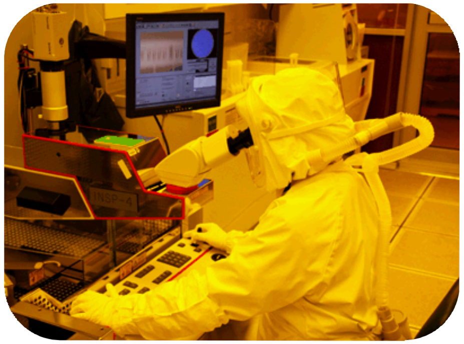
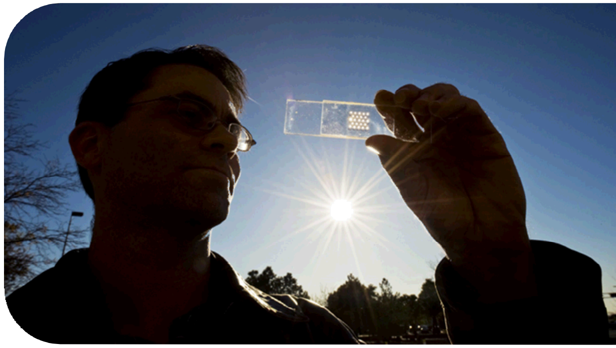
SAND2014-17946PE

Exceptional service in the national interest

Sandia National Laboratories





Exploiting Physics at the Nanoscale: Innovative Microsystems Process and Device Technologies at Sandia National Laboratories

Gilbert V. Herrera

Director, Microsystems Science& Technology

Sandia National Laboratories

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U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

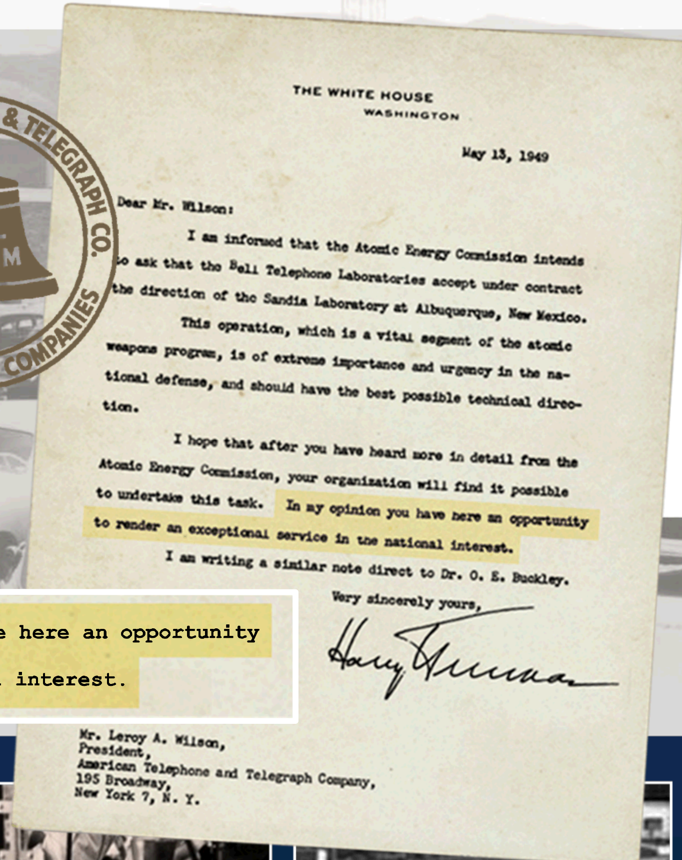
Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Outline

- Sandia and MESA overview
- Lessons learned from the development of the SUMMiT V MEMS Process Technology
- Selected Microsystems examples
- Summary

Sandia's history

Exceptional service in the national interest



THE WHITE HOUSE
WASHINGTON

May 13, 1949

Dear Mr. Wilson:

I am informed that the Atomic Energy Commission intends to ask that the Bell Telephone Laboratories accept under contract the direction of the Sandia Laboratory at Albuquerque, New Mexico.

This operation, which is a vital segment of the atomic weapons program, is of extreme importance and urgency in the national defense, and should have the best possible technical direction.

I hope that after you have heard more in detail from the Atomic Energy Commission, your organization will find it possible to undertake this task. In my opinion you have here an opportunity to render an exceptional service in the national interest.

I am writing a similar note direct to Dr. O. E. Buckley.

Very sincerely yours,

Harry Truman

Mr. Leroy A. Wilson,
President,
American Telephone and Telegraph Company,
195 Broadway,
New York 7, N. Y.

to undertake this task. In my opinion you have here an opportunity to render an exceptional service in the national interest.

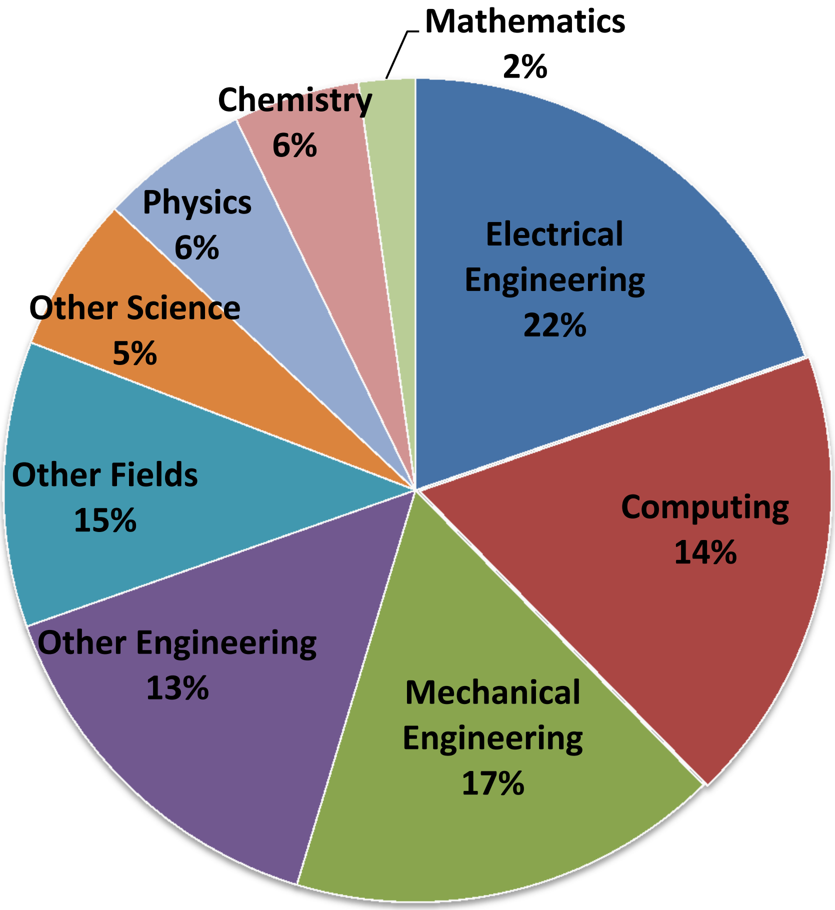
- **July 1945:** Los Alamos creates Z Division
- Nonnuclear component engineering
- **November 1, 1949:** Sandia Laboratory established

Our Workforce

- On-site workforce: 11,711
- Regular employees: 9,494

Data as of April 12, 2013

R&D staff (4,799) by discipline

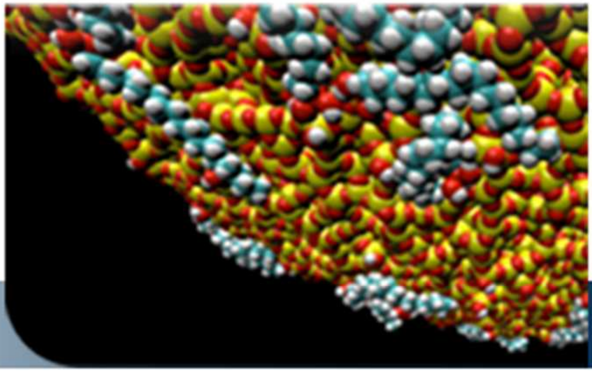


Foundations in Science and Engineering

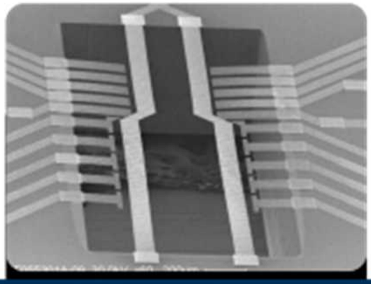
Sandia National Laboratories

Computing and information science

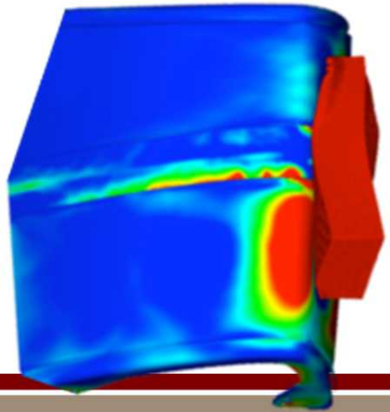
Materials science



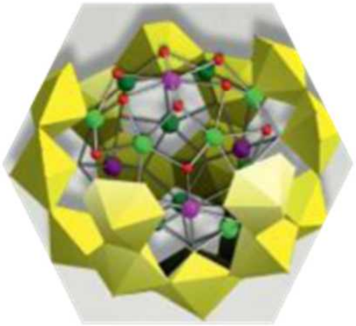
Nanodevices and microsystems



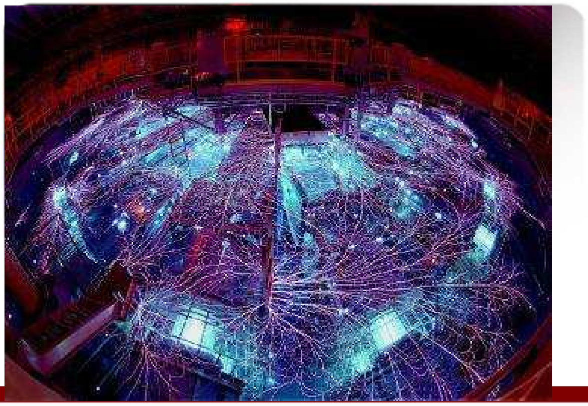
Engineering sciences



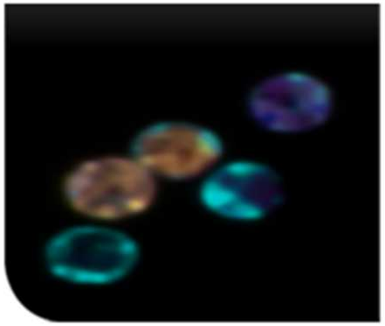
Geoscience



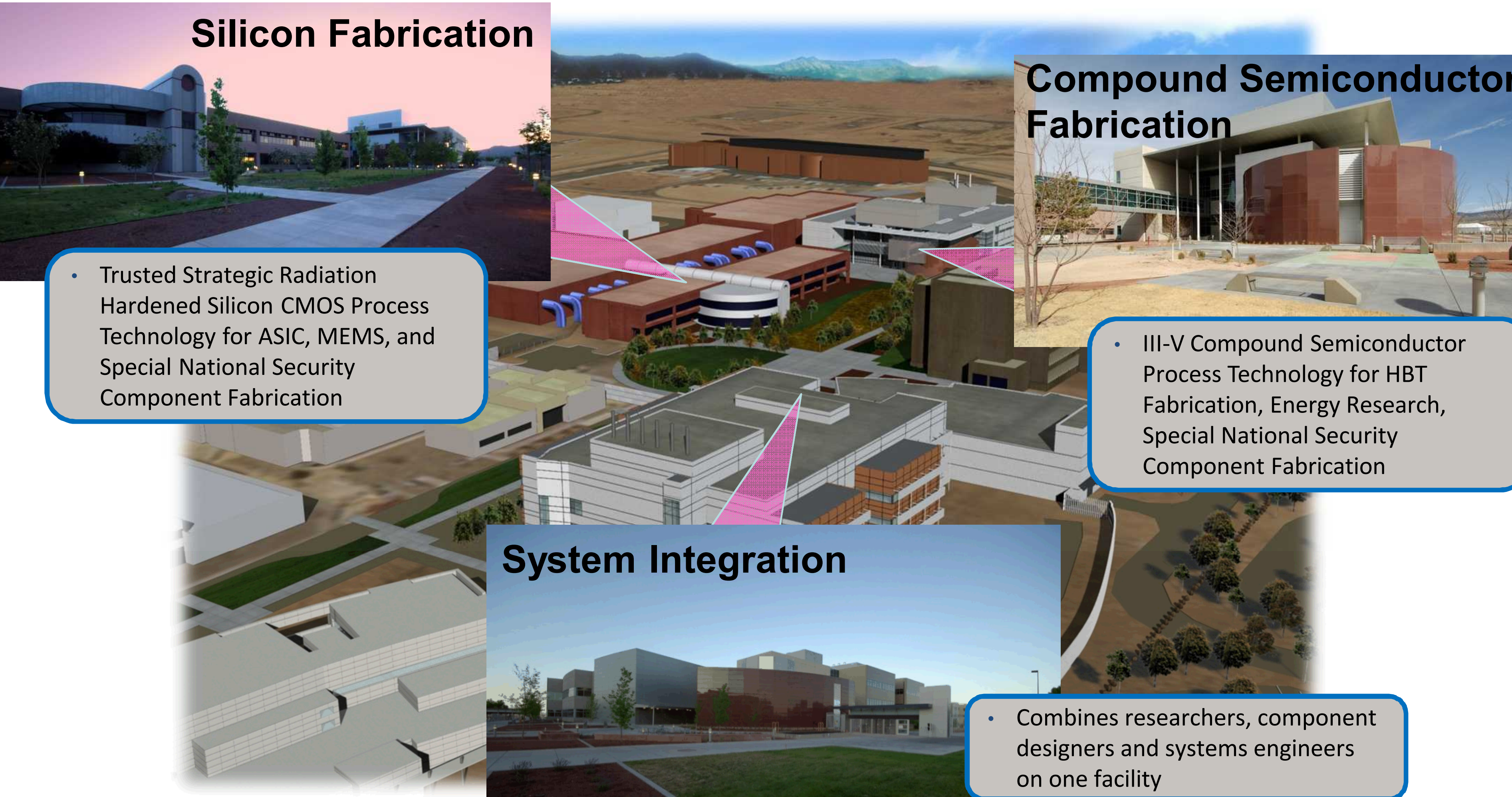
Radiation effects and high-energy density science



Bioscience



MESA provides a Strategic National Security Resource for the US Government



Silicon Fabrication

- Trusted Strategic Radiation Hardened Silicon CMOS Process Technology for ASIC, MEMS, and Special National Security Component Fabrication

Compound Semiconductor Fabrication

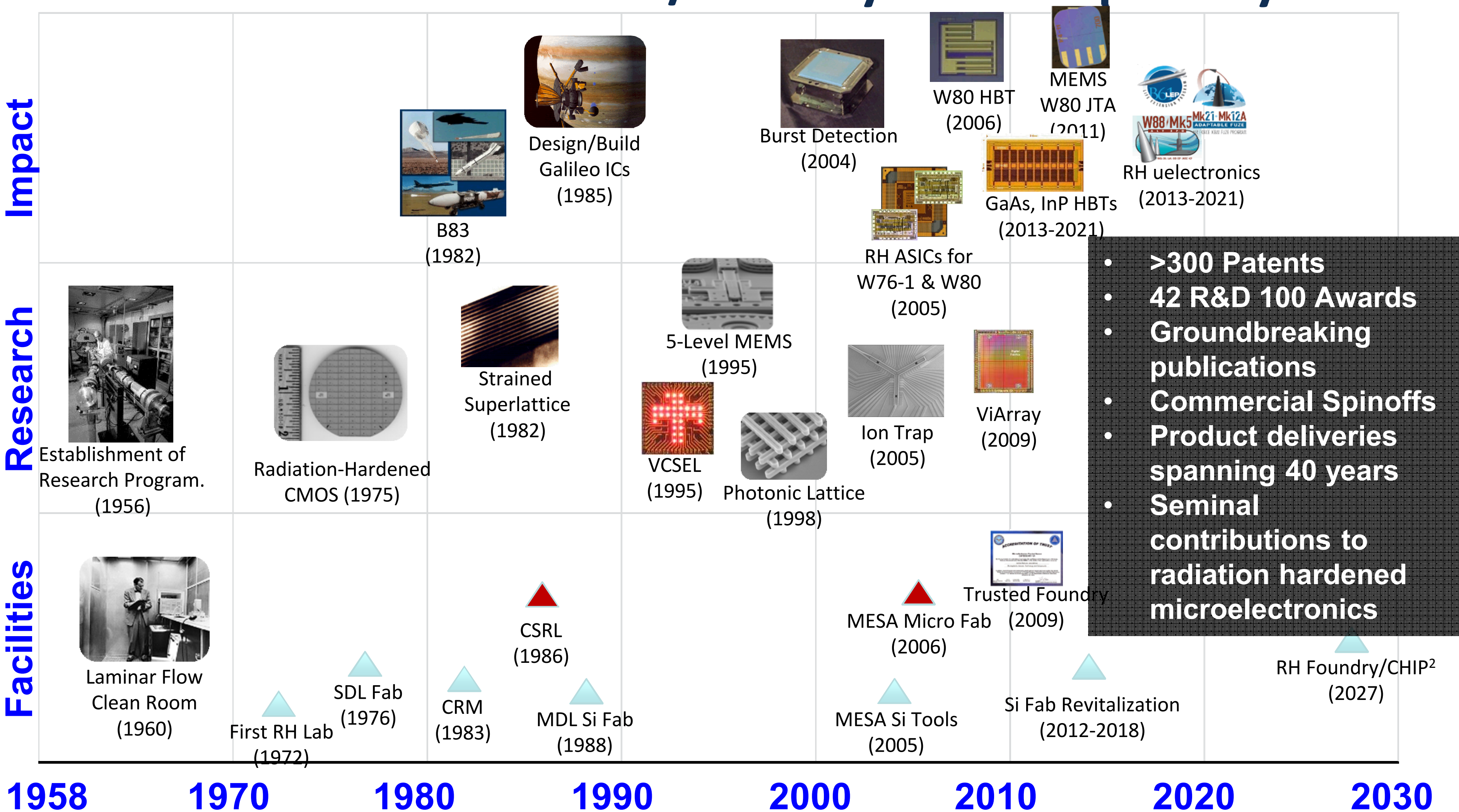
- III-V Compound Semiconductor Process Technology for HBT Fabrication, Energy Research, Special National Security Component Fabrication

System Integration

- Combines researchers, component designers and systems engineers on one facility

MESA provides a fundamental research through production environment that rapidly advances technologies through the TRL's

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



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

Outline

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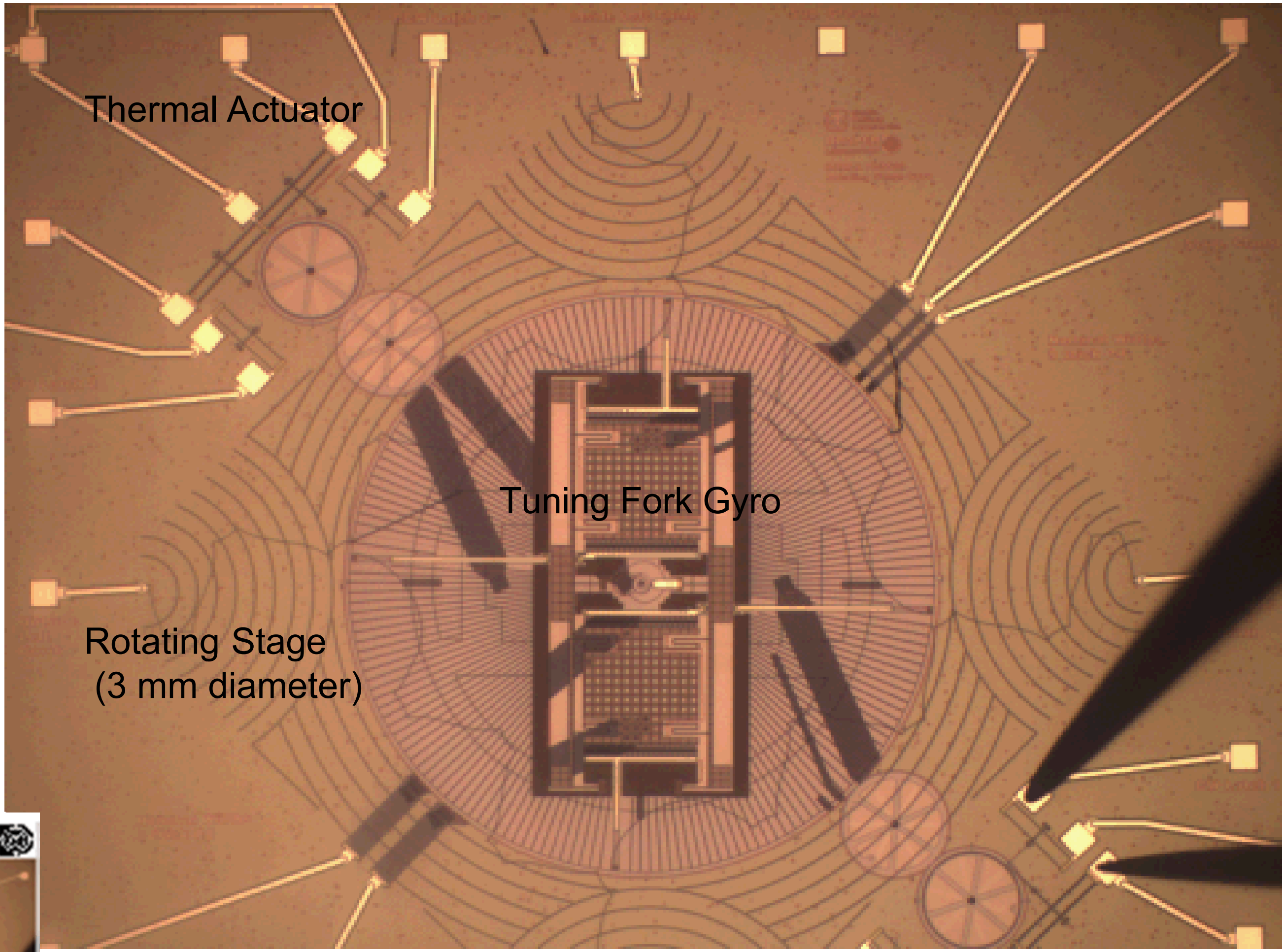
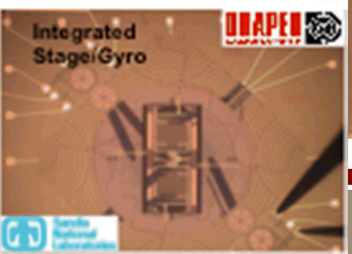
SUMMiT Today: PASCAL

DARPA MicroPNT Project: Primary and Secondary Calibration on Active Layer (PASCAL)

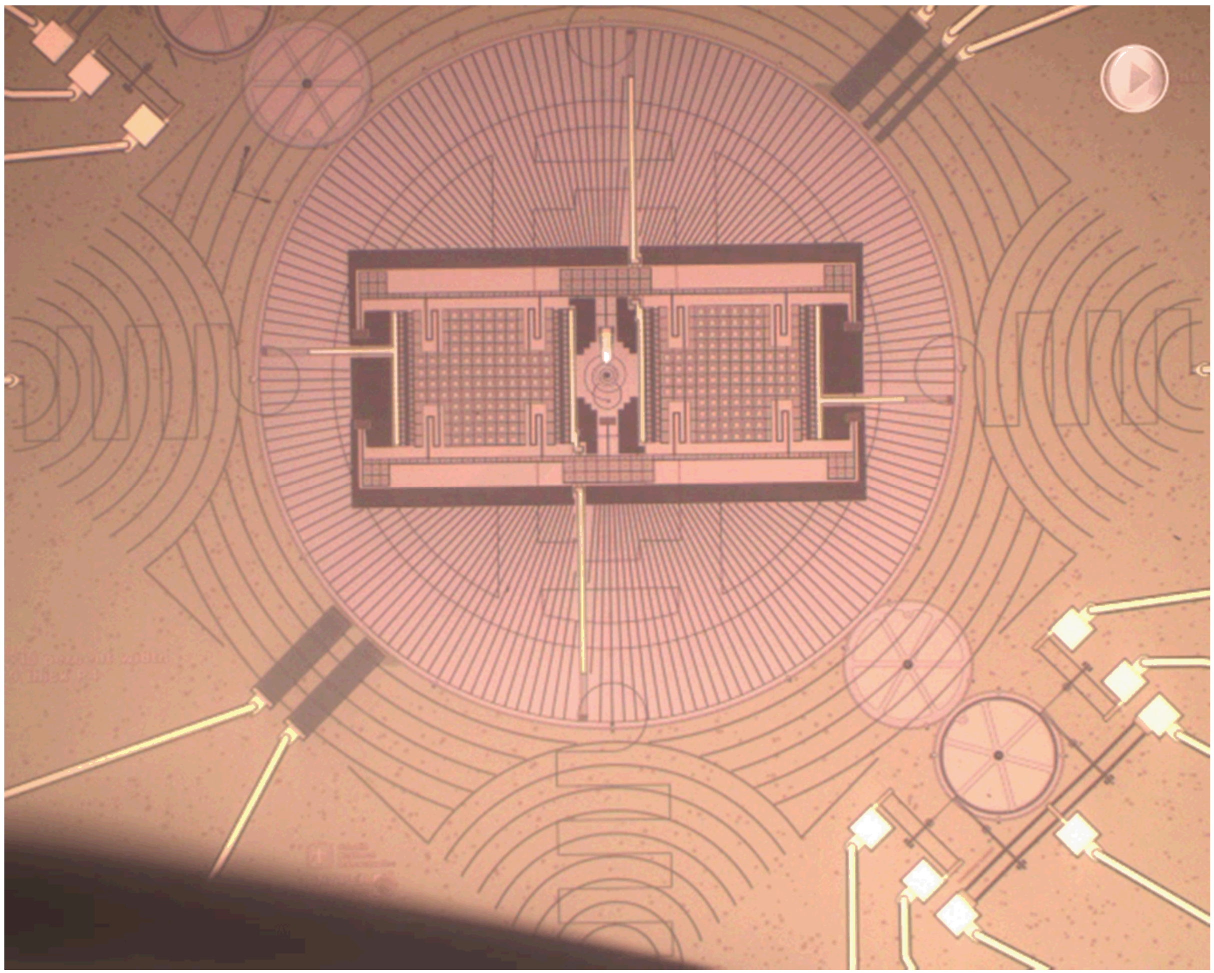


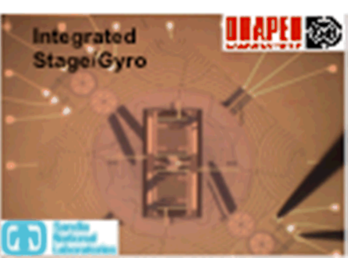


PASCAL Details

Sandia National Laboratories

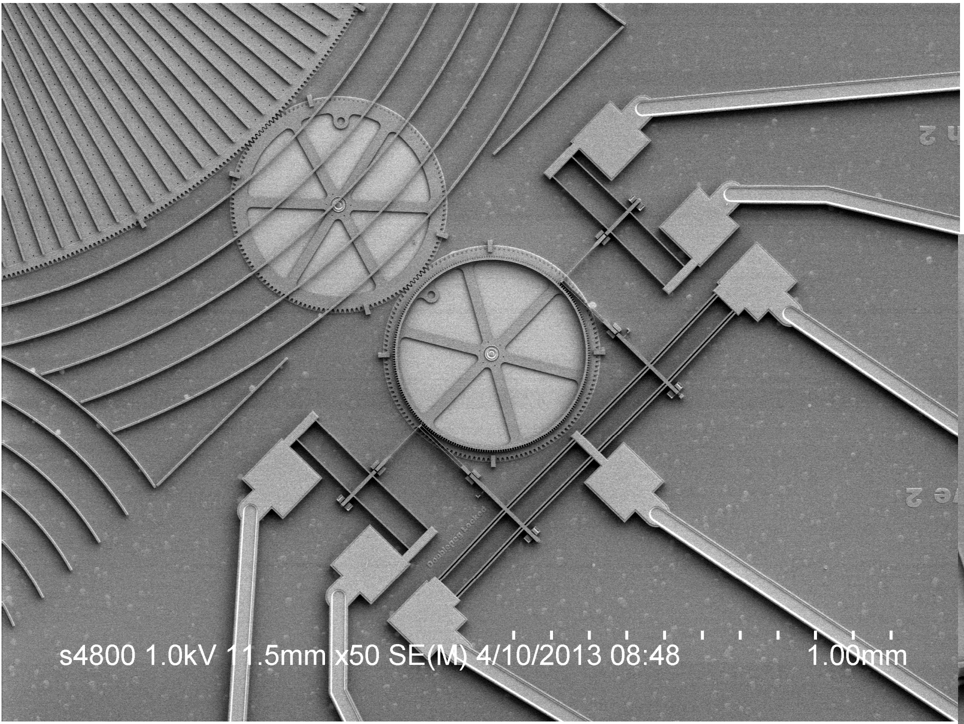
Bias reduction and scale factor calibration achieved by "carouselling" of rotating stage.

