Patterning of Sub-10 nm Optical Apertures on Single Crystal Metallic Films with the Helium Ion Microscope

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Metallic nanostructures, resonant at optical frequencies, provide controlled enhancement and concentration of electromagnetic energy in the near-field. One example is the enhanced transmission and field localization through sub-wavelength C-apertures on thin metallic films, where transmission gains of 6x and field enhancements of 550x have been reported by others.[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 used 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's tail, and the shift in the optical characteristics or quenching of the resonant metal's properties due to gallium implantation[3].

Last year (EIPBN 2011), we presented high order, sub-10 nm optical fractal apertures (free of implanted metal impurities) through optically thick, polycrystalline metallic films by employing a Helium Ion Microscope for direct patterning. Our initial measurements of the near-field mode profiles with electron energy loss spectroscopy (EELS) were encouraging, demonstrating tight field confinement in multiple modes as predicted, Figure 1a,b. However, the EELS measurements also revealed experimental challenges, evident in the finest featured devices (<30 nm) where asymmetrical field distributions and a significant deviation from the expected field profiles were often observed, Figure 2a,b. These studies suggested preferential etching of the polycrystalline grains, most likely the result of channeling. To avoid the influence of the grain orientation and grain boundaries on the patterns, we have extended our investigations to single crystal gold platelets (~100 nm in thickness). This has resulted in extremely high fidelity, optically-active resonant structures (down to 10 nm critical dimension), Figure 3 and Figures 4a-c. Controlled fabrication of structures on this size scale opens fascinating prospects for engineering complex multi-modal structures which were previously unrealizable by other techniques. We report our investigations in this arena and detail a variety of novel structures that are now accessible with this technique.

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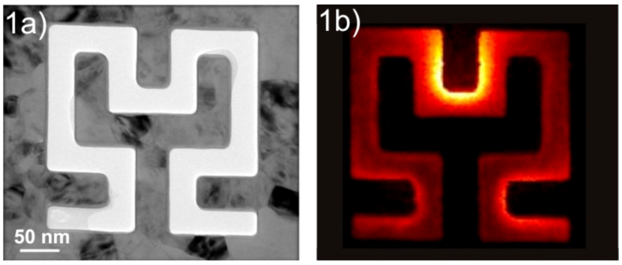


Figures 1a,b: *Hilbert fractal aperture with 40nm critical dimension in polycrystalline aluminum film:* The initial work on fractal extensions of the C aperture patterned directly on 60 nm aluminum films showed great promise by virtue of the nearly vertical side-walls, minimal interior rounding of corners and lack of implanted metal impurities (TEM image, 1a). Field distributions in qualitative agreement with our predictions were routinely achievable at this size scale.

