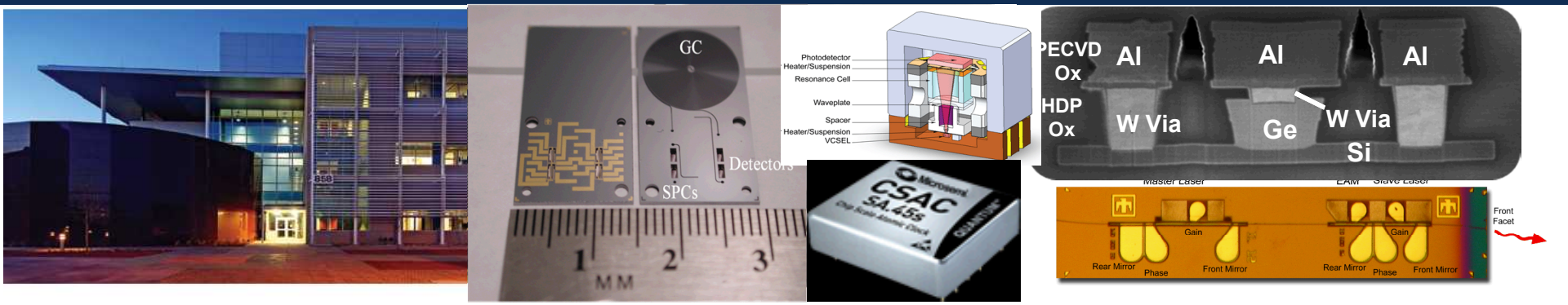
SAND2015-5662C

Exceptional service in the national interest

Sandia National Laboratories



III-V's from Lab to Fab: Compound Semiconductor Devices and Integration Paths to Manufacturing

Greg Peake

Principal Member Technical Staff

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U.S. DEPARTMENT OF ENERGY

National Nuclear Security Administration

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Introduction to Sandia National Laboratories and MESA

Foundational Technologies at MESA

Integration Challenges

Integration Paths

- **Mechanical**
- **Flip-Chip**
- **Wafer Bonding**
- **Direct Growth**
- **Micromachining**

Working With Sandia

Microsystems and Engineering Sciences Applications (MESA): 400,000 Sq-ft Complex with >650 Employees in Secure Facility

Sandia National Laboratories

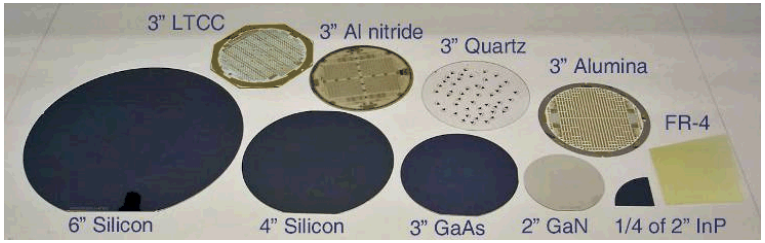
MESA is an FFRDC-based development and production facility for any microsystem component or technology that cannot or should not be obtained commercially.

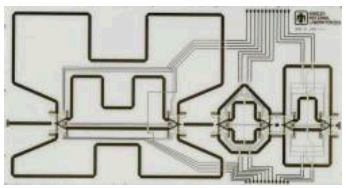
MESA Microfabrication Facilities

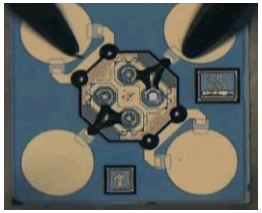
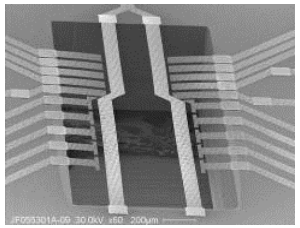
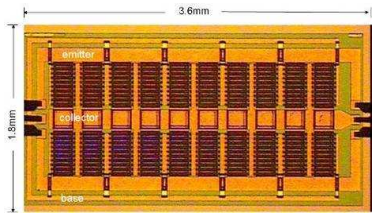
- MESA specializes in custom microelectronics, photonics, microtechnologies, and integrated systems
- NNSA's primary supplier of custom rad-hard ICs for weapon life extension programs and satellite systems
- Fast turn product capability: structured ASIC architecture
- Silicon bulk *and* silicon surface micromachining
- 6" silicon post-processing facility to support hybrid substrates and 3D integration (8" compatible)
- Compound semiconductor epitaxial growth
- Compound semiconductor discretes, IC's and MEMs
- Mixed-technology integration and processing
- Particularly suited to rapicly advance research concepts from TRL1-6 and deliver qualified products from TRL 7-9

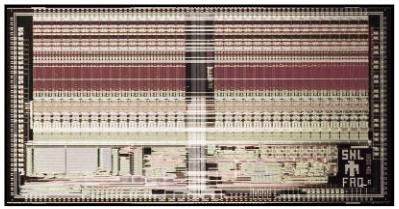
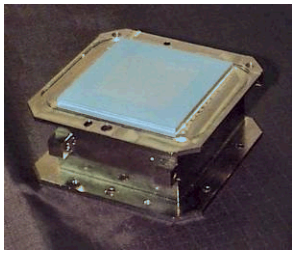
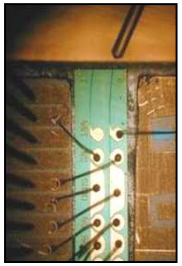
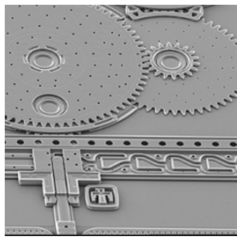
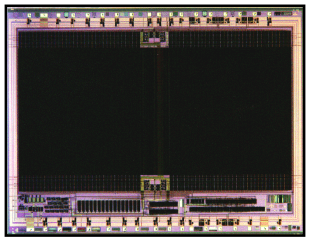
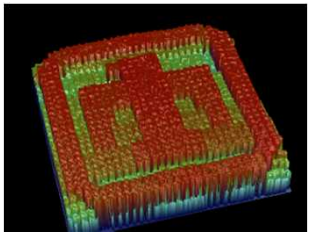
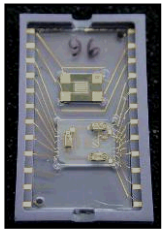
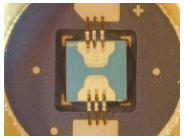
SiFab: 33,000 ft² Class 1/10/100

