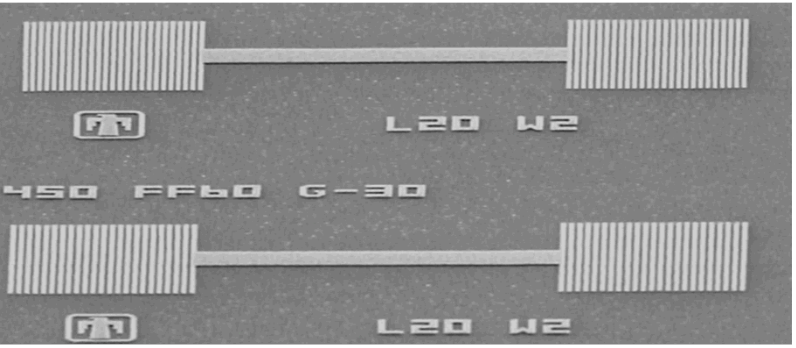
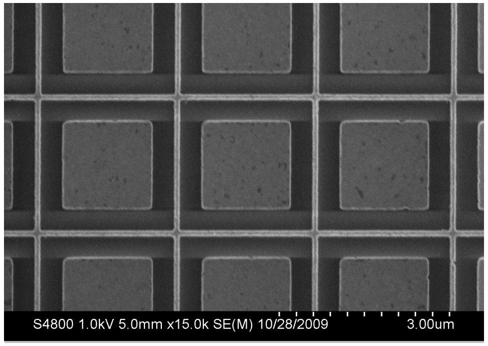
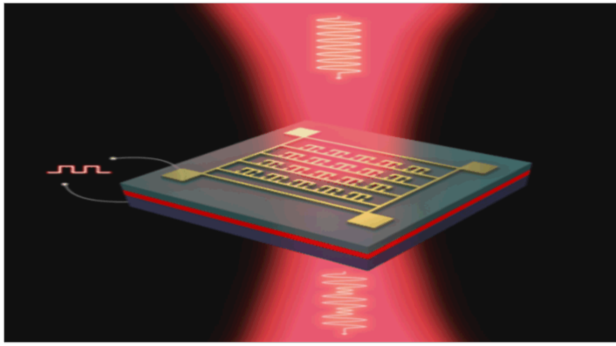
SAND2014-20201PE

*Exceptional service in the national interest*

Sandia National Laboratories



# Surface Wave Enabled Infrared Detectors

## (and other photonic and plasmonic devices)

**David W. Peters**

dwpeter@sandia.gov

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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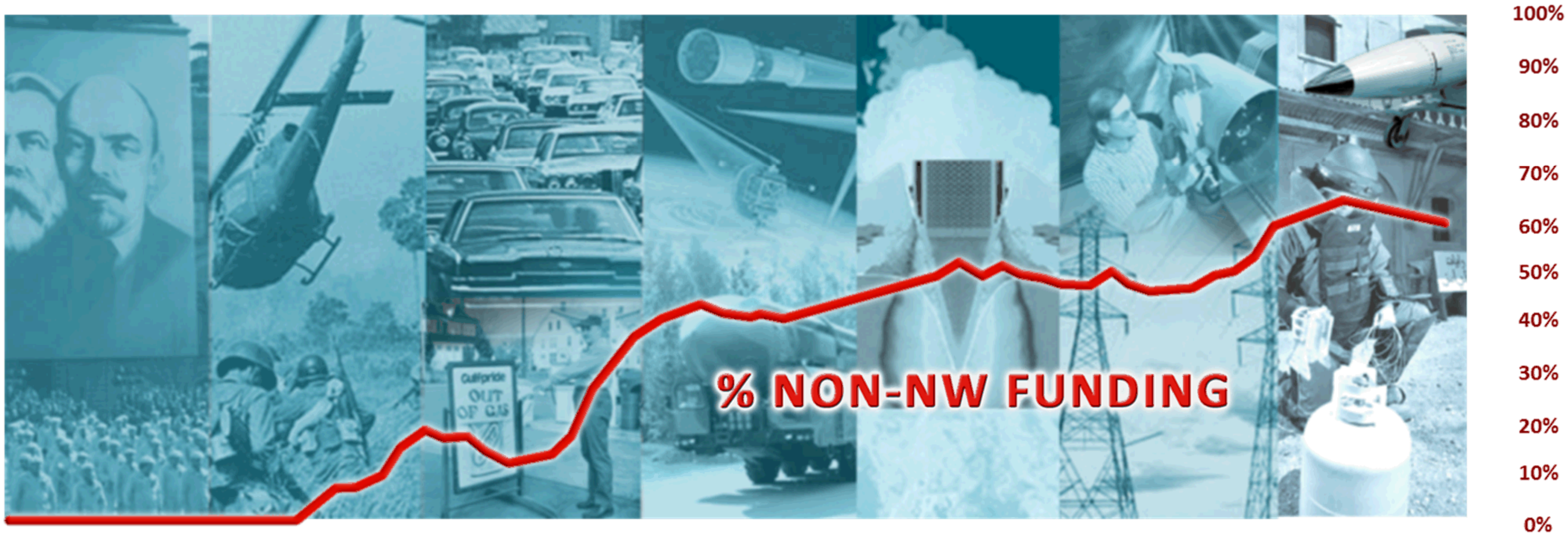
# Sandia National Laboratories

Sandia National Laboratories

| 1950s | 1960s | 1970s | 1980s | 1990s | 2000s | 2010s |
|---|---|---|---|---|---|---|
| NW production engineering & manufacturing engineering | Development engineering<br>Vietnam conflict | Multiprogram laboratory<br>Energy crisis | Missile defense work<br>Cold War | Post–Cold War transition<br>Stockpile stewardship | Expanded national security role post 9/11 | LEPs<br>New START<br>Evolving national security challenges |




- DOE FFRDC: Initially Z-division of Manhattan Project (Non-nuclear components, weaponization of NEP)
- **National security tech transition**: Gov't agencies (and/or academia) ➔ SNL ➔ Industry
- Our Big 3: Non-compete with Industry, Fairness of Opportunity, No Organizational Conflict of Interest
- Managed by LMC (but see OCI above)
- CRADAs with many defense contractors, many STTRs & SBIRs, BAA response teaming
- Experience handling sensitive & proprietary information
- DOE supports our "Strategic Partnership Projects" (with industry & other gov't agencies (OGAs))

# Microsystems and Engineering Sciences Applications (MESA)

Sandia National Laboratories

Manufactures strategic radiation-hardened trusted components for nuclear weapons


**Radiation Hardened ASICs**
- >25,000 deliveries

**Radiation Hardened HBTs**
- >150,000 deliveries

***TRUST environment (NW, DMEA)***

***Strong Failure Analysis/Reliability***

# MESA: 400,000 ft$^2$ Complex with >650 Employees in a Secure Facility

- Trusted Digital, Analog, Mixed Signal & RF Integrated Circuits Design & Fabrication
- Custom IC Design
  - Secure microcontrollers
  - Sensor Readout ICs
  - Analog/Digital/RF
  - IBM Trusted Foundry
  - Tamper Resistant
- Micromachining
- RAD Effects and Assurance
- Failure Analysis, Reliability Physics
- Test & Validation
- 3-D Integration Features

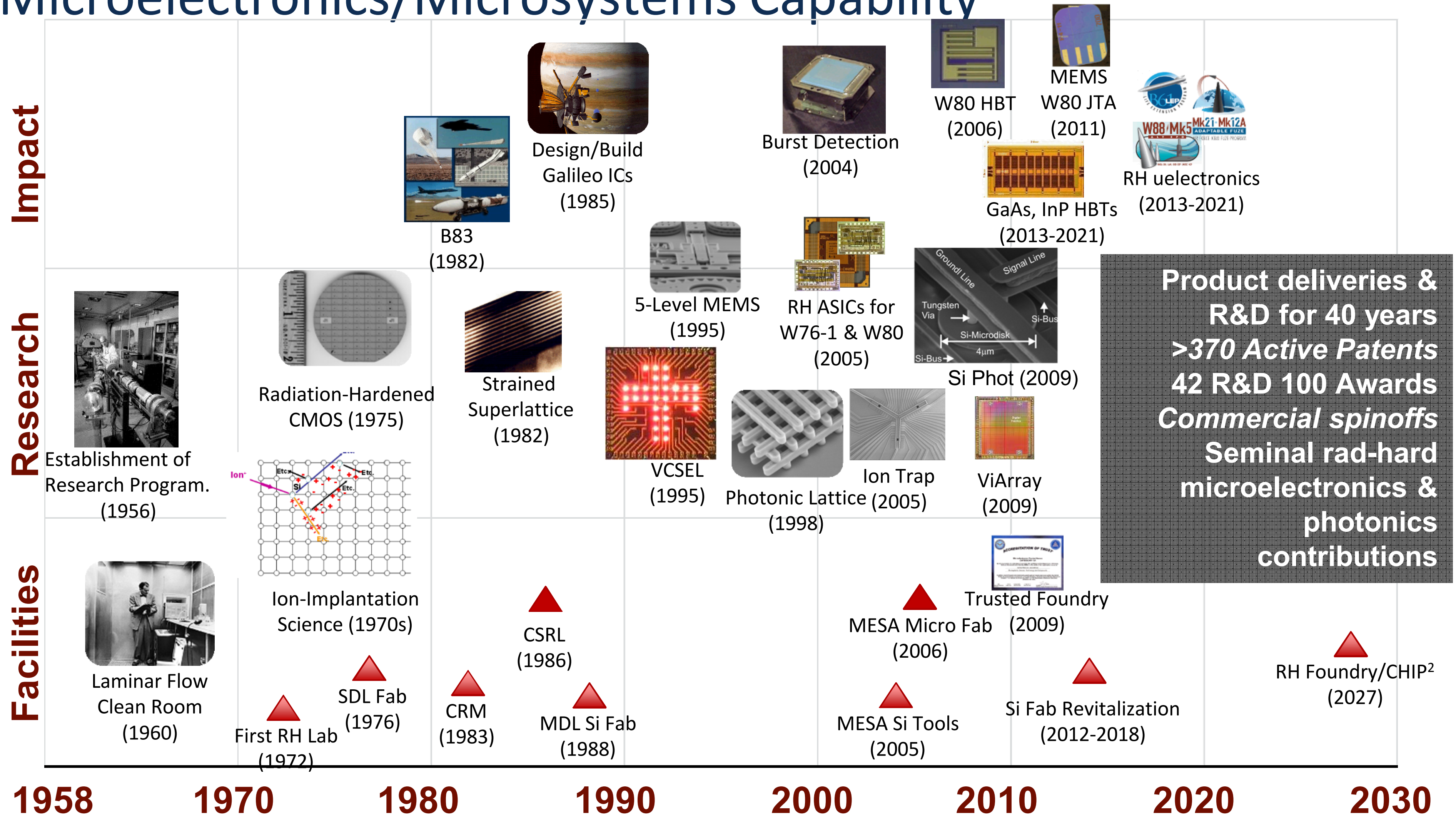

- Advanced Computation
- Modeling & Simulation
- COTS Qualification
- Advanced Packaging
- Custom Electronic Components
- System Design & Test

- Compound Semiconductor Epitaxial Growth (UV-THz)
- Photonics: Si & III-V
- MEMS, VCSELs, Plasmonics
- Specialized Sensors, FPAs
- Materials Science, Graphene
- Nanotechnology, Chem/Bio
- Heterogeneous-Technology Integration & Processing
- III-V Semiconductor Devices
  - Neutron-Immune HBT
  - Rad-hard Optical Links
  - Solid-State RF Devices
  - GaN Power Electronics

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

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

Sandia National Laboratories

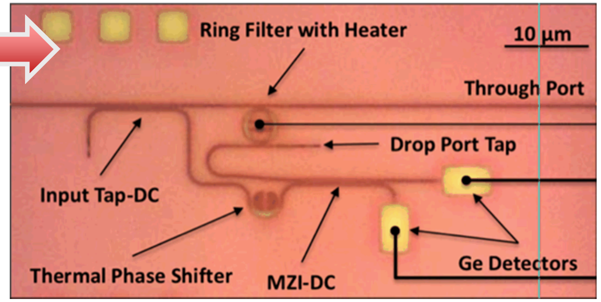


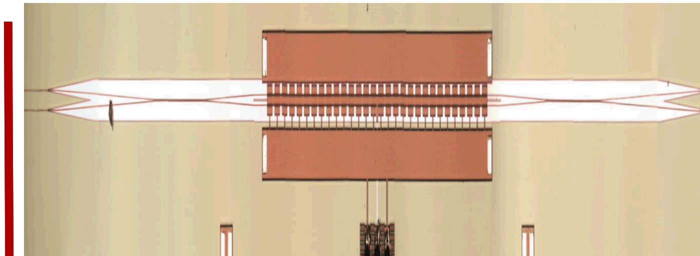

***MISSION: Invent and mature integrated circuit and microsystems technologies that provide differentiation and impact for NW and other national security missions.***

# Trusted Advanced Pathfinder Products: Si Photonics

Sandia National Laboratories

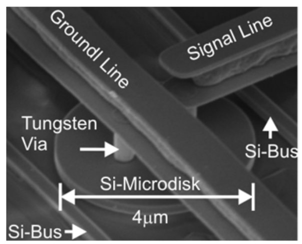
| | |
|---|---|
| 2014 | *balanced homodyne resonant wavelength stabilization > 55C* |
| 2013 | *Si Photonics MPW (CIAN NSF ERC)* |
| 2012 | *24 GHz Si TW MZM* |
| 2011 | *45 GHz Ge Detector* |
| 2010 | *3 fJ/bit resonator modulator, 1V-cm MZM* |
| 2009 | *wavelength tunable rings over 35 nm* |
| 2008 | *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* |



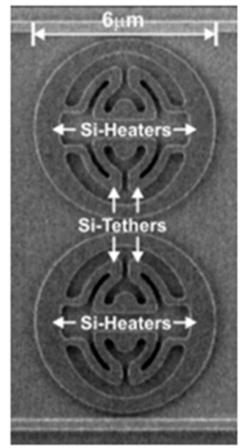



***24 GHz 0.7V-cm Travelling Wave MZI Modulator***

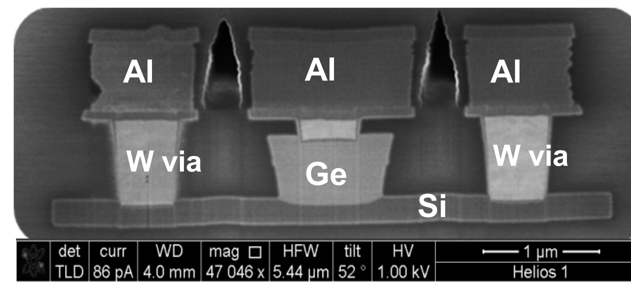
*3.2fJ/bit at 12Gb/s*




***Resonant Optical Modulator/Filter***

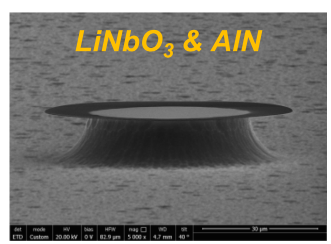


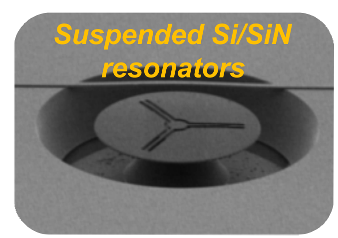

***Tunable Resonant Filter***

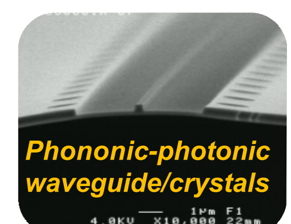



***45 GHz High-speed Ge Detector on Si***

***MEMS process for additional capability***

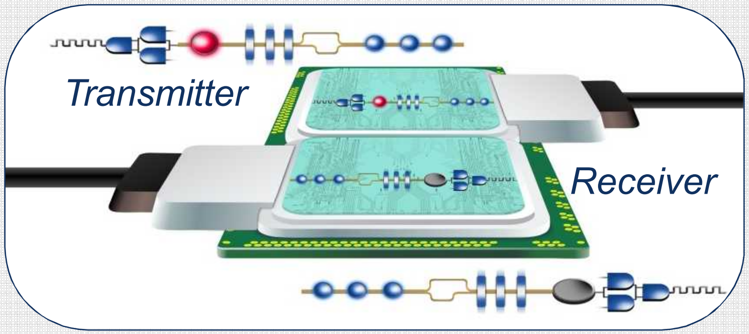


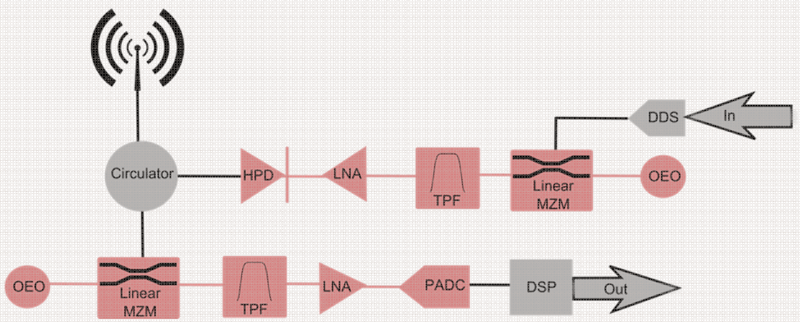



# Photonics Enabled System Applications

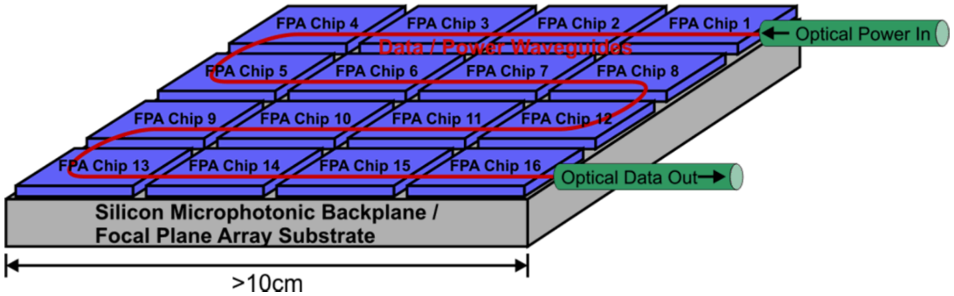

High Performance Computing




Secure Quantum Communication

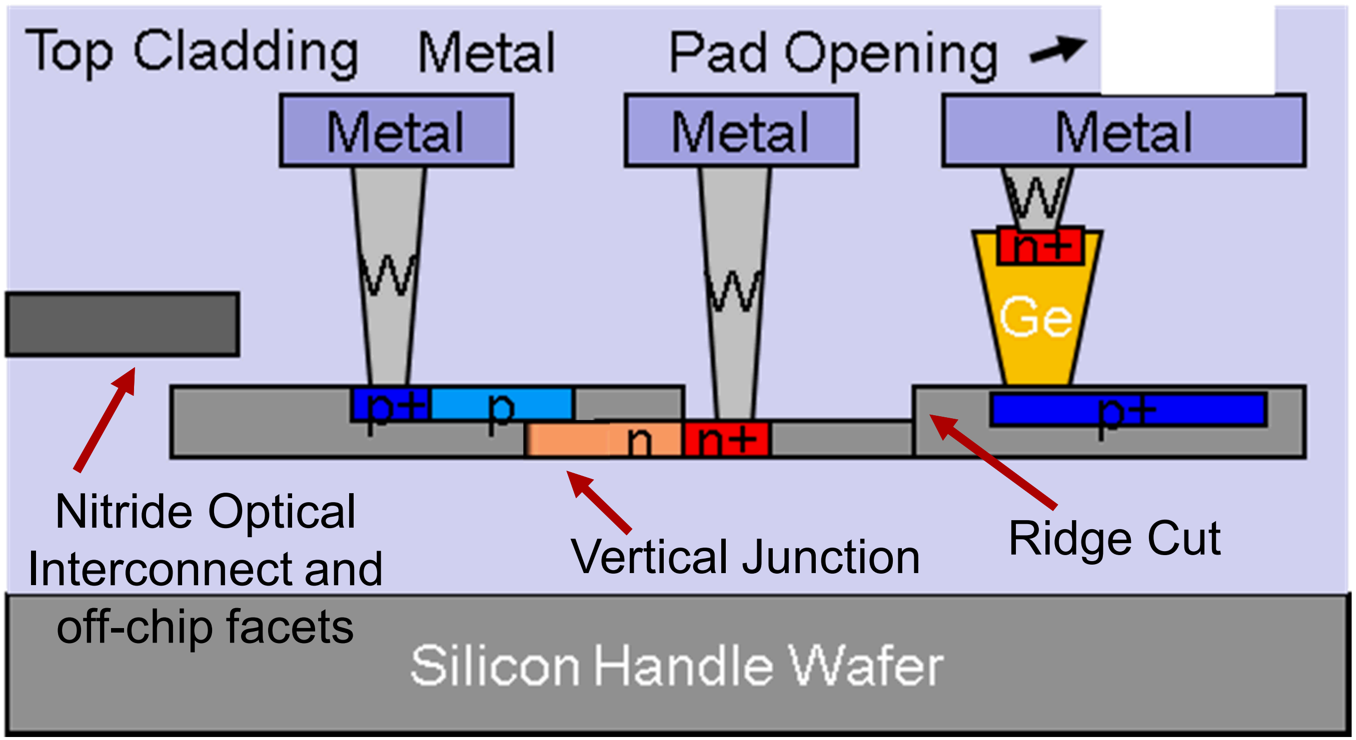


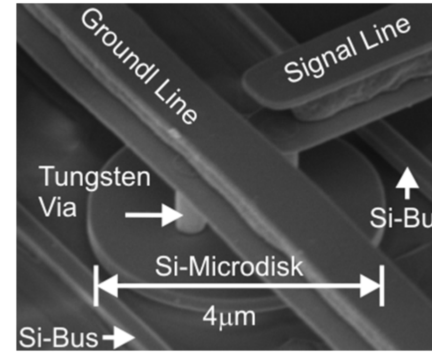

RF Sensing and Communication



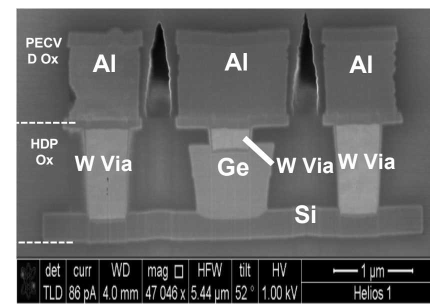

Focal Plane Array Communications

# SNL Silicon Photonics Process




*Optical modulator 12.5GHz, 3fJ/bit*




*Ge photo detector with 45GHz BW, 3nA dark current*

- CMOS compatible
- Passive and active photonics devices
  - Silicon and silicon nitride waveguides, couplers, splitters, gratings, filters, modulators, Germanium detectors, switches, etc.

