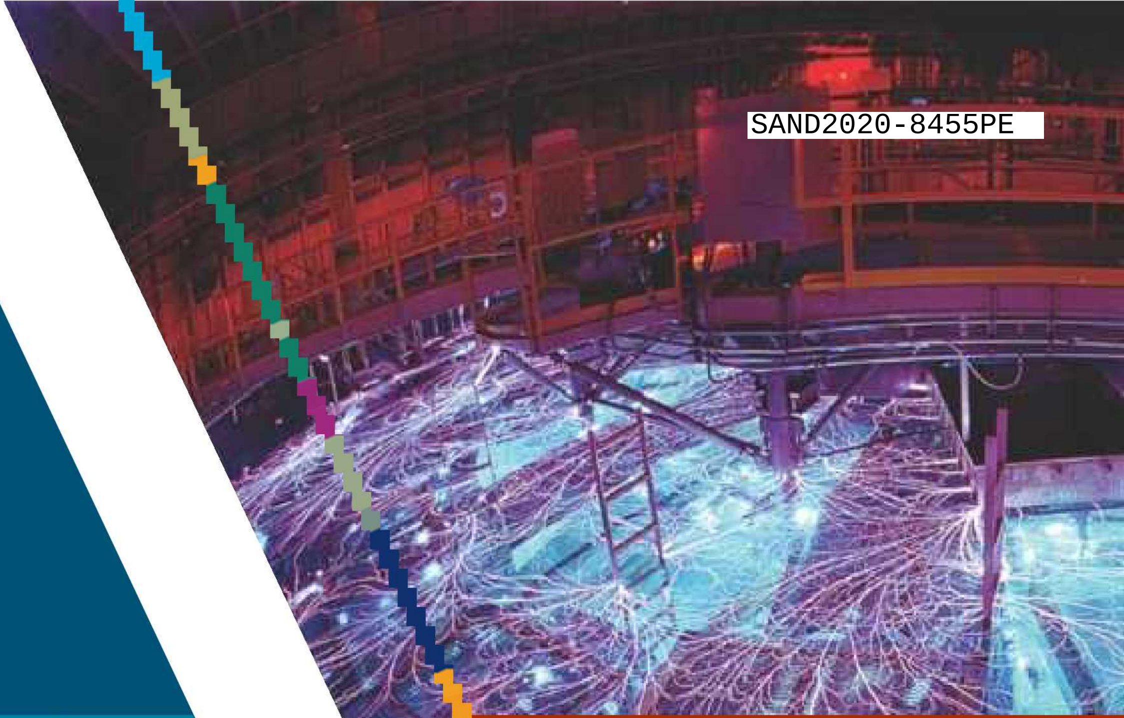
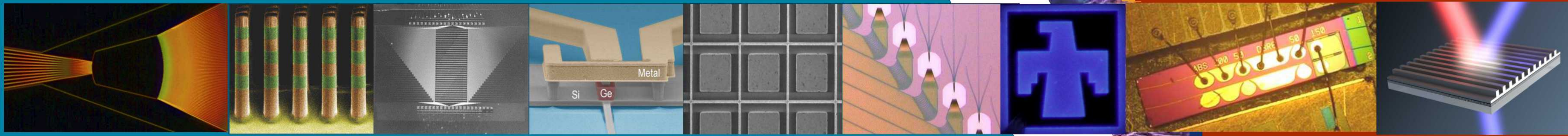
SAND2020-8455PE

Exceptional service in the national interest





Sandia's Quantum Photonics Research Foundry

Dr. Michael Gehl, Senior Member of Technical Staff
National Security Photonic Center

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia LLC, a wholly owned subsidiary of Honeywell International Inc. for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.
SAND

Quantum Facilities & Capabilities

Built on significant investments over 15 years

- Over **70 projects (>$135M) funded by Laboratory Directed Research and Development** (LDRD)
- Many projects funded by DOE & OGA (IARPA, DARPA, NIH, LPS,…). Over $100M to date.
- >150 staff involved in quantum at Sandia

Unique, hard-to-replicate capabilities

- Producing quantum devices in **multiple qubit technologies**
- Deep understanding of how device **architecture** impacts quantum applications and algorithms
- Facilities: **MESA fab, Center for Integrated Nanotechnologies (CINT), Ion Beam Lab (implantation), High Performance Computing**

Trusted advisor to multiple government agencies

- Key agency rotations and workshop leadership


MESA

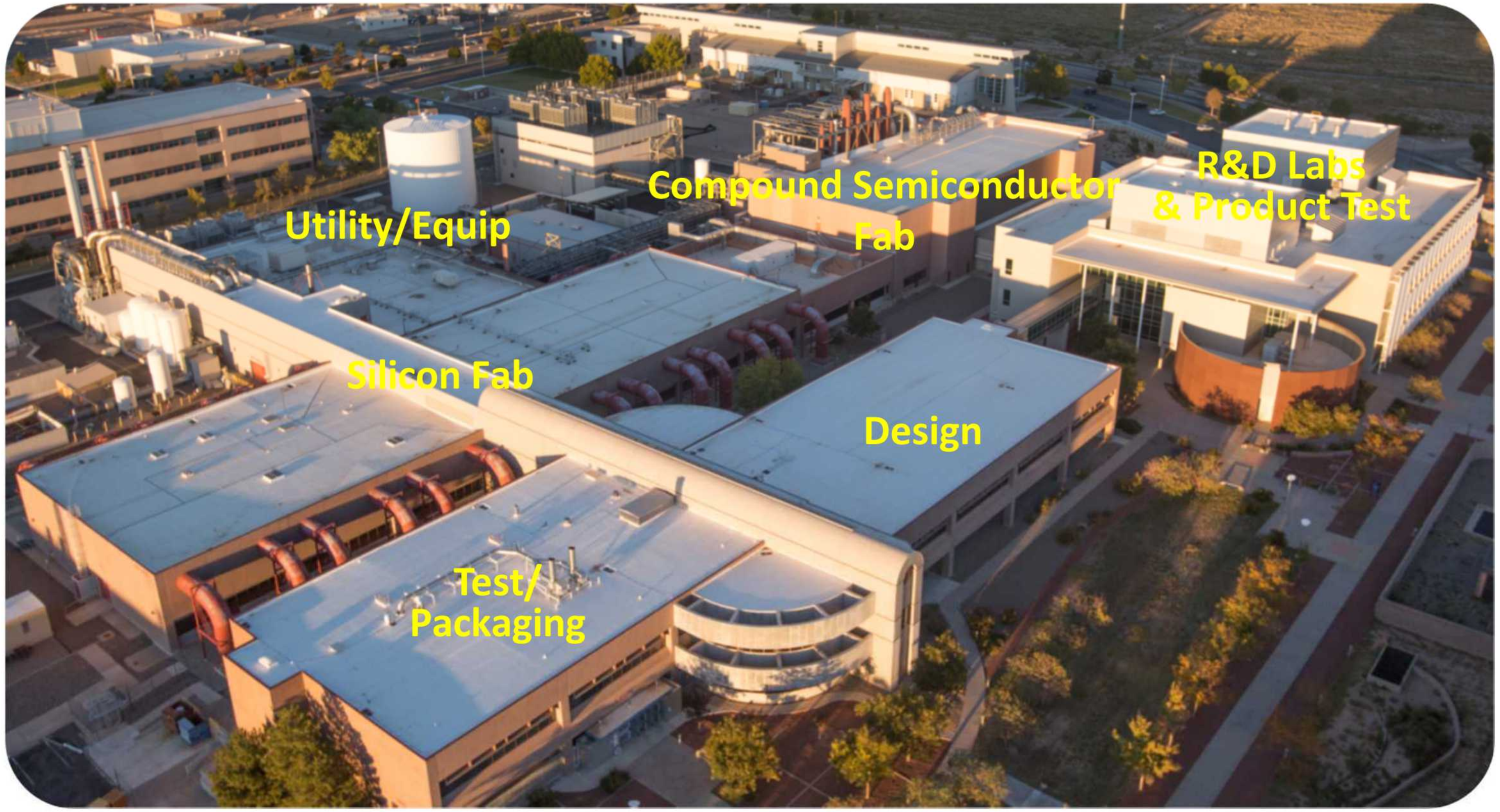

CINT


IBL

Quantum Facilities & Capabilities

Microsystems Engineering, Science and Applications

- Co-located research & production
- Currently dozens of products: ASICs, III-V SSICs, MEMS, FPAs, RFICs, Optoelectronics
- 400,000 Square Foot Complex, >650 Employees
- Co-located CMOS Foundry and Compound Semiconductor Fabrication



