Extended Process Window Using Variable Transmission PSM Materials for 65 nm and 45 nm Node

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ABSTRACT

The bilayer approach of embedded attenuated Phase Shift Masks (EAPSM), causing phase shift and transmission by two different materials offers advantages compared to the single layer solution. Three different PSM blank types with the stacks Ta/SiO_2-6%, Ta/SiO_2-30% and Ta/SiON-30% have been manufactured and characterized. Afterwards, identical line pattern of different feature sizes and duty cycles have been patterned in each of the three PSM types as well as in MoSi for reference. Using the AIMS™ fab 193i tool we have evaluated the lithographic performance of the four PSM in terms of contrast, normalized image slope (NILS), process latitude and process window. Improvements of up to 20% contrast, 10% NILS and 65% exposure latitude have been achieved for the Ta/SiO_2 6% stack compared to the MoSi material with the same transmittance. In addition, the high transmission PSM clearly offers advantages in contrast, NILS and exposure latitude especially for smaller features.

Keywords: Process window, process latitude, AIMS, dry etching, EAPSM, plasma etching, 193nm lithography

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 the optical lithography from 65nm down to 45nm node. For the mask blank manufacturer this goes along with tighter requirements for defect performance, layer uniformity, layer stress, flatness and material uniformity. From mask makers' perspective the defect, resolution, registration, overlay and CD uniformity requirements become tighter. Further on lithographers ask for higher contrast, better depth of focus (DOF) and large process window.

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

Embedded attenuated phase shift masks (EAPSM) are widely used to reduce the k_1-factor for a better resolution because manufacturing and design is much easier compared to alternating PSM. A single MoSi layer of a thickness providing a phase shift of 180° and a transmittance of 6% at 193nm is the commonly used material of EAPSM so far. However, such a single layer solution does not provide the flexibility to adjust the optical properties of the material in order to meet the lithographic requirements.

The separation of phase shift and transmittance reduction by a two layer stack of silica and metal offers this crucial advantage. [1,2]. On one hand the two layer combination allows the independent adjustment of phase and transmission in a wide range between 6 and 40%, and on the other hand different diffraction efficiencies between MoSi and the two layer approach may provide a better lithographic performance even for identical transmittance [3].

We investigated the lithographic performance of EAPSM with Ta/SiO_2 and Ta/SiON stacks of different transmittance using a state-of-the-art aerial image measurement system at 193nm, the AIMS™ fab 193i tool. The AIMS™ tool allows a very fast and cost efficient assessment of new mask concepts and materials without extensive printing experiments on wafers followed by CD metrology. Different scanner equivalent illumination conditions have been used to optimize

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printability. The lithographic performance of the different approaches was evaluated in terms of contrast, normalized image slope (NILS), exposure latitude and process window. Finally, we compared the measured results with those of MoSi EAPSM.

2. RESULTS AND DISCUSSION

2.1. Mask Blank Preparation

The SCHOTT Cr/SiO_2/Ta-quartz-stack has been introduced as an EAPSM material in 2003. The Ta layer serves for transmission control; by thickness adjustment only, transmission of the EAPSM can be therefore tuned to any desired value. This Ta layer also provides a reliable etch stop for patterning the phase shifting layer. Therefore a minimum Ta thickness of about 5nm is assumed, which limits the achievable transmission to about 40% (Fig 1). The second layer, based on silica, controls the phase shift. Its thickness is tuned to reach the desired 180°. Silica is a highly stable material even in a corrosive environment. Particularly, such a bilayer PSM can be cleaned several times without changing the optical values phase shift and transmission which is a strong advantage over MoSi PSM. The chrome layer on top acts as a hardmask during patterning and as a shielding material on the final mask. The patterning capability of Ta/SiO_2 has already been shown [4].

The higher SiON refractive index of 1.9 compared to 1.63 of SiO_2 (Fig 2) allows reducing the total layer thickness by 40 nm from about 160 nm down to 120 nm and may reduce undesirable topological effects.

Three different EAPSM mask blanks were produced by SCHOTT Lithotec to evaluate the influence of both, PSM transmission and PSM phase shifting material on the lithographic performance:

- Ta / SiO_2 6% standard transmission,
- Ta / SiO_2 30% high transmission,
- Ta / SiON 30% high transmission.