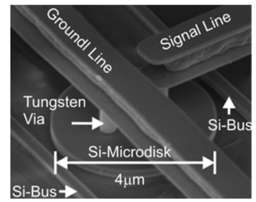
# Si Photonics for Detector Communication

## Silicon Photonics Capabilities:

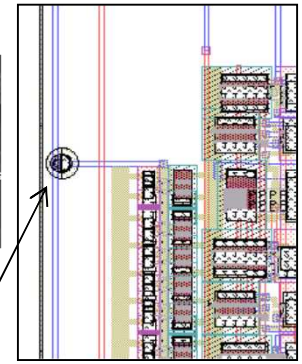
- Modulator energy < 1 fJ/bit
  - 10,000 X lower than commercial optical transceivers in radiation environment
- Low voltage CMOS drive < 0.5V
- Bit rates > 10 Gb/s, future 25 Gb/s
- DWDM: > 1 Tb/s per fiber connection
- Scalable beyond Petabits per sec total

***Si Photonics-CMOS Integration***

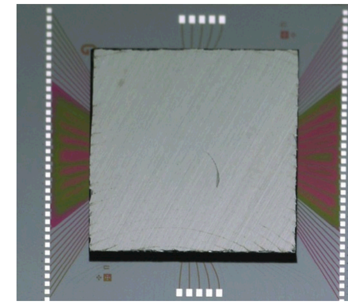
***Monolithic*** ***Flip-chip bonding***



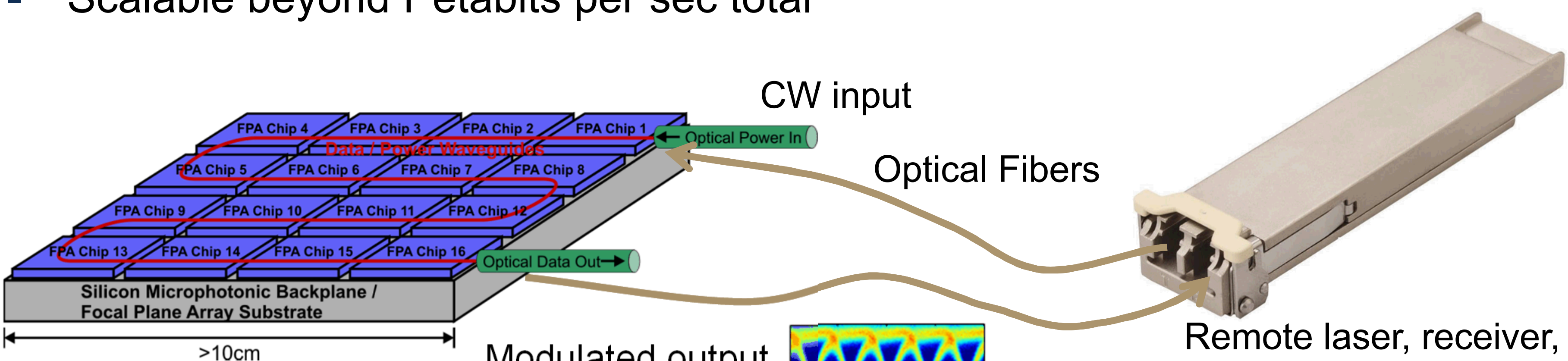

***Resonant modulator***



***CMOS-7***

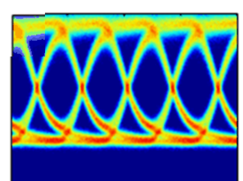


***Trusted CMOS***




Modulators ONLY in cold environment

Modulated output



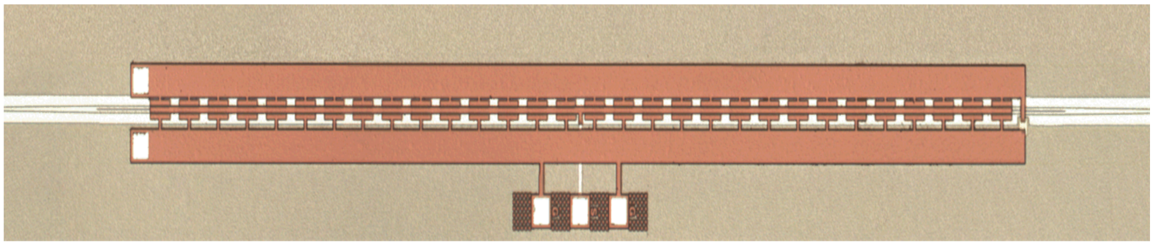
Remote laser, receiver, wavelength alignment

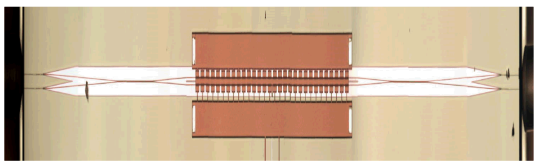
# SNL RF Si Photonics Technologies

Sandia National Laboratories

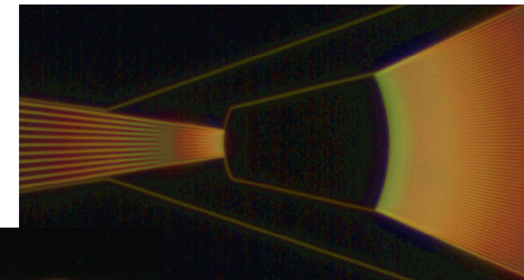
## Silicon Photonics

Optical modulation and spectrum analysis up to 100GHz

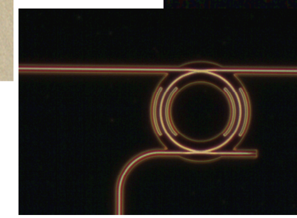




*Mach-Zehnder Modulator with Traveling-Wave Electrodes 20GHz, Vpi x L = 0.8Vcm*



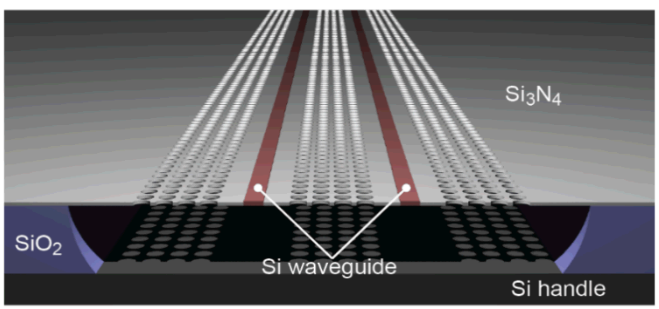
*Array Waveguide Grating Coupler*

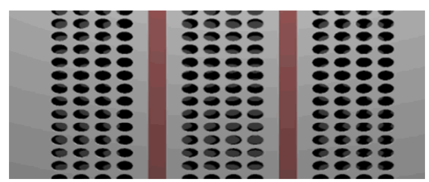


*Micro-ring Tunable Filter (MHz – GHz)*

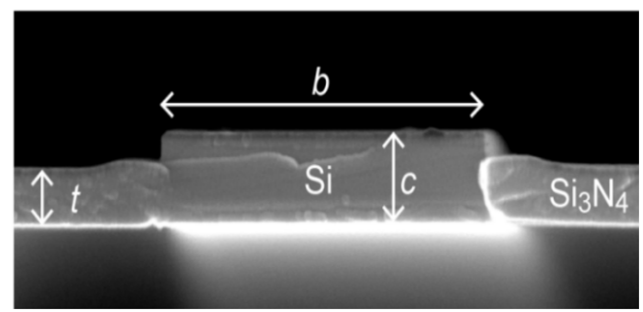
## Silicon / SiN Nano-Optomechanics

Photon-phonon transduction for signal processing with up to 20GHz BW



*Suspended Si waveguides with phononic crystals*

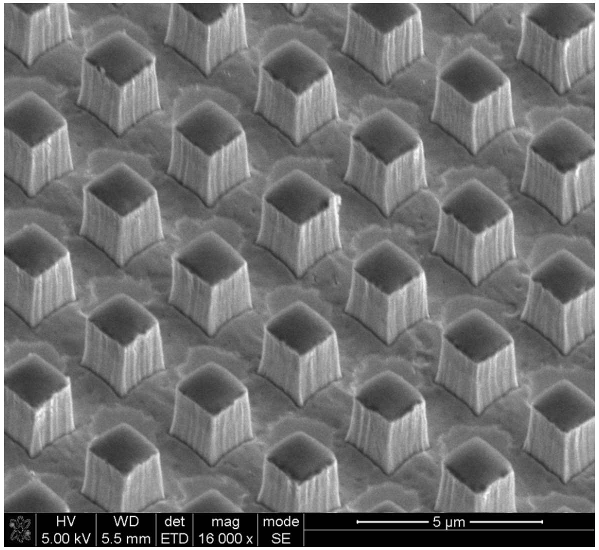



- New paradigm for RF signal processing (ex. filtering) in optical domain to reduce size, weight, and power, and improve performance

# Dielectric and Metallic Metamaterials

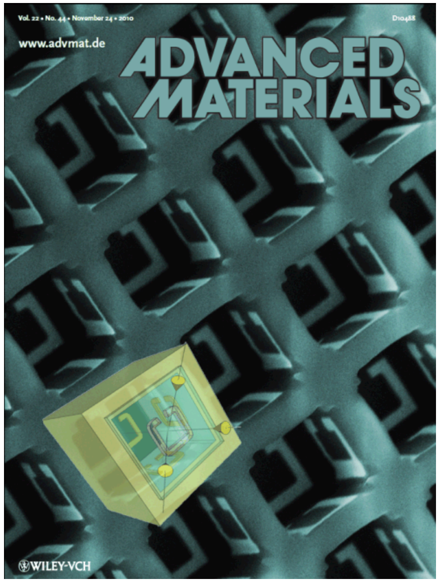
**First ever all dielectric infrared metamaterial:**

- best route to low loss metamaterials
- demonstrated negative permeability and permittivity at IR wavelengths
- new resonator designs for negative index behavior




**Membrane Projection Lithography:**

- a new 3D fabrication tool
- metallic resonators with out-of-plane currents
- isotropic metamaterials.




**Polynorbornene:**

- SU8 of the IR
- low IR loss polymer
- photo cross-linkable
- wide ranging applications

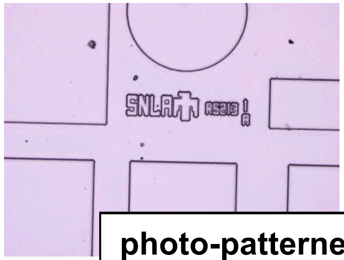
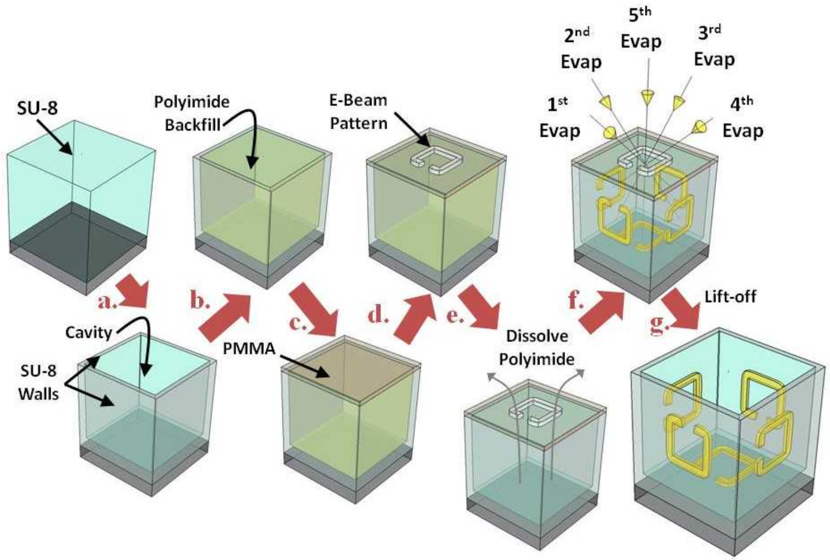
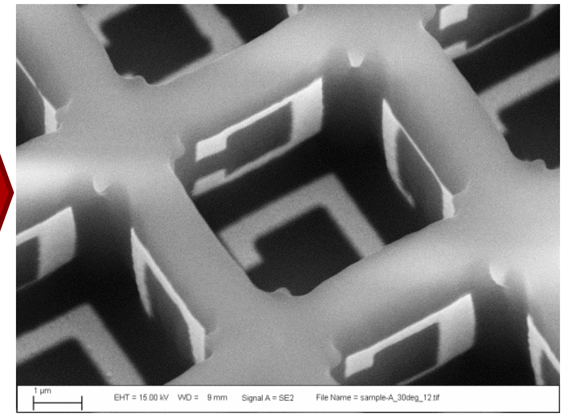
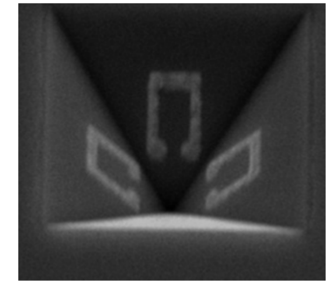


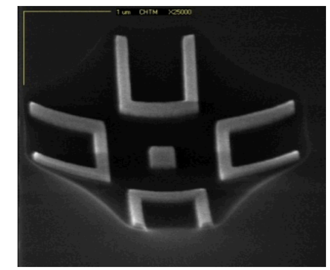
**photo-patterned polynorbornene**

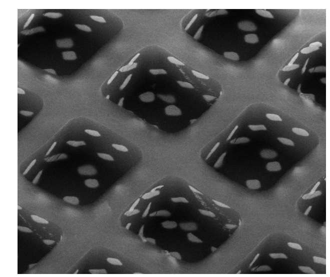
# Membrane Projection Lithography

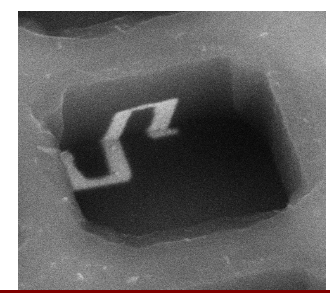


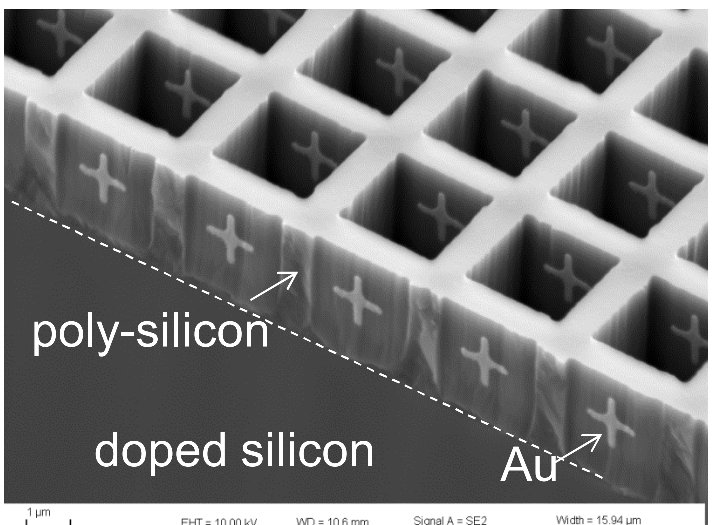





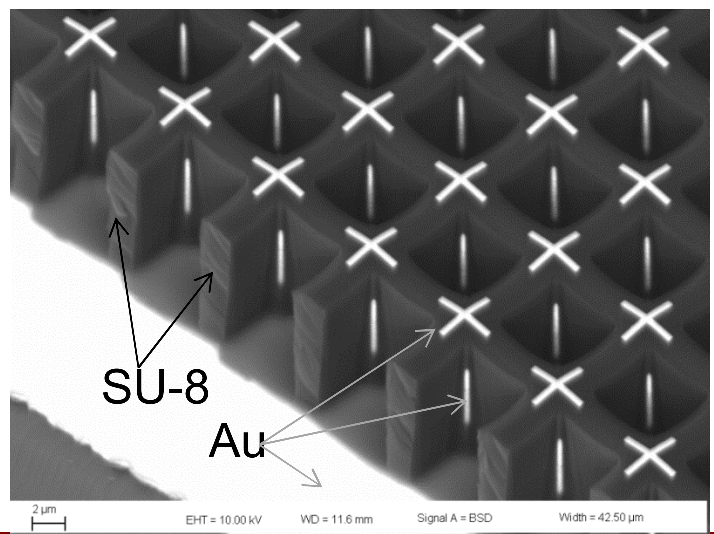




**CMOS Compatible Inorganic Material Set**




**Polymer-Based Material Set**



# 3D Pyrolyzed Carbon

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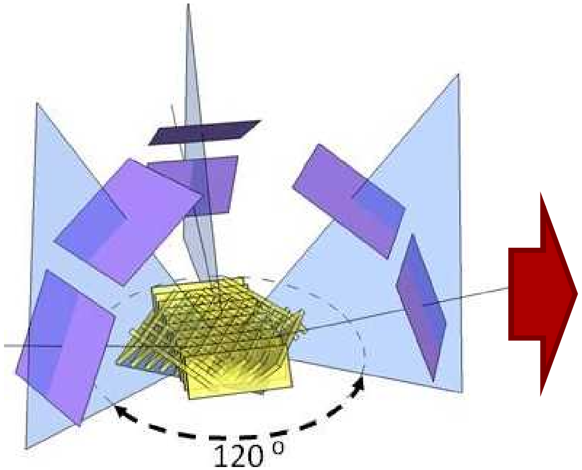
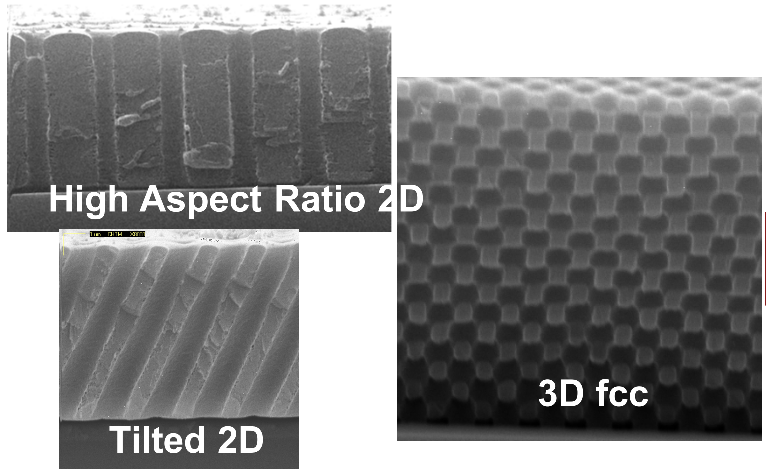
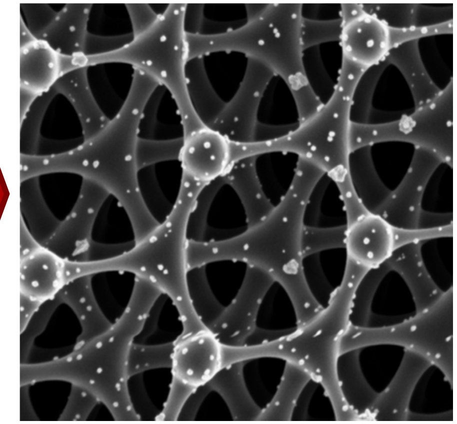



