LEHIGH UNIVERSITY

Center for Optical Technologies

Type-II InAs/GaSb Superlattices and Quantum Wells

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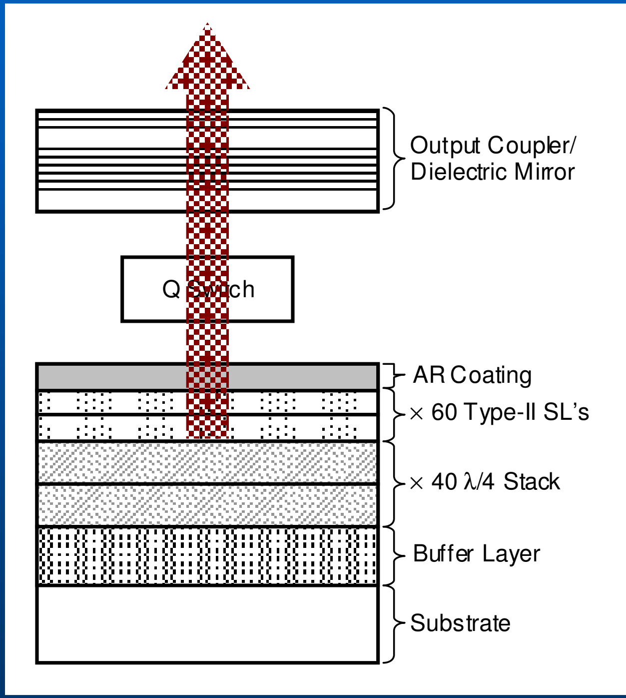
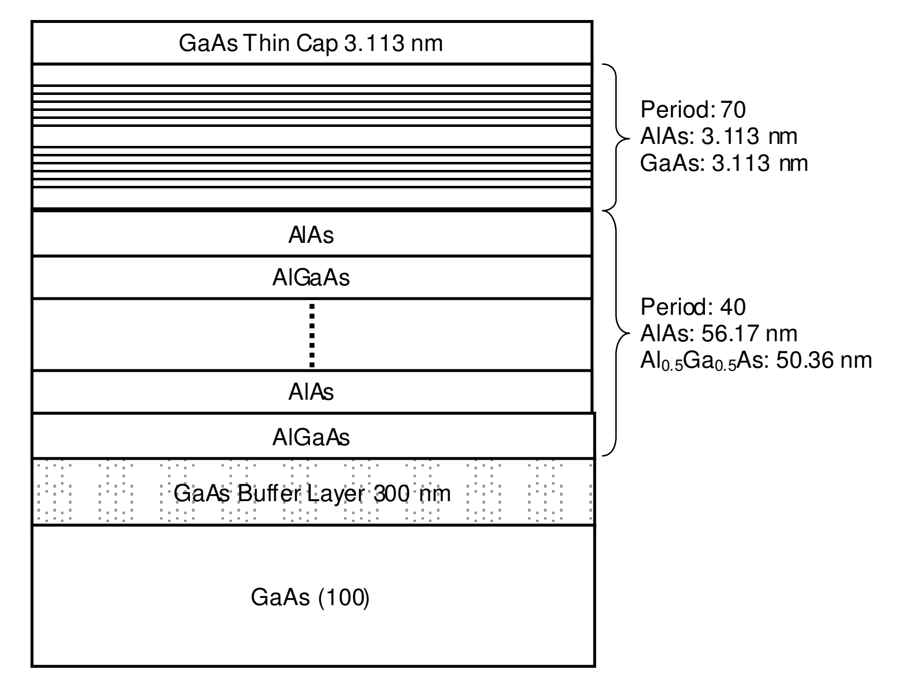
Type-II GaAs/AlAs SL's Optimized for Q-Switched Laser





- This structure was recently grown at University of Arkansas & it is currently being characterized by us

Earlier Work on Type-II InAs/GaSb SL’s During 1980’s

- *Bastard (1981):*
  Calculated minibands formed in InAs/GaSb SL’s
- *Voisin, Bastard, da Silva, Voos (1981):*
  Measured photoluminescence spectra & observed low-energy tail due to impurities & interface defects
- *Chang, Kawai, Mendez, Chang, Esaki (1981):*
  Confirmed semi-metallic SL’s due to existence of zero energy gap
- *Mailhiot & Smith (1989):*
  Demonstrated infrared detectors made from InAs/GaInSb strained-layer type-II SL’s for long wavelengths ($\lambda_c > 10$ μm)

