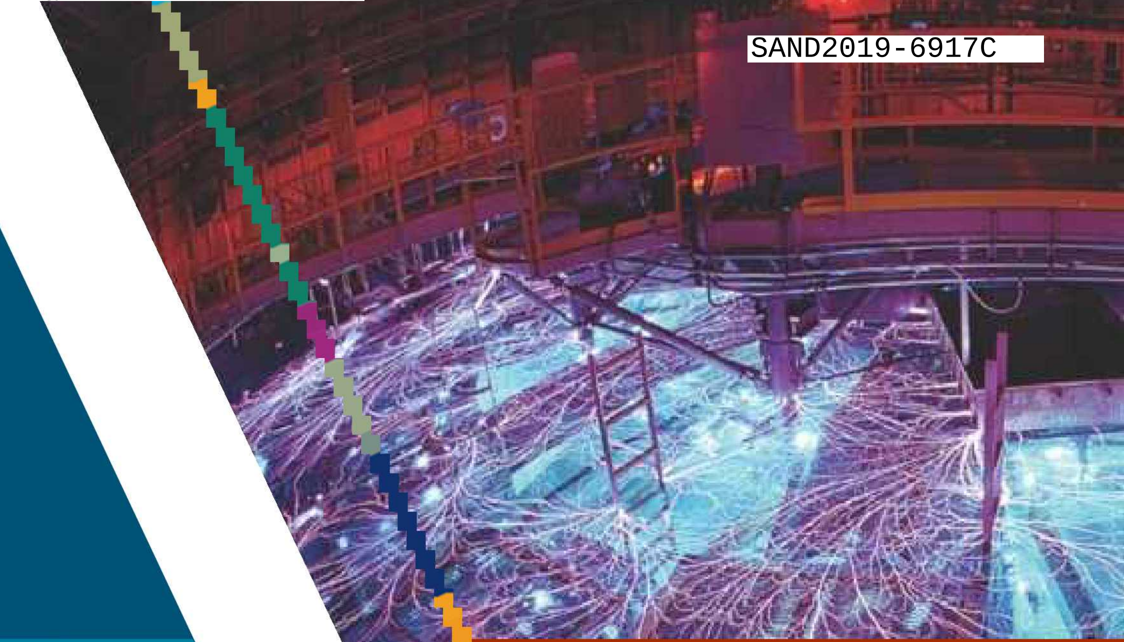
SAND2019-6917C

Exceptional service in the national interest



Advanced Fabrication Capabilities at SANDIA NATIONAL LABORATORIES

Christopher Long, Photonic & Phononic Microsystems

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########

SILICON PHOTONICS OF THE FUTURE

Recent research areas

- national security to everyday life
- solutions to mass-manufactured applications.

Silicon photonics investment at Sandia

- key roles in miniaturizing complex systems
- accessing difficult-to-reach components

Overview

- Sandia Labs MESA Complex and the NSPC
- achievements using our established Si photonics process
- recent work at in new materials and heterointegration

MESA Complex: Microsystems Engineering, Science, and Applications

Charter
- design, develop, fabricate, qualify and produce at low-volume for DOE applications
- conduct leading research

DOD Defense Microelectronics Activity (DMEA) Category1A Trusted Supplier

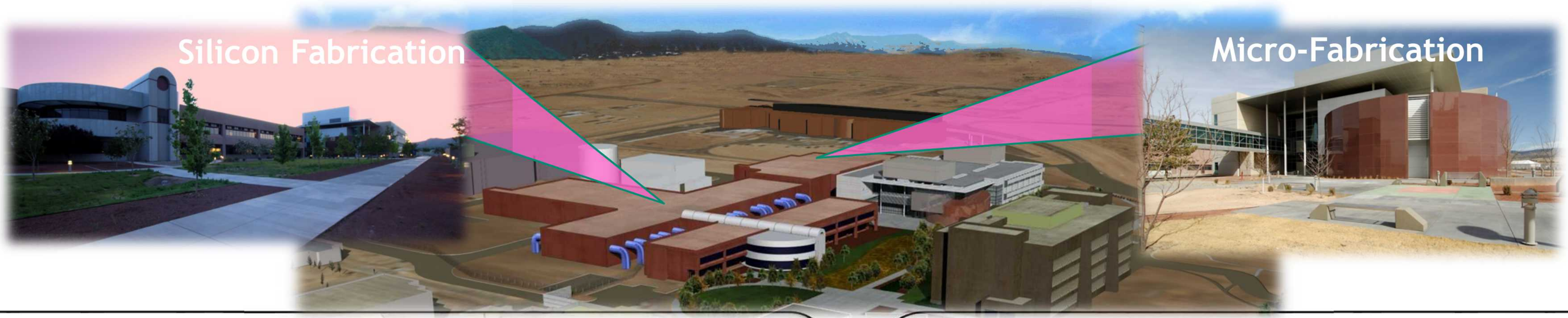
Resources
- 400,000 ft^2 complex
- >650 employees
- secure facilities (TA-1 limited area)

Dual fab facility
- silicon CMOS fab
- general purpose Micro Fab

Products
- ASICs, III-V ICs, MEMS, FPAs, RFICs, optoelectronics

Center for Integrated Nanotechnologies

MESA's Fabs: Co-located Production and R&D



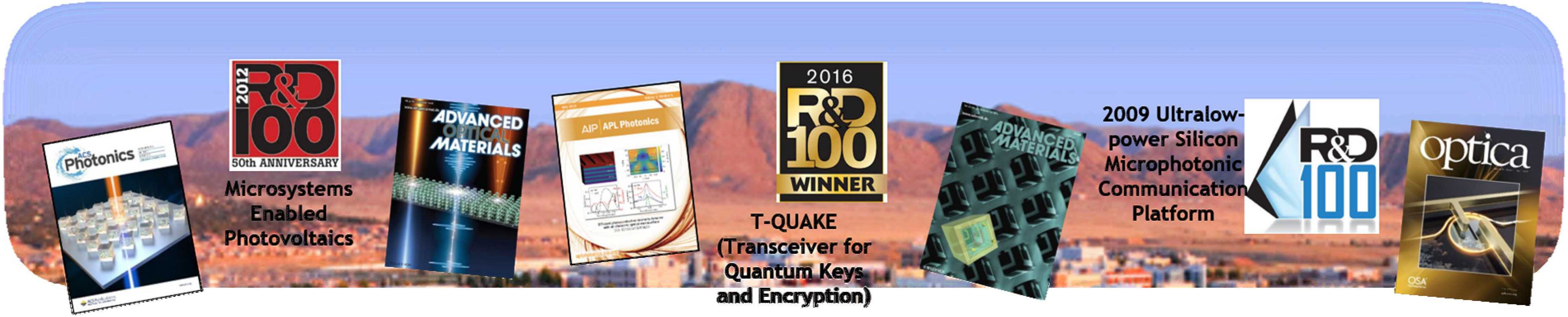
- Clean room area 34,500 ft2 (11,900 ft2 Class 1)
- 23 laminar flow clean bays
- 3.3V 350nm SOI Rad Hard CMOS (CMOS7) in production
- 3.3/1.8V 180nm SOI Rad Hard CMOS (CMOS8) in development
- Supplier of custom Rad-Hard ICs for life extension programs
- DOD Defense Microelectronics Activity (DMEA) Category1A Trusted Supplier for design, fab, and test
- Micro-Electro-Mechanical System (MEMS)
- Custom Technologies: Ion Traps, Silicon Photonics, AlN Resonators

