

# High-resolution and high-precision pattern placement metrology for the 45 nm node and beyond

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## ABSTRACT

In order for the lithography world to continue on its path to ever smaller features, process solutions such as OPC assist features and double patterning / exposure strategies put more and more focus on the quality of photomasks. The community roadmap requires for the 45nm/32nm node nominal mask features of 120 nm and 85 nm, respectively. Small feature sizes in combination with tight overlay budgets of only 4.8 nm or even 3.4 nm for the 32 nm node illustrate the need for a registration metrology tool with high resolving power and yet unprecedented specifications on reproducibility and accuracy. Carl Zeiss reports on the concept and the project timeline of its new registration tool currently under development. Novel concepts such as the high resolution at-wavelength imaging optics, an integrated full-field autofocus system, and a correlation algorithm for image analysis are presented as examples for the innovative approach to achieve the very demanding goal.

**Keywords:** photomask metrology; registration; pattern placement; 193 nm optics; autofocus; image correlation

## 1. BACKGROUND

As the lithography world continues on its path to ever smaller features, the introduction of immersion lithography with numerical apertures beyond unity enables 193 nm systems to satisfy the 45 nm node requirements. Process solutions such as OPC assist features and double patterning / exposure strategies allow to extend the system capabilities even further towards the 32 nm node – yet at the same time, they put more and more focus on the error budget of photomasks. The ITRS 2005 roadmap [1] requires for the 45nm/32nm node nominal mask features of 120 nm and 85 nm, respectively. Small feature sizes in combination with tight overlay budgets of only 4.8 nm or even 3.4 nm for the 32 nm node (as seen in Fig.1) illustrate the need for a registration metrology tool with high resolving power and yet unprecedented specifications on reproducibility and accuracy for image placement. Assuming that the measurement uncertainty (3 sigma) is only allowed to consume 1/7 of the mask specifications, the registration tool has to meet daunting requirements of e.g. only 0.5 nm for the 32 nm node (identical to the 'double patterning' requirement of the 45 nm node in the ITRS 2006 roadmap). An analogy in our macroscopic world illustrates how 'unbelievable' these numbers are: measuring the relative location of structures on a 6 inch mask to better than a nanometer, is the equivalent of determining the distance of two objects anywhere in the world with an error less than the size of an orange.

*ITRS 2005 Table 78a Optical Mask Requirements—Near-term Years*

Year of Production	2005	2006	2007	2008	2009	2010	2011	2012	2013
DRAM ½ pitch (nm) (contacted)	80	70	65	57	50	45	40	36	32
DRAM/Flash CD control (3 sigma) (nm)	8.8	7.4	6.6	5.9	5.3	4.7	4.2	3.7	3.3
MPU/ASIC Metal 1 (M1) ½ pitch (nm)(contacted)	90	78	68	59	52	45	40	36	32
MPU gate in resist (nm)	54	48	42	38	34	30	27	24	21
MPU physical gate length (nm)	32	28	25	23	20	18	16	14	13
Gate CD control (3 sigma) (nm) [B]	3.3	2.9	2.6	2.3	2.1	1.9	1.7	1.5	1.3
Overlay (3 sigma) (nm)	15	13	11	10	9	8	7	6	6
Image placement (nm, multipoint) [F]	9	8	7	6.1	5.4	4.8	4.3	3.8	3.4
CD uniformity allocation to mask (assumption)	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4

**Metrology requirement**  
(3 σ ~ SPEC / 7)

**45 nm node:**  
4.8 nm → 0.7 nm

**32 nm node (45 nm DP):**  
3.4 nm → 0.5 nm

**32 nm node (DP):**  
2.4 nm → 0.35 nm

Fig. 1. Excerpt of the 2005 ITRS roadmap [1] showing requirements for photomasks in the near-term years. The budget for image placement leaves 4.8 nm for the 45 nm node and 3.4 nm for the 32 nm node – these numbers are even reduced to 3.4 nm and 2.4 nm, respectively, when looking at the double-patterning requirements of the 2006 ITRS roadmap. Derived requirements for registration metrology tools consequently lead to sub-nm specifications.

