doi:10.1017/S1431927615010697 Paper No. 0990 Microsc. Microanal. 21 (Suppl 3), 2015

Focused Ion Beam Micromachining Enables Novel Optics for X-ray Microscopy

Kahraman Keskinbora[1], Umut T. Sanli[1], Corinne Grévent[1], Michael Hirscher[1] and Gisela Schütz[1]

[1.] Max Planck Institute for Intelligent Systems, Dept. Modern Magnetic Systems, Stuttgart, Germany

X-ray microscopy is a strong analytical tool with a plethora of applications in physics, materials science and life sciences [1]. In many high resolution X-ray microscopes, a focusing optic such as a Fresnel zone plate (FZP) is utilized as a lens to form an image. The FZP is a diffractive optic composed of a series of concentric rings (zones) of radially varying grating period, where the width, Δr, of the outermost zone determines the resolution. Synchrotron radiation facilities are required as bright and coherent X-ray sources as the FZPs are usually quite limited in diffraction efficiency. The diffraction efficiency depends on FZP properties such as geometry, material, structure thickness and on the outermost zone width for small Δr. Conventional FZP profiles are binary and can have up to 10-40 % diffraction efficiency for ideal absorption and phase reversal zone plates, respectively. In practice the efficiencies are lower due to fabrication difficulties and errors. Electron beam lithography (EBL), the usual fabrication method, allows fabrication of binary FZPs with ultra-high resolution *via* processes of ever increasing complexity. However, due to the scattering of electrons within the resist, it is very difficult to fabricate ultra-high resolution FZPs with high structural thicknesses to achieve high aspect ratios. This, so called, proximity effect limits the aspect ratio, restricting the utilization of high resolution FZPs to softer X-ray energies. One special type of refractive/diffractive X-ray optic is the kinoform lens, with a continuous 3D surface profile. Ideally, it has a theoretical diffraction efficiency of 100 %. While in a real lens absorption would hinder 100 % efficiency, diffraction efficiencies well above 40 % are already demonstrated [2] using these lenses. Nevertheless, in order to fabricate these kinoforms, researchers resorted to step approximations using several consecutive overlay EBL steps, which is complicated and lead to much lower efficiencies than theoretically expected due to the vulnerability of the optics to fabrication errors amplified by error accumulations.

To solve the issues that are intrinsic limitations of the EBL-FZPs we introduced novel, precise and mostly direct methods relying on the FIBs. The powerful method potentially allows for higher resolutions than EBL [3] and precise 3D sculpting capability enables the realization of highly efficient X-ray optics with high fidelity [4]. We have used a standard multi-purpose FIB instrument (Nova 600 NanoLab, DualBeam, FEI) to fabricate binary FZPs, kinoform lenses and multilayer FZPs (Figure 1).

Fabrication of binary FZPs using IBL is a simple process (Figure 1a) which delivers high resolution FZPs in a very short time frame, in the order of 10 min, (*e.g.* 13 min [5]). Using these binary FZPs made out of gold, we were able achieve 30 nm effective Δr and half-pitch X-ray image resolutions down to 21 nm. Further progress down to 25 nm Δr (50 period), is possible (Figure 2a) *via* optimization of processes and materials.

Various kinoform lenses were fabricated using a gray-scale IBL approach by taking advantage of the 3D fabrication capability of the FIB instrument (Figure 1b) [4]. It was possible to use these lenses for high efficiency soft X-ray focusing and imaging. The diffraction efficiency up to about 14 % was achieved and was limited by the strong absorption, a characteristic of the soft X-rays. Nevertheless, an experimental diffraction efficiency up to 90 % of the theoretical efficiency was achieved, thanks to the high surface quality of the lens (Figure 2b) and the high precision fabrication process [4].

Furthermore, in another approach, micro-machining and micro-manipulating capabilities of FIBs can also be utilized for high precision slicing, transfer and polishing of the multilayer (ML) FZPs, for both the hard and the soft X-rays (Figure 1c). By using an FIB, slices of a multilayer deposit have been successfully cut out and transferred onto a TEM grid where the surfaces were further polished to a fine optical finish and finally a Pt beamstop was deposited *via* focused ion beam induced deposition (Figure 1c). The proper function of the ML-FZP (Figure 2c), was demonstrated at a synchrotron radiation facility by resolving ~20 nm (half-pitch) features, without any apparent astigmatism [6].

