First results for hyper NA scanner emulation from AIMS™ 45-193i

Axel Zibold[1,◆], Ulrich Strössner[1], Norbert Rosenkranz[1], Andrew Ridley[1],
Rigo Richter[1], Wolfgang Harnisch[1], Alvina Williams[2]

[1] Carl Zeiss SMS GmbH, Jena, Germany

[2] SEMATECH, Austin, Texas USA

ABSTRACT

Immersion lithography offers the semiconductor industry the opportunity to extend current ArF processes before switching to shorter wavelengths. As numerical apertures of scanners for hyper NA move above 1.0 with immersion lithography, increased attention must be paid to the photomask or reticle and its wafer printability. Feature sizes on the photomask become increasingly critical as they behave more like partial wire grid polarisers, as they become comparable to, or smaller than the wavelength. Besides challenges to address reticle polarisation effects, lithographers must also consider the polarisation state of the illumination and subsequently the contrast loss for light with a TM polarisation state. Such an effect, also called the vector effect, is caused by the increasing angle of incidence of the diffracted light for larger numerical apertures on the scanner. Therefore, for wafer printing using hyper NA scanners, the industry consensus is that TE polarised illumination must be used to meet the stringent requirements of imaging contrast.

In this paper, initial results of measurements using the optical test stand and the alpha tool of a completely new AIMS™[1] tool for the 45nm node will be presented. The system covers all aspects of immersion and polarisation lithographic emulation. Measurements have been made on binary and phase shift masks with different sizes of features and on programmed defects.

Keywords: aerial image, AIMS, immersion, polarisation, TE, TM, numerical aperture, high NA, hyper NA, vector effects

1. NOVEL SYSTEM: AIMS™ 45-193i

Since the middle of 2004, Zeiss and SEMATECH have been involved in a joint development project to develop an AIMS™ tool suitable for the 193 nm lithography requirements for the 45 nm node. AIMS™ tools are state-of-the-art in the photomask industry for development, quality control, repair verification and defect classification of photomasks and reticles.[2-9] The novel AIMS™ tool, the AIMS™ 45-193i, is based on a newly developed mechanical platform and new Zeiss 193 nm high precision optics. A test stand as well as an alpha tool is available at Zeiss, and the first measurements have been completed. First deliveries will start in August 2006.

Key features of the new AIMS™ platform are increased numerical apertures up to 1.4 (4x scanner), scanner equivalent polarisation settings and vector effect emulation, in addition to significant other tool improvements. Some of the most important improvements on this platform are: a new temperature controlled acoustically isolated measurement chamber, new features to reduce the risk of mask contamination, a high accuracy air bearing stage, and a robotic mask handling system with SMIF interface which handles the mask face down in the same orientation as in the scanner. The newly designed optics path includes polarisation settings equivalent to those of the most advanced scanners. These include linear polarisation in both reticle edge directions, and tangential polarisation of 4 poles, 8 poles, and 12 poles.

◆ zibold@smt.zeiss.com

Fig. 1: Picture of the AIMS™ 45-193i alpha tool. The left side shows the environmental chamber including the stage, optics and mask loading interface. Environmental control unit is integrated on the right side.

Especially for hyper NA, it is important to use the resist image to analyze defects, repairs, or critical features for wafer printability. Therefore, additional to the conventional scalar mode, a new AIMS™ "Scanner Mode" available in two operational functions is introduced on the AIMS™ 45-193i. The AIMS™ "Scanner Mode" takes the vector effects into account and provides the intensity distribution of the reticle features inside the resist. One mode is an approximation with fast throughput, called AIMS™ "Fast Scanner Mode", which can be used for unpolarised or linear polarised illumination and negligible reticle polarisation effects. The other mode, called AIMS™ "Scanner Mode", is a general purpose mode covering all various polarised illumination and reticle polarisation effects. In this paper all work is focusing on the general purpose mode: AIMS™ "Scanner Mode". This mode is accomplished using a proprietary hardware/software technique based upon measurements in different polarisation states followed by subsequent data analysis including the input of the refractive index n_r of the resist. In this paper we used n_r = 1.7. In previous papers detailed studies are given of the AIMS™ "Fast Scanner Mode"[10] and AIMS™ Scanner Mode"[11] used at NA = 0.93.

Figure 2 shows first measurement results of lines and spaces of a binary mask taken on the test stand. The aerial image including polarisation and vector effects of 180 nm mask (45nm) features is displayed. An intensity distribution is shown that is equivalent to that which would occur in the photoresist under these optical conditions.

