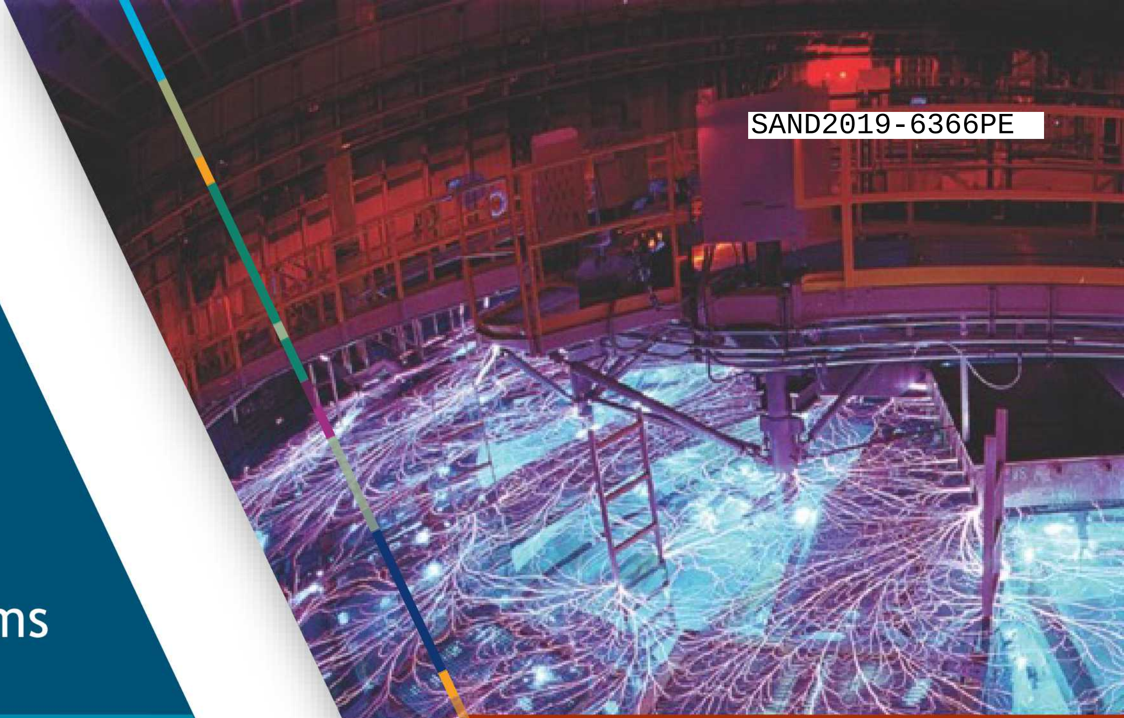
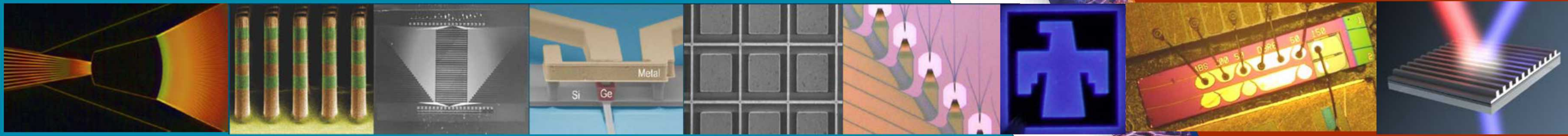
SAND2019-6366PE

Sandia National Laboratories

Exceptional service in the national interest



Sandia Overview for Integratic Photonics MPW Programs



Technology Partnerships with

SANDIA NATIONAL LABORATORIES

U.S. DEPARTMENT OF ENERGY
NNSA

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SAND2019-5161 C

SANDIA IS A FEDERALLY FUNDED RESEARCH AND DEVELOPMENT CENTER MANAGED AND OPERATED BY

National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc.: 2017 – present

Government owned,
contractor operated

SANDIA HAS FIVE MAJOR PROGRAM PORTFOLIOS

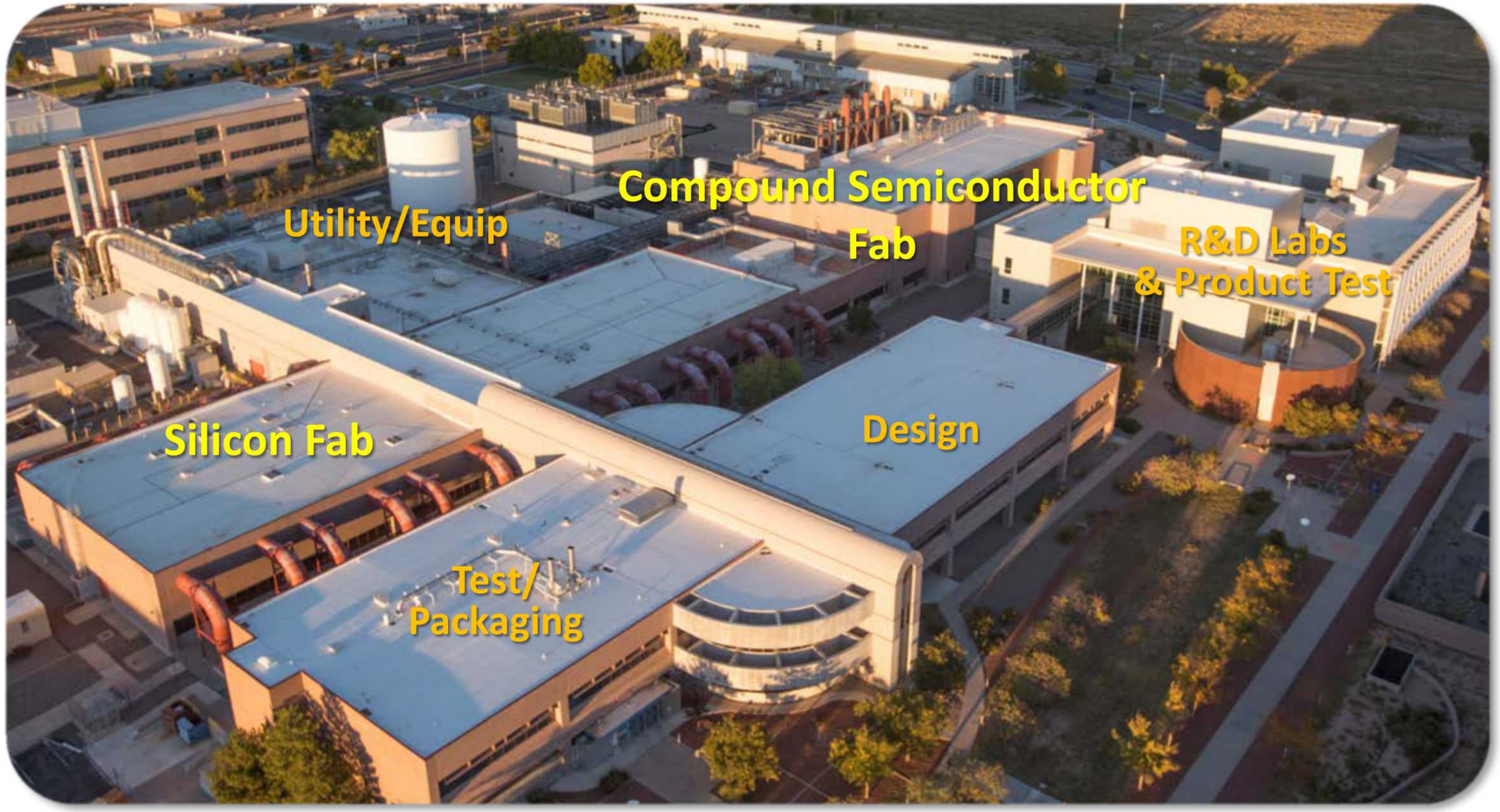
SANDIA's MESA COMPLEX

MESA= Microsystems Engineering, Science and Applications

Co-joined Fab Facility
- Silicon Fab
- Compound Semiconductor Fab

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

Currently dozens of products:
- ASICs, III-V SSICs, MEMS, FPAs, RFICs, Optoelectronics

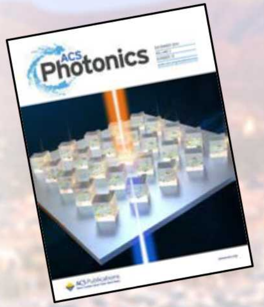


Co-located R&D and Production

SANDIA's NATIONAL SECURITY PHOTONICS CENTER

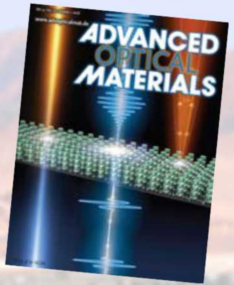
Serve the nation as a center of excellence for national security photonics through scientific excellence and innovations and leading-edge integrated photonics solutions

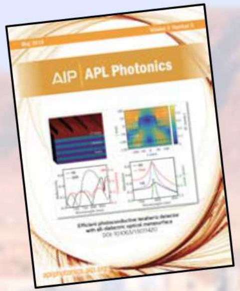
- >60 photonics staff (plus postdocs and students) with expertise in device design, modeling, simulation, epitaxy, device fabrication, integration, assembly, and test
- Partnership with government agencies, industry, and universities
- Technology transfer to industry
- Areas of interests: communication, sensing, computing, imaging, quantum applications