Interferometric Lithography



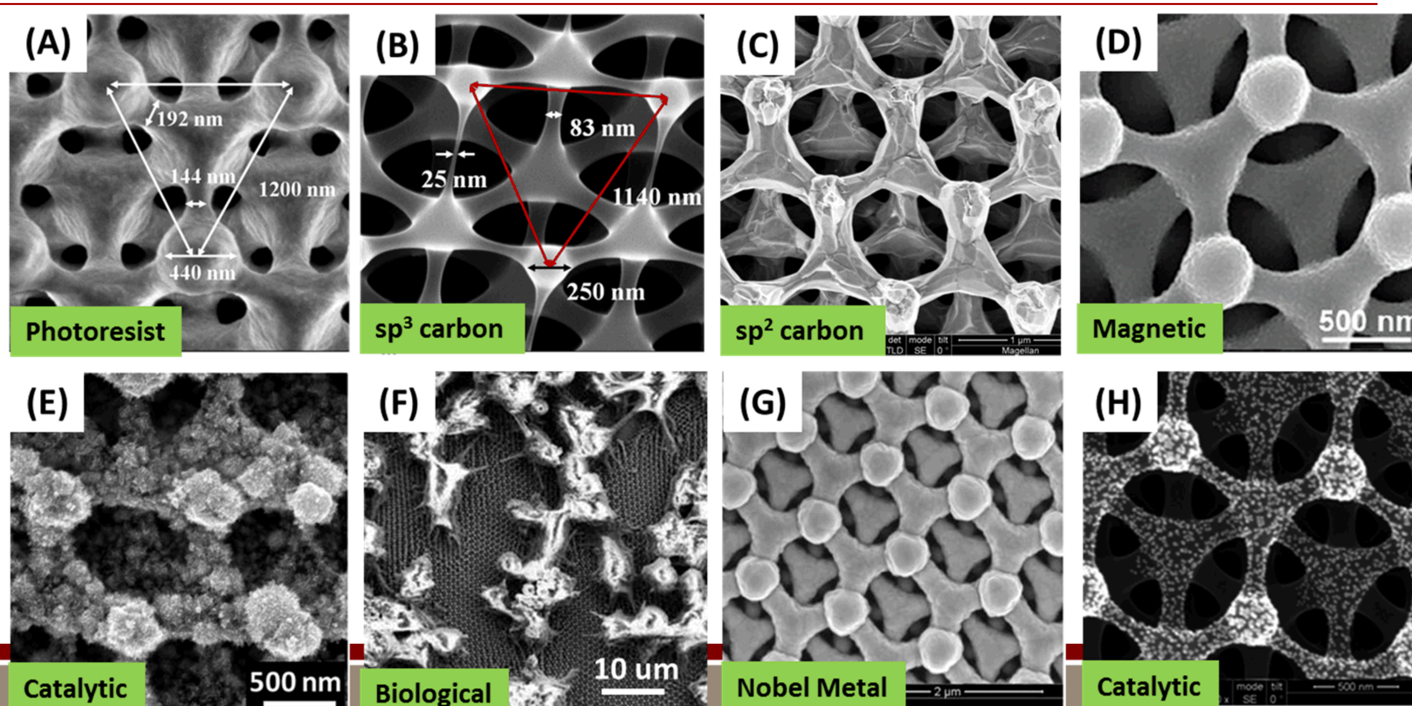

Resist Patterns

Pd nanoparticles in 3D carbon matrix



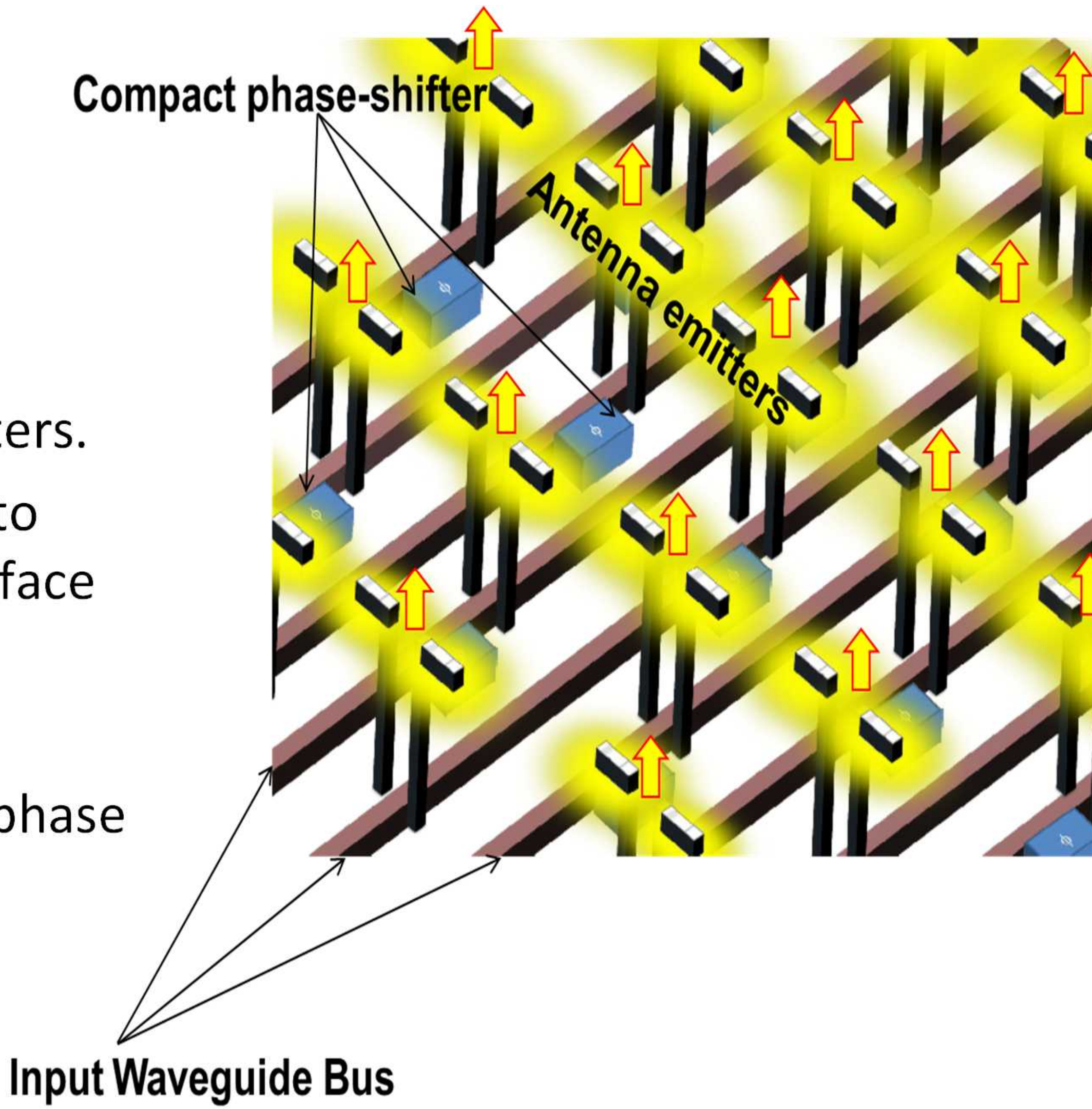
Carbon Scaffold

Scaffolds readily modified using a variety of methods and materials



# Free-Space Infrared Communication

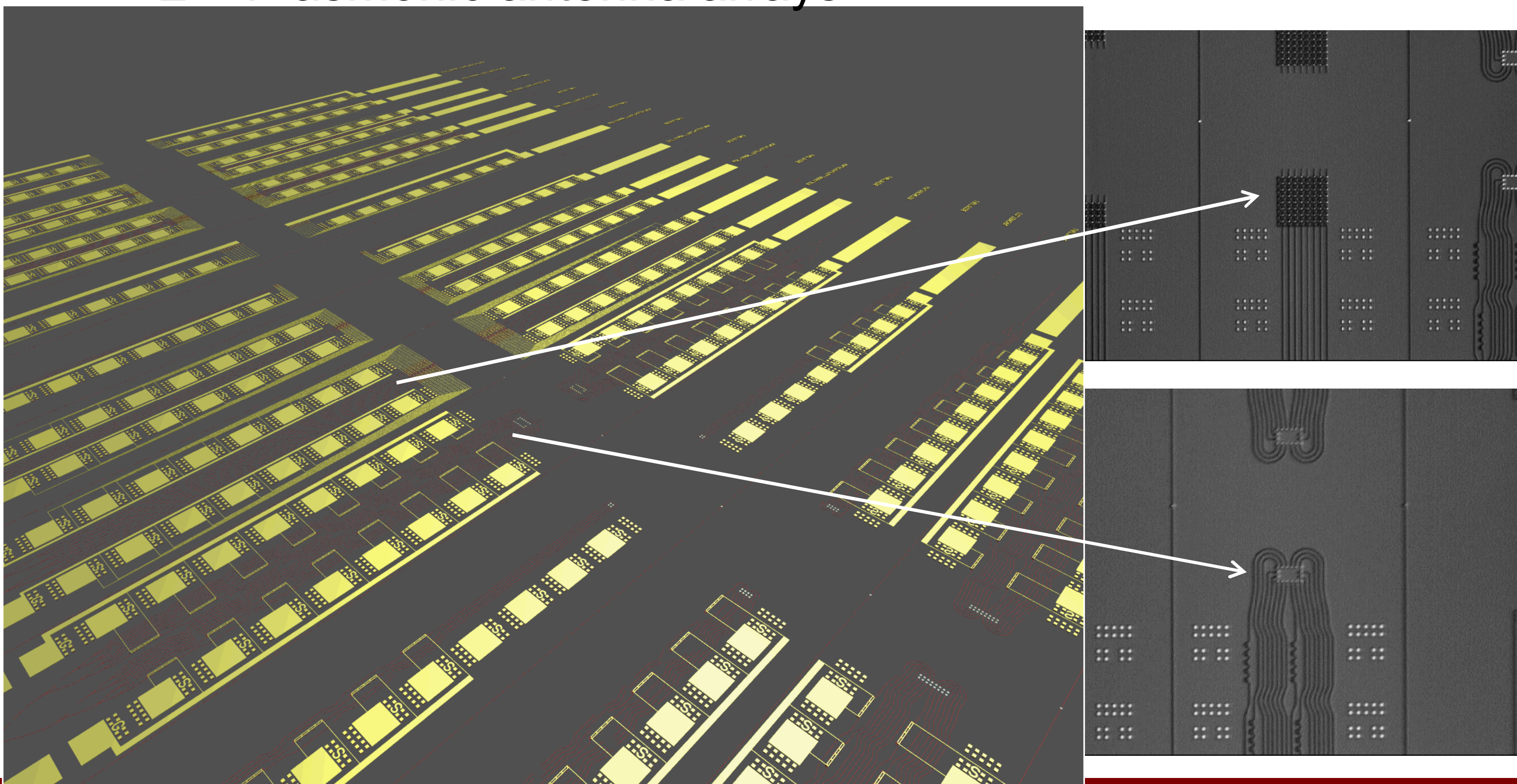
- Use Si Photonics Platform
  - Low loss dielectric waveguides. (light distribution)
  - Integrate compact waveguide phase shifters.
  - Use metallic antenna to radiate efficiently (surface normally)
- Place in periodic array
  - Electronically control phase of each antenna



# Phased Array Test-Chip

Key elements:

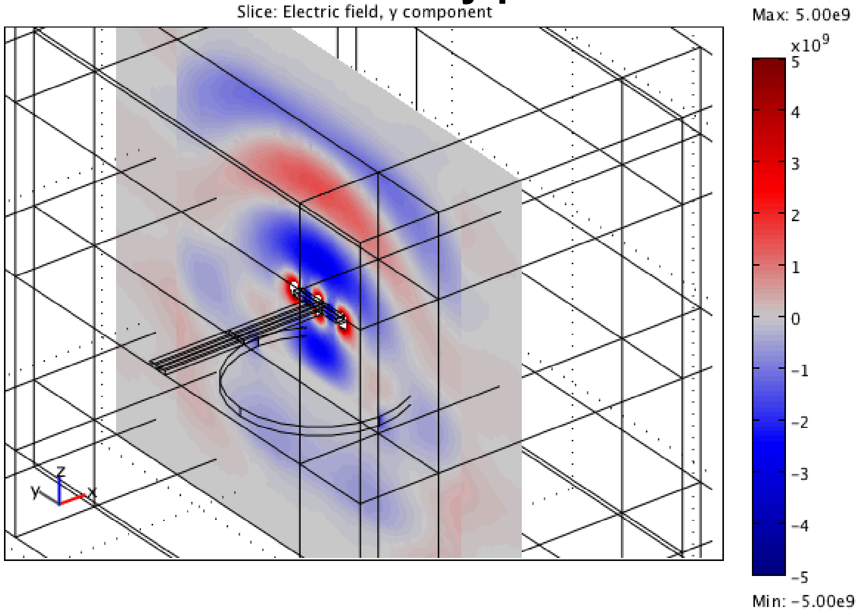
1. Integrated waveguide phase shifters
2. Plasmonic antenna arrays



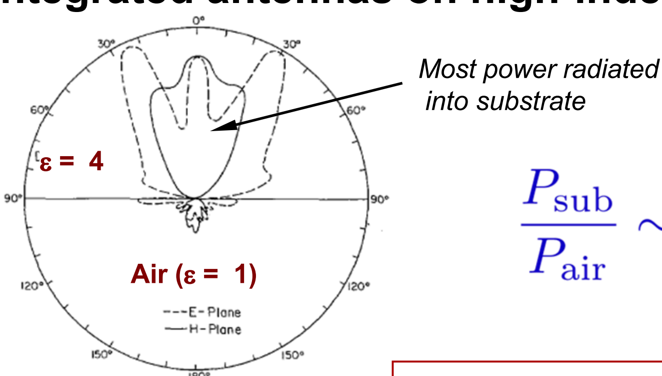
# Radiation Pattern of MIM-fed Antenna

Sandia National Laboratories

## Surface-normal radiation by planar antennas




## Integrated antennas on high-index substrates

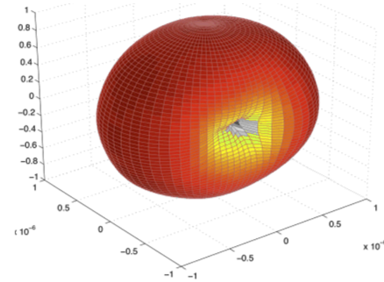



*IEEE Trans. Ant. & Prop.* **30** *535 (1982)*

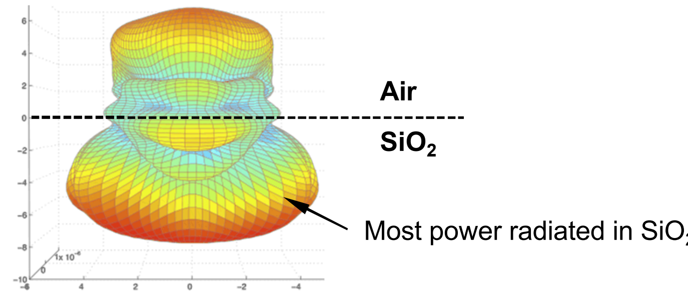
$$\frac{P_{\text{sub}}}{P_{\text{air}}} \sim \epsilon^{3/2}$$

**Ground-plane is necessary !**

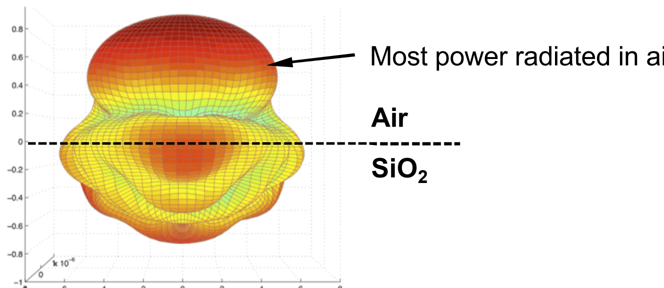
## MIM-fed dipole in Air



## MIM-fed dipole in on $SiO_2$ (No ground-plane)




## MIM-fed dipole in on $SiO_2$ (With ground-plane)



# E-Beam Nanoantenna Template

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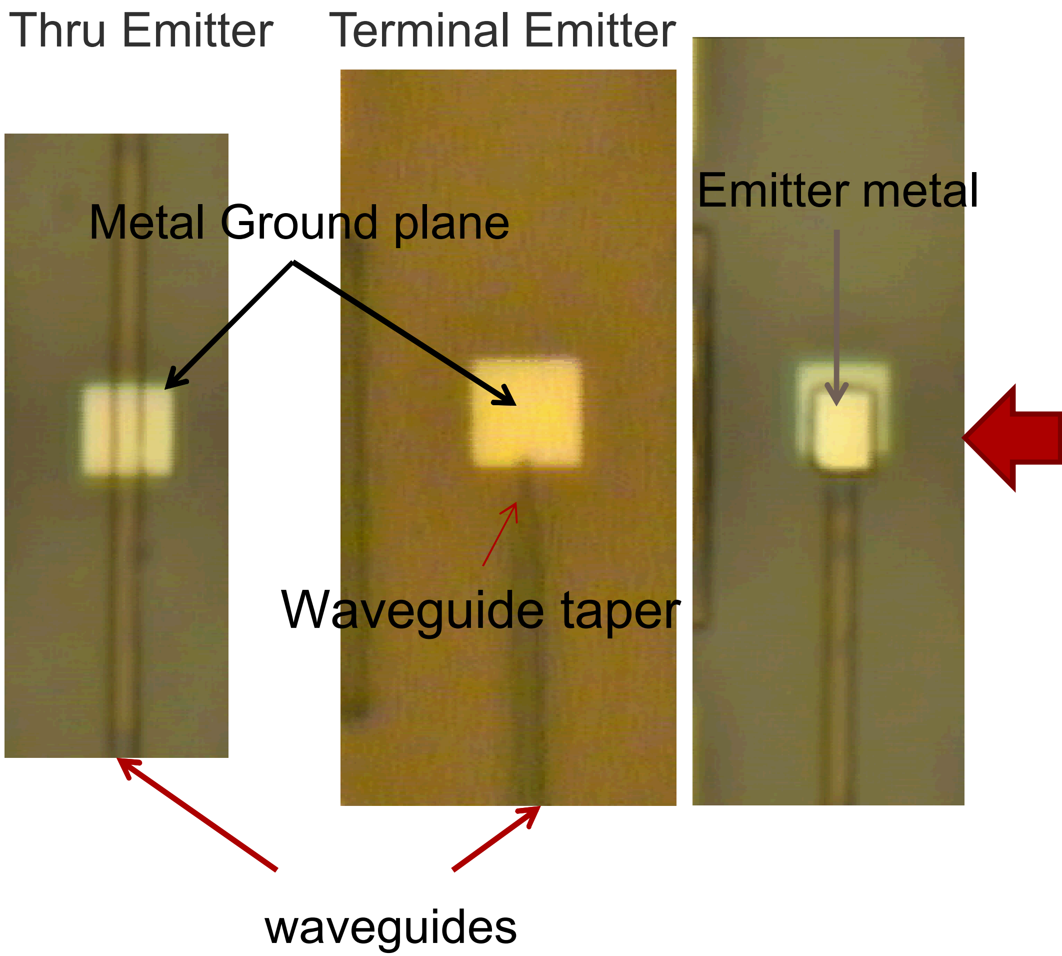
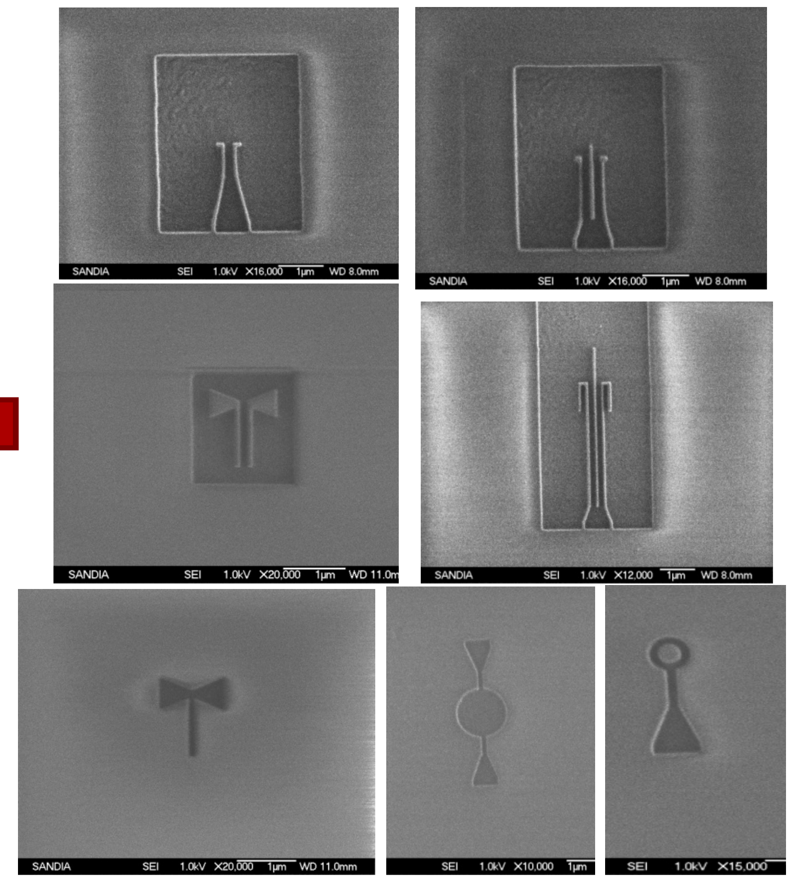
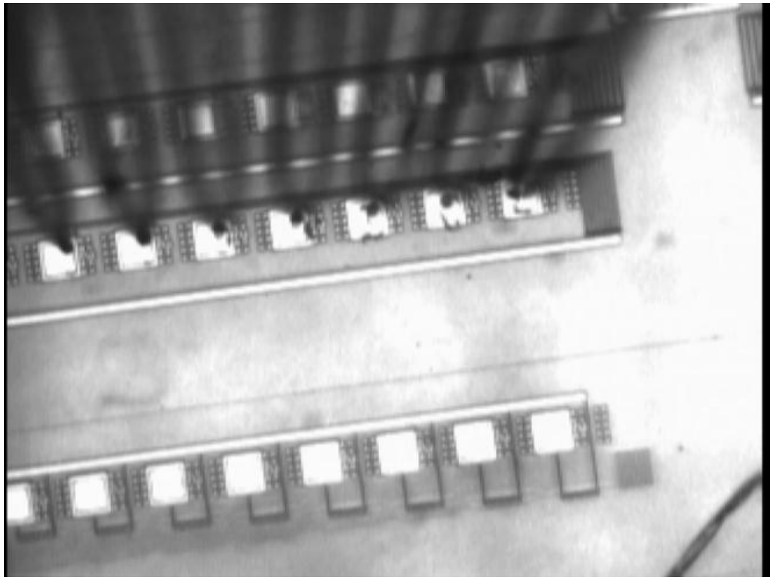
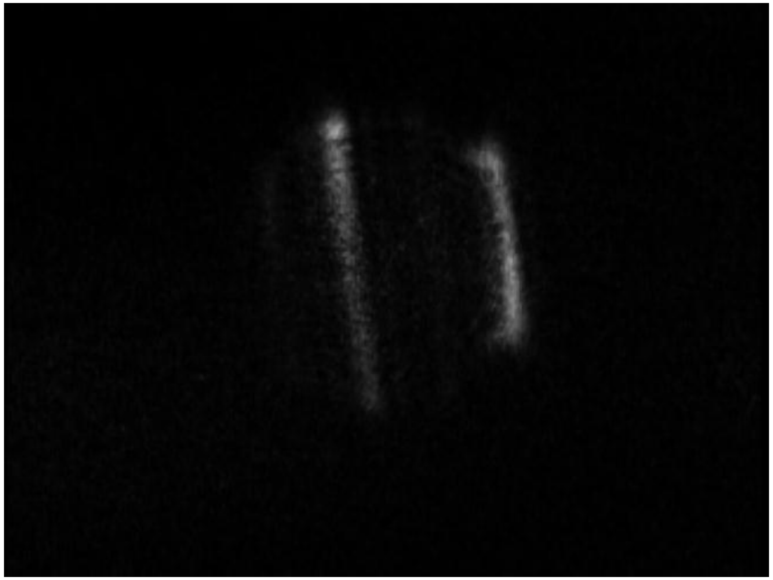