MicroFab: 16,600 ft² Class 10/100



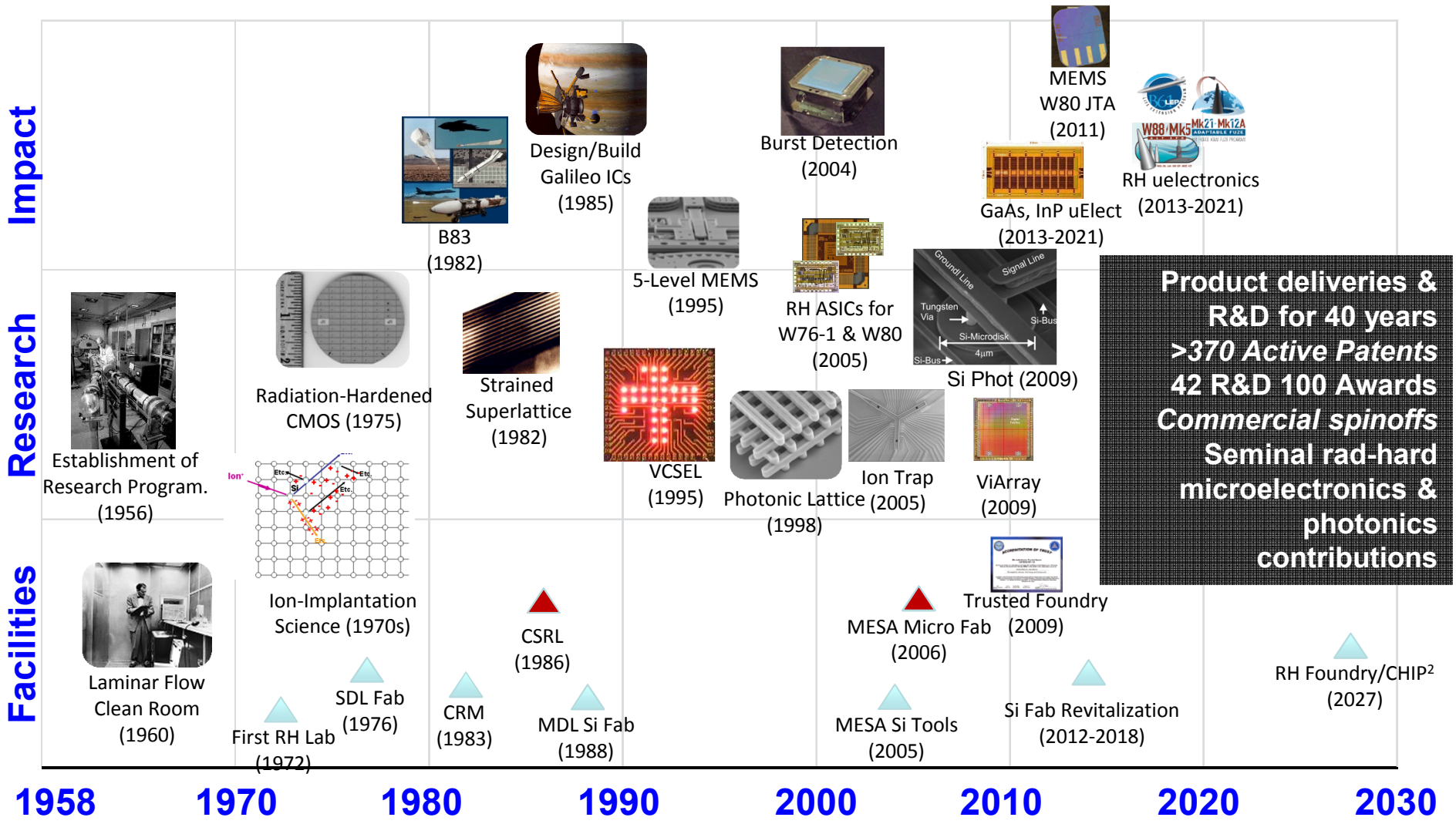


R&D enables and sustains Sandia's Radiation-Hardened Microelectronics/Microsystems Capability

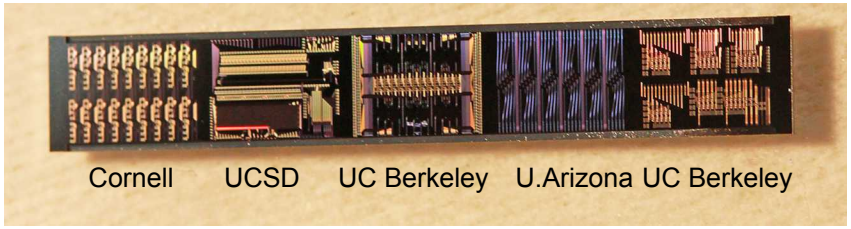
Sandia National Laboratories

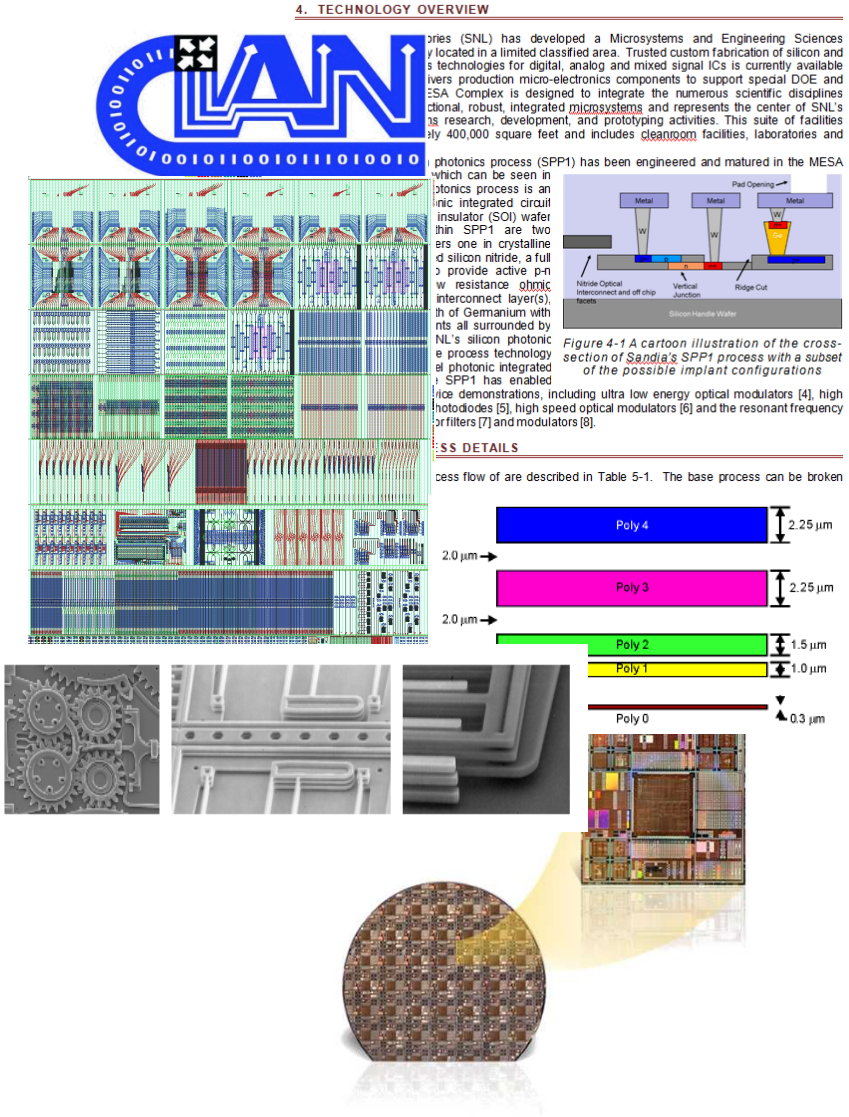


MISSION: Invent and mature integrated circuit and microsystems technologies that provide differentiation and impact for NW and other national security missions

Sandia and MPW Fabrication

- **SUMMIT V: 5 layer polysilicon MEMS process**
  - Developed design manual, DRC, many MPWs over the last decade
- **CMOS7 Electronics:** Rad-hard, mixed-signal ASIC/ViaArray: 0.35um, 3.3V core, 3.3V I/O, Cadence, MPWs since 2009
- **SPP1 Silicon Photonics Process:**
  - 250nm Si/3000nm BOx
  - fJ/bit mods, 45 GHz dets, filters, etc.
  - SiN 2-layer guides/xovers
  - Design manual, initial DRC, pilot MPW runs

