# AIMS™ and Resist Simulation

Ulrich Strößner, Holger Seitz, Robert Birkner, Rigo Richter, Thomas Scherübl
Carl Zeiss SMS GmbH (Germany)

## ABSTRACT

The AIMS™45-193i is the established tool for mask performance qualification and defect printing analysis in the mask shop under scanner conditions. Vector effects are taken into account by the proprietary Zeiss vector effect emulator. In several studies an excellent correlation to wafer prints has been reported. However, a systematic offset to wafer prints in terms of mask error enhancement factor (MEEF) and exposure latitude has been observed which is attributed to well known resist effects.

The AIMS™ measures the aerial image in resist whereas in a real lithography process further image blur of the latent image is caused by photo acid diffusion during wafer processing and resist development. To explain the gap between the AIMS™ and wafer prints we have investigated aerial images in combination with an easy to use resist model. It does take resist effects into account with sufficient accuracy to explain printing behavior of photo masks but without the need to calibrate lots of parameters of the actually used resist which usually are not known to a mask shop.

The resist effects predominantly reduce the image contrast and thus increase the MEEF and the sensitivity to mask defects. This somewhat counterintuitive behavior is labeled **"contrast enhancement by contrast reduction"**. Additionally application of the resist model improves the agreement of e.g. the exposure latitude or MEEF measured by the AIMS™ compared to wafer prints.

Keywords: AIMS, Hyper-NA imaging, lithography simulation, resist modeling, mask qualification

## 1 INTRODUCTION

### 1.1 AIMS™ principle

For 15 years AIMS™ has been established in the mask shop to be the methodology of choice for the qualification of the printing behavior of photo masks. The mask is illuminated under the same conditions (wavelength, mask side NA, illumination setting and polarization) as in a scanner. The light diffracted by the mask is collected by an objective lens and magnified onto a CCD camera. Thus, the camera captures the aerial image of the mask under the same conditions as a scanner would see it or in other words: the scanner is emulated by AIMS™.

Defects and mask features like OPC and assist features can precisely be evaluated by an AIMS™ tool concerning printability on the wafer. In contrast to a simulator no assumptions on the parameters of the real mask which often are difficult to measure precisely (e.g. actual structure geometry separated from the influence of the SEM, absorption coefficient, refractive index, thickness, side wall angle, corner rounding etc.) have to be taken into account. Therefore, this method is well established in the mask shop for defect analysis and repair verification under scanner conditions making test wafer prints obsolete.

### 1.2 Vector effect emulation

The latest generation of the AIMS™ tool family is the AIMS™45-193i[1] which is designed to emulate immersion scanners with an NA up to 1.40. It is equipped with the new Zeiss proprietary vector effect emulator which allows emulating the contrast of aerial images in resist which are formed under high angles (see figure 1).

The contrast loss on the wafer due to vector effects of high NA imaging cannot be described by an AIMS™ image alone as the AIMS™ has a magnifying lens which results in a low NA at the camera side. Therefore, for the AIMS™45-193i the scanner mode has been developed which generates an image-in-resist from several AIMS™ images. The image-in-resist is the distribution of the light intensity inside the resist just below the resist surface and takes into account both the contrast loss due to vector effects and the refractive index of the resist.

Reflections from the resist top or bottom surface are not taken into account. It is assumed that a BARC and TARC are present, both acting as a perfect antireflective coating. Consequently no standing waves over the resist thickness are taken into account. Also light absorption inside the resist is neglected. This is justified as the AIMS™ usually is operated by using an open frame normalization (i.e. the intensity is normalized to a clear field measurement) and the clear image experiences the same light absorption as the measurement image.

The scanner mode has been extensively tested by comparing AIMS™ results in scanner mode to wafer prints and to simulations. Excellent agreement has been reported in recent publications[2,3,4,5,6,7].

