SAND2017-1502C

Quantum Testbed Stakeholder Workshop

Hosted by the Advanced Scientific Computing Research Program

Sandia National Laboratories

Quantum Computing Capabilities and Interests

February 14 – 16, 2016

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Sandia National Laboratories: Capabilities and Interests Summary

Primary Expertise & Interest Areas

- **Fundamentals:** atomic and condensed matter physics, noise models, photonics, optics, QIS theory
- **Fabrication:** quantum device design/modeling, micro-electronics fab, packaging, integration, nanotechnology, photonics, failure analysis (including superconducting electronics)
- **Quantum Devices:** theory, qubit devices, quantum and classical architectures, error correction, controls, mod/sim, testing
- **Quantum Systems:** algorithms, applications, assessments
- **Data Systems:** HPC HW/SW design, operating system development, date warehousing/analytics/mining, data visualization, user interfaces
- **Infrastructure:** vacuum chambers/systems, dil fridges, cryogenics, mechanical/electronics/optics fab, test facilities

Most Differentiating Factors

- **MESA Silicon Fab and Micro Fab:** world-wide supplier of ion traps and silicon-based dot devices
- **Center for Integrated Nanotechnologies (CINT):** device testing, materials/devices characterizations, fabrication. *A DOE/SC National User Facility*
- **High Performance Computing:** critical enabler for qubit design/simulation/testing/analysis, data analyses
- **Materials Science:** creation/synthesis, prototyping processes, measurements, characterization, modeling
- **Deep, broad technical base:** foundation from $75M LDRD investment (2006-2019)
- **Multidisciplinary, integrated cross-laboratory team:** basic science to engineering to systems integration to outreach/partnerships – deep, broad domain expertise

Main Contribution/Role

- **System and Program Integration:** end-to-end design, fabrication, test, operations, analyses from the physical qubit layer through quantum information applications and device operations
- ***We make available the depth and breadth of our capabilities to ensure the success of the DOE testbed***

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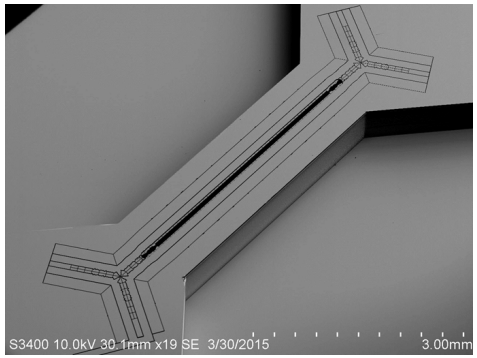
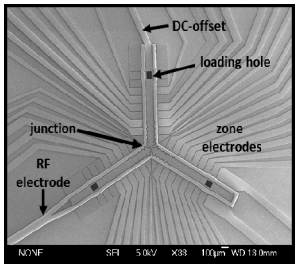
Quantum Computing Hardware Capabilities

SNL Primary Platforms: Trapped Ions and Si-based Dots/Donors

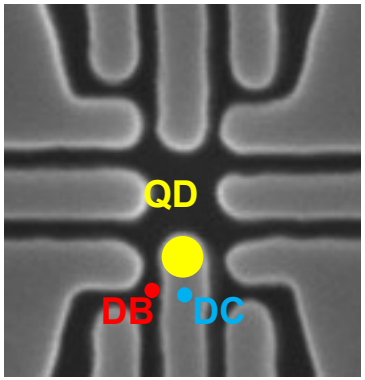
- **Ions in Microfabricated Surface Traps**
  - Ion trap foundry: multiple designs; Ca, Yb, Mg
    - Delivered to >15 groups, 5 countries
    - IARPA MQCO, LogiQ supplier
  - HOA-2: workhorse platform
    - >100 h trapping time, >5 min w/o cooling (Yb)
    - World-leading fidelities: 1Q G_X, G_Y, G_I > 99.99%, 2Q Mølmer-Sørensen > 99.5%
- **Si-based Dots/Donors**
  - Double QDs (e^- spin, charge qubits)
  - Coupled QD-donor hybrid (world first):
    - F ~ 99.5%, 2-axis control of electron
    - Exploring extensibility (LDRD)
  - Cryoelectronic amplification for readout (low power, low noise), fidelities ~99.7%
  - Flexible qubit construction platform
- **Extensive theory, design, modeling, simulation tools**
- **Expertise in other qubit systems**
  - Neutral Atoms, Hole spins in GaAs, EONS, Majorana anyons



