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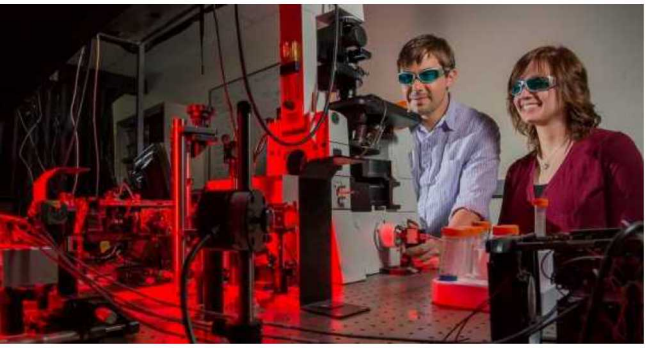
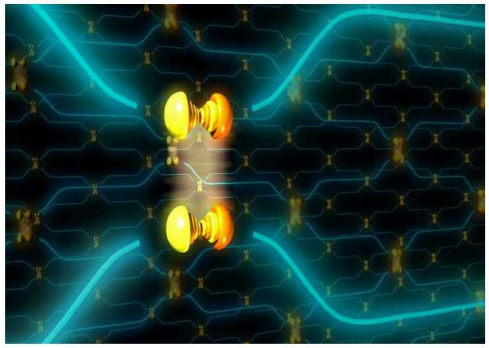
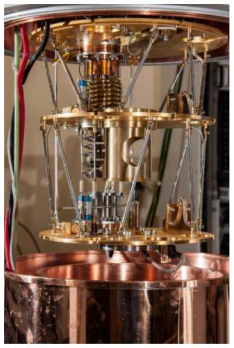
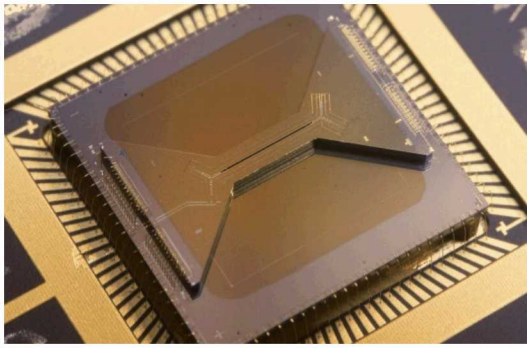

The Science & Engineering of Quantum Information Systems

Steven M. Rinaldi, PhD
Dept 05843

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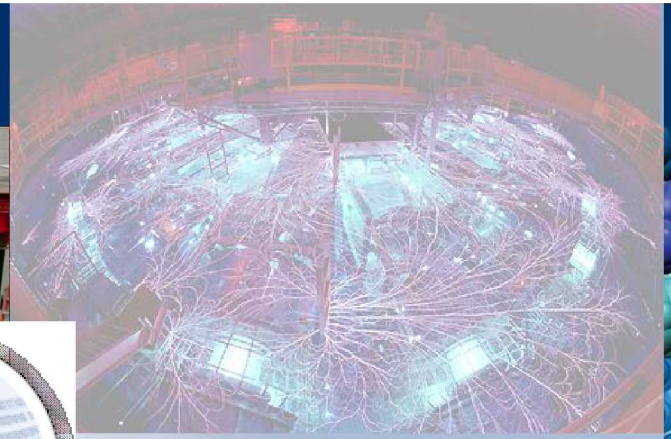
Our QIS Research reaches across our laboratories' core Research Foundations

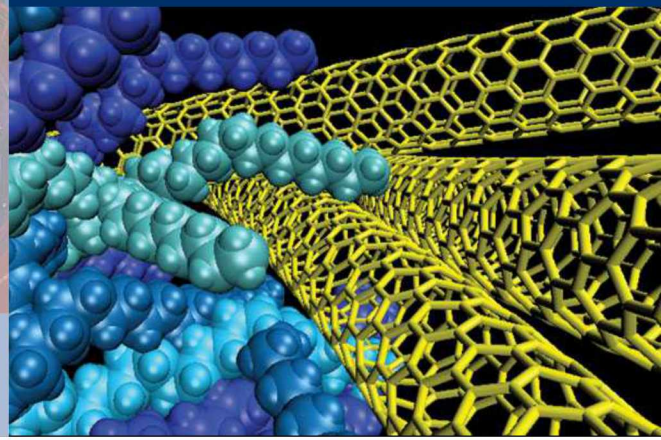
Sandia National Laboratories

Computing & Information Sciences

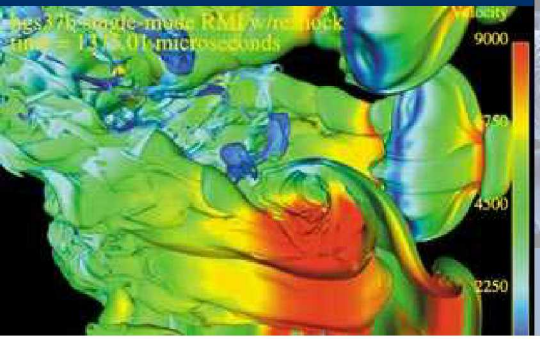


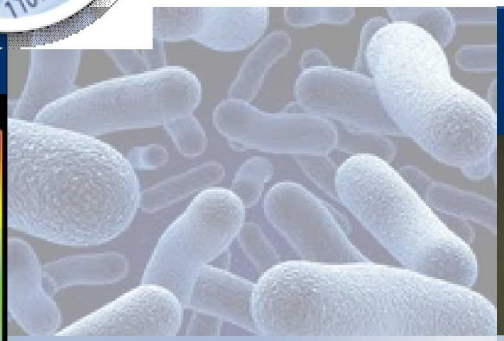
Radiation Effects & High Energy Density Science

Materials Sciences



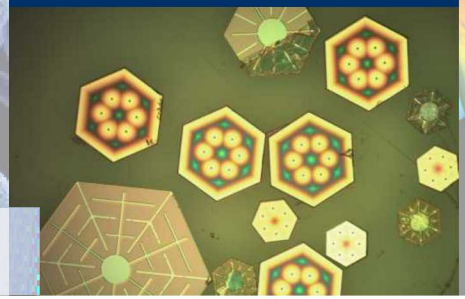
Engineering Sciences

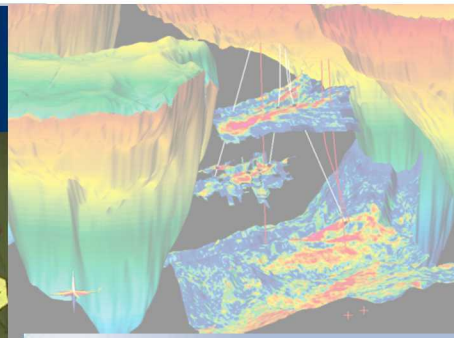




Bioscience

Nanodevices & Microsystems





Geoscience

Summary: Our QIS Capabilities and Interests

Sandia National Laboratories

Primary Expertise & Interest Areas

- **QIS:** Quantum Computing, Quantum Sensing, Quantum Communications/QKD
- **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 $77.5M LDRD investment (2006-2020)
- **Multidisciplinary, integrated cross-laboratory team:** basic science to engineering to systems integration to outreach/partnerships – deep, broad domain expertise

MESA

CINT

ASC Supercomuters

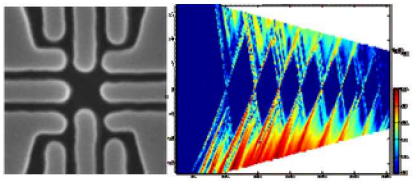
IBL

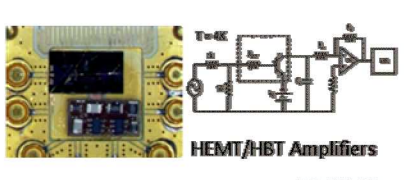
Quantum Computing: Expertise in Multiple Qubits

Sandia National Laboratories

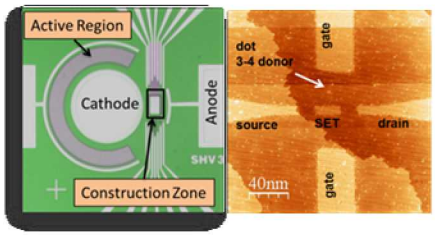
MOS-QD/Donor Platform

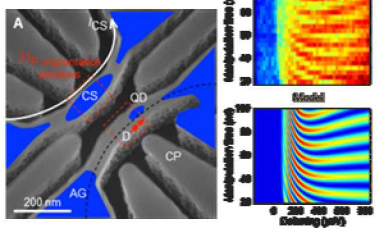
Cryogenic Electronics





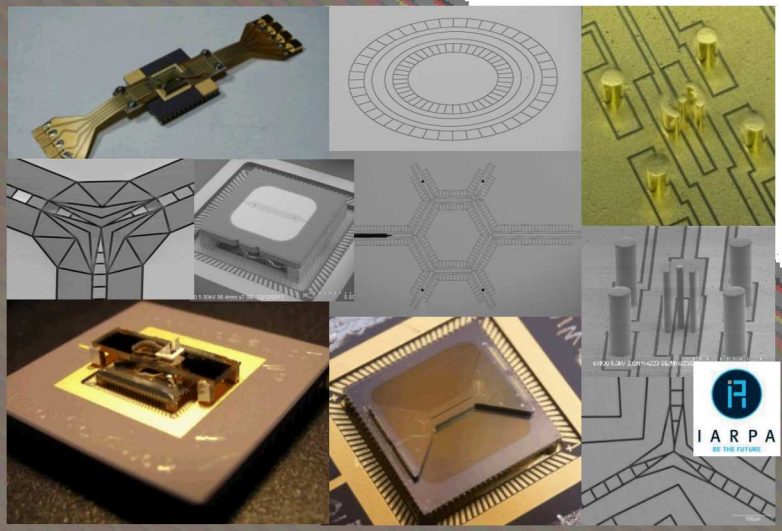
HEMT/HBT Amplifiers

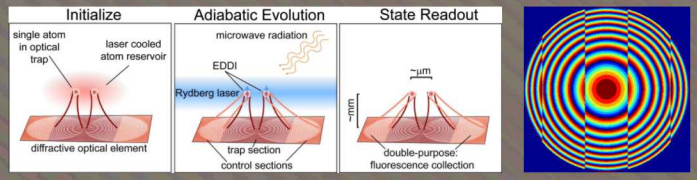


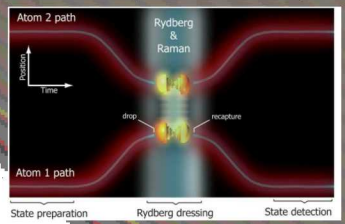


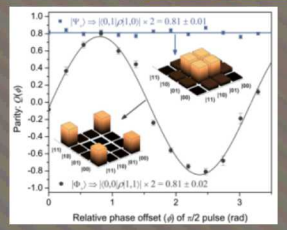
Individual Donor Incorporation

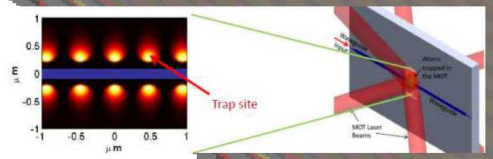
Coupled MOS/Donor Qubits

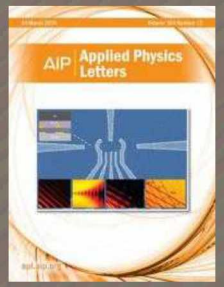


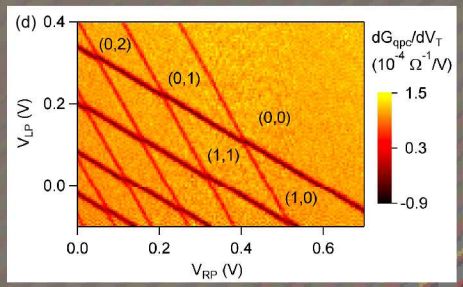




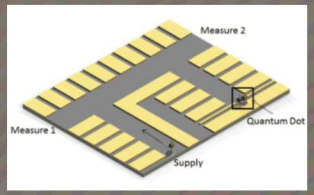




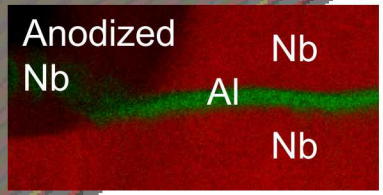




Hole DQD



EON Trap



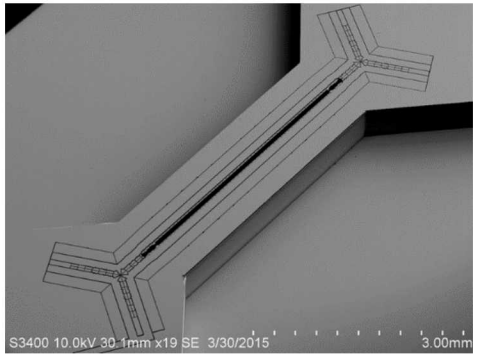
Josephson Junction

Quantum Computing Hardware Capabilities

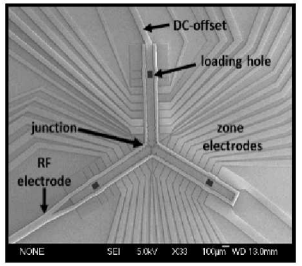
Sandia National Laboratories

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

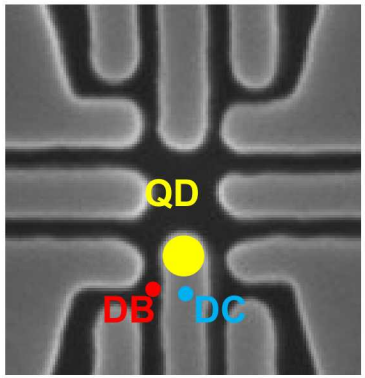
- **Ions in Microfabricated Surface Traps**
  - Ion trap foundry: multiple designs; Ca, Yb, Mg
    - Delivered to >15 groups, 5 countries
    - IARPA MQCO, LogiQ supplier
  - HOA-2: workhorse platform
    - >100 h trapping time, >5 min w/o cooling (Yb)
    - World-leading fidelities: 1Q G_X, G_Y, G_I > 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



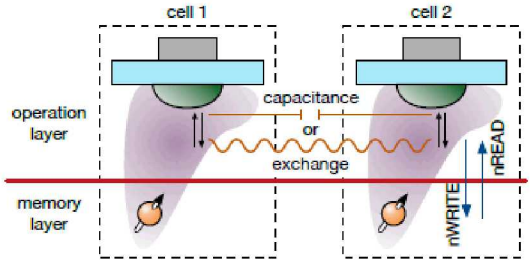
SNL HOA-2: best characteristics of any microfabricated surface trap at room T



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



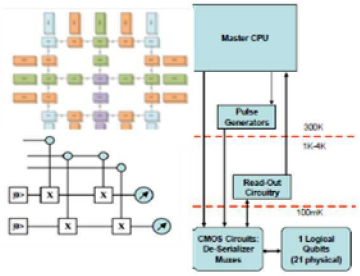
MAJIQ-SWAG Hybrid QD-D Device: P donor nuclear spin – ST qubit



Extension to 2-unit cell device (current LDRD)

Quantum Computer Science Capabilities

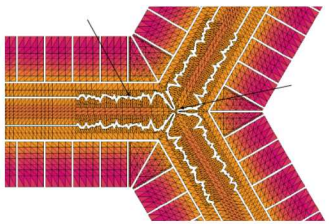
Sandia National Laboratories



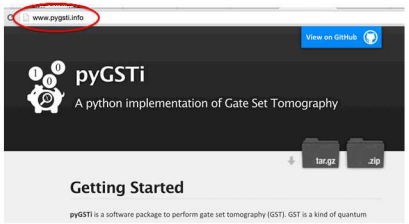
Schematic of components in Sandia small logical qubit design

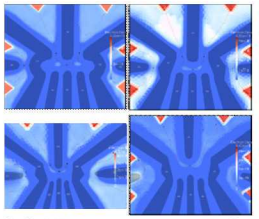
A Sampling of Sandia's Capabilities

- **Architectures:** Theoretical and experimental expertise
  - Circuit (CQC), adiabatic (AQC), holonomic, topological
  - Error correction/suppression:
    - 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, …



TRAPSIM: electrostatic modeling intended for RF trapped ion device design



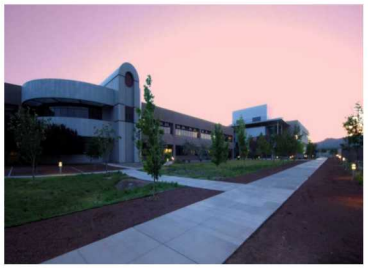


QCAD results on DQD

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

Fabrication and Characterization Capabilities

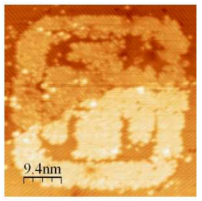
- **MESA Fabs**: Trusted design, fabrication, packaging, testing – underpinning Quantum Info at Sandia
  - Silicon Fab: CMOS process, custom technologies (e.g. ion traps, Si quantum dots, Si photonics)
  - MicroFab: III-V compound semiconductor fab
  - *Wafer-level to die-level processing*
- **Center 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



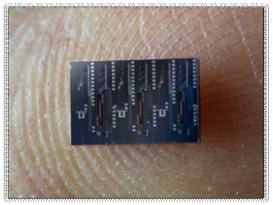
MESA

CINT

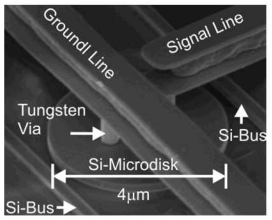
Atomic Precision Fab @ CINT



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



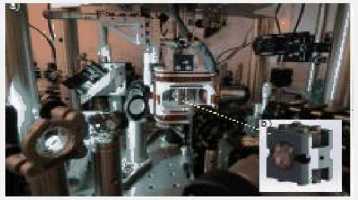
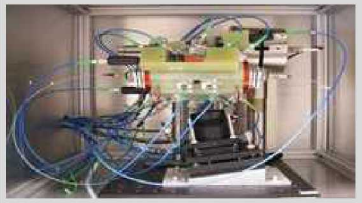
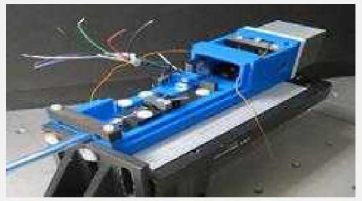
World-first chip scale Si photonics quantum transceiver



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***

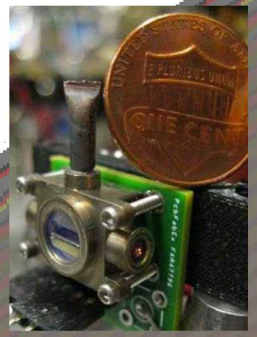
Quantum Sensing Advantages

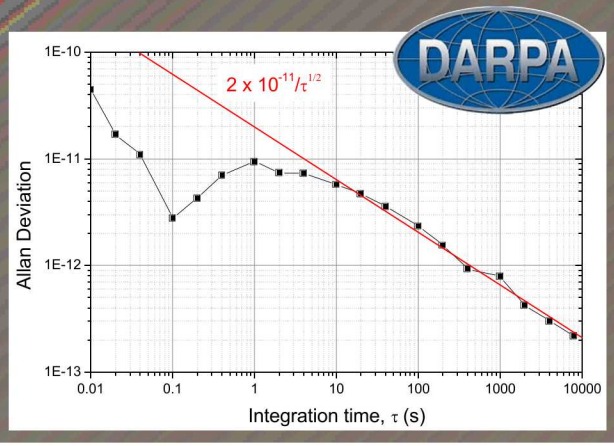
Measurand	Current SOA	Potential	Approach
Electric Field	4 mV/m√Hz (FET based)	1 nV/m√Hz (Rydberg atoms)	
Rotation	100 nrad/s√Hz (FOG)	1 nrad/s√Hz	
Magnetic Field	2fT/√Hz (SQUID)	160aT/√Hz (OPM)	
Portable Time	1e-11/√τ w/ 30 kg and 30,000 cc	1e-12/√τ w/ 300 g and 100 cc	

Quantum Sensing

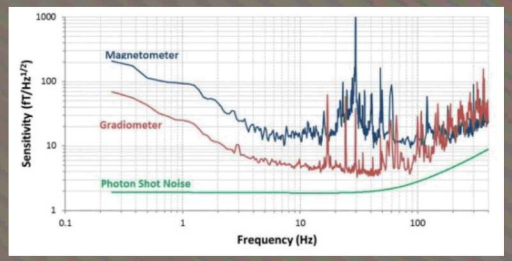
Atomic Clocks

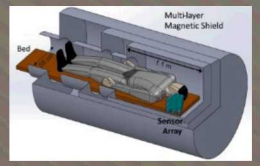
Maximized Precision and Stability
Minimized Volume and Power

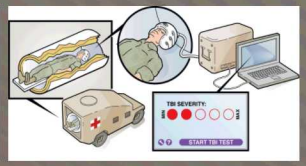




Atomic Magnetometry for Magnetoencephalography

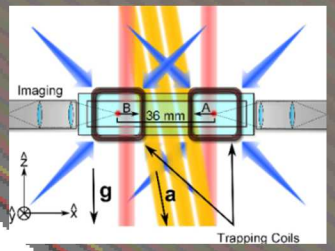


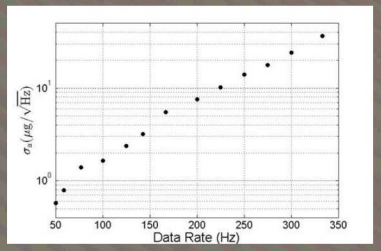


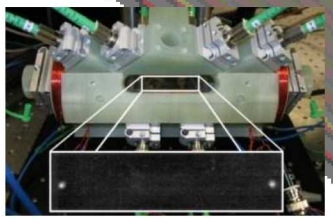


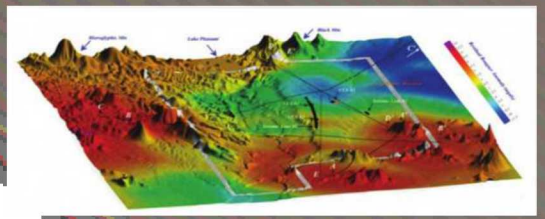
NIH

Atom Interferometry



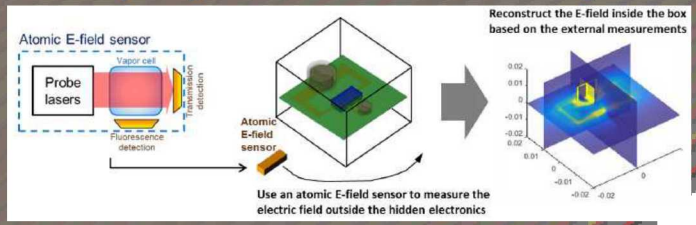


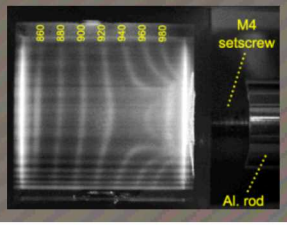




Field Sensing

Rydberg atom based electric field sensing





Passive magnetic field sensing

Fescenko, I., Weis, A. "Imaging magnetic scalar potentials by laser-induced fluorescence from bright and dark atoms," *Journal of Physics D*, **47**, 235001, (2014).

Quantum Communication & Networking

Sandia National Laboratories

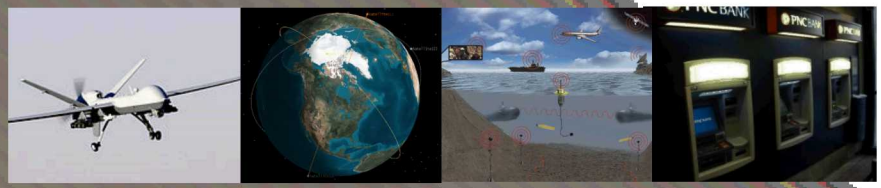
Photonic quantum states have broad security applications

Heisenburg Uncertainty Principle → Measuring a quantum state *changes* the state
Photons are robust, environmentally unaffected → Transmittable over distances (ms to kms)

Secure Communication

Chip-based Quantum Key Distribution and Rotation with the One Time Pad (OTP) protocol is Unconditionally Secure

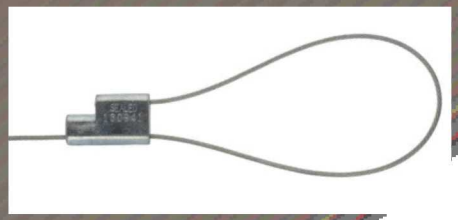
Authentication



Digital Signatures: Trusted Couriers, Hybrid Networks (Satellite, Ship-Ship-Plane), Smartphone & ATM Networks (Banking, Hospitals, Telecommunications)

Distributed Computing, Sensing, and Time Synchronization

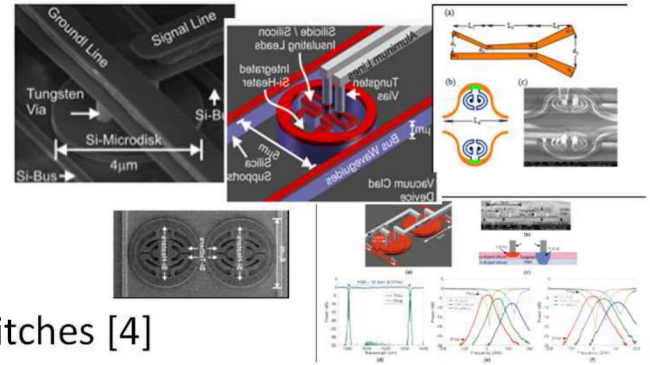
Physical Security and Use Control



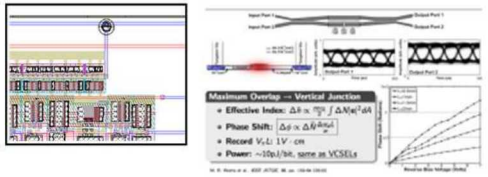
Technical Capabilities: Si Photonics

Sandia's Leadership in Si Photonics

Best In Class Devices



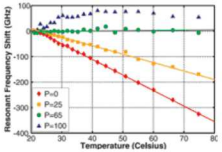
- Lowest energy (3.2 fJ/bit) 12 Gb/s optical modulator [1]
- Low-voltage, compact broadband phase modulators and 2 × 2 thermo-optic switches [2]
- Full C-band tunable second-order filters [3]
- Fastest (2.4 ns) reconfigurable 2 × 2 wavelength selective switches [4]
- Ultra-low V-π length product of < 1V-cm in a 23 GHz broadband Mach Zehnder modulator [5]
- Among the highest speed (45 GHz) Germanium on Si detectors [6]



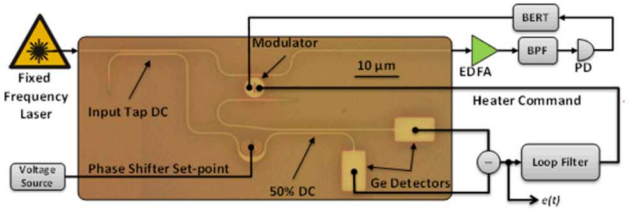
Unique Device Integration and Fabrication

- Homogeneous integration of Si photonics with rad-hard CMOS7 [7]
- Flip-chip bonding with advanced CMOS circuits and minimal parasitic capacitance [8]
- 1st reported measurement and analysis of uniformity of manufactured resonant wavelength [9]

System-Level Research and Control-Circuits



- Integration of a micro-heater, sensor with modulator for thermal stabilization [10]
- Balanced Homodyne locking of resonant filters [11]
- Bit Error rate locking of resonant microdisk modulators [12]
- Integrated Optical Phased Locked Loop [13]
- 4 x 10 Gbps silicon microdisk modulator transmitter

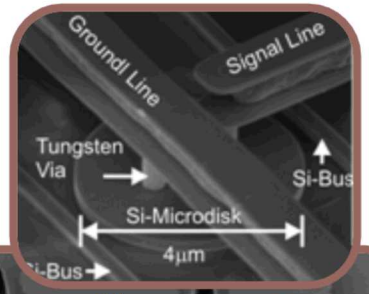


Large IP Portfolio (> 20 patents and Technical Advances filed)

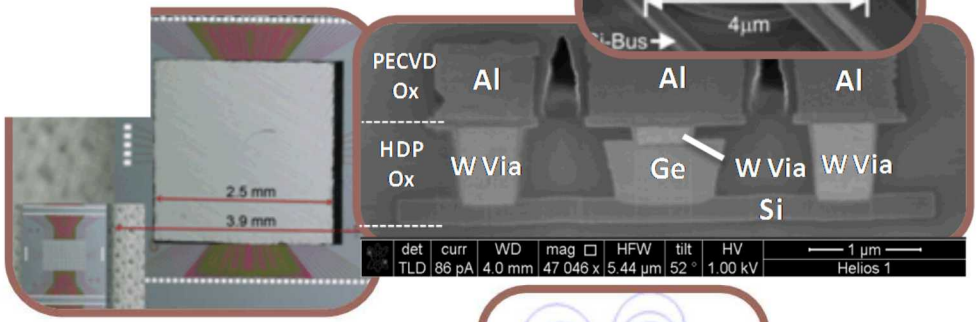
Technical Capabilities: Si Photonics

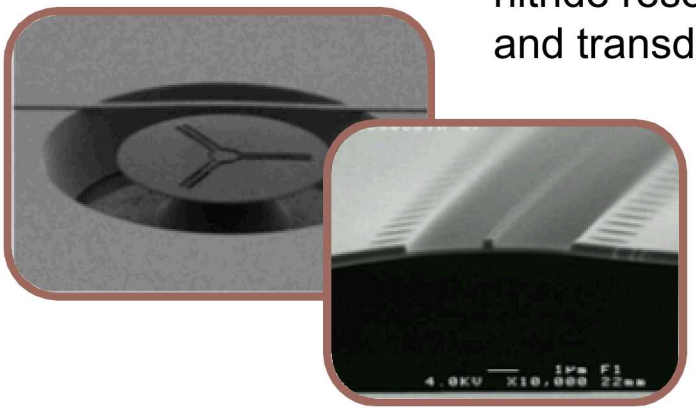
Integrated Photonics at Sandia

- 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

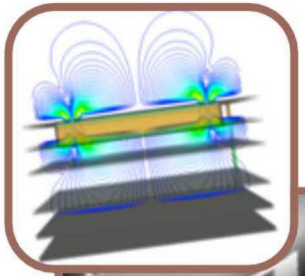


- Suspended Si/SiN waveguides/resonators phononic/photonic crystals, aluminum nitride resonators and transducers.

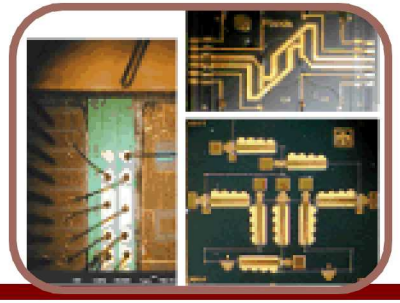


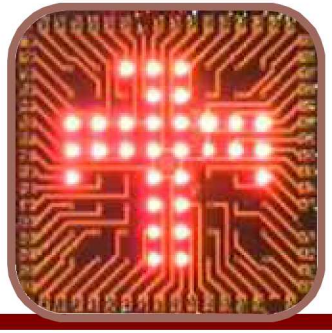


- Near to long wave IR plasmonics and metamaterial based devices.

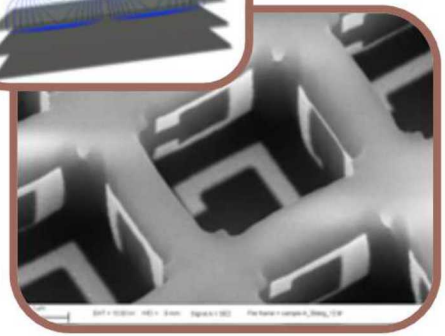


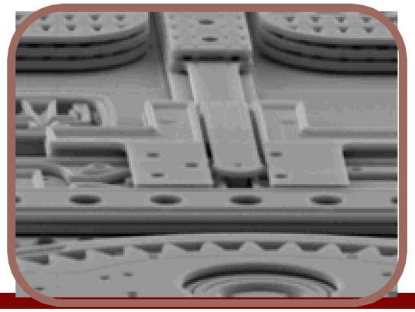
- Compound semiconductor devices and fabrication





- 5 layer poly silicon MEMS process



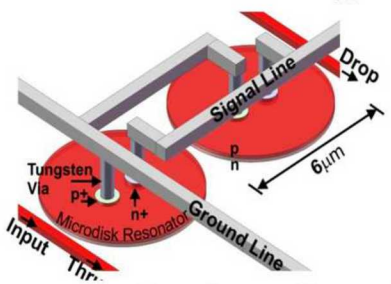


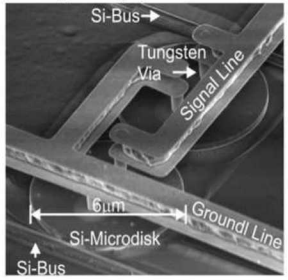
Technical Capabilities: Si Photonics

Sample devices and integration capabilities

Sandia National Laboratories

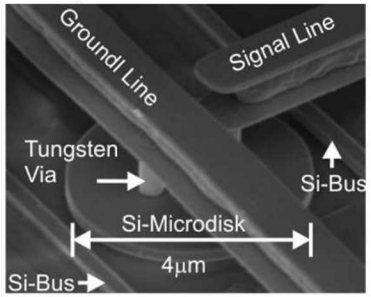
Free-carrier Effect (high-speed)

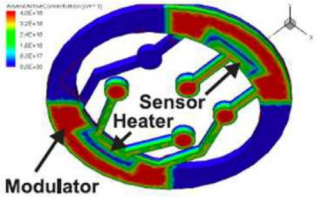


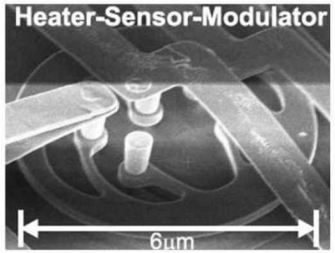


Fast Reconfigurable Interconnects

3.2fJ/bit at 12Gb/s





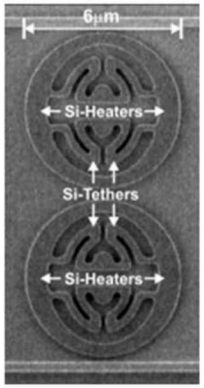


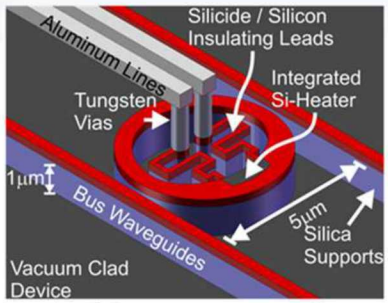
Resonant Optical Modulator/Filter

Thermally stabilized modulator

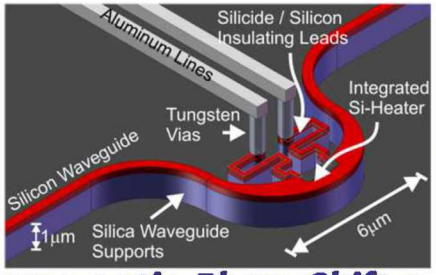
Broadband Mach-Zehnder Filter/Switch **< 1V-cm at 10 Gb/s**

Thermal Optic Effect (wide-band)

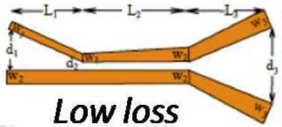




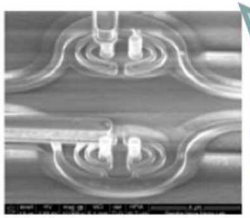
Tunable Resonant Filter



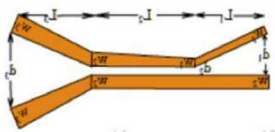
Thermo-optic Phase Shifter



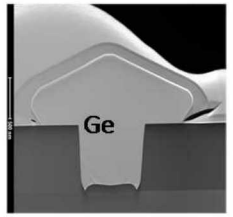
Low loss optical coupler



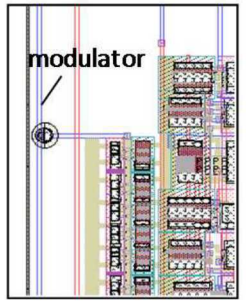
Switch Arrays



High-speed Ge Detector in Si



Si Photonics-CMOS Integration



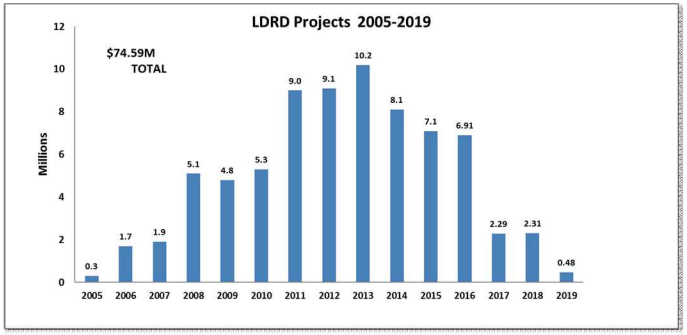
Investments in Quantum Information Sciences

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

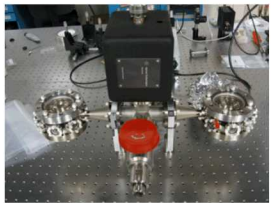
FY08 – FY10
Si-based qubits

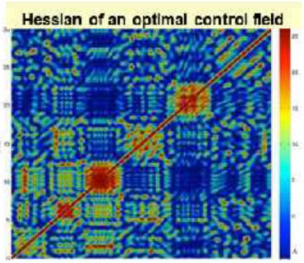
FY11-FY13
Architectures

FY14-FY16
Comms/QKD

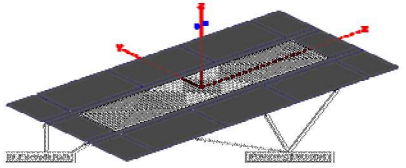


- *Build foundational capabilities while exploring novel, high risk areas*
- Focus on the engineering challenges of QIS
- $77.5M investment, FY05-20
- *Essential* vehicle for academic collaborations





- 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**

External Partnerships

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

Sandia National Laboratories

Questions?

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E-mail: smrinal@sandia.gov