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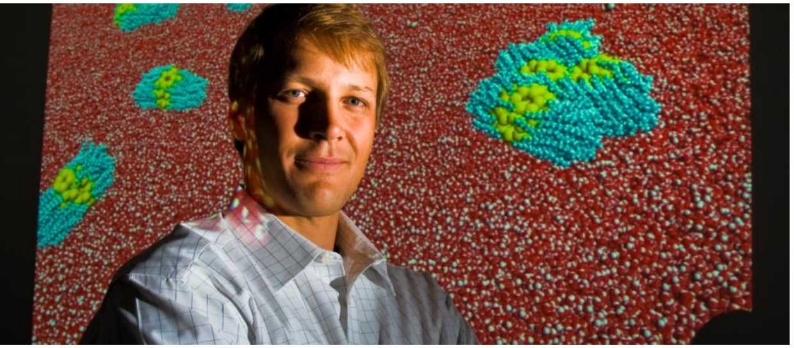

Microelectronics-Based Radiation Detectors Using Compound Semiconductors

G. Pickrell and E. Padilla

U.S. DEPARTMENT OF ENERGY NNSA National Nuclear Security Administration

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Outline

- Introduction – G.W. Pickrell and E. Padilla
- Motivation for new Radiation Detector Project
- Radiation Detector Project Description
- Sandia's Compound Semiconductor Technologies (III-N and III-Sb)
- Summary

Introduction

- **Greg Pickrell**
  - Compound semiconductor device expertise
  - Principal Investigator on this project
  - Semiconductor Material and Device Sciences Group
  - 15+ years in commercial sector
    - Semiconductor crystal growth by Molecular Beam Epitaxy
    - Device design, fabrication, and characterization
    - Technical Management and Product Development
- **Eduardo Padilla**
  - Radiation Science expertise
  - Global Monitoring and Verification Research and Development Group

- Additional team members at Sandia with expertise in semiconductor materials and devices and radiation effects modeling and characterization

Motivation

- Compound semiconductors enable a new class of sensors with improved performance over state of the art technology
  - Significant SWaP (Size, Weight, and Power) reduction with no loss in performance
  - Room temperature operation of compact detectors
  - Improved energy resolution compared to competing technologies
  - Improved capability for sensitive information collection (through design)
  - Widely distributable, compact networked detectors and detector arrays
  - High levels of integration with other technology
- Sandia is ***well-positioned*** to develop this technology
  - Expertise in radiation sciences
  - Expertise in compound semiconductor materials and devices

Reduced SWaP Enables New Potential Applications/Customers

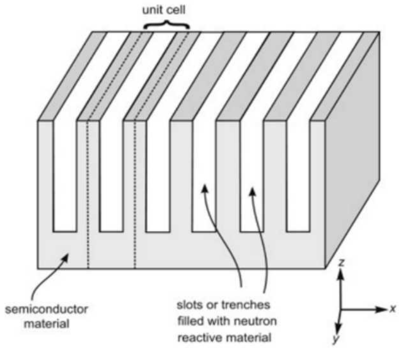
- Global Monitoring and Verification
  - Unattended monitoring
  - Integration with tags/seals
  - Integration on mobile platforms.
- NA-22
  - Portable (reduced SWaP) detectors for pre-event security/screening and first-responders
- DTRA
  - Wearable radiation sensors (reduced SWaP)

- Pixelated arrays of detectors integrated on read-out integrated circuits
- Distributed networks of small, compact detectors

Neutron Detection – Competing Technologies

- He^3 Tubes are the Current State of the Art
  - Large, bulky detectors with pressurized volumes
  - Require high voltages (>1000 V)
  - Lower detection efficiencies

- Indirect Detection using Hybrid Semiconductor Structures
  - Limited efficiency due to volume being partitioned between neutron detection and charged carrier collection
  - Planar Design: Gd on Si (previous Sandia project)
  - Micro-fabricated Design (RadTech Inc.): Etched structures into semiconductors and fill with neutron detecting materials (Domino)



- Direct Detection using h-BN
  - Same material used for neutron detection and charged carrier collection (high efficiency).
  - No complicated micro-fabrication processes needed.

Previous Work – BN Growth

- Growth of thin BN layers for optoelectronic applications
  - Previous Sandia project
  - Material growth parameter space explored
- Demonstration of BN neutron detectors at Texas Tech. University (using B^{10})
  - Professor H.X. Jiang’s group
  - Grows and fabricates N-based devices including BN
  - Grown using same MOCVD growth method with various precursor gases
  - Demonstrated moderated neutron detection efficiencies ~ 50% for film thickness ~ 40 µm

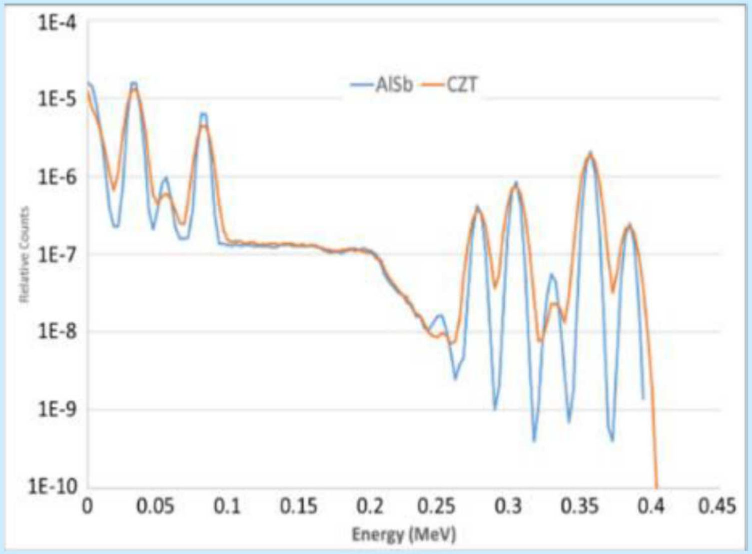
Gamma Detection – Competing Technologies

- Cryogenically-Cooled Ge Detectors are the Gold Standard
  - Require bulky cryogenic cooling and complicated electronics making it unusable for certain applications.
  - AlSb promises room temperature operation with reduced SWaP.

- Cadmium Zinc Telluride (CZT)
  - Difficult growth – Only a few high quality sources.
  - H3D Inc. Polaris product suite uses array of small area CZT crystals.
  - ≤1.1% energy resolution at 662 keV
  - AlSb promises better energy resolution than CZT .
  - MBE growth method promises large area wafers with high quality crystal growth (ultra-high vacuum, high purity sources)

Simulated ^{133}Ba spectra for CZT and AlSb 1cm^2 devices

➡*AlSb offers 40% better resolution*



AlSb – Pioneering Work

- Previous attempts to grow AlSb for gamma detectors used bulk crystal growth method (~10 years ago)
  - Limited size for single domain growth (polycrystalline)
  - High impurity concentrations for C, Si, O, S
  - High defect concentrations (primarily vacancies and interstitials)
  - Low resistivity films with non-reproducible results
  - Required high temperature anneals to get better quality material
  - Oxidation in atmospheric environment

- MBE growth method uses layer by layer growth in UHV (clean) environment using ultra-high purity source material
  - Previously demonstrated high quality, high resistivity material (thin films)
  - Low impurity concentrations
  - Large area, single crystal material with excellent uniformity
  - UHV operation prevents oxidation

Compound Semiconductor Technologies

I. **III-N Materials and Devices**

II. **III-Sb Materials and Devices**

III-N Materials and Devices

Distinctive Properties of
Wide Bandgap (III-N) Semiconductors

Properties of Wide bandgap Semiconductors (AlGaN in particular)

-Direct bandgap, tunable through huge energy range

-High bond energy (~11.5 eV/bond)→ ***radiation hardness***

-High melting point (2200C)→ ***high temperature applications***

-Robust in harsh chemical environments

-Good thermal conductor

-Strong piezoelectric / electro-acoustic properties

Connection to devices

-Emit photons efficiently (visible through deep UV)

-Detect photons (including visible blind) and various particles

-Generate high power efficiently

-Robust to high temperatures, radiation, and chemicals

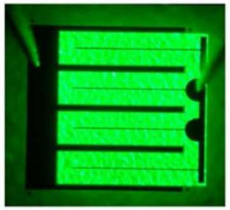
-Sense environment (bio, gases, strain)

-Actuate (micro-mechanical systems)

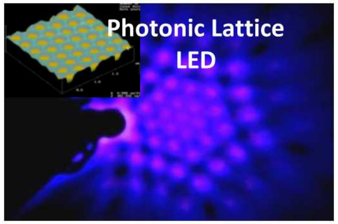
Sandia Wide Bandgap Materials and Device Research (1996-2017)

Visible Optoelectronics (Solid-State Lighting)

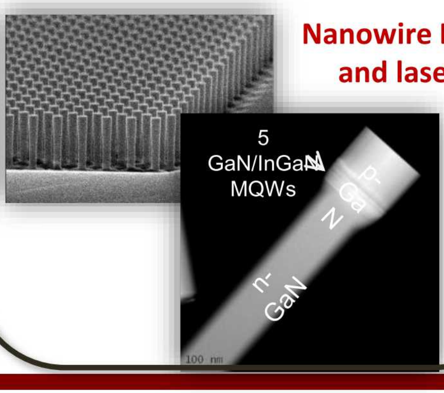
-GC LDRD 2000-2004; DOE EERE 2005-2013, EFRC 2010-2014



Filling the LED "green gap" in LED efficiency

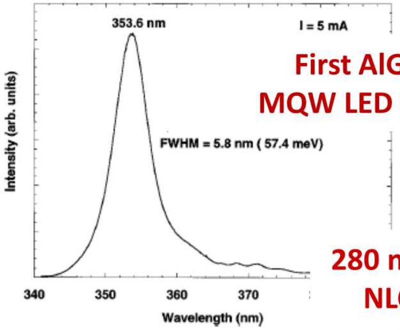


Photonic Lattice LED



Nanowire LEDs and lasers

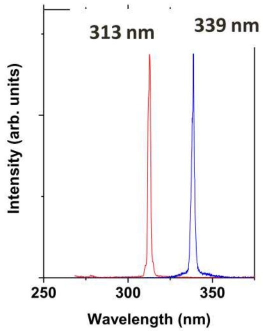
Ultraviolet Optoelectronics

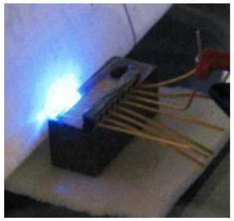


First AlGaN MQW LED (1998)