MESA

CINT

IBL

Quantum Facilities & Capabilities

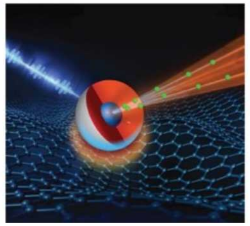
Center for Integrated Nano-Technology (CINT)

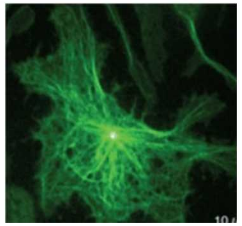
Quantum – Dr. Michael Lilly, mplilly@sandia.gov
Photonics – Dr. Igal Brener, ibrener@sandia.gov

Research areas:

- **In-Situ Characterization & Nanomechanics –** Developing and implementing world-leading capabilities to study the 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 collective or emergent electromagnetic phenomena (plasmonics, metamaterials, photonic lattices).
- **Soft, Biological & Composite Nanomaterials –** Synthesis, assembly, and characterization of soft, biomolecular, and composite nanomaterials that display emergent functionality.
- **Quantum Materials Systems –** Understanding and controlling quantum effects of nanoscale materials and their integration into systems spanning multiple length scales.

https://cint.lanl.gov
https://cint.sandia.gov
cint@lanl.gov





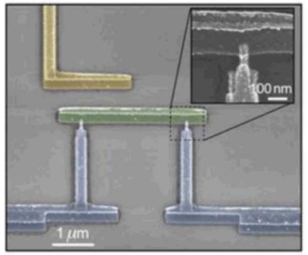
MESA

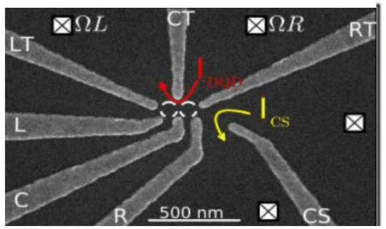
CINT

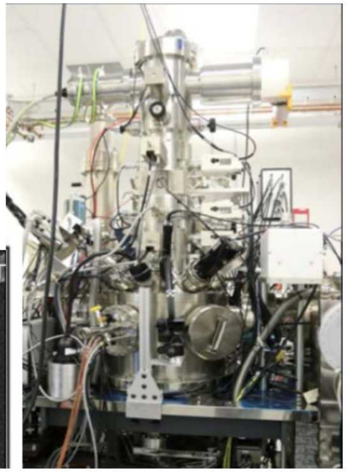
IBL

Center for Integrated Nano-Technology (CINT)

Quantum Information Science
- Quantum Transport and qubits
- Quantum Sensing
- Focused ion implantation

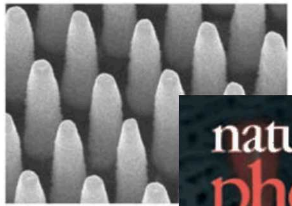


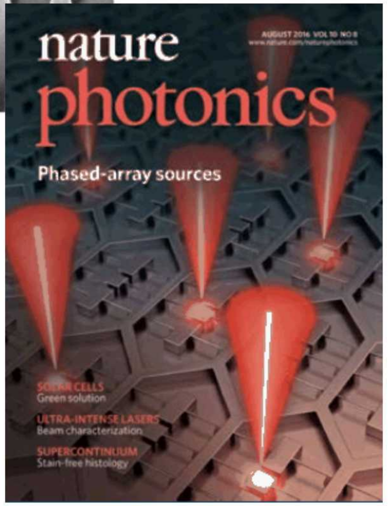


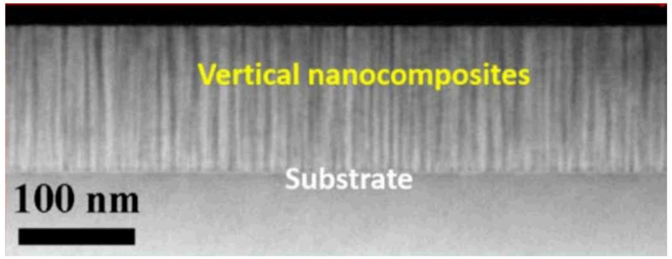


Theory for Correlated Systems
- Techniques for strongly correlated models
- Many-body approaches
- Mean-field modeling for quantum materials

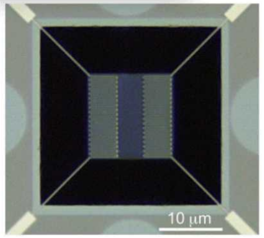
Materials synthesis
- Ultra-High Mobility MBE
- Complex Oxide PLD
- CVD Nanowire Growth

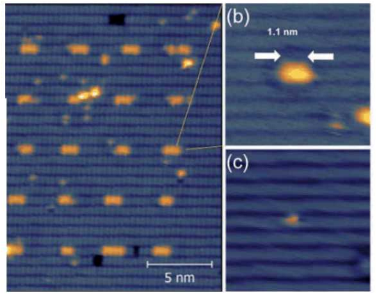






Forefront Lithography
- Atomic-Precision Lithography
- Nanoscale devices



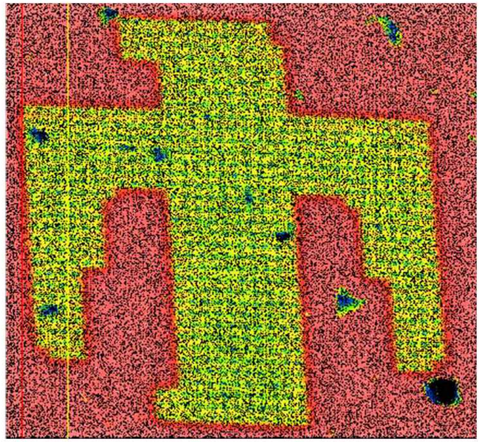


Quantum Facilities & Capabilities

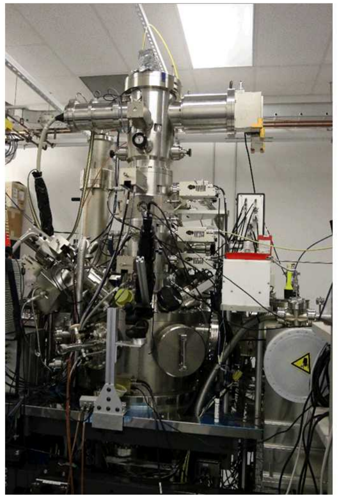
Ion Beam Laboratory (IBL)

Dr. Edward Bielejec, esbiele@sandia.gov

- 6 Operational micro/nano implant systems
  - Spot sizes from 0.5nm to mm's
  - Energies from 5keV to 70MeV
  - Single ion implantation
  - <40nm targeting resolution possible
- 26 ion species in use, 40+ ions possible

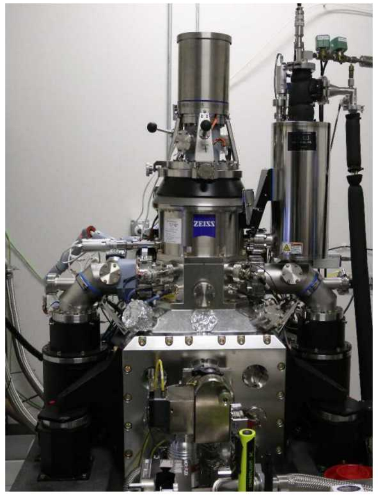


Ion Beam Induced Charging on PIN Diode

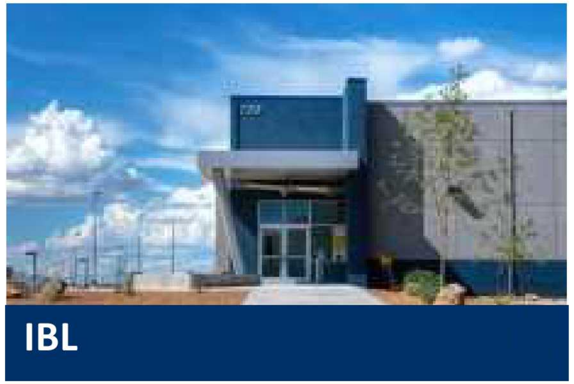


100 keV A&D FIB100NI

35 keV Raith Velion



100 keV Zeiss Orion Plus



Sandia's National Security Photonic Center

Silicon Fab:
Silicon Photonics

Microfab:
Compound Semiconductor
Photonics

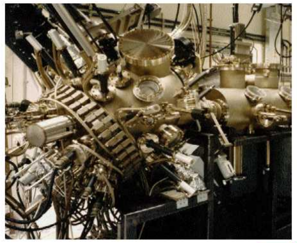
Member of

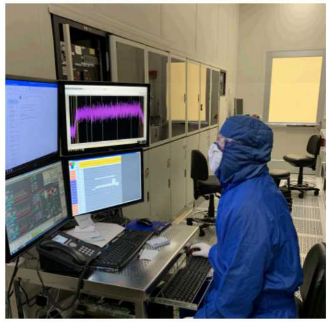
PDK and
8" Multi-Project Wafers

60+ Photonics Staff

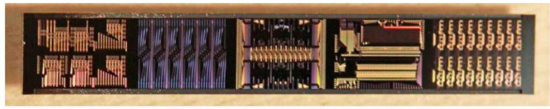
Device Design, Modeling, Simulation
Semiconductor Device Fabrication
Microsystem Fabrication
Testing, Rad Effects, Cryo
Reliability

