InAs/InGaSb Infrared Lasers and Detectors

Naval Research Laboraotory
Key Personnel

Ming-Jey Yang
Brian Bennett
Jim Moore
Ben Shanabrook

Objective

- Improve GaInSb/InAs/AlSb Infrared Detectors and Lasers
- Optimize growth parameters for optical applications
  - Characterize growth process and improve device performance
  - Transfer improved materials to ongoing device programs
    - ***InAs/InGaSb LWIR detectors (Waterman, NRL Code 6818)***
    - ***InAs/InGaSb/AlSb MWIR lasers (Meyer, NRL Code 5613)***
  - Transfer improvements in growth procedures to other Navy and Air Force Programs

Impact

- GaInSb/InAs MWIR Lasers for IR countermeasures, chemical sensing and IR illumination
  - Reduced Auger recombination
    - ***room temperature operation***
  - High powers - optically pumped and interband cascade
  - Problem: Achieve theoretically predicted performance
    - ***issues related to growth and interface disorder***
- GaInSb/InAs IR FPAs with superior properties
  - 3-18μm tunable cutoffs
    - ***multi-spectral capability from MWIR to VLWIR***
  - Predicted Long Auger Lifetime
    - ***higher temperature operation (lighter, lower power, more reliable cooling system)***
  - Predicted Reduction of Dark Currents
    - ***superior performance in the VLWIR***
  - Problem: Short Carrier lifetime and large dark current
    - ***uncontrolled defects (point and extended)***

Research Plan

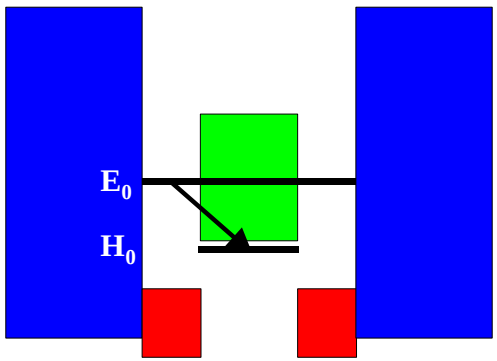
- Perform growth experiments that improve device performance
  - Determine key growth parameters (temperature, fluxes)
    - ***Transition information to other groups (HRL, Lincoln Labs, Sarnoff)***
  - Use X-ray diffraction as a structural probe
    - ***Lattice-matching of thick layers required***
  - Use intensity of intrinsic PL as a qualitative probe
    - ***Probe improvements with photoluminescence (PL)***
    - ***Obtain spectrally narrow and intense PL in laser and detector structures***
- Provide Improved Materials to Ongoing Device Efforts
  - InAs/InGaSb LWIR detectors (Waterman, NRL Code 6818)
  - InAs/InGaSb/AlSb MWIR lasers (Meyer, NRL Code 5613)

Laser Development

- Standard structures, grown on GaSb substrates, consist of 20 - 35 periods of W-structure* with a 1μm AlSb buffer and a 0.2 μm AlSb top layer.

* J. R. Meyer et al., APL 67, 757 (1995).

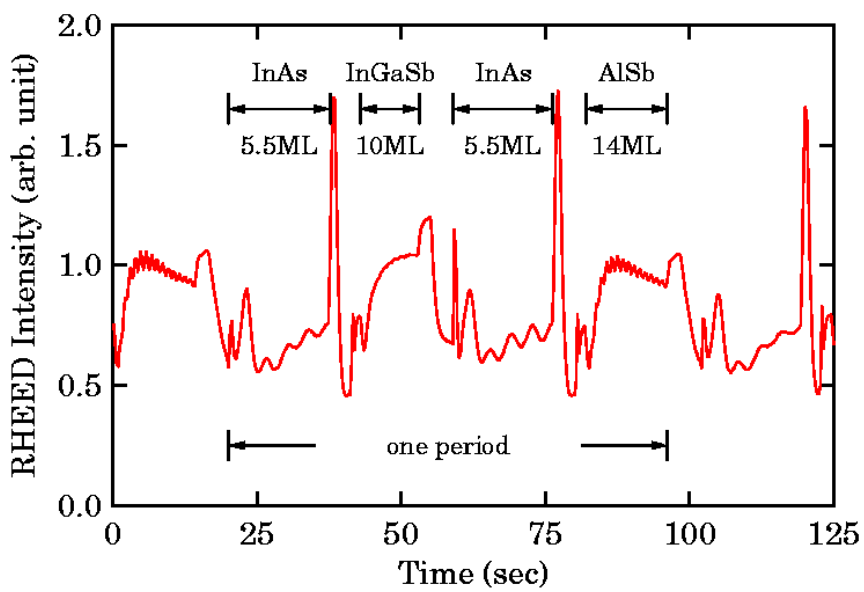
AlSb / InAs / $In_{.28}Ga_{0.72}Sb$ / InAs / AlSb



	meV	μm
8-10-8-14	182	6.8
7-10-7-14	214	5.8
6-10-6-14	243	5.1
5.5-10-5.5-14	280	4.4

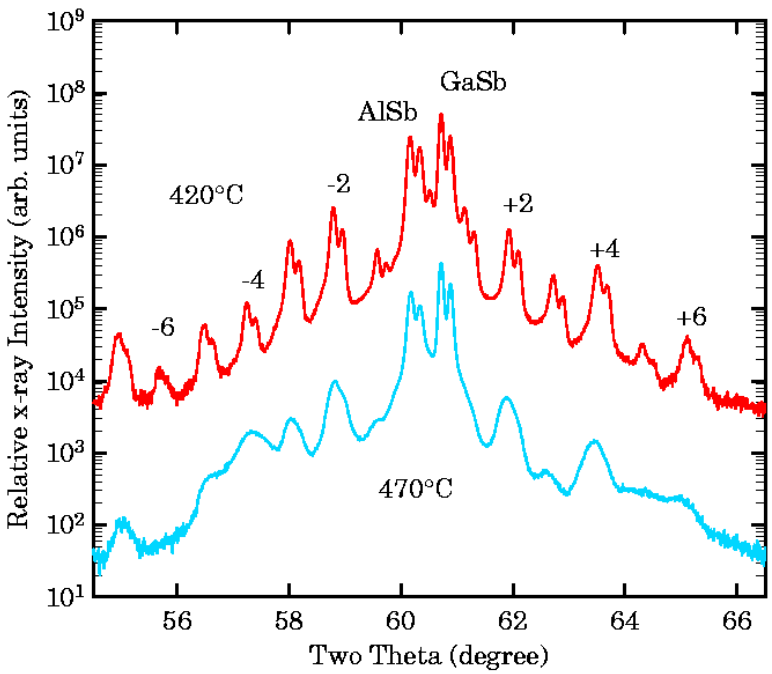
Monolayer Control Required

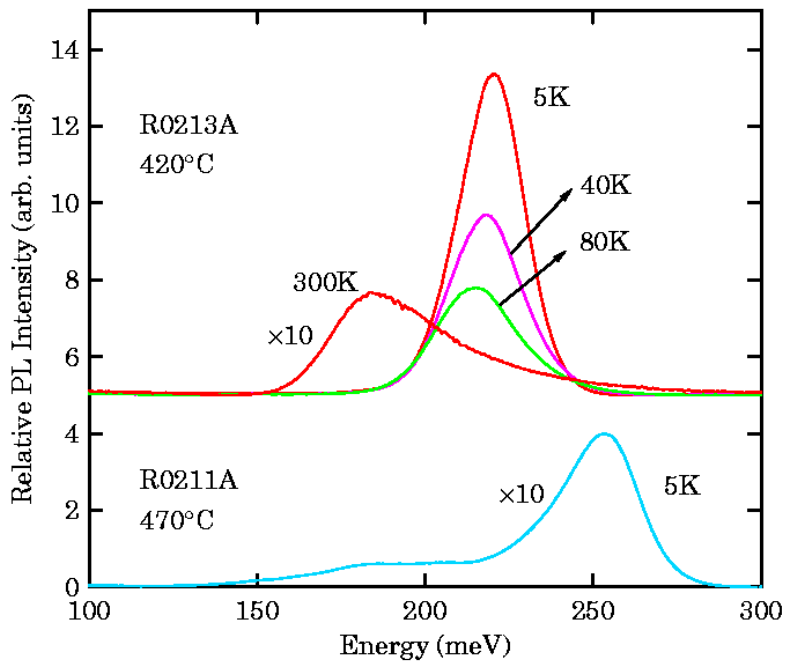
- The growth rate of each material is calibrated by RHEED before growth.
- Layer thickness is monitored by RHEED during the growth
- Interfacial bond type is controlled by shutter sequence.



Importance of Growth Temperature

- X-ray diffraction indicates superior quality of material grown at 420 C.
- PL intensity increases 10 times for growth at 420 C as opposed to 470 C. PL energy shifts from 6.8 μm (420 C) to 5.4 μm (470 C).
- These findings suggest interlayer mixing, which results in a rougher interface, lower radiative efficiency, and a higher emission energy.