280 nm LED arrays for NLOS comm. link

Optically pumped Lasing



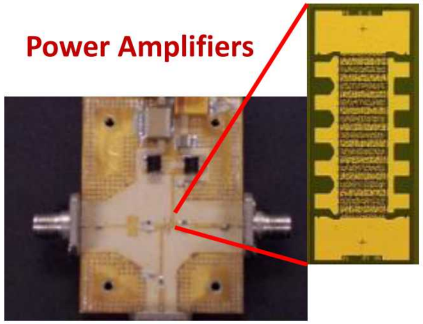


Deep UV LDs ~ 350-360 nm

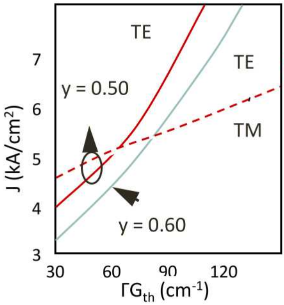
UV Detectors

Power Electronics

Power Amplifiers

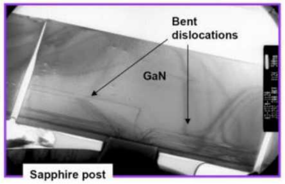


Advanced Modeling and Characterization

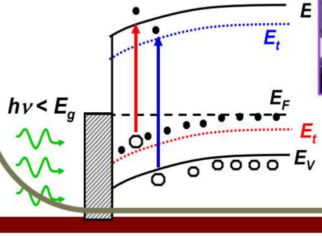


Gain modeling/many-body physics of of nitride lasers

Transmission electron microscopy



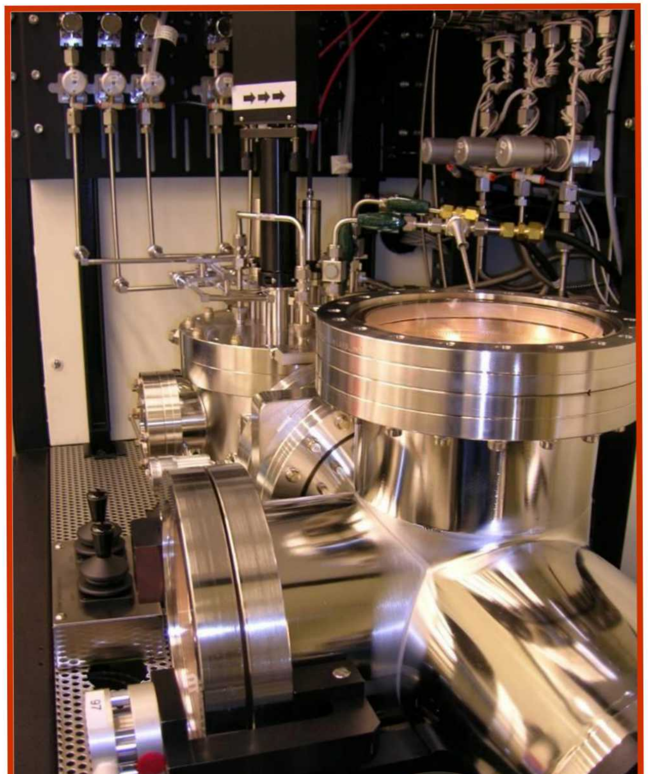
Defect Spectroscopy



Epitaxial Growth of Nitride Semiconductors by Metal-organic Vapor Phase Epitaxy at Sandia

Sandia National Laboratories

Veeco D-125 Rotating Disk MOVPE System

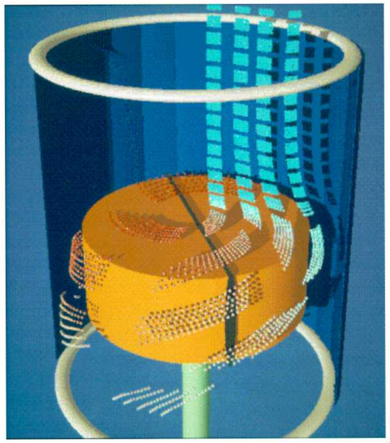


AlGaN Growth

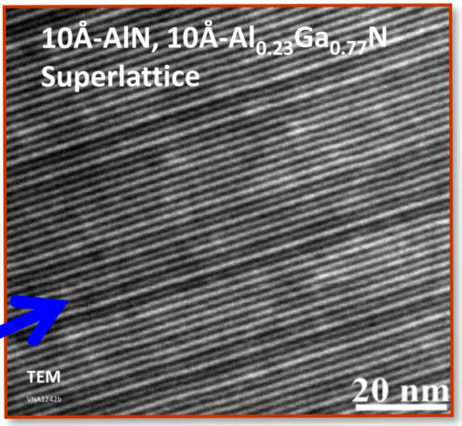
Sources: TMGa, TMAl, NH_3
Temp: 1035-1100°C
Pressure: 75-300 torr
Growth rates: 0.3-1 mm/hour

Dopants:

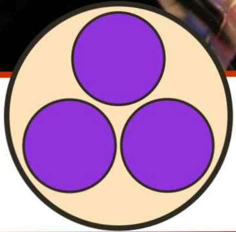
n-type: SiH_4
p-type: Cp_2Mg



Rotation ~ 1500 rpm



3 two-inch wafers



3 reactors dedicated to WBG

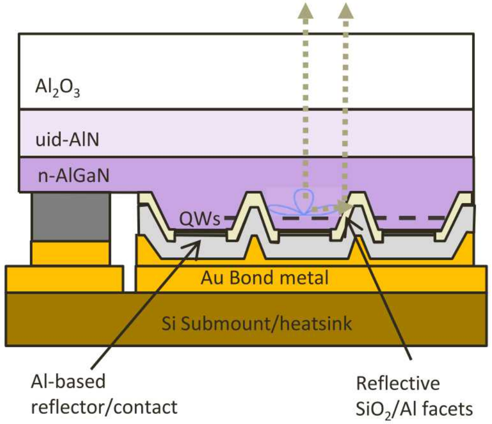
Highly reproducible
Ultra-thin layers possible

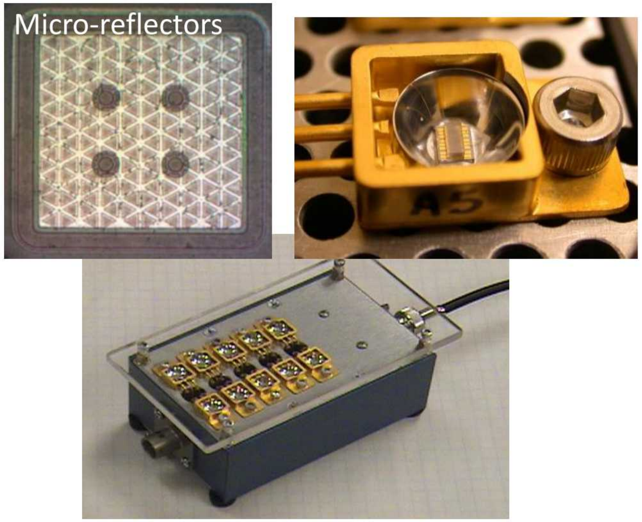
Andy Allerman (01876)

MESA fab facilities for device processing

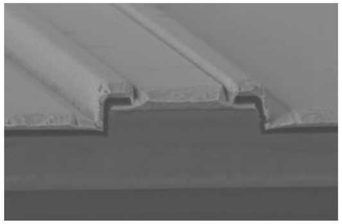
Examples of Processed WBG devices:

