

## Direct Imaging of Low-Dimensional Nanostructures

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Low-dimensional nanostructures are technologically desirable for their novel physical properties, as well as the benefits of packing density due to scale. In quantum computing, an ideal structure might consist of single dopant atoms precisely positioned a few nanometers below a surface [1]. There is also a need for truly atomic-scale interconnects and ancillary structures. However, due to their nanoscale dimensions, the physical properties of nanowires and related structures will depend on the environment in which they are embedded as well as their composition. This problem is particularly relevant for samples grown on ultra-clean surfaces, which may not survive outside of high-vacuum systems or which might be substantially affected by adatoms. The question then arises as to what happens to surface nanostructures or single dopant atoms during encapsulation or overgrowth.

Silicon is the ideal substrate to explore such questions, both because it is compatible with existing electronic components and manufacturing technologies and, for quantum computing applications, because of the possibility of preparing isotopically purified samples (a “spin-vacuum”). Group V elements, such as bismuth, are promising candidates for use as qubit dopants in Si. Rather remarkably, Bi can be made to self-organize into 2-atom wide nanolines on Si(100), as shown in Figure 1. These nanowires were first reported in pioneering work by Miki *et al.* [2], and the driving force for their formation and the subsurface Si “Haiku” core structure was later elucidated by other workers [3]. Despite this understanding, there remain questions as to what happens to the Bi nanolines during capping with Si. Previously work presents apparently conflicting evidence as to whether the nanowires can survive overgrowth with a protective capping layer. Z-contrast STEM is able to resolve this question by directly imaging the dopant positions as well as the core structures.

We are able to demonstrate the creation of 1D homo-endotaxial Si nanostructures with a lattice structure that is different from the Si diamond lattice in which they are embedded. We use a combination of scanning tunneling microscopy and spectroscopy, scanning transmission electron microscopy, density functional theory, and conductive atomic force microscopy to elucidate their formation and properties [4]. Depending on kinetic constraints during growth, they can be prepared as endotaxial 1D Si nanostructures completely embedded in crystalline Si or underneath a stripe of amorphous Si containing a large concentration of Bi atoms. These homo-endotaxial 1D nanostructures have the potential to be useful components in nanoelectronic devices in silicon. Moreover, the atomically precise control of the electron probe in STEM suggests the possibility of manipulating nearby dopant atoms, in a manner similarly to that recently demonstrated for atoms in 2D materials [5,6]. [7]

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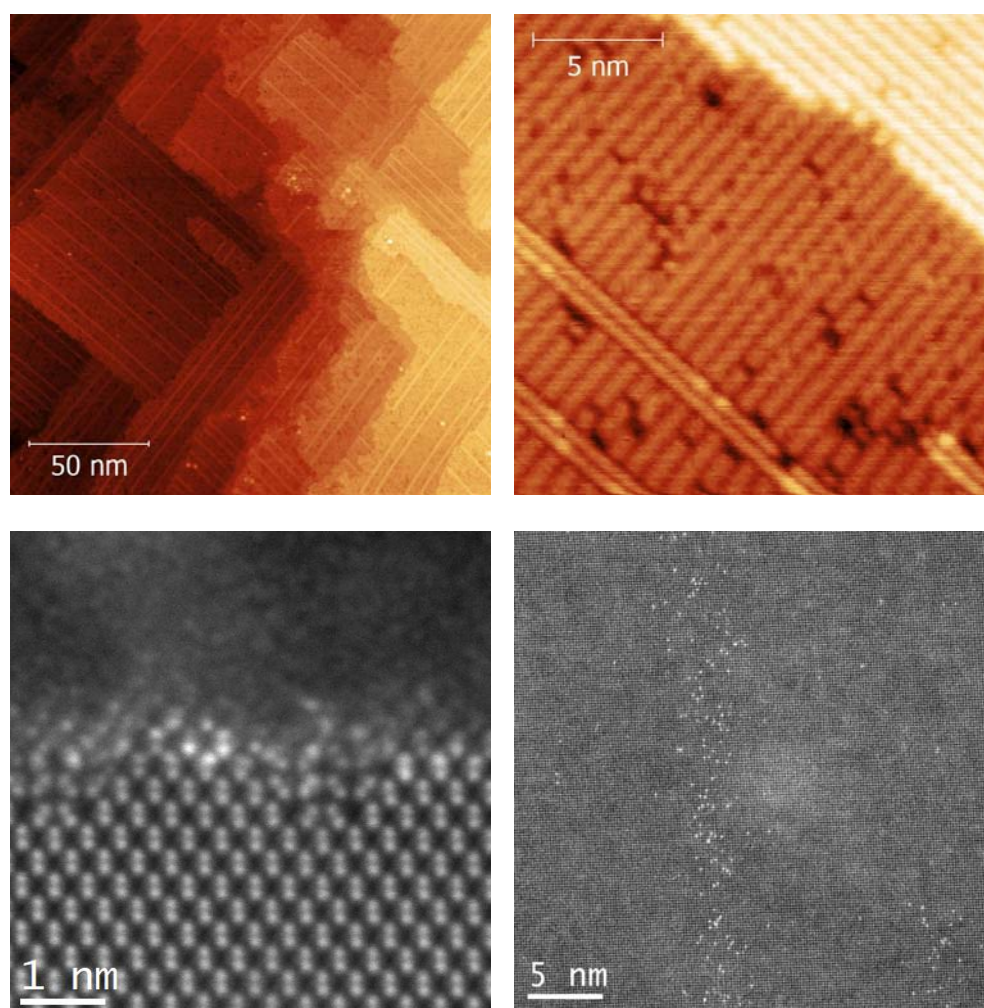
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**Figure 1.** (Top) STM images show the coverage of as-grown nanowires on a terraced Si(100) surface (left) and at higher resolution reveal the characteristic 2-atom wide nanoline perpendicular to the (2x1) surface reconstruction. (Bottom) After capping with a protective Si layer, STEM images in cross-section (left) reveal that the “Haiku” core remains intact, but that the Bi is dispersed, with single dopants remaining in the vicinity (right). Adapted from reference [4].