## E-Beam nanoantenna



# Electronically Phase Controlled 1x8 Array





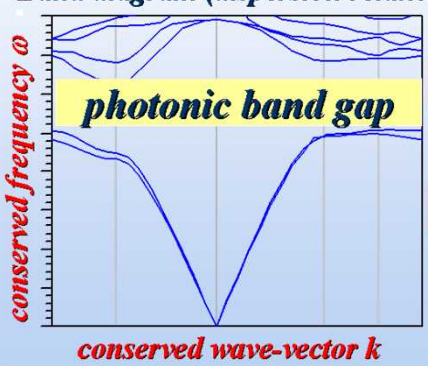
Demonstrated an optical phased array beam steering system comprised of

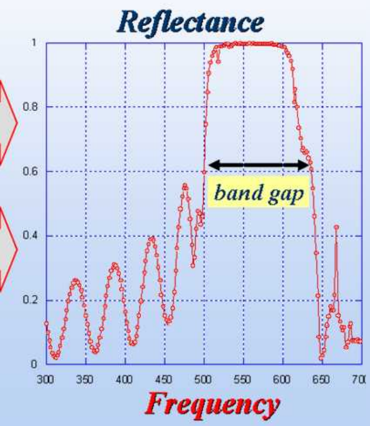
- Periodic array of plasmonic antennas
- Individually electronically addressed waveguide phase shifters ($2\pi$ phase shift)
- Surface normal emission and steering at fixed wavelength.

# Photonic Crystals (PhCs):

## Molding the Flow of Light at the Nano Scale

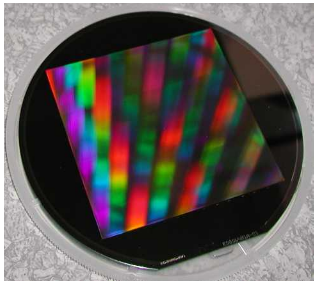
Photonic crystals create bandgaps where photons are forbidden to propagate.

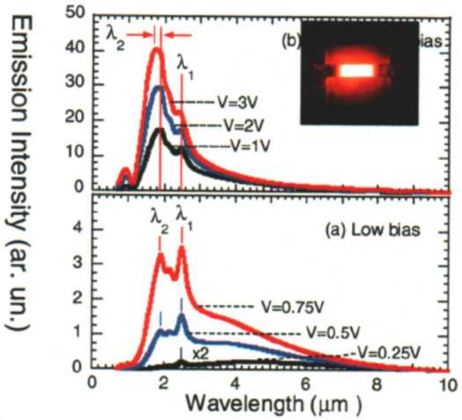



## 1st 3D IR Metallic PhC 2001-04

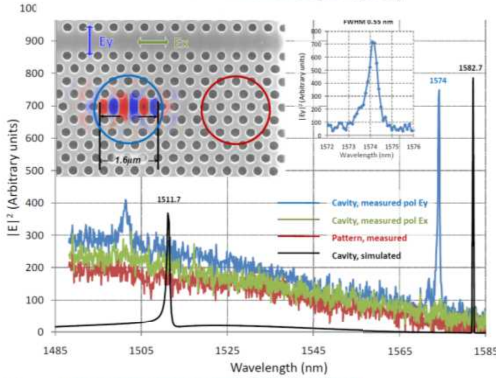
Tungsten PhC, Nature
Directional Emitters
PhC TPV App SNL



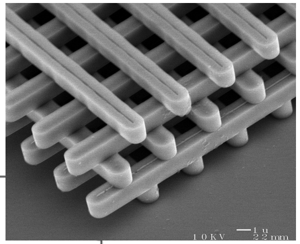


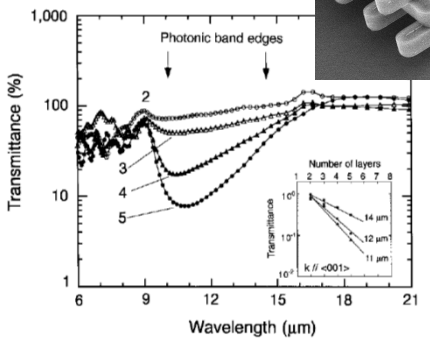

## PhC Cavity QED 2007

Single photon sources
Quantum computing



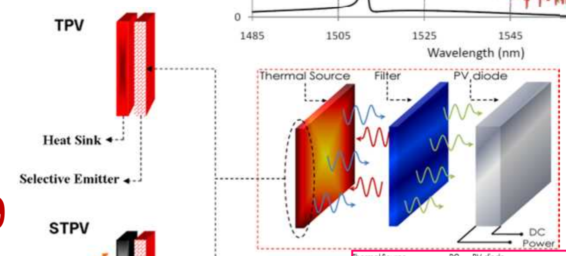

## 1st 3D Silicon PhC 1998-99

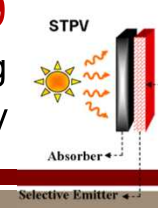


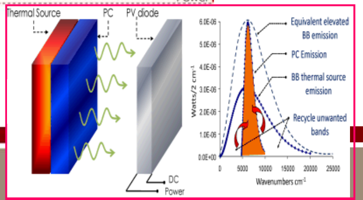



## PhC Near Field TPV 2009

Thermal Energy Harvesting
Renewable Energy



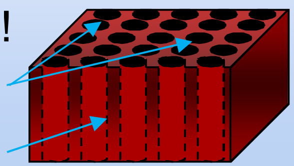


# Phononic Crystals (PnCs):

## Phonon Manipulation at the Micro and Nano Scale

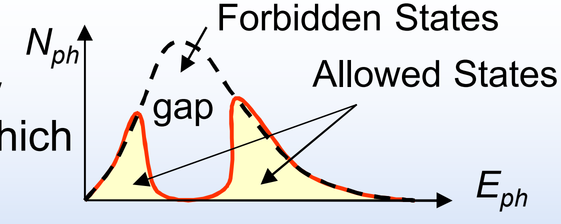
### Phonons (What?)

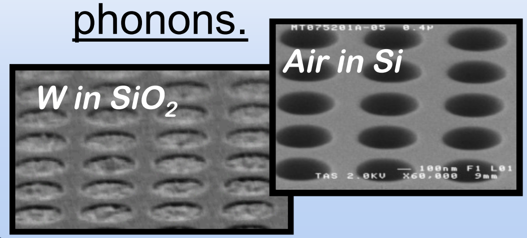
- The quantum mechanical rendering of lattice vibrations (normal modes)
- The quanta of mechanical oscillations
- Heat and Sound!




### Phononic Crystals (How?)

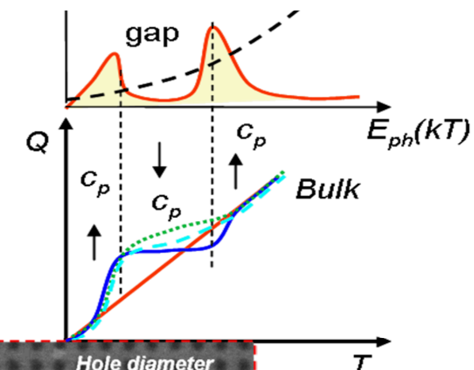
Array of high impedance scattering centers in a low impedance background which exhibits stop bands for phonons.

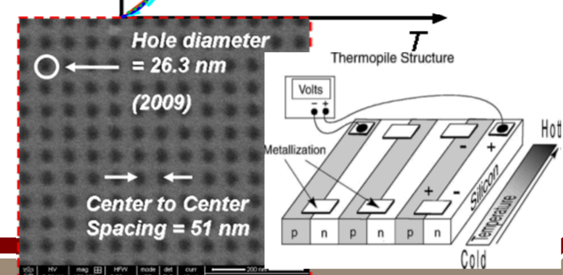



### 2009 1St THz PnC

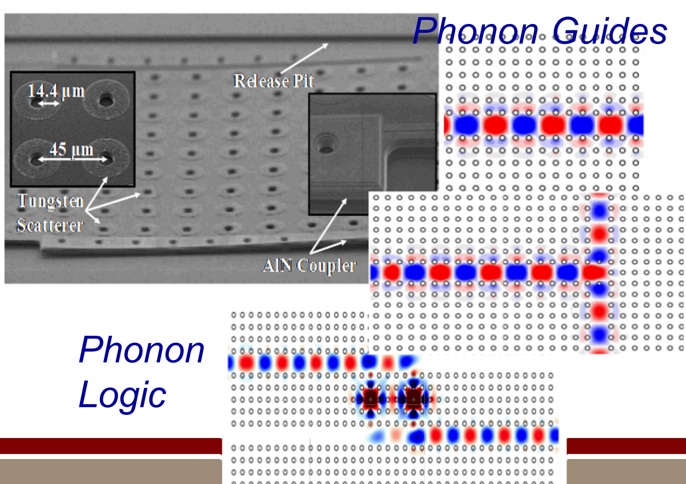
- Engineer thermal properties
- Thermal management
- Thermal energy scavenging
- TE cooling



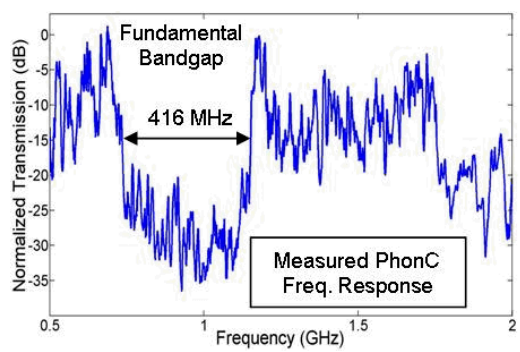

### 2007 1st MHz PnC

- *Solid-Solid material sets*
- *RF Applications*
- *PnC-PhC Transformation*




### 2008 1St GHz PnC

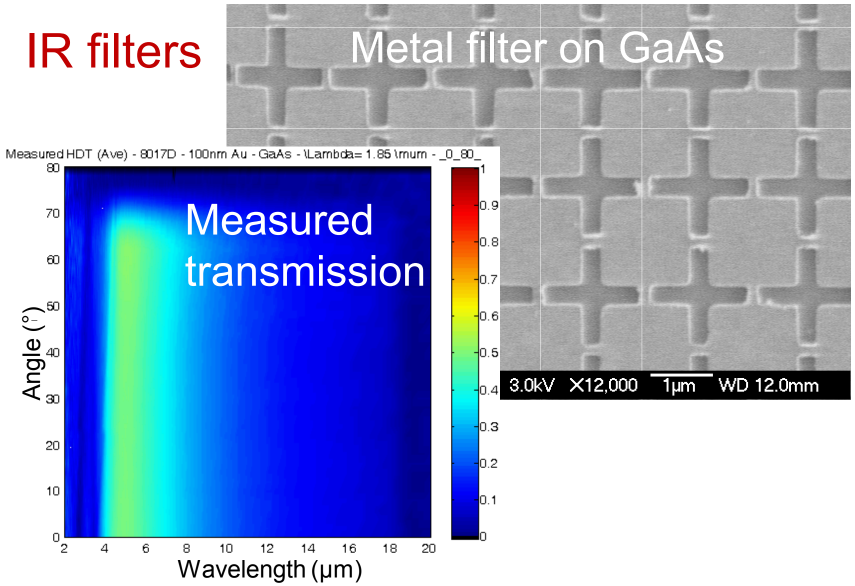
- Low loss RF devices and resonators
- RF communications, radars and spectral sensors



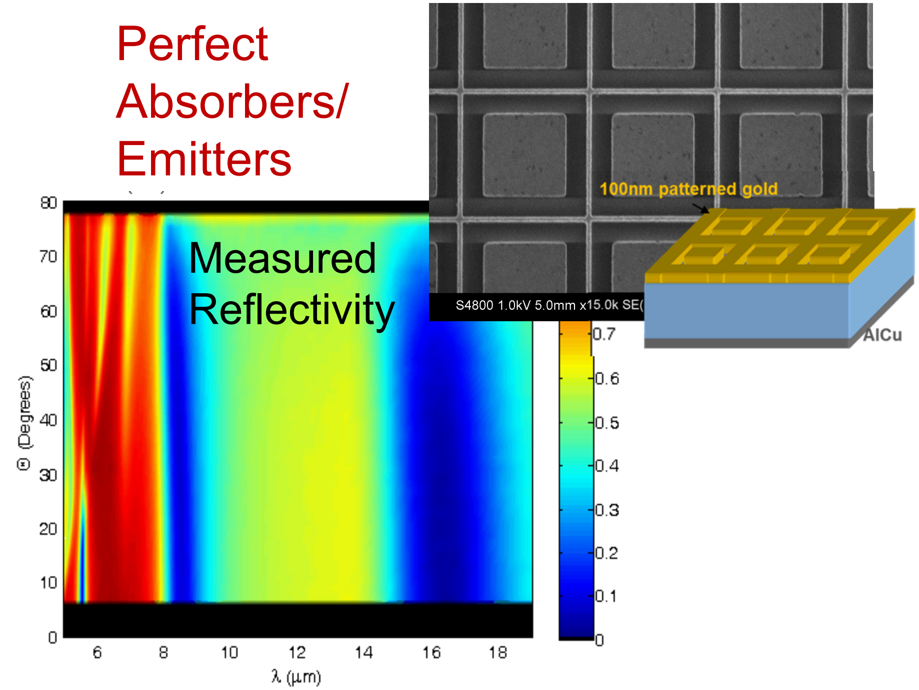
# Planar Metallic Infrared Devices

## Metal Optics for New Capabilities

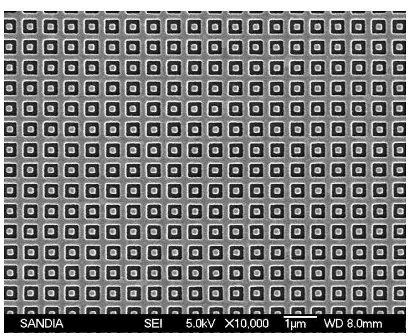
IR filters

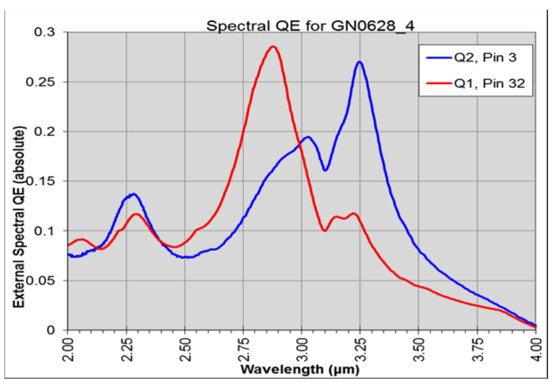


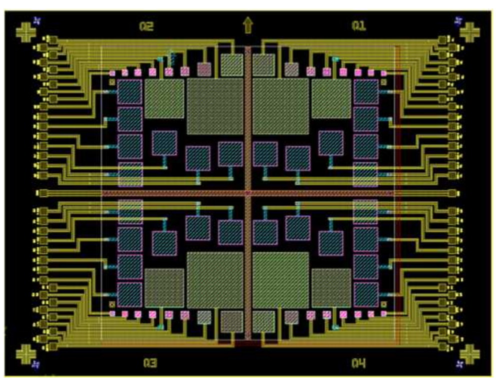

Perfect Absorbers/ Emitters



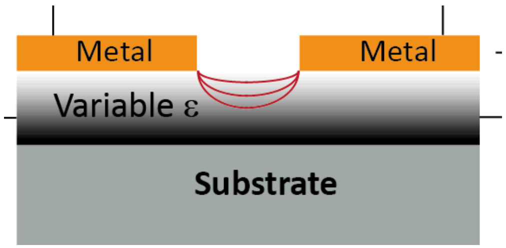

Next-Gen Low-Noise IR Detectors

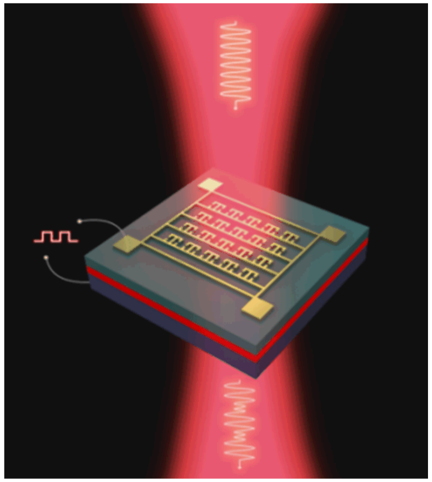


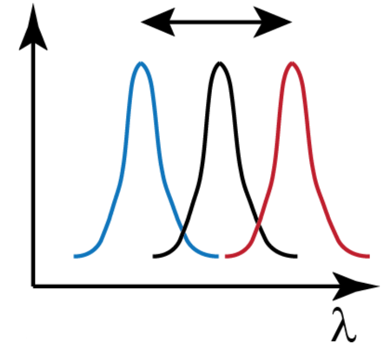



# Electrically Tunable Metamaterials for Agile Filtering in the Infrared






By controlling the interaction between planar metamaterials and semiconductors we created voltage tunable IR filters.