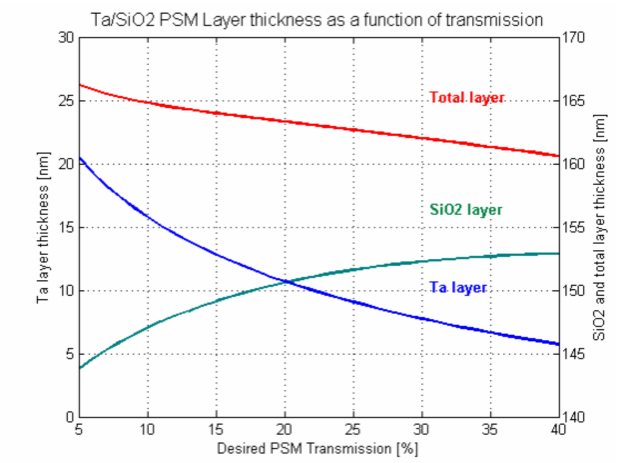


Fig 1: Ta/SiO2 layer thickness vs. PSM transmission

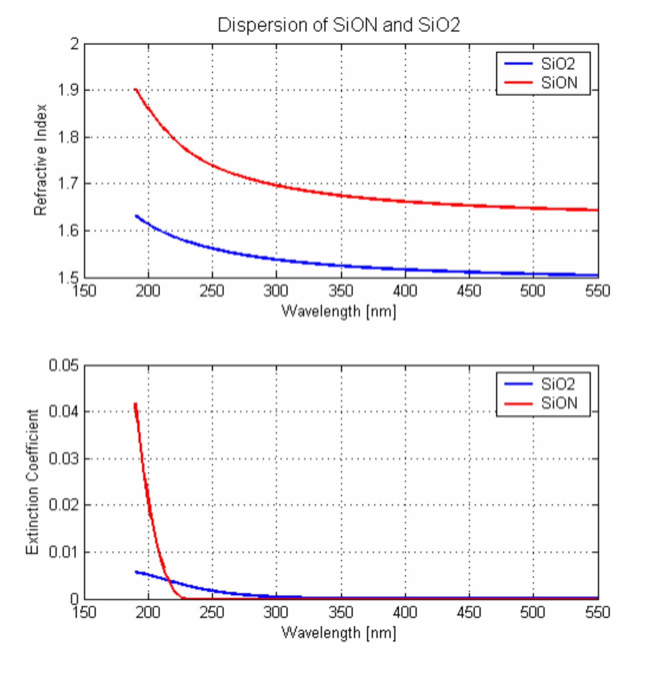
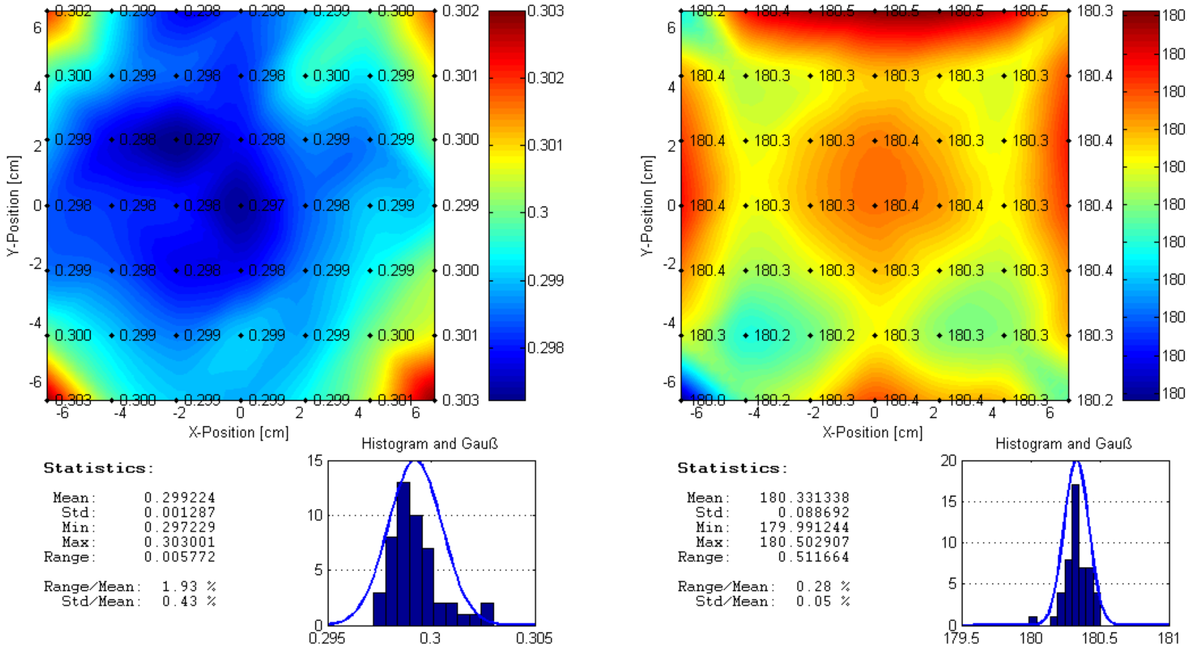


Fig 2: Refractive index and extinction coefficient of SiO_2 and SiON

All EAPSM samples have been produced using dual ion beam sputter technology. This yields very dense, compact and therefore environmentally stable films. Surface roughness of the sputtered layers equals the roughness of the uncoated substrate, a typical value is about 2 Å rms. In addition, ion beam sputtering enables an excellent thickness uniformity of the deposited layers, which is a prerequisite to meet the phase, transmission and also CD requirements for the mask. Fig

