography (DUV) business. DUV is expected to remain a significant and growing engine of sales and profit and will be well positioned to support and balance customer needs for EUV and immersion multiple patterning, ASML said.

ASML will manage Cymer's commercial operations as an independent division based in the U.S. Cymer said it would continue to deliver and service DUV and EUV sources for all customers, including competitors.

IHS Lowers Forecast for Semiconductor Market

Debbie Cai – Wall Street Journal

Industry researcher IHS iSuppli Inc. lowered its outlook for global semiconductor sales for the year, now projecting a 2.3% decline. Increasingly weak economic conditions were cited as weighing on electronics spending. Preliminary research results show chip sales worldwide are expected to drop to $303 billion in 2012, from $310 billion in 2011, marking the first annual decline in the industry since 2009. September's forecast called for a 1.7% drop.

"Five out of the six major application markets for semiconductors—including the key computer segment—are expected to contract in 2012, pulling down the overall performance of the chip market," said Dale Ford, senior director for electronics and semiconductor research for IHS.

"An extremely weak global economy resulted in poor demand for electronics. As a result, the semiconductor industry slipped from stagnation in the first half of 2012 to a slump in the second half. Still, one of the few silver linings is that the fourth quarter is expected to bring a mild recovery in year-over-year growth, setting the stage for a market rebound in 2013."

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.

Individual Membership Benefits include:

- Subscription to BACUS News (monthly)
- Complimentary Subscription *Semiconductor International* magazine
- Eligibility to hold office on BACUS Steering Committee

www.spie.org/bacushome

Corporate Membership Benefits include:

- Three Voting Members in the SPIE General Membership
- Subscription to BACUS News (monthly)
- One online SPIE Journal Subscription
- Listed as a Corporate Member in the BACUS Monthly Newsletter

www.spie.org/bacushome

Calendar

2013

SPIE Advanced Lithography

24-28 February 2013
San Jose Convention Center and
San Jose Marriott
San Jose, California, USA
www.spie.org/al

SPIE Photomask Technology

10-12 September 2013
Monterey Marriott and
Monterey Conference Center
Monterey, California, USA
www.spie.org/pm

SPIE is the international society for optics and photonics, a not-for-profit organization founded in 1955 to advance light-based technologies. The Society serves nearly 225,000 constituents from approximately 150 countries, offering conferences, continuing education, books, journals, and a digital library in support of interdisciplinary information exchange, professional growth, and patent precedent. SPIE provided over $2.7 million in support of education and outreach programs in 2011.

SPIE®

International Headquarters
P.O. Box 10, Bellingham, WA 98227-0010 USA
Tel: +1 360 676 3290
Fax: +1 360 647 1445
help@spie.org • www.SPIE.org

Shipping Address
1000 20th St., Bellingham, WA 98225-6705 USA

SPIE Europe
2 Alexandra Gate, Ffordd Pengam, Cardiff,
CF24 2SA, UK
Tel: +44 29 2089 4747
Fax: +44 29 2089 4750
spieeurope@spieeurope.org • www.spieeurope.org

You are invited to submit events of interest for this calendar. Please send to lindad@spie.org; alternatively, email or fax to SPIE.