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New overlay technique for fabrication of 15 nm half-pitch zone plate

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In e-beam lithography, fabrication of dense line patterns of sub-20 nm half-pitch is challenging. For the first time, we have successfully developed a new fabrication technique for dense patterns, based on overlaying semi-isolated patterns, and using the technique, we have fabricated Fresnel zone plates of 15 nm outermost zone width. A placement accuracy of less than 2 nm was achieved, and sub-15 nm spatial resolution, the highest ever achieved in optical microscopy, was obtained with an x-ray microscope.

Zone plates consist of dense lines and spaces, the outermost zones have been restricted to no less than 25 nm in size because of effects such as poor aerial image contrast, forward scattering, intrinsic resist resolution and development issues. However, isolated features can be made almost arbitrarily small by over-developing, ashing, etc., and linewidths of 10 – 15 nm can be achieved routinely without special processing.

Since the spatial resolution of zone plate lenses is approximately equal to the outer zone width (\(\Delta r\)), zone plate resolutions of sub-20 nm have not been possible because of the difficulties of patterning dense lines and spaces. To overcome this limit, a dense zone plate pattern is subdivided into two semi-isolated, complementary patterns [Fig. 1], which are fabricated separately and then overlaid with high accuracy to yield the desired pattern. The key to the success of this technique is very high alignment accuracy. For diffractive optics of this type, a feature placement accuracy better than 1/3 of the smallest zone width is required. To achieve such accuracy, an internally developed, sub-pixel alignment algorithm, based on auto/cross-correlation methods, is employed. A zero-level mark layer is used to eliminate systematic errors between the complementary exposures and to provide the initial beam alignment.

The 15 nm zone plates were written with a 2 nm pixel size, but a sub-pixel alignment accuracy of 1.7 nm (1\(\sigma\)) was achieved, which well satisfies the zone placement requirement of 5 nm in this case. The complete zone plate fabrication was conducted in-house, using our vector scan electron beam lithography tool, the Nanowriter, which has a measured beam diameter of 6.5 nm (FWHM), at 100 keV. 950k molecular weight PMMA resist with a 3:1 IPA:MIßBK development was used, while all exposed zones were electroplated in gold to form the zone plate structure. Fig. 2 shows the SEM micrograph of one of the zone plates.

Using one of these zone plates, a full-field transmission x-ray microscope was used to image cross-sections of multilayer coatings of various periods, at a 1.52 nm wavelength. Drastic improvement in image fidelity and resolution were observed over the previous result, obtained with \(\Delta r = 25\) nm. In particular, an image of a 15.1 nm half-pitch test pattern, shown in Fig. 3(a), exhibits excellent modulation, whereas the image of the same test pattern obtained with our previous zone plate showed no modulation [Fig. 3(b)]. The new resolution result is a breakthrough in optical microscopy – it allows the extension of x-ray microscopy’s capabilities, including in-situ imaging in numerous conditions, bulk elemental and chemical sensitivity, and larger sample thickness, to the research in nanoscience and nanotechnology. With the overlay fabrication technique developed here, we anticipate producing zone plates with even smaller zone widths, and other ultra-dense patterns that cannot be fabricated using conventional e-beam lithographic techniques.

Figure 1. Illustration of the overlay fabrication technique. A dense zone plate pattern is divided into two semi-isolated, complementary patterns, which in this case are zone patterns with alternating opaque zones (black and grey zones) missing. The divided zone patterns are fabricated separately, and then overlaid with high accuracy to yield the desired zone plate pattern.

Figure 2. SEM micrograph of a 15 nm zone plate, fabricated with the new overlay technique. The outer zones have a width of 15 nm. The zone placement accuracy is 1.7 nm, 1 σ.

Figure 3. X-ray images of a 15.1 nm half-pitch multilayer test object, formed by multilayer coatings in cross section, obtained with the (a) 15 nm zone plate and (b) previous 25 nm zone plate. The new image exhibits excellent modulation, while the image obtained before shows no modulation.