# Photomask Registration and Overlay Metrology by means of 193 nm Optics

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## ABSTRACT

This paper reports on the current status of PROVE™ - a new photomask registration and overlay metrology system currently under development at Carl Zeiss. The scope of the project is to design and build a photomask pattern placement metrology tool which is serving the 32 nm node. Performance specifications of the tool are actually driven by double exposure/ double patterning approaches which will help to extend the 193 nm lithography platforms, while keeping the semiconductor industry conform to ITRS roadmap requirements. A secondary requirement of pattern placement metrology tools is the CD measurement option for design features of interest. Combining both registration and CD measurement reduces the number of process operations a photomask has to encounter during manufacture. Optical design considerations are discussed, which led to the tool being designed for 193 nm illumination corresponding to at-wavelength metrology for most current and future photomask applications. The concept enables registration and CD metrology by transmitted or reflected light. The short wavelength together with a NA of 0.6 also provides sufficient resolution even at working distances compatible with the use of pellicles, hence enabling the tool for qualification of final, production ready masks. Imaging simulations with a rigorous Maxwell solver prove our chosen optical concept to be adequate for the various mask types (e.g. COG, MoSi, EUV) commonly used today and presumably in the future. The open concept does enable a higher NA for future, pellicle free applications.

**Keywords:** registration metrology, pattern placement, optical design, resolution, imaging performance

## 1. INTRODUCTION

The pattern placement error of a photomask called registration has recently gained more and more attention. For many years, this error contribution was an important but usually achievable part of the overall overlay error budget. Writing tools as well as registration measurement tools were able to keep up the pace with the increasing demands from technology node to technology node [1]. At 45 nm and sub–45 nm manufacturing technologies and with the introduction of sophisticated patterning schemes general assumptions on the distribution of the registration error across the photomask are no longer valid. The painful experience that the measured global registration error does not necessarily represent the local situation is just one example. In order to avoid any misclassification, state of the art registration measurement tools have to not only fulfill stringent repeatability and accuracy performance targets, but also have to satisfy resolution requirements needed for local registration measurements on design features. In addition, there is an increased demand to perform the qualification of the final masks including the influence of different types of pellicles, which requires a sufficient working distance between the substrate and the objective lens. The goal of the present paper is to discuss constraints and considerations for the optical beam path during the design phase for PROVE, the new registration and overlay measurement tool which is currently under development at Carl Zeiss. The PROVE project is supported by SEMATECH and leading edge device manufacturers. It addresses the registration and resolution

requirements needed for the 32 nm node. After a brief presentation of the current status of the project, the paper emphasizes general optical design considerations for high resolution registration measurements, optical simulations for various types of commonly used masks and a discussion on substrate particularities.

## 2. PROVE – STATUS OF PROJECT

In previous public presentations about the project e.g. at EMLC [2] in January or at PMJ [3] in April of this year, we were able to report on the final design of the tool and could present a few selected highlights, such as the 193 nm at-wavelength imaging and auto-focus optics for improved optical performance. In the meantime the PROVE team was busy to put their ideas one step closer to reality. Executing according to the project plan and in time for BACUS we are happy to report further significant progress on the tool. Figure 1 illustrates the arrangement of the main components comprising the entire registration tool: the extensive climate control unit with system electronics, the 193 nm laser source, the precision stage with illumination and imaging optics, and the mask handling unit with two robots for fully automated integration into a fab environment. Most of these key components have already been assembled and passed their respective individual acceptance procedures.

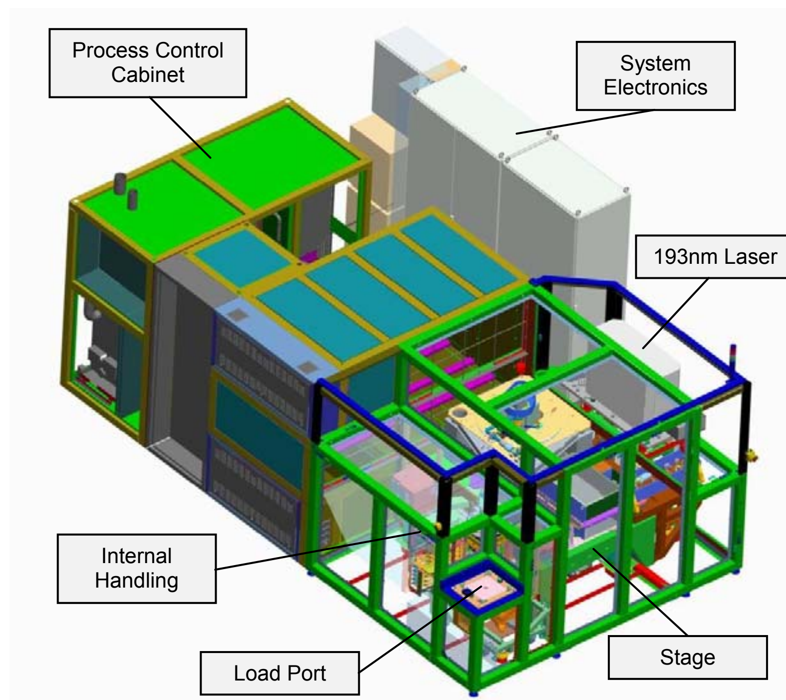


Figure 1: Schematic drawing of the PROVE™ tool

The climate control unit was assembled and successfully tested at the supplier's site, and meanwhile shipped to the Carl Zeiss SMS GmbH. The mask handling unit was also put together as a separate unit, passing its tests and it will soon be attached to the stage unit. The precision stage itself, which is an in-house development of the Carl Zeiss SMT Lithography Division based on a decade long experience with similar stage designs in the metrology group, has also been assembled and adjusted. Last but not least, the optics for the key optical elements, such as the microscope objective lens in the imaging path or the condenser in the illumination path have been manufactured, mounted, assembled and are in the process for the final steps of adjustment to reach their targeted performance.