3 shows the uniformity of a 30% transmission Ta/SiO_2 EAPSM blank measured in an area of 132 x 132mm². The measured transmission uniformity of ±1.2% of the nominal value (±0.3% absolute) is well below the specified 4%. The Phase shift uniformity, typically specified as ±1°, is measured to be 0.6°.



```
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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Fig 3: Uniformity maps of a 30% transmission Ta/SiO_2 PSM
Transmission range: ~ 0.6 %, phase shift range: ~ 0.6°

2.2. Mask Patterning

The patterning process has been developed and performed at IMS Chips in Stuttgart, Germany, using a state-of-the-art tool set as follows:

- Mask coater STEAG HamaTech ASR5000,
- 50 kV variable shaped beam writer Leica SB350 MW,
- Hot and coolplate STEAG HamaTech APB5500,
- Developer Steag HamaTech ASP5000,
- UNAXIS Mask Etcher Gen III / IV, equipped with a laser reflectometer for end point detection
- Zeiss SEM Leo 1560 for cross section and top down SEM investigations.

The test pattern consists of two different parts:

- Semi dense lines for AIMS™ measurements: 45nm / 65nm (wafer level), each with a duty cycle of 1:2 and 1:3,
- Long cleavable dense and isolated lines from 80 nm up to 250nm for cross-section investigations.

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

PSM stack patterning has been executed in 4 steps (Fig 4):

- Patterning of Cr/CrO$_x$ (called Cr) with a thickness of 48/12nm by a chlorine/oxygen/ helium plasma. The patterned Cr layer acts as a hardmask for the following dry etch steps.
- After resist strip the SiO$_2$ or SiON layer has been etched in fluorine/oxygen based plasma stopping on Ta.
- Chlorine based plasma without oxygen guarantees sufficient selectivity to Cr and the quartz substrate for Ta etching.
- Finally Cr is etched in the inner mask region.

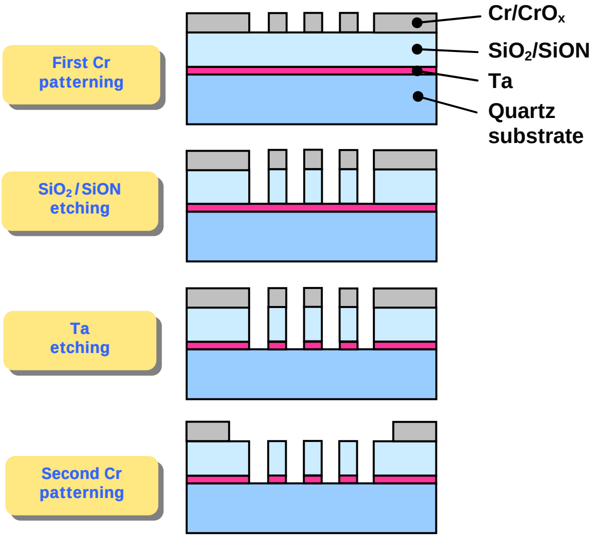


Fig 4: PSM stack patterning process flow

Fig 5 shows the signals of the laser reflectometer for SiO$_2$ and SiON etching. With the same fluorine/oxygen based dry etch process, nearly identical etch rates have been achieved for SiO$_2$ and SiON. The laser signals show parts of sinusoidal waves, originated from interfering laser beams reflected from both the etched silica surface and the underlying tantalum surface. The maximum signal corresponds to the end of the main etch. The high etch selectivity to Ta provides a reliable stop on the 7 to 21nm thick Ta layer.

