White Paper

Plasmonic Devices Fabricated with Helium Ion Microscopy

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Plasmonic Devices Fabricated with Helium Ion Microscopy

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Localized surface plasmons (LSP's) are electron density oscillations, which are concentrated on the exterior of nanostructured materials. Research into plasmonic devices is an active field, with applications such as bio-sensing[1], chemical sensing[2], and photonics[3]. The size, shape, and composition of the nanostructures can all be engineered to produce a desired optical response to excitation. To give an example in the domain of photonics, massively parallel electron sources for high throughput lithography have been envisioned[4], based upon an array of C-shaped nano-apertures. Each aperture needs to be about 40 nm in dimension, with a sharply defined rectilinear boundary. In this and other applications, the ability to make structures with the required shape fidelity is critical to device performance.

Challenge

Creation of the requisite shapes requires a method with high spatial precision for nanofabrication. For example, the interparticle coupling between neighboring nano-particles grows in strength as $1/d^3$, where d is the gap between the objects. Thus it is desirable to have control over the gap on the nanometer scale. Bottom-up and self-assembly methods, while inexpensive, make precise positioning difficult, while top-down lithographic methods are more expensive and also limited in spatial precision[5]. Direct write of structures with the standard gallium focused ion beams (FIB), offers excellent structural control, but experience teaches that the minimum feature size obtain-able is on the order of 50 nm.

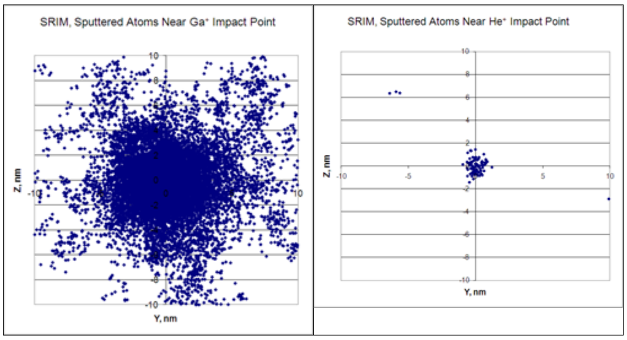

Figure 1.
TRIM-calculated origin of sputtering events. Left: incident 30 keV Ga ion beam. Right: incident 30 keV He ion beam.

[1] H.M. Hiep et al., Sci. Technol. Adv. Mat. 8 (4), 331 (2007).
[2] R.A. Potyrailo, Proc. Transducers '09 2378-2380 (2009).
[3] X. Shi and L. Hesselink, J. Opt. Soc. Am. B 21, 1305 (2004).
[4] ibid
[5] W.-S. Chang, PNAS 108 (50), 19879 (2011).

ORION NanoFab Solution

Using a beam of helium or neon ions from a high brightness gas field ion source, ORION NanoFab produces a sub-nanometer probe. In addition to this, the damage cascade from the ion impact into the sample is reduced for lighter ions. This can be seen in Figure 1, which shows the results of two TRIM[6] simulations. For an incoming point ion beam, the lateral damage from sputtering spreads out much further for a gallium ion beam than for helium. This enables the helium ion microscope (HIM) to be used for finer structuring, with a minimum machining precision of 3-5 nm (i.e. the smallest writable hole). This is to be compared to a value of 30-50 nm for Ga FIB. FDTD simulations[7] indicate that a bowtie antenna pair with 5 nm radius of curvature of the antenna elements and a 5 nm gap has a field enhancement 20 times higher than a structure where this critical dimension parameter is 30 nm. Finally, the advanced patterning engine in the ORION NanoFab allows a wide variety of structures to be designed and written in minutes.
To illustrate this by an example, the plasmonic response of opposing nano-antenna pairs were investigated. Samples had previously been prepared by dispersing nano-wires onto a TEM grid, and selecting pairs whose gap spacing was both of the correct magnitude and also positioned over an opening in the grid. It was difficult to obtain a pair with the desired gap. Samples also were fabricated by FIB and HIM, then characterized by HIM and TEM imaging, and also by energy filtered STEM (EF-STEM) to probe surface plasmon excitations. The samples used were 50 and 100 nm (nominal) thickness free-standing gold membranes, both single- and poly-crystalline.

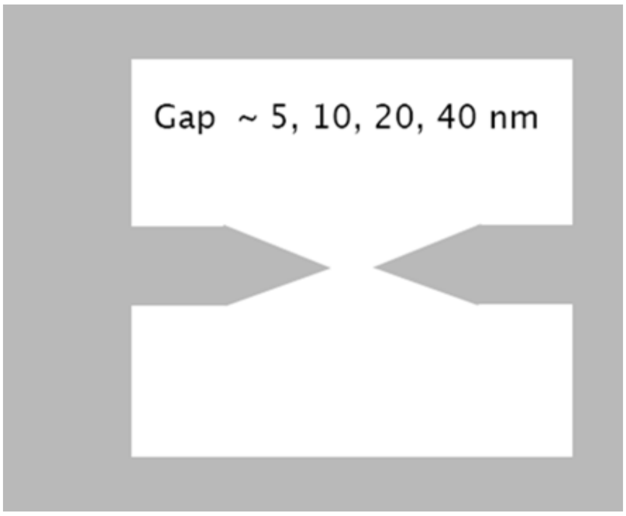

Figure 2
Antenna design sketch.

