Progress in Type-II Superlattice Diodes for LWIR Focal Plane Arrays

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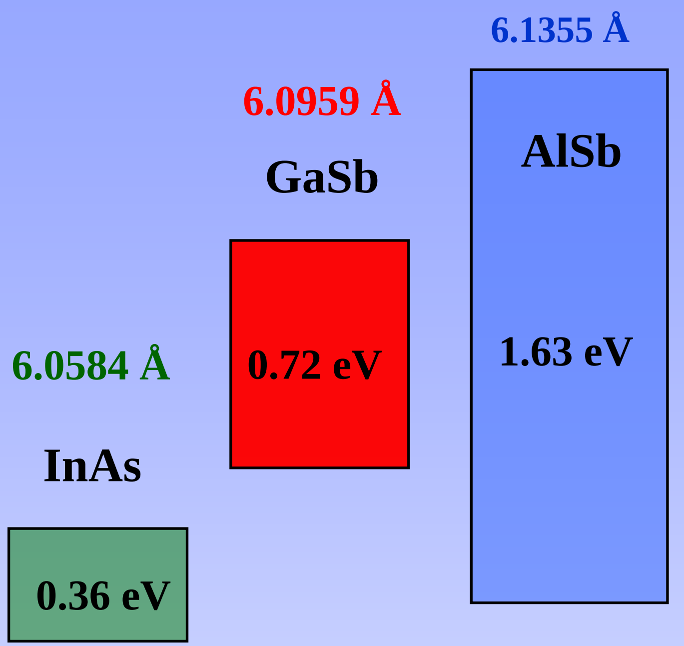
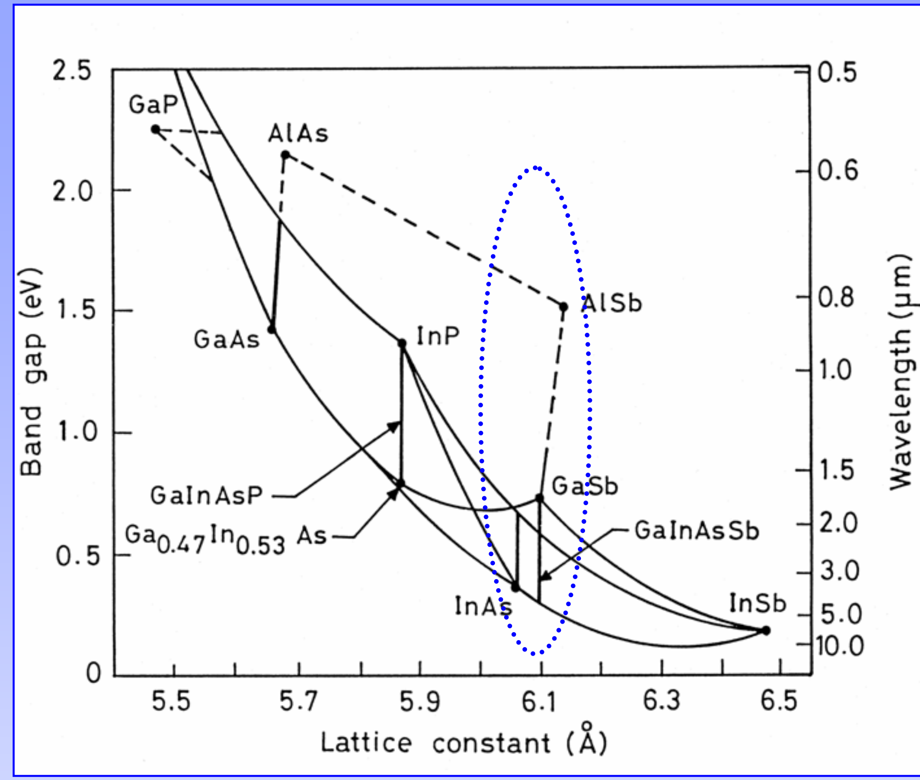
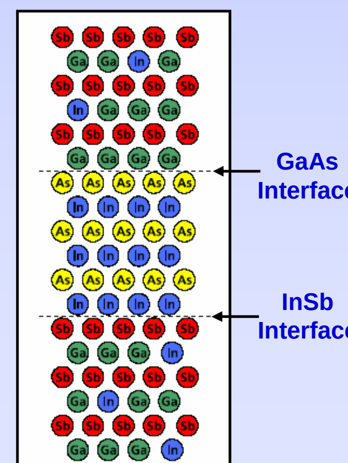
Making Superlattice Material