Custom Epitaxial Growth & III-V Devices
(GaAs, InP, GaSb, GaN) – **11 Growth Chambers**
PDK and Multi-Project Wafers (InP)

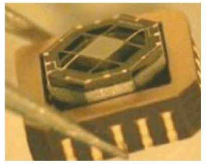


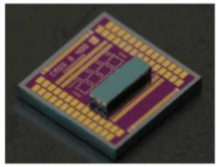


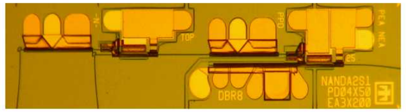
Microsystems and Heterogeneous Integration
(Flip Chip Bonding, micro-optics, assembly, packaging)

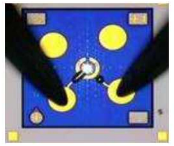


Photonic circuits









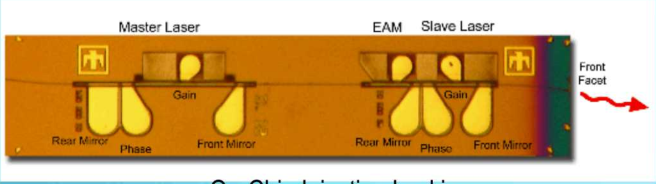
Photonic circuits & Lasers

Multi-Project Wafer Offerings

InP Photonics

- **3 tier offerings at 1550nm**
  - Tier 1: one regrowth
  - Tier 2: 2 regrowths (High P_{sat} Amplifier)
  - Tier 3: Full custom process

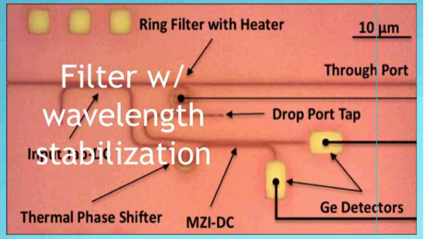
RF-Optical Channelizing Filter
1-20 GHz RF on C-Band Light



On-Chip Injection Locking
Enhanced Modulation > 50 GHz, C-Band

Silicon Photonics

- **MPW Device Library**
  - 20 Active, 22 Passive Components
  - Synopsis OptoDesigner
  - 200mm SOI Platform
  - Three Deliverables
    - Passive
    - Passive + Active
    - Passive + Active + Germanium



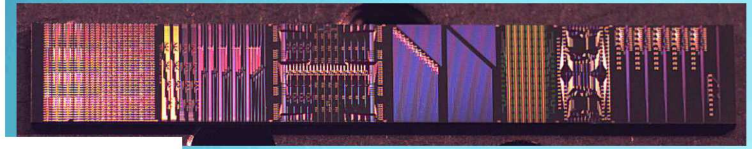
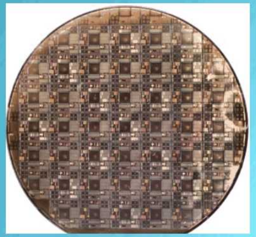
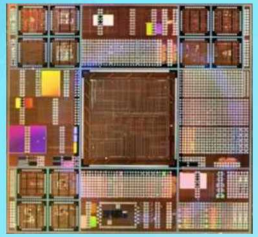


Image of MPW run, supporting Columbia, U of AZ, UC Berkeley, UCSD & Caltech

CMOS7

- **Multiple Engagement Models**
  - Full design & implementation by customer
  - Full design & implementation by Sandia
  - Anywhere in between
- **Non-Standard, custom processes**
  - AlN for resonators
  - Large-area graphene deposition
  - Deep trench capacitors
  - Prototype non-volatile memory
  - Thick metal
  - RF devices





For more information:
photonics@sandia.gov

MPW & CMOS Design Contact:
Ann Petersen, Manager
Advanced CMOS Products/Design
505-844-3160
annpete@sandia.gov

Photonics Collaborators & Sponsors

University

The University of Arizona
Massachusetts Institute of Technology
Rice
University of Colorado Boulder
Georgia Tech Research Institute
University of Virginia
The University of New Mexico
UC San Diego
Purdue University
Texas A&M
Columbia University
Cornell University, Founded A.D. 1865
Iowa State
Illinois, University of Illinois at Urbana-Champaign
Yale University
The University of Texas at Austin

Small Business

Stellar Science
Photonics
OEwaves
AP Sci
Plasmonics Inc. Infrared Nanotechnology

Large Business

Lockheed Martin
Lumileds
Raytheon
Teledyne Scientific & Imaging, Everywhereyoulook™
parc, A Xerox Company

Government

NIST
AFRL, The Air Force Research Laboratory, Lead | Discover | Develop | Deliver
AIM Photonics
JPL, Jet Propulsion Laboratory
U.S. Army
DARPA
MITRE
arpa·e, Changing What's Possible
U.S. Department of Energy, Office of Science

MESA Capabilities – Silicon Photonics Platform

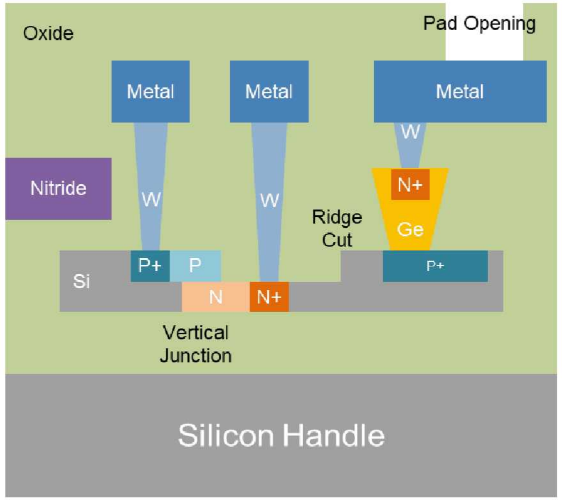
Dr. Anthony Lentine, allenti@sandia.gov
Dr. Michael Gehl, mgehl@sandia.gov

Mature silicon photonics capability developed through 12 years of investment

- Low power, high bandwidth modulation & detection
- Low loss optical waveguides (<0.1 dB/cm @ 1550nm)
- 200mm SOI CMOS process
- Silicon, Silicon Nitride & Alumina Waveguides
- Selective area germanium epitaxy
- Cryogenic (<1K) optimized devices

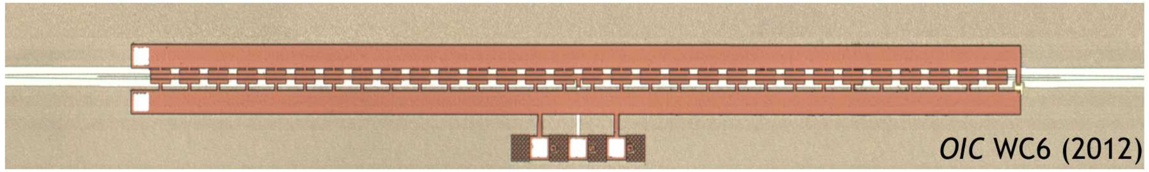
Applications in Quantum

- Quantum Networking/Communication
- Linear Optical Quantum Computing
- Laser Source Generation & Control
- Classical Control & Data Communication



