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High-NA EUV imaging: challenges and outlook

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ABSTRACT

The continuation of Moore's law demands the continuous development of EUV lithography. After the NXE:3400B scanner, currently being inserted in high-volume manufacturing (HVM), the next logical step is to increase the numerical aperture (NA) of the EUV projection optics, from 0.33 to 0.55, resulting in a high-NA EUV scanner.

Looking back at the history of lithography tools developed in the last decades, we can see that such an increase of NA is, in relative terms, unprecedented (0.55 = 0.33 + 67%). This significant step forward in the NA is a challenge on many fronts and requires many adaptations. In this paper you will find an overview of the key concepts that make high-NA lithography different on imaging end, how the imaging assures the continued life of Moore's law for the years to come and what are potential mask-related developments that would contribute to high-NA's success.

Keywords: EUV, high-NA, lithography, illumination optics, projection optics, imaging

1. INTRODUCTION

Previous decades have seen a steady shrinkage of the smallest feature size, see Figure 1. The introduction of EUV scanners, which are currently establishing their position as standard high-volume manufacturing (HVM) tools [1][2], allows the industry to approach the 10 nm resolution limit in a single exposure. "Approach," but not actually break that limit, since even for the theoretical lowest limit of the imaging k_1 factor of 0.25, the Abbe-Lin equation [3] yields the value of the Critical Dimension equaling $CD = k_1 \cdot {}^{\lambda}/_{NA} = 0.25 \cdot {}^{13.5}/_{0.33} = 10.3$ nm. To break the 10 nm resolution limit, while staying within the boundary conditions of the EUV lithographic paradigm (wavelength $\lambda = 13.5$ nm), the numerical aperture (NA) of the optics has to be enlarged. With the introduction of the high-NA optics, operating at NA = 0.55, instead of previously NA = 0.33, you are getting the capability to print 8 nm product features when operating at k_1 imaging factor of 0.325.

The reduction of the smallest feature size that can be printed, thus enabling the continuous shrinkage as dictated by Moore's law, is only one way of looking at the benefit of high-NA EUV lithography. An equally important benefit is the fact illustrated in Figure 2a: increasing the NA of the imaging optics allows you to print features with a higher lithographic contrast (NILS, normalized image log-slope, Figure 2b).

Increasing the NILS is as important as the shrink, since via the following relation [4]:

$$LCDU = k_4 \cdot {}^{1}/_{NILS} \cdot \sqrt{{}^{h\nu}/_{dose}}$$

the lithographic contrast is related to the local CD uniformity (LCDU), which is a measure of CD variability. If you want to have yield that is high enough, or defectivity that is low enough (or a defect-free process window [5] that's large enough), it is essential that LCDU remains low. Looking at the above formula you can tell that increasing the NILS reduces the LCDU.

Since NILS is a property of the aerial image, it is directly impacted by the optical parameters like illumination, NA, aberrations, *etc.* [4] In the following, you will find an imaging discussion from the point of view of an imaging scientist.

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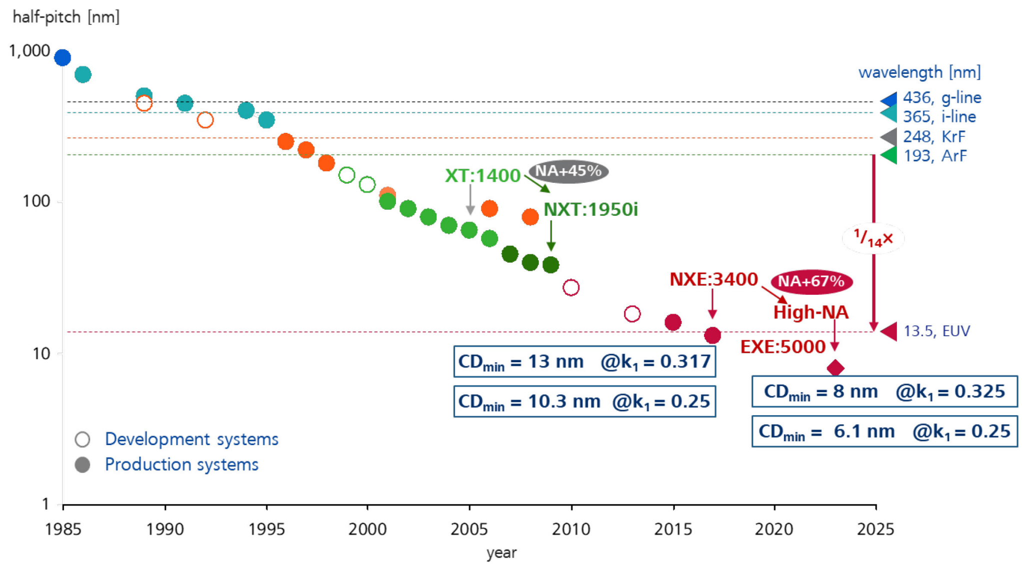

