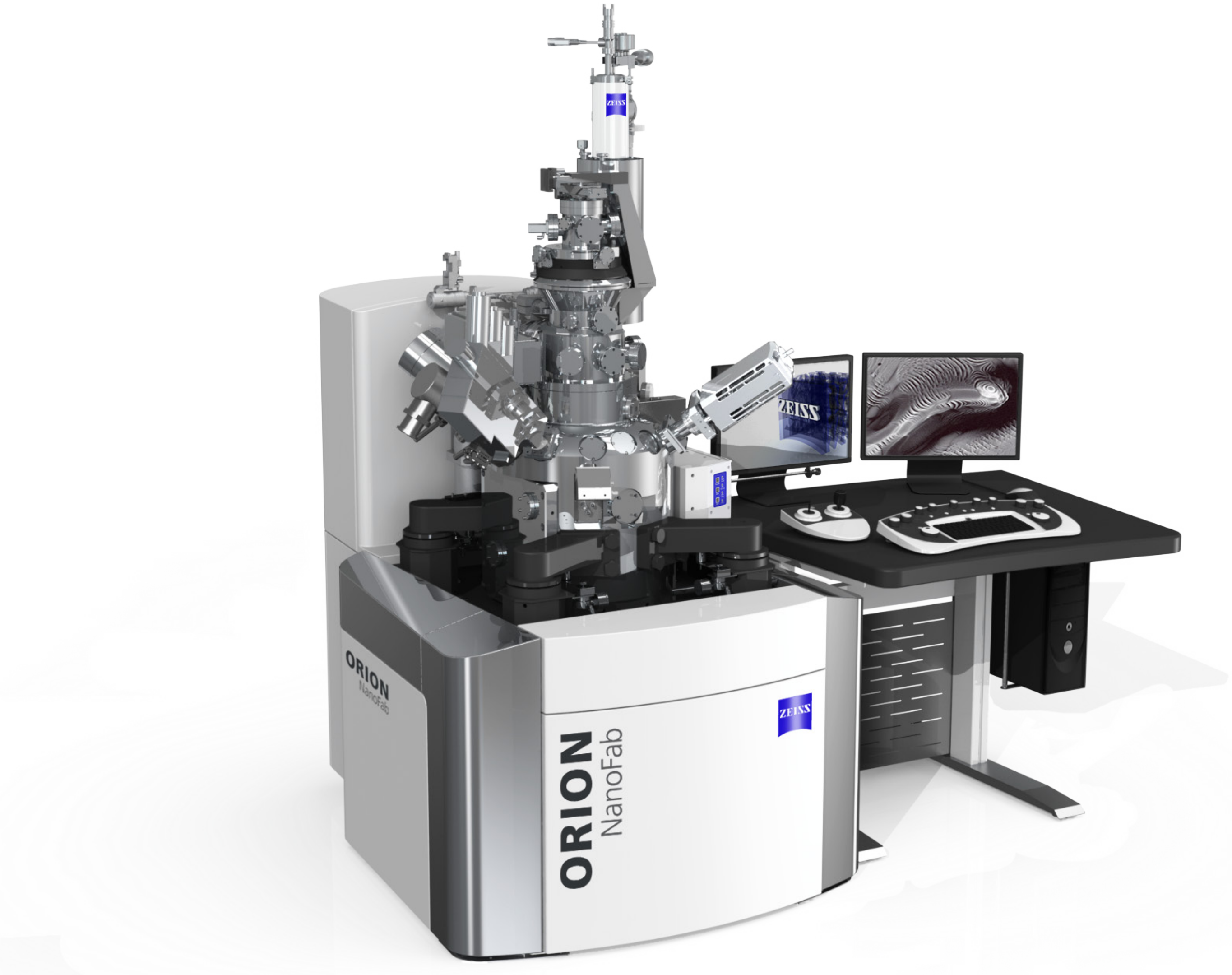
White Paper



Sub-10 nm Nano-machining with Multiple Ion Beams
for High Precision and High Throughput Applications

We make it visible.

