Silicon Nanostructures Through Guided Recrystallization

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The continuous technological development of modern civilization is based on the development of methods for the patterning of matter on progressively smaller length scales – from photolithography to 3D printing. However, it is the atomic scale fabrication that can be expected to be the key technology of the XXI century. The need for such fabrication is by now well realized - in particular, biological sequencing, quantum communication, quantum computing, and single spin magnetoelectronic devices all need fabrication at the atomic level, including precise positioning of functional dopant atoms and avoiding even atomic-scale defects in the active region of the device and interconnects. Over the last decade, this electron beams have been used to enable direct atomic motion [1, 2], building homo- and multiatomic artificial molecules in 2D materials [3], and atomic-plane sculpting of 2D and 3D materials [4, 5]. Here, we harness the power of electron beams assisted by machine learning-based control for atomic fabrication of quantum materials and devices.

We recrystallize amorphous silicon locally with the small electron beam of an aberration corrected electron microscope. At an acceleration voltage of 200 keV the electrons provide enough momentum transfer to the silicon atoms to accelerate those atoms in crystalline and amorphous silicon. In crystalline samples with a rather high current of 210 pA the electron beam is powerful enough to drill a hole as seen in figure 1 on left. At lower currents the number of atoms moved is much smaller and less frequent so that an electron beam can provide sufficient energy to recrystallize silicon but not drill holes.

Figure 1 on right shows a structure that is grown with this low current at 200keV. The grow these structures the electron beam was scanned perpendicular to the surface from the crystalline silicon into the amorphous region for several minutes. The structure establishes within a few seconds depending on dose and does not grow or dissociate afterwards. This method is therefore quite robust. The small scale of the structure of less than 3 nm is determined by the (111) planes of silicon. In effect we produce little pyramidal structures. Lower currents (< 40pA) result in longer times to fabricate those pyramids. At slightly larger currents (80pA) larger structures can be recrystallized as seen in figure 2.

The samples were prepared by implanting xenon atoms with a plasma FIB into silicon perpendicular to the surface. The Xe atoms accumulate close to the surface in silicon. The electron beam can only recrystallize the amorphous silicon below the implanted region, with little xenon still present (see figure 1 right: bright spots). Energy dispersive spectrum images show Xe accumulation collaborating the intensity in the Z-contrast image. The structures are grown at the interface between amorphous silicon and crystalline silicon. This interface is not ideal because of its roughness. However, an annealing step cannot be applied because of the potential for recrystallization of the whole sample. Rather one can take advantage of the roughness and only recrystallize on top of protrusions of crystalline into amorphous silicon.

The manufacturing at this point is manually, however, a remote-controlled system can automate this process. Thus, an atomic-scale controlled nano-structuring process with varying beam currents as readily available with a modern TEM/STEM is possible directly [6].

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**Fig. 1.** A small hole was drilled with an electron beam of 210 pA. While a 2nm high pyramidal feature was recrystallized with a beam of 40 pA.
Fig. 2. Before and after recrystallization with a beam current of 80 pA. The recrystallized feature is 16 nm by 7 nm

References
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