Our developed Ta etch process provides a high selectivity to both, Cr and silica, which guarantees no Cr stripping and a negligible erosion of the quartz substrate even applying a constant process time independent on Ta layer thickness.

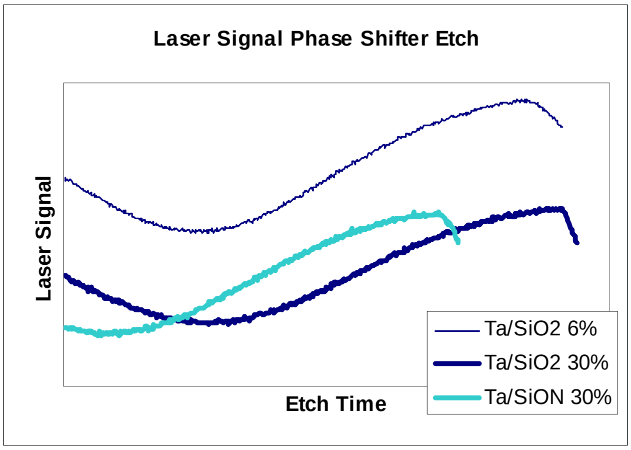


Fig 5: Laser reflectometer signal of SiO$_2$ and SiON etching

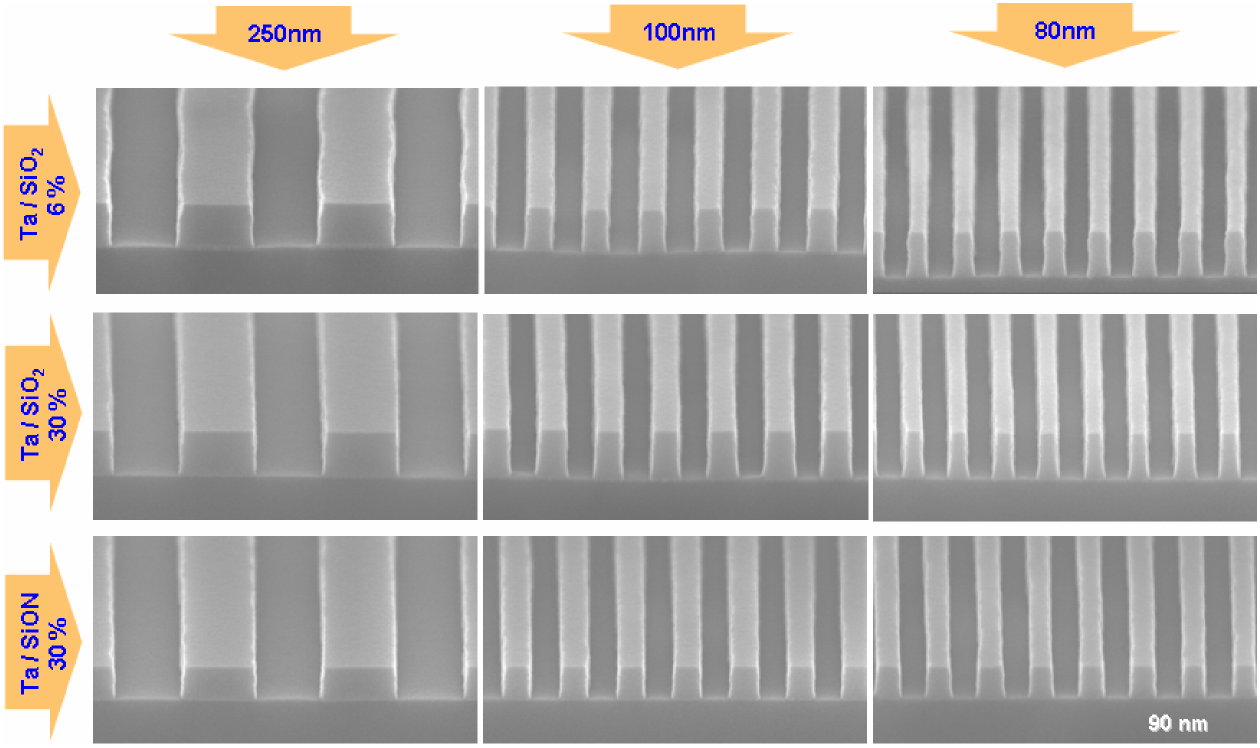


Fig 6: SEM cross sections of 250 nm / 100 nm / 80 nm dense lines (mask level)

Fig 6 shows the cross sections of the different PSM stacks after the second Cr etch and proves the patterning capability for dense lines down to 80nm (in the case of Ta/SiON 90nm) with nearly vertical sidewalls, no etch residuals, no underetch or footing and perfect etch stop on the quartz surface. The remaining profile slope was in the range of 7 – 10 nm. The above mentioned high selectivity of each single etch step avoids changes of phase shift and transmission due to unwanted etching. These parameters stay at the values that are predefined by the layer thicknesses of silica and Ta, respectively.

2.3. PSM stack evaluation using AIMS

Aerial images have been captured and analyzed by Zeiss AIMS™ fab 193i. The AIMS™ is an optical system for evaluating reticles under the specific stepper or scanner settings of wavelength, numerical aperture (NA), partial coherence of illumination (sigma: σ) and illumination type such as annular, quadrupole, disar or dipole [6]. The latest AIMS™ tool is the AIMS™ fab 193i which offers advanced capabilities to emulate dry and immersion scanners for NA up to 0.93. Fig 7 shows a picture of the AIMS™ fab 193i plus which is equipped with mini environment, mask handler and SMIF mask loader.

This second generation tool has undergone a series of major system improvements. Increased system stability, new beam homogenization and energy monitoring provide new performance parameters such as long term illumination stability with drifts less than 2.5%/h and CD repeatability down to the 1nm range at wafer level.

