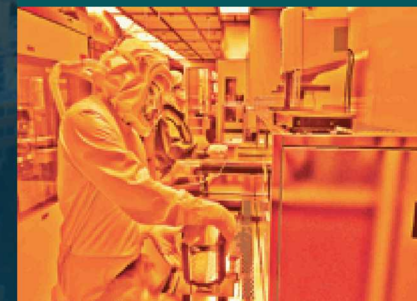
SAND2019-10199PE



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

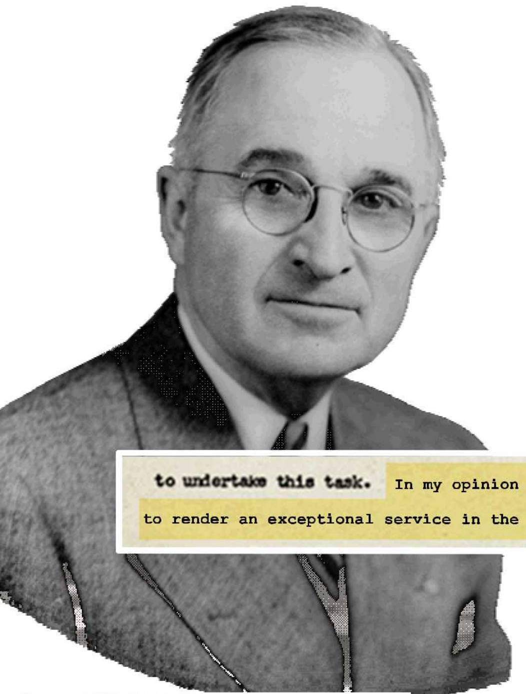
PRESENTED BY

Michael R. Descour, *Manager*
Photonic Microsystems Technologies Department
MESA: Microsystems Engineering, Science and Applications

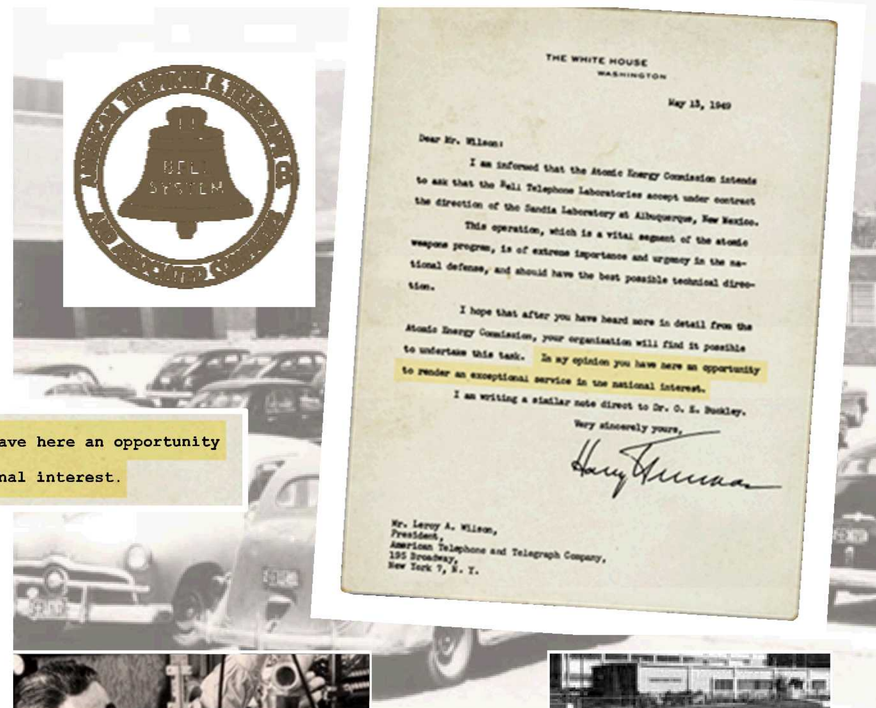
[SAND Number]

Who are Sandia National Laboratories?

Exceptional service in the national interest



to undertake this task. In my opinion you have here an opportunity to render an exceptional service in the national interest.



THE WHITE HOUSE
WASHINGTON

May 13, 1949

Dear Mr. Wilson:

I am informed that the Atomic Energy Commission intends to ask that the Bell Telephone Laboratories accept under contract the direction of the Sandia Laboratory at Albuquerque, New Mexico.