Type-II band gaps & alignments

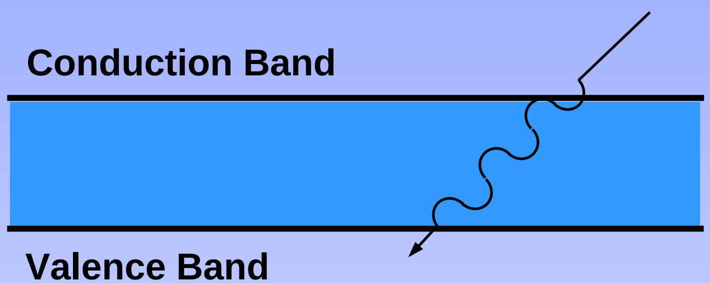


- Start with GaSb substrates
- Deposit alternating layers of InAs and Ga(In)Sb with atomic layer precision using MBE
  - Compensate net strain with alloying or interface engineering
- Form a p-i-n detector structure by doping the superlattice layers with trace amounts of Be, Te, or Si
- Conceptually simple process
  - Requires complicated capital equipment

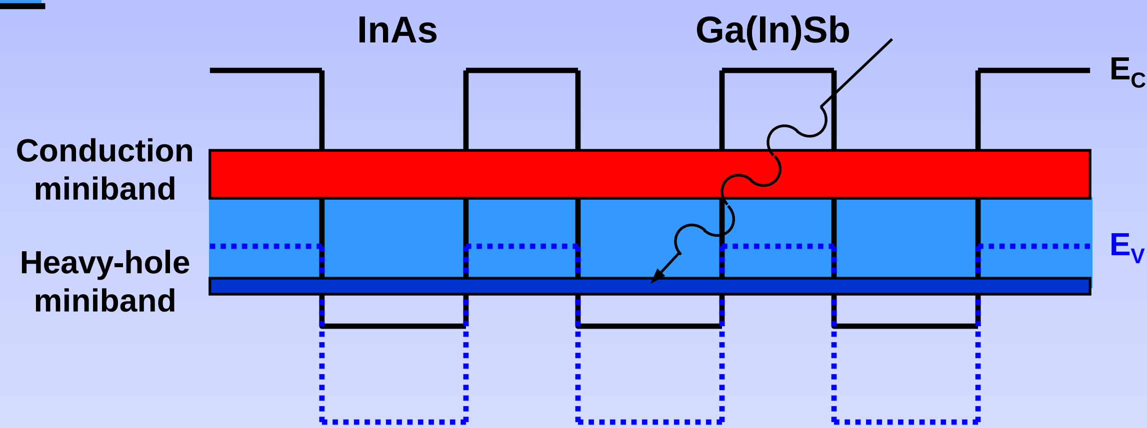


Infrared Detector Structures

Conventional Intrinsic Infrared Photodetector



Schematic Band Diagram of a Superlattice



Disadvantage

- No Lattice Matched Substrates
- Difficult to Grow & Process
- Mid-Gap Metastable Traps
- Radiation Soft

Advantage

- Lower Cost Substrates
- Ease of Wavelength Tunability
- Higher Operating Temperature
- Higher Uniformity

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Advantages of Superlattice Detectors

Superlattice Characteristic	Advantage	Tangible Benefit to FPAs
Band structure engineering	Suppress Auger related dark current	Higher operating temperature
Large electron effective mass	Smaller leakage currents	Higher detectivity
Interband transitions	Normal incidence absorption	High quantum efficiency (fast arrays)
Adjustable bandgap	Tunable cutoff from 3 to 20µm	Multicolor capability
III-V semiconductor based	Highly uniform	Cheap, robust, uniform