Cross section of Sandia's standard silicon photonics process

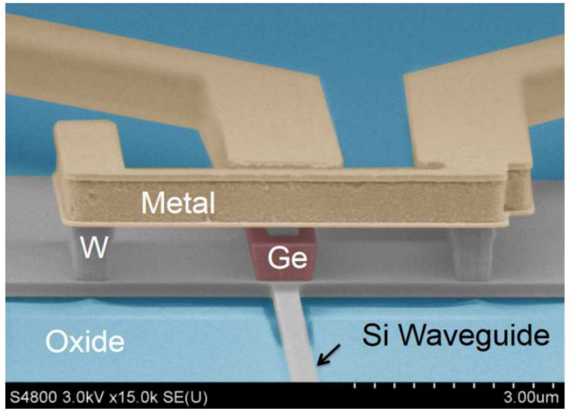
20+ GHz Electro-Optic Modulator



10 Gb/s Cryogenic Optical Modulator

Optica **4**, 374 (2017)

Ge Single Photon Detector



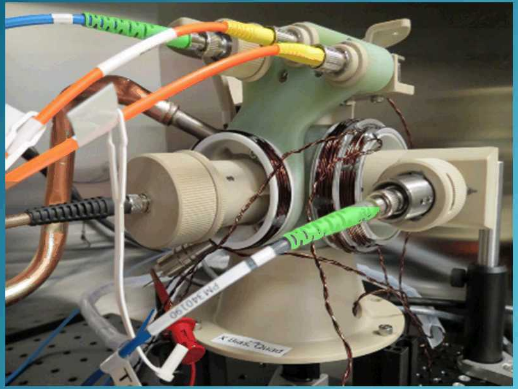
Optics express **25**, 16130 (2017)

MESA Capabilities – Silicon Photonics Platform

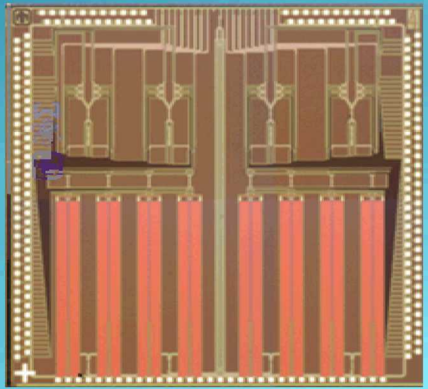
SIGMA - Accelerometer

Strategic Inertial Guidance with MAtterwaves

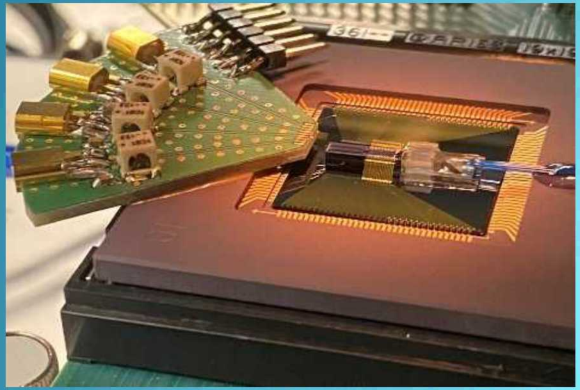
Alignment-free AI Sensor Head



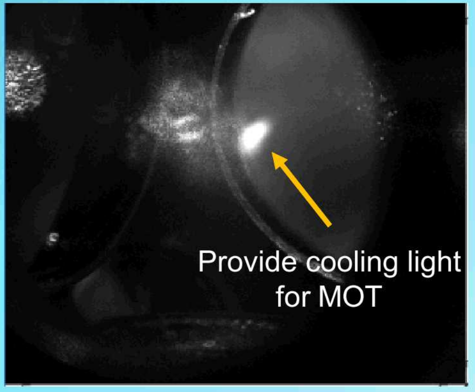
4-Channel SiP Frequency Shifter



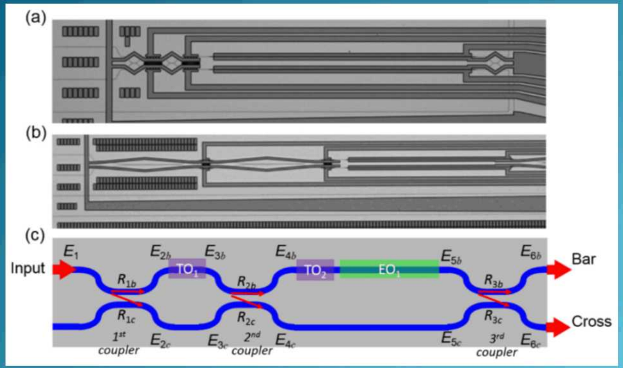
Packaged SiP Frequency Shifter



MOT Generated using SiP



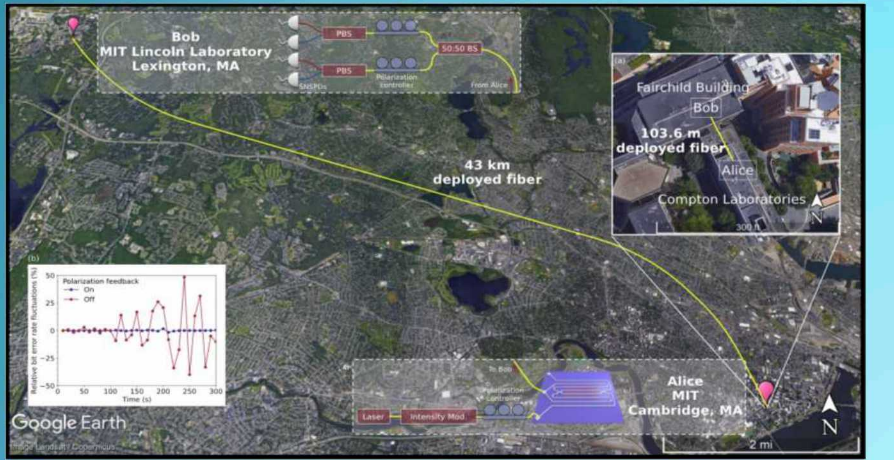
Quantum Key Distribution



High-speed (10GHz) high-extinction ratio (>65dB) silicon amplitude modulator for CV QKD & Q-Sensing

2016 R&D 100 WINNER

T-QUAKE (Transceiver for Quantum Keys and Encryption)



MIT LINCOLN LABORATORY

High-speed polarization-based DV QKD field tests (BB84) demonstrated

Dr. Peter Schwindt, pschwin@sandia.gov

Dr. Paul Davids, pdavids@sandia.gov

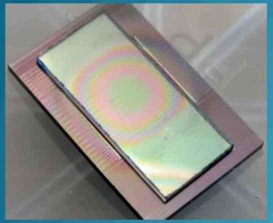
MESA Capabilities – Heterogeneous Integration

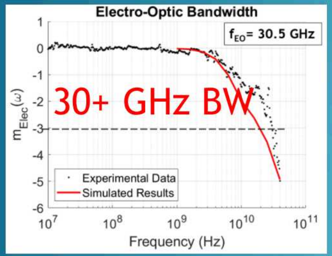
Dr. Anthony Lentine, allenti@sandia.gov

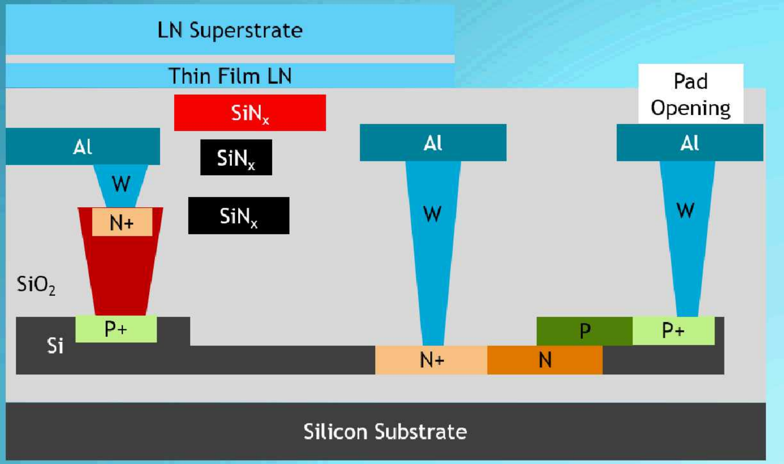
Heterogeneous integration enables miniaturization with independent material and device optimization

- Integration of $LiNbO_3$ and III-V Lasers on Silicon Photonics
- Integration of CMOS with InGaAsP/InP, InGa/GaAs, Silicon Photonics, and other materials

