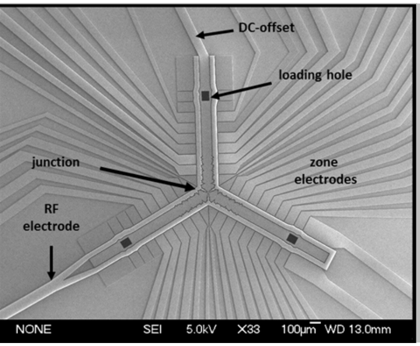
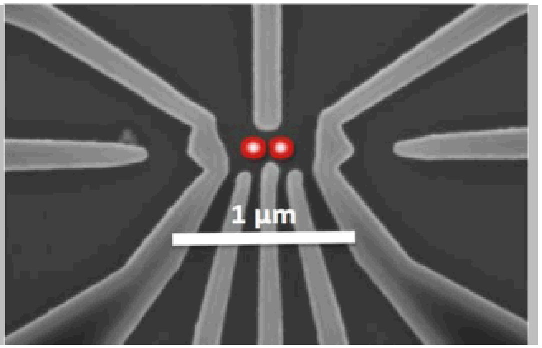
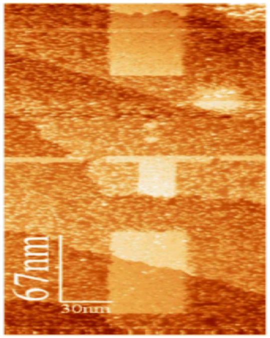
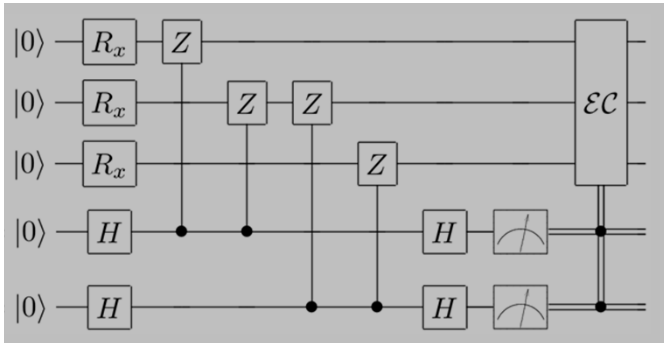








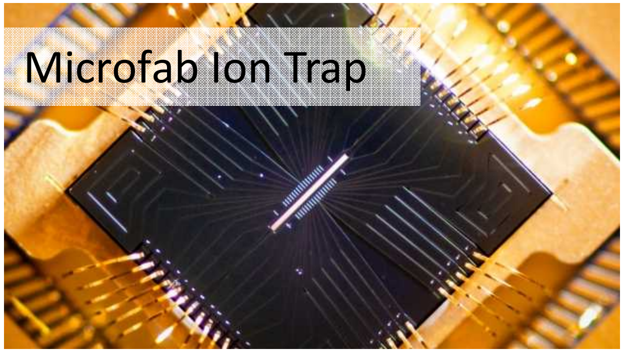
Sandia Capabilities for Quantum Information Sciences

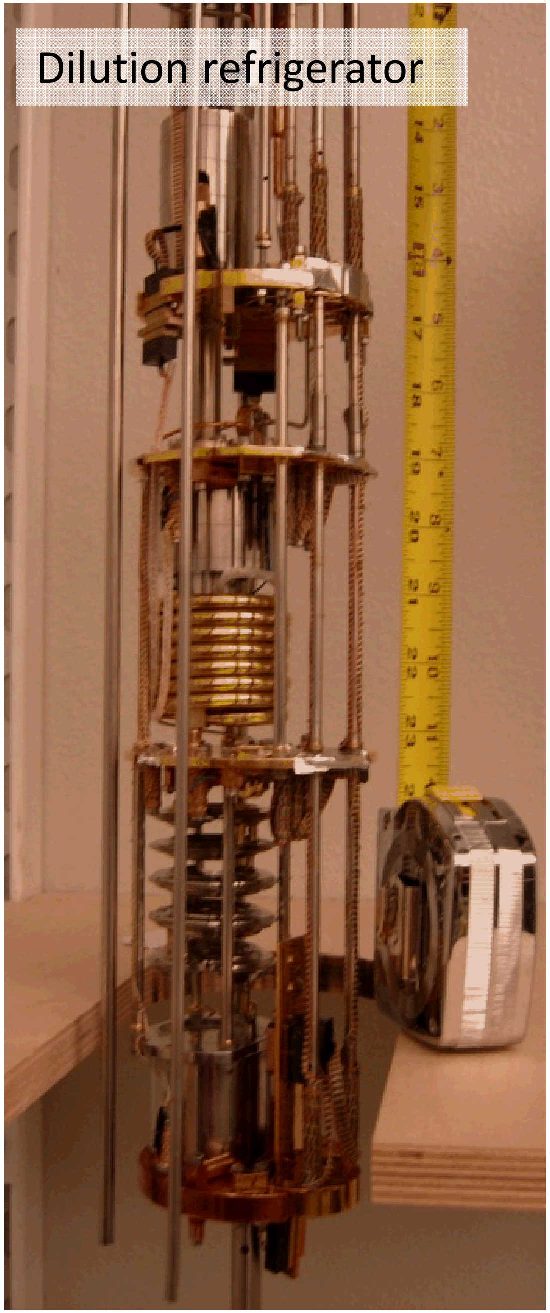
U.S. DEPARTMENT OF ENERGY | Office of Science | NNSA National Nuclear Security Administration

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.

Why Quantum?

- Quantum Information Sciences (QIS) combines
  - Quantum effects at small scale, with
  - Information theory to
  - Revolutionize sensing, computing, & communications
- Enables sensing with few photons
- Selected algorithms run dramatically faster
  - Shor's algorithm, Eigensystems, Linear Systems
  - Simulating quantum systems
- QKD provides theoretically secure comms.





Sandia's Foundations for QIS

Sandia National Laboratories

MESA Fab

Center for Integrated Nanotechnology

ASC
Supercomputers

National Nuclear Security Administration

Facilities: MESA Fabs

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

MESA Silicon Fab

- Radiation Hardened CMOS Process
  - 350nm, 3.3V, Radiation Hardened, Silicon on Insulator Digital and Mixed Signal Technology
  - 5-Level MEMS Technology
- Custom Technologies
  - Ion Traps / Si DQDs
  - Chem/Bio Detection Technologies
  - Si Photonics
  - AlN Resonators
  - 3-D Integration
- Part of the US Govt Trusted Supplier Network DoD Category 1A Trusted Supplier Certification

MESA Micro Fab

- III-V Compound Semiconductor Fabrication
- Compound Semiconductor Epitaxial Growth
- Compound Semiconductor Discretes, IC's and Optoelectronics

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

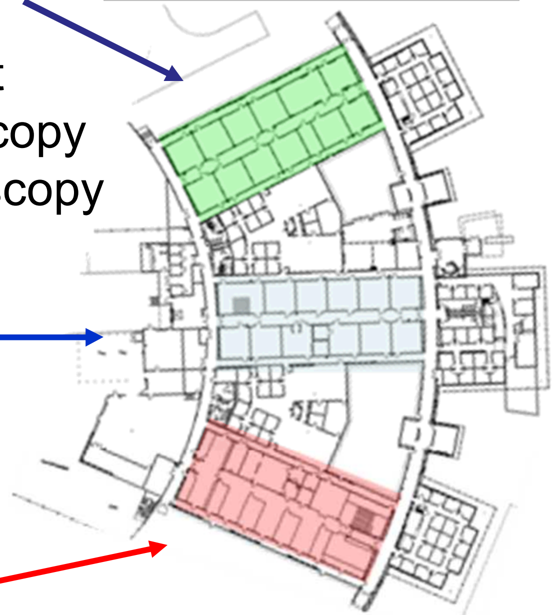
Facilities: Center for Integrated Nanotechnologies (CINT)

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

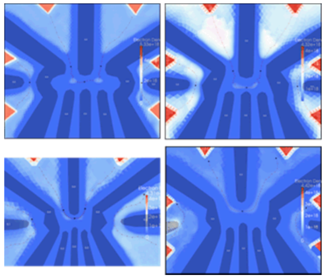
Core Facility

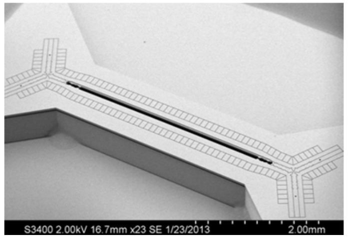


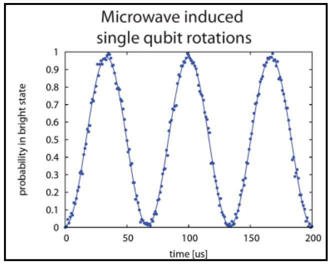
- A DOE/SC National User Facility
  - Defined by a scientific field, not specific instrumentation
  - NSRC staff support user projects and conduct original research
  - Capabilities involve hardware plus research expertise
- Vision: “One scientific community focused on nanoscale integration”
- Gateway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

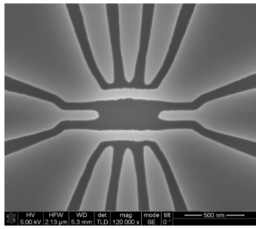
Quantum Information Processing (QIP) at Sandia

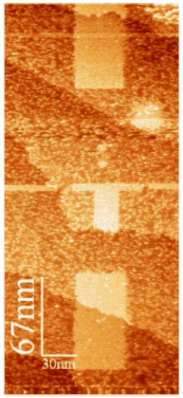
- QIP at Sandia: multidisciplinary, cross-Labs activity
  - **Fundamentals:** atomic and condensed matter physics, noise models, photonics, optics, QIS theory
  - **Fabrication:** device design/modeling, microelectronics fab, atomic-precision fab, integration, nanotechnology, photonics
  - **Quantum 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***



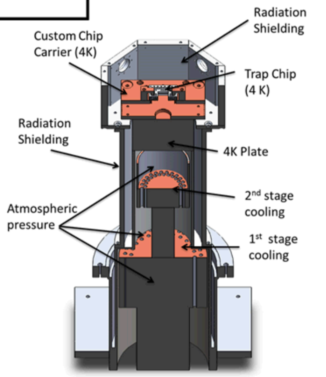








Sandia is engaged in QIS research in support of its missions. This research is motivated by advanced computing architectures and the fact that future engineered systems will require increased understanding of quantum effects.



