Recent Advances in VLWIR Type II Superlattice Photodiodes

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AFRL Infrared Materials Research Team

- Dr. Gail Brown - Team Leader, Photoresponse studies
- Dr. Frank Szmulowicz - Theoretical Modeling of SL design and optical properties
- Dr. William C. Mitchel - Hall Effect studies (temperature & magnetic field dependence)
- Dr. K. Mahalingam - Cross-sectional TEM Analysis & Modeling
- Dr. Chris Hegde - IR Photoluminescence
- Dr. David Tomich - MBE Growth & X-ray Analysis
- Mr. Larry Grazulis - AFM surface studies, XSTM
- Dr. Heather Haugen - Wafer bonding & X-ray Analysis
- Lt. Tony Cain - Wafer bonding

External Research Partners

InAs/GaSb:

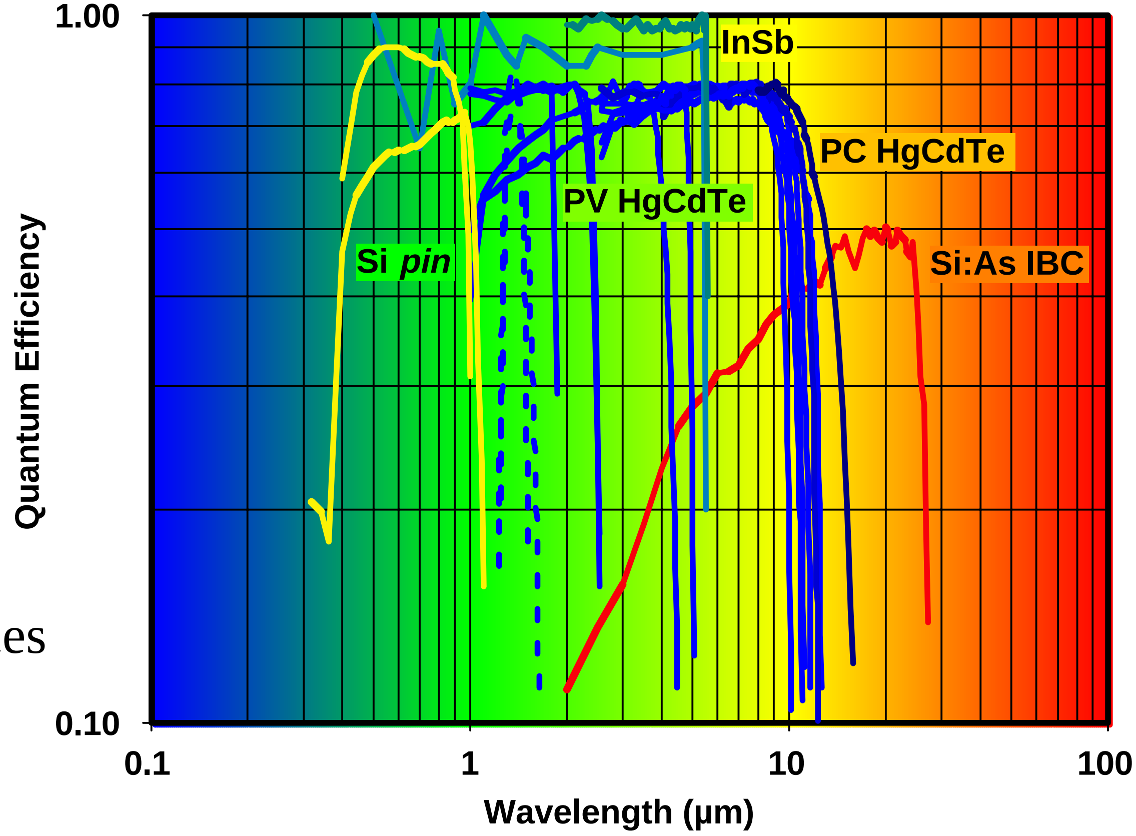
Dr. Manijeh Razeghi, Hooman Mohseni
Center for Quantum Devices, Northwestern University

InAs/$In_{0.23}Ga_{0.77}Sb$:

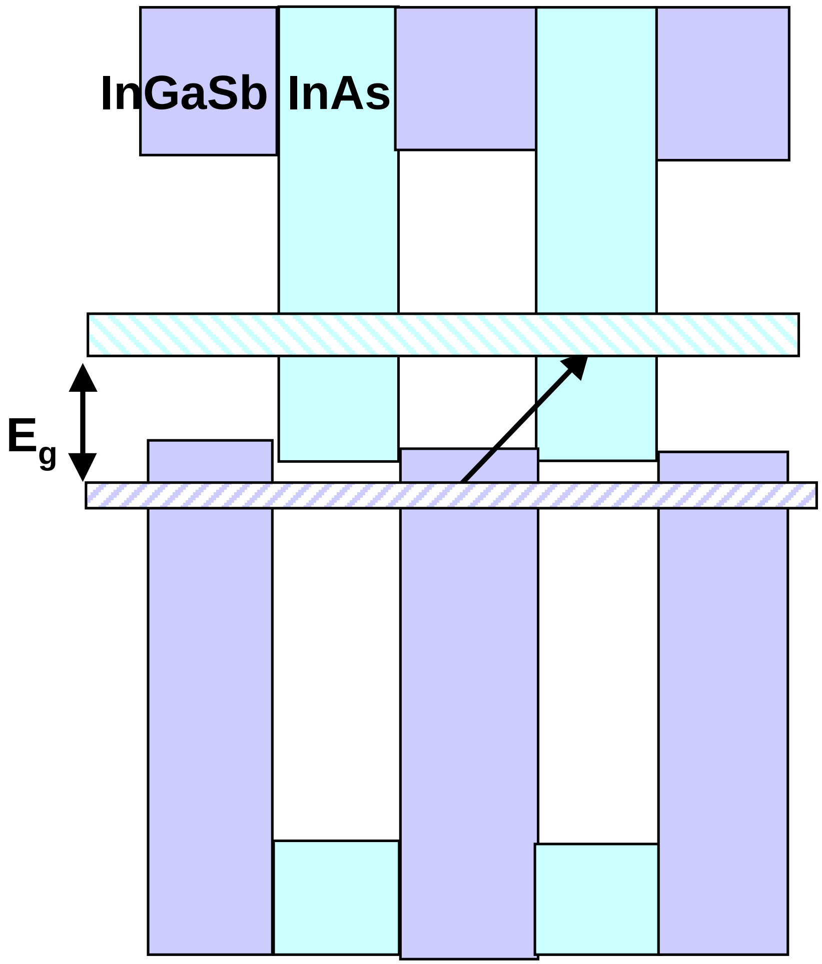
Dr. C.-H. Lin, Dr. J. Johnson, Dr. K. Anselm
Applied Optoelectronics Inc.