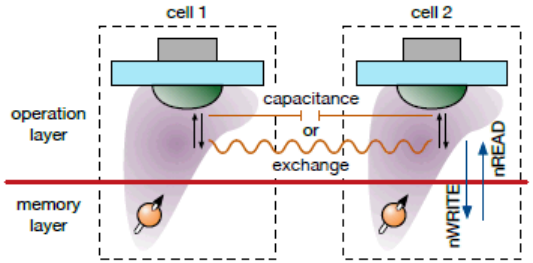
SNL HOA-2: best characteristics of any microfabricated surface trap at room T



Sandia Y-junction surface trap
Dynamic shuttling of Ca^+ thru junction ($>10^6$ cycles)



MAJIQ-SWAG Hybrid QD-D Device: P donor nuclear spin – ST qubit



Extension to 2-unit cell device (current LDRD)

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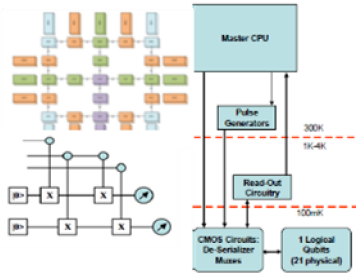
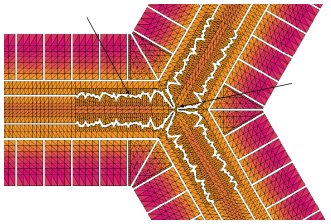
Quantum Computer Science Capabilities

A Sampling of Sandia's Capabilities

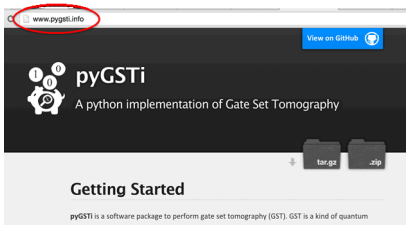
- **Architectures:** Theoretical and experimental expertise
  - Circuit (CQC), adiabatic (AQC), holonomic, topological
  - Error correction/suppression:
    - CQC: Error corrected logical qubit + optimal scheduling under hardware constraints
    - AQC: World-first error correction schemes with repetition codes; error suppression strategies; Non-equilibrium dynamical models of error suppression / error correction
    - Extensive university collaboration on surface codes, color codes
- **Controls and Noise Modeling**
  - Extensive theory/simulations for ions, traps, Si, neutrals
  - Optimal control, robust control protocols for uncertain qubits
- **V&V:** Gate Set Tomography (GST) and Randomized Benchmarking (RB)
  - GST: characterize/calibrate/debug qubits; detect non-Markovian noise; validate Diamond norm. Many users world-wide, multiple qubit systems
  - pyGSTi – open source GST software – www.pygsti.info
- **Modeling and Simulation:** SNL-designed, open source, and commercial tools
  - Architectures: circuit simulators, threshold simulators, cluster expansion simulators, vector state simulators, complex quantum networks, controls, stochastic quantum systems, noise models, …
  - Si: QCAD, COMSOL, NEMO-3D, valley-aware effective mass theory, strain, …
  - Ions: TRAPSIM (design tool), gate simulators, …

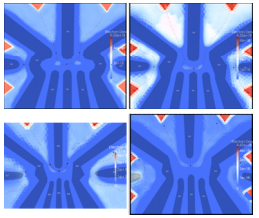


Schematic of components in Sandia systems-level logical qubit design



TRAPSIM: electrostatic modeling intended for RF trapped ion device design





QCAD results on DQD

***Many tools and capabilities** – but with **deliberate, tight integration** among experiment, theory, design, fabrication, and analysis*

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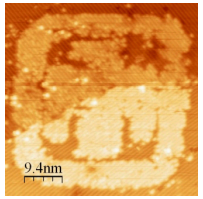
Fabrication and Characterization Capabilities