Foundations: LDRD

Sandia National Laboratories

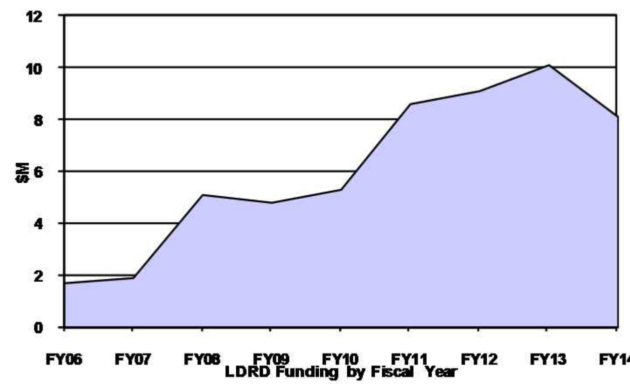
- Integral to Sandia's QIS R&D strategy

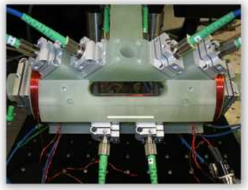
FY08 – FY10	FY11-FY13	FY14-FY16
Si-based qubits	*Architectures*	*Comms/QKD*

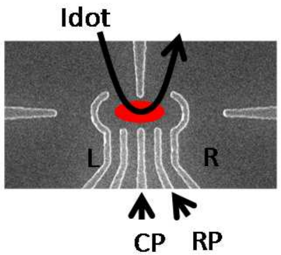
QIST Quantum Information S&T — AQUARIUS™ Adiabatic quantum architectures in ultracold systems — SECANT QKD

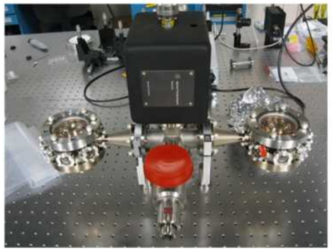
  - *Build foundational capabilities while exploring novel, high risk areas*
  - Focus on the engineering challenges of QIS
  - $62.6M investment, FY06-15
  - Includes early career, traditional, and grand challenge LDRDs
  - *Essential* vehicle for academic collaborations

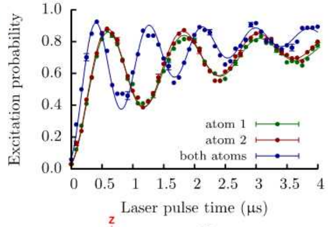
- Broad and deep portfolio, spanning many facets of QIS:
  - Qubits: physical qubit development, logical qubit design, entanglement, noise modeling
  - Quantum engineering: architectures, robust controls for quantum gates, on-chip microwave control of ion traps, tomography
  - Algorithms/applications: demonstration of few-qubit apps, algorithm design
  - Simulation: design toolkits, error correction threshold simulators
  - Sensing: matter-wave sensors, atom interferometry
  - Comms: QKD, photon source development, single photon detectors

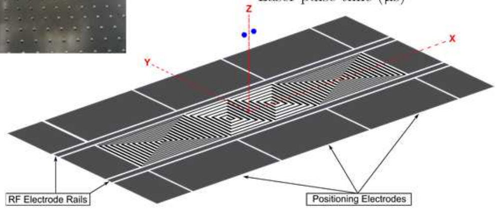












Foundations: SEQIS Research Challenge

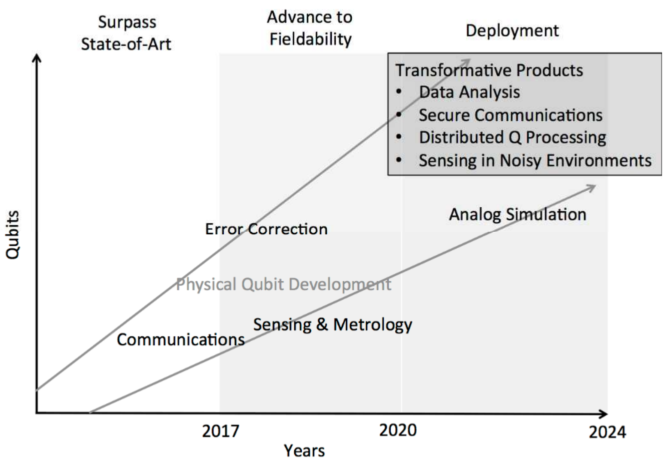
Sandia National Laboratories

Science and Engineering of Quantum Information Systems

Jim Hudgens, Dave Sandison • *Director Champions*
Richard P. Muller, John B. Aidun • *RC Deputies*

- 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

SEQIS Technology Roadmap



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

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.

Foundations: QIST Grand Challenge LDRD

FY08-10

Dr. Malcolm S. Carroll • *Principal Investigator*
Dr. Rebecca D. Horton • *Project Manager*

GOALS:

- Develop physical silicon qubit
- Design logical qubit with Si hardware

Multidisciplinary, cross-SNL team:

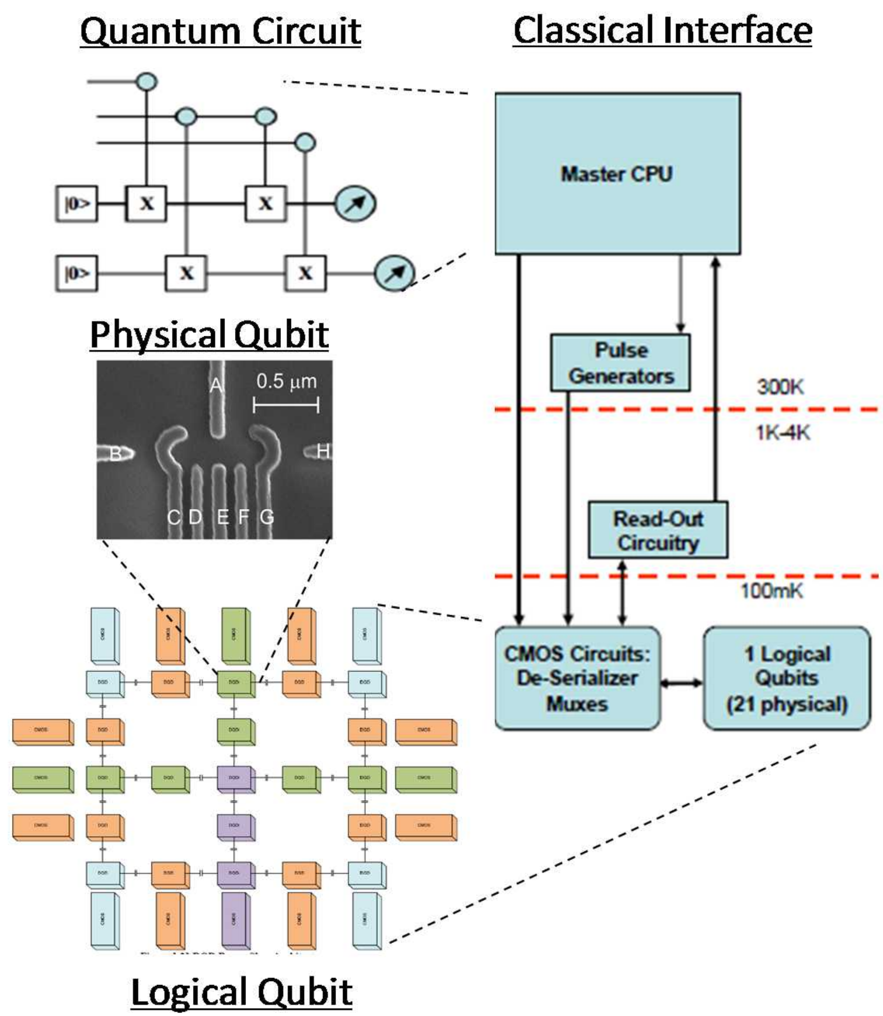
- Physical qubit (DQD + hybrid design)
- Measurement
- Modeling
- Classical electronics
- Architecture

<u>Evaluation by external board of program managers & researchers</u>

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."

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



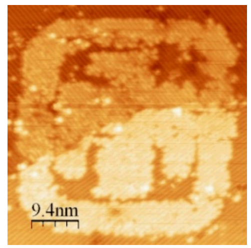
Foundations: AQUARIUS GC LDRD

FY11-13

Dr. Andrew J. Landahl • *Principal Investigator*
Dr. Steven M. Rinaldi • *Project Manager*

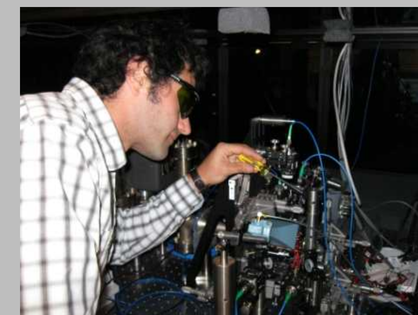
Quantum computing 101

Quantum computers promise to take computing to its ultimate quantum-coherent limit, just as lasers did for light. Multiple applications in fields like energy, medicine, and optimization are already known. The primary roadblock to development is exceptional noise sensitivity. On paper, the adiabatic quantum architecture is expected to dramatically improve robustness by maintaining a quantum computer in its lowest-energy configuration. Understanding whether this robustness is borne out in practice is an important R&D question.