- Clean room area 30,400 ft2 (14,900 ft2 Class 10/100)
- 6 Class 100 clean bays and 20 Class 10 clean bays
- Reconfigurable tools from wafer pieces to 6” wafers
- III-V compound semiconductor epitaxial growth and circuit fabrication
- Gallium Arsenide & Indium Phosphide HBT production
- Breadth of III/V materials
- Optoelectronics, VCSELs, and photo diodes
- 3D Packaging & Heterogeneous Integration Post-processing hybridization

Sandia's National Security Photonics Center

Serve the nation as a center of excellence for national security photonics through scientific excellence and innovations and leading-edge integrated photonics solutions

- >60 photonics staff (plus postdocs and students) with expertise in device design, modeling, simulation, epitaxy, device fabrication, integration, assembly, and test
- partnership with government agencies, industry, and universities
- technology transfer to industry
- areas of interests: communication, sensing, computing, imaging, quantum applications
- www.sandia.gov/mesa/nspc

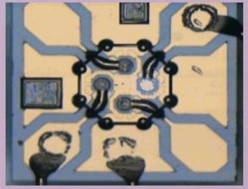


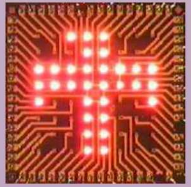
Extensive integrated photonics research

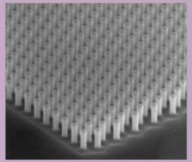
Advanced photonics R&D: design, model, fab, package, and test

Materials: Silicon, III-V (Phosphides, Arsenides, Antimonides, Nitrides), Lithium Niobate, Graphene, etc.

Sources

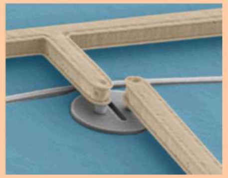

Single-frequency tunable VCSELs


High efficiency VCSELs

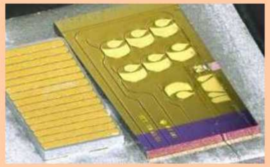

Nanowire Laser

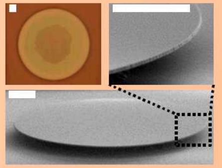

High power GaAs laser

Control / Manipulation

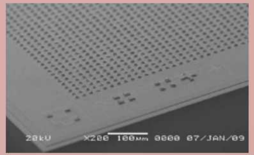

Resonant optical modulator/filter

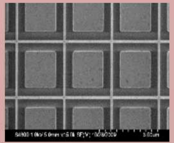

Array waveguide grating channelizing filter

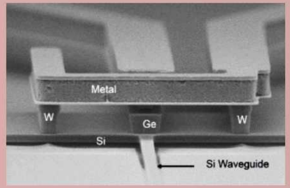

RF channelizing filter


LiNbO3 Freq. converter

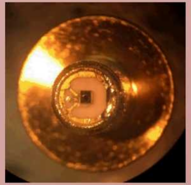
Detection


Mid-IR detector


Plasmonic perfect absorber

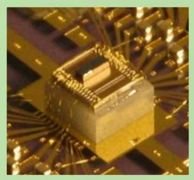


Germanium detector on silicon

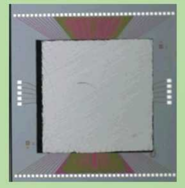

X-ray detector

CMOS Integration

III-V on CMOS



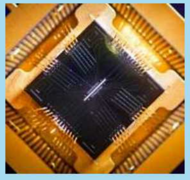
CMOS on Si Photonics

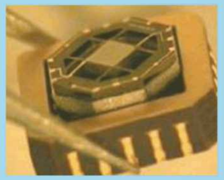

High-speed optical transceivers

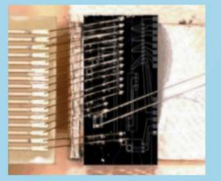
nBn on CMOS


IR Focal Plane Array w/ ROIC

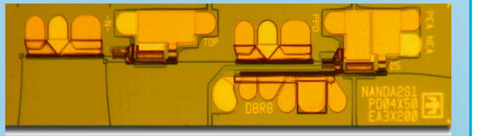
Chip-scaled MicroSystems


Quantum surface ion trap


Atomic clock


Quantum Key Distribution transceiver


Photovoltaics w/ microlenses


High-speed all-optical logic

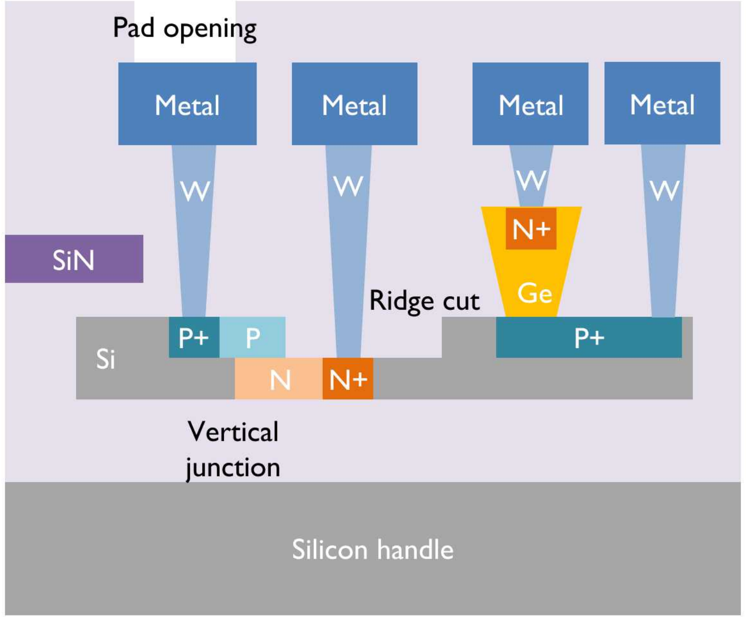
Silicon photonics capability

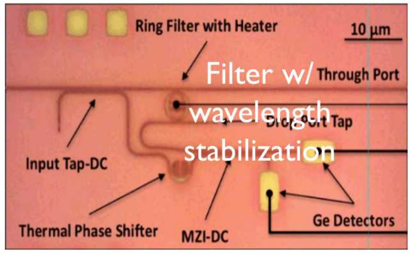
Overview
- 10 years of development
- leverages existing CMOS infrastructure
- 200 mm SOI wafers with 3um BOX
- two waveguide layers: Si and SiN
- selective area epitaxy for Ge detectors

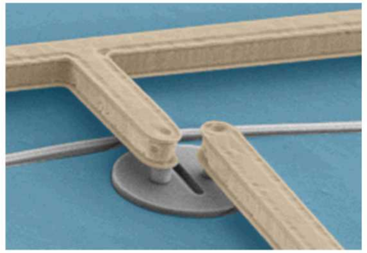
Passive devices
- Si rib and ridge-type waveguides
- ring filters
- grating couplers (1D and 2D)
- waveguide crossings
- splitters (amplitude and polarization)

