Atomic precision advanced manufacturing

Ezra Bussmann, C. T. Harris, T.M. Lu, T. S. Luk & M. P. Lilly
Center for Integrated Nanotechnologies, Sandia National Laboratories Albuquerque NM

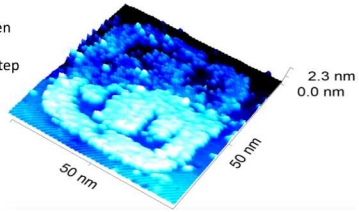
SAND2019-5351D

U.S. DEPARTMENT OF ENERGY
Office of Science

Overview of capability & application opportunities

- Full fabrication & characterization of Si electronic devices with deterministic atom-precision features
- Quantum materials & digital devices at the physical limit of atom precision
- Structure-function relationships in thin-film materials for quantum electronics
- Atomic-resolution imaging & lithography via two scanning tunneling microscopes (STMs) with Si and Ge thin-film epitaxy (MBE)
- 1st/only user lab in world offering atom fab

Sandia logo written in atoms draped over a Si atomic step

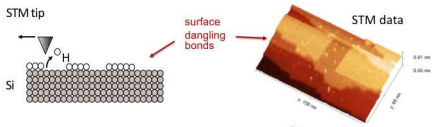


- Capability POC: Ezra Bussmann (ebussma@sandia.gov)

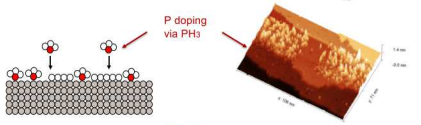
Detail of capability - atomic precision Si device fabrication & characterization

- Fabrication recipe for Si nanoelectronic devices

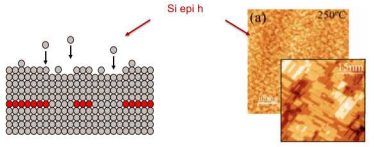
1. **Atomic-precision litho template on Si surface**



2. **Atomic-precision doping via template**



3. **Si cap**

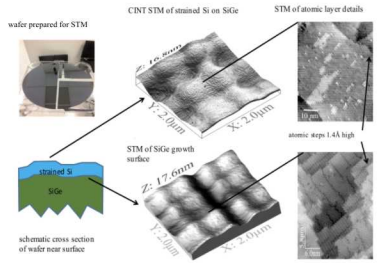


4. **Fab electrical contact metal**

- Device & material characterization at CINT
  - Magnetoelectronic transport -Tzu Ming Lu, Tom Harris, or Mike Lilly
  - Optical response- Willie Luk

Detail of associated capability - surface characterization

- Classical physics- structure and electronic properties of surfaces and thin films
- Quantum electronics- structure-function relationship in thin film heterostructure materials

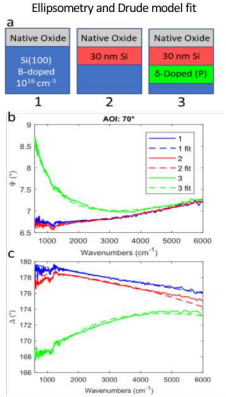


- Interface roughness and atomic-steps strongly influence quantum coherence in Si/ SiGe devices
- Surface imaging in CINTs atomic-precision lab provided feedback to inform development of new semiconductor growth process at one manufacturer

Examples of some recent results

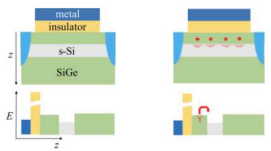
- First demo mid-IR ellipsometry of atomic-precision doped Si material
- Drude model fits both optical & electronic response, reasonable agreement between approaches
- Electron density n = 7.2x10^{13} cm^2 mobility μ = 77 cm^2/Vs
- Optical method cuts materials characterization cost, provides input for future optoelectronics apps

Ellipsometry and Drude model fit

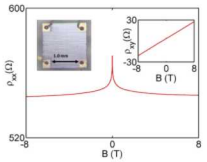


Assessing adsorbate-based delta doping of Si with mid-IR ellipsometry *Advanced Functional Materials*, forthcoming issue on atom fab (submitted)

- First demo atomic-precision recipe for SiGe strained-layer materials
- Opens door to new quantum device engineering concepts utilizing remote doping in pristine heterostructure, e.g. tailored band structure via doping



Hall transport characterization of Si/SiGe hereostructure with atomic-layer doping



Longitudinal magnetoresistance and Hall (inset) resistance at T = 0.3 K of an atomic-layer doped Si/SiGe heterostructure along with a photo of the test device. The aluminum contact pads appear bright gold hue.

Atomic-layer doping of SiGe heterostructures for atomic-precision donor devices,. *Phys. Rev. Materials 2, 066004* (2018) arXiv:1710.06449

Recent users & publications

Assessing adsorbate-based delta doping of Si with mid-IR ellipsometry *Advanced Functional Materials*, forthcoming issue on atom fab

Atomic-layer doping of SiGe heterostructures for atomic-precision donor devices,. *Phys. Rev. Materials 2, 066004* (2018) arXiv:1710.06449

All-optical lithography fabrication process for contacting atomically-precise devices, *Appl. Phys. Lett.* 111, 193101 (2017) arXiv: 1708.05411

Heterogenous nucleation of pits via step pinning during Si(100) homoepitaxy, *New J. Phys.*19, 113023 (2017) arXiv:1706.05127

Determining the resolution of scanning microwave impedance microscopy using buried atomic-precision donor structures, *Appl. Surf. Sci.* 423, 1097 (2017)

Users: National Institute of Standards and Technology, University of Maryland, University of Wisconsin-Madison, Intel Inc, Zyvex Labs Inc

This work was performed, in part, at the Center for Integrated Nanotechnologies, an Office of Science User Facility operated for the U.S. Department of Energy (DOE) Office of Science. Sandia National Laboratories is a multi-mission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC., a wholly owned subsidiary of Honeywell International, Inc., for the U.S. DOE's National Nuclear Security Administration under contract DE-NA-0003525. The views expressed in the article do not necessarily represent the views of the U.S. DOE or the United States Government.

LA-UR or SAND number

Los Alamos NATIONAL LABORATORY EST 1943

Sandia National Laboratories