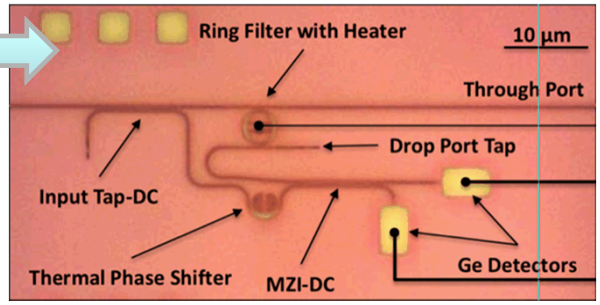


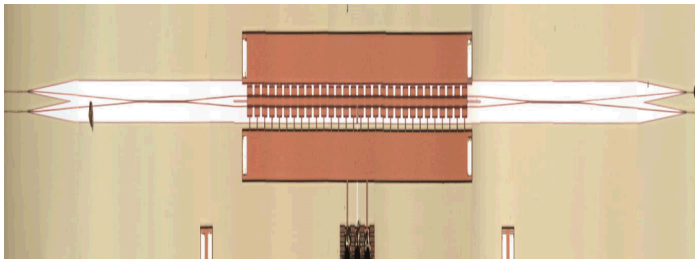


Trusted Advanced Pathfinder Products: Si Photonics

Sandia National Laboratories

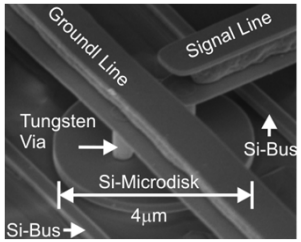
2014	*balanced homodyne resonant wavelength stabilization > 55C*
2013	*Si Photonics MPW (CIAN NSF ERC)*
2012	*24 GHz Si TW MZM*
2011	*45 GHz Ge Detector*
2010	*3 fJ/bit resonator modulator, 1V-cm MZM*
2009	*wavelength tunable rings over 35 nm*
2008	*2.4 ns Wavelength selective switch*
2007	*MicroDisk resonator infrared detector*
2005	*Si_3N_4 low-loss waveguides*
2000	*SiON / SiO2 (Clarendon Photonics)*
1990s	*Si PhC & Optical MEMS*



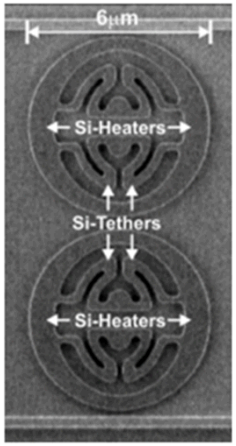


24 GHz 0.7V-cm Travelling Wave MZI Modulator

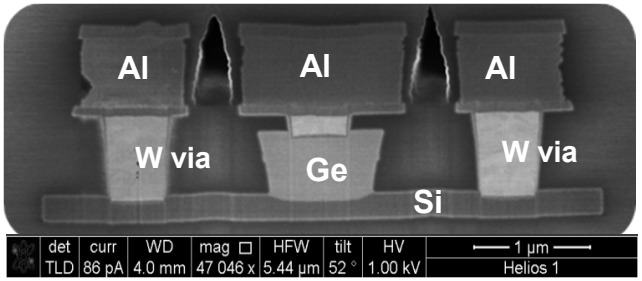
3.2fJ/bit at 12Gb/s



Resonant Optical Modulator/Filter

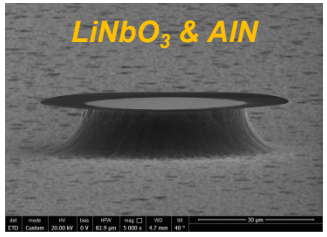


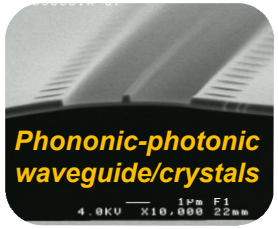
Tunable Resonant Filter



45 GHz High-speed Ge Detector on Si

MEMS process for additional capability

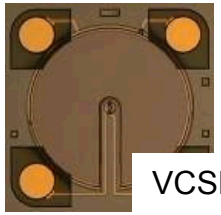




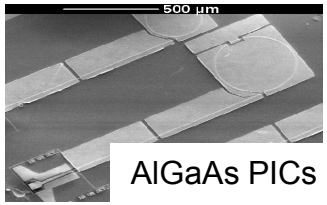
Trusted Advanced Pathfinder Products: III-V Photonics

2010s

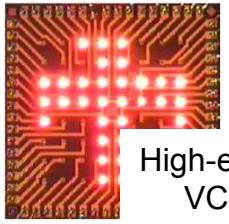
InGaAsP PICs



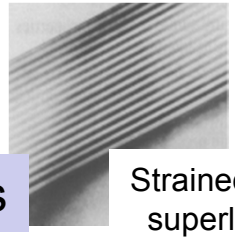
VCSEL+ PD



AlGaAs PICs

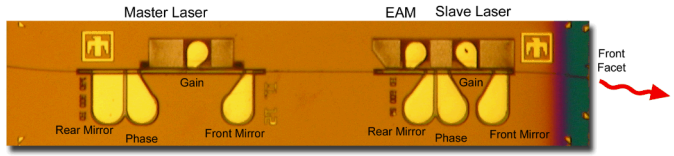


High-efficiency VCSELs

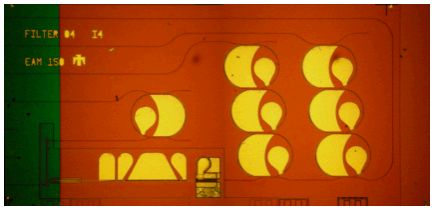


Strained-layer superlatices

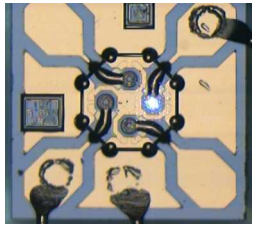
1980s



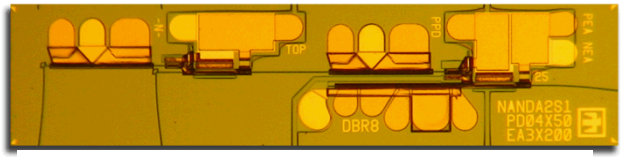
On-Chip Injection Locking
Enhanced Modulation > 50 GHz, C-Band



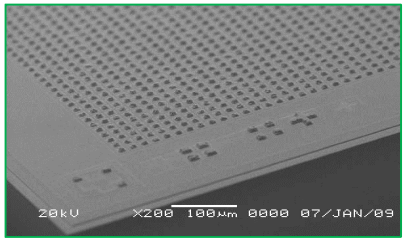
RF-Optical Channelizing Filter
1-20 GHz RF on C-Band Light