This operation, which is a vital segment of the atomic weapons program, is of extreme importance and urgency in the national defense, and should have the best possible technical direction.

I hope that after you have heard more in detail from the Atomic Energy Commission, your organization will find it possible to undertake this task. In my opinion you have here an opportunity to render an exceptional service in the national interest.

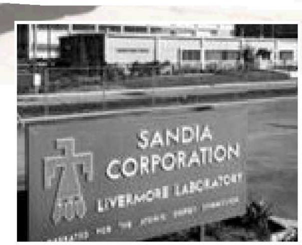
I am writing a similar note direct to Dr. O. E. Buckley.

Very sincerely yours,

Harry Truman

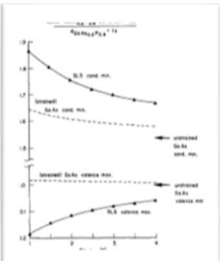
Mr. Leroy A. Wilson,
President,
American Telephone and Telegraph Company,
195 Broadway,
New York 7, N. Y.

- **July 1945:** Los Alamos creates Z Division
- Nonnuclear component engineering
- **November 1, 1949:** Sandia Laboratory established
- Mission broadened to National Security



Quantum R&D at Sandia

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



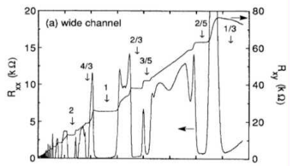
Simulating physics with computers, R.P. Feynman, *Int J Theo Phys* 21 (1982)

Simulating Physics with Computers

Richard P. Feynman

1980s

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



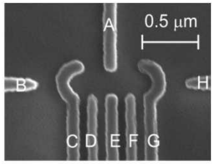
Functional single electron transistor, J.A. Simmons, T. Eiles (1997/98)

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

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

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

1990s

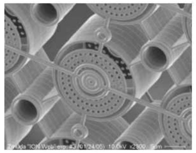


QIST Grand Challenge LDRD: Si quantum bits & logical qubits (2008-10)

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

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)

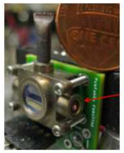


1st external QIS funding at Sandia: Trap foundry, M. Blain, *et al*. (2005); LDRD: Traps for QC & Qsim (2005)

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

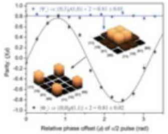
2000s

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



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

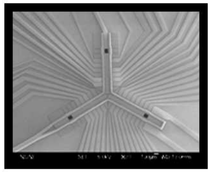
AQUARIUS GC LDRD: Adiabatic QC (2011-13)



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

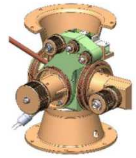
SECANT GC LDRD: QKD (2016-18)

2010s

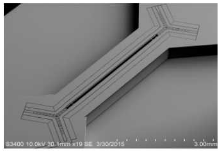


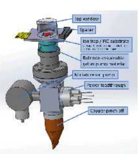
IARPA MQCO: Microfabricated surface traps for multiple qubits (2010-2015)

