Process window enhancement for 45 nm node using alterable transmission phase shifting materials

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ABSTRACT

A case study was carried out investigating the influence of different transmission and phase shift materials on lithographic performance at 45 nm node. The bilayer approach for embedded attenuated Phase Shift Masks (EAPSM) offers the advantages to adjust phase shift and transmission independently. The transmission of Ta/SiO2 can be tuned up to 40% depending on the required application. Three different PSM blank types with the stacks Ta/SiO2-6%, Ta/SiO2-30% and Ta/SiON-30% have been manufactured and characterized. Afterwards, an identical line pattern, consisting of different feature sizes and duty cycles, has been patterned in each of the three PSM types as well as in the MoSi-6% for reference. Using the AIMS™ 45 193i tool we have evaluated the lithographic performance of the four PSM in terms of contrast and process latitude using unpolarized and TE polarized illumination. The case study showed that the process window for Ta/SiO2-6% is comparable to standard MoSi-6%. For dense line application a 6% EAPSM is preferable. The Ta/SiO2-30% EAPSM provides a significantly larger process window for higher duty cycles compared to MoSi-6%. This means a 50% increase in depth of focus (DOF) at 10% exposure latitude (EL). Therefore for logic application with higher duty cycles a EAPSM material with 30% transmission is preferable.

Keywords: Process window, PSM, AIMS, dry etch, HT EAPSM, plasma etching

1. INTRODUCTION AND MOTIVATION

The use of Phase Shift Masks (PSM) for wafer printing with 193nm scanners of high or even hyper numerical apertures (NA) and especially adapted illumination conditions pushes the resolution limit of optical lithography from 65 nm down to 45 nm node. For the mask blank manufacturer this goes along with tighter requirements for defect performance, layer uniformity, layer stress and flatness. From mask makers perspective the defect, resolution, registration, overlay and CD uniformity requirements become tighter. Furthermore the lithographers ask for higher contrast, better depth of focus (DOF) and a large process window. The process window is investigated by analyzing the exposure latitude (EL) versus depth of focus.

The intrinsic material properties like composition, layer stress and uniformity directly impact the mask performance whereas refractive and absorption indices, thus phase shift and transmission, dominate the lithographic performance.

SCHOTT has introduced a new attenuated PSM material consisting of a Tantalum layer topped by a Silica layer[1,2]. This stack offers the advantage of independent adjustment of transmission and phase shift. The Ta layer thickness controls the transmission. Two mask material types for 6% standard and 30% high transmission have been investigated in this study[3]. A 180° phase shift is achieved by adding an appropriate SiO2 layer. Alternatively, SiON has been used as the phase shifting material. On three different PSM stacks the impact of transmission and phase shift material on lithographic relevant parameters, especially on the process window has been evaluated. The results have been compared with the standard MoSi-6%.

The patterning process has been developed and performed by IMS Chips, Stuttgart, using VSB E-beam writer Leica SB350, Steag Hamatech resist processing tools and an UNAXIS Gen III / IV cluster for dry etching[4]. It has been applied a four step process for patterning the different material stacks: (1) standard chrome etch stopping on the SiO2 or SiON layer, (2) SiO2 / SiON etching with a fluorine based chemistry and high selectivity to chrome hardmask and tantalum etch stop, (3) Ta etching with chlorine chemistry and high selectivity to quartz and chrome and (4) removing of chrome hardmask with the standard chrome etching process. This combination of etching processes allows perfect etch stops of every single etch step and thereby guarantees maintaining the outstanding phase and transmission uniformities of the material. A dense line resolution of 80nm on mask level has been achieved.

We investigated the lithographic performance of the Ta/SiO2 and Ta/SiON EAPSM with different transmission using the new state-of-the-art AIMS™ 45-193i. The AIMS^{TM} tool allows a very fast and cost effective assessment of new materials and concepts without extensive wafer printing experiments. The mask features are measured under scanner equivalent settings with numerical apertures up to NA 1.35 using unpolarized and TE polarized illumination. Through-focus measurements were made and the lithographic performance was assessed in terms of contrast and process latitude. Finally, the results have been compared to standard MoSi-6%

2. RESULTS AND DISCUSSION

2.1. Mask blank preparation

SCHOTT has introduced a novel attenuated PSM material consisting of a Tantalum layer topped by a Silica layer in 2003. Figure 1 shows a schematic drawing of the layer stack. The Tantalum serves as transmission control layer; by thickness adjustment only transmission of the PSM can be tuned to any desired value. The Tantalum layer also provides a reliable etch stop for the phase shifting layer. Therefore a minimum Tantalum thickness of about 5 nm is assumed, which limits the high end of transmission to about 40%. The second Silica layer controls phase shift, its thickness is tuned to reach the desired 180°. Silica is a highly stable material even in a corrosive environment. Thus, the PSM can be cleaned several times without changing the optical values phase shift and transmission.