Single-Frequency Tunable VCSELs,
For atomic spectroscopy and sensors



All-Optical Logic at >40 Gb/s, C-Band



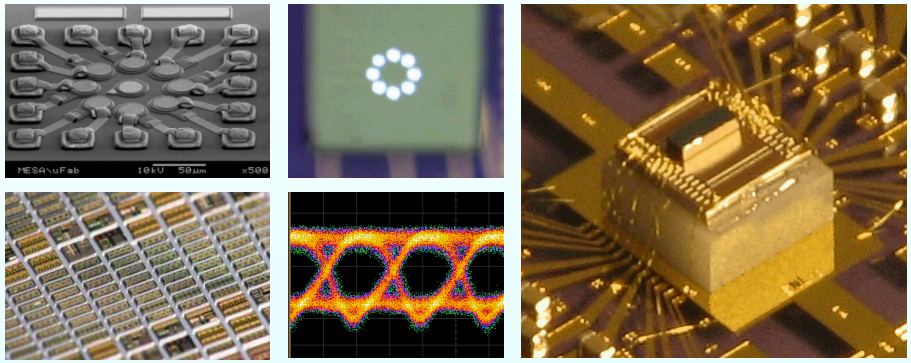
nBn FPAs in the SWIR, MWIR and LWIR,
leveraging novel III-P and III-Sb materials

- **Foundational Capabilities**
  - **III-V compound semiconductor epitaxy, microfabrication, integration**
  - **Device physics, modeling, simulation**
  - **Microelectronics/optoelectronics, and complex mono/hetero-circuits**
- **Prove, Advance Technology Readiness Level, Productize**
  - **TRL1-6+: create, develop, prototype**
  - **NNSA QMS/QC-1-10; trusted**
- **Trusted, low-volume, high-reliability products for harsh environments**

Trusted Advanced Pathfinder Products: Heterogeneous Integration

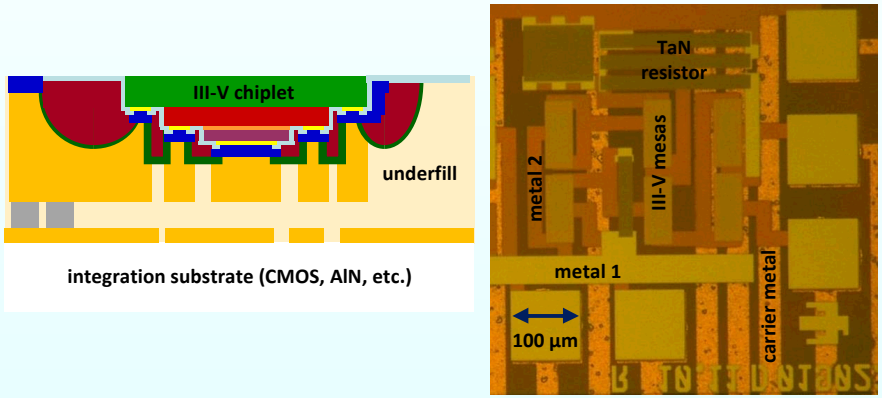
Sandia National Laboratories

Optical Data Communications



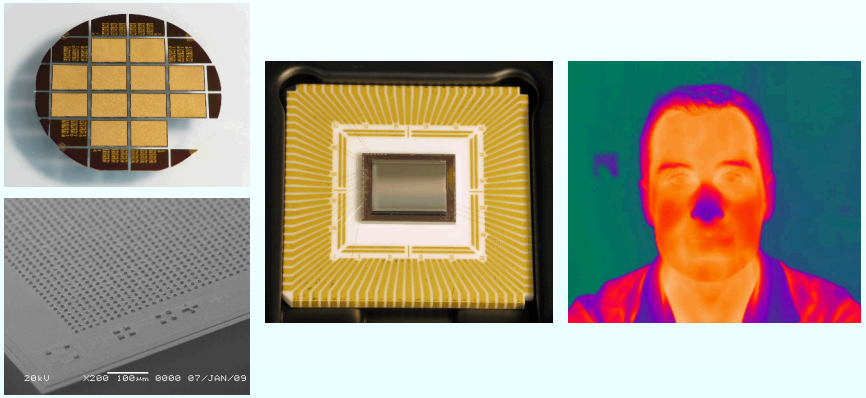
- GaAs- and InP-based devices: VCSELs, modulators, photodiodes
- dense integration onto 32-nm and 45-nm CMOS

Heterogeneous III-V/CMOS Microelectronics



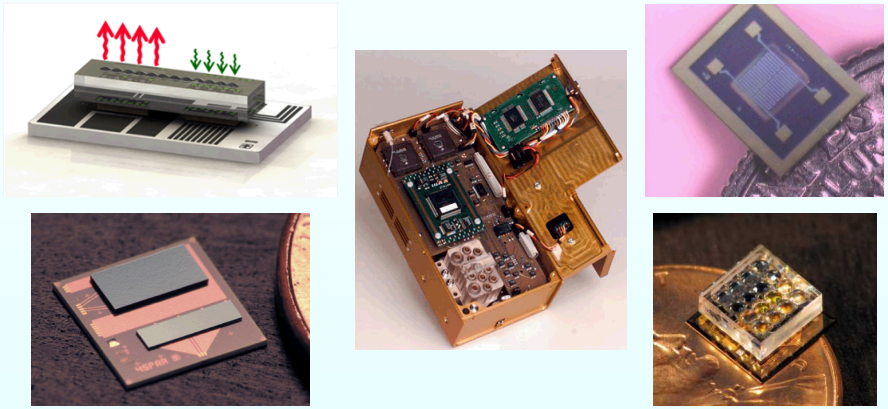
- complementary integration of GaAs and InP microelectronics
- III-V microelectronics circuitry on CMOS ASICs

IR Imagers for Remote Sensing



- nBn InAs/GaSb MWIR/LWIR detector arrays for large-format FPAs
- 10µm indium bump bonding, underfill, thinning, AR coating
- hybridization to silicon ROICs with >99.99% interconnect yield

Optical and MEMS-based Microsensors

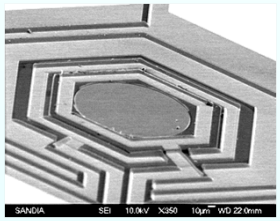
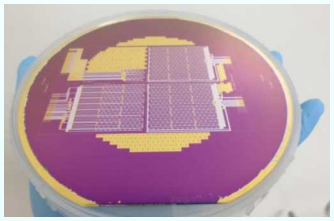
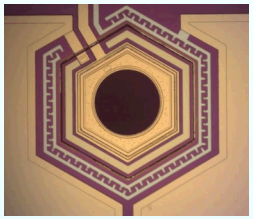


- chemical and bio sensors using MEMS and SAW devices
- g-hard optical microsensors with in-house photonics
- hybrid device integration with custom micro-optics

Trusted Advanced Pathfinder Products: Heterogeneous Integration

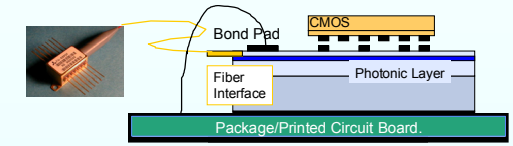
Sandia National Laboratories

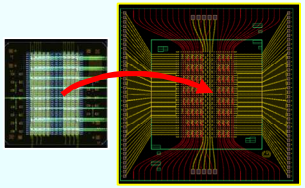
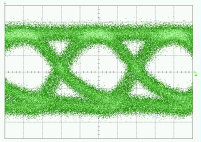
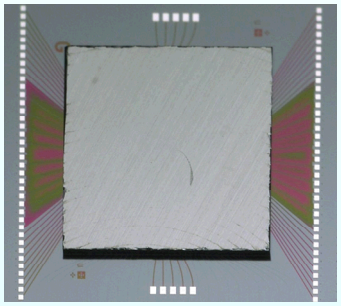
Microsystem-Enabled Photovoltaics