Progress on the tool has been steady, and the coming months will see the integration of all components to form a complete and functioning unit. Hence it is fair to say, that the status of the project has moved from ideas on paper to tangible hardware in the lab.

## 3. OPTICAL DESIGN CONSIDERATIONS

The current and the next generation of registration tools [2, 4] are based on an optical concept of illumination and imaging, which was already used from the beginning of microscopy. In its latest incarnation within a registration tool, the mask is placed on a high precision stage in order to be able to position any feature on the mask surface into the imaging field of an optical microscope, which then enlarges the mask features onto a CCD camera. By accurately determining the position of the feature in the field of view, as well as determining the exact travel of the stage, it is possible to precisely measure the relative distance of two features on the mask. Whilst the required precision of such a measurement is unprecedented in microscopy and requires enormous efforts especially on part of the stage, the basic principle of the registration measurement is still that of a microscope. Hence all modern registration tools are sophisticated optical instruments and their optical design has to take the customer's expectations into consideration.

Mask makers expect from a new registration tool, that they can use it to resolve small features comparable to the design structures in order to even detect local registration errors correctly. High resolution additionally permits to reduce the real estate on the mask used solely for registration measurement purposes by using smaller markers or eventually even by utilizing design features themselves. At the same time, however, the registration tool should still be all-purpose especially with regard to qualifying final masks – i.e. being able to measure the influence of the various pellicle types on the mask. Unfortunately some of these expectations cannot be optimized simultaneously; rather a compromise has to be found. As will be pointed out later, the quest for highest resolving optics comes at the cost of a reduced free working distance and vice versa. However, by addressing all parts of the involved optics, it is possible to balance the contradicting goals in a way that can satisfy the mask maker.

Any optical instrument consists at least of the following basic components contributing to its imaging performance (Figure 2):

- an illumination, which can vary in its wavelength $\lambda$, its intensity and partial coherence $\sigma$, and its degree of polarization
- an object to be imaged, which can vary in its material properties, its feature width (CD), and its feature separation (pitch)
- an imaging optic, which collects the light from the illuminated object and images it onto a detector. Its optics can vary in the available free working distance, the collection angle for the light (the numerical aperture NA), the magnification and the aberration level.

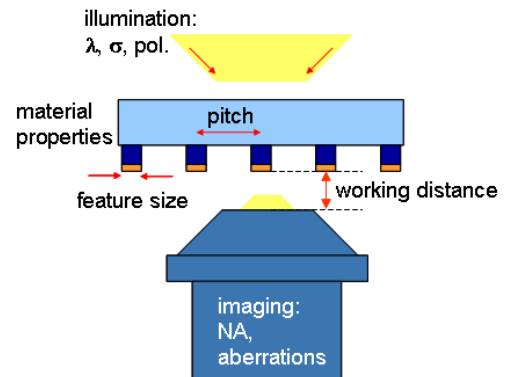


Figure 2: Basic optical imaging components

The imaging performance of the instrument depends on the interaction of all involved components. An optical designer can influence both the illumination, as well as the imaging optics, while the objects are given by the application. Illumination is often restricted to a mere discussion of the wavelength, neglecting the potential of optimizing the other important parameters like partial coherence and polarization. The imaging optics on the other hand is often described by the numerical aperture and its magnification alone, not mentioning its aberration level. For the registration tool the objects are the various masks to be used, which are a few selected different types such as the standard chrome-on-glass (COG) mask in transmission, MoSi masks in transmission or e.g. EUV masks with absorber stacks in reflection. The feature size and pitch is typically given by the current node [1]. Furthermore the free working distance can be constrained, if masks with attached pellicles are to be measured. In order to achieve highest performance in registration and CD metrology, the main challenge for the imaging optics is to produce high contrast images even for smallest features of the upcoming technology nodes. This implies not only using perfectly corrected imaging-optics itself with high resolving power, but also to exploit the potential of flexible illumination schemes for further contrast enhancement. Hence the combination of both, imaging- and illumination-optics, is the key to resolve the partially contradicting requirements an optical mask qualification is facing.

**Optical Resolution:**

The primary task of the imaging optics is to map the desired field of view suitably onto a detector area, which immediately yields the required magnification. Detector areas are given by the available camera chips, while the field of view is determined by the application. The magnification itself can be achieved with the proper combination of microscope objective and tube lens. For this optical property, the compromise stems from the contradictory goals to keep the imaging optics small for reasons of stability, but rather design it long for optical purposes on the other hand.
Optical resolution (not to be mixed up with magnification) describes how small a structure with others nearby can be imaged as a distinct feature onto the detector. While single structures can always exhibit some contrast, dense lines will disappear beyond the resolution limit of the optic. This optical property is therefore important in order to be able to utilize small, dense design features for registration purposes. The theoretical optical resolution limit is given by the following simple relationship [5]:

$$hp_{\min} = \frac{\lambda}{2 \cdot (1+\sigma) \cdot NA} \geq \frac{\lambda}{4 \cdot NA} \qquad \text{(Equation 1)}$$

