The evolution of pattern placement metrology for mask making

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ABSTRACT

The image placement is and remains an important aspect of photomask metrology. Not only the position accuracy of features for an individual mask – representing one layer in a complete chip design have to meet stringent requirements, the complete mask set for all layers have to match in order to get a functional device. At a time were registration and overlay errors were counted in micrometer it was enough to compare one mask with another by a so called overlay machine. This approach works sufficiently until placement specification reached the “nanometre range” and the development of dedicated 2D coordinate measurement systems became necessary. Since then, pattern placement metrology tools became “enabler” for the continuous improvement of pattern placement accuracy on photomask and the improvement of the final wafer overlay error. This paper reviews and discuss current trends of pattern placement metrology on photomasks, highlighting the major error drivers and will focus on current and future requirements for in – die registration.

Keywords: photomask metrology; registration; pattern placement; in – die measurements; mask overlay

1. BACKGROUND

Since the creation of the first integrated circuit in the early 1960, there has been a permanent increasing density of devices manufactured on semiconductor substrates. CMOS technology has been the dominant driving force in integrated circuit fabrication and is likely to retain this position for the foreseeable future. As with previous generations it is the production worthy lithographic pattern transfer of data from design to silicon, via the medium of the photomask, which holds the key.

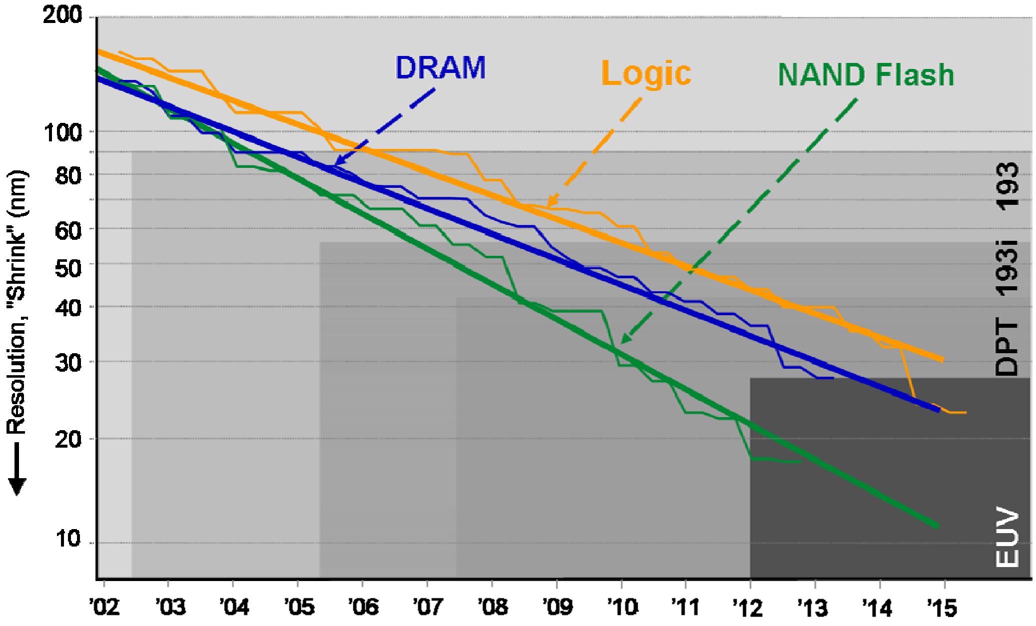
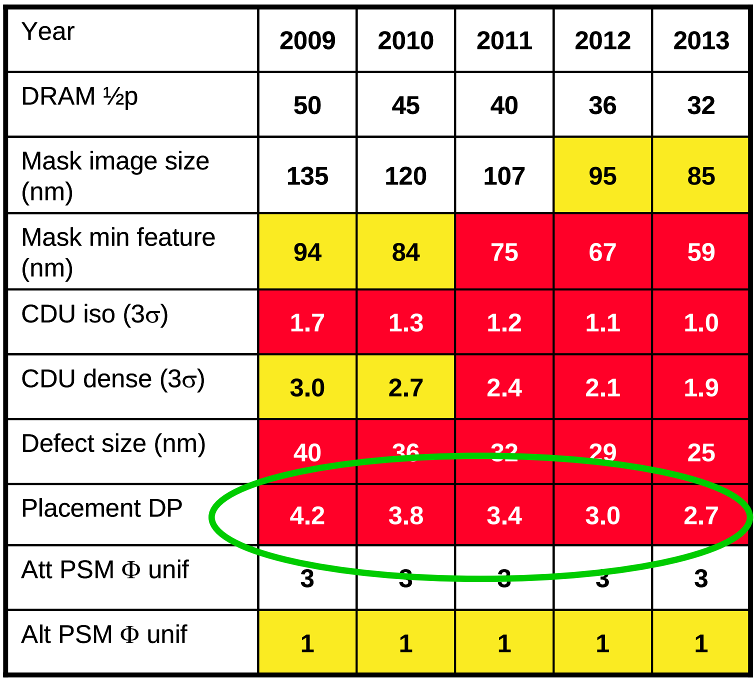


