Machining at the Nanoscale: Applications of the Focused Ion Beam (FIB)/Scanning Electron Microscope (SEM) System

Paul Blanchard, Kris Bertness, Ann Chiaramonti Debay, Alexana Roshko, Aric Sanders, Norman Sanford, and Joel Weber

National Institute of Standards and Technology (NIST), Boulder, CO

NIST National Institute of Standards and Technology

Introduction

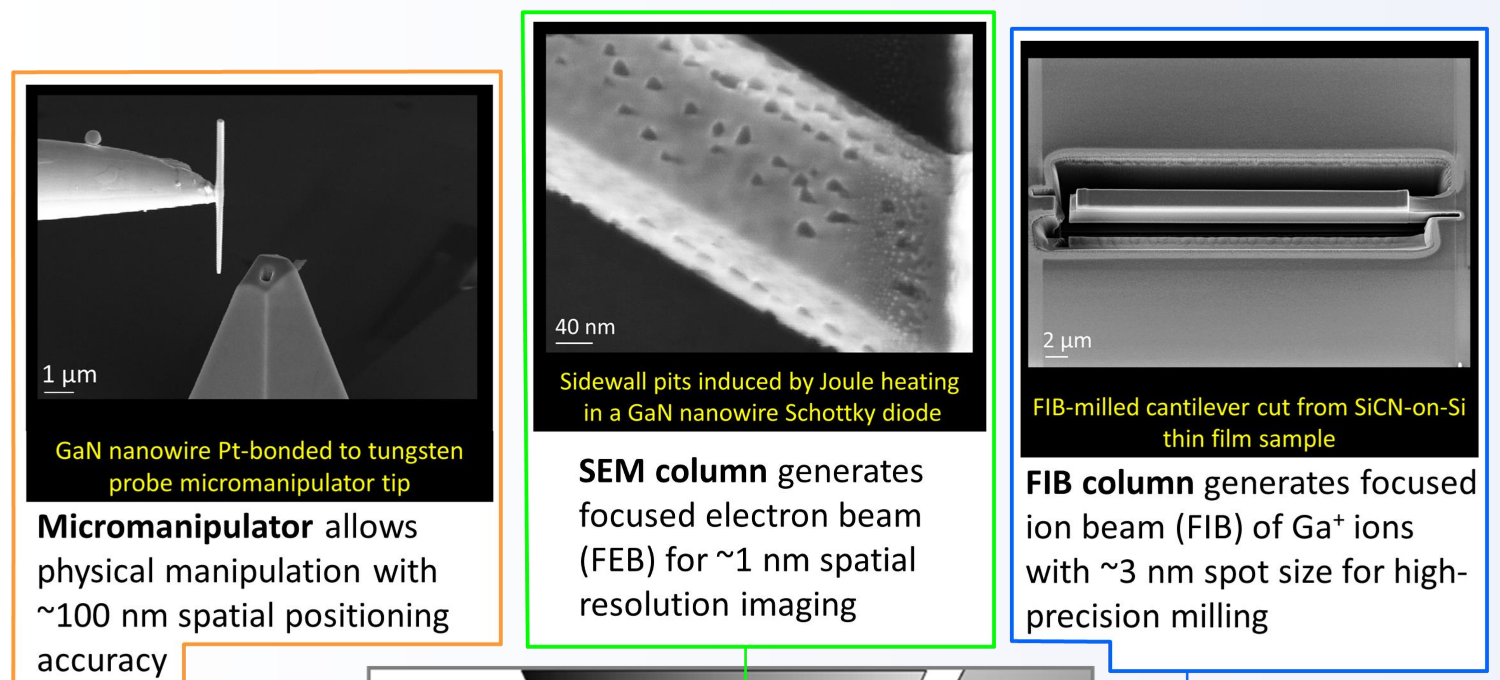
Transmission electron microscopy (TEM) and atom probe tomography (APT) are **powerful imaging techniques** that allow quantitative material analysis on the scale of individual atoms.

However, each of these techniques places **stringent constraints on the geometry of specimens** that can be analyzed. Sample cross sections for TEM must be thinned to electron transparency (< 100 nm thickness); APT requires a needle-shaped tip with a diameter on the order of 50 nm or less at its apex.

The dual-beam focused ion beam (FIB)/scanning electron microscope (SEM) system enables the **machining and manipulation of samples with nanometer-scale control**. As a result, high-quality samples for TEM and APT can be fabricated from a wide variety of material systems. In addition, dual-beam techniques can be adapted to the fabrication of novel test structures and prototype devices.

