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Optimized phase-shifting masks for high-resolution resist patterning by interference lithography

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ABSTRACT

The EUV laboratory exposure tool (EUV-LET) is a versatile stand-alone resist patterning tool. Main applications are resist characterization for industrial lithography as well as the patterning of high-resolution arrays over large areas as required in research and small-volume production. High-resolution patterns are achieved by interference lithography based on the achromatic Talbot effect. The theoretical resolution limit for achromatic Talbot lithography (ATL) of 10nm half-pitch (HP) is mainly resist-limited, as long as necessary high-resolution transmission masks can be fabricated. In this paper we focus on the transmission mask fabrication technology with a low number of process steps that allows to maximize yield and offers high flexibility. Diffraction order efficiencies (DOEs) of the masks are optimized to achieve maximal aerial image contrast (MTF) in the achromatic Talbot distance. The developed four-step mask fabrication process of contact-hole masks with HPs of 50nm, 40nm and 30nm over areas of 1 x 1 mm² is presented. The transmission masks

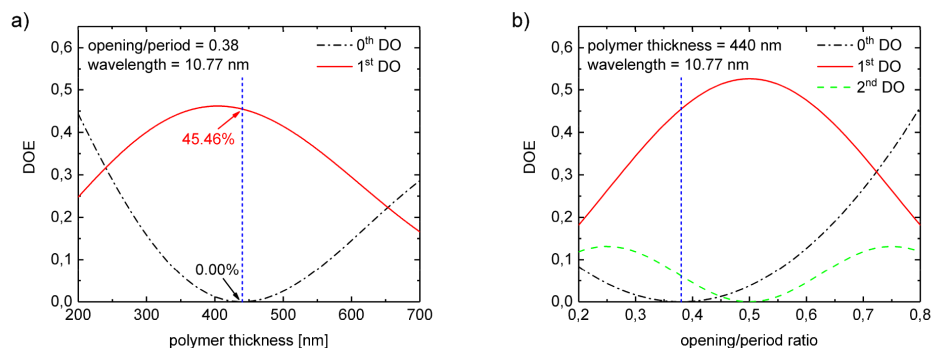


Figure 1. Calculated DOEs of individual DOs (intensities of $\pm 1^{\text{st}}$ DOs summed up) as a function of the polymer thickness at constant fill factor (a) and as a function of the fill factor at constant polymer thickness (b). The blue dashed vertical lines indicate the optimal parameters when masks are used for ATL.

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EDITORIAL

IoT – Driving the Revival of Sub 90nm Processes?

Jan Hendrik Peters, bmbg consult

Traditionally the main focus of many research people (like myself) and hence related contributions to conferences is on the high-end of the mask making infrastructure – especially EUV on the major new production technology. Recent major investments in Germany in the Saxony region that follow the well known mega trends of IoT and industry 4.0 make me think that we should maybe also pay more attention to this growing business side of topics.

A summary of the activities ongoing had been given in the annual general meeting of the Silicon Saxony Network end of November 2017 showing a total investment of several billion Euros in the coming years into extension of existing and the creation of new production and research facilities related to the Digital-Hub initiative of the Federal Republic of Germany. Companies like Bosch, GLOBALFOUNDRIES, Infineon, and X-fab, as well as BMW, VW and Daimler and many others are investing into “Industrial IoT” and “Smart Infrastructure” related activities. Applications are seen in the areas related to the automotive sector and autonomous driving, electromobility, smart cities, energy, or e-health. Activities are bundled and coordinated between the players and are partially supported by public funding and financed by major private investments.

Bosch, for example, is building a brand new 300 mm fab in Dresden first for mixed-signal and later for MEMS applications to start operations in 2021. A major part of the produced chips will be going to the automotive sector. With the choice for 300 mm technology due to the high availability of processes and equipment also the classical 90 nm structure sizes will be in higher demand again. The cooperation with other local players will be clearly be enhanced. Another major player in this field is GLOBALFOUNDRIES. IoT chip technology for the automotive industry is also in the focus of their major investments in their Dresden activities. Based on their FDX technology they will be able to meet the low power demands of their IoT and automotive customers.

With the foundation of a new Research Fab Microelectronics Germany, the German Federal Ministry of Education and Research (BMBF) supports 11 Fraunhofer and 2 Leibnitz Institutes to jointly work on solutions bridging the value chain from chip to industrial products. Goal of this new cross-location Research Fab is to support customers from large industry as well as small and medium size enterprises in the area of micro- and nanoelectronics.

Together with the investments of the major fabs these will clearly give a large benefit to the small and medium sized enterprises of the supplying industry of the region. For mask shops there is a clear opportunity for a broader business case ranging all the way from IoT triggered business to the EUV world for the coming years.