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



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



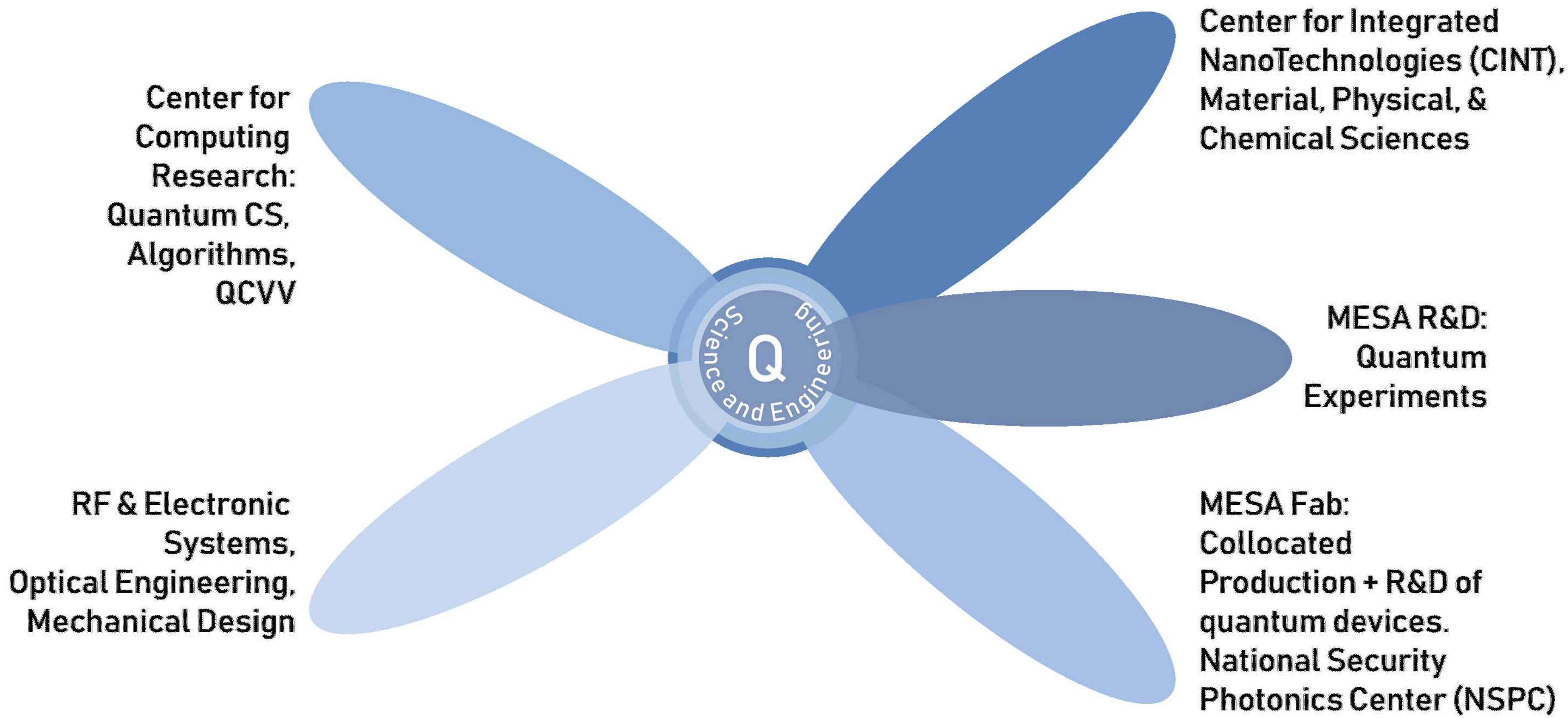


DARPA TICTOC: Ion optical clock (2019-21)

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
- Examples of results: QSCOUT, SIGMA (coming up later in talk)



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.

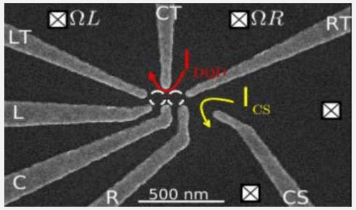
Quantum material systems

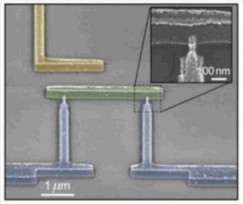
- Understanding and controlling quantum effects of nanoscale materials and their integration into systems spanning multiple length scales.

Quantum material systems details:

Quantum information science

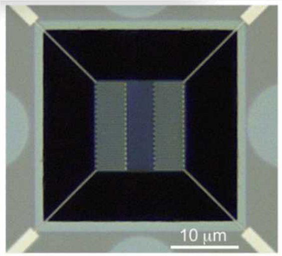
- Quantum transport & qubits
- Quantum sensing
- Focused ion implantation

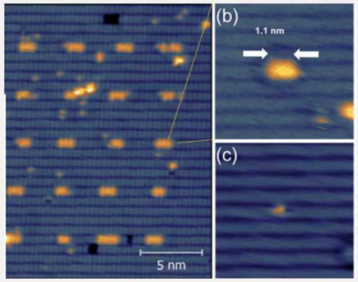




Forefront lithography

- 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

QSCOUT: An open quantum testbed at Sandia

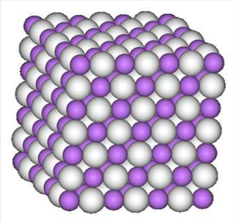
DOE/SC Advanced Scientific Computing Research (ASCR) **QSCOUT** (PI: P. Maunz)