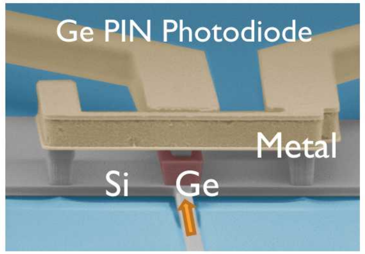
Active devices
- microdisk and MZ modulators
- thermal and EO phase shifters
- Ge PIN and APDs

Demonstrated circuits
- quantum cryptography (DV and CV QKD)
- RF processors (channelizer, SSB modulators)
- data links in harsh environments









PROCESS FLEXIBILITY

Wafer bonding: III/V and other materials

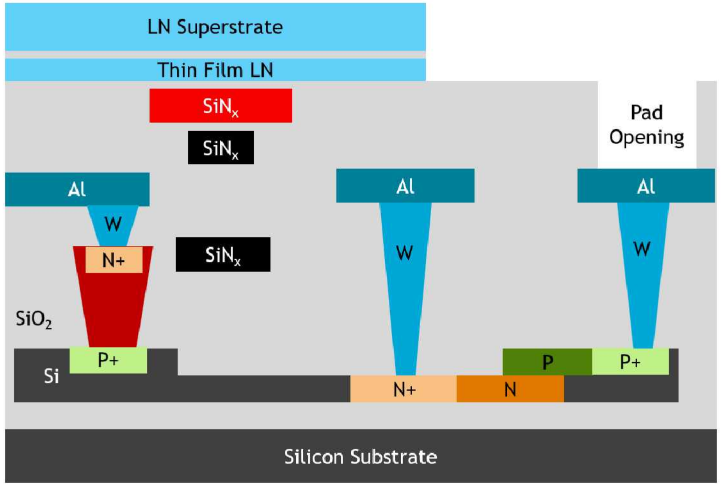
Extra waveguide layers for transitions

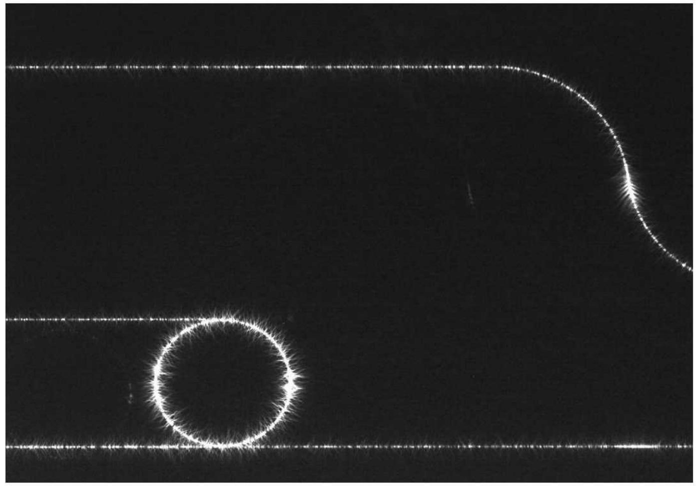
Multi-mask exposures with low stitching errors

Mix and match standard litho with e-beam

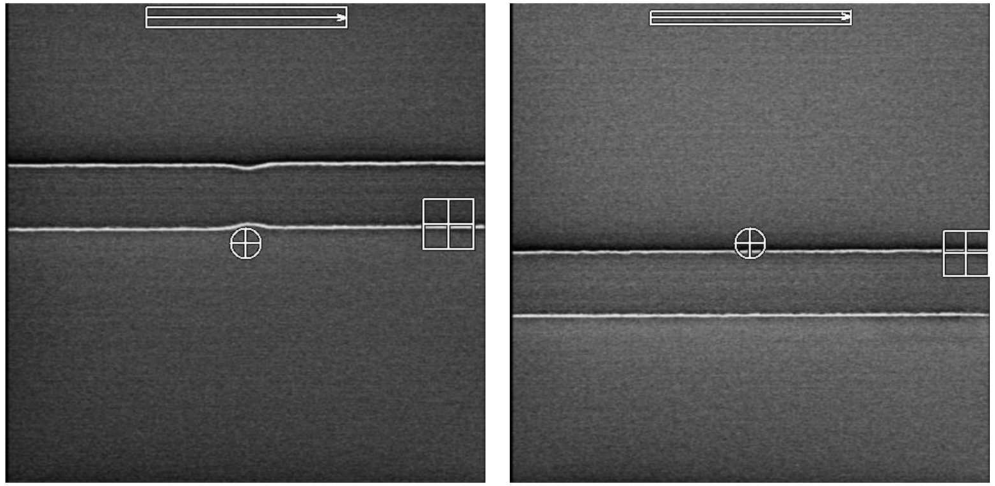
Alternative waveguides: Al_2O_3 and AlN

Optical MEMS demonstrations





Alumina waveguides for visible light photonics



Images of waveguides crossing between reticles. Proper mask design eliminates stitching errors and ensures low optical loss.

InP PIC capability

Overview

- 20 years of development
- multiple band edges via quantum well intermixing and regrowth steps
- ridge, buried and deep etch waveguides
- top side n- and p-type contacts

Passive devices

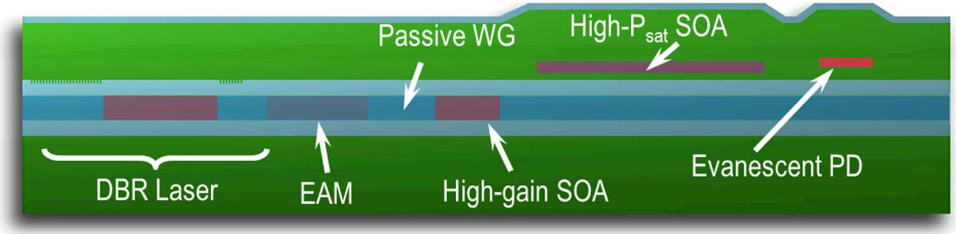
- arrayed waveguide gratings
- ring resonators
- TIR mirrors
- resistors and capacitors

Active devices

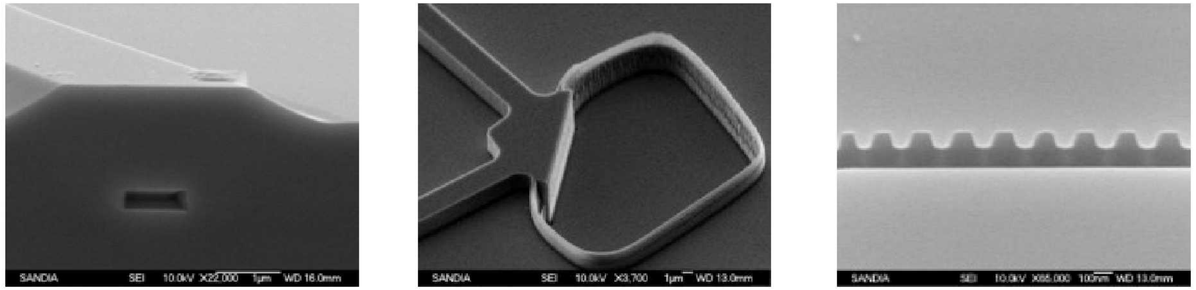
- lasers (DBR, DFB, etc.)
- modulators (EAM and MZ)
- SOAs (high-gain and high-power)
- photodetectors (evanescently coupled and QW)