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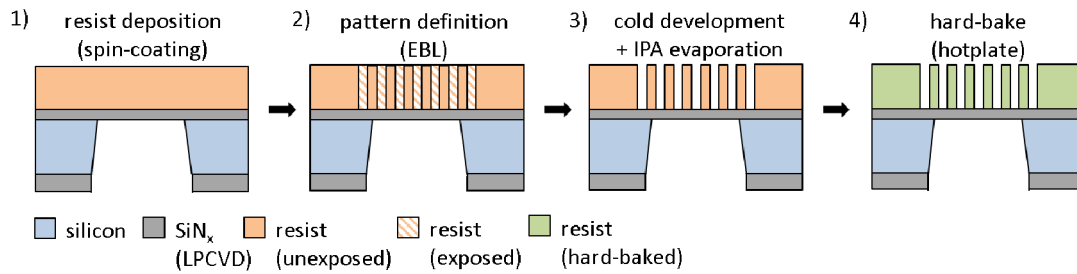


Figure 2. Schematic cross-sectional view of the four main process steps in the mask fabrication. The different layer materials are indicated by different colors.

Table 1. Overview of the measured DOEs and the expected MTFs at wafer plane for the investigated masks. As a reference the calculated values for an optimal line grating as calculated by [22] are given.

Mask type	Polymer thickness [nm]	0 th DOE [%]	1 st DOE [%]	2 nd DOE [%]	Absorption [%]	MTF [%]
Optimal mask (theory)	440 (ratio=0.38)	0.00	45.46	6.16	<42.97	100.00
50 nm HP	320 (ratio=0.45)	14.42	41.67	1.32	< 34.90	63.73
40 nm HP	270 (ratio=0.47)	24.11	36.15	0.28	< 36.02	45.27
30 nm HP	200 (ratio=0.44)	44.49	9.84	0.51	< 44.54	10.97
40 nm HP (exposed by EUV)	270 (ratio=0.46)	22.51	34.90	0.35	< 37.03	47.33
40 nm HP (EBL dose +20 %)	265 (ratio=0.48)	26.53	35.41	0.18	< 34.55	42.31

are characterized within the EUV-LET to determine the achievable MTF that can be used for resist patterning and characterization. Based on the carried out in-tool measurements the achievable MTF is 63.7% and the total diffraction efficiency into the 1st diffraction orders (DOs) is 41.7% (both for 50-nm-HP masks) which makes the masks perfectly suited for the achromatic Talbot approach. Furthermore, we demonstrate high-resolution patterning down to 28nm HP describing an effective in-lab tool that can be used at facilities for the characterization of photoresists for the upcoming lithography generations.

1. Introduction

High-resolution nanopatterning techniques are required not only in science and research¹⁻³ but also in the lithographic industry for resist characterization^{4,5}. The quality of the resist pattern in terms of critical dimension uniformity or line edge roughness is directly linked to the quality of the aerial image that is utilized for the exposure of the photoresist⁶⁻⁸. Approaches that are based on interference effects can provide very homogeneous intensity modulations over large areas⁹. The intensity modulation in the mask-based interference approaches is defined only by the transmission mask and the source emission properties since there are no additional optical elements in the beam path. Moreover, the local mask uniformity requirements are relaxed, since local mask

defects can be smoothed out by interference effects^{10,11}. The manufacturing of the masks is also easier than for 1:1 approaches, such as nanoimprint, since the structure sizes on the wafer are typically smaller than on masks¹².

The realized EUV laboratory exposure tool (EUV-LET) is based on the achromatic Talbot effect, which is an effective method for sources with broadband emission. The main components of the EUV-LET are the discharge produced plasma (DPP) EUV source^{13,14}, the transmission masks and the high-precision mask and wafer positioning system. Exposures need to be performed within the distance window where a stationary achromatic intensity modulation is formed by the source emission and the transmission mask¹⁵. For the use of broadband EUV emission the distance window is situated in a sub-150 μm mask-wafer distance and its width is limited by the spatial coherence that can be achieved in the mask plane. The depth-of-field (DOF) of the intensity modulation is 10 to 20 μm which allows for reliable patterning if the mask-wafer distance can be controlled precisely. Within the distance window many DOs are overlapping and contribute to the intensity modulation leading to a high throughput with typical exposure times of several seconds for EUV-resists. Size-scalable single exposure fields of several square millimeters can be achieved and repeated to cover even larger areas since no unused DOs surround the patterned field at this short exposure distance¹¹.

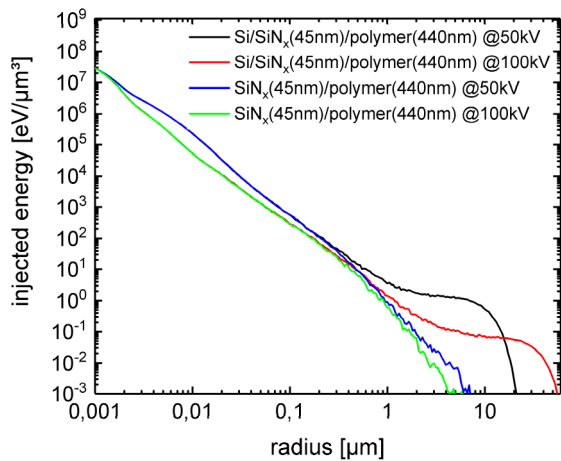


Figure 3. Monte Carlo simulation on the electron trajectories for the different layer systems. Comparison of the influence of the substrate and the acceleration voltage on the deposited energy density per injected electron in distance to the electron injection point.