- 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

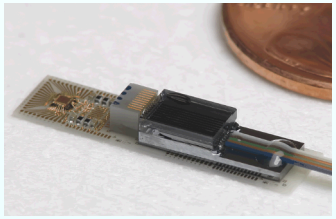
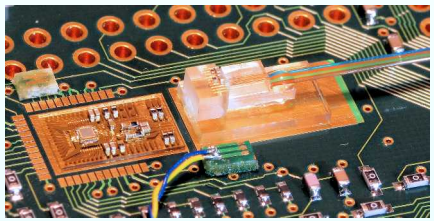
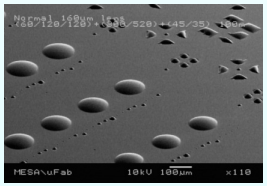
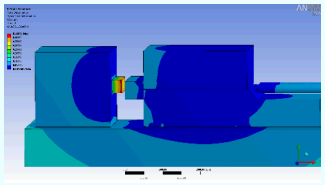
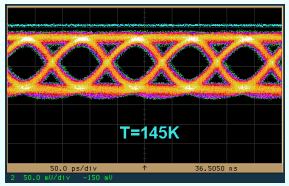
High Performance Computing



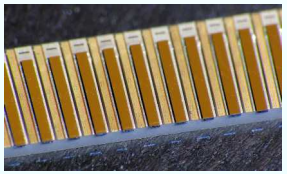
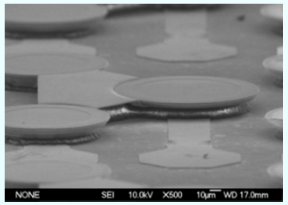
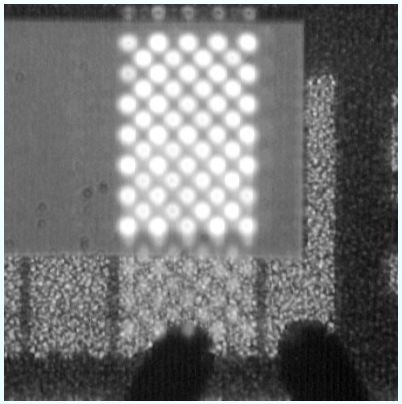
- silicon photonics on high-speed silicon ASIC
- independent optimization of electronics & photonics

Extreme Environment Applications

- custom photonics, optics, electronics for cryogenic interconnects
- advanced optoelectronics and integration for radiation hardness

High Performance Photonics

- high-power emitters on AlN and diamond
- RF packaging for high-speed test and measurement

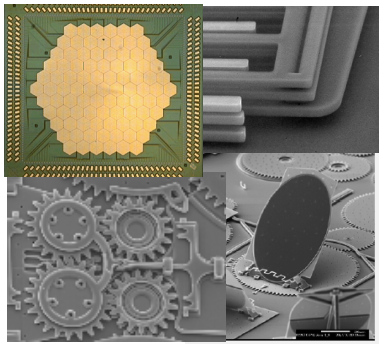
How Can Sandia Help?

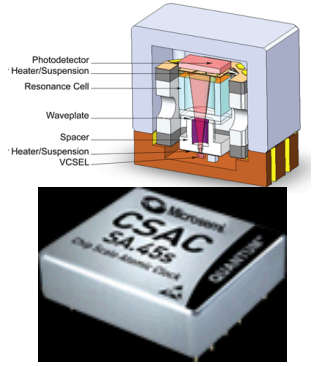
Sandia National Laboratories

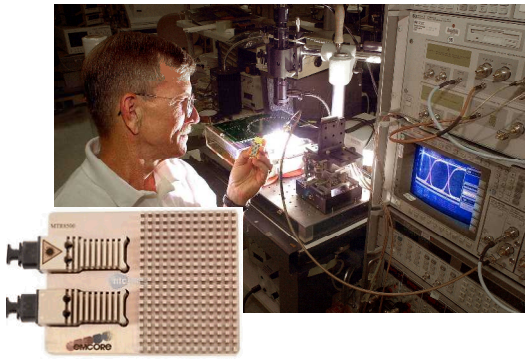
- **Expertise**: >30 years in III-V & Silicon Photonics R&D:
  - Toolboxes for internal and contract R&D
- **Capability**: Large flexible Si & III-V R&D Fab, Production rigor:
  - 65kft^2 fab, 10 epi reactors, >60 photonics staff, (60% Ph.D.)
  - Here today, here tomorrow…(NW IC deliveries)
  - Secure environment & staff, robust info-control (TRUST)
- **History of Technology Transfer to Industry**:

Processes → Devices → Subassemblies → Systems

MEMS (Fairchild)	**VCSEL CSAC (Microsemi)**	**POM (EMCORE)**	**SAR (General Atomics)**
Transfer of Sandia's Summit IV™ MEMS technology. Network Photonics Optical MEMS	Narrow λ temp-stable VCSEL for Chip-scale Atomic Clock (DARPA)	OC-192 Transponder Parallel Fiber Optic Module prototype development using VCSEL & PD arrays	Copperhead & Lynx SAR (w/ GA Aero) on TigerShark & Predator UAVs (IED detector being transferred to Army)







Understanding the Challenges of III-Vs on Si

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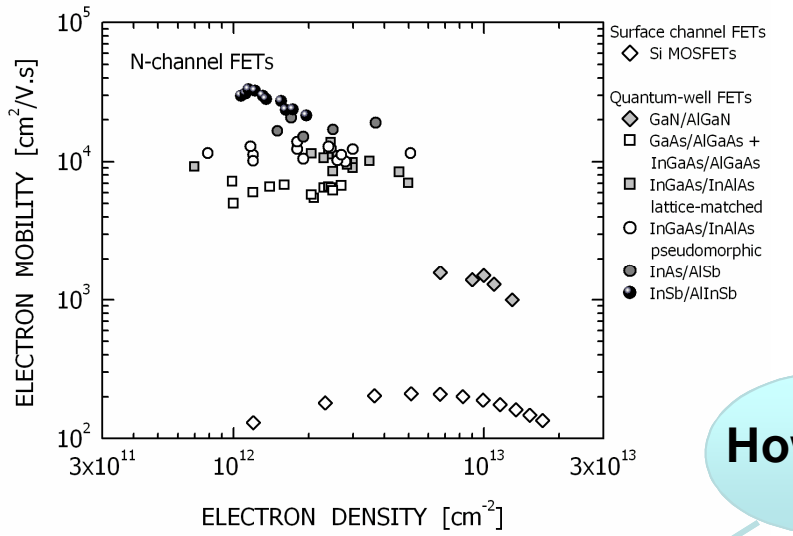
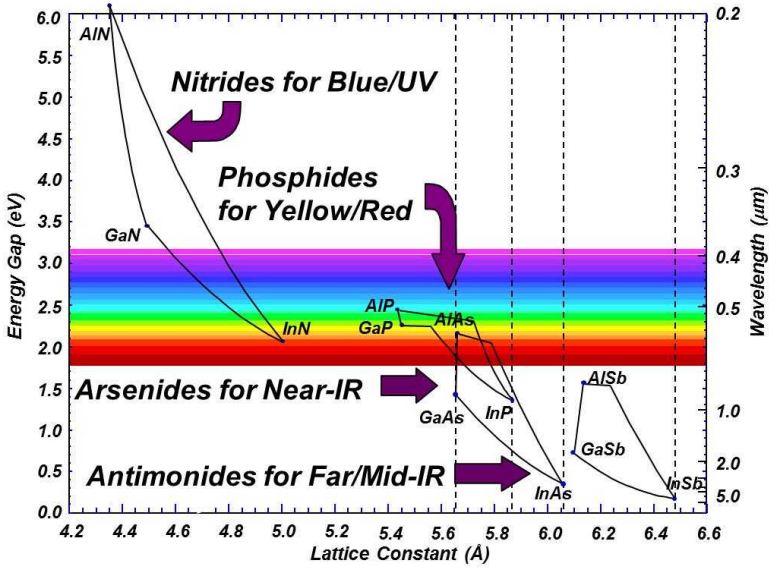
Superior Characteristics



