

# Milling of extremely thin silicon-on-insulator using the helium ion microscope

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Keywords: Helium ion microscope, nanofabrication, SOI

The helium ion microscope (HIM) is emerging as a promising tool for nanofabrication, in addition to providing high resolution surface imaging [1]. This is owing to its ability to generate a pico-amp beam of helium ions focused to a sub-nm probe which can be scanned across a surface in any defined pattern with the use of the integrated (or an external) pattern generator. Three forms of nanofabrication are being developed with the HIM: Firstly, exposure of thin layers of resist in a process analogous to electron beam lithography is being investigated for defining nanoscale patterns [2]. Secondly, augmenting the microscope with a gas injection system allows the localised deposition of material in a process analogous to ion beam induced deposition in a Ga Focused Ion Beam (FIB) [3]. Thirdly, the direct ablation of material with the helium beam is being developed as a nano-milling process to go beyond what is possible with Ga FIB milling, enabling finer features to be defined, whilst avoiding Ga contamination [4], [5]. This third type of nanofabrication process is the focus of the work presented here, with the HIM being used for direct milling of surface material to define fine patterns in extremely thin (<10 nm) silicon-on-insulator (SOI) samples. The potential for higher resolution patterning compared to what is achievable with conventional technologies could find applications in the rapid prototyping of next-generation field effect transistors and novel spin qubit devices.

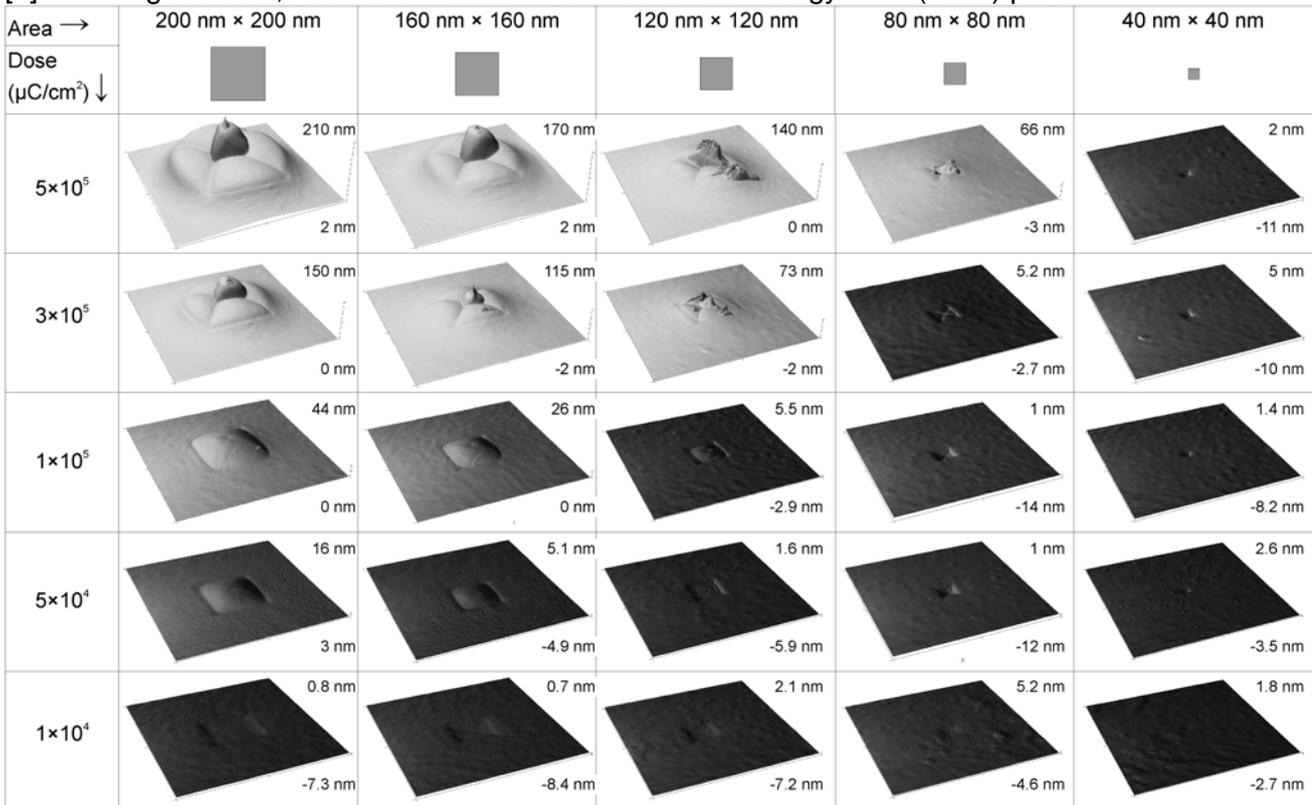
The top silicon layer on an SOI wafer was thinned from 100 nm to ~7 nm through a series of oxidations and HF etching treatments. A section of the wafer was then exposed to the helium beam in the HIM in a series of square areas with edge lengths of 40, 80, 120, 160 and 200 nm, using various doses from  $1 \times 10^4$  to  $5 \times 10^5$   $\mu\text{C}/\text{cm}^2$ , controlled by varying the dwell time. The exposed areas were then analysed by atomic force microscopy (AFM) to reveal the modified surface profiles.