The transmission masks are the key elements of this approach and need to be fabricated for each target HP size. Efficient fabrication of the masks has been achieved by minimizing the number of required process steps. Optimized parameters for the electron beam lithography of a spin-on polymer on an ultrathin membrane lead to high-aspect ratio mask structures. The developed mask fabrication process and the realized mask structures are presented in the first section. The polymer thickness of the transmission masks is optimized to achieve maximum 1st DOE and low intensity into the 0th DO which will result in high aerial image contrast (described as the modulation transfer function, MTF) at the exposure distances for ATL. For the pre-exposure characterization, the fabricated transmission masks are mounted onto a special mask holder that is placed in short distance in front of the CCD camera that is normally used for beam adjustment. For mask-HPs below 50nm the DOs are separated on the CCD camera and the intensities can be integrated and evaluated for the calculation of the expected MTF in wafer plane. With the knowledge about the incoming intensity I_{in} the DOEs can be directly extracted out of the CCD images. The experimental setup and results on MTF and DOEs are shown in the second section. In the third section we present the latest exposure results that have been achieved with the EUV-LET, the characterized transmission masks and the available photoresists.

2. Mask Fabrication Process

Mask-based lithography schemes are advantageous when large areas need to be patterned. The single exposure field can be scaled with the mask size and exposed in parallel which leads to a high throughput. Especially in the ATL approach single exposure fields can be easily stitched together since there are no unused DOs surrounding the interference pattern. The width of the un-patterned area that surrounds the field is just depending on the bandwidth of the radiation that is used for exposure¹⁶. Interference effects can facilitate mask fabrication due to defect compensation and pattern demagnification but nevertheless masks need to be patterned with high-resolution structures on the nanoscale. This normally requires a transfer process from the patterned resist into the target material. The target material can either be a material that has a strong absorption in the EUV wavelength range like

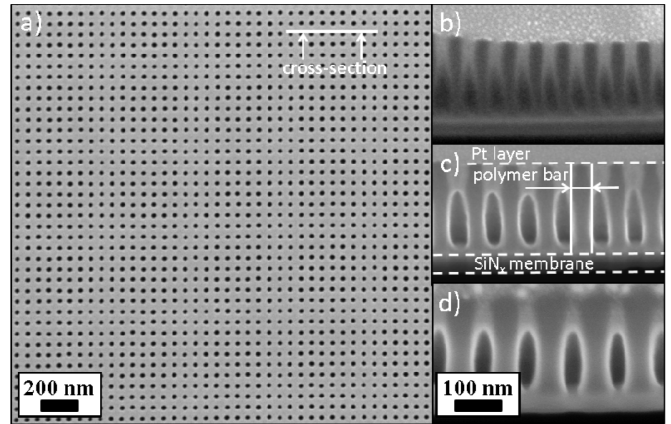


Figure 4. a) Top-down overview SEM image of 30-nm-HP mask structures (scale bar = 200nm). Right side: Cross-sectional SEM images of the fabricated mask structures with HPs of 30nm (b), 40nm (c) and 50nm (d) (scale bar = 100nm). The Pt-layer is deposited only for sample preparation and penetrates into the polymer openings.

chromium (Cr), nickel (Ni) or tantalum nitride (TaN) or a material that has suitable phase-shifting properties like molybdenum (Mo)¹⁷, molybdenum nitride (MoN)¹⁸ or several polymers that are available as spin-on EBL photoresists like polymethylmethacrylate (PMMA) or the 1:1 copolymer of α -chloromethacrylate and α -methylstyrene (ZEP520A, $C_{13}H_{15}ClO_2$, density = 1.053 g/cm³)^{19,20}. To avoid the pattern transfer we decided to use the EBL photoresist as a phase-shifting material. Since PMMA is not long-term-stable against EUV radiation²¹ and offers low contrast and sensitivity, we have used ZEP520A for the mask fabrication process.

We assume that for the ATL all DOs contribute to the intensity maxima of the aerial image and the intensity minima or background of the aerial image is defined mainly by the 0th DO. Achieving a minimal background or lowest intensity into the 0th DO will then lead to a maximized MTF. By optimizing the polymer thickness for a π -phase-shift between the directly transmitted beam and the shifted one that passes the polymer there is almost no intensity in the 0th DO (Fig 1a). The opening/period ratio of the mask structures also influences the intensity into 0th DO. The minimum 0th DO intensity can be achieved at a ratio of ~ 0.4 (or exactly 0.38 for 440nm polymer thickness²²) leading to the maximum MTF (Fig. 1b). Note that if only the 1st DOE needs to be maximized the polymer thickness needs to be slightly reduced from 440nm to 404nm leading to a phase-shift that is less than π to account for absorption. Additionally the opening/period ratio needs to be set to 0.5²²⁻²⁴.