2012 R&D 100 50th ANNIVERSARY

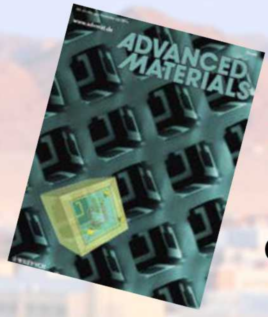
Microsystems Enabled Photovoltaics





2016 R&D 100 WINNER

T-QUAKE (Transceiver for Quantum Keys and Encryption)



R&D 100

2009 Ultralow-power Silicon Microphotonic Communication Platform

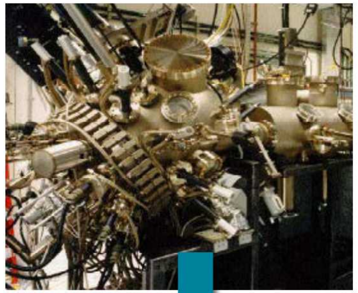
SANDIA's NATIONAL SECURITY PHOTONIC CENTER

Silicon Fab:
Silicon Photonics

Microfab:
Compound Semiconductor
Photonics

PDK and
Multi-Project Wafers

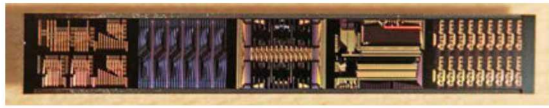
Custom Epitaxial Growth
(GaAs, InP, GaSb, GaN)
Custom III-V Devices



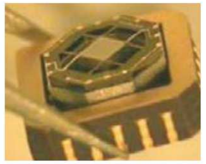
60+ Photonics Staff

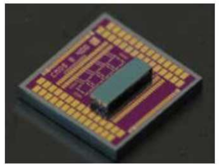
Device Design, Modeling, Simulation
Semiconductor Device Fabrication
Microsystem Fabrication
Testing, Rad Effects, Cryo
Reliability

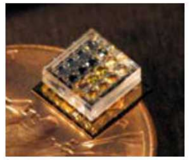
Microsystems and Heterogeneous Integration
(Flip Chip Bonding, micro-optics, assembly, packaging)

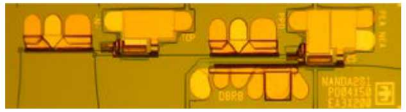


Photonic circuits









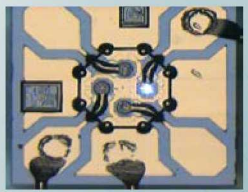
Photonic circuits & Lasers

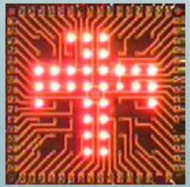
SANDIA's PHOTONIC MICROSYSTEMS

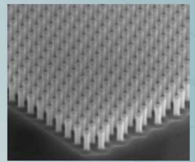
National Capabilities for Advanced Photonics R&D: design, model, fab, package, and test

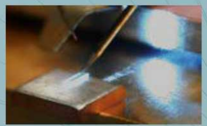
Materials: Silicon, III-V (Phosphides, Arsenides, Antimonides, Nitrides), Lithium Niobate, Graphene, etc.

Sources

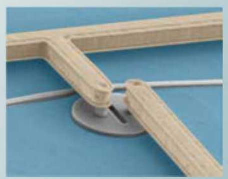

Single-Frequency Tunable VCSELs


High Efficiency VCSELs

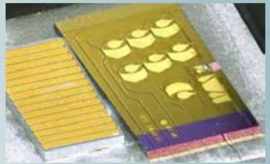

Nanowire Laser

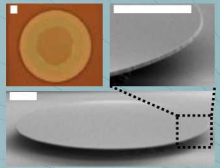

High power GaAs laser

Control / Manipulation

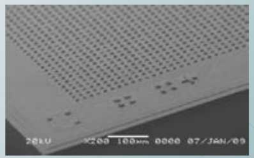

Resonant Optical Modulator/Filter

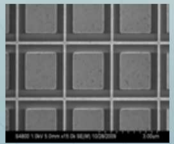

Array Waveguide Grating Channelizing Filter

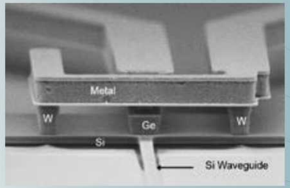

RF Channelizing Filter


LiNbO3 Freq. Converter

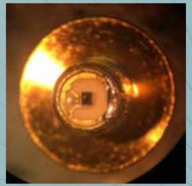
Detection


Infrared Detector


Plasmonic Perfect Absorber



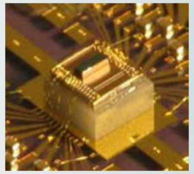
Germanium Detector on Silicon


X-ray Detector

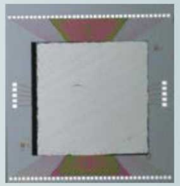
Chip-scaled MicroSystems

Heterogeneous Integration

III-V on CMOS

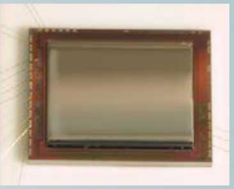


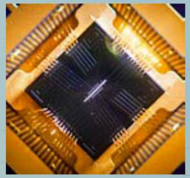
CMOS on Si Photonics

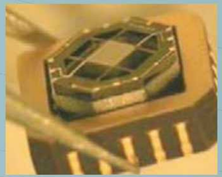


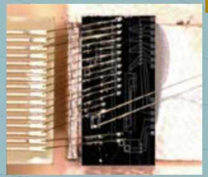
High-speed Optical Transceivers

nBn on CMOS

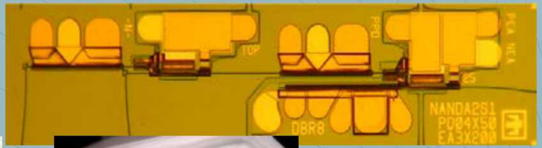

IR Focal Plane Array w/ ROIC


Quantum Surface Ion Trap


Atomic Clock


Quantum Key Distribution Transceiver


Photovoltaics w/ microlenses

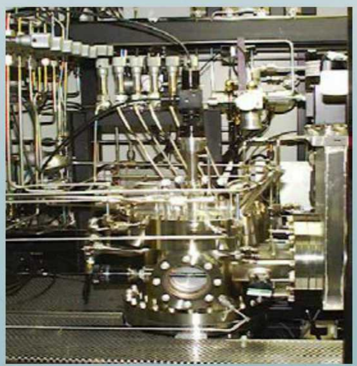

High-speed All-Optical Logic

III-V OPTOELECTRONICS CAPABILITIES

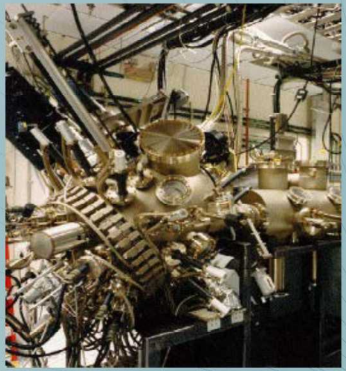
Custom, trusted, low-volume, high-reliability products for harsh environments when industry is unwilling or unable to deliver

Custom Epitaxial Growth

MOCVD:
As, P, Sb, Ga, In, Al, Zn, Si, Te, N, H_2

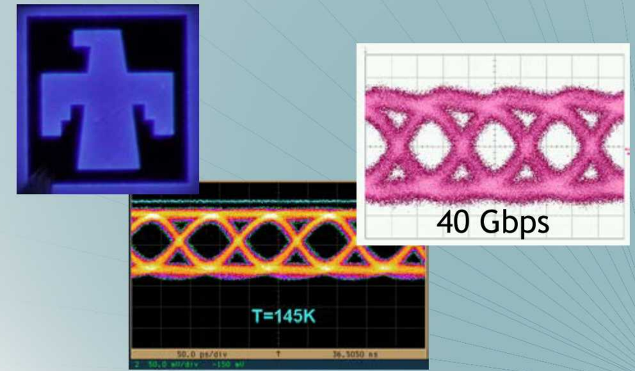


MBE:
Sb, Ga, As, In, Al, Si,Be,Te, N, H_2



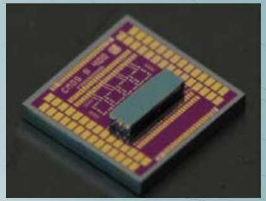
Device Design, Fabrication, and Characterization

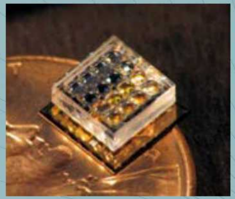
- Device design, modeling, simulation
- TRL 1-6+: create, develop, prototype
- Fabrication: 16,600 sq. ft Class 10/100 Cleanroom
- Optical Comm testing to > 40 Gbps
- Cryo-testing
- Reliability and Rad Effects



Microsystem Heterogeneous Integration

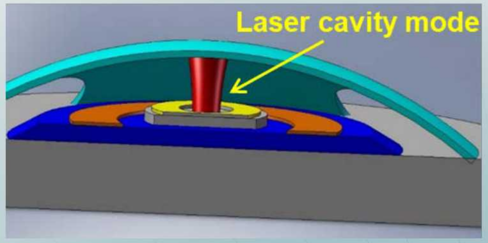
- Flip chip bonding
- Wafer level oxide bonding
- solder dam and bumps
- Grind, thin and polish
- Substrate removal
- Epoxy underfills
- AR coatings
- Micro-optics: diamond turning and molding
- Active alignment
- Dicing, scribe and break

