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Double patterning HSQ processes of zone plates for 10 nm diffraction limited performance

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Double patterning HSQ processes of zone plates for 10 nm diffraction limited performance

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In e-beam lithography, fabrication of sub-20 nm dense structures is challenging. While there is a constant effort to develop higher resolution resist processes[1-4], the progress of increasing pattern density is slow. For zone plates, consisting of dense lines and spaces, the outermost zone width has been limited to slightly less than 20 nm due to effects such as low aerial image contrast, forward scattering, intrinsic resist resolution, and development issues. To circumvent these effects, we have successfully developed a new double patterning HSQ process, and as a result, we have fabricated zone plates of 10 and 12 nm using the process.

We previously developed a double patterning process[5] in which a dense zone plate pattern is sub-divided into two semi-isolated, complementary zone set patterns [Fig. 1]. These patterns are fabricated separately and then overlaid with high accuracy to yield the desired pattern. The key to success with this process is the accuracy of the overlay. For diffraction-limited zone plates, accuracy better than one-third of the smallest zone width is needed. In our previous work, the zone set patterns were formed using PMMA and gold electroplating, which were overlaid and aligned to the zero-level mark layer with sub-pixel accuracy using our internally developed algorithm. The complete zone plate fabrication was conducted in-house. With this process, we successfully fabricated zone plates of 15 nm outermost zone. Using this zone plate, we were able to achieve sub-15 nm resolution at 1.52 nm wavelength, the highest resolution ever demonstrated in optical microscopy at that time. We attempted to extend the process to fabricating 12 nm and smaller zones. However, the modest PMMA contrast, combined with a relatively large electron beam size compared to the target feature sized limited the process latitude. To overcome this problem, we developed a new overlay process based on high resolution negative tone resist of hydrogen silsesquioxane (HSQ). With the development in TMAH at 45^{o}C, we can reliably achieve zone width as small as 8 nm with negligible line edge roughness in the semi-dense zone set. Such narrow zones in HSQ, however, detach easily from the gold plating base substrate needed for the electroplating step. We developed a process to condition the gold substrate with (3-mercaptopropyl) trimethoxysilane, or 3-MTP, which can form a homogeneous hydroxylation surface on gold surface and bond with hydroxyl in HSQ. Fig 2 shows the basic process steps of the double patterning HSQ process. Unlike the PMMA process, both zone sets are formed in HSQ and overlaid, and the complete zone plate pattern is converted to gold using electroplating in the final step.

Using the new process, we successfully realized zone plates of 10 nm and 12 nm outermost zones. Fig. 3 shows the SEM micrographs of the zone plates' outer regions. The zone plates are 30 nm thick in gold. To the best of our knowledge, these zone plates have the smallest zonal features ever fabricated using e-beam lithography. 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. An internally developed, sub-pixel alignment algorithm, based on auto/cross-correlation methods[6], was used for the overlay. A 12 nm zone plate was tested with a full-field transmission x-ray microscope at the LBNL's Advanced Light Source. Fig. 4 shows an x-ray image of a 40 nm thick gold radial spoke pattern taken with the zone plate at 1.75 nm wavelength (707eV, FeL3 edge), along with the scanning transmission electron micrograph of same object. Numerous small features in the object can be seen in the x-ray image. Data analysis indicates that a near diffraction limited performance was achieved using the zone plate. In our presentation, we will discuss the details and subtleties of the overlay fabrication as well as the zone plate image results.

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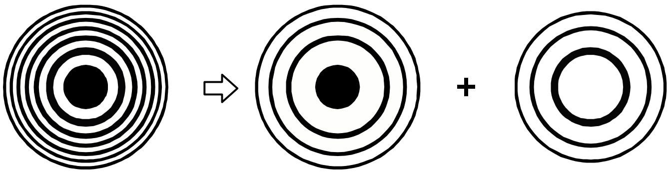

Figure 1. Illustration of the overlay fabrication technique. A dense zone plate pattern is divided into two semi-isolated, complementary patterns, which in this case are zone patterns with alternating opaque zones (black zones) missing. The divided zone set patterns are fabricated separately, and then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