With these specifications the tool enables wafer level printability analysis for 65nm node masks with appropriate high numerical aperture (NA0.9x) and contrast. In addition to these improvements the system can take into account that scanners using an immersion liquid provide an extended depth-of-focus and thus increase the process window. Optionally, the process window or process latitude analysis can be shown for dry and immersion conditions. The latest features are linear polarization adjustments in illumination.[8]

Fig 7: Picture of an AIMS™ fab 193i plus

Using the AIMS™ fab 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 65nm lines with duty cycles 1:2 and 1:3 and the 45nm lines with a duty cyle of 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.

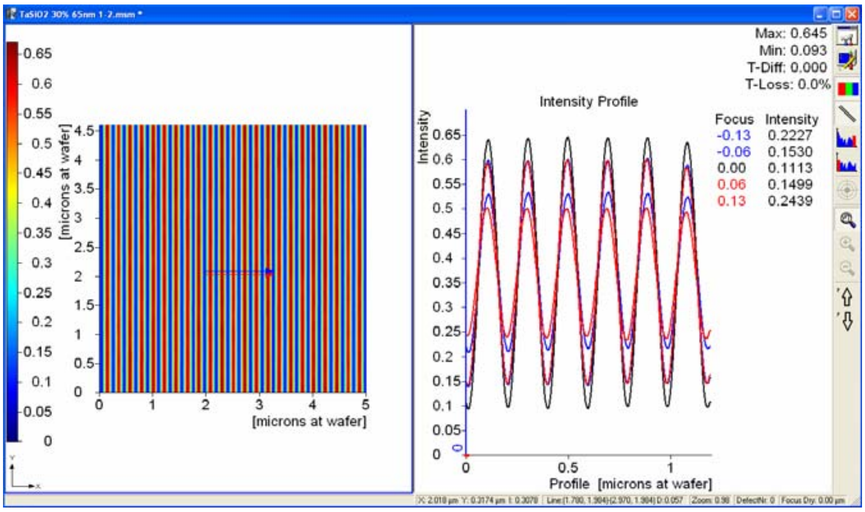
The AIMS™ fab 193i tool with a maximum numerical aperture of 0.93 is dedicated first of all for the 65nm node. Investigations of smaller features with a lower duty cycle are critical as the diffraction orders resulting in the image performance cannot be captured anymore due to the maximum possible aperture size. The result assessment will then appear difficult. In order to be able to investigate the 45nm line group we have chosen the duty cycle of 1:3.

Feature	**65nm 1:2**	**65nm 1:3**	**45nm 1:3**
Wavelegth	193nm	193nm	193nm
Numerical Aperture	0.93	0.93	0.93
Part. coherence σ	0.9	0.55	0.9
Illumination type	Disar 78%	Annular 66%	Disar 78%

Table 1: Illumination settings

A typical AIMS measurement result of our patterned test design is shown in Fig 8. The left hand picture illustrates the aerial image captured in best focus while intensity profiles at different focus positions are demonstrated on the right hand diagram. The best focus profile curve shows largest modulation between minimum and maximum intensity, thus the largest contrast.

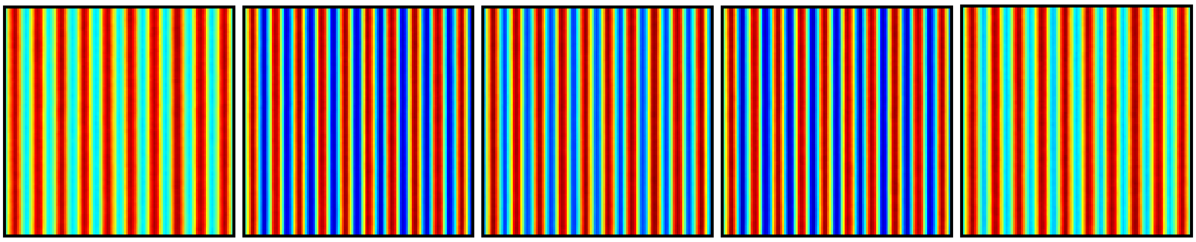
Fig 9 shows the aerial image captures in the through focus measurement for extra-, best focus and intrafocal planes which illustrates the decreasing contrast at larger defocus.



Max: 0.645
Min: 0.093
T-Diff: 0.000
T-Loss: 0.0%

Focus	Intensity
-0.13	0.2227
-0.06	0.1530
0.00	0.1113
0.06	0.1499
0.13	0.2439

Fig 8: Aerial image and selected Intensity Profile; $TaSiO_2$ 30%; L&S 65 nm , duty cycle 1:2;
Settings: λ=193nm, NA=0.93, σ=0.9, disar 78%