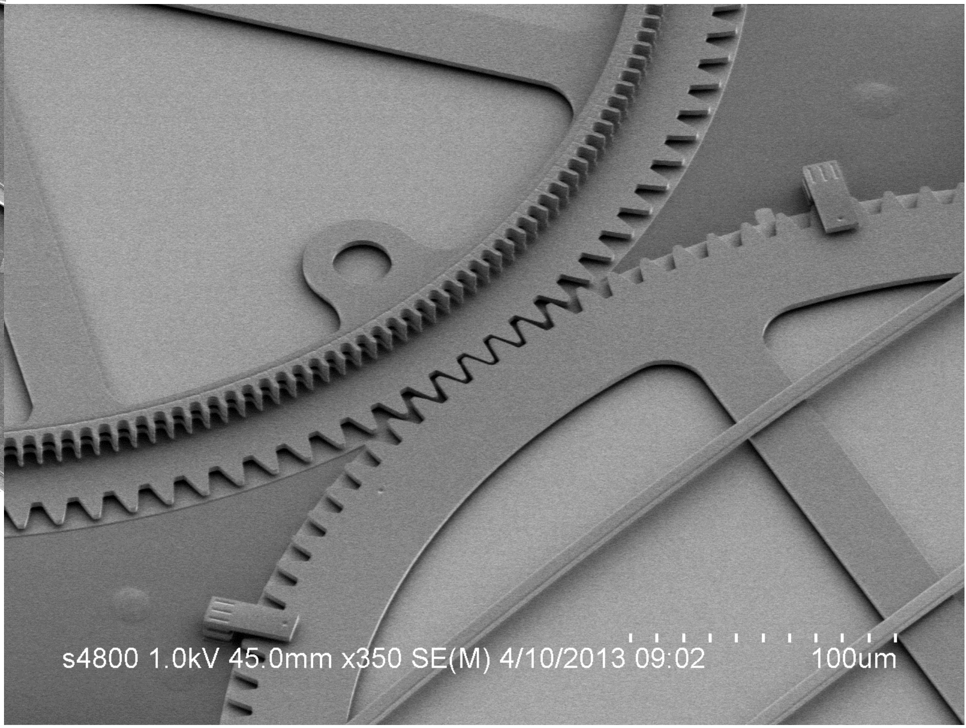




PASCAL Details

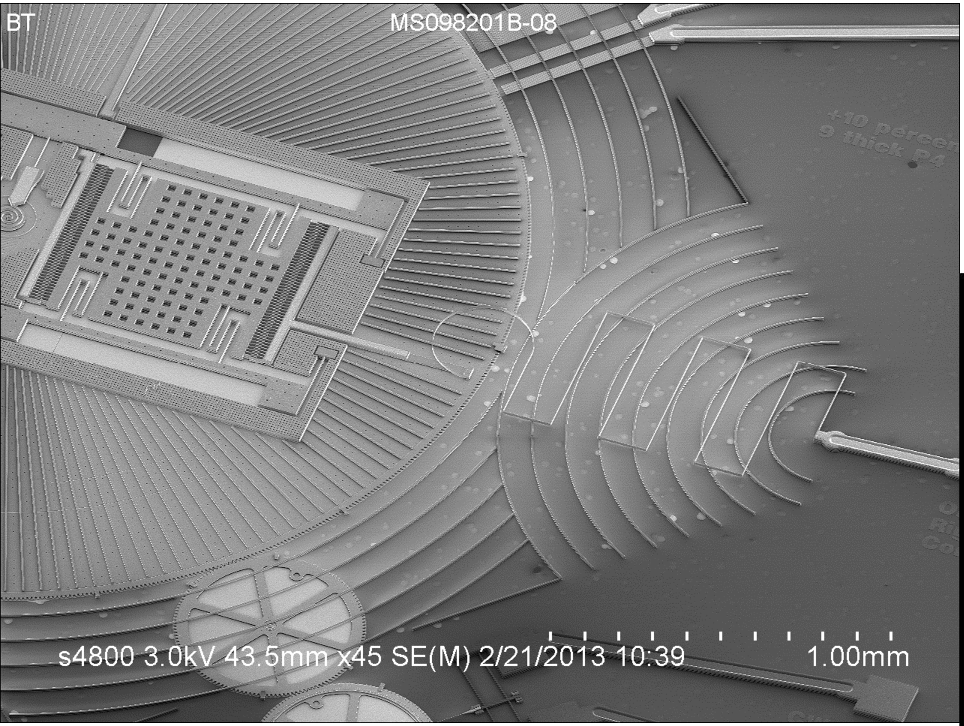
Bidirectional motion of rotating stage driven by thermal actuators and gears.

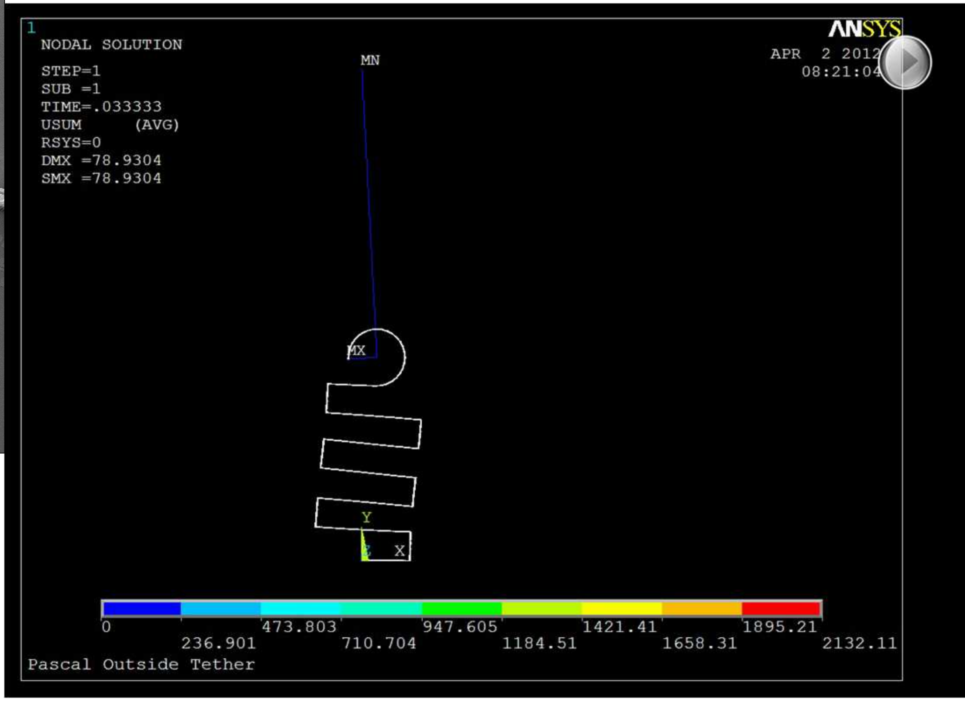




PASCAL Details

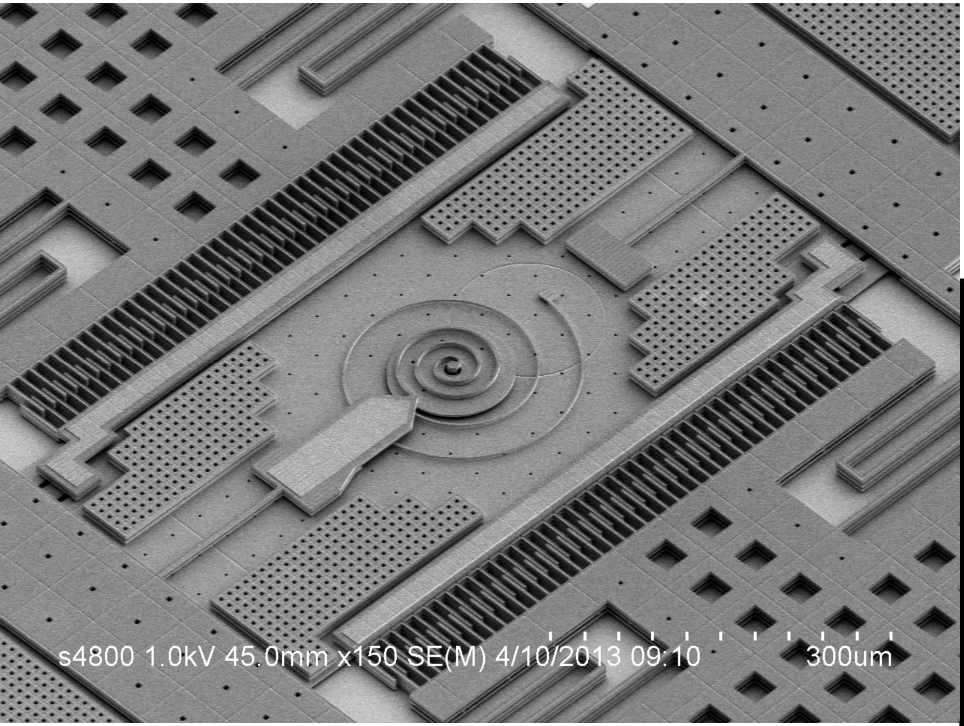
Ohmic contacts maintained continuously by doped-silicon spring-wires. (Left/right tether)





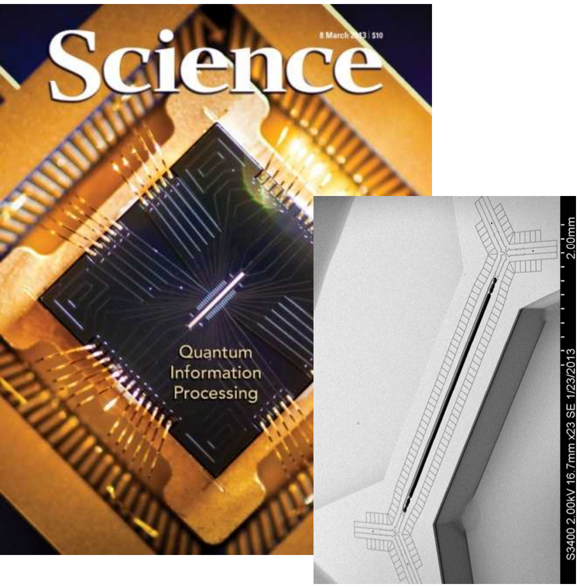
PASCAL Details

Ohmic contacts maintained continuously by doped-silicon spring-wires. (Hub spirals)



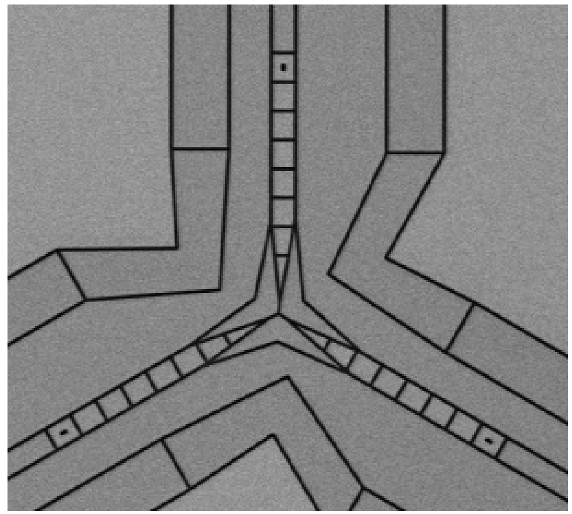
Quantum technologies and applications

Quantum Information Processing



- **2008**: Sandia's 1st "workhorse" trap
  - Used worldwide
  - Quantum operations
- **2013**: Sandia's latest surface ion trap
  - Bowtie shape enables improved control of ions & quantum operations

Advanced surface ion trap concepts



The world's most advanced Y-junction trap:

- "Railroad switch" for ions
- Designed for reordering of ions with minimal disturbance
- Made for David Wineland at NIST/Boulder

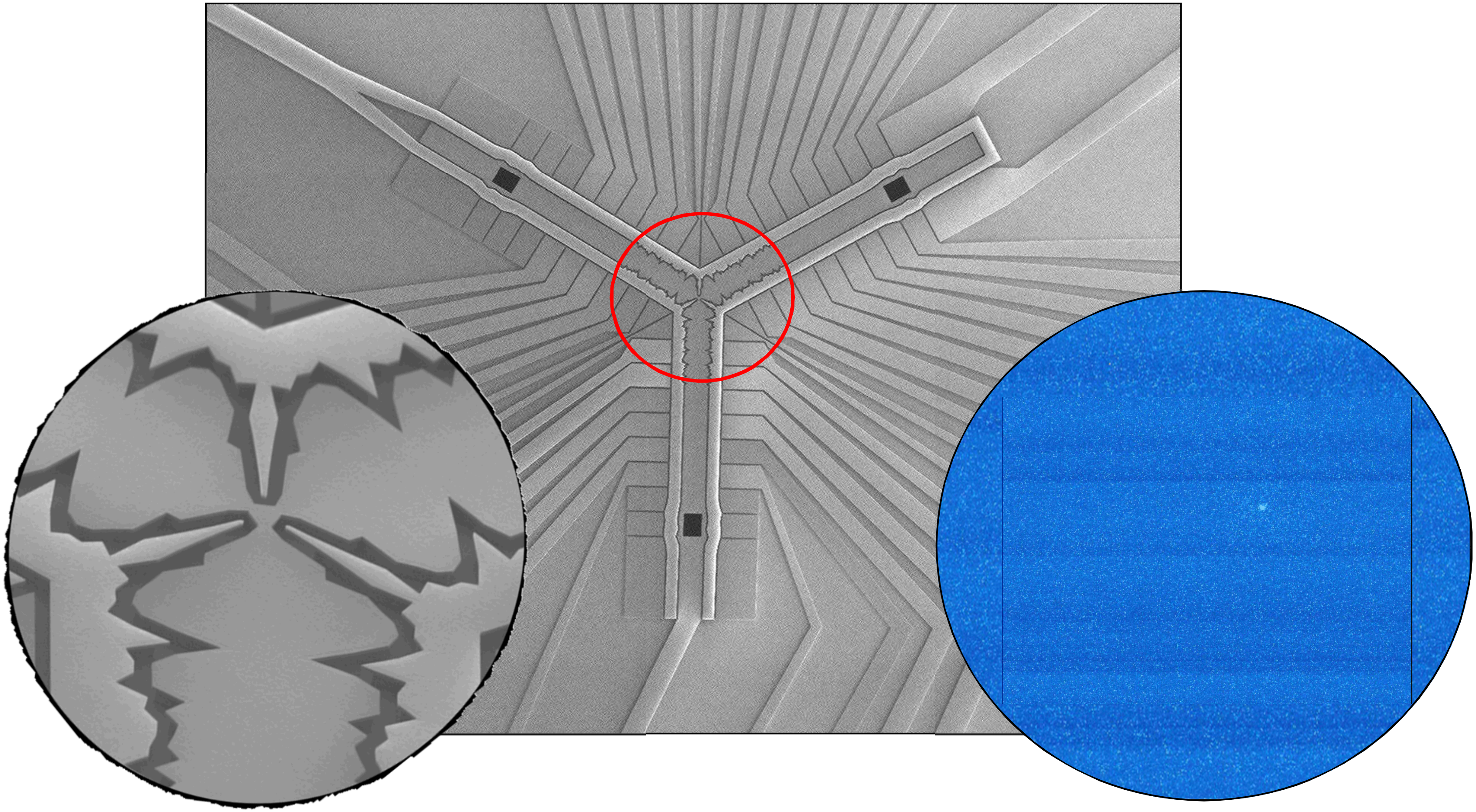
Accurate time-keeping with ions

Tiny trapped-ion clock:

- Small size (5 cc) and low power (50 mW)
- Excellent long term stability (loses 32 ns in 1 month)
- Clock prototype passed demanding testing at NIST for 49 days

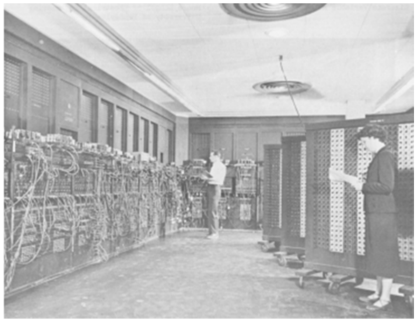
Ion Y-Trap

Electrostatic design allows fine control of ion loading and motion.

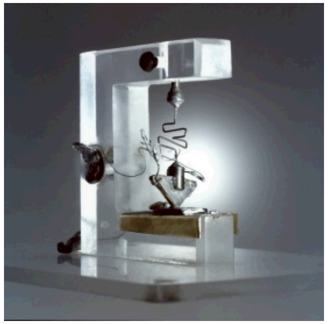


Sandia National Laboratories

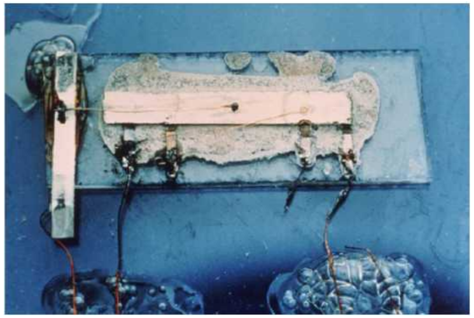
ENIAC



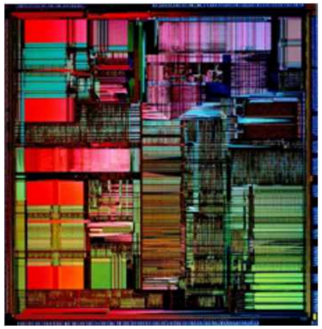
Ge BJT(1947)
Nobel Prize
***MOSFET patent (1928)**



Integration in Ge (1959)
Nobel Prize

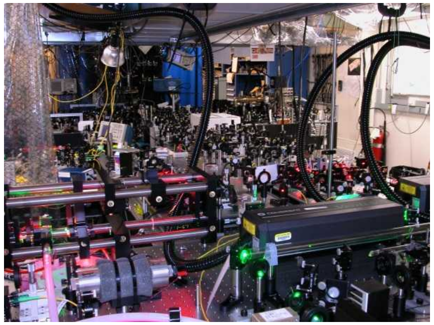


Modern CPU

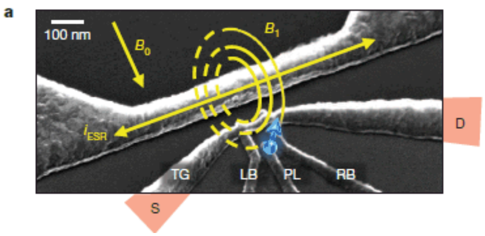


Ion traps at NIST (N < 10 qubits)

Nobel Prize (2012)



Si qubit (2012)



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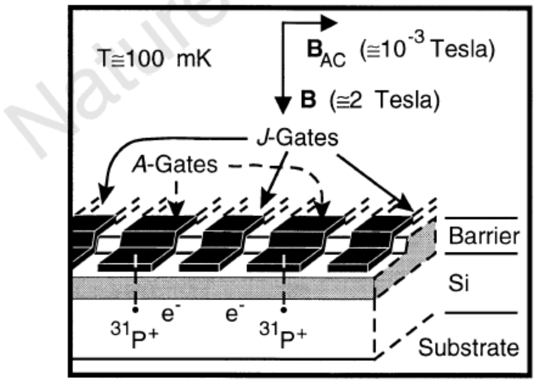
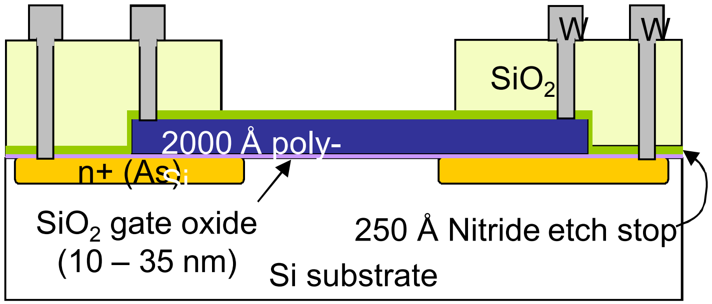
Kane (1998)

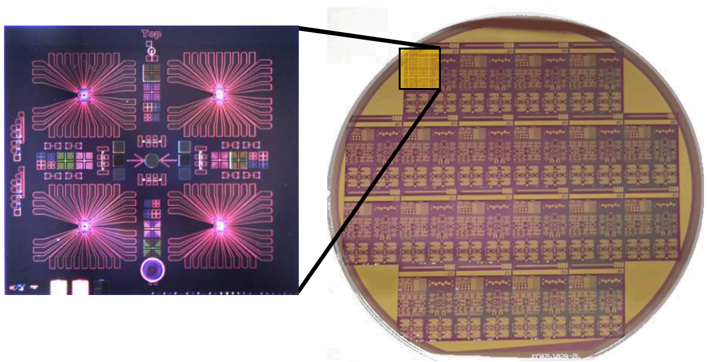


- Recent successes in silicon qubit technologies are exciting
- Historical perspective: two central nobel prizes in QC, one of which was for integration
- Donor based qubits have a lot of potential
- One of the big next steps: two qubit coupling
  - This talk: two paths towards exchange interaction between donor electrons at the surface

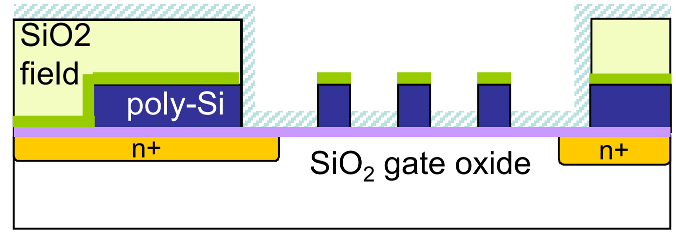
Nanostructure fabrication at Sandia National Labs

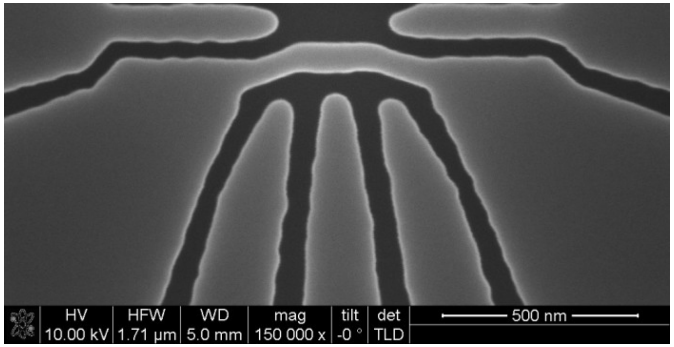
Front-end in silicon fab





Back-end nanolithography





Goal: Use Poly-Si etched structures to produce donor-based qubits

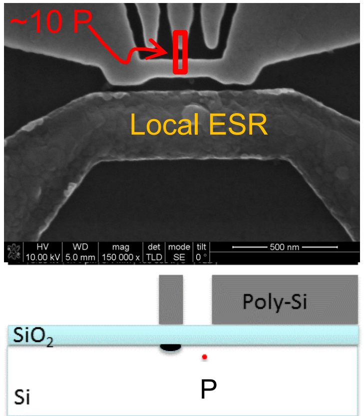
Rationale:

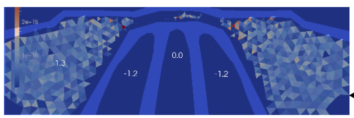
Self aligned implant

Foundry like processing

Summary

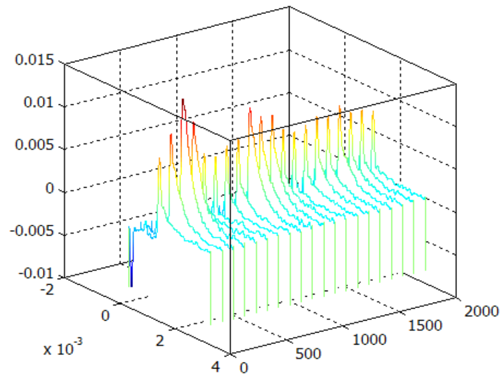
Silicon P donor qubit w/ self-aligned implant



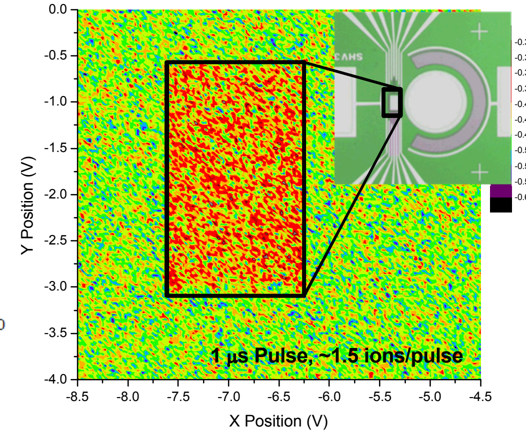


← & Si QD simulation

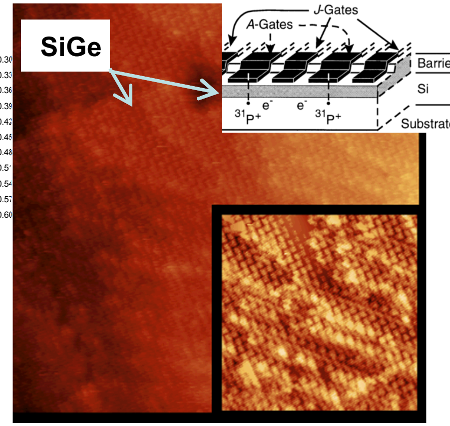
Spin read-out, T1 of Sb &Rabi



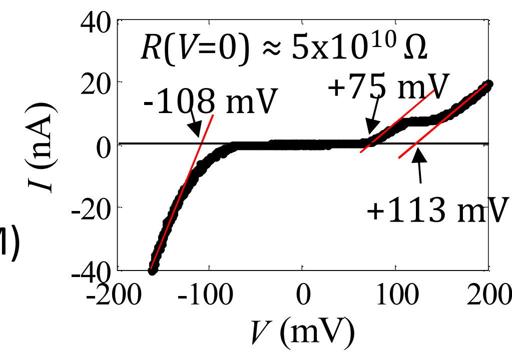
Single Sb⁺ implant map (50 keV)



SiGe/ssOI STM assisted nanofabrication

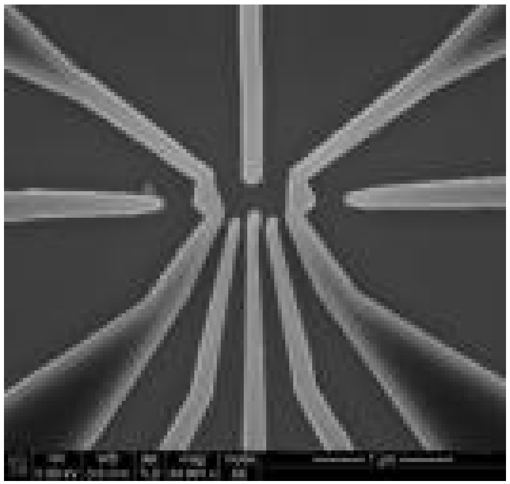


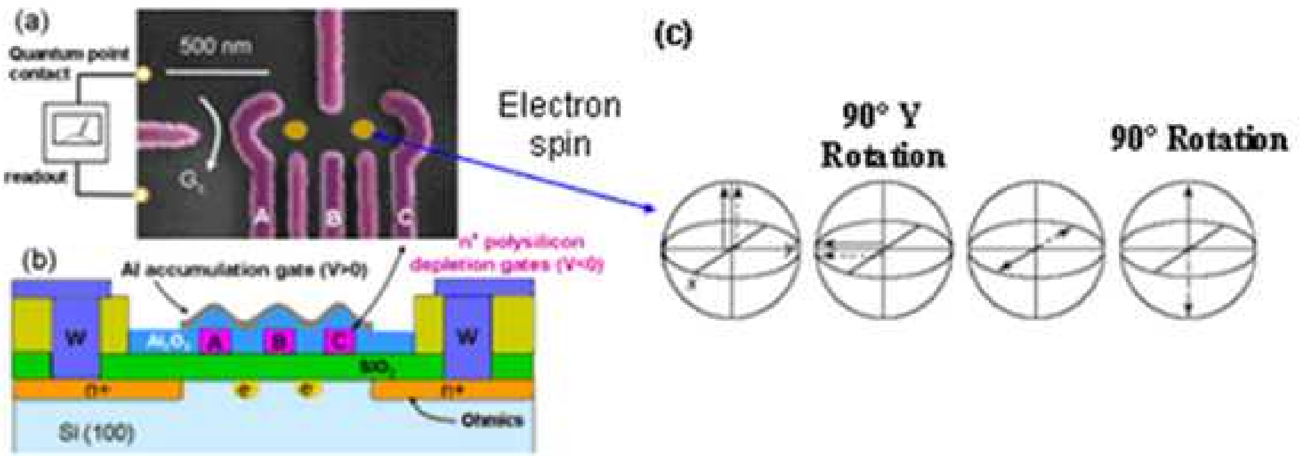
Field emission STM tunnel barrier

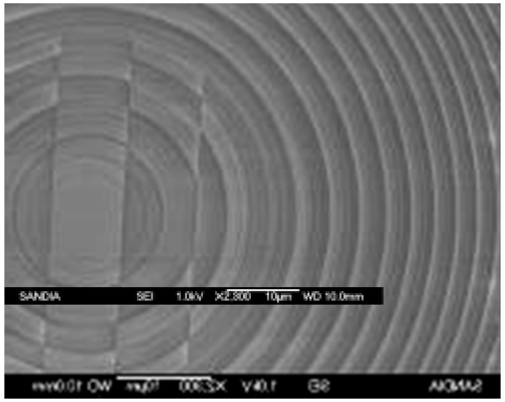


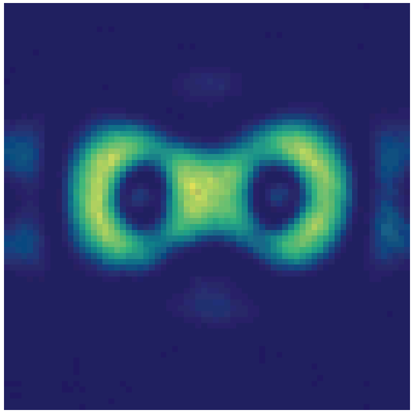
- Local ESR demonstrated in poly-Si process flow
- Dot behavior is more regular in newer designs
  - Device modeling agrees reasonably well with measured QDs
- We're looking at surface J-gate approach for two qubit path (implant or STM)
- Single ion implant capability integrated w. similar process flow
  - Activation of single donors near interface is a future challenge for this path
- STM assisted tunnel barrier fabricated (examining limits of field emission writing mode)
- SiGe growth on sSOI in STM system for STM path for 2 qubit