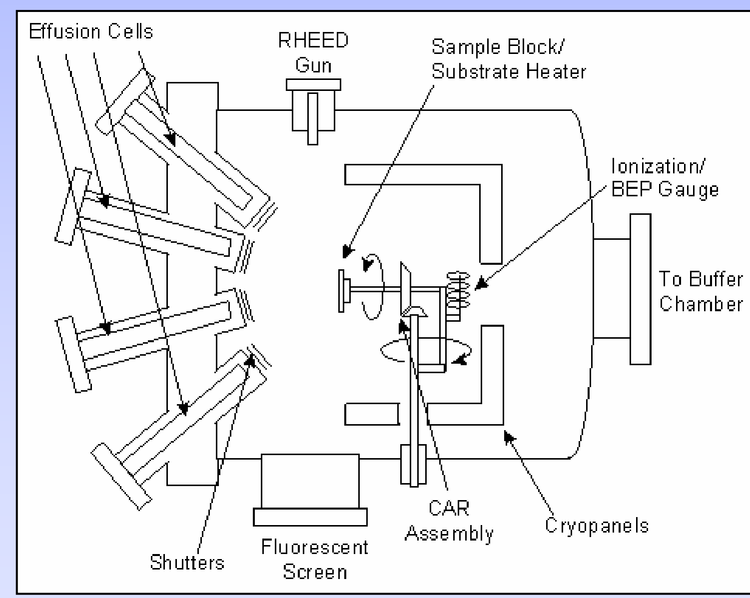
- **Bandgap tunable in the complete infrared spectral range (3 - 20 µm)**
- **Low tunneling currents**
  - **higher detectivity**
- **High responsivity (quantum efficiency) at normal incidence**
  - **short integration times**
- **Produced by MBE-growth:**
  - **High design freedom: Dual-color devices, heterodiodes, etc…**
  - **No alloy fluctuations - excellent homogenity**
    - **Translates to high uniformity FPAs**
  - **No cluster defects**
- **III-V processing**
  - **High-quality GaSb substrates commercially available**
    - **2 and 3” substrates are an order of magnitude less expensive than MCT substrates**

MBE Growth of Superlattices

- Use a 22Å GaSb/ 48Å InAs superlattice
- Heat bulk sources to evaporate (sublime) atomic species
- Fluxes form a “molecular beam” which impinges on the substrate and take the appropriate lattice sites
- Group V’s:
  - As, Sb
- Group III’s:
  - Ga, In, Al
- Dopants:
  - Si, Be, GaTe
- Atomic layer precision
- Same system used for QWIP and Qdot FPAs, as well as superlattices and antimonide interband cascade lasers

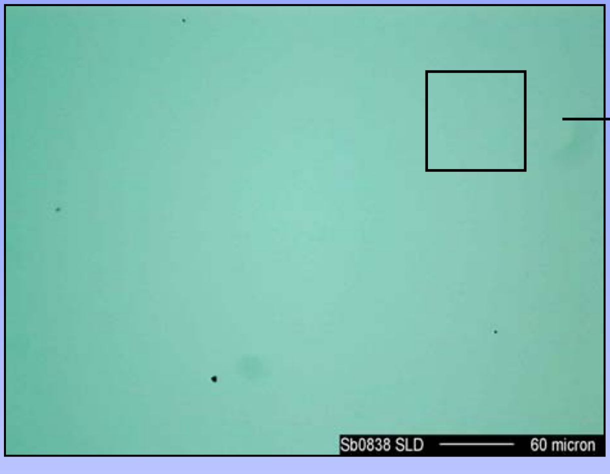
200Å n^+ ($5e10^{18}cm^{-3}$) InAs:Te contact layer
80 period n-superlattice InAs:Te 5e18
200 period intrinsic superlattice
80 period p-superlattice GaSb: 2e18
500nm p^+ (5e18) GaSb:Be contact layer
p ($\sim10^{17}cm^{-3}$)GaSb substrate