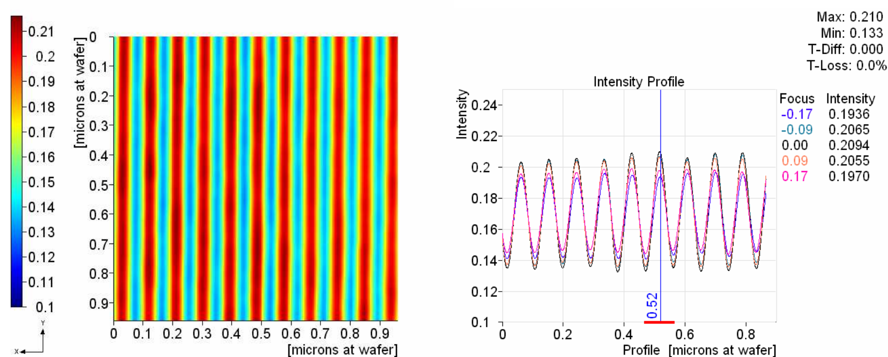

Figure 2: AIMS™ "Scanner Mode" on BIN, 180 nm lines, 1:1 pitch, 1.2 NA .95 sigma (60% dipole), unpolarised illumination. Scanner image in best focus (left image) and intensity distribution in resist (right image).

Figure 3 demonstrates the system stability of the AIMS 45-193i alpha tool. Static CD repeatability measurements have been performed with 10 repeated measurements without stage movement. A range (min, max) of 1.8 nm on mask level was found which corresponds to a CD repeatability of 1.2% fulfilling ITRS roadmap requirements for the 45nm node.

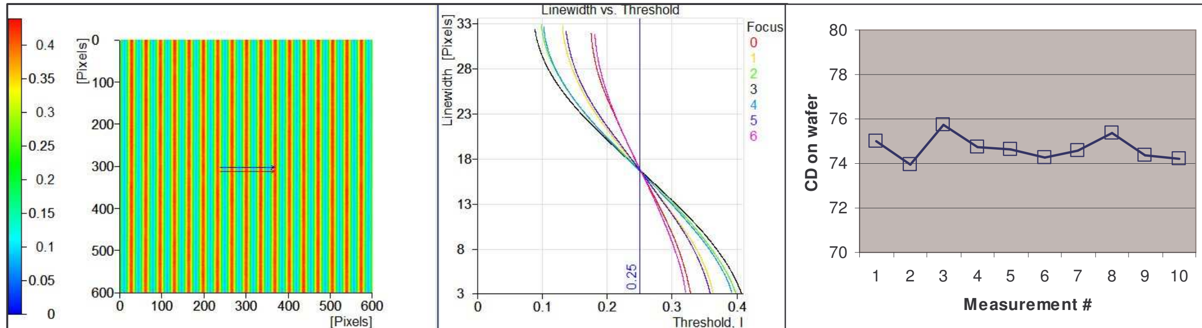

Figure 3: AIMS™ "Scanner Mode" on BIM, 300 nm lines, 1:1 pitch, 1.4 NA .98 sigma, unpolarised illumination. Scanner image in best focus (left image), linewidth versus threshold analysis (middle image) and CD value for each repeat measurement (right image).

2. POLARISATION EFFECTS

With printable feature sizes becoming so small on the wafer, scanners are required to use numerical apertures approaching 1 and with use of immersion liquid achieving values even above 1 (hyper NA). It is generally understood that polarisation effects from imaging will occur due to the large angles of incident light into the resist which will impact printability. Two states of polarisation can be defined: one as transverse magnetic (TM) having its electric field parallel to the plane of incidence and the other transverse electric (TE) having its electric field perpendicular to the plane of incidence as it is illustrated in the figure 4. As a result of the higher angles of incidence when using an NA greater than 1.0, the TE state continues to fully interfere even with increasing angle of incident light, but the TM state is less and less interfering. Therefore, in hyper NA imaging vector effects result in a loss of contrast for the TM polarised light contribution, in extreme cases even causing contrast reversal, whereas TE contributions are imaged without such loss.[12,13] To optimise the printing process it is necessary for scanners to work with TE polarisation such as dipole off-axis illumination combined with linear polarisation vectors perpendicular to the dipole axis, or with tangential polarisation schemes. In addition photomask induced polarisation can even enlarge TM polarised light contribution since photomasks can act as wire grid polarisers[14,15] and thus enhance the contrast loss in the resist. Therefore it is important for mask inspection and evaluation that the mask has to be observed with the correct polarisation in illumination. Comparing scanner to AIMS™ illumination there is an equivalent image generation which makes sure that the polarisation effects are captured on the AIMS™ with the same effects as on the scanner.