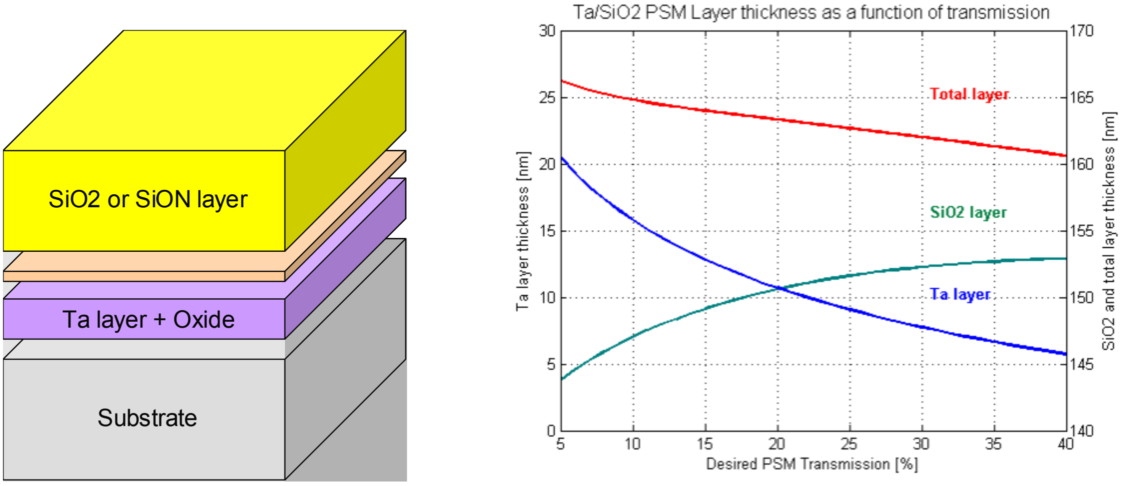


Figure 1: Schematic drawing of the two layer PSM stack (left). The right graph shows that by layer thickness adjustment PSM transmission can be tuned up to 40% leaving total layer thickness nearly unchanged.

In order to reduce undesirable topological effects, SiO2 was substituted by SiON as the phase shifting layer, alternatively. Thickness of the phase shifter material depends on its refractive index, the higher the refractive index the lower the layer thickness. Figure 2 shows the dispersion curves of SiO2 and SiON. The refractive index at 193 nm of SiO2 is 1.63, refractive index of SiON is 1.9. This allows to reduce the total layer thickness by 40 nm from about 160 nm down to 120 nm and may reduce undesirable topological effects. Three different PSM mask blanks were produced by SCHOTT Lithotec to check the influence of both, PSM transmission and PSM phase shifting material to the optical lithography performance:

- Ta / SiO2-6% standard transmission
- Ta / SiO2-30% high transmission
- Ta / SiON-30% high transmission

All PSM samples were produced using dual ion beam sputter technology. This yields very dense and compact and therefore environmental stable films. Surface roughness of the sputtered layers equals the roughness of the uncoated substrate, a typical value is about 2 A rms. In addition ion beam sputtering, enables an excellent thickness uniformity, which is a prerequisite to meet the phase, transmission and also CD requirements for the mask. Figure 3 shows the uniformity of a 30% transmission PSM measured in a 132 x 132 mm area. The measured transmission uniformity of ±1.2% of the nominal value (±0.3% absolute) is well below the specified 4%. Phase shift uniformity, typically specified to be 180° ± 1° which allows 2° range, is measured to be 0.6° range only.