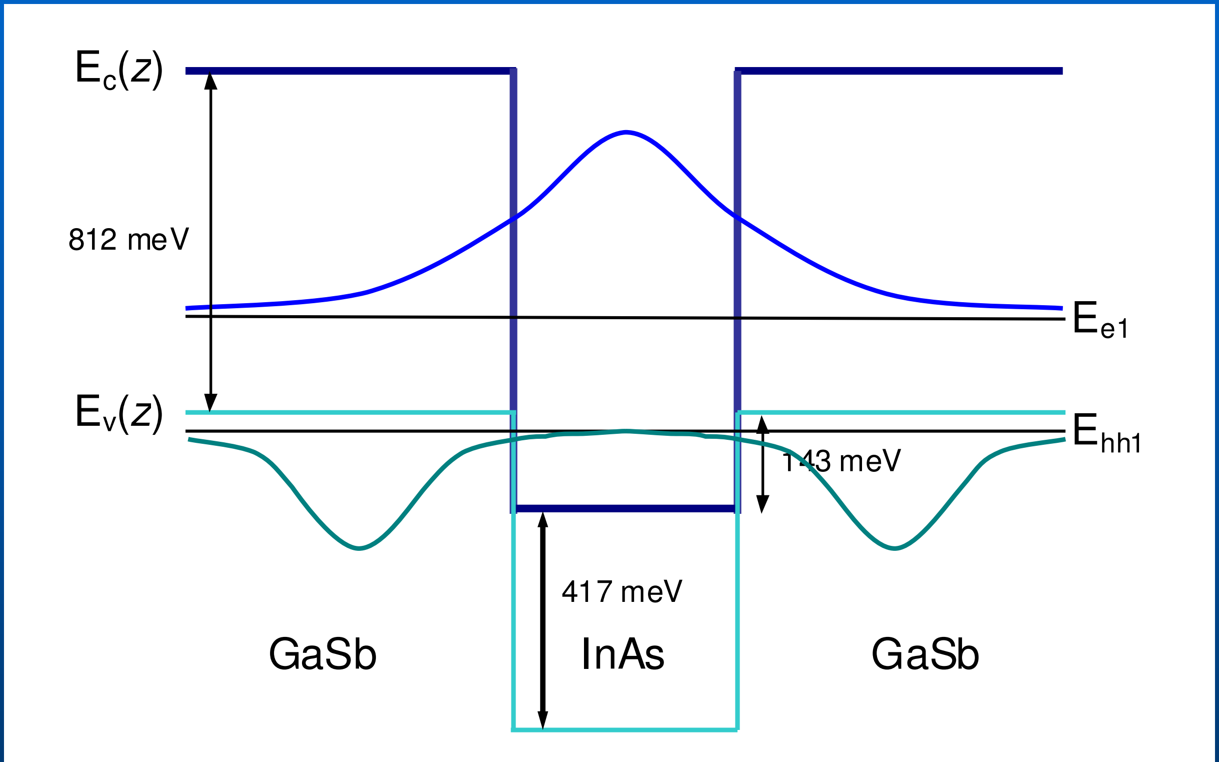
More Recent Work Since 1990

- *Yang & Bennett (1994):*
  Implemented InAs/GaSb infrared photovoltaic detectors at 77 K; 3-8 μm, $R \approx 0.07$ A/W
- *Youngdale, Meyer, Hoffman, Bartoli, Miles, Chow (1994):*
  Measured Shockley-Reed lifetimes 0.13-6 ns; Auger coefficients $\gamma_3 \approx 8\times10^{-25}$ cm^6/s (300 K) & $\gamma_3 \approx 1.3\times10^{-27}$ cm^6/s (77 K)
- *Olafsen, Vurgaftman, Bewley, Felix, Aifer, Meyer, Waterman, Mason (1999):*
  Observed negative luminescence from type-II InAs/GaSb SL photodiodes by extracting majority & minority carriers (cooling effect)
- *Ongstad, Dente, Tilton, Gianardi, Turner (2000):*
  Analyzed PL linewidths in InAs/GaSb/InAs/AlSb type-II coupled QW's (strain-compensated & strong e-h confinement)
- *Ongstad, Kaspi, Moeller, Tilton, Gianardi, Chavez, Dente (2001):*
  Observed spectral blueshift & improved luminescence intensities with increasing GaSb layer thickness in InAs/GaSb type-II SL's
- *Wei, Gin, Razeghi, Brown (2002):*
  Implemented InAs/GaSb type-II SL photovoltaic detector; cut-off wavelength of 25 μm; operating temperature of 34 K
  (approaching THz region: 30-3000 μm)

Unique Structures & Properties of Type-II InAs/GaSb SL's

- Peculiar band alignment: bottom of InAs conduction band is 143 meV below top of GaSb valence band:
  Electrons in InAs; holes in GaSb (spatially separated)
- Effective mass $m_e^* \approx 0.026 m_0$ – extremely light electron mass of InAs ($\boldsymbol{m_e^*} \approx 0.067 \boldsymbol{m_0}$ for GaAs): much wider miniband for SL, e.g. bandwidth ≈ 190 meV for 2.5-nm InAs/2.5-nm GaSb SL's
  - ➨ *Quasi-3D character of SL's; density of states – much lower compared with GaAs/AlAs*
- Exciton binding energy ≤ 1 meV:
  Exciton effects – negligible for most structures
- Heavy-hole confinement energy predicted by standard envelope-function approximation – much higher than measured value
  e.g. *Haugan, Szmulowicz, Brown, Mahalingam (2004):*
  Interface coupling of heavy, light, and spin-orbit holes resulting from in-plane asymmetry at InAs/GaSb interfaces
  - ➨ *Time-resolved PL may confirm such hypothesis!*

Electron & Hole Wave Functions



- Electrons & holes – spatially separated (type II)
- Effective mass for InAs – extremely small
- Exciton binding energy ≤ 1 meV

ARL Interest

- InAs/GaSb SL's as infrared detectors in mid-IR region for night vision

Lehigh Team

- Optical properties
- Time-resolved PL to determine nature of carrier relaxation & recombination processes
- Cooling by absorbing phonons and/or removing carriers
- THz emitters & detectors (e.g. RTD)

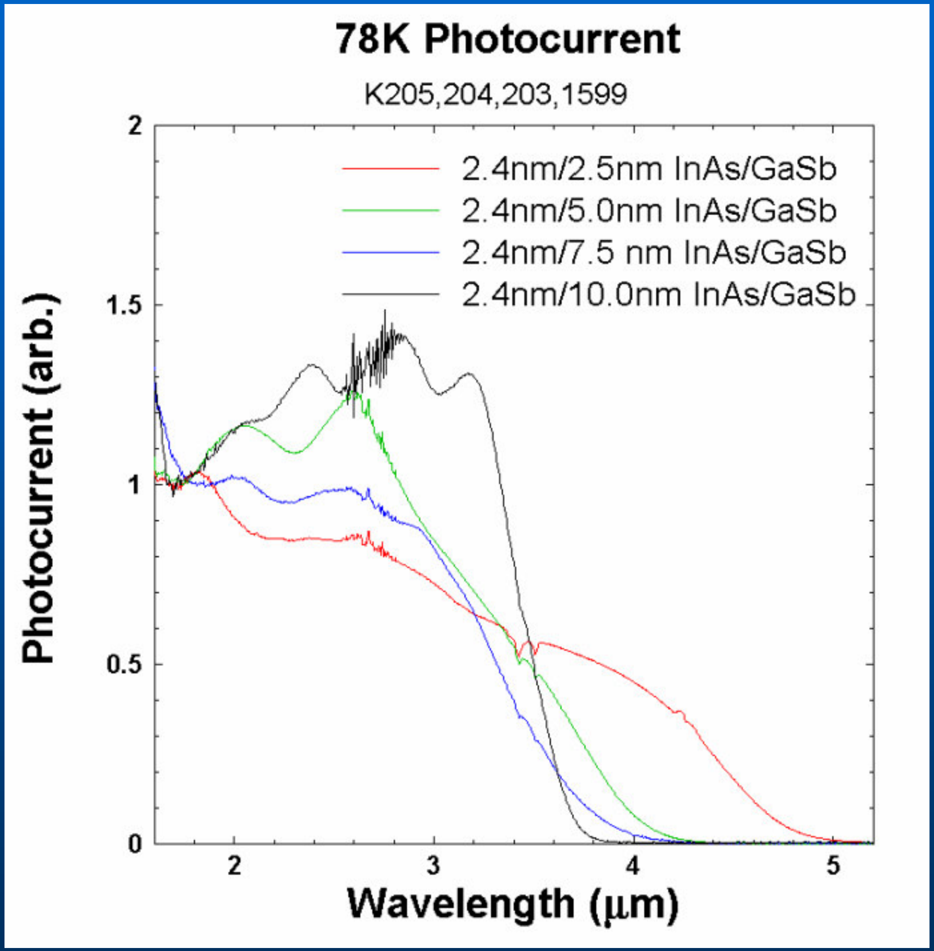
ARL/Lehigh Collaboration

- To gain fundamental understanding of optoelectronic processes in InAs/GaSb type-II SL's, and therefore, to improve performances of mid-IR/THz emitters & detectors

Type-II InAs/GaSb Structures Grown at ARL & Studied by ARL/Lehigh Team

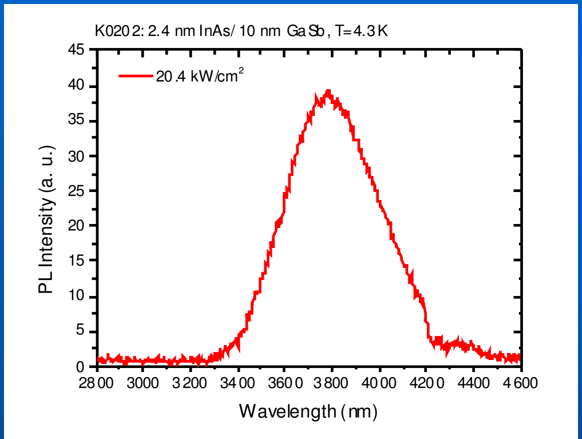
Sample #	InAs Width (Å)	GaSb Width (Å)
K0202	24	100
K0203	24	75
K0204	24	50
K0205	24	25
K0288	22.5	100
K0290	40.3	100
K0291	45.2 (h)	100
K0294	45.2 (ℓ)	100