Specs:

- Mid to long wave IR
- Pixel size: 5um$^2$ and up
- Tuning by 1-2 FWHM
- Q ~ 10-20
- Voltage <10V
- Made from III-V semiconductors

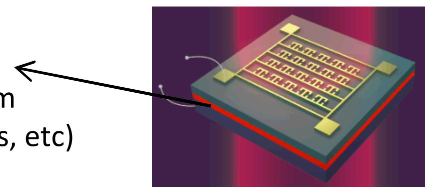
PI: Igal Brener

# Two Voltage-Controlled Tuning Mechanisms

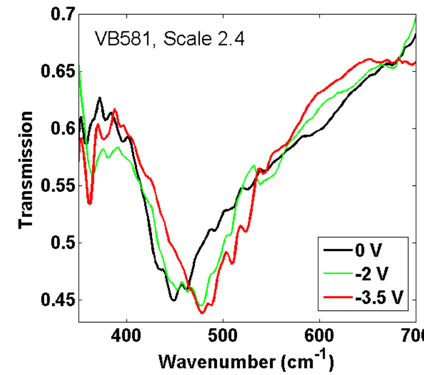
Sandia National Laboratories

- Interaction with plasmons in highly doped semiconductor layers

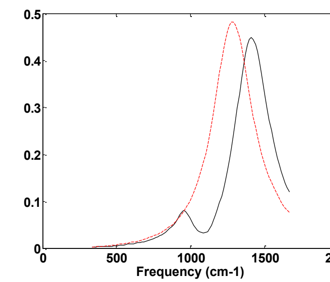
n++, 20-40nm
(3e19 InGaAs, etc)



Preliminary results, long wave IR

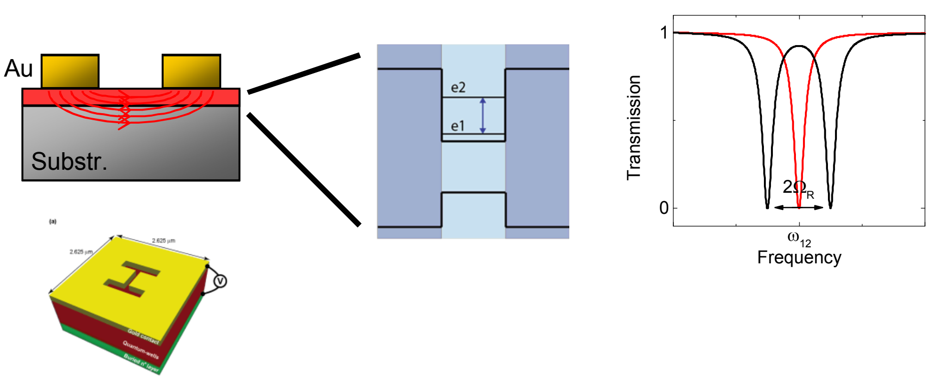



Recent modeling:

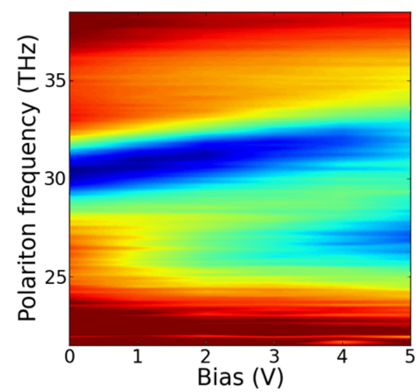


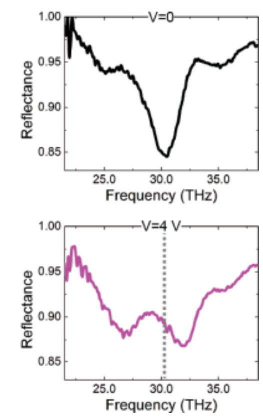

*Nano Letters 13, 5391 (2013)*

- Interaction with intersubband transitions in quantum wells




Preliminary results, thermal IR




*Nature Communications 4, (2013) ; APL 103, 263116 (2013)*

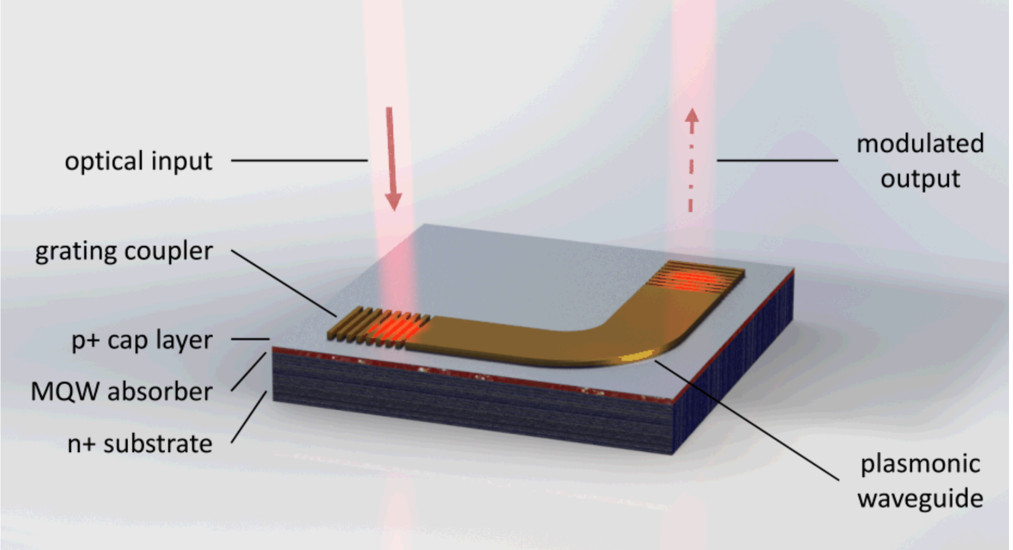
# Near Infrared Active Plasmonics:
## Modulators, Emitters, Detectors

Plasmonics enables extreme field concentration and nanophotonic devices

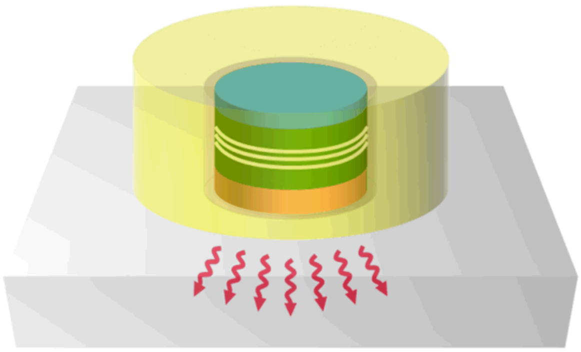
- explosive field of study for the past decade (passive devices & MWIR/LWIR)
- devices promising for future photonic applications (speed, power, density)

Here we are investigating NIR active plasmonics in semiconductor materials

- leveraging strong resident photonics capabilities
- a wide range of practical devices that have not yet been explored



surface plasmon modulators


nanocavity emitters

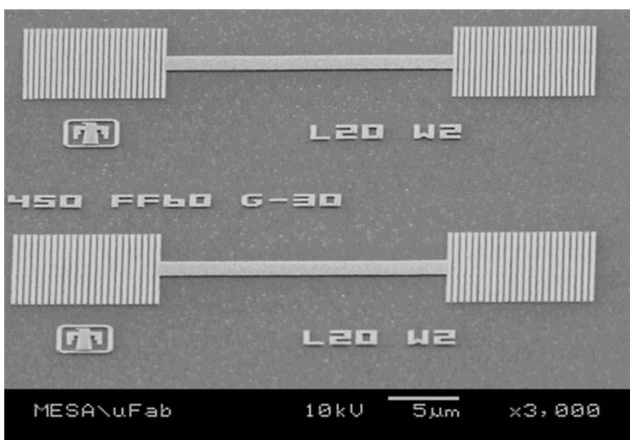
# Nanofabrication of III-V Active Plasmonics

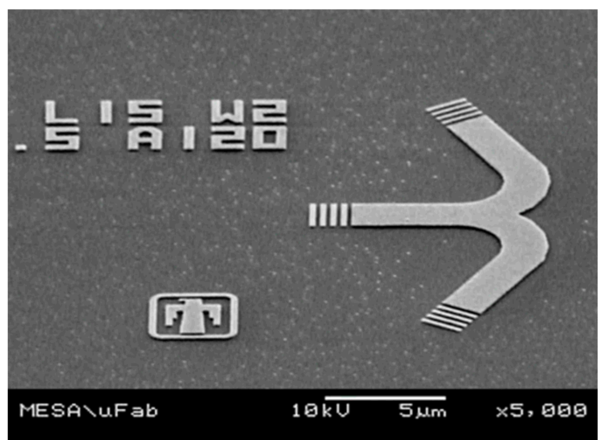
Growth and fabrication in Sandia's MESA and CINT nanofabrication facilities

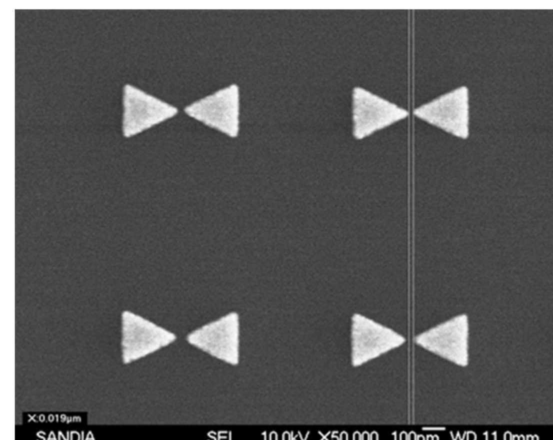
- epitaxial growth on GaAs, GaSb, and InP by MBE and MOCVD
- patterning using a combination of contact and e-beam lithography
- standard III-V processing using wet/dry etch, metallization, anneal, etc.

Nanoscale devices under study

- modulators, nanoemitters, plasmonic crystals
- surface-normal grating couplers with varying fill factor, pitch, thickness
- waveguide bends, splits, dot waveguides, concentrators, gap antennas



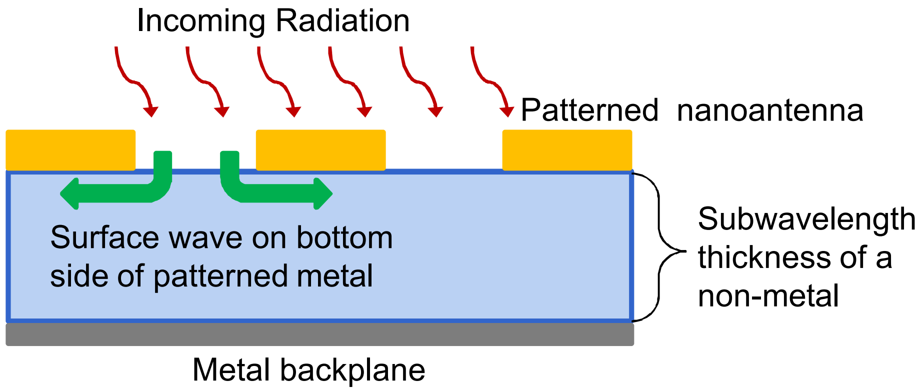



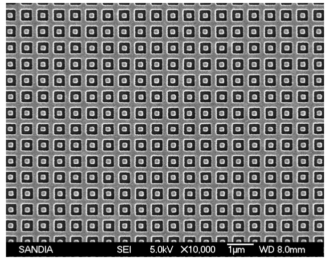

active nanoplasmonic devices fabricated on compound semiconductors

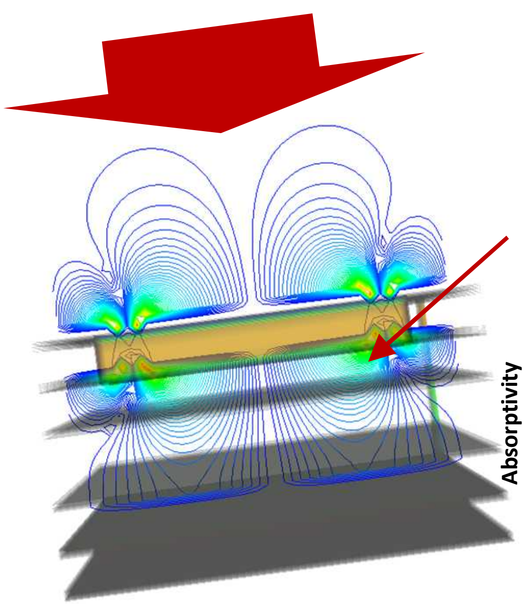
# Nanoantenna-Enabled Thin Detectors

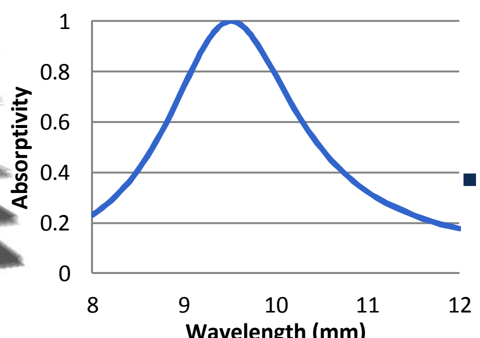
Sandia National Laboratories

## What is a nanoantenna?



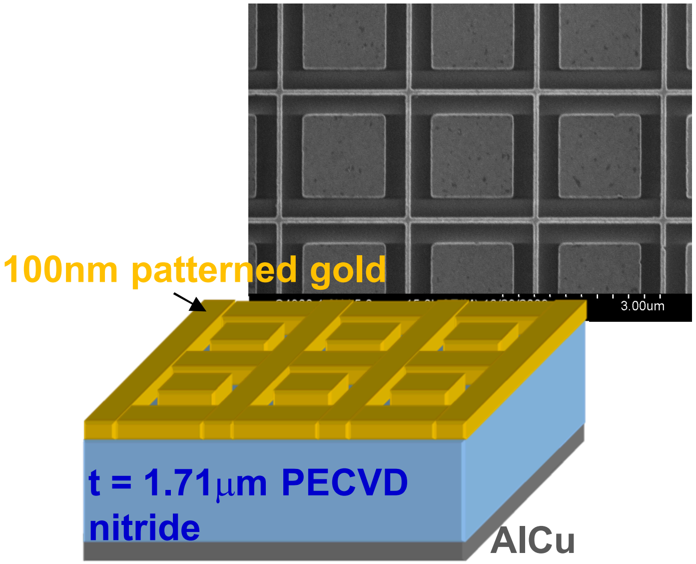



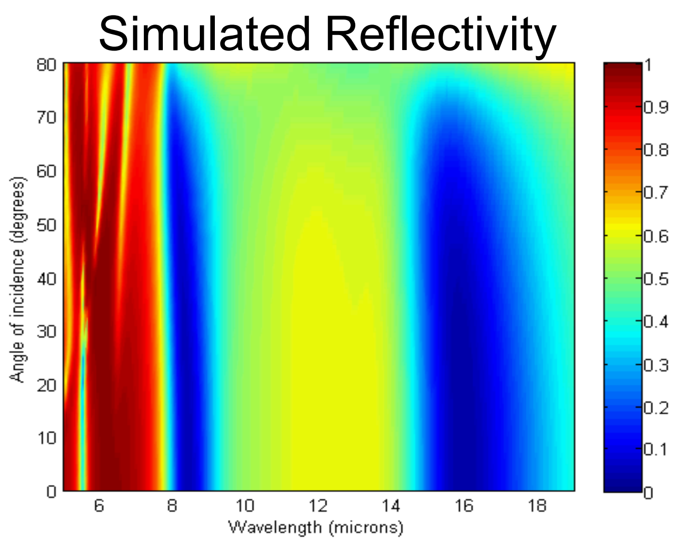



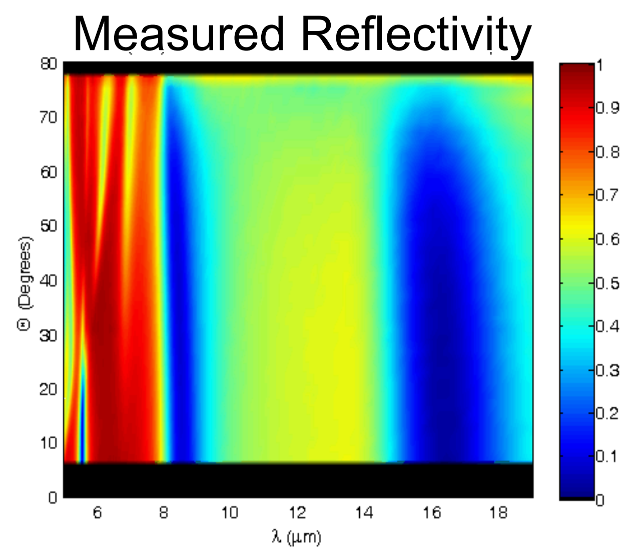

- Nanoantennas are a fundamental technology that spans numerous sensor types
- Nanoantennas are an enabling technology for new applications such as 2D materials
- A nanoantenna is a distributed energy conversion device: the entire surface is the device
- A nanoantenna converts incoming radiation to a surface wave with energy confined to a small volume under the nanoantenna
- This confinement is what enables us to look at interesting applications
- The pattern is subwavelength, with many nanoantenna periods per device pixel. This pattern may be changed on a pixel-to-pixel basis allowing adjacent pixels to have different spectral or polarization response
- Our IR devices are enhanced by, or completely reliant on, the radiation conversion achieved by the nanoantenna

# Background: Perfect Absorbers

- We designed and made a dual-band perfect absorber.
- Excellent agreement between simulation and measurement → Great confidence in our models.
- Measured absorption of 99% in two bands.
- If we can absorb it, why not use that energy?



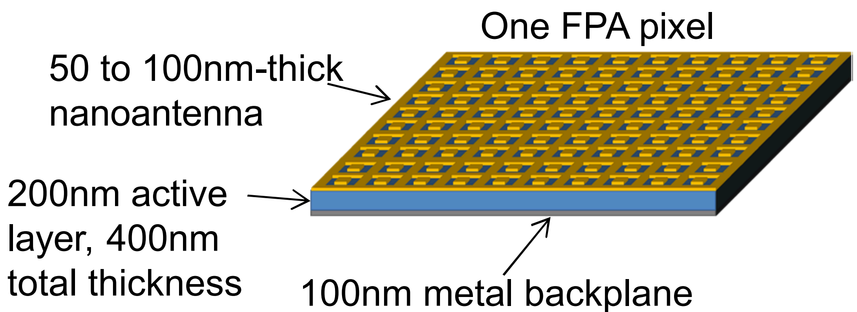



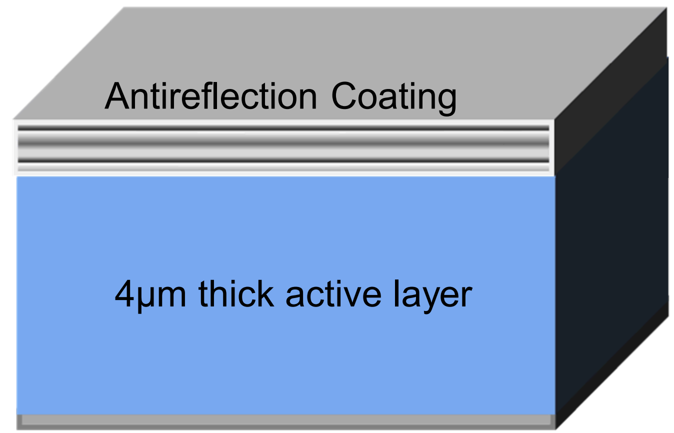
# Incorporation with Existing Detector Materials in the Midwave

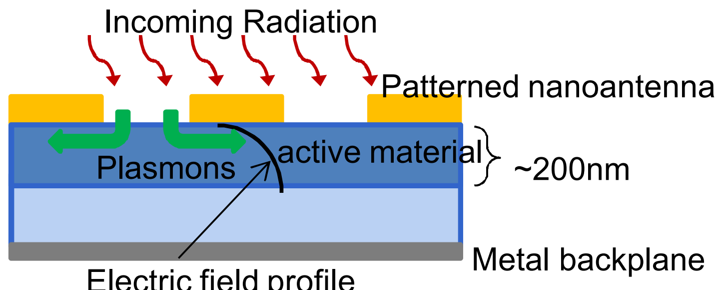


**Integrate subwavelength nanoantenna with active material (MCT or InGaSb) for high-performance focal plane array (FPA).**

**Using dense fields to thin the active region.**

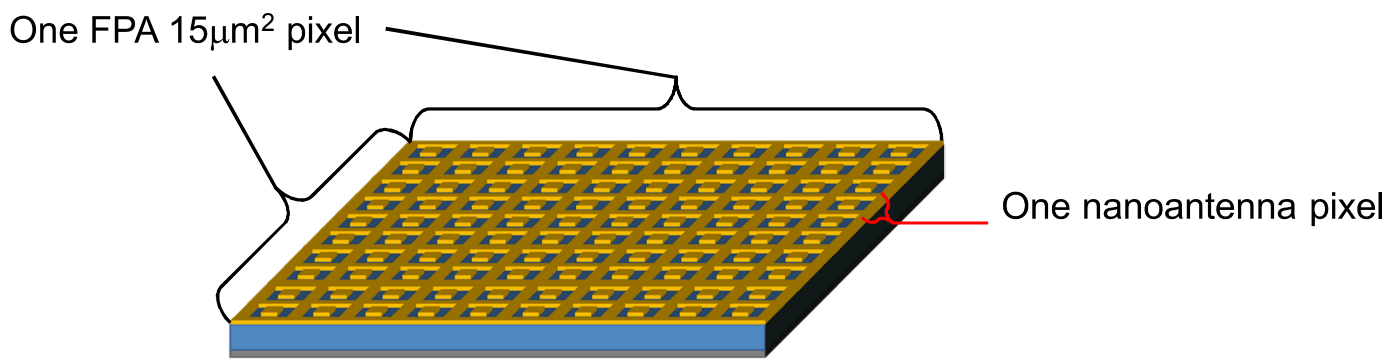


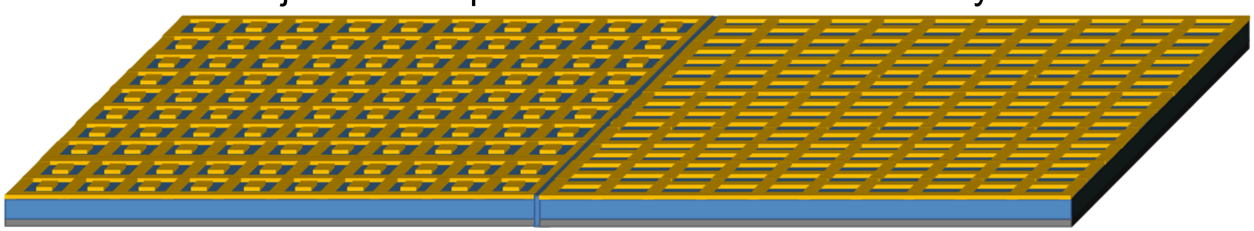



# Advantages of the Nanoantenna Structure

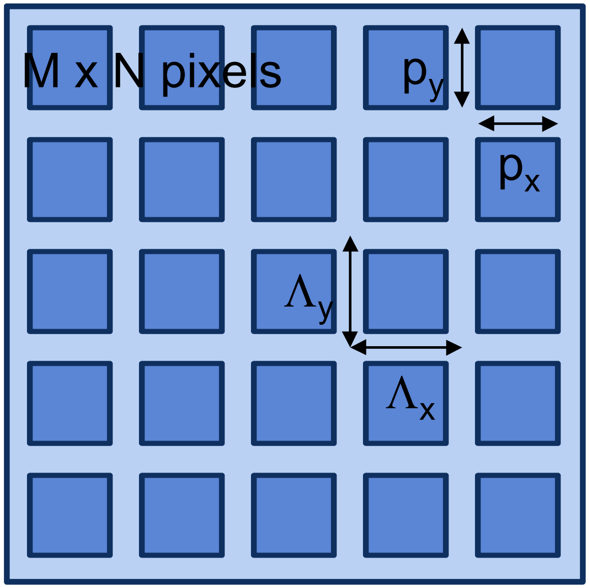
- Top and bottom contacts allow direct connection.
- Filtering can be changed from FPA pixel-to-pixel simply by changing the antenna pattern (Spectral or polarization). This is difficult to do with thin films.
- Small antenna unit cell allows multiple unit cells per FPA pixel (for broadband).