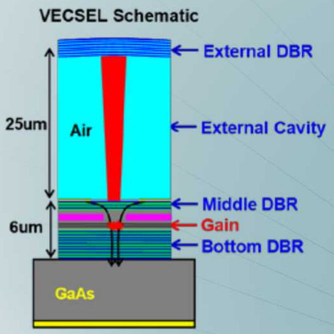


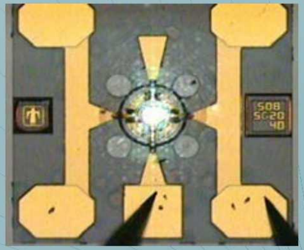


SANDIA's VCSEL RESEARCH and GaAs CAPABILITY

VCSEL



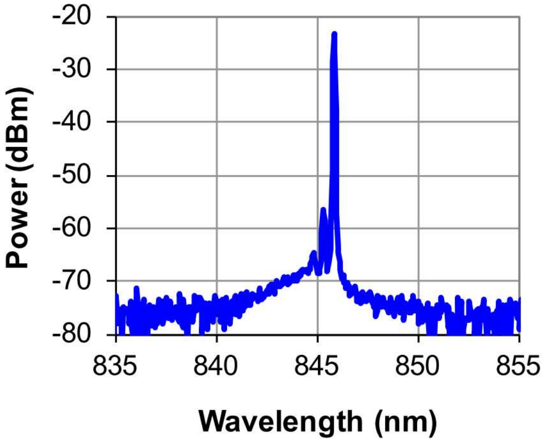




Narrow Line Width VECSEL

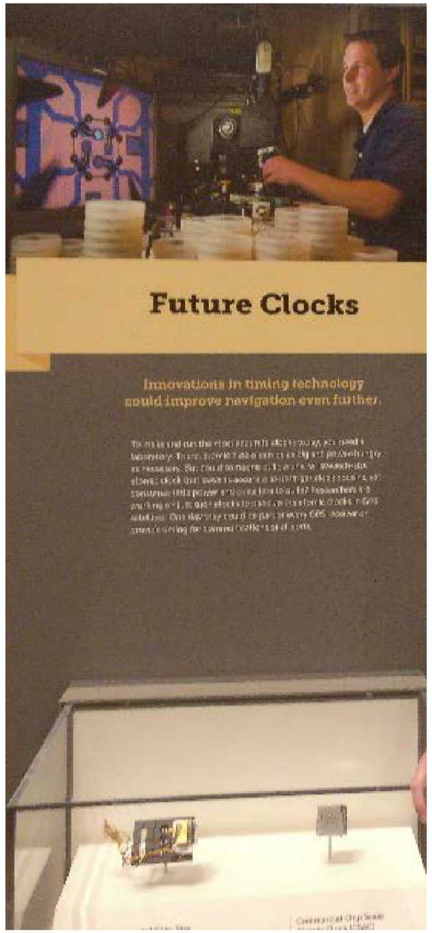
Sandia develops custom VCSELs & Photodiodes for emerging applications

- Innovative VCSEL research since 1990 with on going R&D and production
- Special VCSELs developed for atomic clocks
  - Narrow linewidth (<10MHz)
  - Technology transferred: Commercialized as a chip scale atomic clock, now manufactured Microsemi.
  - Current work focuses on VECSELs
- Custom VCSELs for high speed, high efficiency, cryogenics, and sensing



Chip Scale atomic clock technology transferred to industry

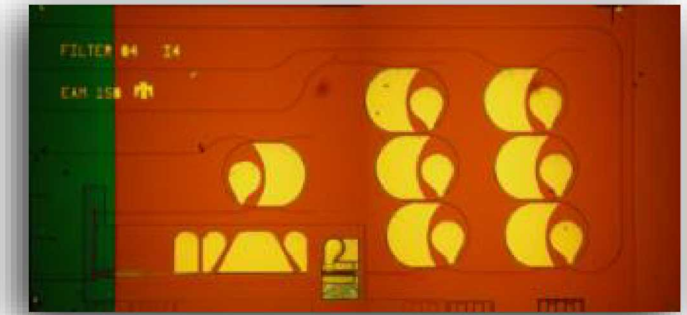
Smithsonian Air and Space Museum Exhibit (Sandian Darwin Serkland (poster))



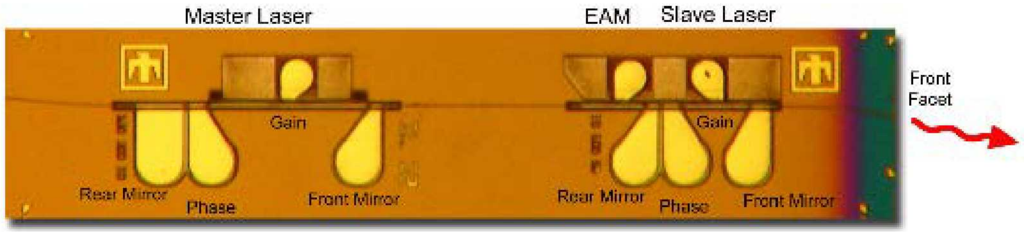
SANDIA's InP PIC CAPABILITY

InP-based Photonic Integrated Circuits

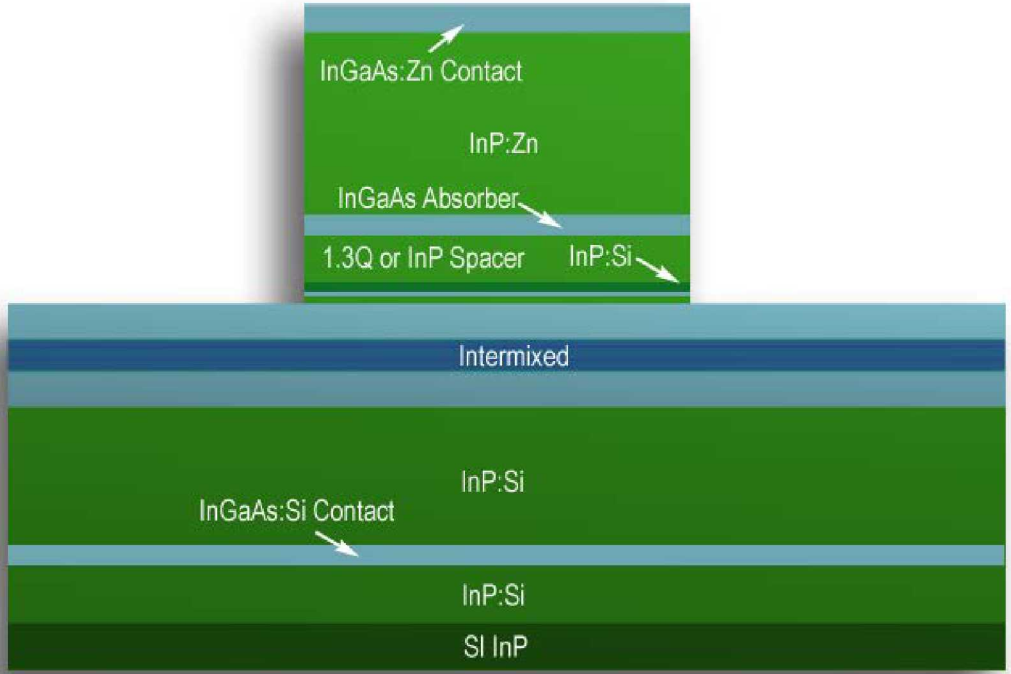
- Multiple band-edges by quantum-well-intermixing and/or regrowth
- Single and/or multiple epitaxial regrowth(s)
- Top-side n-type and p-type contacts
- Ridge, buried, and/or deep etch waveguide architectures



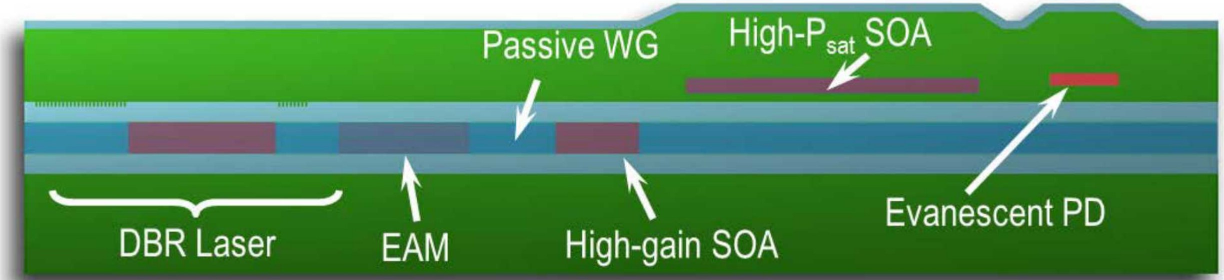
RF-Optical Channelizing Filter
1-20 GHz RF on C-Band Light



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



Device Cross-section (Lateral)



Device Cross-section (Longitudinal)

SANDIA's InP 'Design-Guided' Multi-project Wafer Runs

Sandia now offers an InP MPW program:

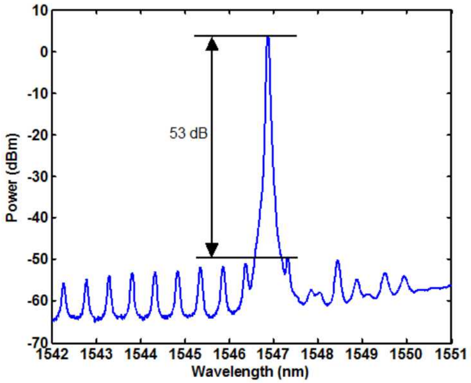
- Designs are being accepted through 9/2019 for the next run.