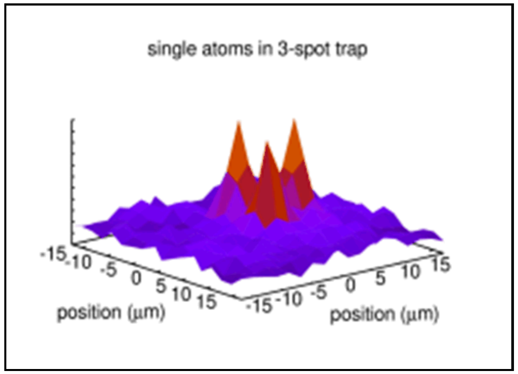
Silicon Quantum Bit (qubit)









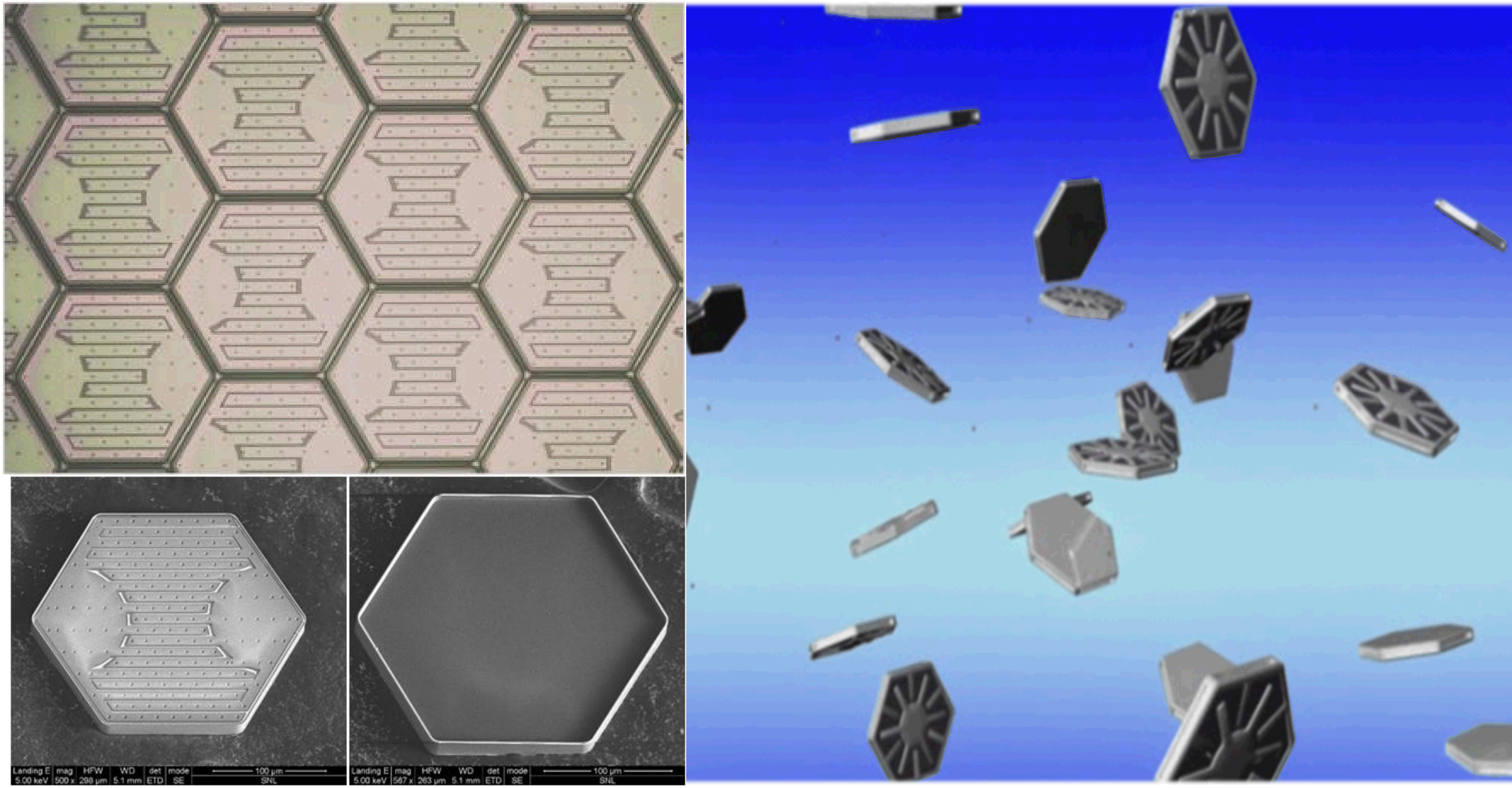


Measured fluorescence of single Cs atoms trapped in a Sandia three-atom diffractive optical element trap.

Microsystems Enabled Photovoltaic Cells

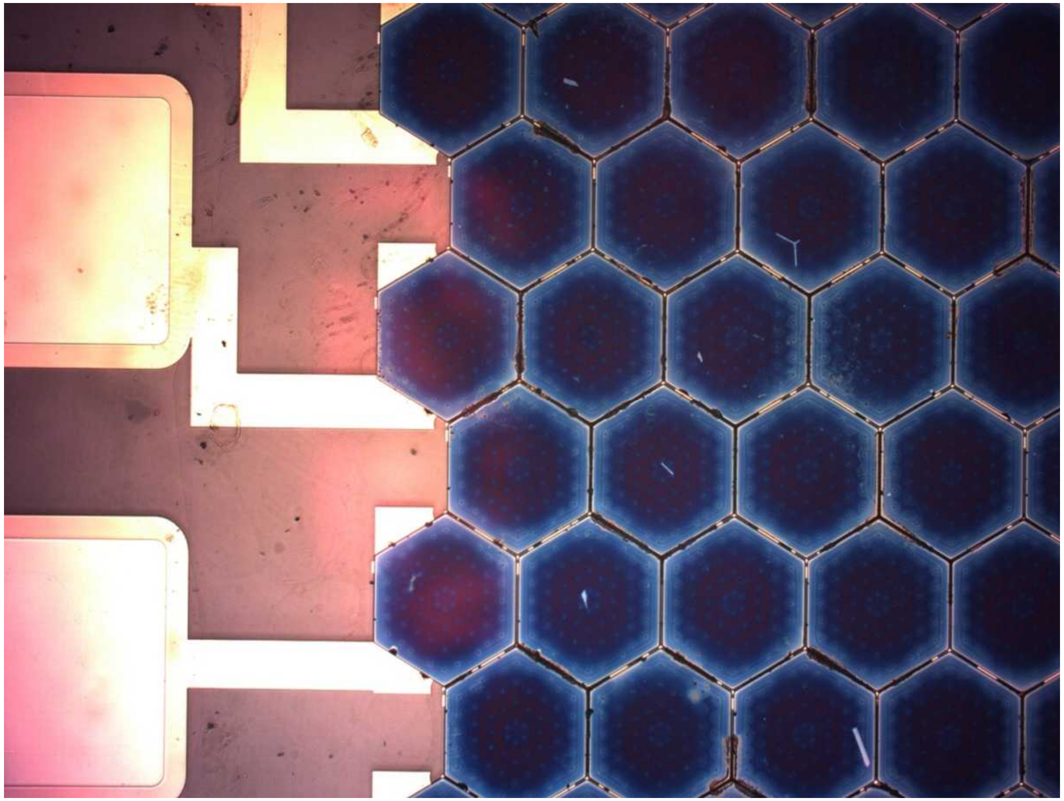
Sandia National Laboratories

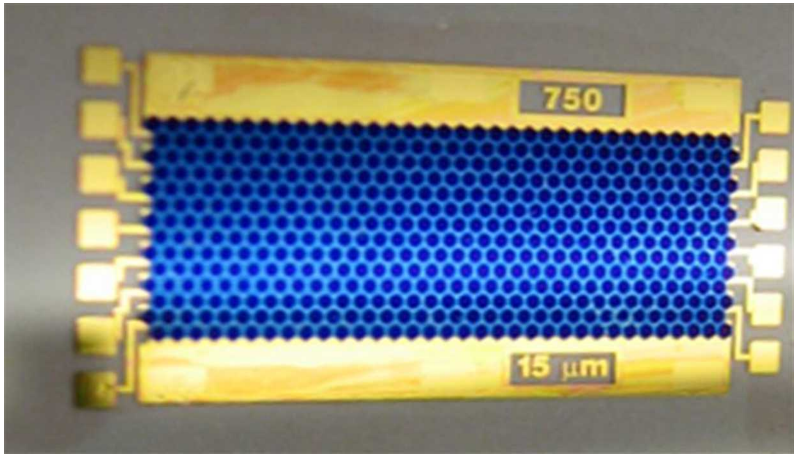
Create micro-PV cells then release them from Si or III-V substrate and reuse substrate.

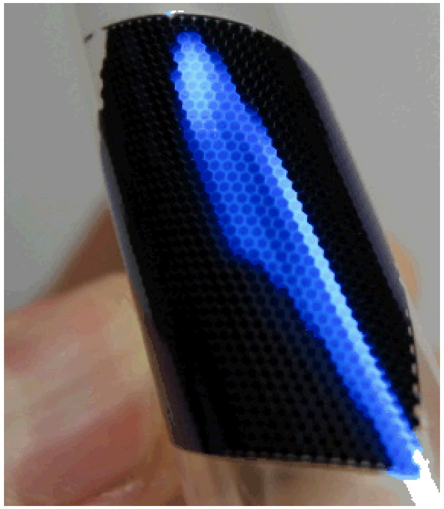


New Manufacturing Paradim

Reassemble cells using standard electronics manufacturing tooling.

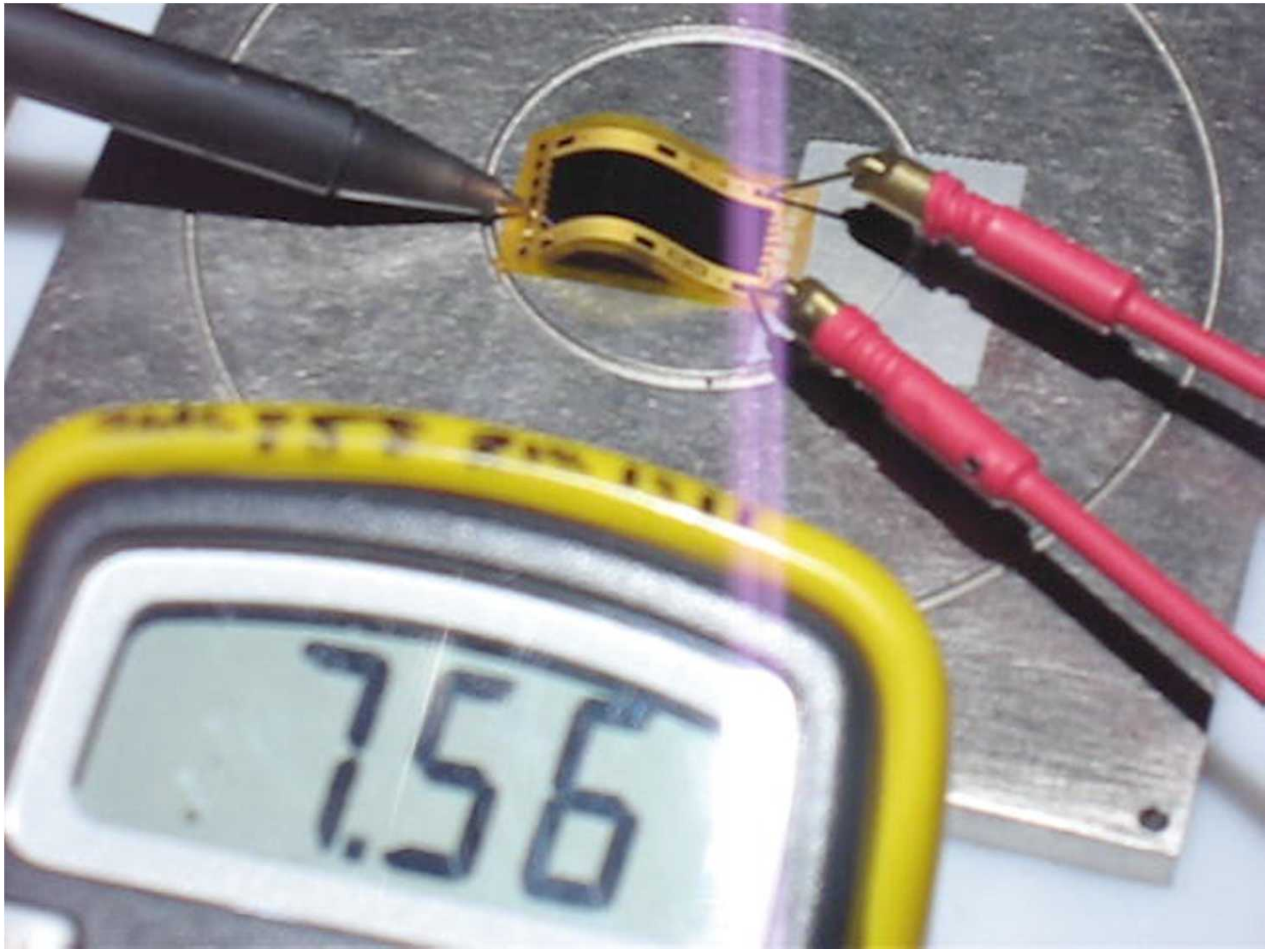






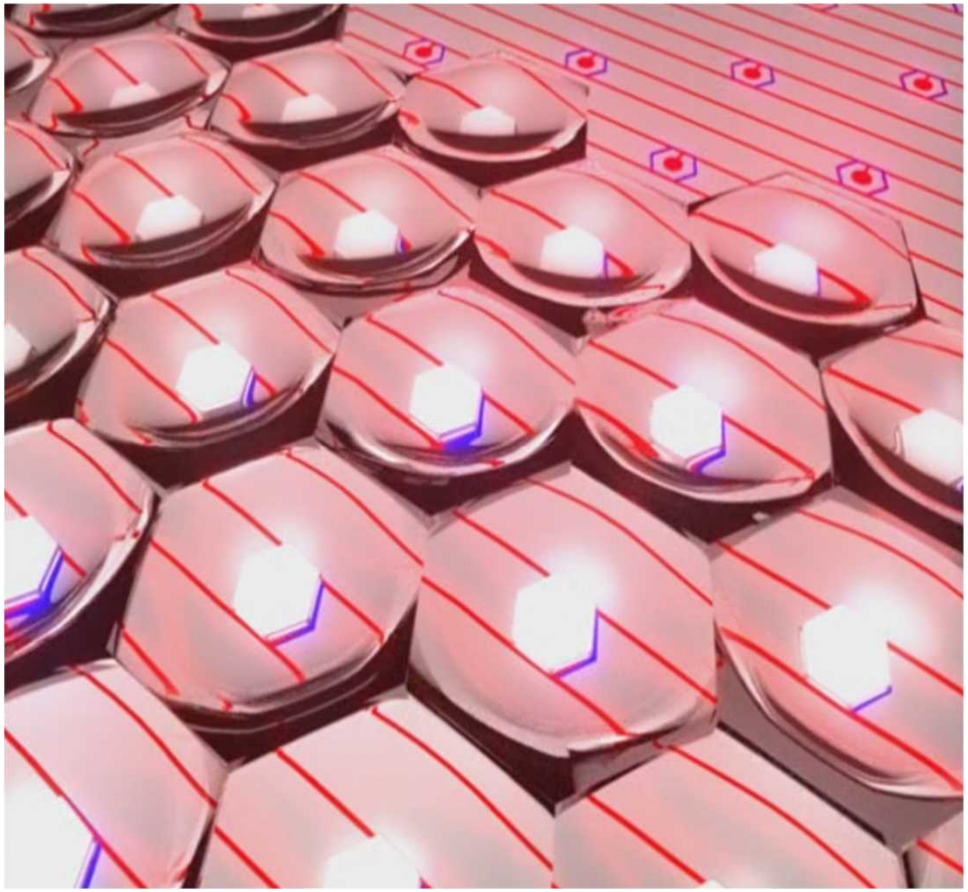
Flexible and Lightweight Arrays

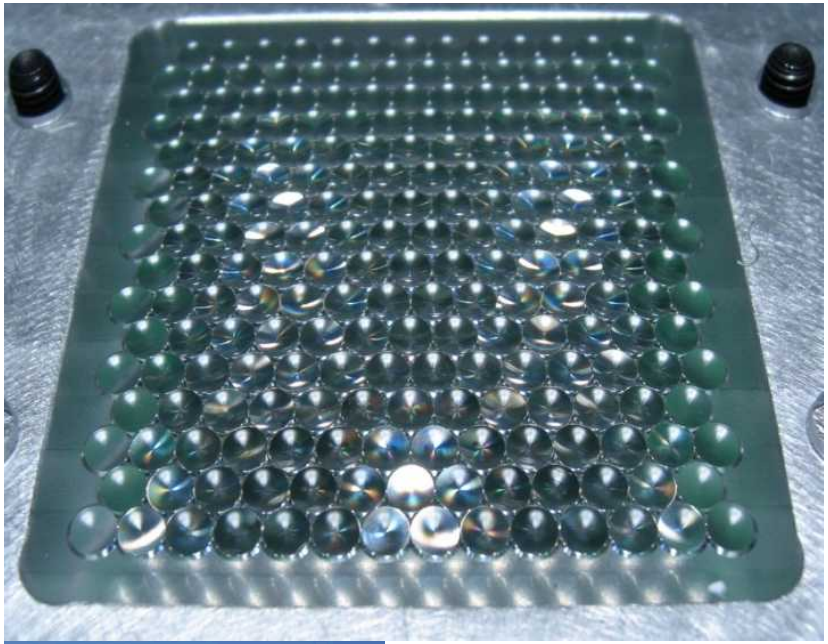
These cells are wired in series and parallel on a flexible substrate.

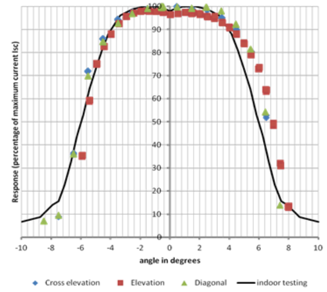


Concentrated PV with Micro-Optics

Concentrating optics scale down with size of PV cell making them smaller and lighter.

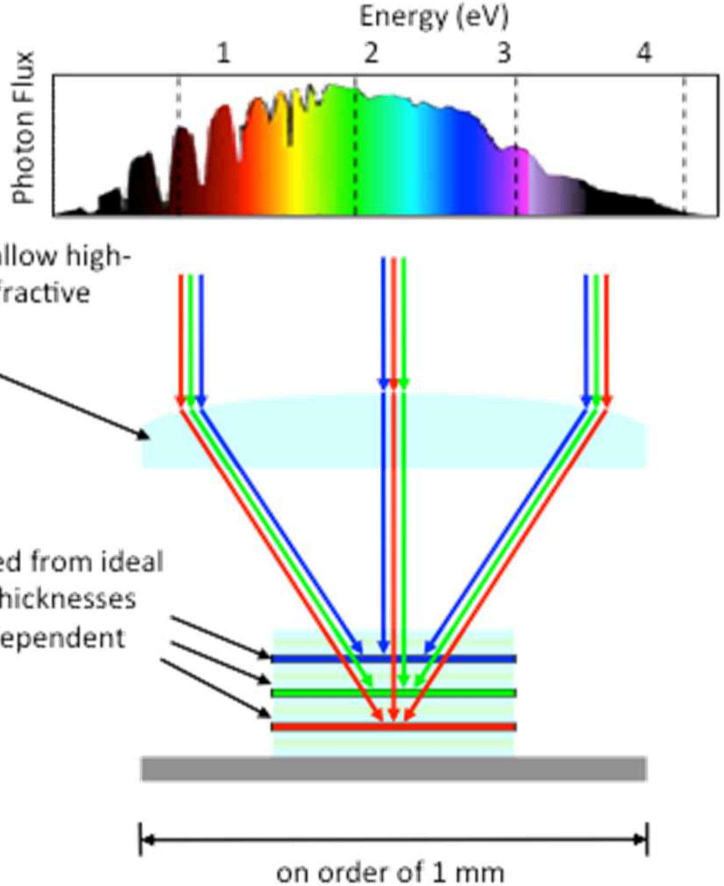






Multi-Junction Cell Stacks

Multi-junction cells can manufactured separately and independently wired.



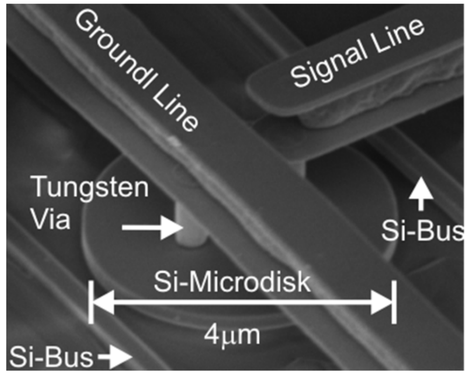
Material	Bandgap
InGaN	*2.5*
InGaP	*1.85*
GaAs	*1.4*
Si	*1.1*
InGaAsP	0.9
InGaAs	0.6

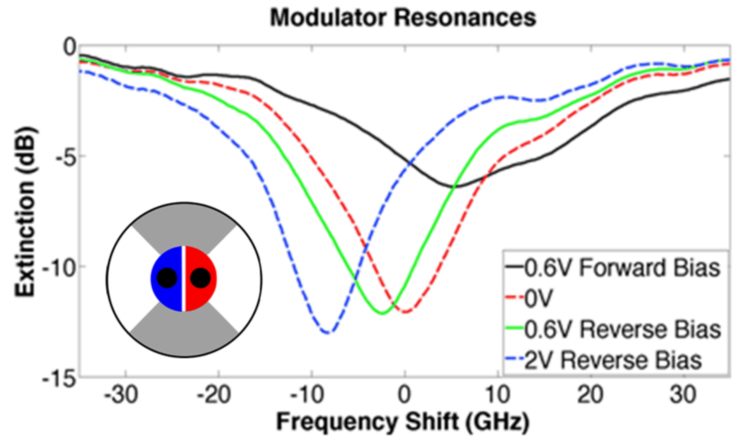
Triple junction Si/GaAs/InGaP cell

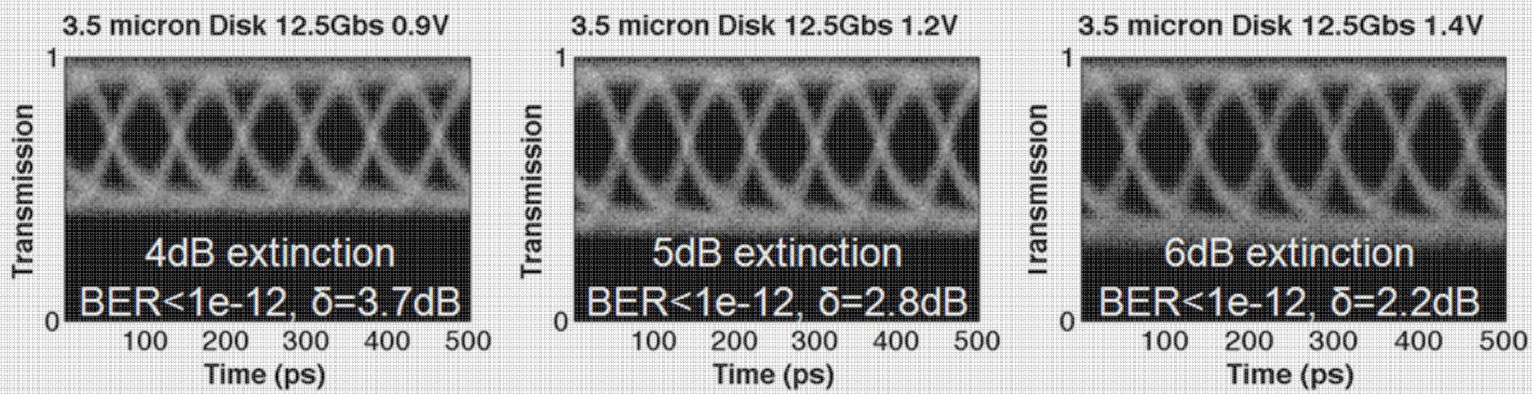
Lowest Energy Optical Modulators

<u>Si disk resonators:</u>

- very small device
- limit doping in ring
- differential Operation





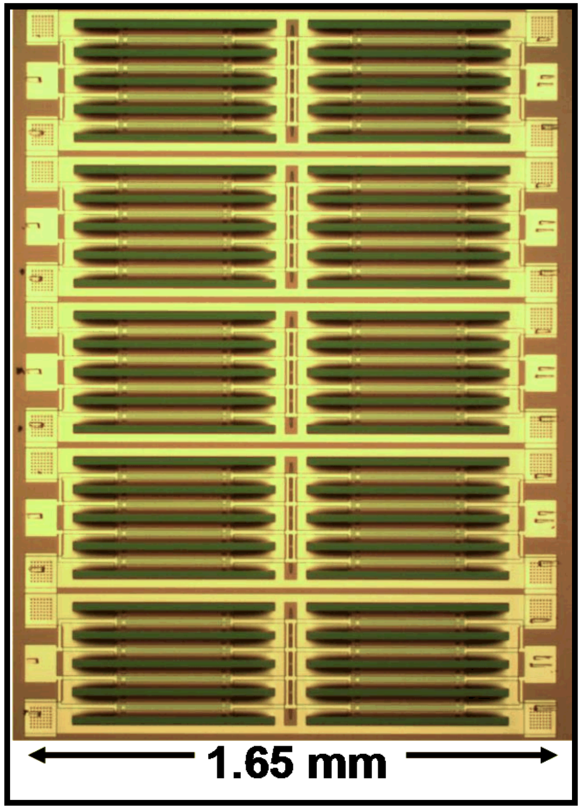


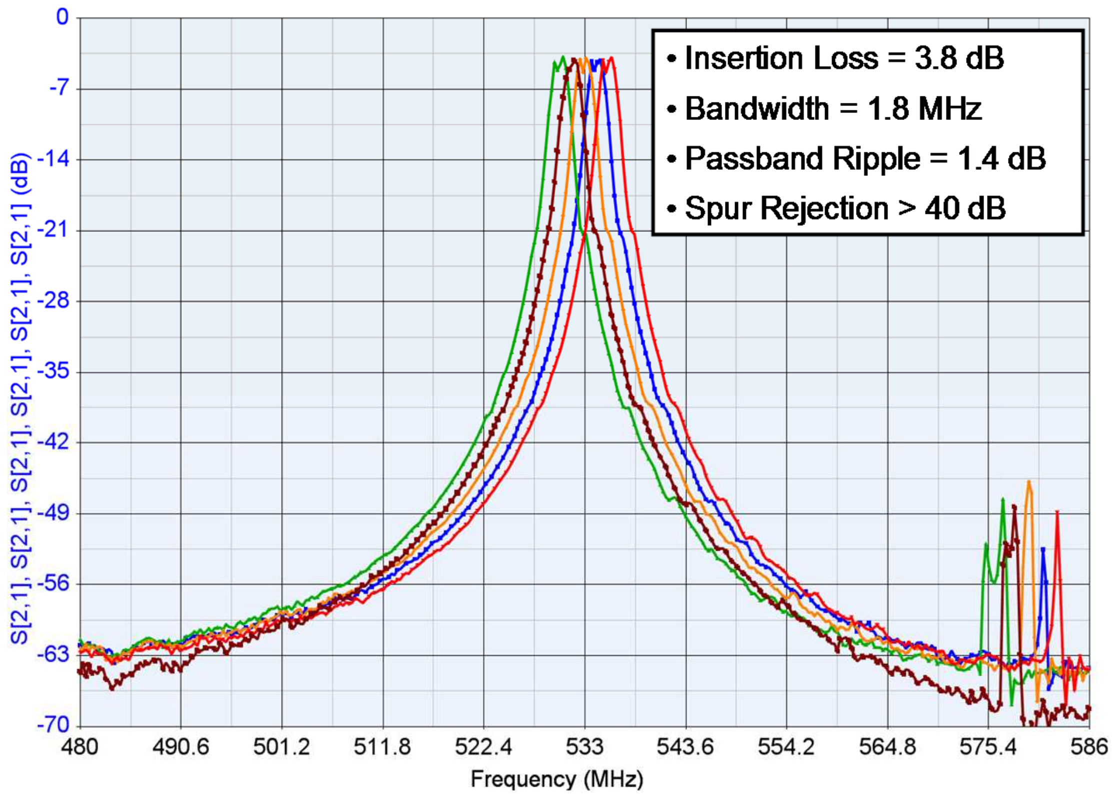
<u>Energy / bit:</u>	<u>0.9V</u>	<u>1.2V</u>	<u>1.4V</u>
Analysis:	3.8fJ/bit	6.8fJ/bit	10.6fJ/bit
Measured:	3.2fJ/bit@1V		10.1fJ/bit@1.5V