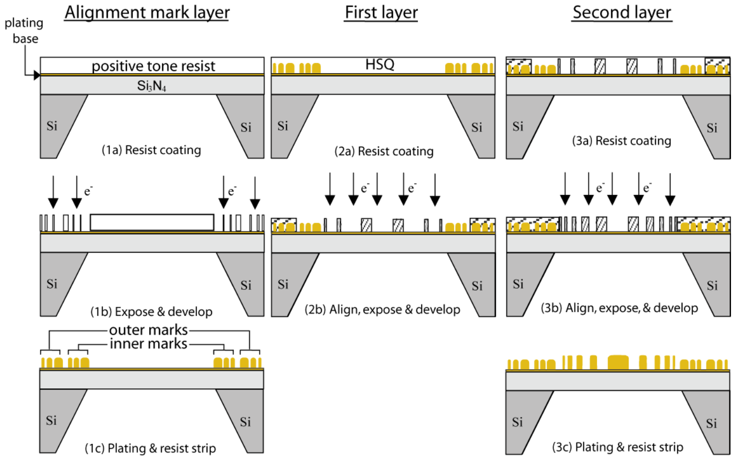

Figure 2. A schematic of the basic steps in the double patterning HSQ process. The process is divided into three parts: fabrication of the zero-level mark layer, patterning of the first zone set and patterning of the second zone set followed by electroplating. Our internally developed cross/auto correlation based algorithm is used to align the two zone sets.

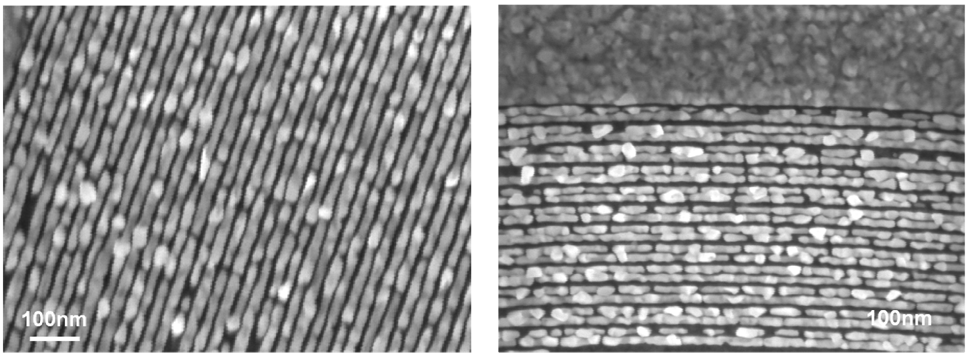

Figure 3. SEM micrographs of 12 nm (left) and 10 nm (right) zone plates, fabricated using the HSQ process. The outermost zones of the optics are 12 nm and 10 nm, respectively. The zone plates have plated gold thickness of 30 nm.

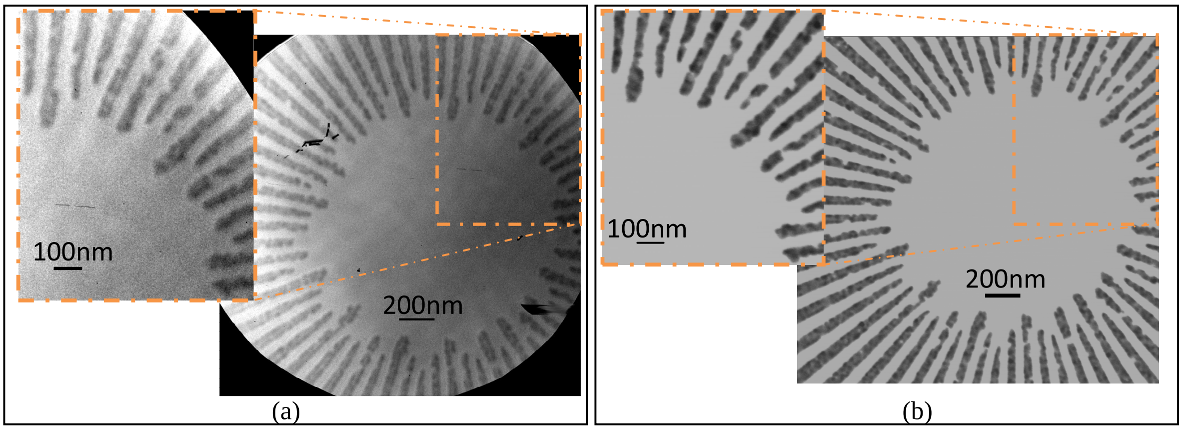

Figure 4. (a) An x-ray image of a 40nm thick gold radial spokes taken with a 12 nm zone plate at 1.75 nm wavelength. (b) A scanning transmission electron micrograph of the same object. Numerous sub-20 nm features can be seen in the x-ray image. Insets of (a) and (b) show magnified views of the top right area of the respective images.