Determination of mask layer stress by placement metrology

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**ABSTRACT**

The present paper will show an approach for a local and global stress determination by the application of a Leica LMS IPRO II mask registration tool. Changes in placement due to a full or partial layer removal on single materials as well as material stacks with respect to a reference grid were determined. Simulation using finite element modeling was conducted to calculate stress values from the placement information. Finally, an estimate was made of the acceptable stress level for a sample design to meet placement requirements for future lithography nodes.

**Keywords:** Stress, Registration, Leica LMS IPRO, EUV, multilayer

1. INTRODUCTION

Attenuated Phase Shift masks and masks for EUV Lithography consist of stacks with several layers, each made of a different material. Due to the mechanical characteristics of the different materials and the deposition process employed, tension or compression results, which affects the geometry of the mask. Each patterning step may change the stress state and mask bowing occurs, referred to as out-of-plane distortions (OPD), as well as corresponding deformations within the mask plane, referred to as in-plane distortions (IPD), leading to a deterioration of the placement accuracy. Meeting the tight mask image placement requirements of future lithography nodes, either the material has to be optimized for low stress, or the stress effect has to be compensated by data pre-processing. In any case the stresses of individual layers and possible local stress distributions have to be known.

Typically, average stress of single layers is obtained by measuring the change in substrate bow between pre- and post-coating using an interferometer and applying Stoney’s equation [1]. However, not all mask houses are equipped with such tools, and this method does not provide any local stress distribution information.

Therefore, an alternative approach is to use a common mask registration tool to determine the change in image placement with respect to a reference grid due to a full or partial layer removal. Similarly to using interferometer measurements, the change in bow can be obtained by analyzing the registration tool focus values. In addition, the movement of pattern elements dependent on their neighborhood can directly be observed. Simulation using finite element (FE) modeling was conducted to calculate stress values from the placement information. This can also give information about the local stress effects, and a separate design was used to estimate allowable stress levels for future nodes.

2. EXPERIMENTAL SETUP

2.1 Tool set

For the mask fabrication a state-of-the-art tool set comprising of the mask coater Steag HamaTech ASR5000, the 50kV variable shaped beam writer Leica SB350MW, the hot/coolplate module Steag HamaTech APB5000, the developer Steag HamaTech ASP5000 and the UNAXIS MASK ETCHER III was available.

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As resist the widely accepted pCAR FEP171 [2] from FujiARCH with a film thickness of 320nm (first layer exposure) and 600nm (second layer exposure) was used. Mask characterization was done for image placement, which was accomplished in a Leica LMS-IPRO II tool, and flatness using an interferometer Minifiz 300 from ADE Phaseshift at Schott Lithotec, Meiningen, Germany. Whether the IPRO is equipped with a horizontal three-point mount, masks are clamped vertically in the Minifiz tool.

2.2 Material
To evaluate the test method, SCHOTT Lithotec performed experiments to get materials with different stress values. In order to see if image placement correction is possible at all for high stress, materials with a stress of 900MPa and higher was especially fabricated. Two kinds of materials were investigated: a single layer and a multilayer system. As single layer material, the EUV system Quartz - TaN (80nm) was chosen. The stack Cr (60nm) - SiO$_2$ (144 nm) - Ta (20.5 nm) - Quartz was investigated as an example of a multilayer system.

2.3 Layouts
The process to visualize the change of the image placement as an effect of absorber stress consists in a simple sequence of removing material and measuring the resulting placement. Before doing so, an array of 29x29 crosses was patterned into the material to set a placement reference grid. Overlay marks are needed to ensure correct positioning for the writing of additional features in subsequent layers. A drawing of the design is shown in. The open area of this so-called design layer 0 is below 1%. The next layout levels are specific for the respective experiment:

Layout A focuses on global effect. Only three design levels are needed: Design level 1 opens the upper left corner (ULC) of the mask with 50% open area and design level 2 the entire mask except of the ULC (Fig. 1). Finally, design level 3 opens the upper left corner of the mask with 100% open area.

