# Determination of mask induced polarization effects on chromeless phase-shifting mask structures and AltPSM mask structures for 50 nm lithography

Ingo Höllein*, Silvio Teuber, Karsten Bubke
Advanced Mask Technology Center GmbH & Co. KG, Raehnitzer Allee 9, D-01109 Dresden, Germany

**ABSTRACT**

In the process of discussion possible mask-types for the 5x nm node (half-pitch) and below, chromeless phase-shifting masks and alternating phase-shifting masks (AltPSM) are potential candidates to be screened. The current scenario suggests using 193 nm immersion lithography with NA values of up to 1.2 and above. New optical effects like 3D shadowing, effects from oblique incident angles, mask-induced polarization of the transmitted light and birefringence from the substrate need to be taken into account when the optical performance of a mask is evaluated. This paper addresses mask induced polarization effects from dense lines-and-space structures of real masks. Measurements of diffraction efficiencies for TE- and TM-polarized light are presented for AltPSM masks. Simulation results for chromeless phase-shifting masks are shown. The structures under investigation include line-space-pattern with varying pitch as well as duty cycle under different angles of incidence. Experimental results show good agreement with simulations. Limits of the masks types are discussed.

Keywords: AltPSM, chromeless phase-shifting masks, Polarization, high NA, immersion, 50 nm lithography

## 1. MOTIVATION

Advanced mask types such as AltPSM and chromeless phase-shifting masks are known since some years. These masks proofed to have better imaging properties such as process window and a better mask error enhancement factor (MEEF) than binary masks. Their obvious benefits can only yield profit in production if certain mask properties like intensity and phase balance are controlled in an advanced way. Disadvantage of these mask types are therefore the more complicated mask making process, which includes the high complexity of the mask design, the manufacturability and inspectability. In order to decide about the mask scenario for a specific node, a trade-off between the imaging properties and the matters of mask making have to be made. Mask polarization is one effect influencing the imaging properties and shall therefore be investigated in order to have a more profound understanding of these mask types.

## 2. INTRODUCTION into POLARIZATION EFFECTS

The resolution limit W of optical lithography is described by:

$$W = \frac{k_1 \lambda}{NA} \tag{1}$$

where $\lambda$ is the exposure wavelength, $k_l$ is a process factor and *NA* is the numerical aperture. NA is determined by the acceptance angle of the lens and the index of diffraction of the medium surrounding the lens:

$$NA = n \sin \alpha \tag{2}$$

* Phone: +49-351-4048-374, Fax: +49-351-4048-9374, E-mail: ingo.hoellein@amtc-dresden.com

With water (n=1.47) as an immersion fluid, a NA of up to 1.2 and above is feasible resulting in a significantly better resolution limit and a corresponding smaller “possible smallest feature size” on the mask.

According the ITRS roadmap, one possible technology option for the 50 nm node is 193 nm immersion lithography. This would be the first node where the polarization effects become significant [1].

Here the feature size on the mask (4 x 50 nm = 200nm) and the wavelength with 193 nm would be about the same. As reported earlier, mask induced polarization effects become a concern when such small features interact with the light [2].

Reticle features with half pitches $\sim\lambda$ act as a partial polarizer. In this case the transmission through the mask is polarization dependent, i.e. the diffraction spectrum for TE- and TM polarized light differs considerably from each other. The efficiency of the mask induced partial polarization is strongly influenced by the pitch, duty cycle, absorber geometry (thickness, shape, sidewall angle), and absorber material.

As the interference of diffraction orders in the resist is substantially different for TE- and TM-components, the mask can have a considerable impact on the imaging properties of the overall system.