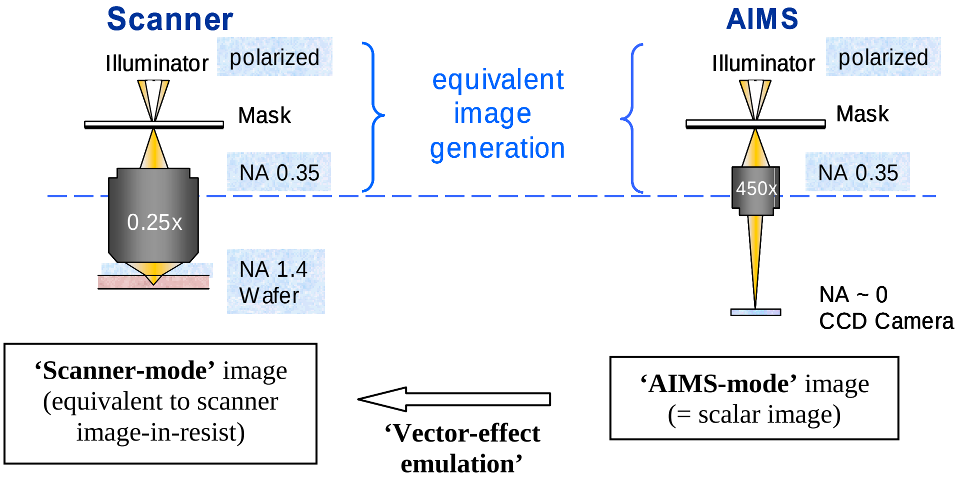

**Figure 1:** Comparison of the operation of an AIMS™ system with a wafer scanner. At reticle-side, both systems are equivalent, but the AIMS™ uses a magnifying lens, whereas the scanner demagnifies. The result is that as-measured AIMS™ images are basically 'scalar' images. The 'vector-effect emulator' used in the so-called 'scanner mode' of the AIMS™45-193i, however, converts the measured images into a scanner-equivalent image, i.e. into a prediction of the intensity distribution inside the resist in the scanner.

## 1.3 Resist emulation

In lithography during wafer exposure a distribution of photo acid is generated in the photoresist. This is the so called "latent image". During resist processing namely during post exposure bake the photo acid diffuses and causes blur of the latent image.

The AIMS™45-193i provides the image-in-resist as output which is the intensity distribution of the light in the resist just below the surface. So, it seems to be straightforward to apply an adequate resist model to this image. Many resist models have been published in literature and many resist simulators are available commercially. These simulators usually work with multi parameter resist models which require exact knowledge of the wafer stack, the resist and the processes used in the wafer fab. The application of multi-parameter resist models to AIMS™ measurements has practical limitations as the AIMS™ is mainly used for defect evaluation. Often there is no access to all resist parameters or calibration models.

On the other hand we do not need to capture all effects arising from the resist chemistry. This relaxes the required precision for resist simulation. E.g. standing waves inside the resist predominantly depend on optimization of the bottom anti reflective coating (BARC) between the wafer and the resist. Capturing these correctly requires precise information on the BARC thickness and material parameters. But this is not relevant as long as only the performance of the mask needs to be evaluated.

For that purpose we have developed a simple resist model. Its main features are:

- Minimum number of parameters so that no extensive resist calibration is required
- Fast computation time
- post processing of aerial images

## 2 MOTIVATION AND BACKGROUND

In lithography during wafer exposure a latent image is generated in the photoresist by creation of a photo acid distribution. During post exposure bake and resist development the photo acid diffuses inside the resist causing image blur and contrast loss to the latent image. Typical diffusion lengths range between 10 and 20nm depending on the type of photo resist and processing conditions. This contrast loss decreases the exposure latitude and increases the mask error enhancement factor (MEEF).

Taking the resist chemistry into account for an AIMS™ measurement will reduce the image contrast and edge slope and hence increase the MEEF. MEEF is the factor by which an error or defect on the mask is enhanced in the wafer print. Consequently, reducing the contrast of the AIMS™ measurement by applying a resist model can result in increased sensitivity to the printing behavior of mask defects on the wafer. We call this somewhat counterintuitive phenomenon **"contrast enhancement by contrast reduction"**.

Figure 2 shows an example measured in collaboration with IMEC[2]. The MEEF measured for different pitches using an AIMS™ was compared to aerial image simulations (also neglecting the resist chemistry) and wafer prints. Whilst the AIMS™ and the simulation agree quite well there is an offset to the wafer prints. This offset is well understood and explained by the resist effects discussed above which apply to the wafer prints but not to the AIMS™ measurement or the simulation.