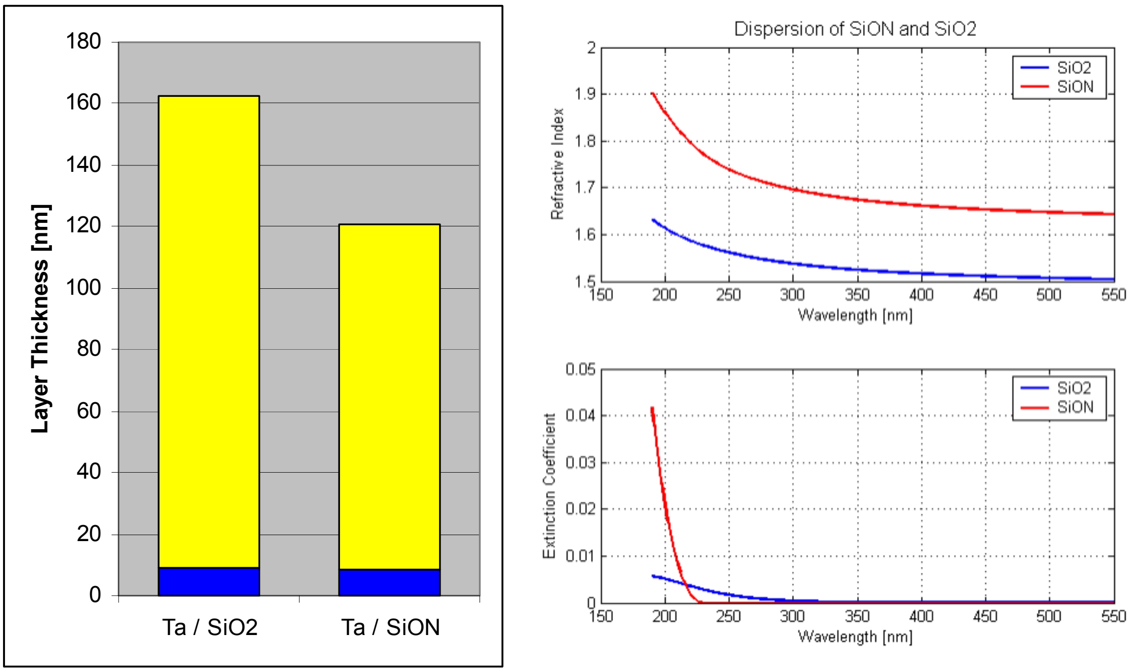


Figure 2: The phase shifter material is either SiO2 or SiON. The higher refractive index (right graph) of SiON enables reduction of PSM layer thickness from about 160 nm down to 120 nm (left graph).

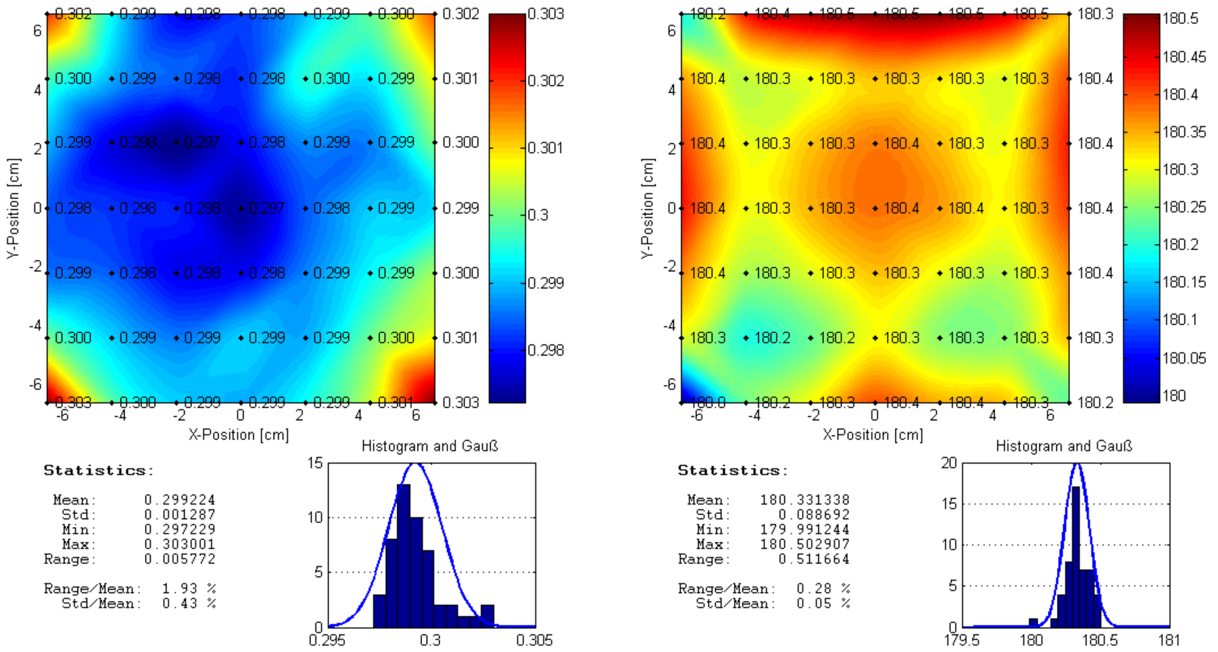
2.2. Mask Patterning

The patterning process has been developed and performed at IMS Chips in Stuttgart, Germany. All dry etching processes have been performed on a UNAXIS Mask Etcher Gen III / IV, equipped with a laser reflectometer for end point detection.