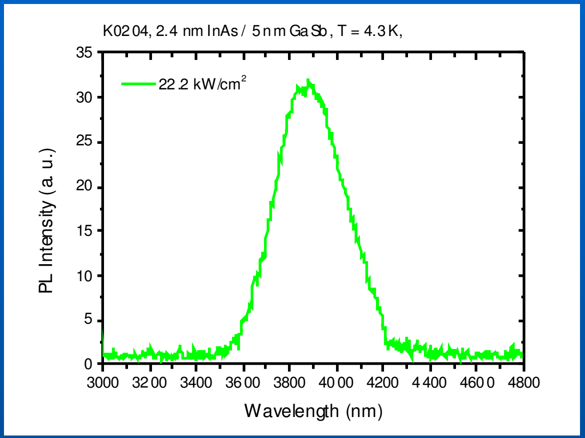
Photocurrent Spectra (ARL)

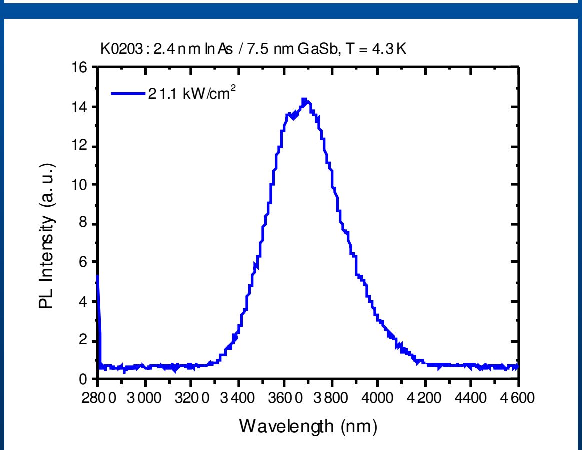


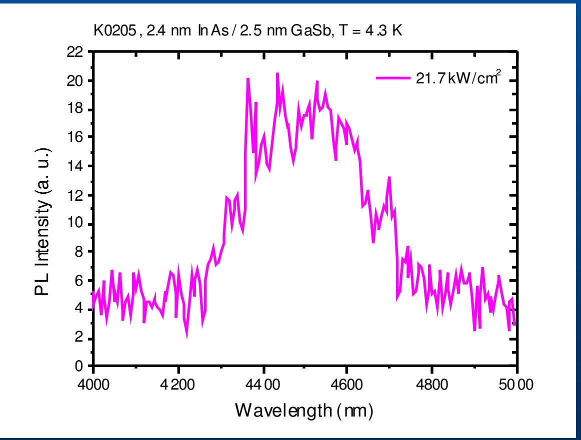
- With increasing GaSb layer thickness, band-edge becomes sharper and sharper

PL Spectra of Type-II InAs/GaSb SL's with Same InAs Width But Different GaSb Widths





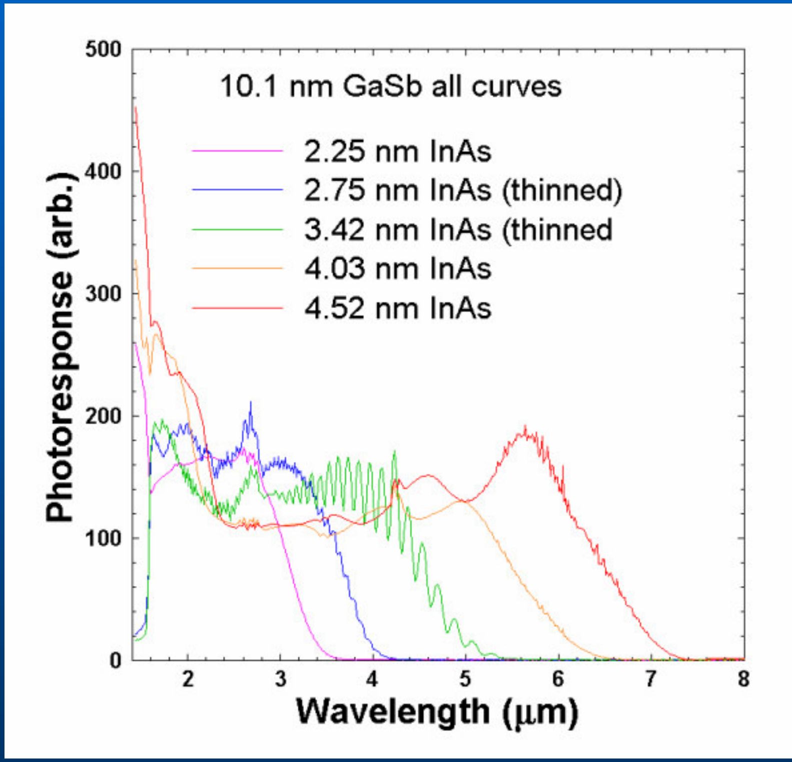


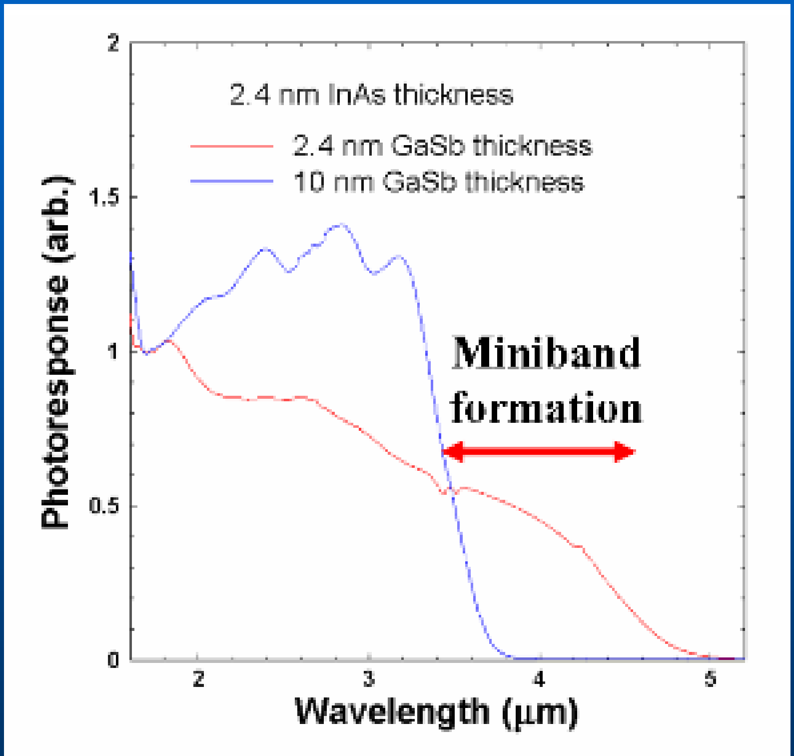


- With increasing GaSb layer thickness, PL peak is blue-shifted whereas PL intensity is enhanced, similar to *Ongstad, Kaspi, Moeller, Tilton, Gianardi, Chavez, Dente (2001).*

Photocurrent Spectra (ARL)