The photomask industry and SEMATECH have approached Carl Zeiss SMS GmbH in 2006 on their quest to secure a viable solution for the very demanding requirements for the 45 nm and 32 nm nodes ahead. The Carl Zeiss SMS GmbH located in Jena is an individual business unit of the Carl Zeiss SMT AG entirely committed to the photomask industry. The well known and accepted tools such as the AIMS™ for mask inspection and evaluation, or the MERIT® system for mask repair and verification, or the recently introduced PHAME® for in-die phase measurements contribute significantly to the mask making process and illustrate the effort of the Carl Zeiss SMS GmbH to support the mask industry with valuable solutions (see Fig. 2).

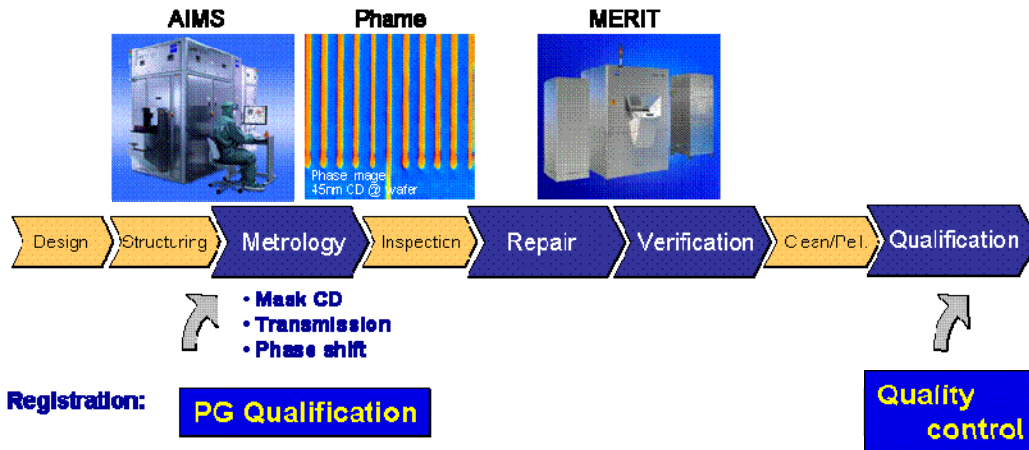


Fig. 2. Symbolic illustration of the mask making process chain. The Carl Zeiss SMS GmbH already provides valuable solutions in the areas of mask inspection/evaluation and repair/verification. A registration tool complements the existing metrology and supports the process of pattern generation, as well as the final step of mask qualification.

The addition of a registration tool to the product portfolio not only complements the existing metrology capabilities and supports the process of the pattern generation, but also extends the company’s presence in the process chain to the final step of mask qualification. Hence the Carl Zeiss SMS GmbH responded to the call and started into developing such a new metrology tool by first assembling a competent and powerful team of various divisions within Carl Zeiss (metrology, optical design, manufacturing and algorithm development) together with external partners with great expertise in particular areas (climate control, mask handling, software). This team successfully participated in the SEMATECH bidder process and was chosen the winning proposal among two other competitors for the next generation registration tool.