Suited materials for membranes are niobium (Nb), Mo, zirconium (Zr) and silicon nitride (SiN_x) but only SiN_x is commercially available as a membrane²⁵. The here presented process is based on SiN_x membranes with a thickness of 45nm, measured with spectroscopic ellipsometry (Sentech SE800) at four positions outside of the membrane area due to a low signal intensity on the membrane. At this thickness silicon-rich SiN_x has a transmission of 47.5% at 10.77nm and 81.5% at 13.50nm²³. Compared to our previously presented transmission mask fabrication process for amplitude masks (Ni-absorber on Nb-membrane) that consists of over 30 process steps²⁶ this process is less complex and requires only an electron beam lithography (EBL) setup and a resist processing wet-bench. The process consists in total of four main process steps that lead to highly efficient phase-shifting masks (Fig. 2).

As a first step, the SiN_x membrane sample (chip size 10 x 10 mm², membrane size = 1 x 1 mm²) is dehydrated on a hotplate at

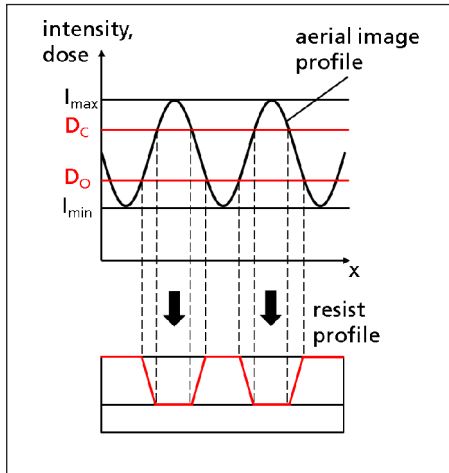


Figure 5. Illustration of the aerial image profile that is used for the creation of a resist profile. Position for successful resist patterning of maximum and minimum intensity (I_{min} and I_{max}) as well as the onset-dose D_o and the dose-to-clear D_c are shown.

180°C for 120 seconds. After a cool-down on the chill-plate for 120 seconds the sample is primed at a low pressure with gaseous hexamethyldisiloxane (HMDS) at a temperature of 130°C. After a cool-down (120 s) the sample is placed off-centered on the vacuum chuck of the spin-coater to protect the SiN_x -membrane during coating. After dispense of the photoresist (undiluted ZEP520A-7) the sample is spin-coated at a rotation speed between 2000 and 3000 rpm. The rotation speed is increased over the shelf-time of the resist to compensate the solvent evaporation and achieve a constant resist thickness of ~440nm. After the resist coating the sample is prebaked at 180°C for 240 s and cooled down on the chill-plate (120 s).

In the next step, the pattern is defined by EBL (Electron-Beam Writer Vistec EBP 5000plus). The patterning of the thick resist layer on top of the thin SiN_x membrane is one of the main challenges of this fabrication process because sub-50nm structure sizes will result in aspect ratios greater than 8. Achieving these high aspect ratios requires optimal EBL parameters and an optimized layer system. With the help of a Monte Carlo simulation on the electron trajectories, the influence of the acceleration voltage and the substrate on the deposited energy around the electron injection point has been analyzed (Fig. 3).

The patterning on the membrane leads to a lower long range scattering (radius > 300nm) for both acceleration voltages due to the absent backscattering in the substrate. The short range scattering (radius < 300nm) is only reduced at higher acceleration voltages. Additionally higher acceleration voltages lead to a lower forward scattering in the 430nm thick resist layer. Based on these simulations the EBL was performed on the membrane at an acceleration voltage of 100 kV with a beam current of 100 pA and a beam-step-size of 1nm. For the investigated masks the layout consists of round openings in rectangular arrangement with an opening/period ratio of 0.4. Optimal dose values have been determined experimentally in a coarse dose-selection scan with a dose step of 100 $\mu\text{C}/\text{cm}^2$. The determined dose window is relatively wide due to the low back- and forward scattering in this configuration. For the 50-, 40-, 30-nm-HP masks this resulted in optimal doses of 1400 to 1700 $\mu\text{C}/\text{cm}^2$. These doses are higher than the standard EBL dose of ~100 $\mu\text{C}/\text{cm}^2$ for ZEP520A due to

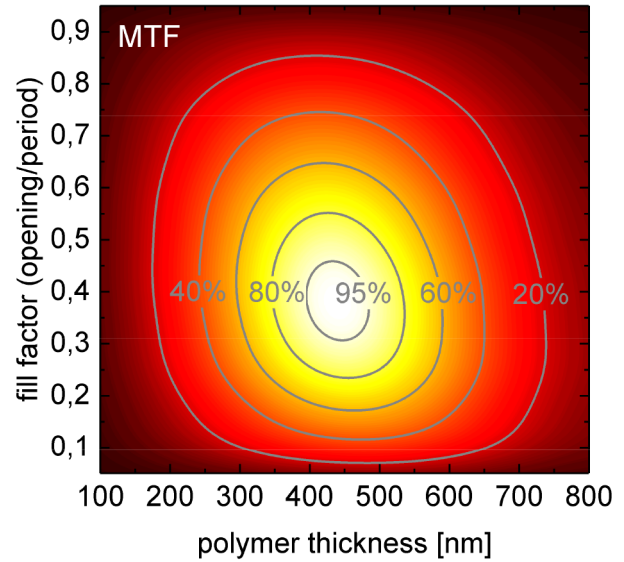


Figure 6. Color map of the calculated MTF as a function of opening/period ratio and polymer thickness.