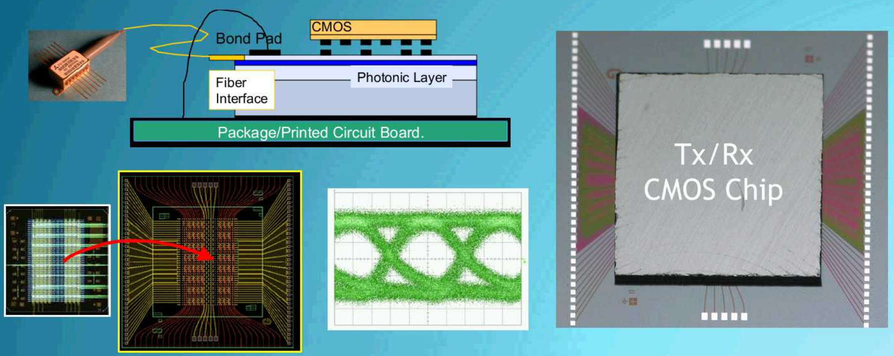
Thin Film Lithium Niobate on Si





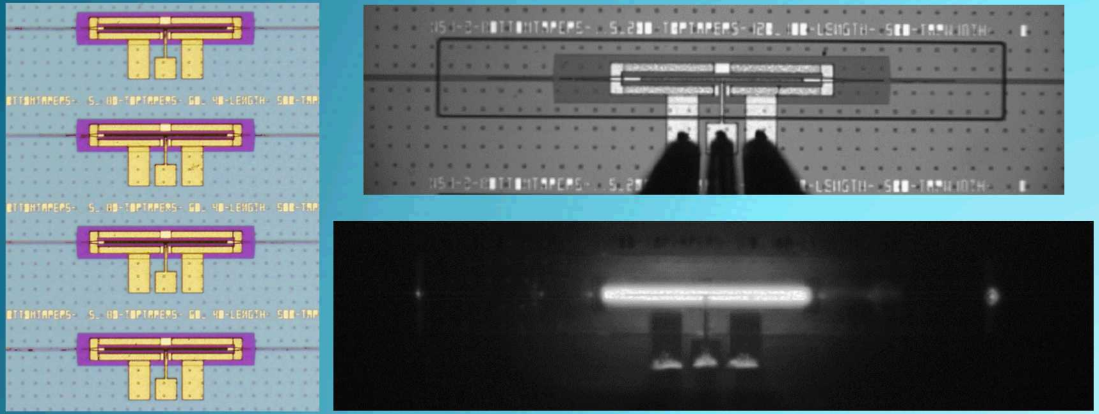


CMOS & III-V or Si PICs



- silicon photonics on high-speed silicon ASIC
- independent optimization of electronics & photonics

III-V Lasers & Amplifiers on Si



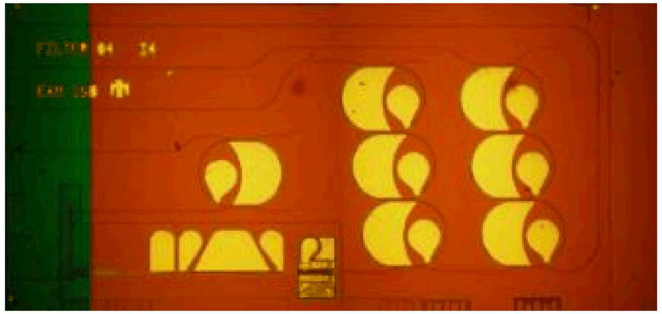
MESA Capabilities – III/V Photonics Platform

Dr. Erik Skogen, ejskoge@sandia.gov

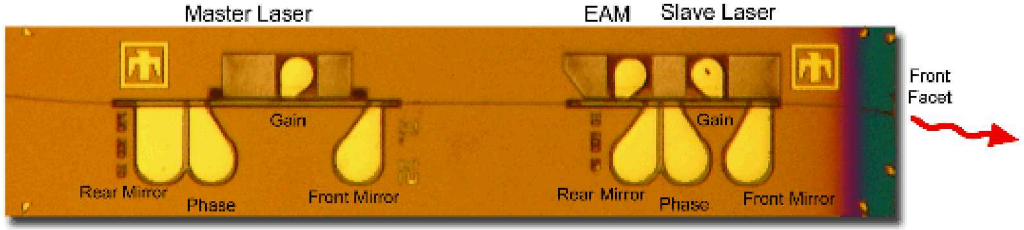
InP-based Photonic Integrated Circuits

- Multiple band-edges by quantum-well-intermixing and/or regrowth
- Single and/or multiple epitaxial regrowth(s)
- Top-side n-type and p-type contacts
- Ridge, buried, and/or deep etch waveguide architectures

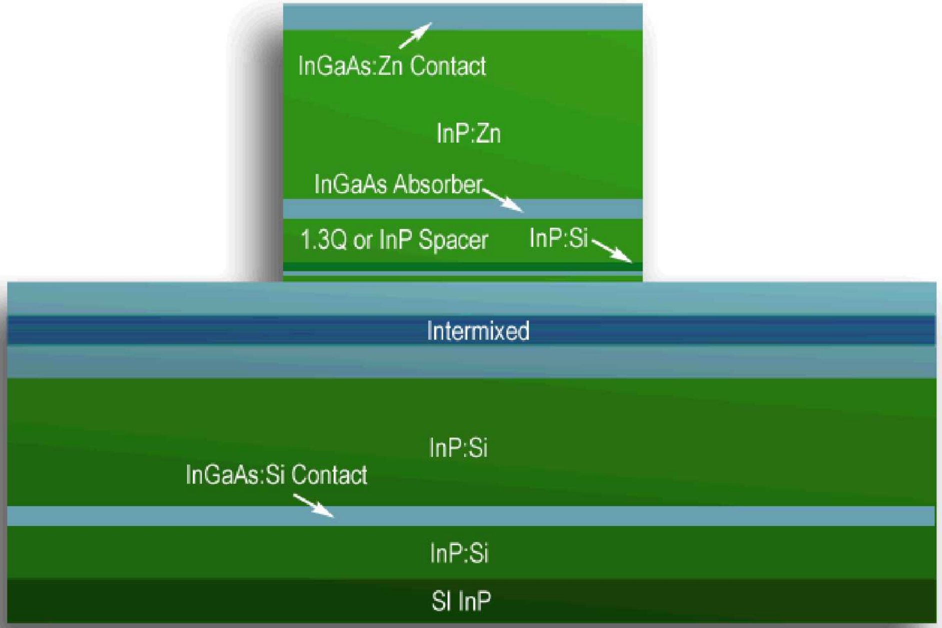
778nm lasers and modulators have been demonstrated



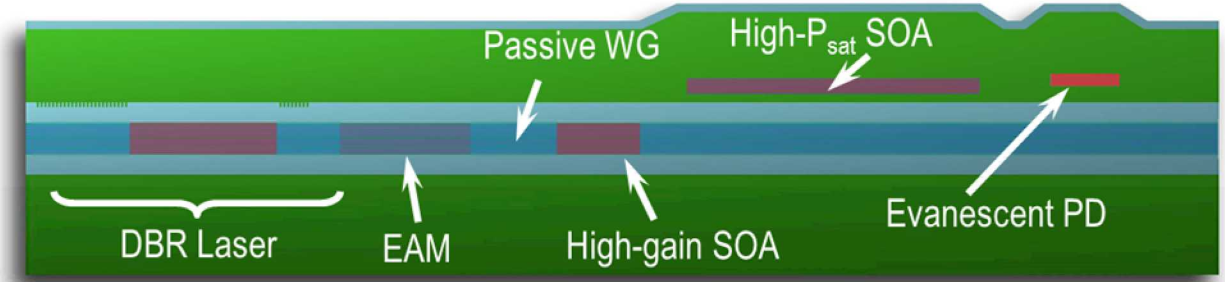
RF-Optical Channelizing Filter
1-20 GHz RF on C-Band Light



On-Chip Injection Locking
Enhanced Modulation > 50 GHz, C-Band



Device Cross-section (Lateral)



Device Cross-section (Longitudinal)