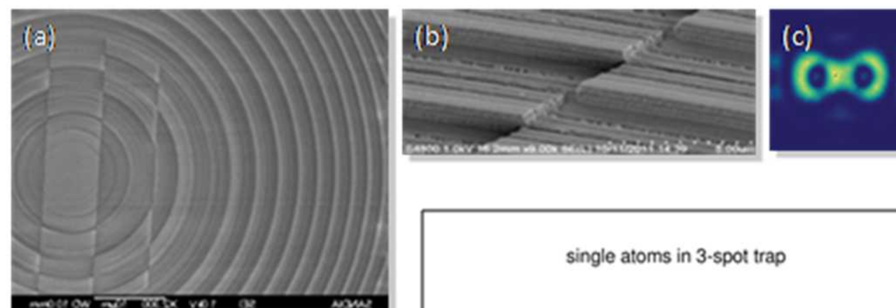
Sandia "nanologo," written to single-atom 0.7 nm precision.

Paul Parazzoli adjusts 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.



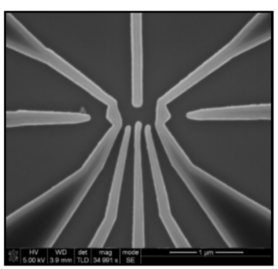
Project objectives

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



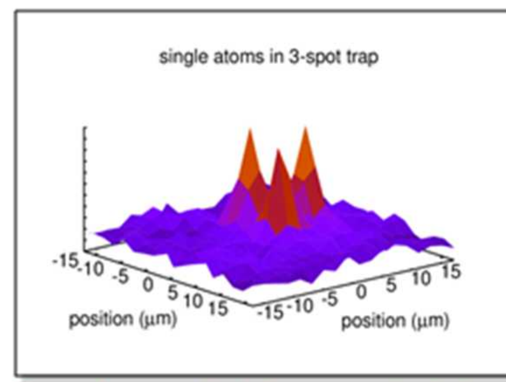
(a) World-first Sandia diffractive optical element (DOE) for a two-atom trap. (b) Isometric zoom-in. (c) Image of light through the DOE.

Major accomplishments



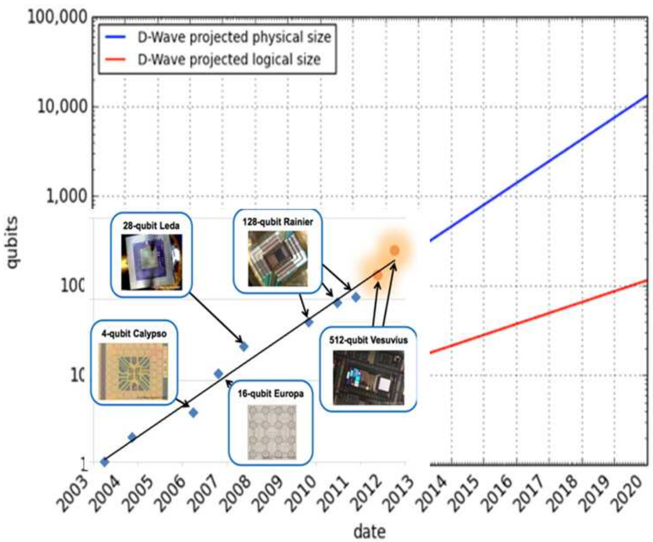
Sandia silicon nanostructure defining an "artificial atom" double-quantum-dot qubit.

- 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



Measured fluorescence of single Cs atoms trapped in a Sandia three-atom diffractive optical element trap.

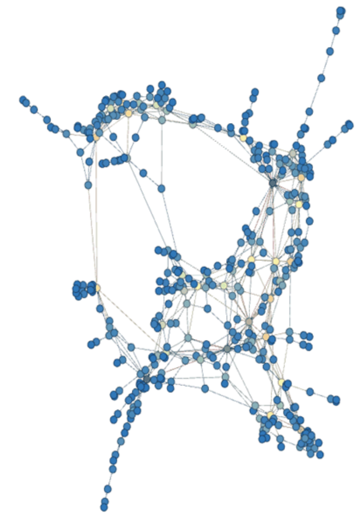
D-Wave Benchmarking Assessment



Hurdles to solving real-world problems: must "compile" logical problem-domain variables to physical qubits and limited-precision couplers

Mathematical evidence that worst-case $O(N^2)$ overhead is unavoidable for current D-Wave architecture

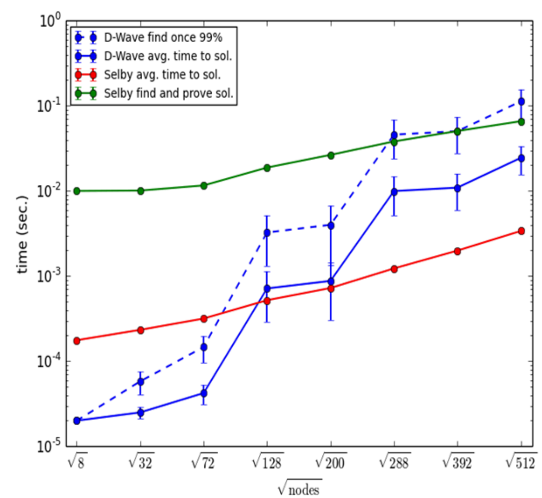
Algorithmic tools for "compiling" real-world problems on emerging quantum architectures are critical!

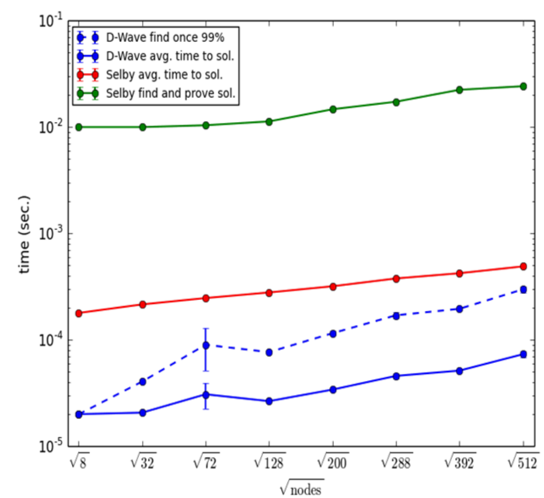


No clear "quantum" speedup: some problem instances are easy/hard for D-Wave and some are easy/hard for other (classical) heuristics.

Empirical complexity can vary widely, even for closely related problems.

Fair benchmarking is challenging: must select and configure variety of classical heuristics employing different algorithmic approaches



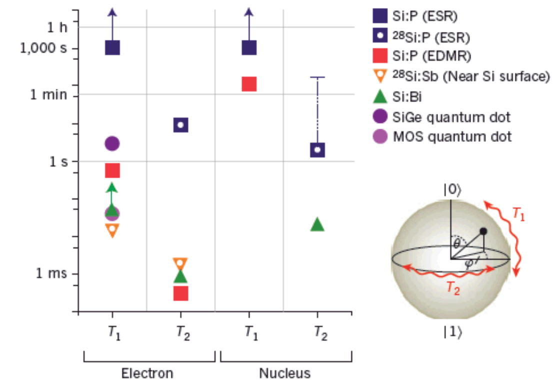


Technical Capabilities: Qubits

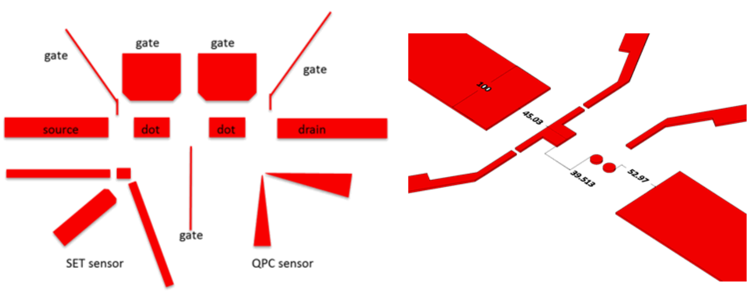
Silicon Qubit Program

Why silicon-based qubits?

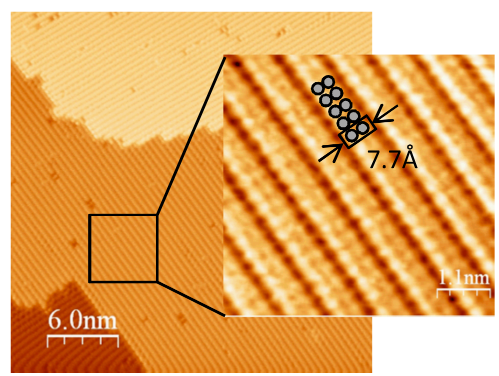
- Long demonstrated spin qubit T_1 and T_2 times
  - Key to high fidelity, controllable, usable qubits
- Large, mature Si microelectronics manufacturing base
  - Leverage manufacturing techniques and technologies
- Ultimate limit in device scaling
  - Atomic precision fabrication provides miniaturization limit on qubit size
  - Design and fab at the sub-nanometer scale



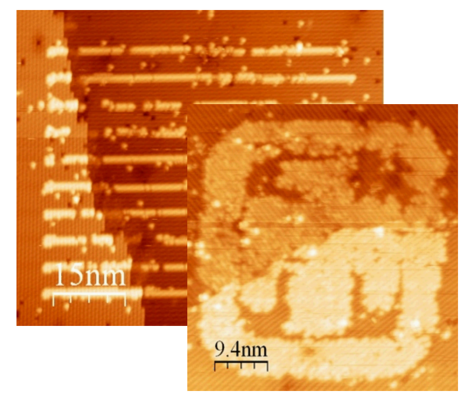
Various spin lifetimes in Si; from Morton et al, Nature, V479, (17 Nov 11), 345.