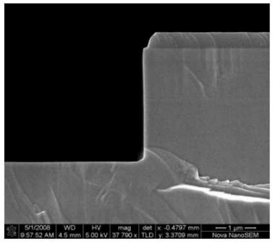
Flip-chip LED arrays

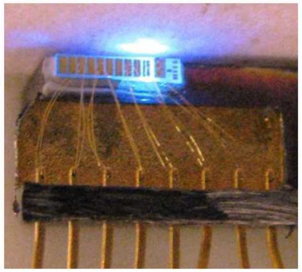




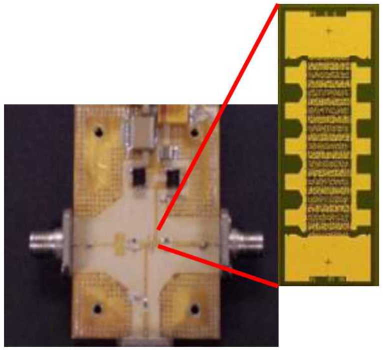
Ridge Waveguide (RWG) Laser structure





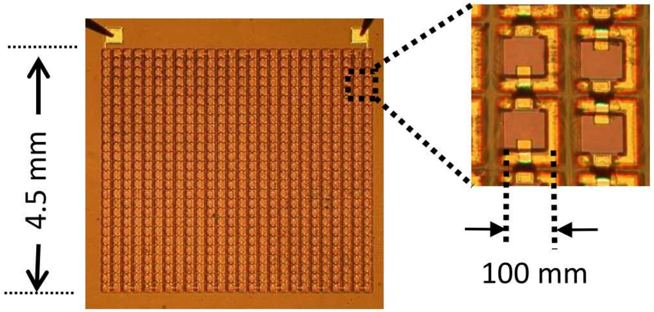


AlGaN/GaN High Electron Mobility Transistors (HEMTs) and power diodes



A. Baca (5266)

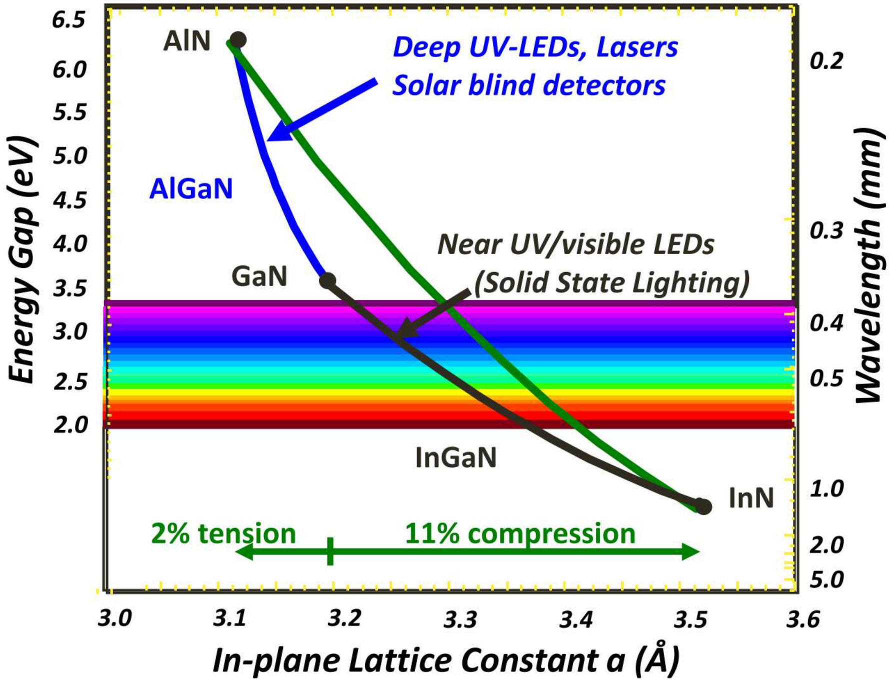
676 element array photovoltaic array



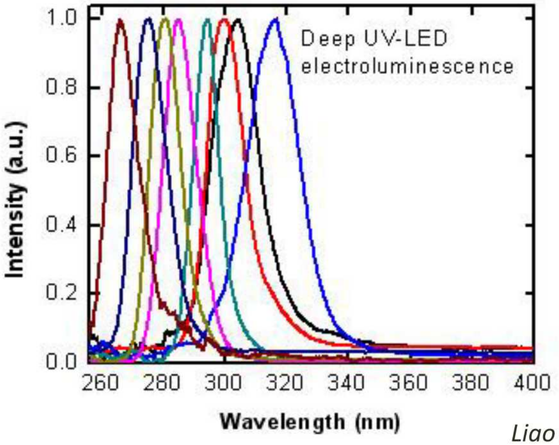
Distinctive Properties of AlGaN Optoelectronics

- Amazing tunability range!
  → 3.4-6.2 eV, customizable with alloy composition control, QW design

Wide-bandgap nitride semiconductor alloys



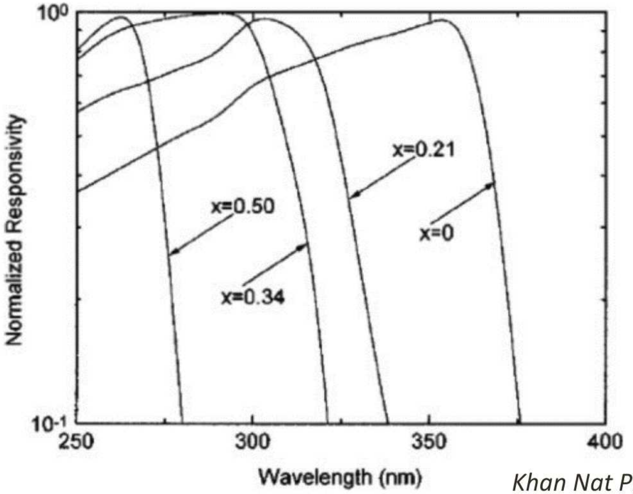
Unique Optical Sources



Custom, Multi-λ

Liao (BU), APL 2011

Tailorable UV detectors



All "Blind" to visible light

Khan Nat Photonics, 2005

Wide-Bandgap Semiconductors for Power Electronics

Decreasing TRL ➡

Property	Si	GaAs	4H-SiC	GaN	AlN
Bandgap (eV)	1.1	1.43	3.3	3.4	**6.2**
Critical Electric Field (MV/cm)	0.3	0.4	2.0	**3.3**	**11.7**
Saturated electron velocity (x10^7 cm/sec)	1.0	1.0	2.0	**2.5**	1.4
Thermal conductivity (W/cm·K)	1.5	0.5	**4.5**	4.0	3.4

Wide-Bandgap Semiconductors

Larger bandgap
➡ ***Higher temperature***

Larger critical E field
➡ ***Higher voltage***

Higher sat. electron vel.
➡ ***Higher switching speed***

Higher thermal conductivity
➡ ***High power***

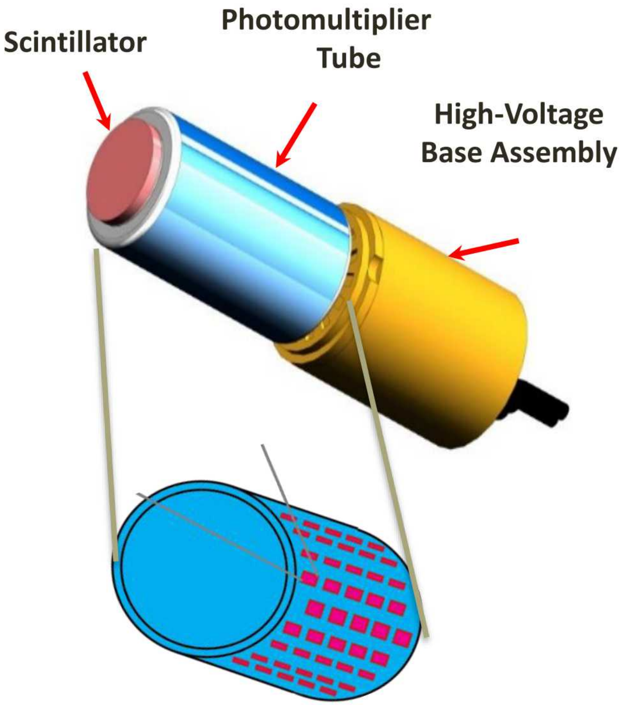
Radiation tolerant
➡ ***Stable devices***

AlN-GaN-InN heterostructures
➡ ***Engineered properties***

➡ ***WBGs enable applications NOT possible in Si***

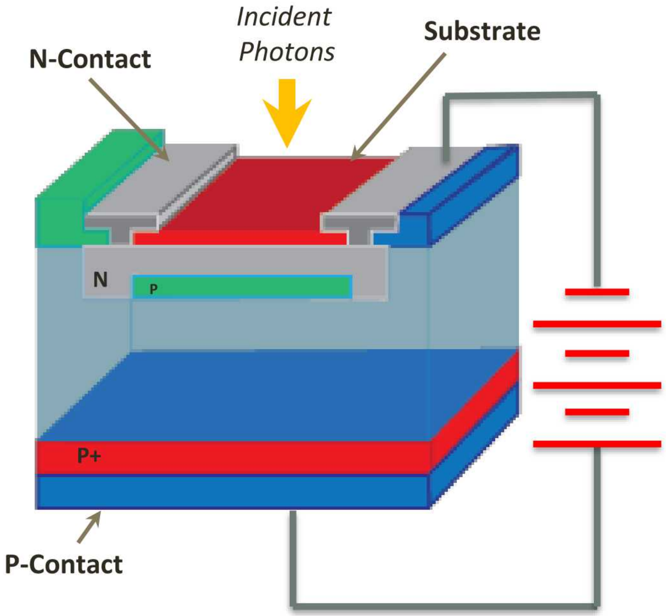
Application: Photodetectors for Scintillators

- Current Nuclear Detector Systems utilize Photomultiplier Tubes (PMT) for photon detection
- PMT Limitations
  - Large, require high voltage
  - Color-Blind, non-pixilated, wavelength limited
- Scintillator Materials must match PMT spectral efficiency
  - Limits selection of possible materials systems for Scintillator
- Microelectronic detectors offer lower power, smaller size, wavelength tailoring, advanced designs (pixelation)

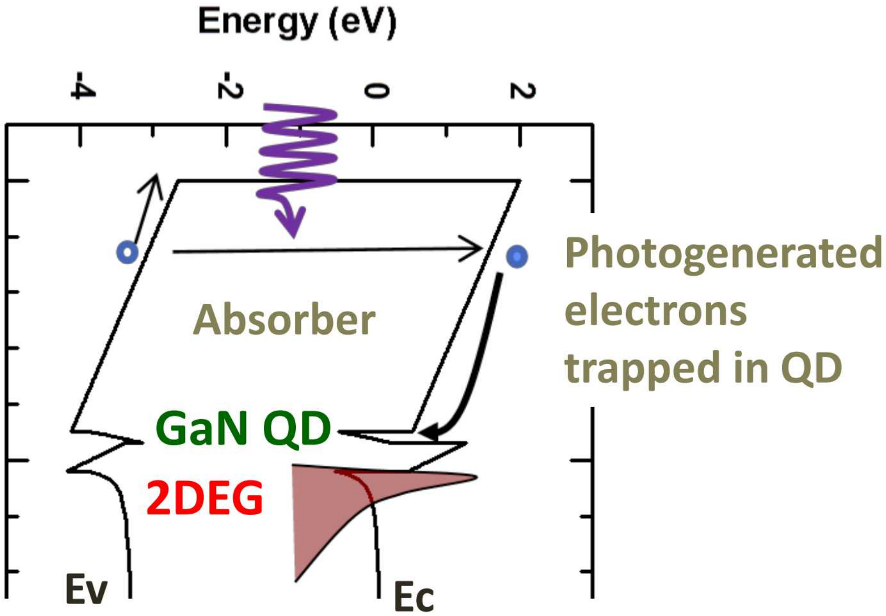


Replace PMTs with pixelated arrays of wavelength-tailored microelectronic detectors

Two Device Structures



Energy Band Diagram



- Avalanche Photo Diode (APD) Structures
- Detection Mechanism
  - Light (above bandgap) creates electron-hole pairs
  - High fields enable avalanche gain (high gain)
  - Wavelength response tailorable by design

- Heterojunction Photo-Transistors (HPTs)
  - AlGaN-based, quantum dot, floating gate high-electron mobility transistor (HEMT)
  - Current program under Andy Armstrong
  - Low-voltage, low-noise, detection mechanisms
  - High gain possible for single photon detection
  - Room-temperature operation

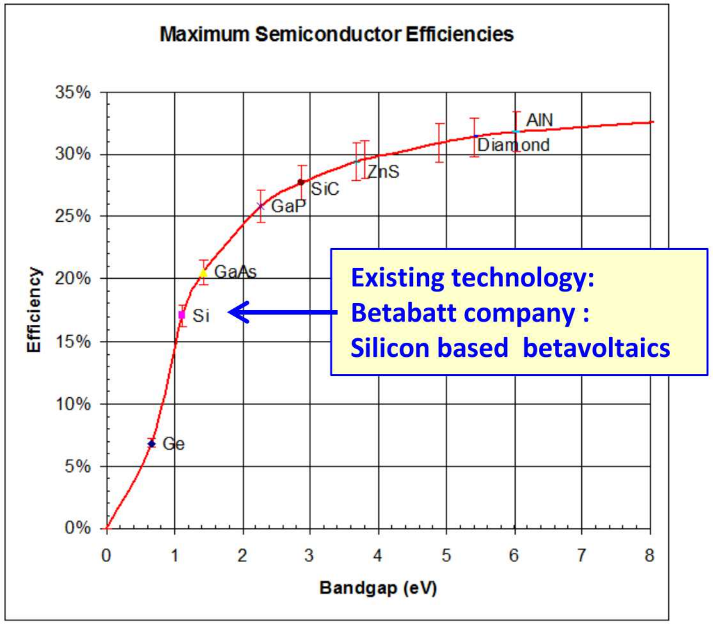
Application: Betavoltaics

→ Very long lived, compact power sources

Table 1: Radioisotope sources for a betavoltaic converter.

