Patterning Plasmonic Nanostructures - Regimes of the Gallium Focused Ion Beam and Helium Ion Microscope

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Subwavelength control and enhancement of electromagnetic energy at optical frequencies achieved by engineering metallic nanoscale devices, provides spatial resolution in the near field beyond the diffraction limit[1,2]. Fabrication of metallic plasmonic structures requires sub-wavelength features and periodicity typically below 100nm. As the optical resonance spectrum shifts to higher frequencies towards the visible and UV, the feature size needs to be scaled down further to sub-10nm dimension. Direct patterning using focused gallium ion beam and helium ion microscope has been employed to fabricate plasmonic devices down to the nanometer scale[3,4]. In this work, we aim to determine the regimes that these two tools operate optimally and identify fundamental and engineering limitations.

In this work, a Zeiss Auriga CrossBeam (FIB-SEM) Workstation and a Zeiss Orion Plus Helium Ion Microscope are employed to fabricate 2nd order Hilbert fractal apertures[5] for plasmonic applications with the critical features ranging from 200 nm to 5 nm on a single crystal gold platelet, Figure 1. The high sputter yield of the gallium beam enables patterning large feature sizes within minutes. However, the smallest critical dimension of the pattern fabricated is limited to 40nm where the degradation of fine features due to the beam tail is observed. Furthermore, rounding of the edges and side wall taper at dimensions below 40 nm becomes significant and deteriorates the optical quality of the structures, Figure 2. Below 40nm critical dimensions, the Helium Ion Microscope can be employed to fabricate optically active structures down to sub-10nm scale. The long patterning duration due to the low sputter yield of the helium beam cause beam instabilities and drift limit the patterning of features with large dimensions (>100 nm). Further, the sub-surface helium implantation introduces limitations when patterning on metallic structures on a substrate. Numerical simulations have been performed to inspect and compare the near-field modal distribution with the experiments. The tunability of the resonance (IR to Vis) and the evolution of the various modes with dimensional scaling are also observed with these simulations, Figure 3. Far-field and near-field optical characterization are currently being performed on these devices and will be presented to evaluate the effects of the gallium contamination and the material properties of the patterned structures. These studies will enable to determine a clear operational regime of the focused gallium and helium beam.

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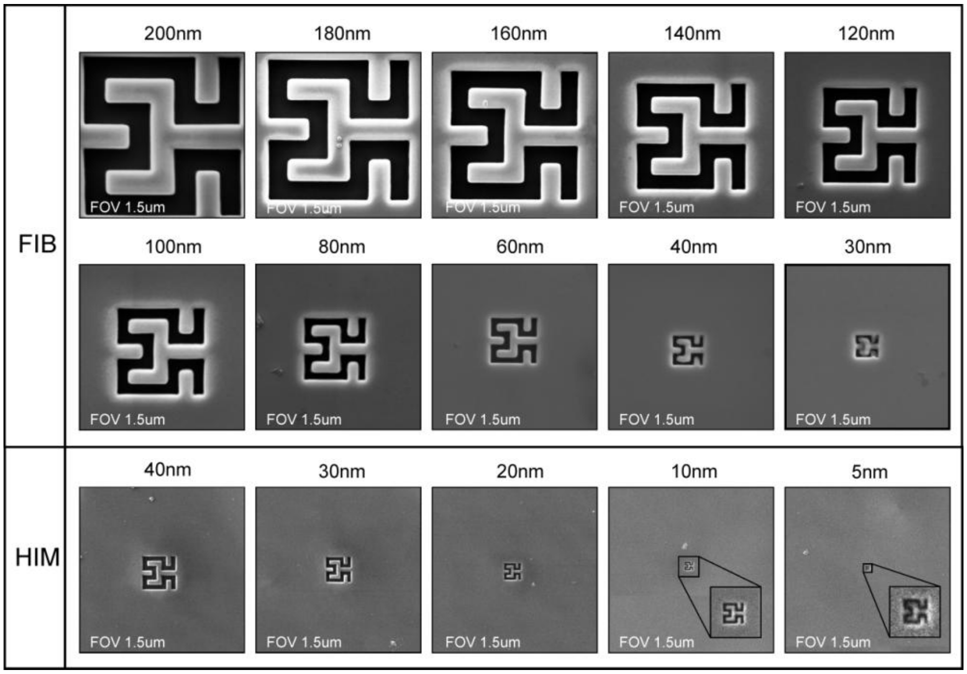

Figure 1. The 2^{nd} order Hilbert structures fabricated using focused Ga+ beam and He+ Ion beam on single crystalline gold platelet. The designed critical dimensions of these structures range from 200nm to 5nm as labeled on the top of each image. The SEM images in the FIB regime show that the finest feature can be achieved is around 40nm while Helium beam can push this limit to 5nm.

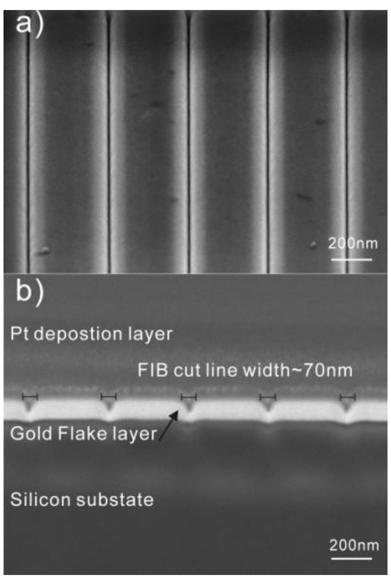

Figure 2. Investigation of the Beam tail of the Ga^+ beam. Single lines are patterned on the single crystalline gold flakes and cross-sectional cut reveal the size of the beam tail is around 70nm. This sets the limit of the finest possible features can be achieved.

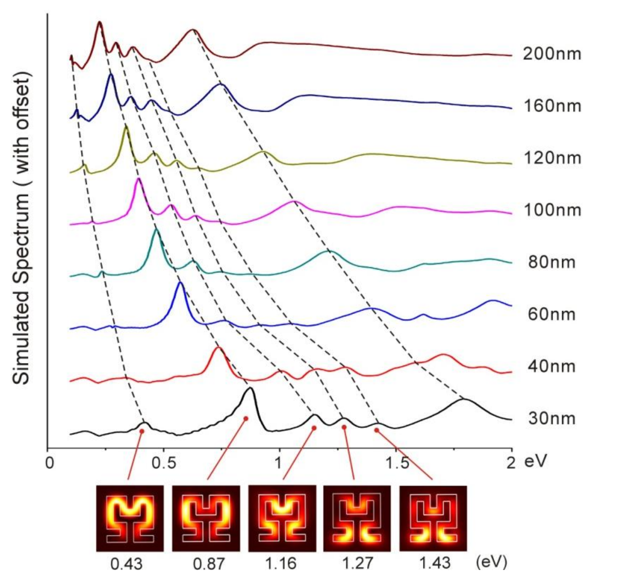

Figure 3. Simulated FDTD transmission spectrums for the 2^{nd} order Hilbert structures with critical dimensions from 200nm to 30 nm. The tunability of the resonance and the evolution of the various modes with dimensional scaling are observed. The resonance peaks covers from the IR to visible range. Resonance patterns for 30nm critical dimension case are listed to illustrate the field confinement.