The test pattern consists of two different parts:

- Semi dense lines for AIMS™ measurements: 45 nm (wafer level), each with a duty cycle of 1:1, 1:2 and 1:3,
- Long cleavable dense lines from 80 nm up to 200 nm for cross-section investigations.

The test design has been exposed into positive tone chemically amplified resist Fuji FEP171 with 250 nm film thickness[5].



```
Statistics:

 Mean:        0.299224
  Std:        0.001287
  Min:        0.297229
  Max:        0.303001
Range:        0.005772

Range/Mean:   1.93 %
  Std/Mean:   0.43 %
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Statistics:

 Mean:     180.331338
  Std:       0.088692
  Min:     179.991244
  Max:     180.502907
Range:       0.511664

Range/Mean:   0.28 %
  Std/Mean:   0.05 %
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Figure 3: Uniformity maps of a 30 % transmission Ta/SiO2 PSM. Total range of transmission is about 0.6 % and phase shift range is about 0.6° only.

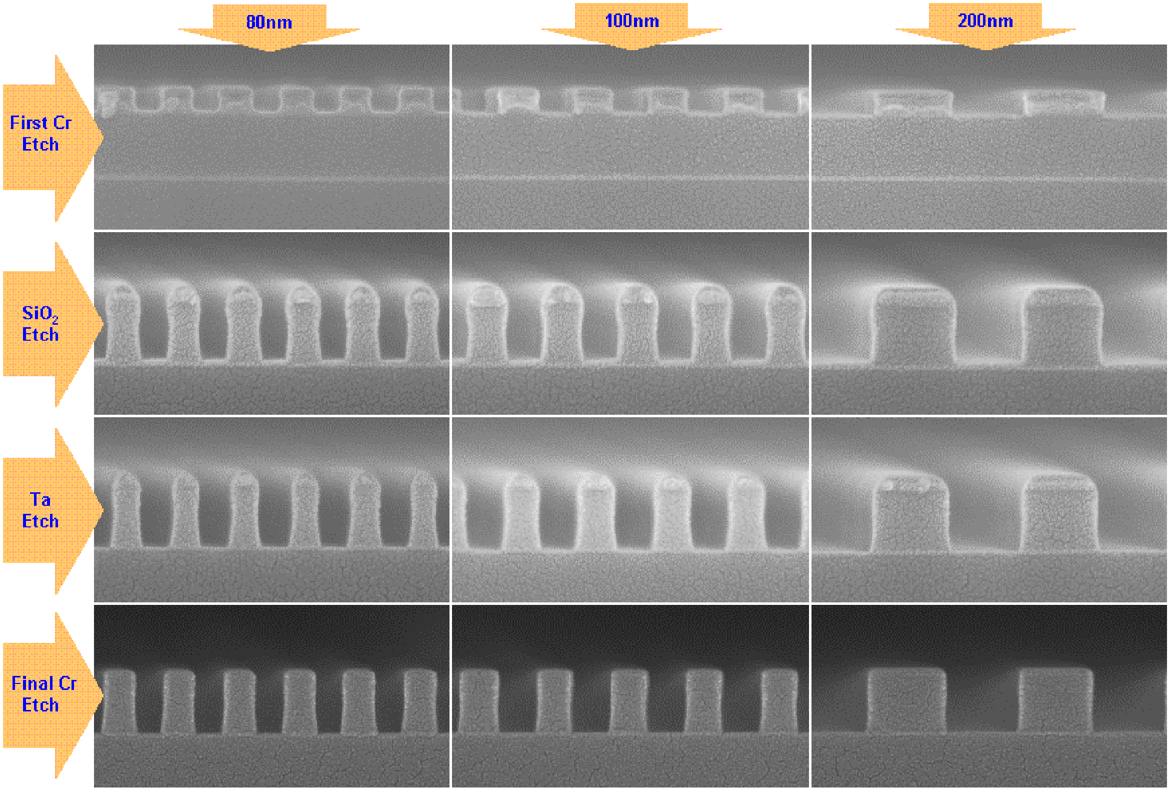

Figure 4 SEM cross sections of 80 nm / 100 nm / 200 nm dense lines (mask level) of a Ta/SiO2 30% mask in different machining phases

PSM stack patterning has been executed in 4 steps:

- The first patterning of Cr/CrOx with a thickness of 48 / 12 nm has been performed with a standard chlorine/oxygen/ helium chemistry. The patterned Cr layer acts as a hardmask for the following dry etch steps.
- After resist strip the SiO2 or SiON layer has been etched in fluorine/oxygen based plasma stopping on Ta.
- For etching the thin Ta layer, a chlorine based plasma without oxygen guarantees sufficient selectivity to Cr and the quartz substrate.
- Finally Cr is etched with a standard Cr etching chemistry.

Figure 4 shows the cross sections of a patterned Ta/SiO2 mask with 30% transmission at every single process step. The figures demonstrate the patterning capability for dense lines down to 80 nm (mask level)with nearly vertical sidewalls, no etch residuals, no underetch or footing and a perfect etch stop on the quartz surface. The remaining profile slope was in the range of 3 - 5 nm. The high selectivity of each single etch step avoids unwanted etching of quartz or Ta. Thus, the excellent phase and transmission uniformities, predefined by the layer thickness of silica and Ta, respectively, are not degraded during the patterning process.

2.3. PSM stack evaluation using AIMS

Figure 5: Picture of the alpha tool AIMS™ 45-193i