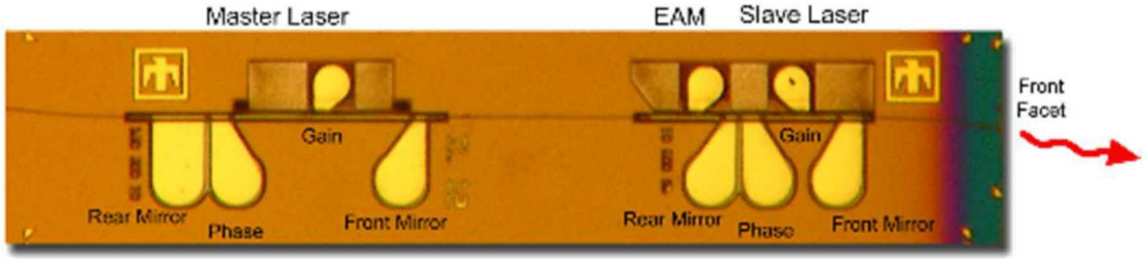
Demonstrated circuits

- optical logic ages
- data links
- coupled-cavity lasers



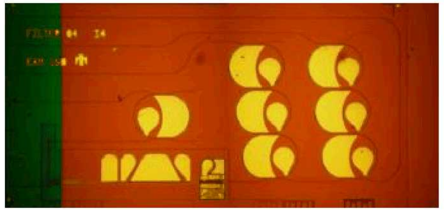
Device cross-section





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

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



Collaborative Multi-Project Wafers

Goal: collaborate with customers to develop novel processes and solutions to support project and application requirements, ***not*** to compete with US commercial foundries

- collaborative and custom work
- academia, industry, other government entities

Silicon photonics

- three deliverables: passive, active, and active+Ge
- typical block size: 4mm x 26 mm
- design manual
- libraries available through Synopsis

InP PICs

- designs accepted until 9/2019
- multiple tiers/process flows available

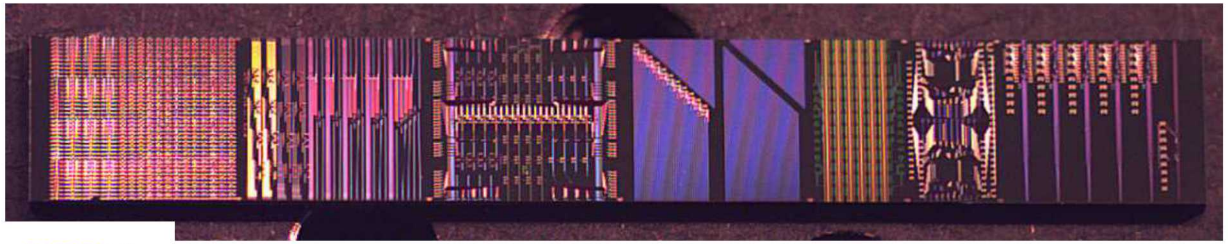


Image of MPW run, supporting Columbia, U of AZ, UC Berkeley, UCSD & Caltech

4. TECHNOLOGY OVERVIEW

Sandia National Laboratories (SNL) has developed a Microsystems and Engineering Sciences Applications (MESA) facility located in a limited classified area. Trusted custom fabrication of silicon and radiation-hardened process technologies for digital, analog and mixed signal ICs is currently available through MESA, which delivers production micro-electronics components to support special DOE and DOD programs. The MESA Complex is designed to integrate the numerous scientific disciplines necessary to produce functional, robust, integrated microsystems and represents the center of SNL's investment in microsystems research, development, and prototyping activities. This suite of facilities encompasses approximately 400,000 square feet and includes cleanroom facilities, laboratories and offices.

More recently, a silicon photonics process (SPP1) has been engineered and matured in the MESA facility, a cross section of which can be seen in Figure 4-1. The silicon photonics process is an electro-optical silicon photonic integrated circuit platform built on silicon on insulator (SOI) wafer technology. Included within SPP1 are two waveguide interconnect layers one in crystalline silicon, the other in deposited silicon nitride, a full suite of dopant implants to provide active p-n junction formation and low resistance ohmic contacts, Aluminum metal interconnect layer(s), and selective epitaxial growth of Germanium with optional n and p type implants all surrounded by optical cladding layers. SNL's silicon photonic process represents a mature process technology upon which to develop novel photonic integrated circuits and systems. The SPP1 has enabled numerous best in class device demonstrations, including ultra low energy optical modulators [4], high speed, low capacitance Si photodiodes [5], high speed optical modulators [6] and the resonant frequency locking of microring resonator filters [7] and modulators [8].

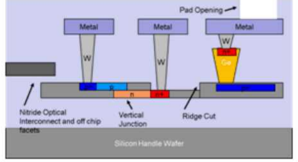


Figure 4-1 A cartoon illustration of the cross-section of Sandia's SPP1 process with a subset of the possible implant configurations

5. BASELINE PROCESS DETAILS

The details of the base process flow of are described in Table 5-1. The base process can be broken down in to three subsets:

SNL Silicon Photonics Design Manual

Process		Tier 1	Tier 2	Tier 3
Description		One MOCVD regrowth	Two MOCVD regrowths	Full custom process
Lasers	Tunable (~5 nm)	YES	YES	YES
	Tunable (~40 nm)	YES	YES	YES
SOA	High Gain (dB/cm)	400	400	400
	High P_{sat}	NO	YES	YES
Detectors	R (A/W)	0.8	0.8	0.8
	P_{in} saturation (dBm)	15	15	15
	Bandwidth (GHz)	> 20	> 40	> 40
Wave-guide	Propagation Loss (dB/cm)	< 2	< 2	< 2
	Turning mirror loss (dB)	N/A	< 0.5	< 0.5
EA-Modulator	Length (μm)	125	125	125
	Efficiency (dB/V/cm)	800	800	800
	Loss (dB)	< 1	< 1	< 1
	Bandwidth (GHz)	> 20	40	40
MZ-Modulator	Electrode Length (μm)	250	250	250
	Efficiency (V_π)	2	2	2
	Loss (dB)	~1	~1	~1
	Bandwidth (GHz)	> 20	> 20	> 40
Phase Modulator	Length (μm)	200	200	200
	Efficiency (°/V)	20	20	20
	Loss (dB)	< 1	< 1	< 1
	Bandwidth (GHz)	> 20	> 20	> 40

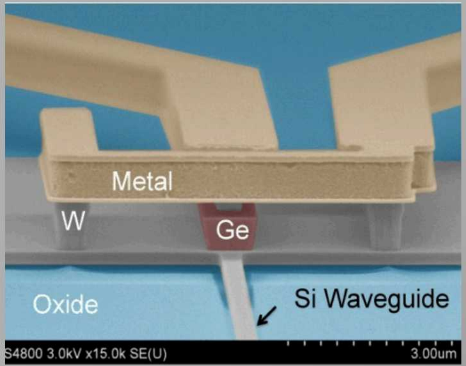
For more information:
photonics@sandia.gov