Early designs of atomic scale charge qubits, Sandia (AQUARIUS, 2012)



STM images of Si(100) surface, Sandia (AQUARIUS, 2011)

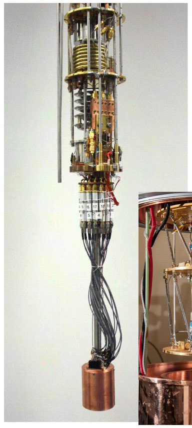
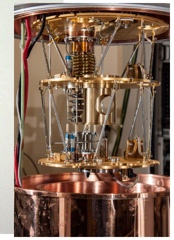
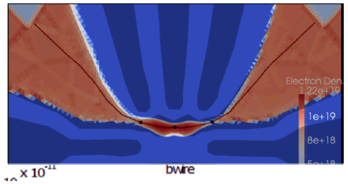


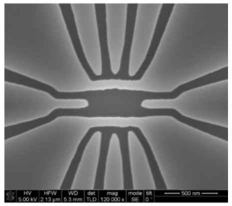
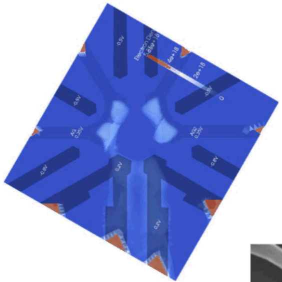
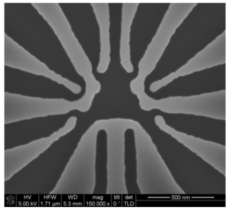
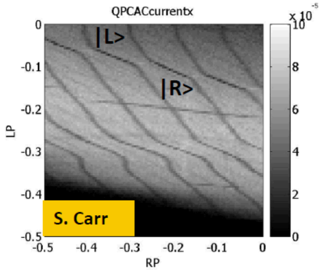
Sandia nanologo and lithographically etched lines, Sandia (AQUARIUS, 2011)

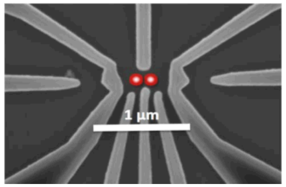
Technical Capabilities: Qubits

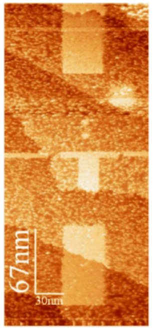
Silicon Qubit Program

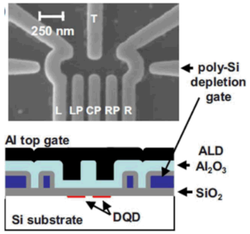
- Two primary device thrusts:
  - Double quantum dots (both spin and charge-based qubits)
  - Donors in silicon
- Under development for over six years
  - Genesis – QIST GC LDRD
  - Adiabatic qubits explored under AQUARIUS
    - Developed charge qubit (provisional patent)
    - Preliminary work on donors in silicon
    - Key result – Pauli blockade on double quantum dots
  - Single and two qubit devices designed, fabbed, tested
    - Multiple generations of 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 in CINT
  - Key result – first spin readout of Sb donor

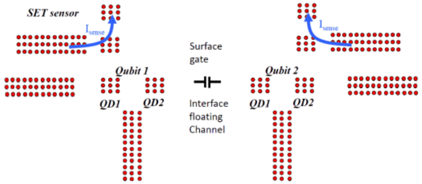








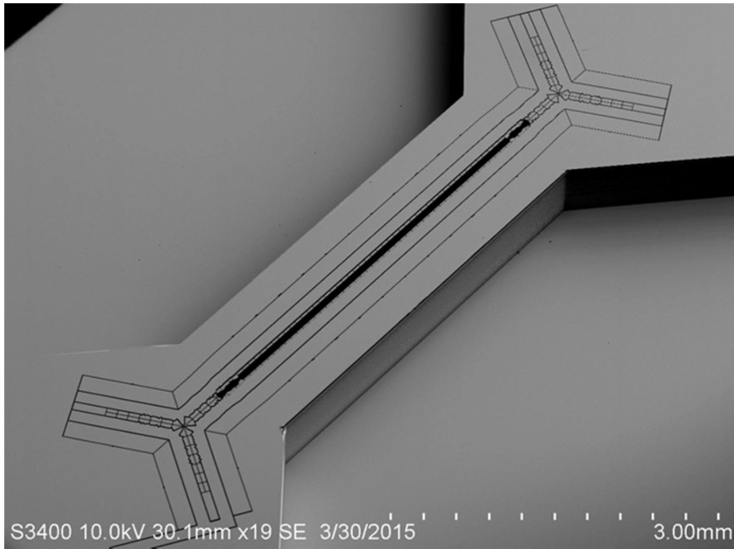


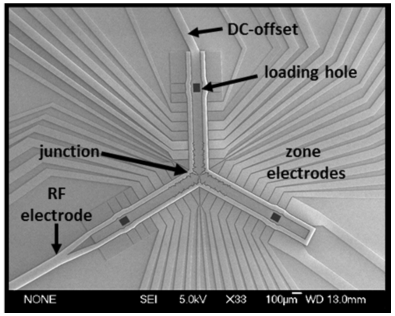
Technical Capabilities: Qubits

Ion Trap Program

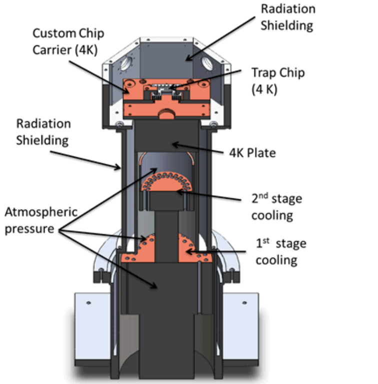
- Deep, broad experience with design/fab/test of multiple microfabricated surface traps
- High Optical Access (HOA)-2 trap: optimized for quantum information processing
  - Scalable trap with linear section and two junctions and integrated slotted section
  - Trap lifetime > 90h while taking measurements
  - Trap lifetime without cooling > 10 min
  - Trap heating rates <100 quanta/s (ytterbium)
  - Shuttling demonstrated through device
- Ion Trap Foundry
  - IARPA/MQCO funded effort
  - Deliver ion traps to multiple customers
    - 12 institutions in 5 countries
    - 8 institutions have successfully trapped using Sandia traps



HOA-2 surface trap (2014)



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

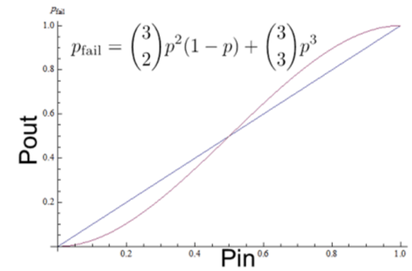


New cryogenic ion trap chamber (2014)

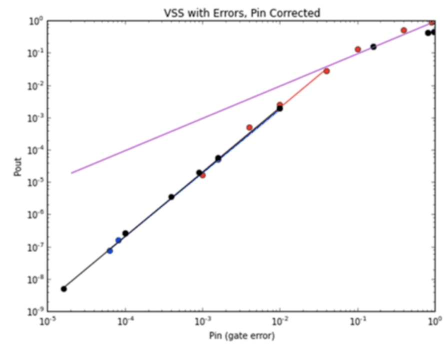
Technical Capabilities: Modeling & Simulation

Sandia National Laboratories

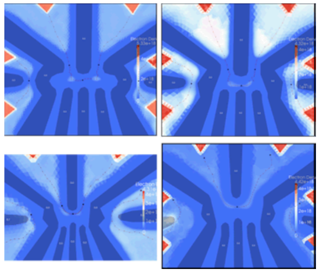
- Multiple mod/sim tools developed under sponsor and internal funds
  - Quantum information systems and related capabilities
- Example tools:
  - **QCAD**: Simulation toolkit for semiconductor donor and quantum dot systems
  - **TRAPSIM**: electrostatic modeling intended for RF trapped ion device design
  - **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

