Towards Sub-10 nm Nanofabrication of Plasmonic and Graphene Devices using Multiple Electron and Ion Beams

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Direct write focused ion beam (FIB) machining represents the quickest, most flexible method to fabricate nano-devices for prototyping and research applications. The use of a FIB combined with SEM allows for immediate inspection and refinement steps in the patterning, assuring the desired fidelity. This technology has thus found wide-spread use in fields such as photonics, nano-fluidics, TEM sample preparation, integrated circuit modification, and MEMS. Conventional gallium FIB based on the liquid metal ion source (LMIS) has many notable drawbacks which include the lower limit for feature sizes that can be achieved and Ga implantation.

As an illustrative example of machining over multiple length scales, we show here an example of a double bowtie plasmonic device, inspired by the work of Zhang1 and co-workers. The device consists of four equilateral triangles patterned into 17 nm thick Au films by electron beam lithography. These elements face into one another giving a shape like two crossed bowties. The dimensions of the device are critical to determine the resonant wavelength. The requirements are that the triangles have a side length of approximately 85 nm, with a radius of curvature of 10 nm at the vertices, and a gap between the points of the triangles of about 30 nm. The gaps are varied to alter the plasmonic response of the device. To date, lithographic methods are necessary to form such small objects since traditional Ga FIB does not have the requisite machining precision.

The Carl Zeiss ORION NanoFab allows these devices to be made by direct write using three different ion species and completely obviating the need for lithographic processing. The critical dimension can in fact be reduced even further. A three step approach was used to fabricate a double bowtie structure in a 100 nm thick gold film on a glass substrate2. During the first step, Ga FIB is used to open up a 1 µm square window into the film, while leaving behind a square island 200 nm wide in the center as shown in Figure 1. Gallium was used for this first step because it has a sputtering yield 120X higher than He and 4X higher than Ne (30 keV; as predicted by TRIM32simulations). The Ga FIB is also capable of higher total beam current for faster material removal of larger volumes. The second step consisted of using the neon beam in the gas field ion source to machine slits in the island which form a cross as demonstrated in Figure 2. Sputtering with Ne avoids Ga contamination into the critical area around the bowtie, yet still provides a 30x speed advantage over helium milling. The sidewall angle of the created features is 82º, but this could be improved with trimming by helium, which has shown, in the work by Scipioni et al.43 with sidewall angles of 88º. Finally, helium ion milling is utilized to separate the four triangular elements as represented in Figure 3. A top-down view of the completed device is presented in Figure 4. The active area of the device had never been exposed to the Ga beam. The fact that the results can be inspected immediately in-situ, using helium ion microscopy (HIM), also provides the quick feedback and process control that traditional FIB-SEM affords. Extremely tight dimensions can be maintained in the most critical area. Figure 5 shows the center of the bowtie structure. The image has been filtered to highlight the edges for measurement purposes. (We do note a small amount of residual material in the gap). The distance between the triangle vertices is 10 nm (line drawn on image), and the radius of curvature of the vertices is also 5 nm (circle drawn on image).

[1] Z. Zhang, et al., Nano Letters, 9, 4505 (2009)
[2] J Notte, "Charged Particle Microscopy: Why Mass Matters", Microscopy Today, 20(5), 16-22 (2012).
[3] http://www.srim.org/
[4] Larry Scipioni, et al., J. Vac. Sci. Technol. B 28(6), C6P18 (2010)

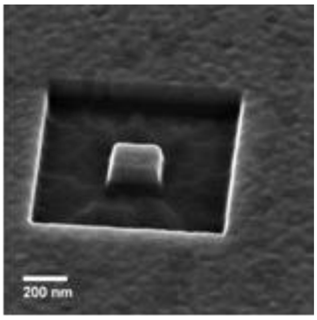

Figure 1: A 200 nm island of 100 nm thick Au on glass created by Ga FIB milling. Helium ion imaging.

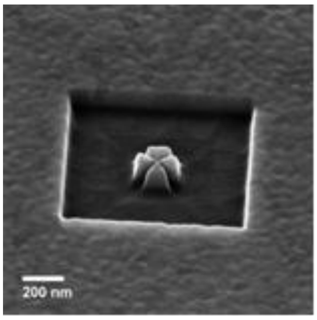

Figure 2: Machining of island with neon beam to form arms of double bow tie structure. Helium ion imaging

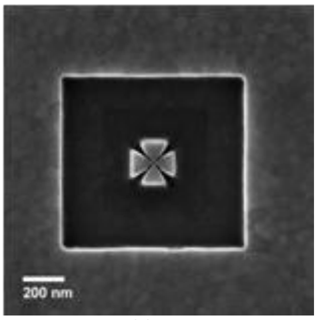

Figure 4: Top down image of final device. Helium ion imaging.

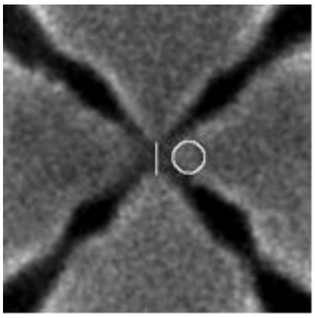

Figure 5: Edge-enhanced HIM image of center 100 nm area of double bow tie structure. Line drawn on image is 10 nm. Circle has radius of 5 nm.