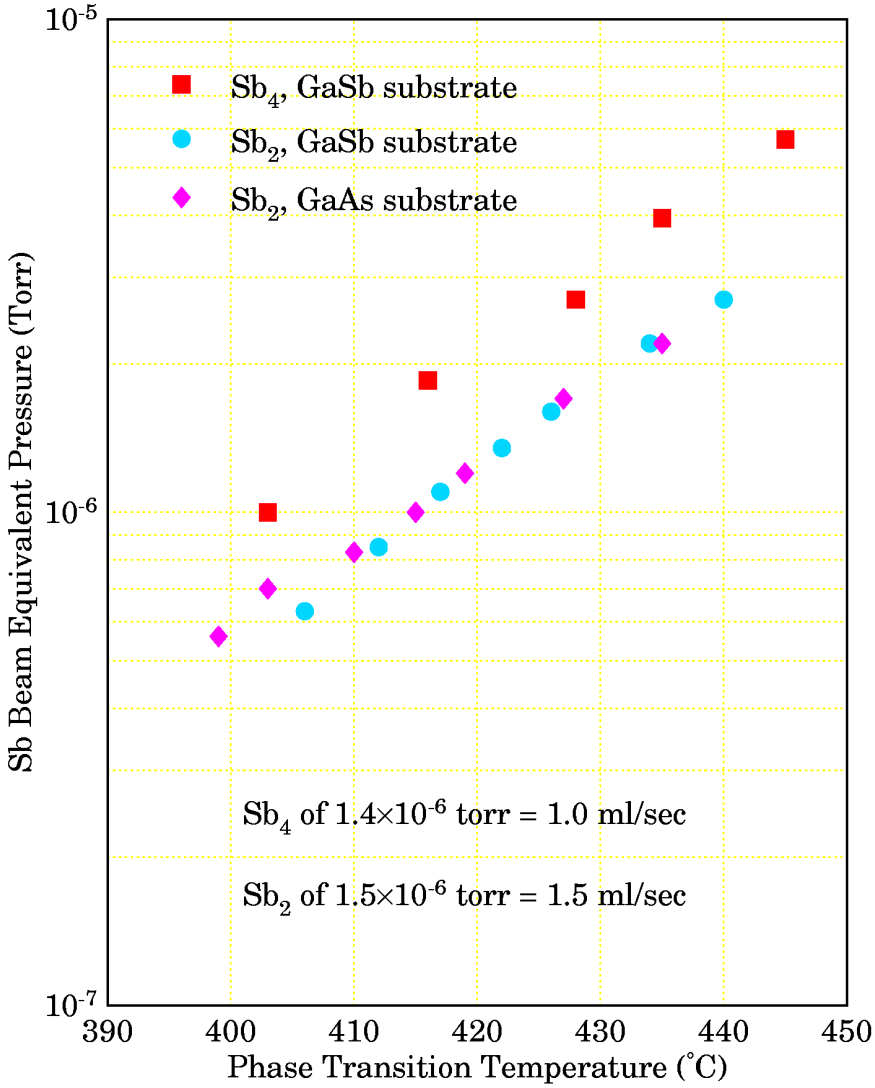




Properties Strongly Influenced by Growth Temperature

Growers Need
a Lab Independent Temperature Standard

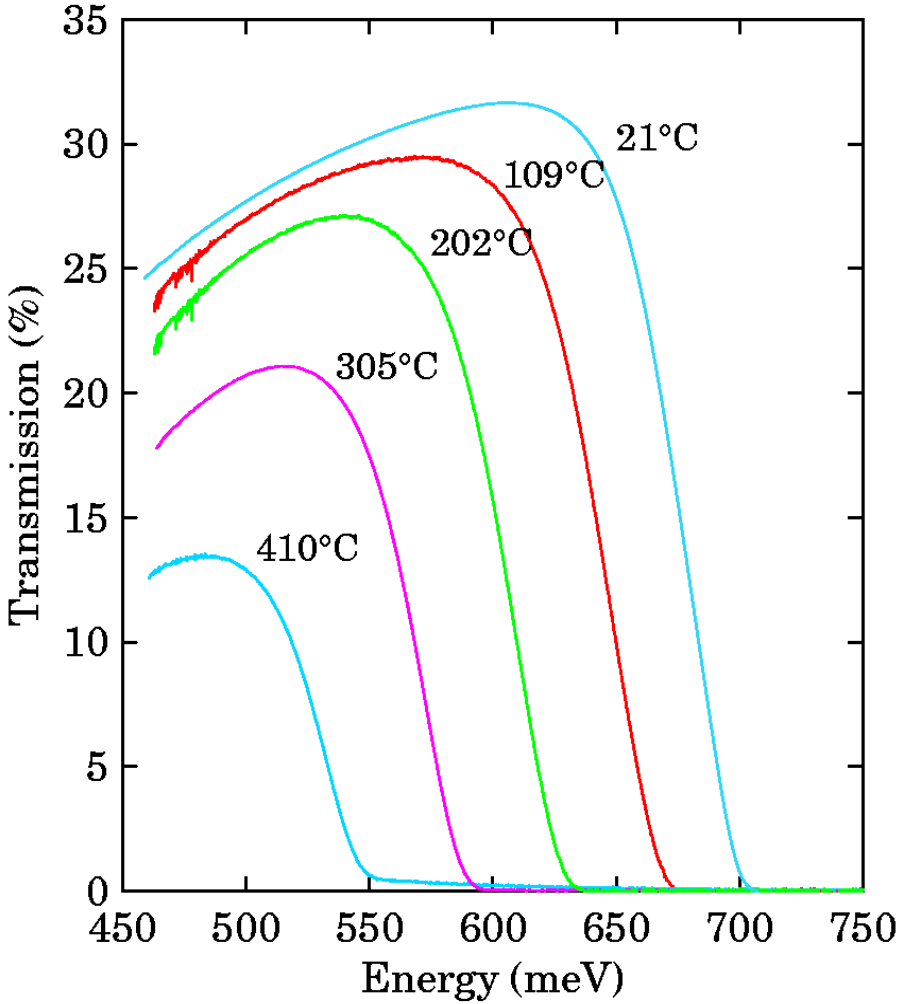
(1 x 5) to (1 x 3) RHEED Phase Transition of GaSb

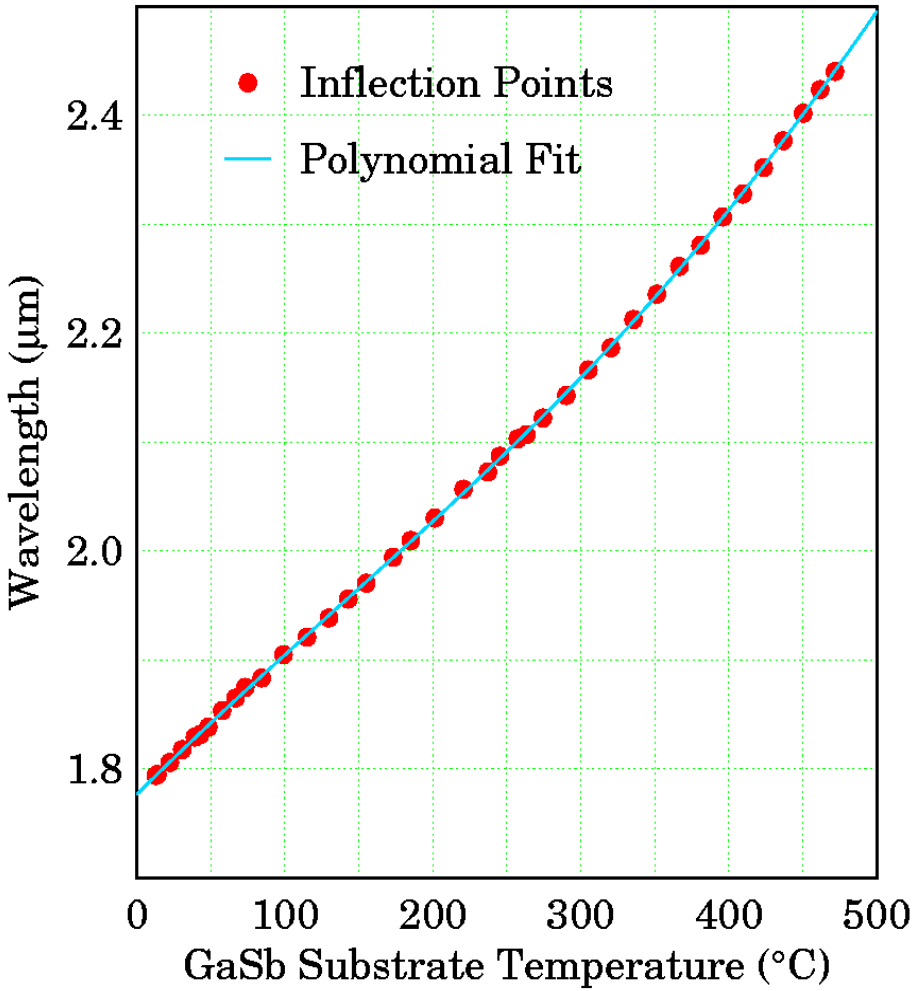


- Standardize method to determine the growth temperature for Sb_4 and Sb_2.
- A transmission thermometry setup designed and applied to GaSb substrates.
- The RHEED phase transition temperature is correlated with transmission thermometry

GaSb Transmission Thermometry

- Vacuum furnace covers a temperature range of 10ºC to 700ºC.
- Spectra are influenced by free electron absorption and blackbody radiation.
- Temperature dependence of GaSb band gap was obtained for the first time.