Integrated Si photonics for quantum communication

Internally funded programs to develop quantum comms

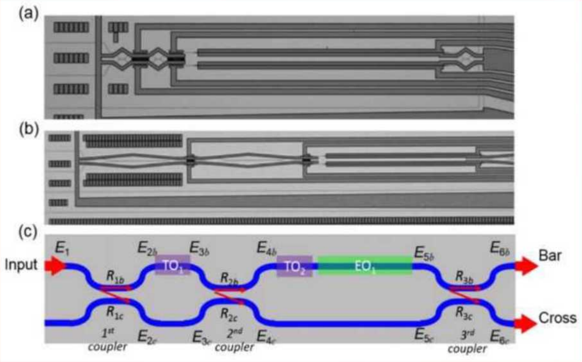
Many foundational building blocks for advancing quantum science developed
- detectors
- modulators
- frequency converters
- amplifiers
- optical transceivers

Demonstration of DV-QKD across 43km link with key generation rates >100 kbps



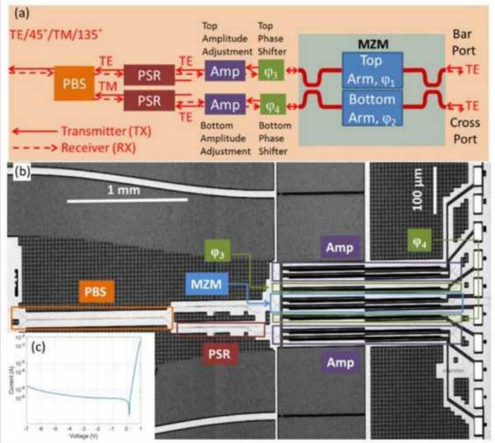
Geiger-mode APD
for single photon detection

CV-QKD



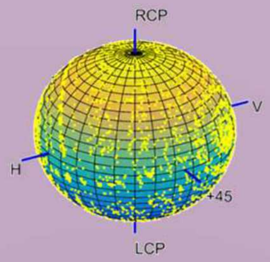
High-speed (10GHz) high-extinction ratio (>65dB) amplitude modulator

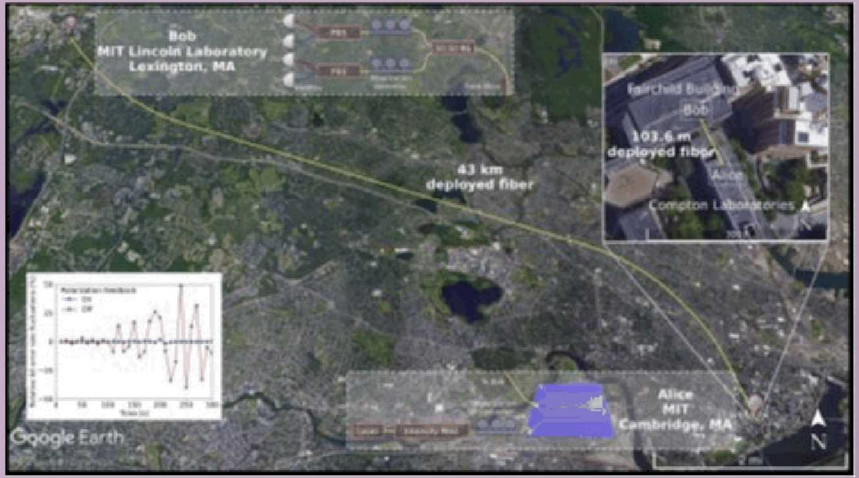
DV-QKD



2016 R&D 100 WINNER

T-QUAKE (Transceiver for Quantum Keys and Encryption)





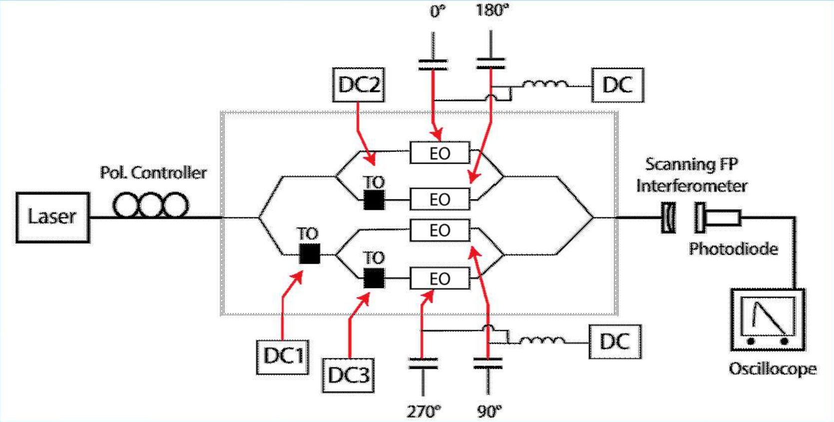
MIT LINCOLN LABORATORY

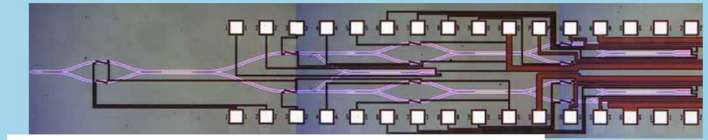
High-speed polarization-based DV QKD field tests (BB84) demonstrated

Optics Express 25(11) 12282-12294, 2017
Phys. Rev. X 8 (021009), 1-12, April 2018

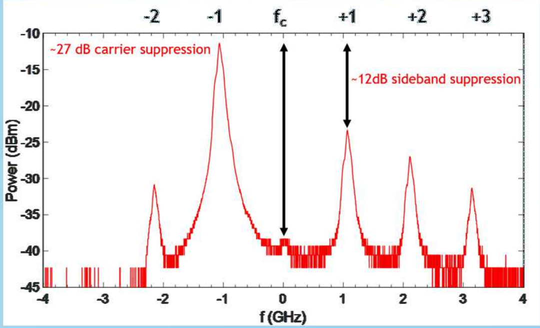
Integrated Si photonics for RF signals

Single-sideband generation with dual-parallel Mach-Zehnder modulators





composite optical image

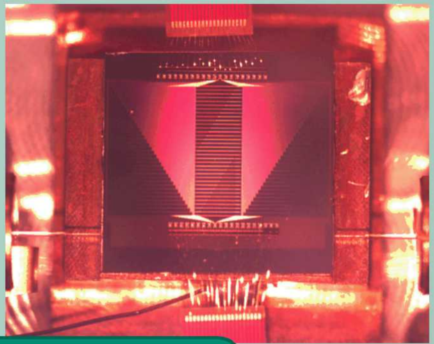


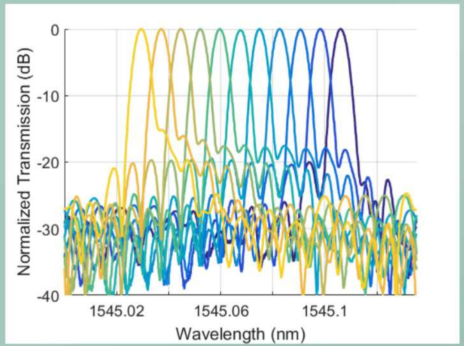
30dB carrier suppression
12 dB sideband suppression / 20 dB with active feedback

CLEO 2019

Photonic processing of RF signals provides significant reduction in SWAP-C for high frequency applications (>40 GHz).