To quantitatively investigate the mask-induced polarization for relevant mask materials a series of experiments and simulations were performed. The experimental setup is shown in Fig. 1. An array of grating structures is illuminated with either TE-, TM- or unpolarized light and the efficiencies in the respective diffraction orders are with an angle resolved detector. As a figure of merit for mask polarization the degree of polarization is introduced:

$$DOP = \frac{I_{TE} - I_{TM}}{I_{TE} + I_{TM}} . \tag{3}$$

A DOP of –100% indicates a fully TM polarized radiation, whereas +100% shows fully TE polarized radiation. $I_{TE}$ and $I_{TM}$ are the intensities diffracted in the respective orders.

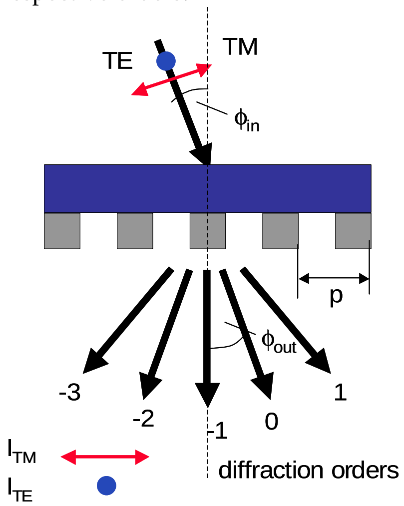



Fig. 1 Schematics of the DoP evaluation set-up

## 3. Lithography concepts and settings for 50 nm hp structures

### 3.1. AltPSM Lithography

First calculations show that the AltPSM mask type would meet the requirements for 50 nm half-pitch under immersion-settings [6]. The unit cell under investigation is shown in Fig. 2.

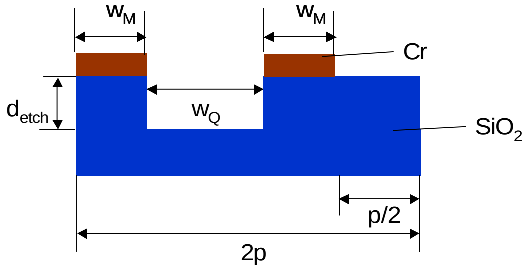



Fig. 2 Structure of unit cell for an AltPSM mask with p: pitch, d: etch depth, $w_M$ : width of chrome absorber, $w_Q$: width quartz

The design goal is to minimize the $0^{th}$ diffraction order. Only the $-1^{st}$ and the $1^{st}$ diffraction order are used for imaging. The etch depth d corresponds to a phase shift of Pi and can be described as follows:

$$d(\Delta\Phi = \pi) = \frac{\lambda}{2(n-1)} \tag{4}$$

In all simulations a mask with an exact Pi-phase shift in the respective structure is assumed. Further, the mask is simplified in the way $w_m = w_Q = p/2$ and does therefore not take into account balancing strategies such as e.g. under-cut or pattern biasing.

### 3.2. Chromeless Phase Lithography

Another viable option for 50nm lithography is the Chromeless Phase Lithography. A wafer feature is formed by two neighboring Pi-phase edges resulting in a high contrast image. It uses a 100% transmission phase –shifting mask in combination with off-axis illumination and high NA. The image on the wafer is created by the interference of the $0^{th}$ and $-1^{st}$ diffraction order (see Fig. 1).

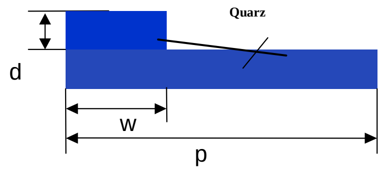



Fig. 3 Structure of unit cell for a chromeless phase lithography mask with p: pitch, d: etch depth, w: line-width

It has been demonstrated that chromeless phase-lithography has a high flexibility for through pitch imaging. Also concerning mask making chromeless phase-lithography masks showed advantages over alternating and attenuated PSM [2]. The manufacturability and the successful utilization has been demonstrated [7].

A Chromeless Phase Lithography mask can be produced in two different types, the mesa- and the trench-style mask. In the case of a mesa-style mask the main part of the pitch on the mask is etched away, whereas in the other case only small trenches are etched into the quartz. Both cases were considered in the simulations. Fig. 4 shows the basic geometry.