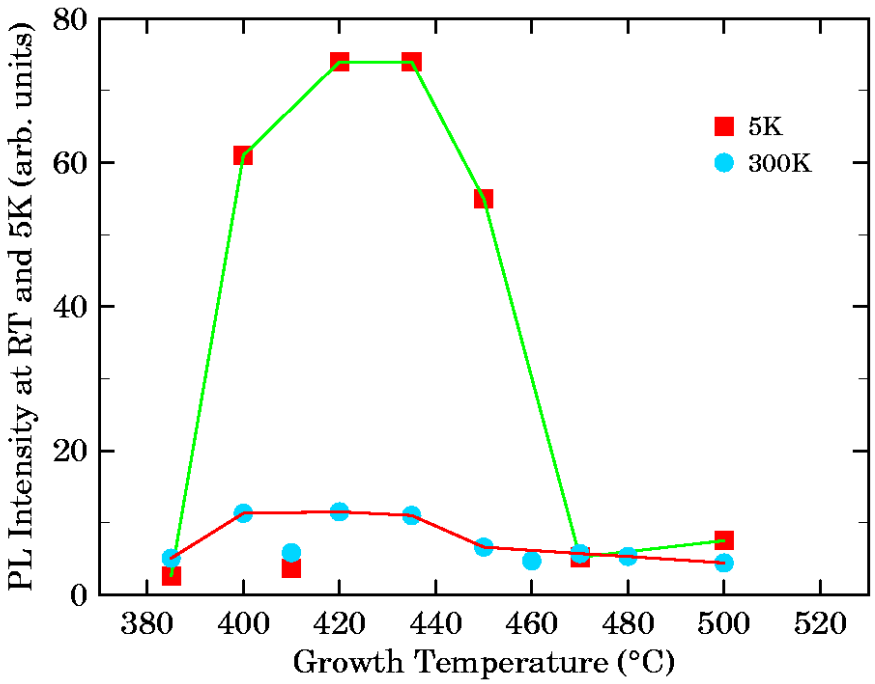




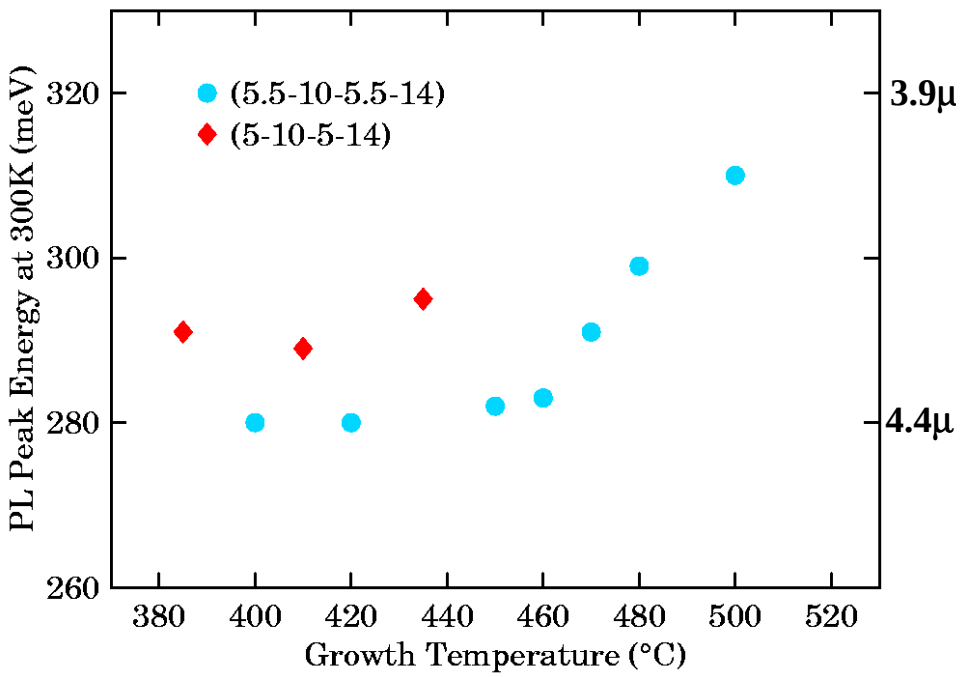
Lab Independent Temperature Standard

Best Growth Window Based on Photoluminescence Data

- At 300 K, the integrated PL intensity for samples grown between 400 C and 450 C is two times stronger than the other samples. This contrast is enhanced at 5 K.
- Accompanied by the low PL intensity, the peak energy moves to a higher energy when the growth temperature is above 450 C, which indicates the onset of layer intermixing at interfaces.



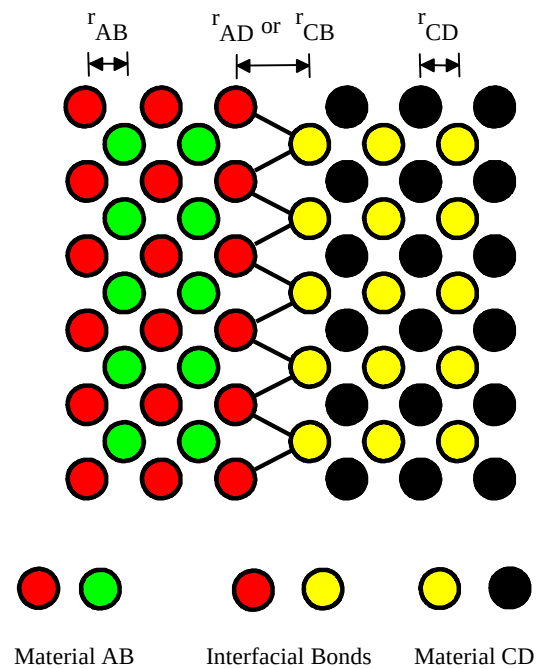
PL Efficiency Strongly Influenced by Growth Temperature

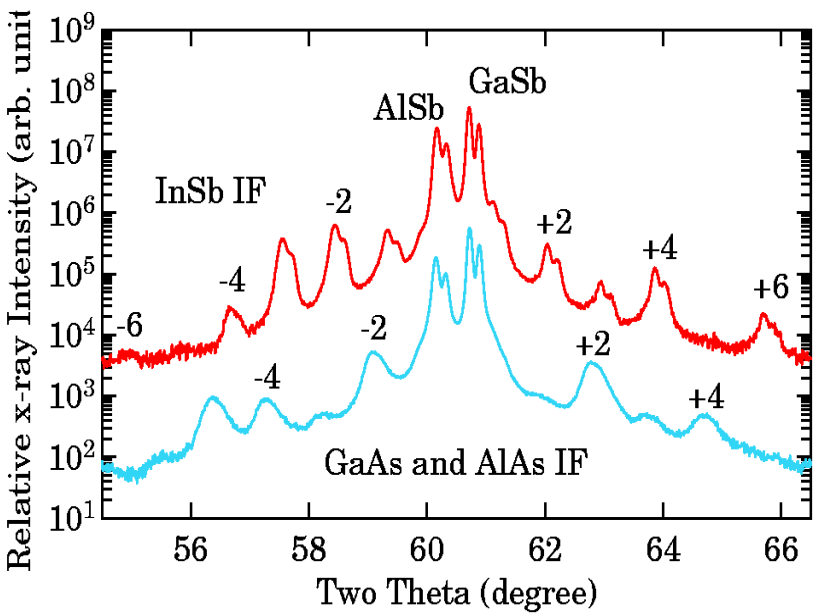


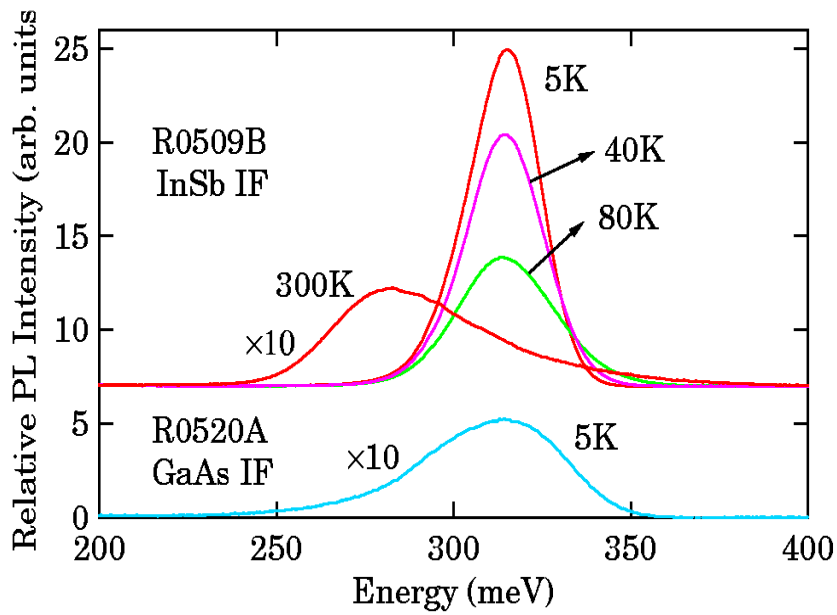
PL Energy Strongly Influenced by Growth Temperature

Importance of Interfacial Bond Types for Laser Structure Grown on an AlSb buffer

- The PL intensity is 10X smaller with GaAs interface bonds relative to InSb bonds.
- The x-ray diffraction shows poor material quality for sample with GaAs interfacial bonds due to a mismatch with AlSb buffer.
- Poor PL performance due to lattice mismatch?