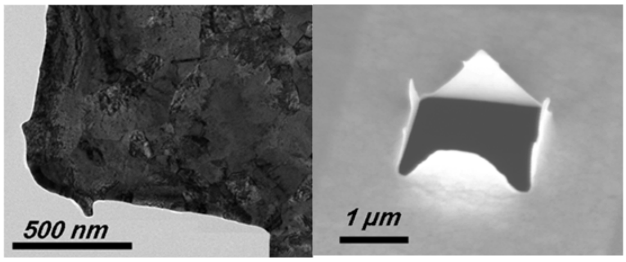

Figure 3
Left: TEM image of nano-antenna created by Ga FIB. Right: SEM image showing stress-induced buckling of antenna arms.

[6]www.srim.org
[7]Using the bowtie simulator available freely at https://nanohub.org/

The patterns to be created are shown in Figure 2. The intent was to vary the gap between them, down to a spacing of 5 nm. The first attempts to create these structures was carried out in a Ga FIB. The results of this are shown in Figure 3. Feature sizes smaller than 50 nm were not possible to obtain in this case, and the large amount of dislocations induced by the beam (observe the contrast variations in the TEM image) led to buckling of the antenna elements. Thus this method is not applicable to the problem at hand.
HIM was then tried to create this structure. Figure 4 shows the result of this: the fabrication took only a few minutes to accomplish, and both images reveal excellent shape fidelity. Antenna gaps down to 4 nm could be fashioned. The radius of curvature at the ends of the antennas is also just 4-5 nm. High resolution TEM imaging (Figure 5) reveals that the atomic level crystal structure is maintained with minimal disruption.
Thus we conclude that HIM machining can be applied to create structures that have the requisite single-digit nanometer sizing for devices of interest. Shape fidelity is excellent, and crystal structure experiences minimum disruption. The viability of the fabricated devices is evidenced by the plasmonic response observed. This technique, using both helium and neon ion beams, has been applied to a number of nano-devices, so it is seen to hold promise for a variety of related applications.

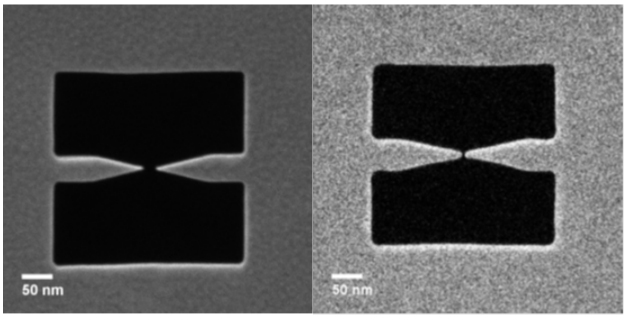

Figure 4

HIM-milled antenna pairs. Left: 20 nm gap; Right: 4 nm gap.

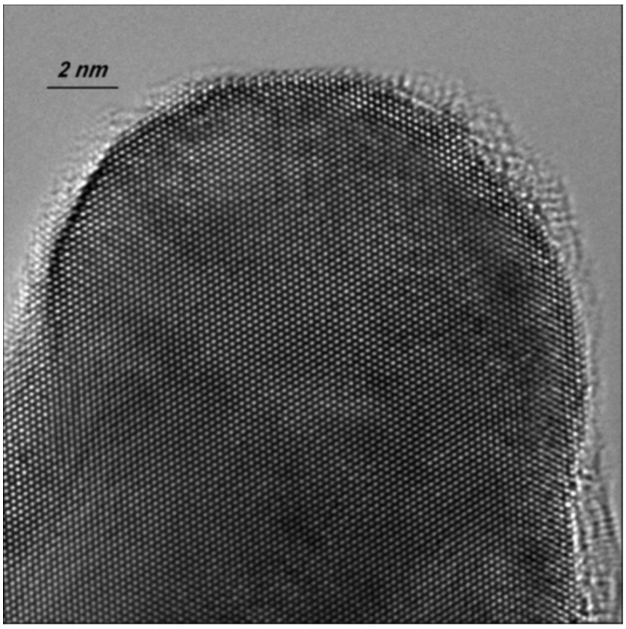

Figure 5

HR-TEM imaging of distal end of an antenna, formed by HIM ion milling.

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