Fig. 1. “shrinking” roadmap for high volume devices in respect to their dominant manufacturing technology as 193nm dry, 193nm immersion, the introduction of Double Patterning (DPT) and Extreme Ultra Violet (EUV).

The 32nm and 22nm node processes exhibit a great challenge to the mask maker and to the wafer fabs who take final responsibility for fully functional devices at competitive costs. That leads to very tight specifications for all related processes from the mask manufacturing through the wafer litho process. Figure 1 displays the shrinking roadmap for the major device types by volume in respect to their preferred manufacturing technology. Optical lithography working with 193nm illumination wavelength is extended by immersion and double patterning to the 2X nodes and EUV is seen as a cost effective lithography solution with high volume manufacturing starting in 2014. Memory devices are the driving forces in terms of critical dimension while NAND Flash products nowadays leaving DRAM’s behind.

The precise placement of the patterns in a mask set during mask manufacturing is a critical requirement. In addition, with the introduction of double pattering schemes most difficult layers in terms of critical dimensions have to be split into separate layouts and overlayed with each other. The ITRS roadmap [1] shown in Figure 2 forecasts small feature sizes in combination with tight pattern placement budgets. These task require registration metrology tools which employ high resolution capabilities and yet unprecedented specifications on reproducibility and accuracy for precise image placement measurements.



Year	2009	2010	2011	2012	2013
DRAM ½p	**50**	**45**	**40**	**36**	**32**
Mask image size (nm)	**135**	**120**	**107**	**95**	**85**
Mask min feature (nm)	**94**	**84**	**75**	**67**	**59**
CDU iso (3σ)	**1.7**	**1.3**	**1.2**	**1.1**	**1.0**
CDU dense (3σ)	**3.0**	**2.7**	**2.4**	**2.1**	**1.9**
Defect size (nm)	**40**	**36**	**32**	**29**	**25**
Placement DP	**4.2**	**3.8**	**3.4**	**3.0**	**2.7**
Att PSM Φ unif	**3**	**3**	**3**	**3**	**3**
Alt PSM Φ unif	**1**	**1**	**1**	**1**	**1**

Fig. 2. The budget for image placement as forecasted by the ITRS roadmap. The requirements for registration metrology tools consequently lead to sub-nm specifications.

Historically, the measurement of special metrology targets for registration, uniformly distributed over the mask was the most common approach. The targets were chosen in a way that they match the resolution capabilities of the metrology tool. However, measuring on test features is no real representation of the mask pattern placement within the die or chip. Relying on standard targets only can lead to incorrect results and hence reduces the yield in the mask shop. For the 32nm and 22nm nodes a move to in – die metrology is not only desirable, but essential as the measurement of test structures no longer reflects the complex interactions that are taking place between patterns and illuminating light in the deep sub-wavelength regime [2].

The need to extend registration metrology into the active area on the photomask is just one trend to improve the lithography performance on the silicon wafer. Other approaches rely on closer cooperation between the mask shop and the wafer fab in order to identify the remaining error drivers on the final wafer overlay. This strategy favours captive mask shops since mask making and wafer litho are united in one company and intellectual property and business aspects are less sensitive. However, the optimization of the mask process flow within the mask shop itself enables better pattern placement when all influencers on mask registration are taken into account. The aspect is highlighted in more detail in the next section.