Layout B is optimized for local stress effect analysis, and therefore somehow different from the previous version. Two design levels contain a large L, which is divided into 50-µm wide stripes. Every other strip is assigned to a separate design level (Fig. 2). Although this pattern differs greatly from a real design, it contains some realistic elements like an isotropic line pattern, which is similar to a gate layer, and a non-uniform load.

2.4 Simulation Support
All simulation work was performed at the AMTC, Dresden, Germany, using ANSYS® FE modeling software. Input parameters for all simulation are the mask layout, the material stack, the thickness of each layer and the Young’s modulus of the layer materials. By fitting the measured results of the LMS IPRO II, the stress of a layer can be determined.

3. RESULTS AND DISCUSSION

3.1 Global Stress
As shown before [3], the application of our stress analyzing method on a photomask with single layer absorber fits very well with the results of the interferometer measurement. Attenuated Phase Shift masks and masks for EUV Lithography consist of stacks with several layers, each made of a different material. Layout A was sequentially patterned on the experimental multilayer system Cr – SiO$_2$ – Ta – Quartz from SCHOTT Lithotec. The process sequence in detail is illustrated below:

1. Exposure of design level 0 10. Placement metrology (PM3)
2. Structuring cross array 11. Exposure of design level 2
3. Placement metrology (PM0) 12. Structuring SiO$_2$
4. Exposure of design level 1 13. Placement metrology (PM4)
5. Structuring Cr 14. Structuring Ta
6. Placement metrology (PM1) 15. Placement metrology (PM5)
7. Structuring SiO$_2$/Ta 16. Exposure of design level 3
8. Placement metrology (PM2) 17. Structuring SiO$_2$/Ta
9. Structuring Cr (removal) 18. Placement metrology (PM6)
The measurement plots PM0 to PM6 are shown in Fig. 3 to Fig. 5. Running PM5, there were problems measuring the ULC and the rest of the mask simultaneously according to the highly different contrasts. A separation of the placement information into the different material layers can be obtained by the calculation of difference plots: Cr (PM1-PM0), SiO$_2$/Ta stack (PM2-PM1), SiO$_2$ (PM4-PM3), Ta (PM5-PM4) and again SiO$_2$/Ta stack (PM6-PM5). As can be seen from Figure 3 (left), the values for the chromium layer are very close to the accuracy of the placement tool. For this reason, any analysis for this layer was skipped. Fig. 6 (left) illustrates the measured distortions induced by the removal of 50% of the SiO$_2$ and Ta layers in the ULC. A FE model was built to simulate the partial removal of layers or portions of layers, and Fig. 6 (right) is a vector plot on a 29x29 grid of the distortions induced by the removal of 50% of the SiO$_2$ and Ta layers in the upper-left quadrant of a mask. Distortions are proportional to the stress of the layers being patterned, thus it is possible to calculate the stress value to input in the FE model so that the magnitude of the distortions match that of the experimental results. The direction of the distortions (inwards in this case) indicates that the material removed was in compression, and compressive stress will be denoted with a minus sign. A value of the stress of the bilayer SiO$_2$/Ta was found to be -1.1 GPa in this manner. A similar method was used to determine stress values from the patterning of the following steps in Layout A. Fig. 7 shows the measured and modeled distortions due to the removal of the full SiO$_2$ layer outside of the upper-left quadrant, and a stress of -930 MPa (also compressive) was calculated for the SiO$_2$ layer. Fig. 8 shows the distortions obtained experimentally and numerically due to the removal of the full Ta layer outside of the upper-left quadrant, and the stress was estimated to be -2.85 GPa (compressive as well) for Ta. Finally, Fig. 9 is a plot of the measured and modeled distortions due to the removal of the remaining 50% of SiO$_2$/Ta in the upper-left quadrant, from which a stress value of -1.2 GPa was extracted, for the bilayer system. The two calculations pertaining to the upper-left quadrant patterning are in good agreement, and an average value of -1.14 GPa can be reported for SiO$_2$/Ta. To verify that the values obtained for single layers are consistent with the average value for the full system, an equivalent stress for SiO$_2$+Ta was calculated from the stress of SiO$_2$ and Ta using the average values of (PM4-PM3) and (PM5-PM4) weighted by the layer thickness, according to equation 1:

$$\sigma_{\text{stack}} = \sigma_{\text{Ti}} * d_{\text{Ti}} + \sigma_{\text{SiO}_2} * d_{\text{SiO}_2} \over d_{\text{SiO}_2} + d_{\text{Ti}}$$

Therefore a value of about -1.2 GPa is obtained. This is in good agreement with the measured value of the -1.14 GPa. For verification, the focus values of the registration tool are analyzed. These values, which are given as a z-value with the unit [nm], directly allow determining the change of the substrate surface shape. For the SiO$_2$/Ta stack (PM6-PM5), Fig. 10 shows the change in shape. Over a 140 mm x 140 mm area, the change in bow is 1.65 µm, corresponding to a stress of -1.19 GPa, according to Stoney’s equation, which is in good agreement with the values determined before.

### 3.2 Local Stress effects

As the reliability of the measurement method was the main focus of the previous experiment, patterning was always done in large areas for simplicity. Layout B, which was applied on an experimental single layer system TaN – Quartz from SCHOTT Lithotec has only an open area of about 10% per layer. Key point of this experiment was the quality of the correlation between simulation and measurement. According to the reduced number of levels, the process sequence is much simpler:

1. Exposure of design level 0
2. Structuring cross array
3. Placement metrology (PM0)
4. Exposure of design level 1
5. Structuring TaN
6. Placement metrology (PM1)
7. Exposure of design level 2
8. Structuring TaN
9. Placement metrology (PM2)
10. Structuring TaN (removal)
11. Placement metrology (PM3)

Similarly to the previous experiment, the calculation of difference plots gives placement information about the same material for the patterning of different layouts: TaN-Design level 1 (PM1-PM0) and TaN-Design level 2 (PM2-PM0). Fig. 11 and Fig. 12 show the distortions measured after the patterning of level 1 and level 2 of Layout B, without and with the application of scaling corrections. As it can be expected, the distortions look similar for level 1 and level 1+2 patterning, since these levels only differ by the amount of TaN that is removed within the L-shape. It is also expected
that the distortions for step 1 be half of the distortions induced by the full removal of TaN within the L, which is roughly verified.

The stress of the TaN layer sample was calculated as in the case of the SiO$_2$/Ta, through the use of finite element analysis. Instead of the patterning of full quadrant, the patterning of the large L-shaped feature depicted in Fig. 2 was modeled. Fig. 13 features the experimental and numerical distortion data, showing an excellent agreement of the effect of this localized patterning, where lines and spaces were written into the L shape. A stress value of -1.9 GPa was calculated for the patterning of step 1 of Layout B. Similarly, Fig. 14 pertains to the effect of step 1 and 2 of Layout B, resulting in the full removal of TaN within the L shape, and a stress value of -1.76 GPa was calculated. Finally, the entire TaN layer was removed, also allowing a stress evaluation (Fig. 15), and a value of -1.92 GPa was obtained, leading to an average stress of -1.87 GPa for this sample material. This was in good agreement with two stress determination experiments that were performed in the past [3].