-0.19 ***-0.09*** ***0*** ***0.09*** ***0.19***

Focal position relative to best focus (0) in µm at wafer level

Fig 9: Through focus analysis: Aerial image of Ta / SiO_2, 65nm, 1:3 at different focus planes;
Settings: λ=193nm, NA=0.93, σ=0.9, annular 66%

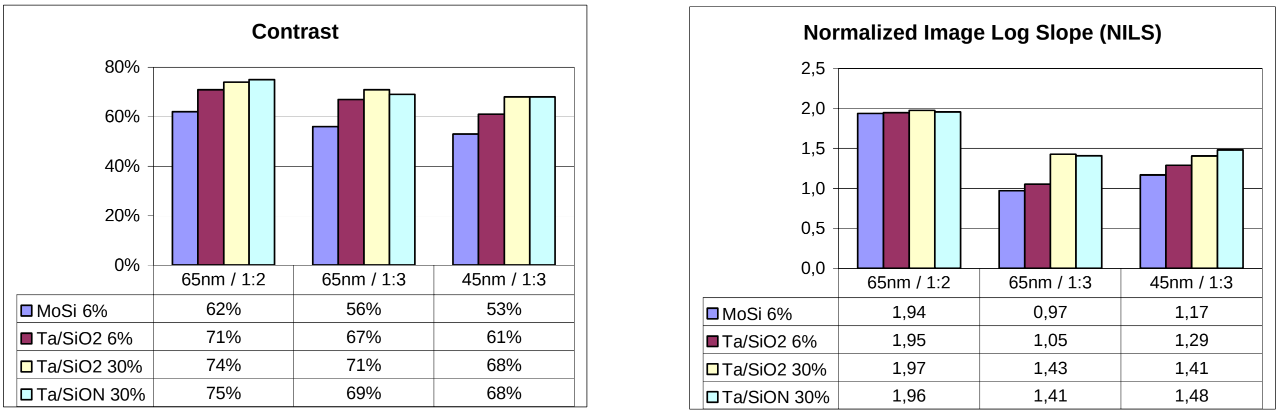
Based on the intensity (I) profile at the best focus, we determined the contrast and normalized image log slope (NILS) for the different line groups of each PSM stack (Fig 10). The contrast is defined as $(I_{max}-I_{min})$ / $(I_{max}+I_{min})$ of the measured intensity, while NILS represents the normalized slope at the normalized intensity (dose), which is required for printing the target CD.

The highest contrast of 68% - 75% (depending on feature size) has been measured on both, Ta/SiO_2-30% and Ta/SiON-30% high transmission masks.

In contrast to MoSi the Ta/SiO_2 stack provides at the same transmission of 6% an increased contrast of up to 20%. Corresponding NILS results show no significant change for 65 nm. At smaller line width and higher duty cycle (it means wider clear lines) we have observed a 10% NILS improvement for the bilayer PSM approach. This confirms simulation results [3], which predict a contrast improvement of Ta/SiO_2 vs. MoSi at small feature sizes at the identical transmission of 6%.

From the performed AIMS™ investigations of the high transmission stacks no significant changes of the SiON phase shift layer have been found. Furthermore, we have measured a higher contrast (4 to 11%) for the high transmission masks compared to the Ta/SiO_2 standard version of 6% transmittance, which is consistent with simulations[7]. An advantageous influence of high transmission on NILS was observed for higher duty cycles. For the 45 nm line group with 1:3 duty cycle a 9% NILS increase has been measured.

Comparing MoSi-6% and Ta/SiO_2-30% materials, we observed for 45nm semi dense lines an overall increase of 28% in contrast and 20% in NILS for the high transmission PSM.



	65nm / 1:2	65nm / 1:3	45nm / 1:3
MoSi 6%	62%	56%	53%
Ta/SiO2 6%	71%	67%	61%
Ta/SiO2 30%	74%	71%	68%
Ta/SiON 30%	75%	69%	68%

	65nm / 1:2	65nm / 1:3	45nm / 1:3
MoSi 6%	1,94	0,97	1,17
Ta/SiO2 6%	1,95	1,05	1,29
Ta/SiO2 30%	1,97	1,43	1,41
Ta/SiON 30%	1,96	1,41	1,48

