SAND2019-10196PE

Quantum Science and Engineering at Sandia National Laboratories: Overview and Opportunities

PRESENTED BY

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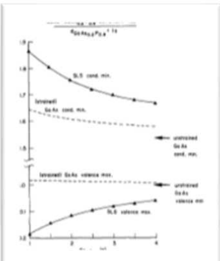
MESA: Microsystems Engineering, Science and Applications

[SAND Number]

Quantum R&D at Sandia

Strained-layer superlattices from lattice mismatched materials, *Journal of Applied Physics* 53, 1586 (1982)



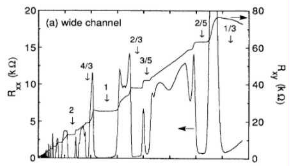
Simulating physics with computers, R.P. Feynman, *Int J Theo Phys* 21 (1982)

Simulating Physics with Computers

Richard P. Feynman

1980s

Fractional quantum Hall effect, J.A. Simmons, *et al.*, *Phys Rev B* 44 (1991).



Quantum error correction, P.W. Shor, *Phys Rev A* 52 (1995)

$$|0\rangle \rightarrow \frac{1}{2\sqrt{2}}(|000\rangle + |111\rangle)(|000\rangle + |111\rangle)(|000\rangle + |111\rangle),$$

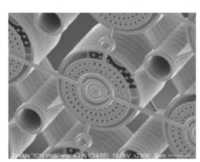
$$|1\rangle \rightarrow \frac{1}{2\sqrt{2}}(|000\rangle - |111\rangle)(|000\rangle - |111\rangle)(|000\rangle - |111\rangle). \quad (3.1)$$

Functional single electron transistor, J.A. Simmons, T. Eiles (1997/98)

1990s

LDRD: "Quantum Computing Accelerator I/O," C.P. Tigges, N. Modine (2003)

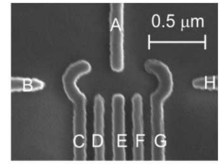
1st QIS presentation by Sandia: Microfabricated ion traps for QC architectures, M. Blain, *et al*. (2004)



16th Electronic Properties of 2D Electronic Systems in Albuquerque (2005)

1st external QIS funding at Sandia: Trap foundry, M. Blain, *et al*. (2005); LDRD: Traps for QC & Qsim (2005)

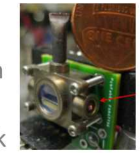
3 LDRD: Ion qubits; Si qubits; QC architecture (2007)

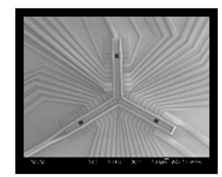


QIST Grand Challenge LDRD: Si quantum bits & logical qubits (2008-10)

2000s

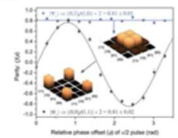
DARPA IMPACT: Ion microwave atomic clock (2009-14)





IARPA MQCO: Microfabricated surface traps for multiple qubits (2010-2015)

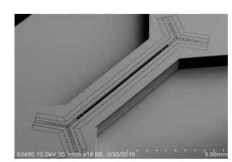
AQUARIUS GC LDRD: Adiabatic QC (2011-13)



IBM Quantum Experience: 1st public access to QC (2016)

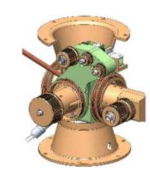
SECANT GC LDRD: QKD (2016-18)

IARPA LOGIQ: Microfabricated traps for a logical qubit (2016-2021)

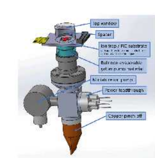


DOE/SC Quantum Science Open User Testbed (QSCOUT) (2018-22)

SIGMA GC LDRD: AI for inertial guidance (2018-20)



DARPA TICTOC: Ion optical clock (2019-21)

