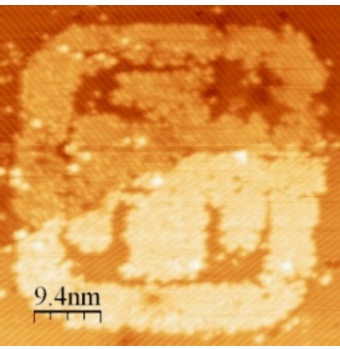
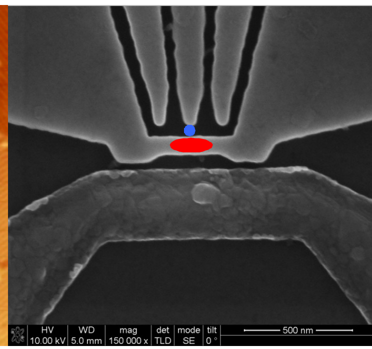
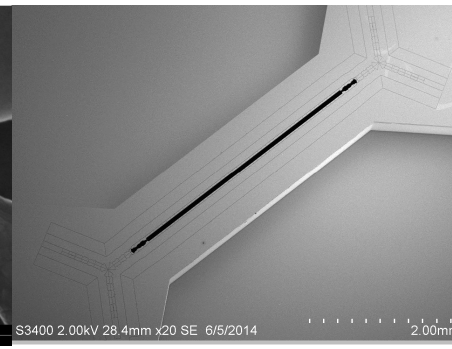
SAND2015-2048PE

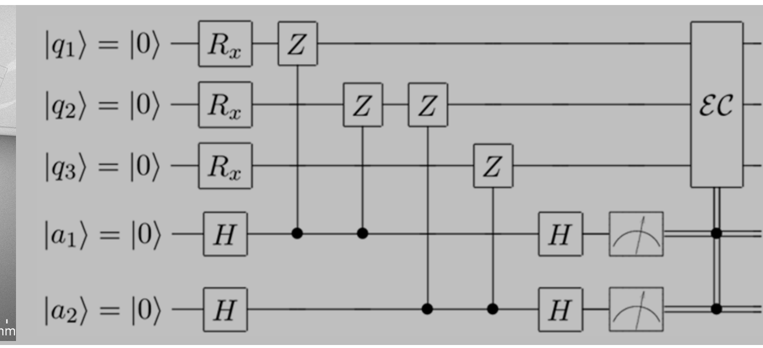
Exceptional service in the national interest

Sandia National Laboratories









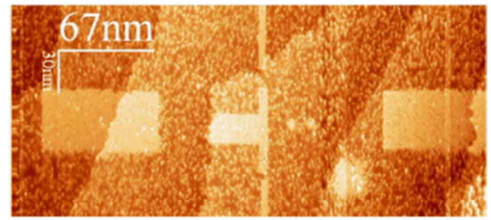
Quantum Information Science Research at Sandia

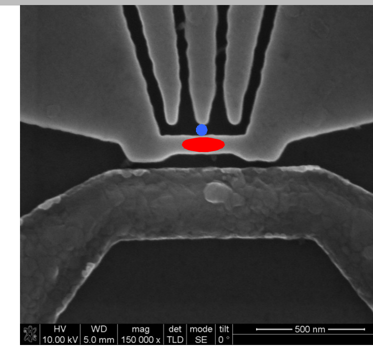
Clark Highstrete, Manager
Advanced Solid State Microsystems Department

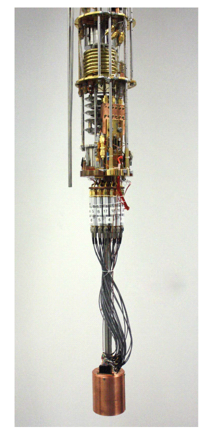
Sandia National Laboratories

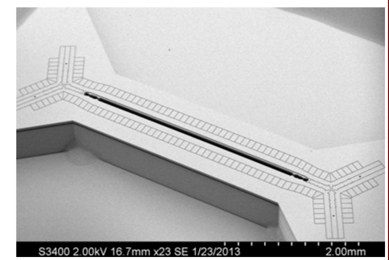
Outline

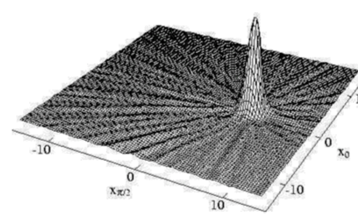
- **Program Overview**
- **Facilities**
- **Foundations**
  - LDRD
  - SEQIS Research Challenge
- **Technical Capabilities**
  - Qubits
  - Architectures / Error Correction
  - Controls and Noise Modeling
  - Tomography
  - Modeling and Simulation
  - Algorithms / Applications

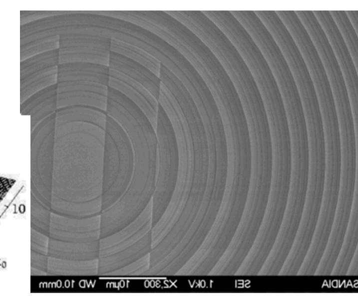


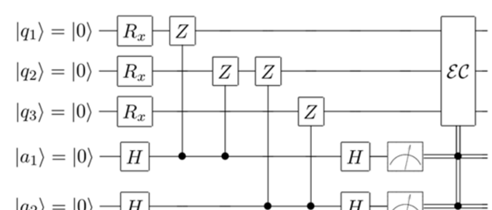








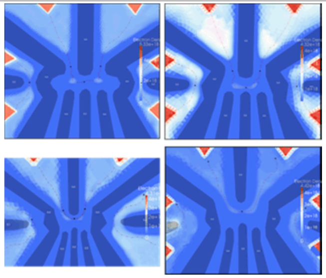


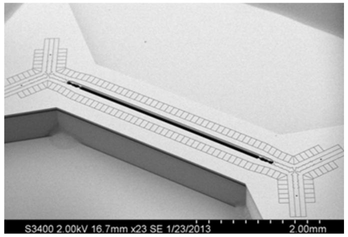


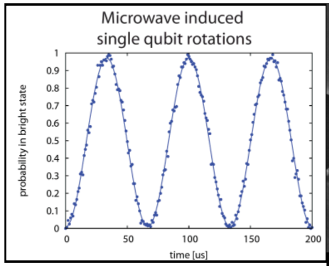
Quantum Information Science at Sandia

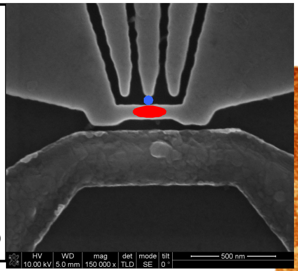
Sandia National Laboratories

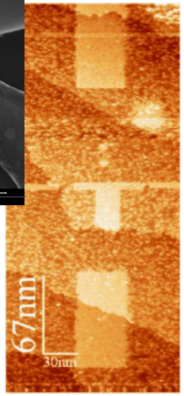
- **QIS at Sandia: multidisciplinary, cross-Labs activity**
  - Fundamentals: atomic and condensed matter physics, noise models, photonics, optics, QIS theory
  - Fabrication: device design/modeling, microelectronics fab, atomic-precision fab, integration, nanotechnology, photonics
  - Quantum devices: theory, quantum/classical architectures, error correction, controls, mod/sim, testing
  - Quantum systems: algorithms, applications, technology assessments
- **Expertise in key technologies**
  - Physical qubits: Si quantum dots/donors, trapped ions, neutral atoms
  - Logical qubits: design
  - Architectures: circuit, adiabatic
  - Algorithms/apps: demonstrations, analysis, development
- **Unique, enabling facilities: microelectronics fabrication, atomic-scale fabrication, HPC**
- **Systems engineering heritage**
- **The technical challenges are vast – solving them is our focus**



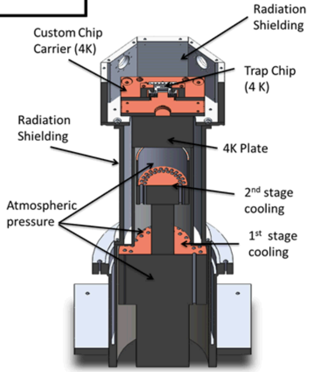








Sandia is engaged in QIS research in support of its missions. This research is motivated by advanced computing architectures and the fact that future engineered systems will require increased understanding of quantum effects.



