Proximity Effect Quantification and Dose Optimisation for High Resolution Helium Ion Beam Lithography

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The development of nanoelectronic devices relies on patterning technologies based on the controlled modification of thin films of resist and the subsequent transfer of the generated pattern into an underlying substrate. Electron beam lithography (EBL) has been the workhorse for defining high resolution nanostructures for decades. However, with the demand for ever smaller feature dimensions, new lithographic techniques are emerging to extend beyond existing limits of EBL. The recent development of the helium ion beam lithography (HIBL) has introduced an alternative to EBL. Preliminary studies have shown that HIBL has several advantages over EBL, including a higher patterning resolution due to a smaller, sub-nanometer spot size [1] and a greatly reduced proximity effect, enabling high density pattern definition whilst avoiding the inadvertent exposure of surrounding material [2, 3]. Here, we present a quantitative study on proximity effect in HIBL using poly(methyl methacrylate) (PMMA), an established benchmark EBL resist, and an investigation into dose optimisation for high resolution HIBL patterning.

Silicon wafers were spin coated with 20 nm thick films of PMMA. Following a pre-exposure bake, the samples were loaded into a helium ion microscope (HIM, Zeiss Orion Plus). Samples were exposed with a 30 keV focused helium ion beam and developed in MIBK/IPA (1:3) to produce various patterns which were then imaged using HIM and atomic force microscopy (AFM).

The dose response curve (Figure 1) obtained from the large area exposures reveals that PMMA exhibits positive tone behaviour at low doses and negative tone at high doses, similar to its behaviour in EBL. High sensitivity is confirmed with full exposure (no resist remaining) achieved with a helium ion dose of only ~2 μC/cm^2 which is two orders of magnitude more sensitive than EBL. Using the doughnut method described by Stevens et al. [4], the proximity effect in HIBL is quantified with the standard deviation of the backscattered ions distribution found to be approximately 36 nm (Figure 2). This value is typically several microns in EBL [4], indicating the significantly lower proximity effect associated with HIBL. Arrays of single pixel lines were exposed using a range of doses to determine the limits of HIBL pattern definition in PMMA (Figure 3). Well-defined lines with widths of approximately 20 nm were achieved (see Figure 3b and corresponding contrast line profile). High resolution AFM scans (e.g. Figure 4) show good correspondence with the HIM images and verify positive tone exposure of narrow lines.

These results collectively demonstrate the potential of the HIM as a high resolution patterning tool for nanofabrication, in addition to its state-of-the-art imaging capabilities.

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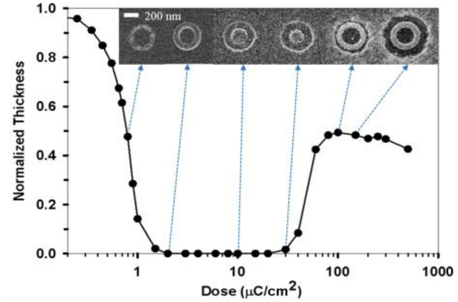

Figure 1. Dose response curve for 20 nm thick PMMA revealing full clearance at 2 μC/cm^2. HIM images of doughnut structures demonstrate both positive and negative behaviour of PMMA upon helium ion exposure and subsequent development.

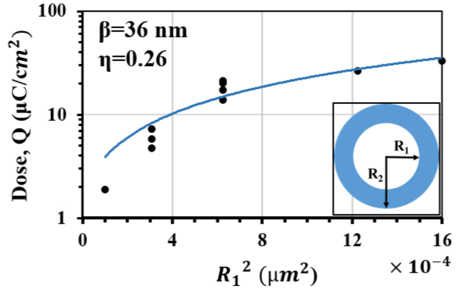

Figure 2. Doughnut arrays (diagram enclosed) with fixed R_2 and various R_1 were used in quantification of proximity effect of SHIBL on PMMA. Preliminary results show backscattered ions distribution of 36 nm and backscatter coefficient of 0.26.

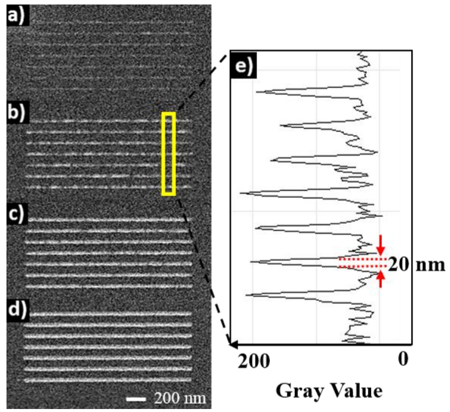

Figure 3. HIM image of single pixel lines on 20 nm PMMA with line doses of **a)** 2, **b)** 3, **c)** 4 and **d)** 7 pC/cm. Line widths of approximately 20 nm were confirmed from the secondary electron (SE) contrast line profile **e)**.

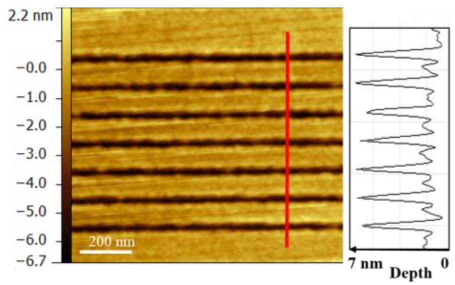

Figure 4. AFM image and line profile of pattern **b)** in Figure 3 demonstrating positive tone exposure as the bright lines in the HIM image correspond to the trenches in AFM scan.