2. INFLUENCES ON MASK REGISTRATION

The flow in Figure 3 shows the different process steps and main sources of mask registration errors. The most obvious error driver is the pattern generation itself since it defines the respective mask design on the substrate. For most advanced nodes 50 kV e-beam writing is used due to its superior resolution capabilities. Nevertheless, laser beam writing plays an important role for less demanding levels and the writing of the second layers for phase shifting masks.

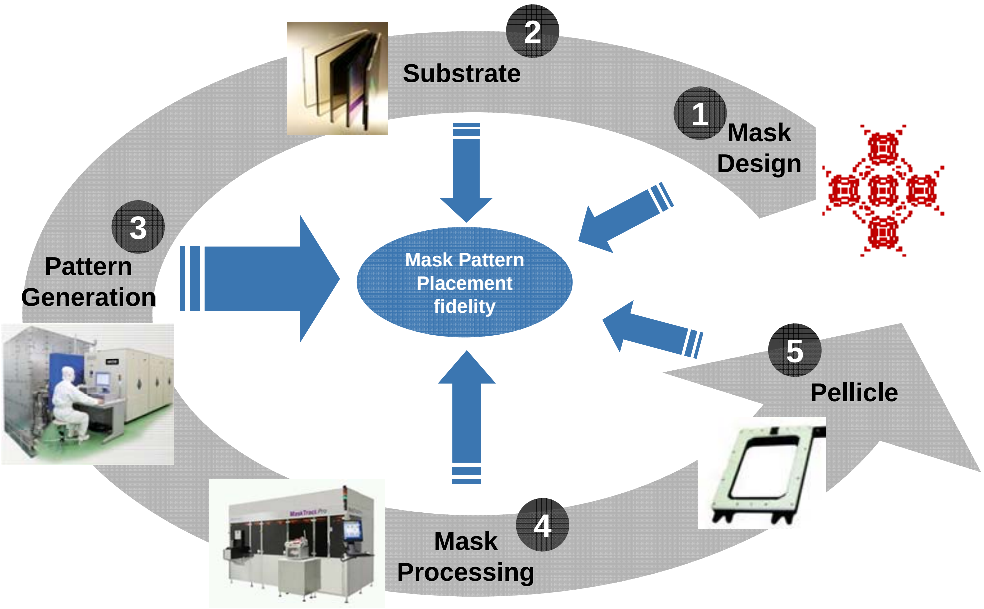


Fig. 3. Mask manufacturing influences on the pattern placement emphasizing the different sources

The dominant error sources for the pattern generation by e – beam writing can be classified as follows:

- **insufficient beam position placement accuracy and reproducibility**
- **e-beam position drift caused by charging effects in the resist layer and mask blank heating**
- **butting or field stitching errors**
- **feature edge shifts introduced by dose corrections**
- **imperfect grid matching to the registration metrology tool**
- **environmental impacts (mainly electro-magnetic fields)**

The pattern placement performance of pattern generators relies fully on registration measurement tools. The best pattern placement performance is achieved when the coordinate system of the pattern generator and the registration metrology tool match. In this sense, registration metrology is a strong enabler for better placement performance and recent improvements were largely due to optimized metrology links. The error sources mentioned above are corrected traditionally by e-beam writing machines. Detailed investigations [3, 4] have highlighted also the impact of mask flatness variations as well as the influence of the mask etching process (mask stress in dependence of the pattern density). The impact of pellicles on registration depends strongly on the mounting process and introduces additional stress. Moreover, the thermal coefficients of expansion between pellicle materials and the mask blank are different. This induces additional, non - constant stress when the mask is heated up during illumination. Therefore, mask registration measurements with and without pellicle are mandatory for a comprehensive mask registration qualification.

3. CONSTRAINS FOR NEW REGISTRATION TOOLS

3.1 Performance evaluation standards

The development of a registration metrology tool to measure the relative location of structures on a photomask with a remaining uncertainty of only half a nanometer is a task at the limits of physics and engineering. As mentioned already in section 1, the current standard to qualify a registration error is based on the sampling of uniformly distributed registration markers. While this approach is not sufficient to evaluate critical locations with varying pattern density, it is widely used still for the performance evaluation of registration metrology tools. Here, the mask shop can easily compare the performance numbers of different vendors by applying the same measurement procedure and statistics evaluation.

