Direct Patterning of Sub-10 nm Optical Apertures with a Helium Ion Microscope

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Sub-wavelength control and enhancement of electromagnetic energy at optical frequencies provides spatial resolution in the near field beyond the diffraction limit. This is achieved by engineering nanoscale features so that the metallic structures are optically resonant. One example is the enhanced transmission and field localization of subwavelength apertures on thin metallic films, where transmission gains of 6x and field enhancements of 550x were reported.[1-2] Typically, the critical dimensions of optical apertures are on the order of tens of nanometers (for low-order structures in the near-IR). These dimensions are accessible with conventional focused gallium ion beam patterning, and this has traditionally been the technique for fabrication. However, for patterning dimensions smaller than 30 nm (typical of visible and ultraviolet structures, or higher order resonant structures), gallium based systems have not performed as successfully. The most critical shortcomings of Ga+ patterning in this regime are the degradation of the fine structure by etching with the beam tails and the shift in the optical characteristics of the metal due to gallium implantation[3]. In this work, we employ a Helium Ion Microscope to demonstrate direct patterning of sub-10 nm features (free of implanted metal impurities) through optically thick metallic films. The probe size of the helium ion beam (<0.5 nm)[4], and negligible beam tails allow the fabrication of extremely fine features (<5 nm demonstrated), enabling experimental realization of resonant structures at shorter wavelengths or with a higher degree of order than previously achievable, Figure 1. Our demonstration explores fractal apertures[5], which feature higher order structures requiring critical dimensions on the order of 10 nm, as well as simpler structures with dimensions appropriate for resonance in the ultraviolet. The present limitations of this technique will be discussed, with an emphasis on re-deposition and requisite writing strategy, influence of grain orientation (channeling) and boundaries, and the depth limitations due to sub-surface helium implantation. The influence of grain orientation and boundaries is avoided by patterning on single grains or alternatively on nanoparticles dispersed on the surface (for demonstration purposes), Figure 2. Optical characterization is in progress, where we are characterizing the spectral transmission at far fields. Near field distributions and resonant modes will be studied with electron energy loss spectroscopy (EELS) and compared with current models based on Finite Difference Time Domain (FDTD) simulations, Figure 3.

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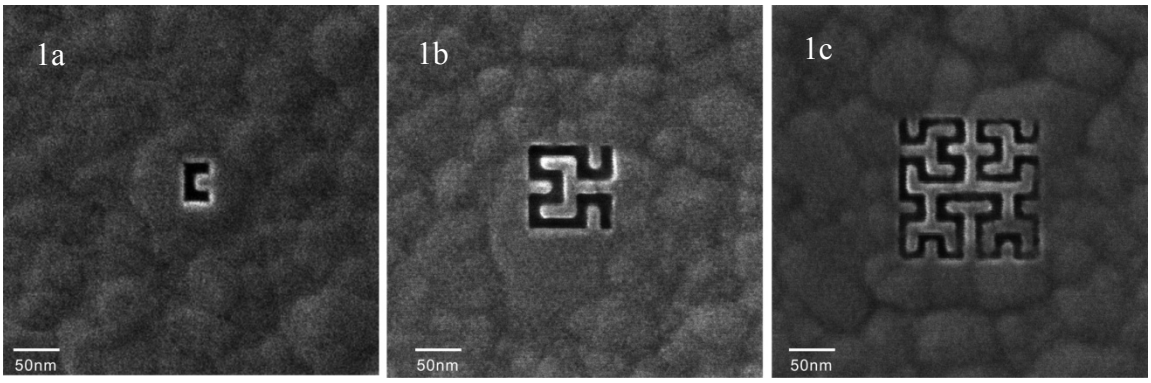
[3] J.B. Leen, P. Hansen, Y.T. Cheng, L. Hesselink, Opt Lett. **33**, 23 (2008)

[4] B. Ward, J. Notte, and N. Economou, *J. Vac. Sci. Technol. B* **24**, 6 (2006)

[5] J. A. Matteo, and L. Hesselink, *Opt. Exp.* **13,** 2 (2005)



Figures 1a-c: *Three orders of Hilbert Fractal Apertures:* Figure 1a-c are Hilbert fractal extensions of the C aperture patterned directly on a 75nm thick silver on a quartz substrate. Figure 1a shows a C aperture with a critical dimension of 12.5nm; 1b a second order Hilbert fractal with a critical dimension of 10nm; and 1c a third order Hilbert fractal with a critical dimension of 7nm.