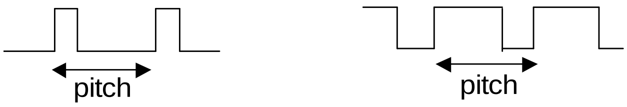



Fig. 4 The two basic geometries of a Chromeless Phase Lithography mask: mesa-style (left) and trench-style (right)

In order to ensure the optimal interference between the $0^{th}$ and $-1^{st}$ order, the etch depth corresponds to a phase shift of Pi as shown for the AltPSM mask in equation (4). The structure of the unit cell under investigation is shown in Fig. 3.

The overall design goal is to equalize the $0^{th}$ and $-1^{st}$ diffraction orders. The optimum line/pitch necessary for the equalization of the $0^{th}$ and the $-1^{st}$ order for the 50 nm node are estimated by diffraction simulations using G-Solver to be 13 nm for mesa-style and 64 nm for trench-style.

The optimal dipole illumination for the 50 nm node corresponds to an incidence angle of 14° in the object space. These settings are later being used in the simulations.

## 4. MASK DESIGN, FABRICATION and EXPERIMENTAL SETUP

The investigations described in this paper are based on three pillars:

I. AltPSM Test mask

The mask blanks were patterned at the AMTC using the standard process. The mask design consists of fields with an area of 4mmx4mm containing lines and spaces with a specified pitch size and duty cycle (=line/pitch). The fields are separated by a distance of 1mm and arranged in a matrix with different fields corresponding to different pitches and line/pitch ratios. The mask pitch ranges from 1200nm to 300nm. The same layout was used for earlier DoP experiments recently published by AMTC [1, 5].

Because of the inherent process bias and the fact that the applied process was not optimized for the whole pitch-range, the real mask structures were measured with a CD-SEM tool. All data in the next section refer to the real mask structures with a confirmed CD.

Further the quartz edge-depths of the trenches were qualified with a Surface Nano-Profiler (SNP). The etch depth variation for the 400 nm structures was <3% (Sigma).

The CD-data of the small structures indicates that corner rounding is an increasing issue for smaller structures.

II. Experimental set-up

The polarization measurements were performed at Fraunhofer Institute (IOF) in Jena using a VUV photospectrometer [2, 3]. The measurement system uses a deuterium lamp as light source, a grating monochromator in order to select a specified wavelength, a Rochom prism of $MgF_2$ as UV-polarizer, a sample holder and a photo multiplier. Angle resolved transmission measurements were performed at 193.4nm at different polarization directions. The mask patterns were illuminated from the backside. The obtained angle resolved transmission spectra were analyzed with respect to the intensities of the $0^{th}$ and the $-1^{st}$ diffraction order. A Gaussian-like pulse shape is fitted to the diffraction order peaks in order to get the angle position and the maximum intensity.

III. Simulations

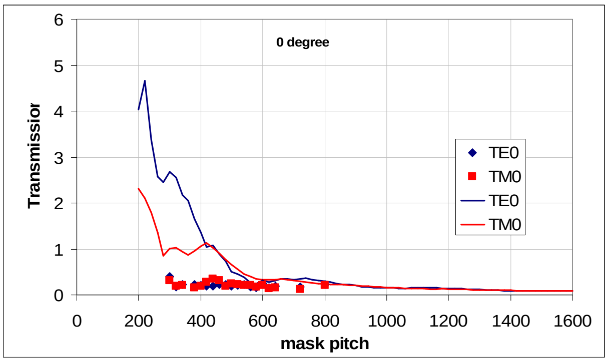
All DoP calculations shown on the next pages were done with the G-Solver Software[4]. The simulations for both the AltPSM as well as for the chromeless phase-shifting mask refers to a mask with a perfect Pi-phase-shift in the respective structure.