W.A. Zortman, et. al., CLEO 2010 CThJ4

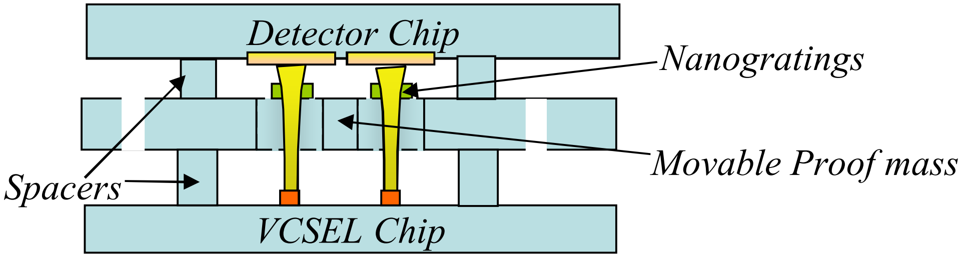
Aluminum Nitride RF Filters

Filter frequencies are defined by lithography, enabling multiple filters on a chip

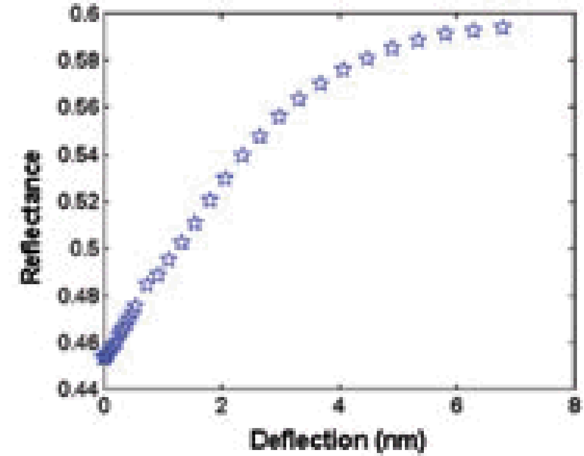




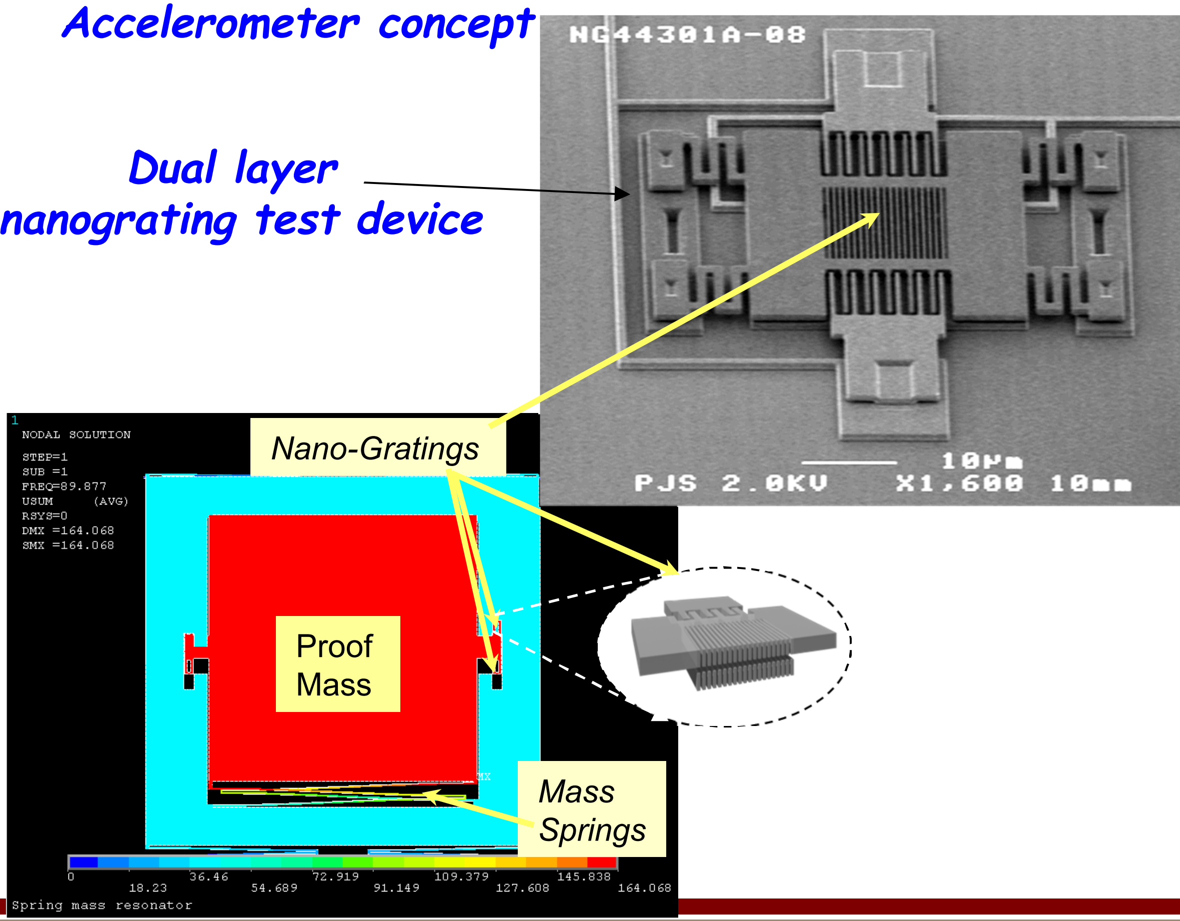
Integrating MEMS with optoelectronics in a single package: Nano-G Accelerometers Using Nanophotonic Motion Detection System



Accelerometer concept



Dual layer nanograting test device



- Displacement sensitivity **12 fm/√Hz**
- Record Mass Resonant Frequency for a MEMS device ~ **40 Hz**
- Record Thermal noise floor **~10nG/√Hz**

NanoG ($10^{-8}m/s^2$) Accelerometer

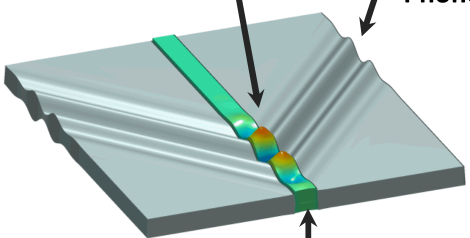
High performance chip-scale RF signal processing.

Sandia National Laboratories

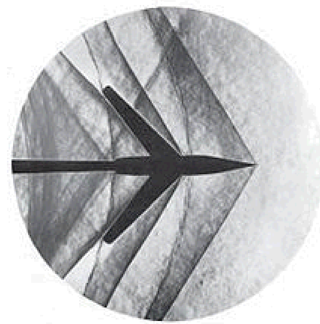
New Physics: Stimulated Mach-wave Phonon emission

Hypersonic optical pulse stimulates phonon

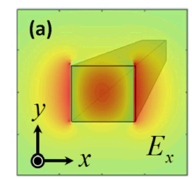
Stimulated Mach-wave Phonon



Nanoscale waveguide



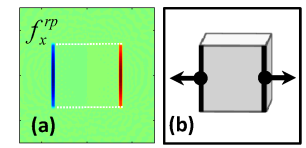
Nanoscale Waveguide.



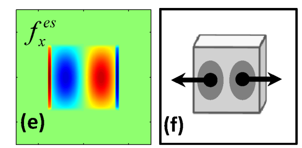
300nm x 300nm

Enhanced optical forces

Radiation Pressure



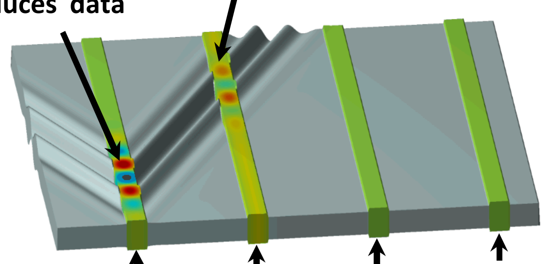
Electrostrictive Forces



Technology: Chip-Scale True Time Delay (TTD)

Optical pulse transduces data

Delayed data imprinted on optical wave



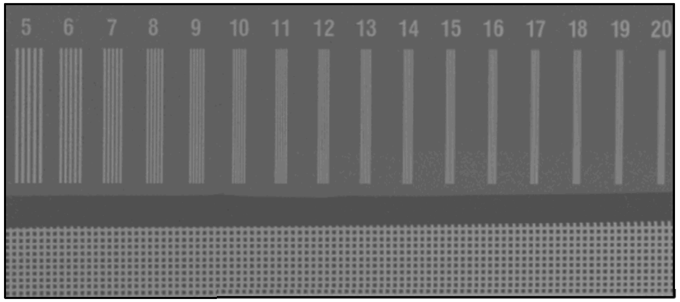
Nanoscale waveguide array provides multiple possible delay lengths

New Business: Device Applications

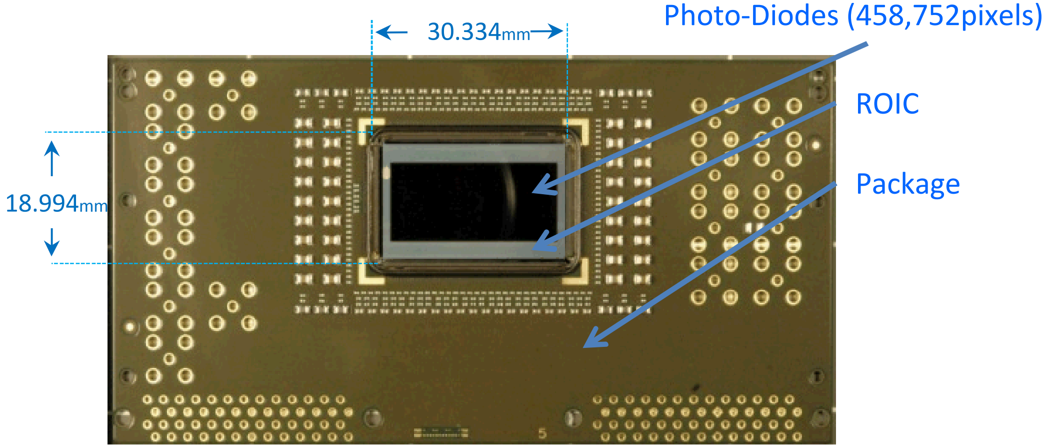
- DARPA: 4-year program with Rockwell Collin, UT-Austin, & MIT.
- Goal: Develop signal processing apps. using optomechanics.

Ultra-fast X-ray Imager

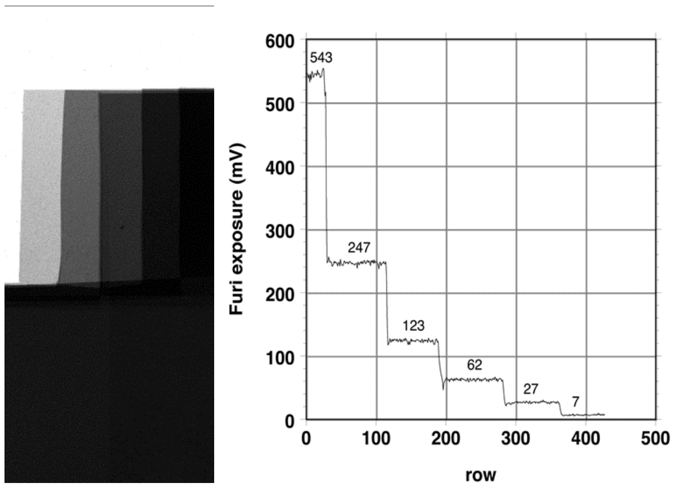
- Objective: Develop a high speed, multi-frame, radiation hardened digital X-Ray imaging system for the Z-Machine
- Solution: MESA-produced Focal Plane Array (FPA) and supporting camera system capable of capturing <u>multiple</u> **1ns** images at a **2ns** frame rate



2ns Line Pair and Calibration Mesh Test Patterns



Packaged FURI FPA

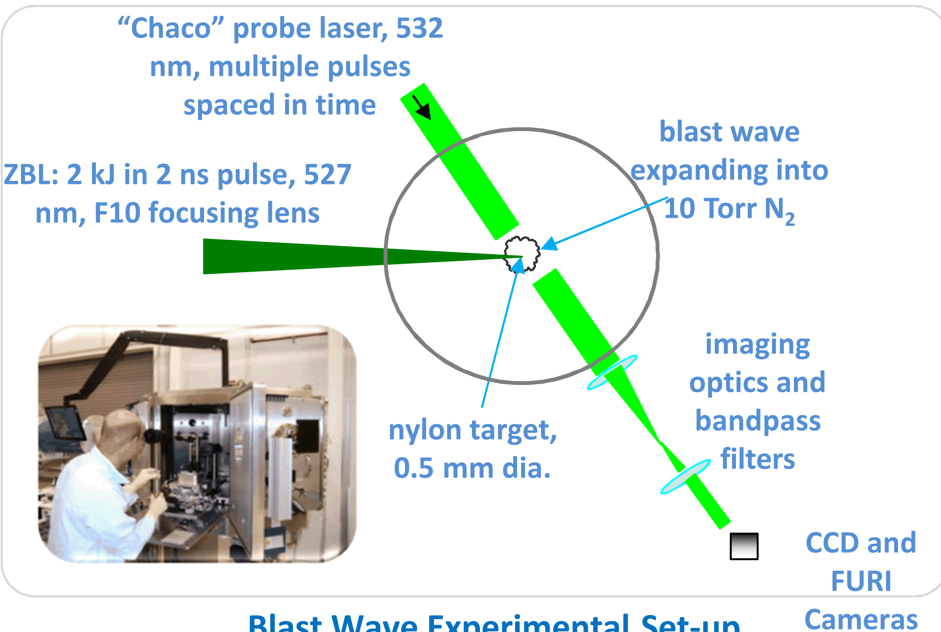


X-Ray Intensity Step Wedge Test Pattern

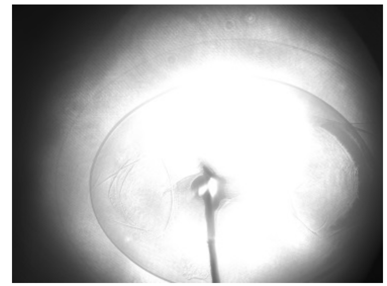
Multi-year effort has resulted in a 1044x448 ns frame rate camera undergoing testing in Z.
Scheduled for test at NIF during 1QCY2015

Ancillary Benefit of UXI Camera

- Blast Wave Imaging Experiments
  - A high powered laser is used to ablate a nylon filament and generate a moving blastwave
  - A second laser backlights the expanding blast wave which is then captured by an imager

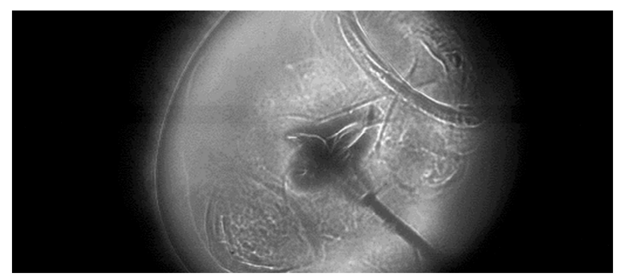


Blast Wave Experimental Set-up



CCD Camera with two superimposed images

FURI Camera Frame 1



FURI Camera Frame 2 Δt = 160 ns

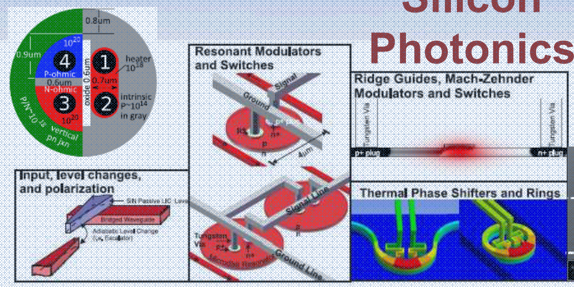
Applied Photonics Microsystems

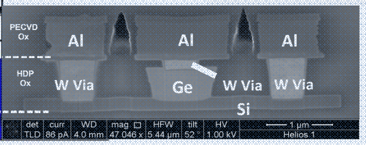
Main Research Thrusts

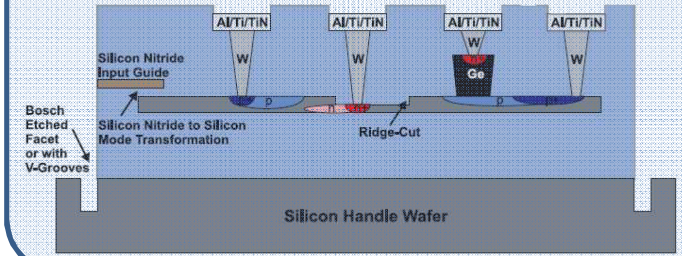
- **Silicon Photonics**
  - Optical Interconnects (waveguides, modulator, filter, switches)
  - Si Germanium detectors
  - Integration (with high-speed or rad-hard CMOS, III-V lasers)
  - RF photonics; mid-IR photonics
- **Nano-photonics**
  - Plasmonics (nano-antennas, emitters, sensors, energy harvesting)
  - Tunable and passive IR metamaterials (dielectric resonators, filters)
  - Solid-state Lighting (III-nitrides, nanowire lasers, strong-coupling)
- **Nano-Optomechanics / Phononics**
  - Nonlinear signal processing
  - RF waveform generation (oscillator, filter)
  - Phononic crystals: thermal management, quantum networks

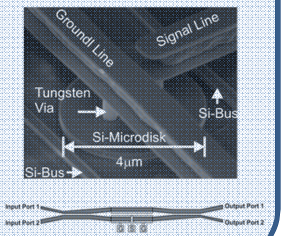
Silicon Photonics

Enabling technology for 100 fJ/bit 10Gbit/s data link and RF signal processing



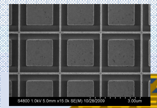


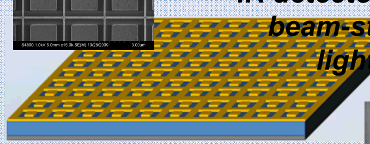


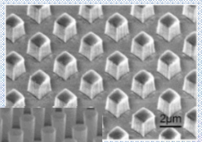


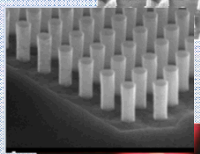
Nano-photonics

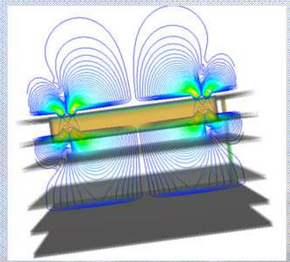
Enabling technology for IR detectors, filters, beam-steering, lighting

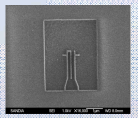


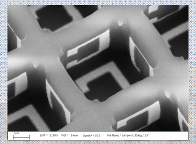


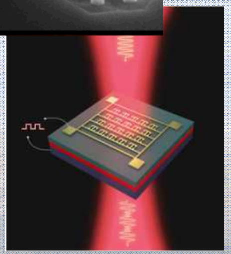






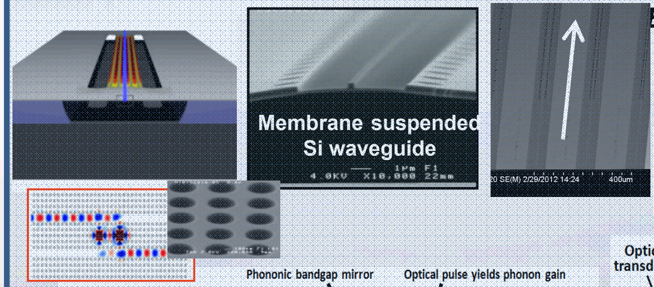


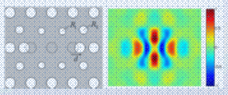


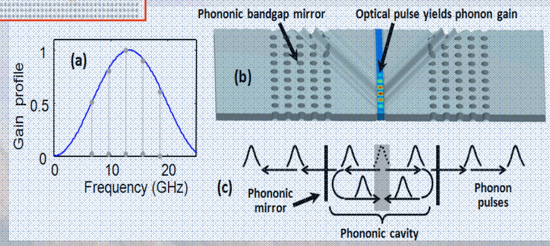


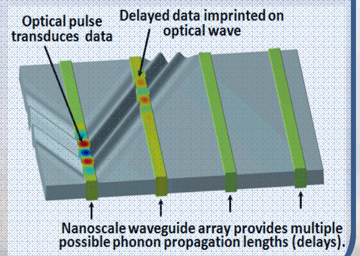
Nano-Optomechanics

Enabling technology for RF signal processing (1-20GHz, high power)





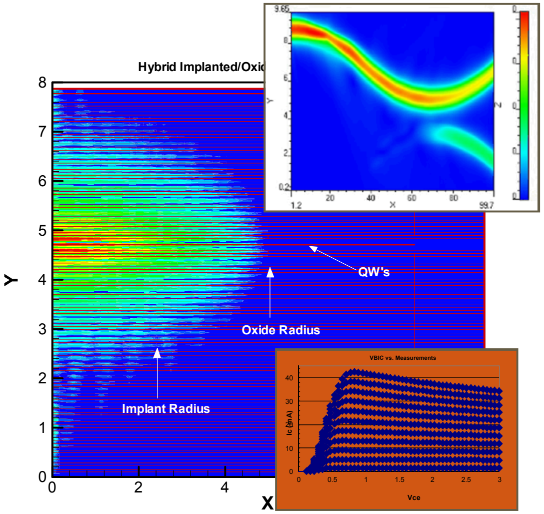




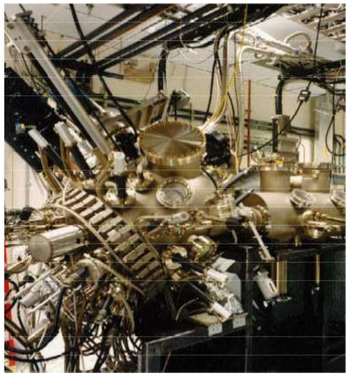
III-V Semiconductors: Optoelectronics & Microelectronics

Sandia National Laboratories

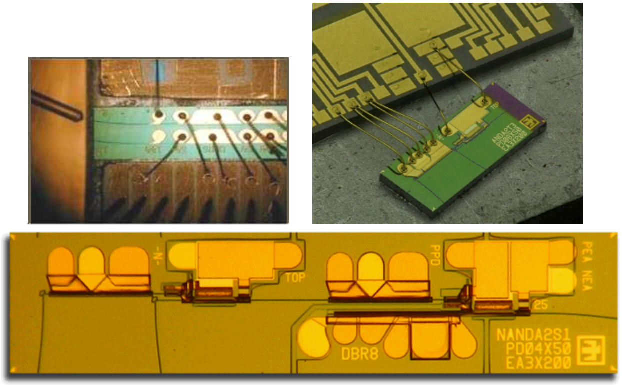
- Foundational Capabilities
  - III-V compound semiconductor epitaxy, microfabrication, integration
  - Device physics, modeling, simulation
  - Microelectronics/optoelectronics, and complex mono/hetero-circuits
- Prove, Advance Tech. Readiness Level, Productize
  - TRL1-6+: create, develop, prototype
  - NNSA QMS/QC-1/10; trust
- Trusted, custom, low-volume, high-reliability products for harsh environments when industry is unwilling or unable to deliver



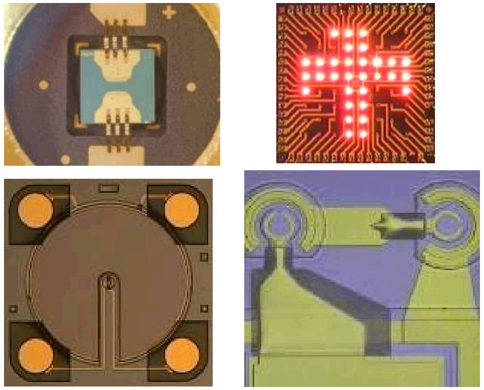
Modeling and Simulation



Epitaxy

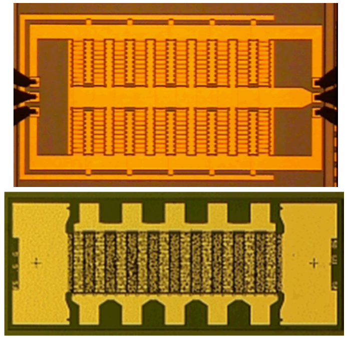


Photonic Integrated Circuits



Surface Normal Optoelectronics

SWIR/MWIR FPAs

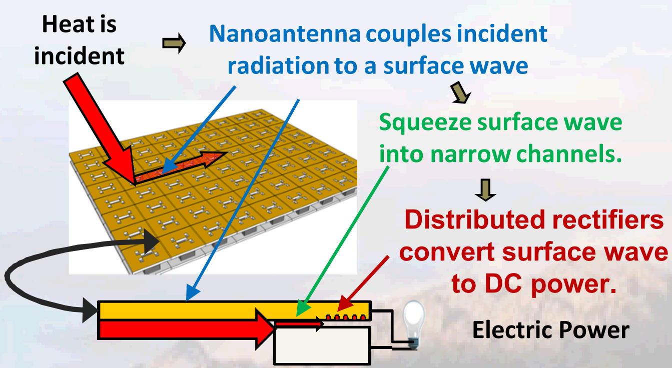


Compound Semiconductor Microelectronics

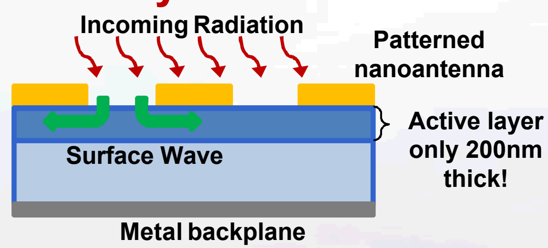
Over an Order of Magnitude Improvement in Three Infrared Devices

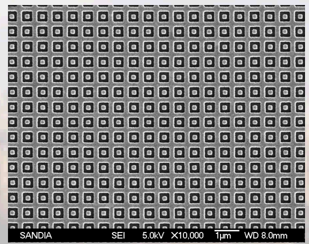
Infrared Rectennas	III-V MWIR Detectors	Graphene Detectors
Heat into power: solar cell enhancer or power for unattended sensor	Improved IR detection: lower noise floor and less crosstalk	Real-time voltage-tunable IR detection

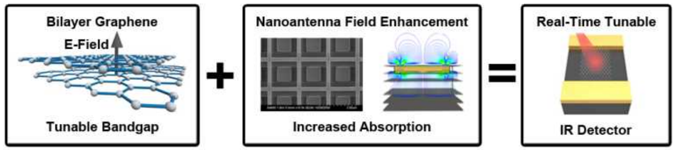
The nanoantenna creates a surface wave that travels to a rectifying tunnel diode. Previous IR rectifiers had 0.1% efficiency: we want a 30X improvement by end of this project.



The nanoantenna allows us to use over an order of magnitude thinner active layer and thus reduce crosstalk, dark current by 10X.

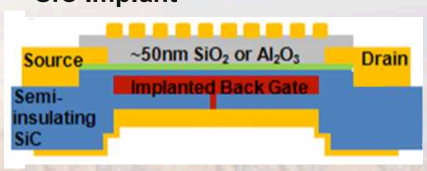






The 2 atomic layers of bilayer graphene only absorb 4.6% of an incident plane wave. We can concentrate the light with the nanoantenna for 10X greater efficiency.

SiC Implant



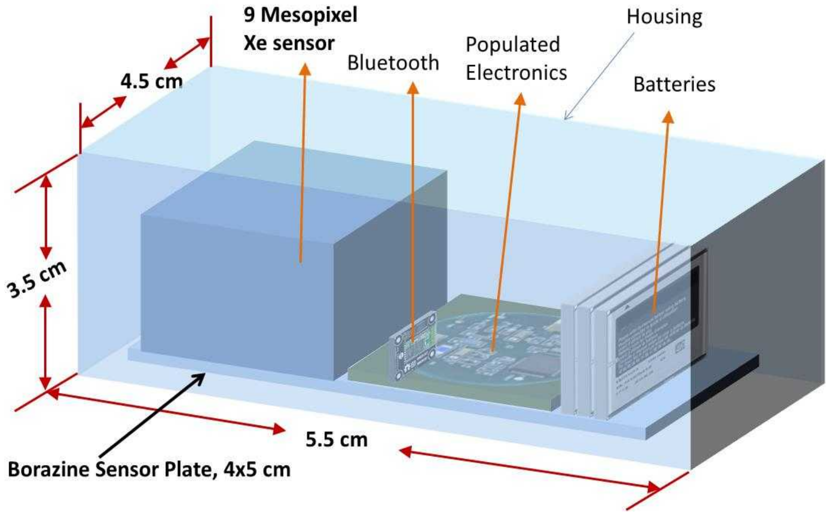
Outline

- Sandia and MESA overview
- Lessons learned from the development of the SUMMiT V MEMS Process Technology
- Selected Microsystems examples
- Summary

Low Cost, High Performance, Radiation Detection (neutron and gamma) Using a Microsystem Platform for Scalability

Sandia National Laboratories, PI: Mark Derzon, msderzo@sandia.gov

CONCEPT



APPROACH

High Resolution Gamma

- Xenon detector array
- Scalable microsystem for reduced cost and maximum detection efficiency
- 3D stacking for directionality detection

High Efficiency Neutron

- Novel borazine based detector technology
- Develop scalable process for borazine synthesis and integration into detector
- Develop highly integrated electronics for scalability

Proposing for both pager and large scale systems

Using a common, scalable technology enables potential To meet System Cost Requirements

Impact

- Gamma resolution that is a factor of 2-7 better than scintillation detectors.
- Significant reduction of gamma detector mass relative to scintillation detectors for comparable detection efficiency at a factor of 10 reduction in cost.
- Easy detection of gamma radiation directionality at an affordable price.
- Neutron detection that rivals He-3 at a fraction of the cost.
- Scalable detector volume for maximum detection efficiency

Context

- Reducing manufacturing costs is the most important aspect of this program
- Second priority is improving performance
- We believe that via integration and bulk sensing in polyborazine, with light and charge readout for gammas in xenon– the system specifications can be met

  - Existing high resolution gamma systems are expensive, are chilled, do not scale, are difficult or prohibitively expensive for directionality detection. Existing neutron detection systems are based on He-3 which is expensive and its future supply is uncertain.