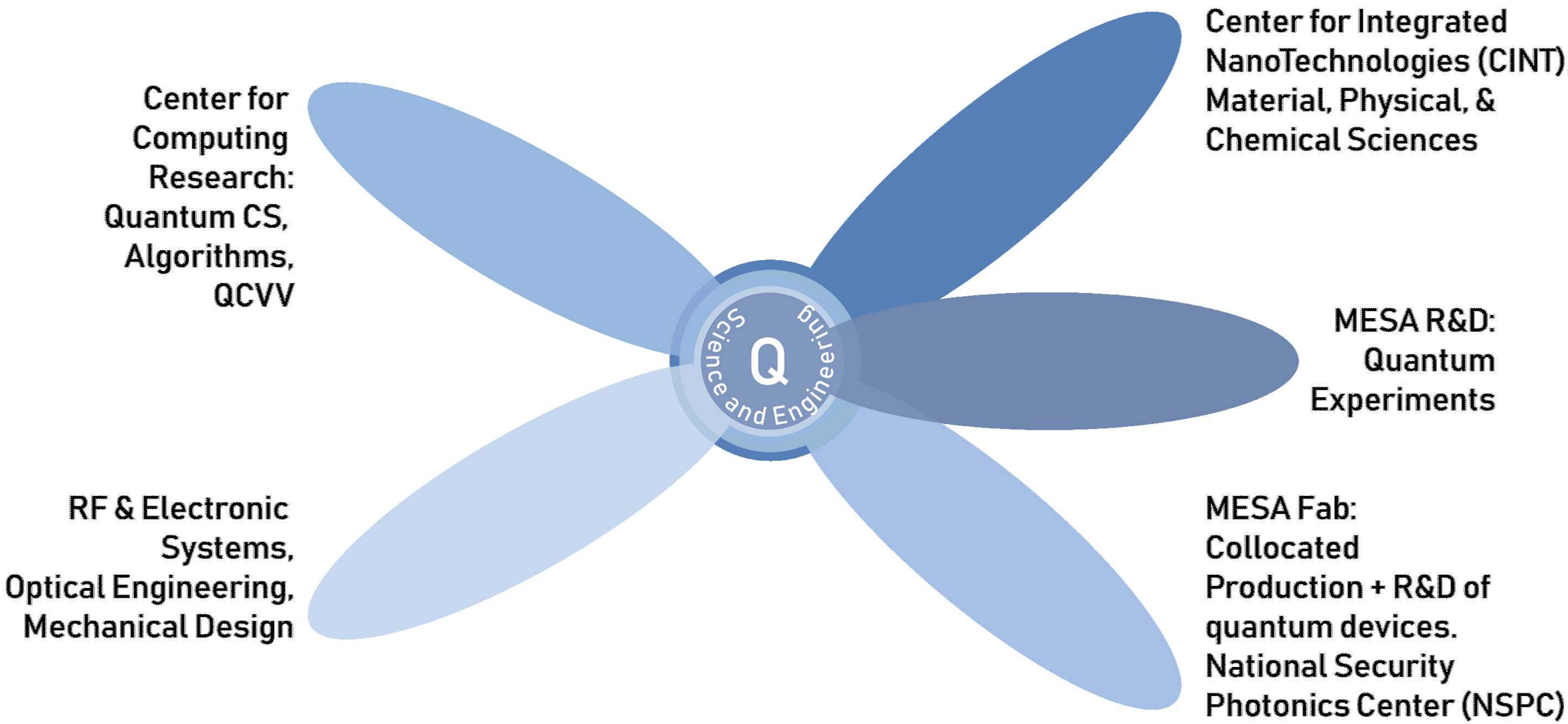


2010s

Sandia Quantum Information Science Organization Chart

QIS work at Sandia draws on skills and resources from across the Labs

- QIS is an exciting opportunity for Sandia's engineers and scientists
- QIS benefits from decades of collective experience in all relevant domains at Sandia
- Example: QSCOUT (next)



QSCOUT: An open quantum testbed at Sandia

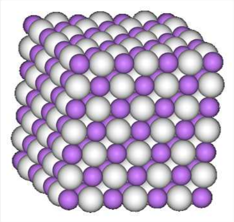
DOE/SC Advanced Scientific Computing Research (ASCR) **QSCOUT** (PI: P. Maunz)

- Quantum processor with **5-15 trapped-ion qubits**
- Goal: **Available to the DOE/SC computing community** in 2020
  - Access to quantum processor with high-fidelity operations
  - Low-level access to gate & quantum circuit implementations
  - Full information on implementation of quantum operations
  - Ability to run any testing circuits

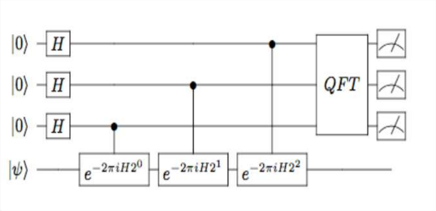
Design approach

- Build on established qubits ($^{171}Yb^{+}$)
- Use Sandia microfabricated traps
- Use established qubit manipulation tools (e.g. pulsed laser as demonstrated at UMD, Duke, Sandia)