References:

[1] D. T. Attwood, “Soft x-rays and extreme ultraviolet radiation: principles and applications”, Cambridge Univ Press, New York (2000).
[2] E. D. Fabrizio, F. Romanato, M. Gentili *et al.*, Nature, **401** (1999), 895-898.
[3] W.-D. Li, W. Wu, and R. S. Williams, J. Vac. Sci. Technol., B, **30**, (2012), 06F304-4.
[4] K. Keskinbora, C. Grévent, M. Hirscher *et al.*, Advanced Optical Materials, (2014), doi: 10.1002/adom.201400411.
[5] K. Keskinbora, C. Grévent, U. Eigenthaler *et al.*, ACS Nano, **7** (2013), 9788-9797.
[6] K. Keskinbora, A.-L. Robisch, M. Mayer *et al.*, Optics Express, **22** (2014), 18440-18453.

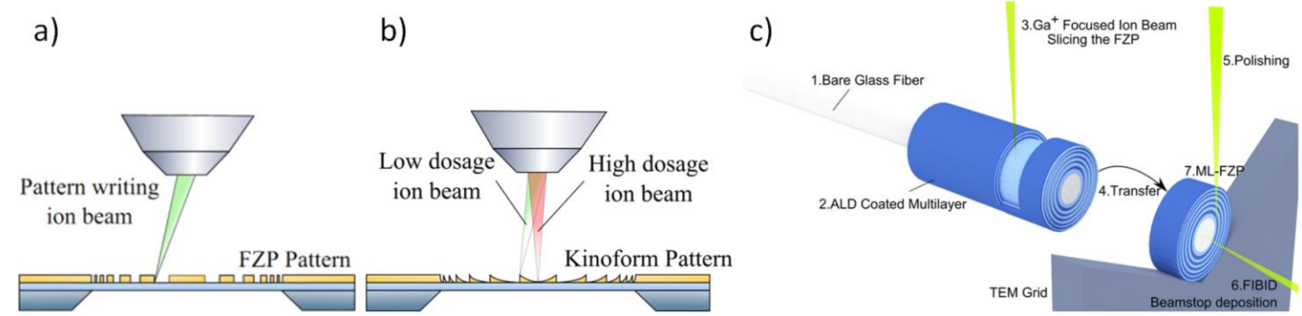

Figure 1. Schematic summary of uses of FIB for X-ray optics manufacturing. a) Single step writing of a binary FZP. b) Single step writing of a kinoform lens using gray-scale IBL. c) Fabrication of the ML-FZPs; slicing, transfer, polishing and beamstop deposition are made by using FIB.

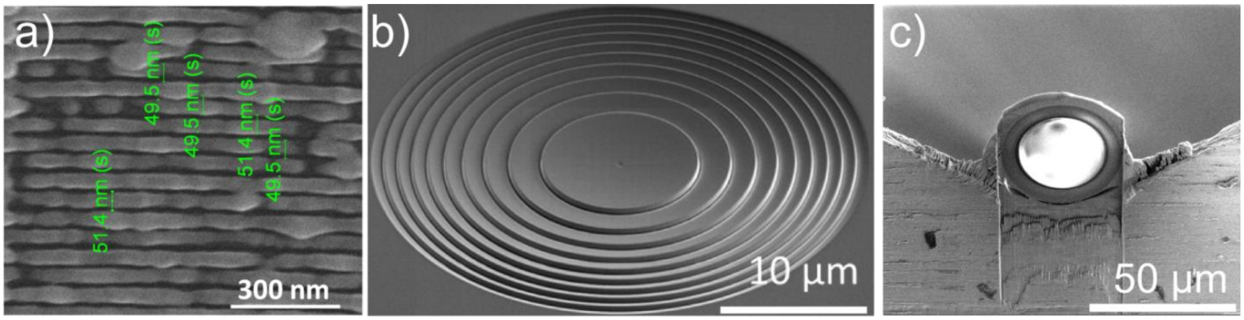

Figure 2. a) Binary zones with 50 nm period written with a FIB. b) A kinoform lens fabricated by using a gray scale FIB, written in a nano-crystalline $Pd_{0.8}Si_{0.2}$ alloy [4]. c) A multilayer FZP transferred onto a TEM grid and polished by FIB, ready for beamstop deposition.