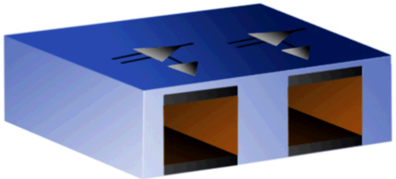
Radiation Sensor Development Program

Where is the radioactive material?

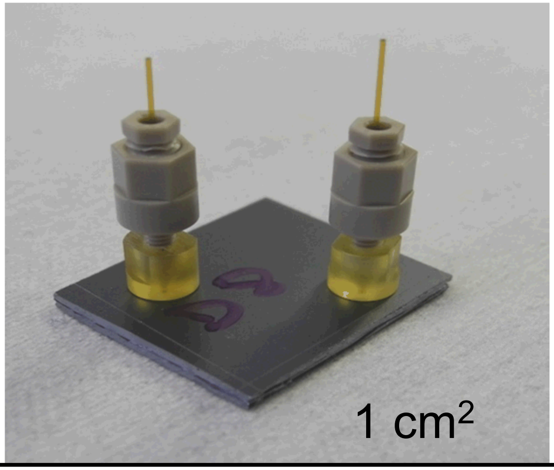
Inexpensive, *distributed* sensors can be quickly deployed across a region to map a disaster or used to find material more quickly than expensive manned systems in many situations.

<u>Why Sandia?</u>

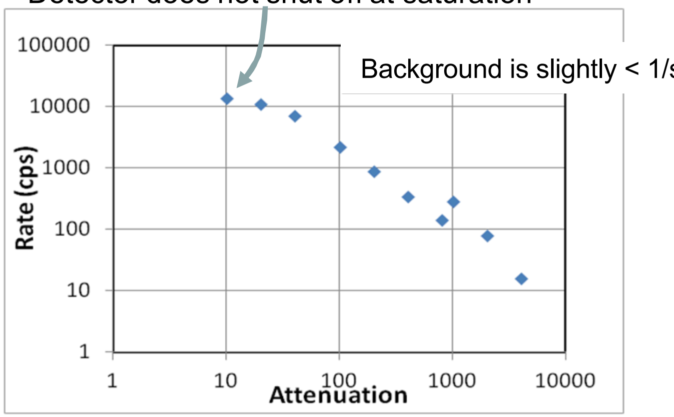
Electronics in device layer (6 microns on surface) use the other 690 microns for sensor material and count charge and light in tracks.



Geiger Counter Equivalent



1cm^2 detector

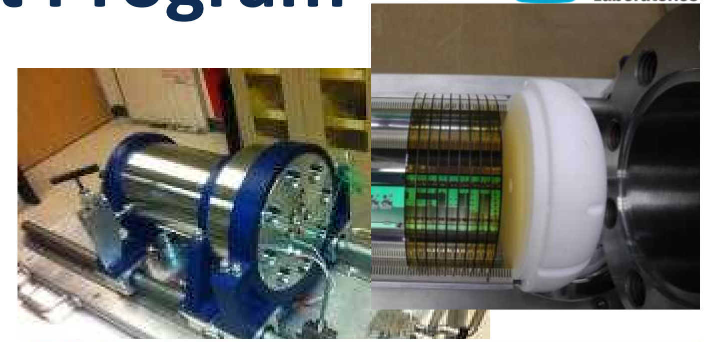


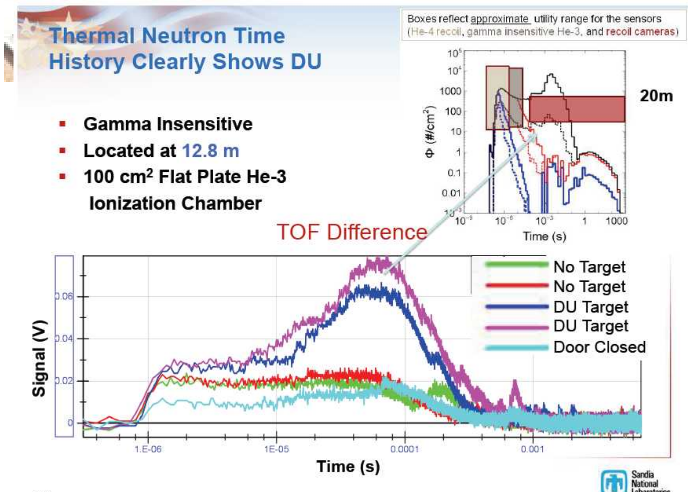
From High Rate to Natural Background (Attenuated Co-60 Source)

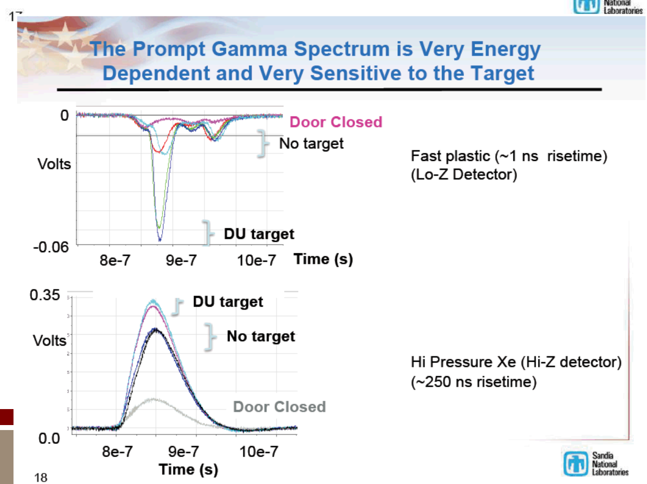
Coupling to SNL rad-hard electronics means the devices will work under abnormal circumstances like Fukushima.

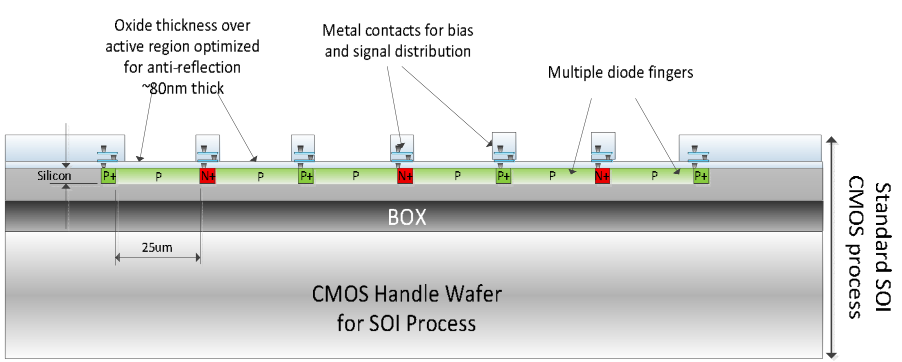
Radiation Sensor Development Program

- Objectives:
  - High efficiency, cost-effective, preferred SWaP space for large and small systems; active and passive detection
  - Large and small volume sensors
- Approach
  - Can scale to large detectors
  - Nearly monolithic fabrication which reduces cost
  - More information per quanta (Charge and light collection)
- Status and Accomplishments:
  - 50 pounds vs 1500 pounds on IPAD experiments
  - Thermal neutron, fast neutron and gamma built and tested
  - Compatible with short pulse, intense radiation sources or DC





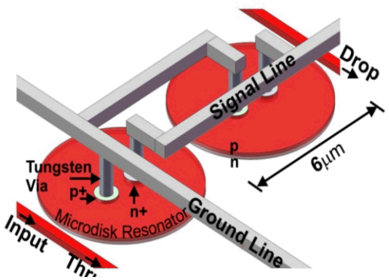


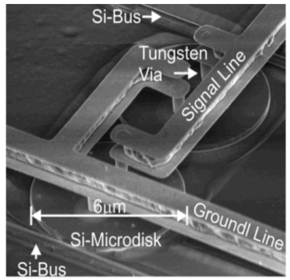


Lateral Photodiode Cross section

Silicon Photonics At Sandia

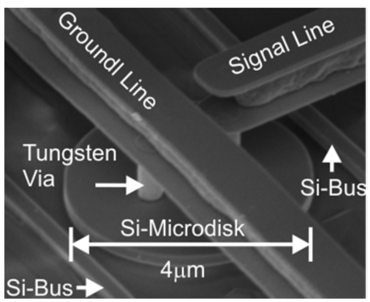
Free-carrier Effect (high-speed)

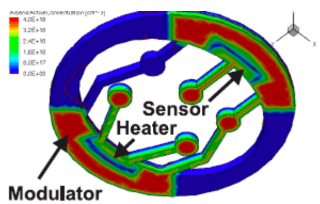


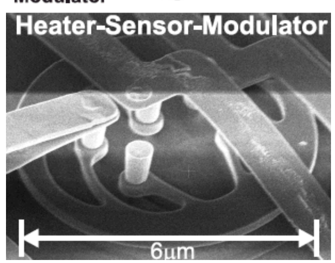


Fast Reconfigurable Interconnects

3.2fJ/bit at 12Gb/s





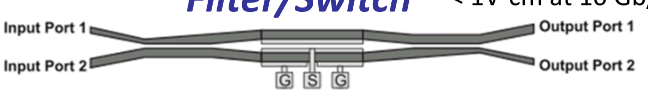


Resonant Optical Modulator/Filter

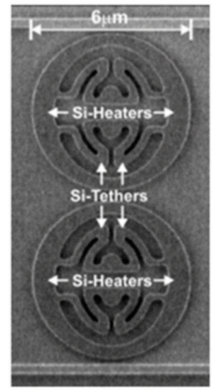
Thermally stabilized modulator

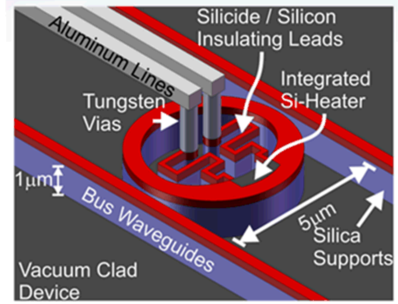
Broadband Mach-Zehnder Filter/Switch

< 1V-cm at 10 Gb/s

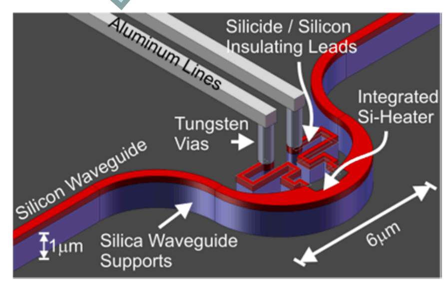


Thermal Optic Effect (wide-band)

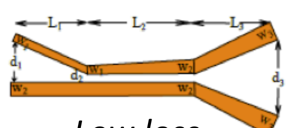




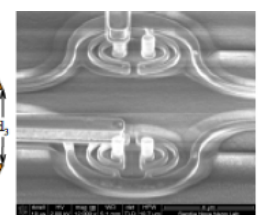
Tunable Resonant Filter



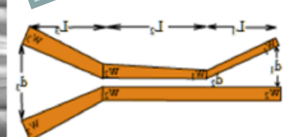
Thermo-optic Phase Shifter



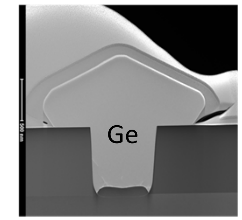
Low loss optical coupler



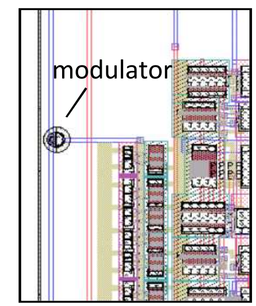
Switch Arrays



High-speed Ge Detector in Si



Si Photonics-CMOS Integration



Germanium Optoelectronics

Challenge: As an indirect band gap material, Ge is an insufficient light emitter

Goals:

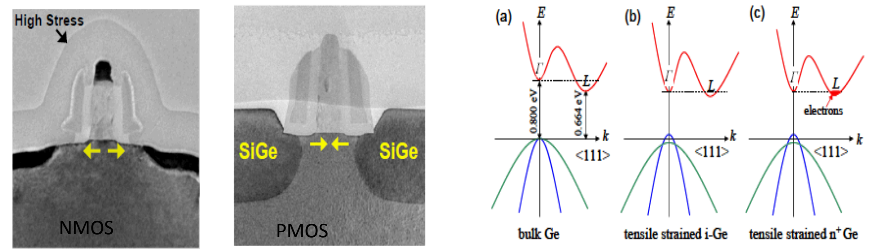
- Develop integrated detectors
- Construct a direct optical gain material at telecom wavelength through band filling by n-doping and strain engineering

Applications: Low-cost monolithic integration of laser source, amplifier, and other silicon photonics with CMOS

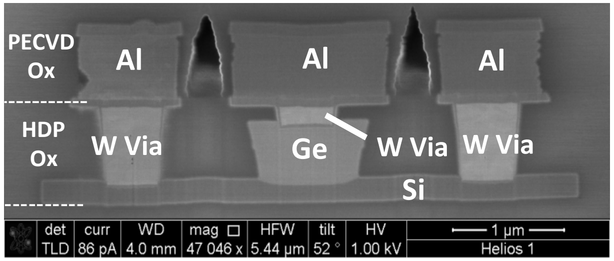
Accomplishments: (Sept 2011)
Demonstrated CMOS compatible Ge photodiode with

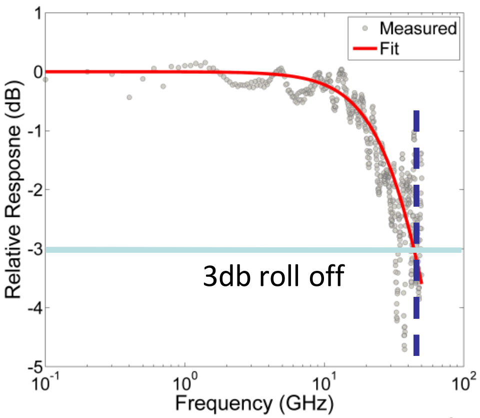
- Record low capacitance (~1 fF)
- Best-in-class dark current (3 nA)
- Best-in-class bandwidth (45 GHz)
- High responsivity (0.8 A/W)
- Small footprint (1.3µm x 4.0µm)

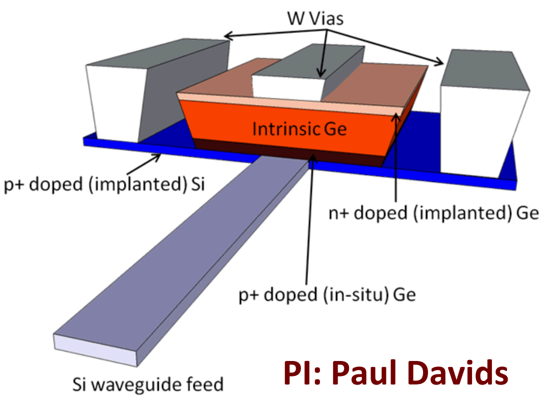
Strain engineering



Band filling n doped fill L valley







PI: Paul Davids

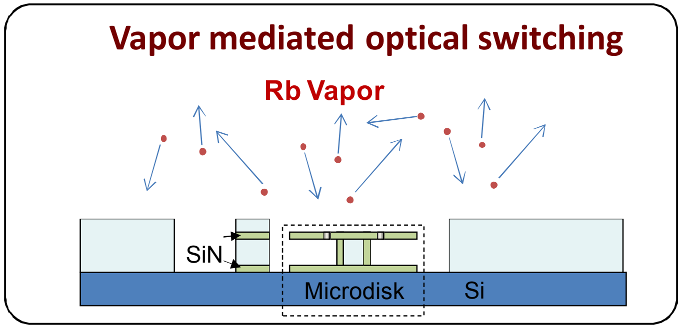
C.T. DeRose, et. al., Optic Express, 19(25), 24897-904 (2011)

Zeno-based OptoElectronics (ZOE)

Sandia National Laboratories

Goal: Understand physics and demonstrate ultra-low power (~ 1E-18 Joule) optical switch via quantum Zeno effect for optical and quantum computing

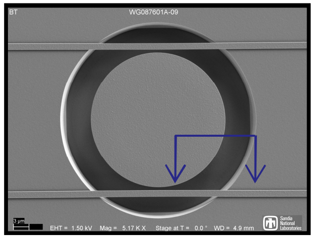
Approach: Using integrated microcavities, dramatically enhanced light-atom interactions enabling ultra-low power optical switching.

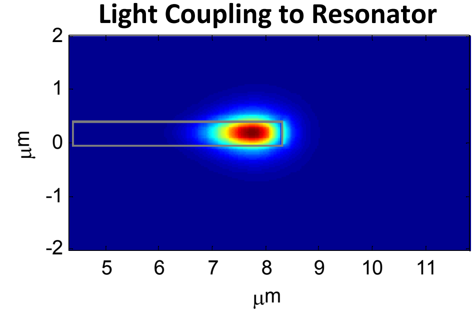


Phase I Key Accomplishments: (Phase II is underway)

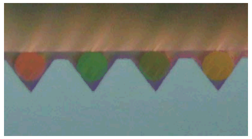
- Developed and fabricated high-Q (Q> 500k) low loss microdisks
- Developed vacuum compatible fiber-packaging technique
- Packaged ultrahigh-Q microdisk resonators for use in switching experiments.

Microcavity resonator fabrication/design

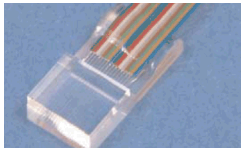


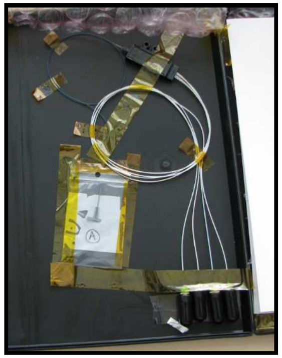


V-groove fiber array:



V-groove fiber array:





Test & Packaging:

- **Micromachining techniques used to couple efficiently.**
- **Vacuum compatible bonding and packaging techniques.**
- **Devices now fiber-connectorized.**

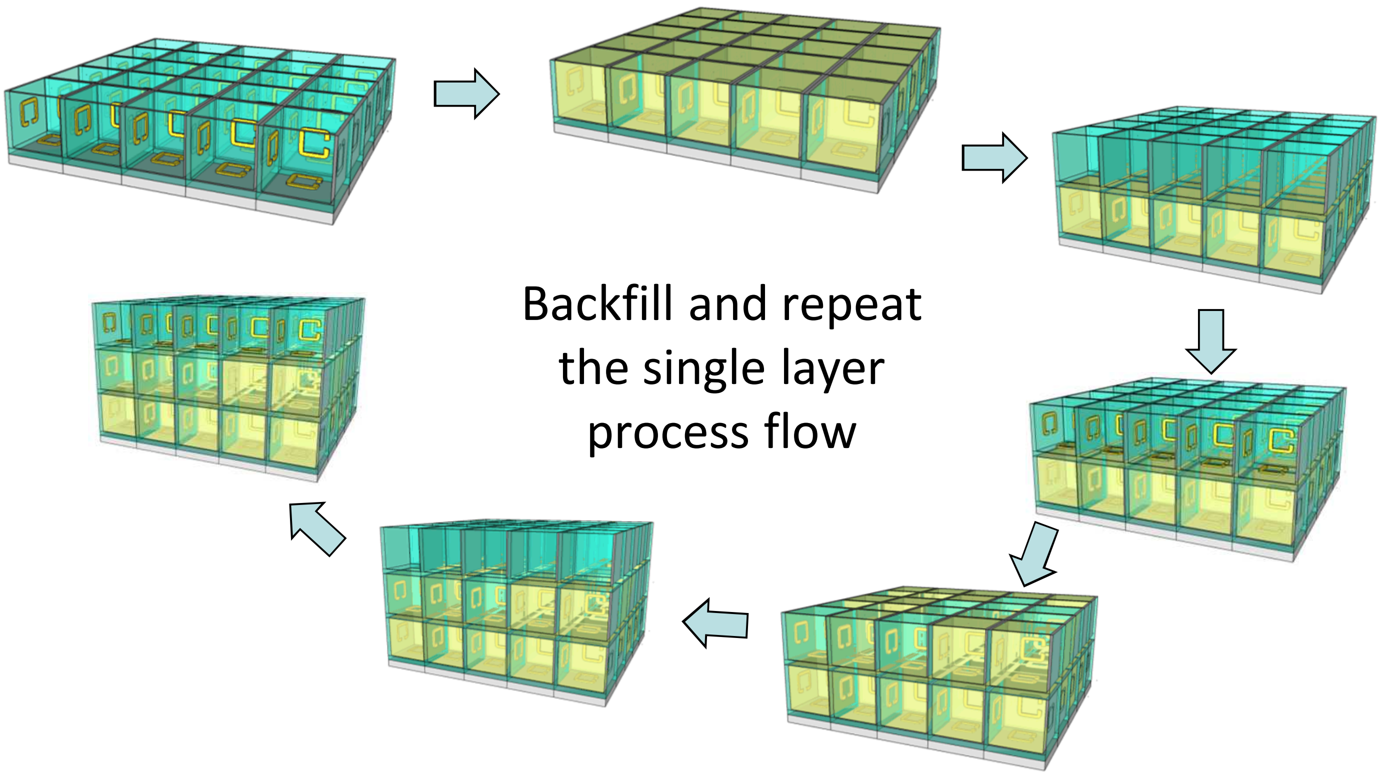
Fiber Connectorized Devices with Q~500k Delivered to JH/APL!

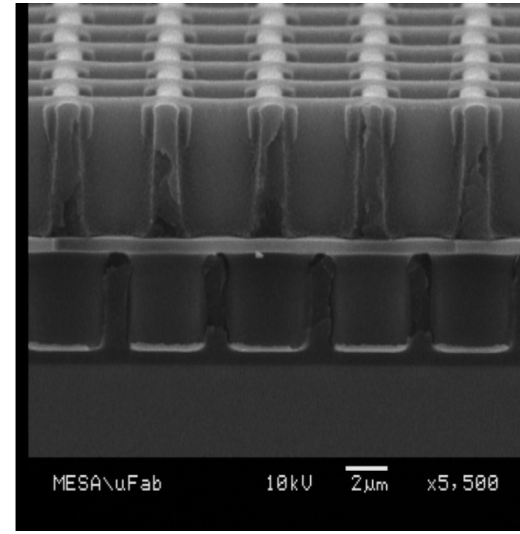
Sandia PI: Ryan Camacho

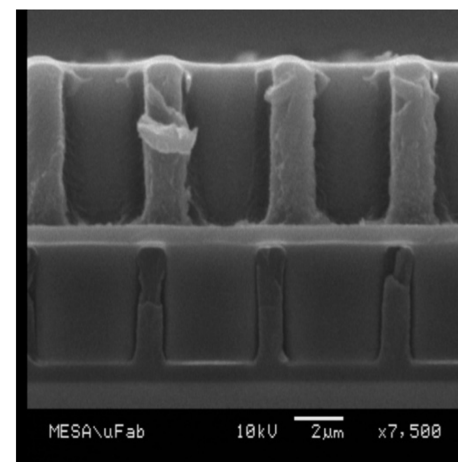
APL The Johns Hopkins University Applied Physics Laboratory | UMBC | NORTHWESTERN UNIVERSITY | DARPA DSO

Multilayer MPL for "Thick" 3D Materials

Sandia National Laboratories





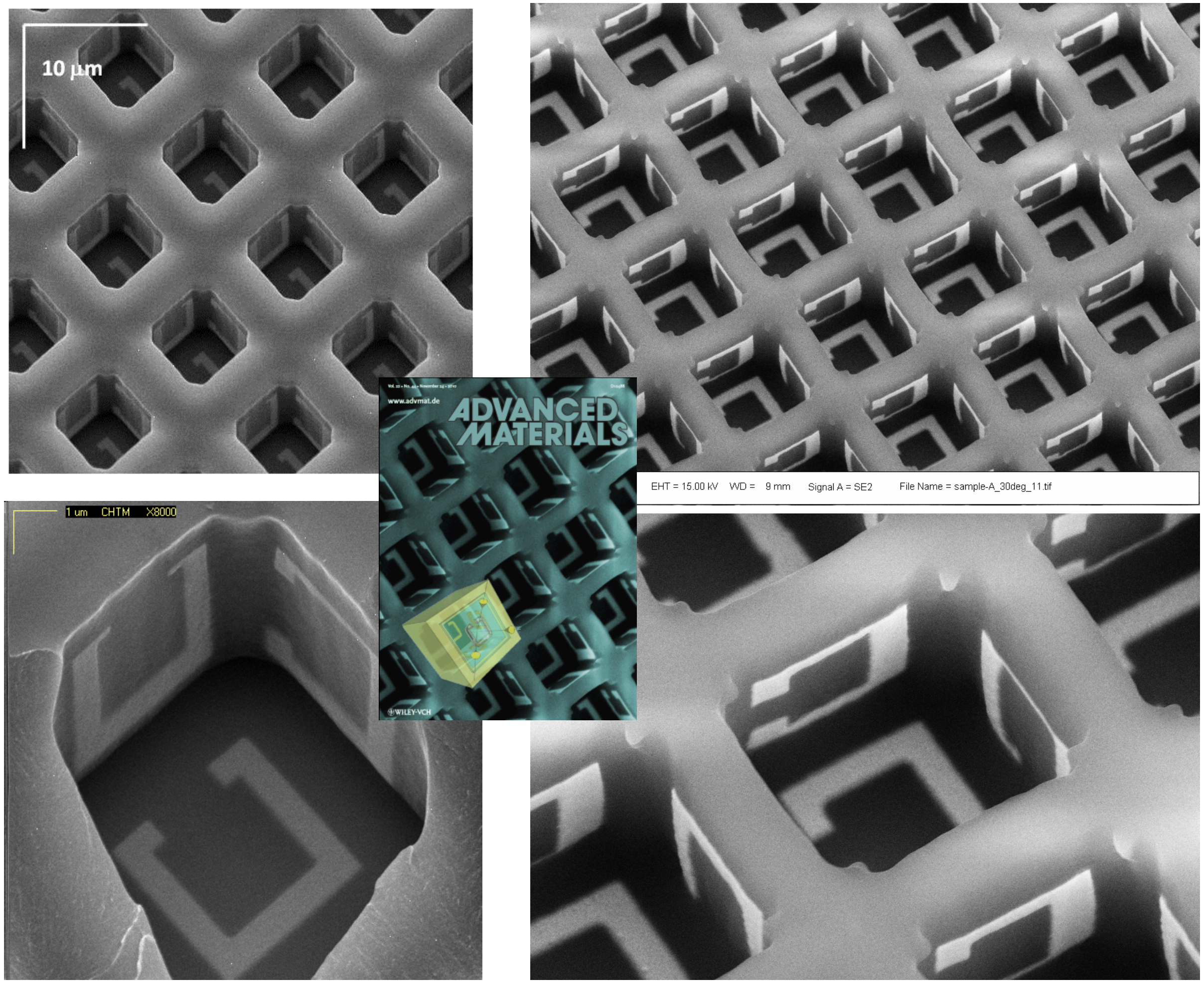


Membrane projection lithography is a promising route for fabrication of complex IR selective absorbers and emitters.