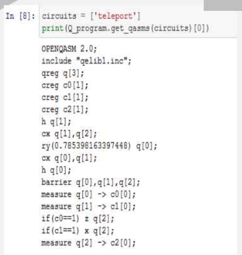
Example QSCOUT workflow:



Lithium hydride example



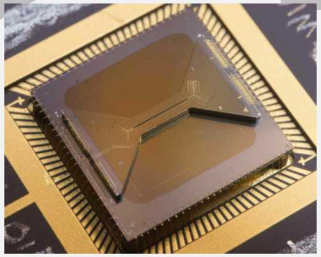
Textbook digital quantum simulation circuit



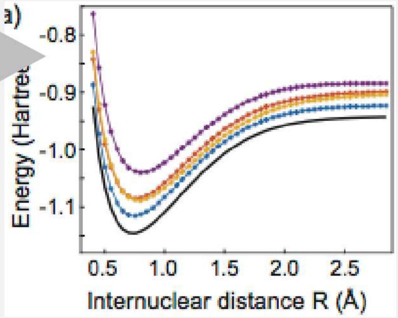
```
In [8]: circuits = ['teleport']
        print(Q_program.get_qasms(circuits)[0])

OPENQASM 2.0;
include "qelib1.inc";
qreg q[3];
creg c0[1];
creg c1[1];
creg c2[1];
h q[1];
cx q[1],q[2];
ry(0.785398163397448) q[0];
cx q[0],q[1];
h q[0];
barrier q[0],q[1],q[2];
measure q[0] -> c0[0];
measure q[1] -> c1[0];
if(c0==1) z q[2];
if(c1==1) x q[2];
measure q[2] -> c2[0];
```

QSCOUT code/ microcode



Implement on hard-ware/trapped ions



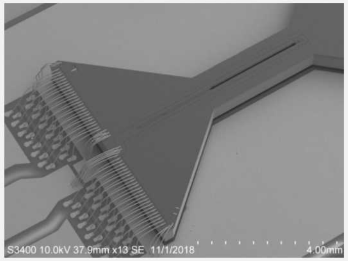
Results

QSCOUT's **main interdisciplinary tasks**

Qubit hardware	Gate modeling	QCVV
Hardware controllers	Software stack	Exemplar apps

QSCOUT **collaborations**

- Duke University (K. Brown)
- Tufts University (P. Love)
- LBNL
- Open to others…



National Quantum Initiative (NQI)

Sandia Center for Integrated Quantum Sciences

The critical bottleneck to achieving quantum goals is **integration**. CIQS attacks this obstacle by addressing an array of **critical S&T challenges**:

- How do we simultaneously increase qubit capacity and fidelity?
- Can we integrate multiple qubit technologies to reap the benefits of hybrid quantum devices?
- How do we create, distribute, and maintain quantum resources?
- Opportunities with integrated quantum computing & sensing?

5 Year Vision: **Integrating Ions and Photons for Science Impact**

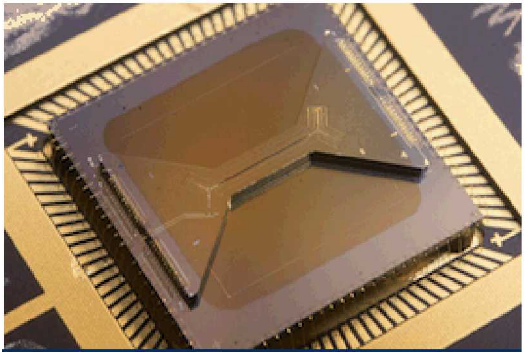
1 - Build on the high fidelity and full connectivity available with trapped ions
2 - Integrate chip-based photonic elements and electronics with existing physics devices
3 - Develop algorithms and protocols to deal with connectivity limitations
4 - Extend to other AMO systems such as quantum sensing with trapped atoms
5 - ***Driven-by and impacting key science applications***

Beyond 5 years:

6 - Extend capabilities to heterogeneously integrate multiple complementary quantum technologies
7 - Develop and demonstrate an agile platform for chiplets representing different computing, communications, and sensing capabilities
8 - Address national needs with more capable quantum devices