- 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

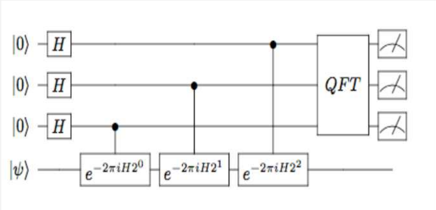
Design approach

- 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

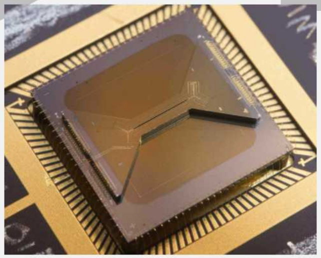


Textbook digital quantum simulation circuit

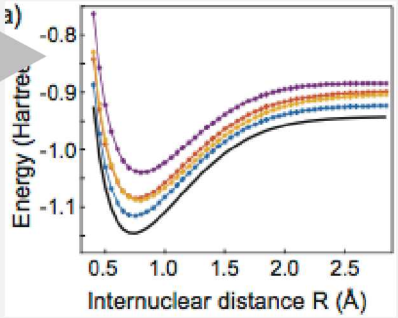
```
In [8]: circuits = ['teleport']
        print(Q_program.get_qasms(circuits)[0])

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



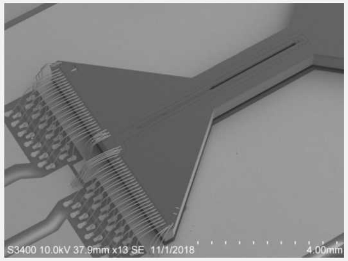
Results

QSCOUT's **main interdisciplinary tasks**

Qubit hardware	Gate modeling	QCVV
Hardware controllers	Software stack	Exemplar apps

QSCOUT **collaborations**

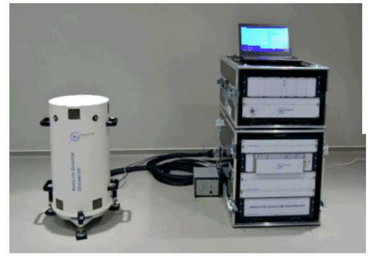
- Duke University (K. Brown)
- Tufts University (P. Love)
- LBNL
- Open to others…



SIGMA Grand Challenge LDRD

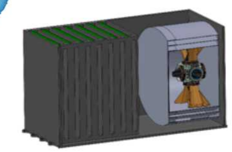
Quantum Sensing GC LDRD **SIGMA** (PI: G. Biedermann)

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



Strategic Inertial Guidance with MAtterwaves

ΣIΓMA