Figure 1. The high-NA EUV lithography is the first one to break the 10 nm resolution limit in one exposure. [6][7]

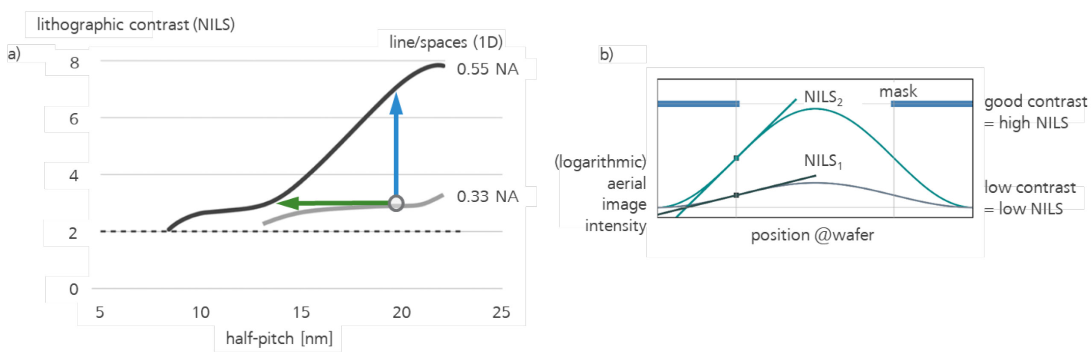

Figure 2. The benefit of increased NA is not only in feature shrink. Potential to increase the lithographic contrast (NILS, normalized image log-slope) is equally important (a) [6]. For clarity, the explanation of NILS follows: the better the contrast of aerial image is, the steeper its slope is, resulting in higher (= better) NILS value (b).

2. THE NEW ILLUMINATION OPTICS: THE EVOLUTIONARY CHANGE

2.1 THE BASIC CONCEPT AND BENEFIT OF THE FLEXIBLE ILLUMINATOR

The high-NA illumination optics, whose main purpose is to deliver a specific angular-resolved illumination (= pupil), uniform across the image field (= slit), is a direct descendant of the Starlith® 3400 Illuminator [8]. You can see an example sketch of such an illumination system in Figure 3. Since one descends from the other, the both illuminators share a plenty of commonalities:

- the basic design concept, resulting in discrete "spotty" pupils, is the same,
- one field facet can address several pupil channels (= pupil facets),
- the lowest pupil fill-ratio (PFR), for which the illuminator can work at full (= lossless) efficiency, is ≥ 20 %. Multiple settings exhibit this property of "lossless-ness" at PFR = 20 %,

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- the optics has a similar total number of facets, making the “granularity” of the high-NA illumination pupils similar to what you are used to seeing in pupils offered by the Starlith® 3400 Illuminator,
- pupil spots fill the complete pupil, meaning that the positions of discrete spots that make up a pupil stretch from the very center (σ = 0.0) right up to the aperture’s edge (σ = 1.0),
- the new illumination optics offers similar flexibility, allowing the user to use any custom illumination setting.