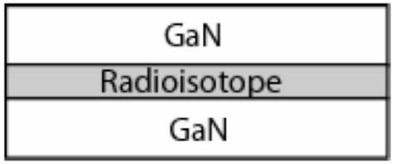
Element	Particle	Half Life	Activity (GBq/g)	Decay energy max	Decay Energy average
Tritium, ^3H	Beta	12.3 years	357,000	18.6 keV	5.7 keV
^{63}Ni	Beta	100 years	2,190	67 keV	17 keV
$^{90}Sr/^{90}Y$	Beta	28.6 years	5,050	546 keV 2.283 keV	196 keV 935 keV

Efficiency directly correlated with bandgap



Existing technology:
Betabatt company :
Silicon based betavoltaics

BetaBatt presentation



(a)

Doolittle paper 2005

Model predictions

Material	V_{oc} (V)	$I_{collected}$ (μA)	FF	Efficiency
Si	0.54	3.2	81	13.7%
GaN	2.3	1.1	94	25.4%
$Al_{0.7}Ga_{0.3}N$	4.9	0.6	97	27.4%

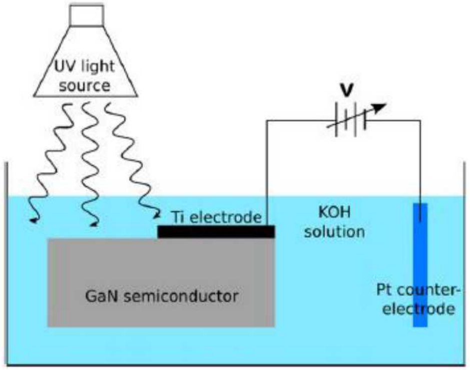
→Major drawback: low powers (< mW)
→ High surface area solutions? (porous GaN, nanorods)

Application: MEMS/NEMS for Harsh Environments

<u>Challenge</u>: processing of complex 3D structures given extreme chemical robustness

Recent progress: 3D processing using photoelectrochemical etching

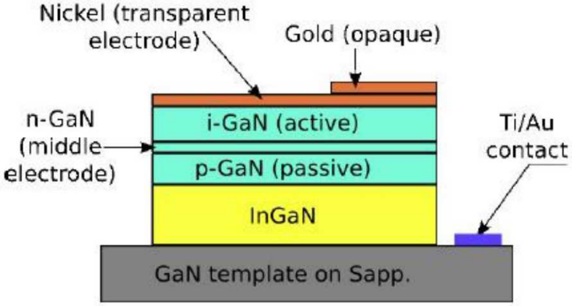
PEC Etching

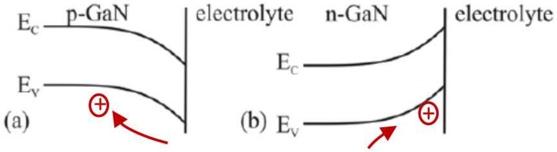


- UV light generates holes
- Allows oxidation of surfaces and subsequent dissolution of oxide

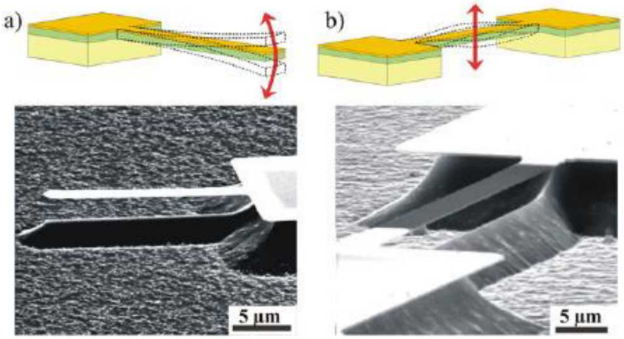
Etching selectivity via:

- Bandgap
- Doping





AlN structures



- AlN piezoelectric coefficients ~100x smaller than best ceramics like PZT

\+ AlN maintains piezoelectric properties up to ~1300°C (vs. 200-300°C for PZT)

\+ AlGaN/GaN dimension control (epitaxy) and integration with electronics

Ramesh et al., Smart Mater. Struct. 2012

Cimalla et al., J. Phys. D, 2007

Application: Strain/Pressure Sensors for Harsh Environments

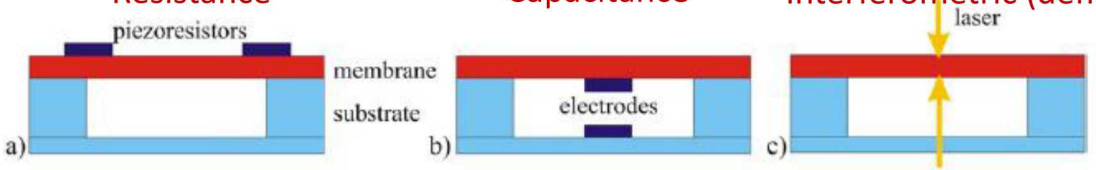
Examples of measurement approaches

Resistance

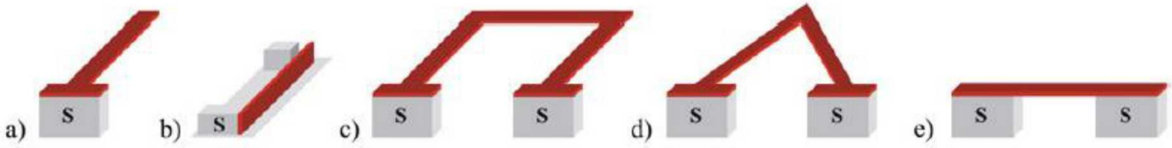
Capacitance

Interferometric (deflection)

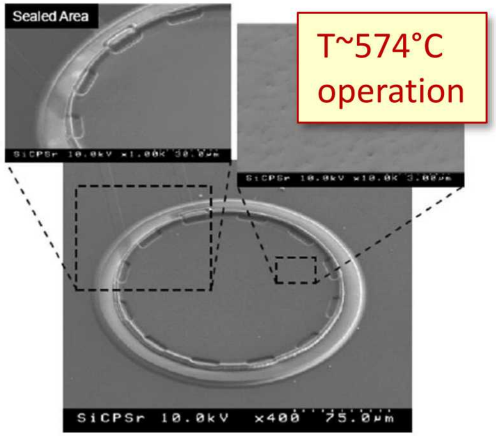
Membranes:



Beams:

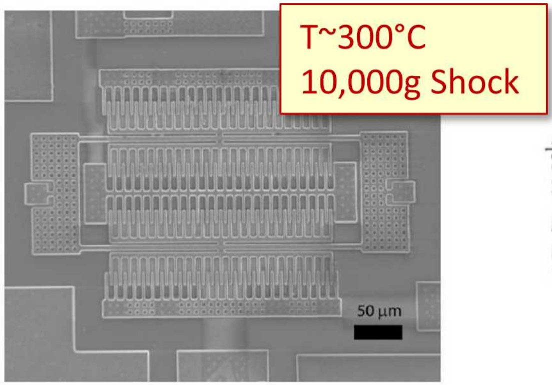


SiC Strain Sensors



T~574°C operation

Fig. 4. SEM of the diaphragm surface of a capacitive SiC pressure sensor that has been operated in pressures up to 4.8 MPa and temperatures up to 574 °C [41].

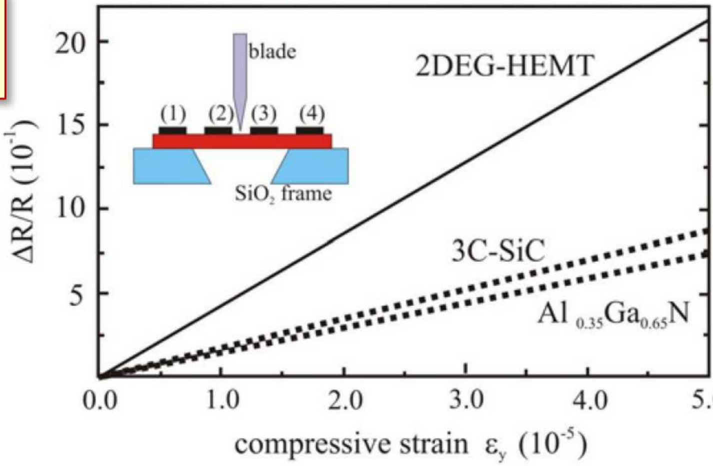


T~300°C 10,000g Shock

Fig. 5. SEM image of a resonant SiC strain sensor that utilizes a balanced double-ended tuning fork design. This sensor has operated at 300 °C and survived shocks of 10 000 g [5].

