

## Helium and Neon Ion Beam Lithography with ORION NanoFab



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Author: Dr. Larry Scipioni,  
*Carl Zeiss Microscopy, LLC, USA*  
Dr. Donald Winston,  
*HP Labs, USA*

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## Application

Direct write lithography in resists for creating high feature density structures with critical dimensions below ten nanometers. This is applicable in nanotechnology research, template fabrication, and device prototyping.

## ORION NanoFab Capabilities

Small writing probe size, unique beam-sample interactions, external pattern engine integration dense pattern writing.

## Background

Direct write lithography is used in all phases of nanotechnology development activities. In research, it is utilized to create nanostructures into which functional materials can be patterned on the nano-scale. In process development, direct patterning allows the flexible creation of devices with varying features to optimize behavior. In manufacturing of semiconductors and data storage devices, direct write exposure with focused beams provides master patterns for processes such as photolithography and nano-imprint lithography.

## Challenge

The fabrication of ever smaller devices pushes the demands on lithography. Feature size and density are the two main considerations in this regime. Ion beam writing offers advantages in reduced proximity effects – allowing ideally for higher feature density, as is often defined by the lithographic half-pitch (half the distance between the most densely packed features). Ion beam writing also offers greater sensitivity. Traditional FIB, based on the liquid metal ion source, does not offer a small enough probe to make the smallest features and hence take advantage of its benefits. Electron beam writing can provide a smaller probe and thus has been the dominant technology for lithography.

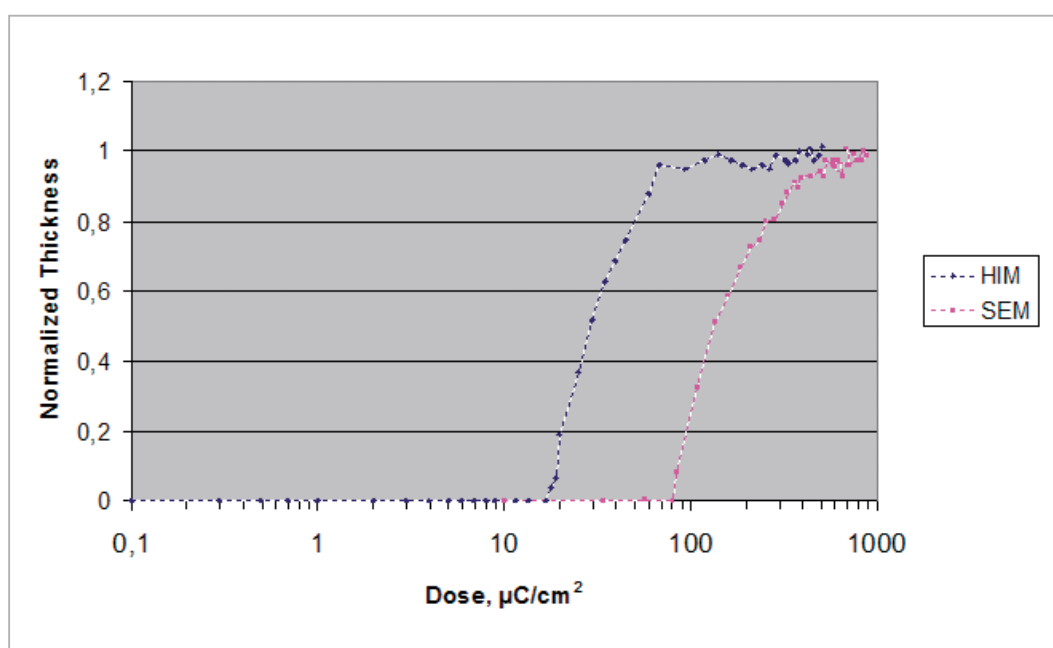
## ORION NanoFab Capabilities

The helium ion microscope (HIM) provides a probe combining the small size available in electron beam systems with the favorable proximity effects of an ion. In fact, the nature of the beam-sample interactions for a helium ion is different from that of any other particle used for FIB, which should allow for even more localization in writing. Some HIM users have begun to do characterization of direct write lithography, and we will highlight some of the achievements here as an illustration of what can be done and also to point to the future research opportunities. The work described herein was carried out by Vadim Sidorkin<sup>1</sup> and co-workers from the Delft University of Technology and from TNO Science and Industry in Delft, The Netherlands. The work involving neon ion beam lithography was done by Donny Winston and co-workers from MIT, USA.