…

MESA



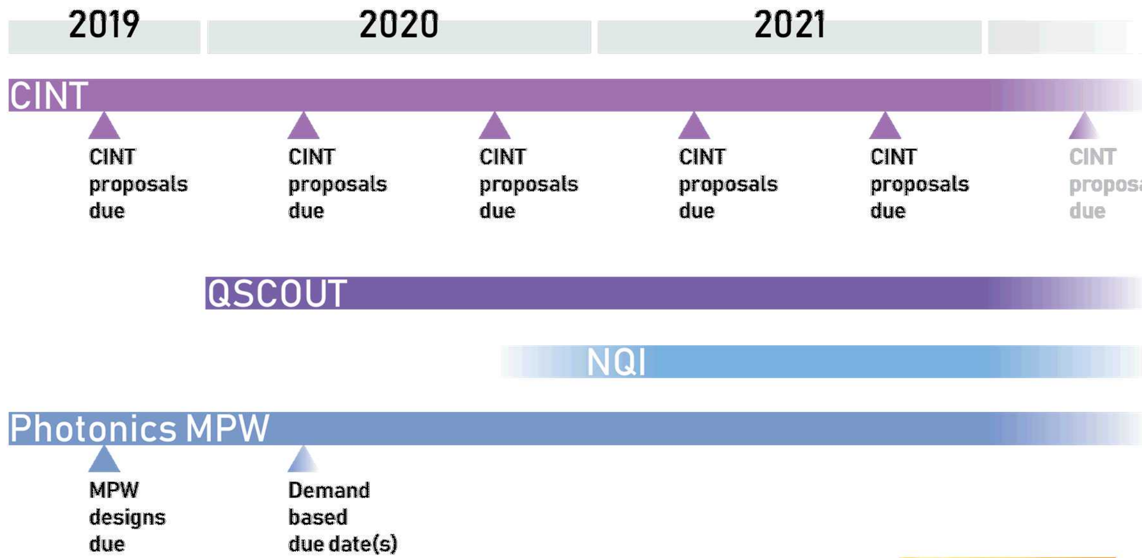
TRAP FOUNDRY

CINT

How to work and partner with Sandia

Numerous technical **partnerships** in place today:

- Academic institutions, industry, & Government
- **CINT**: semi-annual proposals cadence: cint.lanl.gov
- **QSCOUT**: coming in 2020
- **NQI**: in progress
- Contact quantum@sandia.gov
- **National Security Photonics Center**: sandia.gov/mesa/nspc
- Contact photonics@sandia.gov



Recruiting (IDs):

- 668518 – Integrated Photonic Researcher/Optical Engineer
- 667985 – Post-doc/Atomic Physics
- 668201 – Post-doc/Silicon Photonics Research
- …and 10 more related post-doc postings

- contact quantumjobs@sandia.gov
- check out sandia.gov/careers, "photonics"

Questions?

Center for Integrated NanoTechnologies (CINT)

DOE funded nano-science user center

- **Free** access to staff expertise and equipment for open science
- Two proposal calls per year - short-term projects proposals accepted continuously

CINT Research Areas

In-situ characterization & nanomechanics

- Dynamic response of materials and nanosystems to mechanical, electrical, or other stimuli.

Nanophotonics & optical nanomaterials

- Synthesis, excitation, and energy transformations of optically active nanomaterials and electromagnetic phenomena

Soft, biological & composite nanomaterials

- Synthesis, assembly, and characterization of soft, biomolecular, and composite nanomaterials that display emergent functionality.

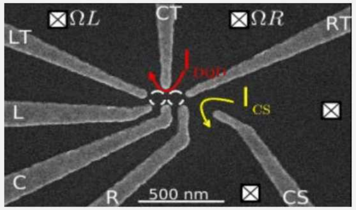
Quantum material systems

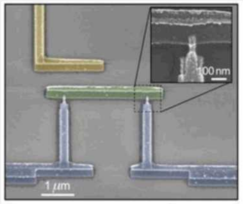
- Understanding and controlling quantum effects of nanoscale materials and their integration into systems spanning multiple length scales.