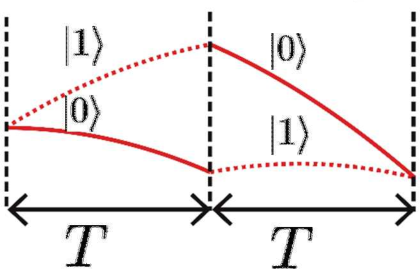
UC San Diego

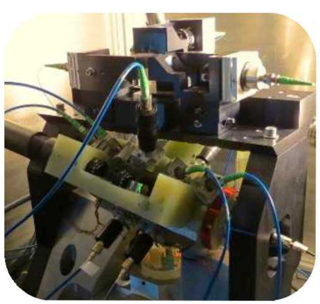
Yale

- 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?

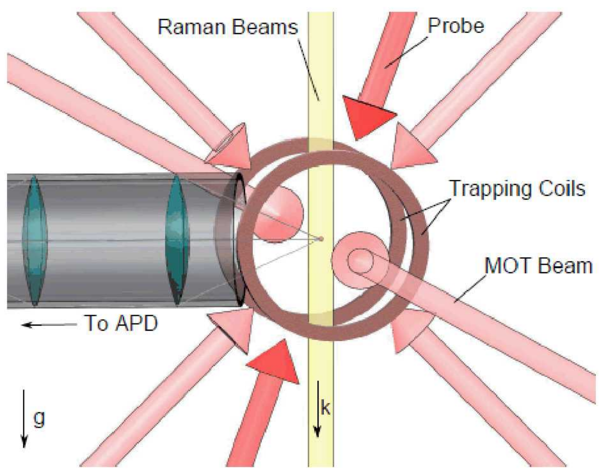
Atom interferometer physics

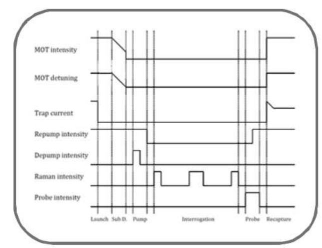




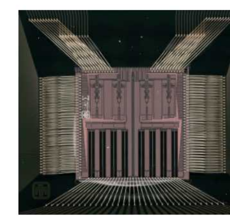
Custom optomechanics

UHV system

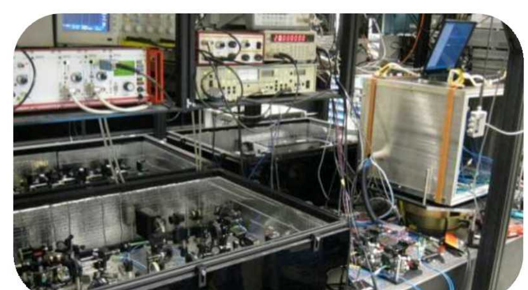




Control electronics



Photonics

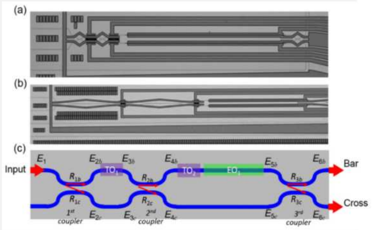


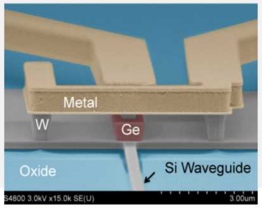
Agile & stable laser system

QIS and the Sandia National Security Photonics Center

Integrated photonics for quantum communications

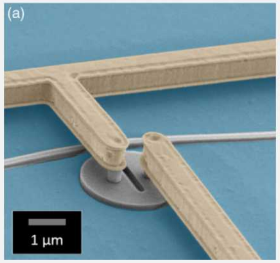
Sandia's silicon, III-V, alumina, lithium niobate heterogeneously integrated photonic platforms: compact microsystems for telecom and visible wavelengths

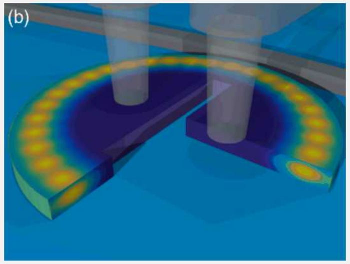




Cryogenic optical interconnects

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

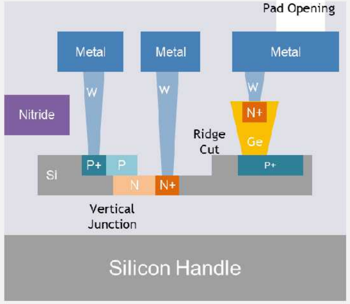