Sandia Contact: David Bruce Burckel dbburck@sandia.gov

3D Metamaterials via MPL

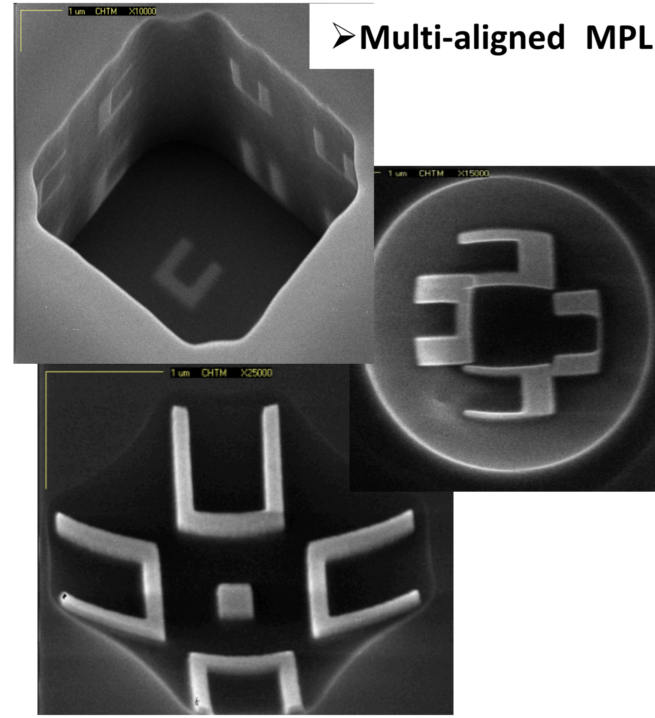
Sandia National Laboratories



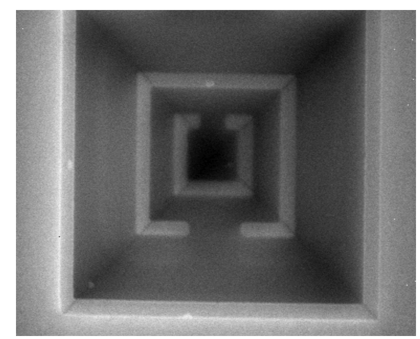
- Unit Cell Dimension = 14 µm pitch
- SRR Dimension = 8 µm
- Resonance wavelength ~ 50 µm

- Unit Cell Dimension = 6 µm pitch
- SRR Dimension = 3 µm
- Resonance wavelength ~ 22 µm

- Multi-aligned MPL

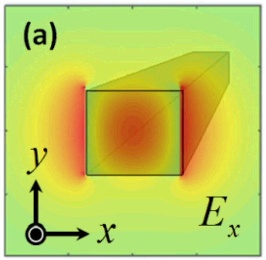


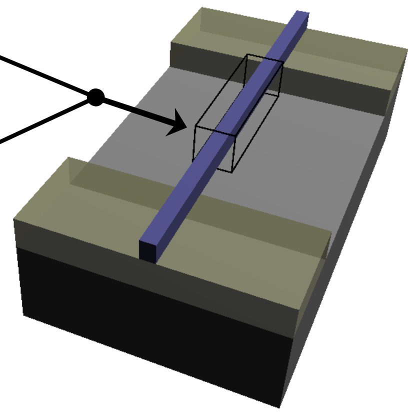
- Self-aligned MPL: spherical cavities



- Pyramidal 3D metamaterials in Si

Narrow-band high-frequency RF oscillators:

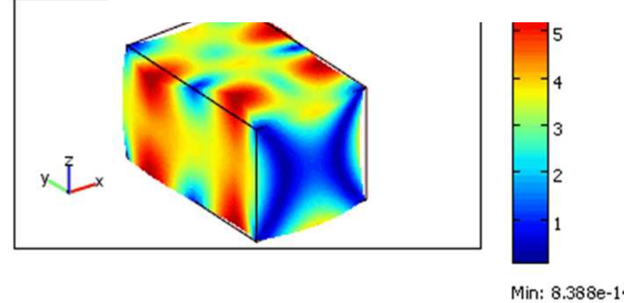




Guided mode within suspended dielectric waveguide. (300x300nm)

Suspended waveguide: L = 100 microns

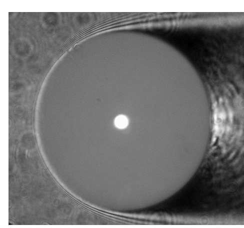
Excitation: 13.8 GHz Phonons

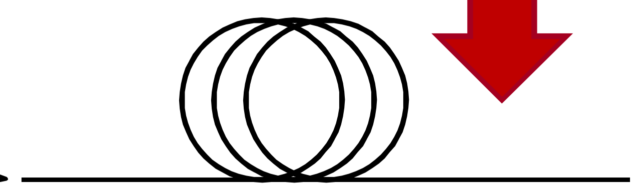


= Equivalent nonlinearity of 10-1000 meters of fiber

New Technologies:

- Tunable RF oscillators (10-20GHz)
- Narrow-band signal amplification and lasers.
- RF filtering.





Fiber optic: L = 10-1000 meters

Peter T. Rakich, Charles Reinke, Ryan Camacho, Paul Davids, Zheng Wang, " Giant Enhancement of Stimulated Brillouin Scattering in the Sub-Wavelength Limit," *Physical Review X Vol 2, No. 1, 011008 (2012*

Coherent Chip-scale Transduction via Optically Induced Mach-waves

<u>Goal:</u> Demonstrate efficient / high-output chip-scale ultra-broadband stimulated phonon generation with photonic-phononic waveguides

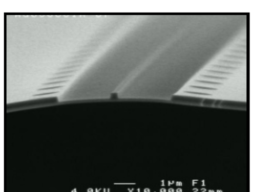
<u>Approach:</u>

Ultra-broadband (5-20GHz) stimulated phonon emission by

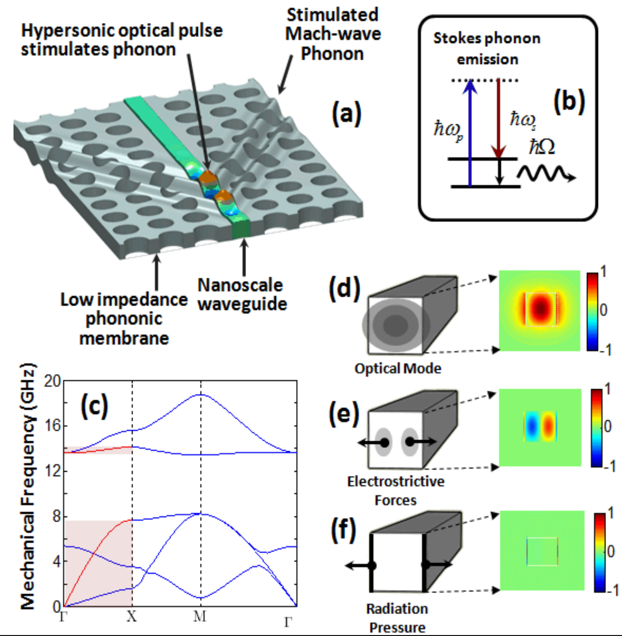
- low impedance phononic media
- electrostriction & radiation pressure
- highly dispersive electromagnetic modes

<u>DARPA Program Milestones:</u>

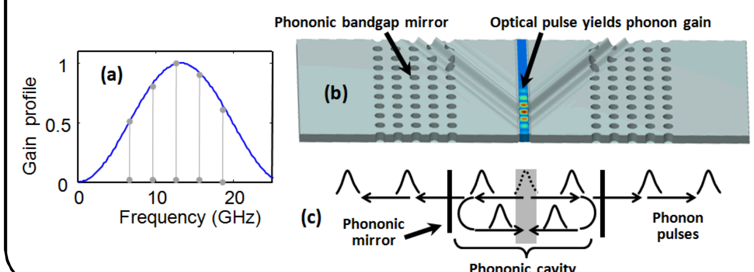
- novel pulsed pico-sec mode-locked phonon laser
- broadband coherent phonon amplification
- widely tunable phonon lasers and oscillators



Membrane suspended Si waveguide



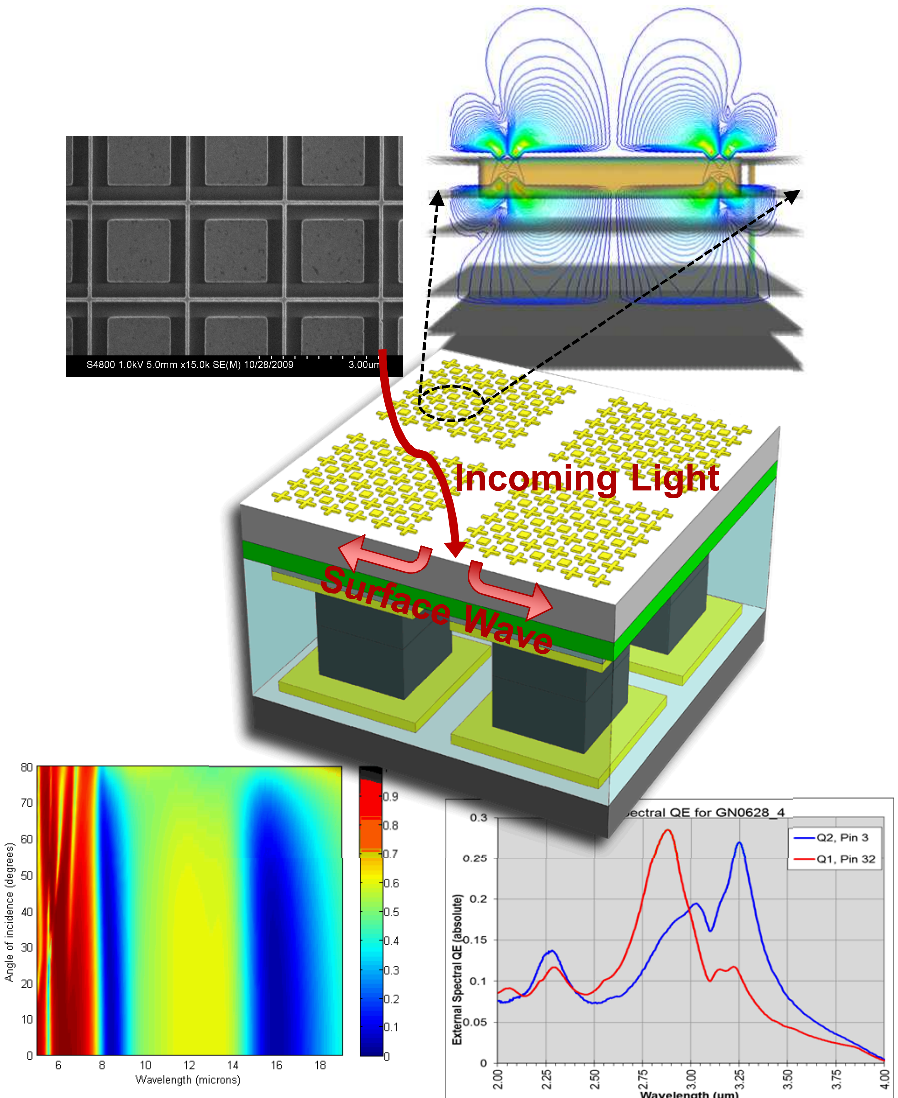
Mode-locked Pico-sec Phonon Laser



The Enabling Technology: Nanoantennas

Sandia National Laboratories

What is a nanoantenna?

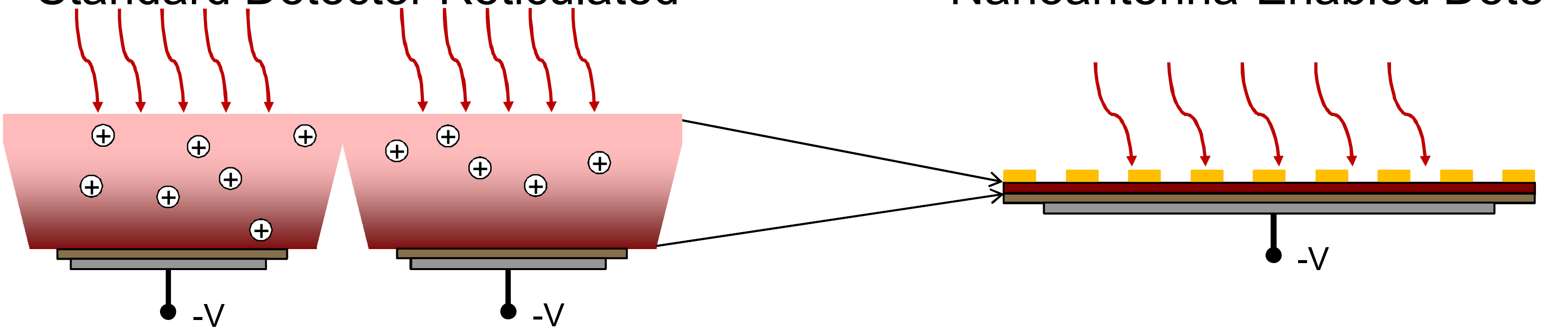


- A subwavelength patterning of metal or high-index dielectric.
- Converts incoming radiation to a surface wave with energy confined to a small volume under the nanoantenna.
- The pattern may be changed from pixel-to-pixel allowing adjacent pixels to have different spectral or polarization response.
- This confinement is what enables us to look at interesting applications.
  - 2D materials
  - Tunable materials
  - Thin detector layers

What confinement buys you

Standard Detector Reticulated

Nanoantenna-Enabled Detector



Lower Dark Current

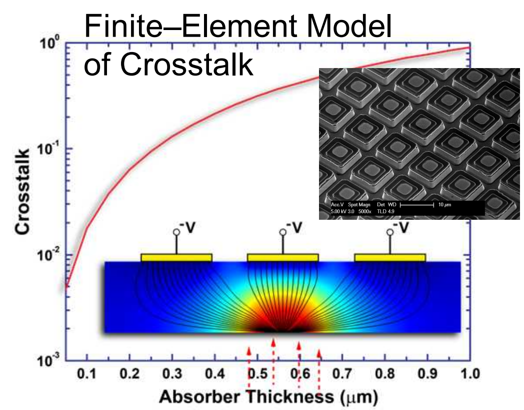
Dark Current $J_{Diff} = \frac{e \cdot n_i^2 \cdot t_{abs}}{N_D \cdot \tau_p}$

- Leads to noise.
- Is reduced by cooling the detector.
- Is proportional to the volume of active material.

Less volume of active material leads to less dark current.

Less Crosstalk

- Causes image blur and loss of resolution.
- Reticulated detectors suffer reduced fill factors.
- Etched sidewalls lead to increased surface recombination/generation.
- Exponential reduction in crosstalk with reduced absorber thickness.
- No loss of fill factor or creation of surface states with nanoantenna detector design.



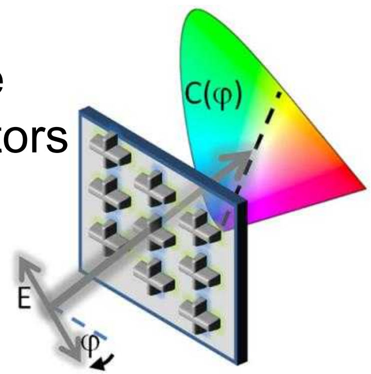
In the IR, the limitation to further reducing pixel size is crosstalk.

Applications

The nanoantenna concept is agnostic to the underlying detector material: we can use this concept to improve detectors across the spectrum.

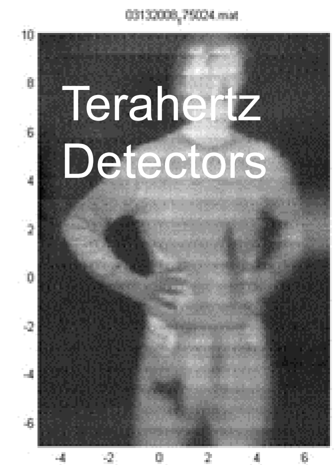
Radiation Detectors

Visible Detectors

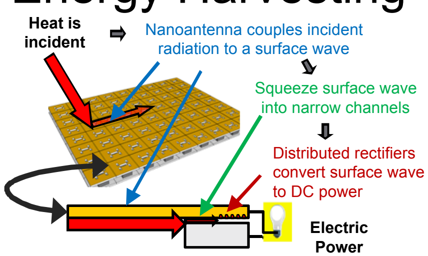


Mobile Infrared Detectors

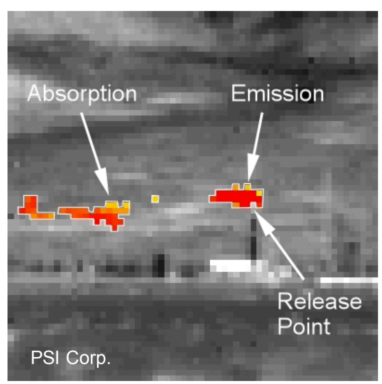
Terahertz Detectors



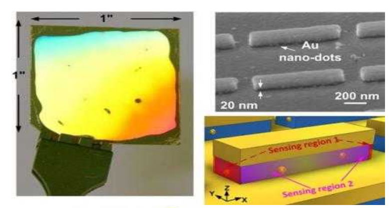
Energy Harvesting

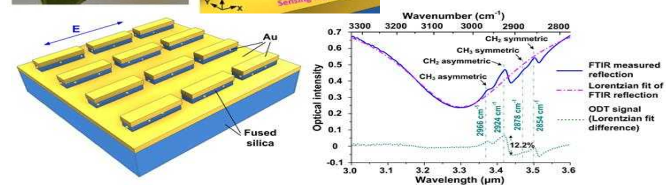


Chemical Detectors



Bio Detectors

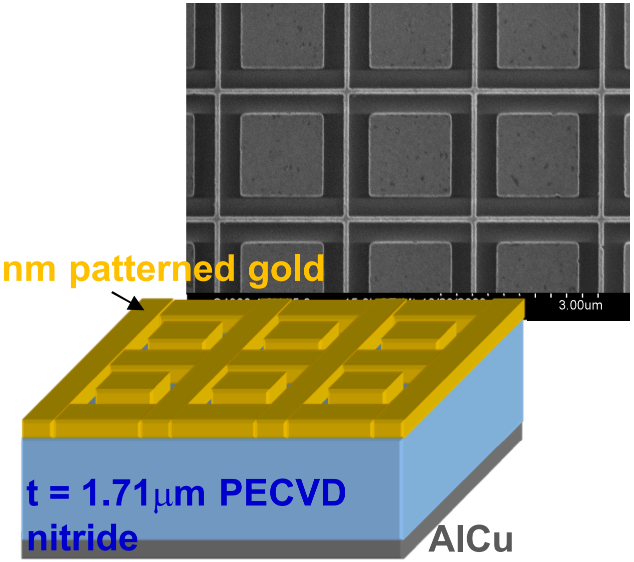


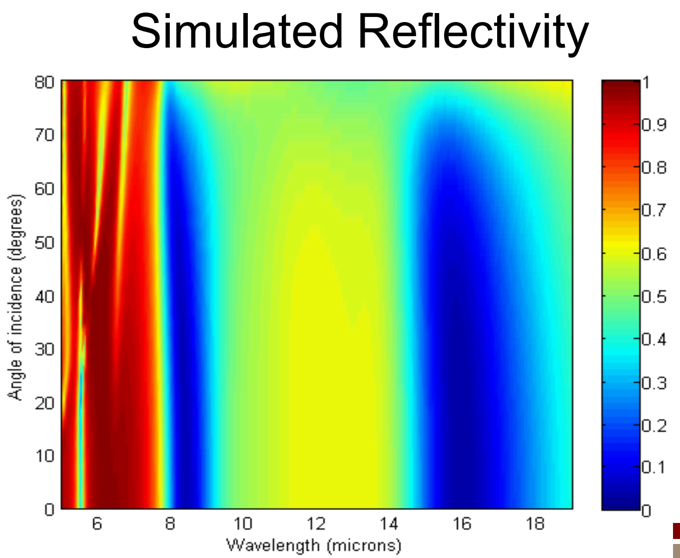


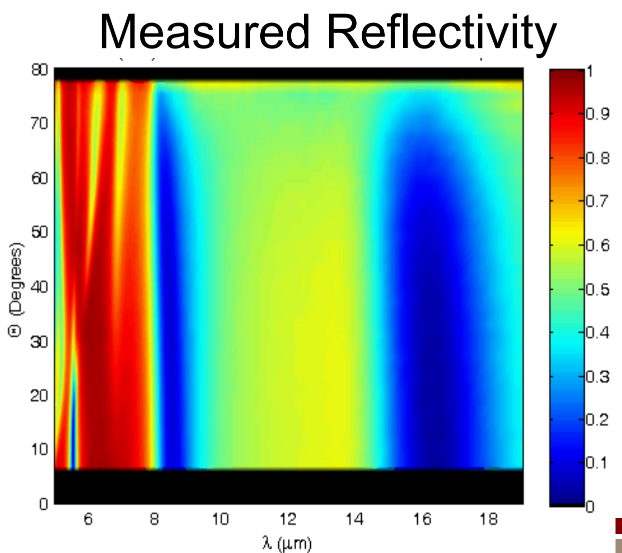
Chao Wang, IBM Watson Center

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?



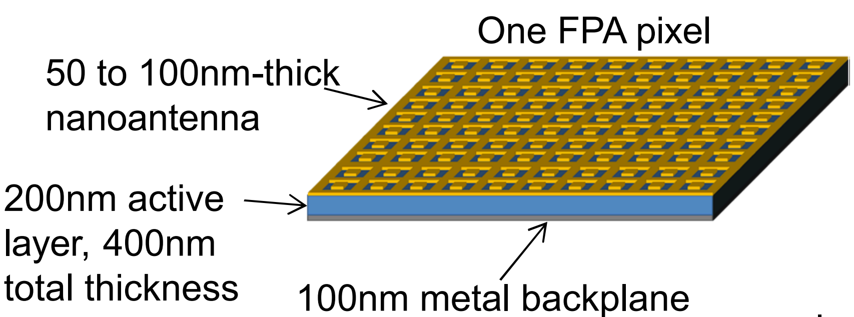


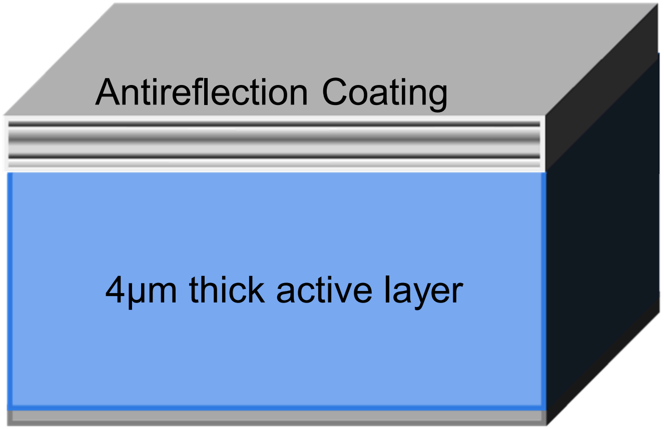


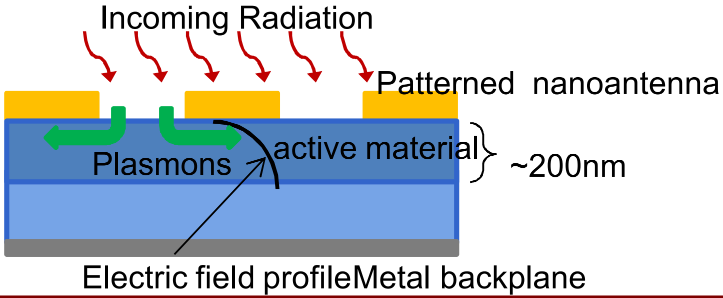
Incorporation with Existing Detector Materials in the Midwave

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

Using dense fields to thin the active region.

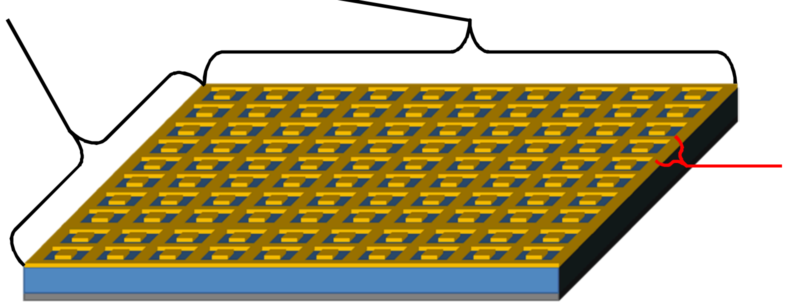




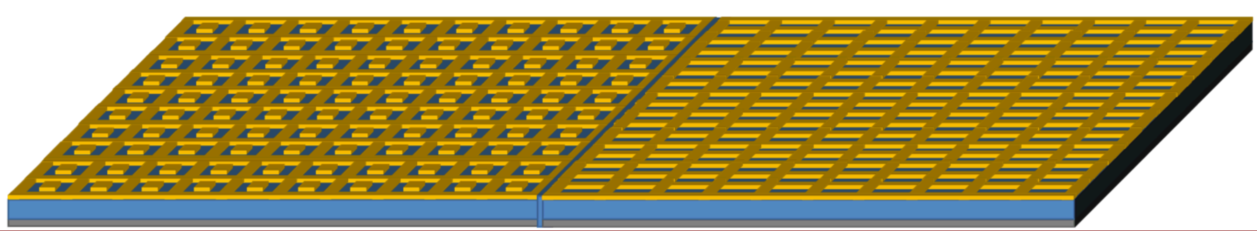


Advantages of the Nanoantenna Structure

- **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).**

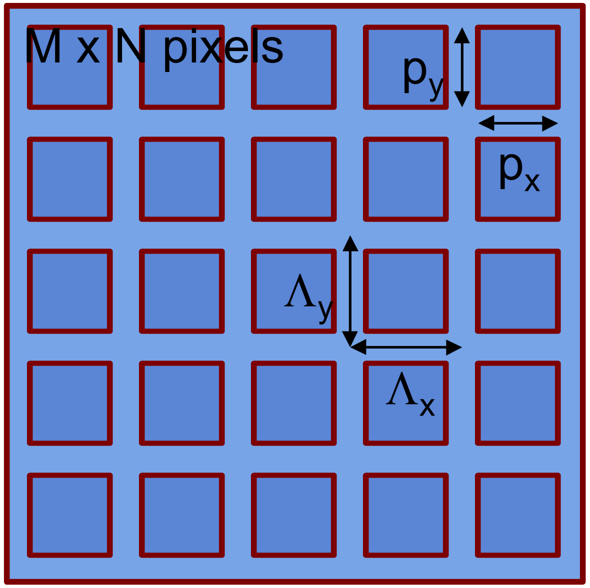


Two adjacent FPA pixels with different functionality.

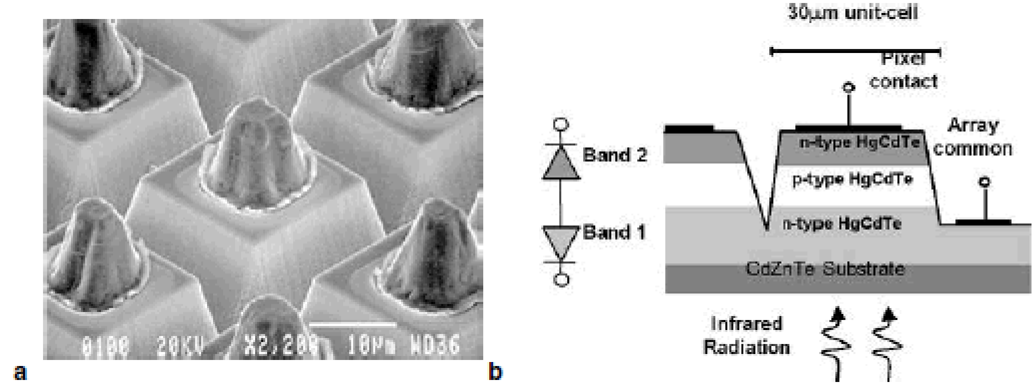


Maximizing Active Area Improves MTF and Signal

Sandia National Laboratories

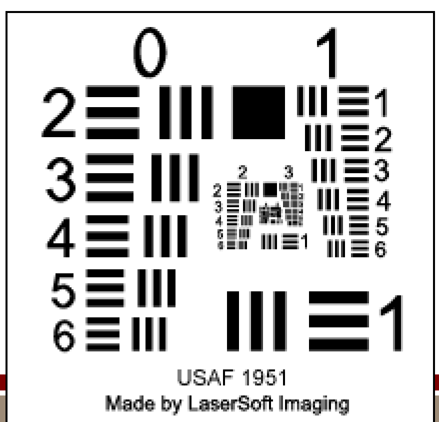


MCT FPA architecture



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 Λ_x, Λ_y and p_x, p_y as small as possible to maximize the MTF.

This is clearly impossible, but we can make Λ_x and Λ_y as small as possible for a given p_x and p_y.

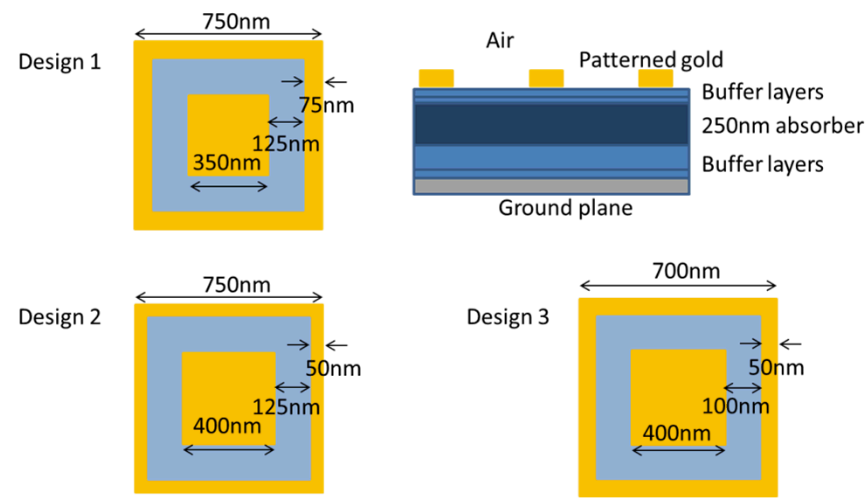
Our architecture gives us near 100% fill factor.

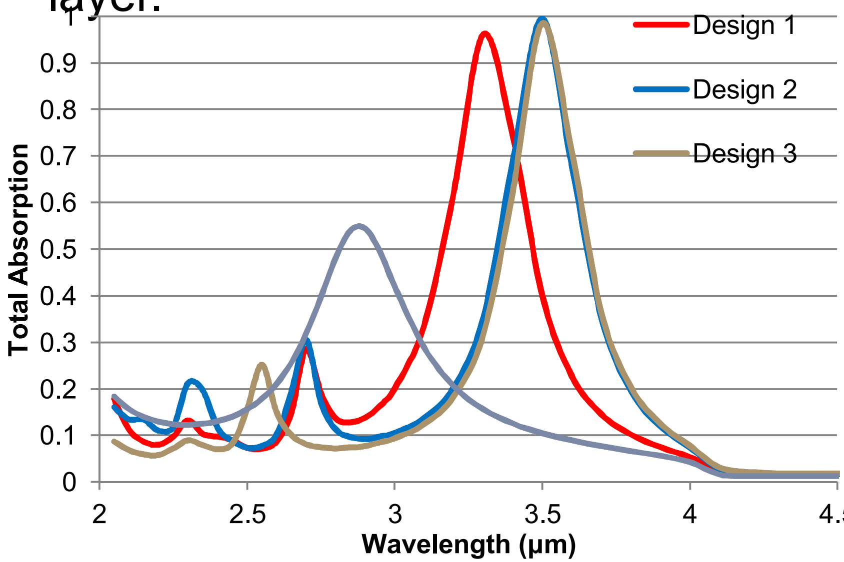
Simulation of InAsSb Design

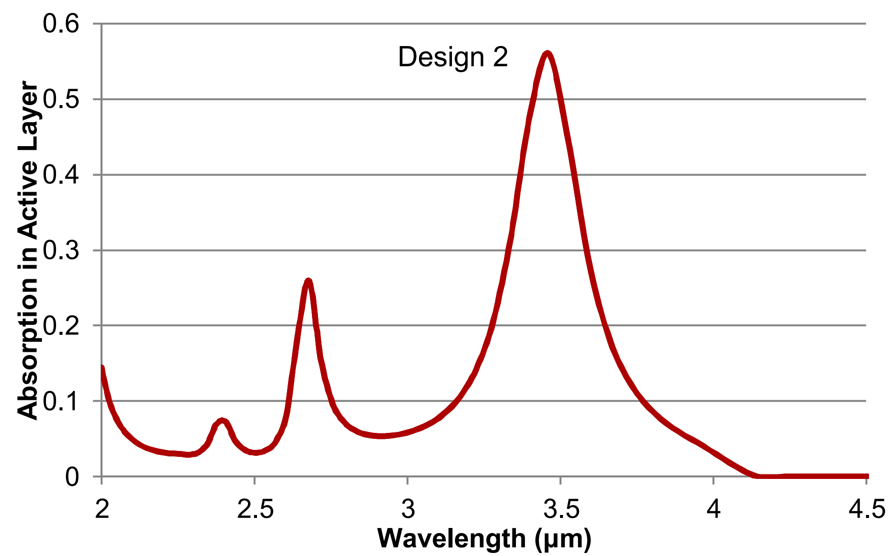
Designs for peak responsivity in the 3.25µm to 3.5µm range.

