Fabrication of Fresnel zone plates by holography in the extreme ultraviolet region

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The focussing of x-rays is of great interest for studies of the chemical, magnetic, structural, electronic and elemental properties of materials at the nanometer scale. In addition, the ability of x-rays to penetrate deep into matter allows one to probe buried materials. Weak refraction and high absorption complicate the use of conventional optics (lenses and mirrors) in this spectral region. Considerable interest has grown in the use of diffractive optical elements, Fresnel zone plates (FZP) being the most common of them. Currently high-resolution FZPs, consisting of concentric circles with varying width, are almost exclusively fabricated by electron beam lithography (EBL) [1,2]. This fabrication method is challenged by difficulties in the placement of the pattern, the proximity effect and problems related to finite pixel-size and reproducibility. Here we introduce a holographic technique that overcomes these difficulties while offering very high resolution potential.

The principle, as illustrated in Figure 1, is to let the spherical wave obtained by diffraction from a pinhole interfere with a plane wave of comparable intensity. The pinhole (Fig. 2a) is produced using EBL on a silicon nitride membrane. A through hole is etched by reactive ion etching (RIE) into the membrane using a chromium layer as a hard mask. An additional layer of gold is deposited on top in order to achieve a reference plane wave of the desired intensity. The mask containing the pinhole is placed in the path of a coherent EUV plane wave at the XIL beamline of the Swiss Light Source and the resulting interference pattern is recorded in a photoresist film. We have shown through electromagnetic simulations and analysis of images recorded in photoresist that the resulting pattern has the exact shape of a FZP, as expected from the holographic nature of the technique. In order to make a FZP, the pattern is recorded on another membrane coated with a CAR EUV resist (MET-2D). The fabrication of the FZP was completed by etching the pattern into Cr and (partially) into the underlying silicon nitride layers (Fig. 2b). The focussing properties of the FZP were tested with a knife-edge scan across the focal spot at the same beamline and at the same wavelength. The knife edge scan confirms that the theoretical resolution has been achieved. The long asymmetric tail of the spot seen on the left hand side of the scan is due to the partial absorption by the sloped edge of the knife edge. (Fig. 3)

The resolution available in this holographic technique is directly related to the diameter of the pinhole, while the number of zones is limited by the bandwidth of the used radiation. In this first demonstration we obtained a sub-300 nm spot size by using a pinhole of comparable size. The technique has potential for producing FZPs with a resolution in the sub-10 nm range.

[1] W. Chao et. al., *Nature,* **435**, 1210 (2005)
[2] K. Jefimovs et. al., *Phys. Rev. Letts*, **99**, 264801 (2007)

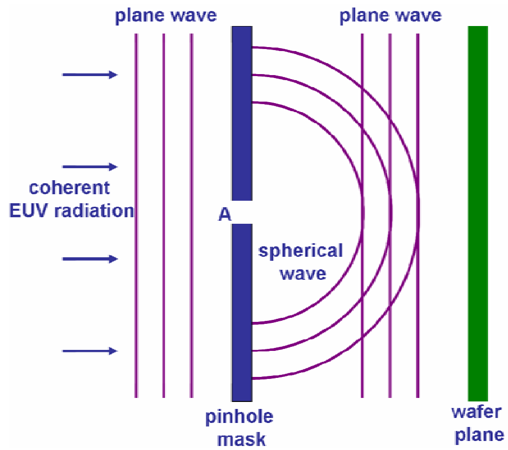

Figure 1. Schematic of the holographic technique. Spherical wave created by diffraction from aperture **A** interferes with the attenuated plane wave partially transmitted through the pinhole mask to produce FZP pattern on the wafer plane.

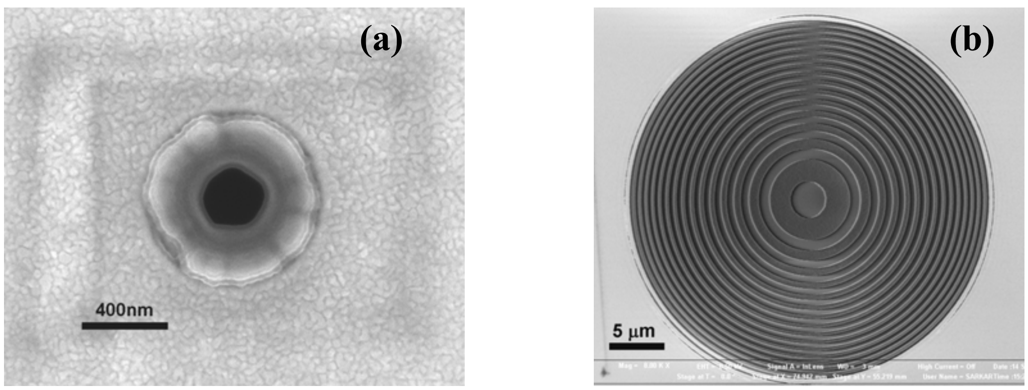

Figure 2. Scanning electron micrograph of **(a)** the pinhole with 300 nm diameter on a 100 nm thick silicon nitride membrane with 25 nm Cr/ 180 nm Au layer. **(b)** FZP produced with holographic technique using the aperture shown in (a). The FZP was fabricated on a 280 nm thick silicon nitride membrane coated with 25 nm Cr and then etched into the Cr layer and partially into the silicon nitride. The FZP is 33 μm in diameter and consists of 30 zones with 260 nm outermost zone width.

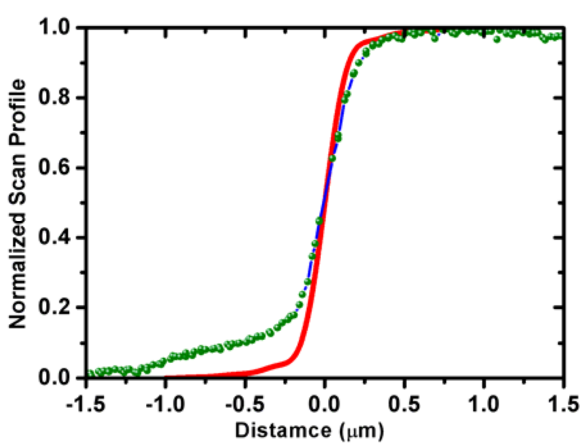

Figure 3. Knife-edge scan profile of the zone plate focal spot. The (green) dotted line represents the measured profile while the red solid line represents the theoretical behaviour.