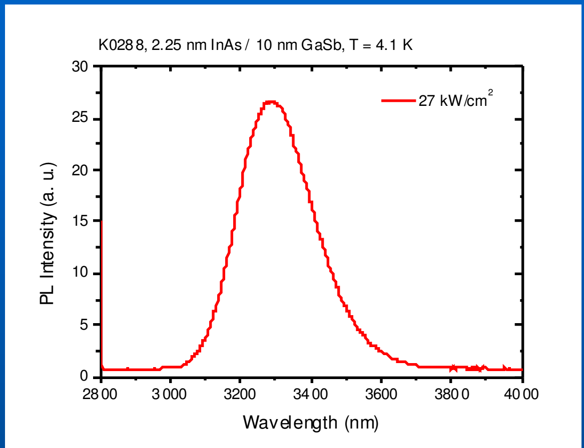
T = 78 K

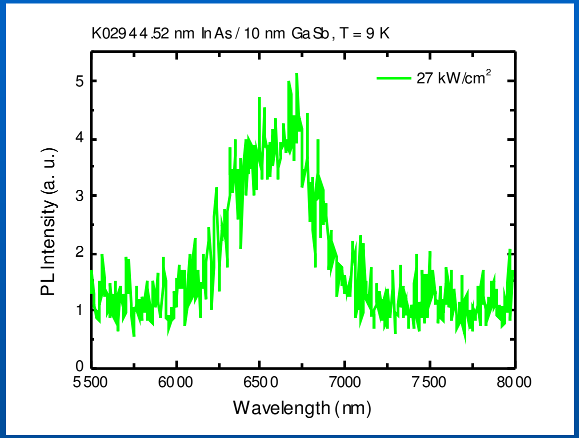


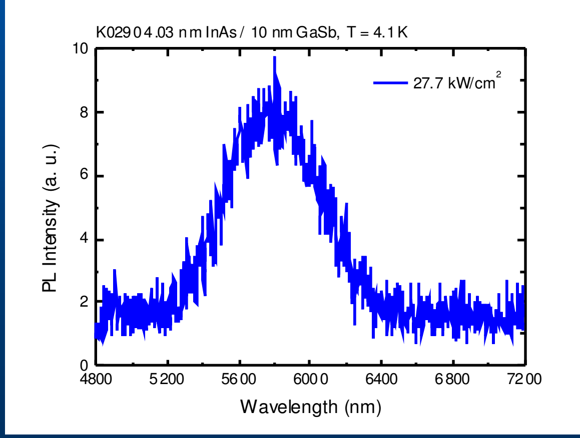


- With increasing InAs layer thickness, band-edge is red-shifted

PL Spectra of Type-II InAs/GaSb SL's with Same GaSb Width but Different InAs Widths

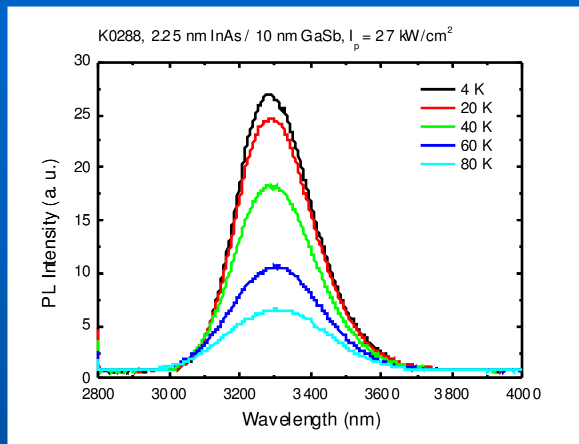


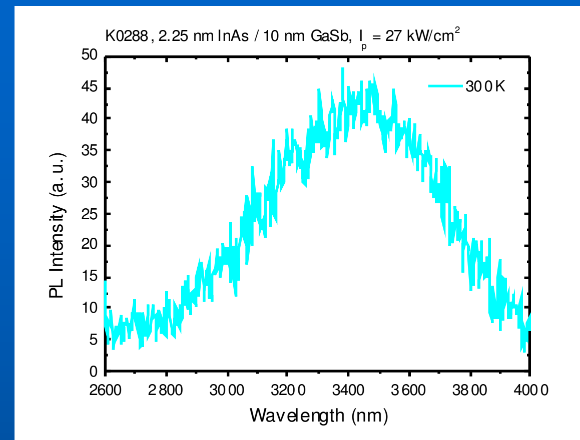


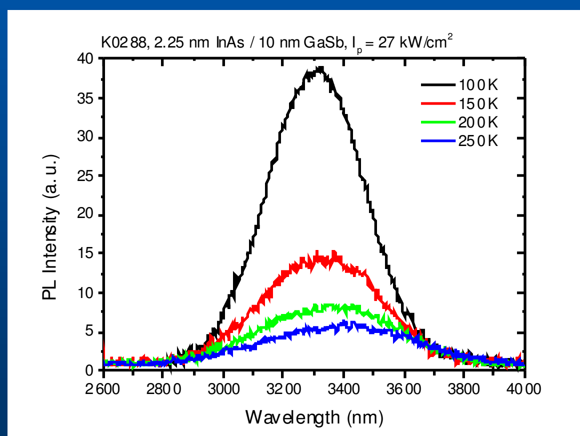


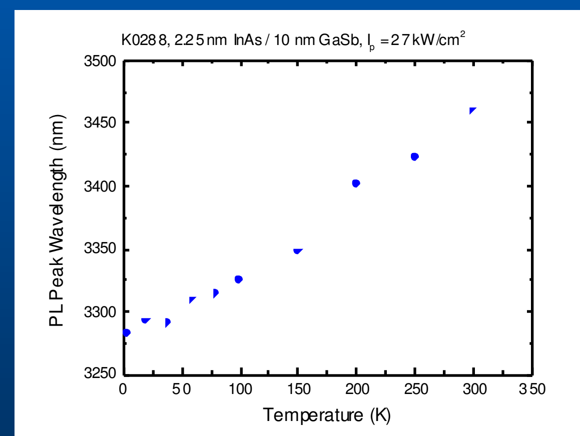
- With increasing InAs layer thickness, PL peak is red-shifted whereas PL intensity is decreased