the fact that the patterning of the relatively thick photoresist is done on a membrane (lower electron backscattering) with a high acceleration voltage (lower electron forward scattering) and that the samples are developed at 0°C (lower resist sensitivity but higher contrast). For each mask an overall area of 1100 x 1100 μm^2 has been patterned by EBL to cover the whole membrane area. The EBL patterning took between 12 and 16 hours for the investigated mask structures. An increase of the beam current or the beam step size has not been further analyzed but would result in a reduced beam-on time.

In the third step the samples are cold developed at a temperature of 0°C (set temperature = -1°C) for 90 s with the standard developer n-amyl acetate (ZED-N50). After this the samples are transferred into a first isopropanol (IPA) bath for development stop (30 s) and into a second IPA bath for further removal of the developer residuals (also for 30 s). The remaining IPA is then evaporated on a hotplate at 55°C. The IPA evaporation is done instead of the nitrogen blow-dry to avoid damage to the membrane and to reduce the influence of the capillary forces during drying²⁷. Further reduction of the capillary forces can be achieved by applying a critical point drying technique²⁸. The fourth step of this fabrication method is the hard-bake of the photoresist at a temperature of 100°C for 180 s. After a final cool-down for 120 s on the chill-plate the transmission masks are ready-to-use for EUV exposures. For the top-down pattern inspection with scanning electron microscopy (Zeiss SEM Gemini 1550VP) it is necessary to deposit a thin (3 - 5nm), conductive layer of iridium (Ir) onto the polymer layer. Otherwise an SEM inspection is not patterned polymer layer have been created with a dual beam setup consisting of a focused ion and an electron beam which are used for material deposition and imaging, cutting and polishing (FEI HELIOS Nanolab 600i Dualbeam). For the preparation of the cross-sectional images a thick layer of platinum (Pt) has to be deposited on top of the resist structures. The top-down and cross-sectional images for the fabricated mask structures are shown in Fig. 4.

The sample preparation for the cross-sectional images consists of several process steps and is quite challenging since the resist layer tends to deform during preparation. It is also not clear if the resist thickness is reduced during the preparation procedure or

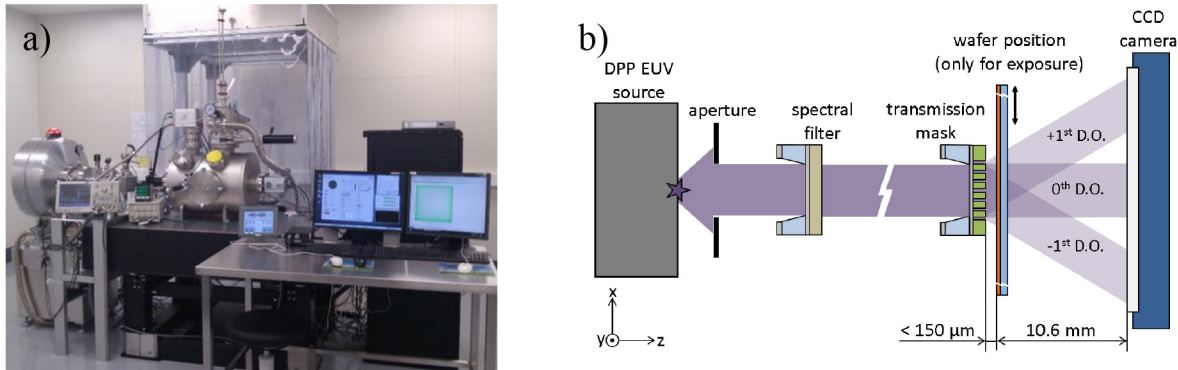


Figure 7. Photograph of the EUV laboratory exposure tool (EUV-LET) in the cleanroom environment (a). Scheme of the experimental setup with all relevant components (b).