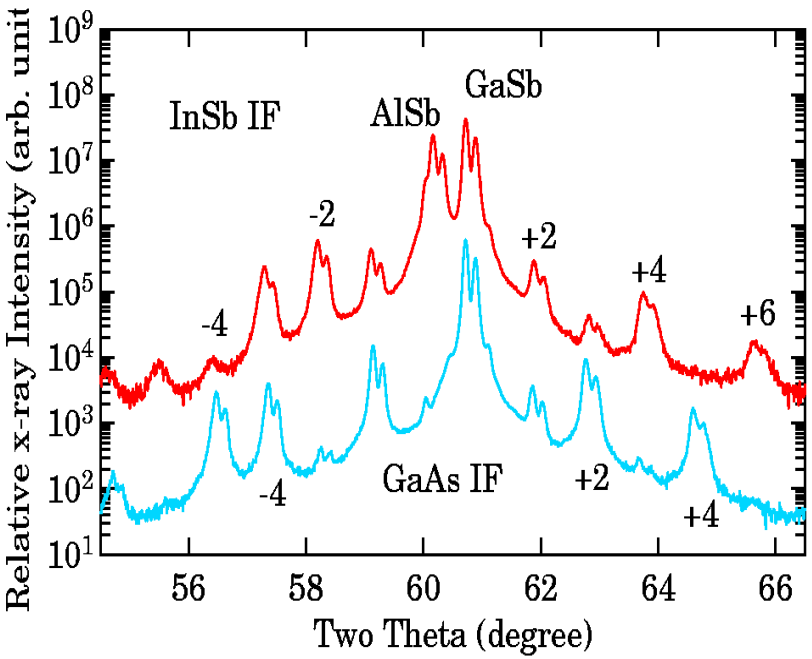


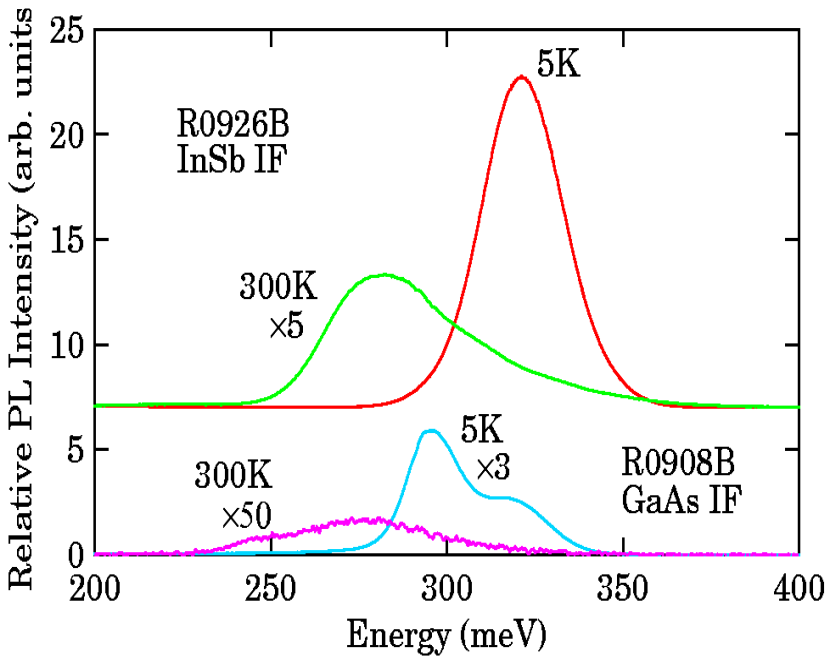




Importance of Interfacial Bond Types for Laser Structure Grown on an GaSb buffer

- The PL intensity is one order of magnitude smaller for the sample with GaAs interfacial bonds
- The x-ray diffraction shows an excellent material quality for the sample with GaAs interfacial bonds lattice-matched to GaSb buffer layer.

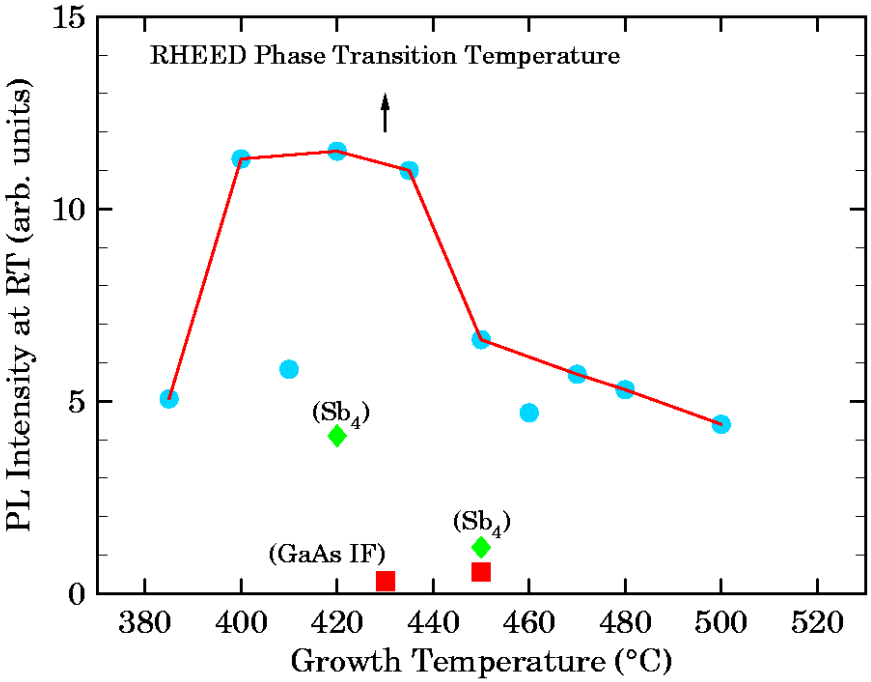


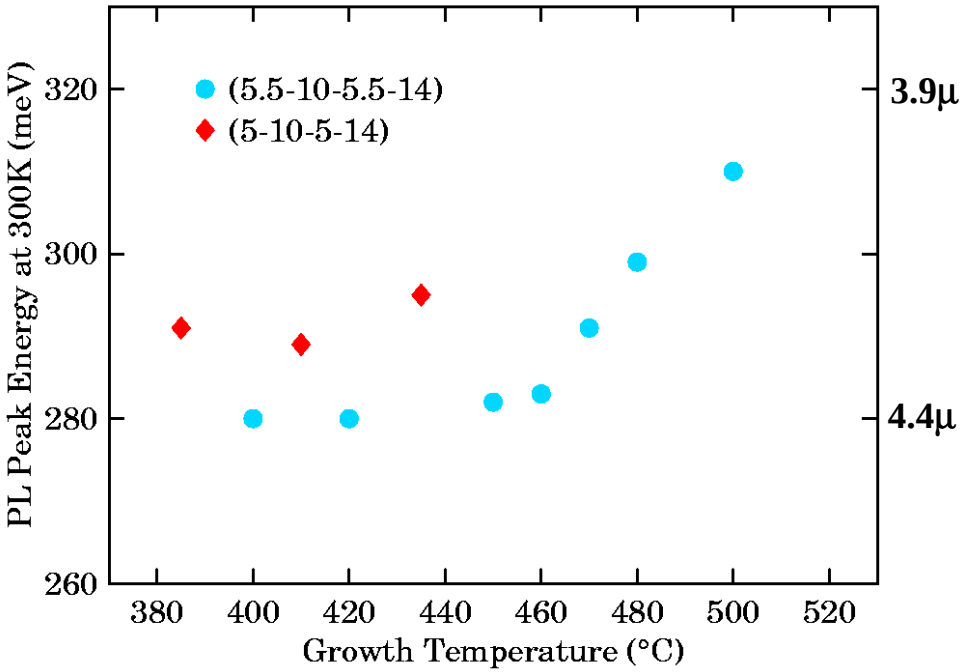


InSb Interface Bonds Result in Superior Performance

Summary of Laser Structure PL Data

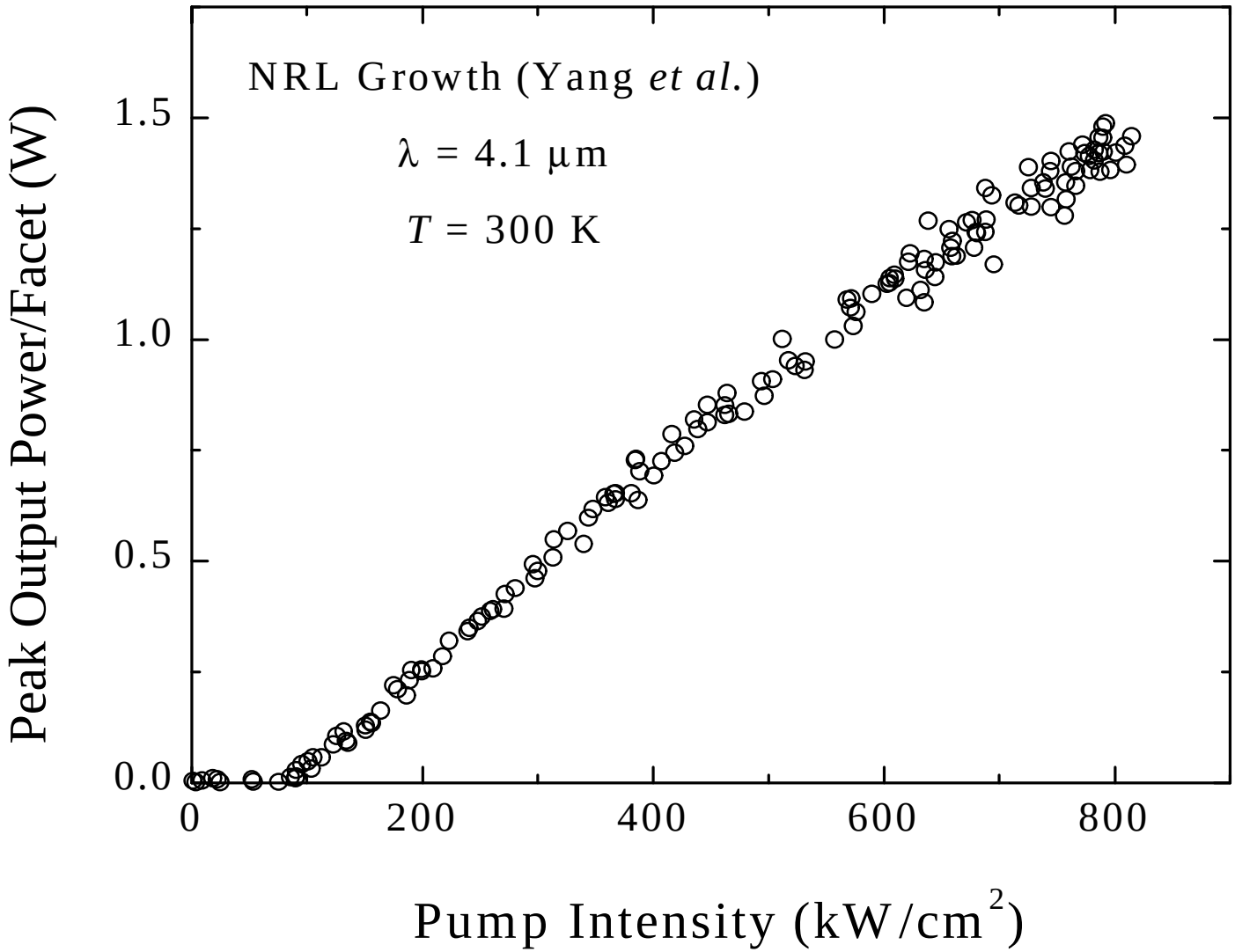
- Grow between 400 C and 450 C.
  - –Better efficiency, better control over wavelength
- InSb interfacial bonds preferred.
- Laser structures grown with Sb_2 show a better efficiency Sb_4.