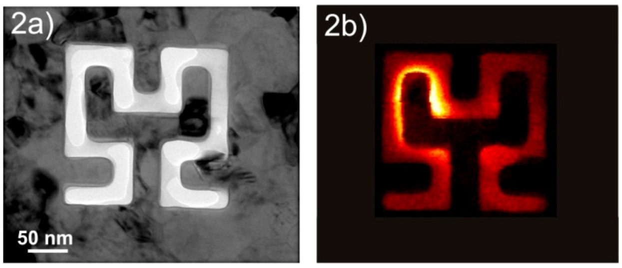
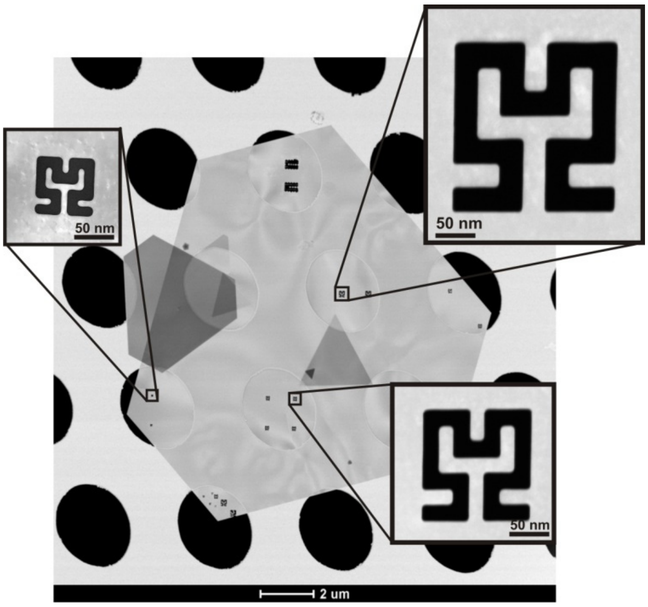
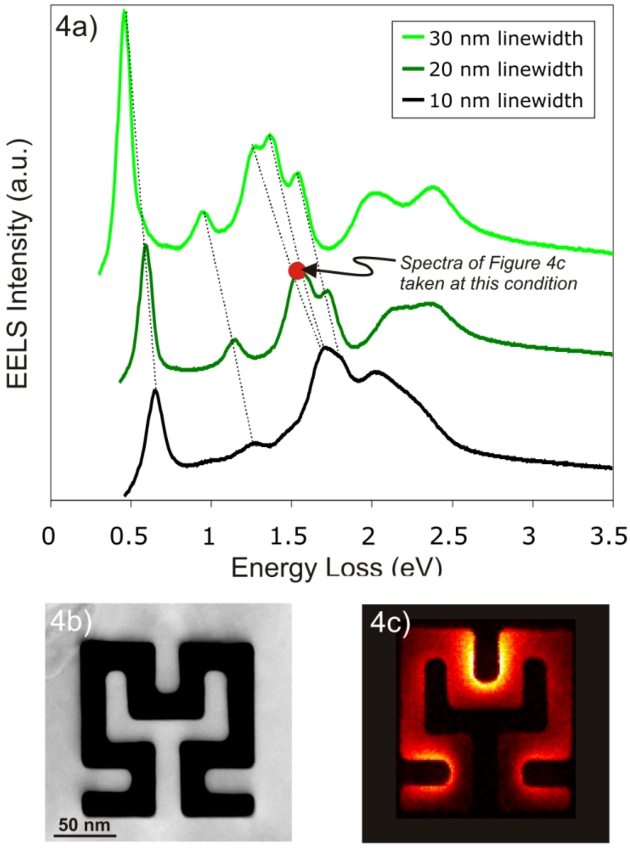


Figure 2a,b: *Hilbert fractal aperture with 30nm critical dimension in polycrystalline aluminum film:* The differential etching rates across varying grain orientations and incomplete removal became problematic at smaller dimensions, visible in the TEM micrograph of 2a. The resultant asymmetrical field distribution of one of the resonant modes (EELS map Fig. 2b) demonstrates the sensitivity of these structures to these variations, particularly at the smaller critical dimensions (< 30 nm).



Figures 3: *Fine patterns in single crystal gold platelets:* The gold platelets (~100 nm thick) were deposited on a conductive coated TEM grid (main figure) enabling EELS measurements and eliminating substrate effects. Many of the challenges encountered with the polycrystalline films were eliminated with this approach, and optically-active devices as small as 10 nm critical dimensions have been fabricated and measured. Three devices are shown (inset figures) 30 nm, 20 nm and 10 nm critical dimensions. The three inset figures are all at the same scale; scale bar indicating 50 nm.



Figures 4a-c: *Spectral and spatial modes of select fractal aperture geometries patterned in single crystal gold platelets:* The EELS spectra (Fig. 4a) reveal a complex modal structure with multiple resonances, with a blue-shift and convergence of resonant modes as the critical dimensions decrease. The spatial profile of one of the modes, as measured by EELS, is illustrated in Fig 4c, and corresponds to the resonance at 1.5 eV of the 20 nm critical dimension aperture (red dot in Fig. 4a). Fig. 4b is the STEM image corresponding to the same 20 nm aperture.