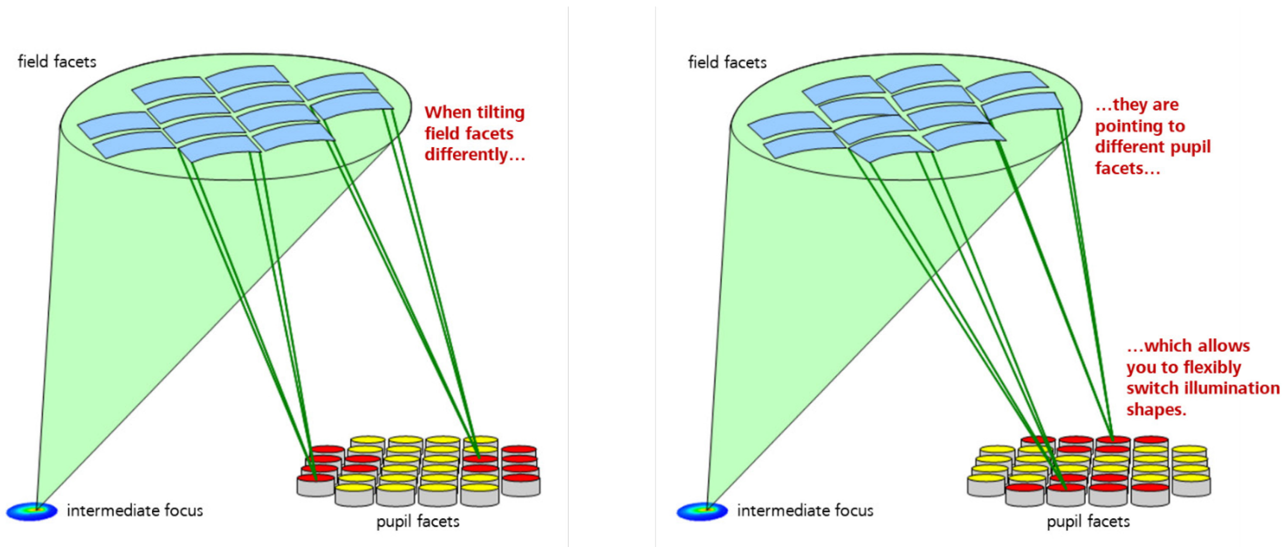

Figure 3. Principle of operation of a flexible EUV illuminator. [8]

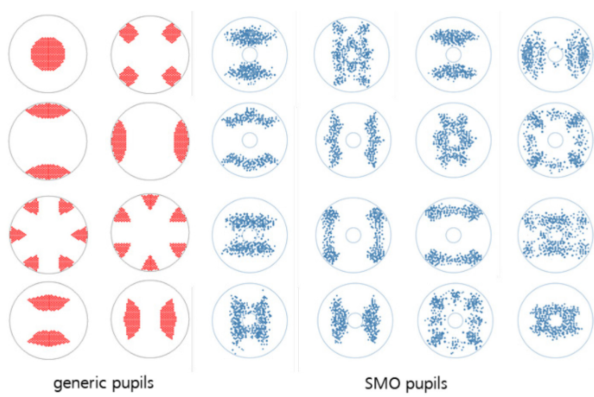

Figure 4. An extract from the illumination settings of the high-NA illuminator. It has enough flexibility to be able to deliver, apart from settings based on simple geometric considerations, also numerous custom SMO (source-mask optimized) settings; plenty of them in a lossless fashion (for pupil fill-ratio PFR ≥ 20%.).

In Figure 4 you can find an extract from the illumination settings that are available on the high-NA illuminator.

Both properties of the illuminator: its setting flexibility and pupil fill-ratio going down (without loss of EUV intensity) to 20 % are powerful instruments that allow for the tuning various aspects of the imaging performance. (Flexible) pupil shape which is matching to product features that are printed, combined with the reduced PFR, improve the NILS, which in turn results in a lower (= better) LCDU, see Figure 5a. Similarly, utilizing the pupil flexibility impacts the proximity iso/dense bias, see Figure 5b.

As you see in Figure 3, the design principle of the illuminator is based on “pairing” field and pupil facets. The “granularity” of the actual high-NA pupils (see Figure 4) is significantly higher than that of the pupils sketched in Figure 3, resulting in a multitude of “pairing” possibilities. Every of these pairings would result, due to different incidence angles in each case,

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in different imaging performance. This is why, apart from assuring the right PFR and flexibility, the verification of possible "pairings" is one of the steps in the illuminator design process, too. This verification is based on the evaluation of aerial images yielded by all potential design solutions. Below you will find a *very* brief explanation of what are the parameters that we evaluate.

