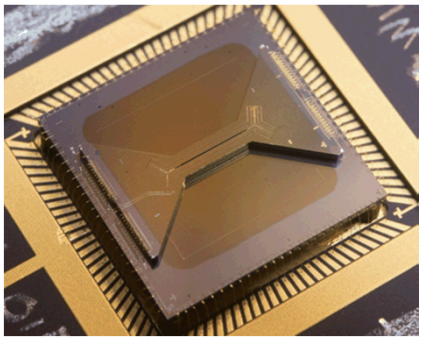
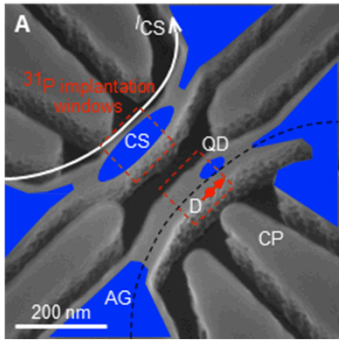
SAND2016-3870PE

Exceptional service in the national interest

Sandia National Laboratories





Nanoscale and Quantum Device Manufacturing at Sandia

Clark Highstrete

Manager, Solid State Microsystems Department

chighst@sandia.gov / (505) 284-8702

U.S. DEPARTMENT OF ENERGY | NNSA National Nuclear Security Administration

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000. SAND NO. 2011-XXXXP

SNL Nanodevice & Microsystem Cornerstones

Sandia National Laboratories

- National security mission + the national interest
  - Nuclear surety, non-proliferation, WMD detection, sensing, cyber
  - National interest: energy, transportation, industry, S&T innovation, HPC
- Three critical responsibilities
  - Strategically radiation-hardened electronics
  - Trusted systems and computing
  - Advanced nanodevice & microsystem R&D
- Sandia nanodevice & microsystem manufacturing focus
  - Low volume
  - High technology mix
  - High consequence

Nanodevices & Microsystems Research Foundation

Sandia National Laboratories

- Trusted Rad-Hard Microelectronics
  - Trusted foundry - ASICs, HBTs, mixed signal, heterogeneous integration
  - Anti-tamper, counterfeit detection, vulnerability analysis
- Optoelectronics and Photonics of the Future
  - Nano-optomechanics, nanolasers, plasmonics, low-power/high-speed
- Ultraportable Multi-function Sensor Systems
  - Sensitive, selective, rapid, low-power, autonomous, integrated
- Nanoscale and Microscale Enabled Devices
  - MEMs, atomic clocks & magnetometers, ion traps, Si quantum dots
- Beyond Moore Technologies
  - Atomic/quantum transistors, neural-inspired computing, quantum information science

Nano/quantum device manufacturing challenges

Sandia National Laboratories

- Atomic/nano/quantum phenomena and device physics
- Comprehensive multiscale models and design
  - Wave-function engineering
  - QCAD
  - Nanoscale TCAD
  - Component models
  - Architectures and software

Key: scalability and reliability

- Materials
  - Purity
  - Reliability
- Fabrication
  - Lithography
  - Chemistry
- Integration
  - Contacts
  - Interconnects
  - Packaging
  - Heterogeneous integration (e.g. CMOS)

Resources

Sandia National Laboratories

Facilities

- MESA Silicon Fab
  - CMOS Trusted Foundry, rad hard, MEMS, photonics, heterogeneous, R&D
- MESA MicroFab
  - III-V compound fab, R&D
- Center for Integrated Nanotechnology
  - DOE/OS joint SNL/LANL user facility
- Ion Beam Laboratory
  - Implantation

Technology Centers

- Microsystems Science & Technology
  - nano/microsystem design, fab, test
- Materials Science & Engineering
  - 10 TEM (ACSTEM, I3TEM), 30+ SEM (MSEM)
- Physical, Chemical & Nano Science
  - eSTM, AFMs, …
- Computing
  - DFT, MD, TCAD, QCAD, Xyce, HPC

Key: integrated comprehensive approach

Exemplar: atomic-scale manufacturing

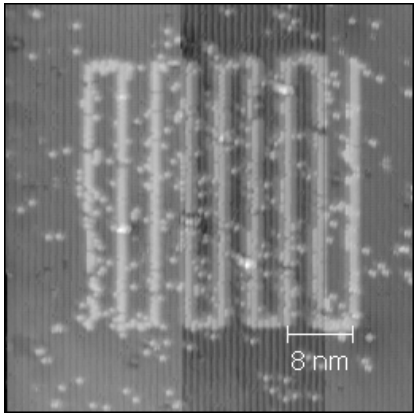
Sandia National Laboratories

Atomic-scale silicon fabrication capability

- Scanning tunneling microscope based lithographic tools
- Lithography of hydrogen passivated silicon on single atom scale – removal of H passivation
- Donor dopant incorporation (phosphorus)
- Leverages conventional silicon processing
- Multiscale devices – angstroms to microns