All details of growth procedures transferred to MIT Lincoln Labs and Sensors Unlimited/Sarnoff

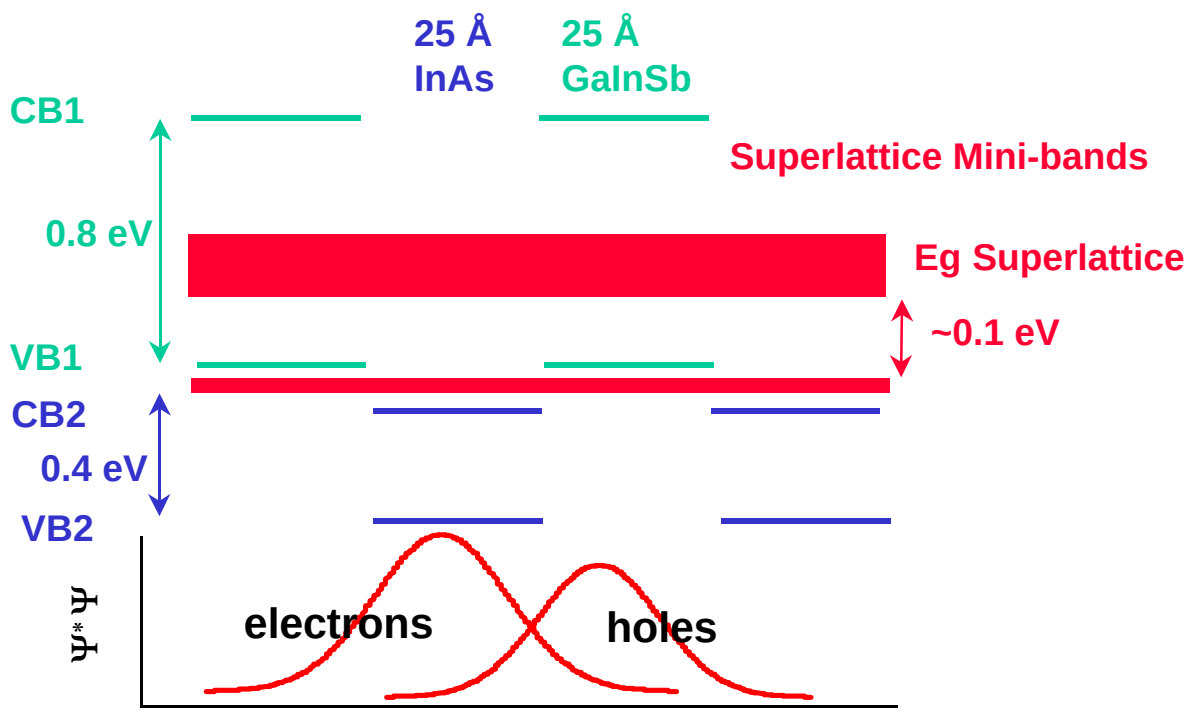
Record-Setting Room Temperature Output Power of an Optically-Pumped Mid IR InAs/GaInSb/AlSb Laser



10X more output power than ever observed from this system

W. W. Bewley, C. L. Felix, E. H. Aifer, J. R. Meyer, M. J. Yang, B. V. Shanabrook, B. R. Bennett

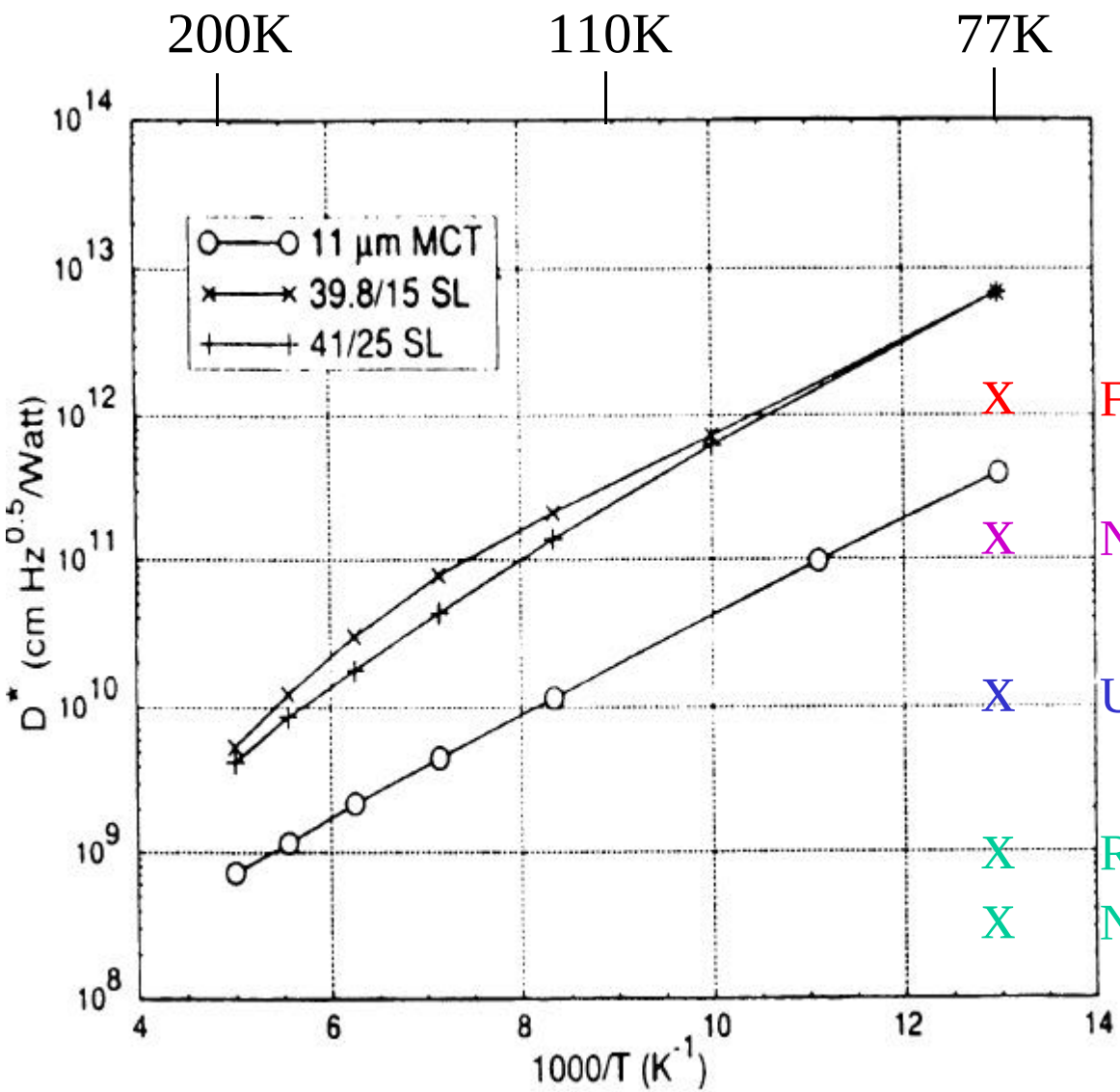
InAs/GaInSb Detector Development



CB - Conduction band edge
VB - Valence band edge

- Type-II band alignment: GaInSb valence band above InAs conduction band
- Quantum confinement and strain effects result in small bandgap semiconductor for layer thicknesses near 25 Å

Theoretical and Experimental Performance of Long-Wavelength InAs/GaInSb Superlattices



Theoretical curves based on achieving intrinsic Auger lifetime at low temperatures and 11 µm

X Fuchs *et al.*, 1997 (8 µm)

X NRL, 1996 (8 µm)

X UCSB/SBRC, 1993-96 (11 µm)

X Razeghi *et al.*, 1997 (10 µm)

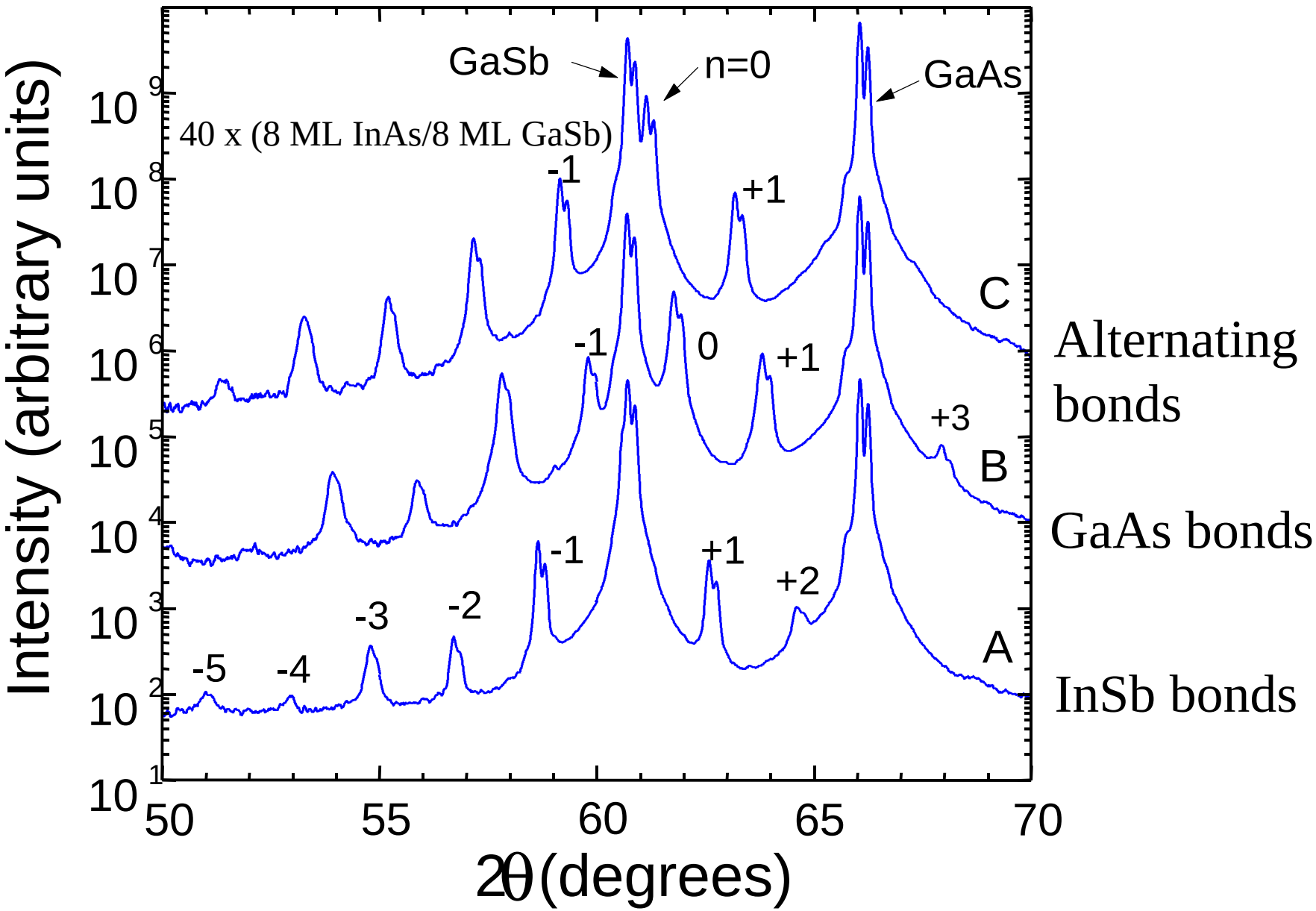
X NRL, 1994 (8 µm)