$hp_{min}$ is the smallest separation of adjacent features (at a pitch of twice its width) which can be resolved, $\lambda$ is the wavelength of the illumination, $\sigma$ the degree of coherence of the illumination, and NA is the numerical aperture of the imaging optics. In order to obtain optics with high resolving power, one would like to utilize the shortest illumination wavelength available, use a maximally incoherent illumination and design the imaging optics with the largest NA possible. Unfortunately, suitable sources of light at short wavelengths are rare, and typically one has to pick either some Mercury-Xenon lamps at about 365 nm, frequency up-converted lasers at e.g. 266 nm, or in the

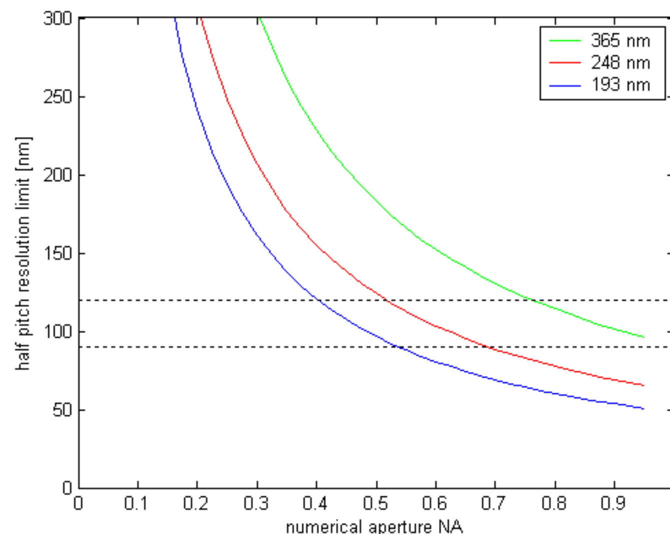


Figure 3: Theoretical resolution limit vs. numerical aperture

lithography world common excimer laser types of KrF at 248 nm or ArF at 193 nm. The drawback of these shorter wavelengths is, that optics for UV light are more difficult to produce, since lens and coating materials with sufficient transmission become rare. Only few companies have been able to build up the experience to provide imaging optics for

e.g. 248 nm or 193 nm. The NA is a measure for the acceptance angle of light being imaged onto the detector. While the theoretical value for non-immersion systems is unity, realistic values can reach up to 0.95. Given these numbers the theoretical resolution limit for various illumination wavelengths and NAs is illustrated in fig. 3. Looking at the 120 nm hp lines, which are given as nominal CD for the 32 nm node, the numerical aperture for the different wavelengths 193 nm, 248 nm and 365 nm has to exceed 0.4, 0.55, or even 0.75 respectively. However, while these numbers represent the theoretical limit, in reality there is a significant loss of contrast close to the limit. This implies that the required NA will be larger than the quoted values in order to properly resolve the 120 nm dense features, and e.g. a 365 nm illuminating wavelength might have a hard time to fulfill this task at all. Based on these considerations, the optical designer will likely pick either 248 nm or 193 nm as an illumination wavelength. In order to be able to compare these two choices later, we restrict our discussion to a NA of 0.6 for 193 nm and 0.8 for 248 nm - both combinations approximately providing similar resolution.

**Free Working Distance:**

Improved optical resolution would dictate to maximize the numerical aperture; however, especially the demand for a large working distance has severe impact on the possible NA of the objective. The free working distance usually depends on the decision whether or not pellicle compatibility will be required. If final mask qualification with an attached pellicle is an essential requirement for the registration tool, only moderate numerical apertures are available with reasonable technical effort. While there is no physical reason which prevents the realization of both a high numerical aperture and a long working distance, technical efforts and costs rise dramatically in this combination. This general tendency can be understood by the following considerations.

The numerical aperture describes the acceptance angle of the light cone to be imaged. Comparing the two NAs of 0.6 and 0.8 in the simple geometrical picture illustrated in figure 4, the relationship between NA and free working distance becomes obvious. Increasing the NA from 0.6 to 0.8, while keeping the same working distance, results in a ~80% larger lens diameter to capture all the light.

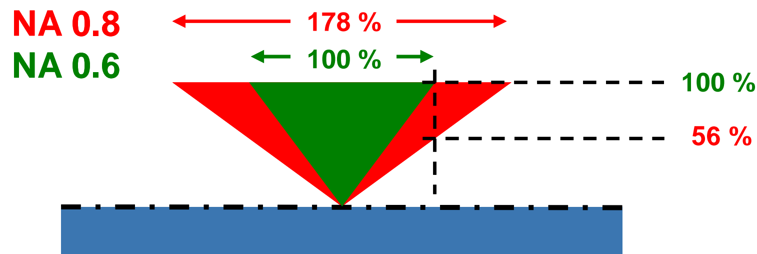


Figure 4: Geometrical relationship between free working distance and NA

This larger lens alone would use about 4-5 times more material, weigh that much more and require sophisticated mounting. Just from this pure geometrical point of view, an increase in NA would result in significantly higher costs. In a similar way, given a fixed NA, the working distance could be increased by scaling the design accordingly, resulting again in larger lenses at drastically higher costs. Beyond the mechanical dimensions themselves, the control of wave front aberrations and chromatic errors of such an objective would also scale by this factor. This would result in even more design effort (e.g. a larger number of lenses) leading to a further increase of costs.