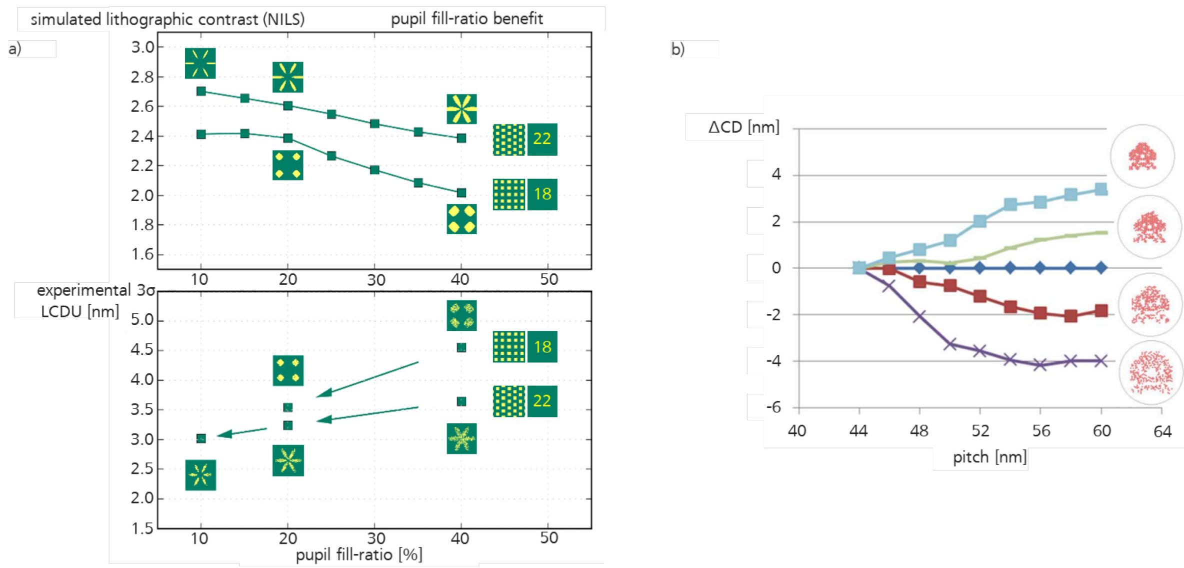

Figure 5. Reducing the pupil fill-ratio and utilizing the pupil flexibility can improve the lithographic contrast (a) [3] and proximity iso/dense bias (b) [9]. Contrast improvement is reflected in LCDU improvement (a).

2.2 A SIDE-STEP INTO AERIAL-IMAGE-BASED IMAGING PERFORMANCE METRICS

For an imaging scientist the aerial image is in the center of interest. The significant part of design and optimization process of the flexible illuminator is centered around making sure that it is "good enough." This specifically means that aerial images are permitted to be imperfect, as long as their parameters are below a certain value – that is: below the allocated budget.

The optimization assumes a certain set of features, which the tested pupils are supposed to print on a wafer, or in this case: generate the aerial image. These features may be line/spaces (dense or isolated) or contact holes at different orientations (like you see in Figure 5a). In each case we look at an aerial image, which after selecting certain intensity threshold yields a certain CD value. In Figure 6 you see an example of such an analysis. For the three evaluated pitches (starting at dense lines and going in the direction of isolated lines) it may be that $CD_2 \neq CD_{2.75} \neq CD_{3.5}$. Similarly, when looking at the dense pitch you evaluate the aerial images at different slit positions and compare the CD values there. When doing so, you arrive at the following parameters:

- CD uniformity: CD variation for smallest pitch thru-slit
- proximity bias range: CD variation thru-pitch and thru-slit

Next to that, when you follow the center of the pattern at each focus position, you will be able to tell whether the aerial image is non-telecentric or not, which is an important factor in overlay considerations. This way you arrive at another imaging performance parameter:

- (non-)telecentricity: thru-focus tilt of pattern shift, thru-pitch and thru-slit

2.3 THE PERFORMANCE OF THE NEW ILLUMINATOR FULFILLS EXPECTATIONS

The design process strives for a solution that provides the imaging performance (according to, among others, parameters defined above) within the allocated budget. In Figure 7 you can see that for the high-NA illuminator the design succeeded in delivering such performance.

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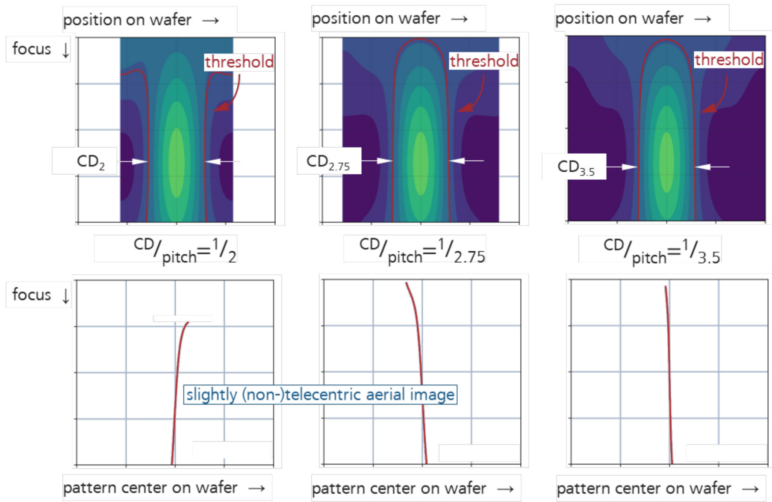

Figure 6. The design process of the Illuminator also comprises aerial image analysis.