Spectral Coverage of Current Infrared Detector Technology

- Visible-Near IR
  - Silicon
  - InSb
- SWIR-MWIR
  - HgCdTe
  - InSb
- LWIR
  - HgCdTe
  - III-V Superlattices
- VLWIR
  - HgCdTe
  - III-V Superlattices
  - Extrinsic silicon



Superlattices for Infrared Detection



Type II Superlattice

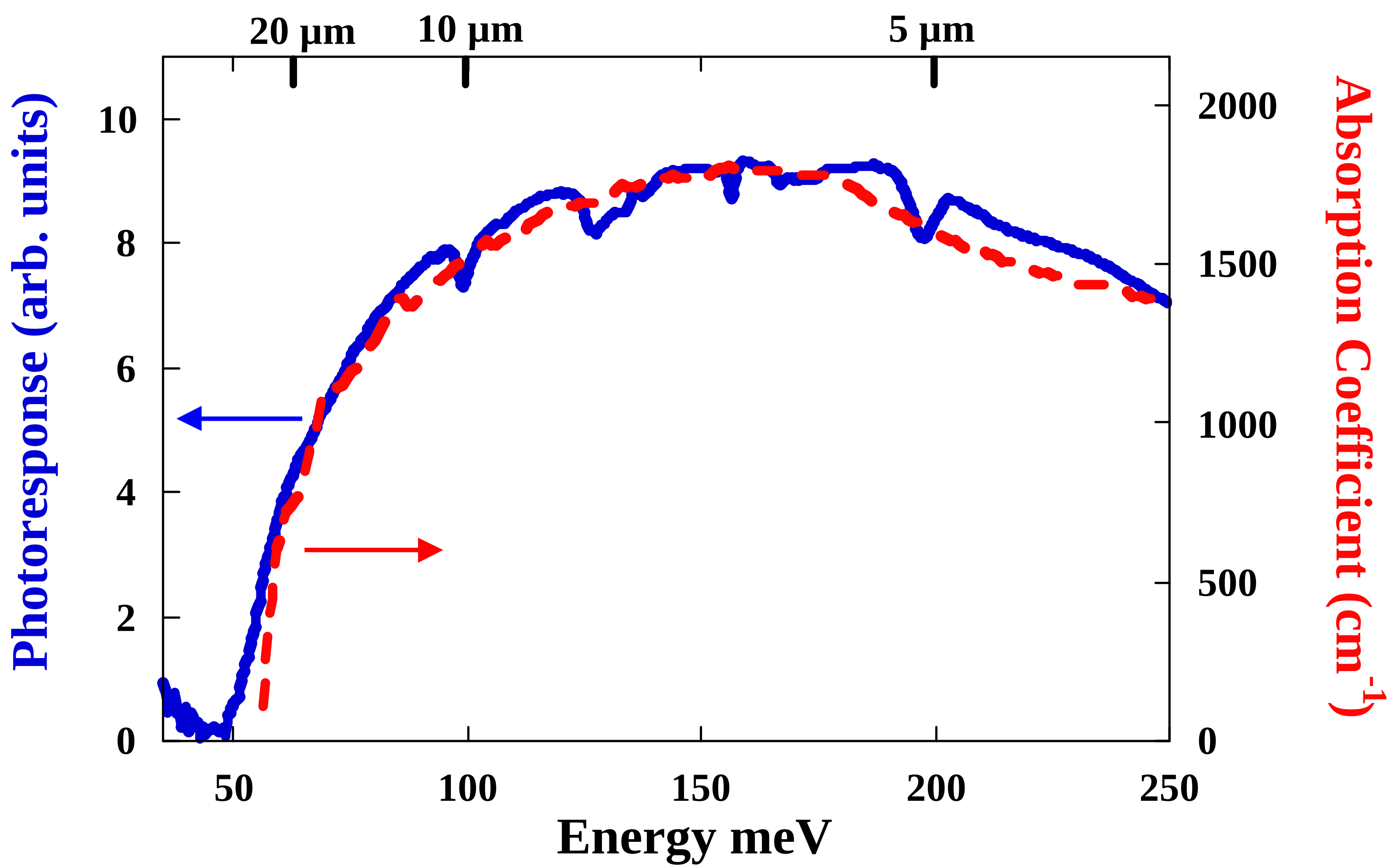
ADVANTAGES

* TAILOR FROM MWIR TO VLWIR
* HIGHER OPERATING TEMP.
* III-V MATERIALS TECHNOL.

ISSUES

* DEFECT REDUCTION
* VLWIR DESIGN RULES
* EXCESS CHARGE CARRIERS
* SL UNIFORMITY & INTERFACE CONTROL
* DIODE PASSIVATION

Comparison of Measured Photoresponse and Calculated Absorption Coefficient Spectra



High Quality of Superlattice Growth

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his picture.

QuickTime™ and a
TIFF decompressor
are needed to see this picture.