Overview of the Dual-Beam FIB/SEM System

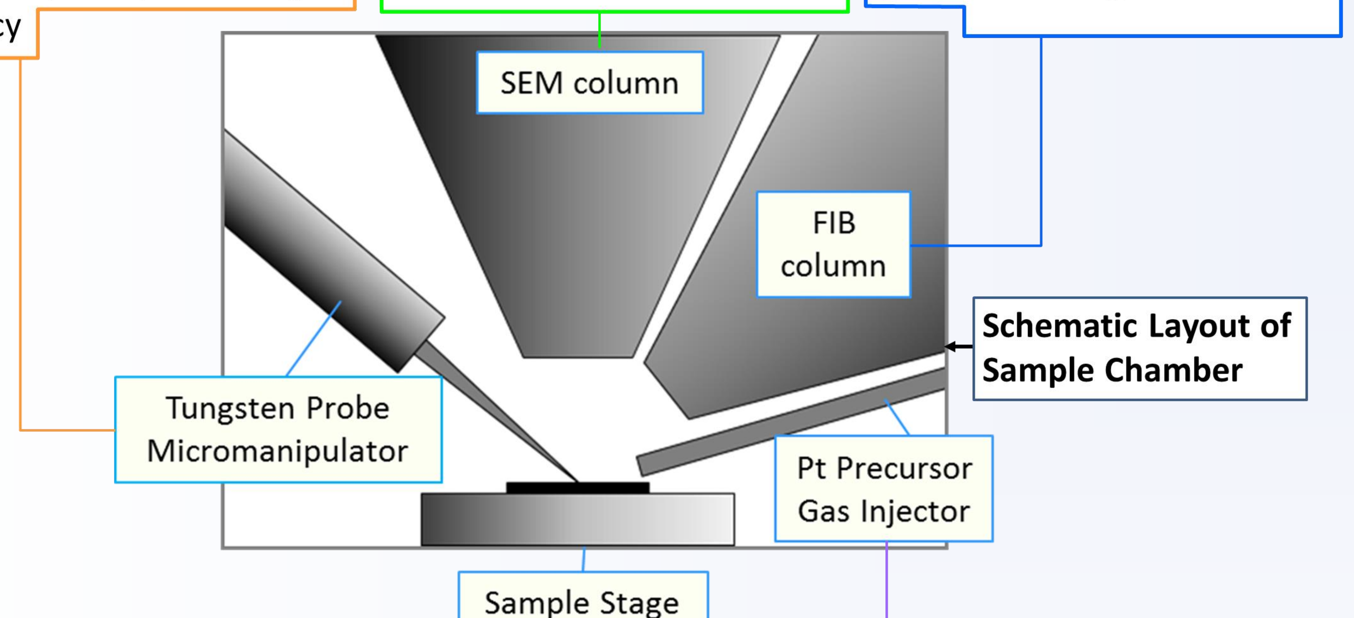
The dual-beam system combines the high-resolution, low-damage imaging of SEM with the precise milling capabilities of FIB. With the addition of a gas injector (for beam-induced deposition) and a micromanipulator, the system allows samples to be imaged, milled, cut, moved, and welded to new substrates.



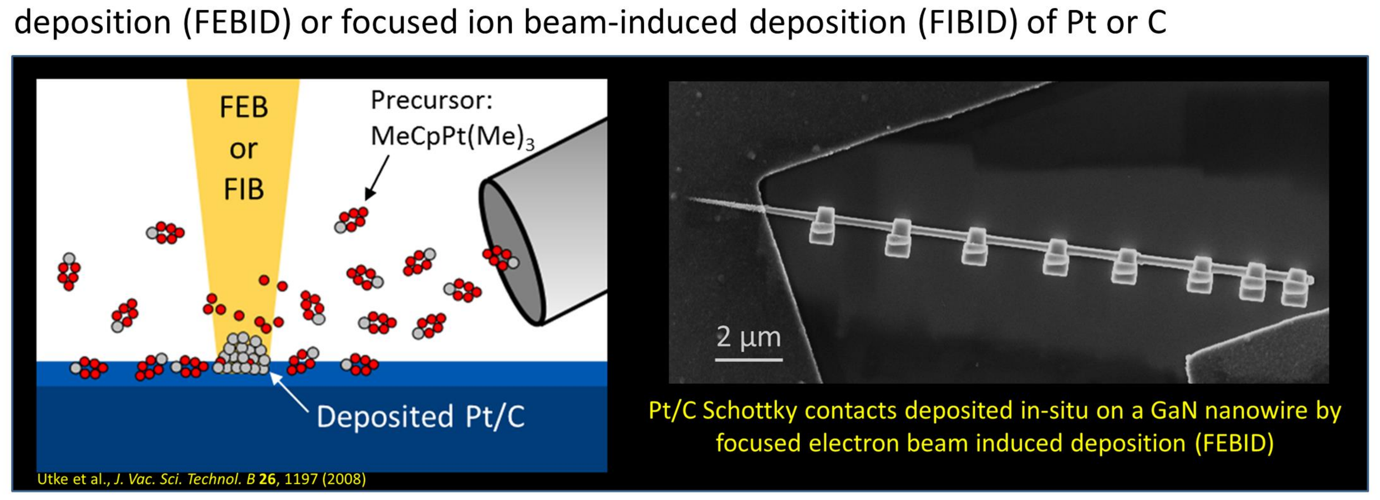
Micromanipulator allows physical manipulation with ~100 nm spatial positioning accuracy