QIS Program Snapshot

- **Research areas :**
  - Physical qubit development – Silicon dots, donors; trapped ions
  - Fault-tolerant architecture design, error correction
  - Quantum sensing / navigation
  - Quantum computer science
  - Quantum communications
  - Algorithms
- **Multiple, world-wide collaborations and outreach**
  - Multiple universities under contract; hosting grad students/postdocs
  - Collaborations with LPS, LANL, NASA, NIST
  - Co-sponsorship of four major international conferences
- **Major Sandia investment portfolio**
  - Cross-Sandia management structure
    - 4 Divisions / 6 Centers
    - NM and CA Sites
  - Internal training courses and invited lecturer series
  - Strategic planning, technical roadmapping
  - Research Challenge: SEQIS Science and Engineering of Quantum Information Systems

CQuIC Associate Faculty

Theory
- Andrew Landahl
- Robin Blume-Kohout

Neutral Atoms
- Grant Biedermann
- Peter Schwindt
- Yuan-Yu Jau

Ions
- Daniel Stick

Solid state
- Steven Carr

Facilities: MESA Fabs

A research, development and production capability that converts concepts into working hardware

MESA Silicon Fab

- Radiation Hardened CMOS-7 Processing
  - 350nm Silicon on Insulator
  - Digital and Mixed Signal Technology
  - 5-Level MEMS Technology
  - 3-D Integration
- Research and Development Technologies
  - Microfabricated multi-layer surface ion traps
  - Si qubit devices - DQDs and donor host device
  - Si Photonics
  - Chem/Bio Detection Technologies
  - AlN Resonators
- US DoD Category 1A Trusted Supplier Certification

MESA Micro Fab

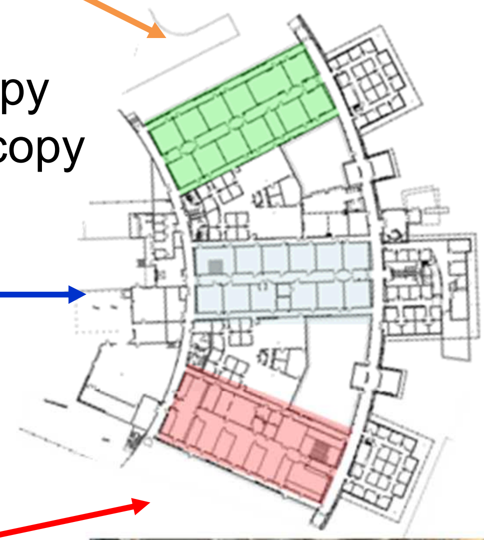
- III-V Compound Semiconductor Fabrication
- Devices, IC's and Optoelectronics
- Compound Semiconductor Epitaxial Growth
- Nano-electronics: electron beam lithography

125 Light Laboratories Support and Extract Value from the MESA Fab
285 Patents - 42 R&D 100 Awards

Facilities: Center for Integrated Nanotechnologies

Sandia National Laboratories

Core Facility

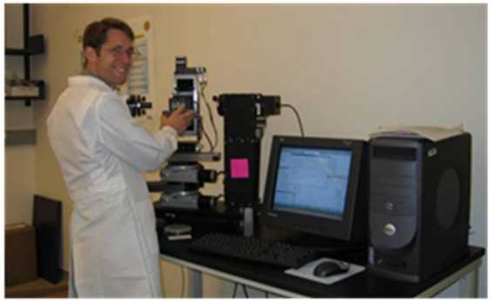


Characterization Wing
- TEM, SEM
- Low Temp Transport
- Scanning Probe Microscopy
- Ultra-fast Laser Spectroscopy

Synthesis Wing
- Molecular Beam Epitaxy
- Chem & Bio labs
- Molecular films

Integration Lab
- E-beam lithography
- Photolithography
- Deposition & Etch
- SEM/FIB
- STM atomic-scale fabrication

- A DOE/SC National User Facility
  - Defined by a scientific field, not specific instrumentation
  - NSRC staff support user projects and conduct original research
  - Capabilities involve hardware plus research expertise
- Vision: “One scientific community focused on nanoscale integration”
- Gateway to Los Alamos National Laboratory capabilities



Los Alamos NATIONAL LABORATORY

U.S. DEPARTMENT OF ENERGY | Office of Science

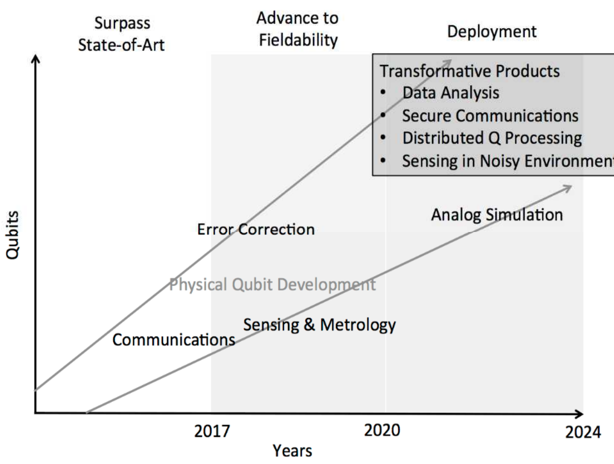
Center for Integrated Nanotechnologies CINT

Foundations
SEQIS Research Challenge

- **Science and Engineering of Quantum Information Systems**
  - RCs are a Sandia-wide initiative to focus efforts on key technological areas with high impacts to our mission areas
- **SEQIS seeks to advance:**
  - Entanglement-enhanced sensors that surpass SOA in multiple areas, including imaging, navigation, gravimetry
  - Entanglement-enhanced information storage/processing devices that surpass SOA classical computing technologies
  - Long distance, secure communications protocols that leverage quantum information-disturbance relationships

Research Challenges will:
- Advance the state-of-the-art in S&E
- Surmount critical path technology obstacles
- Bring together broad cross-section of Labs' capabilities
- Require interdisciplinary approach
- Engage expertise from fundamental science through technology application
- Result in long-term S&E legacy

SEQIS Technology Roadmap



VISION

By 2024 Sandia will develop and prototype functioning quantum devices and algorithms that run on them that realize transformative advances in information sensing, processing, and communication to address needs of Sandia's customers.