Quantum material systems details:

Quantum information science

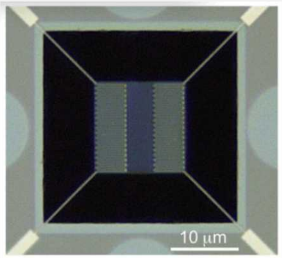
- Quantum transport & qubits
- Quantum sensing
- Focused ion implantation

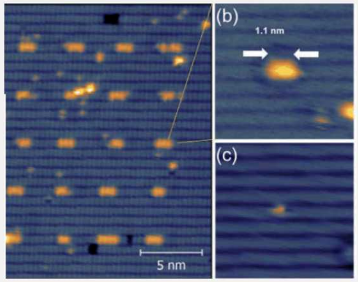




Forefront lithography

- Atomic-precision lithography
- Nanoscale devices





Materials synthesis

- Ultra-high mobility MBE
- Complex oxide PLD
- CVD nanowire growth

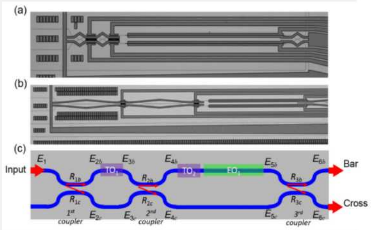
Correlated systems

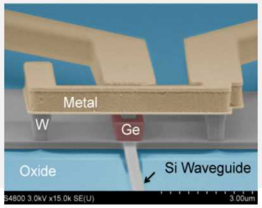
- Mean-field modeling for quantum materials
- Many-body approaches

QIS and the Sandia National Security Photonics Center

Integrated photonics for quantum communications

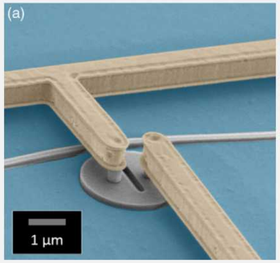
Sandia's silicon, III-V, alumina, lithium niobate heterogeneously integrated photonic platforms: compact microsystems for telecom and visible wavelengths

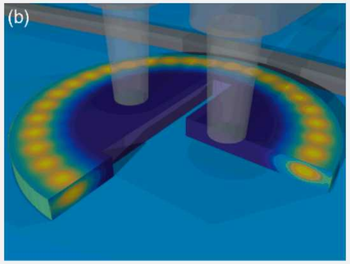




Cryogenic optical interconnects

High-speed low-power resonant modulator operating at cryogenic temperatures (≤ 4 K)

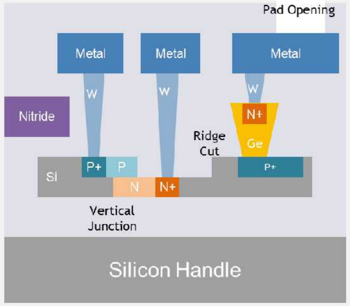




Optica **4**, 374-382 (2017)

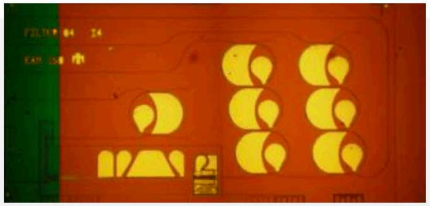
Silicon photonics integrated circuits

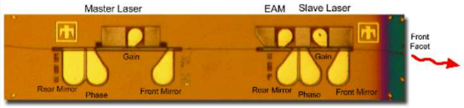
- Leverage CMOS (200 mm SOI)
- 22 passive devices, 20 active devices, design guide and library
- **MPW runs available**, up to passive+active+Ge devices



III-V photonic integrated circuits (PICs)

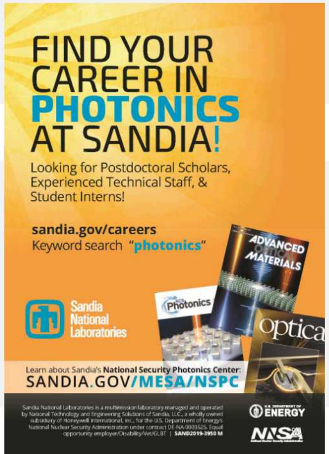
- InP, GaAs, GaN
- Elements: Waveguides, lasers, amplifiers, modulators, detectors, phase shifters
- **MPW runs available**





More information on photonics MPW opportunities:

- National Security Photonics Center: `sandia.gov/mesa/nspc`
- Contact `photonics@sandia.gov`



SIGMA Grand Challenge LDRD

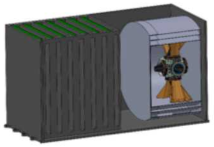
Quantum Sensing GC LDRD **SIGMA** (PI: G. Biedermann)

- Miniaturized atom interferometer to enable **sub-100 ng sensing** performance in **1000× smaller package**