To address the challenging requirements of today's photolithography mask qualification is the key to success. AIMS™ tools are state-of-the-art in the photomask industry for development, quality control, repair verification and defect classification of photomasks. The novel AIMS™ tool, the AIMS™ 45-193i, is based on a newly developed mechanical platform and new Zeiss 193 nm high precision optics and enables full emulation of future 193 nm immersion scanner down to the 45 nm node.

Key features of the new AIMS™ platform are increased numerical apertures up to 1.4 (4x scanner), scanner equivalent polarization settings and vector effect emulation, in addition to significant other tool improvements.

The AIMS™ 45-193i is equipped with a totally new thermally controlled measurement chamber isolating the measurement process from both contamination and vibration influences resulting in tight transmission and CD repeatability.

Other important improvements on this platform are a high accuracy air bearing stage, and a robotic mask handling system with SMIF interface. By handling the mask in the same orientation as in the scanner (face down) optimum system stability has been accomplished.

The newly designed optics path includes customized multi off-axis illumination apertures and polarization settings equivalent to those of the most advanced scanners. These are linear polarization in both reticle edge directions and tangential polarisation. A totally new beam homogenizer is present in the AIMS™ 45-193i and provides best uniformity results for field and pupil homogeneity.

Using the AIMS™ 45-193i tool we have evaluated the lithographic performance of the three manufactured test masks as well as the MoSi reference sample. For each stack the test designs of 45 nm lines with duty cycles 1:1, 1:2 and 1:3 have been investigated.

First step of the assessment procedure was the selection of appropriate illumination settings providing the maximum contrast. As shown in Table 1 the illumination type was varied dependent on line width and duty cycle, however, it was kept as constant for the different stacks within one line group.

Feature	**45nm 1:1**	**45nm 1:2**	**45nm 1:3**
Wavelength	193nm	193nm	193nm
Numerical Aperture	1.35	1.05	1.00
Part. Coherence σ	0.97	0.83	0.7
Illumination type	Dipole 83.5%	Dipole 65%	Dipole 65%

Table 1: Illumination settings

The different features were measured with both unpolarized and TE polarized illumination. Vector effects have not been considered.

First we compared the 6% materials. Based on the intensity (I) profile at the best focus, we determined the contrast for the different line groups (Figure 6). The contrast is defined as (Imax-Imin) / (Imax+Imin) of the measured intensity.