SEM column generates focused electron beam (FEB) for ~1 nm spatial resolution imaging

FIB column generates focused ion beam (FIB) of Ga⁺ ions with ~3 nm spot size for high-precision milling

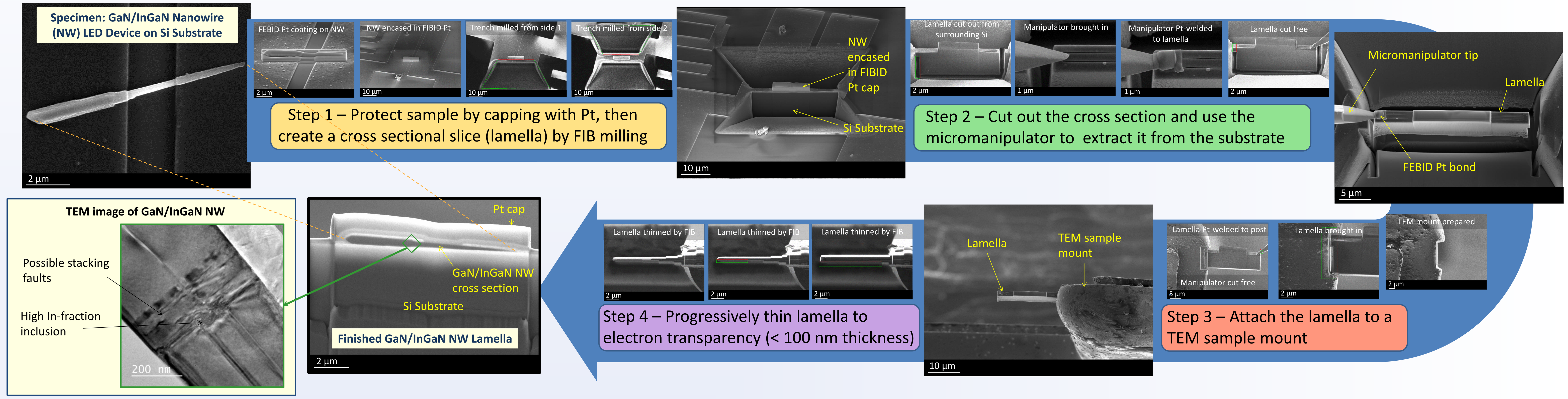


Gas injector supplies organic precursors for precise focused electron beam-induced deposition (FEBID) or focused ion beam-induced deposition (FIBID) of Pt or C



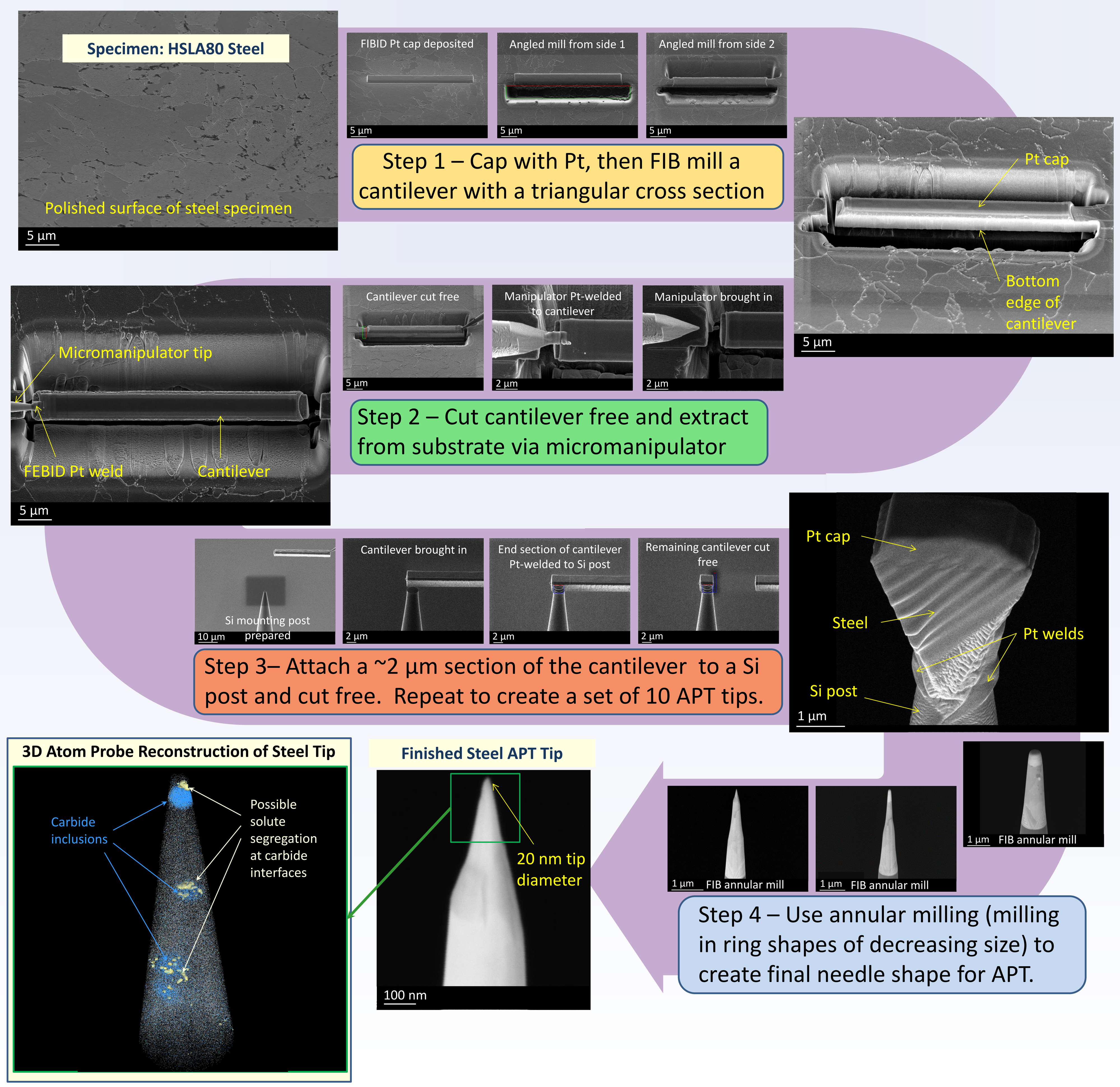
Sample Preparation I: the Transmission Electron Microscopy (TEM) Lamella

Goal: from an arbitrary specimen of interest, create an ultra-thin (< 100 nm thick) cross-sectional slice (a *lamella*) suitable for TEM imaging



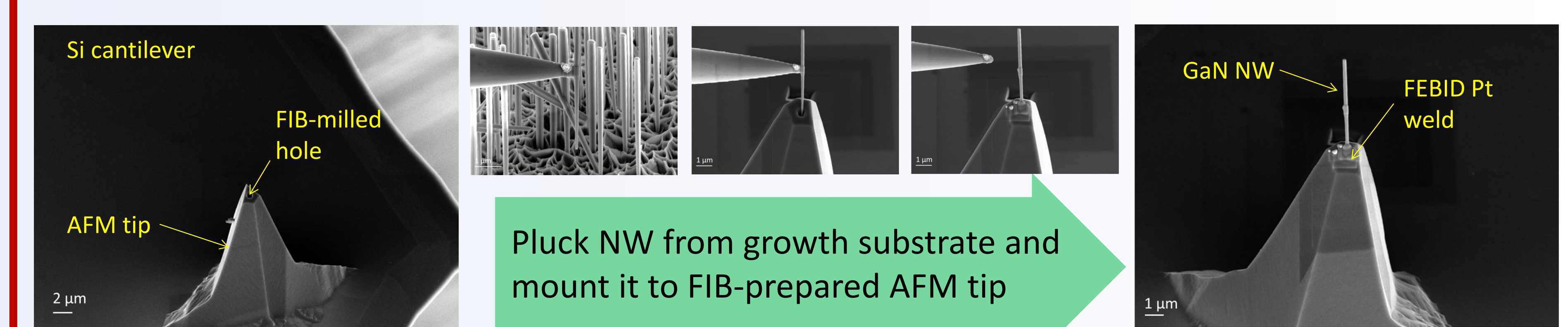
Sample Preparation II: the Atom Probe Tomography (APT) Tip

Goal: from an arbitrary specimen of interest, remove a sample of material and shape it into an ultra-sharp (< 50 nm diameter at tip apex) needle suitable for APT

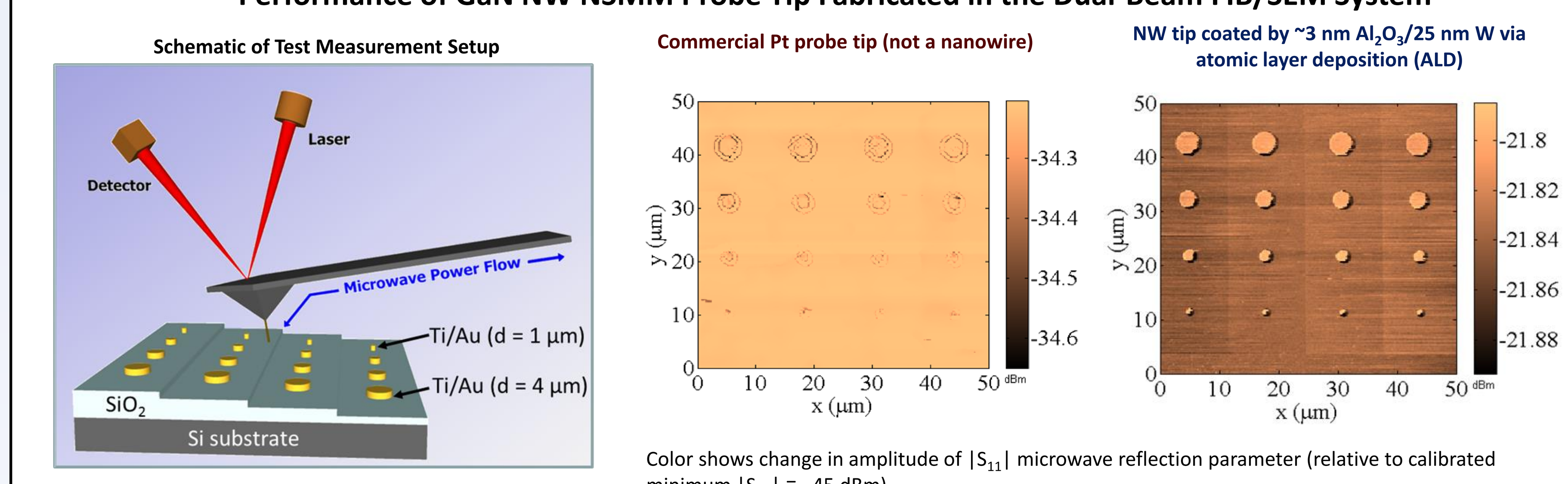


Prototype Device Example: the Nanowire (NW) Scanning Probe Tip

In addition to the preparation of samples for TEM and APT, the dual-beam system can be used to fabricate prototype nanoscale device structures, such as the GaN nanowire (NW) near-field scanning microwave microscopy (NSMM) probe.



Performance of GaN NW NSMM Probe Tip Fabricated in the Dual-Beam FIB/SEM System



Color shows change in amplitude of $|S_{11}|$ microwave reflection parameter (relative to calibrated minimum $|S_{11}| \approx -45$ dBm)

Weber *et al.*, *Appl. Phys. Lett.* **104**, 023113 (2014)

Other applications

The dual-beam FIB/SEM is a versatile system that continues to be adapted to new applications , such as

- **3D tomography.** By taking a series of successive SEM images while FIB milling through a region of interest, a 3D reconstruction of the material volume can be obtained.
- ***In situ* electrical and mechanical testing.** With the tungsten probe micromanipulator operating as an electrical or mechanical probe, materials and devices can be characterized *in situ* with high spatial resolution and simultaneous SEM observation.
- **Custom nano-milling.** Because the FIB position and dwell time can be precisely controlled, arbitrary nanoscale shapes can milled into substrates, and existing nanostructures can be reshaped.