The manufacturing and balancing constraints and the test masks´ deviations from the perfect-mask-structure indicate, that only a qualitative comparison between experiment and simulation is possible.

## 5. SIMULATION and MEASUREMENT RESULTS of AltPSM MASK

### 5.1. Transmission of the AltPSM mask @ perpendicular incidence: Comparison of experimental data and simulation

Fig. 5 and Fig. 6 show the normalized transmission for TE and TM measured behind the mask using the experimental set-up described in the last section. Comparing the absolute magnitude of the normalized transmission of for the $0^{th}$ and the $1^{st}$ diffraction order, it becomes obvious that the transmission of the $0^{th}$ order is about one order of magnitude smaller than the transmission of the $1^{st}$ order. This is in-line with the design goal of minimizing the $0^{th}$ diffraction order. The real masks shows even less transmission than the simulated ideal mask. This is due to the mentioned simplification of the simulation, which not taking into account balancing strategies. The transmission of the $1^{st}$ diffraction order is in good agreement between simulation and measurement.



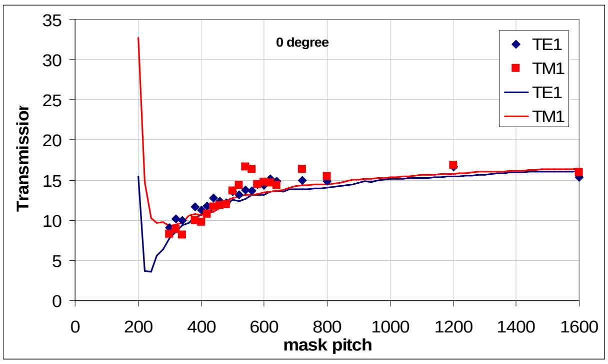
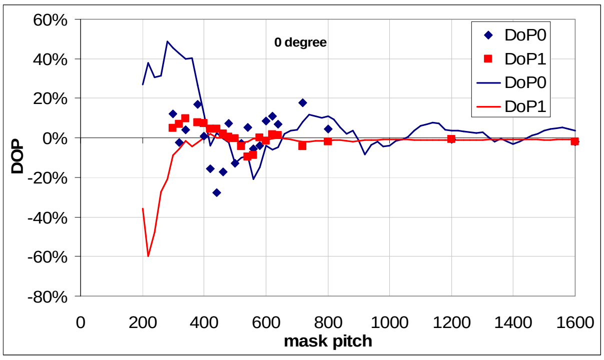




Fig. 5 Normalized transmission of the $0^{th}$ diffraction order of illuminated dense lines /space gratings with fixed duty cycle (line/space=0.5) and varying pitch size under normal incidence illumination: comparison between measurement (squares) and simulation (line).

Fig. 6 Normalized transmission of the $1^{st}$ diffraction order of illuminated dense lines /space gratings with fixed duty cycle (line/space=0.5) and varying pitch size under normal incidence illumination: comparison between measurement (squares) and simulation (line).

### 5.2. DoP versus pitch @ perpendicular and 10 degree incidence: Comparison of experimental data and simulation results

Figure 7 and 8 show the measured DoP data for different illumination angles derived from the transmission experiments. The solid curves represent the simulation results.



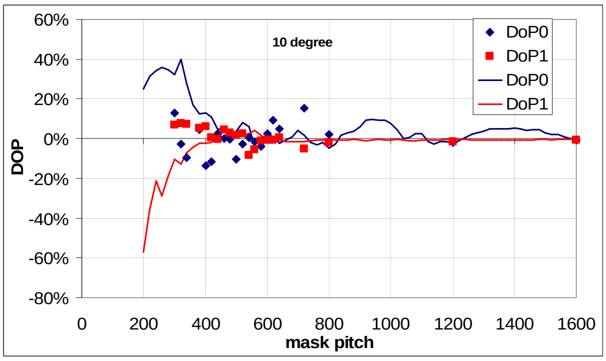




Fig. 7 Degree of polarization (DoP) of 0[th] and 1[st] diffraction orders of illuminated dense lines /space gratings with fixed duty cycle (line/space=0.5) and varying pitch size under normal incidence illumination: comparison between measurement (squares) and simulation (line).