This general dependency also manifests itself when looking at the commercially available micro objectives of major optics suppliers in the visible region. As illustrated in figure 5, the possible working distances reduce as the numerical apertures increase. Especially for NA > 0.6 highly corrected micro objectives have working distances below 1mm.

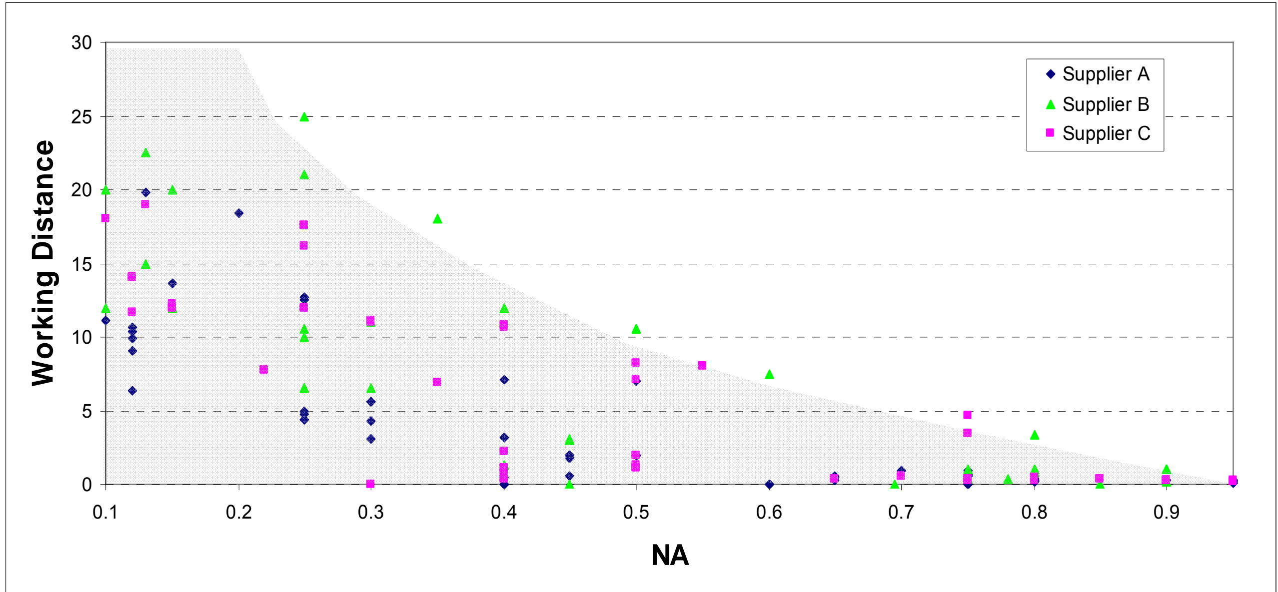


Figure 5: Working distance [mm] vs. NA for commercially available micro objectives of different major suppliers (visible wavelengths and various aberration levels)

This comparison with micro objectives in the visible region does not reflect all relevant optical parameters (e.g. the aberration level) and cannot be transferred one-to-one into the realm of UV lenses, but it nonetheless illustrates that NA and working distance are connected - at least via a technological and financial limit.

**Illumination conditions:**

The illumination wavelength λ was already discussed in the context of optical resolution. However, other illumination parameters like the degree of coherence or polarization have also a significant impact on the imaging. While different types of masks (COG, MoSi, EUV), as well as the dimension and shape of the structure affect the contrast, this can be partially compensated by adjusting the illumination properties. Hence, a registration tool can benefit from the design of a well-conditioned illumination optic. The simulations in the next section will underline the suitability of this concept.

**Impact on Registration Repeatability:**

The optical design parameters do not only affect the resolution and thus the smallest features to be observed, it has also a direct impact on the registration performance. As the structures on the mask approach the resolution limit, the contrast of the obtained image diminishes severely. A low contrast image in combination with the inherent noise of the imaging system (CCD camera & electronics) yields an uncertainty in determining the exact position of the features. While this error typically does not constitute the limiting factor in the tool's precision, it certainly can contribute a significant portion in the case of low contrast imaging. A theoretical analysis shows that the noise contribution of the imaging system enters the registration error in the following way:

$$reg.repro \propto \underbrace{\sigma_p \cdot \sqrt{p_x \cdot p_y}}_{CCD} \bullet \underbrace{\frac{(1+\gamma)}{2\gamma}}_{contrast} \bullet \underbrace{\sqrt{\frac{\lambda/NA}{2L \cdot N_t}}}_{\substack{edge\ geometry \\ and\ averaging}} \qquad \text{(Equation 2)}$$

The first term in Eq. 2 represents the parameters of the CCD camera ($\sigma_p$: pixel noise; $p_x$, $p_y$: pixel size in x/y-direction), the second term reflects the influence of the aerial image contrast γ, and the last term describes the effect of the imaging parameters wavelength λ, numerical aperture NA, and the spatial and temporal averaging parameters L (length of feature) and $N_t$ (number of images). The image contrast scales the registration error contribution in a nonlinear fashion,

which can be seen as a ‘penalty factor’ for low contrast imaging. Figure 6 illustrates this behavior and shows that below a contrast of 30% the impact on the registration increases sharply. Table 1 actually estimates the error for an example registration situation (2% CCD noise, 20 µm feature length, 5 images averaging) with varying contrast values. In order to maintain a registration error below a certain level, one would have to compensate lower contrast with more averaging (larger feature, more images):