The common standard uses a 15 x 15 grid over the quality area of a photomask as shown in Figure 4. The stability of the metrology tool under ideal conditions can then be evaluated as short term repeatability, defined as maximum 3Sigma using 20 measurement loops without unloading the substrate from the measurement tool. The statistical evaluation of measured data may vary from mask shop to mask shop (max. 3Sigma, confidence limit, ANOVA…).

State of the art registration metrology tools should have a short term repeatability performance better then 0.5nm when taking the ITRS roadmap in section 1 as an orientation.

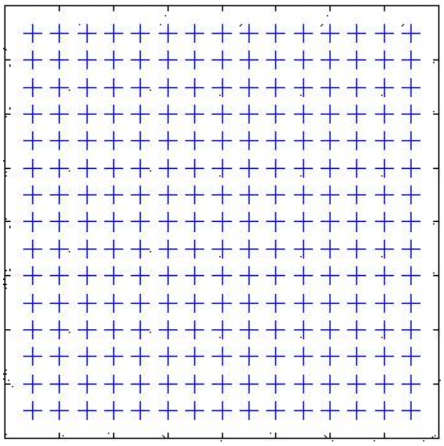


Fig. 4. Standard 15 x 15 grid on a 6025 chrome on glass mask (CoG) as used for the qualification of registration metrology tools

Long term repeatability data can be obtained from the daily monitoring of the same mask with a limited number of loops in order to save measurement time. This specification is very important to the user of any metrology tool since it demonstrates the tool stability over a long period of time under practical measurement conditions. In addition to short term repeatability it takes into account the repeatability of the mask loading and unloading process as well as the sensitivity of the tool against environmental changes.

The pattern placement accuracy should be measured to an absolute grid. Here, a standard reference is needed which is far more accurate as the registration metrology tool used. This represents a dilemma for all registration metrology tools since there is no such standard available. Even more, no 2 – dimensional length standard exists which is close to the precision of current systems. In order to evaluate accuracy, self – consistency tests have been developed which were called then “nominal accuracy”. Such a test consists of a measurement of a standard mask grid as displayed in figure 4 in different orientations, usually in 0°, 90°, 180° and 270°. All orientations are measured 10 times or more in order to gain enough statistical certainty. The complete procedure is at least similar to an evaluation of short term repeatability but here done in all mask orientations. Despite the lack of an absolute length standard, traceability of the results is essential to the user when the masks of a mask set are manufactured at different locations and qualified with different tools. In this case, a customer reference standard is used defining the length scale of chips. Calibrated standards can be also provided by national institutes of standardization [5].

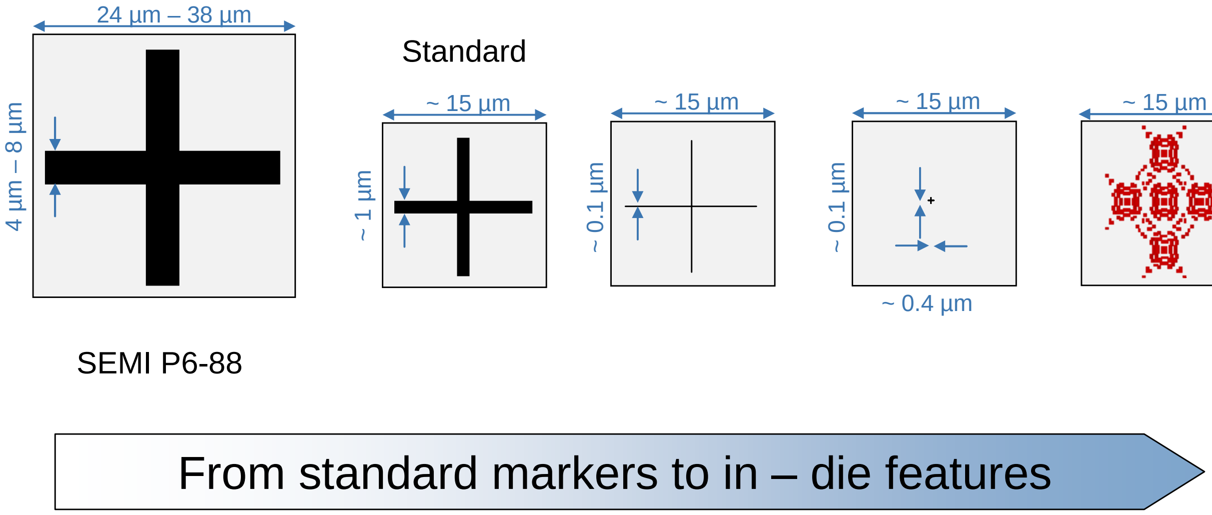


Fig. 5. The evolution of registration markers to smaller and more complex patterns within the field of view of a registration metrology tool.