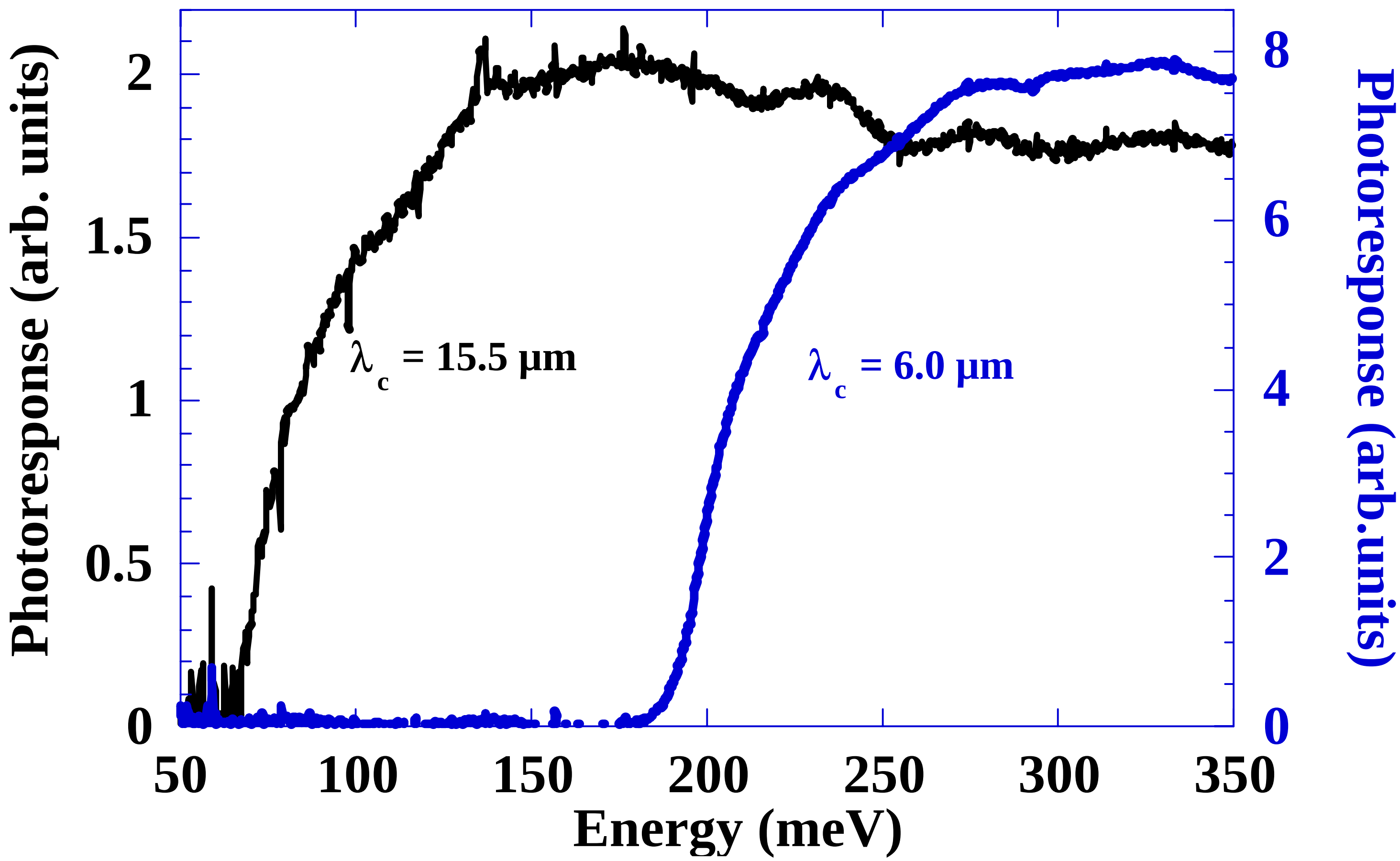
Cross-sectional TEM

Plan-view TEM

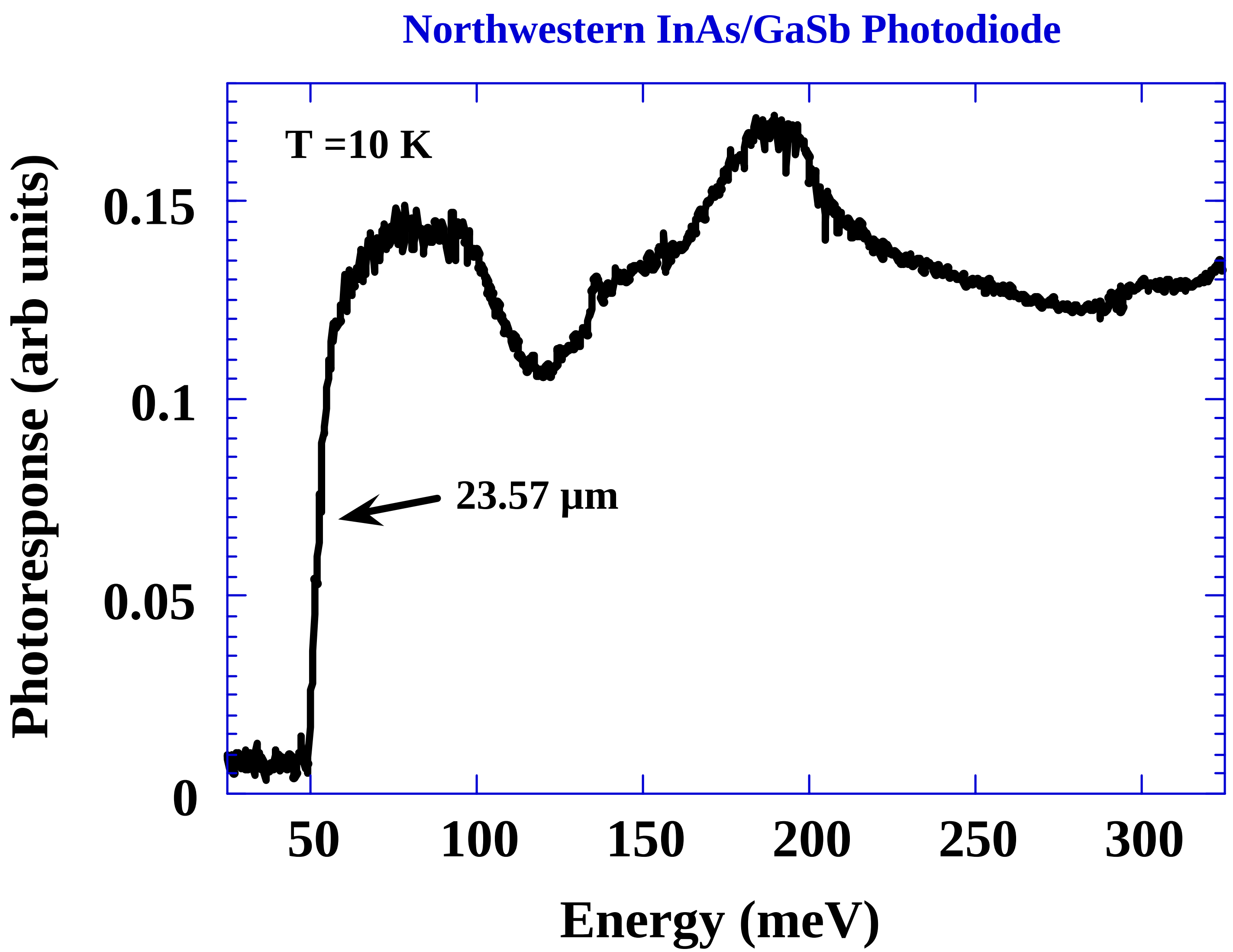
Good control and repeatability of SL layers. No dislocation defects in either image.

Optical Characterization of SL Diodes

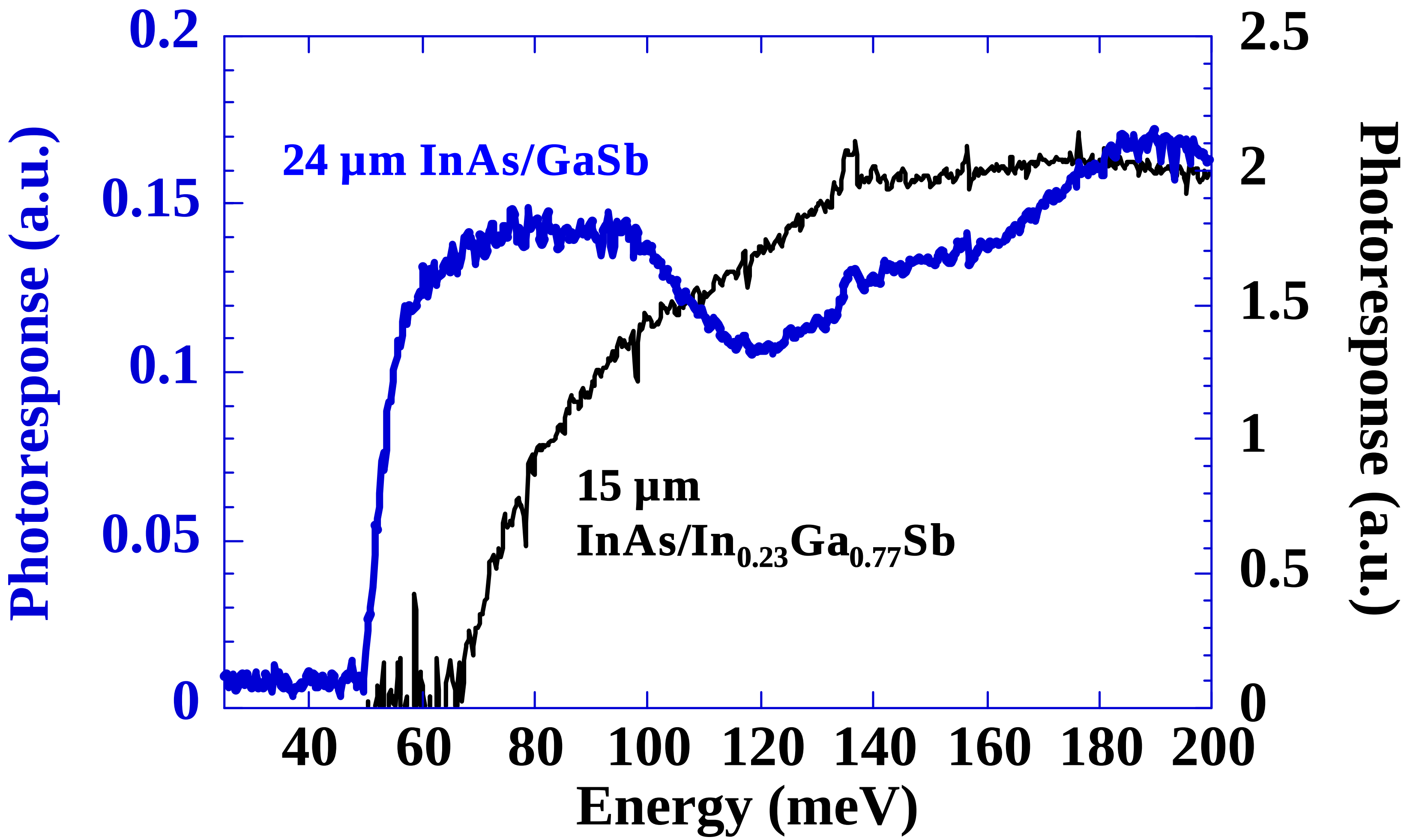
Tunability of SL Photodiodes from LWIR to VLWIR