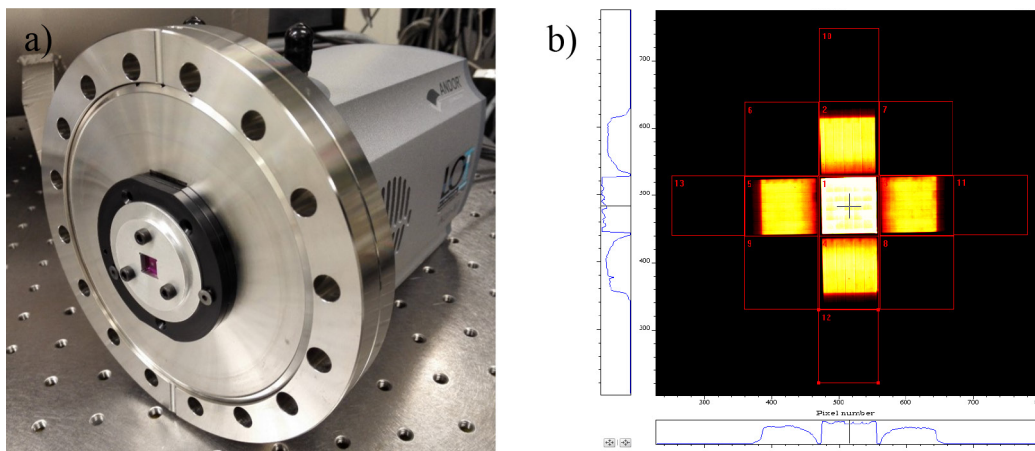


Figure 8. Photograph of CCD camera with attached mask holder and inserted transmission mask (a). CCD image of the diffraction pattern for 50-nm-HP mask at a mask-camera distance of 10.6 mm. At this distance the 1st DOs are clearly separated from the 0th DO. The 13 different regions of interest (ROIs) are outlined red and numbered (b).

already during EBL patterning of the structures. The thickness reduction is the largest in the densely patterned area of the resist. From the cross-sectional images one can identify slightly negative sidewalls due to the dominant forward scattering in the resist layer which seems to limit this process to mask HPs with a minimal size of 30nm. For HPs below 30nm one would need to change the process to other spin-on polymers or other phase-shift materials that allow for a lower layer thickness.

3. Diffraction Efficiencies and Aerial Image Contrast

The diffraction efficiency for transmission gratings can be calculated if the exact geometry of the grating is known in terms of the actual bar thickness, the opening-to-period ratio and the cross-sectional shape. Additionally, the chemical composition of the grating material needs to be known to include the optical material constants (complex refractive index) into the calculation^{22,29-31}. Although the calculated diffraction efficiency is independent of the grating period, in practice smaller periods lead to lower diffraction efficiencies since processing becomes more challenging and results in stronger deviations from the targeted shape. In the presented fabrication process a smaller period leads to a degradation of the cross-sectional shape and the same is likely to occur if a process with a pattern transfer is employed. Also the exact chemical composition of the polymer after EBL, development, hard-bake and EUV exposures can change which can result in a

change of the refractive index³². Additionally the total diffraction efficiency is influenced by the actual emission spectrum of the source, especially if radiation with a certain bandwidth is used. For these reasons a more practical approach for the estimation of the diffraction efficiency is presented.

With the knowledge of the intensities into each DO and the incoming intensity I_{in} , the DOEs and the MTF of the aerial image profile can be calculated. By knowing the MTF in the wafer plane one can already conclude if the mask can be used for successful resist patterning. This is possible because the resist performance can be also determined experimentally by open-frame exposures and the plotted characteristic curve. Out of the characteristic curve the resist contrast (γ -value) and the critical modulation transfer function (CMTF) can be extracted. Both are a function of the onset-dose D_o and the dose-to-clear D_c . The relationship between the resist performance and the MTF is schematically shown in Fig. 5. For a perfect photoresist D_o and D_c are equal, meaning that even the smallest MTF is sufficient for patterning. In reality a $MTF > CMTF$ is required to produce a height profile in the resist (Fig. 5)^{6,33,34}.

For Talbot lithography the minimal intensity of the aerial image profile can be defined as the intensity into the 0th DO as $I_{min} = I_{0th}$. The maximal intensity I_{max} is then the sum of the intensities into the 0th DO and all other DOs and can be calculated as $I_{max} = I_{0th} + I_{1st} + \dots + I_n$. The MTF can therefore be calculated as:

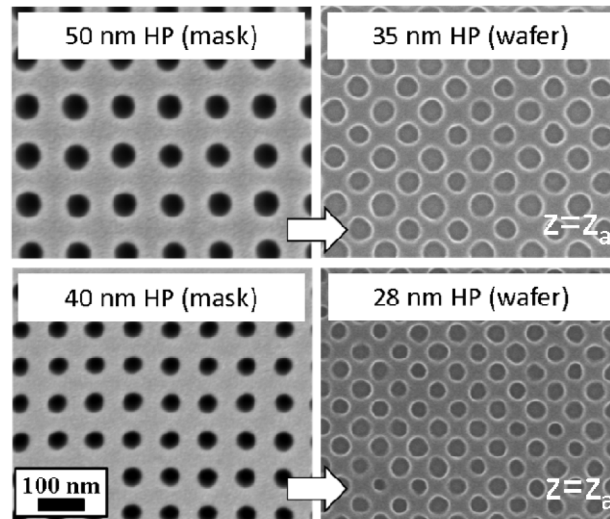


Figure 9. Top-down close-up SEM images of the transmission mask structures (left side) and the therewith achieved resist structures in the exposure result at achromatic Talbot distance. Note that the pattern in the exposure result is tilted by 45° due to interference effects. Additionally the HP of the exposure result is reduced by a factor of $\sqrt{2}$ compared to the mask-HP (scale bar = 100nm for all).