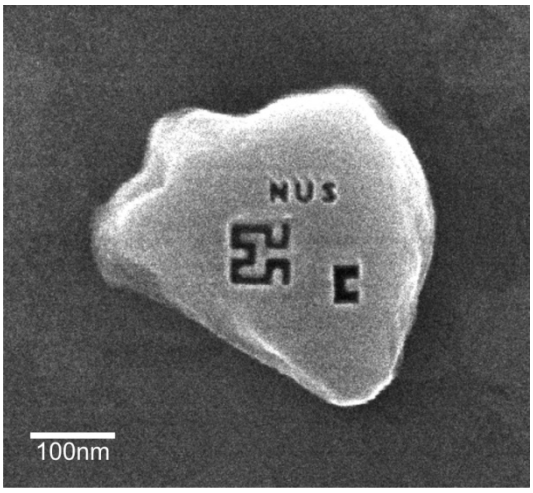
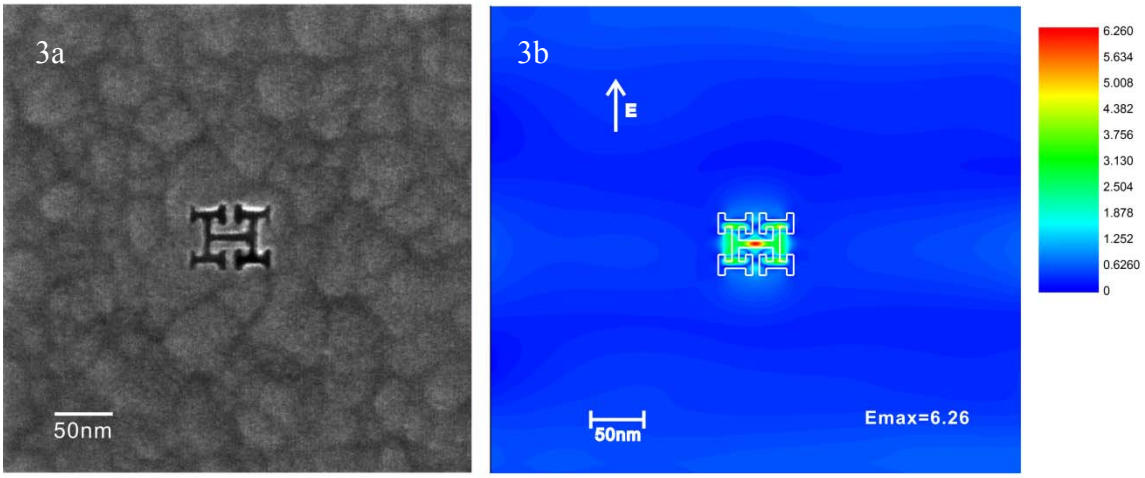


Figure 2: *Patterning on a nanoparticle:* 1st and 2nd order Hilbert fractals apertures with critical dimensions of 12.5nm and 10nm respectively. The line widths of the characters in 'NUS' are ~4.5nm. The patterning of the nanoparticle was performed as a patterning demonstration to avoid differential etching rates across different grain orientations, but could also be employed as a hybrid approach of fine-trimming structures made by alternative techniques. Deposition of single crystal films is also being explored for our devices.



Figures 3a,b *H-tree fractal:* A second order H-tree fractal with a line width of 6nm, Figure 2a. The sample is a 75nm thick silver film on a quartz substrate. FDTD analysis of the pattern at a distance of 1nm from the aperture, Figure 2b. The mode confinement is smaller than λ/25 (λ = 488nm) 1nm away from the aperture with an enhancement factor greater than 6.