Senesky et al. IEEE sensors, 2009

AlGaN/GaN: 2DEG improves sensitivity of pressure sensors

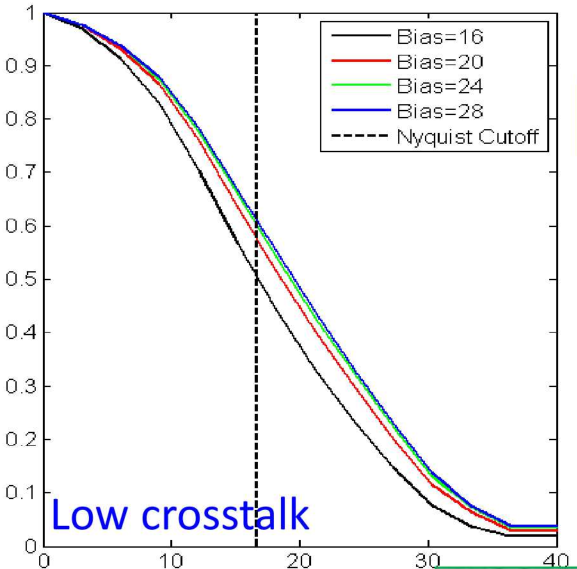


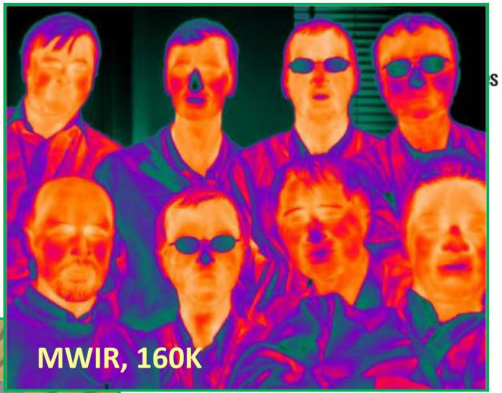
Cimalla et al., J. Phys. D, 2007

III-Sb Materials and Devices

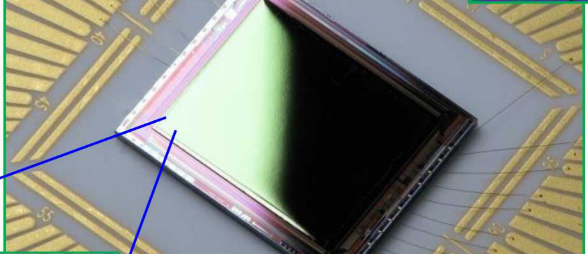
Sandia IR FPA Capabilities

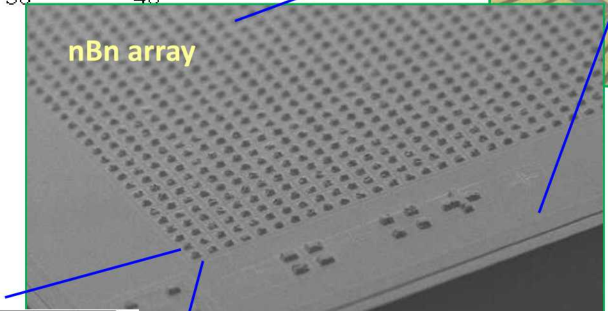
TRL-2 in 2007 → TRL-5 in 2017



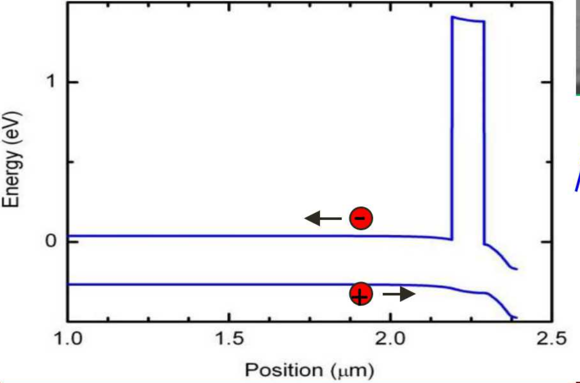


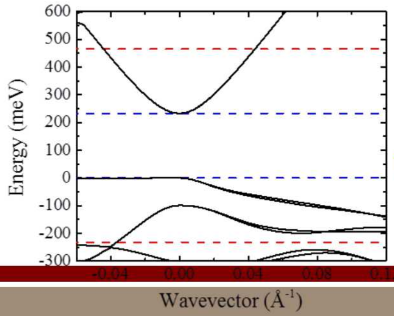
nBn FPA



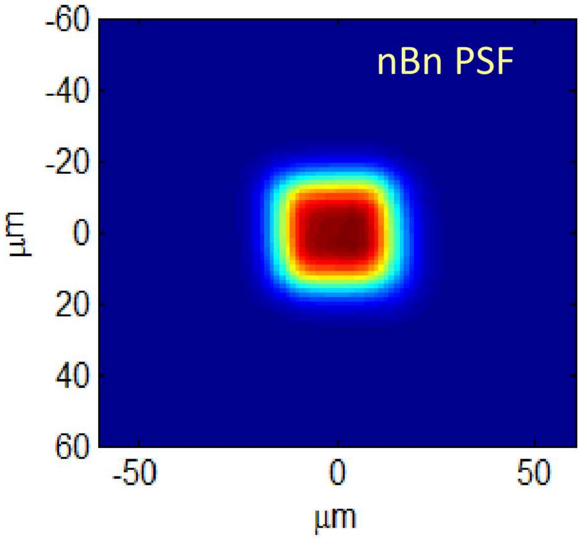


nBn band diagram

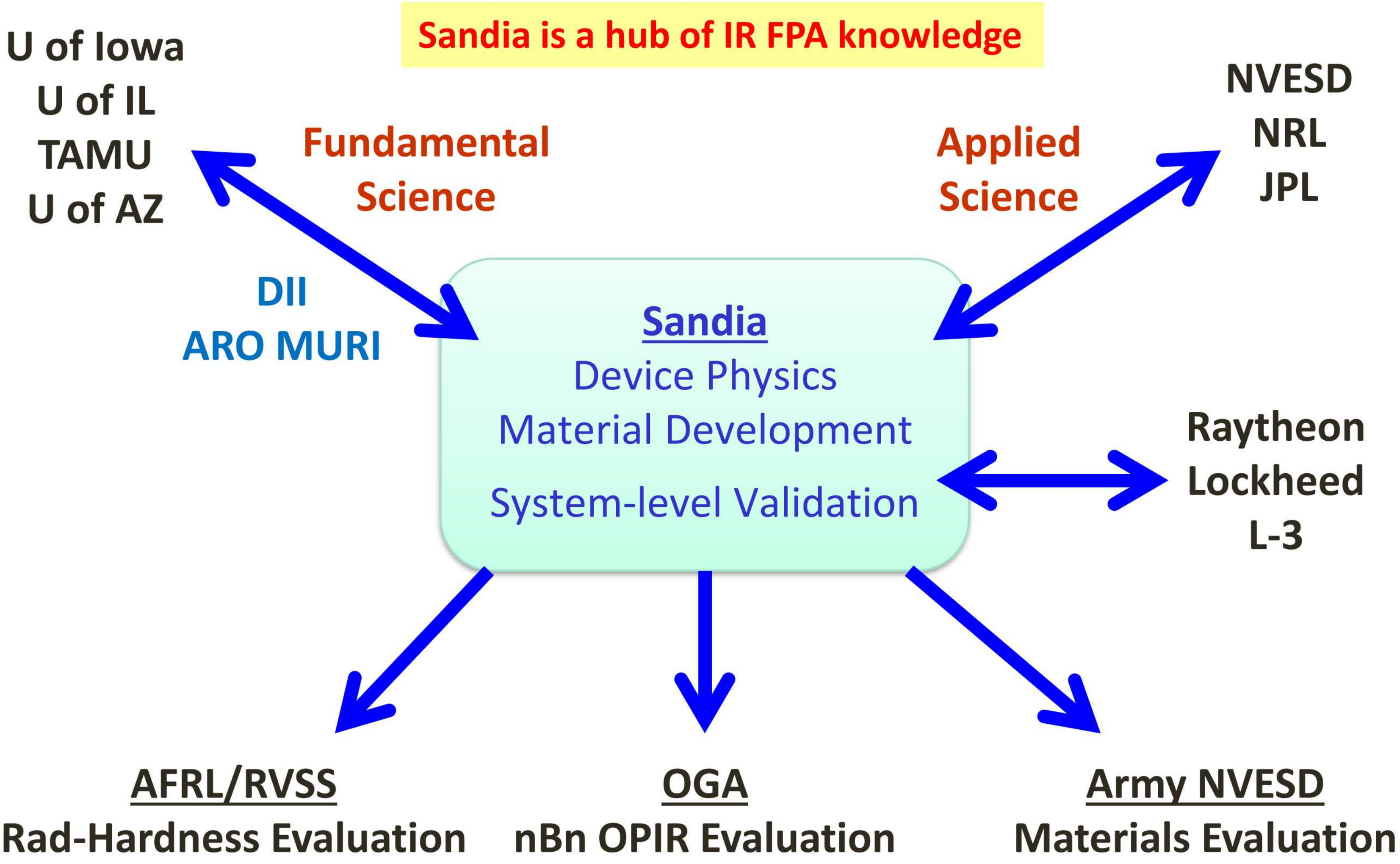




T2SL band structure



Success Through Collaborations



Sandia is a hub of IR FPA knowledge

U of Iowa
U of IL
TAMU
U of AZ

Fundamental
Science

DII
ARO MURI

Applied
Science

NVESD
NRL
JPL

Sandia
Device Physics
Material Development
System-level Validation

Raytheon
Lockheed
L-3

AFRL/RVSS
Rad-Hardness Evaluation

OGA
nBn OPIR Evaluation

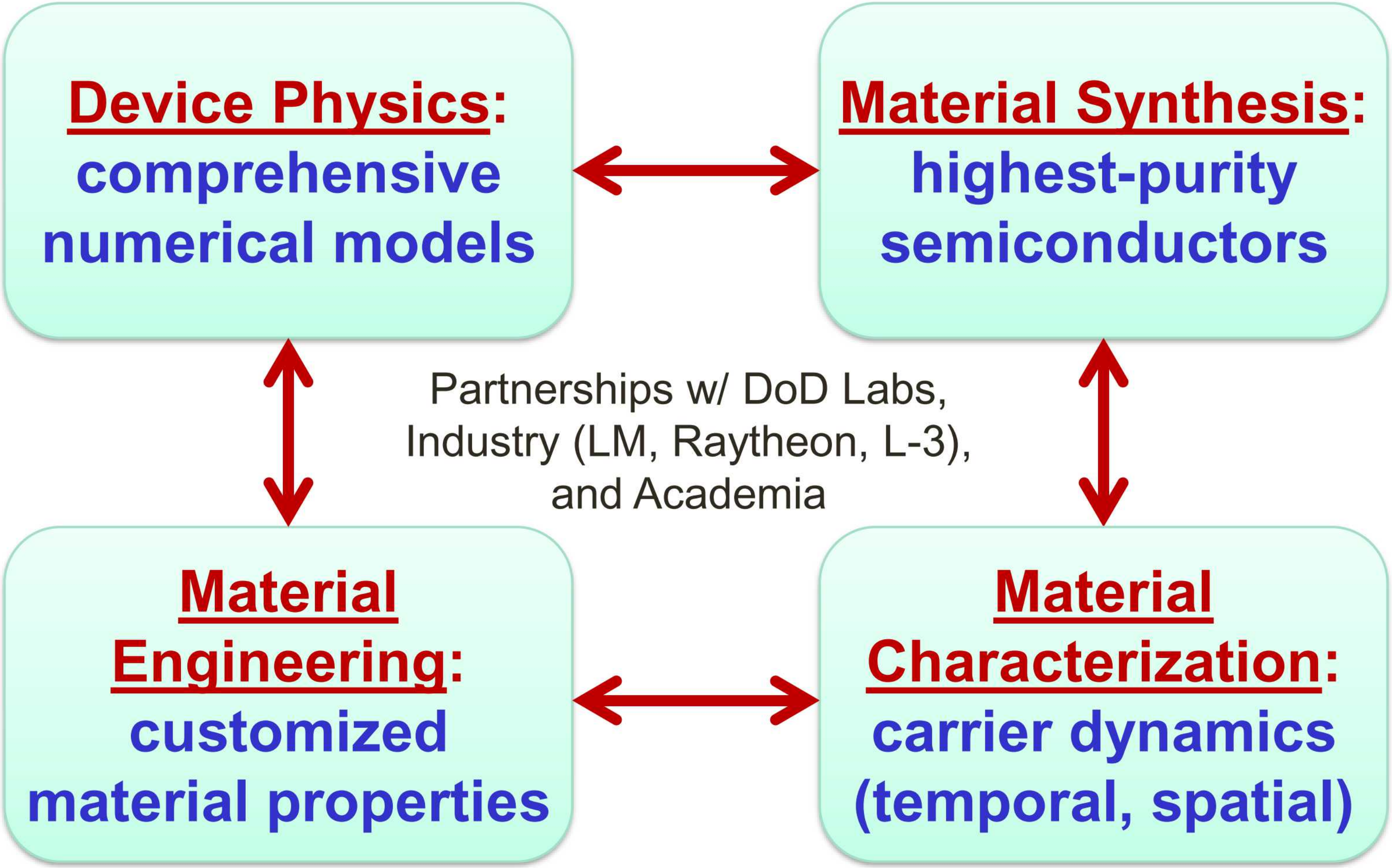
Army NVESD
Materials Evaluation

Similarities / Difference in Materials Requirements

	IR FPA	Gamma FPA