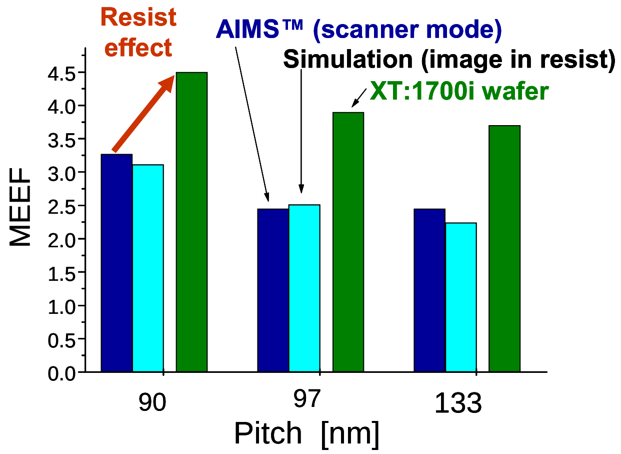

**Figure 2:** MEEF extracted from an AIMS™ measurement, a simulation and wafer prints for 3 different pitches. The AIMS™ measurement coincides well with the simulation. The difference to the wafer prints mainly has to be attributed to the blur of the "latent image" during post exposure bake and resist development.

Figure 3 shows another example. An aerial image (AIMS™ image) of a line structure with a defect (one of the 6 lines is wider than the others) has been simulated. Additionally, the resist contour produced by this aerial image has been simulated. The threshold for the AIMS™ image and the dose for the resist simulation were chosen to produce the target-CD of 45 nm for the regular (defect-free) lines. The CD of the defect line was measured. As the resist process causes a larger MEEF the CD change of the defect is larger in the simulated resist contour than in the simulated AIMS™ image. Thus taking resist effects into account can increase the sensitivity for photo mask defect printing behavior.

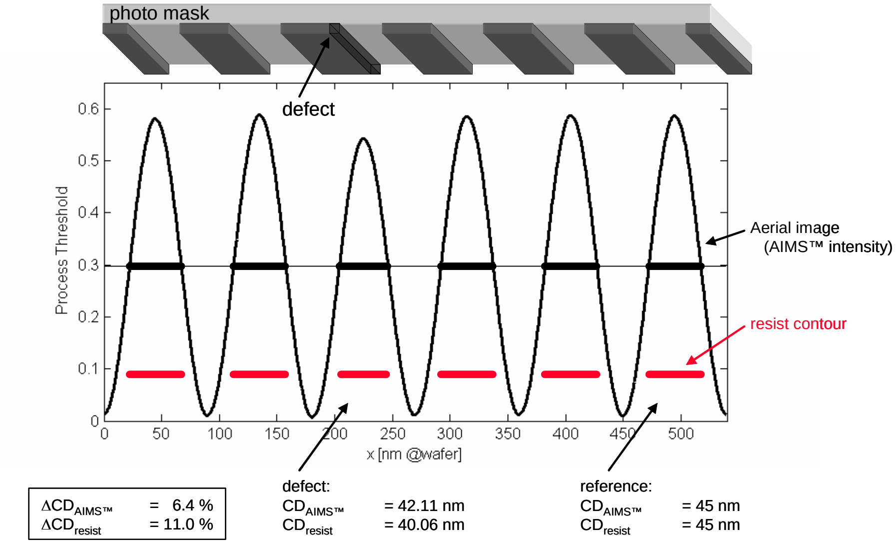

**Figure 3:** Simulation of half pitch = 45nm lines (NA=1.35, Sigma=0.96, dipole illumination, y-polarized). On the mask one line is wider than the others (“defect”).

For the AIMS™ image a process threshold of 0.298 was chosen to produce 45 nm target CD.
For the resist simulation the dose was chosen to produce also 45 nm CD for the unperturbed line.

In the AIMS™ image the defect causes $\Delta CD_{AIMS}$ = 6.4 %. Applying the resist model reduces the contrast and hence increases $\Delta CD_{resist}$ to 11 %. Thus the application of a resist model increases the sensitivity to mask defects.