Sub-10 nm Nano-machining with Multiple Ion Beams
for High Precision and High Throughput Applications

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Direct write focused ion beam (FIB) machining represents the quickest, most flexible method to fabricate nano-devices for prototyping or research applications. Most materials can be processed directly by ion beam sputtering, without excessive material selectivity as may be found with chemical etching. No masking is required, since pattern design packages can readily steer the beam in complex patterns with a high degree of control over the scanning strategy. The use of a FIB combined with an imaging column also 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.

The Challenge

The most commonly used ion beam for machining applications is the gallium FIB based on the liquid metal ion source (LMIS). Large beam currents and a significant sputtering yield provide good throughput and patterning fidelity in a device range from about a few tens of micrometers to a few tens of nanometers. However, there are some notable drawbacks to gallium FIB machining. One is the lower limit for feature size possible. Holes and slots are generally limited to 30-40 nm in breadth, and a fairly sloping sidewall angle means that the hole aspect ratio is somewhat limited. Another issue is that of gallium implantation. Photonic devices, for example, often consist of patterns formed in thin metal films on optical substrates. Contamination with metal ions will alter the dielectric response of the device in undesired ways. For electrical devices, gallium ion implantation can create unintended resistive pathways. Finally, for materials containing group III elements (Al, Ga, In – such as in III-V semiconductors) the additional amount of gallium implanted by the beam causes chemical changes and even phase separations in those compounds[1].

ORION NanoFab Solution

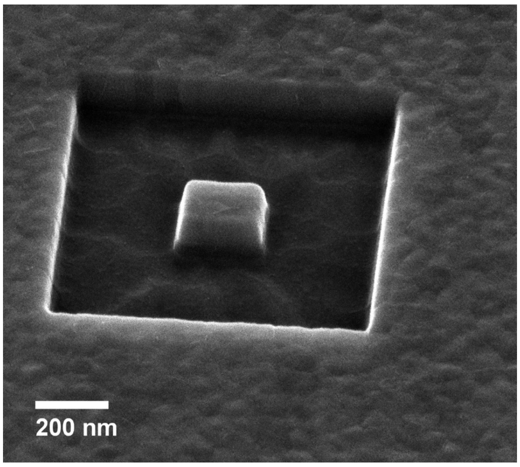
The ORION NanoFab combines up to three ion beams in one instrument: helium and neon from the unique Gas Field Ion Source (GFIS) column, and a separate high resolution gallium FIB column. With this solution, larger volumes can be removed with Ga at higher speeds, while neon and helium can be utilized for smaller feature dimensions. For example, helium ion machining has been demonstrated to accomplish nanofabrication down to a dimension of about 5 nm, with almost vertical sidewalls in gold films.[2] Metallic contamination is eliminated when using inert gas ion beams for the ion milling. To complete the set of tools for device design, machining strategies of high complexity can be realized with the ZEISS Nano-Patterning and Visualization Engine (NPVE). This hardware and software combination allows a great variety of beam writing shapes, scanning routines, and ion dose factors to be incorporated into user-defined recipes. Rapid device definition can be accomplished from designs imported from CAD, from bitmaps, or simply built up on the screen from fundamental elements.

[1] See for example the Carl Zeiss application note, "Applications of Cryo-FIB on Ga-beam Sensitive Materials".
[2] Larry Scipioni, et al., J. Vac. Sci. Technol. B 28(6), C6P18 (2010).

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 Zhang 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, so we note that the requirements are that the triangles have a side length of about 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.) Lithographic methods are necessary to form such small objects, since the traditional Ga FIB does not have the requisite machining precision.