} GaAs substrate

One order of magnitude higher detectivity at a given operating temperature

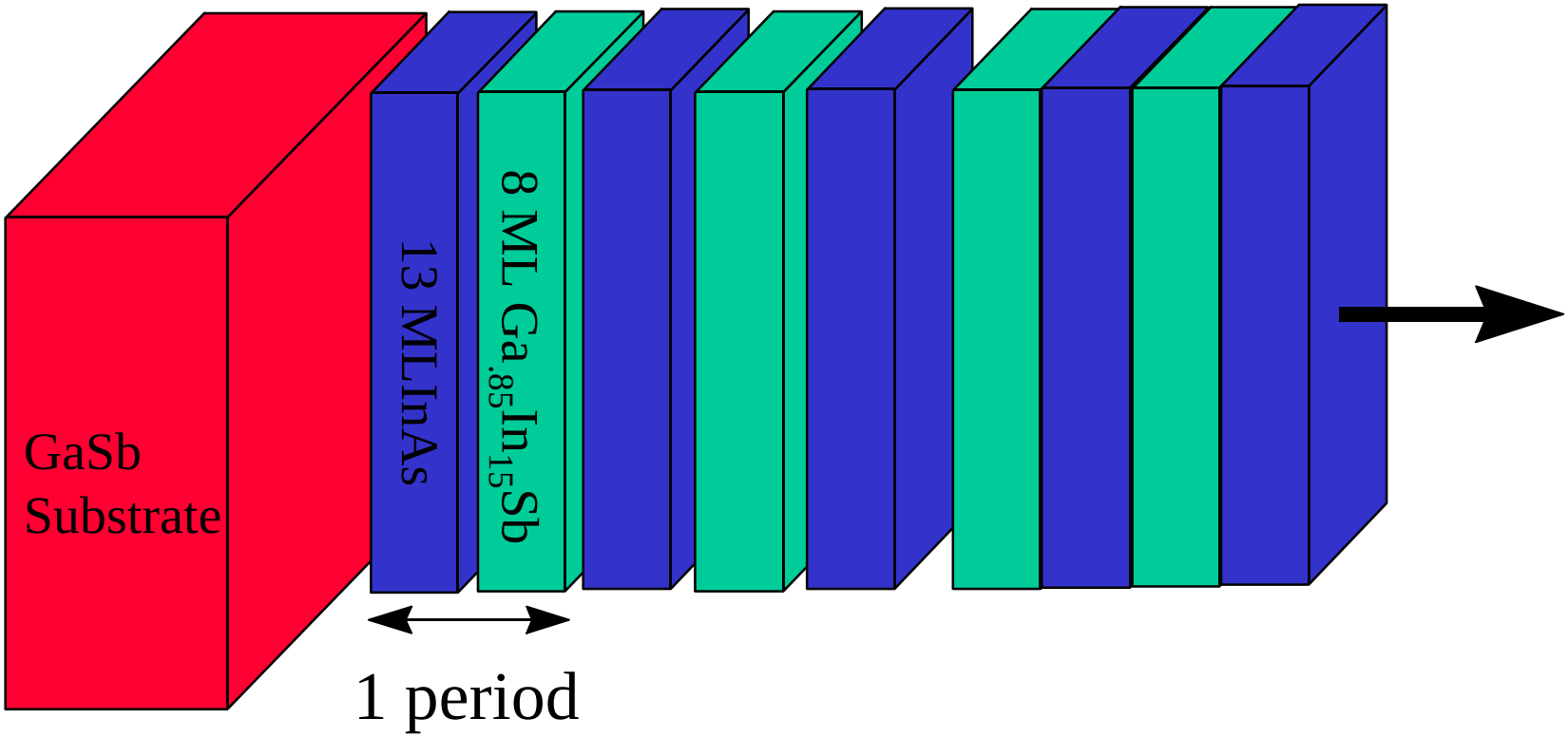
or 30 K higher operating temperature for a given detectivity