MESA Capabilities – Nano-Opto-Mechanics (NOMS) & Piezo-Electrics

Dr. Matt Eichenfield, meichen@sandia.gov
Dr. Nils Otterstrom, ntotter@sandia.gov

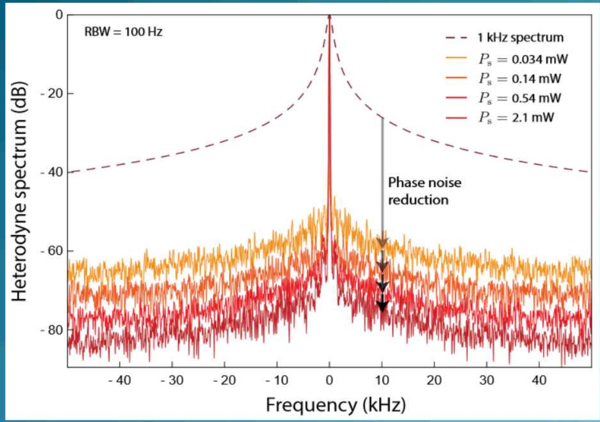
Leveraging MEMS expertise to generate new classes of optical devices

- Narrow linewidth filters
- Brillouin amplification & lasing
- Optical isolators
- On-chip delay
- Frequency Shifting
- Modulation & phase shifting

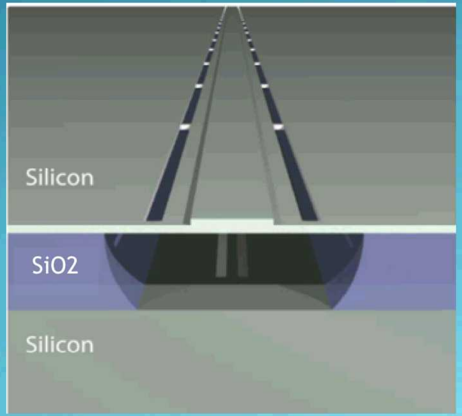
On-going quantum research

- Squeezed states
- Qubit transduction
- Opto-mechanical cooling

Injection locked Brillouin laser in silicon

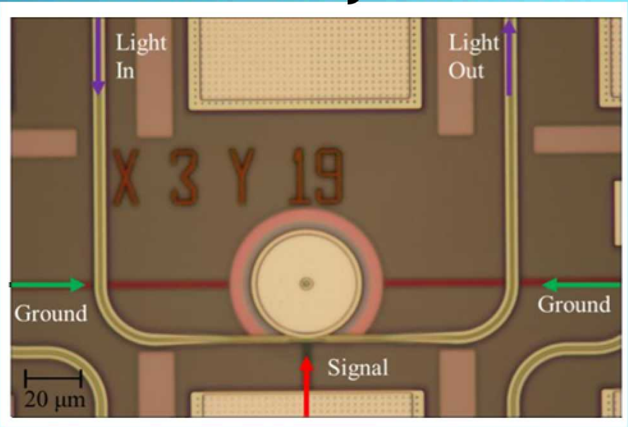


N. T. Otterstrom, arXiv:2001.04871 [physics.optics]



N. T. Otterstrom, *Optica* **6**, 1117 (2019)

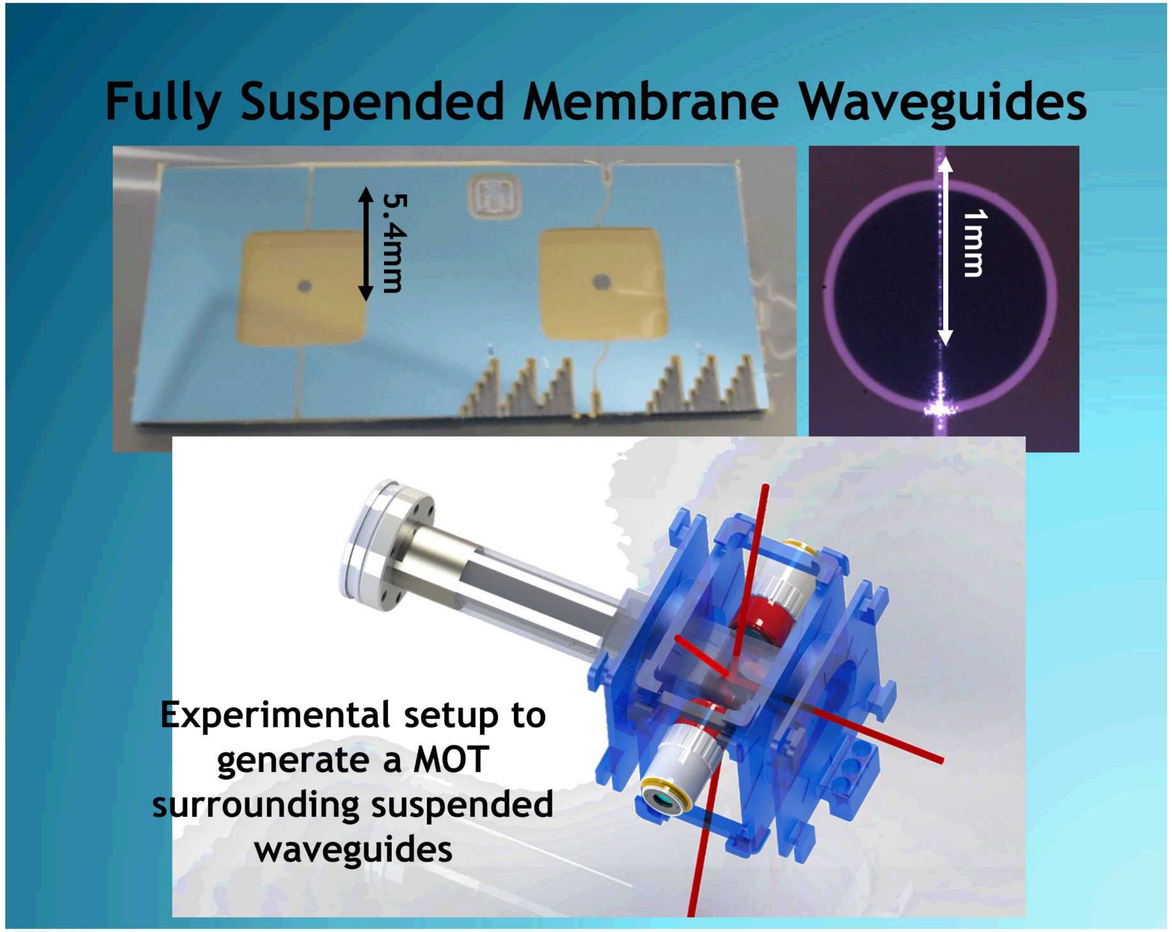
Piezo-optomechanically tunable modulator