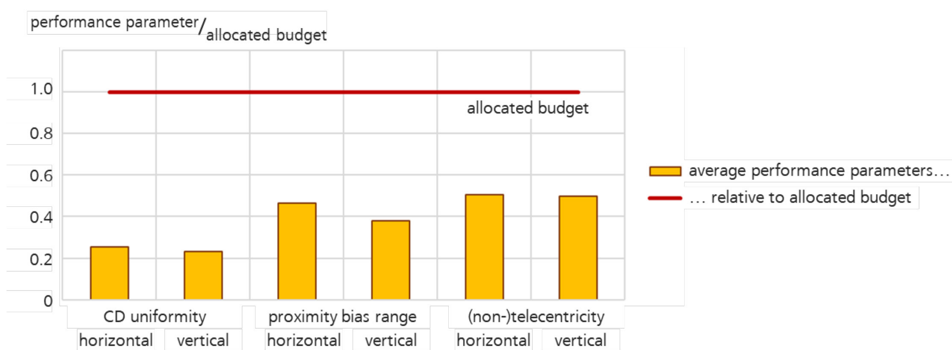

Figure 7. The successful result of the high-NA illuminator design process.

3. THE HIGH-NA PROJECTION OPTICS HAS A CENTRAL OBSCURATION

Above, you could find arguments that the high-NA illuminator represents a rather evolutionary development of lithography optics. This is not so much the case when you look at the projection optics.

Making sure that the projection optics handles the increased numerical aperture (NA), while at the same time is keeping the angular load on its mirrors at the lowest possible level, resulted in a design that is similar to telescope optics and comprises a central obscuration [10].

The presence of the obscuration leads to certain new properties of the projection optics which are interesting from the point of view of an imaging scientist. As you can see in Figure 8, the presence of the obscuration means that light travelling from certain directions will not reach the wafer, meaning that there is an “interruption” in the image transfer process from the reticle to the wafer. It may be not only the zeroth diffraction order that is blocked. The same situation may occur for first (and other) diffraction orders, depending on the pitch at the reticle level. In Figure 8 you can see that this is the case for first diffraction orders starting at pitch 26 nm, when they start “touching” the obscuration edge.

The questions we study are:

- what is the impact of the obscuration on imaging?
- how to implement the fact that the projection optics has an obscuration into the design of illumination settings?

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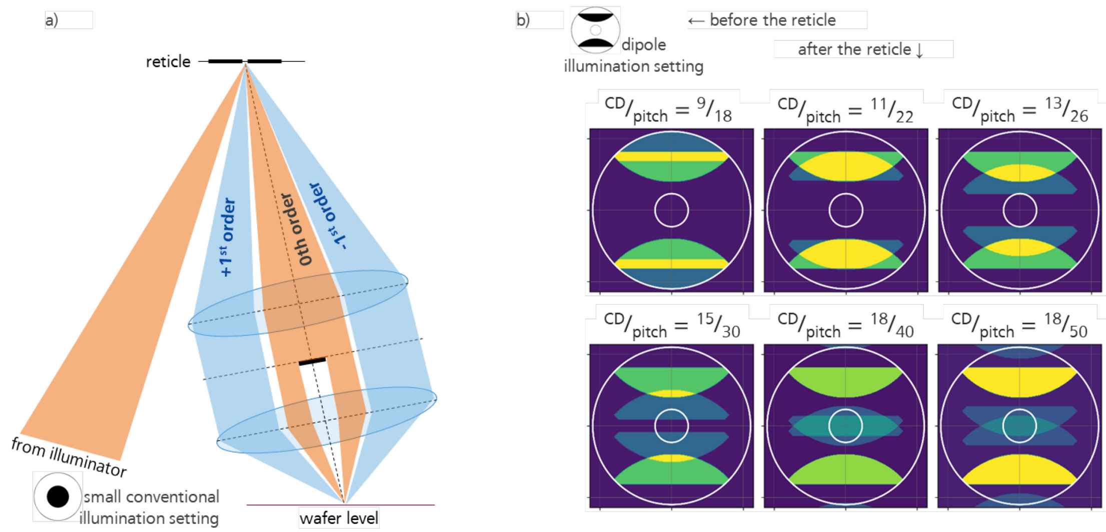

Figure 8. The presence of the obscuration means that some part of information contained in the diffraction orders (zeroth order, a, or higher ones, b, depending on the reticle's pitch) might not be reaching the wafer. The CD and pitch units are in nanometers.

3.1 SCENARIO ONE: AVOID THE OBSCURATION [6]

In Figure 9 you can see a situation similar to the one presented above. Namely: we illuminate a horizontal line/space pattern with a dipole illumination (a). In this study we look at NILS. You see that, as above, starting from around pitch of 26 nm we experience a contrast loss. We can explain that by looking back at Figure 8 – the first diffraction orders start being blocked by the obscuration.