VLWIR SL Diode



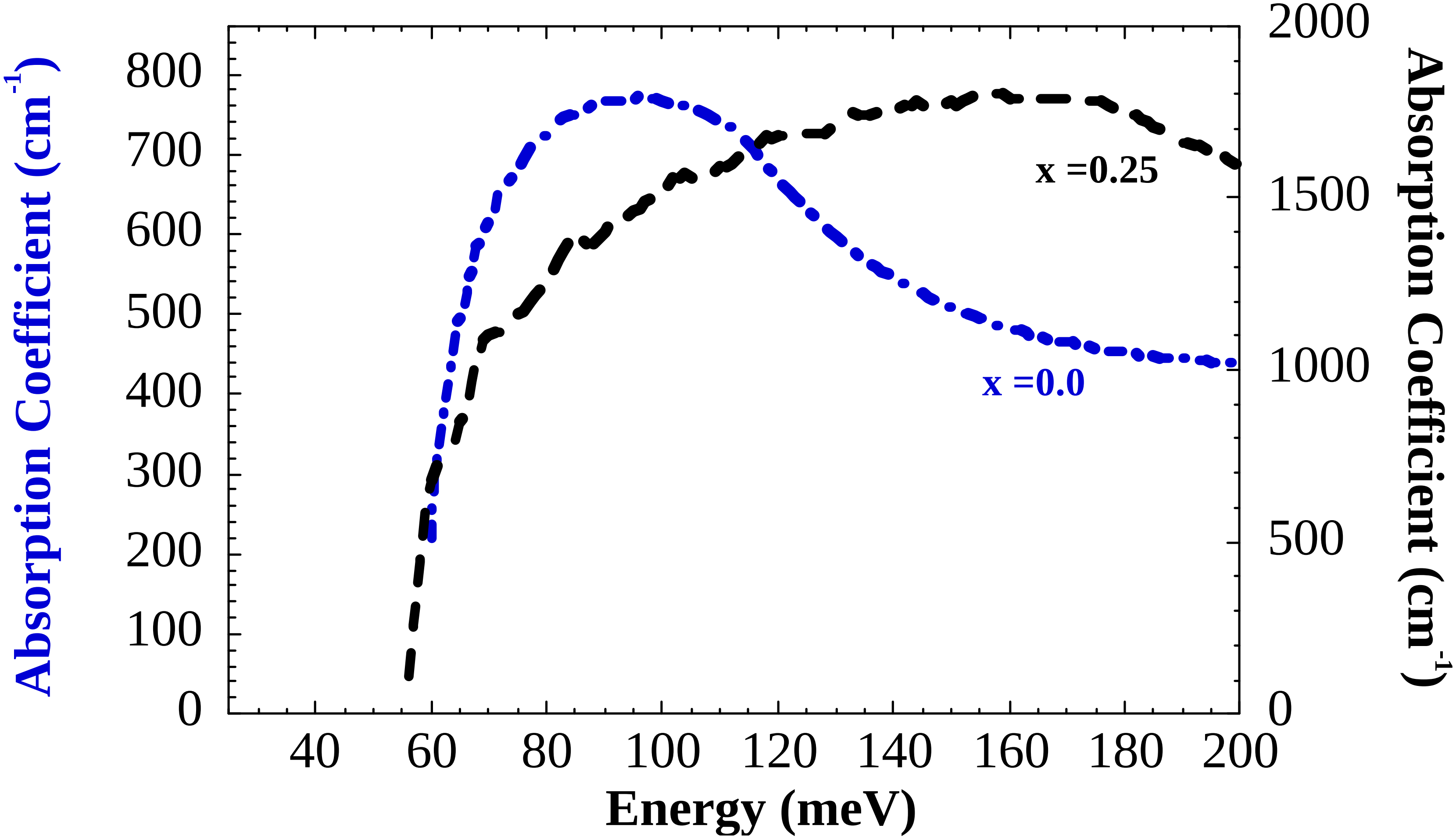
Photoresponse Spectra Comparison



Band Edge is sharper for the InAs/GaSb Photodiode (Δ= 10.6 vs 58 meV), and signal per unit area is larger (0.16 mm^2 vs. 6.25 mm^2).