RF channelizer



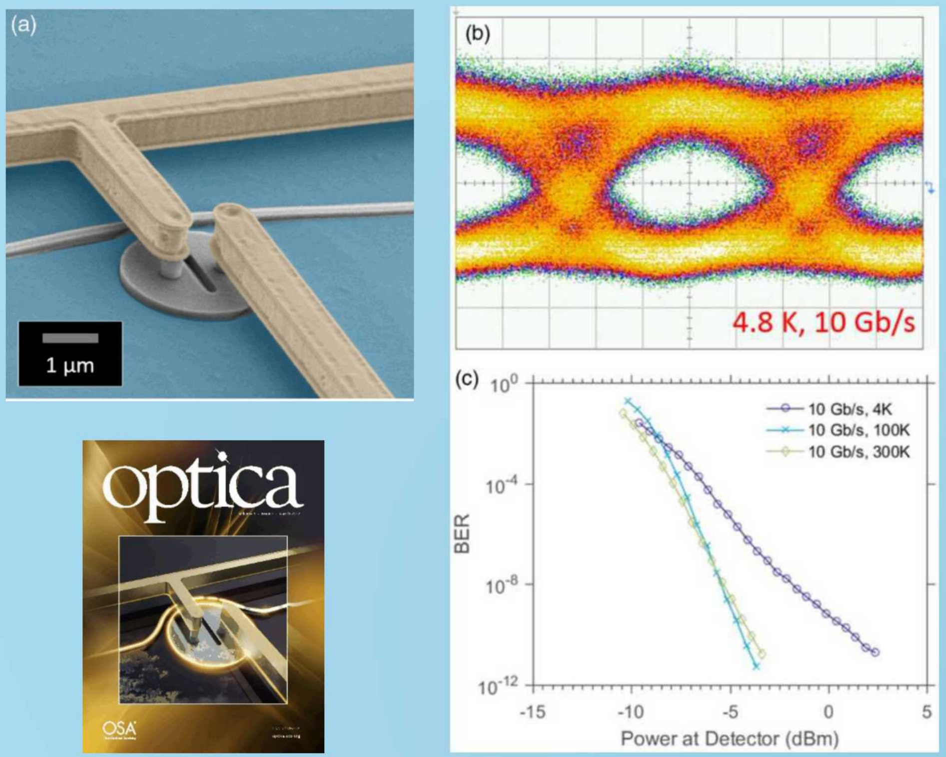


- 11 channels
- <1 GHz resolution
- <-15 dB optical cross-talk
- 1.1 cm^2 total area

1st demo of 1GHz RF channelization in a Si photonics array waveguide grating

Optics Express 25 (6), 6320-6334, Mar. 2017

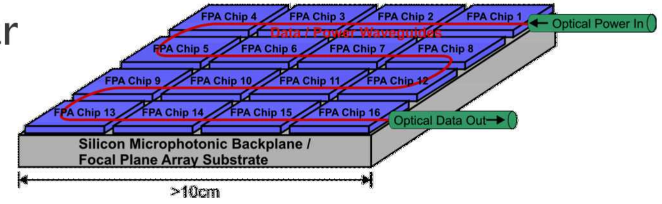
PROCESS FLOW OPTIMIZATION: CRYOGENIC DATA LINKS



High-speed low-power resonant modulator operating at cryogenic temperatures (50K, 4K, and below)

Applications

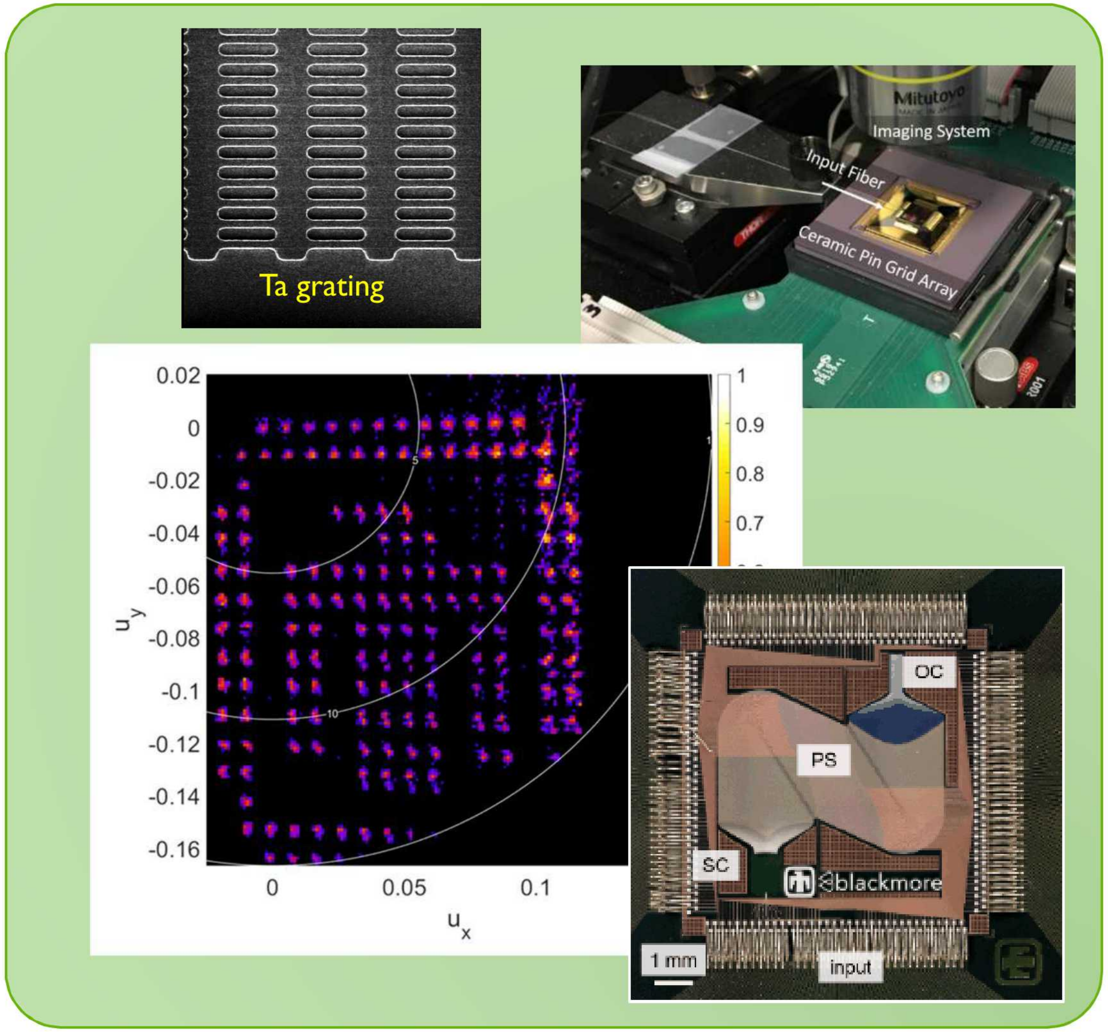
- superconducting computing
- optical backplane for focal plane ar
- quantum system interface



Succinct summary

- increased doping concentrations prevent freeze out
- 10Gbps operation at 4.8K
- RC time constant limited error-free operation