Temperature Dependence of PL Spectrum



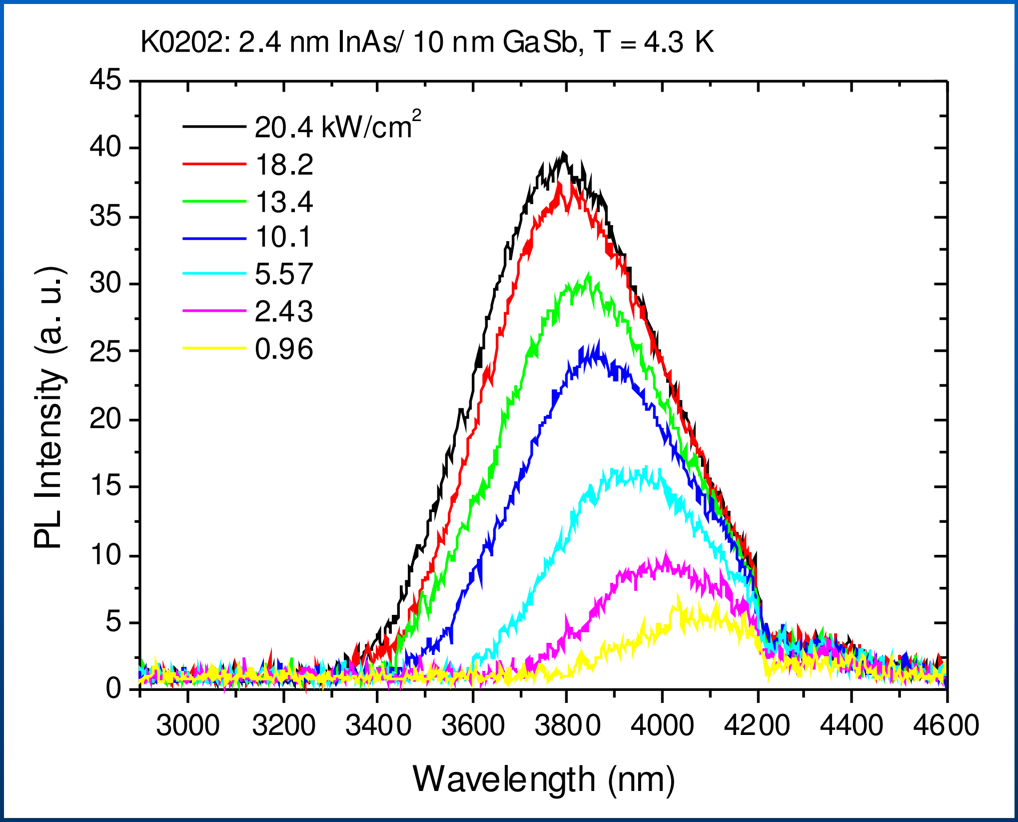






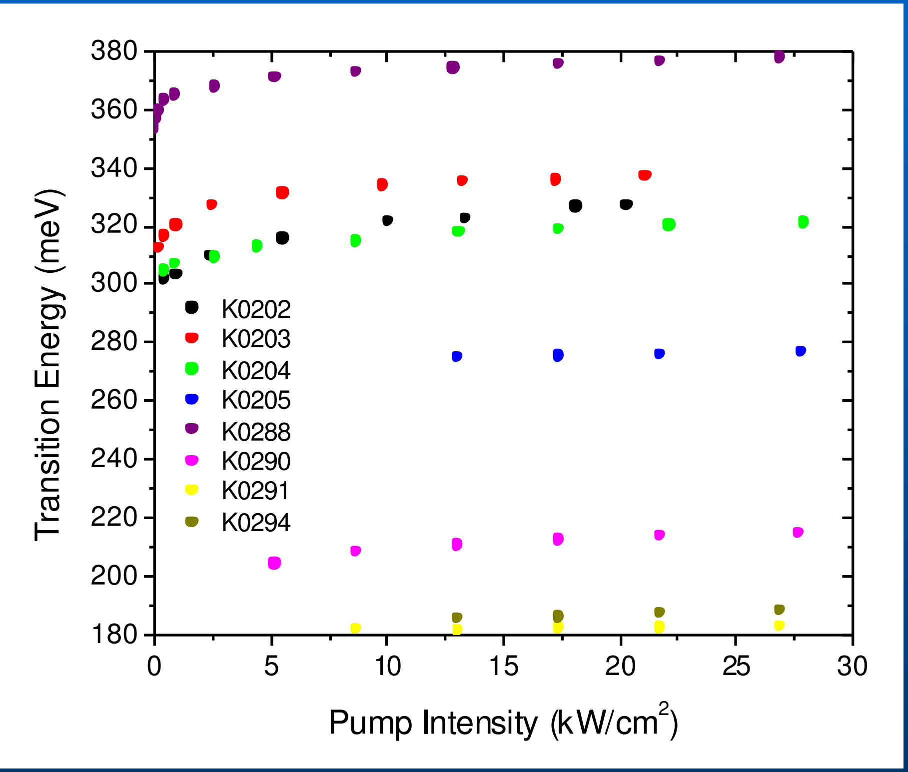
- Below 150 K, PL peak is linearly red-shifted as temperature is increased
- Above 150 K, PL peak is more dramatically red-shifted as temperature is increased
- PL strength is significantly reduced as temperature is increased

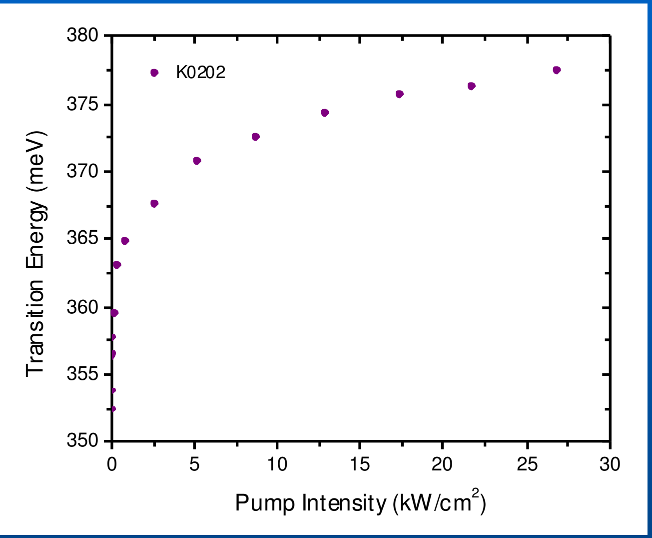
PL Spectra at Different Pump Intensities: Observation of Anomalously Large Band-Filling Effects



- Define intensity range for linear response of mid-IR detectors & output power of mid-IR emitters

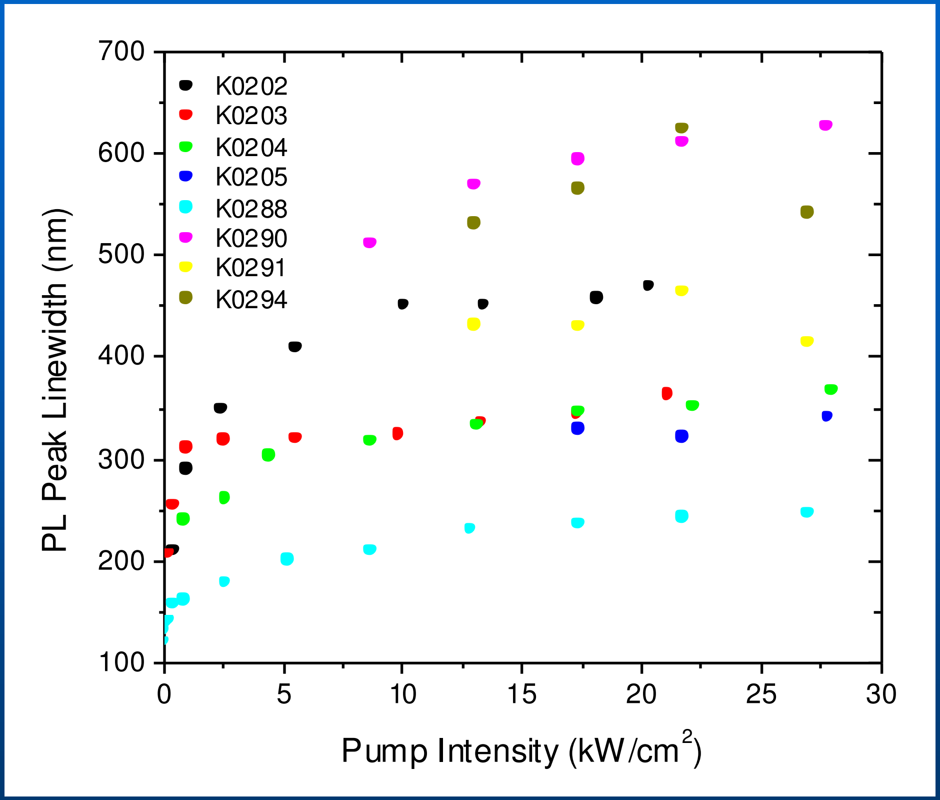
Peak Transition Energy vs. Pump Intensity





- Largest shift: 25.4 meV for 2.4 nm InAs/10 nm GaSb, K0202, (2D)
- Smallest shift: 1.82 meV for 2.4 nm InAs/2.5 nm GaSb, K0205, (quasi-3D)
- Shifts exhibit strong saturation much faster than linear dependence