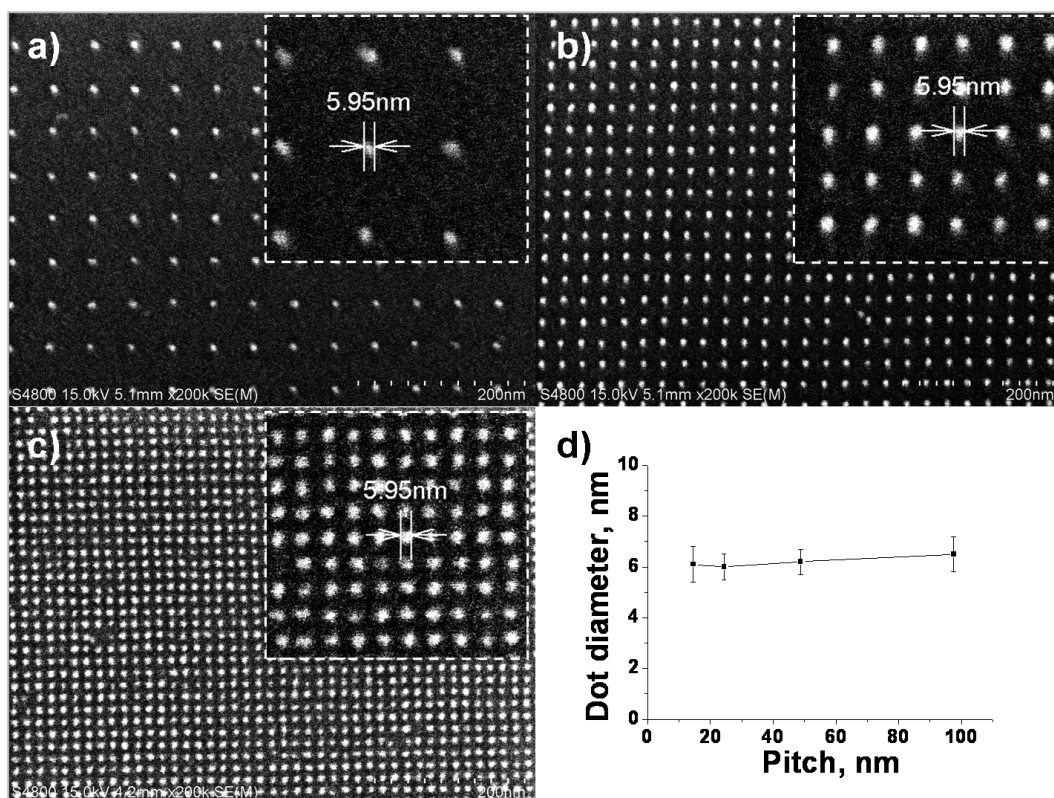
A lithography application requires two basic components. The first need is a thin film of material (resist) which will alter chemically when irradiated with the beam, becoming either resistant to dissolving during the development step (negative tone) or becoming more soluble (positive tone). The second need is a method to address the beam according to a pattern that is desired to be written. ORION NanoFab offers two methods for accomplishing this. The system software offers the user an interface to set all the parameters that define an exposure. The total dose applied can be set using one of several measurement units, with the beam current being provided from the beam blanking unit in the ion column. The user defines a rectangular scanning area with arbitrary size and orientation. Either pixel density or spacing can be set within the box. The scanning pattern is also user selectable, with raster and serpentine scans in any orientation within the box. One can also acquire imaging signal during the operation. The scan parameters can also be saved as presets, for quick recollection and re-use. It is also possible within the user interface to import a bitmap with 256 gray levels to drive the scan. In this case, the relative dose at each pixel is defined by the gray level of the bitmap. For more complex patterns, or for more flexibility, the system is capable of being driven by an external pattern generator. There are several commercially available generators that offer advanced functionality and which have already been successfully implemented on the microscope.