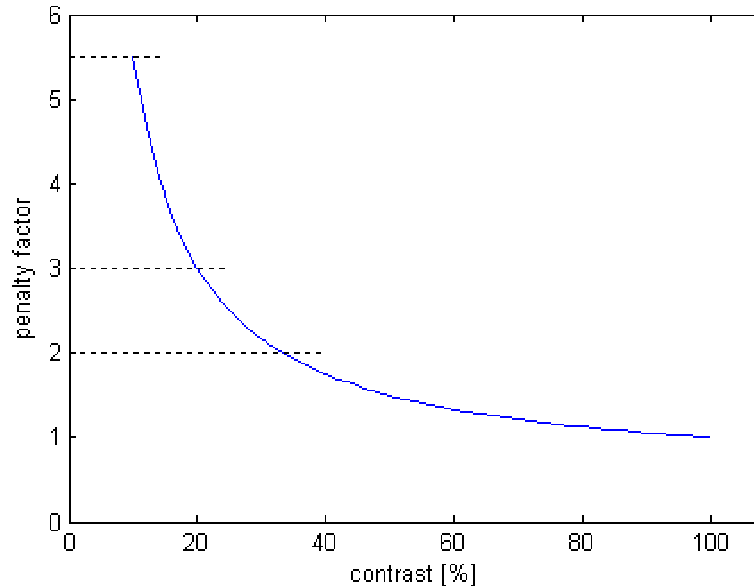


Figure 6: Contrast influence on reg. error

| Contrast [%] | 100 | 80 | 60 | 40 | 30 | 20 | 15 | 10 | 5 |
|---|---|---|---|---|---|---|---|---|---|
| Penalty factor | 1.0 | 1.1 | 1.3 | 1.8 | 2.2 | 3.0 | 3.8 | 5.5 | 11 |
| Camera induced reg. error [pm] | 50 | 57 | 67 | 88 | 109 | 151 | 193 | 277 | 529 |

Table 1: Influence of contrast on reg. error contribution

Equation 2 indicates that the resolution criterion and the obtained image contrast dominate the registration error contribution due to the imaging system. Hence a shorter wavelength and a larger numerical aperture also improve the registration performance within the limits discussed before. One more side aspect of the optical parameters $\lambda$ and NA is, that they also define the available depth of focus (DOF) via $\lambda/NA^2$. That is, if one has two systems with the identical resolution, the one with the shorter wavelength yields a larger DOF, as compared to the one with the larger NA. The larger the DOF, the less sensitive is the system on focusing errors. Hence, larger DOF values are considered beneficial, though DOF is not the driving force for registration performance.

Comparing three potential optical configurations illustrates the interplay of the various optical parameters considered (table 2). One design consists of a 193 nm illumination in combination with a NA of 0.6, which is suitable for resolving dense structures of the 32 nm node. This system serves as a benchmark, hence its performance indicators are set to 100%. A second system offers a comparable resolution, but uses the longer wavelength of 248 nm with increased NA, and a third system utilizes 248 nm without increasing the imaging NA. The contrast values have been simulated for a COG mask with dense lines (260 nm pitch and 130 nm CD) and conventional illumination.

| Imaging configuration | 193 nm, NA 0.6 | 248 nm, NA 0.8 | 248 nm, NA 0.6 |
| --- | --- | --- | --- |
| Optical resolution | 100 % | 104 % | 78 % |
| Contrast<br>→ reg. error contribution | 88.1 %<br>1.00 | 87.3 %<br>0.99 | 50.7 %<br>1.58 |
| Depth of focus | 100 % | 72 % | 128 % |
| Free working distance | 100 % | 30 % | 100 % |

Table 2: Overview of three [λ, NA] configurations of the imaging system

Both systems with similar optical resolution achieve comparable contrast values and hence reg. error contribution. The 248 nm system with the larger NA, however falls short with respect to DOF and the free working distance. The third system with a NA of 0.6, suffers from the reduced resolution capability resulting in lower contrast images and therefore increased reg. error contribution. This last system on the other hand would also be pellicle compatible and exhibits an even larger DOF. This simple comparison clearly illustrates, that the shorter illumination wavelength is key to achieve a balanced optical design, when the demanding requirements of optical resolution, high contrast imaging and large working distance all have to be met simultaneously.

## 4. SIMULATIONS

The previous chapter outlined basic optical design considerations in balancing optical resolution, impact on registration and limits on the free working distance. In order to arrive at a well-suited optical design for the registration requirements of the 45 nm, 32 nm or even 22 nm node, both illumination, as well as the imaging optics have to be adapted to the task. Operating at the physical borderline of optical imaging, the properties of the mask themselves play an essential role to create high contrast images. In order to properly assess the performance of all components working together, and being able to separate the influence of different parameters, we performed systematic investigations based on rigorous imaging theory using MicroSim [6].

The simulations were performed for a typical 32 nm node requirement of dense lines with a pitch of 260 nm and a CD of 130 nm. Starting with the properties of the mask features (material composition, optical constants, dimensions etc.) rigorous diffraction spectra were calculated for different illumination conditions. In a second step the microscopic image was synthesized using Fourier theory and the model of Hopkins effective source [7, 8], properly modeling the real imaging process in every detail. These simulations enable to identify both general trends of imaging and illumination conditions, as well as explore specific peculiarities of mask and illumination parameters.