## 3 SIMPLE RESIST MODEL

### 3.1 Operation principle

The aerial image (intensity distribution of the light inside the photoresist) is measured by the AIMS™ using the scanner mode at different focal positions (focus stack). A 3-D-bulk image of the intensity distribution over the resist thickness is composed of several focal planes of the AIMS™ measurement. From the bulk image the resist diffusion and development for a chemically amplified positive or negative resist (CAR) is simulated using a set of formulas that is similar but simplified compared to a full resist model[8,9,10].

Thus the calculation time is reduced to less than a minute for a standard focus stack.

### 3.2 Parameter calibration

Quite important is the number of calibration parameters. The simple resist model uses maximum 5 parameters, but only 2 parameters are critical. Compared to this a full resist model employs more than 20 parameters. This simplification can be done as the main purpose of the simple resist model is to increase the sensitivity of the aerial image concerning printing behavior of photo masks rather than fully modeling the physics and chemistry of the lithographic process.

The most important parameter is calibration parameter 1 which is comparable to the resist diffusion length in nm. It controls the contrast loss. It can be calibrated e.g. by comparing an AIMS™-exposure latitude measurement or MEEF measurement to wafer-SEM-data.

Calibration parameter 2 affects the iso-dense bias. The influence to the final result is not as important as parameter 1. Advanced users can calibrate it experimentally using patterns of different pitches. For standard applications a default value will be sufficient.

Thus it is relatively easy to calibrate the resist model by a limited set of wafer prints even without detailed knowledge of the lithography process or the resist parameters. In case no information on the resist is available at all it is still possible to use a set of standard parameters.

### 3.3 Limits of the model

Lithography simulation programs with full physics resist simulators are established on the market. Beside wafer print prediction those programs provide complex information about resist behavior used to optimize the wafer stack. 3-D resist profiles or details like resist footing, pattern collapse etc. can be simulated. But using these programs requires detailed knowledge about the wafer stack and usually more than 20 resist parameters that have to be calibrated. Hence these full simulators are not easy to use.

In contrast to this the simple resist model is not intended to provide detailed information about the resist behavior itself. Therefore it can not replace the full simulation programs and can not be used for wafer stack optimization or full lithography simulation. Yet it shows sufficient accuracy to explain the gap between wafer data and AIMS™.

## 4 EXPERIMENTAL RESULTS

This section compares results obtained with the simple resist model to actual wafer prints as well as simulations using different full resist models. To investigate the capability of the simple resist model to cover photoresist effects on the lithographic performance, we examined intensity profiles, exposure latitude and MEEF measurements.

### 4.1 Comparison to a full physics resist simulator

In a first example we did a simulation of a CoG line structure with half pitch 45nm, NA 1.35 and polarized dipole illumination with Sigma 0.96. One of the six lines has a defect i.e. it is wider than the others. The aerial image was simulated rigorously using Panoramics. To obtain the resist contour the simple resist model was applied to this aerial image. For comparison the resist contour was also simulated using the Panoramics full physics resist simulator and a resist model that was calibrated against wafer prints.

The process threshold for the simulated AIMS™ image as well as the dose for the simple resist model and the Panoramics resist simulator have been chosen to produce the target CD of 45nm at the regular (defect-free) line. The CD of the defect line was analyzed (see figure 4).

For the AIMS™ image we obtained $\Delta$CD = 3.89 nm = 6.4%. When taking the resist chemistry into account the photo acid diffusion reduces the contrast of the latent image and hence increases the MEEF as explained in chapter 2. Thus the CD change is substantially larger in the resist contour namely 4.94 nm = 11.0% for the simple resist model and 5.11 nm = 11.4% for the full physics resist model. The agreement between the two resist models is very good. The difference is 0.4 % only.