Superlattice device structure

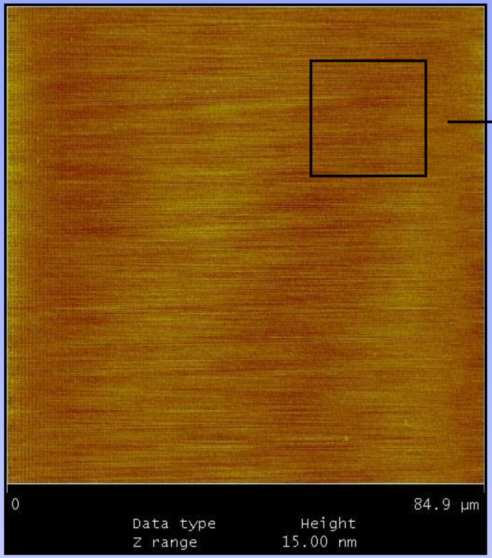


Schematic of an ultra high vacuum MBE chamber

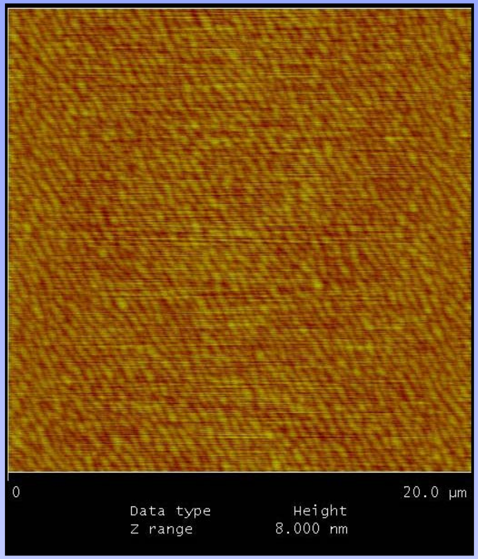
SL Surface Analysis



Optical microscopy



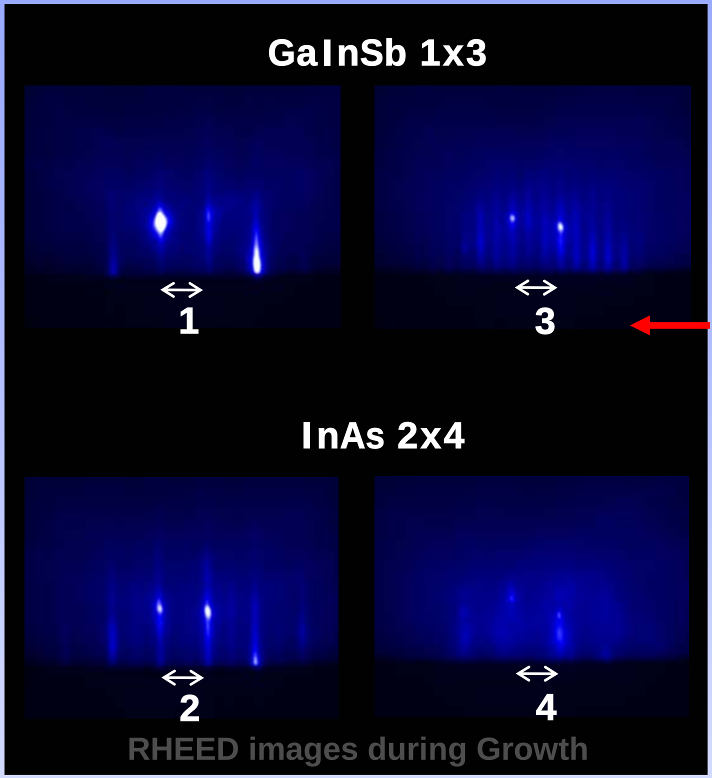
Atomic Force Microscopy
85µm x 85µm



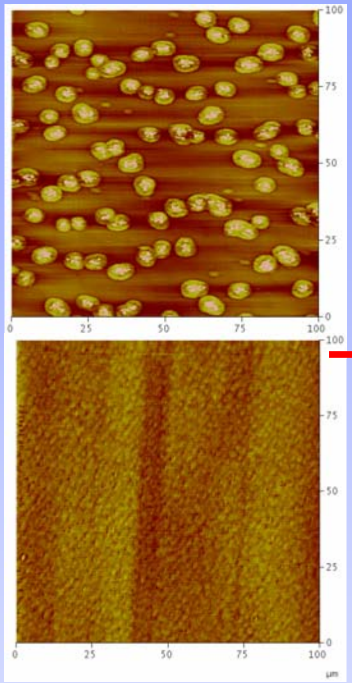
Atomic Force Microscopy
20µm x 20µm

- **Progression from large area optical microscopy (left) to single-pixel sized AFM scan (right)**
- **These are the type of results one wants to see**
  - **Low density of large defects (epi spits, non-epi dust, etc.)**
  - **Large area AFM scans without large epitaxial defects**
  - **High resolution images showing roughness on the order of a few atomic layers**