The most commonly used masks today are chrome on glass (COG) and MoSi. The standard illumination for imaging consists of an unpolarized and incoherent illumination in transmission. Figure 7 shows the dependency of the image contrast on the imaging NA for 193 nm and 248 nm illumination wavelength and conditions of $\sigma=0.7$ and $\sigma=0.95$, respectively. The parameter $\sigma$ hereby defines the radius of the illumination disc with respect to the full imaging aperture radius. For the COG mask all the well-known and expected features can be seen: increasing the imaging NA at one wavelength leads to a rise in contrast, while for a fixed NA the usage of the shorter 193 nm wavelength provides better contrast than with 248 nm. This is especially true for a moderate NA of 0.6 and $\sigma=0.7$, which could be used in a pellicle compatible registration tool. 248 nm illumination wavelength yields a contrast of only 5%, while 193 nm rises above 50%. Utilizing the more incoherent light with a sigma $\sigma$ of 0.95, the contrast improves to 20% and 55% for 248 nm and 193 nm, respectively. Thus requiring pellicle compatibility, the shorter wavelength improves contrast at least by a factor of 2-3, depending on the degree of coherence used in the illumination. This improvement of contrast with wavelength is

especially important in this region of lower contrast, as the penalty in registration error due to camera noise rises sharply below 30% contrast. If one is willing to sacrifice the free working distance, i.e. the pellicle compatibility, optics with a higher NA up to 0.9 could be employed. For this higher NA the difference in contrast with respect to the wavelength gets smaller, ending up with approx. 90% in comparison to 75% at 193 nm and 248 nm, respectively. This contrast difference yields only to a negligible 'penalty' in registration error.

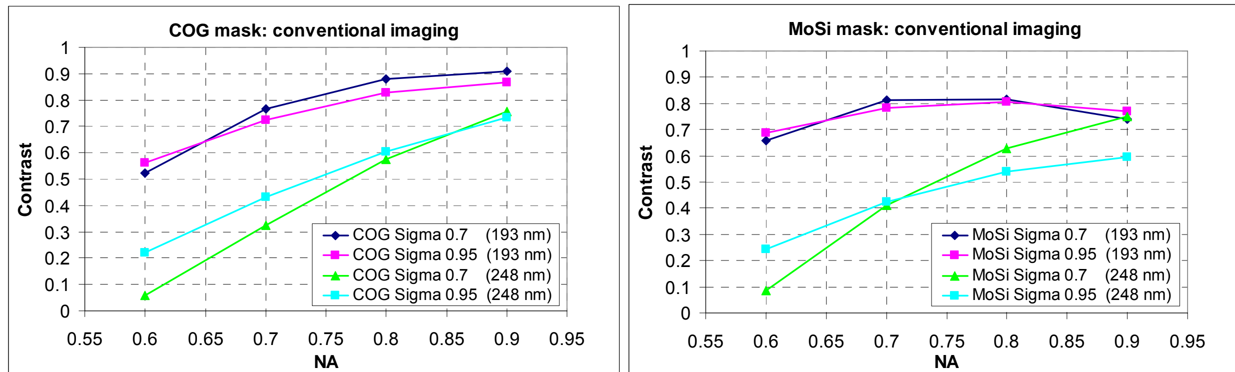


Figure 7: Image contrast vs. numerical aperture for conventional imaging using wavelength of 193 nm and 248 nm.
Left: simulations for dense lines (half pitch 130 nm) on a COG mask in transmission.
Right: simulations with corresponding parameters for a MoSi mask.

Looking at MoSi structures, the situation is different as illustrated in figure 7 on the right hand side. Using 193 nm wavelength the simulations yield a pronounced contrast of approx. 70% for an imaging aperture NA of only 0.6. The contrast rises only slightly up to 80% with increasing NA and even falls down back to 75% for NA=0.9. Hence utilizing 193 nm illumination with MoSi masks already provides almost optimal contrast at an NA which is pellicle compatible – a sacrifice of working distance for the sake of improving contrast could not be justified. At the longer illumination wavelength of 248 nm, the achievable contrast values resemble the COG situation. At a pellicle compatible NA of 0.6 the contrast is limited to 10% or 25% depending on the degree of coherence of the illumination. At the highest NA of 0.9, a maximum contrast of 60% or 75% can be obtained, again depending on the degree of coherence. The reason for the striking behavior that 193 nm illumination yields superior contrast is due to the fact, that structure parameters of the MoSi masks have been adapted for 193 nm lithography. The $\pi$–phase shift inherent in the mask design for lithography-reasons employing 193 nm also helps to generate pronounced image-contrast when measuring registration at the same wavelength. Inspection at 248 nm can not profit from this design, because the phase step is detuned at that wavelength. Based on these simulations it becomes clear that the actinic inspection of MoSi masks leads to higher contrast values already at a moderate NA of 0.6, which permits a pellicle compatible working distance. Hence 193 nm is the inspection wavelength of choice.

In both cases of COG and MoSi masks the simulations have generally shown, that a higher NA helps achieving a better contrast, especially if the structural dimensions approach the resolution limit. Unfortunately the numerical aperture cannot be increased without paying a price in terms of free working distance. If the pellicle compatible working distance is a customer requirement, numerical apertures beyond 0.6 are not feasible. Under these constraints one has to find other ways to achieve high contrast images even with a limited NA. Here the illumination conditions of the mask come into play. The following example will demonstrate how an optimized illumination, which is adapted to the structures on the mask, can be used to improve imaging contrast and therefore at least partially compensate for a reduced imaging NA.