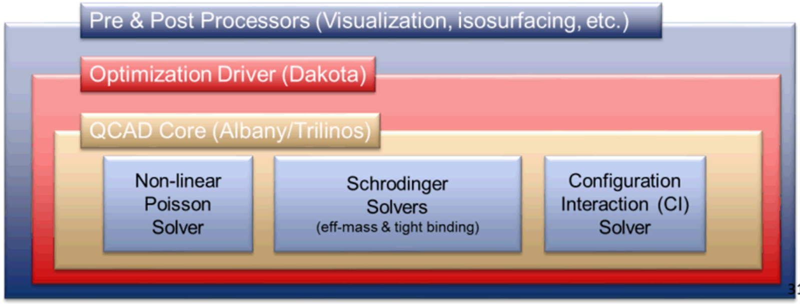


Threshold calculations



QCAD results on DQD and QCAD structure

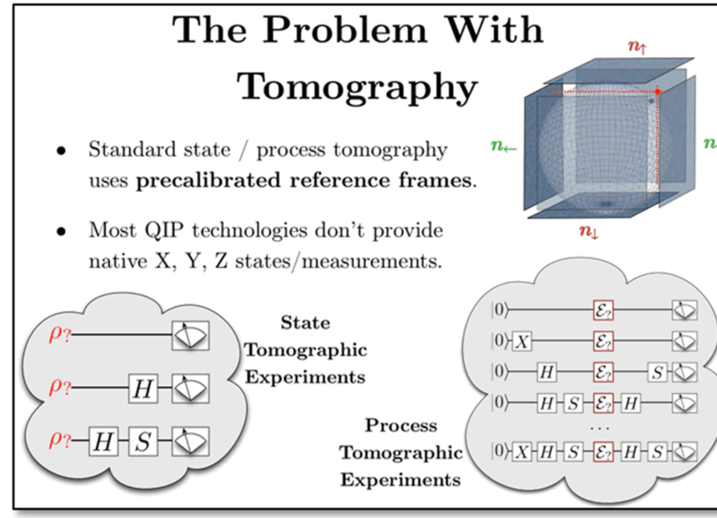


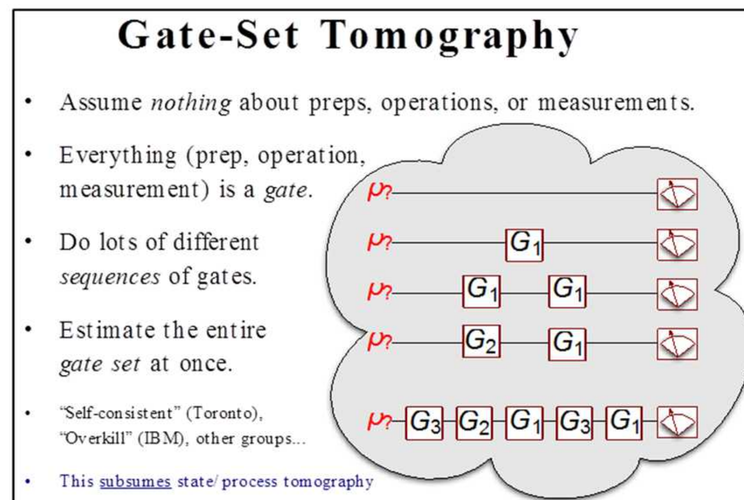


Technical Capabilities: Tomography

Sandia National Laboratories

- Theory developed under LDRD; in use by multiple groups
- Turbocharging Quantum Tomography LDRD (FY13-14)
  - Objectives:
    - Discover methods for characterizing quantum information processing hardware that are efficient, accurate and reliable
    - Develop (dramatically) improved protocols for quantum state and process tomography
    - Apply them to rapidly characterize and improve experimental quantum devices
  - **Key accomplishment**: invented linear gate set tomography (GST) ; robustly diagnoses faulty operations without precalibrated gates
  - Single qubit GST done and "deployable" – most precise single qubit characterization technique
  - Demonstrated in multiple qubit technologies (Si, ions, neutrals)
- Quantum Graph Analysis (FY13-15)
  - Serving as initial experimental platform for GST
  - GST realized for single ^{171}Yb+ qubit and microwave operations





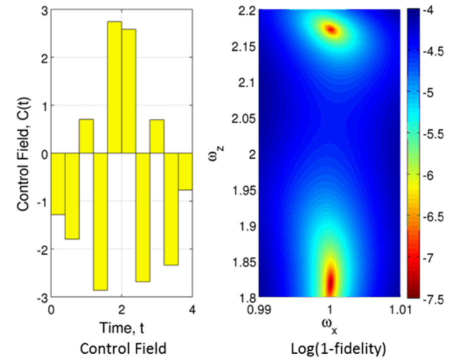
Technical Capabilities: Controls and Noise Modeling

Sandia National Laboratories

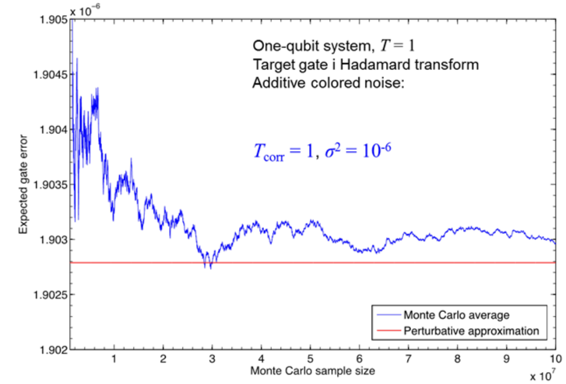
Extensive capabilities developed under multiple projects, including hardware-specific, realistic noise models

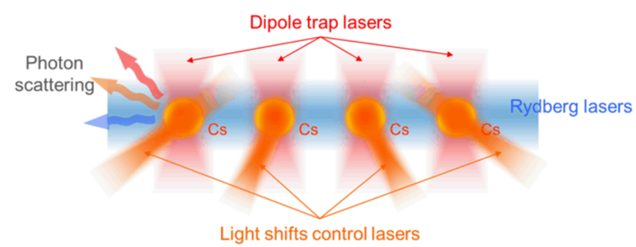
- AQUARIUS GC LDRD (FY11-13)
  - Developed noise models and associated control and error correction/suppression strategies for neutrals and Si qubits
  - Ex: Photon scattering leading to qubit leakage in neutrals; did not find an effective code space to protect against these errors; examined limits to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

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

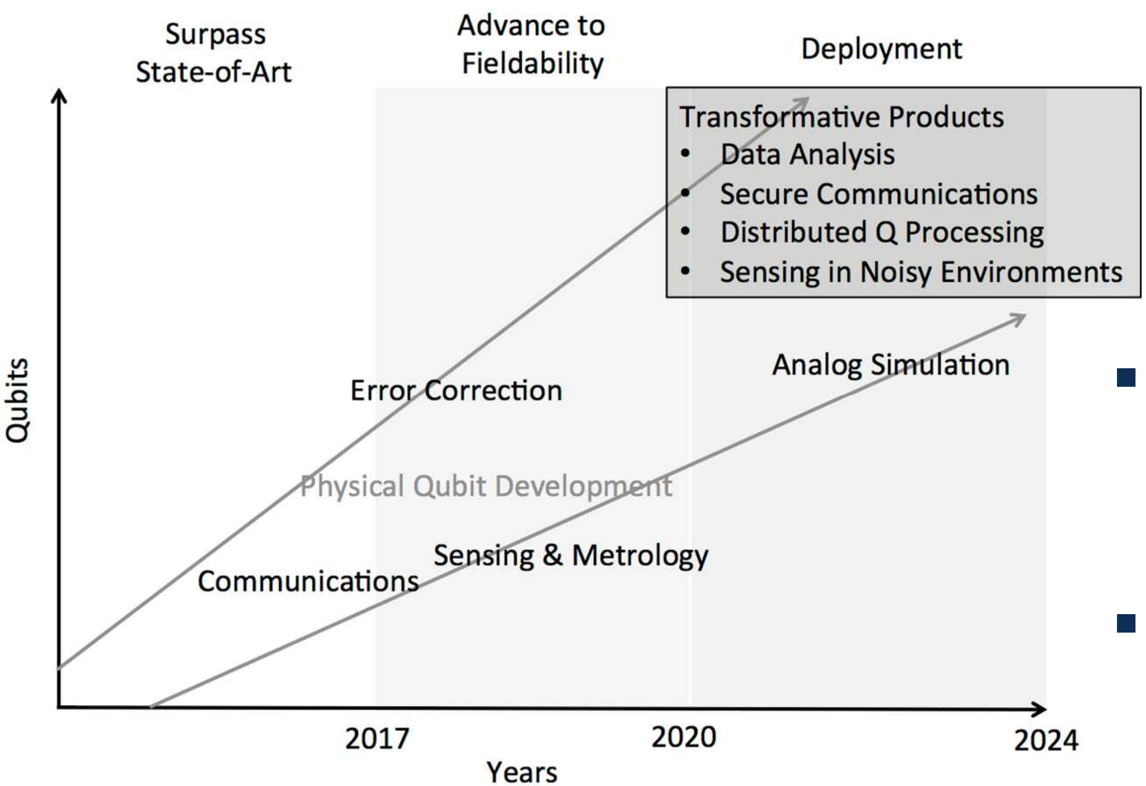


Hadamard gate





Roadmap to functioning QIS devices

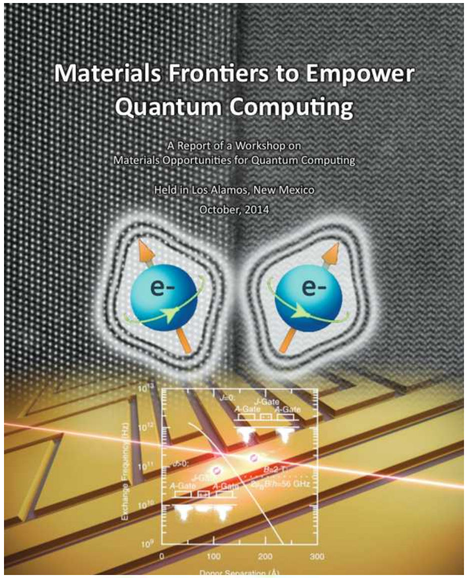


- SEQIS Focus:
  - **robust**, few-qubit devices;
  - their algorithms and protocols; and
  - their applications to problems of interst to Sandia customers
- Identify and develop robust algorithms on high quality hardware.
- Dramatically advance qubit performance based on understanding quantum defects.