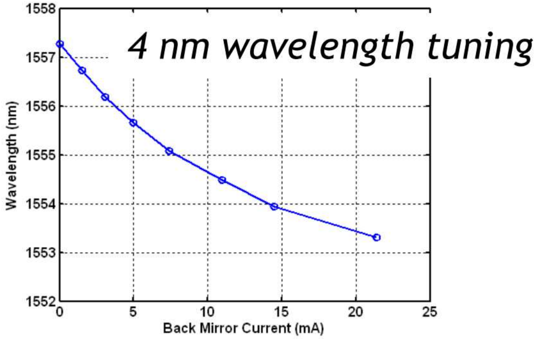
For more information:
email photonics@sandia.gov

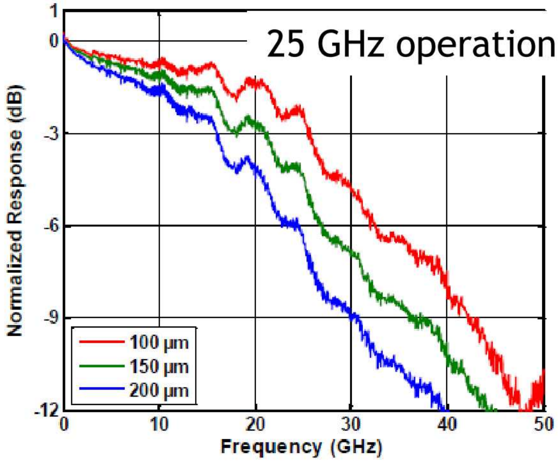
Process		Tier 1	Tier 2	Tier 3
Description		One MOCVD regrowth	Two MOCVD regrowths	Full custom process
Lasers	Tunable (~5 nm)	YES	YES	YES
	Tunable (~40 nm)	YES	YES	YES
SOA	High Gain (dB/cm)	400	400	400
	High P_{sat}	NO	YES	YES
Detectors	R (A/W)	0.8	0.8	0.8
	P_{in} saturation (dBm)	15	15	15
	Bandwidth (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

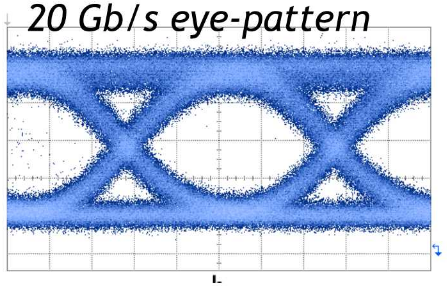
Inaugural Device Library

InP PIC Example: High-Speed Electrical-to-Optical (EO) Transmitter









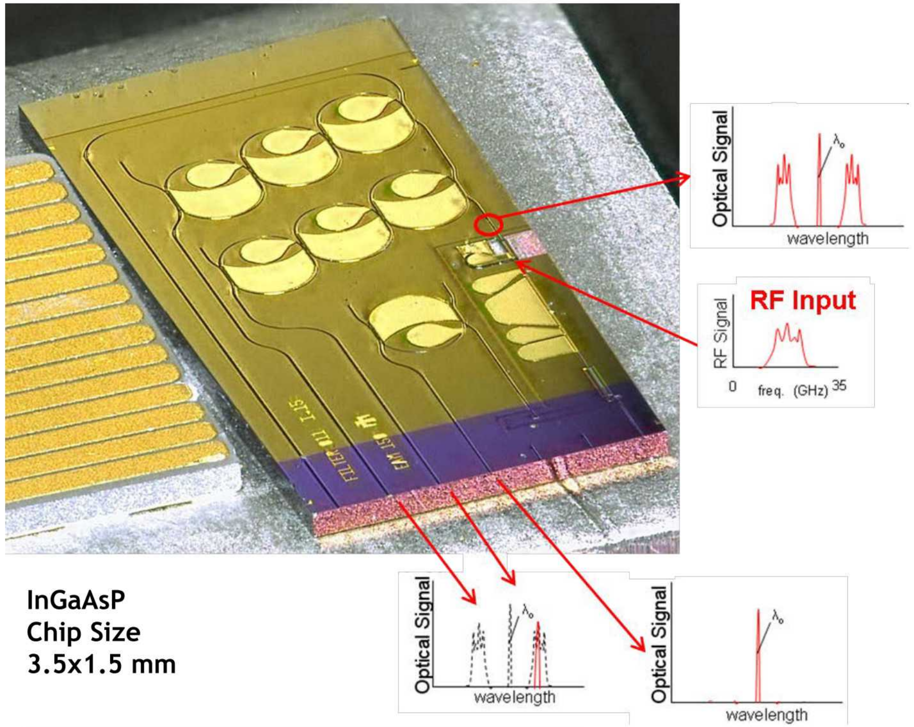
InGaAsP Diode laser and modulator chip
- DBR lasers
  - 6 mW fiber-coupled power
    - ~20 mW out from chip
  - 4 nm wavelength tuning
- EAMs
  - Efficiency ~19dB/V DC
  - Bandwidth 20GHz

Wavelength tuning
- Track filter frequencies
- Tune to WDM channels

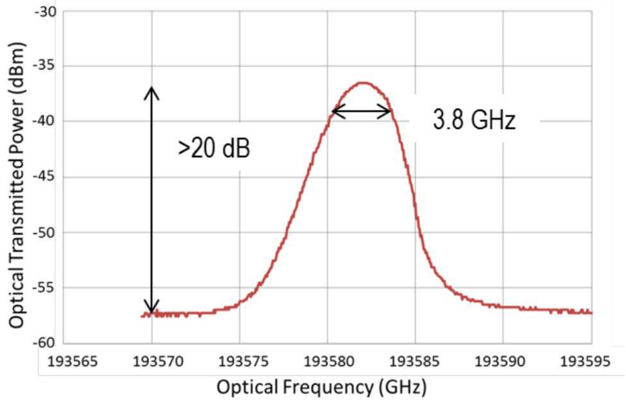
Power for RF photonics
Wavelength agility

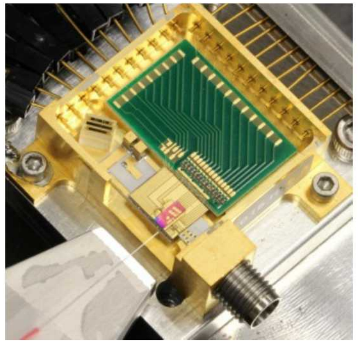
Scalable to mm-wave

InP PIC Example: Optical RF Channelized Receiver



InGaAsP
Chip Size
3.5x1.5 mm





Analyze an RF signal for frequency content

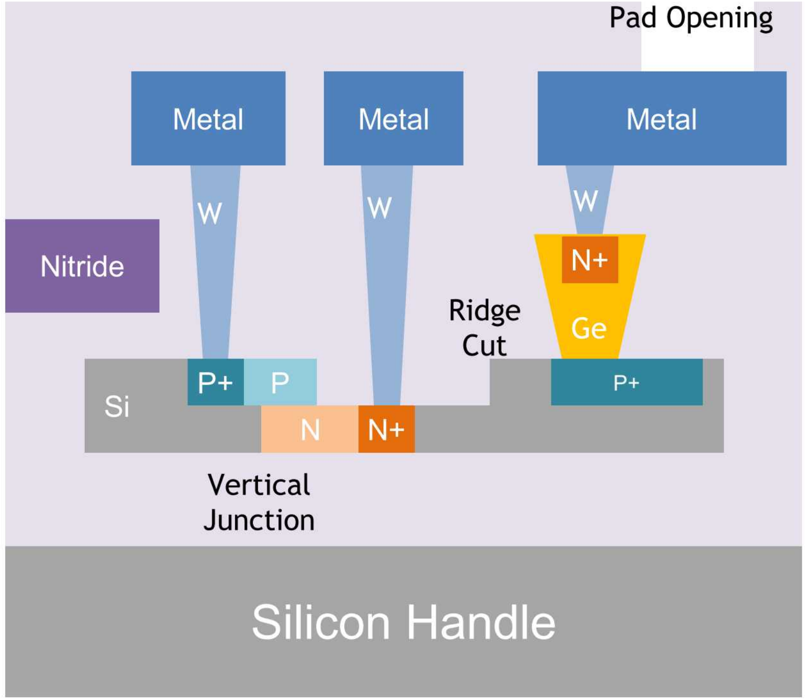
- Filter outputs are spectral power density integrated over the filter bandwidth

Compact, highly functional photonic integrated circuits (PICs) features:

- 3-pole ring resonator filters
  - Tunable over 10's GHz
  - GHz-class pass bands
  - 65 GHz free spectral range
- Integrated laser-modulator
  - Signal to EAM provides the RF input
- Integrated extra filter for wavelength monitoring