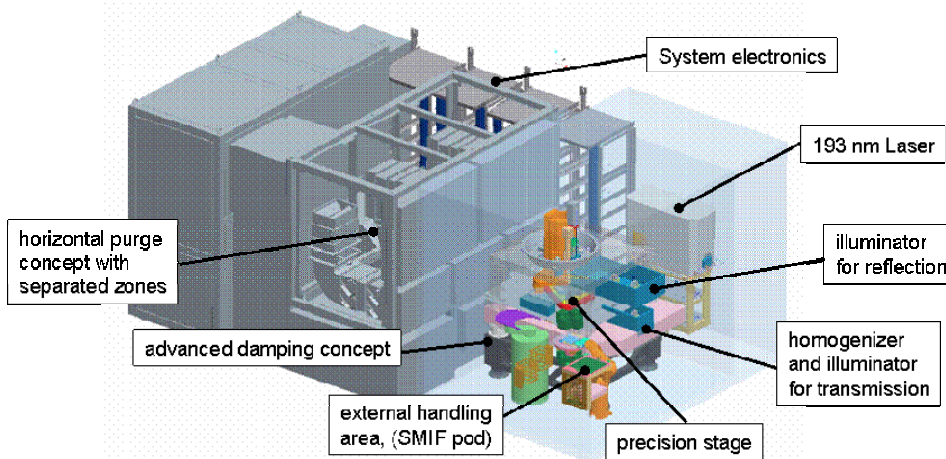


Fig. 3. Layout of the registration tool.

Since then the Carl Zeiss SMS GmbH has strongly invested into the development, and the various groups have been detailing out the initial concept. Figure 3 illustrates an overview of the registration tool with the metrology core in front of the extended climate unit, which provides a temperature stabilized horizontal purge flow through the system. The metrology unit exists of an in-house developed ultra-precision stage and 193 nm imaging optics to be able to measure the locations of structures on the mask. The 193 nm excimer laser source is seen adjacent to metrology unit. The tool illuminates the masks in transmission, but also provides the option to measure in reflection. Photomasks will enter the tool on the front left corner via a SMIF pod loading station and are automatically handled by a robot on the inside – no manual interference is required and the tool will smoothly integrate into a fab environment.

## 2. SPOTLIGHT ON SELECTED NOVELTIES

Developing a registration tool to measure the relative location of structures on a photomask with a remaining uncertainty of only half a nanometer requires paying attention to virtually any detail of the entire unit. However, describing the tool at such level of detail is neither recommendable (for various reasons), nor particularly enlightening for the reader. Therefore we have chosen to highlight in particular three topics in the metrology unit, where Zeiss is introducing some novel ideas into realm of current registration metrology [2].

Figure 4 outlines a functional sketch of the metrology unit with a ultra-precision stage holding the mask ‘face-up’ and providing lateral and vertical motion to be the only moveable part in the imaging path. Another key component is the diffraction limited, high resolution NA 0.6 imaging optics operating at 193 nm (at wavelength for the majority of current photomask applications). Two illumination paths offer measurements both in transmission and reflection (e.g. for opaque EUV masks), providing variable illumination for maximum contrast imaging. An autofocus system and auxiliary optics for coarse alignment further support the measurement process. In the following paragraphs the imaging optics, the autofocus system and the data processing are highlighted in more detail.

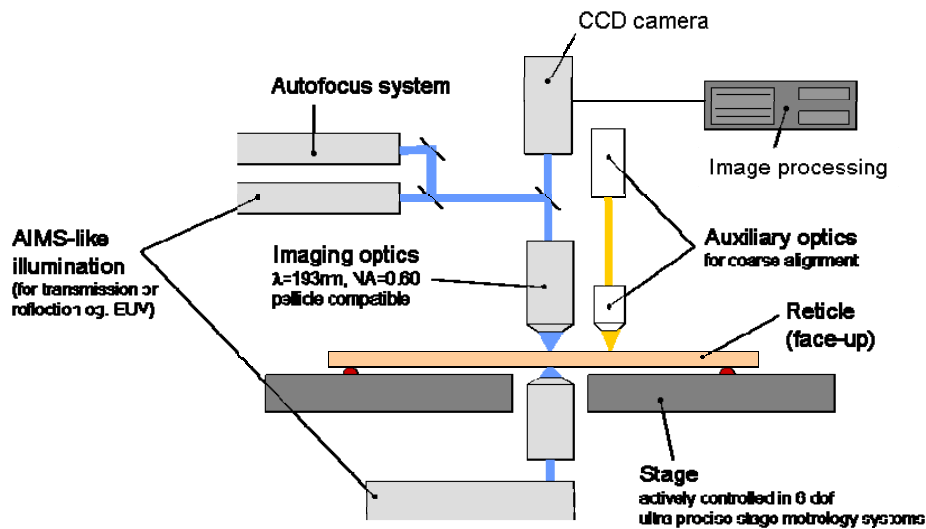


Fig. 4. Functional sketch of the metrology unit with key components: ultra-precision stage, 193 nm illumination and imaging optics, additional autofocus system and coarse alignment optics.