Strategic Inertial Guidance with MAtterwaves

UC San Diego

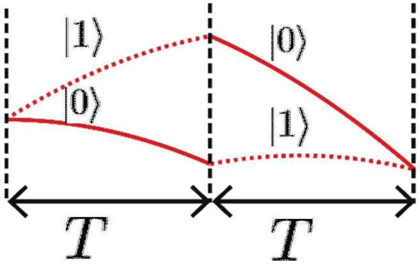
Yale



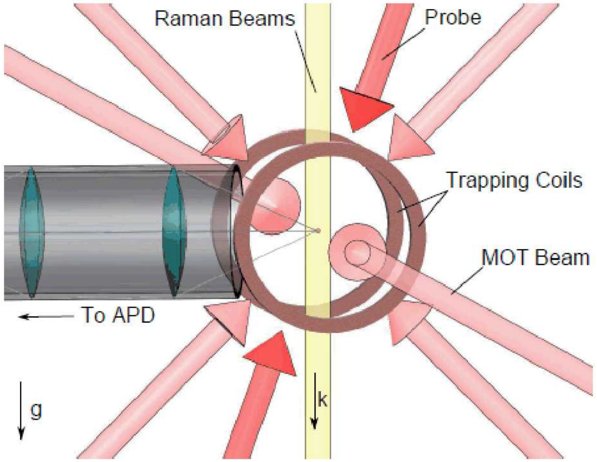
- Atom interferometers operate spectacularly well in laboratory environments
- Fielding is challenging in a compact form and in all but the most benign environments
- Result of: system reliability issues, system size, and dynamic range

What will it take?