$$\text{MTF} = \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}} = \frac{I_{1st} + \dots + I_n}{2I_{0th} + I_{1st} + \dots + I_n}$$

This calculated MTF can be understood as the maximal intensity modulation at the first Talbot distance and serves as a measure for the mask quality. The real MTF is further reduced at subsequent Talbot planes by the limited temporal and spatial coherence of the source³⁵. The MTF calculated as a function of the opening/period ratio and the polymer thickness is shown in the color map (Fig. 6). For the calculation the intensities up to the 6th DOs are included.

For the calculation of the DOEs the intensities into the different DOs need to be compared to I_{in} . The absorption of the grating structure A_{grating} is defined as $A_{\text{grating}} = I_{in} - I_{0th} - I_{1st} - \dots - I_n$. Light that is scattered into larger angles or DOs is not included in this assumption. Therefore A_{grating} represents the upper limit for the absorption losses.

The fabricated transmission masks are characterized in the EUV-LET (Fig. 7 a). The experimental setup for the mask characterization consists of the DPP source, an aperture (diameter = 1 mm) for beam definition, a spectral filter (Nb (500nm)/Si₃N₄ (10nm)), the transmission mask to be characterized and the CCD camera for the detection of the DOs (Fig. 7 b). In the standard configuration¹⁵ for photoresist exposures a thinner spectral filter (Nb (100nm)/Si₃N₄ (10nm)) is used and the wafer is positioned in a mask-wafer distance below 150 μm .

For this series of experiments the transmission mask is fixed in a special mask holder that is directly mounted onto the connection flange of an EUV-sensitive back thinned CCD camera (Andor i-Kon M934, 1024 x 1024 pix², 13 x 13 μm^2) (Fig. 8 a). Thereby a mask-camera distance of 10.6 mm is realized where the DOs for a 50nm mask HP with an area of 1 x 1 mm² are separated by $\sim 150 \mu\text{m}$ (for $\lambda = 10.77\text{nm}$). For all measurements the CCD and EUV source settings have been kept constant. The utilized EUV source is operated at a frequency of 100 Hz with a xenon (Xe) and argon (Ar) gas mixture¹⁴ of Xe/(Xe+Ar) = 8.3%. The exposure time of the CCD camera is set to 150 μs and 10 single images are accumulated and corrected by dark images that are taken in the same manner (= 150 pulses/image). Dark signal is minimized by

cooling-down the CCD chip to -40°C for all measurements. For the measurements first a SiN_x-membrane is fixed to the CCD-camera. This membrane belongs to the same batch that has been used for transmission mask fabrication and is used for the measurement of I_{in} . After this, the SiN_x sample is replaced by a transmission mask. The CCD image that is recorded for the 50-nm-HP mask is shown in Fig. 8 b.

The CCD image provides information on the diffraction pattern that is generated by the grating structure. For image processing 13 different regions of interest (ROIs) have been defined as shown in Fig. 8 b. It shows the 0th DO (ROI #1) that is surrounded by the 1st DOs (ROI#2 to 5). If the scaling is adjusted it is also possible to identify the 1st DOs (ROI #6 to 9) that appear for the diagonal axis and also the 2nd DOs can be found (ROI #10 to 13) for some gratings. The 2nd DOs for the diagonal axis and higher DOs do not appear in the measurements. The DOs for the diagonal grating axis are only included in the calculation of the MTF and absorption. The position of the ROIs is slightly adjusted for masks with smaller HPs and the number of counts are integrated in each ROI and correspond to the intensity into this DO. For the determination of the 0th DOE the integrated counts into the 0th DO are compared to I_{in} (integrated counts of SiN_x-membrane measurement). The 1st DOE is calculated by comparing the counts of the 1st DOs (ROI#2 to 5) with the I_{in} and the same for higher DOs. The results of these measurements for the investigated masks are summarized in table 1 and compared to an optimal mask with a polymer thickness of 440nm with an opening/period ratio of 0.38 (Fig. 6) which can lead to a theoretically achievable MTF of 100%.

In a first experiment, the transmission masks with three different HPs were tested directly after fabrication. For the 50-nm-HP almost 42% of I_{in} is in the 1st DOs, only 14% is in the 0th DO. For all masks there is less than 1.5% of I_{in} in the 2nd and higher DOs. For the 40-nm-HP the intensity in the 0th DO increases by 10% and is reduced by the same amount in the 1st DOs. Thereby the absorption of the mask is almost constant since the opening/period ratio is same for these masks due to good pattern quality. Already by SEM/FIB inspection a lower pattern quality has been observed for the 30-nm-HP mask (Fig. 4b) which results in a strong reduction of

MTF to ~11%. To check the stability of the polymer against EUV radiation, an already exposed 40-nm-HP mask was inspected with no indication of radiation damage after a total exposure dose of 2 J/cm². An additional mask was fabricated where the EBL dose was increased by 20% in comparison to the optimal EBL dose. This results in slightly larger openings but the effect on the MTF is small (~3% reduction) since the patterning is done on the membrane and the EBL dose window is wide. The absorption is almost similar for the 50- and 40-nm-HP masks meaning that the I_{max} has to be also similar for these two masks. For resist patterning this would result in a similar dose-to-size for the different HPs which is advantageous. Achieved high MTF values of up to 63.7% allow for flexible patterning also of low contrast photoresists.