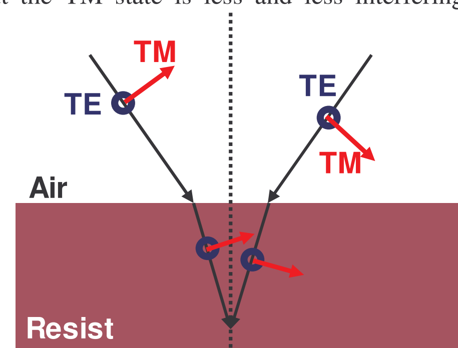

Figure 4: Sketch demonstrating the incident light of a scanner into the resist and the two states of polarisation (TE, TM).

Very strong polarisation effects have been demonstrated by investigation of patterns comparing TE to TM polarised illumination with all other settings kept fixed at highest possible NA. For a 6% attenuating phase shift mask (attPSM: MoSiON) and an NA of 1.4, 72% ±4% relative contrast loss due to vector effects was observed when linear polarised illumination perpendicular to the lines and spaces was used. This is in direct accordance with rigorous simulations which

predict contrast loss of 73% for perpendicular polarisation. Conversely, for illumination polarised in the parallel direction rigorous simulation predicts a contrast loss of only 5% for the vector effect image. Measurements verify this also with an excellent result of 4% ±2% contrast loss.

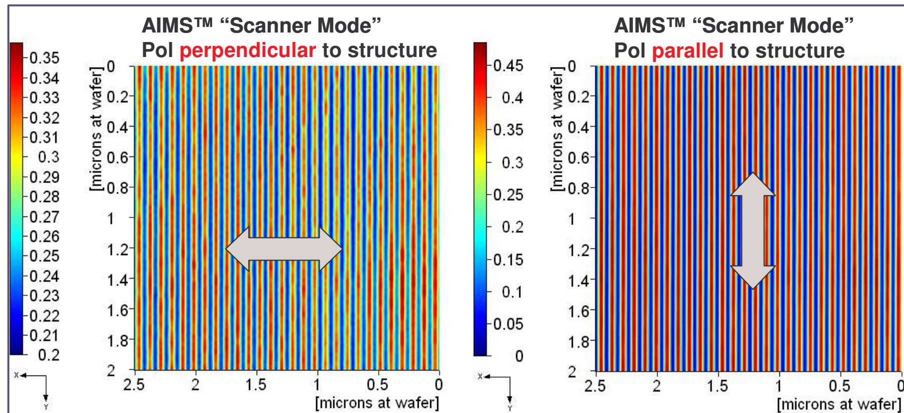

Figure 5: AIMS™ "Scanner Mode", 6% MoSiON, 180 nm lines, 1:1 pitch, 1.4 NA .96 sigma (60% dipole), linear polarised illumination.

Figure 5 shows the difference in relative contrast between TE and TM polarisation under consideration of vector effects using the AIMS™ "Scanner Mode". Clearly can be seen, that unlike rigorous simulations, AIMS™ takes into account all real world mask effects such as line edge roughness, sidewall angle effects, and birefringence of the mask substrate.

3. INVESTIGATION OF HYPER NA MASK PRINTABILITY ON AIMS™ 45-193i ALPHA TOOL

3a. DEFECT PRINTABILITY ANALYSIS

One of the major applications for AIMS™ tools is defect analysis and repair verification. To understand the sensitivity of the new AIMS™ 45-193i a defect analysis study was performed on a binary reticle of 180 nm ½ pitch with lines and spaces 1:1 with programmed defects. Defects were either clear or opaque, clear intrusions or chrome extrusions respectively. Sizes ranged from 1,600 to 25,600 nm^2. It covers on the low side a 40 nm by 40 nm defect on the mask which is a reasonable boundary for critical defects at the 45nm node. The programmed defects were designed to investigate CD variations from 2.5% up to 60%. Figure 6 shows an AFM image of one of the larger defects on the 180 nm pattern. The AFM scan reveals a chrome extrusion of a width of 104 nm and a length of 207 nm (size 21,528 nm^2).