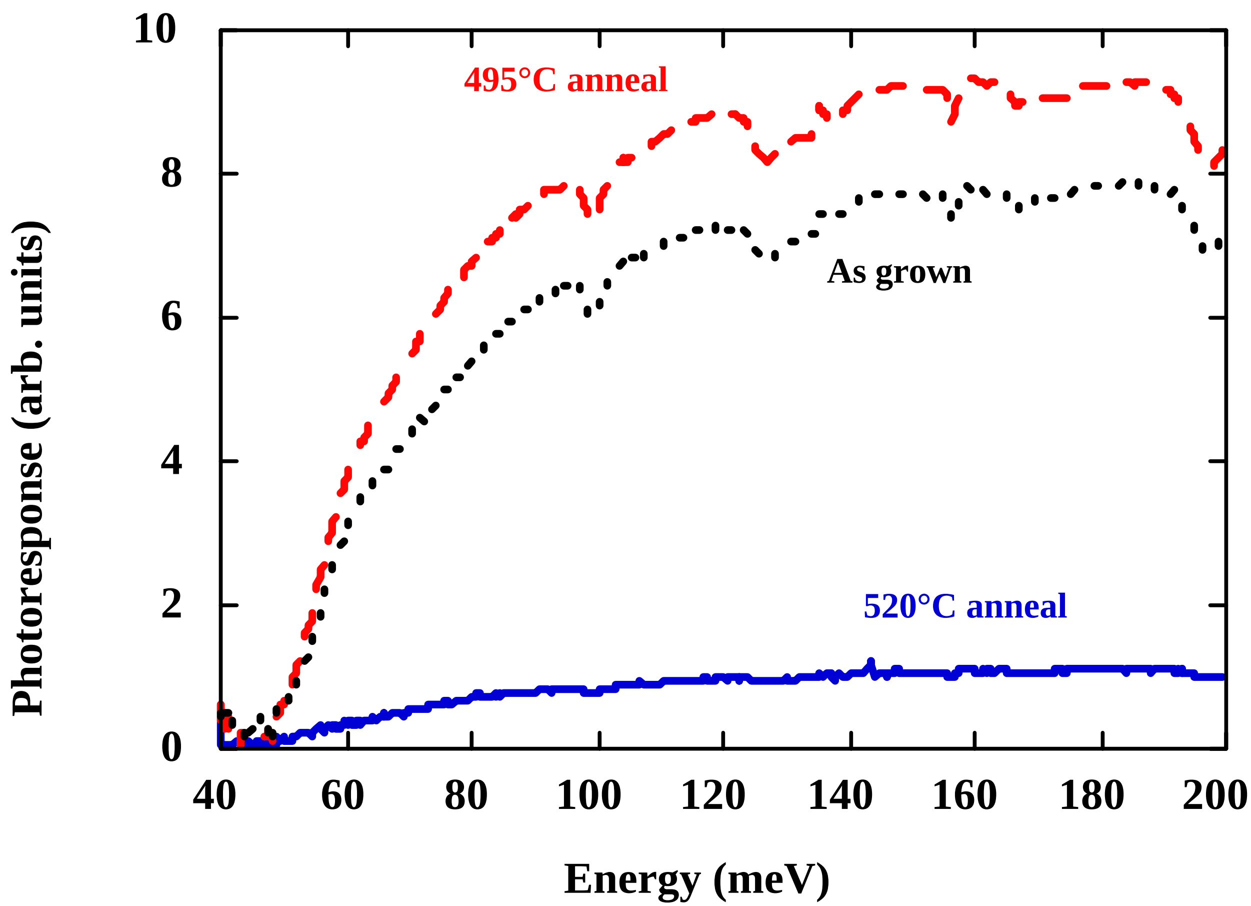
Comparison of Infrared Absorption

$In_xGa_{1-x}Sb$ versus GaSb Layers



Modeling predicts a sharper band edge for InAs/GaSb SL

Effect of Post-Growth Anneal



A short post-growth anneal at the proper temperature can enhance the photoconductive signal

Limitation of Post Growth Annealing

QuickTime™ and a
TIFF decompressor
are needed to see this picture.

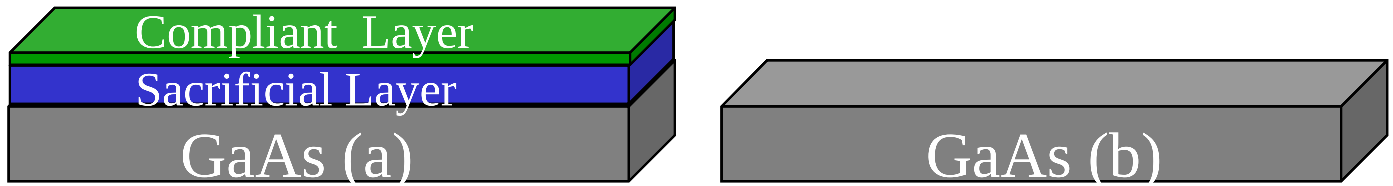
After 520°C anneal, dislocation loops with Stacking fault contrast are observed in plan-view TEM.

Alternative Substrate Technology
Background

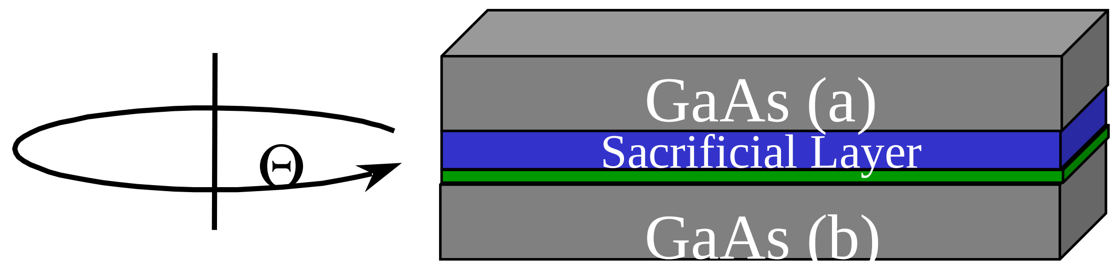
- Stimulated by too high defect density for reliable operation of minority carrier devices (i.e. laser diodes & LN photodetectors)
- “Compliant Substrates”
  - generally consists of a thin template layer ‘decoupled’ from a mechanical host
    - free-standing
    - oxide bonded
    - borosilicate-glass bonded
    - direct twist bonded

Compliant substrate formation

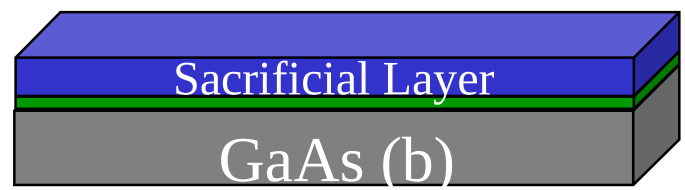
Step 1:
Grow the desired epilayers



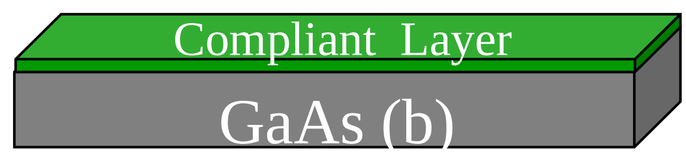
Step 2:
Invert and twist bond the epilayers to another substrate



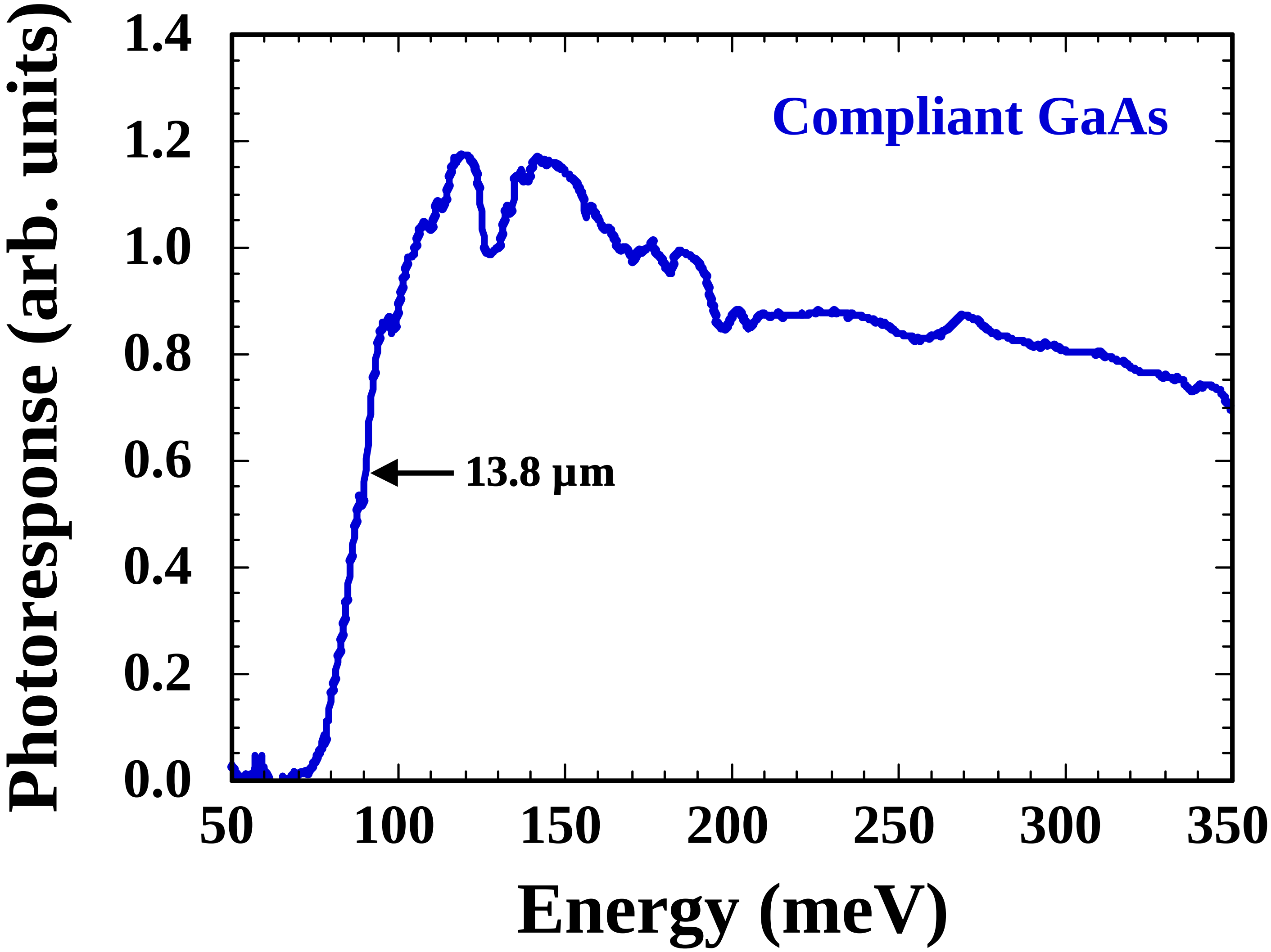
Step 3:
Selectively remove GaAs (a)



