Single Atom Scale Manipulation of Matter by Scanning Transmission Electron Microscopy

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Fabrication of atomic scale structures remains the ultimate, and yet not achieved, goal of nanotechnology. The reigning paradigms are scanning probe microscopy (SPM) and synthesis. SPM assembly dates back to seminal experiments by Don Eigler, who demonstrated single atom manipulation and writing. However, stability and throughput remain issues, and only in the last decade synergy of STM and surface chemistry was used to make several-qubit devices. The molecular machines approach harnesses the power of modeling and synthetic chemistry to build individual functional blocks, yet strategies for structural assembly remain uncertain.

In this presentation, I discuss research activity towards a third paradigm – the use of atomically focused beam of the scanning transmission electron microscope (STEM) to control and direct matter on atomic scales[1-5] (See Fig. 1). Traditionally, STEM's are perceived only as imaging tools, and any beam induced modifications are undesirable beam damage. In the last five years, our team and several groups worldwide demonstrated that beam induced modifications can be more precise. We have demonstrated controlled atomic-layer by atomic-layer crystallization and amorphization transformations and atom motion in solids using by e-beam, as well as controlled defect formation, directed introduction of single dopant atoms into a lattice, and controlled motion of single dopant atoms within the lattice of 2D materials. What is remarkable is that these changes often involve one atom or small group of atoms, and can be monitored real time with atomic resolution. This fulfills two out of three requirements for atomic fabrication. I will introduce several examples of beam-induced fabrication on the atomic level, and demonstrate how beam control, rapid image analytics, better insight through modelling, and image- and ptychography based feedback allows for controlling matter on atomic level.

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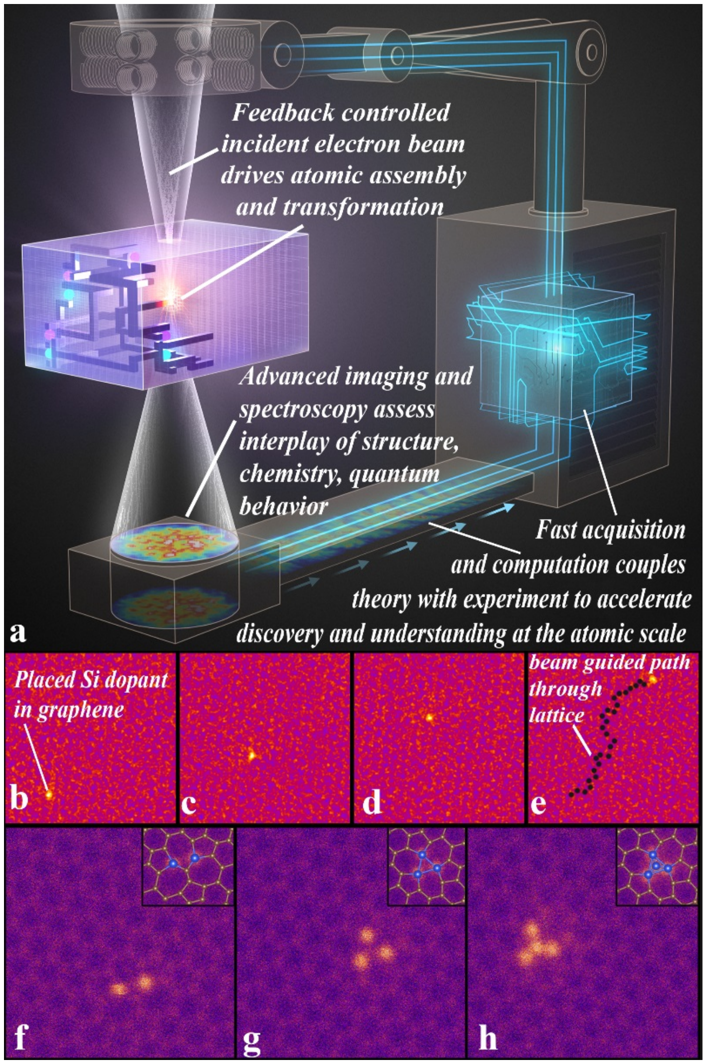

Figure 1: Directed Atomic Assembly using STEM (a) Enhanced STEMs enable building and editing atomic assemblies and assessment of their chemical, physical, and quantum properties. (b-d) Directed doping and guided motion of Si atom through graphene lattice. (f-g) Beam directed atom-by-atom fabrication of Si dimer, trimer, and tetratramer. Further development will automate assembly of complex superlattices of multiple chemical constituents.

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