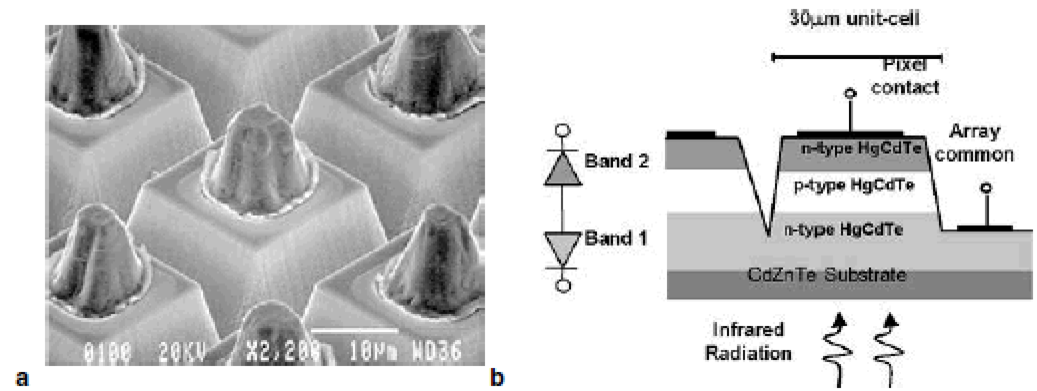

Two adjacent FPA pixels with different functionality.



# Maximizing Active Area Improves MTF and Signal

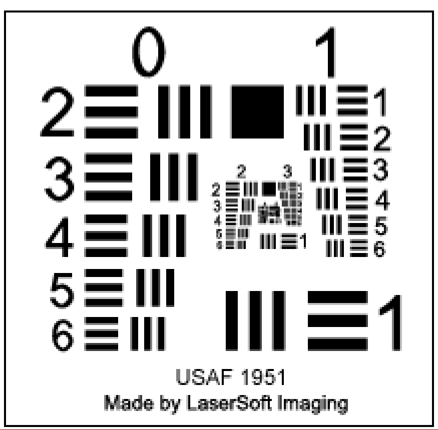



**MCT FPA architecture**




from E.P.G. Smith, et al, *J. of Electr. Matl.*, 2004.

$$MTF(f_x, f_y) = [\mathrm{sinc}((M \cdot \Lambda_x) \cdot f_x, (N \cdot \Lambda_y) \cdot \eta) * \mathrm{comb}(\Lambda_x \cdot f_x, \Lambda_y \cdot f_y)] \cdot \mathrm{sinc}(p_x \cdot f_x, p_y \cdot f_y)$$




Ideally for the mathematical MTF function, we want $\Lambda_x$, $\Lambda_y$ and $p_x$, $p_y$ as small as possible to maximize the MTF.

This is clearly impossible, but we can make $\Lambda_x$ and $\Lambda_y$ as small as possible for a given $p_x$ and $p_y$.

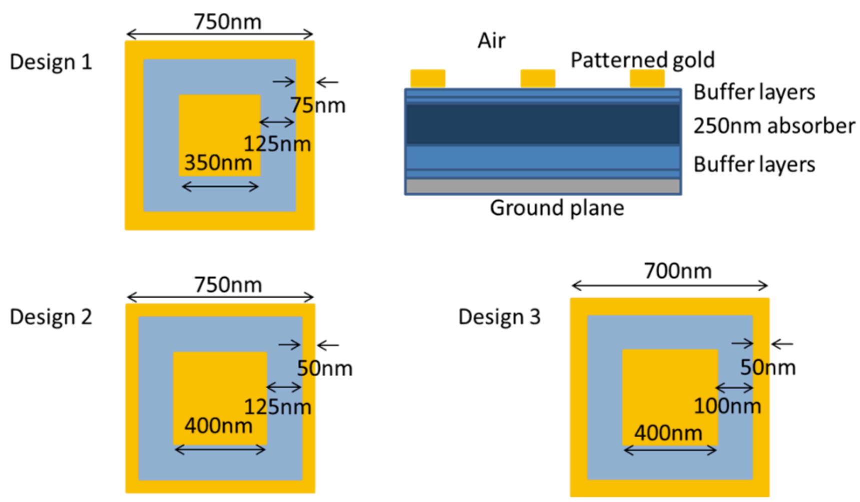
**Our architecture gives us near 100% fill factor.**

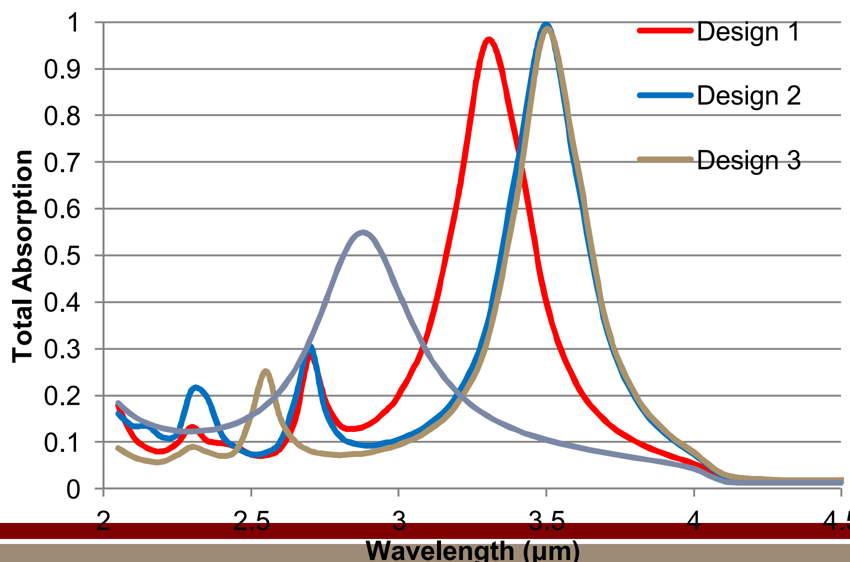
# Simulation of InAsSb Design

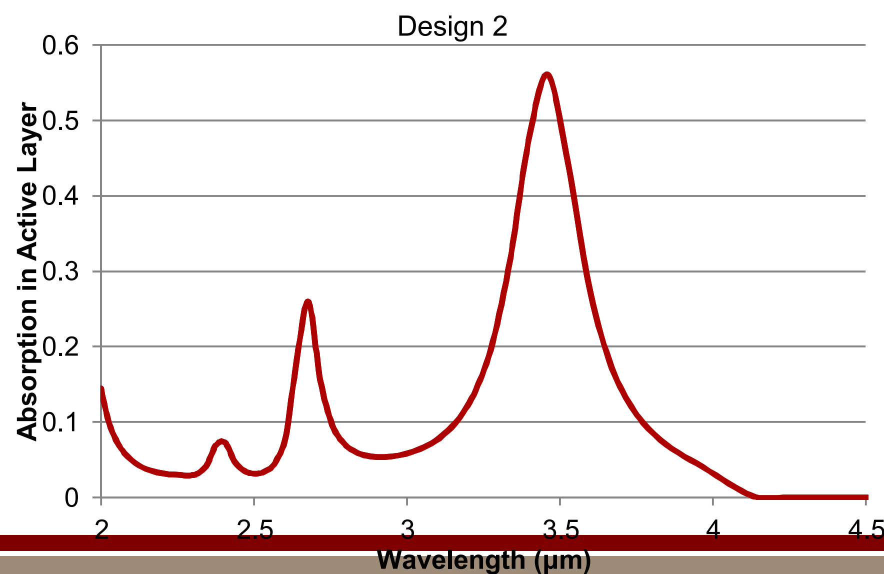
Designs for peak responsivity in the 3.25μm to 3.5μm range.

Three designs were fabricated with different patterns but similar peak resonances.

Designs were not optimized to maximize absorption in the active layer.

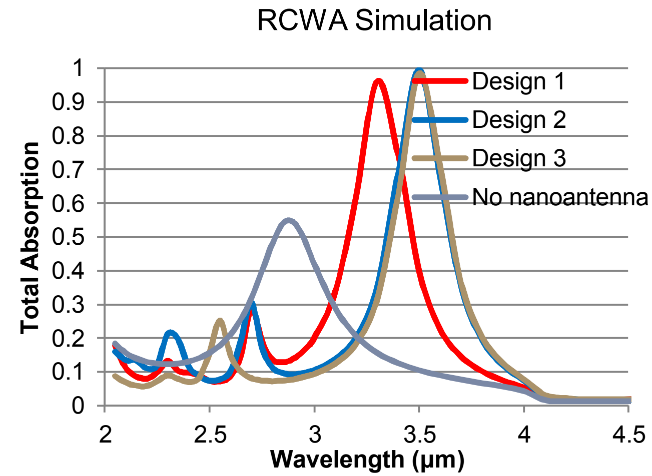


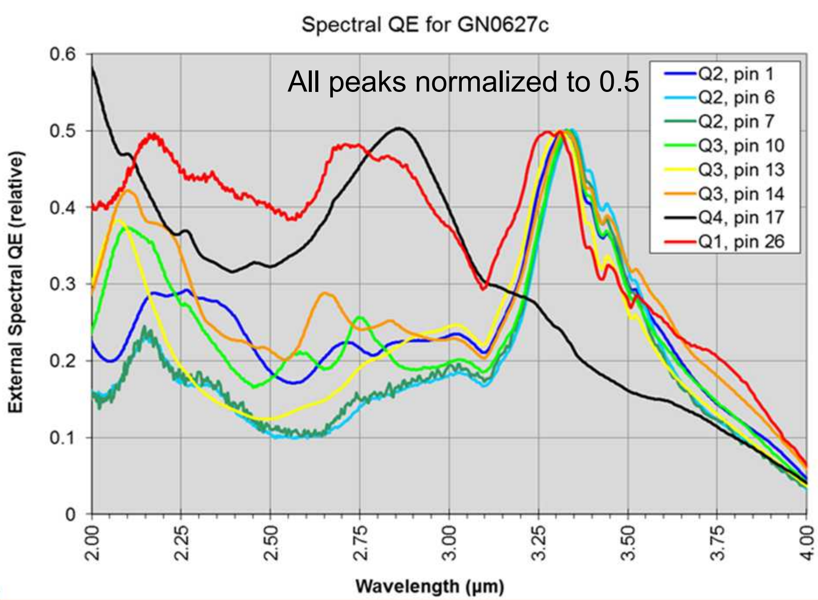



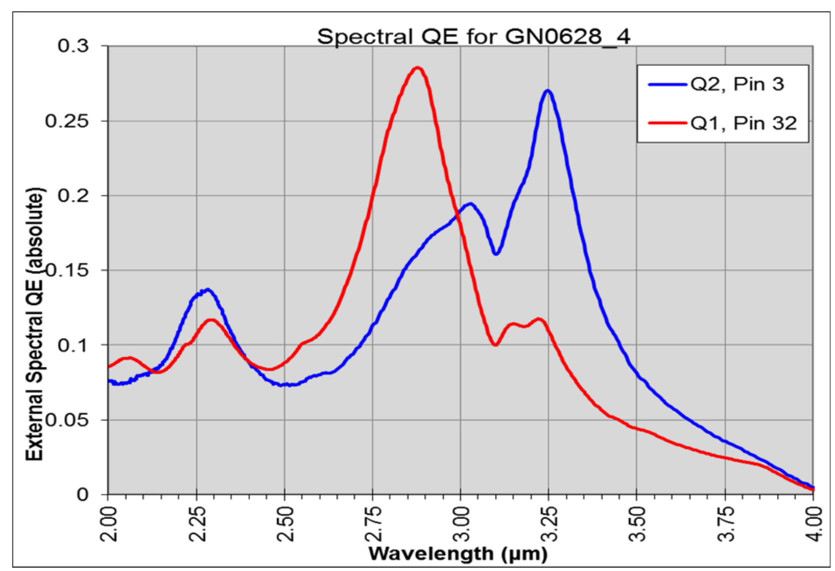



# Nanoantenna-Enhanced InAsSb Detector Results

- Epitaxial growth of two designs for integration with NA for test/ evaluation.
- Successful fabrication of detectors with integration of NAs using a flip-chip bonding process and selective substrate removal.
- Room for optimization in modeling and in characterization procedures.



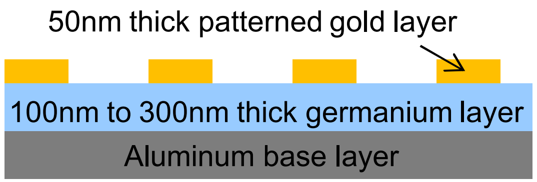



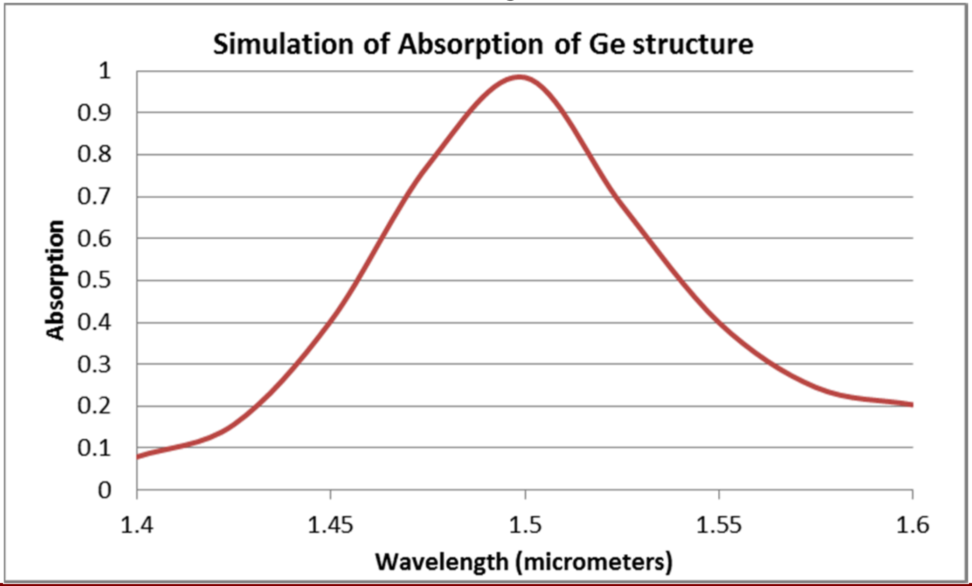
# Germanium Detector

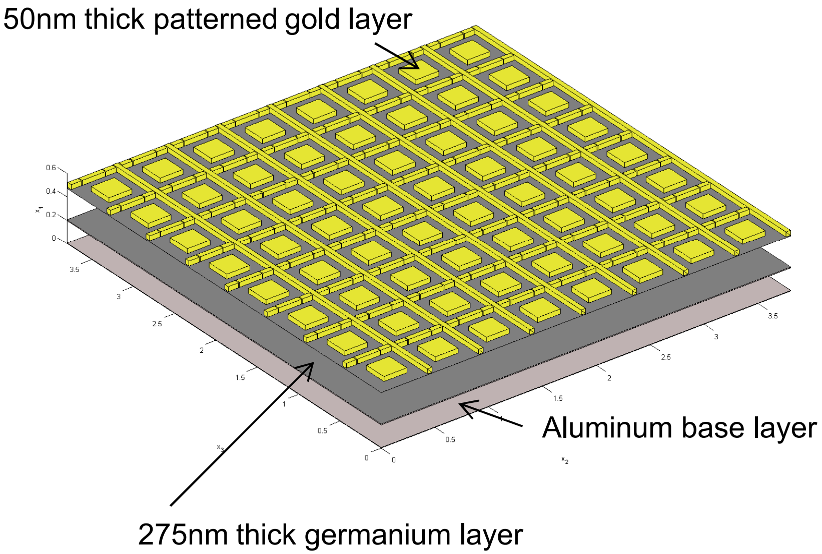
As with the MWIR designs, this one involves a detection material between two metal layers. Since it is for the near-IR, the detector layer is quite thin. The metal top and bottom layers act as contacts.

As it is thin, it is very fast as carriers move to a metal electrode quickly. Since the metal wire grid is not a large solid piece of metal, the capacitance should also be low.

We designed and simulated a structure with dimensions below to work at 1.5µm. This is in the telecommunications wavelength band.



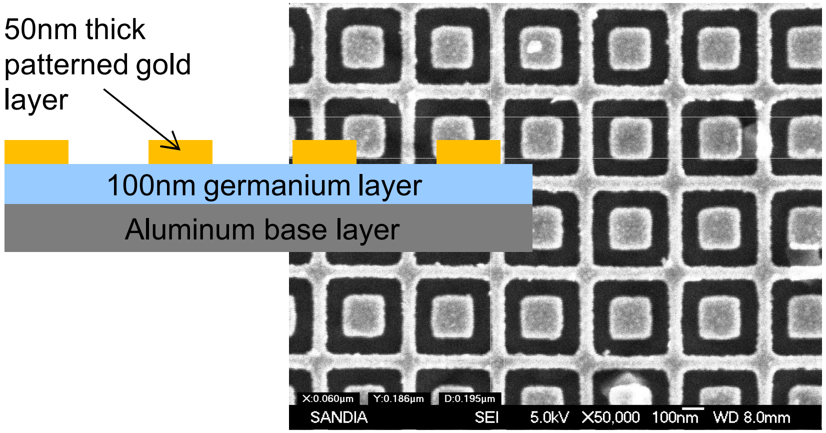




Period of nanoantenna = 475nm
Width of continuous gold bars = 50nm

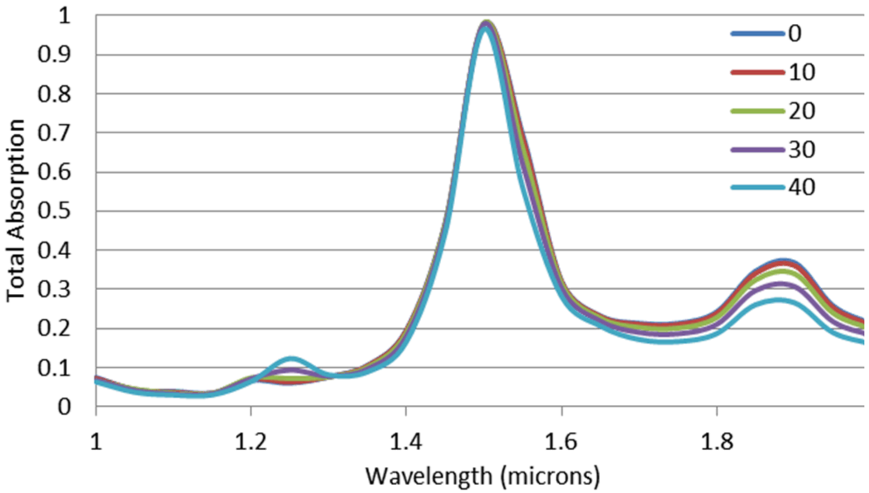
# Germanium Detector Design

There is virtually no change from normal out to 40° in the 100nm thick design. In any practical imaging system, this is more than enough.