Lattice Match Influenced by Interface Bonds



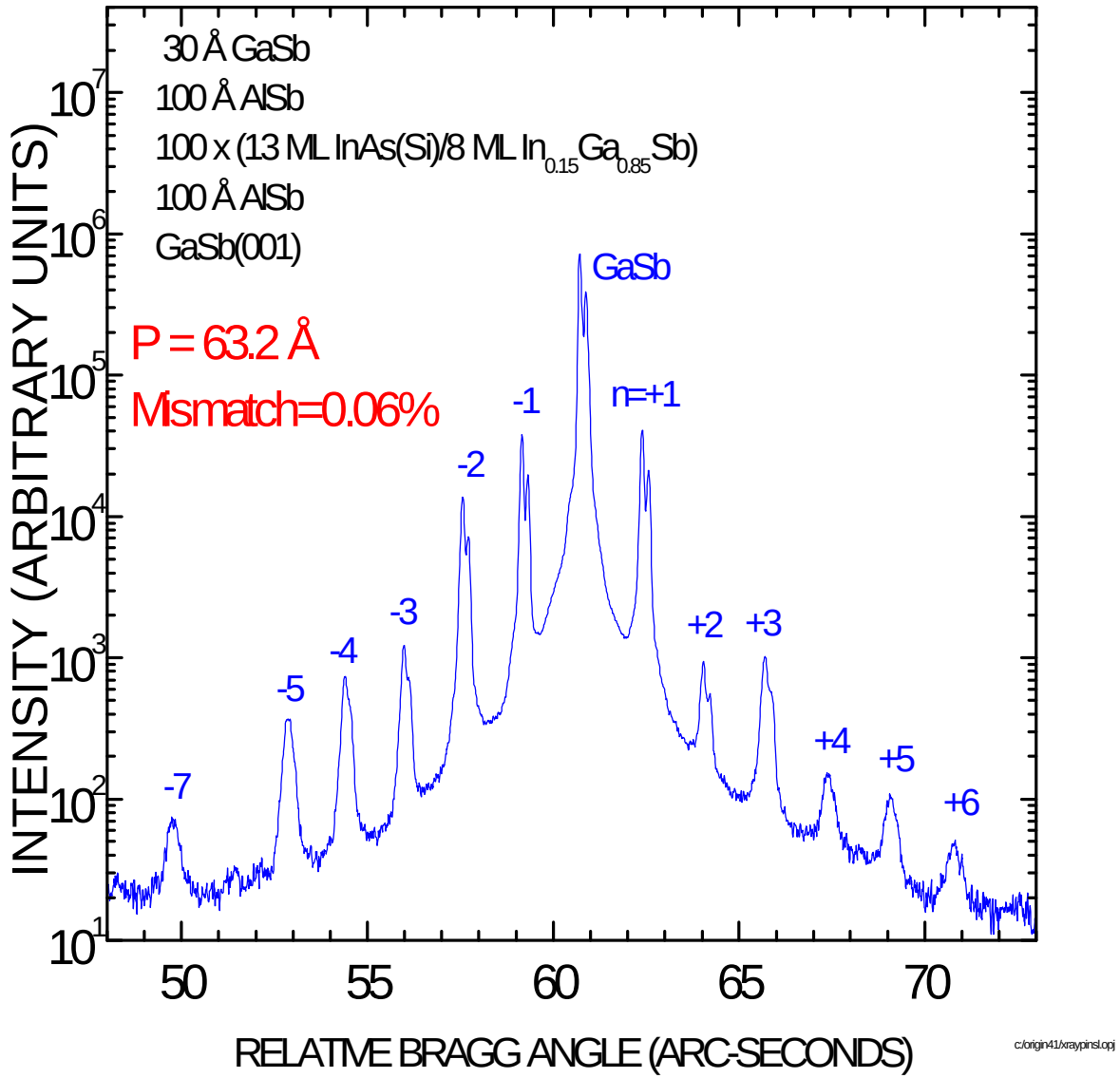
X-ray Diffraction of Superlattices

Superlattice for 10 μm Detector



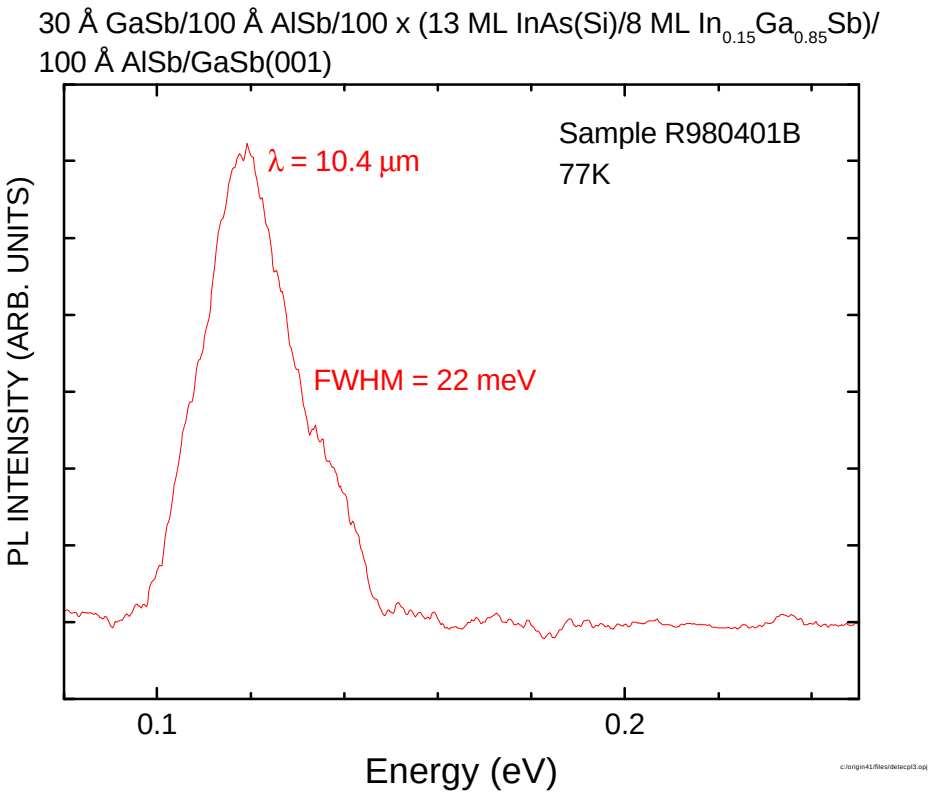
- Alternating InSb and GaAs interface bonds
  - –should result in lattice match with GaSb substrate
  - –should reduce dislocations (leakage currents)
- Test structure: 100 periods clad by 100 Å AlSb
  - –characterized by x-ray diffraction, optical microscopy and PL
- Device structure: p-i-n: 90 periods-15 periods-50 periods

X-ray diffraction of InAs/InGaSb SL



Good Lattice-matching Achieved
with alternating GaAs and InSb Bonds

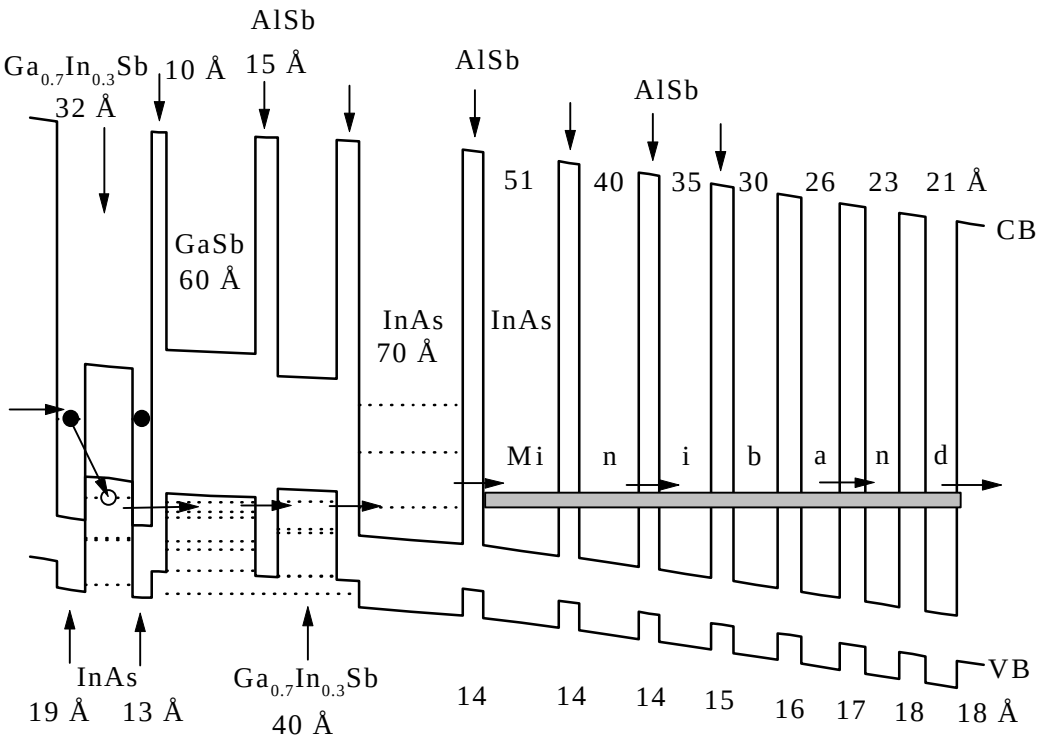
Luminescence from IR detector structure



- PL at target wavelength of 10 μm
- First attempt at p-i-n structure using InGaSb/InAs SL failed to exhibit diode-behavior
  - Previously fabricated working p-i-n diodes with InAs/GaSb SLs
  - Working to understand problem--possibly doping levels/MBE contamination problem
- Need a larger effort to solve these issues
  - Program transferred to FY99 NRL 6.2 Base
  - Joint Device-Materials Program

Research Plans and Work in Progress

- Determine impact of new growth procedures on the performance of MWIR lasers, e.g., V/III flux ratio.
- Investigate the tunneling process in the injection region of cascade lasers under a high current operation.



- Explore different alternatives for capping layers such as ternary, quaternary, and superlattices.
- GaSb/InGaSb FPA research transferred to Bennett/Waterman NRL 6.2 Base program starting in FY99

Transitions/Transfers/Synergy

- Growth studies transitioned to Air Force IRCM program at Lincoln Labs (G. Turner) and to ONR SBIR (Sensors Unlimited).
- Temperature measurement procedure and results transitioned to DARPA programs at HRL (J. Roth)
- Improved materials transferred
  - Meyer's 6.2 ONR mid-ir IRCM program
  - Waterman's 6.2 NRL LWIR program
- Synergistic interactions
  - Air Force (M. Falcon) and Navy (J. Meyer) IRCM programs
  - DARPA's Virtual Integrated Prototyping Program (HRL, M. Gyure)
  - DARPA's ULTRA (HRL, D. Chow)
  - ONR Dual Use S & T Quantum Devices and Ultra-High Frequency Digital Signal Processing Program (HRL, D. Chow)
  - DARPA's Integrated Multi-Sensor Control Consortium (HRL, J. Roth)
  - Joint ONR/NRL/DARPA Workshop planned

Output

- **Published Papers**
  - "Growth and Characterization in InAs/InGaSb/InAs/AlSb Laser Structures", M.J. Yang, W.J. Moore, B.R. Bennett and B.V. Shanabrook, Electronics Letters **34**, 270 (1998).
  - "Modulation Doping of InAs/AlSb Quantum Wells Using Remote InAs Donor Layers", B.R. Bennett, M.J. Yang, B.V. Shanabrook, J.B. Boos and D. Park, Applied Phys. Lett. **72**, 1193 (1998).
  - "AlSb/InAs HEMTs using Modulation InAs(Si) Doping", J.B. Boos, B.R. Bennett, W. Kruppa ,D. Park, M.J. Yang and B.V. Shanabrook, Electronics Letters **34**, 403 (1998).
  - "Interfacial Disorder in InAs/GaSb Superlattices", M.E. Twigg, B.R. Bennett, P.M. Thibado, B.V. Shanabrook and L.J. Whitman, Phil. Mag. A76, 7 (1998).
  - M. J. Yang, W. J. Moore, B. R. Bennett, B. V. Shanabrook, and J. O. Cross, To be published in MRS proceeding, “The Growth of Type-II Infrared Laser Structures.”
  - J. R. Meyer, L. J. Olafsen, E. H. Aifer, W. W. Bewley, C. L. Felix, I. Vurgaftman, M. J. Yang, L. Goldberg, D. Zhang, C. H. Lin, S. S. Pei, and D. H. Chow, submitted to IEE Proc. Optoelectronics, “Type-II W, Interband Cascade, and Vertical-Cavity Surface-Emitting Mid-IR Lasers.”

Output (cont.)

- **Invited Presentations**
  - J. R. Meyer, I. Vurgaftman, C. L. Felix, W. W. Bewley, E. H. Aifer, L. J. Olafsen, M. J. Yang, L. Goldberg, D. Zhang, C. H. Lin, S. S. Pei, and D. H. Chow, Mid-Infrared Optoelectronics Material and Devices, (26-27 March, 1998, Prague), "Type-II W, Interband Cascade, and Vertical-Cavity Surface-Emitting Mid-IR Lasers."
  - J. R. Meyer, W. W. Bewley, C. L. Felix, E. H. Aifer, I. Vurgaftman, L. J. Olafsen, M. J. Yang, L. Goldberg, D. H. Chow, H. Lee, and R. U. Martinelli, Optical Society of America Annual Meeting, (4-9 October, 1998, Baltimore), "Type-II VCSEL and Other Novel Mid-IR Lasers."
  - J. R. Meyer, I. Vurgaftman, C. L. Felix, W. W. Bewley, E. H. Aifer,L. J. Olafsen, M. J. Yang, H. Lee, R. U. Martinelli, J. C. Connonlly, A. R. Sugg, and D. H. Chow, Workshop on Middle Infrared (2-15 μm) Coherent Source, (22-26 September, 1998, Cargese, France), "Antimonide Infrared Lasers."
- **Contributed Presentations**
  - M. J. Yang, W. J. Moore, B. R. Bennett, B. V. Shanabrook, and J. O. Cross, MRS 1997 Fall Meeting, (Dec. 1-5, 1997, Boston), "The Growth of Type-II Infrared Laser Structures."
  - J. R. Meyer, W. W. Bewley, L. J. Olafsen, C. L. Felix, E. H. Aifer, I. Vurgaftman, M. J. Yang, L. Goldberg, D. H. Chow, D. Zhang, C. H. Lin, S. S. Pei, 11th Diode laser Technology Conference (2-4 March, 1998, Albuquerque, NM), "Vertical-Cavity, Interband Cascade, and W Mid-IR Lasers."