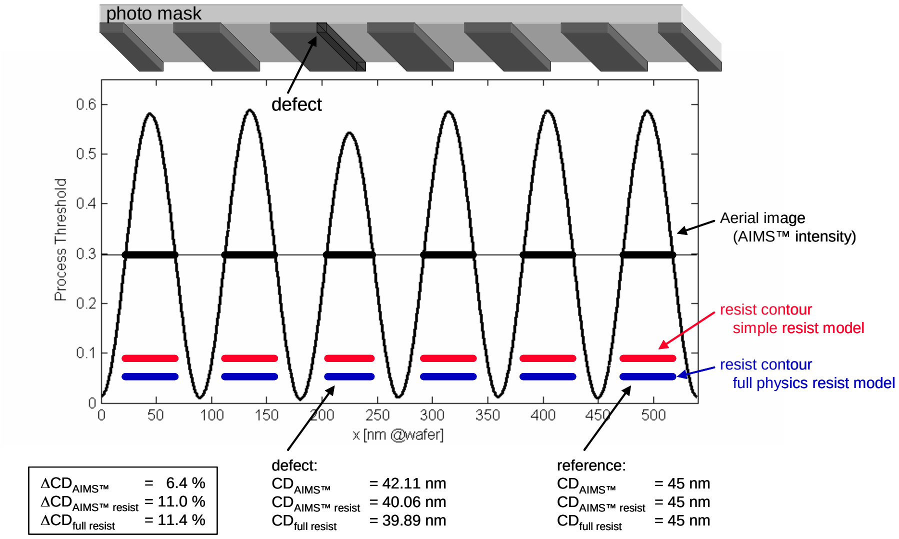

**Figure 4:** Simulation of half pitch = 45nm lines with a defect (NA=1.35, Sigma=0.96, dipole illumination, y-polarized). Simulation of the aerial image as well as the resist contour using the simple resist model and a calibrated full physics resist model (Panoramics). The process threshold for evaluating the aerial image and the doses for both resist models were chosen to produce 45 nm target CD each.

The defect visibility is strongly enhanced by applying the resist simulation. The results of both resist models coincide 10 times better than the AIMS™ threshold analysis.

We repeated the simulation using the same mask and the same aerial image but setting the target CD to different values i.e. changing the threshold or the dose respectively. The result is shown in figure 5. The differences in the defect CD between the simple resist model and the full resist model is about 5 – 10 times smaller than the difference between the aerial image (neglecting resist effects) and the full resist model. This shows that the simple resist model can predict printing performance of defects with sufficient accuracy.

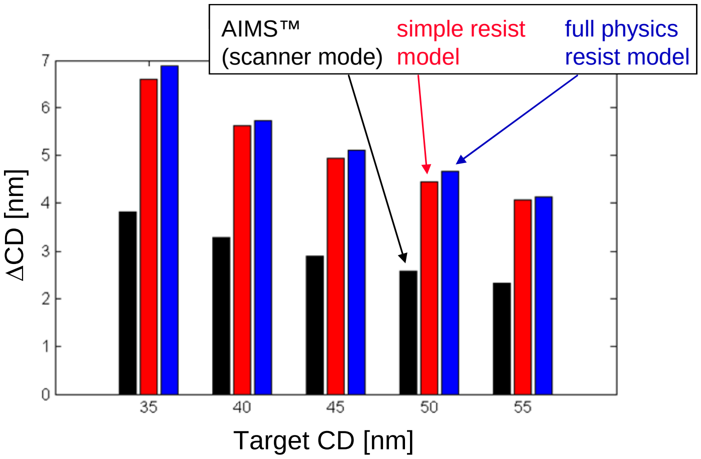

**Figure 5:** The same simulation as shown in figure 4 but different target CDs applied to the same aerial image. The offset in ΔCD between the aerial image and resist is almost leveled by the simple resist model.

From figure 5 it can be seen that there is an offset of the absolute value of the CD difference between AIMS™ and the resist print. However, the delta CD value measured by AIMS™ and applying the simple resist model shows a very good correlation to the delta CD measured in printed resist. This is why the aerial image measured by AIMS™ can be used to evaluate defects concerning printing behaviour without using wafer prints. The use of the simple resist model reduces the offset and brings the delta CD data closer to the wafer prints.

### 4.2 Exposure latitude in comparison to wafer prints

In a second example in collaboration with IMEC and the IISB Fraunhofer Institute[11] we obtained maximum exposure latitude data from wafers printed on an ASML XT:1700i scanner (NA = 1.20 cQuad20 $\sigma_{outer}$/ $\sigma_{inner}$ = 0.97/0.84, XY-polarized), using a binary chromium on glass (CoG) mask. We measured the maximum exposure latitude (i.e. the exposure latitude at best focus) as the relative dose latitude for which the printed wafer CD is within the nominal CD +/- 10%.

