Atomic Scale Fabrication Using the Scanning Transmission Electron Microscope

Ondrej Dyck[1], Andrew Lupini[1], Mina Yoon[1], Stephen Jesse[1]*

[1] Oak Ridge National Laboratory, Oak Ridge, TN, USA
* Corresponding author: sjesse@ornl.gov

The scanning transmission electron microscope (STEM), a workhorse instrument in materials characterization, can not only be used to observe dynamic processes with atomic resolution, but also drive and control synthesis with atomic precision. Through custom control of the electron beam position that actively feeds back on image, spectroscopy, and other data streams from electron detectors, it is possible to use focused beam energy to precisely initiate, direct, and terminate material transformations. This high degree spatial and temporal control can be used to generate point defects, drill holes that are a single or few atoms in size, and mill thin lines or other patterns in materials, change phase, modify bond coordination, and reposition dopants.

Control over the local environment in the vicinity where the beam meets the sample provides additional and critical capabilities to control and observe reactions. Custom MEMS devices for heating and biasing, in situ evaporators, and laser irradiation provide the means to dose the sample with thermal energy, optical excitation, and reactant or dopant materials to provide the conditions for reactions and targeted synthesis and transformation of atomic scale structures to occur. Finally, to close the loop, the STEM can then be used in its more traditional characterization modes to image transformation processes as they occur and assess if new functional properties emerge.

Presented here are recent results highlighting advancements towards such a "synthescope"[1] including new insights gained by studying the generation and temperature dependent diffusion of beam-generated single vacancies in suspended 2D materials [4,5], strategies to restrict vacancy diffusion so they can serve as sites for dopant insertion, demonstration of patterning of arrays of dopants [3,6], and in situ delivery of dopant atoms to the sample [2,6]. Furthermore, results of in-depth modeling and analysis of the often-counterintuitive behavior of material transformations where the exceedingly small reaction area/volume is defined by the beam are discussed. The development of this combination of experimental methods with theory and modelling (both operating at the atomic level) provides a window into the dynamic processes at fundamental length scales and a path towards fabricating materials and devices with atomically precise components.

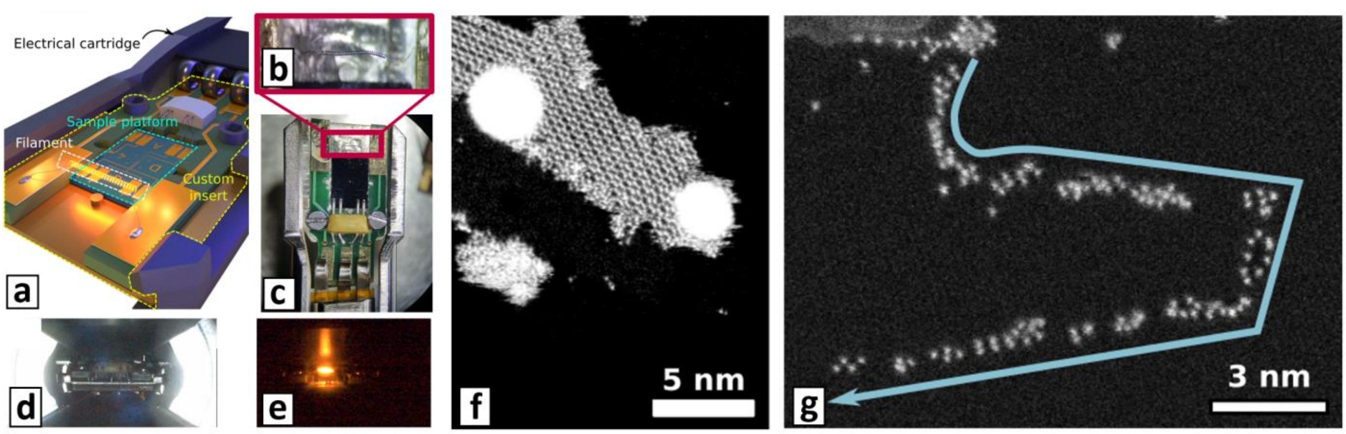

Fig. 1. In situ evaporation in STEM. (a) Schematic of custom-built insert for Nion electrical cartridge with filament evaporation. (b) Photographs of filament and (c) insert. Photographs of full assembly in microscope with (e) heated filament. (f) Self-assembled 2D tin flake on graphene and (g) e-beam guided insertion of a line of tin atoms into a single layer of suspended graphene.

References:

1. O. Dyck, A.R. Lupini, S. Jesse, Advanced Materials **35** (2023) https://doi.org/10.1002/adma.202301560
2. O. Dyck, A.R. Lupini, S. Jesse,. Small Methods **7** (2023) https://doi.org:10.1002/smtd.202300401
3. O. Dyck, et. al. Advanced Materials **32** (2023) https://doi.org:10.1002/adma.2023029064
4. M.G. Boebinger, Advanced Materials **35** (2023) https://doi.org:10.1002/adma.2022101166
5. O. Dyck, et. al., Carbon **201** (2023) https://doi.org:10.1016/j.carbon.2022.09.006
6. O. Dyck, A.R. Lupini, S. Jesse, Nano Letters **23** (2023) https://doi.org/10.1021/acs.nanolett.3c00114
7. This work was supported by the U.S. Department of Energy, Office of Science, Basic Energy Sciences, Materials Sciences and Engineering Division, and was performed at the Center for Nanophase Materials Sciences (CNMS), a U.S. Department of Energy, Office of Science User Facility.