Lattice Matching Challenges



However

ESH Challenges

Hazardous Production Materials

AsH_3 – 3 ppm IDLH

PH_3 – 50 ppm IDLH

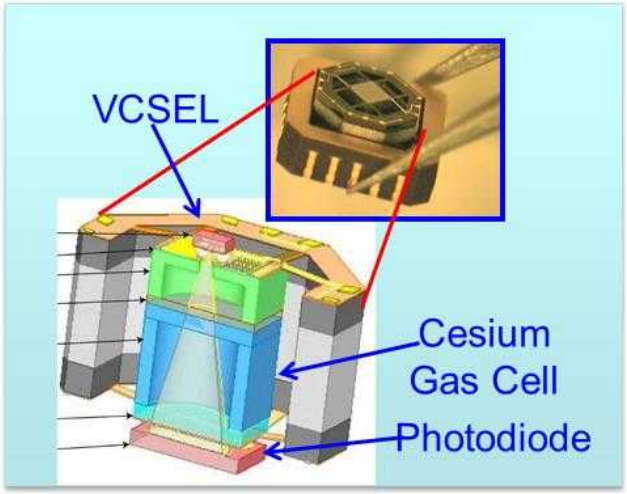
$III(CH3)_3$ are pyrophoric

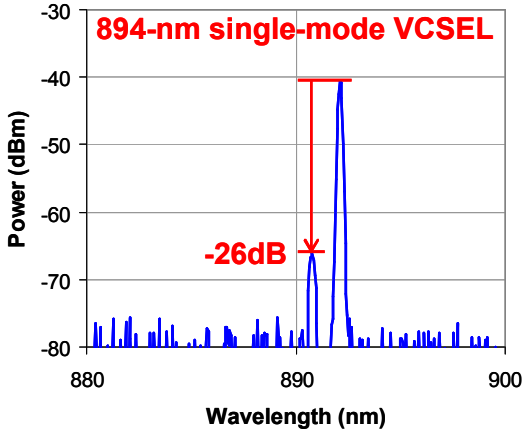
H2 carrier gas run at 24 lpm/Tool

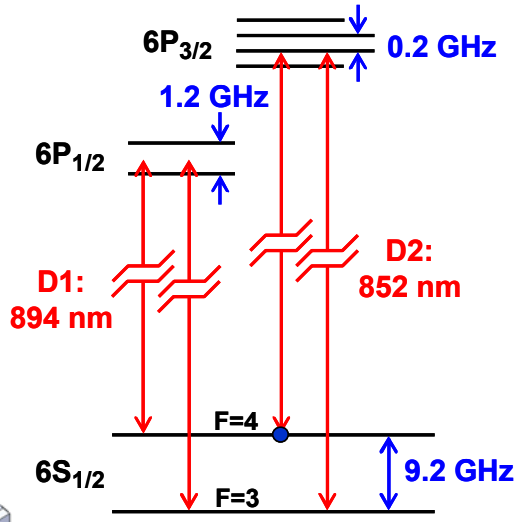
And more…

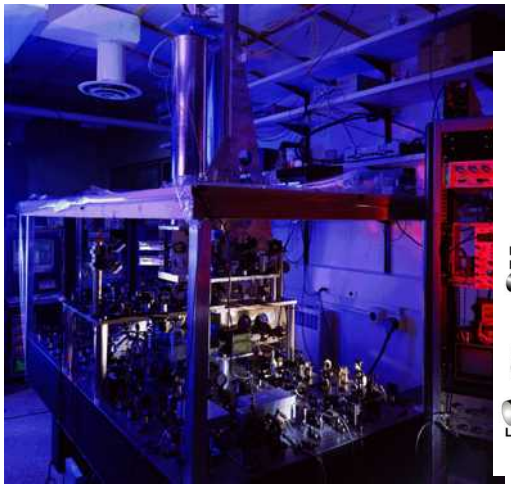
Widely varying TCE
Directional Properties
Surface Termination is complex
Heterogeneous interfaces must be understood
Etc…

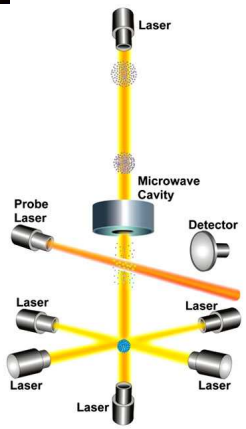
Mechanical Integration – Chip Scale Atomic Clock

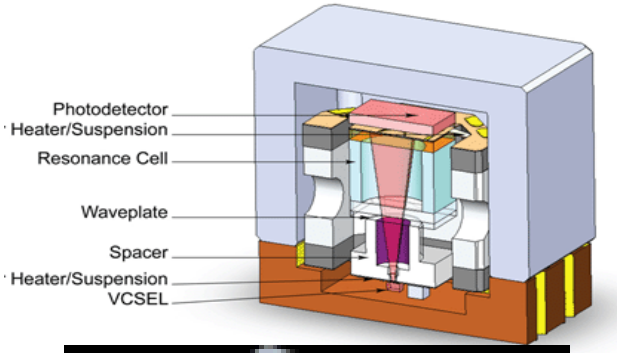












Silicon Micromachining – µChemlab

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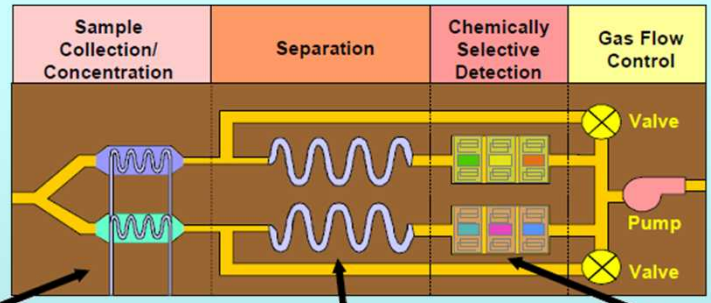
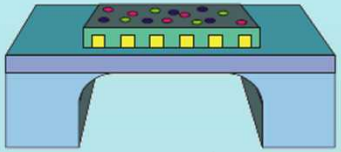
Unifying Concept of Operation