Figure 8 shows the imaging contrast achieved for the same structures (pitch of 260 nm, CD 130 nm) as used in the previous simulation, but now utilizing different imaging methods at a wavelength of 193 nm. Besides the conventional illumination with a coherence degree of $\sigma$=0.7 and $\sigma$=0.95, other optimized imaging methods labeled with 'A', 'B', 'C' are depicted. The illumination with $\sigma$=0.7 and $\sigma$=0.95 achieved at the moderate NA of 0.6 contrast values of 50% - 55%. Employing the method 'A', however, yields an improved contrast of 93%. This is almost twice the contrast compared to a conventional illumination at the same NA. The direct comparison to imaging optics with a maximum NA of 0.9 at a conventional illumination yields an equivalent contrast of 91%. The right hand side of figure 8 tells the same story for MoSi masks. Using optimized illumination conditions the contrast level can be improved by 10% - 20% at

every NA investigated. These simulations illustrate the fact, that to some degree an adapted illumination scheme can replace the need for a high NA in order to obtain sufficient contrast values.

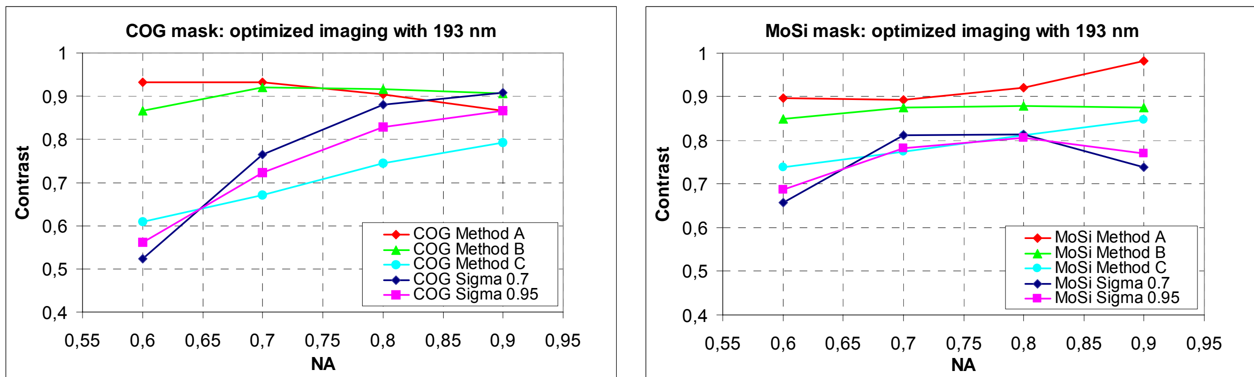


Figure 8: Benefit of optimized imaging methods for contrast enhancement.
Left: simulations for dense lines (half pitch of 130 nm) on a COG mask in transmission
Right: simulations for a MoSi mask in transmission.

The previous examples represent typical structures of the 32 nm node, in the following we want to demonstrate that for even smaller feature sizes close to the resolution limit this concept is beneficial. Figure 9 shows the achievable contrast values depending on the imaging NA for COG and MoSi masks for structures which might be typical for the 22 nm node – the simulations have been performed with dense lines with a pitch of 170 nm and a CD of 85 nm.

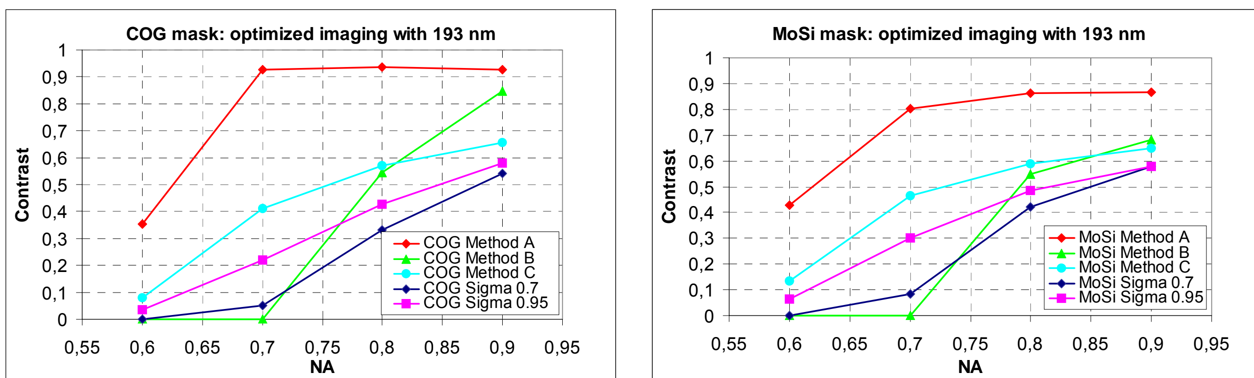


Figure 9: Corresponding simulations to figure 8 for dense lines with a half pitch of 85 nm.

For a NA of only 0.6, where the 85 nm dense lines are close to the resolution limit, the contrast values are limited for COG masks to a mere 5% - 10%. However, employing the method ‘A’ can help rise the contrast up to 35%. Otherwise, increasing the NA is the design parameter of choice to obtain better results, though at the cost of a reduced working distance. The situation is comparable for MoSi masks illustrated in the right hand side of figure 9. Adapted illumination conditions cannot violate physical limitations, yet they gradually help achieving better performance, especially in the regime of low contrast images, where slight improvements in contrast can immediately reduce the impact of image noise on the registration error.