We can mitigate this contrast deterioration by "fixing" our illumination. We do that by simply "switching off" light in the parts of poles which, when diffracted, would interact with the obscuration (b). Indeed, the contrast drop which starts at around 26 nm is minimized. This simple solution has a significant drawback, though. The PFR in this case is only 14 %, which means that the high-NA illuminator can offer such a setting only in a lossy manner.

Tachyon™ SMO software circumvents that limitation and comes up with a pupil of PFR = 20 % (c), which still has a performance on-par with the performance of the lossy "fixed" dipole, while we may use this new pupil in a lossless manner. You may see this as another example of the importance of SMO studies and their potential, and of the benefit coming from the flexibility that the high-NA illuminator is offering.

The fact that even the source-mask optimization process comes up with a solution with "holes" which, when diffracted, try to avoid the obscuration, seems to suggest that in cases similar to the one we study here, you should generally design the illumination pupil in such a way, in which you make the diffraction orders *avoid* the obscuration.

3.2 SCENARIO TWO: UTILIZE THE OBSCURATION [6]

Contrary to what you have just seen, another class of use-cases (contact holes) seems to prefer placing the illumination light in the area that corresponds to obscuration, see Figure 10. You can see there that pupil (a) is characterized by around 10 % higher contrast (NILS), when compared to pupil (b) which "avoids" the obscuration.

We can explain this by looking at the part of the illumination that points only at the obscuration (c). The fact that first diffraction orders are not blocked, whereas the zeroth order does, results in an aerial image of double spatial frequency. It adds constructively to the aerial image generated by the pupil (b), so that the compound aerial image may only have *larger* contrast.

The downside of a solution which shines light onto the obscuration area is that part of light is being blocked by it. This means that the exposure dose needs to be increased accordingly, in this case around 2.5 %, see Figure 11. Despite that, placing light in the obscuration area is still a preferred solution, since the benefits of enlarged process window, increased contrast and reduced LCDU, overweigh the need to increase the dose.

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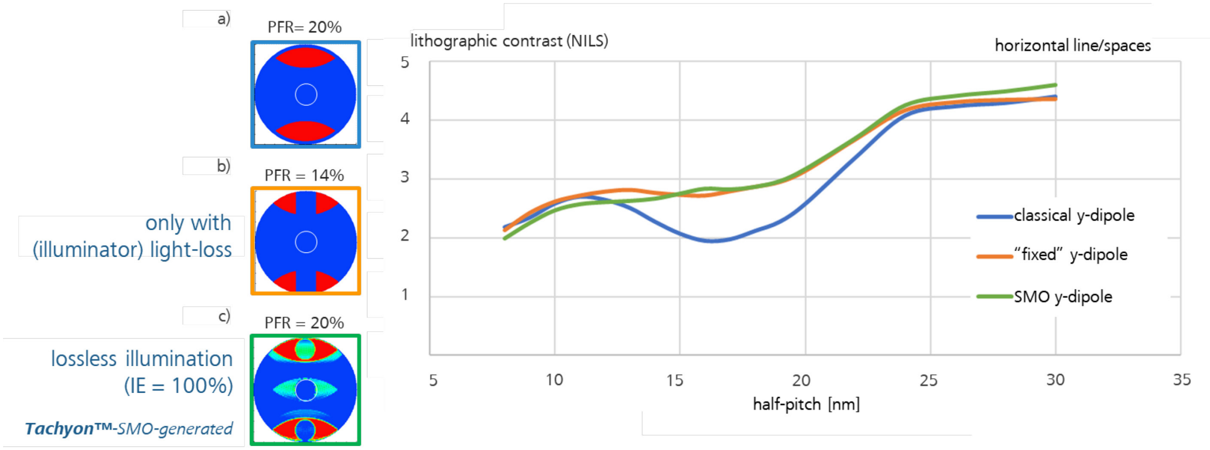

Figure 9. The solutions for line/space structures seem to prefer to avoid the obscuration. [6]