The mask was also characterized by the AIMS™. Aerial images were measured at 11 focus steps within a focus range of 500nm in the immersion liquid and the simple resist model was applied. Figure 5 shows a comparison between wafer prints, the AIMS™ measurements with and without the simple resist model applied as well as a calibrated efficient acid resist model (EARM) which was used as a reference full resist simulator.

Whilst the AIMS™ measurements show an offset to the wafer prints, both resist models coincide with the wafer prints within the experimental error bars.

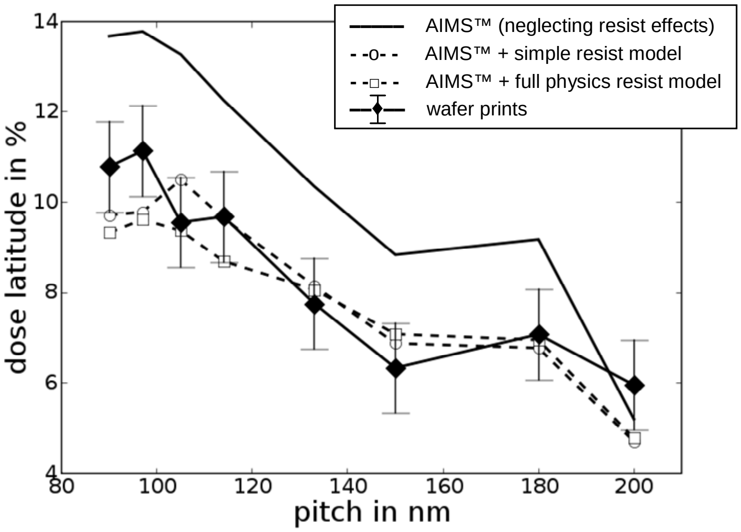

**Figure 6:** Dose latitude at best focus measured for pitches from 90 to 200nm from 4 different sets of data.

### 4.3 MEEF in comparison to wafer prints – parameter calibration

In a third example we used a CoG-mask with lines & spaces, half pitch = 45 and 65 nm. The line width varied between 45-50 nm and 65-70 nm respectively. The mask was characterized by wafer prints at IMEC in Belgium and AIMS™ measurements at Carl Zeiss. For the 45nm structures a quasar illumination was used with Sigma=0.96. The 65nm structures were measured with an annular illumination of Sigma=0.9. For both features the measurements were done with NA=1.2 and x-y-polarization. The chemical effects of the resist were taken into account by applying the simple resist model to the AIMS™ measurements.

For all 6 sets of data we evaluated image-CD versus mask-CD (see figure 7). The slope (linear part) of the linear fit line is the mask error enhancement factor (MEEF). The threshold at which the CD is evaluated from the AIMS™ measurement and the dose for the simple resist model were adjusted so that the first measurement point coincides for all 3 graphs. Varying the threshold changes the constant part of the fit line only which has no meaning. The offset arises from the fact that the first data point happens not to be exactly on the fit line.

We used these measurements to calibrate the resist parameters (see table 1). In a first step we varied calibration parameter 1 (diffusion length) and found the best match for the MEEF at 14.5. But no parameter value provided a perfect match for the 45 as well as the 65 nm structures. For the 65nm structures the AIMS™-MEEF always was lower than the wafer print-MEEF whilst it was the other way round for the 45 nm structures. In a second step we varied calibration parameter 2 (influencing the iso-dense-bias) and simultaneously we slightly adjusted parameter 1. The best match was found setting the parameters to 14.3 and 0.20 respectively. Thus we found a set of calibration parameters fitting the MEEF for both structure sizes using different illumination settings simultaneously.