We want to conclude our discussion with simulations on EUV masks in reflection. The details of the structure are depicted in figure 10. This type of structure is typical for EUV masks, though different materials are in discussion for the buffer and capping layer – our simulations, however, did not reveal significant differences. The calculations have been performed with line structures with a pitch of 170 nm and a CD of 85 nm.

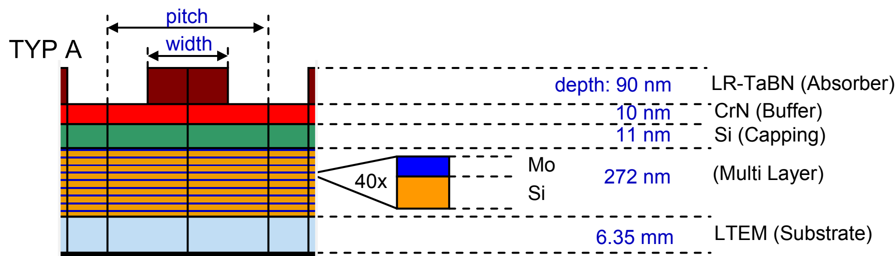


Figure 10: Structure of a typical EUV mask, which was used for the simulations.
The pitch was 170 nm, the width of the absorber was 85 nm.

Figure 11 illustrates the achieved contrast on the EUV-masks using an imaging NA of 0.6 and 0.9 for illumination wavelengths of 193 nm and 248 nm, respectively. For 248 nm and a NA of 0.6 the simulated 85 nm lines and spaces are beyond the resolution limit, hence on the left hand side of the graph there are no contrast values for the longer wavelength visible. At 193 nm most illumination conditions do not provide good contrast, except for method 'A' reaching a sufficient contrast of over 20%. While measurements of such small features are still possible with a NA 0.6 optical design, the simulations clearly indicate, that even at 193 nm a higher NA is much more suitable for EUV registration applications in the future.

Hence focusing on an imaging NA of 0.9, using a wavelength of 193 nm provides more than 30% contrast for any imaging conditions considered. With an adapted illumination contrast can be increased to higher values up to 67% (method 'A'). At the longer wavelength of 248 nm conventional illumination conditions only yield contrast values below 10%. Adapted methods can improve the situation, but in comparison with 193 nm the longer wavelength is at a disadvantage in resolving these small features with sufficient contrast.

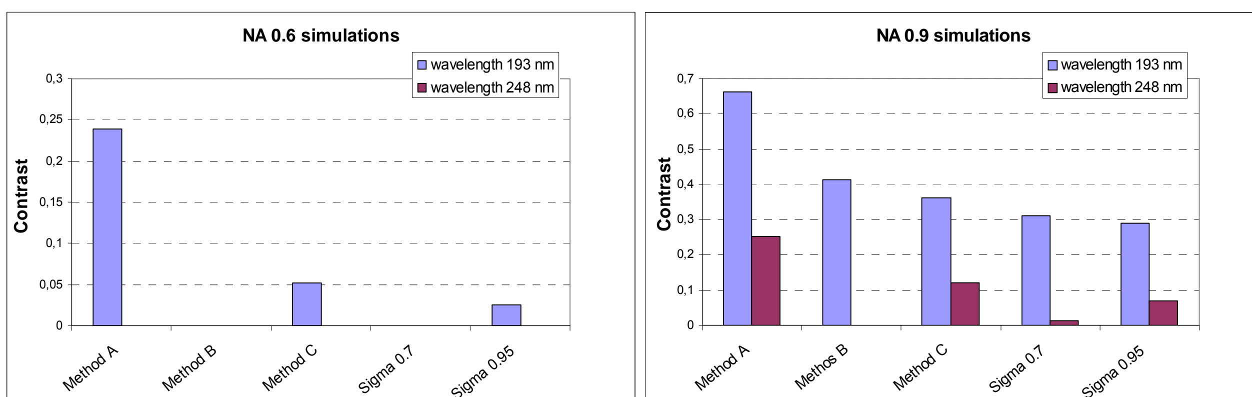


Figure 11: Corresponding simulations to figure 7 for dense lines on an EUV mask (Figure 10) with a half pitch of 85nm.

## 5. CONCLUSION

PROVE a strategic equipment development project at Carl Zeiss and driven by SEMATECH is on track and has made continuous progress since its first publication in January 2007. The process control unit, as well as the handling system are assembled and finalized.
This paper shows based on simulation results, that the initial design considerations for the optical beam path fulfill the requirements for a high resolution and yet pellicle compatible registration measurement tool. The chosen wavelength of 193 nm at a numerical aperture of NA 0.6 together with optimized illumination methods enable superior contrast imaging for a wide variety of measurement tasks. Compared to a longer wavelength, the utilized 193 nm illumination yields higher contrast images. The imaging features provide a solution to maintain high resolving optics while being able to satisfy pellicle compatibility requirements. A first outlook to future EUV masks with smaller feature sizes

indicates, that 193 nm illumination will likely be a must, and a higher numerical aperture would be beneficial for registration purposes with dense structures. The PROVE design provides the possibility to be extended to an even higher NA for potential pellicle free applications such as EUV lithography.

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