High responsivity (signal)	Long carrier diffusion length (μ,τ)	Long carrier drift length (μ_{sat},τ)
Low dark current (noise)	Low $N_d \cdot \tau$	Low N_d , τ
Material	InAsSb	AlSb
Bandgap	~ 200 meV	2.4 eV
Absorber Thickness	5 – 10 µm	>100 µm
Operating Temperature	100K – 150K	Room T

Techniques and capabilities established for IR FPAs are very relevant and available for gamma FPA R&D.

Sandia’s Competencies in IR Materials



Device Physics: comprehensive numerical models

Material Synthesis: highest-purity semiconductors

Partnerships w/ DoD Labs, Industry (LM, Raytheon, L-3), and Academia

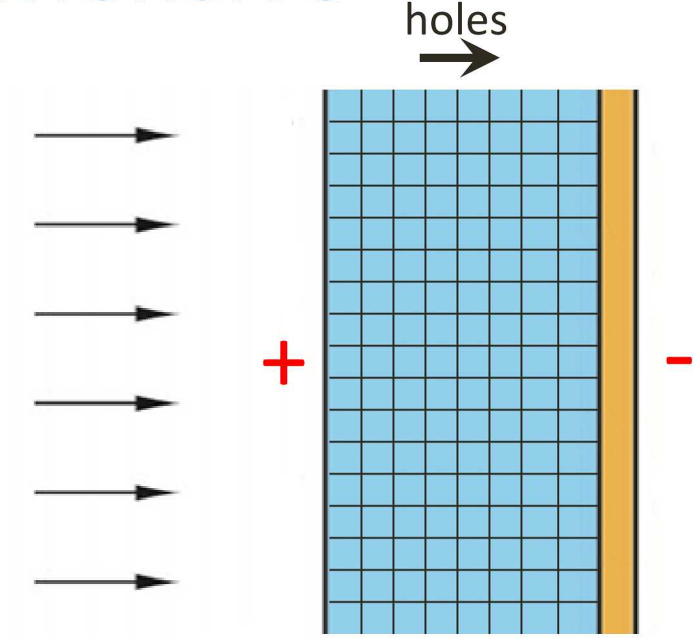
Material Engineering: customized material properties

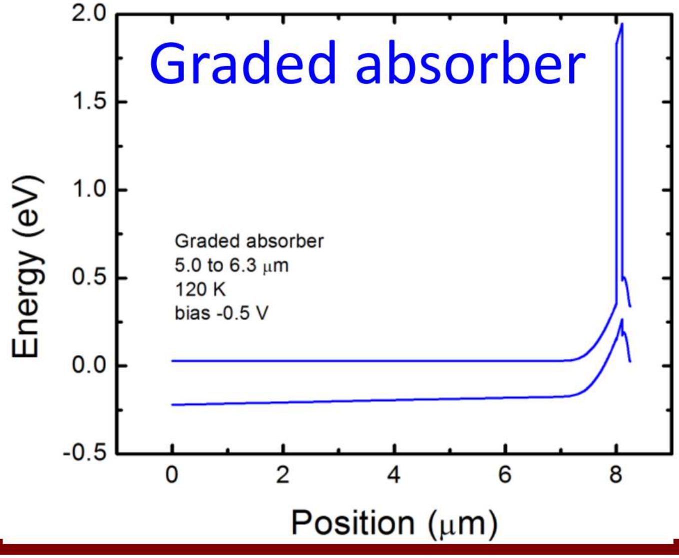
Material Characterization: carrier dynamics (temporal, spatial)

Device Physics: Comprehensive Numerical Models

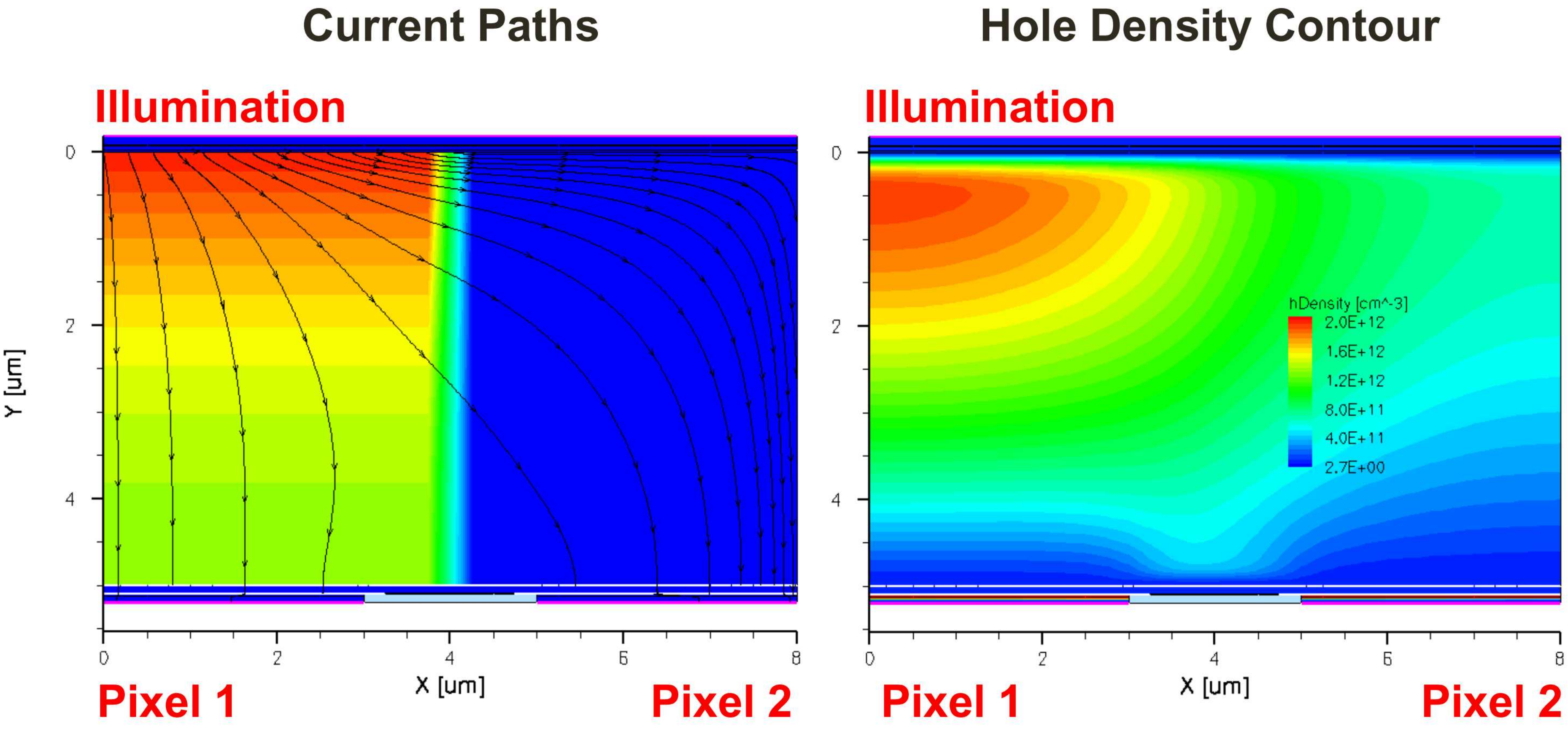
- Sentaurus commercial simulator
- 1-D or 2-D meshes
- Effective medium approximation for T2SL
- Solves Poisson & continuity equations
  - Electrostatic potential
  - Quasi-Fermi levels
  - Carrier densities
  - Current densities (e^- and h^+)

