Helium Ion Beam Processing for Nanofabrication and Beam-Induced Chemistry

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INTRODUCTION
Charged particle optical beams have wide use for the creation of nanostructures. Such systems offer the flexibility for arbitrary pattern definition and also the highest spatial resolution. In this article we discuss two examples where the helium ion microscope (HIM) shows the ability to write small, dense patterns that will be enablers for advanced nanofabrication applications. The first of these examples is direct-write lithography in a resist, and the second is the deposition of small features utilizing beam-induced chemistry. We will consider both of these in turn.

DIRECT-WRITE LITHOGRAPHY
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 nanoscale. In process development, direct patterning allows the flexible creation of devices with varying features to optimize behavior. In the 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. Traditional focused ion beams (FIB), based on the liquid metal ion source, cannot produce a sufficiently focused probe to make the smallest features, and the technique is inherently damaging due to sputtering. Electron beam writing can provide a smaller probe and thus has been the dominant technology for lithography. The fabrication of advanced devices puts higher demands on lithography, however. Feature size and density are the two main considerations in this regime. As we will see below, helium 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).

NANOLITHOGRAPHY WITH A HELIUM ION MICROSCOPE
HIM provides a probe combining the small size available in electron beam systems with the favorable proximity effects of a helium ion. This reduced proximity effect can be understood considering the deep penetration distance of helium into materials. The beam remains highly collimated near the surface, whereas the resist is being exposed. 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 here was carried out using an Orion Plus helium ion microscope from Carl Zeiss NTS. A lithography application requires two basic components. The first is a thin film of material (resist) which will alter chemically when irradiated with the beam, becoming either insoluble against 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. The need to write complex patterns is usually taken care of by driving the beam steering with an add-on lithography package. 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, an Elphy Plus (Raith GmbH) pattern generator was used.

Figure 1: Response of hydrogen silsesquioxane (HSQ) under helium ion and electron exposure.

BIOGRAPHY
Paul Alkemade earned his PhD at Utrecht University on surface analysis with MeV helium ion beams. He was a postdoc at the University of Western Ontario in London, Canada. Since 1990 he has held a position at the Delft University of Technology, originally on secondary ion mass spectrometry. Currently, he is an associate professor at the Kavli Institute of Nanoscience in Delft. His present research interests includes particle beam technologies for nanofabrication. He has published over 130 papers in peer-reviewed scientific journals.

KEYWORDS
helium ion microscopy, scanning electron microscopy, focused ion beam, lithography, nanostructures, nanopatterning.

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As a first step, 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 5 pA beam current. The results of this are 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 $2000 \times$ less than for electron beam exposure, which was carried out in a 100-keV electron beam lithography tool. 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 a 5 nm thick HSQ resist. A dot writing size of $6 \times 1$ nm was achieved from a 1 pA beam at 100 µs exposure time per dot. Most interesting is the fact that the dot size showed no measurable proximity effect due to 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 µm $\times$ 10 µm area can be written with such pixel density in about 70 seconds. For thicker resist layers, the dot size does grow. Figure 3 shows 6 nm dots obtained in thin resist as compared to 14 nm dots which were obtained in the thicker sample. The resist, however, is 10$\times$ 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.

**BEAM INDUCED CHEMISTRY**

Another commonly used technique for nanofabrication in charged particle microscopes is direct write using beam-induced chemistry. For this purpose, gas injection systems (GIS) are commonly employed on SEM and FIB tools. The use of the beam to induce local chemical reactions on a substrate allows direct writing of nanostructures without the added pattern transfer steps that lithography requires. One can carry out both additive (deposition) and subtractive (etch) writing processes. Deposited features from metal-bearing precursor gases, in particular, can be used to create devices with tailored electromagnetic responses: they can provide conductive pathways and electrical contacts to other small features of interest; they can be used to...
introduce topology, such as for anchoring biomolecules to a surface in a predetermined pattern, or give protection (coating) for objects already on the substrate. Since deposited material will grow upon itself as well, three dimensional objects can also be grown, which is quite difficult to do with conventional lithography. This technology is thus applied in fundamental research. Semiconductor manufacturing also makes use of such processes for photomask repair and circuit editing.

We have been exploring beam chemistry for the last year. The HIM can be equipped with an Omniprobe (Omniprobe) and currently can run deposition of platinum and insulator (from TEOs), as well as etching with XeF$_2$. The first goal is to determine the size of the structures that can be realized. We have been looking to date at two types of small structures grown with Pt deposition: lines and pillars. Small feature size and tight patterning pitch can indeed be achieved. Figure 4 shows, by way of comparison, what can be expected for pillars created by conventional gallium LMIS FIB. The structures have large minimum diameter (160 nm) and extremely rough profiles. There is also a considerable proximity effect, in that two adjacent pillars must be more than 2500 nm apart during growth, or else the size of one will be affected by the presence of the other.

Pillars are formed by exposing one spot on the sample to the beam during gas flow. Pillar height and diameter are the two features of interest to control. These are determined by the ion current and dose. To grow a higher pillar, more exposure time at low current is used; to obtain a wider pillar, more beam current is applied. As can be seen in Figure 5, the narrowest pillar obtained to date is 36 nm in diameter, grown at 0.8 pA beam current. Note that this is 4.5x smaller than what can be obtained with a Ga$^+$ FIB. The volume growth rate, however, is equivalent to the rate for Ga FIB processes. The pillars grow with a conical pointed top, as can also be seen in Figure 5. This pointed top also demonstrates that negligible sputtering is occurring in HIM. The pillars also can be grown closer to one another, as compared to Ga$^+$ FIB processed structures, due to the reduced proximity effect when using the helium ion beam. It can be seen in Figure 6 that programmed spacing between adjacent pillars can be as low as 200 nm.

Lines are grown along the substrate surface by scanning the beam along a desired path. Using a small pixel spacing along this path ensures that the deposits from neighbouring pixels overlap, yielding a continuous line. 15 nm wide lines can be obtained. Figure 7 shows a set of five lines grown with a 15 nm width and 100 nm pitch. The minimum pitch that has been obtained by the ideal recipe is 30 nm – that is a 1:1 line:space ratio. If one considers that the deposition occurring at each pixel is simply the conical top to a pillar, then increasing the number of repeats used will grow the base, influencing both line width and height. Looking at Figure 8 we can appreciate that the proximity effect is quite low, since the lines on the ends have the same shape as those in the middle of the array.

**CONCLUSION**

We see that nanostructuring by a helium ion beam is a viable method that holds promise for high-resolution, high-density pattern creation. Lithography can be carried out readily and shows no observable proximity effects. Deposition of Pt features in HIM shows great ability to achieve small features and increased feature density as compared to Ga FIB. The tool also has the hardware and software features needed, including the external pattern generator interface, to write complex scans.

**REFERENCES**


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