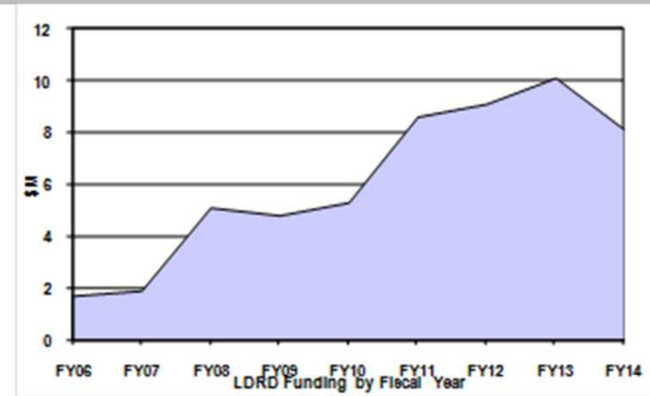
Sandia National Laboratories

Foundations
Laboratory Directed R&D (LDRD)

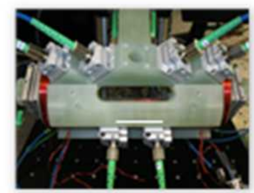
QIST Quantum Information S&T — **FY08 – FY10** *Si-based qubits*

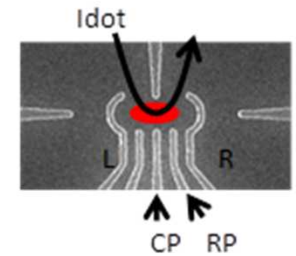
AQUARIUS™ Adiabatic quantum architectures in ultracold systems — **FY11-FY13** *Architectures*

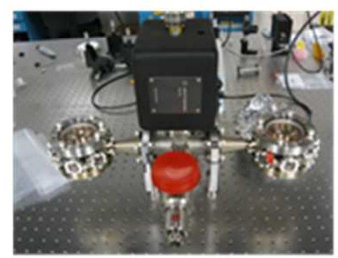
SECANT QKD — **FY14-FY16** *Q-Comm/QKD*

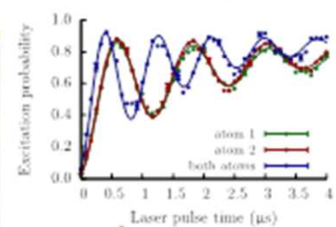


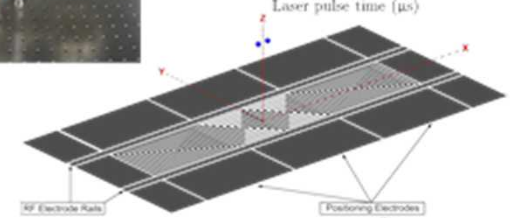
- **Integral to Sandia's QIS R&D strategy**
  - Build foundational capabilities while exploring novel, high risk areas
  - Focus on the engineering challenges of QIS
  - $54.7M investment, FY06-14
  - Includes early career, traditional, and grand challenge LDRDs
  - Essential vehicle for academic collaborations
- **Broad and deep portfolio, spanning many facets of QIS:**
  - Qubits: physical qubit development, logical qubit design, entanglement, noise modeling
  - Quantum engineering: architectures, robust controls for quantum gates, on-chip microwave control of ion traps, tomography
  - Algorithms/applications: demonstration of few-qubit apps, algorithm design
  - Simulation: design toolkits, error correction threshold simulators
  - Sensing: matter-wave sensors, atom interferometry
  - Q-Comm: QKD, photon source development, single photon detectors











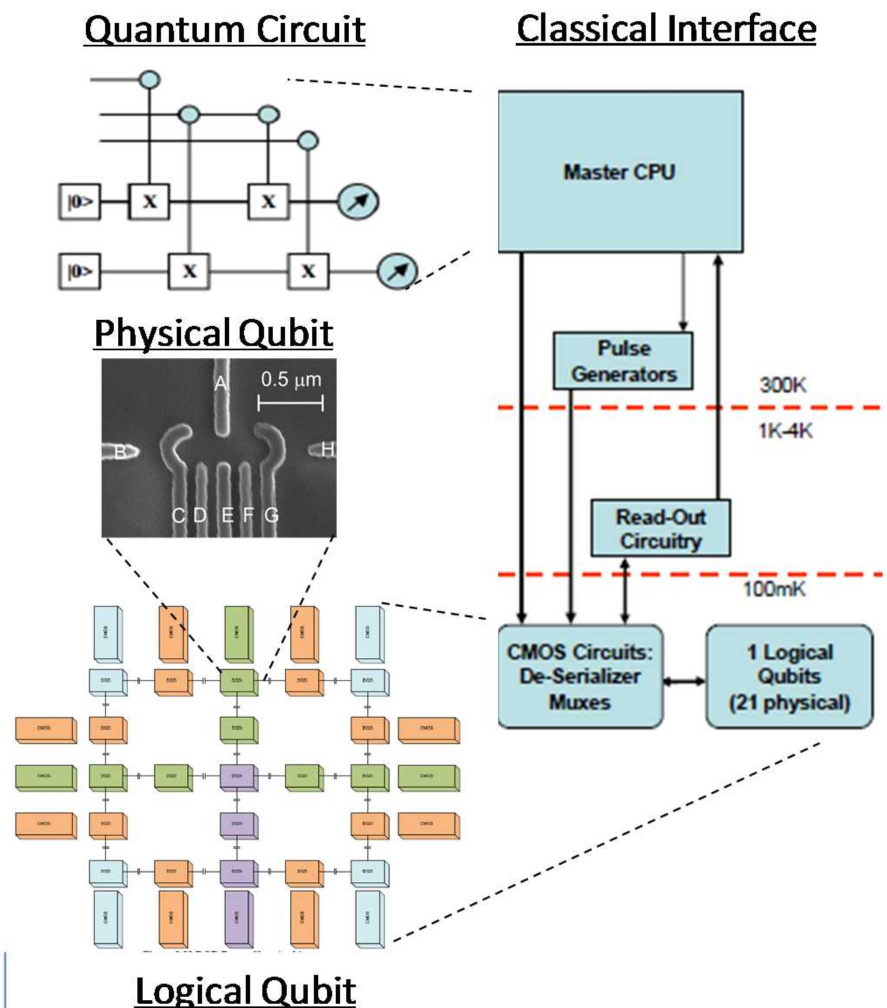
LDRD LABORATORY DIRECTED RESEARCH & DEVELOPMENT

Foundations: LDRD QIST Grand Challenge FY08-10

Sandia National Laboratories

- **GOALS:**
  - Develop physical silicon qubit
  - Design logical qubit with Si hardware

- **Multidisciplinary, cross-SNL team:**
  - Physical qubit (DQD + hybrid design)
  - Measurement
  - Modeling
  - Classical electronics
  - Architecture



Evaluation by external board of program managers & researchers

1. "Such a multi-disciplinary multi-talented ***team is not easily replicated***." ..."there are few, if any, comparable [QIS] projects.

2. "... the EAB sees ***Sandia as a leading national resource*** ... with ***cryoCMOS chips*** and ***systems engineering*** capabilities."

Supplied Si devices to LBNL, NIST, Princeton, and Australian Centre for Quantum Computing Technologies

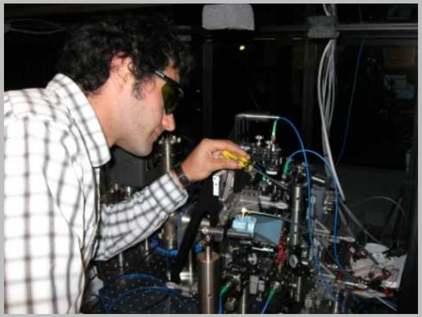
LDRD LABORATORY DIRECTED RESEARCH & DEVELOPMENT

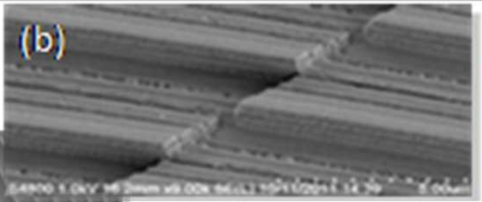
Foundations: LDRD AQUARIUS GC FY11-13

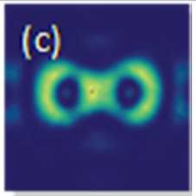
- **Project objectives**
  - Demonstrate special-purpose two-qubit adiabatic quantum optimization algorithms in
    - Neutral atoms trapped in a nanofabricated optical array.
    - Electrons trapped in silicon nanostructures.
  - Assess the potential for general-purpose fault-tolerant adiabatic quantum computing.