### 2.1 193 nm Metrology

The optical heart of the registration tool is the illumination and the imaging optics to project the structures of the mask onto the CCD camera, where their exact position can be determined by further data processing. The design of the optics is essentially driven by the application requirements of the customer. Unfortunately, these requirements often lead to contradictory design goals, yet a satisfactory compromise has to be found.

As the features on the mask become smaller with every node, customers accordingly demand increasing resolution, as they prefer to measure registration with similar structures. In addition customers want to also measure the uniformity of the critical dimensions (CD) across the mask, and they would like to perform all these measurements even when a pellicle is applied to the mask during final qualification. Since there are various types of masks in use, the tool should be

able to cope with the variety and -obviously- always provide accurate measurements. Hence the main requirements could be summarized as:

- **“Better resolution”** ...  
... for smaller features and lower noise
- **“Reasonable NA”** ...  
... for greater depth of focus, better CD metrology
- **“Large free working distance”** ...  
... for pellicle compatibility
- **“Accuracy”**...  
... to correctly include the material properties of the mask
- **“Flexibility”**...  
... to work with different types of masks (COG, MoSi, PSM, EUV ...)

In order to fulfill all of these requirements, Zeiss decided to utilize a 193 nm illumination and imaging optics. The short wavelength significantly improves the resolution, and at the same time permits a moderate NA of 0.6, which benefits the CD metrology and enables a pellicle compatible free working distance of about 7.5 mm. In terms of resolution the 193nm-NA0.6 optics is equivalent to a 248nm-NA0.77 system or even an ‘immersion’ 365nm-NA1.13 system. Extensive rigorous simulations have shown, that 193 nm generally exhibits significantly better contrast than longer wavelengths. One additional advantage of the 193 nm illumination is, that the metrology happens at the same wavelength as most advanced masks are used with, hence the effect of material properties are properly taken into account. The desired flexibility to work with different types of masks is supported in the system by providing variable illumination options (transmission/reflection and the degree of coherence) for optimal contrast.

In short, 193 nm is the wavelength of choice for registration optics, as it allows a design compromise, which can satisfy the customer requirements. Furthermore, Zeiss has a decade long experience in design, manufacturing, assembly and metrology of 193 nm optics to ensure the success of this novel feature in the tool.

## 2.2 Autofocus Concept

As the mask surface might be slightly tilted in the tool, and in addition the bending of the mask under its own weight leads to a variation of the best focal position, an autofocus (AF) system can support the measurement process. Typically confocal AF systems at visible or infrared wavelengths are often used for surface measurements. These commercially available units, however, did not meet our requirements of easy integration into the optical system and of robustness in its use. As confocal AF focus the light onto the surface and analyze its reflection, any scattering due to an undefined structure at the focal point can lead to erroneous results. Since the AF system is supposed to work with any mask and pattern, confocal types were omitted and a totally different concept was developed.

The solution to our requirements is the concept of tilted fringe projection [3], which can be easily integrated into the optical path and utilizes both the 193 nm illumination as well as the existing CCD camera (see Fig. 5), hence avoiding costs for extra light sources, sensors and a broadband design of the imaging optics. The principle of operation can be easily understood and is illustrated in Fig. 5. A tilted grating is projected onto the mask, reflects off and is imaged onto the camera. The AF system is adjusted in a way that if the mask is in focus, the fringes in the center of the pattern also give a sharp image. As the AF grating is tilted the other fringes are out of focus. However, if the mask is out of focus, the fringes reflecting of the surface are also imaged with twice that defocus onto the camera. Consequently other fringes off the center due to their tilt appear sharp, hence a defocus of the mask is mapped to a lateral shift of highest contrast fringes on the CCD.