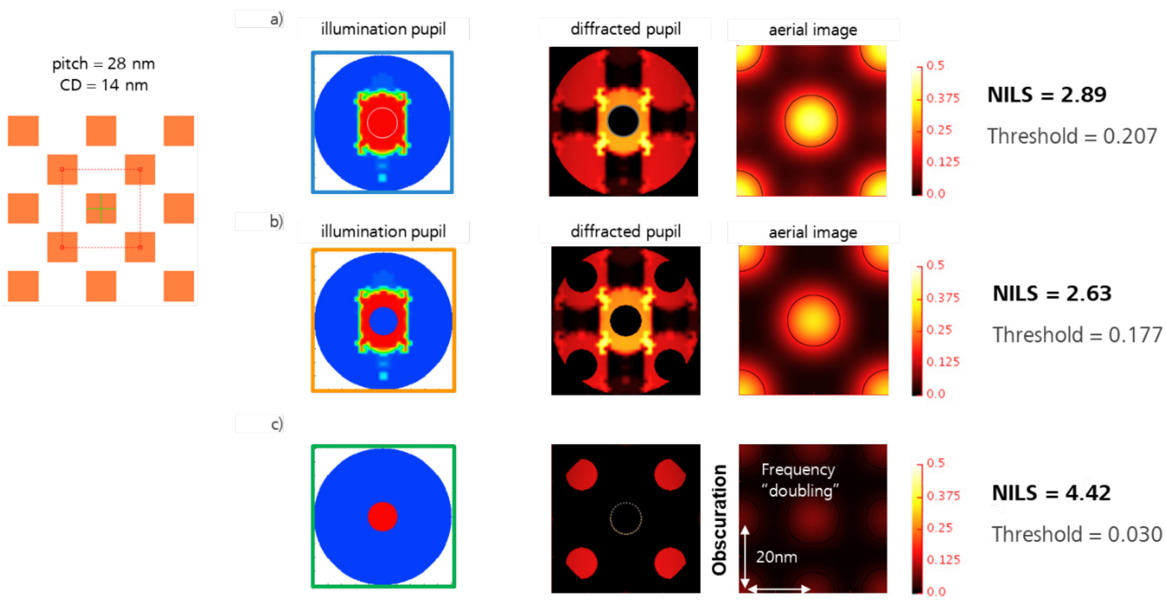

Figure 10. Contact hole type of use cases benefits from placing the light in the obscuration area. [6]

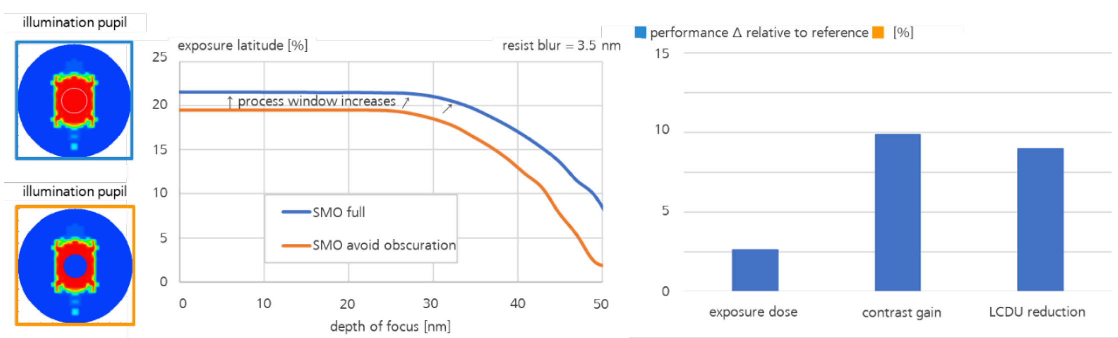

Figure 11. The benefits of shining light onto the obscuration area overweigh the 2.5 % increase in needed dose. [6]

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4. MASK LANDSCAPE OPPORTUNITIES

The subject that deserves (and also receives) a plenty of attention is the need for a high-k absorber material [6][11][12]. In the eyes of an imaging scientist such a material may indeed offer multiple benefits.

Firstly, the introduction of a right high-k absorber for the contact hole class of masks would lead to another contrast improvement, see Figure 12. In Figure 11 you have seen that when compared to "avoid obscuration" pupil (b), the contrast gain from shining light onto the obscuration is about 10 %. By introducing the high-k material on the mask this gain may increase to 15 %. Also when staying with "avoid obscuration" setting, the contrast gain is around 5 %.