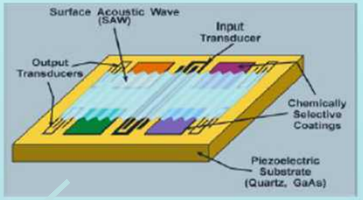
Preconcentrate

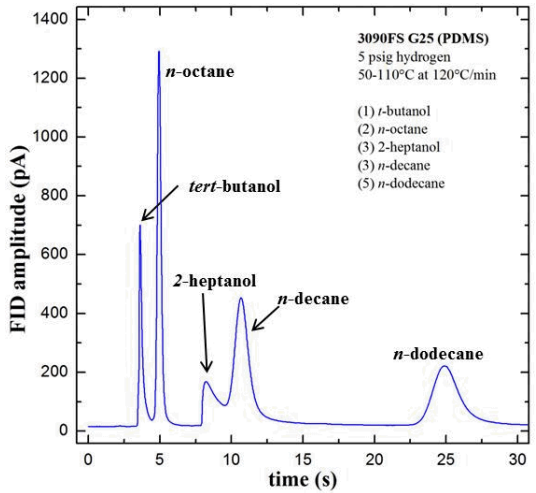


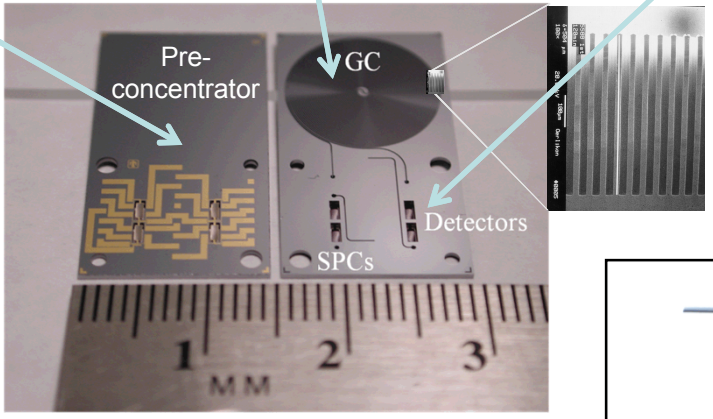


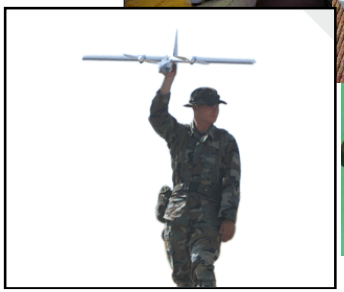
Separate

Detect





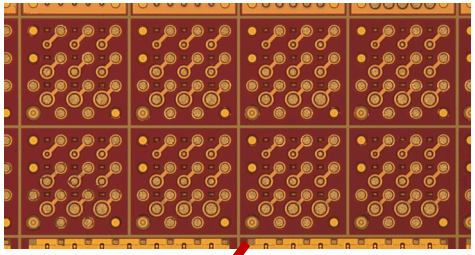


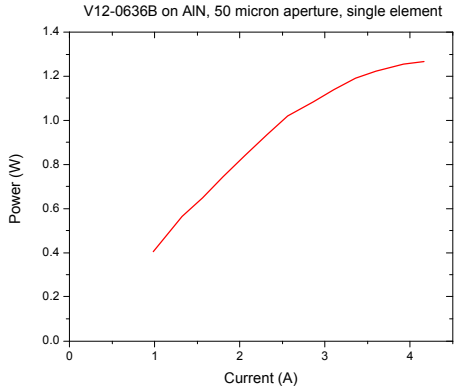


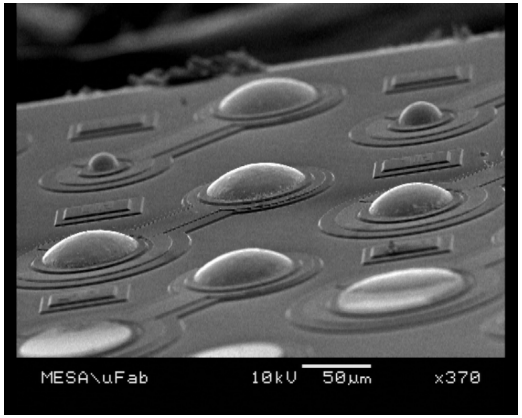
Flip-Chip Integration – Tx Rx Assemblies

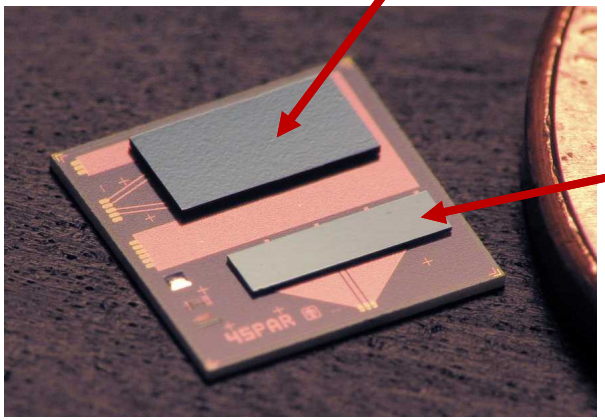
- **1x4 VCSEL arrays & 2x4 detector arrays attached to submount**
  - **parallel drive of VCSELs for low impedance**
  - **parallel connection of PDs to sum photocurrent signal**
- **Assemblies tested electrically prior to microlens integration**

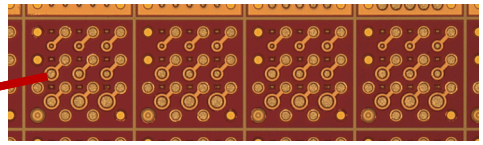
2x4 InGaAs photodiode array



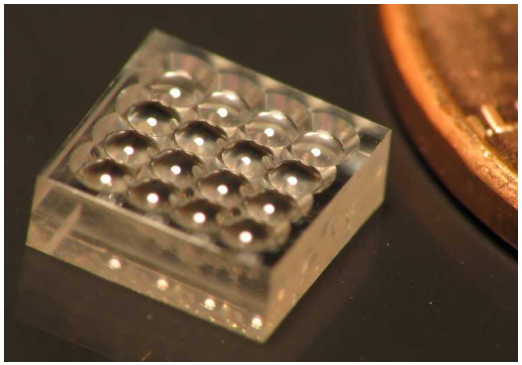








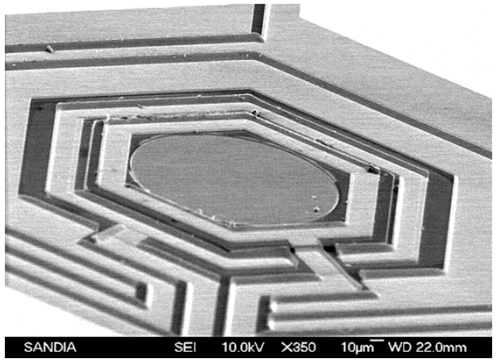
1x4 high-power VCSEL array
(980nm, bottom-emitting)