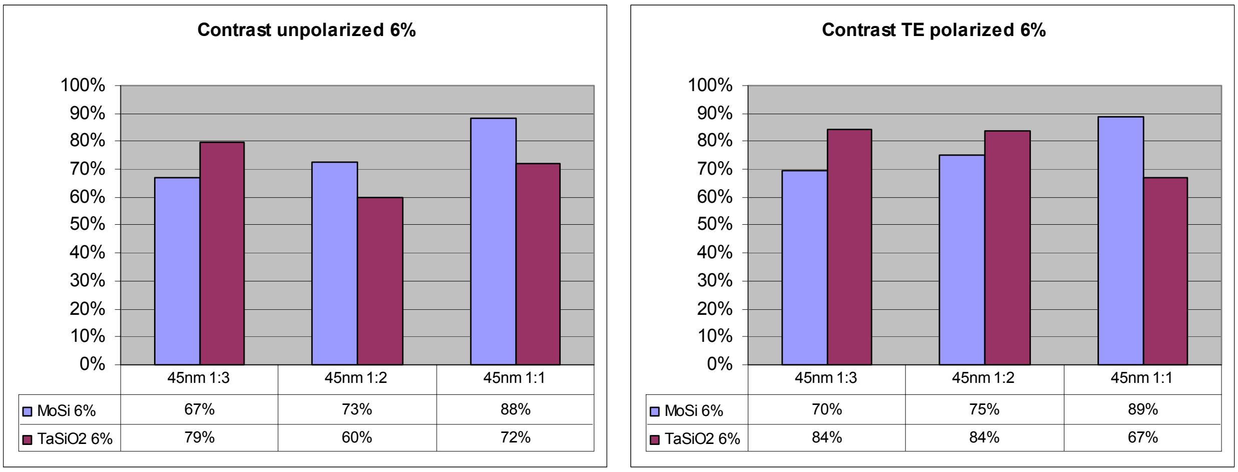

Figure 6: Comparison of contrast with unpolarized and TE polarized illumination for the 6% PSM materials and different duty cycles. Line width on wafer level

The 6% EAPSM materials show a relatively high contrast over all duty cycles. There is a difference between the two materials for the different duty cycles. Regarding the 1:1 structures, it has been observed up to 22% higher contrast values for the MoSi. For the 1:3 structures the Ta/SiO2 material showed higher contrast (up to 14%). For this two duty cycles the unpolarized and the TE polarized results showed the same trend. Comparing the results of the 45 nm 1:2 duty cycle there was a different trend for the unpolarized and TE polarized illumination. The unpolarized measurements showed 13% higher contrast for the MoSi, but with the TE polarized illumination the Ta/SiO2 material showed 9% higher contrast. This effect is not completely understood yet and needs further investigations.

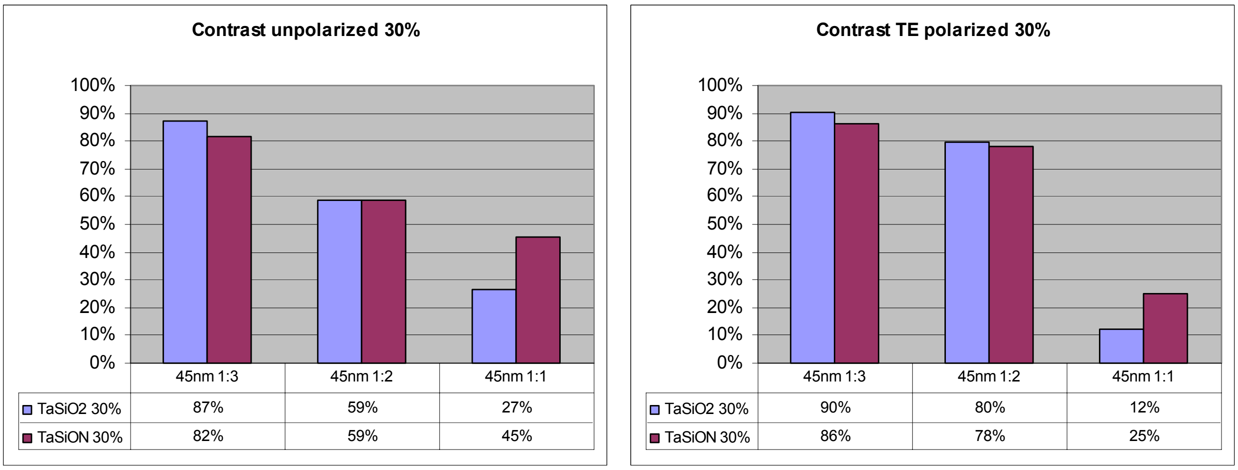

Figure 7: Comparison of contrast with unpolarized and TE polarized illumination for the 30% PSM materials and different duty cycles. Line width on wafer level

The 30% Ta/Si materials showed the best contrast values (82 to 90%) for the 1:3 duty cycle (Figure 7). It has been observed no significant difference between the SiO2 and SiON as phase shifter for the 1:2 and 1:3 structures. The lowest contrast values were achieved for the 1:1 structures. But the Ta/SiON showed better contrast as the TaSiO2 which might be due to 3D effects caused by the higher layer thickness of Ta/SiO2.

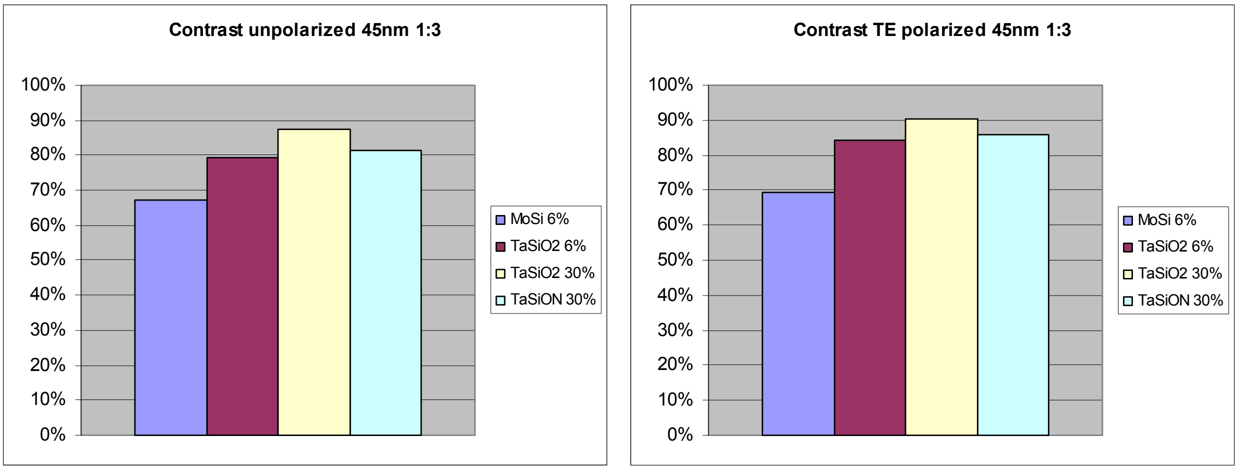

Figure 8: Comparison of contrast with unpolarized and TE polarized illumination for the different PSM materials with 1:3 duty cycle. Line width on wafer level

Another analysis we made was the comparison of the contrast results of the different materials for the 45 nm 1:3 structures (Figure 8). The bilayer PSM materials show a larger contrast compared to the single layer MoSi-6%. The 30% materials achieved the best results for both the unpolarized as well as the TE polarized measurements. The contrast increase of TaSiO2-30% compared to MoSi-6% has been 20%. The lowest contrast values of the considered materials showed the MoSi (maximum of 70%). Highest contrast of 90% was achieved by Ta/SiO2-30%.

For data analysis a more generalized information is given by process latitude. Process latitude describes how the depth of focus behaves to the exposure tolerance for the target CD. Figure 9 shows the comparison of the process latitude for the 45 nm 1:3 structures of the considered PSM materials.