By taking into account the measured values for the DOEs the effective polymer thickness and opening/period ratio can be calculated (2nd column in tab. 1). The calculations show that the effective thickness is reduced down to 200nm for the HP of 30nm. A thickness reduction can also be observed in the cross-sectional SEM images (Fig. 4 b-c) which is larger for smaller half-pitches. One needs to note, that for all calculations a rectangular cross-section is assumed. This is definitely not the case for the 30-nm-HP where the non-rectangular shape degrades the DOEs. The calculated effective polymer thickness doesn't take the shape change into account which leads to an underestimation of its value.

The MTF that can be experimentally used for resist patterning might be further reduced by positioning system instabilities, thermal drift or vibrations between the mask and the wafer.

4. EUV Exposures

The characterized masks have been used for exposure series in the EUV-LET to create a height profile in a photoresist. For the exposures we used a high-sensitivity chemically amplified EUV resist with identical pre- and post-exposure processing as in our previous investigations for the analysis of the process window at 50nm wafer HP¹⁵. The resist thickness has been measured by spectroscopic ellipsometry (Sentech SE800) to be 37nm and the dose-to-clear at a wavelength of 10.77nm is 14 mJ/cm². The shown exposure results are achieved at a mask-wafer distance <20 μm and an exposure dose of 17 mJ/cm² leading to exposure times of less than 90 s (Fig. 8).

The mask-HPs are reduced by a factor of $\sqrt{2}$ (and tilted by 45°) in the exposure result leading to 35 and 28nm wafer HPs which is to our knowledge the record resolution for ATL. So far the exposure results for the 30-nm-HP mask led to a modulation of 21nm HP in the exposure result which is reasoned by the lower MTF that is not matching the resist performance of our test EUV resist. To approach the theoretical resolution limit of 10nm HP³⁴ or even $\lambda/4$ further hardware upgrades, mask optimizations and access to high-contrast resists are necessary.

Especially for sub-40nm mask HPs we can already observe a pattern demagnification at the mask-wafer contact point for the utilized emission spectrum and transmission masks¹⁵. This distance has been determined experimentally out of the diffraction pattern to be ~8 μm . This seems to be the minimal mask-wafer distance achievable in practice due to limited positioning accuracy and mask surface imperfections.

5. Conclusions

In this paper we presented a four-step mask fabrication process that is based on thin SiNx-membranes with a spin-on polymer. This process allows to produce high-efficient phase-shifting masks within short processing time that are perfectly suited for the achromatic Talbot approach. The simple and robust fabrication process has been scaled down to 30nm mask HP. With on-membrane 100kV EBL patterning high aspect ratios and large EBL dose windows have been achieved that lead to a high reproducibility for the mask fabrication process. Furthermore the masks are stable against incoming EUV radiation.

For the characterization of the transmission masks we established an in-tool inspection method within the EUV-LET. By measuring the intensities into the DOs and comparing these to the incoming intensity the DOEs and the maximal MTF for each mask can be estimated. With this method transmission masks can be inspected for long-term radiation stability and pattern quality. For this experimental method of DOE determination no exact knowledge of material composition or mask geometry (thickness, shape and opening/period ratio) is needed. The structure period can be easily extracted out of measurements. The inspection of the fabricated phase-shifting transmission masks resulted in 1st DOEs up to 42% and 36% for 50nm and 40nm HP respectively. For all masks the aspect ratio is in the range of six to seven. The absorption of these masks is below 40% which leads to comparable throughput for all HPs (almost same dose-to-size). The cross-section of the 30-nm-HP mask shows negative sidewall angles and further reduced polymer thickness leading to a 1st DOE of 10%.

The maximal MTF of almost 64% is measured for the fabricated mask HP of 50nm, for 40nm HP it is still 45% and drops down to 11% for the 30nm mask HP which is still sufficient for the patterning of high-contrast photoresists. By matching the polymer thickness to a π -phase-shift the 0th DO can be suppressed even more leading to higher MTF and throughput. The presented mask fabrication process can be pushed to MTF values of >90% by matching the polymer thickness and the opening/period ratio of the fabricated masks to the optimal values.

The exposure results demonstrate the great potential of the exposure tool and the developed transmission mask technology. With the available EUV resists, the patterning of nanostructures down to 28nm HP are shown. The further optimization of the mask fabrication process will lead to larger MTFs for smaller HPs and therefore more relaxed requirements on resist contrast.

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Note: this article was originally published 3 November 2017.

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