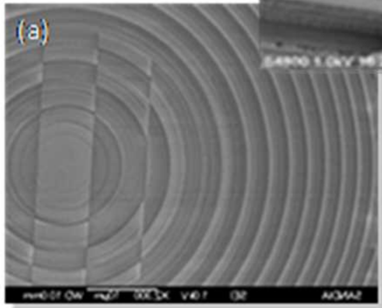
- **Major accomplishments**
  - Demonstration of isolated silicon "charge" qubit
  - Demonstration of atomic-scale Si lithography – second in world
  - World-first fabrication of diffractive optical elements for Cs atom trapping & control
  - World-first trapping of three separated Cs atoms
  - World-first entangling and control of 2-qubit Cs atom AQC
  - World-first layouts for general purpose AQC in silicon and Cs-atom technologies
  - World-first error correcting codes for AQC
  - World-first "smoking gun" tests of adiabaticity

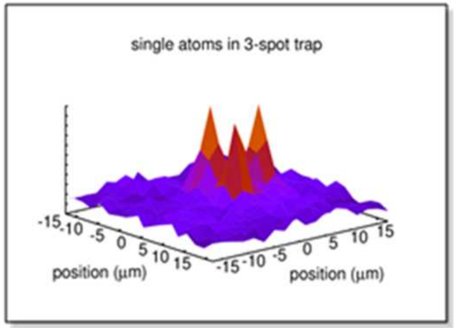
Sandia's first quantum bit (qubit). It processes information stored in an optically trapped cesium atom that is laser-cooled to 100 microkelvin in an ultra-high vacuum chamber.

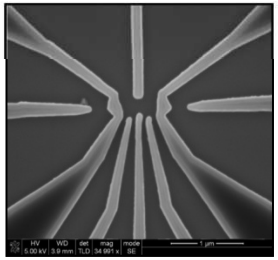




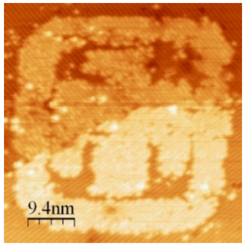








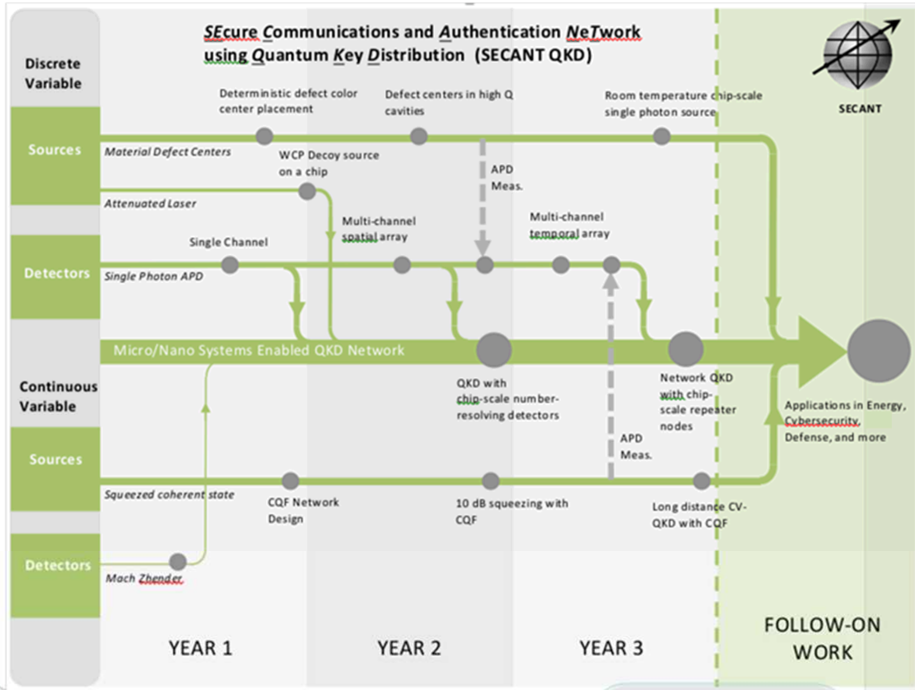
Sandia silicon nanostructure defining an "artificial atom" double-quantum-dot qubit.

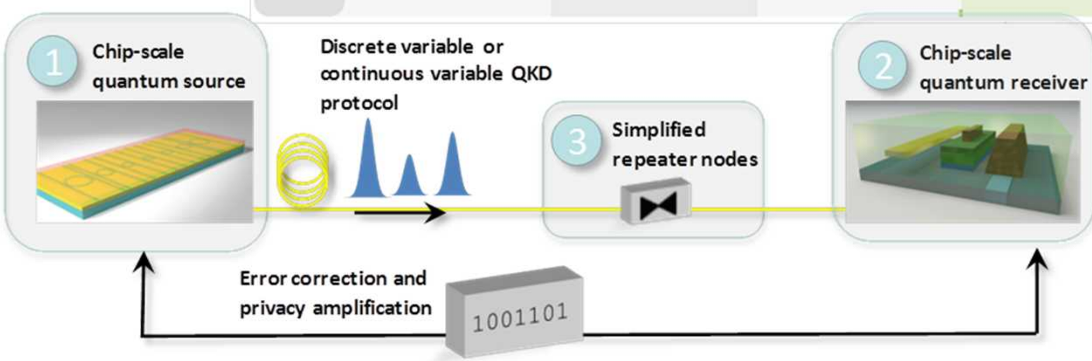


Sandia "nanologo," written to single-atom 0.7 nm precision.

Foundations: LDRD SECANT QKD GC FY14-16

- **Description/Goals:**
  - Enable large scale deployment of QKD systems through chip-scale photonic integration of sources, receivers, and repeaters
  - Enhance performance through investments in advanced single photon and squeezed light sources and integrated single photon and photon number resolving detectors
  - Align investments with commercial, Government, and National Lab interests through enabling investments in discrete variable (DV) and continuous variable (CV) implementations of QKD
  - Demonstrate technology through in-fiber and free space test beds

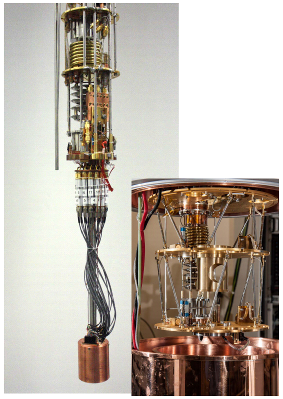


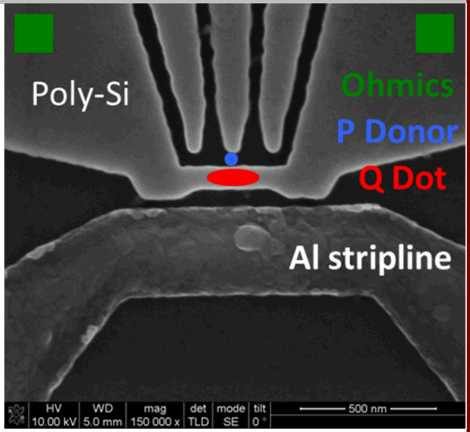


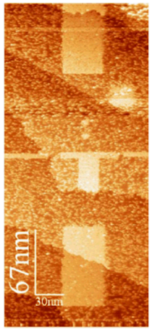
SECANT QKD system overview with the three new key technologies highlighted: (1) Novel chip-scale quantum sources, (2) novel chip-scale multiplexed quantum receivers, and (3) simplified chip-scale repeater nodes.