Output (cont.)

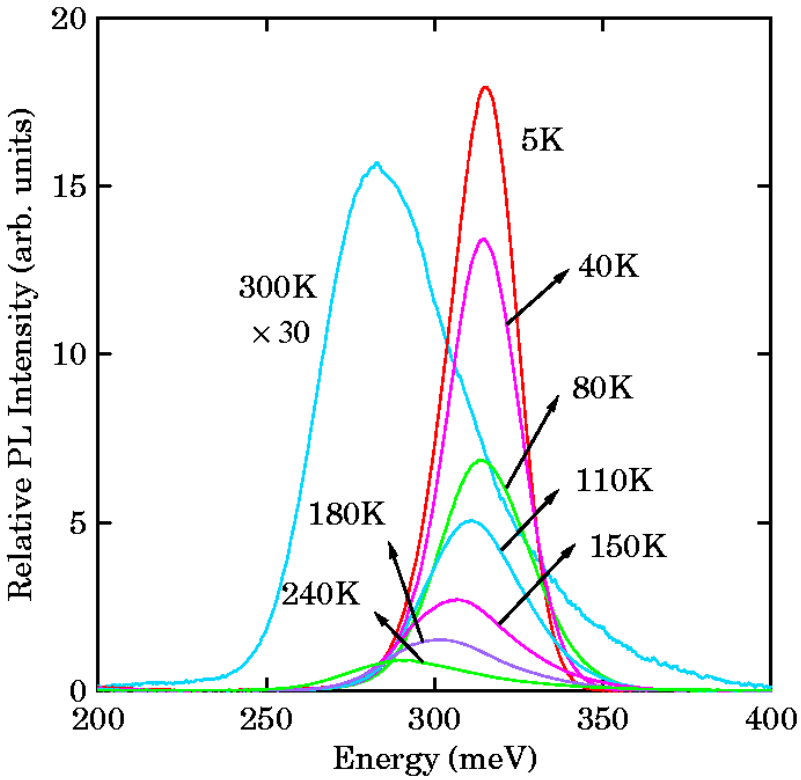
- **Book Chapters**
  - M.E. Twigg, B.R. Bennett, P.M. Thibado, B.V. Shanabrook, and L.J. Whitman, "Interfacial Disorder in InAs/GaSb Heterostructures Grown by Molecular Beam Epitaxy," book chapter in Antimonide Related Strained-Layer Heterostructures, editor: M.O. Manasreh, Gordon and Breach, pp. 55-93 (1997).
  - B.R. Bennett and B.V. Shanabrook, "Molecular Beam Epitaxy of Sb-based Semiconductors," book chapter in Heteroepitaxy: Thin Film Systems, editors: W.K. Liu and M. Santos, World Scientific, in press (1998).

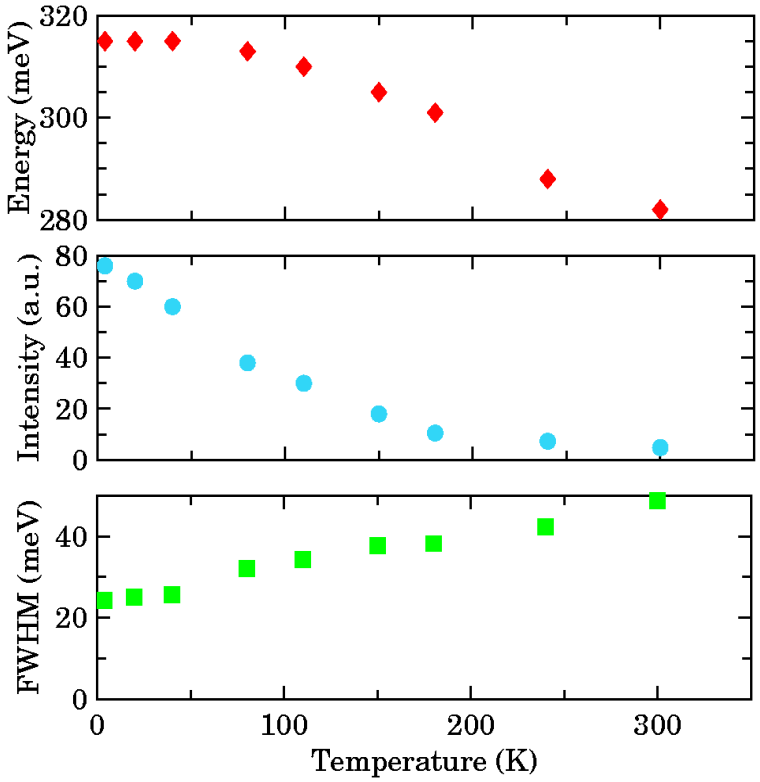
Summary

- MBE Growth temperature is related to laser efficiency
- Developed a transferable temperature standard for growth of laser and detector structures
- Produced record-setting laser performance
- Procedure developed to allow minimization of dislocation generation in p-i-n diodes

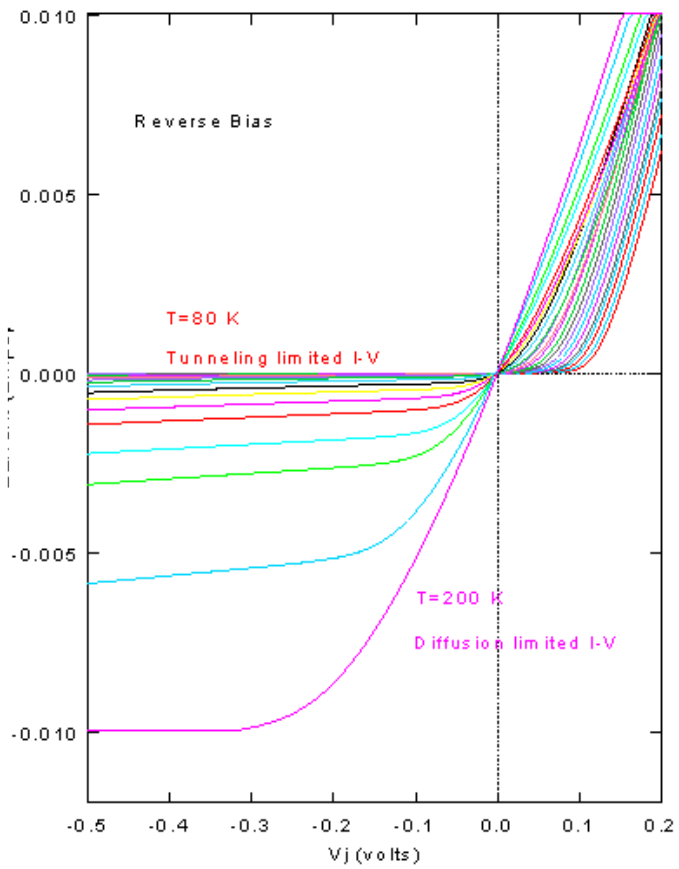
Photoluminescence Measurements from 5 K to 300 K
20 periods of (5.5 - 10 - 5.5 - 14) grown at 420 C

- The type-II band gap increases from 280 meV at RT to 315 meV at 80 K due to the increase of InAs band gap.
- For samples with high luminescence efficiency, the integrated intensity increases 10 to 20 times as the measured temperature is decreased from 300 K to 5 K.
- Above 80 K, the spectrum shows an exponential tail; below 80 K, the width is dominated by inhomogeneous broadening due to interface roughness.

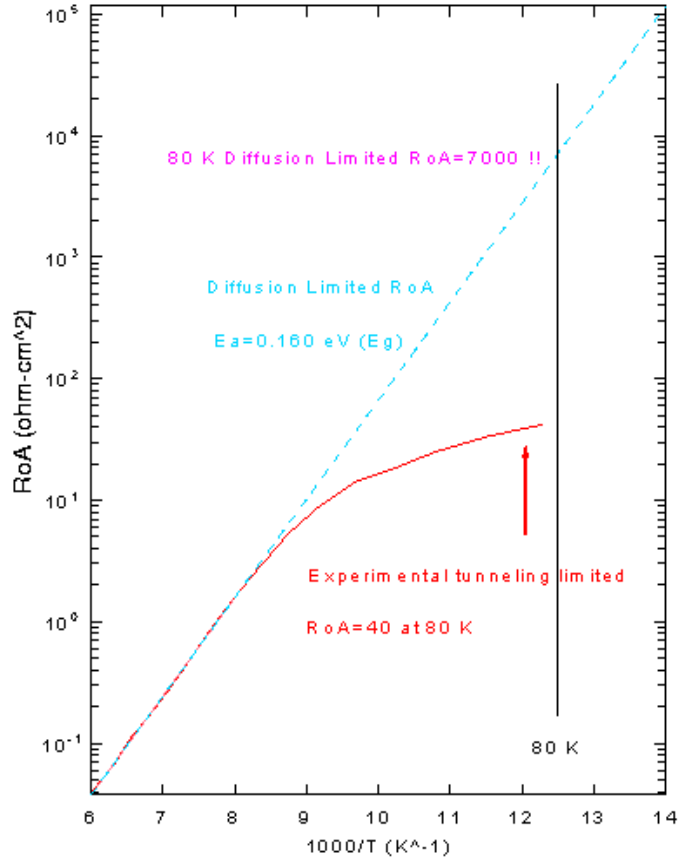




GaSb/InAs Superlattice Long Wavelength Photovoltaic Detectors-Dark Current Mechanisms



λ=8 μm



- High temperature dark current is diffusion limited, low temperature is trap assisted tunneling limited
- R_oA(80K)=40 Ω-cm^2
- D*=1.4x10^{11} cm-Hz$^{1/2}$/W

- Elimination of defect related tunneling mechanism would result in high R_oA's (7000) at 80 K
  - D*= 2x10^{12} cm-Hz$^{1/2}$/W (BLIP at low backgrounds)