- **MESA Fabs**: Trusted design, fabrication, packaging, testing – underpinning Quantum Info at Sandia
  - Silicon Fab: CMOS process, custom technologies (e.g. ion traps, Si quantum dots, Si photonics)
  - MicroFab: III-V compound semiconductor fab
  - *Wafer-level to die-level processing*
- **Center for Integrated Nanotechnologies (CINT):** *a DOE User Facility*
  - Integration Lab: Clean room with E-beam lithography, photolithography, deposition/etch, SEM/FIB
  - Characterization Lab: SEM/TEM, STM, Si qubit characterization/measurement, transport
- **Special Capabilities:**
  - Atomic Precision Fabrication (CINT): H-lithography for ultimate scale quantum dots and digital electronics
  - Si Photonics: devices thru CMOS integration, cryo SiP
  - Failure analysis: CMOS, superconducting electronics
  - Ion Beam Laboratory: nanoImplanter
- **Materials Science:** creation/synthesis, prototyping processes, measurements, characterization, modeling

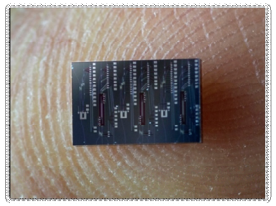
MESA

CINT

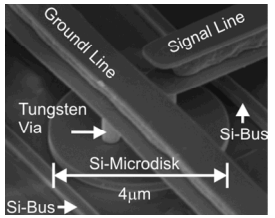
Atomic Precision Fab @ CINT



World-smallest Sandia "nanologo," at 0.7 nm precision.



World-first chip scale Si photonics quantum transceiver



Si Photonics resonant optical modulator/filter

Co-location with Si foundry: industrial fab rigor, defect reduction (function and performance), semiconductor yield engineering - ***QIS program accelerator***

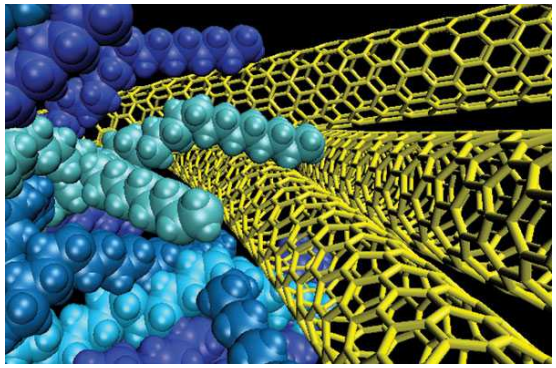
Capabilities in Engineering and Supporting Technology

Building, operating, upgrading, maintaining the testbed – ***providing the user experience*** – requires far more than expertise in building and operating qubits

- Relevant SNL expertise:
  - **Systems engineering and integration:** weapons laboratory heritage
  - **Computational systems:** High Performance Computing (HPC) HW/SW design, operating system development, data acquisition/warehousing/analytics/mining, data and scientific visualization, user interfaces
  - **Codesign:** conventional computing systems
  - **Lasers, Optics, Photonics:** component and system design, fabrication, integration, diffractive optical elements, operations
  - **Electronics:** design (component to circuit to IC to board), fabrication, test, burn-in, yield analysis, failure analysis, integration. *Includes cryoelectronics*
  - **Mechanical:** design, fabrication, test
  - **Infrastructure:** vacuum, pressure, cryogenics, power, environmental control (temperature, vibration, EM field, …)
  - **Testbed design/development/operations:** Advanced Systems Technology Test Beds, National Cyber Range team member

Applications to Domain Science

- **Sandia QIS Vision:** *Institutionalize Quantum*
  - **Mission area problems**: Move from classical to quantum enhanced to quantum solutions
  - **QIS program partnering:** spans Sandia Mission Areas, including Nuclear Weapons, Cyber, Materials, Homeland Security
  - **QIS spin-offs**: near-term "wins" – e.g., Atomic Precision Fab



*Quantum applications may be mid- to long-term – but we need to be thinking hard about them **today***

- **Current Areas of Emphasis at Sandia**
  - Properties of matter in extreme environments
  - Material properties and aging
  - Design of new materials with tailored properties
  - Cyber Security

Sandia is engaged in QIS research in support of its missions. This research is motivated by advanced computing architectures and the fact that future engineered systems will require increased understanding of quantum effects.