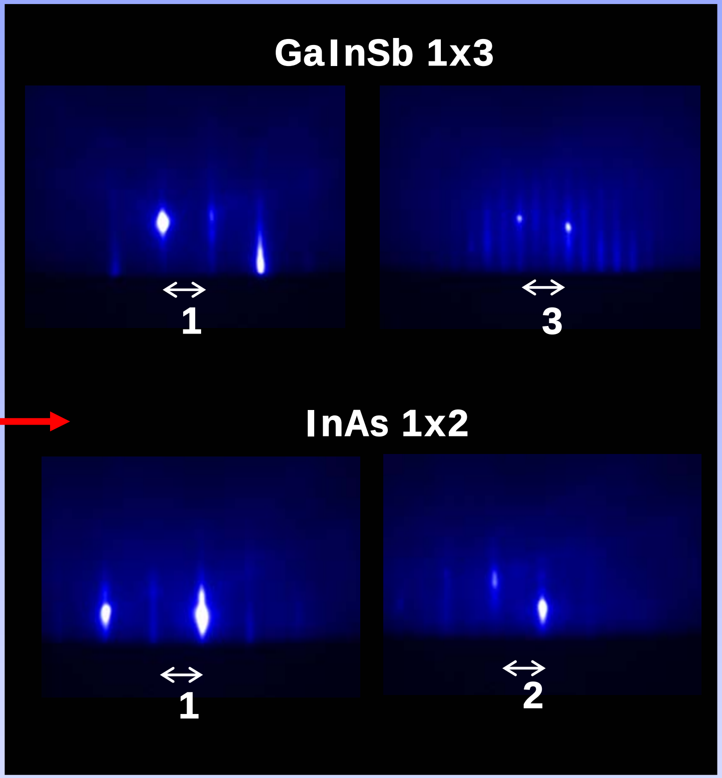
MBE Growth Optimization



AFM defect density
8.4×10^5 cm^{-2}



Optimized recipes
with 1 nm RMS
roughness



- **Crystal quality is excellent in a wide temperature range**
  - **We use $T_{substrate}$ ~ 400°C**
- **Necessary to optimize the III-V flux ratios (e.g. In and As)**
  - **Immediate feedback into the surface evolution trough RHEED**