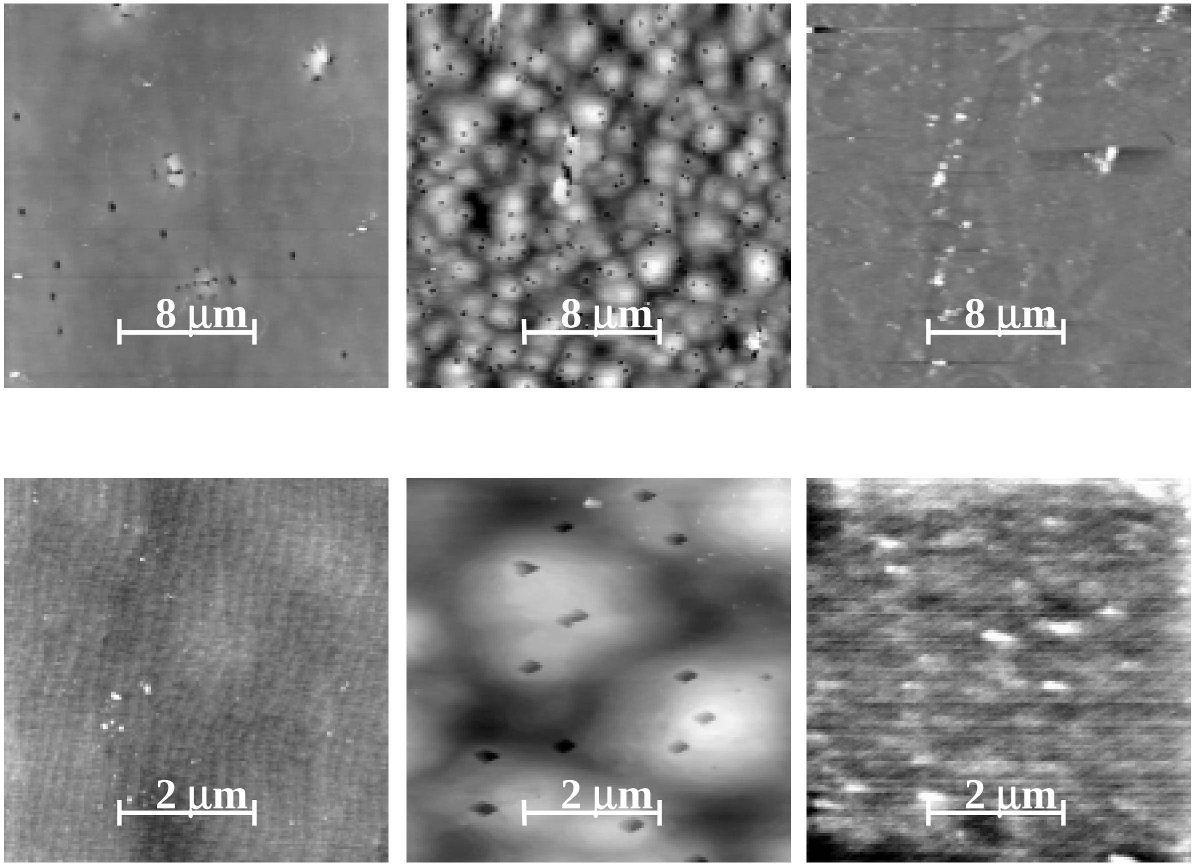
Step 4:
Selectively remove the Sacrificial layer



InAs/InGaSb SL on Compliant Substrate



Atomic Force Microscopy of InGaSb/InAs SLS



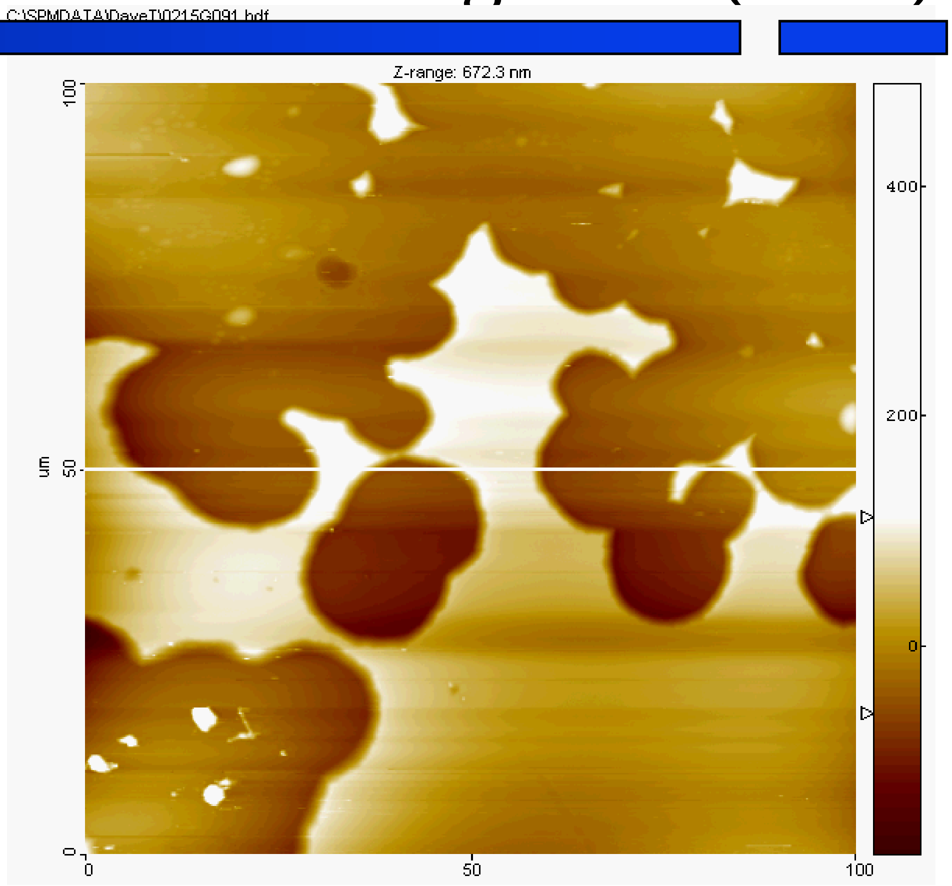
- InGaSb/InAs Superlattice Layers grown on
  - a) standard GaSb substrate
  - b) standard GaAs substrate
  - c) compliant GaAs substrate