Optica **4**, 374-382 (2017)

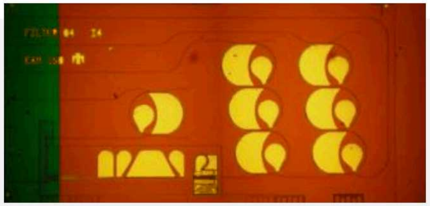
Silicon photonics integrated circuits

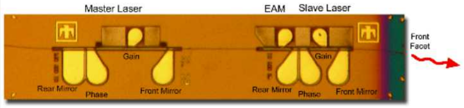
- Leverage CMOS (200 mm SOI)
- 22 passive devices, 20 active devices, design guide and library
- **MPW runs available**, up to passive+active+Ge devices



III-V photonic integrated circuits (PICs)

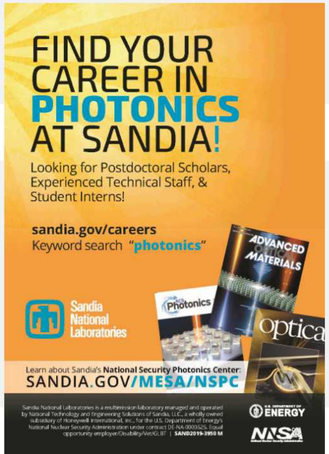
- InP, GaAs, GaN
- Elements: Waveguides, lasers, amplifiers, modulators, detectors, phase shifters
- **MPW runs available**





More information on photonics MPW opportunities:

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



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**

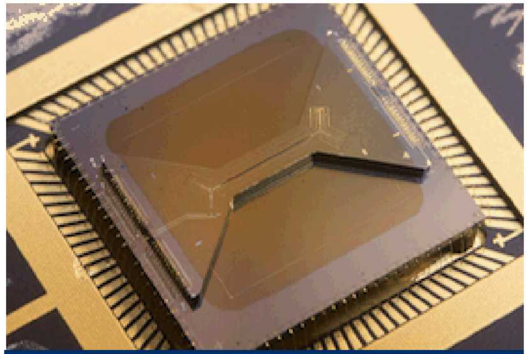
1 - Build on the high fidelity and full connectivity available with trapped ions
2 - Integrate chip-based photonic elements and electronics with existing physics devices
3 - Develop algorithms and protocols to deal with connectivity limitations
4 - Extend to other AMO systems such as quantum sensing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