at each point of mesh





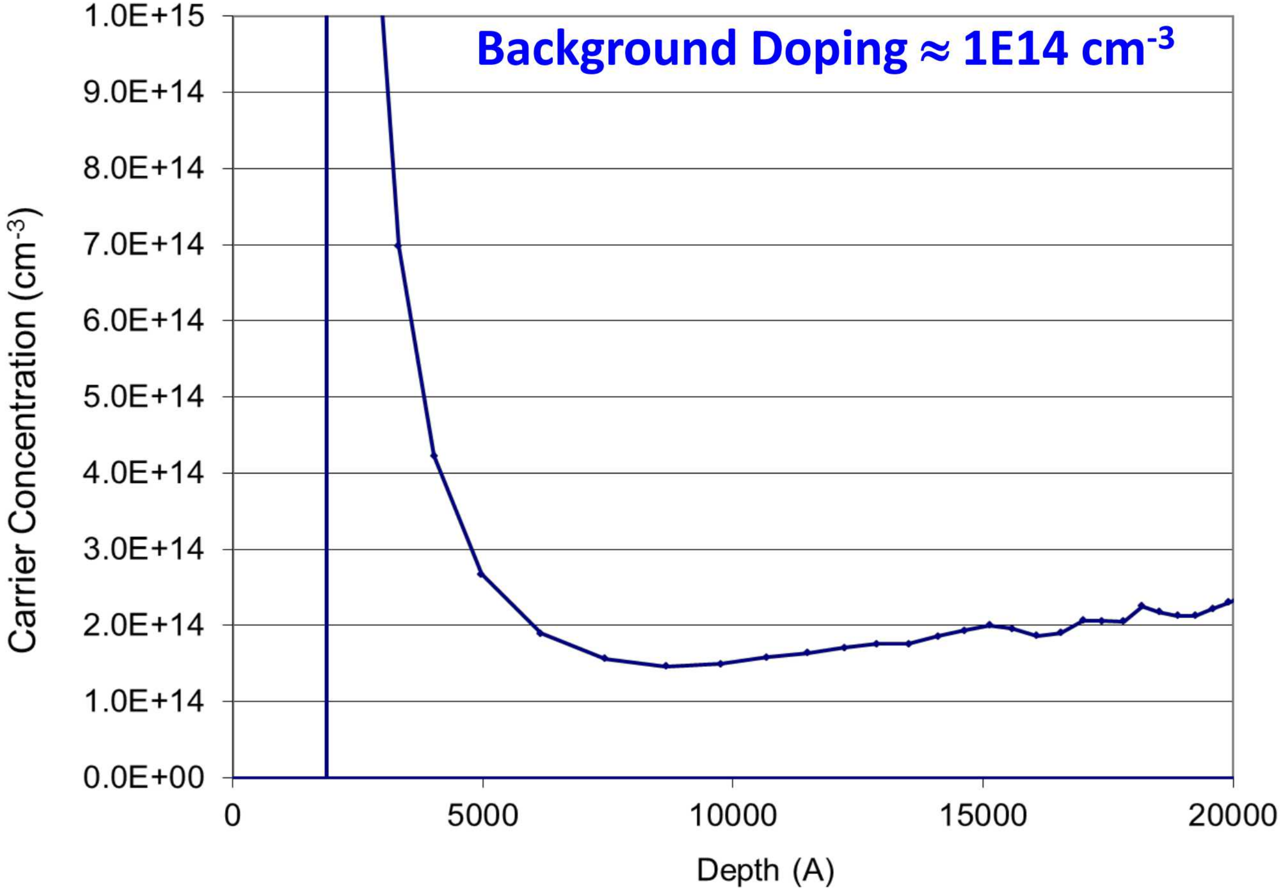
2-D Numerical Device Simulation Capability



Useful for analyzing 2-D effects: crosstalk, optical concentrator.

Material Synthesis: Highest-Purity Semiconductors

- Absorber doping density determined from nBn photodetectors by C-V method, Ɛ=13.2
- Material purity (background doping concentration) 10x lower than others