Monolithic integration: Chip-scale optical beam steering



Phase Optimization of Si Photonics 2D Electro-optic Phased Array

CLEO 2019 & Optics Express 21(4), 5198-5208, 2013

2D silicon photonic optical beam scanner

- huge push for integrated solutions
- small output couplers desired → high index contrast materials
- developed CMOS-compatible process in Ta

Results

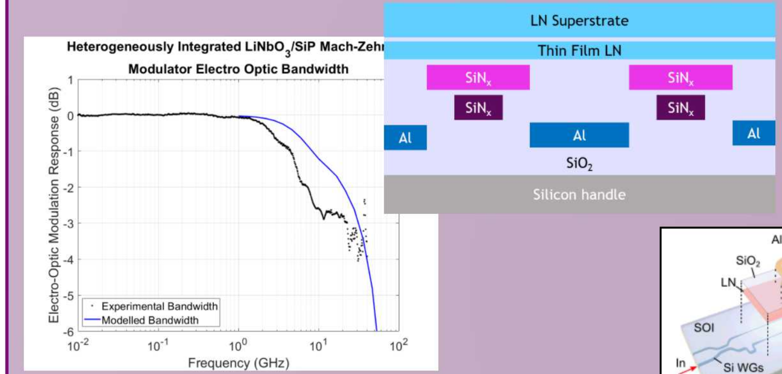
- electronic (low-power EO phase shifter) and wavelength steering
- field of view: 24° × 10°; divergence angle: 0.3° × 0.3°
- 256 independent channels with 3-μm pitch
- area: 750μm x 750μm with high fill factor
- electronic packaging with interposer and chip carrier

blackmore

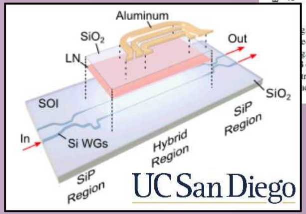
SANDIA NATIONAL LABORATORIES CRADA COOPERATIVE RESEARCH AND DEVELOPMENT AGREEMENTS

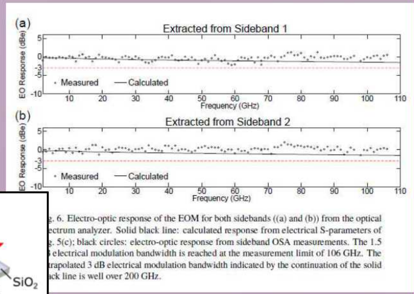
HETEROGENEOUS INTEGRATION

Si Photonics / Lithium Niobate



3dB bandwidth >20GHz

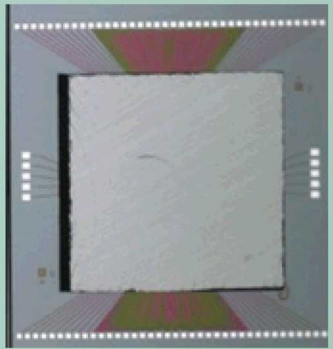




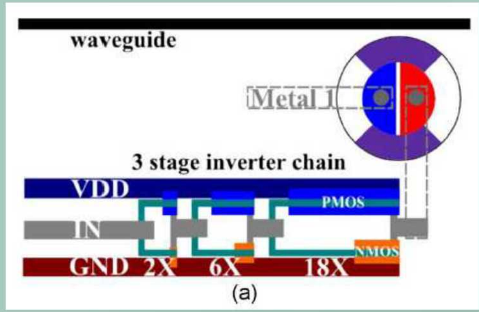
3dB bandwidth >100GHz

OIC2019 & Optics Express 26 (18), 23728-23739, 2018

Si Photonics / CMOS



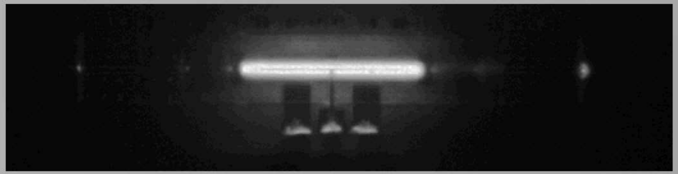
2D integration with IBM/Global 45nm process

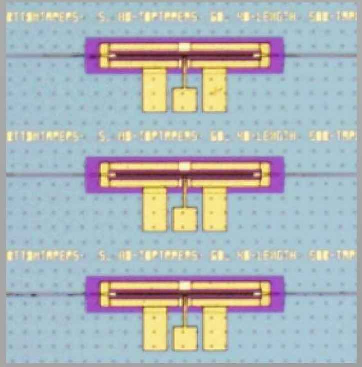


monolithic integration

IEEE Aerospace 2015 & IEEE Photonics 4(1), 242-249, 2012

Si Photonics / III-V





Light emission from an HI SOA

Heterogeneous integration enables miniaturization with independent material and device optimization

- integration of $LiNbO_3$ and III-V Lasers on silicon photonics
- non-traditional materials such as Epsilon-Near-Zero In_2O_3 and CdO, graphene
- integration of CMOS with silicon photonics, InGaAsP/InP, InGaAs/GaAs, and other materials

Sandia National Security Photonics Center

Distinguishing capabilities
- flexible process flows and materials
- co-located design, fab, packaging and test facilities

Non-traditional application spaces

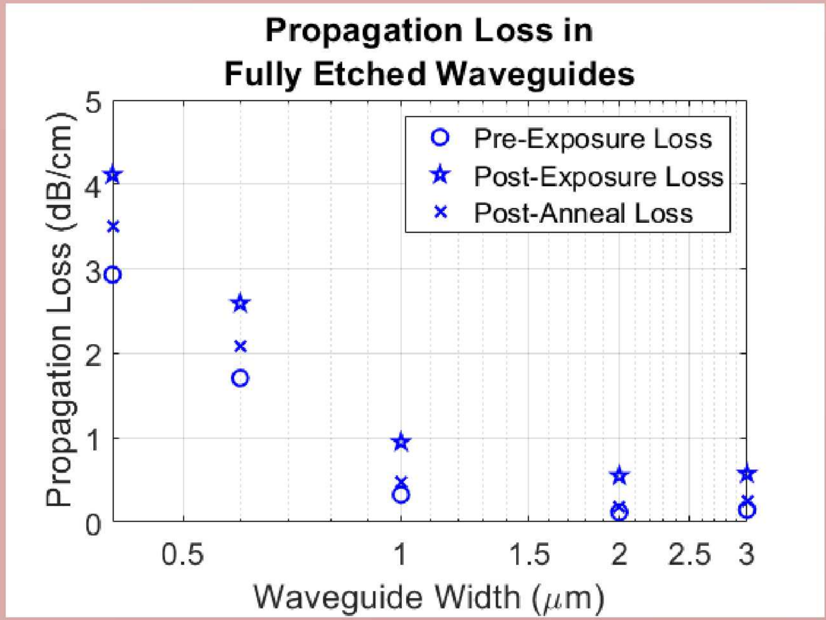
Si photonics and optoelectronics

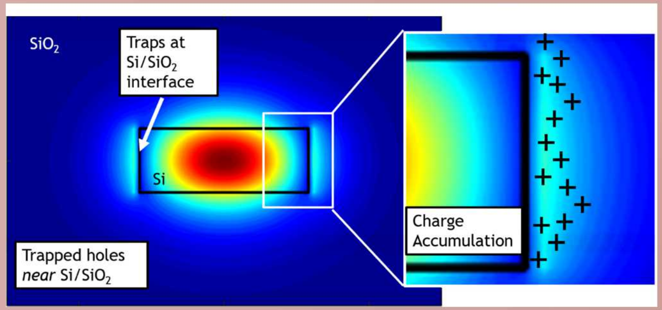
DOD Defense Microelectronics Activity (DMEA) Category1A Trusted Supplier