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

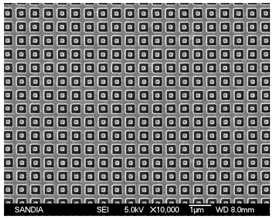
Designs were not optimized to maximize absorption in the active layer.



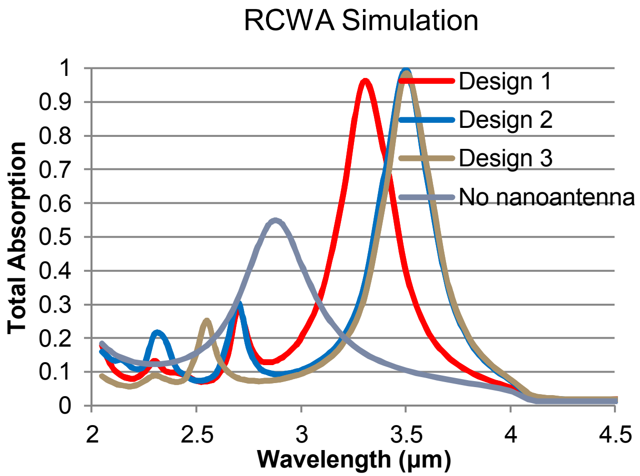


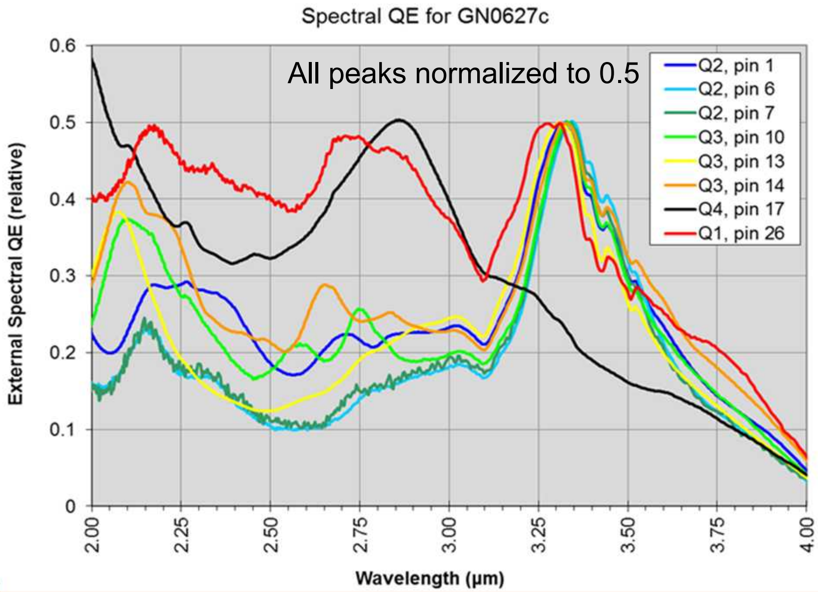


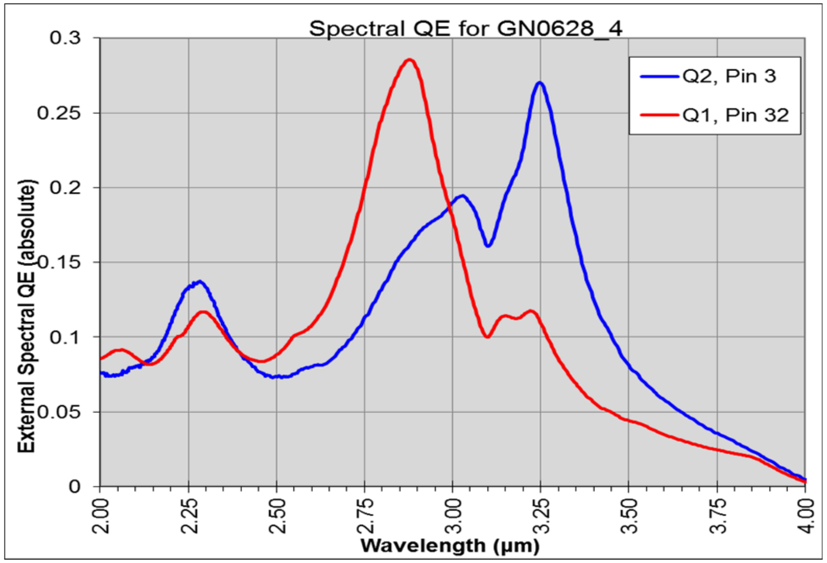
Nanoantenna-Enhanced InAsSb Detector Results



- 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.





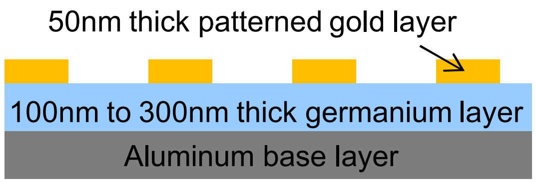


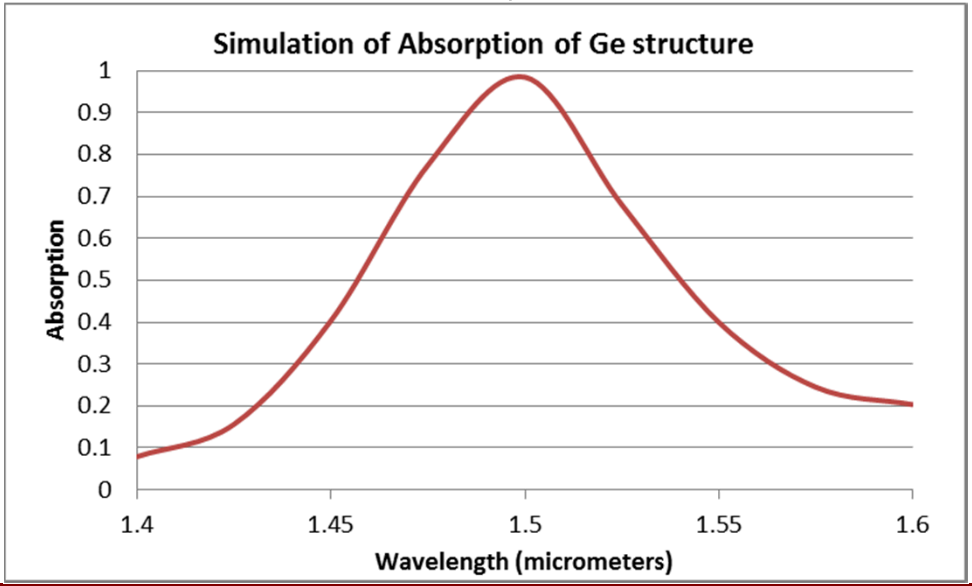
Germanium Detector

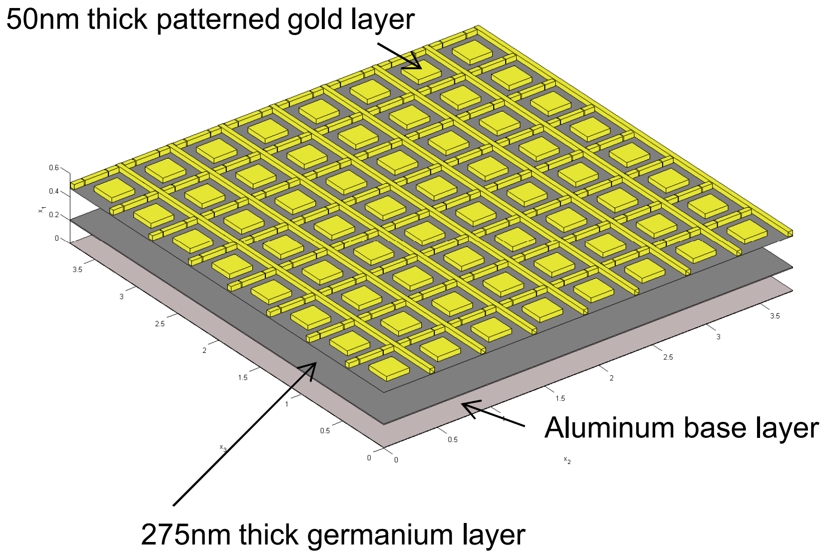
As with the MWIR designs, this one involves a detection material between two metal layers. Since it is for the near-IR, the detector layer is quite thin. The metal top and bottom layers act as contacts.

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.





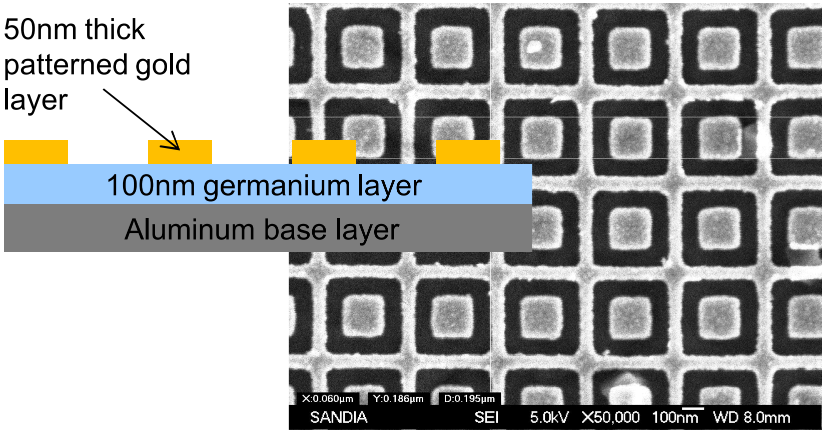


Period of nanoantenna = 475nm
Width of continuous gold bars = 50nm

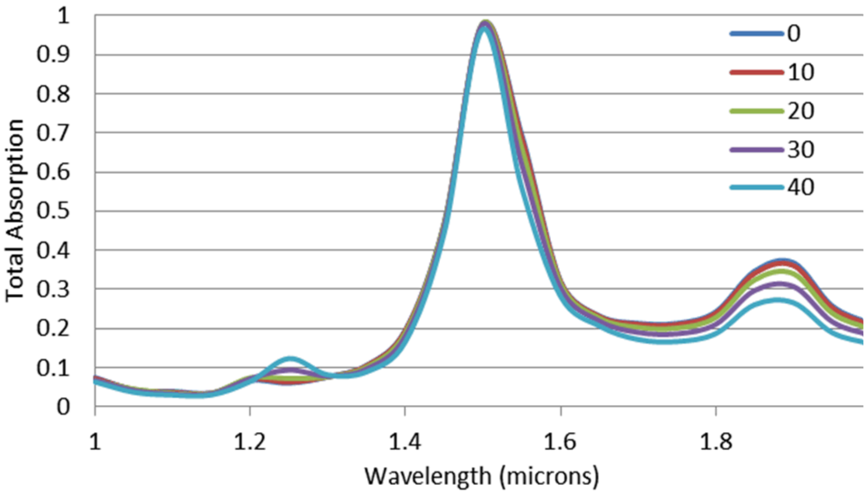
Germanium Detector Design

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.

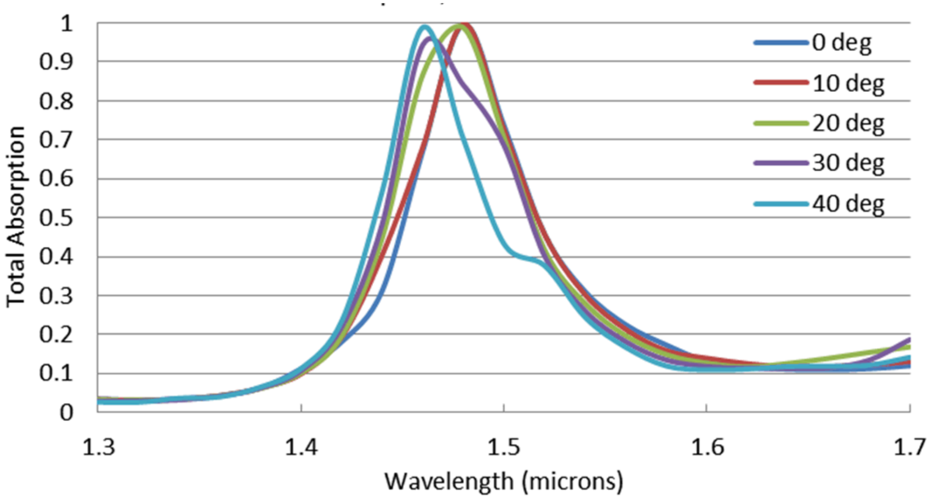
In the 275nm-thick design we see a change in peak wavelength between 20° and 30°.



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

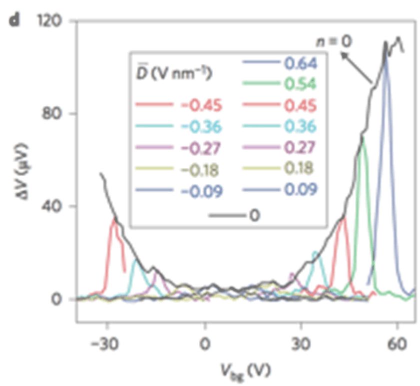
Direct observation of a widely tunable bandgap in bilayer graphene

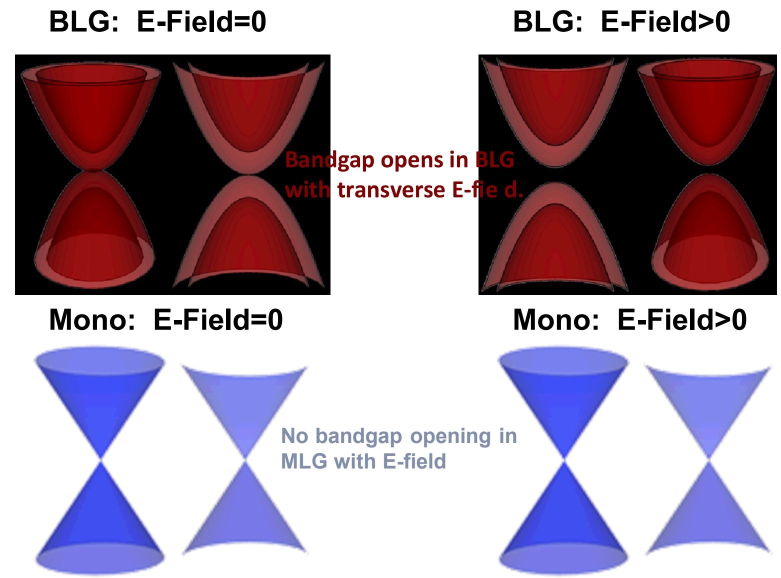
Yuanbo Zhang[1]*, Tsung-Ta Tang[1]*†, Caglar Girit[1], Zhao Hao[2,4], Michael C. Martin[2], Alex Zettl[1,3], Michael F. Crommie[1,3], Y. Ron Shen[1,3] & Feng Wang[1,3]

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]



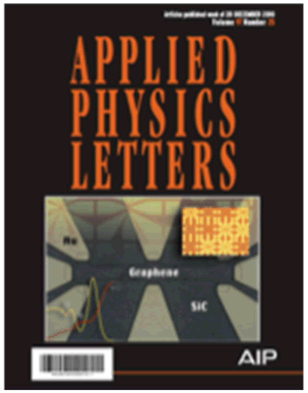


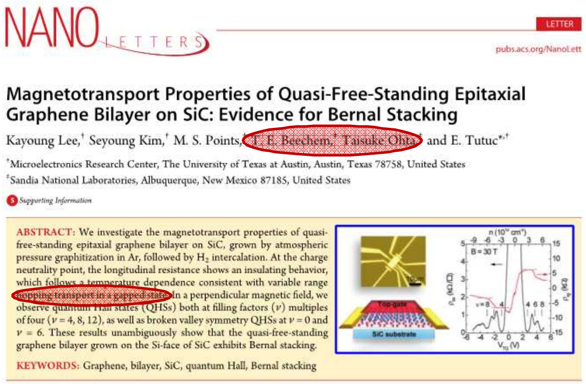
Problems:

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[*,†]

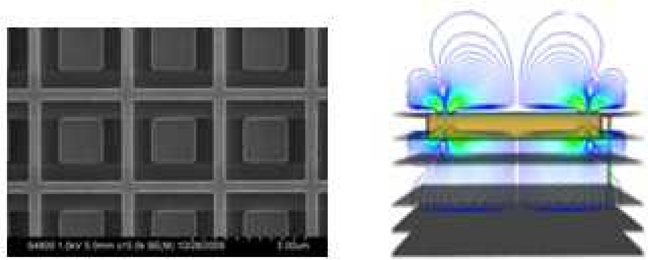
[†]Microelectronics Research Center, The University of Texas at Austin, Austin, Texas 78758, United States
[‡]Sandia National Laboratories, Albuquerque, New Mexico 87185, United States

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 (ν) 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



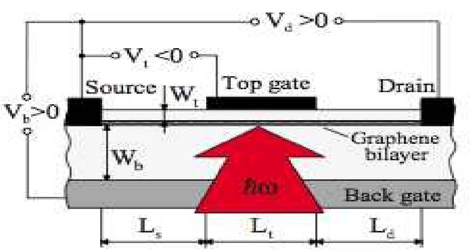
Nanoantenna-Enabled Midwave Infrared Focal Plane Arrays

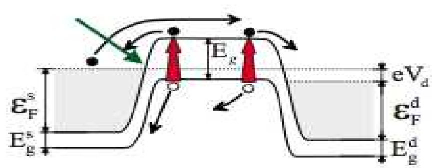
David W. Peters*, Charles M. Reinke, Paul S. Davids, John F. Klem, Darin Leonhardt, Joel R. Wendt, Jin K. Kim, Sally Samora

Sandia National Laboratories, P.O. Box 5800, Albuquerque, NM, USA 87185-1082

Proc. of SPIE Vol. 8353 83533B-1

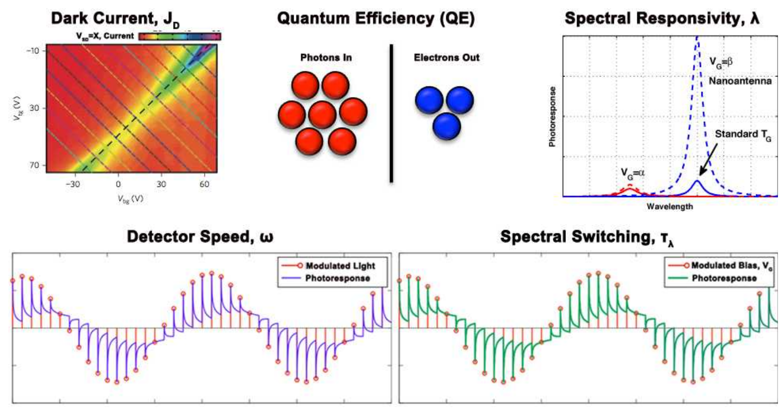
Phenomenon: PhotoFET



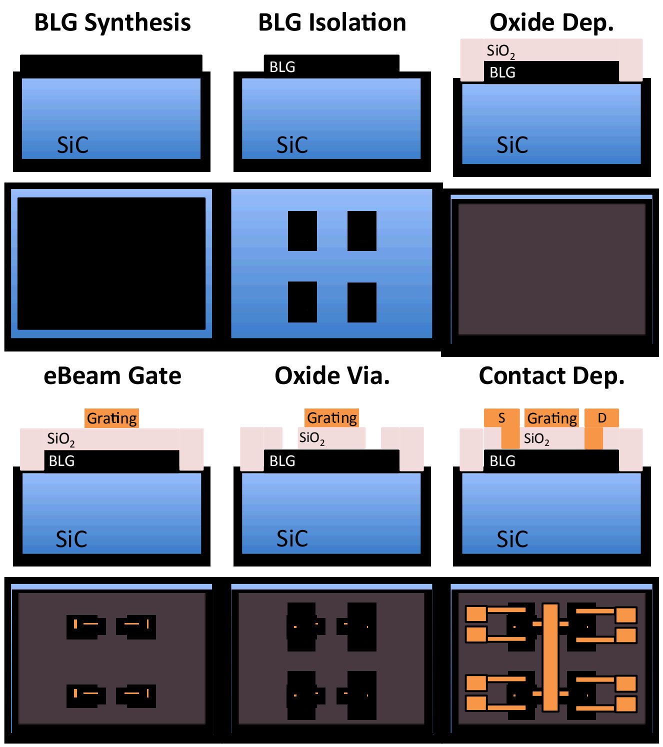


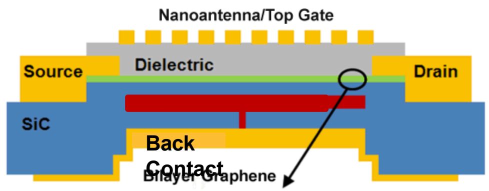
Ryzhii et al. PRB (79) 245311, 2009

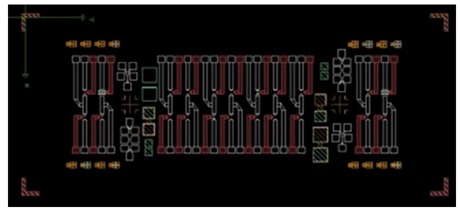
Next Steps: Technology Maturation

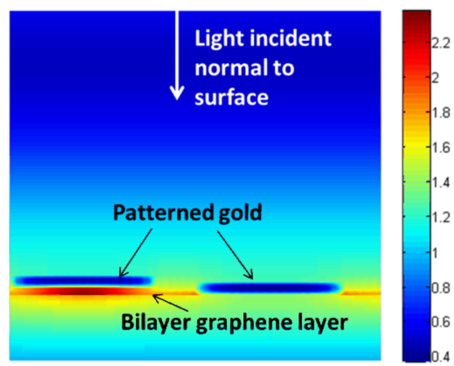


Graphene Detector: Early Fab and Results



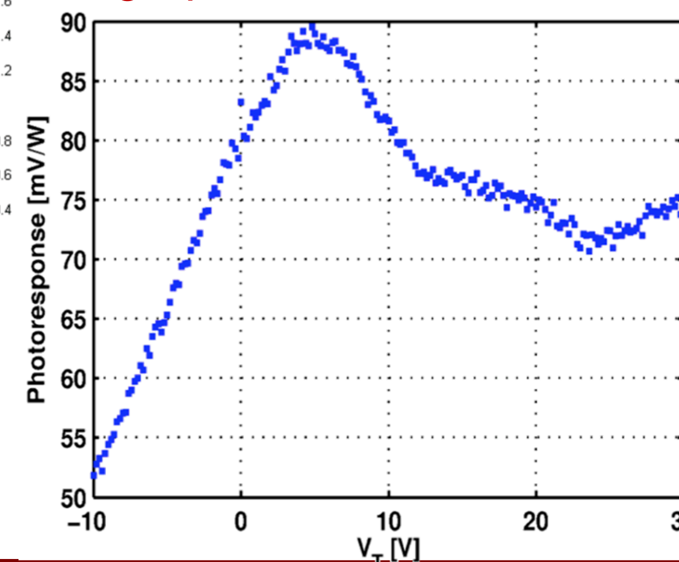






- Scalable fabrication using "standard" techniques
- Multiple operational devices on a chip
- Opens path towards arrays
- Developed an improved understanding of the graphene/SiC interface

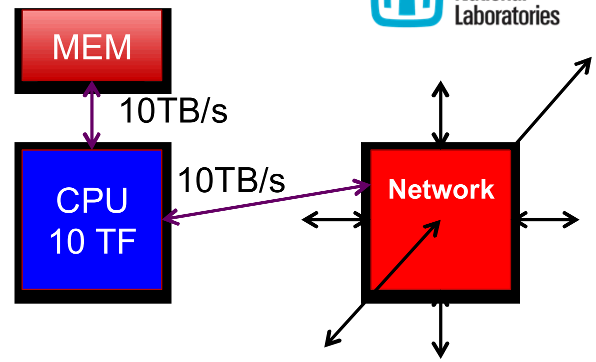
Devices show bias dependent tunability with a signal enhanced by nanoantennas.



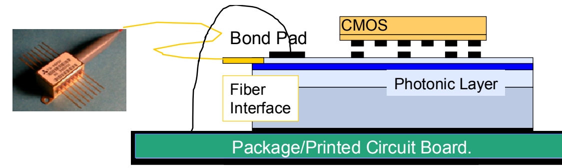
Summary

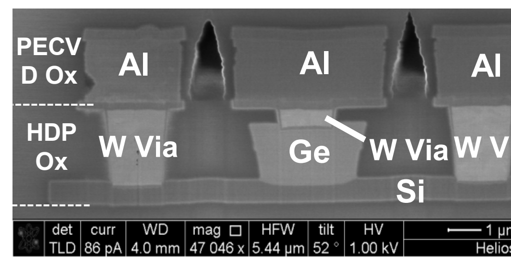
- **Nanoantennas offer methods of enhancement in traditional and new detector platforms.**
- **We have designed and fabbed structures in three different infrared detector materials.**
  - InAsSb detectors in the MWIR.
  - Germanium detectors in the Near-IR.
  - Graphene detectors that offer new capabilities.