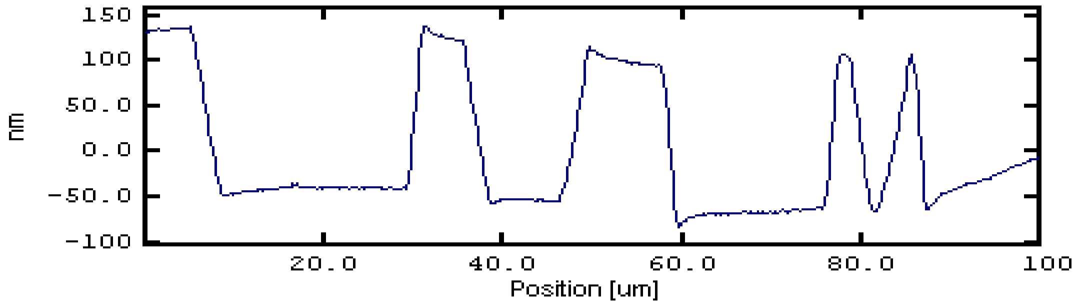
Ultra Thin SOI Theory
(Powell et.al., Huang et.al. IBM)

- New approach for low dislocation relaxed SiGe material
  - Normally circumvent large lattice mismatch via graded or superlattice buffers.
  - Due to substrate compliance the strain on epi layer can be xfered to substrate
    - allows growth of layer much thicker than conventional critical thickness
    - analyzed theoretically & increase in critical thickness observed with a decrease in substrate thickness

SiGen Ultra Thin SOI

Full strength HF (49%)





Common Bonded-wafer Characterization Techniques

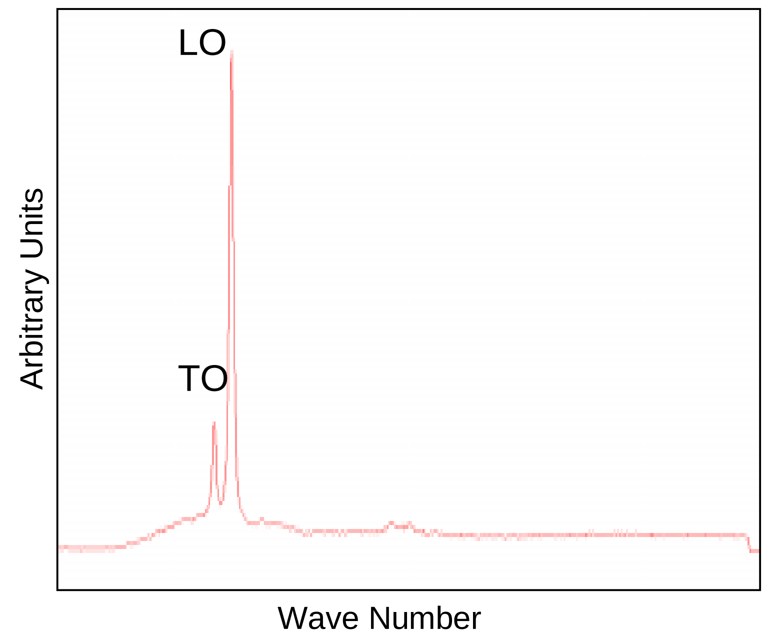
- Infrared transmission microscopy
  - Pros: Non-destructive, real-time, >5μm resolution
  - Cons: Poor resolution, no indication of material quality
- Scanning Acoustic Microscopy
  - Pros: Non-destructive, Interface sensitive, >1μm resolution
  - Cons: Coupling medium, slow, no indication of material quality
- High-resolution x-ray Diffraction
  - Pros: Non-destructive
  - Cons: Excessive depth of penetration
- Cross-sectional Transmission Electron Microscopy
  - Pros: High Resolution, details of the interface structure
  - Cons: Destructive, expensive, slow

Desired Characteristics of Imaging Technique

- Non-destructive
- Must be usable to characterize thin (< 10 nm) layers
- Provide quantitative indication of the quality of the transferred layer
  - Glancing Incidence X-Ray Diffraction
  - Micro Raman Spectroscopy
  - Atomic Force Microscope