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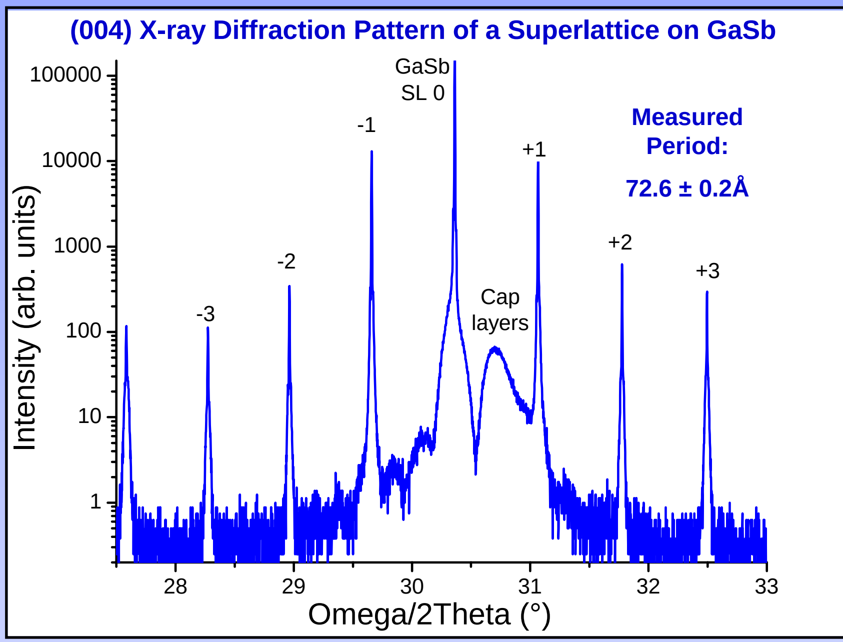
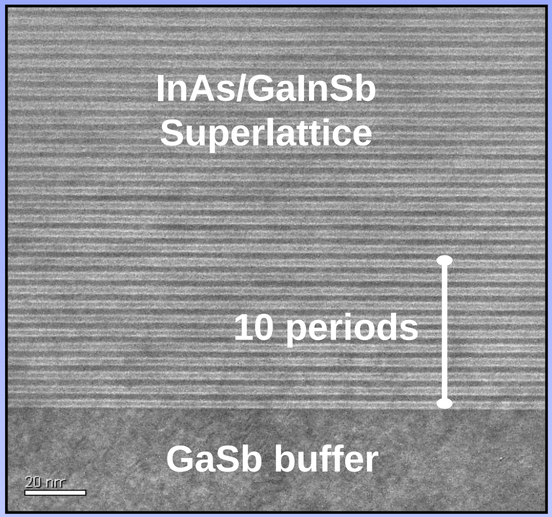
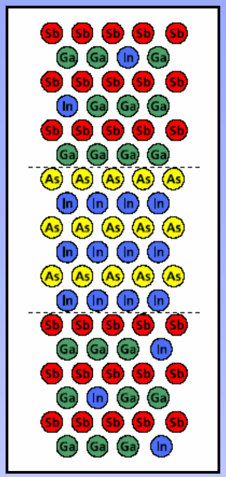
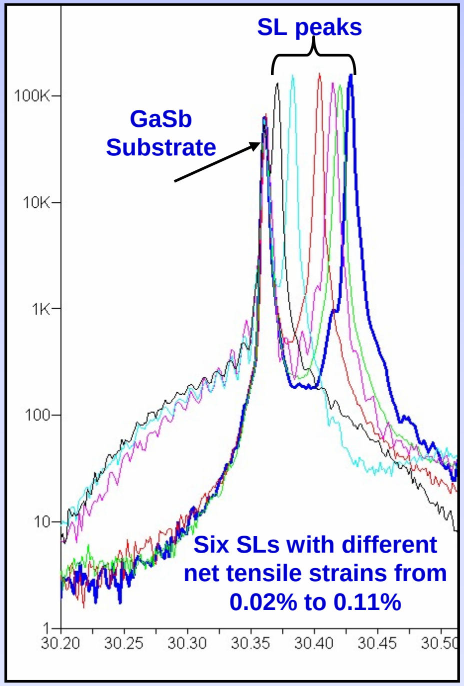
Analyzing Superlattices – X-ray