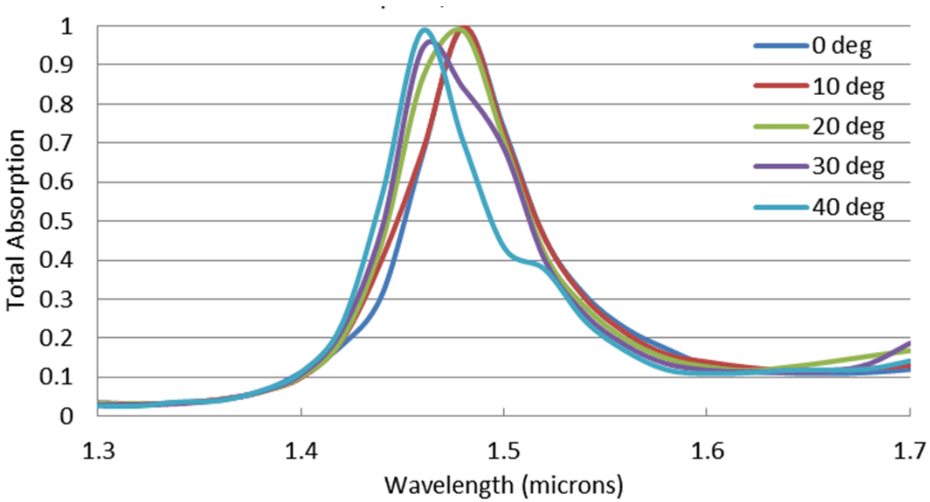
In the 275nm-thick design we see a change in peak wavelength between 20° and 30°.




Function of angle: 100nm Ge layer, 400nm period

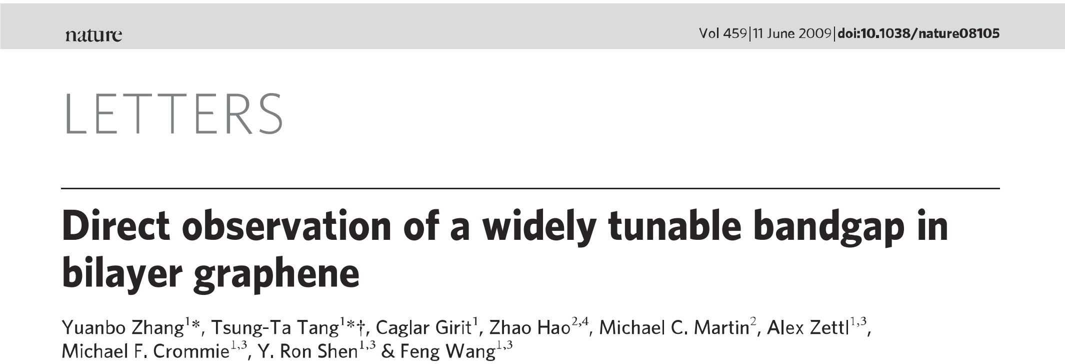



Function of angle: 275nm Ge layer, 450nm period



# Graphene Detectors: *Bilayer* Graphene Tunability

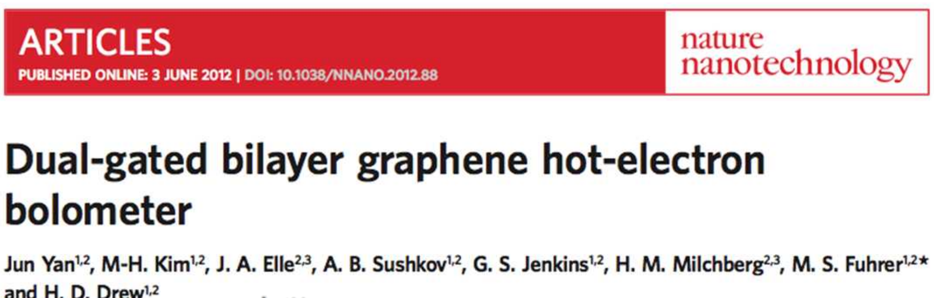
Sandia National Laboratories


nature Vol 459|11 June 2009|doi:10.1038/nature08105

LETTERS

**Direct observation of a widely tunable bandgap in bilayer graphene**

Yuanbo Zhang[1]*, Tsung-Ta Tang[1]*†, Caglar Girit[1], Zhao Hao[2,4], Michael C. Martin[2], Alex Zettl[1,3], Michael F. Crommie[1,3], Y. Ron Shen[1,3] & Feng Wang[1,3]

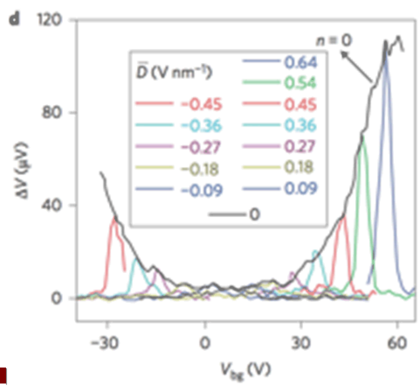

ARTICLES

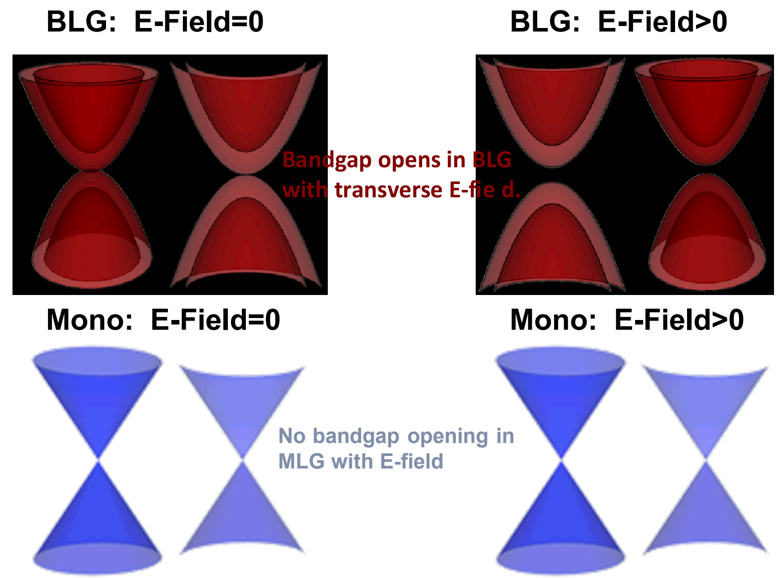
PUBLISHED ONLINE: 3 JUNE 2012 | DOI: 10.1038/NNANO.2012.88

nature nanotechnology

**Dual-gated bilayer graphene hot-electron bolometer**

Jun Yan[1,2], M-H. Kim[1,2], J. A. Elle[2,3], A. B. Sushkov[1,2], G. S. Jenkins[1,2], H. M. Milchberg[2,3], M. S. Fuhrer[1,2]* and H. D. Drew[1,2]



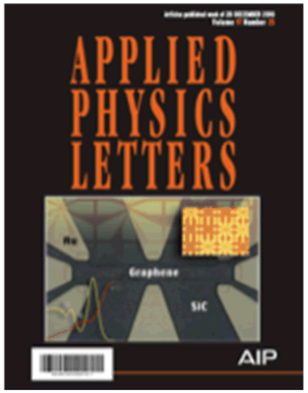



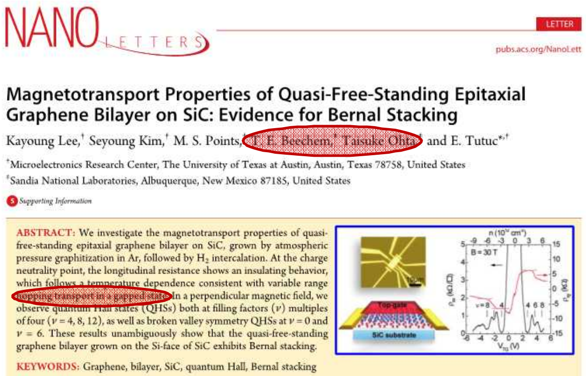

Problems:

1. Scalability
2. Low absorption
3. Multiphysics problem

# Approach: Combination of Technologies

## Scalability: Wafer-Scale BLG





NANO LETTERS

LETTER

pubs.acs.org/NanoLett

**Magnetotransport Properties of Quasi-Free-Standing Epitaxial Graphene Bilayer on SiC: Evidence for Bernal Stacking**

Kayoung Lee,[†] Seyoung Kim,[†] M. S. Points,[†] T. E. Beechem,[‡] Taisuke Ohta,[‡] and E. Tutuc*,[†]

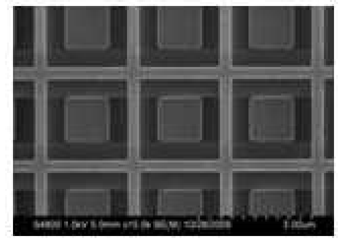
[†]Microelectronics Research Center, The University of Texas at Austin, Austin, Texas 78758, United States
[‡]Sandia National Laboratories, Albuquerque, New Mexico 87185, United States

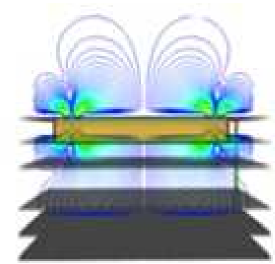
Supporting Information

ABSTRACT: We investigate the magnetotransport properties of quasi-free-standing epitaxial graphene bilayer on SiC, grown by atmospheric pressure graphitization in Ar, followed by $H_2$ intercalation. At the charge neutrality point, the longitudinal resistance shows an insulating behavior, which follows a temperature dependence consistent with variable range hopping transport in a gapped state. In a perpendicular magnetic field, we observe quantum Hall states (QHSs) both at filling factors ($\nu$) multiples of four ($\nu = 4, 8, 12$), as well as broken valley symmetry QHSs at $\nu = 0$ and $\nu = 6$. These results unambiguously show that the quasi-free-standing graphene bilayer grown on the Si-face of SiC exhibits Bernal stacking.

KEYWORDS: Graphene, bilayer, SiC, quantum Hall, Bernal stacking

## Low Absorption: Nanoantennas



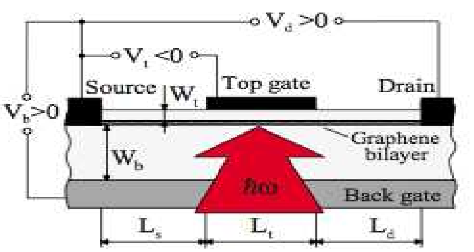


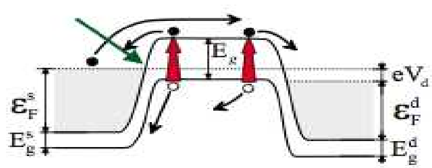
**Nanoantenna-Enabled Midwave Infrared Focal Plane Arrays**

David W. Peters*, Charles M. Reinke, Paul S. Davids, John F. Klem, Darin Leonhardt, Joel R. Wendt, Jin K. Kim, Sally Samora
Sandia National Laboratories, P.O. Box 5800, Albuquerque, NM, USA 87185-1082

Proc. of SPIE Vol. 8353 83533B-1

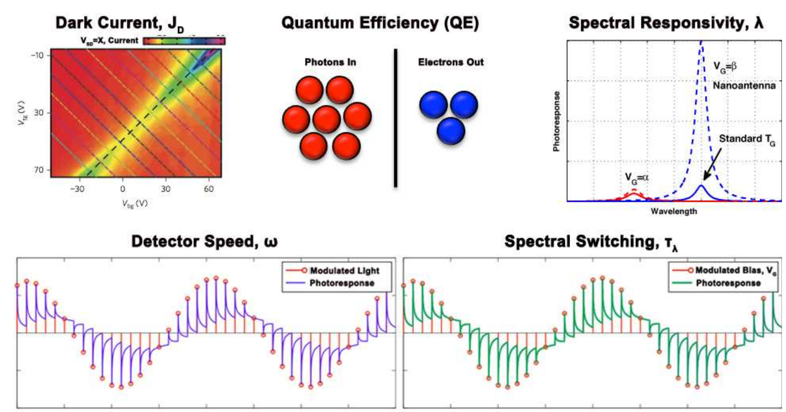
## Phenomenon: PhotoFET



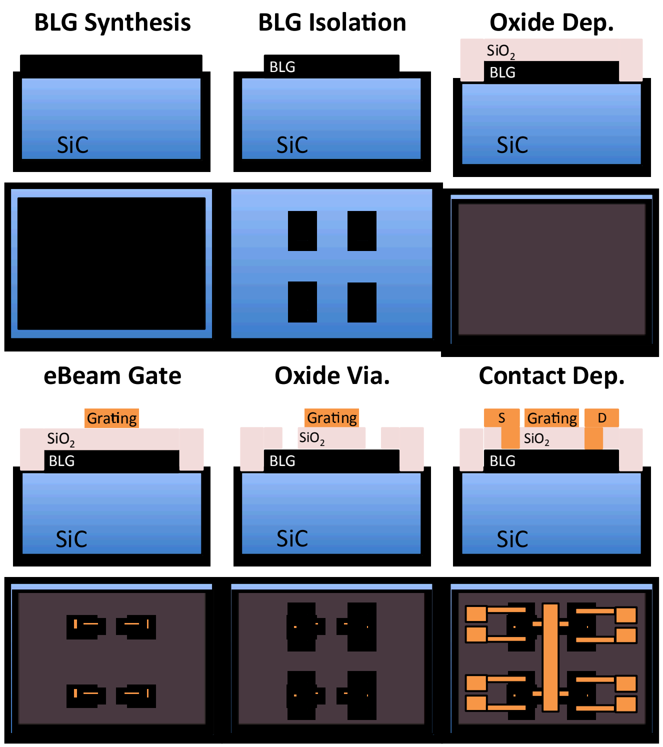



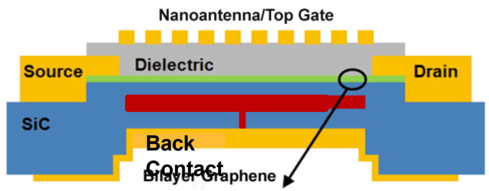

Ryzhii et al. PRB (79) 245311. 2009

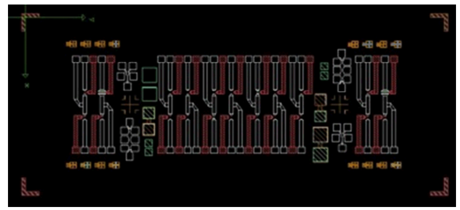
## Next Steps: Technology Maturation

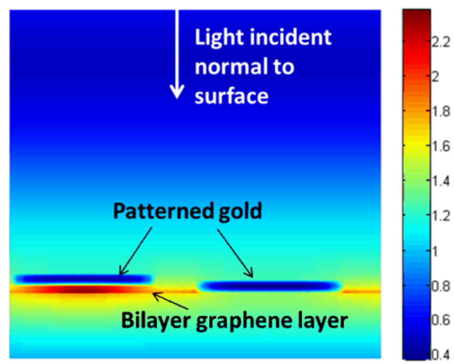


# Graphene Detector: Early Fab and Results

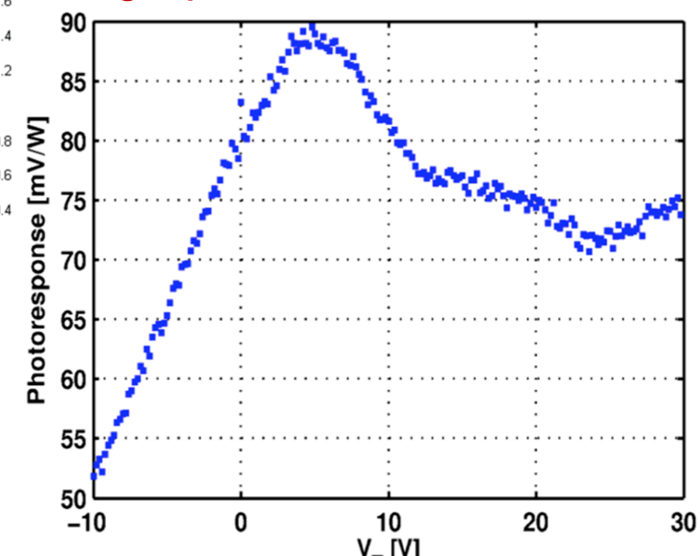





- Scalable fabrication using "standard" techniques
- Multiple operational devices on a chip
- Opens path towards arrays
- Developed an improved understanding of the graphene/SiC interface




**Devices show bias dependent tunability with a signal enhanced by nanoantennas.**

# Summary

Sandia National Laboratories

**Nanophotonics is an integral part of Sandia MESA research and fabrication.**

- Plasmonic devices.
- Infrared detectors.
- New materials such as graphene and pyrolyzed carbon.

**Nanoantennas offer methods of enhancement in traditional and new detector platforms.**

- InAsSb detectors in the MWIR.
- Germanium detectors in the Near-IR.
- Graphene detectors that offer new capabilities.

# Extra Slides

# Si Photonics Publications in FY14

- J. A. Cox, A.L. Lentine, Douglas C. Trotter, and Andrew L. Starbuck, "Control of integrated micro-resonator wavelength via balanced homodyne locking," Opt. Express **22**, 11279-11289 (2014)
- R. Aguinaldo, A. Forencich, C. DeRose, A. Lentine, D. C. Trotter, Y. Fainman, G. Porter, G. Papen, and S. Mookherjea, "Wideband silicon-photonic thermo-optic switch in a wavelength-division multiplexed ring network," Opt. Express **22**, 8205-8218 (2014)
- J. A. Cox, A.L. Lentine, D. J. Savignon, R. D. Miller, D. C. Trotter, and A. L. Starbuck, "Very Large Scale Integrated Optical Interconnects: Coherent Optical Control Systems with 3D Integration," in *Advanced Photonics for Communications*, OSA Technical Digest (online) (Optical Society of America, 2014), paper IM2A.1.
- C. DeRose, “Integrated RF Silicon Photonics from High Power Photodiodes to Linear Modulators,” in *Advanced Photonics for Communications*, OSA Technical Digest (online) (Optical Society of America, 2014), paper IW2A.1.
- D.A. Bender ; C. T. DeRose ; A. Starbuck ; J. C. Verley and M. W. Jenkins, “Precision laser annealing of silicon devices for enhanced electro-optic performance”, *Proc. SPIE* 8967, Laser Applications in Microelectronic and Optoelectronic Manufacturing (LAMOM) XIX, 89670S (March 6, 2014).
- J. A. Cox, A. L. Lentine, D. J. Savignon, D. Trotter, and A. Starbuck, “Wavelength Control of Resonant Photonic Modulators with Balanced Homodyne Locking,” in *CLEO: 2014*, OSA Technical Digest (online) (Optical Society of America, 2014), paper STh4M.7.
- C.T. DeRose, R. Kekatpure, A. Starbuck, A. Pomerene and A. L. Lentine, "A CMOS Compatible External Heater-Modulator", IEEE Opt. Interconnect Conf., MC3, pp.17-18, May 2014.
- C.T. DeRose, N.J. Martinez, R.D. Kekatpure, W.A. Zortman, A.L. Starbuck, A. Pomerene and A. L. Lentine, “Thermal Crosstalk Limits for Silicon Photonic DWDM Interconnect", IEEE Opt. Interconnect Conf., WC5, pp.125-126, May 2014.
- T. Iatchu, M. Pochet, N.G. Usechak, C. DeRose, A. L. Lentine, D.C. Trotter, and W. Zortman, "Power-Penalty Comparison of Push-Pull and Traveling-Wave Electrode Silicon Mach–Zehnder Modulators", IEEE Opt. Interconnect Conf., MC7, pp.25-26, May 2014.
- R. Aguinaldo, A. Forencich, C. DeRose, A. L. Lentine, A. Starbuck, Y. Fainman, G. Porter, G. Papen, S. Mookherjea, "Characterization of a silicon-photonic wideband switch in UCSD's MORDIA ring network", IEEE Opt. Interconnect Conf., TuD4, pp.102-103, May 2014.
- R. Aguinaldo, P.O. Weigel, H. Grant, C. DeRose, A. L. Lentine, A. Pomerene, A. Starbuck, S. Mookherjea, "Characterization of a silicon-photonic multi-wavelength power monitor", IEEE Opt. Interconnect Conf., WD5, pp.139-140, May 2014.

- 2 at Integrated Photonics Research Conf., 5 at Optical Interconnect Conf., 1 SPIE, 1 CLEO; 2 journals.