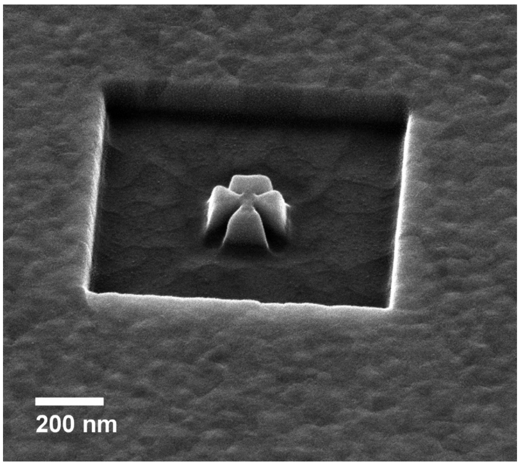
With ORION NanoFab solution, these devices can be made by direct write, completely obviating the need for lithographic processing. The critical dimension can be reduced even further, in fact. A three step approach was used to fabricate a double bowtie structure in a 100 nm thick gold film on glass. In the first step, a 1 µm square window is opened into the film, but leaving in the center a square island 200 nm wide – see Figure 1. Ga FIB was used for this step, as it has a sputtering yield 120x higher than He and 4x higher than neon at the beam energy applied (30 keV; as predicted by TRIM simulations). FIB is also capable of higher total beam current. In the second step, neon based machining produced slits in the island, forming a cross – see Figure 2. This method avoids putting Ga contamination into the critical area around the bowtie, but still provides a 30x speed advantage over helium milling. The sidewall angle of the created features is 82°, but this could be improved with trimming by helium, which has shown, in the work by Scipioni et al. (already referenced) sidewall angles of 88°. Finally, helium ion milling is utilized to separate the four triangular elements – see Figure 3. A top-down view of the completed device is seen in Figure 4. Again, this area of the device never had to be exposed to the Ga beam.The fact that the results can be inspected immediately in-situ, using HIM, also provides the quick feedback and process control that traditional FIB-SEM affords.

Figure 1



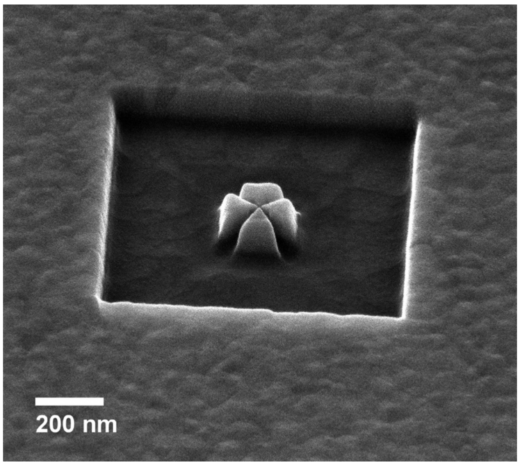
A 200 nm island created by Ga FIB milling. HIM imaging

Figure 2



Machining of island with neon beam to form arms of double bowtie. HIM imaging.

Figure 3

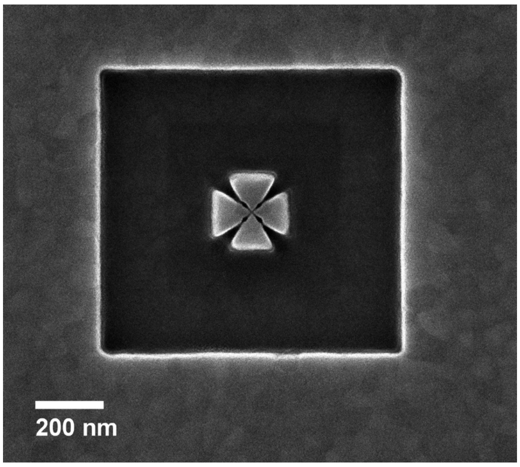


Final machining with helium beam to separate the four elements

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).

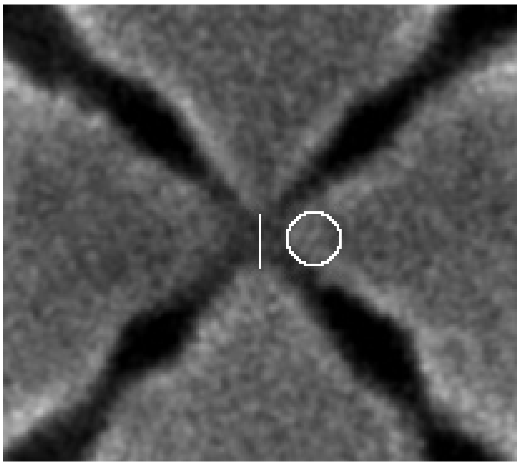
In conclusion, the ORION NanoFab multiple beam solution permits direct write ion machining from the meso-scale provided by FIB down to the nanometer scale made possible by HIM. This integrated instrument provides throughput, flexibility, and device dimension gains over what is possible with lithographic or FIB-only approaches.

Figure 4



Top-down HIM image of final device.

Figure 5



Edge-enhanced HIM image of center 100 nm area of double bowtie. Line drawn on image is 10 nm.

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