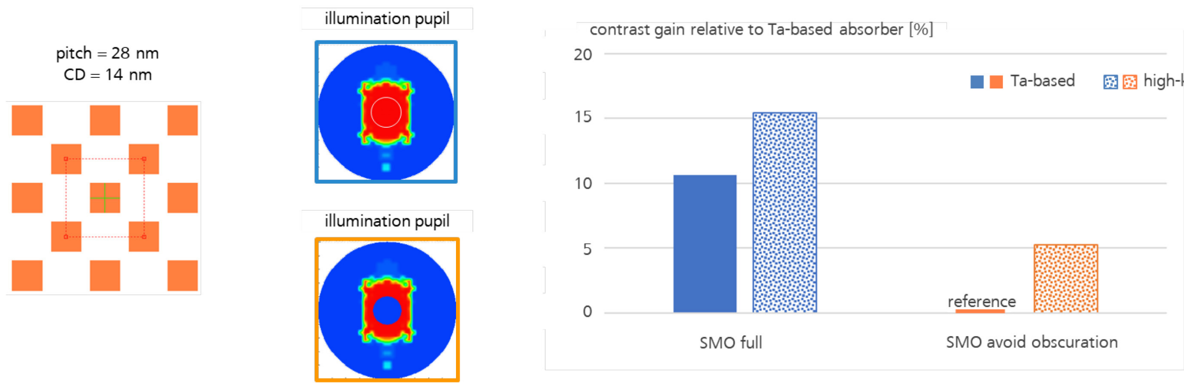

Figure 12. High-k absorber benefit for the contact hole class use-cases. [6]

Secondly, also for line/spaces class of structures the introduction of the right high-k absorber would be beneficial, see

Figure 13. Whereas in all cases the exposure latitude is greater than 20 %, to approach 25 % with the standard Tantalum-based absorber you would need to reduce the PFR of the pupil to below 20 %. This would mean a lossy pupil (b, c). As such, you would be forced to trade-offs between the exposure latitude and illuminator efficiency (= and the corresponding throughput impact).

The situation would change if you worked with a high-k absorber mask. All three pupils (a, b, c) deliver comparable exposure latitude performance, therefore the need for trading it off with PFR disappears.

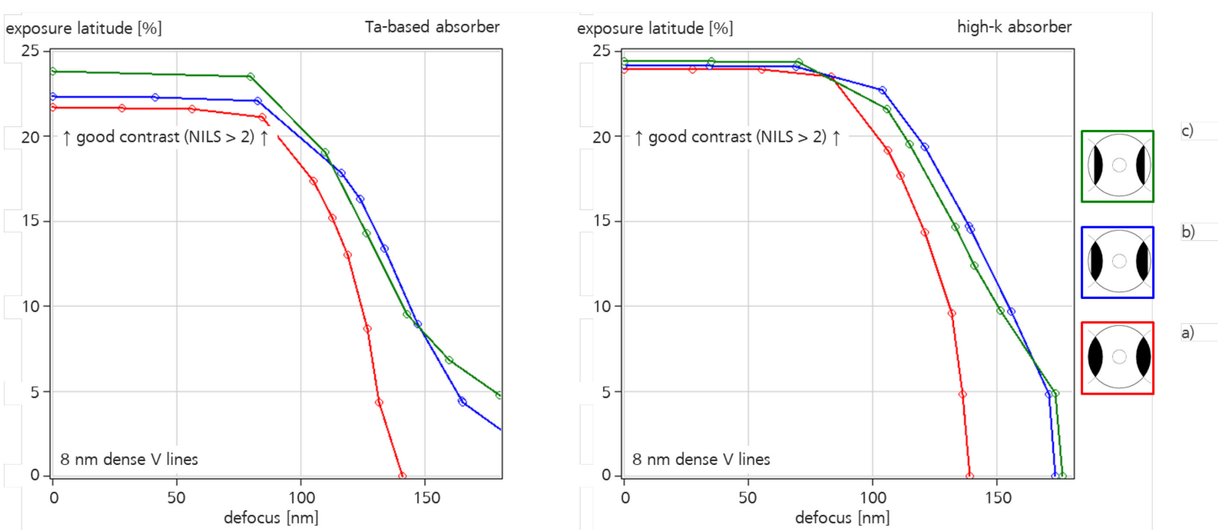

Figure 13. High-k absorber benefit for the line/spaces class use-cases. This result is simulation-based, for an ideal scanner with zero resist blur.

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On the other hand, though, the higher absorption of the high-k absorber might result in a higher dose that is needed for exposure. You should not forget that fact when enjoying the good exposure latitude already at PFR = 20 %. Even though you will not suffer from illuminator-induced throughput-hit (since at PFR = 20 % and above it operates in a lossless manner – no EUV light is lost), you will suffer from a throughput-hit due to higher dose you would need.

5. SUMMARY

High-NA EUV optics provides resolution and contrast improvements for the continuation of Moore´s law. Its illuminator provides high flexibility that supports customer needs. Its projection optics has a novel design comprising a central obscuration. The incorporation of the central obscuration into the design of the projection optics enables the high-NA lithography. We understand the impact the obscuration has on the imaging process and how can you use it to your benefit. In the high-NA mask landscape a high-k absorber is beneficial to imaging performance.

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