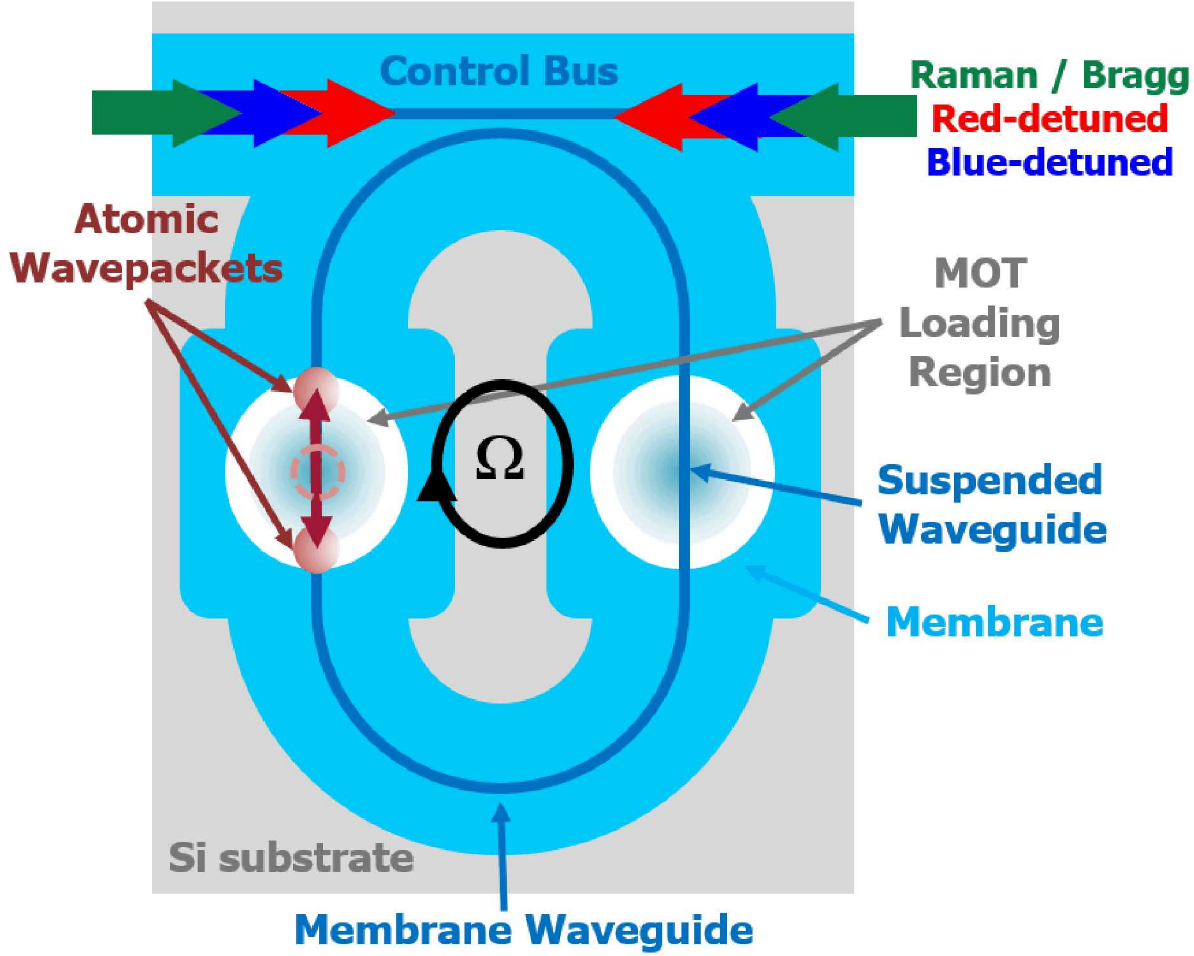


M. Eichenfield, *Optics Express* **27**, 28588 (2019)

Matterwave Sagnac Inteferometer

Dr. Jongmin Lee (PI) jlee7@sandia.gov, Dr. Michael Gehl

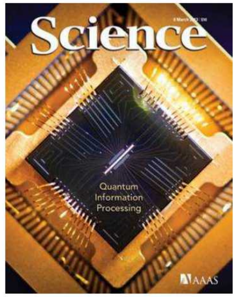




Atomic-Photonic Integration (A-PhI)

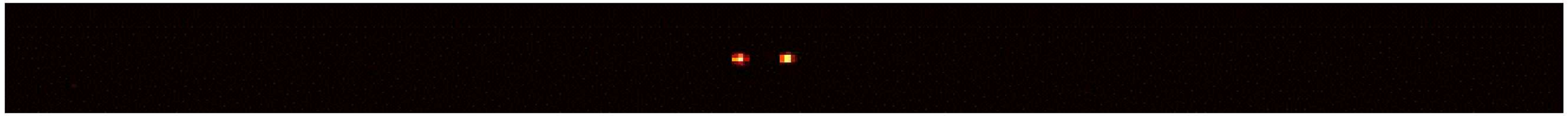
MESA Capabilities – Ion Trapping Platform

Dr. Daniel Stick, dlstick@sandia.gov



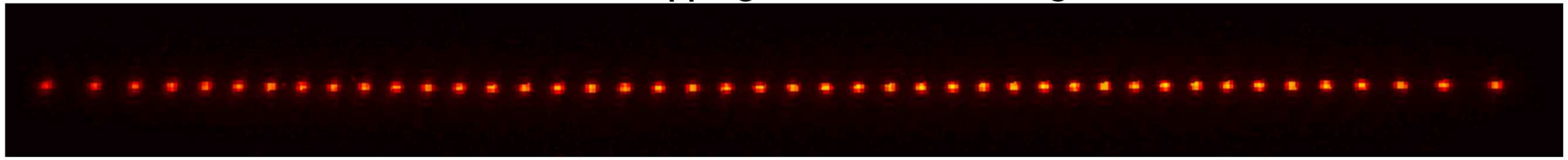
- Fabricating traps for quantum computing since 2005
  - Delivered fully functioning, packaged ion traps to >12 collaborations
  - Integration capabilities include**:**
    high optical access, up to 6 metal levels, low loss UV/Vis optical waveguides,
    high performance SPADs, through-trap loading holes/slots, ion shuttling junctions.
- Sandia has demonstrated:
  - Calcium and Ytterbium ion trapping with high fidelity 1- and 2- qubit gate operations
  - Room temperature and cryogenic operation
  - Custom RF and electronic control system for qubit manipulation
  - Custom optical systems for individual addressing and detection of ions in linear chains
  - Low-induced-heating ion shuttling

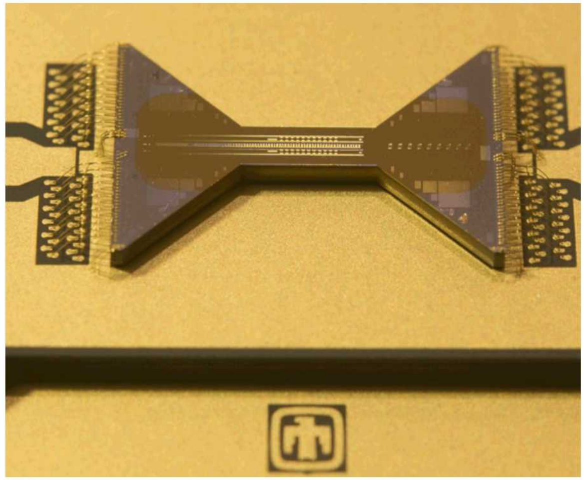
Ion Split/Merge Control Solutions

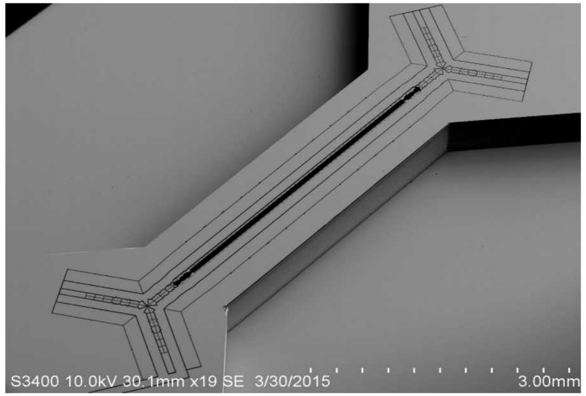


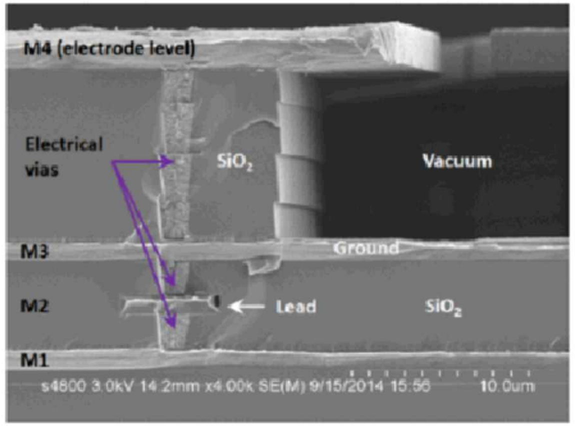
Demonstration of Sophisticated Ion Control in a Linear Trap

Simultaneous Trapping of 44 Ions in a Single Well









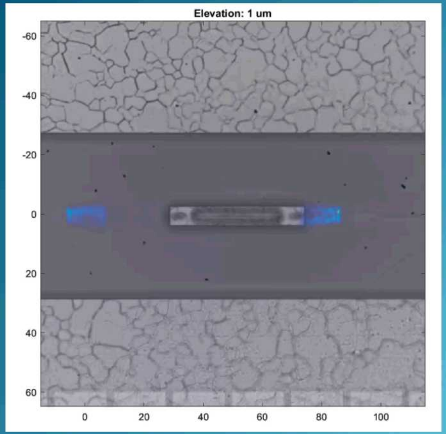
MESA Capabilities – Ion Trapping Platform

TICTOC

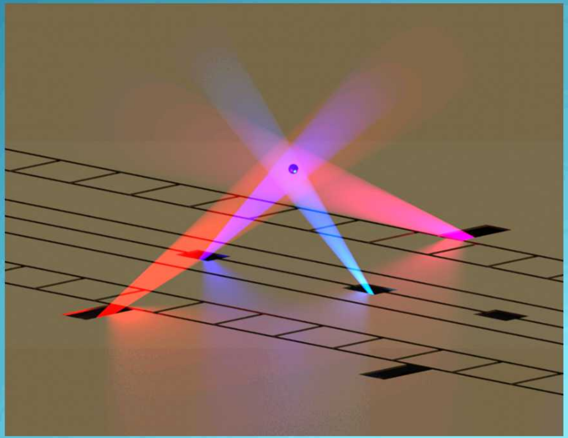
Trapped Ion Clock using photonic Technology On Chip