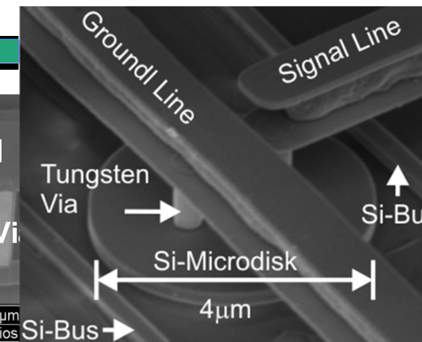
A new approach to high performance computing

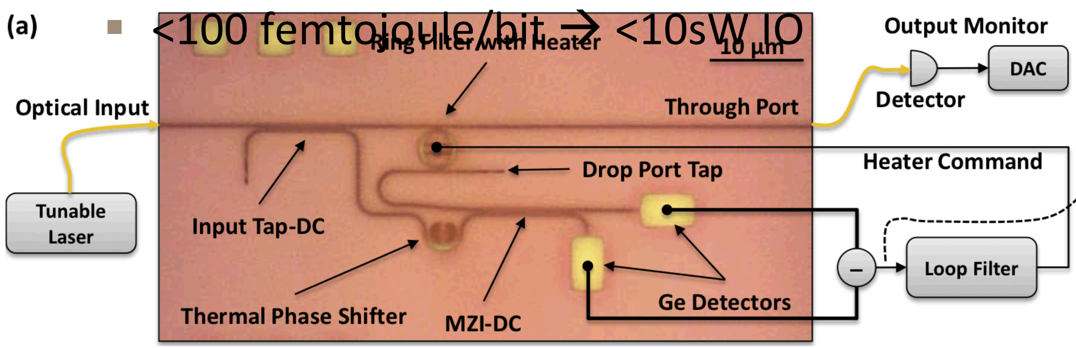


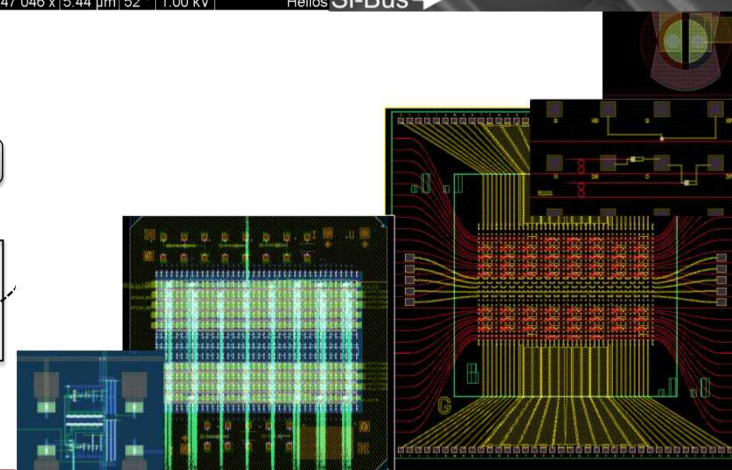
- ***Instead of … Evolutionary architecture approach***:
  - Design around limited (network and memory) interconnect bandwidth (<< 1 bit per second/flop)
- ***Pursue … Revolutionary approach***:
  - Small silicon micro-photonic devices intimately integrated with network and processor ICs
  - Chip-scale 100s Tbps IO
  - <100 femtojoule/bit → <10sW IO





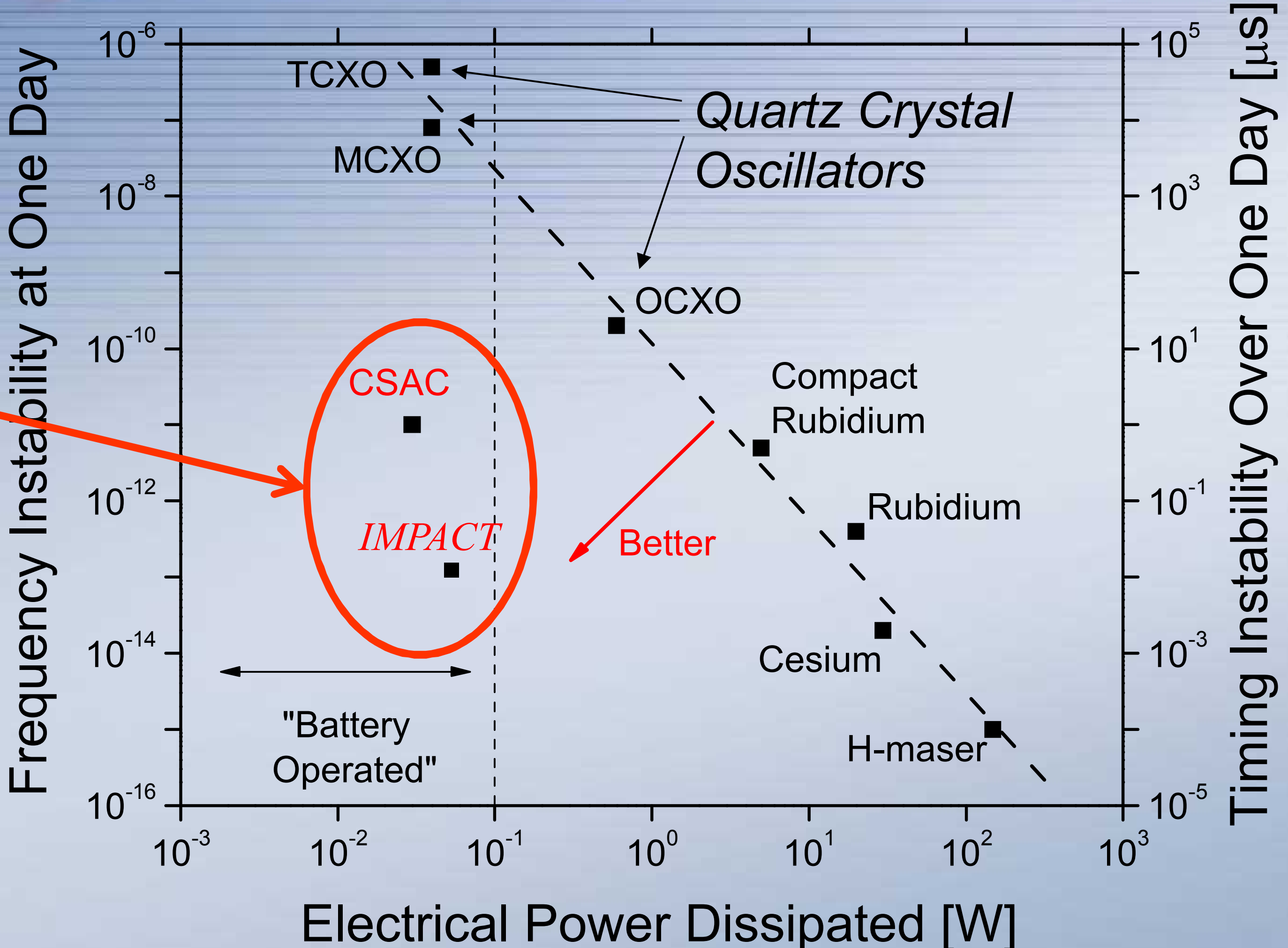






Atomic Clocks - Commercial

This IS what Sandia is developing



Adapted from figure by M. Garvey, Symmetricom

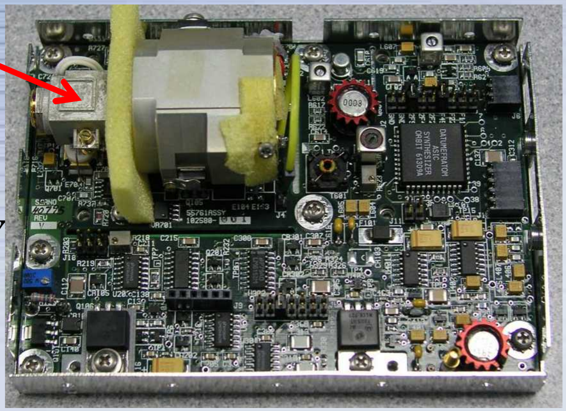
Chip-Scale Atomic Clock (CSAC)

- **DARPA Goals (2002-present)**
  - **400-fold reduction in power and volume**
    - Power < 30 mW
    - Volume < 1 cm^3
    - (In)stability: σ(1hr) < 1×10^{-11}
- **Teams:**
  - **Symmetricom/Draper/Sandia, Honeywell, Teledyne, Sarnoff/Princeton, NIST**
- **Applications**
  - **Mobile comm networks**
  - **GPS navigation aids**

Today: Commercial Rubidium Clock

5W Rb Lamp

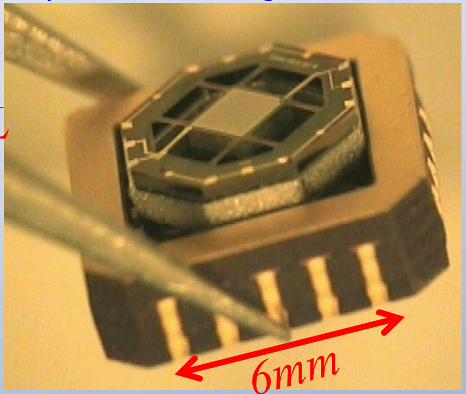
Total Power: 12W



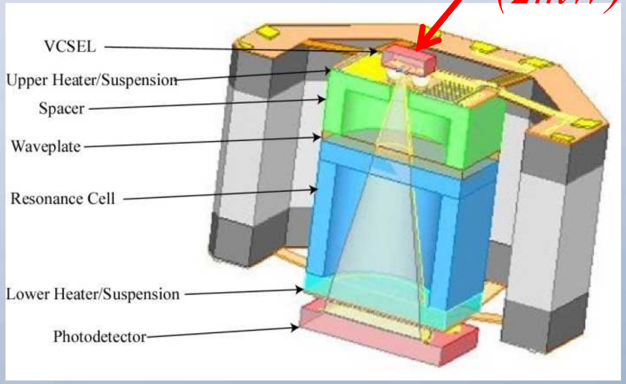
92mm

Tomorrow:
30 mW
1 cm^3

Symmetricom/Draper/Sandia

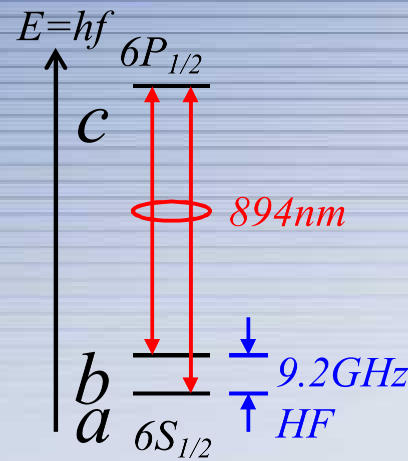


VCSEL (2mW)

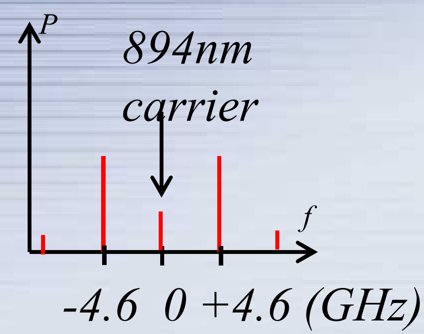


Coherent Population Trapping Atomic Clocks

- **Cs (Rb) energy levels**
  - **9.2GHz (6.8) hyperfine splitting**
- **Coherent Population Trapping (CPT)**
  - **FM modulation at 4.6GHz**
    - Creates sidebands split by 9.2GHz
  - **Superposition of |a> and |b>**
    - Dark state (less absorption)

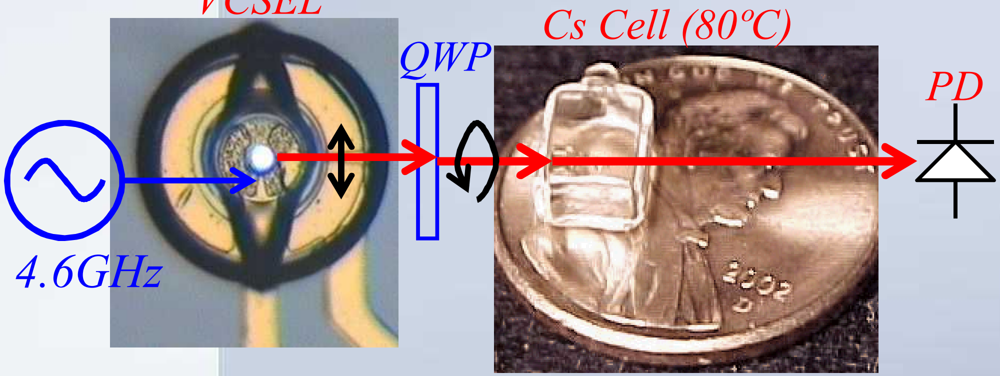


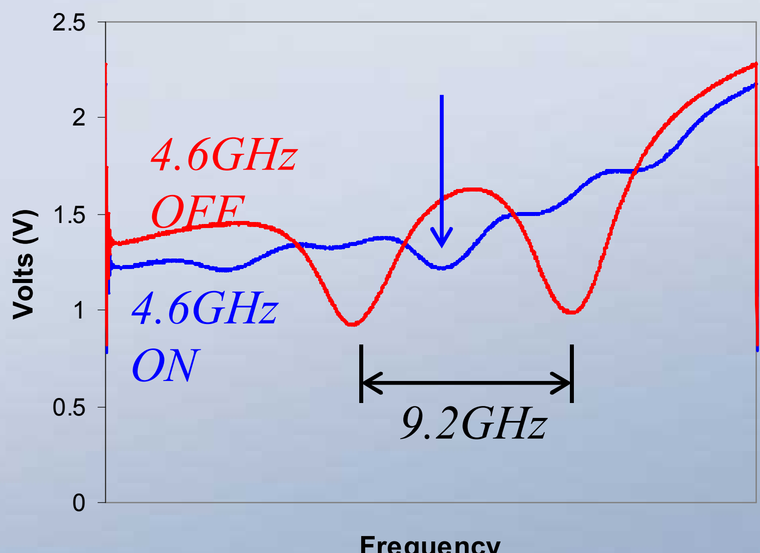
Ideal FM:



Fo = 9,192,631,770 Hz

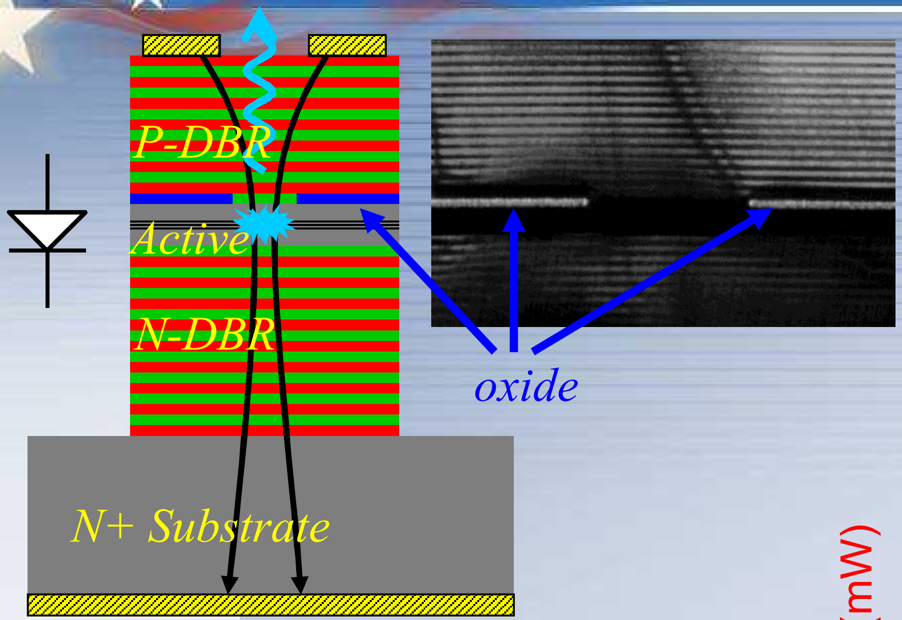
CPT Clock Layout:

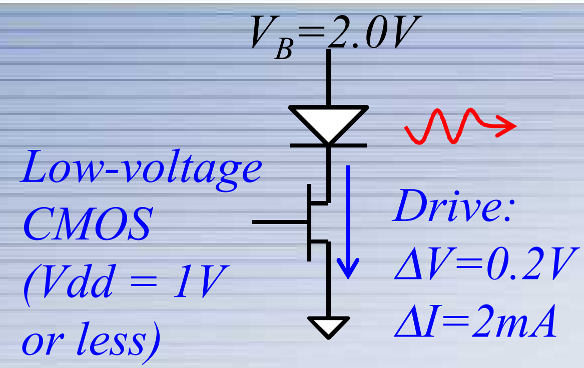


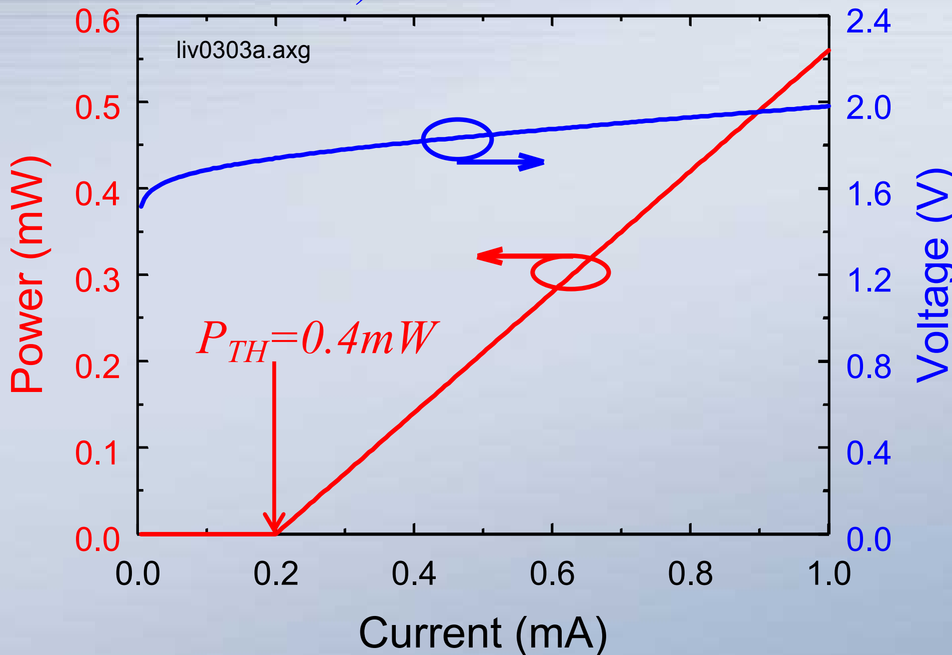


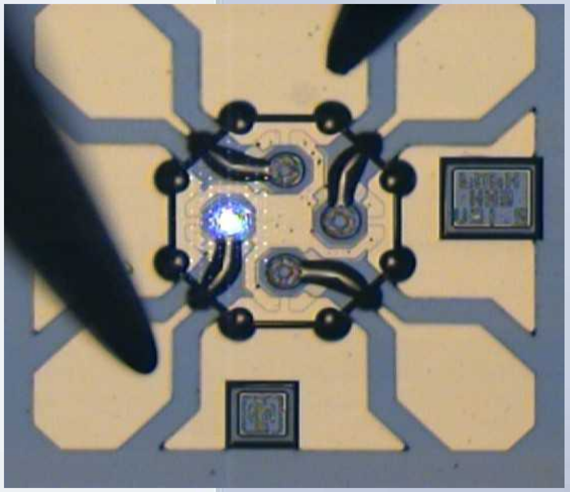
- *J. Kitching, et al., IEEE TIM v.49, p.1313 (2000). – 852nm CPT Clock*

Vertical-Cavity Surface-Emitting Lasers (VCSELs)









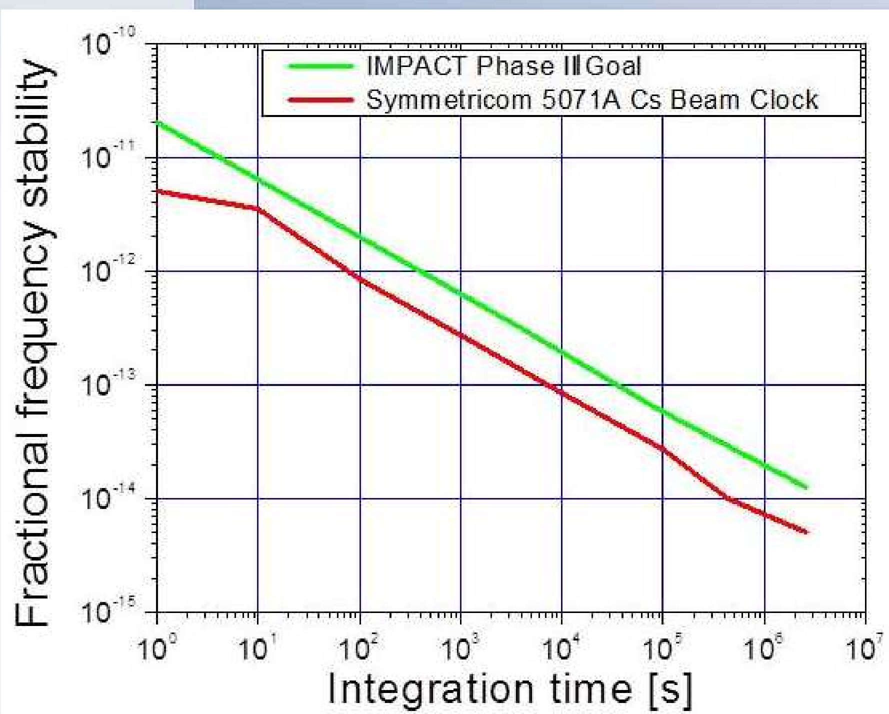
VCSEL is low-power laser of choice for microsystems.

CSAC - Summary

- Chip-scale atomic clocks shrink size and power consumption by 100 times
  - Smallest commercial clocks: $122cm^3$,10W
  - MAC prototypes: $16cm^3$, 125mW
  - DARPA goals: $1cm^3$, 30mW (nearly achieved)
- Enabling technologies
  - VCSELs: Single-frequency laser consuming only 1mW
  - MEMS: Thermal isolation of cesium cell, heated to 85C with only 7mW of power
- Emerging small high-performance atomic sensors, using small cesium gas cells and VCSELs
  - Atomic clocks
  - Magnetometers
  - Gyroscopes

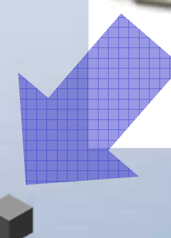
DARPA's IMPACT Project

Goals
- Achieve Cs Beam Clock performance in a mass and power constrained package
- 5 cm^3 ,50 mW, 10^{-14} performance



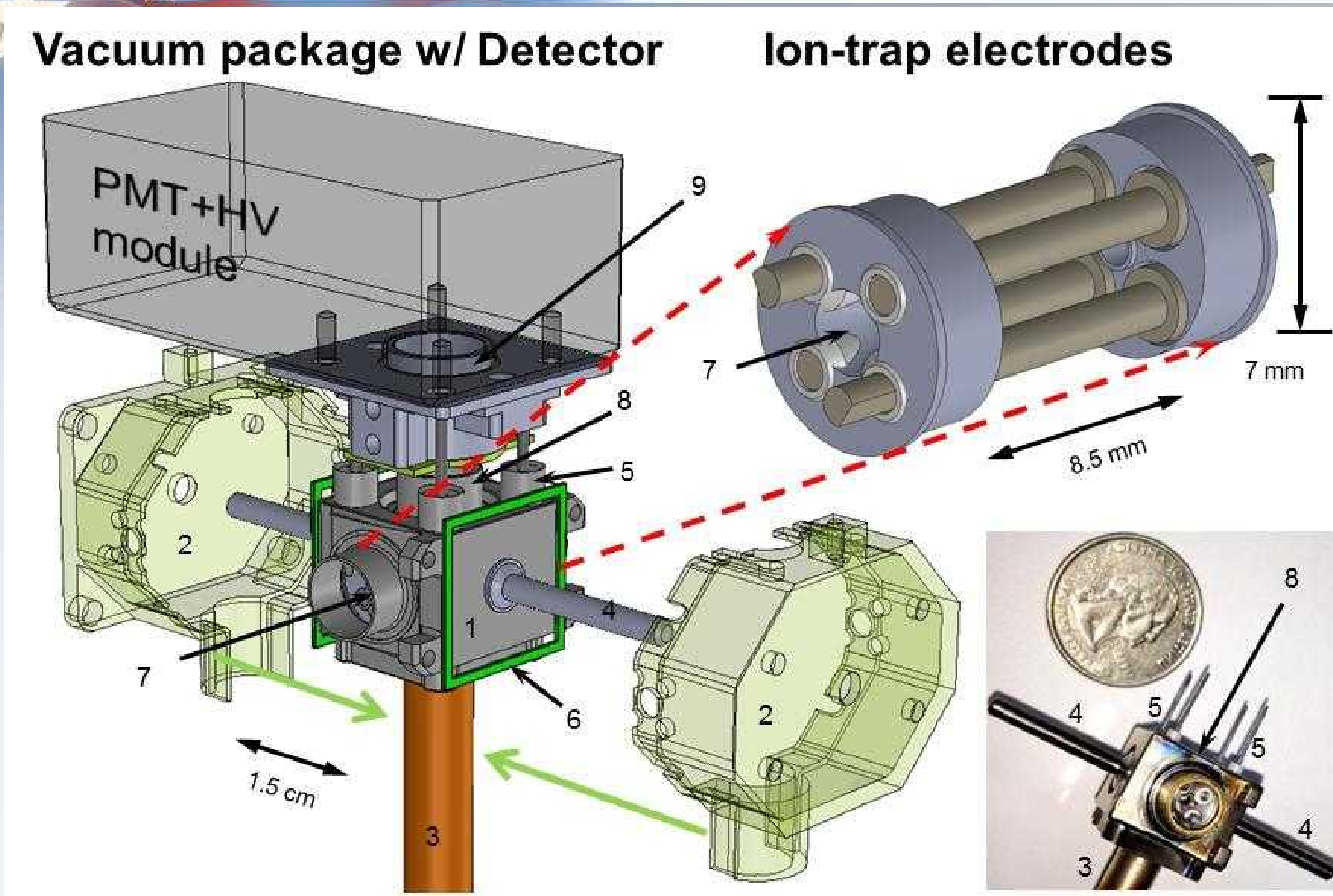
Applications--Excellent timing for:
- Nano/pico (cube) satellites
- Rapid GPS acquisition, and GPS denied navigation and timing
- Pulsed radio and spread spectrum communications

Microsemi (Symmetricom) 5071A



Miniature primary frequency standard

IMPACT – Phase 2 , 3 cm^3 Vacuum Package and Ion Trap



1. Vacuum package

2. μ-metal shield

3. Copper pump-out tube

4. Yb oven appendage

5. Electrical feedthroughs

6. C-field coils

7. Laser port (sapphire)

8. Fluorescence collection window (sapphire)

9. Lens and filters tube

- ***Titanium body with sapphire windows***
- ***Linear Quadrupole RF Paul Trap***
- ***Getter pumped***

- ***Pinched off since April 25th, 2012***
- ***Trapped ion lifetime > 3 weeks***

IMPACT - Independent Testing at NIST, July-August 2012

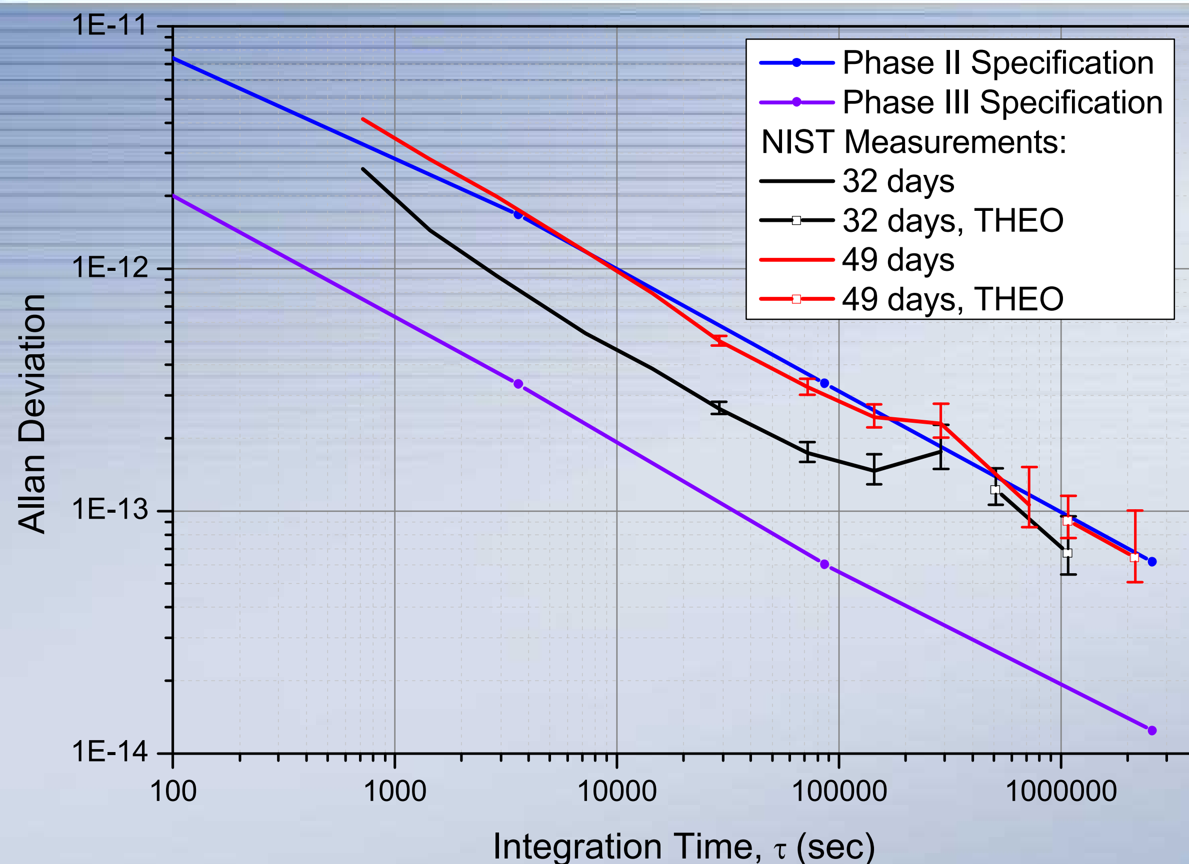
Demonstrated 31 days of continuous operation, 49 days of data collected

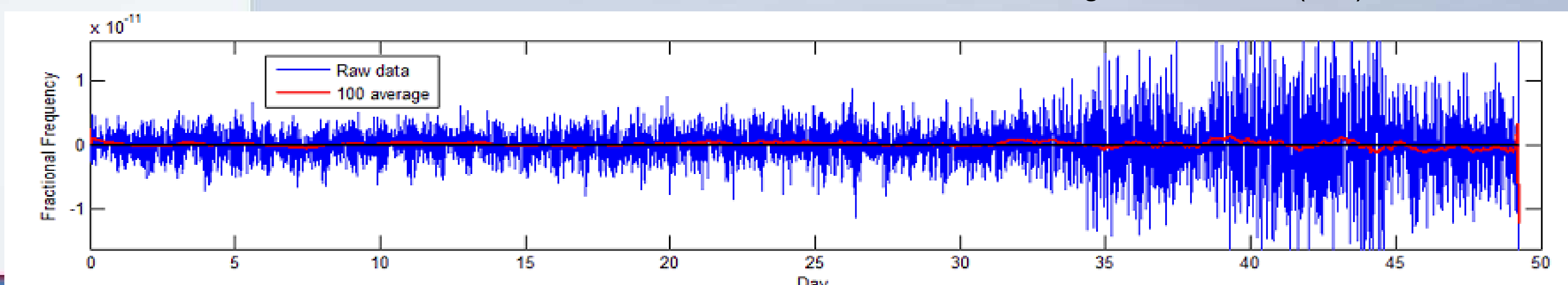
Allan deviation derived from data sets of 6 days, 26 days, 3 days, 4 days, and 10 days. Phase steps removed.

Frequency reproducibility between data sets: 2 x 10^{-13}

Physics Package Power Consumption = 435 mW

Physics Package Size = 68 cm^3





Summary

- Need to miniaturize and integrate many technologies
  - Ion trap, vacuum package, and micro Yb source
  - Light sources, local oscillator, and control electronics
- Developed a clock prototype using the sealed 3 cm^3 vacuum package
  - Long-term stability: 6×10^{-14} @ 1 month
- Completed integrated physics package shows $3 \times 10^{-11} / \sqrt{\tau}$
- Future: Work toward final goals of project.
  - Develop a physics package around the Phase III vacuum package
  - Develop 369 nm laser.