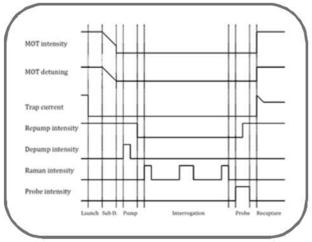
Atom interferometer physics



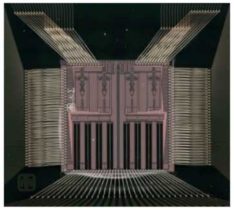
UHV system

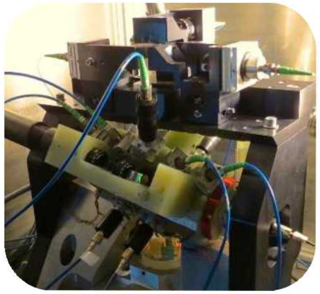


Control electronics

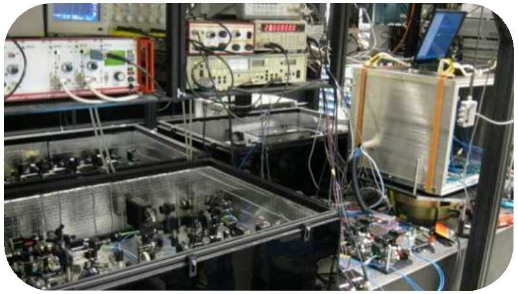


Photonics





Custom optomechanics

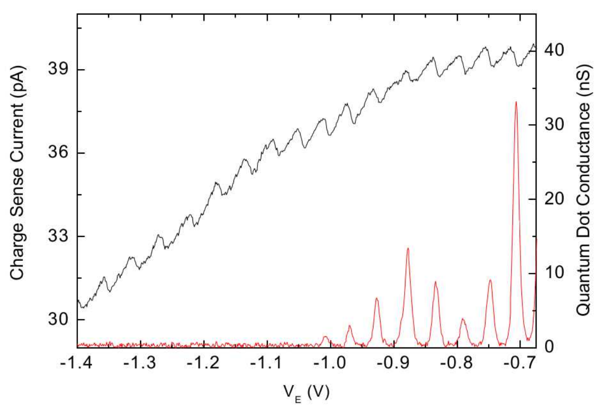


Agile & stable laser system

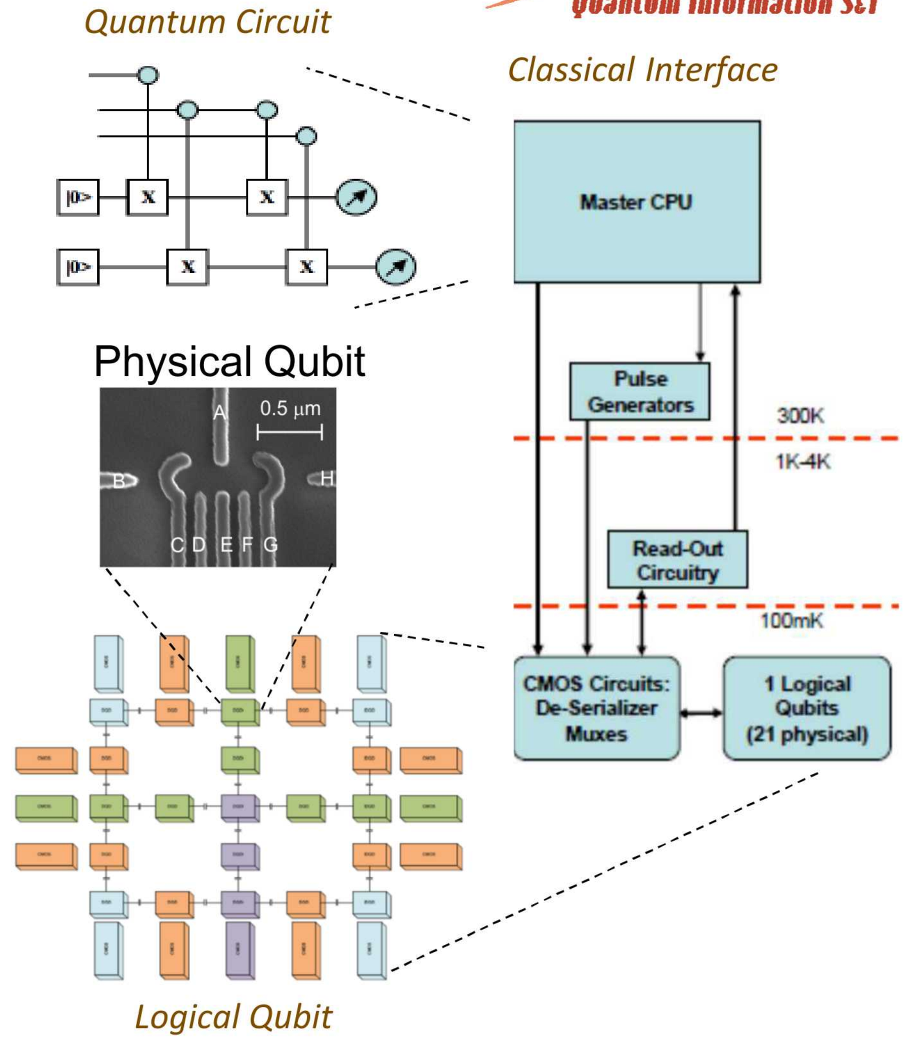
Quantum Information Science & Technology (2008-2010)

Project accomplishments:

- **Fabrication and measurement techniques for silicon quantum bit** (qubit) using double quantum dots
- **End-to-end design** (qubits to quantum circuit) **for error corrected logical qubit** with Si double quantum dot hardware
- **Modeling tools to guide the fabrication, measurement, and assessment** of Si qubit and circuits.



World's first single electron charge sensing in Si MOS system



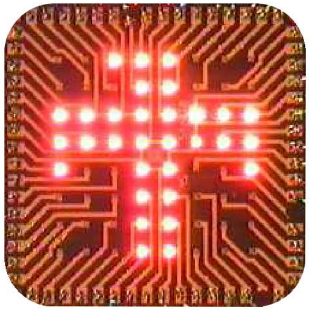
Sandia has a long history in Microelectronics and Microsystems