For many years, registration markers were represented by large crosses not only used for the performance evaluation of registration metrology systems but also for production mask were the markers were placed at specific design locations outside the active area. The size of the crosses did limit smaller and more local sampling. Figure 5 represents the development of registration markers over time showing a clear trend towards smaller markers and the need to measure suitable features within the active area. This trend sets an important constraint for the development of new registration tools and forces the development of optical concepts with sufficient resolving power.

3.2 General tool concepts and error sources

When developing a tool for upcoming registration measurements, special care has to be taken to several components which are crucial for the performance of the entire system. Basic sub-systems like the x/y precision stage, the illumination unit and imaging optics as well as the handling system are integrated into an extensive climate control box. Nanometer precision requires a well controlled environmental system in order to suppress weather influences like air pressure fluctuations, to maintain a well controlled air flow in order to avoid turbulences and most important, temperature stabilization in the mK range. The position of the stage as the heart of the system is tracked by a laser interferometer system. Since the laser of the interferometer travels through the atmosphere, the wavelength depends on the refractive index of the ambient air. In order to minimize these effects, a real time wavelength tracking device, the “Etalon” was introduced to correct the refractive index of the air during a measurement.

Other key components are the optical beam path and the image analyses which have to be adapted to the resolution requirements. Modern systems also support measurements in reflection and transmission. The metrology concept does not favor reflective or transmission measurements in terms of repeatability: However, as displayed in Figure 6, one can not expect to receive the identical results upon measuring a mask in both modes, as different properties of the mask are imaged.

Among many other error sources for insufficient tool stability, the sensitivity of the measurement to thermal drifts requires a sophisticated thermal management concept to avoid additional heat sources which might influence the repeatability and accuracy of the system. Even internally well controlled tools are sensitive to temperature differences between clean room and measurement chamber. This may add substantial throughput time since the mask as the measurement object has some heat capacity.

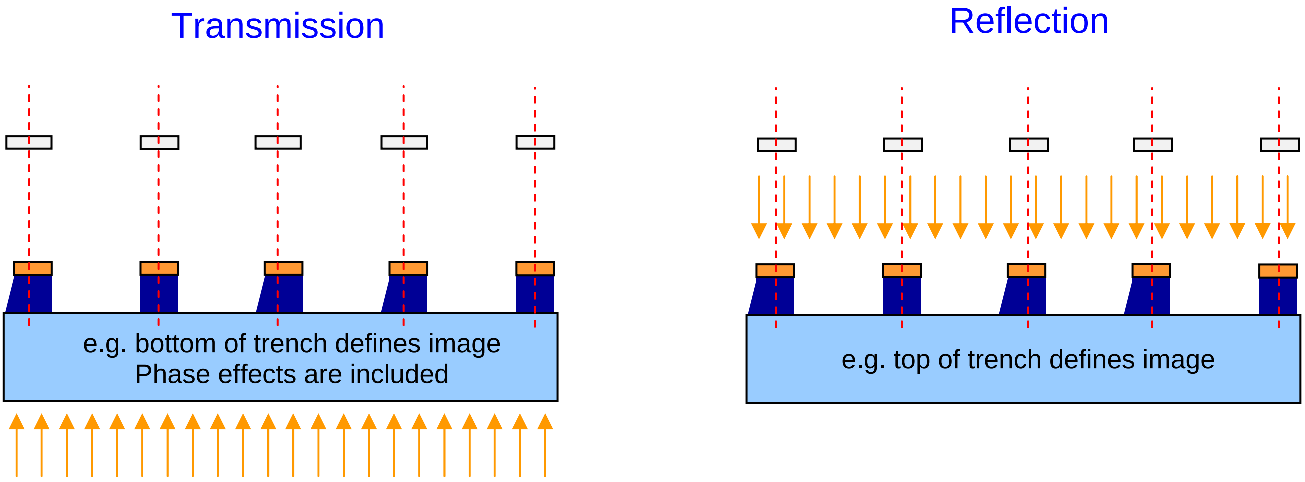


Fig. 6. The difference between measurements in transmission and reflection. Different parts of the trench define the image leading to different measurement results.