Materials Limits of Quantum Devices

Sandia National Laboratories

- Understanding the quantum nature of materials defects is a generational challenge
  - Yield dramatically better quantum devices
  - Develop metrology and materials characterization capabilities at the single defect level
- Given its role as a gateway to nanoscience research, CINT can play a central role in this endeavor
  - Engage a broad community at this challenge
  - Leverage expertise at Sandia, LANL, and other National Laboratories
  - Requires participation from university and industrial partners



The key challenges are rooted in material science

- A lack of fundamental understanding of defects, disorder and noise in semiconductor and superconducting materials is a key knowledge gap
- Understanding the physics of materials at the Single Defect Limit is a fundamental materials question that is also the key limit to the performance of quantum devices.
  - Few atom systems are inherently sensitive to defects, disorder, and noise at the atomic level and serve as a exemplar test system to explore key science questions that are common to a wide range of materials, not just q-bits.
  - The scale of quantum materials make them sensitive to interface disorder and the devices that are built with these materials make they excellent diagnostics of that disorder.
  - The sensitively of quantum entanglement and q-bits also make them excellent probes to study subtle environmental effects on the interaction of states within materials
  - Models of these exquisitely sensitive interactions will need to include new physics that can be broadly utilized to understand many allied material questions.

A broad team will be required

- To make the required progress on the key questions will require a consortium of industry, government and national laboratory partners
- Each partner brings key strengths and insights
- There is precedence for such a consortium
  - SEMATECH – solving common semiconductor processing and manufacturing problems
  - Joint BioEnergy Institute (JBEI) – accelerate fundamental research breakthroughs for the development of next generation biofuels.
  - Joint Center for Energy Storage Research (JCESR) – overcome critical scientific barriers and create breakthrough energy storage technology
  - DOE Energy Innovation Hubs – removing the scientific barriers to the development of complete energy systems.

Past experience shows that joint, well focused teams can advance fundamental science understanding which serves as the basis for technical progress

Potential stakeholders and cross cuts

- We propose to engage a number potential stakeholders as the proposal moves forward
  - National Labs
    - Los Alamos, Oak Ridge, Lawrence Livermore, Pacific Northwest, NIST have existing programs in quantum sciences and relevant expertise
  - DOE / NNSA
    - Office of Science (BES, ASCR)
  - Other government departments and agencies
  - Private Industry
    - Microsoft, Google, Intel, IBM, …
  - Academic Partners
    - Princeton, Yale, Wisconsin, Maryland, UNM, …

- Explore overlaps with the recent White House NSCI

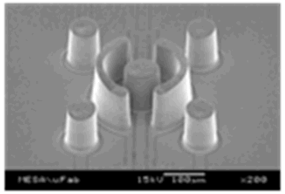
Partners gain access to the integrated resources of a team which is held accountable for maintaining the goals of the consortium, as opposed to a balkanized collection of individual researchers

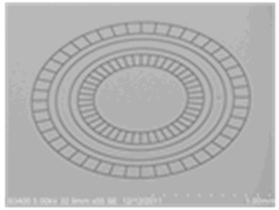
Backup Slides

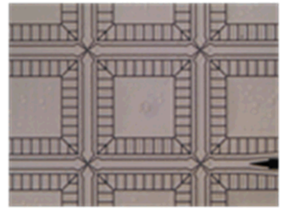
Technical Capabilities: Qubits

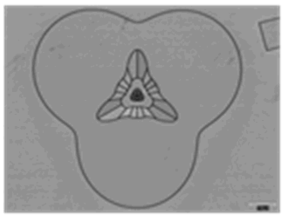
Sandia National Laboratories

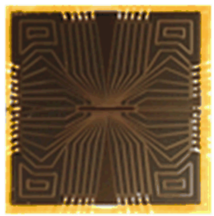
The Ion Trap Foundry

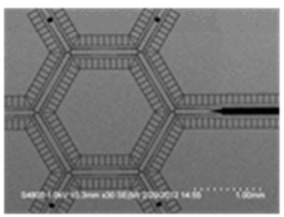


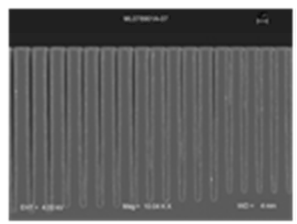


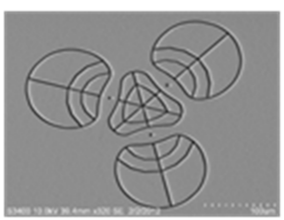


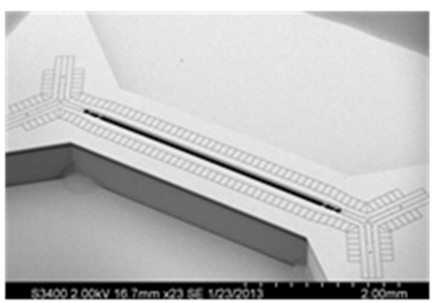








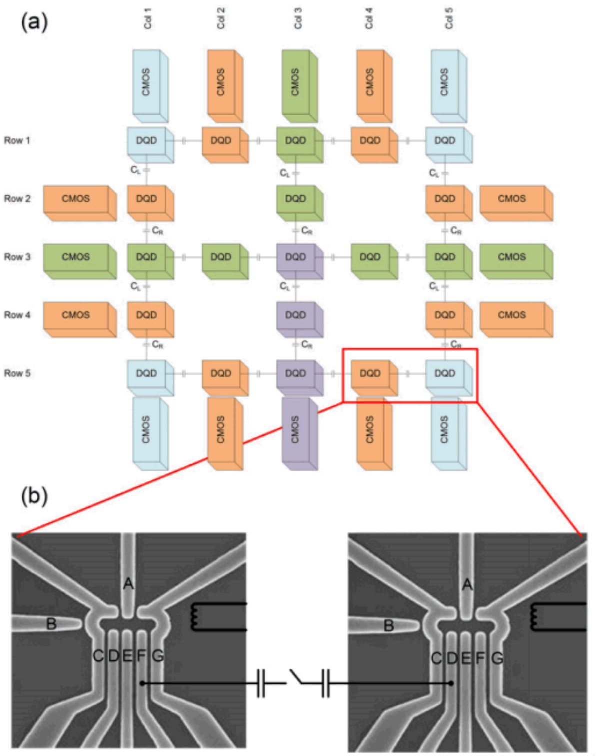




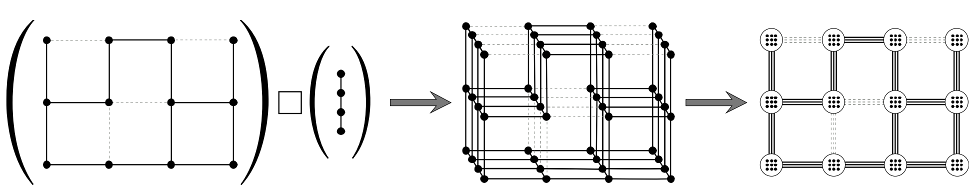
- Multiple designs delivered to multiple customers
  - 12 institutions, 5 countries
  - 8 institutions have successfully trapped using SNL designs
- Traps used with Ca, Yb, Mg
- Sponsored trap fabrication program - MQCO
- Examining key device issues through:
  - Integrated diffractive optical elements (eliminate bulk optics)
  - Microwave on-chip control of ions (decrease laser/optics requirements)
  - Multiple metal layers (routing of control signals, increased design flexibility)

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



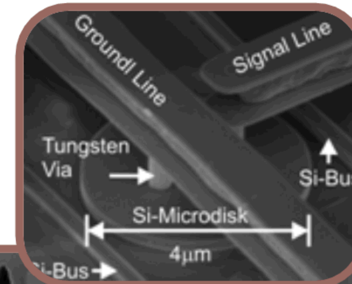
Conceptual scheme for incorporating a repetition code into an Ising model optimization problem in an adiabatic quantum computer, from AQUARIUS

Technical Capabilities: Si Photonics

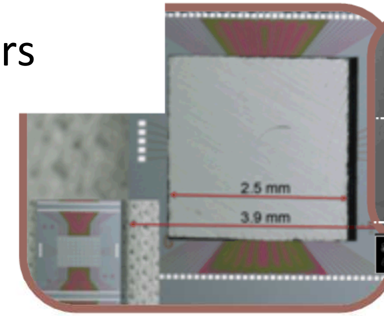
Sandia National Laboratories

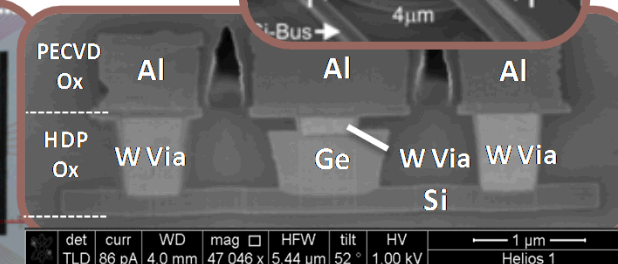
Integrated Photonics at Sandia

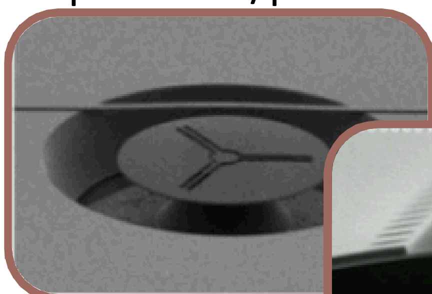
- Low energy modulators, detectors, low loss waveguides, SiN edge couplers, travelling wave Mach-Zehnder modulators, grating couplers, advanced CMOS flip chip bonding, direct CMOS integration



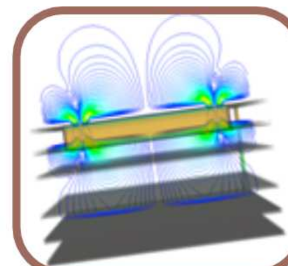
- Suspended Si/SiN waveguides/resonators phononic/photonic crystals, aluminum nitride resonators and transducers.

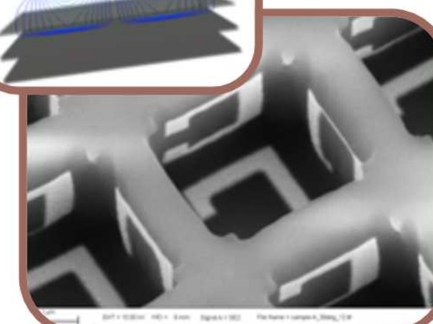






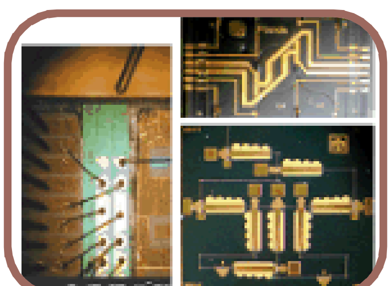
- Near to long wave IR plasmonics and metamaterial based devices.

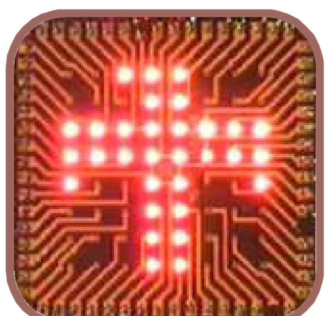


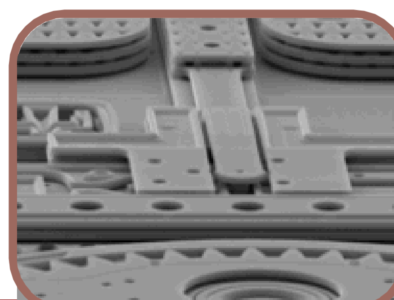


- Compound semiconductor devices and fabrication

- 5 layer poly silicon MEMS process





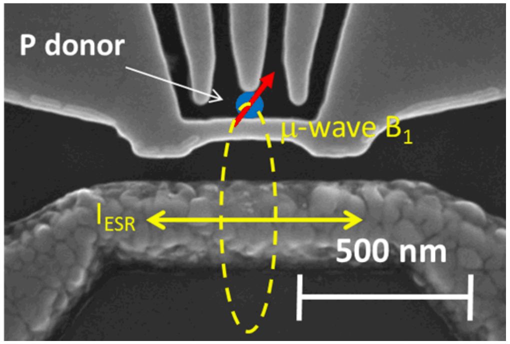


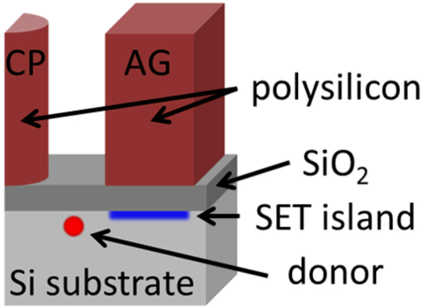
Technical Capabilities: Qubits

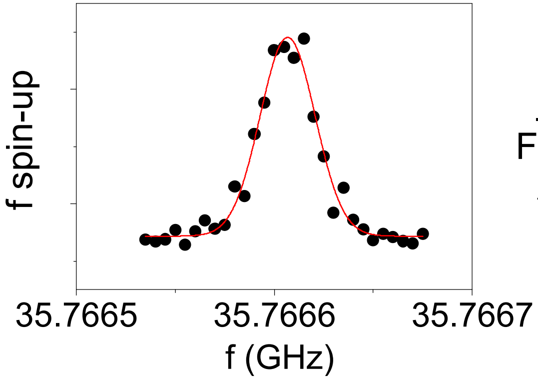
Silicon Qubit Program: Recent Highlights

- Demonstration of single P donor electron spin qubits
- Isotopically enriched ^{28}Si device results:
  - 45 kev P donor implants
  - 500 ppm ^{29}Si concentration
  - Donor e^- spin readout through single electron transistor (SET)
  - Microwave antenna produces local B_1 for electron spin resonance (ESR) experiments
  - $T2^* = 18$ µs; $T2 = 310$ µs, $F_c = 99.3 \pm 0.4\%$
- Natural Si device results:

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

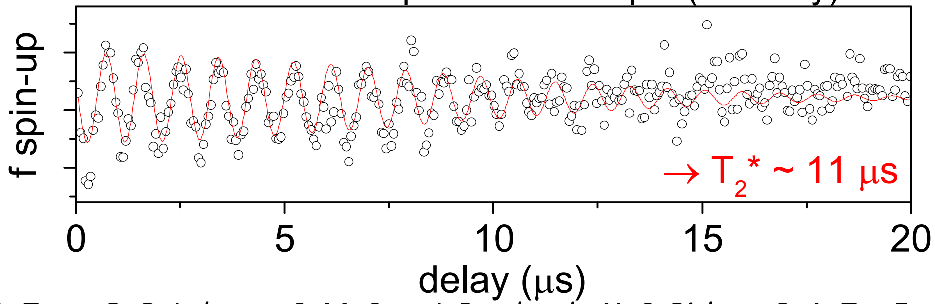






ESR linewidth:
FWHM = 33 kHz
$\rightarrow T_2^* = 10$ µs

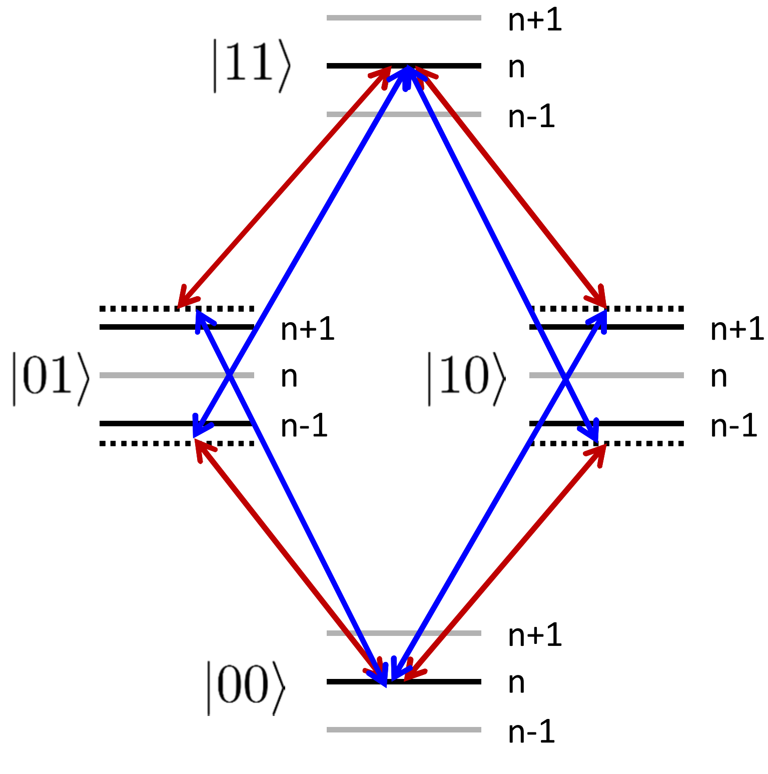
Coherent manipulation of e^- spin (Ramsey)



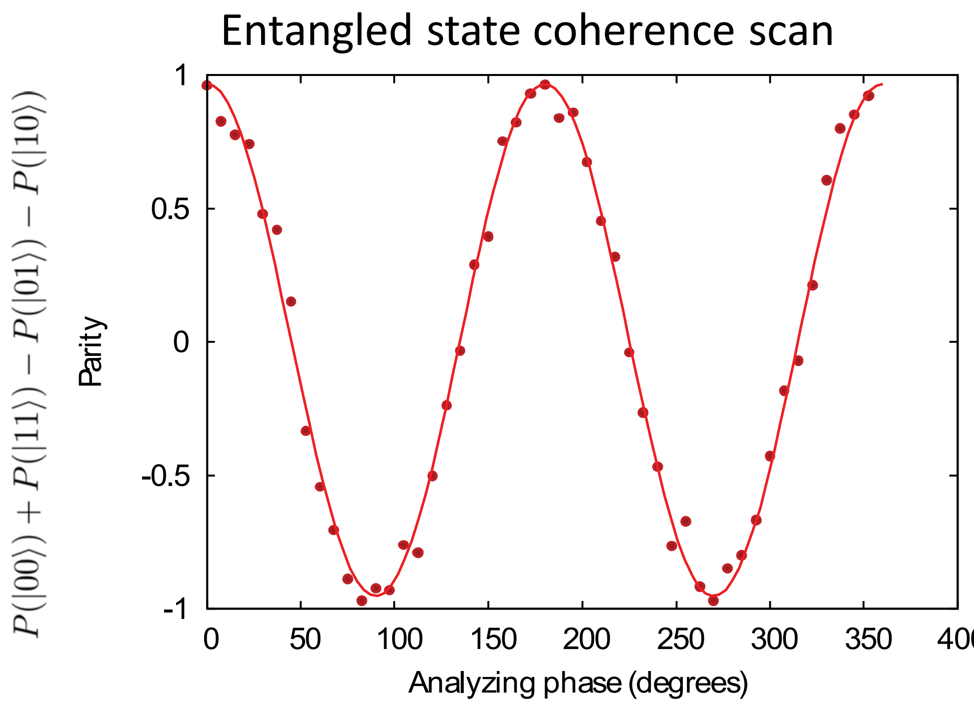
L. A. Tracy, D. R. Luhman, S. M. Carr, J. Borchardt, N. C. Bishop, G. A. Ten Eyck, T. Pluym, J. Wendt, M. P. Lilly, M. S. Carroll

