Large area fabrication of high aspect ratio sub-micrometer Si structures by displacement Talbot lithography and deep reactive ion etching

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Displacement Talbot lithography (DTL) [1] is a growing trend in patterning of large area samples with periodic micro/nano structures. It is a non-contact method which provides the high resolution of Talbot lithography with the depth of focus of interference lithography. Additionally, DTL is simple to use, similar to a standard mask aligner, and utilizes a photomask to create interfering beams through the diffraction of a collimated laser beam from the periodic structures of the mask. Like traditional Talbot lithography, the diffracted beams form a Talbot pattern in the proximity of the mask. However, the distance between the mask and substrate is not fixed in DTL, but rather it is continuously scanned over one or more Talbot orders [1, 2]. This allows to integrate the intensity of the Talbot carpets (see Figure 1) and makes the method essentially insensitive to surface planarity, resulting in extremely uniform, high quality and higher resolution exposures compared to those produced with standard contact mask aligners in UV-lithography (see Figure 2).

Previously, we demonstrated structures with the period of 1.2 µm and the depth of 30 µm, i.e. the aspect ratio of 50:1, using Cr as an etching hard mask [3]. Here, we show almost twice-smaller structures with the period of 650 nm and the depth of ~21 µm, corresponding to even higher aspect ratio of ~65:1. To perform the DTL step, Si wafers were coated by 180 nm thick AZ Barli II bottom antireflective coating (BARC) from Microchemicals GmbH and 1.7 µm thick PFI88B1E photoresist from Sumitomo Chemical Co., Inc. and exposed with Eulitha PhableR200C tool using 377 nm wavelength. After development of the PFI (Figure 3), the BARC layer was first etched in a non-switch SF_6/C_4F_8 process and then the Si was etched in three step Bosch process using SPTS Rapier DRIE system utilizing the ramping of the etching step time and HF Power to fine tune the sidewall shape. An example of the etching result is shown in Figure 4. The average selectivity of Si over the PFI photoresist was 18:1.

Our results demonstrate the route towards fabrication of large area small pitch uniform Si gratings, which are the key components for X-ray and neutron optics. In particular, such gratings enable compact and sensitive systems for phase contrast and dark field X-ray imaging with wide-range applications in medicine, biology and materials science. The method is also promising for applications in the fields of MEMS, photonics and structured biointerfaces.

[1] H. Solak at al., *Opt. Express* **19** (2011) 10686.
[2] Z. Shi at al., *Jpn. J. Appl. Phys.* **60** (2021) SCCA01
[3] K. Jefimovs et al., *Proc. SPIE* **10146** (2017) 101460L

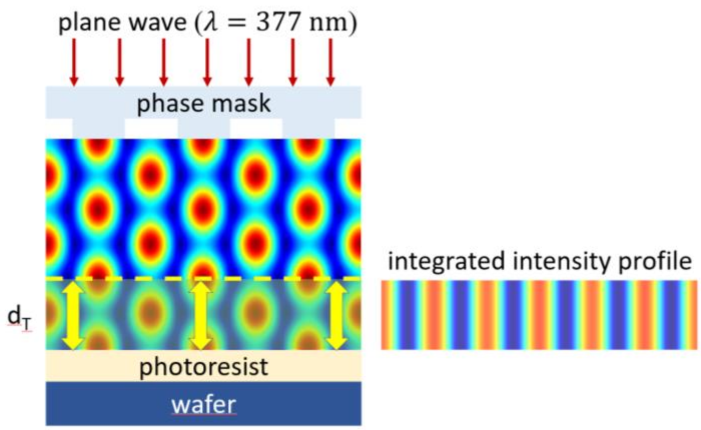

Figure 1. Principle of DTL. The collimated laser light diffracts on periodic structure of the mask and form Talbot pattern below the mask. The distance between the mask and the sample is scanned over one or more Talbot distances d_T during the exposure. The resulting integrated intensity profile due to substrate movement shown on the right has "infinite" depth of focus.

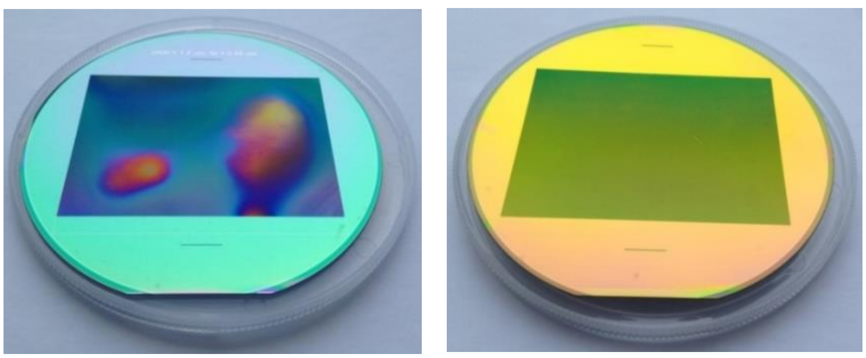

Figure 2. Examples of period p=1.2 µm grating exposures on 4-inch wafers by UV contact mask aligner (left) and by non-contact UV displacement Talbot lithography (right).

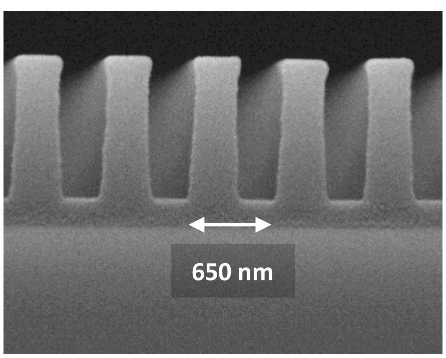

Figure 3. Cross-sectional SEM image of the 1.7 µm thick PFI photoresist after development (grating pitch: 650 nm).

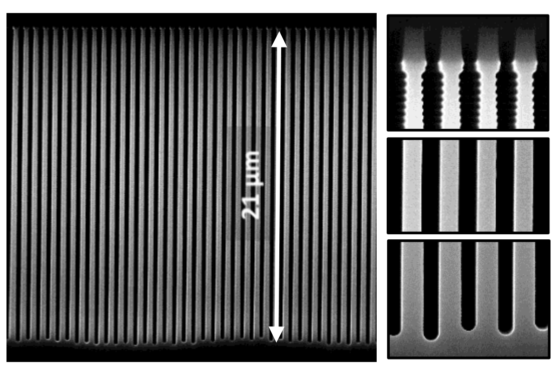

Figure 4. Cross-sectional SEM-image of Si grating etched to a depth of 21 µm through the PFI mask. Zoom-in SEM images of the top, middle and bottom parts of the grating are shown on the right.