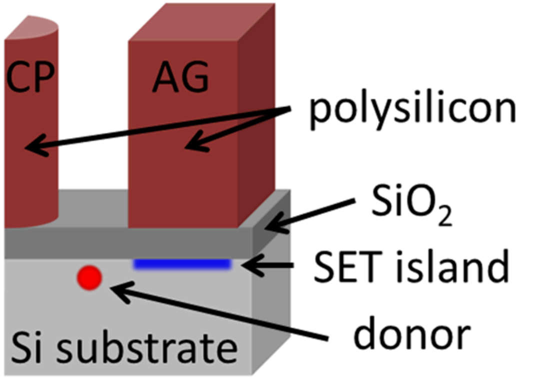
Technical Capabilities
Silicon Qubits

- **Capabilities / focus**
  - Donors in silicon
    - Ion implantation
    - Atomic scale fabrication (STM hydrogen litho)
  - Double quantum dots
    - spin and charge qubits
- **Under development for over seven years**
  - Genesis – QIST GC LDRD
  - Adiabatic qubits explored under AQUARIUS
    - Developed charge qubit (provisional patent)
    - Preliminary work on donors in silicon
    - Key result – Pauli blockade on double quantum dots
  - Current focus: one and two qubit devices
- **Design-fab-test-evaluate cycle**
  - Design – multiple tools (e.g., QCAD)
  - Fab – MESA Fab, CINT (STM-based atomic precision fab, EBL), ion beam lab (nano-implanter)
  - Test – cryogenic test facilities
- **Accomplishments:**
  - ESR characterization of implanted donor device
  - First spin readout of Sb donor
  - Spin readout in ^{28}Si device









T_1 (ESR prepared)	3.3 ± 0.1 s
T_2^*	77 ± 5 ns
T_2 (Hahn Echo)	88 ± 4 μs
T_2 (DD; XYXY)	220 ± 20 μs
F_c	62%

Natural silicon ESR results

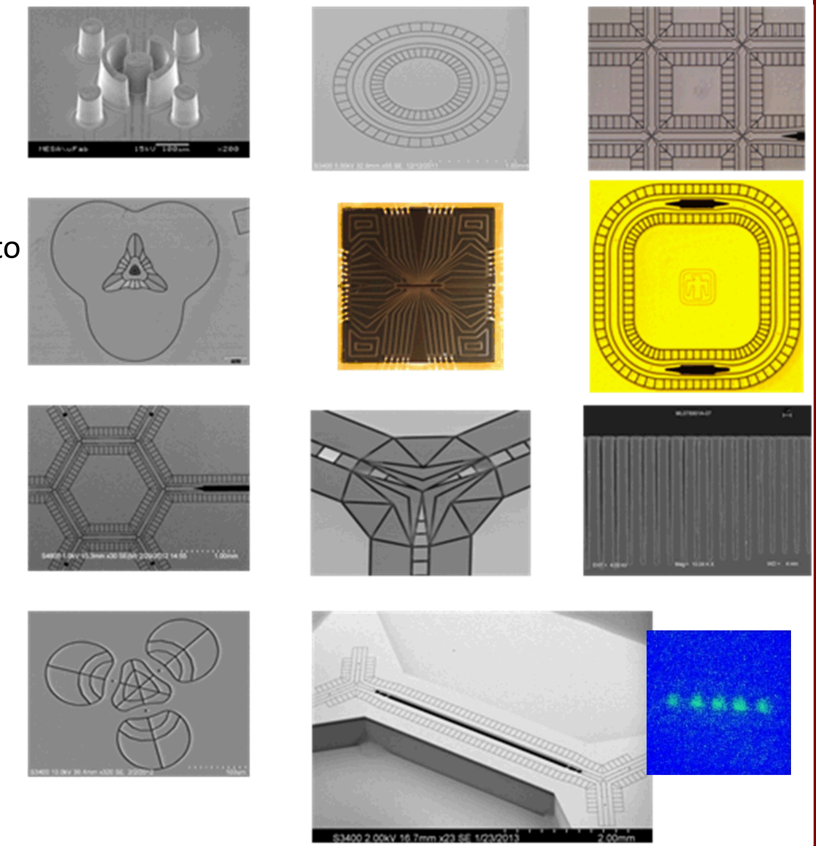
Sandia National Laboratories

Technical Capabilities Ion Traps

- **Capabilities / focus**
  - Multiple metal layers
  - Integrated diffractive optical elements
  - Microwave on-chip control of ions

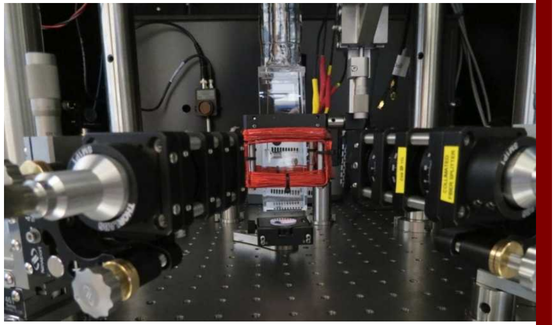
- **Projects**
  - MQCO (IARPA) – trap fabrication and testing for multiple collaborators (Duke, Maryland, NIST, MIT)
  - SPRINT – collaboration with NIST to design, fabricate, and demonstrate lattice traps
  - Graph Analysis LDRD – Demonstrate Gate Set Tomography to measure and characterize errors in single qubit gates

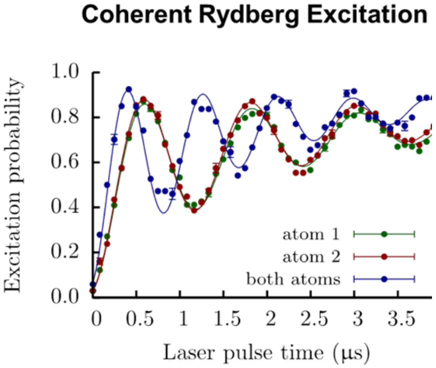
- **Accomplishments**
  - Ion trap foundry
    - 12 institutions, 5 countries
    - 8 institutions have successfully trapped using SNL designs
    - Traps used with Ca, Yb, Mg
  - Single qubit gates:
    - Gate Set Tomography (GST) and Randomized Benchmarking to characterize single qubit gate
    - Using GST for debugging and improving the system
    - Average infidelity 4.9 x 10-5
    - worst case infidelity 2.0 x 10-4
  - Trap heating rates
    - Heating rate of single ion transversal mode <70 quanta/sec
    - Radial tilt mode heating rate estimated <1 quantum/sec
  - Two qubit gates
    - Molmer-Sorensen two-qubit gate with 97% fidelity realized in a scalable surface trap