- **Testbed Major Roles – some preliminary thoughts**
  - **Near term:** gate-based quantum computing (e.g., demos of fault tolerant quantum error correction), probing/characterizing noise and errors
  - **Mid to long term:** Algorithm development/testing – pathfinder scale, but progressively larger / greater realism as testbed advances

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Investments in Quantum Computing Technology

- LDRD: Integral to Sandia's QIS R&D strategy

QIST Quantum Information S&T

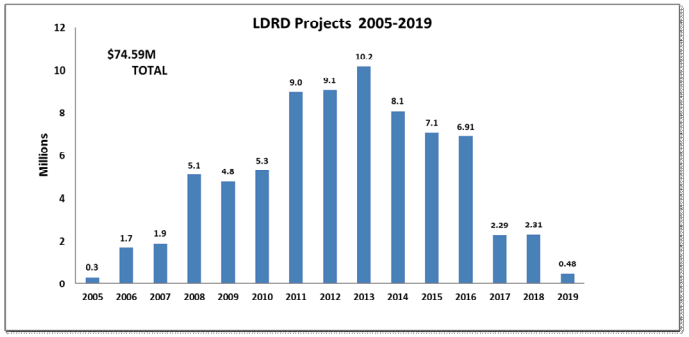
FY08 – FY10
Si-based qubits

AQUARIUS™ Adiabatic quantum architectures in ultracold systems

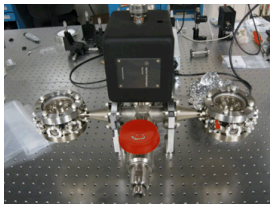
FY11-FY13
Architectures

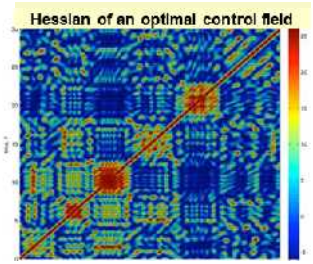
SECANT QKD

FY14-FY16
Comms/QKD

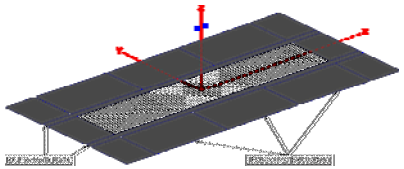


- *Build foundational capabilities while exploring novel, high risk areas*
- Focus on the engineering challenges of QIS
- $74.6M investment, FY05-19
- *Essential* vehicle for academic collaborations





- Broad and deep portfolio, spanning many facets of QIS:
  - **Qubits:** physical qubit development, logical qubit design, entanglement, noise modeling, design tools
  - **Quantum engineering:** architectures, robust controls for quantum gates, on-chip microwave control of ion traps, tomography (GST)
  - **Algorithms/apps:** demonstration of few-qubit apps, algorithm design
  - **Simulation:** design toolkits, error correction threshold simulators
  - **Comms:** QKD, photon source development, single photon detectors
  - **Sensing:** Precision location and time for NW and DOD needs



***Key Outcome:* Integrated, cross-SNL, multidisciplinary QIS team / program**

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Facility Management Experience

- **Center for Integrated Nanotechnologies (CINT)**
  - DOE/Office of Science national user facility: joint SNL-LANL facility
  - Substantial QIS resources: fabrication, measurement, characterization
  - CINT staff: 50% CINT, 50% “other” projects; numerous QIS staff are *also* CINT staff

- **Combustion Research Facility (CRF)**
  - DOE/Office of Science Collaborative research facility
- **Advanced Systems Technology Test Beds**
  - Part of NNSA’s Advanced Simulation and Computing project

- **Experience in critical and pertinent facility functions:**
  - **Hosting visitors:** academia, industry, government, foreign researchers
  - **High Performance Computing:** data warehousing, remote access, data analysis, data security
  - **Multiple collaboration models:** user agreements, CRADAs, contracts, industrial partnerships
  - **IP protection:** NDAs, CRADAs. Data protection and security. *Critical enabler with private sector*
  - **Student programs:** internships (Intern Institutes), postdoc programs
  - **Continuing education:** ongoing workforce education through internal QIS courses, invited world-class lectures

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External Partnerships

Sandia's Quantum Information Science program is rooted in collaborations: