SAND2019-8294PE

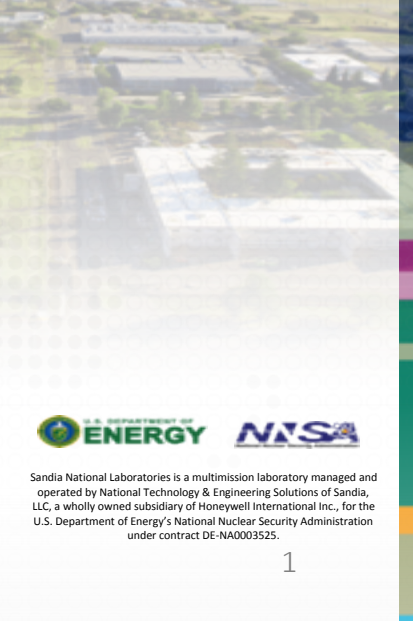
QIS Research at Sandia National Laboratories

NTESS Board of Managers/Committee

July 24, 2019

Rick Muller

Senior Manager, Sandia National Laboratories



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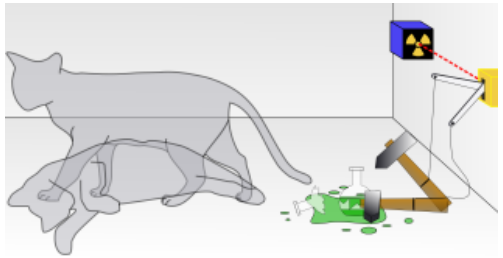
Quantum Information Sciences

- Quantum Mechanics is the physics of the small, and presents novel physical resources and resulting paradoxes:
  - Schrodinger's Cat is a thought experiment demonstrating quantum superpositions: that a particle could be in multiple states at once.
  - Bell's Theorem considers the implications of quantum entanglement.
- Quantum Information Sciences looks at the implications of quantum on Information Sciences
- What is surprising is that many of these implications are relevant to National Security
  - Factoring, Searching, Simulation
  - Sandia's strengths in integrating science and engineering make it central to understanding the national security implications and the engineering challenges QIS poses.

Erwin Schrodinger

Werner Heisenberg



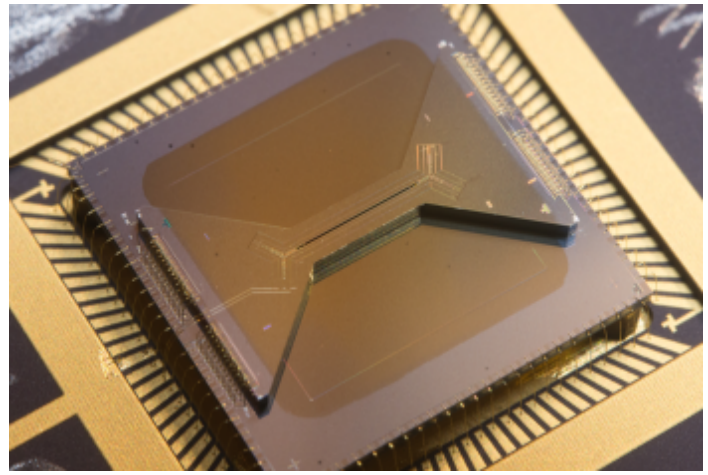
Schrodinger's Cat

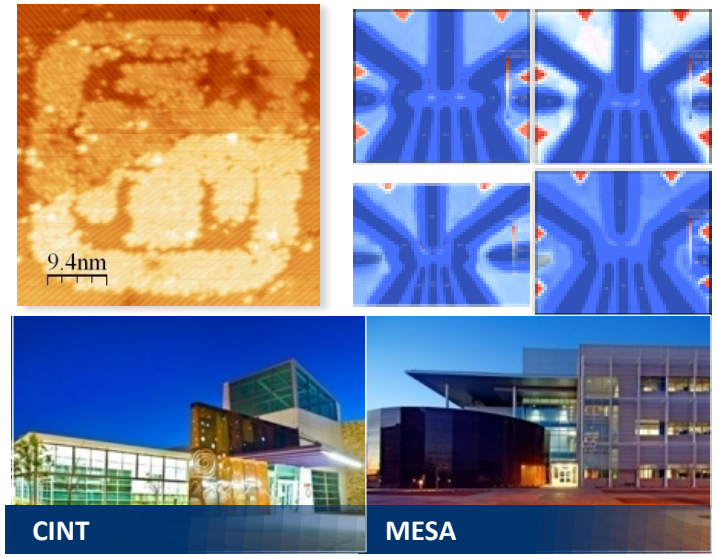
Dick Feynman

Peter Shor

Sandia Is a Leader in QIS

- Built on significant investments over 15 years
  - Over $100M of LDRD
  - Sizable return on investment in DOE & OGA projects
- Unique, hard-to-replicate capabilities
  - Producing working quantum devices in multiple technologies
  - Deep understanding of how device architecture impacts quantum applications and algorithms
  - Strong cross-organizational team with deep quantum expertise and appropriate clearances
- Trusted advisor to multiple govt agencies
  - Decade of performance on government projects
  - Key agency rotations and workshop leadership





Sandia QIS Capabilities Built on DOE Infrastructure

- MESA Silicon & Micro Fabs:
  - Design, build, test world-leading semiconductor and atomic qubits.
  - Capabilities for exotic materials, novel processing and fabrication
- Center for Integrated Nanotechnologies (CINT):
  - DOE/SC National User Facility - device testing, materials & devices characterization, Atomic Precision lithography
- Ion Beam Lab:
  - Phosphorous implantation for Donor & Donor-Dot qubits
- Extensive Computing Facilities:
  - Critical enabler for qubit design, physical modeling, testing, data analyses, and system evaluation
- Materials Science:
  - Synthesis, process prototyping, measurements, characterization, modeling


MESA


CINT


IBL

Aggressive LDRD Investments Built Sandia QIS Foundations

~$100M LDRD investment anchored by ~$55M for the 4 Grand Challenge Projects:

FY08 – FY10
Si-based qubits

- Silicon quantum dot qubits
- Architecture & logical qubit design

FY11-FY13
Alt. Architecture

- Adiabatic architecture assessment
- Atomic precision lithography development
- Neutral atom computation

FY14-FY16
Comms/QKD

- Quantum key distribution development
- Photonic communications/networking development

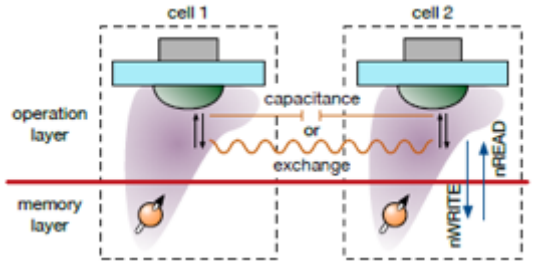
FY18-FY20
Atom Interferometer

- Develop deployable quantum devices
- Quantum sensing based location determination

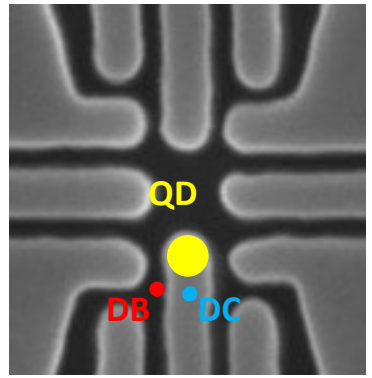
Capability to Fabricate High Fidelity Quantum Devices

- MESA ion trap foundry distributes traps to the world
  - World-leading 1,2-qubit fidelities
  - Delivered to >15 groups in 5 countries
- Silicon semiconducting qubits
  - Leverage professional semiconductor fab for improved qubit arrays
  - Demonstrated quantum dot capabilities
  - Developed worlds-first donor-dot qubit
  - Associated cryoelectronic control and readout capabilities
- Expertise in *other* qubit systems
  - Atoms (world record fidelity), electrons on Helium, topological qubits, hole spins in GaAs and Ge, …

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



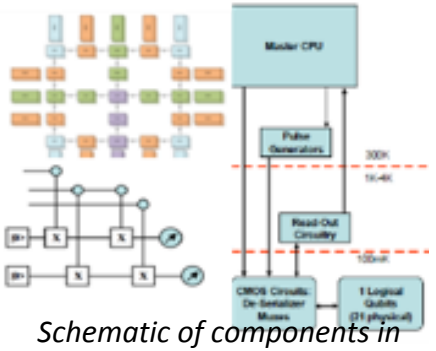
Extension to 2-unit cell device (recent LDRD)



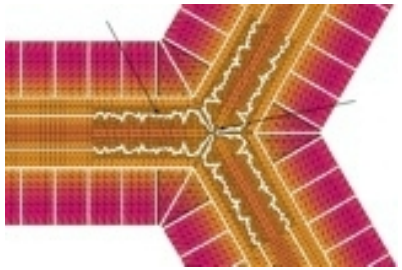
MAJIQ-SWAG Hybrid QD-D Device: P donor nuclear spin – ST qubit

Capabilities to Model and Design Quantum Systems

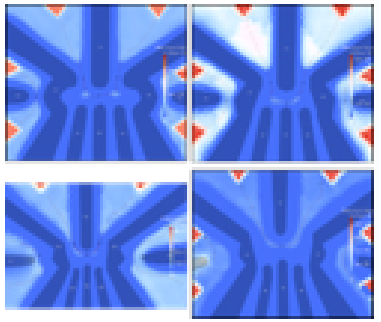
- Architectures: Theoretical and experimental expertise
  - Circuit (CQC), adiabatic (AQC), topological
  - Dynamically corrected gates and error correction/suppression
- Controls and Noise Modeling
  - Extensive theory/simulations for ions, traps, Si, neutrals
  - Optimal control, robust control protocols for uncertain qubits
- Quantum Characterization
  - GST: characterize/calibrate/debug qubits; detect non-Markovian noise; validate Diamond norm. Many users world-wide, multiple qubit systems
  - pyGSTi – open source GST software – http://www.pygsti.info
- Modeling and Simulation: SNL-designed, open source, and commercial tools
  - Architectures: circuit simulators, threshold simulators, cluster expansion simulators, vector state simulators, complex quantum networks, controls, stochastic quantum systems, noise models, …
  - Si: QCAD, COMSOL, NEMO-3D, valley-aware effective mass theory, strain, …
  - Ions: TRAPSIM (design tool), gate simulators, …



Schematic of components in Sandia small logical qubit design



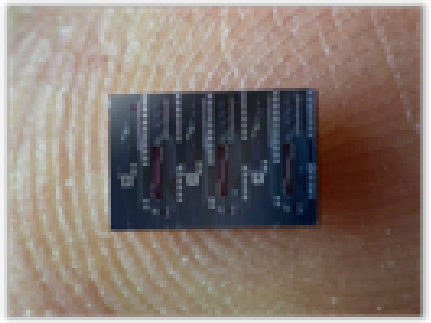
TRAPSIM: electrostatic modeling intended for RF trapped ion device design

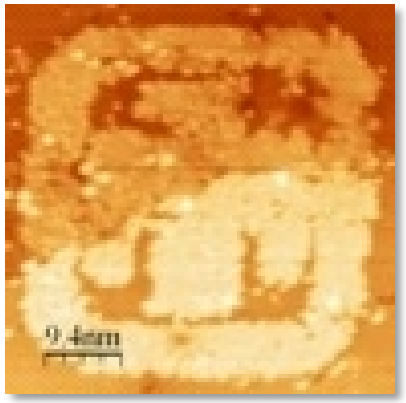


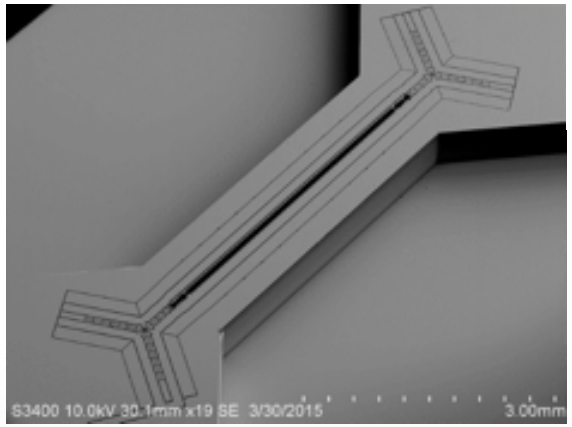
QCAD results on DQD

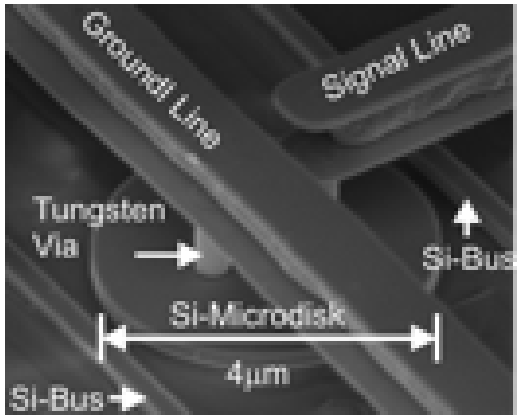
Sandia has produced a number of unique products

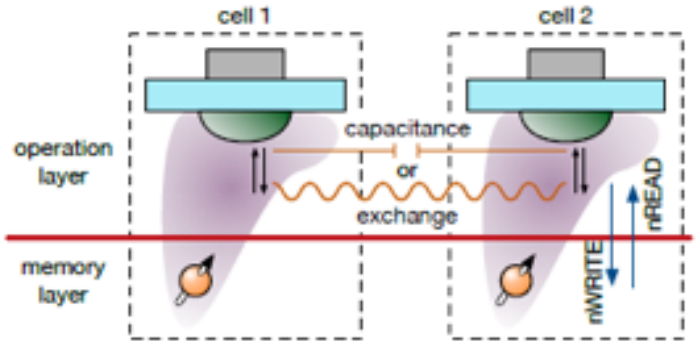
- World-first chip scale Si photonics quantum transceiver
- Si Photonics resonant optical modulator/filter
- World-smallest Sandia “nano-logo,” at 0.7 nm precision
- Developed worlds-first donor-dot qubit
- HOA2 - Best characteristics of any microfabricated surface trap at room temperature





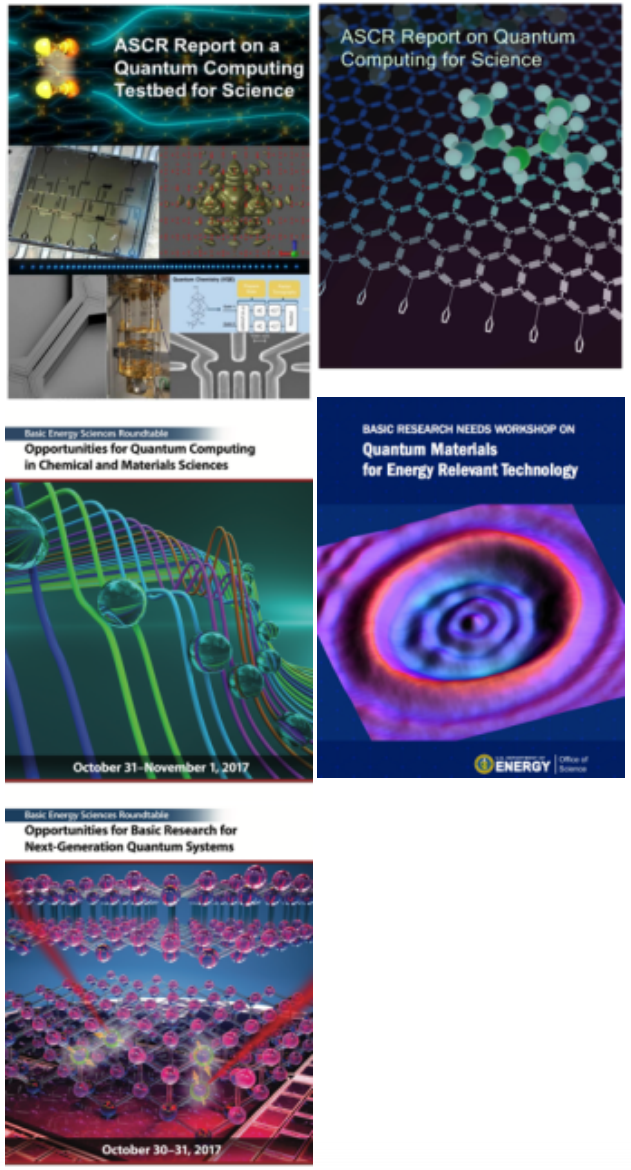






Sandia has benefitted from recent DOE interest in QIS

- Office of Science (SC) intends to make major moves into QIS
- Sandia is helping SC understand how QIS will impact DOE mission
- Sandia has won ~$40M in new DOE/ASCR projects
  - QOALAS - algorithms for approximate optimization and learning
  - QSCOUT - testbed to implement and explore NISQ hardware
  - QPERFORMANCE - benchmarking effort of assess the performance of NISQ processors
  - OVER-QC - capabilities for validating, assessing, and optimizing quantum circuits



Quantum Simulation *May* Have Potential for Stockpile Stewardship

- Understand promise of quantum simulation for materials modeling
  - Classical algorithms force a choice between unquantifiable accuracy at polynomial cost and systematic improvability at exponential cost
  - Quantum algorithms achieve systematic improvability at polynomial cost – an exponential speedup
- Understand resources required for DOE stockpile relevant problems:
  - Relatively small problems can be intractable with high accuracy methods
  - Compute how many qubits at what accuracy would be required for a quantum calculation
  - E.g. 64 atom H/D cells at high T,P

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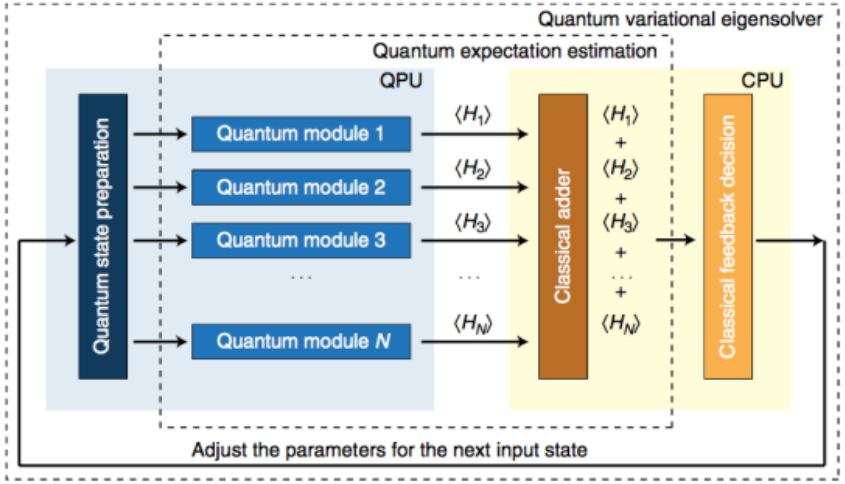
A variational eigenvalue solver on a photonic quantum processor

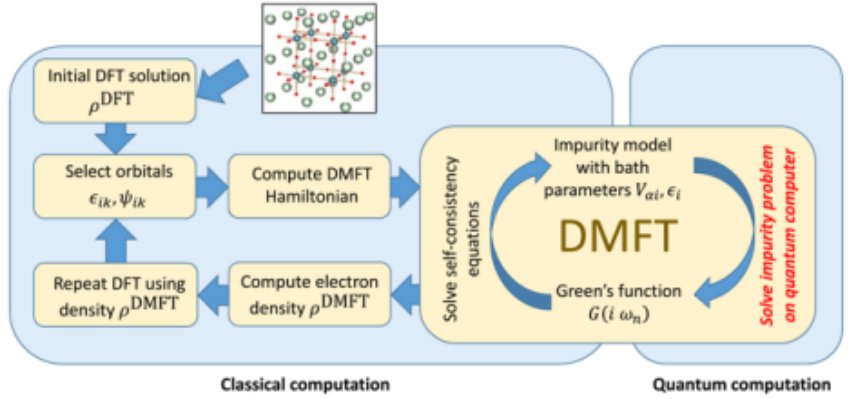
Alberto Peruzzo[1,*,†], Jarrod McClean[2,*], Peter Shadbolt[1], Man-Hong Yung[2,3], Xiao-Qi Zhou[1], Peter J. Love[4], Alán Aspuru-Guzik[2] & Jeremy L. O'Brien[1]



PHYSICAL REVIEW X 6, 031045 (2016)

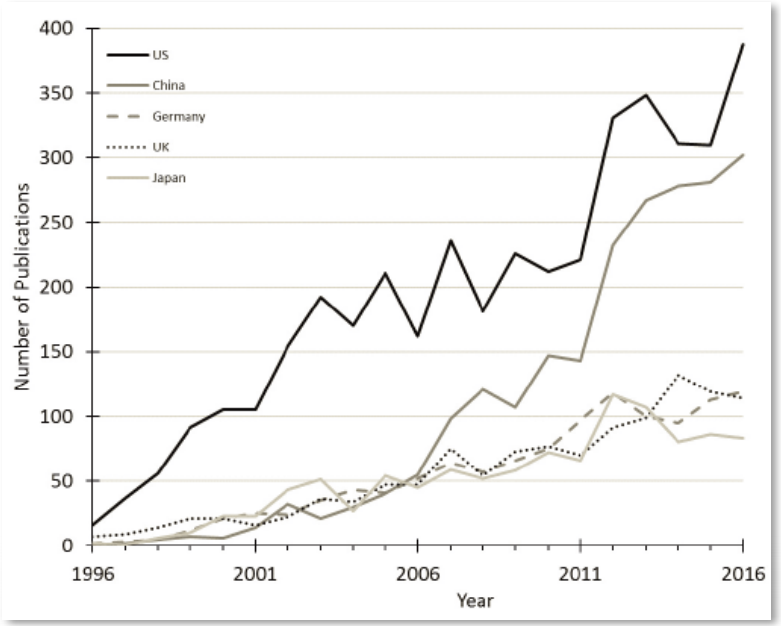
Hybrid Quantum-Classical Approach to Correlated Materials

Bela Bauer,[1] Dave Wecker,[2] Andrew J. Millis,[3] Matthew B. Hastings,[1,2] and Matthias Troyer[4,2]



National Quantum Initiative Defines US Govt QIS Strategy

- National Quantum Initiative
  - QIS has important implications for US National and Economic Security
  - The rest of the world is investing heavily in QIS: US cannot outspend the world.
  - Create an all-of-government approach to coordinate US research in QIS
- NQI Bill (H.R. 6227)
  - Unified version of House and Senate Bills
  - DOE ($125M/yr), NIST ($80M/yr), NSF ($50M/yr) funding
  - Signed by POTUS 12/21/2018
  - Authorized but not Appropriated
- Opportunities:
  - NSF: Quantum Leap Challenge Institutes call open
  - NIST: Quantum Economic Development Consortium (QED-C) underway
  - DOE Quantum Centers RFI out, FOA expected 2020



Sandia's Future Vision is Integrated Quantum Science

- The critical bottleneck to achieving quantum goals is integration.
  - The only way to simultaneously increase qubit capacity and fidelity is to modularize and integrate repeatable units.
  - Challenge: what capabilities can be integrated for hybrid quantum devices?
  - Challenge: how to we create, distribute, and maintain quantum resources?
  - Challenge: what opportunities are available with integrated computing and sensing?
- 5 Year Vision: Photonic qubit integration for national impact.
  - Build on the high fidelity and full connectivity available with trapped ions
  - Integrate chip-based photonic elements and electronics with existing physics devices.
  - Develop algorithms and protocols to deal with connectivity limitations
  - Extend to other Sandia quantum systems
- Beyond 5 years:
  - Extend capabilities to heterogeneously integrate multiple complementary quantum technologies
  - Develop and demonstrate an agile platform for chiplets representing different computing, communications, and sensing capabilities.
  - Address national needs with more capable quantum devices.