PL Linewidth vs. Pump Intensity



- Largest linewidth increase: from 210 nm to 470 nm for 2.4 nm InAs/10 nm GaSb (K0202)
- Smallest linewidth increase: from 330 nm to 341 nm for 2.4 nm InAs/2.5 nm GaSb (K0205)

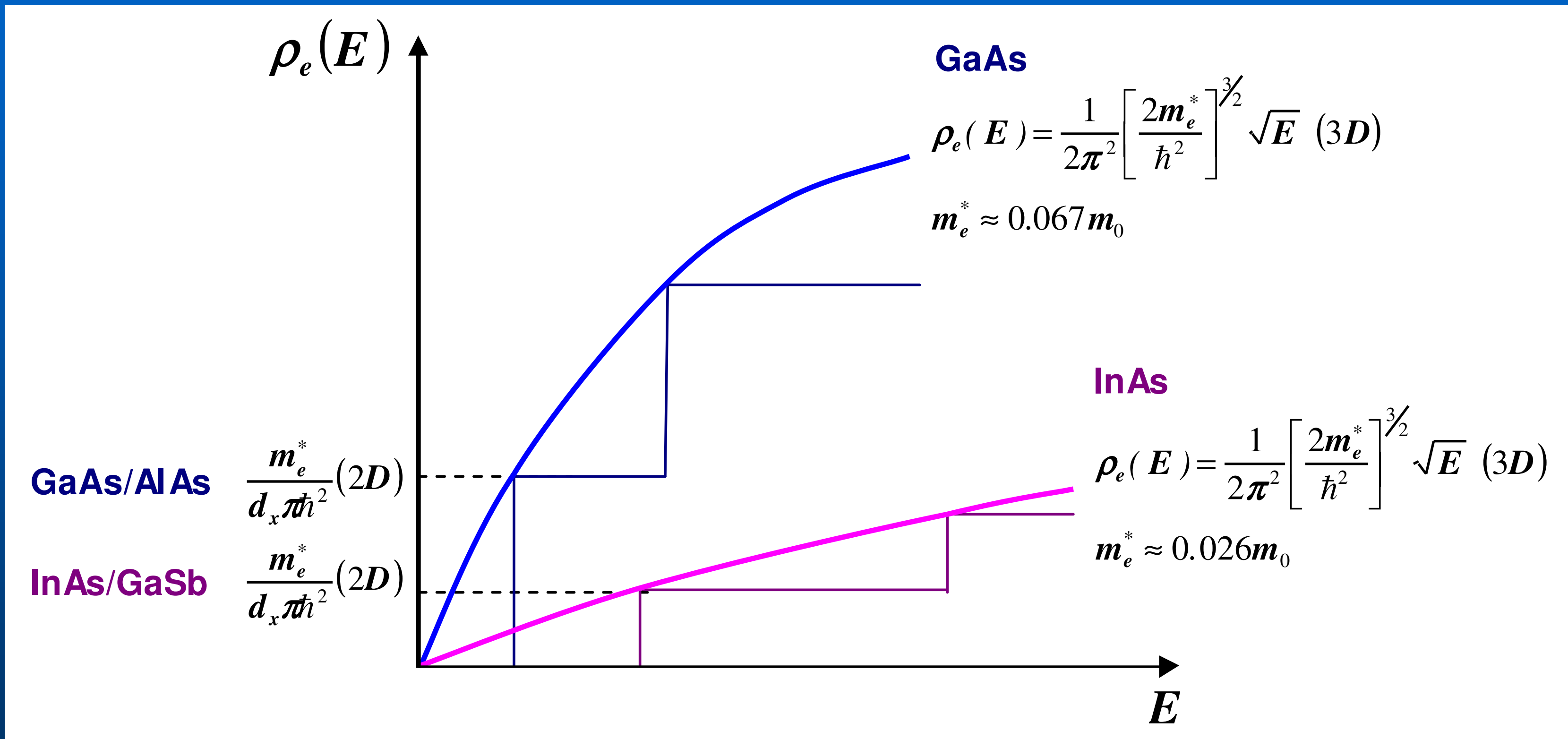
Why Do Type-II InAs/GaSb SL's Exhibit Anomalously Large Band-Filling Effects?

- Extremely light electrons (mass ≈ 0.026 m_0)
  ⇒ Density of states – reduced compared with type-II GaAs/AlAs SL's

- Density of states:
  If electron wave function spreads over many periods, miniband – widen
  ⇒ $\rho_e(E) \propto (0.026\ m_0)^{1.5}\ E^{0.5}$ (increase as energy is increased)
  ⇒ Reduced band-filling effect

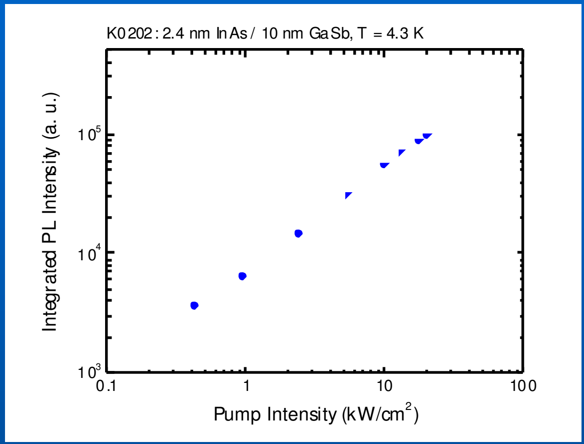
  If electron wave function – more localized in one unit, miniband – reduced to zero
  ⇒ $\rho_e(E) \propto (0.026\ m_0)^{1}\ E^{0}$ (independent of energy)
  ⇒ Enhanced band-filling effect

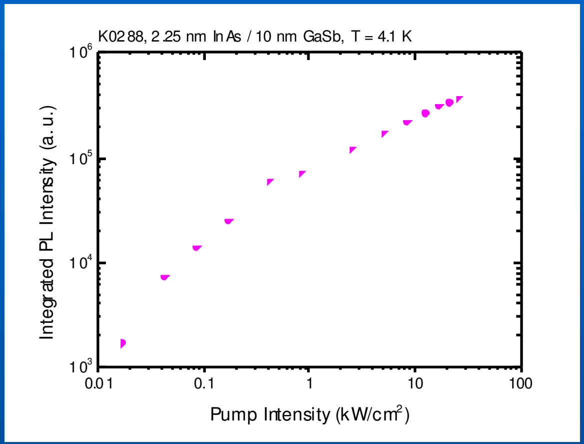
Densities of States for Electrons

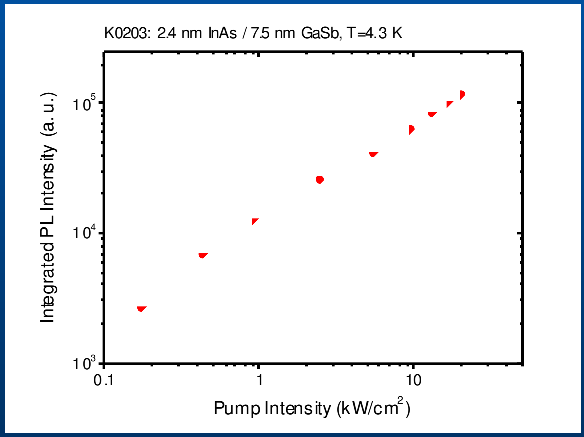


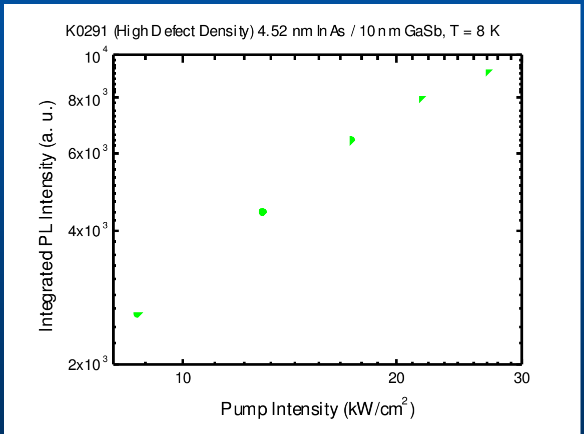
- For 3D, density of states – reduced by a factor of 4.14 compared with type-II GaAs/AlAs SL's: pronounced band-filling effect – observed even in CW regime!