Dr. L. Paul Parazzoli (PI) lpparaz@sandia.gov, Dr. Hayden McGuinness, Dr. Michael Gehl

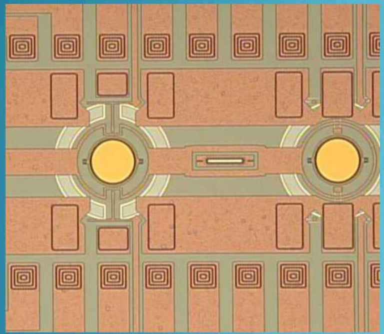
Ionization Beams Converging



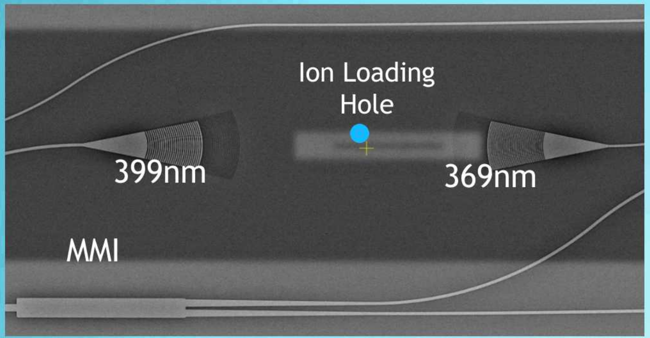
Multi-Wavelength Integrated Photonics

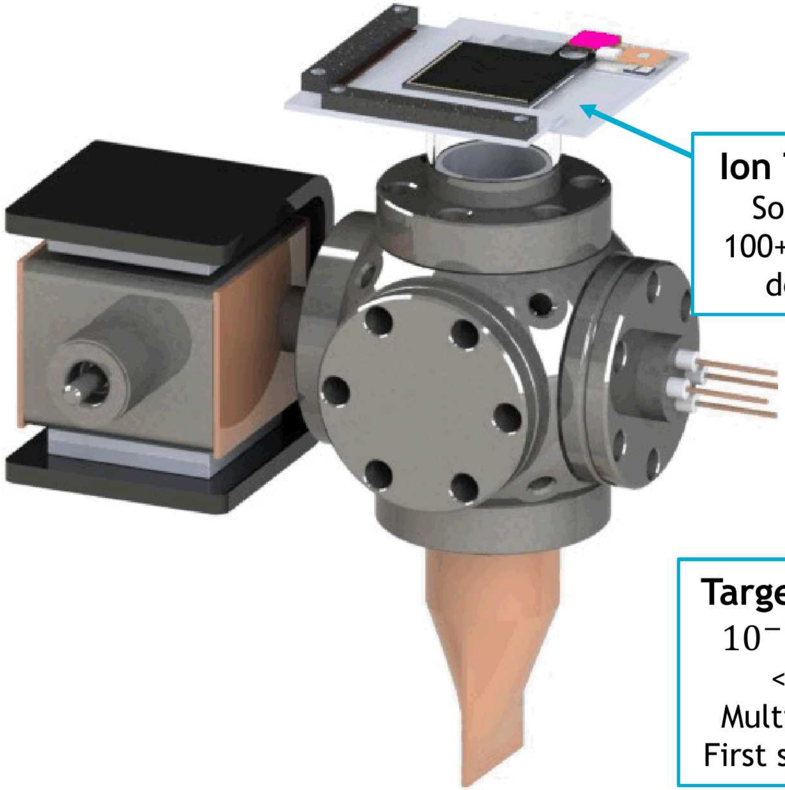


Integrated Single Photon Detectors



Low loss waveguides & gratings





Ion Trap/PIC Interposer
Solder Attached to UHV
100+ electrical & optical IO delivered through PIC

Target Demonstrations
$10^{-14}/\sqrt{\tau}$ for 100,000 s
<1/2 liter volume
Multi-ensemble protocol
First surface ion trap clock

NIST · OEwaves · Yale University · PURDUE UNIVERSITY

MESA Capabilities – **QSCOUT**

Quantum Scientific Computing Open User Testbed

Dr. Susan Clark, sclark@sandia.gov, qscout@sandia.gov

Goals

- Quantum processor for Scientific applications
- High fidelity operations
- Full connectivity between qubits
- Open system, fully specified operations and hardware
- Quantum assembly language enabling low-level access for control down to gate pulses
- Open for vertical integration by users

Realization

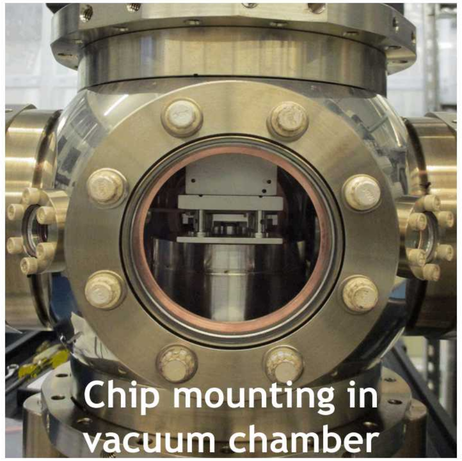
- Trapped ion system using chain of ytterbium-171 ions:
  - Near-ideal prep and measure, no idle errors, lowest gate errors
- Reconfigurable in software
- All-to-all Connectivity

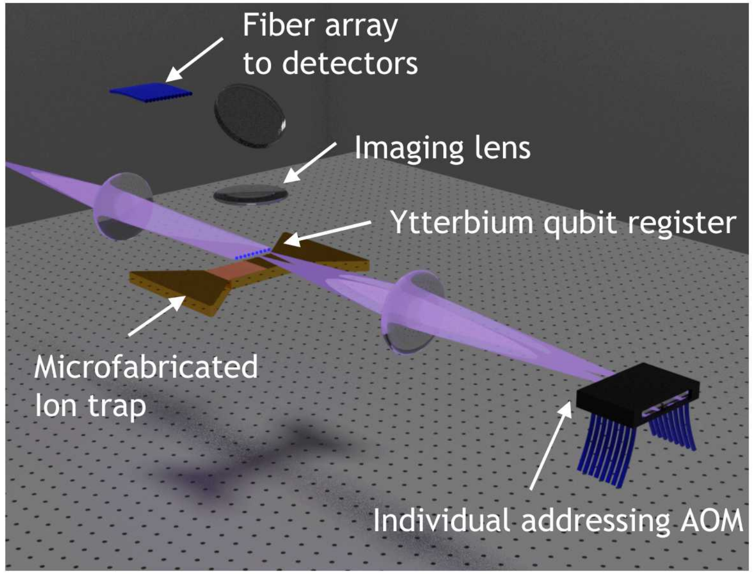
User Access

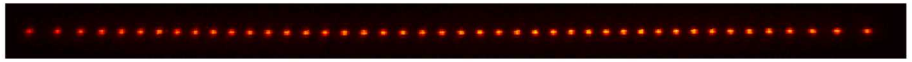
- In collaboration with SNL QSCOUT scientists
- First round of users includes operations with 3 qubits
- Expected start November 2020
- Calls for user proposals: https://qscout.sandia.gov

Current Status

- System design complete
- Realized high-fidelity single-qubit operations
- Qubit Coherence times > 13s







Chain of trapped ions

Gate	Entanglement Infidelity	1/2 Trace Distance	1/2 Diamond-Dist	Eigenvalue Ent. Infidelity	Eigenvalue 1/2 Diamond-Dist
Gi	0.00019	0.000817	--	0.00019	0.001081
Gx	0.00004	0.001003	--	0.000039	0.000073
Gy	0.000001	0.001151	--	3×10^{-7}	0.000876

Measured QSCOUT gate infidelities

Conclusion

15+ years of significant investments resulting in world-class quantum expertise and quantum enabling technologies

- Ion traps
- Neutral atoms
- Donors in silicon
- Diamond vacancies
- Silicon & III/V photonics spanning UV to SWIR

Large number of existing collaborative quantum research projects

- QSCOUT – User testbed
- TICTOC – Compact ion trap clock
- Photonic/CMOS multi-project wafers

Developing a quantum workforce through graduate students, post-docs and early career staff

- 60+ photonic staff, 150+ quantum staff

MESA

CINT

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