3.3 Maximum allowable stress
The maximum allowable mask displacements are listed for each node in ITRS documents [4]. As requirements are often tightened from one edition of the roadmap to the next, a maximum allowable image placement error of 6 nm is assumed for the 32-nm node, i.e., smaller than the value quoted in the 2004 edition. This is the maximum 3-sigma value of the mask displacements after the application of scaling correction. A simple mask placement error budget can be used to determine the maximum allowable stress for the 32-nm node. Mask placement errors depend on three main factors: e-beam writer accuracy, layer stress and thickness as well as design. Another factor taking into account in an error budget is the measurement accuracy of the registration tool. Therefore, the statistical sum of these four contributions should be below 6 nm. An e-beam writer positioning accuracy of 5 nm can be expected for the 32-nm node, and was assumed in this paper. The L-shaped Layout B level 1 used for the monitoring of local stress effects is rather simple, but it contains realistic features such as lines and spaces and is asymmetric, which makes it more challenging. Therefore it was taken as an example of design determination the error budget. The required accuracy of the measurement tools is chosen as 25% of the maximum allowed value, as a rule of thumb. As a worst case, it was assumed that the measurement accuracy would only be 2 nm, i.e., 33% of the image placement target specification.

Finally, stress-induced distortions can be estimated for the design chosen, using the image placement results after scaling correction in the previous section (Fig. 11 right). The absorber thickness was kept at 80 nm, although it would naturally be interesting to employ materials with reduced thickness. Using these numbers, a stress value of 700 MPa leads to a total image placement error of 6.02 nm, and a value of 650 MPa yields a maximum placement error of 5.94 nm. For more safety, using an absorber with a stress of 600 MPa would induce image placement errors below 5.9 nm.

4. CONCLUSIONS
The application of a mask registration tool for the analysis of global and local stress effects is a promising approach. It allows getting more information on the used blank material without the need of additional measurement tools. Also no additional steps but the standard blank patterning process is needed. Results on the global stress may be obtained by two different methods, which are the change of the focus z-values and the image placement results. These two methods (focus data and image placement) can be regarded as separate measurements, which are leading to very similar results according to our experiments.

The simulation of a simplified design taking into account local stress effects matches experimental data, which makes it possible to build predictive models of complex designs instead of having to process large numbers of masks. The modeling of a simple error budget in turn permits to estimate an allowable stress level to reach image placement requirements for the 32-nm node.

According to the methodology itself, it has to be noted that there is a limit in measurement accuracy: Therefore it is not precise to measure thin layers with stress below 400 MPa. This limit may be shifted by using an even more advanced and more accurate placement tool.
ACKNOWLEDGMENTS

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REFERENCES


Fig. 1: Layout A, step PM1 (left) and PM4 (right)
Fig. 2: Layout B, step PM1 (left) and PM2 (right)

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Scale [ppm] - -

Fig. 3: Experimental results: PM1-PM0 (left) and PM2-PM0 (right)

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Scale [ppm] - -
Fig. 4: Experimental results: PM3-PM0 (left) and PM4-PM0 (right)

Fig. 5: Experimental results: PM5-PM0 (left) and PM6-PM0 (right)
Fig. 6: (PM2-PM1): Experimental (left) and numerically FE result for -1.1 GPa total stress (right)

Fig. 7: (PM4-PM3): Experimental (left) and numerically FE result for -0.9 GPa total stress (right)
**Table 1:** Summary of experimental results for -2.8 GPa total stress

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**Figure 8:** (PM5-PM4): Experimental (left) and numerically FE result for -2.8 GPa total stress (right)

**Table 2:** Summary of experimental results for -1.1 GPa total stress

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**Figure 9:** (PM6-PM5): Experimental (left) and numerically FE result for -1.1 GPa total stress (right)
Fig. 10: (PM6-PM5): Measured change of substrate surface shape

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Fig. 11: (PM1-PM0) Experimental result without (left) and with scaling correction (right)

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Fig. 12: (PM2-PM0) Experimental result without (left) and with scaling correction (right)

Fig. 13: (PM1-PM0): Experimental (left) and numerically FE result for -1.9 GPa total stress (right)
Fig. 14: (PM2-PM0): Experimental (left) and numerically FE result for -1.76 GPa total stress (right)

Fig. 15: (PM3-PM0): Experimental (left) and numerically FE result for -1.92 GPa total stress (right)