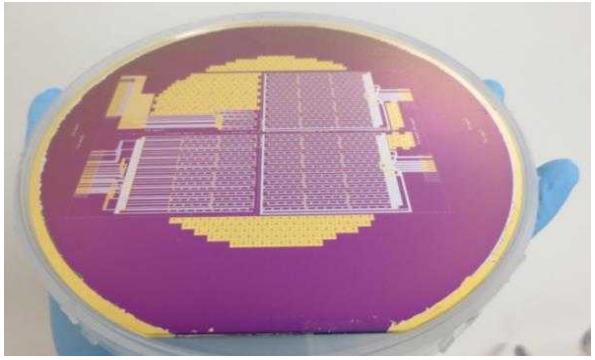


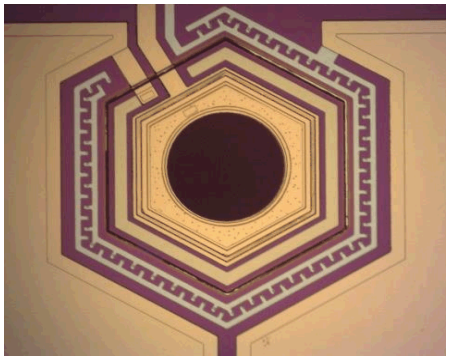
populated AlN fuse submount

Direct Wafer Bond Integration – Microsystems Enabled Photovoltaics

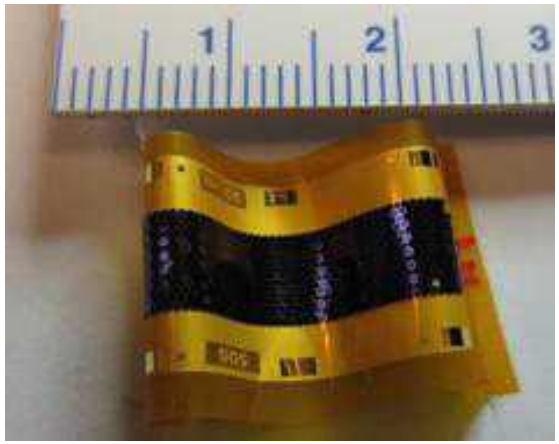
Sandia National Laboratories







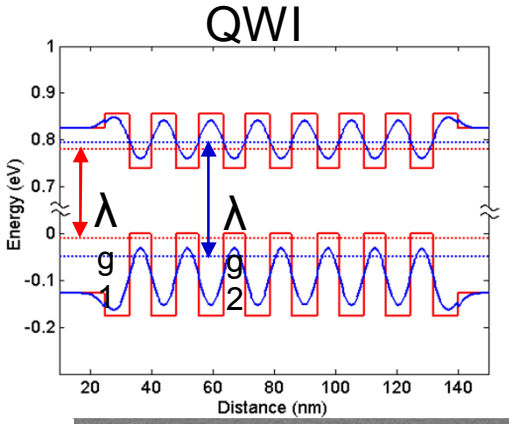
InGaAsP/InP and InGaP/GaAs devices on silicon

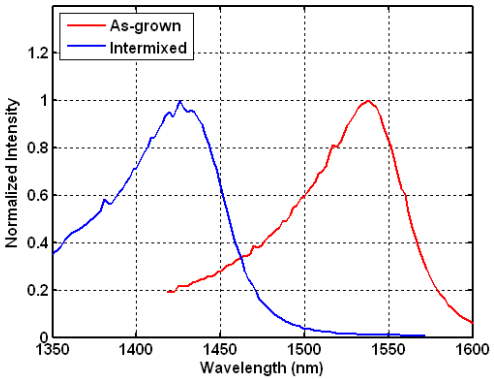


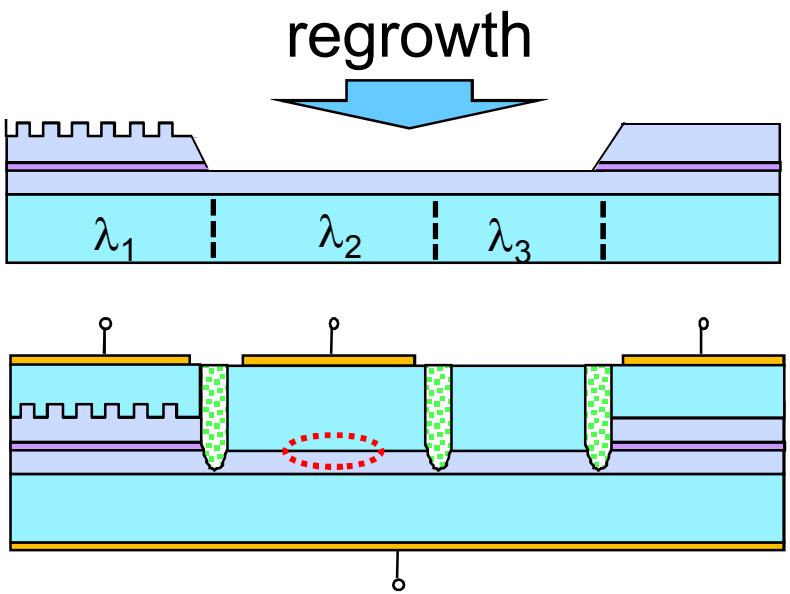
Flexible Substrates

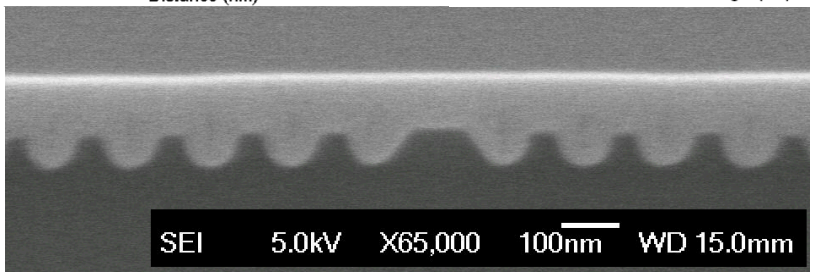
Collection Optics

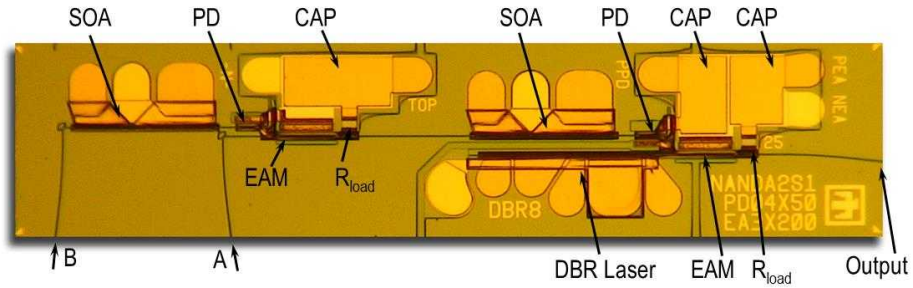
Direct Growth for Integration – Photonic Integrated Circuits



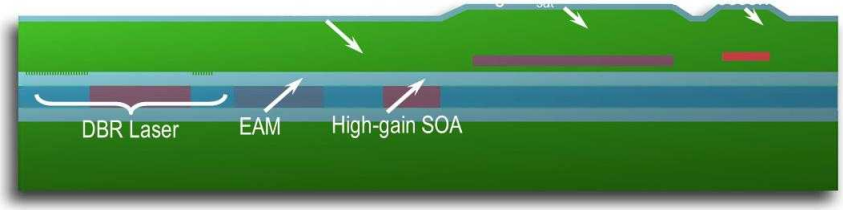




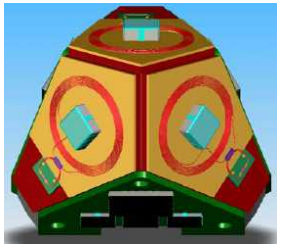




Top View of Photonic Integrated Circuit



Integrated PIC Assembly



Potential Roles and Engagement

Sandia National Laboratories

- **Competency and commitment in custom solutions for high reliability when industry is unable or unwilling to engage**
- **DOE supports National Lab involvement in strategy and project development for U.S. companies and universities with fairness of opportunity, without competing with industry, and with no organizational conflict of interest**
- **Decision to engage depends on unique value Sandia may contribute for enabling new understanding and securing a supply chain for national security applications**

Sandia has a diverse array of technical expertise and co-located SMEs allowing us to