Three-dimension renderings of the AFM data (Figure 1) reveal substantial variations in the resulting features, from depressions or trenches down to depths of ~12 nm to large protuberances with heights of several 100 nm as the exposed area and dose are varied. In general, smaller areas and lower doses lead to trenches, as expected from the removal of surface material through sputtering by the helium beam. Cross sections of the protuberances formed for larger areas and higher doses indicate they are due to the build-up of trapped helium in the underlying substrate which forms bubbles and leads to swelling [6]. Plotting the variation of height at the centre of the exposed regions as the dose and area are varied (Figure 2) reveals that for the smallest area investigated (40 nm) a trench is formed for all doses, increasing in depth with dose. For the 80 nm area, the trench also initially increases in depth but subsurface swelling is seen to take effect for the highest applied dose, limiting the depth to ~12 nm. For the larger areas, swelling causes the centre point height to increase with dose.

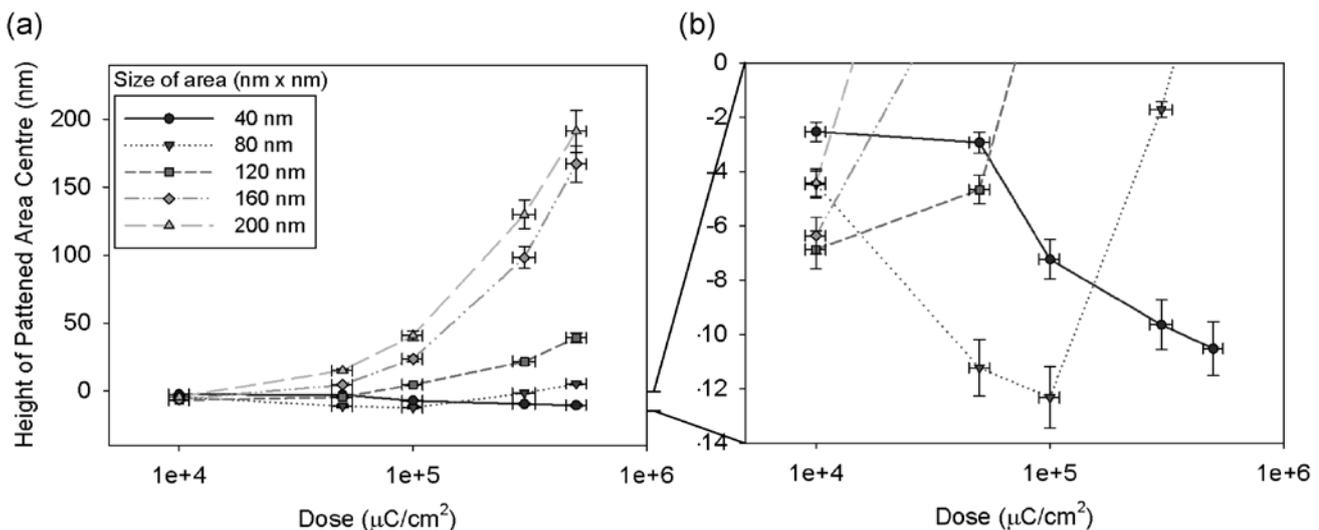
The results demonstrate that it is possible to mill features down to depths exceeding the thickness of the silicon layer (~7nm). This is promising for nanoelectronic device fabrication as it indicates that HIM milling can be used to successfully isolate sections of thin silicon. The study also shows, however, that the process is complicated by sub-surface swelling due to implanted helium. It may therefore be wise to use other patterning techniques such as optical and e-beam lithography to fabricate all but the very centre of a prototype device. Small amounts of swelling can be tolerated and may even offer a route to the engineering of strain into the thin silicon device, with potential for tuning of the device properties. For scaled CMOS and novel quantum devices, the definition of features smaller than 40 nm x 40 nm will be required. Accurate AFM characterization at these length scales is limited by tip-surface convolution effects and so future work will concentrate on developing methods of electrically characterizing fabricated devices, in addition to further experimental optimization of the milling conditions such as beam energy, dose and writing strategy.

## References

- [1] BW Ward *et al*, Journal of Vacuum Science and Technology B **24** (2006), p. 2871-2874.  
 [2] D Winston *et al*, Journal of Vacuum Science & Technology B **27** (2009), p. 2702.  
 [3] P Chen *et al*, Nanotechnology, **21** (2010), p. 455302  
 [4] SA Boden *et al*, Microelectronic Engineering, **88** (2011), p. 2452-2455.  
 [5] DC Bell *et al*, Journal of Vacuum Science & Technology B **27** (2009), p. 2755.  
 [6] R Livengood *et al*, Journal of Vacuum Science & Technology B **27** (2009) p. 3244.



**Figure 1.** AFM scans of various areas of thin SOI exposed to a range of doses by the scanning helium beam generated in the HIM. The numbers on each image represent the height scale. All AFM images are rendered with 1:1 scaling and identical orientations and simulated lighting conditions.



**Figure 2.** (a) Graph of the variation in exposed area centre point height, as measure by AFM, as the dose and area are varied; (b) zoom on (a) showing negative heights (depressions). Note that the lines connecting data points are a guide to the eye only.