Fig 10: Comparison of contrast and NILS for different PSM materials, feature sizes and duty cycles. Line width on wafer level

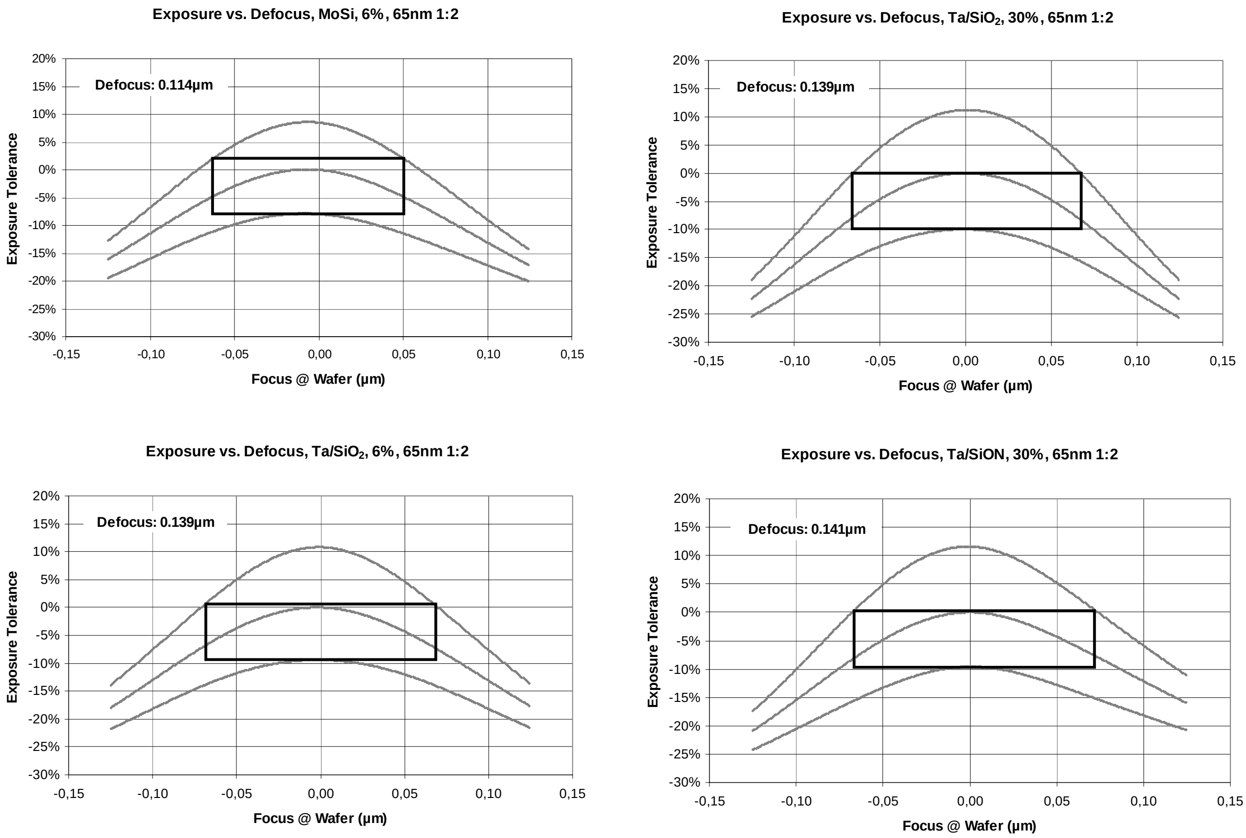


Fig 11: Process window for 65nm l/s, duty ratio 1:2, CD +/- 10% tolerance and 10% exposure tolerance

Based on the through focus intensity profiles, the exposure vs. defocus correlation for each material has been calculated (Fig 11). The three lines in the diagrams correspond to the dose/focus combinations for target CD and ±10% CD respectively. The rectangle inside the plots represents the process window for 10% exposure tolerance and allowable focus variation. The x dimension of this rectangle is identical to the available depth of focus range.

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. In Fig 12 comparison of the process latitude for the considered PSM materials is shown.

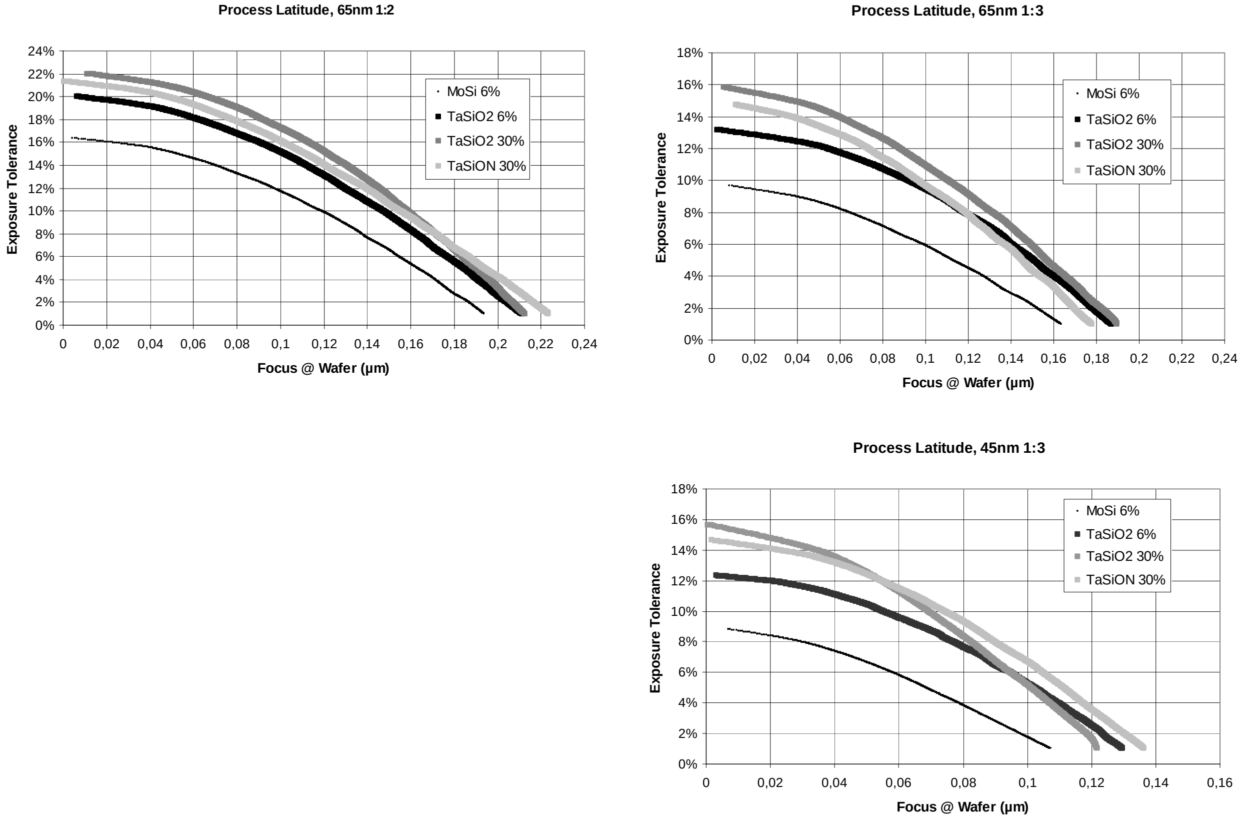


Fig 12: Process Latitude

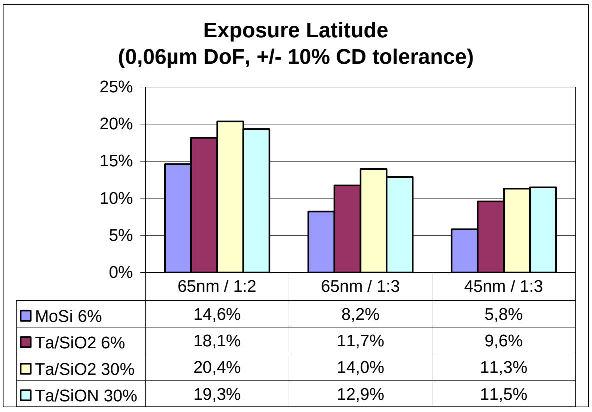
For all measured line groups and transmission values, Schott's Ta/SiO_2 and Ta/SiON materials show significantly improved process latitude compared to MoSi-6%. The results based on maximum contrast as well as the best process latitude imply best performance for both 30% transmission materials SiO_2 and SiON. Particularly, for a line width of 45nm and a 1:3 duty cycle, the high transmission mask provides a significant improvement of the process window.

A different view on the results shown in Fig 12 is given by the comparison of the exposure tolerance at a given defocus value. Common are higher values for the bilayer materials indicating their preferred suitability for the printing process.

Fig 13 summarizes the exposure latitudes, assuming a depth of focus of 0.06µm at wafer level. The small focus range was chosen for the illustration of principal tendencies. The non ideal investigation conditions for the 45nm feature size (limited NA) would not allow this demonstration for a larger focus range.

The process window behaviour is very similar to the contrast behaviour, which has been shown in Fig 10: A transmittance of 30% is better than 6% and Ta/SiO_2 is better than MoSi. For 45nm line width and 1:3 duty cycle we have observed 65% higher exposure latitude for Ta/SiO_2-6% compared to MoSi with 6% transmission. Finally, for the high transmission approach a further exposure latitude improvement of 18% could be detected for the smallest line group.

