# Direct-write Method for Machining Fluidic Structures with Helium Ions

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While helium ion microscopy (HIM) has proven valuable for imaging on the nanometer scale, its non-negligible mass focused ion beam (FIB) makes substrate milling or "machining" possible in several cases.[1] Structures with feature sizes of 5 nm or smaller have been fabricated in thin membranes,[2,3,4] however varying results have been observed in bulk substrates where the irradiated region often swells rather than mills.[5] The depth and breadth of the interaction volume scales with beam energy and, to a certain extent, with probe size and dose. The sputter (removal) of atoms in bulk silicon materials is surpassed by helium accumulation rates, thereby inducing dramatic swelling of the substrate surface at high doses. When energetic helium ions irradiate silicon substrates at doses higher than typical imaging levels ($\geq 10^{17}$ ions/cm$^2$), they form small bubbles that eventually coalesce to form large cavities ($\geq 10^{18}$ ions/cm$^2$).[6] With controlled dose patterning, larger and longer cavities can form to make tube-like structures directly under the silicon surface. A considerable number of researchers have noted helium implantation and bubble formation in various substrates, however few have *utilized* the bubble coalescence and swelling phenomenon. To our knowledge, this work we are reporting is the first effort to exploit this phenomenon for the purpose of fabricating pipe structures in silicon substrates. The tube-like cavities have been investigated via Ga$^+$ FIB sectioning and imaging. Our paper will report on the effects of dose and dose rate on cavity formation and uniformity. Finally, the optimum parameters and write geometries as well as scalability will be discussed. This direct-write fabrication of small tubes embedded in surfaces could be useful in the rapid-prototyping design of fluidic devices to transport nanoliter volumes of fluids.

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[1] E.M. Mutunga, *et al*., Microscopy and Microanalysis 20, **S3**, 2014.
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[3] L. Scipioni, *et al*., J. Vac. Sci. Technol. B **28**, C6P18 (2010).
[4] S. Tan, *et al*., J. Vac. Sci. Technol. B **32**, 06FA01 (2014).
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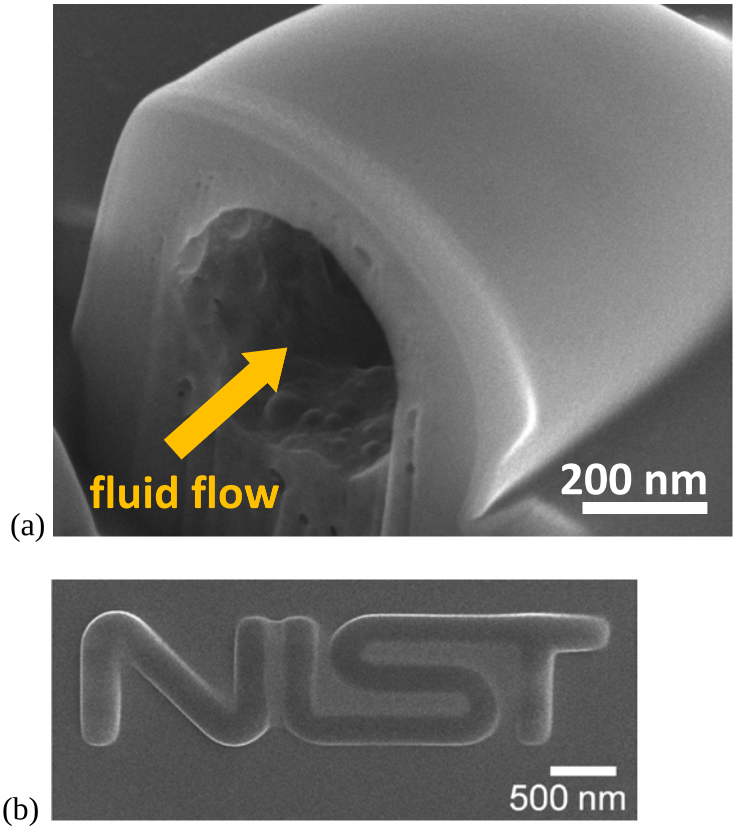
[6] R. Livengood *et al*, J. Vac. Sci. Technol. B **27** (2009) 3244.



Sectioned silicon nanopipe (a) shows the optimum conditions for continuous hollow cavity formation. Virtually any pipe geometry (b) can be produced using this technique.