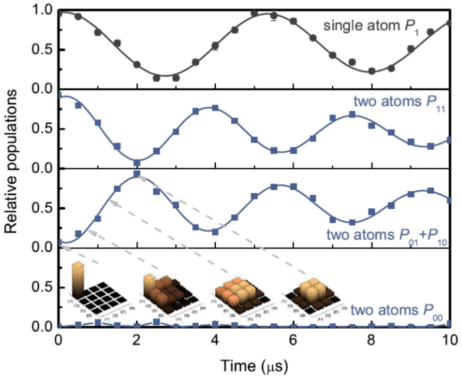


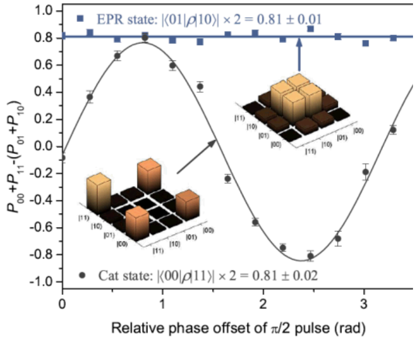
Technical Capabilities
Neutral Atoms

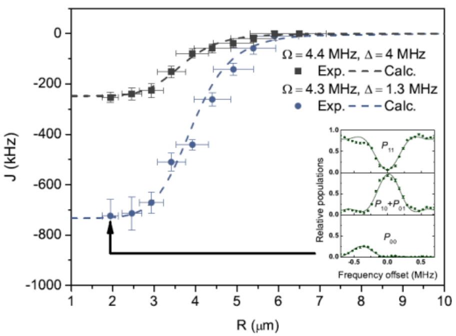
- **Projects**
  - IMPACT ion clock
  - Magnetometers for magnetoencephalography
  - Atom interferometers
  - Neutral atom qubits
    - AQUARIUS Grand Challenge
    - LDRD
- **Neutral Atom Qubit LDRD**
  - Goals:
    - Develop Rydberg atom entanglement
    - Develop new entangle gate techniques
    - Develop optimal control algorithms for improved bell-state generation
  - Applications to quantum computing and sensing





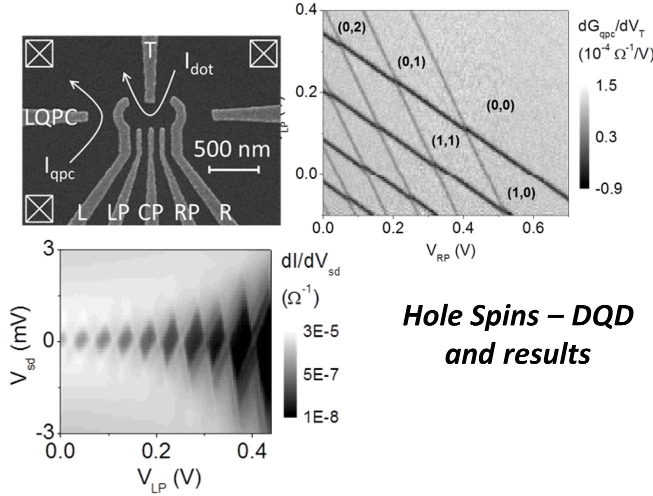






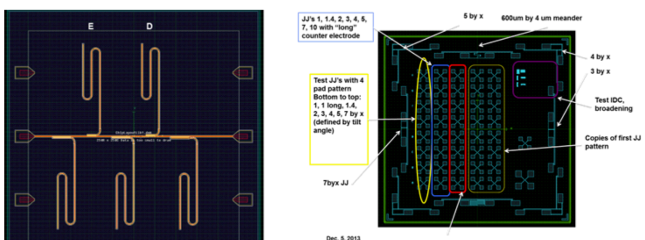
Technical Capabilities
Additional Qubit Expertise

- **Hole Spins in GaAs**
  - Supported under two LDRDs (FY11-15)
  - Goals:
    - develop single hole transistor devices in GaAs
    - investigate hole spin physics,
    - eventual qubit evaluations
  - Observing regular Coulomb blockade, diamonds, few hole occupation



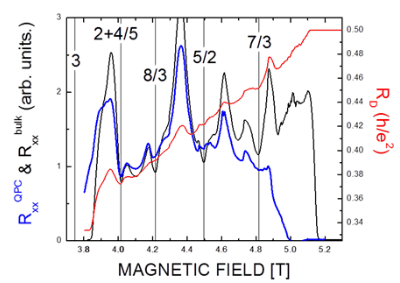
Hole Spins – DQD and results

- **Josephson Junctions**
  - Supported under LDRD (FY13-15)
  - Goals:
    - isolate transmon qubits
    - develop scaling techniques
    - enable single/multiple high fidelity gates



JJs – initial layouts

- **Fractional Quantum Hall Effect – Majorana Fermions**
  - Supported under multiple LDRDs
  - Goals:
    - examine physics of FQHE states
    - determine bulk and edge transport properties
    - quasiparticle charge, possible non-abelian properties

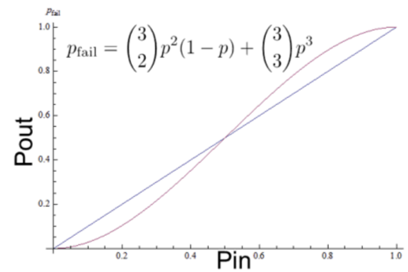


Experimental results - FQHE

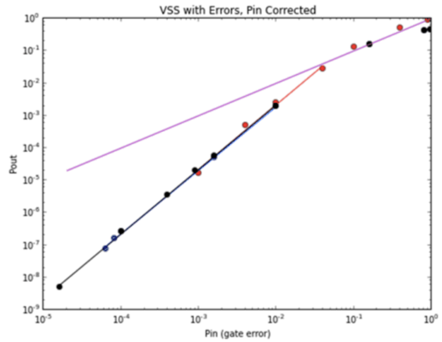
Technical Capabilities Modeling & Simulation

- **Multiple modeling tools developed under sponsor and internal funds**
  - Quantum information systems and related capabilities

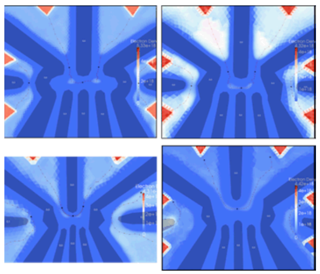
- **Example tools:**
  - **QCAD**: Simulation toolkit for semiconductor donor and quantum dot systems
  - **TRAPSIM**: electrostatic modeling intended for RF trapped ion device design
  - **Gate simulator**: single and two qubit trapped ion gates
  - **Threshold Simulator**: simulates quantum error correction circuit performance subject to schedule and noise models
  - **Cluster expansion simulator**: uses cluster expansion techniques to compute the decoherence of small spin systems due to environmental interactions with background spins
  - **Vector state simulator**: tracks full state vector of qubit(s), simulates small over/under rotations with error models
  - **Bloch-Aware Effective Mass Theory**: quantitatively accurate approximation for rapid device analysis

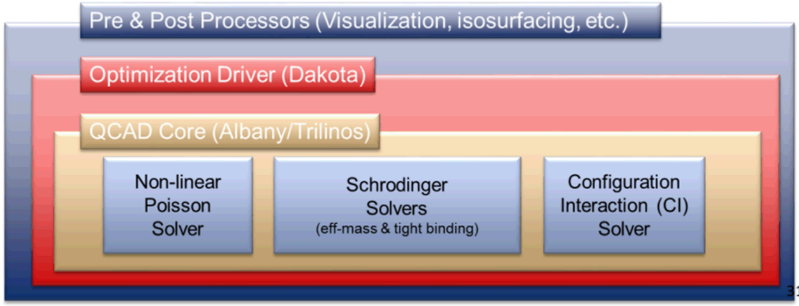


Threshold calculations



QCAD results on DQD and QCAD structure





Technical Capabilities
Controls and Noise Modeling

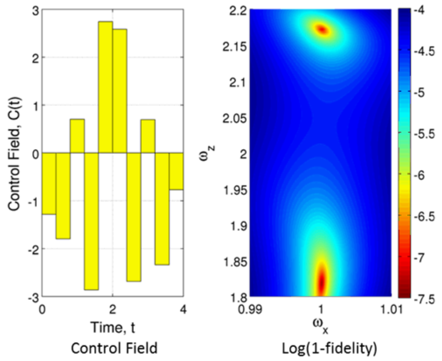
- **Extensive capabilities developed under multiple projects, including hardware-specific, realistic noise models**

- **AQUARIUS GC LDRD (FY11-13)**
  - Developed noise models and associated control and error correction/suppression strategies for neutrals and Si qubits
  - Ex: Photon scattering leading to qubit leakage in neutrals; did not find an effective code space to protect against these errors; examined limits to scaling of QUBO in neutrals
  - Examined effects of dephasing, control errors, relaxation – AQC should be immune, but this isn't always the case!