4. POTENTIAL SOLUTIONS

Past generations of mask registration tools were not necessarily limited in their tool stability but in their resolution capabilities. Recent projects have therefore put more effort into the development of new optical imaging and analysis concepts [6 - 11]. Carl Zeiss did enter the mask registration metrology market in 2007 with a new tool concept after wining the SEMATECH bidder process for a next generation metrology tool. The development progress of PROVE^{TM} has been reported continuously at all major mask making conferences starting with EMLC 2008. The SEMATECH project could be finalized successfully in 2010 and in the mean time the first 3 tools were accepted and delivered to customers. Figure 7 shows the PROVE^{TM} alpha tool as it is currently used for customer demonstrations.

Fig. 7. View of the PROVE^{TM} Alpha tool with all major components

The metrology unit of PROVE is located in an environmental chamber which provides a temperature stabilized horizontal purge flow through the system. The laser controlled stage is situated on a frame resting on advanced damping devices. Masks are loaded into the systems via standard SMIF pod and handled internally with a robot which can rotate and flip the mask if required.

Since the imaging performance of the instrument depends on the interaction of all involved components, detailed simulations have been performed in order to derive the optimal setup. The theoretical optical resolution limit is given by the well known Raleigh criterion [12]:

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

were $hp_{\min}$ is the smallest separation of adjacent features which can be resolved, λ is the wavelength of illumination, σ the degree of coherence of the illumination and NA the numerical aperture of the imaging optics. A simulation for various illumination wavelength and NAs is illustrated in Figure 8.

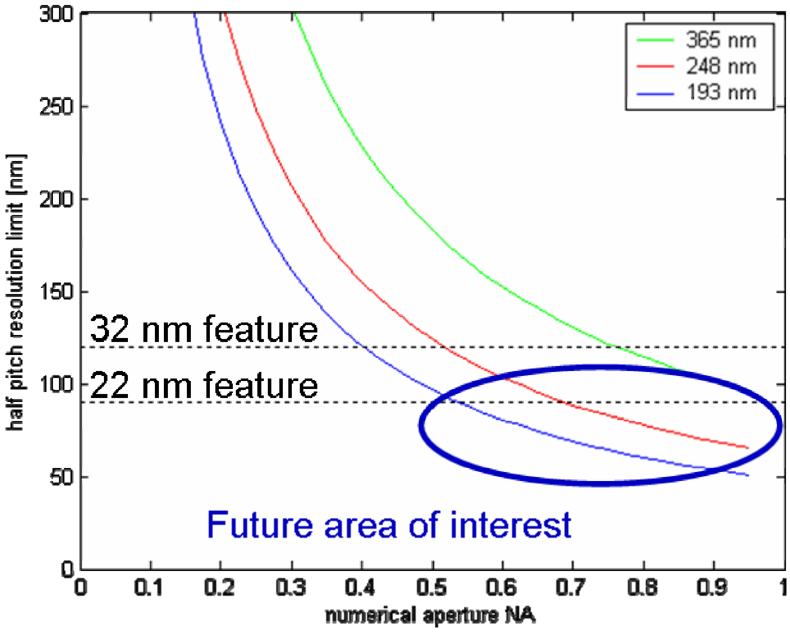
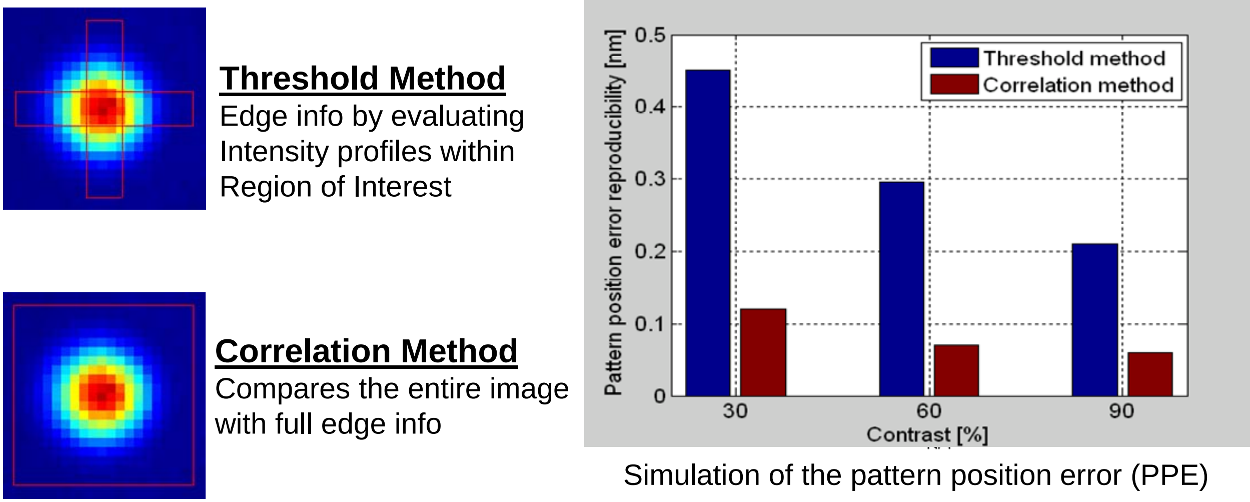