Integrated PL Intensity vs. Pump Intensity: Radiative vs. Nonradiative Recombination



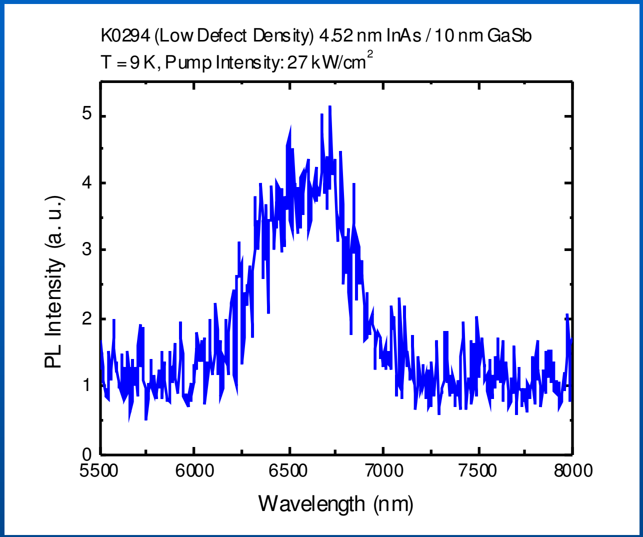


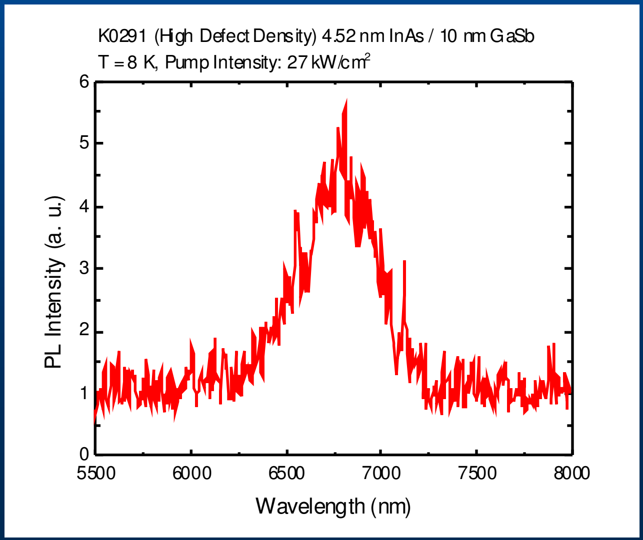




- Linear – radiative recombination dominates (2.4 nm/10 nm)
- Sub-linear (2/3) – nonradiative (Auger) recombination dominates (2.4 nm/7.5 nm & 2.25 nm/10 nm)
- Square – nonradiative recombination at interface & barrier traps (4.52 nm/10 nm)

Comparison between PL Properties of Low & High Defect Densities





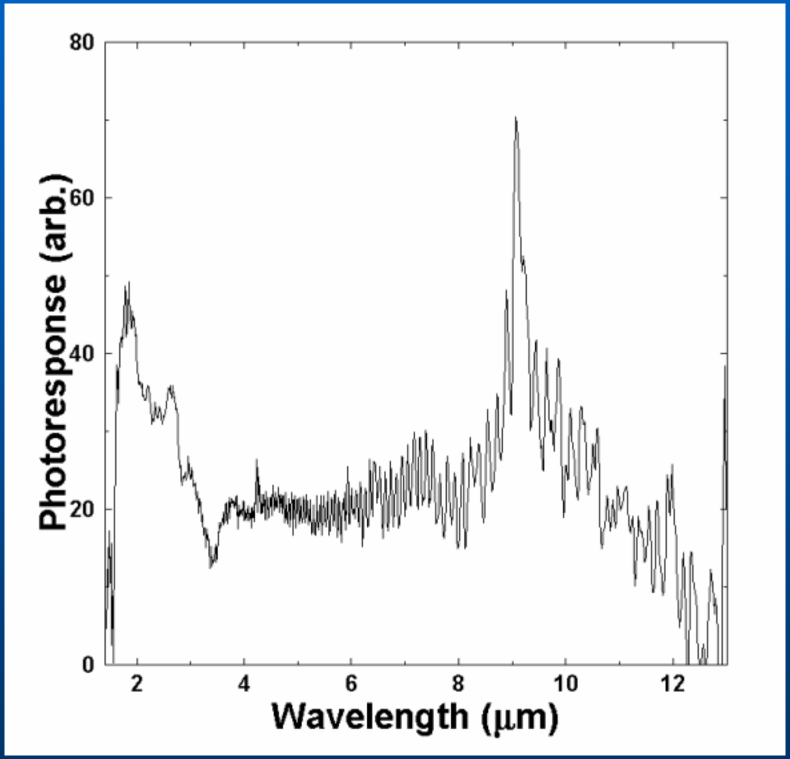
- PL peak has shoulder at short-wavelength side for sample with low defect density (2 transitions)
- PL linewidth for each transition is probably narrower for sample with low defect density
- Total PL intensity is lower for sample with high defect density due to nonradiative recombination at defects
- Dependence of PL intensity on pump intensity for sample with high defect density is between linear and square

Most Recent Result on New Type-II InAs/GaSb Structures

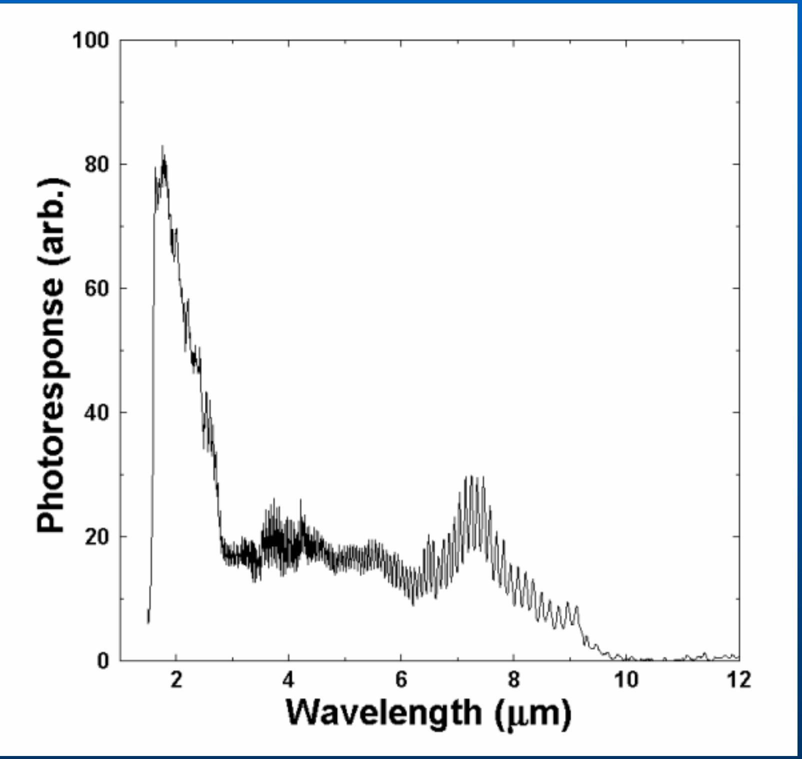
Sample #	InAs Width (Å)	GaSb Width (Å)
K0323	65	100
K0325	55	100