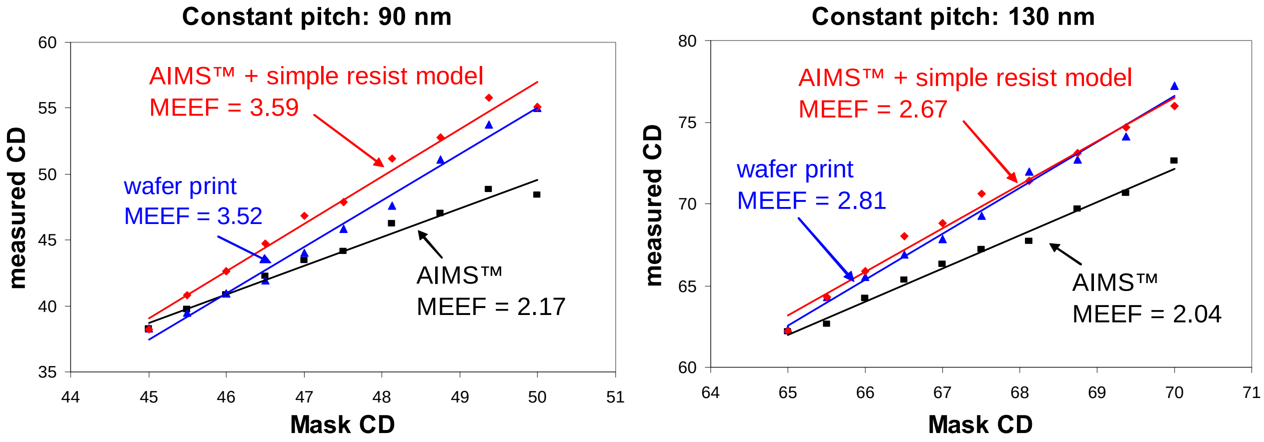

**Figure 7:** MEEF extracted from AIMS™ measurements, AIMS™ measurements plus simple resist model and wafer prints. The MEEF is the slope of the fit line.

There is an offset between the aerial image-MEEF and the wafer prints. One set of resist parameters almost levels this offset for both structure sizes and both illumination settings simultaneously.

**Table 1:** Calibration of the resist parameters to MEEF measurements for 2 different feature sizes.

| | **Parameter 1** | **Parameter 2** | **MEEF (45 nm)** | **MEEF (65 nm)** |
|---|---|---|---|---|
| Wafer print | | | **3.52** | **2.81** |
| AIMS™ aerial image | | | 2.17 | 2.04 |
| Simple resist model calibration start | 12.0 | 0.40 | 3.06 | 2.49 |
| Simple resist model calibration step 1 | 14.5 | 0.40 | 3.58 | 2.62 |
| Simple resist model calibration finished | 14.3 | 0.20 | **3.59** | **2.67** |

### 4.4 Line end shortening

The resist effects do not only influence the line width but also the appearance of 2-D-structures. As an example figure 8 shows line ends of dense lines measured using an AIMS™.

From the aerial image we drew a contour plot. The threshold was set to 0.181 to produce a CD of 45 nm. The simple resist model was applied to the aerial image and the resist contour was drawn as well. To produce the same line width we had to use a slightly different process threshold of 0.174. As can be seen the contours of the lines coincide whilst the line ends in the resist are 13 nm shorter than in the AIMS image.

Thus when looking closely into the details of complex logic structures the resist effects will influence not only the CD but also the line edges, corners etc.

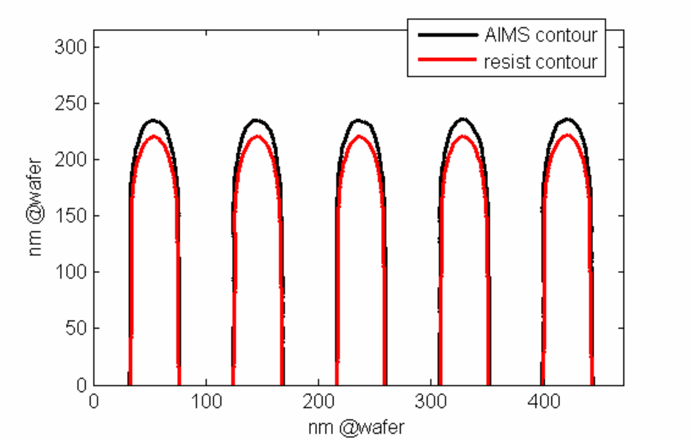

**Figure 8:** Line end shortening:

CoG, dense lines, half pitch = 45nm, NA 1.40, Sigma 0.98, quadrupole illumination.