OFC 2011 & CLEO 2013

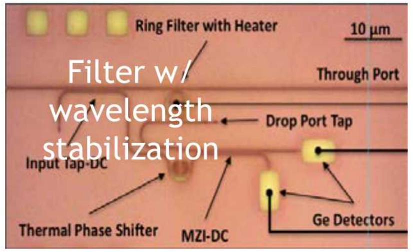
SILICON PHOTONICS CAPABILITIES

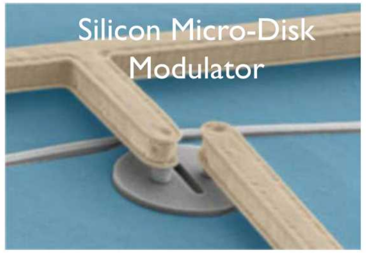


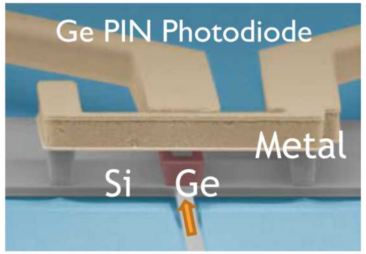
- Leverage existing CMOS infrastructure (200mm SOI)
- Low Power, High Speed Devices
- Low Loss Optical Waveguides (<0.1 dB/cm)
- Two waveguide interconnect layers:
  silicon and silicon nitride
- Selective Area Germanium Epitaxy for PIN/APDs
- 39 issued patents

Multi-project wafer runs

- Collaborative and custom work within or outside of MPW
- Academia, industry, other government entities
- Typical block size: 4 mm x 26 mm
- Three Deliverables:
  1) passive (Si+SiN), 2) Passive+ Active,
  3) Passive+ Active+ Germanium







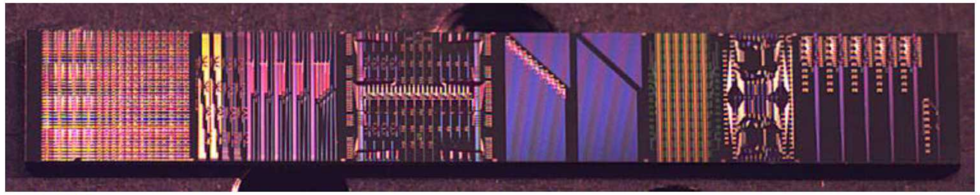


Image of MPW run, supporting Columbia, U of AZ, UC Berkeley, UCSD & Caltech

For more information:
email photonics@sandia.gov

SNL SILICON PHOTONICS LIBRARY

1st Rev. in Synopsis Optodesign Software)

22 Passive Devices

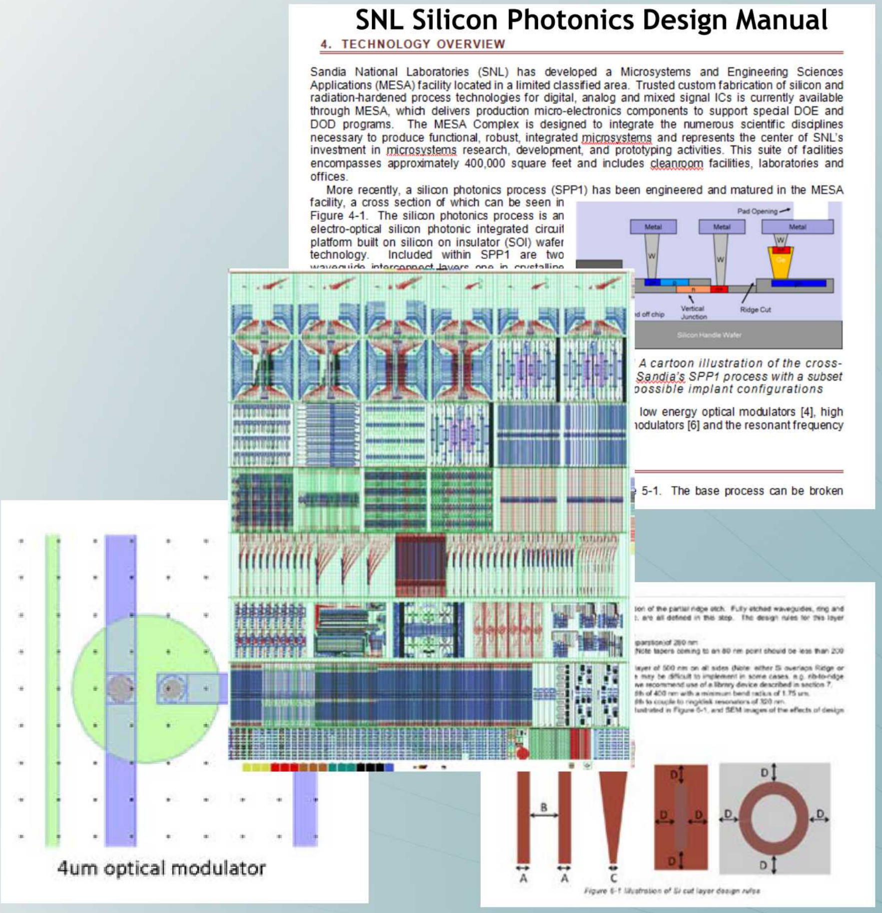
- Si rib and ridge waveguides (including transitions, auto routing, phase aware routing)
- Nitride waveguides (si to nitride transitions)
- Si rings [6] (standard, adiabatic, cascaded)
- Grating couplers (1D & 2D)
- Edge couplers (silicon, SiN)
- Waveguide crossings (nitride over silicon)
- Beam splitters (amplitude and polarization, MMI, adiabatic and directional couplers)

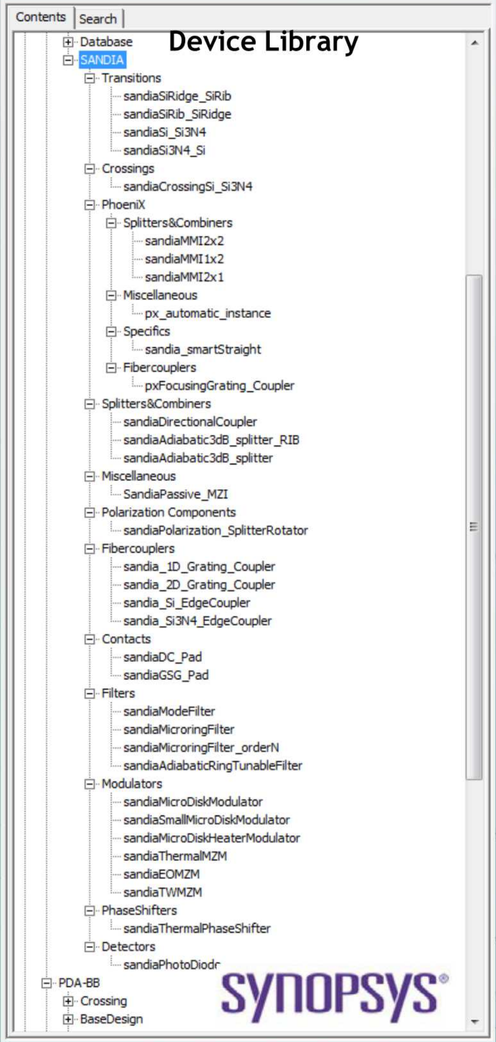
20 Active Devices

- Disk modulators (different size, dopants)
- Disk modulators and filters with heaters (int. & ext.)
- Ring modulators (adiabatic)
- Thermal phase shifters
- Thermal and electro-optic traveling wave MZM
- Ge PIN detectors

Design Tools & Features

- Design Guide
- Library (GDS/Scripted)





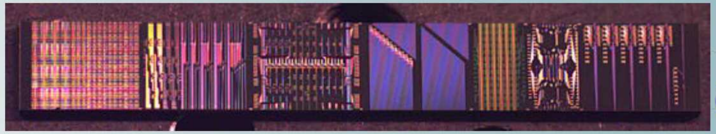
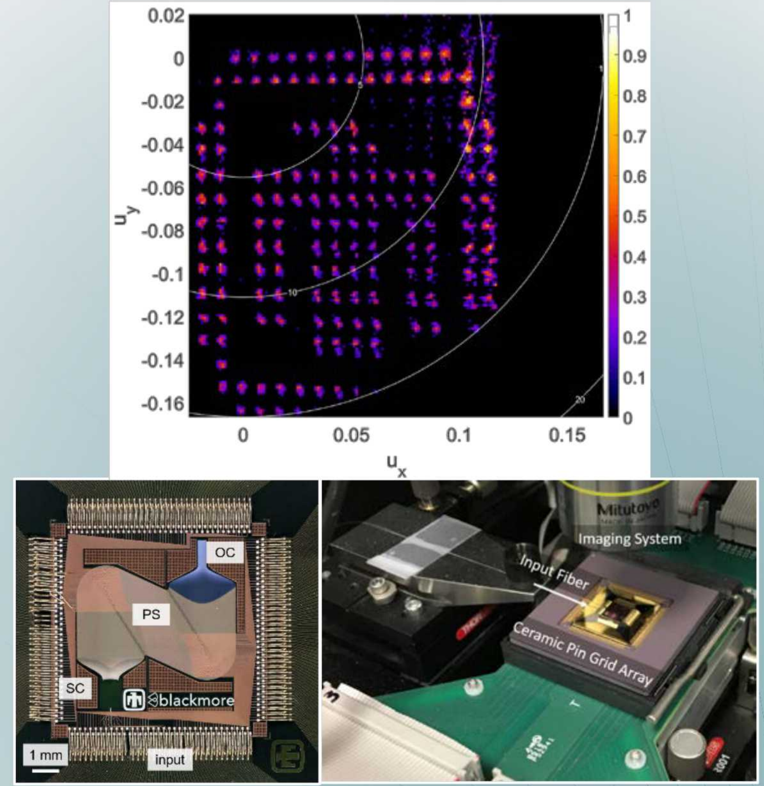


Image of MPW run, supporting Columbia, U of AZ, UC Berkeley, UCSD & Caltech

*** Synopsis may provide other generic components in addition.**

CHIP-SCALE OPTICAL BEAM STEERING

blackmore



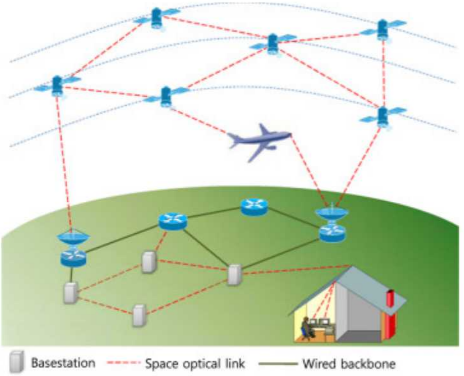
Phase Optimization of Si Photonics
2D Electro-optic Phased Array
(CLEO -Thur May 9 JTh2A.39)

2D Silicon Photonic Optical Beam Scanner

- 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-mm pitch
- Area: 750mm x 750mm with high fill factor

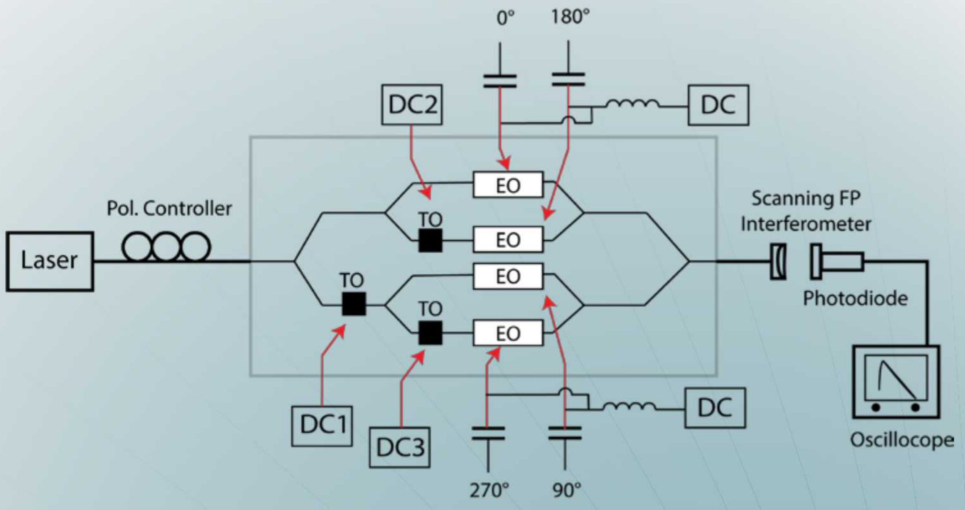
Applications

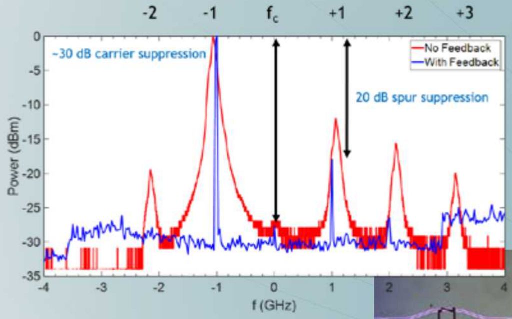
- Imaging and sensing
- Free-space communication



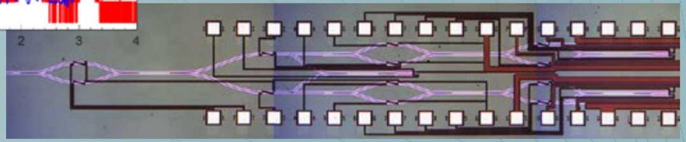
Digital Communications and Networks, 3(2), pp. 67-77, May 2017

SILICON PHOTONICS OPTICAL SINGLE-SIDEBAND MODULATOR





30dB carrier suppression
20dB sideband suppression
with active feedback



Silicon Photonic Single-Sideband Generation
with Dual-Parallel Mach-Zehnder Modulators
(Thur May 9 STh4N.6)

Frequency shifting/conversion for many applications

- high-resolution spectroscopy
- dense wavelength division multiplexed (D-WDM) networks
- atom interferometry / quantum sensing

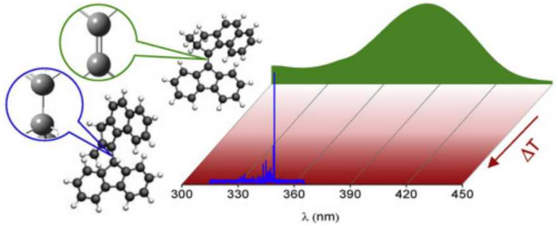


Photo Credit: Tetrahedron, 73(33, pp. 4887-4890, Aug 17, 2017

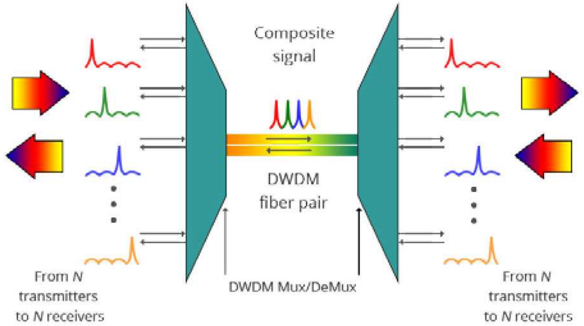


Photo Credit: https://community.fs.com/blog/an-overview-of-dwdm-technology-and-dwdm-system-components.html

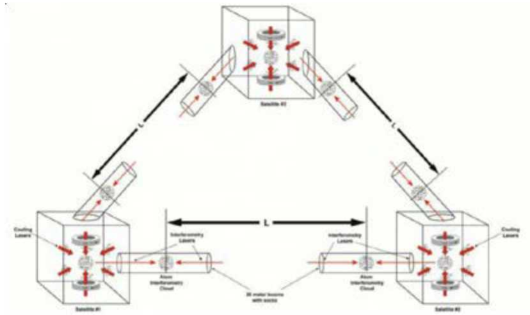
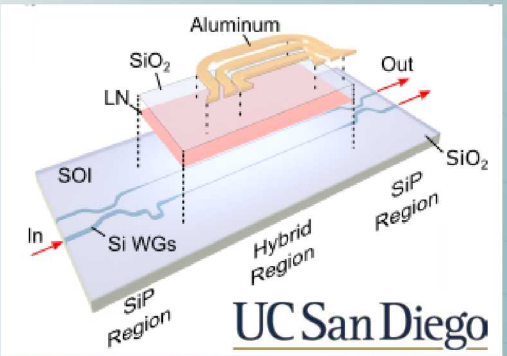


Photo Credit: https://www.nasa.gov/content/atom-interferometry-for-detection-of-gravity-waves-a/

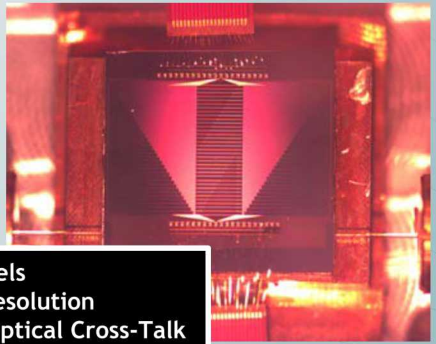
INTEGRATED SILICON PHOTONICS for RF SIGNAL PROCESSING

Optics Express 26 (18), 23728-23739, July 2018

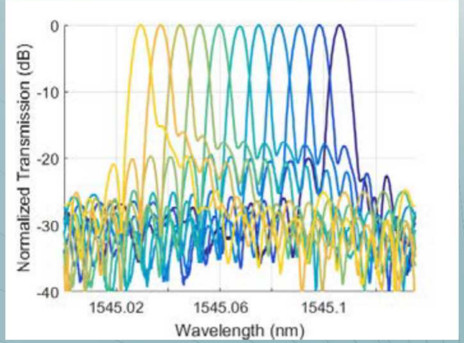


Lithium Niobate on Silicon
100+GHz Bandwidth demonstrated

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



11 Channels
<1 GHz Resolution
<-15 dB Optical Cross-Talk
1.1 cm^2 Total Area

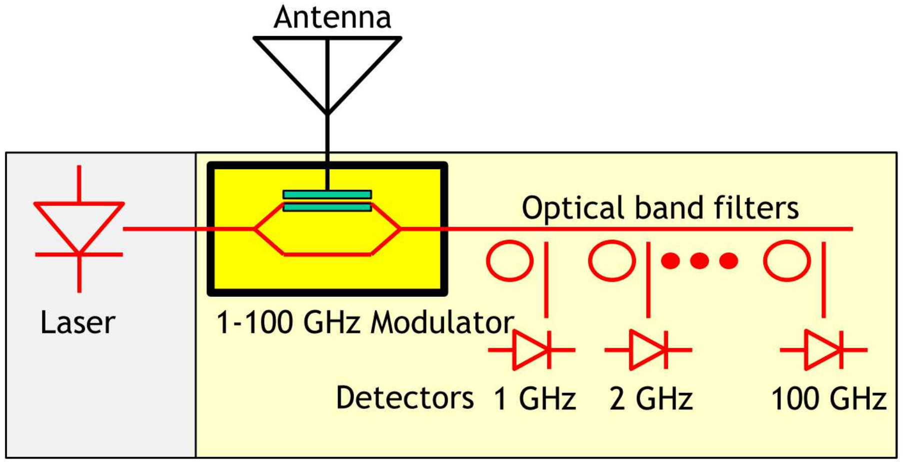


1st Demo of 1GHz RF Channelization in a Si Photonics Array Waveguide Grating

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

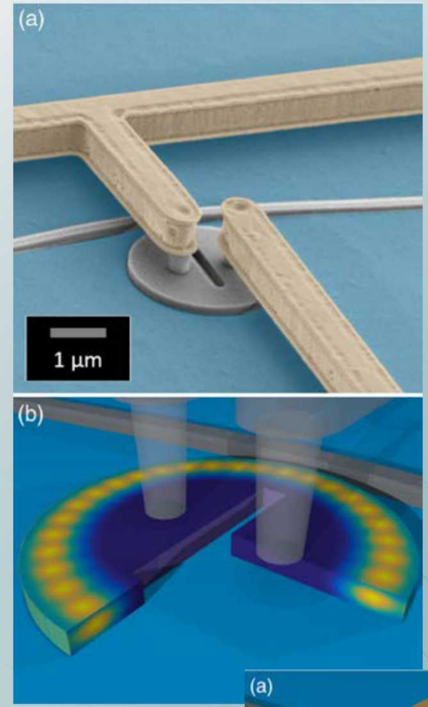
Applications in space and avionic platforms for electronic warfare and situational awareness

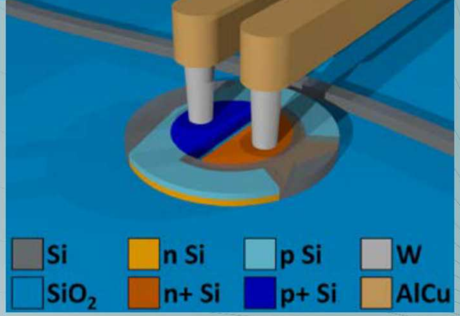
- Frequency up/down-conversion
- Antenna remoting
- RF over fiber
- Wide-band channelization
- Low loss RF delay lines



Example integrated wide-band channelizer

CRYOGENIC OPTICAL INTERCONNECT

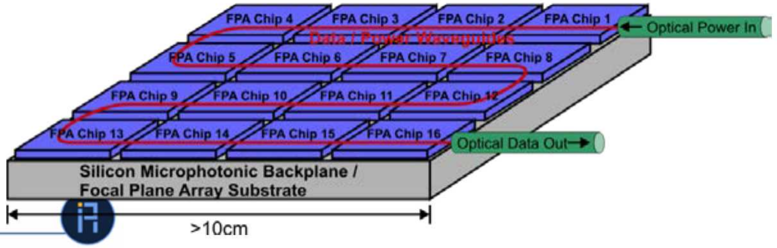


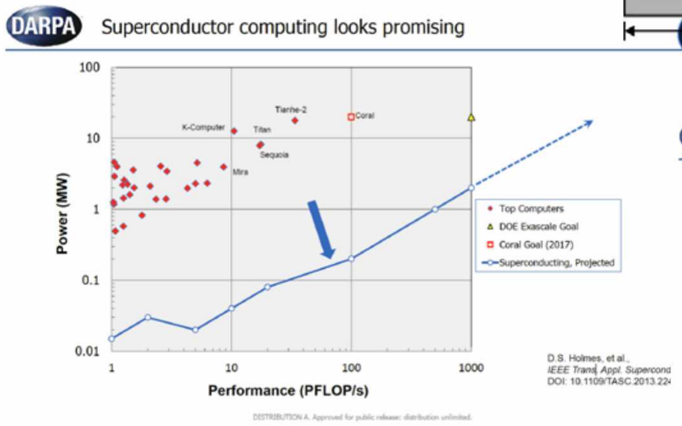


Optica **4,** 374-382 (2017)

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

- Superconducting Computing
- Optical backplane for focal plane array





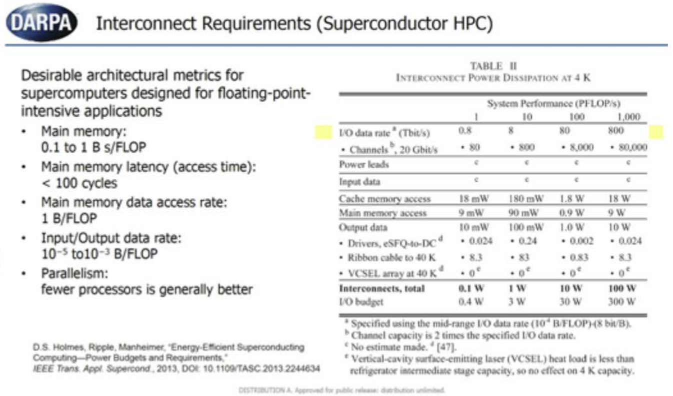


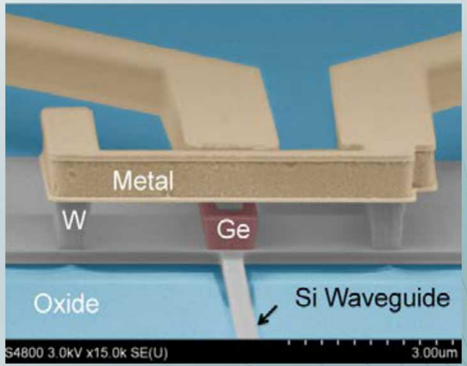
TABLE II
INTERCONNECT POWER DISSIPATION AT 4 K

	System Performance (PFLOP/s)			
	1	10	100	1,000
I/O data rate [a] (Tbit/s)	0.8	8	80	800
• Channels [b], 20 Gbit/s	• 80	• 800	• 8,000	• 80,000
Power leads	c	c	c	c
Input data	c	c	c	c
Cache memory access	18 mW	180 mW	1.8 W	18 W
Main memory access	9 mW	90 mW	0.9 W	9 W
Output data	10 mW	100 mW	1.0 W	10 W
• Drivers, eSFQ-to-DC [d]	• 0.024	• 0.24	• 0.002	• 0.024
• Ribbon cable to 40 K	• 8.3	• 83	• 0.83	• 8.3
• VCSEL array at 40 K [d]	• 0 [e]	• 0 [e]	• 0 [e]	• 0 [e]
Interconnects, total	**0.1 W**	**1 W**	**10 W**	**100 W**
I/O budget	0.4 W	3 W	30 W	300 W

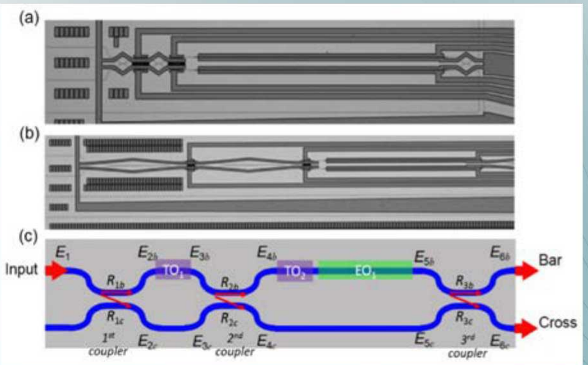
[a] Specified using the mid-range I/O data rate (10^{-4} B/FLOP)·(8 bit/B).
[b] Channel capacity is 2 times the specified I/O data rate.
[c] No estimate made. [d] [47].
[e] Vertical-cavity surface-emitting laser (VCSEL) heat load is less than refrigerator intermediate stage capacity, so no effect on 4 K capacity.

D. Scott Holmes DARPA MTO Program Manager
2nd Photonics and Electronics Technology for Extreme-scale Computing (rePETE) Workgroup presentation 2019-05-02

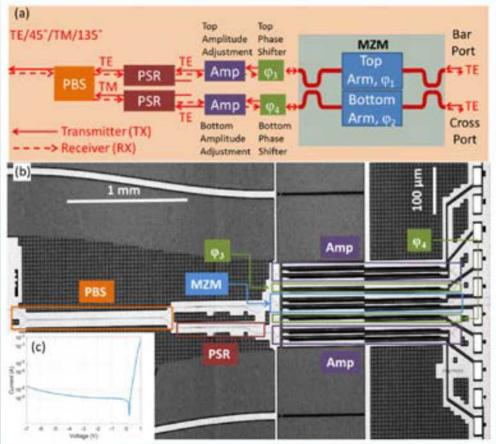
INTEGRATED PHOTONICS for QUANTUM COMMUNICATION



Geiger-mode APD
for single photon detection



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

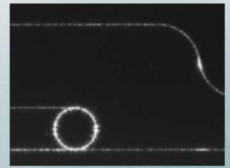


2016 R&D 100 WINNER

T-QUAKE (Transceiver for Quantum Keys and Encryption)

Phys. Rev. X 8 (021009), 1-12, April 2018

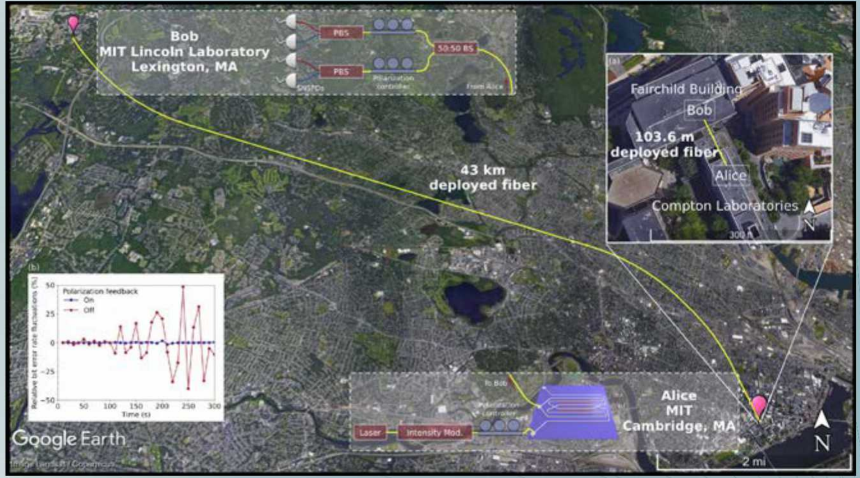
Sandia's silicon, III-V, alumina, lithium niobate heterogeneously integrated photonic platforms enable compact microsystems for telecom. and visible wavelengths



Alumina ring filter /waveguide for visible wavelength

Many foundational building blocks for advancing quantum science have been or are being developed

- detectors, modulators, frequency converter, amplifiers, optical transceivers, etc.



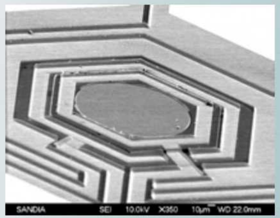
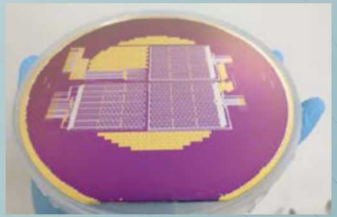
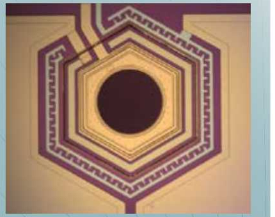
MIT LINCOLN LABORATORY

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

FedBizOpps Announcement: Technology Commercialization Opportunity:
Partnership Opportunity for On Chip QKD Technology Development:
16_462 9/29/2016

HETEROGENEOUS INTEGRATION CAPABILITIES

Microsystem-Enabled Photovoltaics

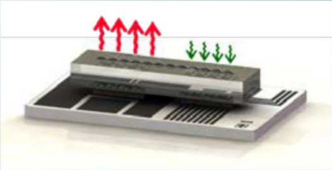
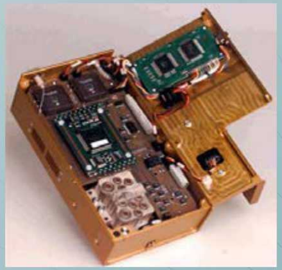
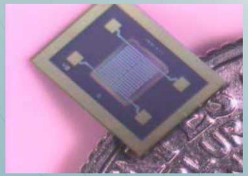
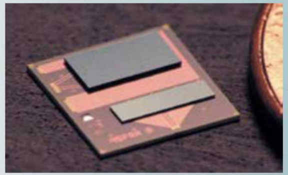
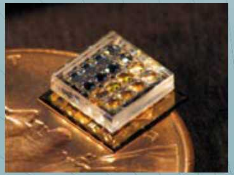




- wafer-level bonding for multi-junction solar cells
- InGaAsP/InP and InGaP/GaAs devices on silicon
- dielectric interfaces with III-V substrate removal
- integration with collection optics

Heterogenerous integration enables miniaturization with independent material and device optimization

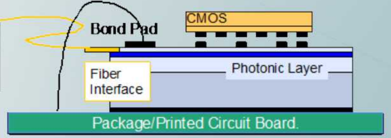
- Integration of $LiNbO_3$ and III-V Lasers on Silicon Photonics
- Non-traditional materials such as Al_2O_3, Epsilon-Near-Zero In_2O_3 and CdO, graphene
- Integration of CMOS with InGaAsP/InP, InGa/GaAs, Silicon Photonics, and other materials

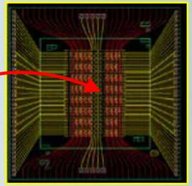
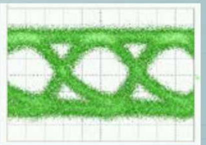
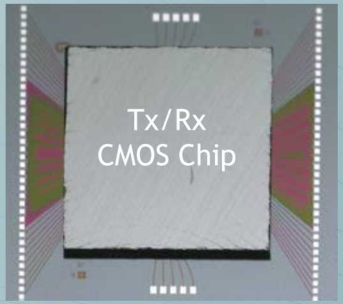
Optical and MEMS-based Microsensors

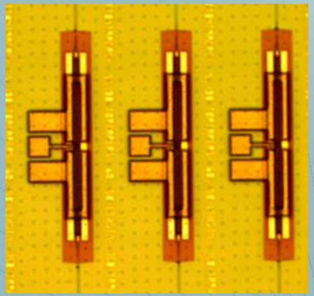






- chemical and bio sensors using MEMS and SAW devices
- g-hard optical microsensors with in-house photonics
- hybrid device integration with custom micro-optics

CMOS / Silicon Photonics / III-V Integration



Tx/Rx Si Photonic Chip

- silicon photonics on high-speed silicon ASIC
- independent optimization of electronics & photonics
- Gain and laser sources on silicon

Photonics Partnerships

Examples of industry and academia partnerships

HISTORY OF TECHNOLOGY TRANSFER SUCCESS

Cleanroom

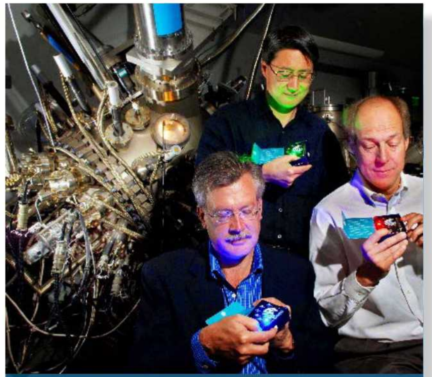
Sandia's invention of the original modern-day cleanroom led to $50 billion worth of laminar-flow cleanrooms being built worldwide within only a few years.

Microelectronics & Semiconductors

Sandia helped revolutionize the semiconductor industry by licensing LIVA/TIVA, VCSEL, EUVL, and 3D-stacking technologies to some of the world's leading semiconductor manufacturing companies.

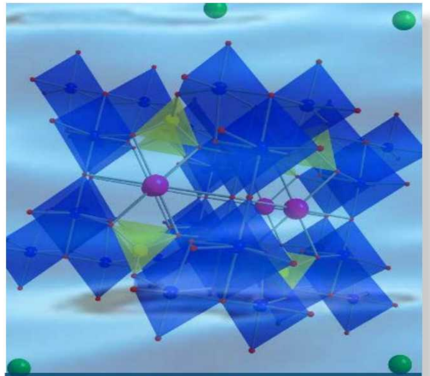
Decon Foam

A Sandia-developed chemistry for neutralization of chem/bio warfare agents that was first used for the anthrax attacks of 2001, is now being used by multiple companies for rapid decontamination applications.



Solid State Lighting

Sandia's early R&D of solid-state lighting has helped establish a global industry for LED/OLED technologies in which improved efficiencies could lead to $120B in estimated annual global energy savings.



Crystalline Silico -titanate (CST)

Sandia's CST technology was used by UOP, LLC to remove radioactive material from more than 43 million gallons of contaminated wastewater at Japan's damaged Fukushima Daiichi nuclear power plant.

Synthetic Aperture Radar (SAR)

Sandia has worked extensively with General Atomics to deploy Sandia's SAR systems for the US military and other customers. One version of the technology has been uncovering IEDs in Afghanistan and Iraq since 2009.

1960s — *1980s* — *1990s* — *2000s* — *2010s*

COLLABORATION WITH SANDIA

Federal agencies can engage in an interagency agreement with NNSA to obtain the Labs' unique services under Sandia's management and operating contract with DOE/NNSA.

Non-federal entities may enter into a variety of technology partnerships agreements with Sandia:

- Commercial License Agreement
  - ~40 Silicon photonics patents
  - >60 III-V patents
  - >15 metamaterials patents
- Cooperative Research and Development Agreement (CRADA)
- Strategic Partnership Projects/Non-Federal Entity (SPP/NFE) Agreement

Collaborate with us!

Visit us:

- @ CLEO Booth 1324
- On-line: sandia.gov/mesa/nspc

Email contact:

- Photonics@sandia.gov

Career Opportunies for staff and students:

- www.sandia.gov/careers