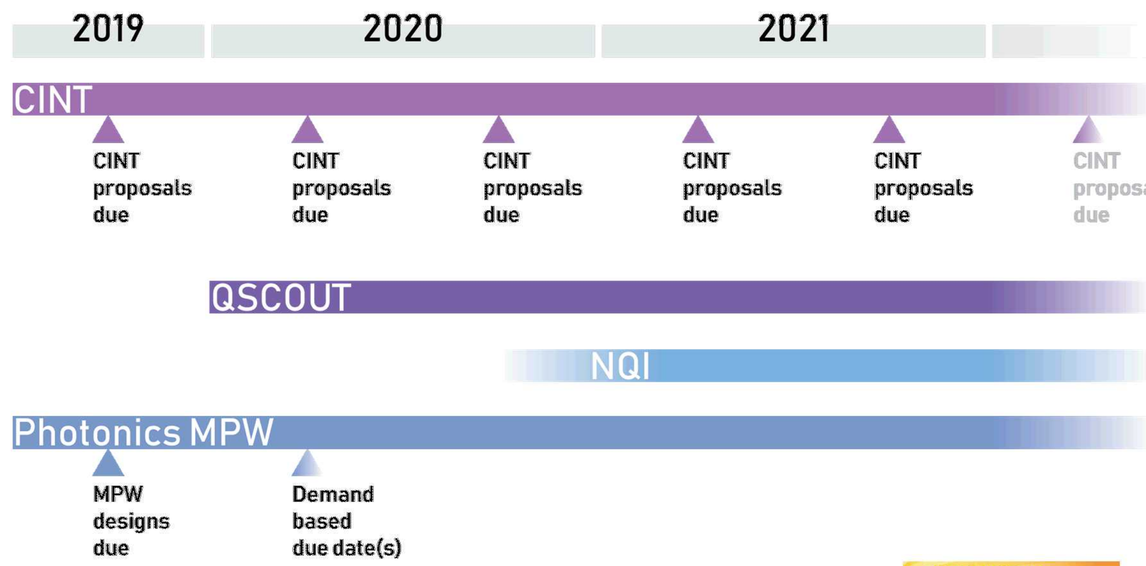
TRAP FOUNDRY

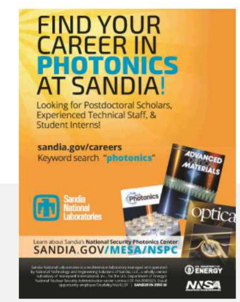
CINT

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):

8/28/2019

- 668518 – Integrated Photonic Researcher/Optical Engineer
- 667985 – Post-doc/Atomic Physics
- 668468 – R&D Laboratory Support Technologist
- …and 10 more related post-doc postings

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

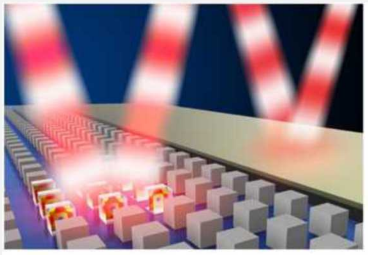
Questions?

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)

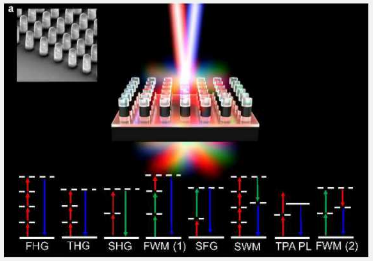
Approach: *Combining **nanostructures** and **metamaterials** with **state-of-the-art compound semiconductors** to achieve new behaviors*

Optical Magnetic Mirror

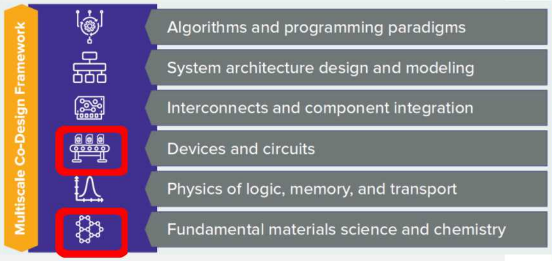


Enhances light field interactions at the mirror surface for absorbers & emitters

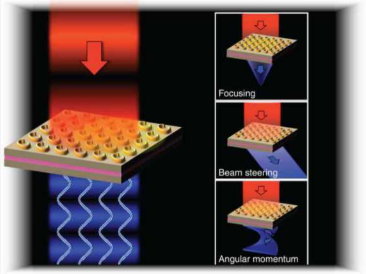
Optical Nonlinear Mixer



Eleven new frequencies (colors) simultaneously generated