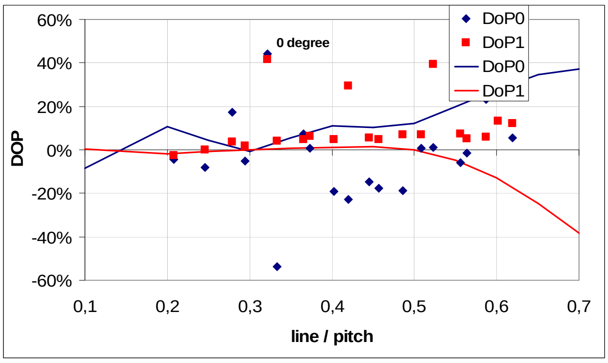
Fig. 8 Degree of polarization (DoP) under 10 degree incidence illumination: comparison between measurement (squares) and simulation (line).

The DoP for AltPSM masks show a complex behavior. The measured TE or TM dominance for certain pitches is in good agreement between simulation and measurement. It can also be clearly seen that the polarization significantly increases from a mask pitch of 400 nm (corresponding to the 50 nm node on wafer-scale) downwards independent from the illumination angle. . Coming from the design goal of minimizing the 0[th] diffraction order and its realization, which has successfully been demonstrated in Fig. 4, it is clear that the DoP0 curve is firstly inaccurate because of dividing small numbers with errors according to equation (3) and secondly, that the result is irrelevant because the 0[th] order would not be used for imaging AltPSM structures anyway. The relevant DoP1 is small for all pitches.

It should be highlighted here that the smallest experimentally explored grating structure of 300 nm (corresponding to the 38 nm node half pitch) shows no increased polarization behavior. AltPSM grating structures seem quite polarization resistant.

### 5.3. DoP versus line/pitch for 50 nm hp structures @ perpendicular and 10 degree incidence: Comparison of experimental data and simulation results

Figures 9 and 10 show the DoP measured and simulated as a function of the line/pitch for the 400 nm pitch structures which corresponds to the 50 nm hp node. Again r two different illumination angles 0 and 10 degrees have been investigated.



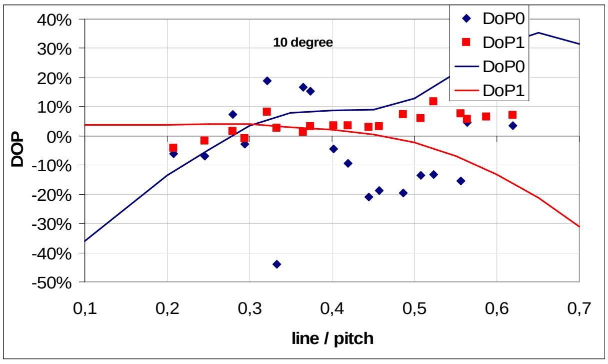



Fig. 9 Degree of polarization (DoP) of 0th and 1st diffraction orders of illuminated dense lines /space gratings with varying duty cycle and fixed pitch size (400nm) under normal illumination: comparison between measurement (squares) and simulation (line).

Fig. 10 Degree of polarization (DoP) of 0th and 1st diffraction orders under 10-degree off-axis illumination: comparison between measurement (squares) and simulation (line).

For the measured mask, the DoP1 as a function of line/pitch shows small polarization effects over the whole range. The incidence angle is of no relevance here. In the line/pitch range between 0.3 and 0.5 the measured DoP1 peaks with values of up 0.2 in TM. (Flyers to be deleted). Whereas the real mask shows predominantly TM polarization behavior in the line/pitch range between 0.4 and 0.6, the simulation results indicate a tendency in TE polarization. The mismatch between measurement and simulation is due to the not considered balancing strategies in the simulation settings and needs to be further explored.
The DoP0 behavior shall not be discussed here..
Advanced simulations performed at the AMTC which are taking into account balancing strategies indicate, that neither pattern-biasing nor undercutting have a significant influence on the DoP.