For the work described here, initial characterization of resist behavior under helium ion writing was carried out. Hydrogen silsesquioxane (HSQ) resist films of thickness from 5 nm to 70 nm were prepared on silicon substrates. The first measurements were of resist sensitivity and contrast. This was carried out by exposing square areas under HIM with a 75 pA beam current, with the results displayed in Figure 1. This shows the normalized thickness remaining in this negative tone resist after development, as a function of dose. The resist became fully exposed at a dose 4.4 x less than for electron beam exposure, carried out in SEM. The contrast is similar for the two beams, so that the threshold between the "written" and "not written" states of the resist has equal performance in HIM.

The intriguing application result is the ability to write dense features. Figure 2 shows the result from writing an array of dots in 5 nm thick HSQ. A dot writing size of  $6 \text{ nm} \pm 1 \text{ nm}$  was achieved from a 1 pA beam at 100  $\mu\text{sec}$  exposure time per dot. Most interesting is the fact that the dot size experienced no measurable proximity effect from the density of the array, even down to a half-pitch of 7 nm. This means that about 25 % of the area could be exposed with 6 nm resolution. To illustrate the throughput capability of this, a  $10 \mu\text{m} \times 10 \mu\text{m}$  area can be written with such pixel density in about 70 seconds. For thicker resist layers, the dot size does grow.



**Figure 1**  
Response of HSQ under  $\text{He}^+$   
and electron exposure.

**Figure 2**

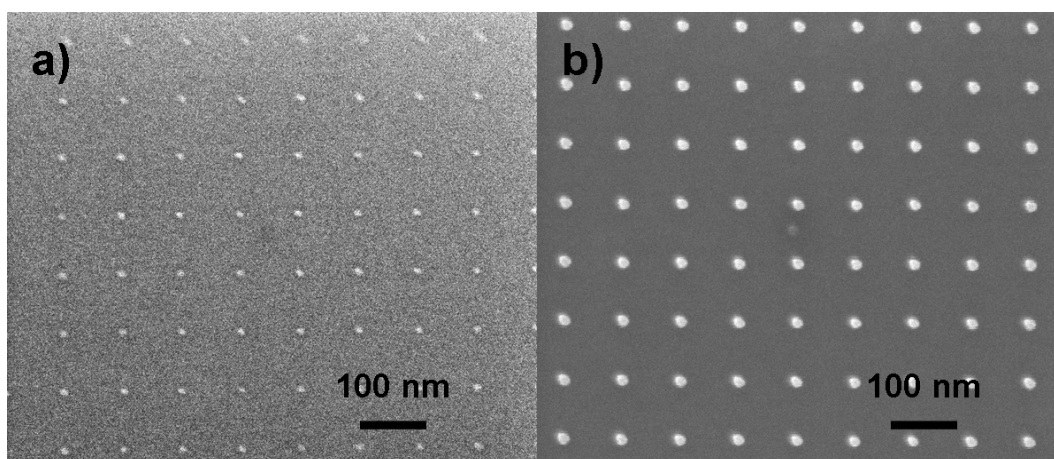
*Dot exposures in HSQ.*

*a) 48 nm pitch,*

*b) 24 nm pitch,*

*c) 14 nm pitch,*

*d) plot of dot diameter vs. pitch.*

**Figure 3**

*Dot exposures in HSQ.*

*Left: 5 nm thick resist.*

*Right: 55 nm thick resist.*

Figure 3 shows 6 nm dots obtained in thin resist as compared to 14 nm dots in the thicker sample. The resist, however, is 10x thicker in the latter case, so the aspect ratio of the features created grew from 1.3 to 3.9. This could offer a greater flexibility in 3D structuring.