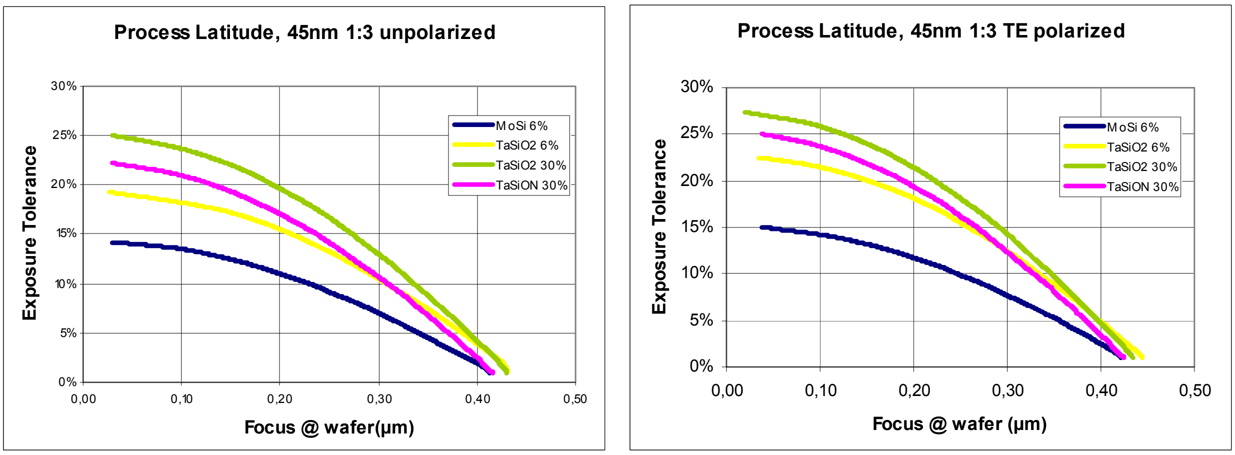

Figure 9: Process Latitude

Comparing per example Ta/SiO2-6% versus MoSi-6% at polarized illumination, duty cycles of 1:3 and DOF of 0.3 µm, we observe an exposure latitude of 13% for Ta/SiO2-6% versus 8% for MoSi-6%. Comparing per example Ta/SiO2-30% versus MoSi-6% at polarized illumination, duty cycles of 1:3 and DOF of 0.3 µm, we observe an exposure latitude of 15% for Ta/SiO2-30% versus 8% for MoSi-6%.

For this measurements, Schott’s Ta/SiO2 and Ta/SiON materials show significantly improved process latitude compared to MoSi-6%. The results based on maximum contrast as well as the best process latitude imply best performance for both 30% transmission materials SiO2 and SiON.

3. SUMMARY AND OUTLOOK

We have carried out a case study that was aimed to investigate and suggest solutions to enlarge the lithography process window using EAPSM masks.

Three test masks with different tunable PSM materials have been fabricated: Ta/SiO2 (6%, 30%) and Ta/SiON (30%). Outstanding transmission and phase shift uniformities of 0.6% and 0.6° respectively have been obtained. Patterning has been realized by a 4-step etch process. High etch selectivity enables perfect etch stop on every single layer of the PSM stack. The process is controlled by a laser reflectometer, which allows an easy adaptation to a varying layer thickness. Thus, the excellent phase and transmission uniformities of the blank material can be maintained on the final mask. Resolution of down to 80 nm dense lines on mask level has been shown.

Aerial images of 45 nm semi dense line groups of the fabricated test masks as well as for a MoSi 6% mask as reference have been captured using the new AIMS^{TM} 45-193i tool. The through pitch behavior with respect to contrast and process latitude has been investigated for duty cycles from 1:1 up to 1:3 for different transmission values and phase shifting materials, applying unpolarized and TE polarized illumination.

At 6% transmission the MoSi as well as the Ta/SiO2 show a relatively similar contrast behavior over all investigated duty cycles. At a duty cycle of 1:1 the MoSi shows a higher contrast than Ta/SiO2 whereas at a duty cycle of 1:3 the Ta/SiO2 shows a larger contrast compared to MoSi. Looking at 30% transmission Ta/SiO2 and Ta/SiON we see a significant increase of contrast at a duty cycle of 1:3 for unpolarized and at duty cycles 1:3 and 1:2 for TE polarized illumination, but a contrast loss for duty cycle 1:1. There is no significant difference between Ta/SiO2 and Ta/SiON except for the 1:1 duty cycle. Here the lower PSM layer stack of the Ta/SiON might play a role in terms of 3D effects.