Polarization effects seem not to be an issue for AltPSM masks for 50 nm grating structures

## 6. SIMULATION RESULTS of CHROMELESS PHASE-SHIFTING MASKS

Figure 11 and 12 show the simulated DoP for chromeless-phase shifting structures under a perfect dipole illumination. DoP0 has a sinus-like shape with the polarization effect being negligible for dense line-space patterns (line/pitch = 0.5) for all structures and peaking depending on the pitch with a TM peak at an approx. line/pitch of 0.4 and a TM peak at a line/pitch of approx. 0.6. Even though the 40 nm structures seem to show the most significant effects, the 2nd strongest effects occur on the 70 nm structures. The DoP0 behavior as a function of the pitch is strongly non-linear. The DoP1 behavior is more linear as a function of pitch. The graph clearly shows that for small line/pitch the polarization increases in TE with shrinking feature size and in TM for bigger line/pitch.

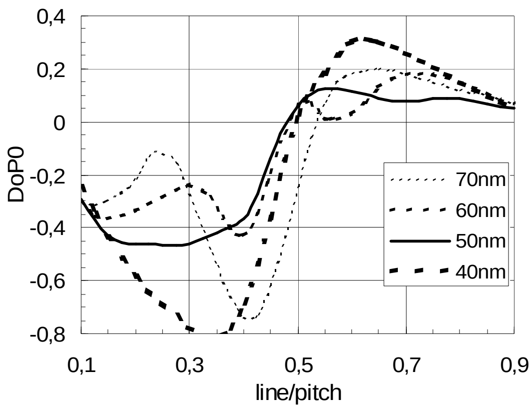



Fig. 11 Degree of polarization (DoP) of the 0th diffraction for chromeless Phase shifting masks for different grating structures under optimal dipole illumination as a function of line/pitch.

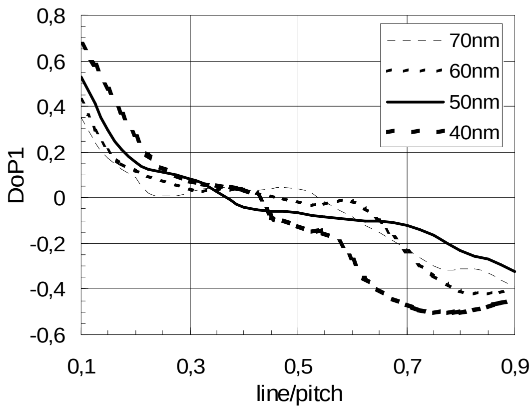



Fig. 12 Degree of polarization (DoP) of the 1st diffraction for chromeless Phase shifting masks for different grating structures under optimal dipole illumination as a function of line/pitch.

For 50 nm half-pitch structures, DoP0 has TM dominance for small line/pitch and TE dominance for big line/pitch. For DoP1 the behavior is just opposite. The relevant line/pitch for a balanced mesa- or trench-style chromeless lithography masks are at line/pitch ≈ 0.14 and line/pitch ≈ 0.64 respectively. The corresponding DoPs are: For mesa-style DoP0≈–0.4 and DoP1≈0.4 and for trench-style DoP0≈0.2 and DoP1≈-0.1.

## 7. SUMMARY

In this paper the polarization effects of AltPSM and chromeless phase shifting masks have been discussed with focus on the properties of 50 nm grating structures. For both mask types rigorous simulations were performed. In addition to this, experiments were performed with a real AltPSM mask with a special grating mask design. Qualitatively the simulation and the experiment are in good agreement. The magnitude and the direction of the polarization effect are consistent.