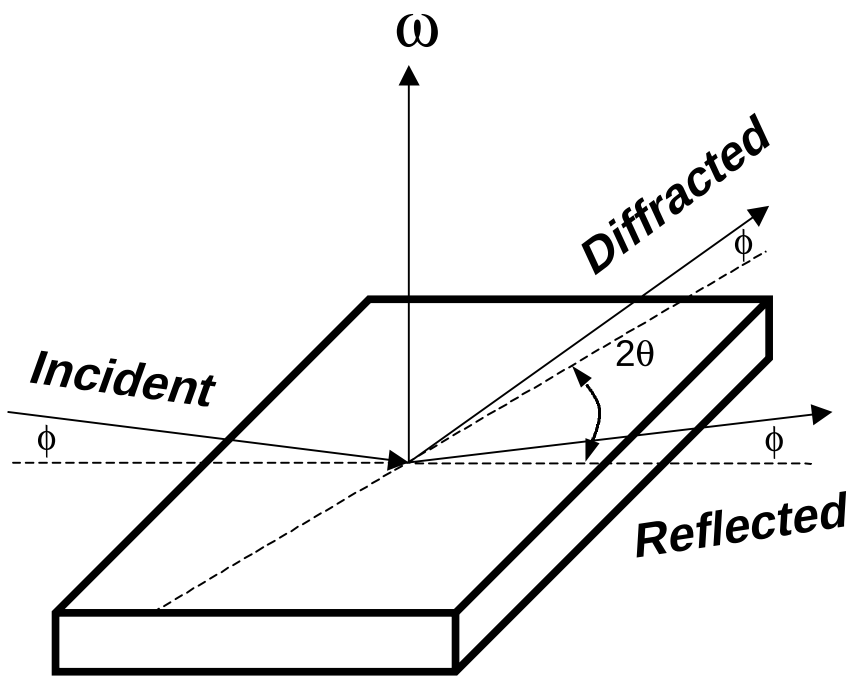
Raman background

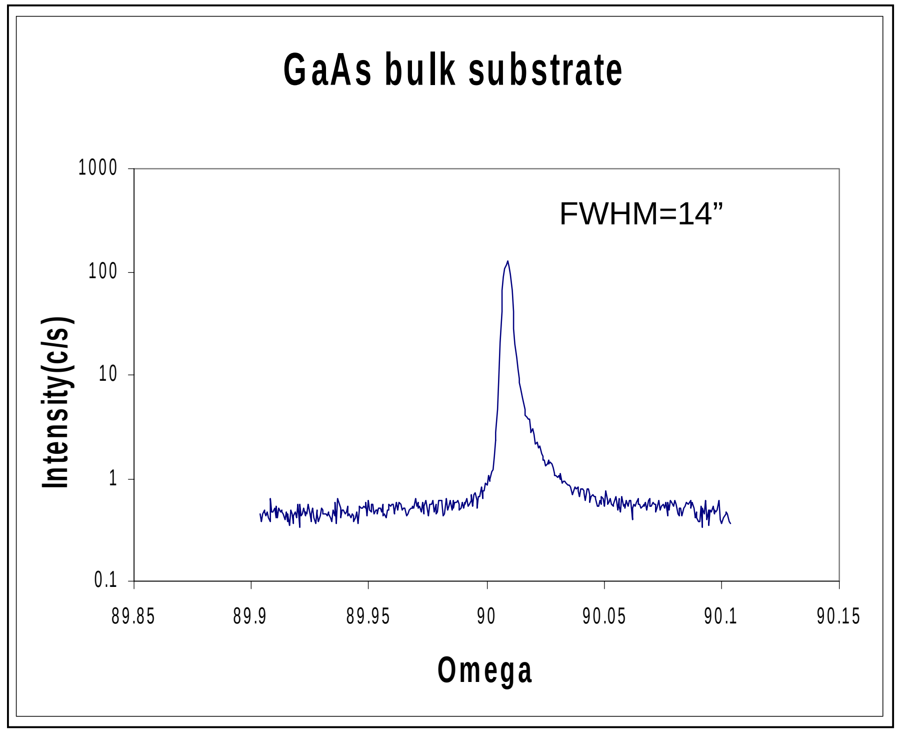
- Disorder (damage) originated from bonding process leads to breakdown of Raman selection rules
- In backscattering geometry, only the longitudinal optical phonon (LO) is allowed; the transverse optical phonon (TO) is forbidden for a non-strained system
- The defect active TO mode can be an excellent probe for structural disorder
- The Ratio of TO/LO - Probe of damage



Representative Raman Spectra

Glancing Incidence X-Ray Diffraction

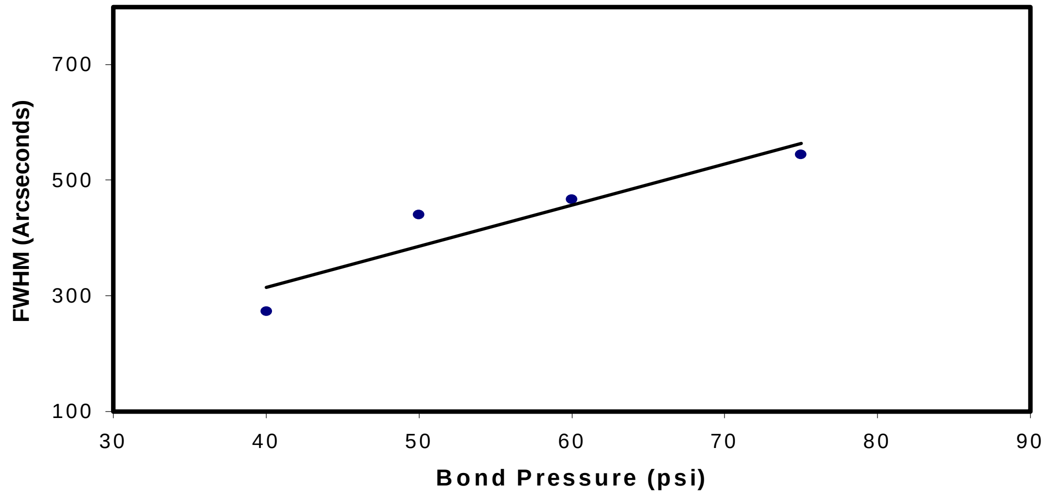




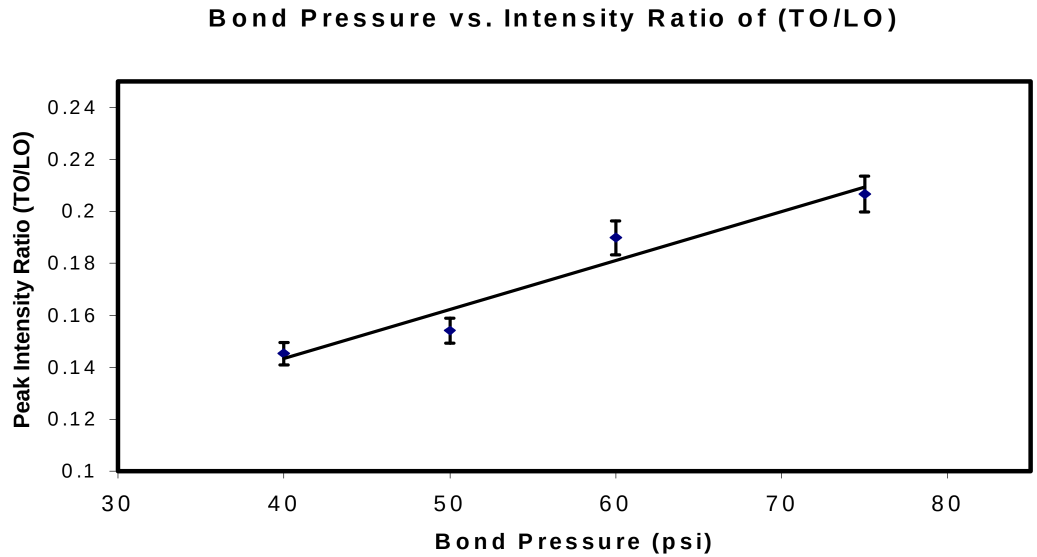
- **Angle of incidence of near critical angle for total reflection**
- **Diffraction from planes perpendicular to the surface**
- **Greatly enhanced surface sensitivity**

Raman & GIXRD Trends vs. Bond-Pressure

- Full width at half maximum increases as a function of bond pressure, indicative of increasing damage of the bonded layer



- The ratio of TO/LO Raman peaks also increases as a function of bond pressure, indicative of increasing strain in the bonded layer



SUMMARY

- Excellent Agreement between measured and calculated superlattice spectra for different designs.
- Trade-offs in various superlattice designs will continue to be explored
- Very Sharp band edges were observed in the photoresponse spectra
- MBE growth of SLs can be well controlled with low defect densities and very smooth surfaces
- Demonstrated cut-off wavelengths out to 24 µm
- Remarkable improvements in photodiode superlattices have been achieved at wavelengths beyond 15 µm.
- To further improve the performance of these devices were are exploring alternative substrate materials

SUMMARY

- **Some initial improvements have been found in surface morphology and photoresponse**
- **Identified two promising techniques for characterizing alternative substrates**
  - **Grazing Incidence XRD**
  - **µRaman Spectroscopy**
- **Multiple avenues of approach with wafer bonding**
  - **GaSb bonded to Si, GaAs, etc. (compliant substrates)**
  - **Ultra thin Si on oxide (<200 A)**
- **Combine to push materials to longer wavelengths with better detectivities and lifetimes.**

Superlattices are a promising material for the next generation of infrared detectors for very long wavelength IR imaging