Photocurrent Spectra (ARL) at 78 K

65 Å InAs/100 Å GaSb



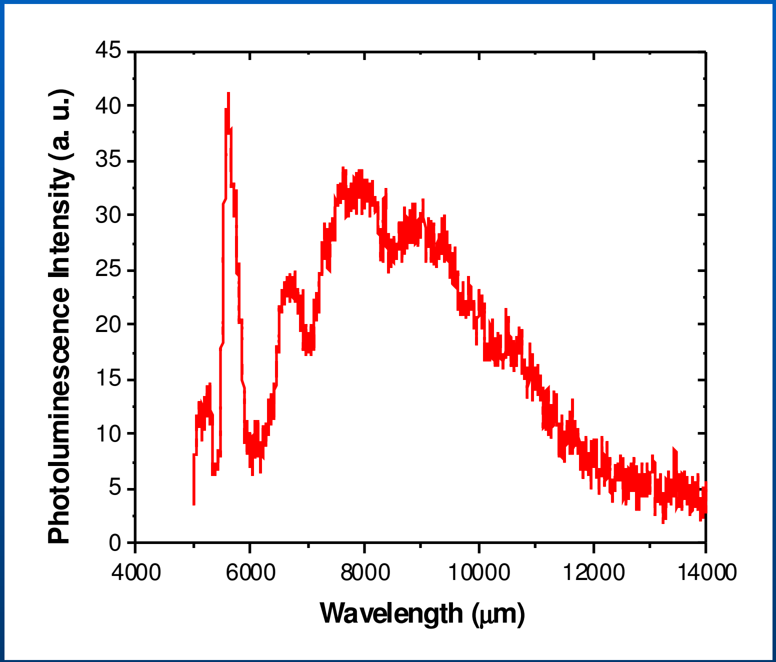
55 Å InAs/100 Å GaSb



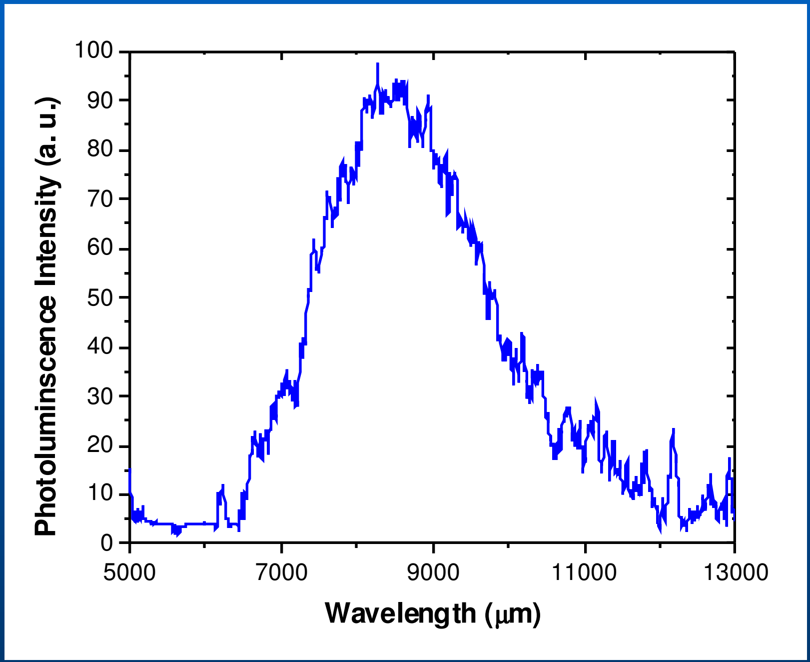
- Periodic modulations – Fabry-Perot effect due to multiple reflections between bottom & top surfaces

Photoluminescence Spectra at 4.3 K

65 Å InAs/100 Å GaSb



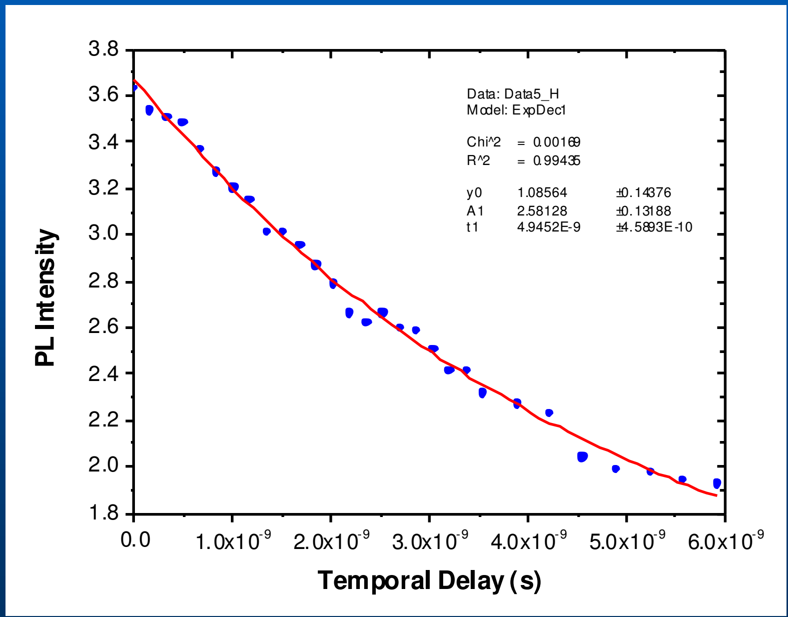
55 Å InAs/100 Å GaSb



- Transition peaks at 9 µm & 10.5 µm – perhaps saturated due to high pump intensity
- PL intensity is much weaker for 65 Å InAs/100 Å GaSb (K0323)

First Measurement of Carrier Recombination Times

- Using slow photodetector, to measure time-integrated PL intensity generated by probe beam as a function of temporal delay between probe and pump beams



- Carrier recombination time – measured to be ~ 2.5 ns for 22.5 Å InAs/100 Å GaSb QW’s (K0288).

Next Step

- To develop theory for anomalously large band-filling effects observed by us in InAs/GaSb type-II structures
- To investigate carrier dynamics: to find out whether interface potentials affect energies of heavy holes, carrier relaxation & recombination processes
- To measure PLE spectra: to determine transition strengths
- To achieve cooling effect: to use phonons to enhance cooling rate
- To fabricate and test THz detectors & emitters: by optimizing InAs/GaSb type-II structures, it is possible to detect & emit radiations in any region of electromagnetic spectrum from mid-IR to THz

Conclusion

- Anomalously large band-filling effects – observed: Define linear-response range of mid-IR detectors & output powers of mid-IR emitters
- Dependence of band-filling effects on GaSb & InAs widths – investigated
- Dependence of integrated PL intensity on pump intensity – studied: Radiative recombination vs. nonradiative recombination at interface & barrier traps and Auger
- Effect of defect density on PL spectrum – investigated
- Comparison between photocurrent & PL spectra – made
- Carrier recombination times – measured

Publication

- So far, one presentation in collaboration with ARL (Dr. John Little) at CLEO 2005, Baltimore, next week