The comparison of the behavior of the two mask types shows, that chromeless phase-shifting masks show much more severe polarization effects than AltPSM masks. A balanced mesa style chromeless phase-shifters is a 40% polarizer in both diffraction orders Trench-style chromeless phase-shifters perform significantly better. AltPSM mask show a negligible polarization effect even for the smallest explored pitches, which correspond to the 38 nm node half-pitch.

Earlier studies at the AMTC have already explored the polarization behavior of CoG and AttPSM masks [1, 5].
Table 2 gives a summary of the polarization behavior of different mask types for 50 nm hp grating structures:

| Mask type | DoP0 (50 nm hp grating structure) | DoP1 (50 nm hp grating structure) | Simulation | Confirmed via Experiment |
|---|---|---|---|---|
| Binary Mask | ≈0 | <0.2 | ✓ | ✓ |
| AttPSM (6%) | ≈-0.2 | ≈0.1 | ✓ | ✓ |
| AltPSM | n.a | ≈0 | ✓ | ✓ |
| Chromeless Phase-Shifting (Mesa) | ≈–0.4 | ≈0.4 | ✓ | - |
| Chromeless Phase-Shifting (Trench) | ≈0.2 | ≈-0.1 | ✓ | - |

Table 2: Summary of the polarization behavior of different mask types for 50 nm hp grating structures

Binary and AltPSM masks show the smallest polarization behavior followed by the AttPSM mask type. Chromeless phase-shifting masks show the strongest polarization effects.

As mentioned in the motivation of this paper, the DoP is one parameter that influences the imaging properties of a mask. In respect to the aerial contrast in the wafer-plane, TE polarized light has a better contrast than unpolarized light. TM polarized light has the worst contrast. On the other hand, TM polarized light may be reflected less from the wafer-resist surface than TE polarized light. The imaging consequences of polarization are partially compensated [8].

The formation of the resist image on the wafer is a complex process with many interdependent parameters. Therefore it is not possible to make a conclusion on the suitability of a specific mask type for 50 nm hp lithography based solely on its polarization properties.

The studies performed so far indicate, that polarization effects are managerable for 50 nm grating structures. With respect to polarization effects, AltPSM masks seem to have a potential for even sub 45 nm lithography.

**REFERENCES**


1. Silvio Teuber et al. , Determination of mask induced polarization effects occurring in Hyper NA immersion lithography in SPIE 2005
2. Estroff, Y. Fan, A. Bourov, F. Cropanese, N. Lafferty, L. Zavyalova and B. Smith, *Mask induced Polarization*, SPIE2004
3. J. Heber, A. Gatto, N. Kaiser, *Spectrophotometry in the vacuum UV*, Boulder 2002
4. Web site reference: http://www.gsolver.com/
5. K. Bubke, S. Teuber, I. Hoellein, H. Becker, H. Seitz, U. Buttgereit, *Investigation of Polarization Effects on new Mask Materials*, t.b.p. in SPIE 2005
6. B.J. Lin, Plenary Speech at SPIE, SPIE Proc. Vol. 4688, p.11, 2002

7. Keun-Taek Park et al. Simulation of Quartz phase etch affect on performance of ArF Chrome-Less Hard Shifter for 65nm technology, t.b.p. in PMJ 2005
8. Bruce W. Smith, Lena Zavyalova, Andrew Estroff, Benefiting from polarization – effects on high-NA imaging in Proc. of SPIE Vol. 5377, p. 68

## ACKNOWLEDGEMENTS

AMTC is a joint venture of Infineon, AMD and DuPont Photomasks and gratefully acknowledges the financial support by the German Federal Ministry of Education and Research (BMBF) under Contract No. 01M3154A ("Abbildungsmethodiken für nanoelektronische Bauelemente")

The authors would like to thank the Fraunhofer Institute IOF in Jena for their measurement capability and also for a lot of fruitful discussions.