Technical Capabilities: Qubits

Ion Trap Program: Universal Two-Qubit Gate in HOA-2



$$|00\rangle \rightarrow |00\rangle + |11\rangle$$



$$\mathcal{F} = \frac{1}{2}(P(|00\rangle) + P(|11\rangle)) + \frac{1}{4}c = 0.97$$

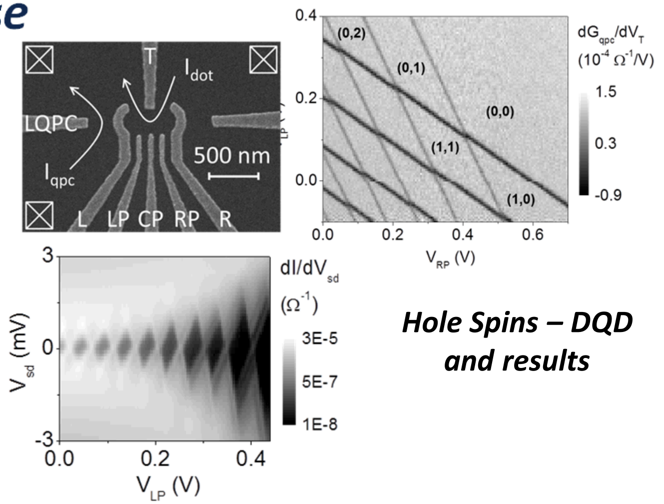
Highest two-qubit gate fidelity in any surface trap: F= 97.7

Technical Capabilities: Qubits

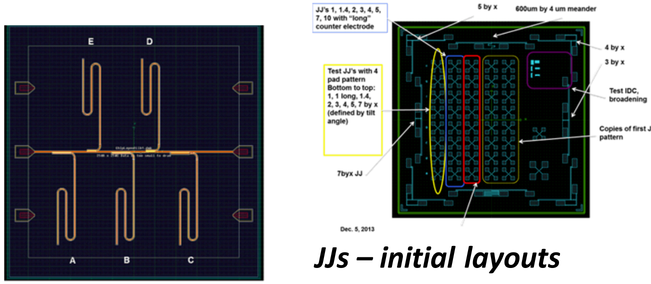
Sandia National Laboratories

Additional Qubit Expertise

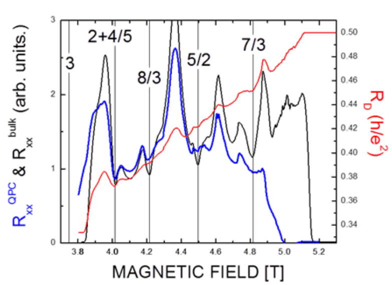
- **Hole Spins in GaAs**
  - Supported under two LDRDs (FY11-15)
  - Goals: develop single hole transistor devices in GaAs, investigate hole spin physics, eventual qubit evaluations
  - Observing regular Coulomb blockade, diamonds, few hole occupation
- **Josephson Junctions**
  - Supported under an Early Career LDRD (FY13-15)
  - Goals: isolate transmon qubits, develop scaling techniques, enable single/multiple high fidelity gates
  - In initial device fabrication stage
- **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
- **Neutral Atoms**
  - Commenced under AQUARIUS; further development under traditional LDRD (FY14-16)
  - Goals: further demonstrate entanglement of neutrals; develop new entangle gate techniques, develop optimal control algorithms for improved bell-state generation
  - FY15 goal – 4 qubit demonstration
  - Applications in quantum computing and sensing



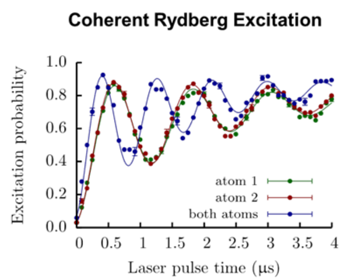
Hole Spins – DQD and results



JJs – initial layouts



Experimental results - FQHE



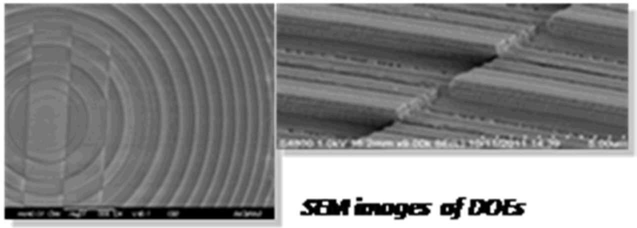
Experimental results – neutral atoms

Technical Capabilities: Diffractive Optical Elements (DOEs)

- Scaling ion trap arrays, neutral atom arrays requires high numerical aperture (NA) optics close to the atoms
- Bulk optics suffer from size (limits # optics in an experiment), setbacks from qubits, significant surface sag
- DOEs: enabling technology for ion, neutral atom qubits
  - Small physical profile: high optical access, enables closer placement to atoms/ions
  - High collection efficiency
  - 100% fill factor
  - Ideal for small spaces, vacuum, and working at a single / multiple wavelengths
- Extensively developed under AQUARIUS
  - Triple trap from single DOE
  - Bottle beam single- and double-traps
  - Multifunctional DOE (trapping, control, readout)
  - Scaling study of multifunction DOE arrays
- MQCO – imaging ions at various locations in traps

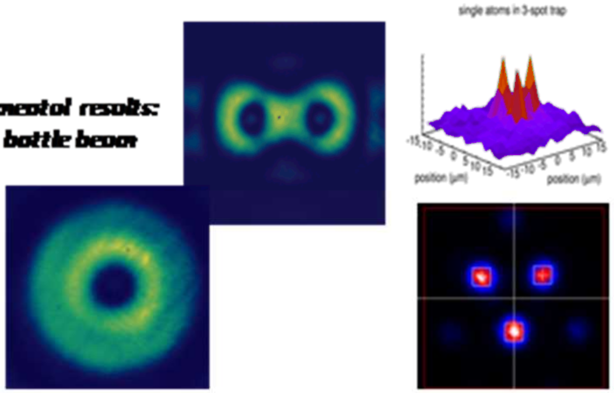
Diffractive Lens

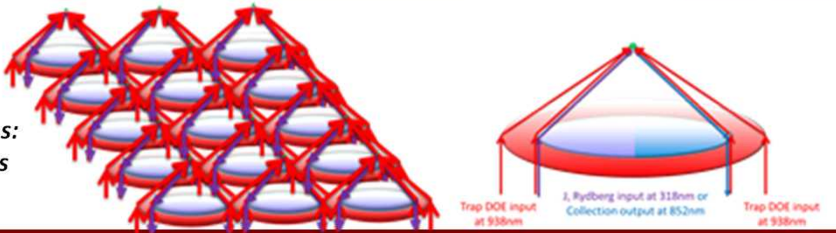
Cross Section, Surface patterning



SEM images of DOEs

AQUARIUS experimental results: Single and double bottle beam traps, triple traps





AQUARIUS DOE scaling studies: multifunction traps and arrays

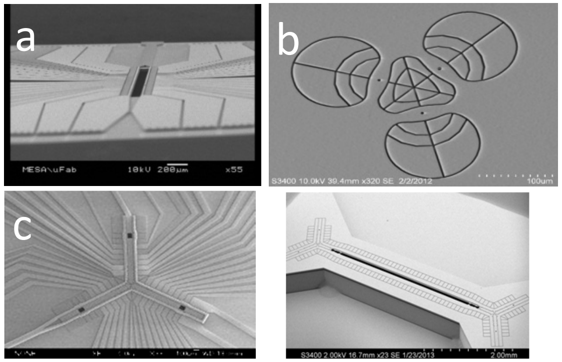
Technical Capabilities: Algorithms/Apps

What useful problems can be addressed with a handful of qubits?

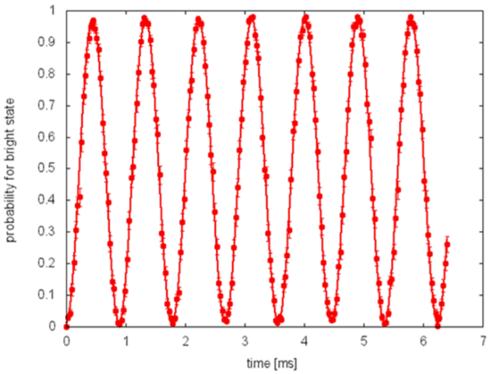
- Addressed in strategic plans, technical roadmaps, SEQIS research challenge
- Driver behind recent SNL internal LDRD proposal calls

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

SEQIS Aims

- The SEQIS RC targets enabling manipulation of information with greater sensitivity, speed, and security.
  - Through
    - Understanding and mastery of quantum systems
  - To realize
    - Sensors that surpass the state of the art in multiple settings, including imaging, navigation, and gravimetry;
    - Information processing devices that surpass capabilities of classical computing technology;
    - Long-distance, secure communication protocols that leverage unique quantum information-disturbance relationships.
  - Goal
    - Within 10 years, field a functioning quantum device that demonstrates the application of a quantum algorithm to solve a problem of interest to Sandia's customers.