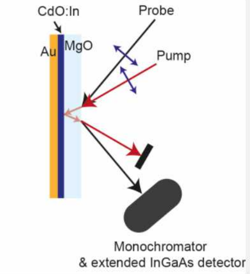


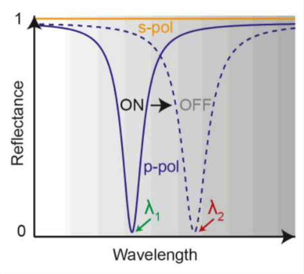
Phased Array Nonlinear Source



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

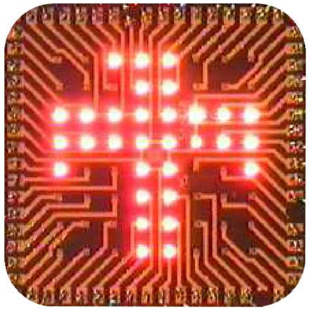
Sandia has a long history in Microelectronics and Microsystems

1960s — Microelectronics and Microsystems — *Present*

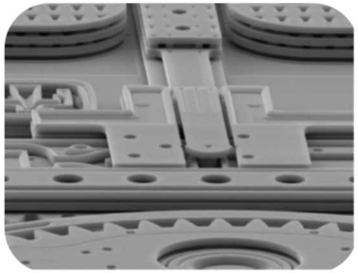
Laminar Flow Clean Room

Design/Build Galileo ICs

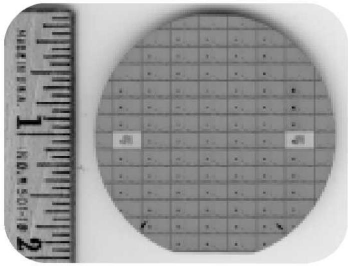
High Efficiency VCSEL



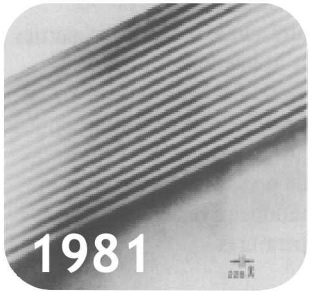
5-Level Surface Micromachining



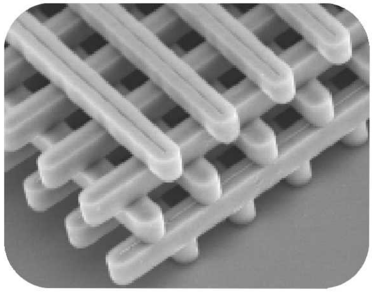
Microsystems-Enabled Photovoltaics



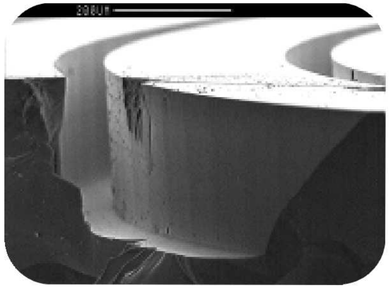
Radiation-Hardened CMOS



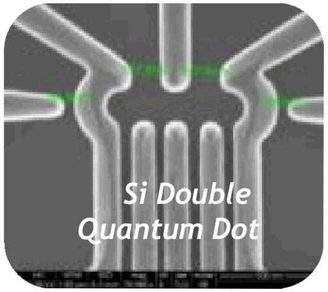
Strained-layer Superlattices



Photonic Lattice



MicroChemLab



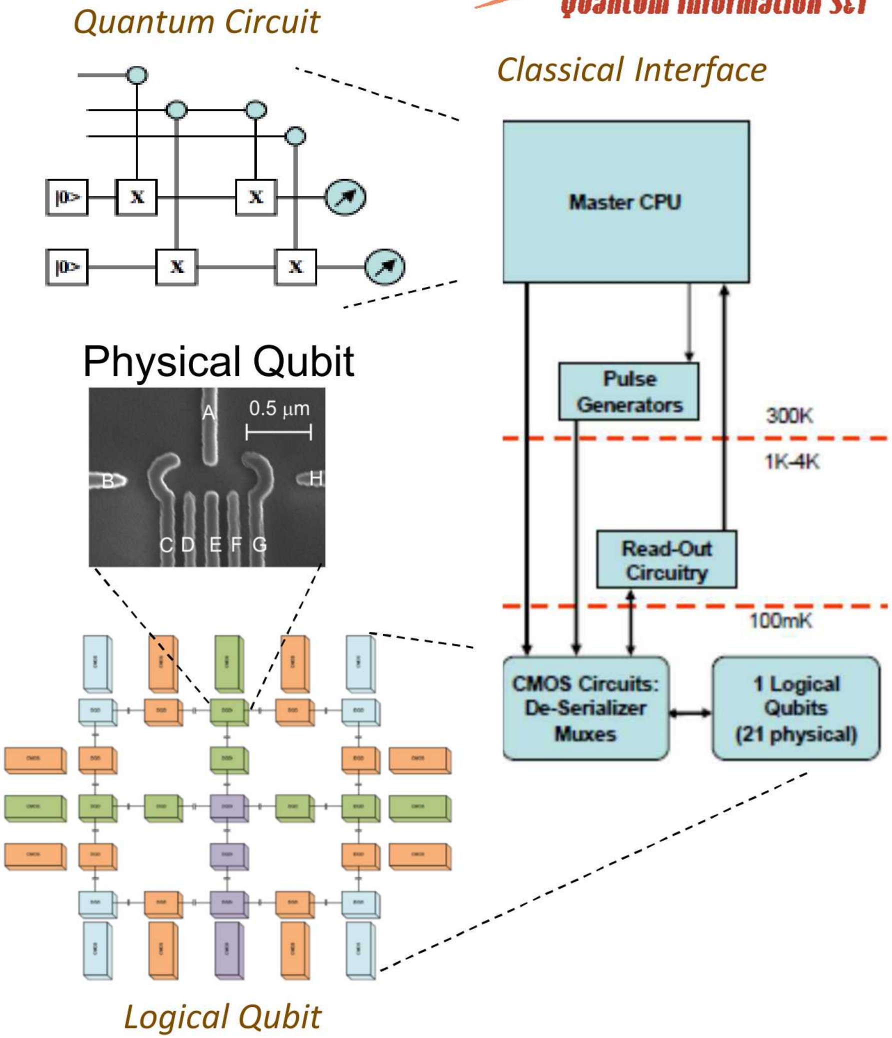
Quantum Computing

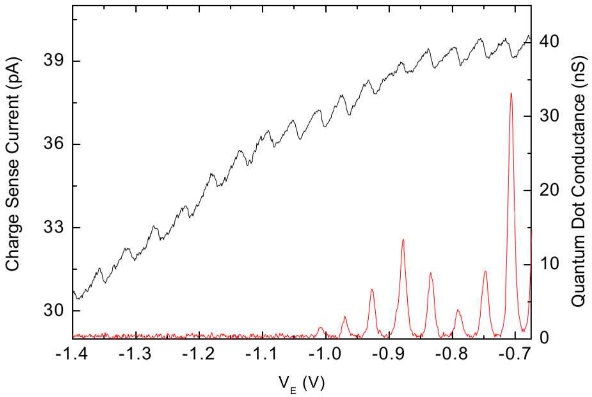
1980s — Quantum Engineering — *Present*

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