For more information:
photonics@sandia.gov

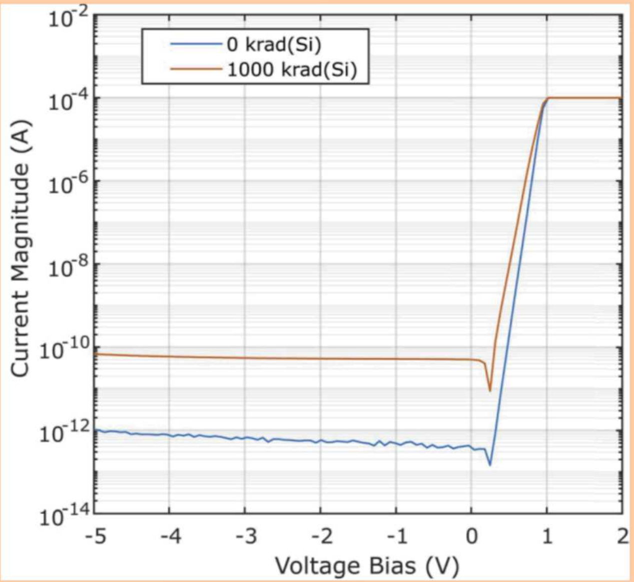
Back up slides

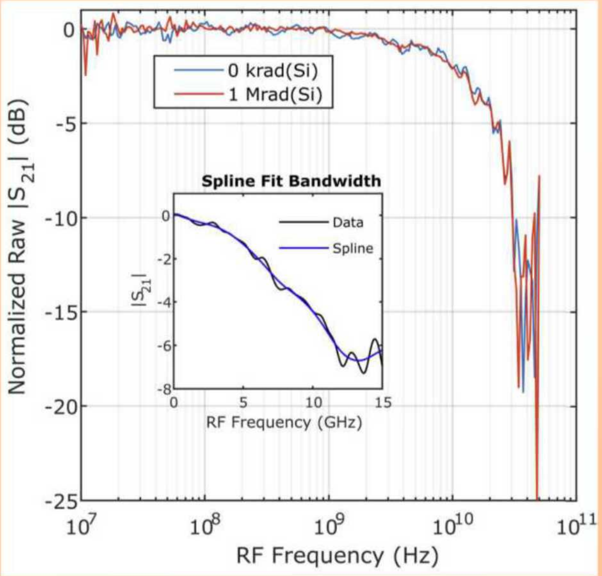
Si photonics in harsh environments: Gamma radiation





Waveguides show small increase in loss due to increased free carrier density. Partial recovery with heat anneal.





Modulators (and detectors) show increased dark current, but negligible decrease in bandwidth.

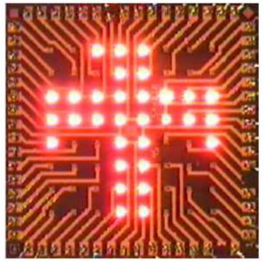
Boynton, *et al.*, "Propagation loss in crystalline silicon photonic waveguides due to gamma radiation," GOMAC Tech, 2019

Hoffman, *et al.*, "The Effect of Gamma Radiation Exposure on Active Silicon Photonic Device Performance Metrics," *IEEE Trans. Nuclear Sci.*, 66(5), 801, 2019

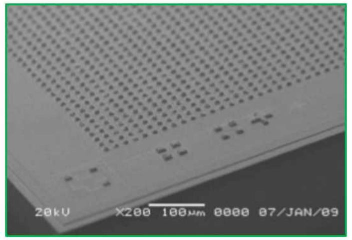
Sandia's Photonics "Toolkit"

<table>
<tr><th></th><th>Compound Semiconductors</th><th>Silicon</th></tr>
<tr><td>Surface Normal</td><td>

VCSELS



nBn Detectors



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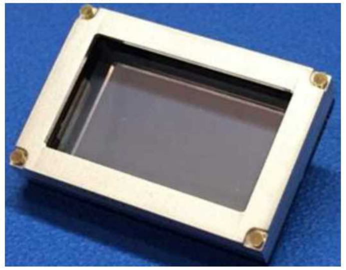
Custom Si Detectors



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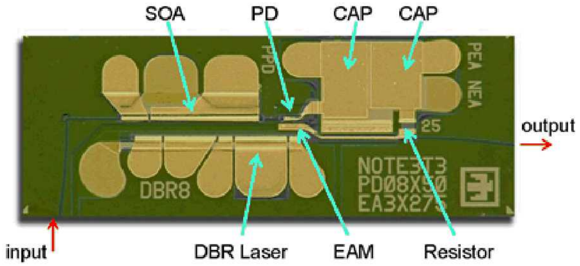
<tr><td>Waveguide</td><td>

PICs



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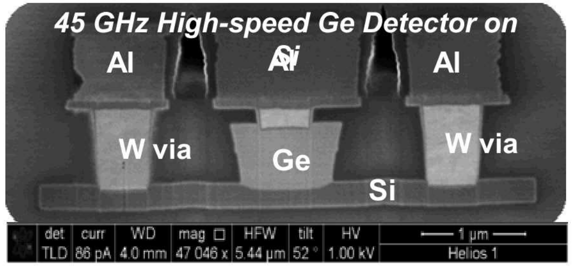
Si photonics



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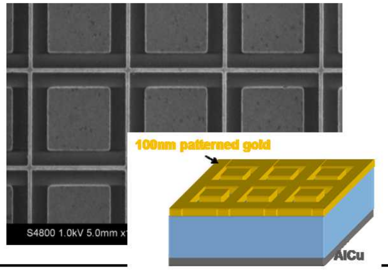
<tr><td>Nanophotonics</td><td>

Nanoantennae FPAs



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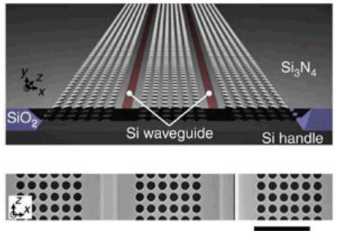
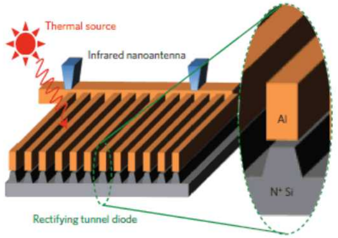
Nano-optomechanics



Rectennae



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SILICON PHOTONICS OF THE FUTURE

Silicon photonics will play key roles in miniaturizing complex systems and accessing difficult-to-reach components. Recent research spans a wide breadth of topics, from national security to everyday life, and niche solutions to mass-manufactured applications.

Achieving these goals requires a multi-disciplinary facility, with the dedication to reproduce established processes and the agility to create new ones.

This report presents recent work at SNL and shows our commitment to bringing in new materials and technologies to established procedures and ensure we can continue to provide photonic solutions to future needs.