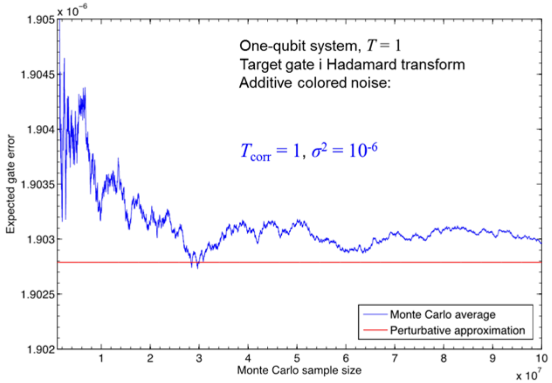
- **Control Algorithms LDRD (FY11-13)**
  - Objective: develop mathematical and computational algorithms to investigate and quantify fundamental limits to controlling quantum systems
  - Accomplishments: developed algorithms for faster (classical) simulation of stochastic quantum systems, designed robust control protocols for uncertain qubits

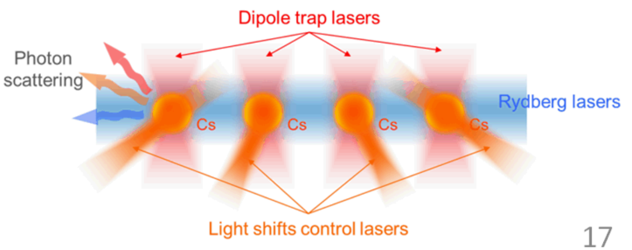
- **Control Robustness LDRD (FY11-12)**
  - Objective: develop quantitative methods for assessing robustness of gates to weak random control noise; identify robust controls for relevant stochastic noise processes
  - Accomplishments: derived general results for robustness to white noise (additive and multiplicative), optimized control robustness to colored noise; examined scaling of noise-induced errors to gate size

$$H(t) = C(t)\omega_x\sigma_x + \omega_z\sigma_z$$



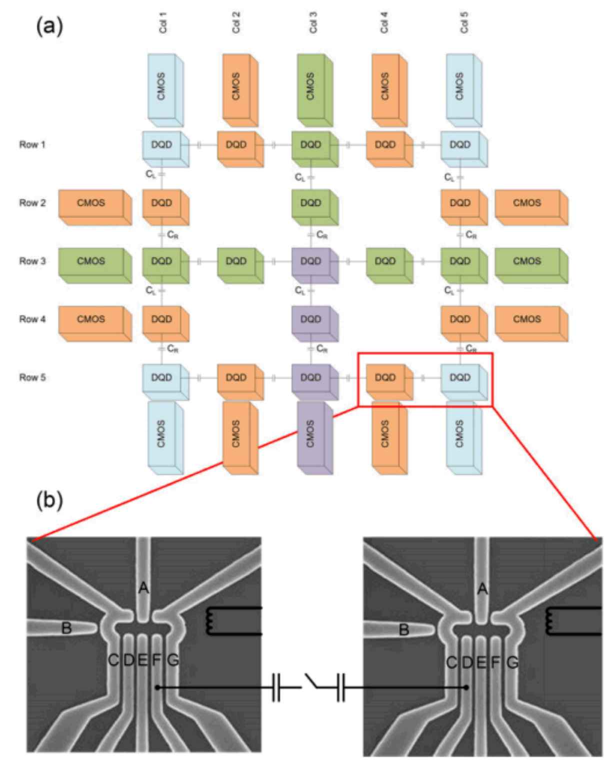
Hadamard gate



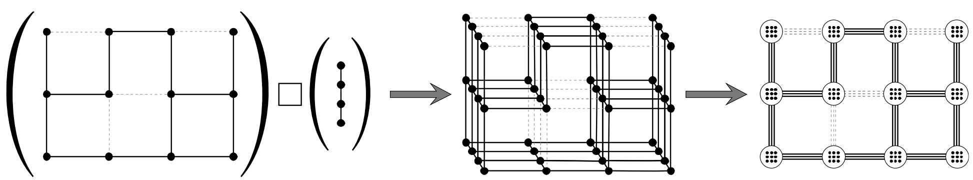


Technical Capabilities
Architectures and Error Correction

- **Theoretical / experimental expertise in multiple architectures:**
  - Circuit model (QIST, LDRDs)
  - Adiabatic (AQUARIUS,ENCELADUS)
  - Holonomic (AQUARIUS)
  - Topological (LDRDs)
- **Error correction / error suppression – extensive work under multiple projects**
  - Developed error corrected logical qubit under QIST, including optimal scheduling under hardware constraints
  - Non-equilibrium dynamical models of error suppression / error correction for AQC (AQUARIUS)
  - World-first error correction schemes with repetition codes for adiabatic quantum computing (AQUARIUS)
  - Error suppression strategies for AQC, including energy gap protection, dynamical decoupling, Zeno effect suppression
  - Collaboration with UNM on surface codes, color codes



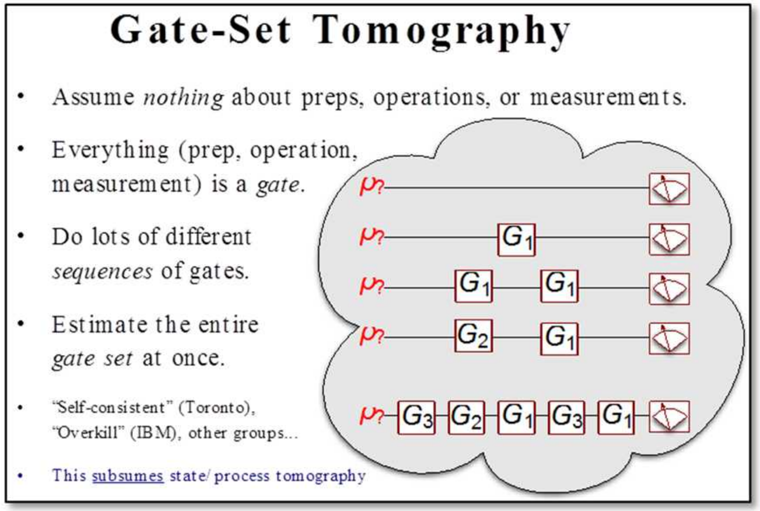
QIST logical qubit and its optimal schedule

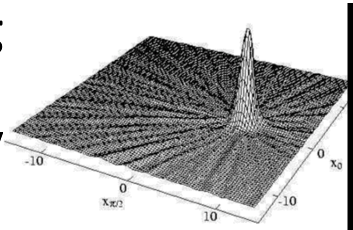


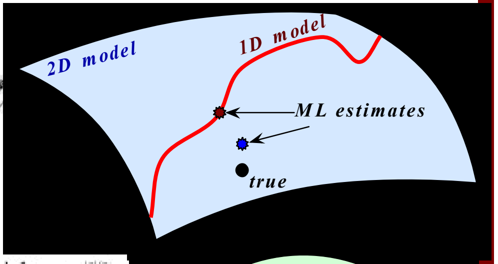
Conceptual scheme for incorporating a repetition code into an Ising model optimization problem in an adiabatic quantum computer, from AQUARIUS

