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 the research activity coordinated by the Institute for Functional Imaging of Materials (IFIM) towards the third paradigm—the use of atomically focused beam of the scanning transmission electron microscope to control and direct matter on atomic scales[1-6]. Traditionally, Scanning Transmission Electron Microscopes (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 ordering of oxygen vacancies, single defect formation in 2D materials, and beam induced migration of single interstitials in diamond like lattices. 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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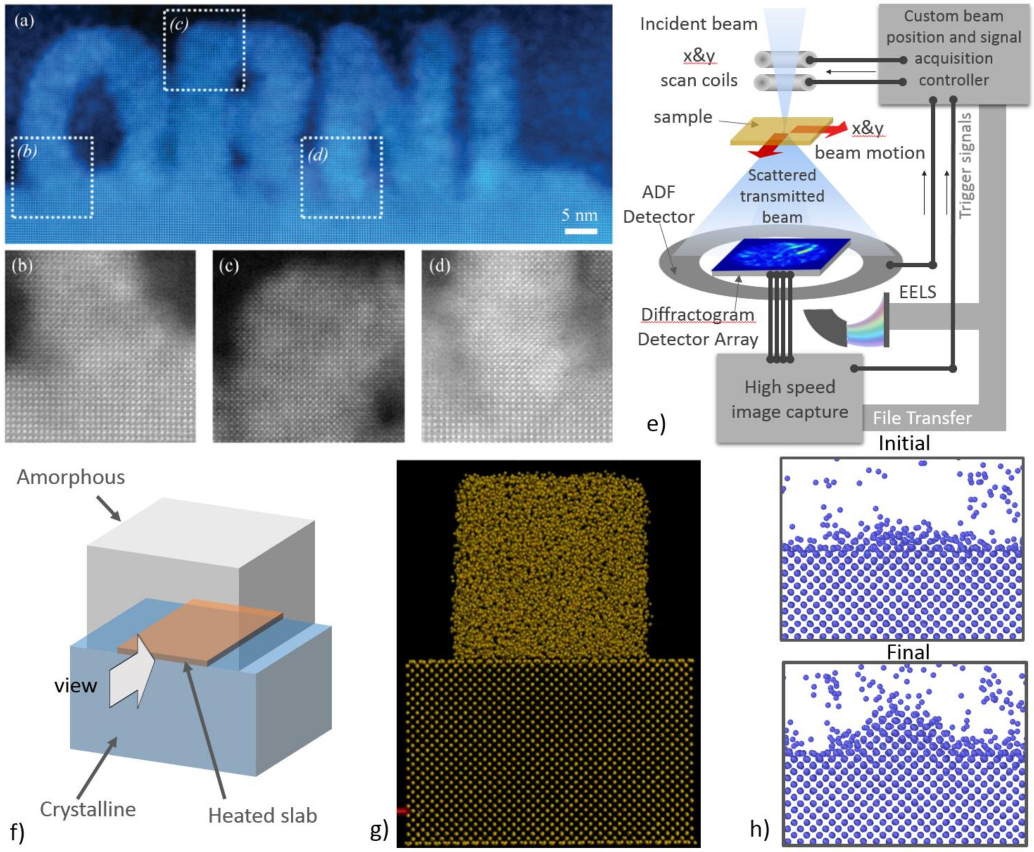

Figure 1: (a-d) results of layer-by-layer beam induced crystallization of strontium titanate. (e) schematic of STEM set-up including additional control and acquisition components. (f) schematic and (g) rendering of molecular dynamics modelling of the crystallization process at the amorphous crystal interface. (h) Initial and final rendering of modeling results showing only atoms in the crystallized state.

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