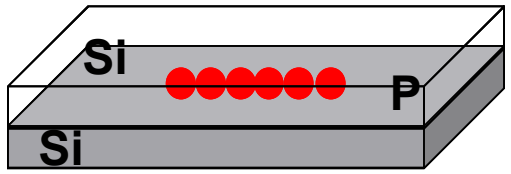
Sandia R&D direction

- 3D integration
  - Atomic scale etching and epitaxy
- Acceptor dopant incorporation (e.g. Boron)
- Extend to other materials (e.g. SiGe)
  - Ge and graphene have been demonstrated in literature
- Surface gate incorporation



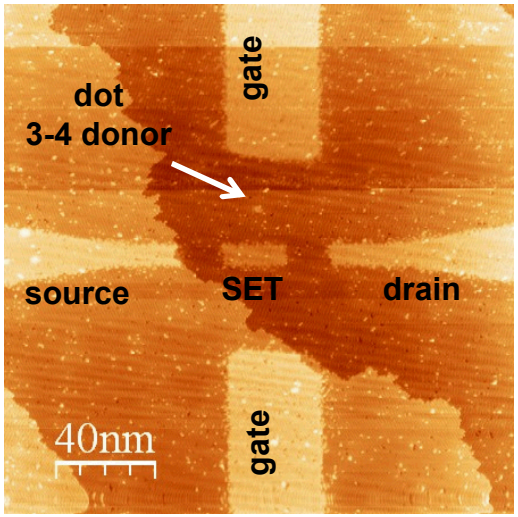
1. Hydrogen Lithography

- **Hydrogen terminated silicon surface**
- **STM removes hydrogen "resist"**
- **Example:**
  - **1 nm lines**
  - **4 nm pitch**



2. Dopant incorporation

- **PH_3 bonds to exposed Si *groups***
- **Anneal and epitaxial silicon cap**
- **P located at Angstrom precision**



3. Precision device

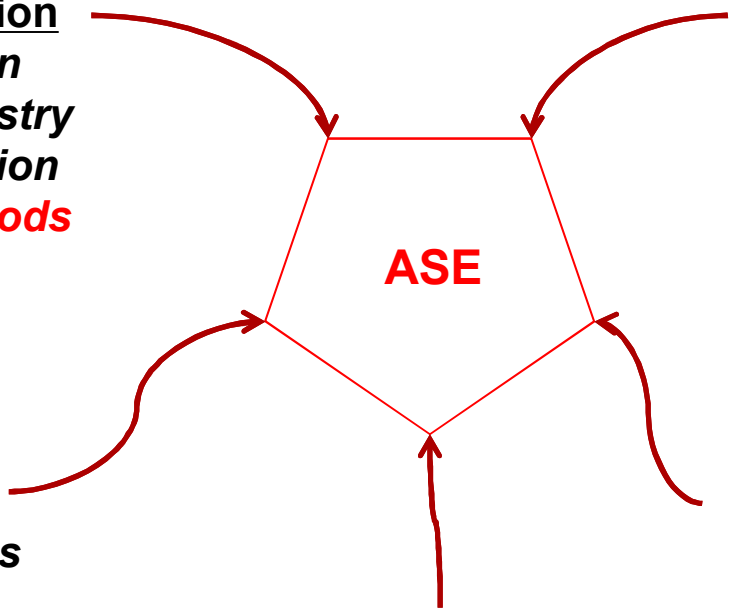
- **Quantum dot coupled to single electron transistor**
- **High conductivity nanowire leads**
- **Contacted with conventional silicon via technology**

Atomic scale engineering approach at Sandia

Sandia National Laboratories

Atomic Scale Fabrication
Dopant incorporation
Surface science/chemistry
Nanofab/Gate integration
Novel fabrication methods

Measurement
Quantum measurement
Device performance
Reliability, yield, failure analysis
Circuit benchmarking



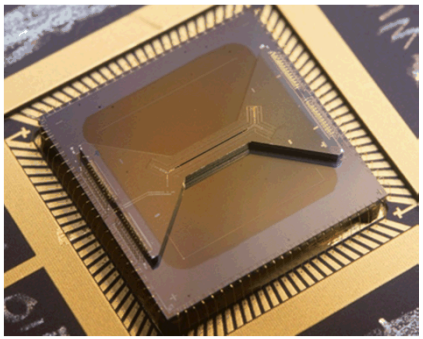
Materials and Device Characterization
Exotic dielectrics
Atomic-scale materials expertise
Materials characterization
Materials reproducibility, reliability

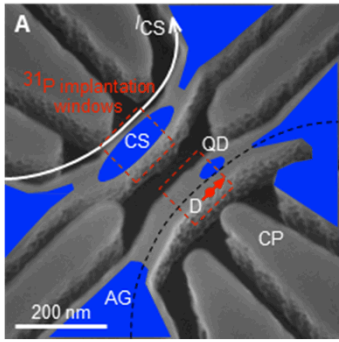
Architecture and Integration
Reduced circuit models
Architecture development
CMOS integration

Quantum Device Modeling
Quantum CAD
Wave-function engineering
Device performance optimization

Exceptional service in the national interest

Sandia National Laboratories





Nanoscale and Quantum Device Manufacturing at Sandia

Clark Highstrete

Manager, Solid State Microsystems Department

chighst@sandia.gov / (505) 284-8702

U.S. DEPARTMENT OF ENERGY | NNSA National Nuclear Security Administration

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000. SAND NO. 2011-XXXXP