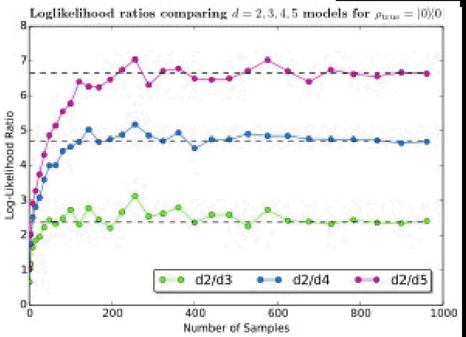
Technical Capabilities
Tomography

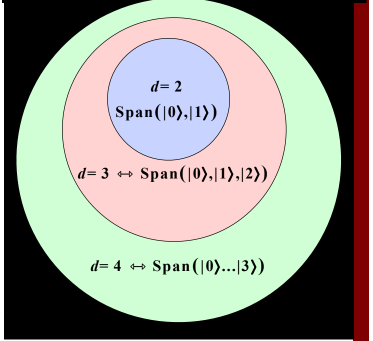
- **Gate set tomography: Sandia-developed protocol for hyper-accurate, calibration-free characterization.**
  - Solves need for precalibrated measurements.
  - Achieves unprecedented gate accuracy (±10^{-5})
  - Used in experiments including trapped ion (SNL) and silicon quantum dot (U of Wisconsin) qubits.
- **Model selection: Sophisticated statistical techniques for testing, choosing, and designing statistical models with varying number of parameters based on data.**
  - Will be critical for multiple-qubit tomography
  - Requires more sophisticated melding of statistical inference w/quantum info physics than has yet been achieved.
  - Current SNL projects:
    - Accurate infinite-dimensional tomography for continuous variables (with T. Scholten)
    - Tomography in the time domain: tracking drifting quantum processes.







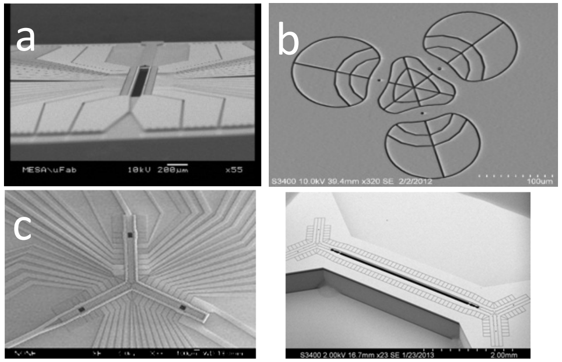




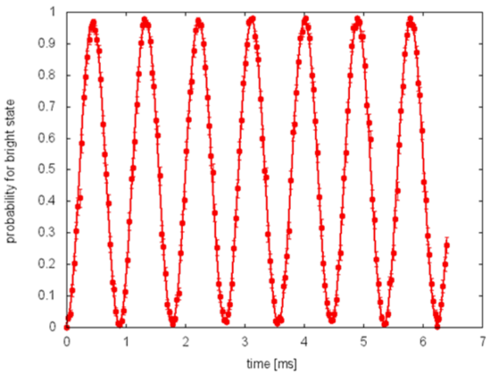
Technical Capabilities Algorithms/Applications

- **What useful problems can be addressed with a handful of qubits?**
  - Addressed in strategic plans, technical roadmaps, SEQIS research challenge
  - Driver behind recent SNL LDRD proposal calls

- **Ongoing projects:**
  - Methodology for benchmarking AQC against classical computing
  - Quantum Graph Analysis LDRD (FY13-15)
  - Theory goal: invent quantum algorithms that outperform classical graph analysis algorithms
  - Experimental goal: demonstrate a quantum graph analysis algorithm using trapped ions



Traps considered for QGA experiments



Rabi Oscillations in ^{171}Yb; precursor tests to two-ion interaction demonstrations

Sandia National Laboratories

Summary

- **Quantum information sciences: a multidisciplinary, integrated activity spanning Sandia**

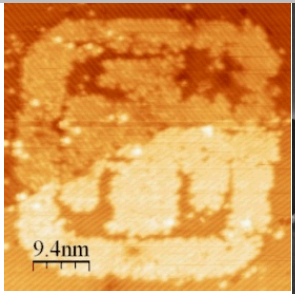
- **Expertise in key technologies:**
  - Fundamental science and engineering of quantum systems
  - Qubits: Si quantum dots/donors, ions
  - Architectures: circuit, adiabatic
  - Algorithms/apps: demonstrations, analysis, development
  - Systems engineering

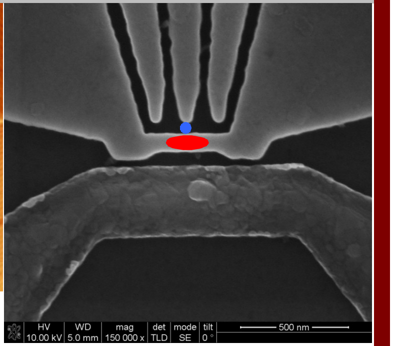
- **Leverages unique facilities: microelectronics fabrication, atomic-precision fabrication, HPC**

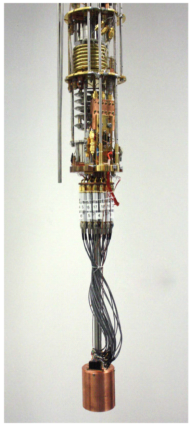
- **Extensive external collaborations**

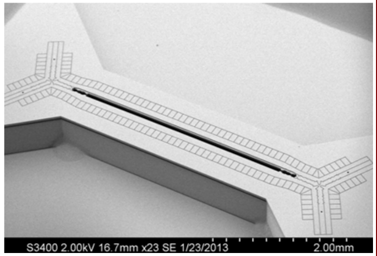
- **Technical capabilities, workforce, and facilities tha cover device physics, classical electronics, architecture, algorithms, fab and test**

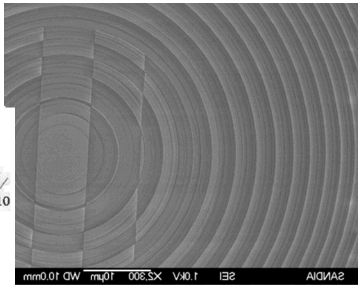
- **The technical challenges are vast – solving them is our focus**

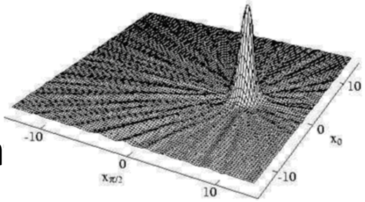


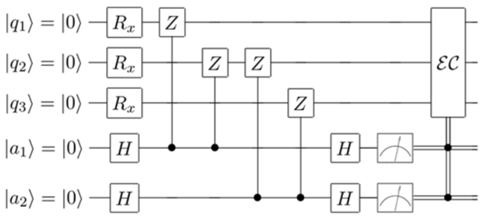












Sandia/CQuIC Partnership

- **Value proposition – force multiplier**
  - CQuIC access to Sandia capabilities
  - Student opportunities, recruiting, pipeline
  - Robust local QIS Community
    - complimentary focus / skillsets
    - breadth and depth of expertise
- **Interaction**
  - Seven faculty / Six PhD Students
  - Graduates
  - Technical interaction / seminars
  - Collaborations
  - SQuInT
- **Sandia commitment**
  - Long term relationship
  - Sandia committed to CQuIC success
  - UNM University Strategic Alliance (one of five)

CQuIC Associate Faculty

Theory
- Andrew Landahl
- Robin Blume-Kohout

Neutral Atoms
- Grant Biedermann
- Peter Schwindt
- Yuan-Yu Jau

Ions
- Daniel Stick

Solid state
- Steven Carr