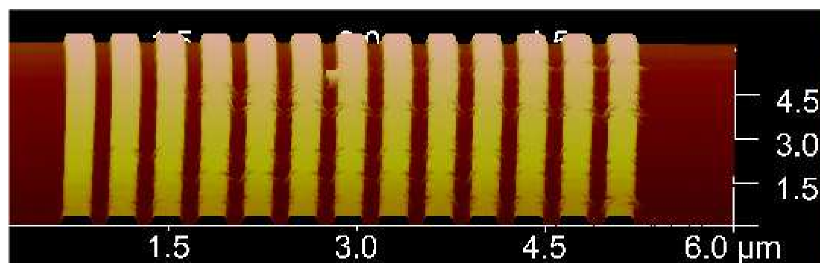

Figure 6: AFM scan showing a chrome extrusion of a width of 104 nm and a length of 207 nm (size 21,528 nm^2) of binary reticle of 180nm ½ pitch with lines and spaces 1:1.

All programmed defects were imaged with an AIMS™ through focus measurement. As an example figure 7 shows the intensity profile of a defect of 3,200 nm^2 size on the smaller side. Feature size is 180 nm ½ pitch 1:1. A transmission loss is found of 12%.

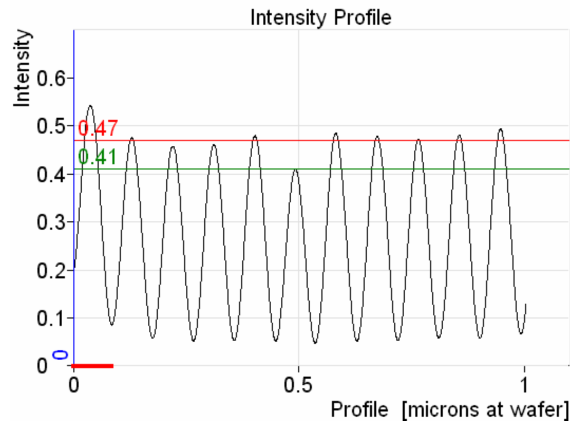

Figure 7: Intensity profile obtained from AIMS™ measurement of a defect of size 3,200 nm^2. The mask is a binary reticle of 180 nm ½ pitch with lines and spaces 1:1. Settings are NA 1.4, sigma 0.96 dipole 60%. TE polarised illumination.

Further analysis of all measured defects has been made for the bright line at best focus using the linewidth versus threshold plot. The threshold was set at the reference/non-defected line to 45 nm linewidth at wafer level. Relative CD change between reference and defected line was calculated as the difference and normalized with the reference. Figure 8 shows the wafer level CD change (ΔCD) in dependency of the defect size. Results are shown for both test stand and alpha tool. It can clearly be seen a very good coincidence for test stand and alpha tool. The results show a linear CD change as a function of the defect size. A larger slope was found for opaque defects, a smaller slope for clear defects. With smaller peak intensities, or decreased dose due to opaque defects the limit of acceptable feature printability is reached faster. The linear behaviour of CD change versus defect size was confirmed with 2D simulation.

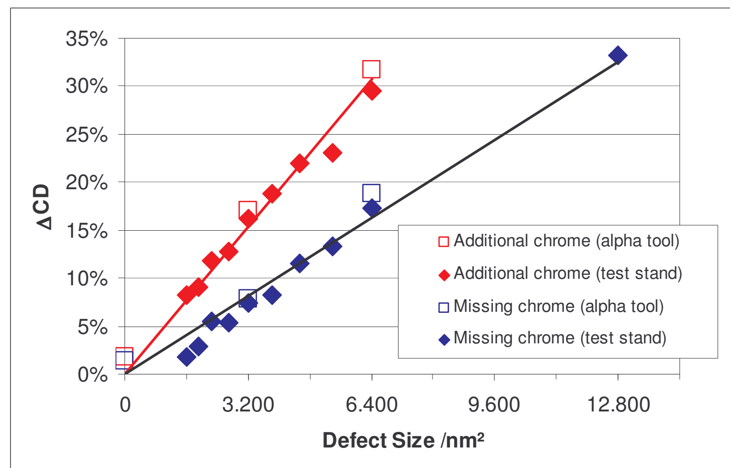

Figure 8: Wafer level CD change in dependency of defect size. Settings: 1.4 NA and 0.96 outer sigma with dipole illumination of radius 0.2. TE polarised illumination, linear parallel to lines and space pattern.

3b. PITCH DEPENDENT PATTERN ANALYSIS

In further measurements polarisation effects of MoSi 6% test features have been examined. Measurements were made on vertical lines/spaces 1:1 through half pitch (starting at 180 nm mask level) at 1.2 NA, 0.95 sigma, and 60% dipole. A series of images was captured using unpolarised light (u), linear TE polarisation (TE), and TM polarisation (TM). All images were captured in scalar mode, and AIMS™ "Scanner Mode". Polarisation efficiency (IPS) of the equivalent scanner was assumed to be 95%, and refractive index of the resist was set at 1.7. AIMS™ through focus captures were made and contrast calculated from the intensity distribution based on C = (Imax – Imin) / (Imax + Imin) with Imax (Imin) the peak (valley) intensity value in the AIMS™ "Scanner Mode". Contrast was measured at each site so that contrast change due to mask polarisation and vector effects under the different polarisation states was calculated.

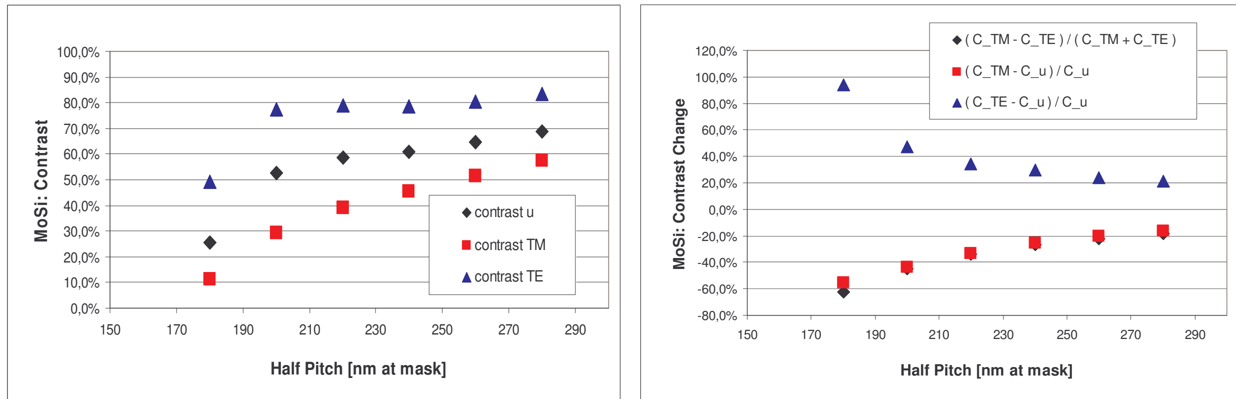

Figure 9: Polarisation dependency on contrast (left image) and contrast change (right image) for MoSi 6% 1:1 through half pitch. Settings are 1.2 NA, 0.95 sigma, 60% dipole.

Figure 9 shows that for a given half pitch value the contrast is drastically reduced for TM polarised illumination which is in accordance with previous findings.[10] All results are measured using the AIMS™ "Scanner Mode". In the unpolarised case we can find an effect roughly of half the amount. This is expected since unploarized illumination can be understood as an appropriate combination of TE and TM contributions. As the half pitch is decreasing the TE mode is not significantly effected however the TM mode shows a continuous drop in contrast. With the diffraction orders getting closer to the edge of the pupil in TM mode larger incident angles into the resist are present and thus cause the larger effect of contrast loss. From the change of contrast calculation we clearly see that for the printing process it is necessary for scanners to work with TE polarisation such as dipole off-axis illumination combined with linear polarisation vectors perpendicular to the dipole axis, or with tangential polarisation schemes.

To capture such effects correctly it is important for mask inspection and evaluation that the mask has to be observed with the correct polarisation. Figure 10 compares the contrast calculated from aerial images without taking vector effects from imaging into account (scalar mode) divided by the contrast from AIMS™ measurements taking vector effects from imaging into account (AIMS™ "Scanner mode"). Additionally to duty cycle 1:1 data points are added from 1:2 lines/spaces. For TE polarisation only a very small effect of contrast loss can be seen towards smaller half pitches due to a very small TM contribution. The situation is dramatically different for TM polarisation in case of unpolarised scanner illumination. It becomes clear that the AIMS™ "Scanner mode" is the choice of operation.

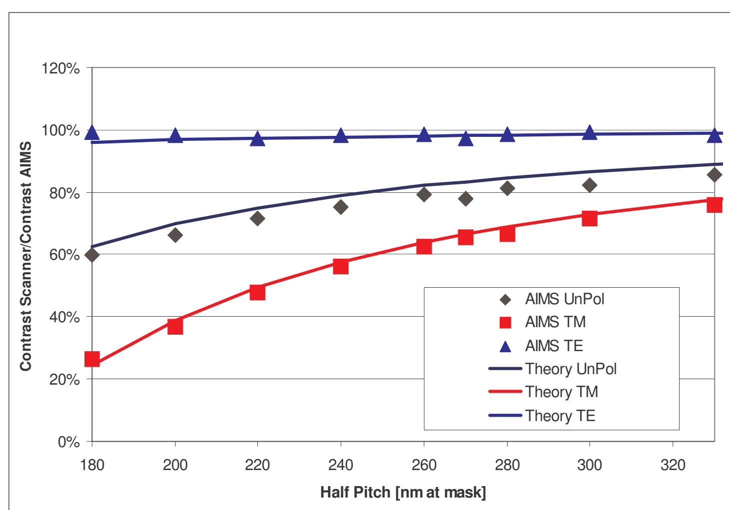

Figure 10: Measured contrast loss due to polarisation and vector effects vs. theoretically predicted loss on MoSi 6%.

The solid lines in figure 10 are obtained from simulation and show the expected contrast loss on the scanner based on the increased angle of incident light into the resist for the given NA and mask pattern sizes. A very good coincidence is found with the measured results. Small deviations to be seen can be attributed to the fact that the AIMS™ technique captures the effects of the real mask such as 3D topography, sidewall angles, line edge roughness and material property variations.

SUMMARY

Initial experiments show great promise for the measurement capabilities of the AIMS™ 45-193i in its ability to predict hyper NA immersion lithography. A completely new system was designed and built in order to fulfil the stringent 193 nm requirements of the 45nm ITRS roadmap. Besides the conventional scalar mode a new imaging capability has been added, called the AIMS™ "Scanner mode". This new mode takes into account the large angle effects of incident light into the resist of the wafer at hyper NA exposure. It allows the prediction of the intensity distribution in the resist. Based on polarisation capabilities these vector effects of imaging are predicted including the reticle polarisation effects.

Experimental results using "Scanner Mode" show excellent correlation to rigorous simulation for predicting contrast on 45nm lines and spaces under TE and TM polarisation at an NA of 1.4 on MoSi 6% masks. Furthermore, through pitch line/space measurements starting at 180 nm mask features on MoSi 6% masks with unpolarised, TE, and TM polarised light at NA of 1.2 revealed sensible behaviour when examining contrast loss. Clearly can be seen that TE polarisation is the preferred scanner illumination for printing of very small feature sizes. AIMS™ mode and AIMS™ "Scanner Mode" show excellent correlations in measurements and are in very strong correlation to theoretically predicted behaviour.

With initial measurements showing such strong results it is clear that with the concept of AIMS™ under hyper NA imaging conditions the AIMS™ 45-193i is expected to become a powerful metrology tool to predict the lithographic behaviour of reticles or photomasks for upcoming scanners and to assure the reticle quality under its strong requirements. Further experiments will be made with complex structures that are difficult to simulate with confidence, and that include real world mask effects such as topographical effects, line edge roughness, sidewall angle effects, and birefringence of the mask substrate.

Also initial analysis has been made on programmed defects. Printability effects have been studied and a linear behaviour was found between CD change and defect size. Even for very small defects of 1,600 nm^2 size the AIMS™ tool reveals sensitivity. Further defects will have to be examined as they may print differently than previously due to polarisation effects. Scanner prints for comparison will complement that work.

Every lithography ‘trick’ will have to be used in order to print patterns correctly onto wafers at the 45nm node. OPC, mask type, illumination shape, circuit design, photoresists, NA, polarisation, and immersion will all be used to meet the requirements to print correctly on the wafer. With each of these RET’s comes added complexities, and of course, a chance for errors or defects to occur. Fortunately, with the novel immersion AIMS™, all rigorous effects are taken into account since it captures reticle effects comparable to the scanner and does not need prior information. Therefore, to deliver future 45 nm masks of production quality, AIMS™ analysis will be a crucial part of the mask making process.

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