# Selected Sandia's Photonics Patents

Sandia National Laboratories

Silicon Photonics

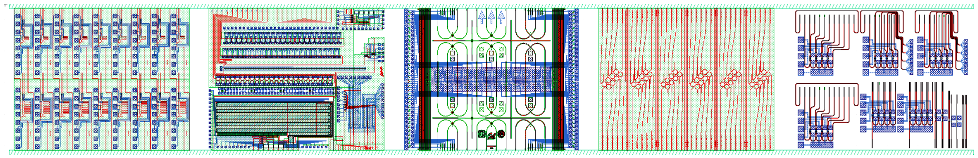
- U.S. Patent 7616850, Wavelength-Tunable Optical Ring Resonators (SD 10791.0)
- U.S. Patent 7941014, Optical Waveguide Device With An Adiabatically-Varying Width (SD 11104.0)
- U.S. Patent 7983517, Wavelength-Tunable Optical Ring Resonators (SD 10791.1)
- U.S. Patent 8027587 , Integrated Optic Vector-Matrix Multiplier(SD 10237.1)
- U.S. Patent 8610994, Silicon Photonics Thermal Phase Shifter With Reduced Temperature Range (SD 11837.0)
- U.S. Patent 8615173, Systems For Active Control of Integrated Resonant Optical Device Wavelength (SD 11555.0)
- U.S. Patent 8600200, Nano-Optomechanical Transducer (SD 11508.0)
- U.S. Patent 8625939, Ultralow Loss Cavities and Waveguides Scattering Loss Cancellation (SD 11631.0)
- U.S. Patent 8822959, Method And Apparatus For Optical Phase Error Correction (SD 12024.0)

Plasmonics for Infrared Sensors

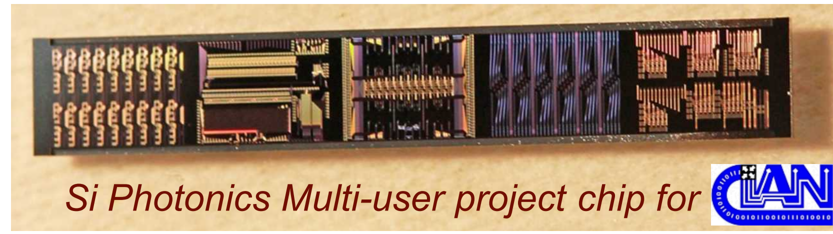
- U.S. Patent 8452134, Frequency Selective Infrared Sensors (SD 11433.0)
- U.S. Patent 8750653, Infrared Nanoantenna Apparatus and Method for the Manufacture thereof (SD 12379.0, SD 12539.0)

- 9 issued patents in Si photonics and 2 in nano-antenna related areas (4 issued in FY2014)
- 21 additional patents pending (9 patents filed in FY2014)

# SiP Multi-User Wafer Project



Cornell UCSD Berkeley Arizona Berkeley

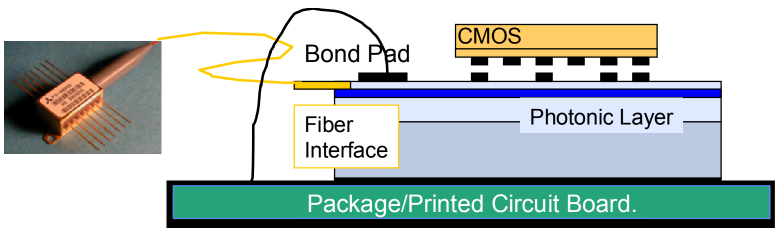


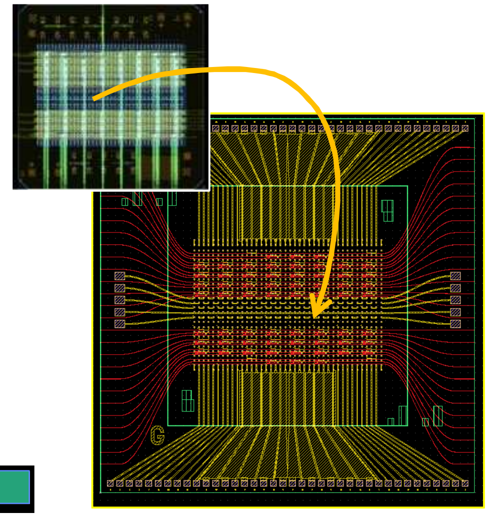

- Successfully completed 3 milestone deliverables to NSF CIAN (Center of Integrated Access Networks) universities
  - Passive chips
  - Active chips (with P/N junctions for modulators, etc.)
  - Active chips with Germanium (with integrated photo detectors)
- On-going discussions for next collaborations (to include CUDOS and University of Bristol)
- Active planning in Photonics Manufacturing Innovation (IMI) led by DOD/AFRL ($110M BAA anticipated in early Nov)

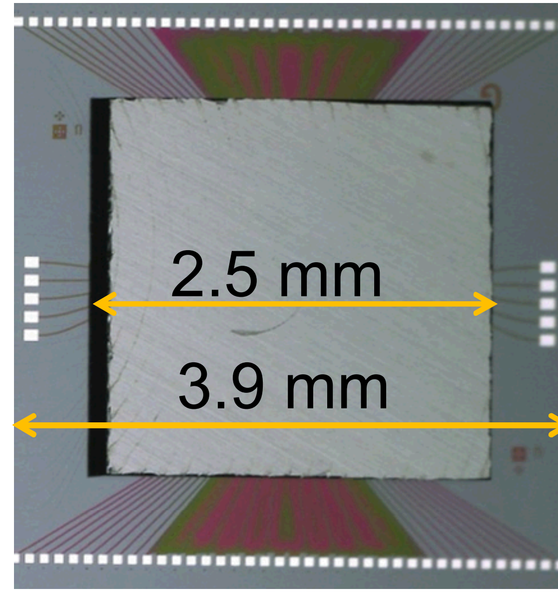
# Electronics – Photonics Integration

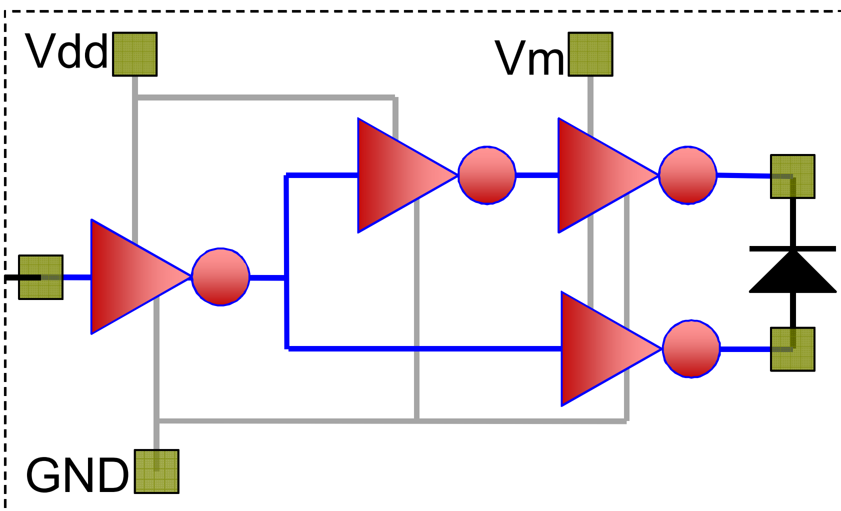
## Heterogeneous Integration

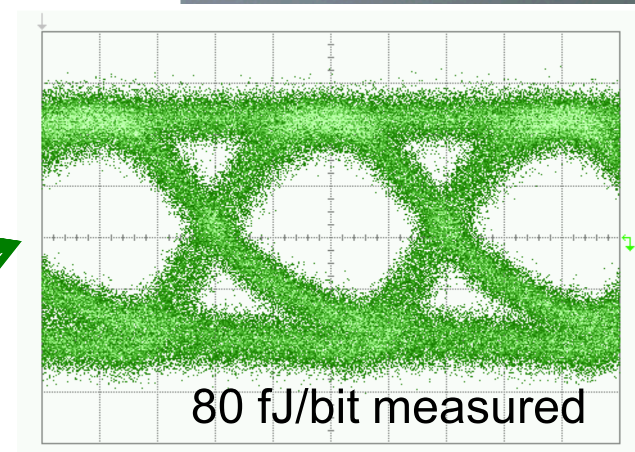
- Independent optimization of electronics & photonics
- Challenge: Need high yields and small bond size



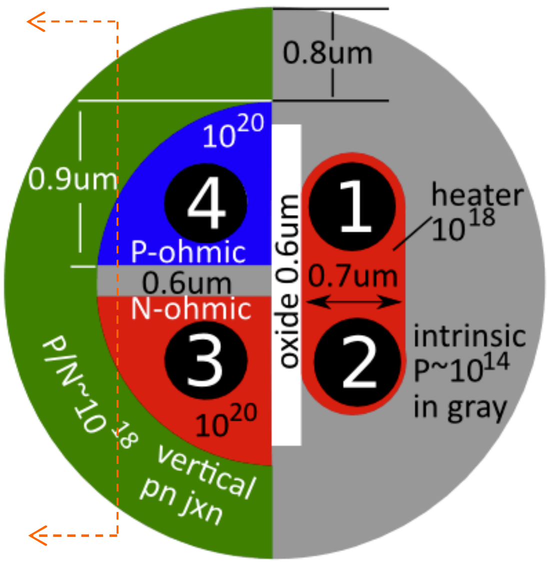


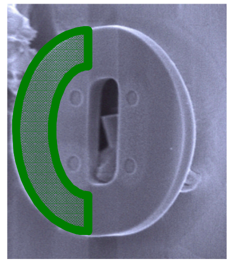




Modulated optical output at 5 Gbps

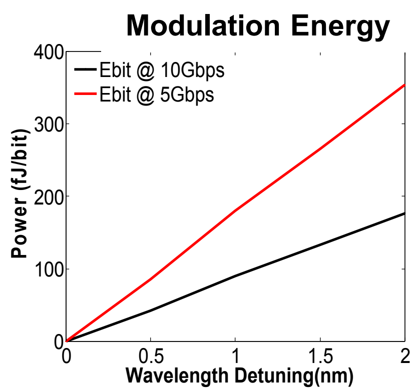
# 10Gbps Resonant Heater Modulator

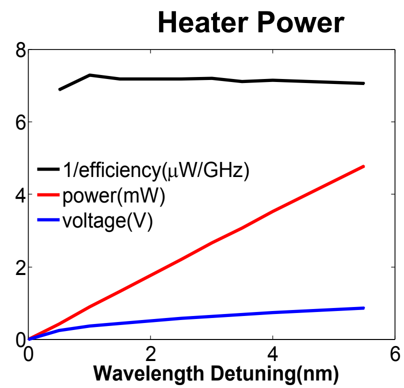


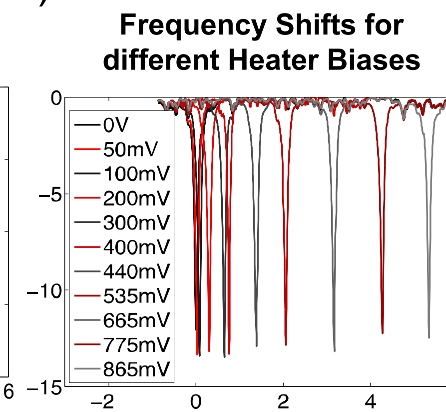

**1,2 – heater contacts**
**3,4 – modulator contacts**

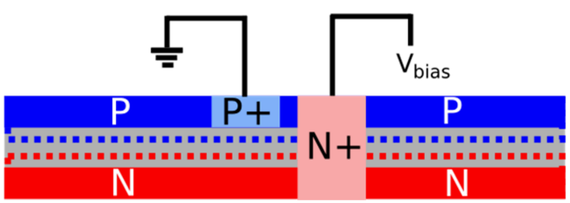


- FSR covers entire C-band
- Low footprint of ~14μm², CMOS-compatible
- Differential signaling compatibility
- Lowest intrinsic tuning energy
  7μW/GHz (0.7fJ/bit-GHz)

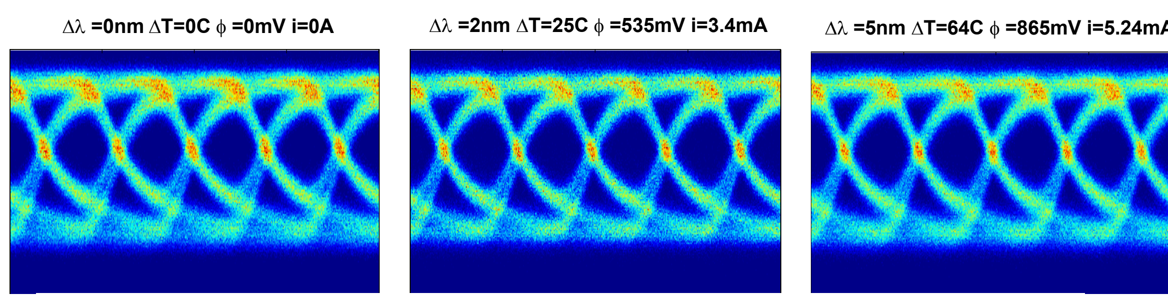



**Cross-section of modulator with vertical P-N junction**



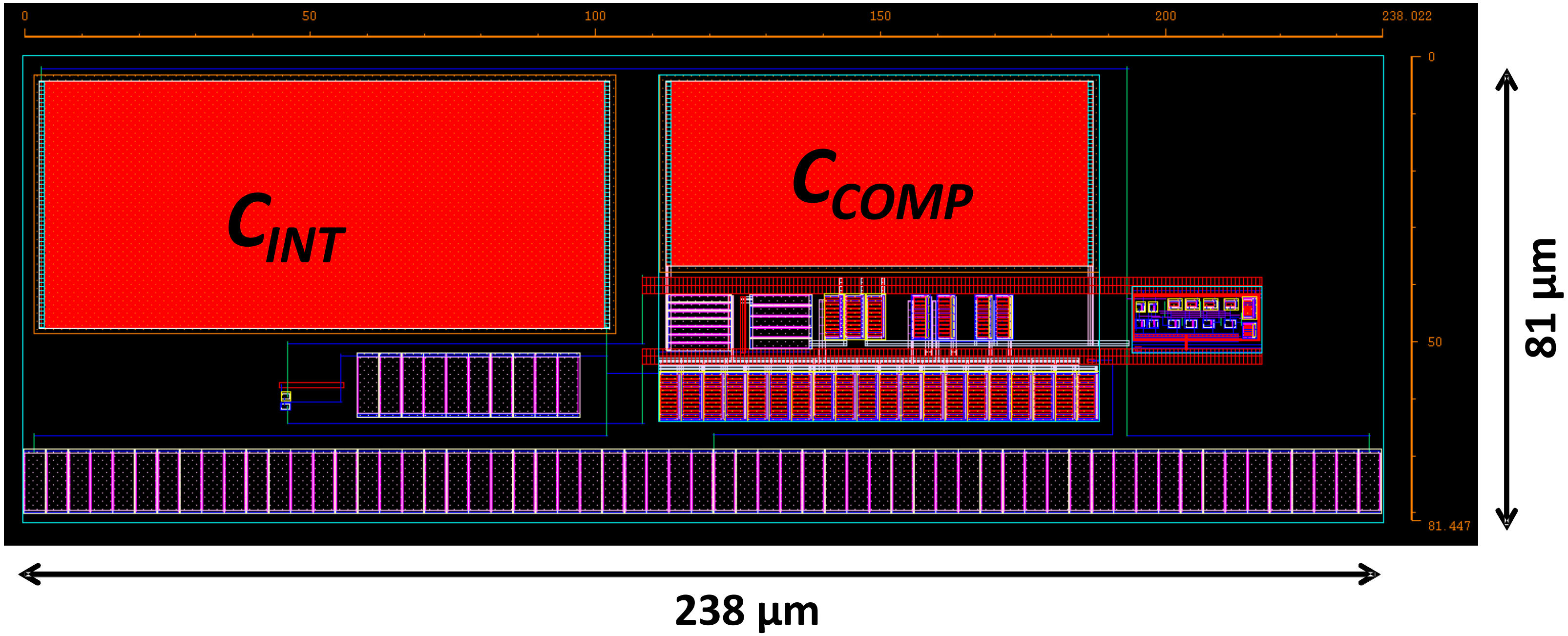

**Similar eye diagrams achieved at different tuning temperatures**

**W. Zortman, et. al., OFC , OW4I.5 (March 2012)**

# CMOS ASIC Design (under fab)

- **IBM 45 nm CMOS** ASIC designed at Sandia
- **Power consumption:** 1.07 mW (steady-state); 0.27 mW (TIA) and 0.8 mW (integrator) (30 – 100 fJ/bit @ 30Gbps-10Gbps) [1]
- **Heater time constant** → large integrator resistor and capacitor in loop filter
- **Heater driver:** Class-B "push-pull"
- **Inverter** implemented with analog switch network

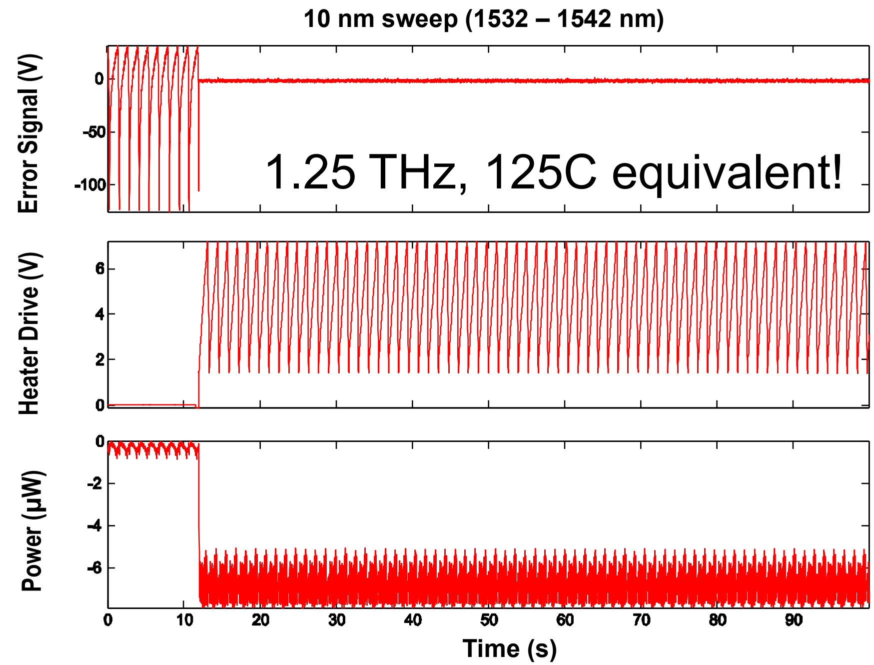
[1] recent result by X. Zheng (OpX 2014)
200μW, 2600 um² for 'power meter' control

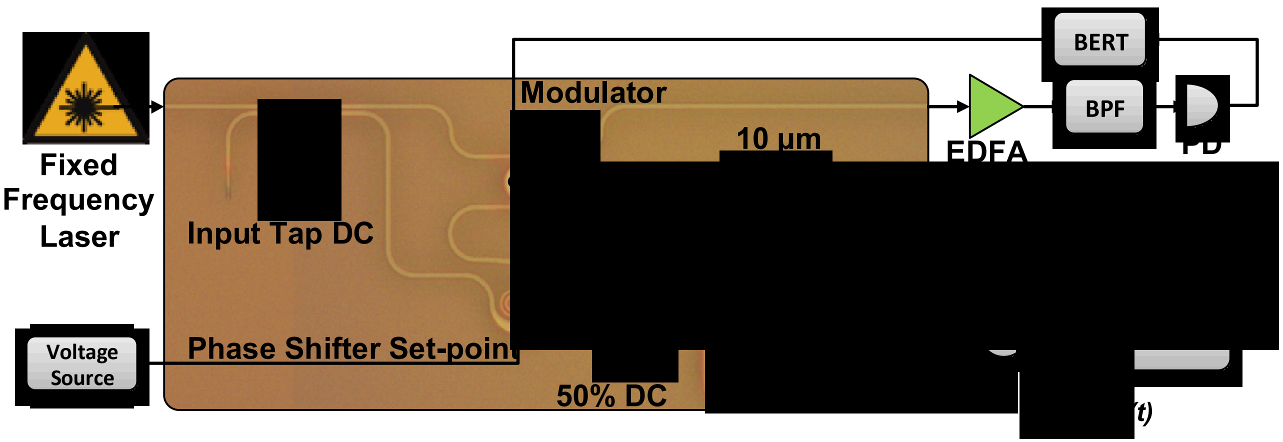


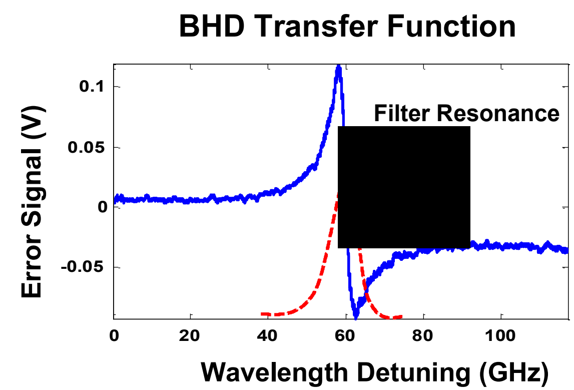

J.A. Cox et. al., Integrated Photonics Research, Paper IM2A.1, San Diego, CA (2014)

# Stabilization of Modulators

- ***Lock to zero:*** No calibration or reference level needed for locking
- ***Amplitude insensitive:*** Locking point not influenced by optical intensity
- ***Precision locking:*** Resonator is not disturbed
- ***Minimum circuit complexity:*** Power and area consumption of control electronics is minimized




J.A. Cox et. al., Opt. Express 22, 11279-11289 (2014)

# 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