The Next Generation of Extreme-Resolution E-beam Lithography

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Abstract: In top down nanofabrication research facilities around the world, the direct-write high-resolution patterning tool of choice is overwhelmingly Electron Beam Lithography (EBL). Remarkably small features can be written in a variety of resists [1]. However, as interests in quantum devices and materials have blossomed along with other regimes of research at the nanoscale where energy levels and tunneling rates are controlled by size, the resolution and precision of these patterning tools have become a limiting factor. Breggren[2] explored the resolution limits of EBL via modeling and experiments. He plotted the normalized deposited energy density in the resist as a function of radial distance from the center of the beam. From that data the deposited energy dropped to 10% of max at a distance of almost 4nm from the center of the beam. By selecting doses and development carefully he was able to form 5nm features. Smaller features have been exposed, but the precision is poor because of the low contrast of the exposure.

Hydrogen Depassivation Lithography (HDL)[3] is a version of EBL. It uses a cold field emitter, a Scanning Tunneling Microscope (STM) tip, to deliver a small spot of electrons on a Si (100) 2x1 H passivated surface to expose a self-developing resist that is a monolayer of H adsorbed to the Si surface. Sub-nm features [4], and even the removal of single H atoms can be routinely accomplished[5]. The fact that there are no optics required for focusing the e-beam and that the atomic resolution lithography is done at biases (4V) much lower and currents (several nA) somewhat higher than conventional EBL is somewhat surprising. Low biases and high currents would be a space charge nightmare in conventional EBL.

The physics of the HDL beam delivery and exposure has been little studied. It is known that the H desorption process at low biases is a multi-electron process[6] but the tunneling distribution of the electrons from the STM tip to the Si surface lattice is not known. We have developed a simple model that demonstrates that the combination of two highly non-linear processes, tunneling current dependence on tunnel distance, and the multi-electron exposure process creates a much higher contrast exposure mechanism than conventional EBL. The HDL depassivation efficiency drops off by 8 orders of magnitude at a radial distance of 0.5nm.

Currently, HDL has been used almost exclusively on the Si (100) surface (fortunately a very important surface) and there is only one resist, a monolayer of H adsorbed on the Si. Furthermore, the number of pattern transfer techniques is still fairly limited to the selective deposition of a number of materials including Si, Ge, TiO_2, and a few dopant atom precursors PH_3 and B_2H_6. Selective epitaxy of Si and Ge have been demonstrated[7]. The selective deposition of dopant atoms followed by incorporation and epitaxial overgrowth are of significant interest to quantum computing and quantum material research[8]. Selective Atomic Layer Deposition (ALD) of TiO_2 can produce an effective reactive ion etching mask for etching very small and precise structures into Si[9]. This allows for highly precise 3D Si nanostructures. While the throughput of HDL is very low, going parallel in a big way appears promising[10].

Compared to conventional EBL, HDL has much slower throughput and presently pattern transfer techniques are fairly limited. However, the most exciting aspect of HDL is its atomic-scale precision, which is key to nanoscale research. We see HDL emerging as the ultimate high resolution patterning tool in top down nanofabrication research facilities.

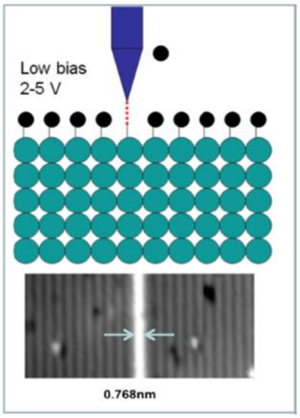

Fig. 1 HDL exposed sub-nm feature

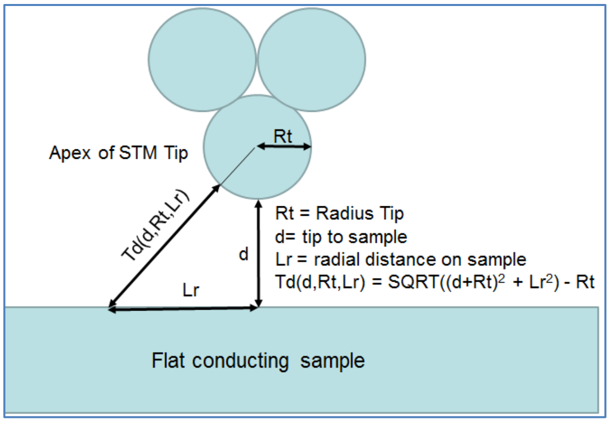

Fig 2. Model for tunnel current distribution

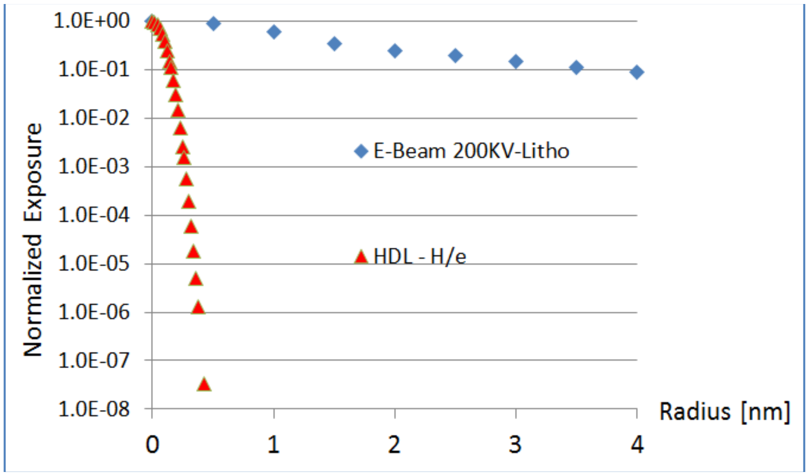

Fig 3. Comparison of deposited energy for exposure of HDL (based on model) to conventional EBL (data taken from Ref 2)

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