The advantage of this AF concept, besides its ease of implementation, is that the complete camera field of view of the mask surface is used, and the local position of a structure or scattering of an edge does not affect the entire reflection of the projected fringes. In addition a focal offset between the projected fringes and the mask surface can be designed into the system, hence rendering the AF system quite insensitive to the structures of the mask, yet sensitive to its focal position. This particular property of this novel AF system makes it uniquely suited for the registration tool, where masks with arbitrary structuring will have to be measured.

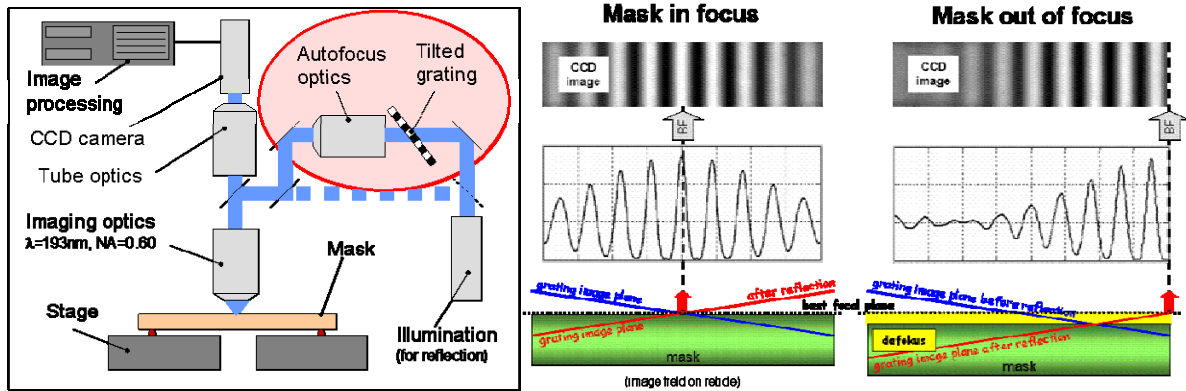


Fig. 5. Functional sketch of the autofocus implementation and the principle of operation. A defocus of the mask plane causes fringes which are not centered to become sharp. Hence, a defocus correlates directly with a lateral shift of highest contrast fringes.

### 2.3 Image Analysis

Another novel feature of the system - though not in hardware – can be found in the data analysis of the captured CCD images. As shown in Fig. 6 a classical registration mark often consists of a relatively large single cross in an unstructured area. As the position information of the mark is only contained in its edge information, it is obvious that one could improve the signal strength of the mark by adding more edges into the free areas. Utilizing high resolution optics, one could also use smaller features, and thus finally evolve to smaller marks with a finer and more complex structure without sacrificing edge information. The benefit of the smaller registration marks, however, requires high resolution optics and an algorithm which can analyze more complex patterns.

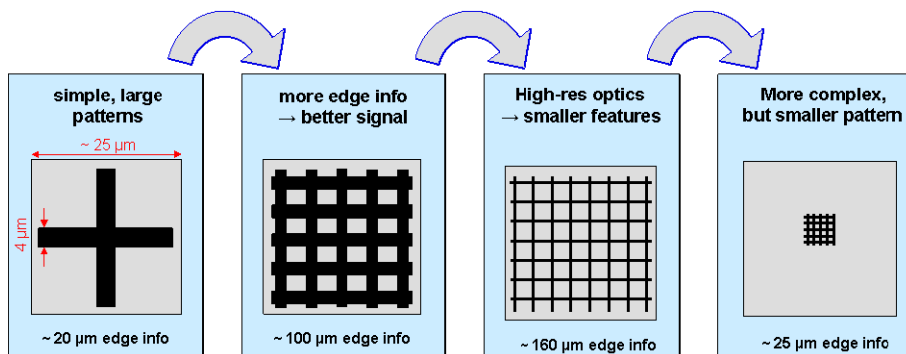


Fig. 6. Possible evolution of simple, large registration marks to much smaller, but more complex patterns. To utilize the benefits of the smaller marks, high resolution optics and image analysis algorithms for arbitrary patterns are required.