We see in conclusion that lithography by HIM is a viable method that holds promise for high resolution, high density pattern creation. The tool also has the hardware and software features needed, including the external pattern generator interface, to write complex scans.

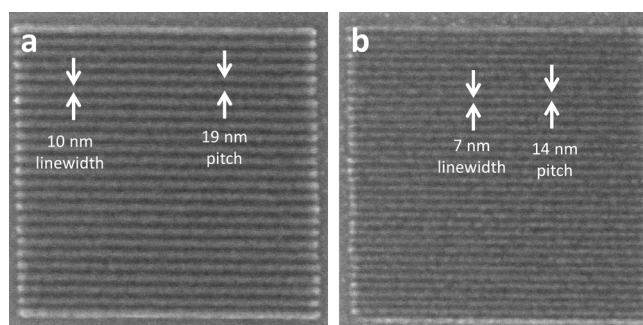


### Advancing to Neon Ion Beam Lithography

Neon ions may also be used for resist-based lithography. Using the same basic process as described previously for helium ions, patterns at sub-10 nm half-pitch have been resolved (see Figure 1)<sup>2</sup>. The principal difference between neon ions and helium ions for writing fine lines is that fewer neon ions per nm are required to be delivered to sufficiently expose the resist. For 20 keV Ne<sup>+</sup>, 7× fewer ions/nm are required relative to 30 keV He<sup>+</sup> for developing fine lines in hydrogen silsesquioxane (HSQ) resist of sub-20 nm thickness using the aforementioned salty developer.

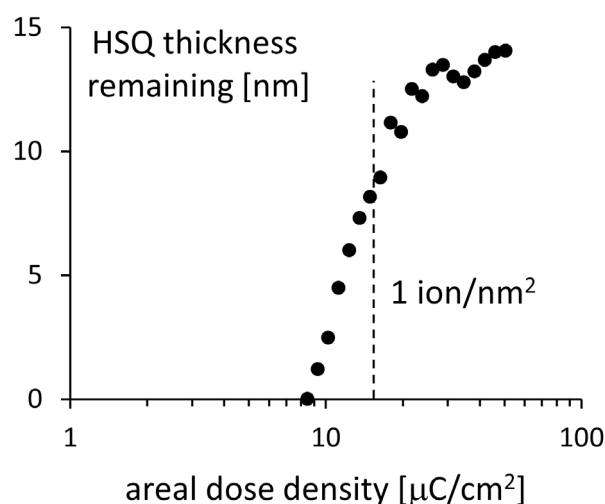
One issue to bear in mind is shot noise. Given an ion beam of 2 nm full-width at half maximum, one should deliver an areal dose density  $\geq 18 \mu\text{C}/\text{cm}^2$  to obtain a ca. 1 nm statistical uncertainty in average linewidth and ripple along the edge of a patterned line<sup>2,3</sup>, even if less dose is necessary for exposure of (rougher-edged) features. As Figure 2 shows, the sensitivity of the HSQ process with 20 keV Ne<sup>+</sup> is near this shot noise limit; thus, with this resist process one may take full advantage of the exposure efficiency of neon ions. For greater exposition on resist-based lithography using He and Ne ions, you may consult a recent dissertation on this topic<sup>4</sup>.

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**Figure 1:**

Scanning electron micrographs of developed gratings written into 16 nm thick hydrogen silsesquioxane (HSQ) on Si using 20 keV Ne<sup>+</sup>. (a) 19 nm pitch gratings written using a linear dose density of 7 ions/nm. (b) 14 nm pitch gratings written using a linear dose density of 5 ions/nm.



**Figure 2:**

A contrast curve for exposure by 20 keV Ne<sup>+</sup> of 16 nm-thick HSQ on Si. A dose array of  $1 \mu\text{m} \times 1 \mu\text{m}$  pads were exposed and, after development, heights of pads were measured using AFM. The onset areal dose density was found to be  $< 1 \text{ ion}/\text{nm}^2 \approx 16 \mu\text{C}/\text{cm}^2$ .

### References:

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