Comparing the different PSM materials at a duty cycle of 1:3 we see clearly an advantage of the bilayer PSM material compared to single layer MoSi-6%. The Ta/SiO2-30% achieves a 20% higher deviation in contrast compared to MoSi 6% for both illumination conditions, which corresponds to a contrast increase of almost 30%. The process window behavior is very similar to the contrast behavior.

Regarding an exposure latitude of 10% it has been observed an increase in DOF of 50% by Ta/SiO2-30% compared to MoSi-6% using unpolarized illumination and an increase of 45% using TE polarized illumination. This means Ta/SiO2-30% shows a DOF of 0.33 µm versus 0.22 µm for MoSi-6% at 10% exposure latitude.

Generally we see no significant differences between unpolarized and TE polarized illumination. This might be due to the fact that in the current AIMS investigations no vector effects have been considered.

Based on the first results there are some open questions which need to be investigated in the future:

- AIMS^{TM} 45-193i investigation with vector effect emulation
- Investigation of polarization effects
- Verification of results by wafer printing

4. CONCLUSION

Evaluating the results of our case study we finally reach the following conclusions:

- It was shown that the Ta/SiO2 bilayer solution can be used to choose the transmission of the EAPSM mask up to 40% based on the requirements of the lithographic application or critical layer.
- The experiments proved that the contrast for Ta/SiO2-6% EAPSM is comparable to standard MoSi-6% EAPSM. For dense lines with 1:1 duty cycle EAPSM with 6% transmission is preferable.
- It was shown that the Ta/SiO2-30% EAPSM provides a significantly larger process window for higher duty cycles compared to MoSi-6%. This means a 50% increase in DOF at 10% exposure latitude..

The current results therefore clearly indicate to use high transmission material for high duty cycles (e.g. logic application) and to stay with 6% transmission if mainly low duty cycles are required (e.g. memory application).

ACKNOWLEDGEMENTS

This work has been supported by the German Federal Ministry for Education and Research, (contract sign 01 M 3154 O)and by the Ministry of Economic Affairs of Baden-Wuerttemberg.
The authors would like to thank Andrew Ridley and Sascha Perlitz from Zeiss, Patrick Martin from Photronics and Peter De Bisschop from IMEC for their support related to the topic.

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