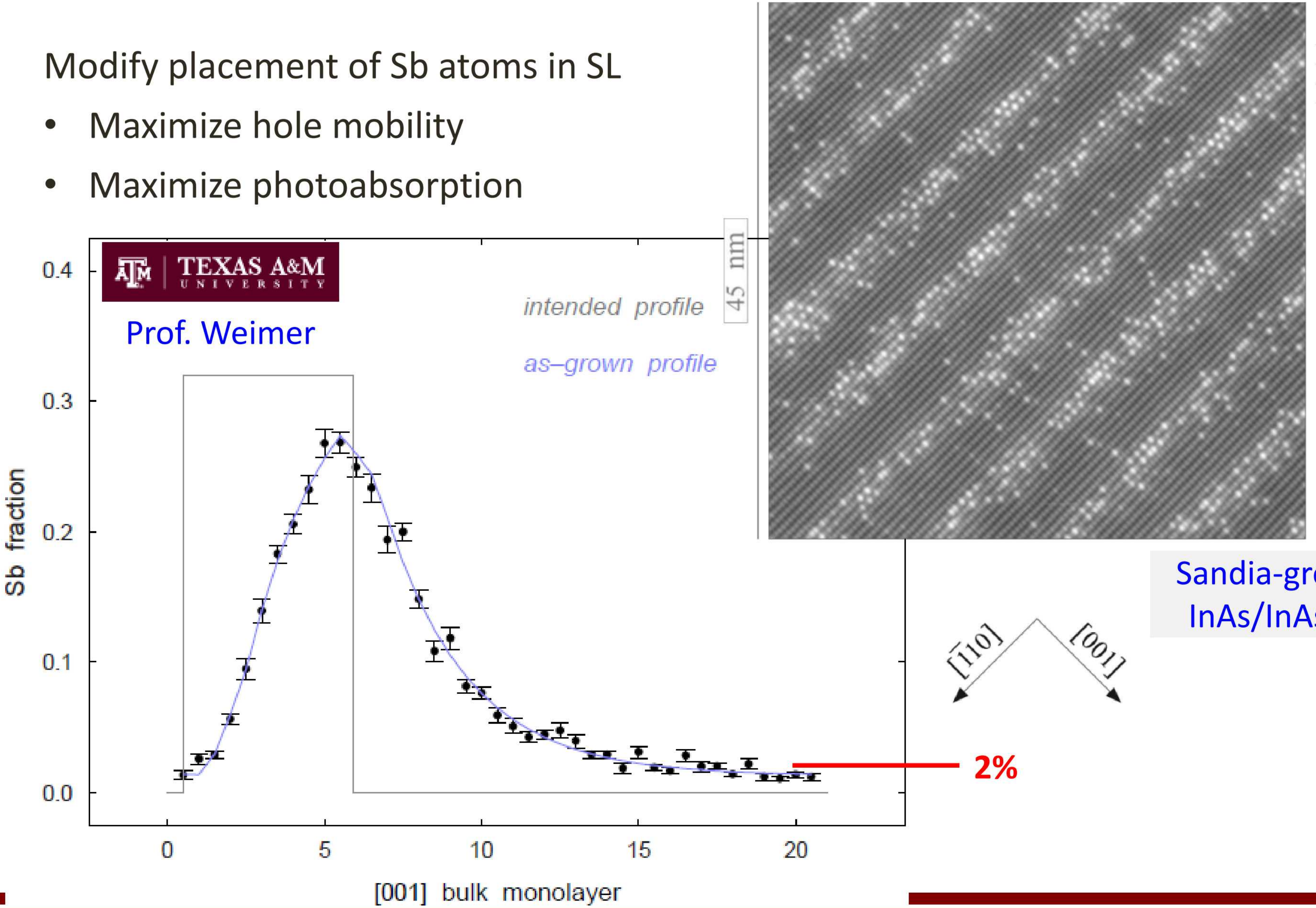


Sb Profile in InAs/InAsSb

Sandia National Laboratories

Modify placement of Sb atoms in SL

- Maximize hole mobility
- Maximize photoabsorption



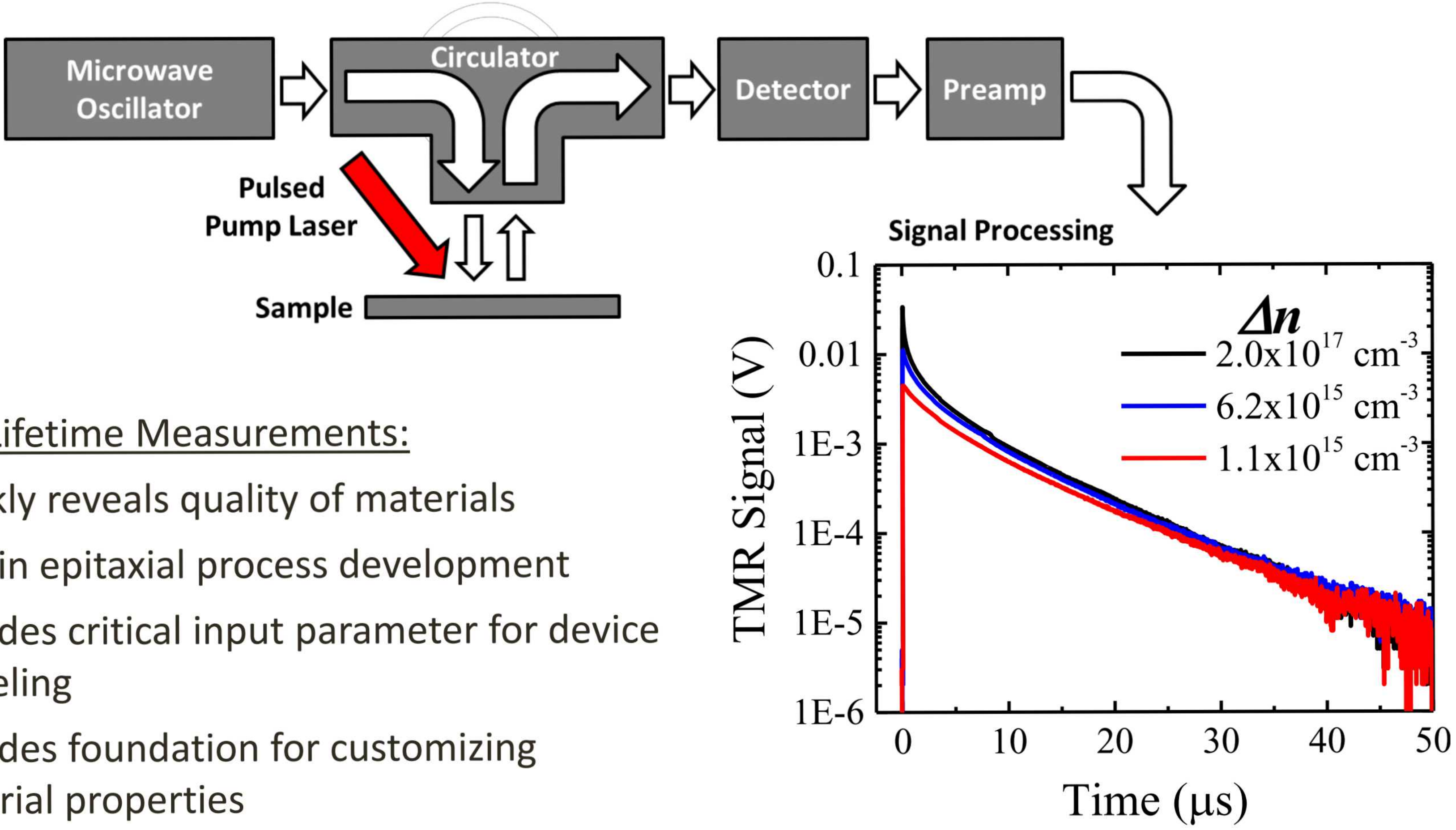
TEXAS A&M UNIVERSITY

Prof. Weimer

Sandia-grown InAs/InAsSb

Material Characterization: Carrier Lifetime

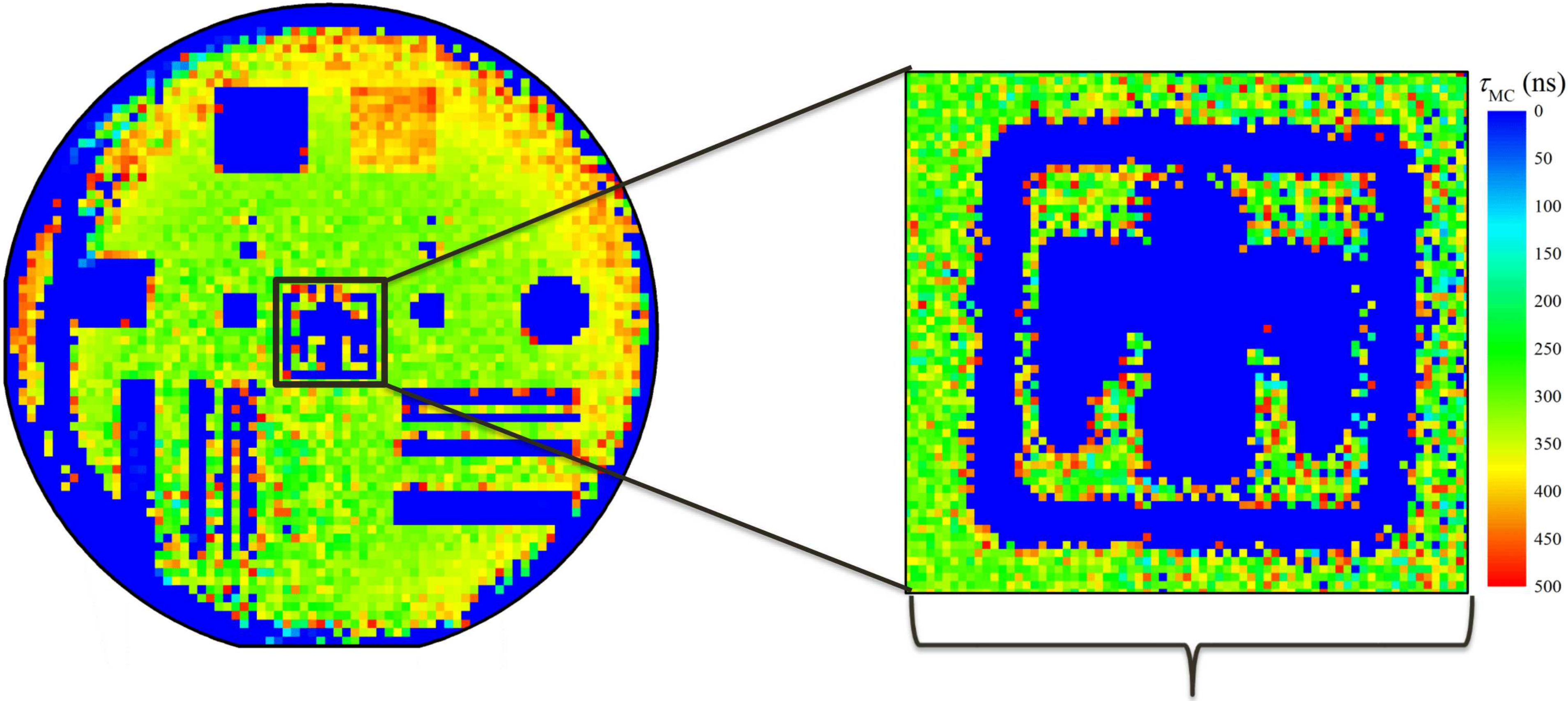
Time-Resolved Microwave Reflectance



Carrier Lifetime Measurements:

- Quickly reveals quality of materials
- Vital in epitaxial process development
- Provides critical input parameter for device modeling
- Provides foundation for customizing material properties

Wafer-Level Carrier Lifetime Mapping

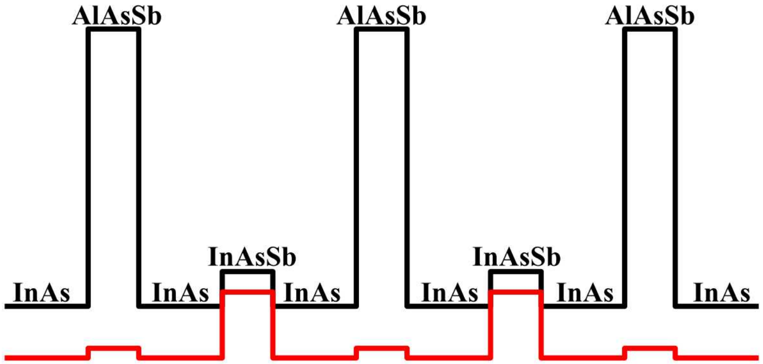


14mm

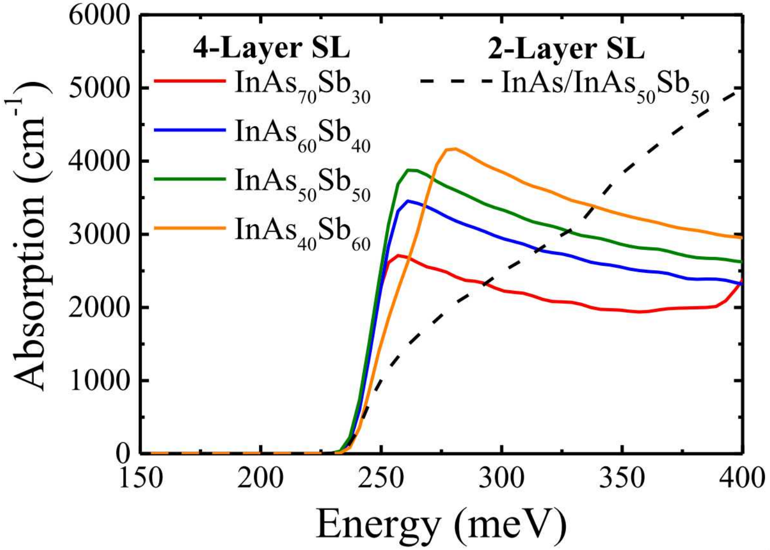
- Temperature = 90 K
- 0.2mm resolution

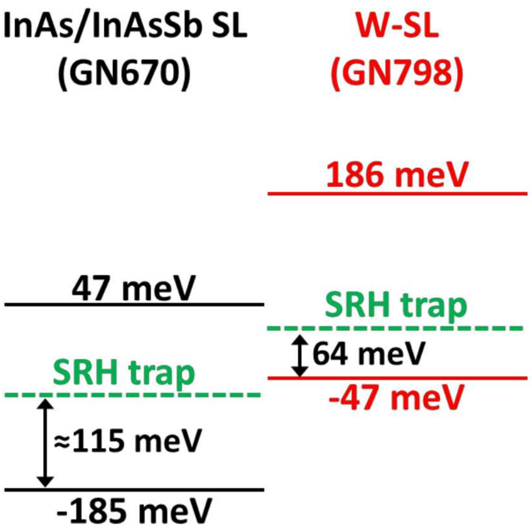
Material Engineering: Modify SRH Energies

- Incorporating additional layer modifies the CB and VB energies
- SRH defect energy moves accordingly



simulation





InAs/InAsSb SL (GN670)

47 meV

SRH trap

≈115 meV

-185 meV

W-SL (GN798)

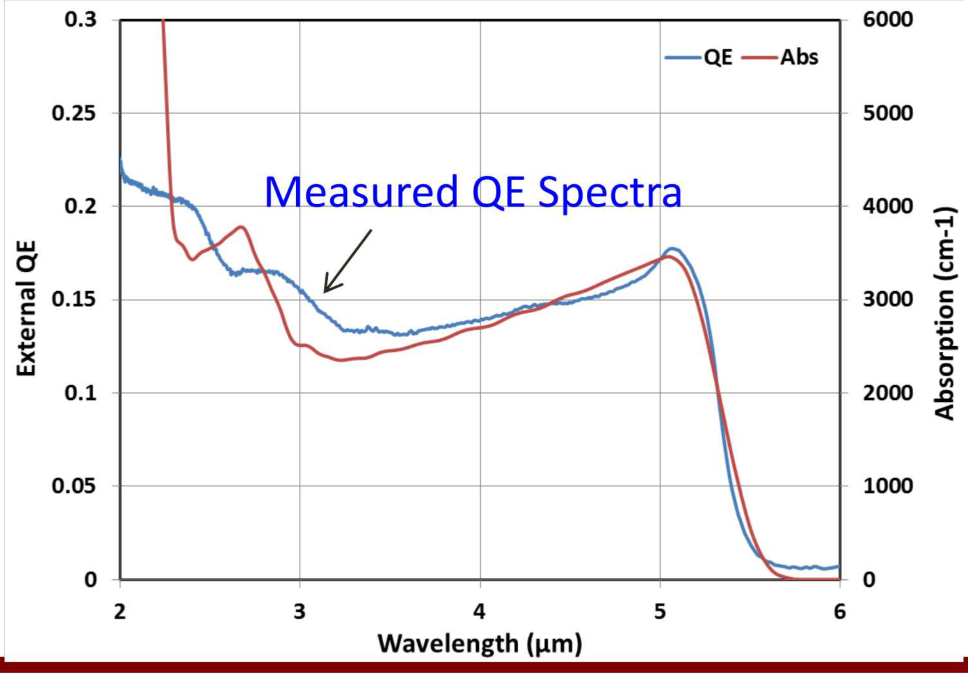
186 meV

SRH trap

64 meV

-47 meV

Modified from NRL design to maximize rad hardness



Summary

- Ongoing project on Microelectronics-based radiation detectors
- Work enables new class of sensors capitalizing on reduced SWaP
- Work leverages expertise in radiation sciences and compound semiconductor materials and devices at Sandia

- Extensive work done in III-N and III-Sb material systems for various applications.
- III-N materials and III-Sb show several possible applications of interest
- III-Sb materials show example of technology maturation at Sandia

- Looking for opportunities to collaborate in this area.