Fresnel zone plates made by holography in the extreme ultraviolet region

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Abstract: We present the fabrication of Fresnel zone plates (FZP) by holography that yields FZPs completely free from imperfections such as zone placement errors and finite pixel size effects found in serial writing techniques such as e-beam lithography (EBL). Our holographic scheme is based on the interference of a spherical wave and a plane wave. A partially transparent membrane containing a pinhole is illuminated by a fully coherent plane wave (λ=13.4 nm). The spherical wave, obtained by diffraction from the pinhole, interferes with the plane reference wave that is transmitted by the membrane. The interference pattern, which is a hologram of the pinhole, is recorded on a photoresist film and used to fabricate a FZP that has resolution similar to the size of the pinhole.

1. Introduction
Focussing of x-rays to the nanometer scale has drawn considerable interest in the Fresnel zone plates (FZP) as diffractive optical elements. Currently high-resolution FZPs are almost exclusively fabricated by electron beam lithography (EBL) [1,2]. This fabrication method is challenging due to difficulties in the placement of the pattern, the proximity effect and problems related to finite pixel-size and reproducibility. A holographic technique of ZP fabrication in the EUV regime was demonstrated by Solak et al. [3], who obtained frequency-multiplied daughter-FZPs using a master made by e-beam lithography. In this paper, we demonstrate a new approach based on the use of a simple pinhole, where the potential imperfections that may arise from the e-beam writing step are completely avoided. EUV lithography enables the fabrication of sub-50 nm scale patterns fabrication and has potential for achieving higher resolutions.

2. Holographic approach
The principle of the holographic approach, as illustrated in Figure 1, is to let the diverging spherical wave obtained by diffraction from a circular aperture (pinhole) interfere with a plane wave of comparable intensity. The pinhole is fabricated on a semi-transparent membrane which also allows the plane wave to pass through, with an attenuated magnitude. The interference between these two waves gives rise to a hologram of the pinhole which is essentially a zone plate pattern. The pattern is then recorded at a certain distance z from the pinhole in a highly sensitive photoresist and subsequently the pattern is transferred to a suitable thin film in order to obtain a working zone plate.

3. Experimental highlights
The pinhole is fabricated [4] by EBL (LION LV1, Leica, Jena) on a chromium (23 nm) coated 100 nm thick silicon nitride (Si₃N₄) membrane using polymethyl methacrylate (PMMA) resist on top. Subsequently the pattern is etched (reactive ion etching, RIE) into the Cr and then etched into the membrane. Additional 160 nm of gold is deposited on the membrane which leaves the pinhole open. The diameter of the pinhole (figure 2, inset) after Au deposition is measured to be 300 nm.
The membrane containing the pinhole is used as a mask for the EUV holographic exposure which is performed at the X-ray Interference Lithography (XIL) beamline at the Swiss Light Source (SLS). The mask is placed in the path of a spatially coherent EUV plane wave of 13.4 nm central-wavelength (transverse coherence length ~ 2.1 mm) with 2.5% bandwidth. The pinhole diffracts the EUV radiation which then interferes with the attenuated plane reference wave transmitted through the rest of the membrane. At a distance of 600 μm from the pinhole mask, the resulting pattern is recorded on another Cr (23 nm) coated silicon nitride membrane (300 nm thick) in a sensitive chemically amplified EUV resist MET 2D [6] (Rohm & Haas). The plane wave is attenuated to 0.012% of the incident intensity by the silicon nitride membrane and the Cr and Au layers. Hence the total transmitted intensity is extremely low and the choice of highly sensitive resist is crucial for keeping the exposure time down to practicable levels. In these experiments, the exposure time was on the order of 10 minutes. The exposure system should remain stable regarding drift and vibrations during this period.

![Figure 1. Schematic of the holographic technique.](image1)

A spherical wave created by pinhole diffraction interferes with the attenuated plane wave partially transmitted through the pinhole mask to produce a FZP pattern at the exposure plane at a distance z.

![Figure 2. Zone plate fabricated with the holographic technique. The pinhole used for the holographic fabrication is shown in the inset.](image2)

The holographic pattern is transferred into the Cr and then etched (RIE) into the Si₃N₄ membrane. A scanning electron microscopy (SEM) image of the structure is shown in figure 2. The diameter of the FZP is 32 μm and the number of zones is 30 (the outermost smallest feature being 260 nm). The micrograph shows an apparent discontinuity (or phase shift) in the zones along a vertical line that goes across the zones, especially in the top half of the picture. We have determined this to be an artefact due to a dynamical charging effect on the insulating Si₃N₄ membrane, as the electron beam of the SEM is scanned across the structure.

4. Performance test:
The focal spot size of the zone plate is measured with a knife edge scan at the same beamline at the same wavelength (13.4 nm) as the holographic exposure which was used to create the FZP. The measured knife edge scan profile is presented in figure 3 and compared with theoretical integrated intensity profile at the focal plane of a lens of same numerical aperture as of the zone plate. The focal spot size is measured to be 300 nm (distance between 90% to 10% of the intensity profile [7]) which is comparable to both the outermost zone width (260 nm) and the diameter of the pinhole (300 nm). The good agreement between the theoretically calculated and experimentally measured curves is a testament to the aberration-free nature of the holographically made FZP.
5. Deviation from an ideal zone plate:
The diffraction from a non-ideal pinhole (due to finite thickness and diameter) is studied using a scheme similar to one discussed by Goldberg et al [8]. The exit field diffracted from a circular cylindrical hole (of 300 nm diameter) embedded in the mask material is simulated by a Finite Difference Time Domain (FDTD) algorithm using the EMExplorer® software package [9] and then propagated to the exposure plane by numerically evaluating the Huygens-Fresnel diffraction integral [10]. The deviation of the diffracted phase front from an ideal spherical wave (shown in figure 4) shows that the phase differs by $\pi/4$ at a numerical aperture (NA) of 0.06. This corresponds to the NA for the 1st Airy minimum of the intensity diffracted from an ideal pinhole of 300 nm diameter. This limit determines the radial region in which a zone plate pattern could be recorded [11]. When the effective zone plate diameter is limited by the 1st minimum of the Airy pattern, the minimum outermost zone width that can be obtained by this technique is given by the pinhole diameter divided by 2.4.

In conclusion, FZPs have been fabricated holographically, by recording the interference pattern formed by a spherical wave and plane wave. The measured performance agrees well with theoretical calculations. Fabrication using EUV light offers the potential for sub-50 nm resolution owing to the short wavelength and the absence of a photoelectron-induced proximity effect in this photon energy range.

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