Fig. 8. Theoretical resolution limit vs. numerical aperture for 3 different illumination wavelengths

In order to fulfill the requirement for high resolution and large working distances for pellicle compatibility at the same time, Carl Zeiss decided to utilize 193nm illumination and imaging optics together with an NA of 0.6. Extensive rigorous simulations have shown that 193nm illumination exhibits significantly better contrast then longer wavelengths [7]. The shorter wavelength automatically supports better accuracy as the 193nm metrology corresponds to the current state of the art immersion scanners used for the 32nm node and double patterning techniques. Hence the material properties of the mask are accurately reflected in the measurements as in their later use in the wafer fab.

In order to be able to measure masks in reflection and transmission the tool provides two illumination paths. Both have the variability to change the degree of coherence (the sigma setting) in order to optimize contrast when imaging features are close to the resolution limit.

Another novel feature of PROVE^{TM} can be found in the data analysis of the captured images. Utilizing high resolution optics, one can 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, as already highlighted in the previous section, requires high resolution optics and an algorithm which can analyze more complex patterns.



Simulation of the pattern position error (PPE) in a registration analysis with noisy images

Fig. 9. Benefit of the correlation method with small and noisy features at low contrast levels. The correlation method is superior to an evaluation of intensity profiles (threshold method) since complete images are analyzed.

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 was already published elsewhere [6]

According to Figure 9, the correlation algorithm compares entire images and not just intensity profiles over a very limited number of pixels as with the standard threshold method. This approach has clear mathematical advantages since the information content is much higher with the correlation method. A simulation of the pattern positioning error (PPE) in a registration analysis with small and noisy images shows better results in particular at low contrast levels. Nevertheless, PROVE^{TM} as a state of the art registration metrology tool supports both methods in order support all applications.

5. CONCLUSIONS AND OUTLOOK

In the previous sections we discussed background, constrains and current trends for registration metrology. We have worked out the need for sub – nanometer precision in combination with high resolution capabilities in order to resolve production features. Especially when it comes to double patterning, the in – die measurement becomes important and registration metrology on arbitrary features is required to qualify mask processes precisely. That holds for the manufacturing of all devises types at the 32nm nodes and below. Registration tool manufactures have developed new concepts addressing the needs of the mask making industry. With PROVE^{TM}, Carl Zeiss has introduced new tool concepts for high resolution in combination with excellent tool stability.

Looking down the road, the introduction of EUV lithography is setting another milestone for registration metrology. Pellicle compatibility might be not required for EUV mask but the mix and match with immersion lithography working with 193nm illumination favours free working distances which allow at least measurements with immersion pellicles. A closer cooperation between the mask shop and their customers, the wafer fabs is ongoing and more R&D effort is put into this interface in order to understand the full picture. Wafer fabs need to know the specific challenges to define mask pattern at their desired locations on the mask and mask shops have to understand that it is the final wafer overlay what matters. In this sense, the evolution of registration metrology remains manageable but will spin around the wafer lithography technology to come.

6. ACKNOWLEDGEMENT

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