The process threshold was set to 0.181 for the AIMS image (black) and 0.174 for the resist contour (red) to produce the same CD of 45 nm each. Evaluated at these thresholds the line ends in the resist are 13 nm shorter than in the AIMS image.

## 5 SUMMARY

The AIMS™ measures the aerial image (intensity distribution) inside the photo resist under scanner equivalent conditions. An excellent correlation between AIMS™ and wafer prints has been observed in several studies. Naturally, the pure aerial image contains no information about the chemical effects during resist processing and development. It is well known that resist effects lead to a blur of the latent image and hence increase MEEF and decrease exposure latitude in the wafer print compared to the aerial image. In some cases this can lead to an underestimation of the printing behavior of defects in terms of delta CD by using the aerial image only. Up to now these effects have been of minor concern for defect qualification. However, for future lithography nodes with larger MEEF it might be necessary to take these effects into account during mask manufacturing.

We have developed a simple resist model. Its computation time is fast and no extensive resist parameter calibration is required. It is tailored for qualifying the printing behavior of photo masks even if no detailed information on the wafer processes and resist parameters is available.

By comparison to simulations as well as wafer prints we have shown that the results are in good agreement with full resist models and real wafer prints.

The predominant effect of the resist chemistry is the reduction of image contrast. Applying the simple resist model does increase the MEEF and hence the sensitivity of the printing behavior of photo masks. Additionally the measurement results get substantially closer to the wafer prints.

## ACKNOWLEDGEMENTS

The authors want to thank Peter de Bishop and Vicky Philipsen from IMEC for doing and analyzing wafer prints and A. Erdmann and B. Meliorisz from IISB Fraunhofer Institute for intense discussing and simulating resist models.

## REFERENCES

[1] T. Scherübl, A.C. Dürr, K. Böhm, R. Birkner, R. Richter, U. Strössner, “Programmed defects study on masks for 45 nm immersion lithography using the novel AIMS™45-193i”, 23rd European Mask and Lithography Conference

[2] P. De Bisschop et al, “Using the AIMS 45-193i for hyper-NA imaging applications”, Proceedings of SPIE, Vol. 6730, 67301G (2007)

[3] E. van Setten, E., Wismans, O., Grim, K., Finders, J., Dusa, M., Birkner, R., Richter, R., Scherübl, T., "The flash memory battle: How low can we go?" in Optical Microlithography XXI, edited by Harry J. Levinson, Mircea V. Dusa, Proceedings of SPIE Vol. 6924 (SPIE, Bellingham, WA 2008) 69244I.

[4] Eelco van Setten, Onno Wismans, Kees Grim, Jo Finders, Mircea Dusa, , Robert Birkner, Rigo Richter, Thomas Scherübl, The imaging performance of Flash Memory masks characterized with AIMS$^{TM,}$ Semiconductor International, September 2008

[5] Philipsen, V., Mesuda, K., De Bisschop, P., Erdmann, A., Citarella, G., Evanschitzky, P., Birkner, R., Richter, R., Scherübl, T., "Impact of alternative mask stacks on the imaging performance at NA 1.20 and above" Proceedings of SPIE Vol. 6730 (SPIE, Bellingham, WA 2007) 67301N.

[6] E. van Setten et al, “Characterizing the imaging performance of Flash Memory masks using AIMSTM”, to be published in Proceedings of SPIE, (2008)

[7] E. Hendricksx et. al. “AIMS™ 45 inspection of CH treated with inverse lithography”, published in proceedings of 5th Immersion Symposium, (2008)

[8] Erdmann A., Henke W., Robertson S., Richter E., Tollkühn B., and Hoppe W.: “Comparison of simulation approaches for chemically amplified resists”, Proc. SPIE **4404** (2001) 99.

[9] Robertson S., Mack C. A., and Maslow M.: “Towards a Universal Resist Dissolution Model for Lithography Simulation”, Proc. SPIE **4404** (2001) 111.

[10] Mack C. A.: “Development of positive photoresist”, Journal of the Electrochemical Society, Solid States and Technology” **134** (1987) 148.

[11] B. Meliorisz et al, “Increasing the Predictability of AIMS™ Measurements by Coupling to Resist Simulations”, Proc. SPIE **7028** (PMJ 2008) 70282S