As mentioned in section 2.1 the tool is already designed to provide a high resolution. In order to be able to analyze the relative position of identical, but arbitrary patterns an iterative two-dimensional (2D) correlation algorithm was developed. The principal concept of operation is illustrated in Fig. 7, where the star symbolizes the arbitrary registration mark. In order to perform a registration measurement, a first mark e.g. is captured by the camera and stored as reference image. The relative position of a second registration mark can now be determined by the stage shift and a correlation analysis of the captured with the stored reference image.

A mathematical correlation is similar to the overlap of the two images, which is not perfect initially. Therefore, the two images are mathematically shifted with respect to each other and iterated until the overlap is optimal (i.e. the correlation coefficient has reached its maximum). In the final result the necessary mathematical shift exactly yields the position shift of the two images at the beginning. The correlation algorithm has already been implemented in software and successfully tested with real camera images. Since the correlation algorithm compares entire images and not just edges, this novel

approach facilitates the registration measurement with arbitrary patterns and is furthermore superior to a simple threshold algorithm in terms of camera noise suppression (see inset of Fig. 7).

### Principle of iterative 2D correlation algorithm

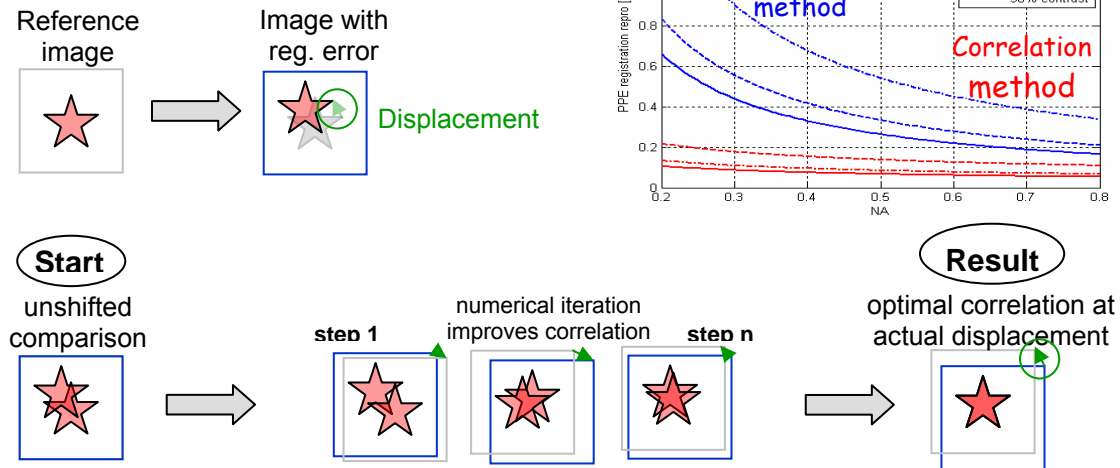


Fig. 7. Comic illustrating the concept of 2D correlation analysis of two images to determine their relative position. The top right insert shows the simulation of the pattern position error (PPE) in a registration analysis with noisy images. The correlation method is superior to a simple threshold algorithm since complete images are analyzed.

### 3. PROJECT TIMELINE

While this paper could only highlight a few selected, but interesting topics of the entire tool, it is clear that the development team is diligently working on all aspects required to transform this promising concept into a real machine. At the time of the EMLC conference the team is about to reach final design status, and first components already being in production. Further key milestones of the project are to have a complete working tool by the end of the year, reaching specifications in late summer of 2009 and providing our new registration tool to the first customer soon thereafter.

Carl Zeiss SMS GmbH has assembled a competent team with expertise in all the required key components, hence being confident to bring this development to a success. In order to build up trust along the way, the Carl Zeiss SMS GmbH will regularly update the community on the progress of the project.

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