1960s — Microelectronics and Microsystems — *Present*

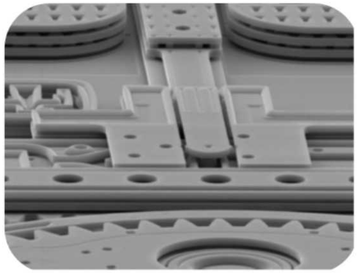
Laminar Flow Clean Room

Design/Build Galileo ICs

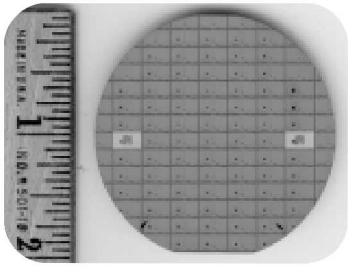
High Efficiency VCSEL



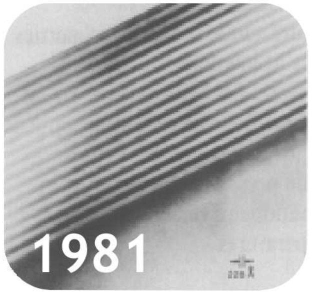
5-Level Surface Micromachining



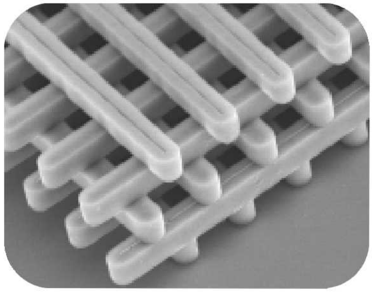
Microsystems-Enabled Photovoltaics



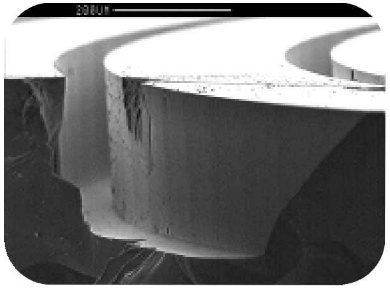
Radiation-Hardened CMOS



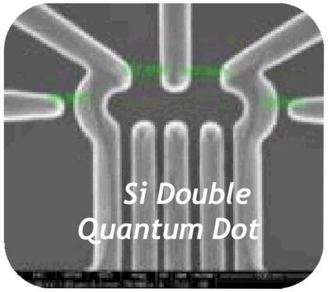
Strained-layer Superlattices



Photonic Lattice



MicroChemLab



Quantum Computing

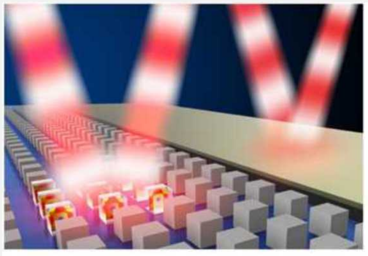
1980s — Quantum Engineering — *Present*

DOE/Office of Science (SC) Project (CINT & MESA)

Light-matter interaction phenomena using subwavelength engineering of material properties (PI: Igal Brener, Sr. Scientist, MESA; DOE/SC BES)

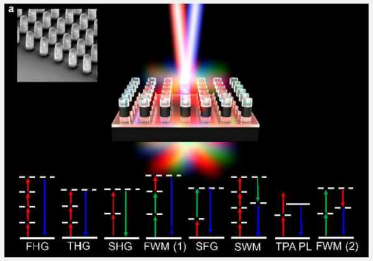
***Approach**: Combining **nanostructures** and **metamaterials** with **state-of-the-art compound semiconductors** to achieve new behaviors*

Optical Magnetic Mirror

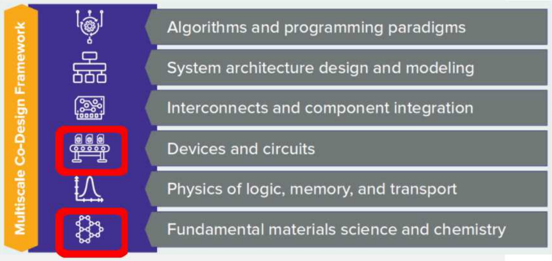


Enhances light field interactions at the mirror surface for absorbers & emitters

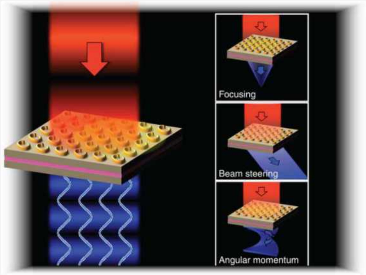
Optical Nonlinear Mixer



Eleven new frequencies (colors) simultaneously generated

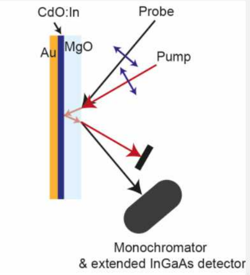


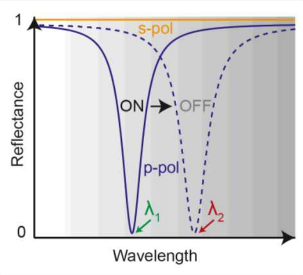
Phased Array Nonlinear Source



Directional Control of Nonlinear (2ω) beams

Terahertz-Speed Optical Switch Using Epsilon-Near-Zero Materials





Near-complete beam switching with femtosecond speed

Enabling III-V growth, sample processing, and subject matter expertise from MESA