Generally there is no significant change found regarding different phase shifting materials (SiO_2 vs. SiON).



	65nm / 1:2	65nm / 1:3	45nm / 1:3
MoSi 6%	14,6%	8,2%	5,8%
Ta/SiO2 6%	18,1%	11,7%	9,6%
Ta/SiO2 30%	20,4%	14,0%	11,3%
Ta/SiON 30%	19,3%	12,9%	11,5%

Fig 13: Exposure Latitude at 0.06µm DoF and ±10% CD tolerance

3. CONCLUSION

Three test masks with different tuneable PSM materials have been fabricated: Ta/SiO_2 (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 process. High etch selectivty enables perfect etch stop on every single layer of the PSM stack. The process is controlled by a laser reflectometer, which allows an easy adoption to a varying layer thickness. Thus, the excellent phase and transmission uniformities of the blank material can be kept on the final mask.
Aerial images of 65nm and 45nm semi dense line groups of the fabricated test masks as well as a MoSi 6% EAPSM as reference have been measured using the latest AIMS^{TM} fab 193i tool.
Improvements of up to 20% contrast, 10% NILS and 65% exposure latitude have been achieved for the Ta/SiO_2 6% stack compared to the MoSi material with the same transmittance.
The high transmission stack clearly offers advantages in contrast, NILS and exposure latitude especially for smaller features, shown for the 45nm line group with 1:3 duty cycle. The results are in accordance with earlier findings from simulation.
The comparison of SiO_2 and SiON as the phase shifting material has offered no significant difference regarding the investigated lithographic parameters. Nevertheless, due to a higher refractive index, the lower stack thickness of the Ta/SiON material might reduce 3-D effects.

Comparing Ta/SiON 30% vs. MoSi 6% materials we have observed almost a doubling of exposure latitude for the high transmission stack, while the contrast is increased by 28%.

Printing 45nm dense lines may require even higher numerical apertures and consideration of polarisation effects. Future studies will comprise such investigations on small structures.

4. ACKNOWLEDGMENTS

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