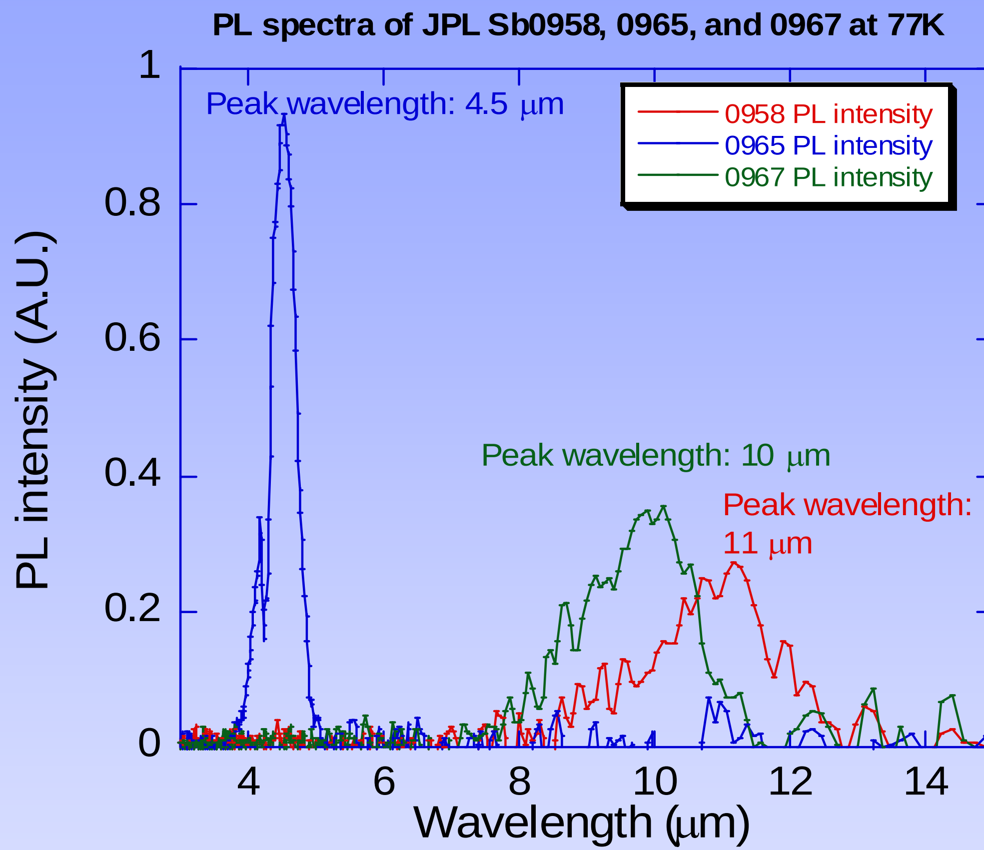
X-TEM of superlattice





- **Two quantitative measurements made in these scans**
  - **Period of the InAs + Ga(In)Sb multilayer structure**
  - **The net strain of the superlattice**
- **The crystal quality can be qualitatively extracted from the width of the peaks**

Photoluminescence



- PL data courtesy Prof. Chuang's group at UIUC
- Strong PL response for samples grown for MWIR and LWIR
- Changing the InAs thickness from 48 to 45Å gives this blueshift in the wavelength from a 10μm to an 11μm PL peak

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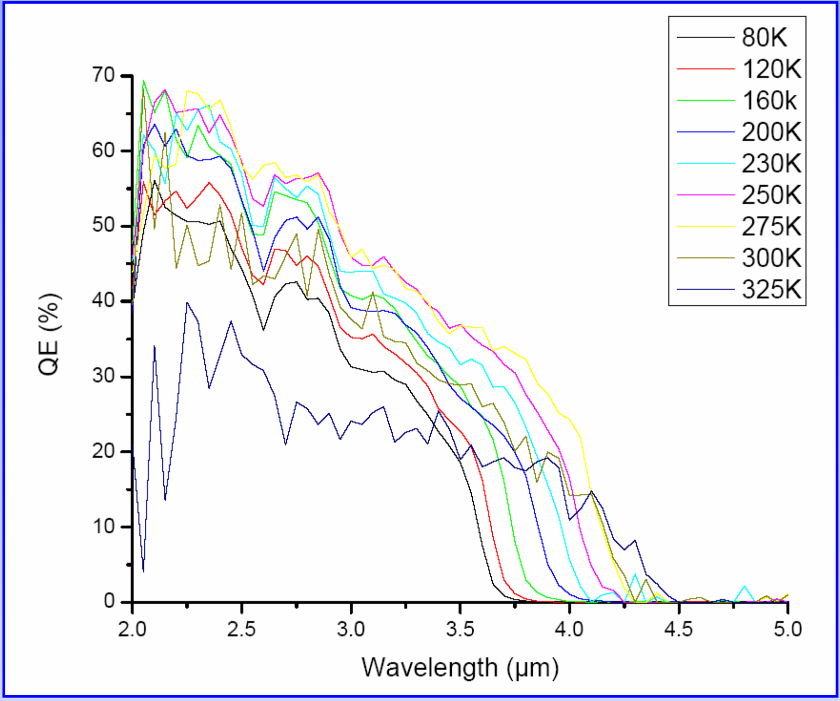
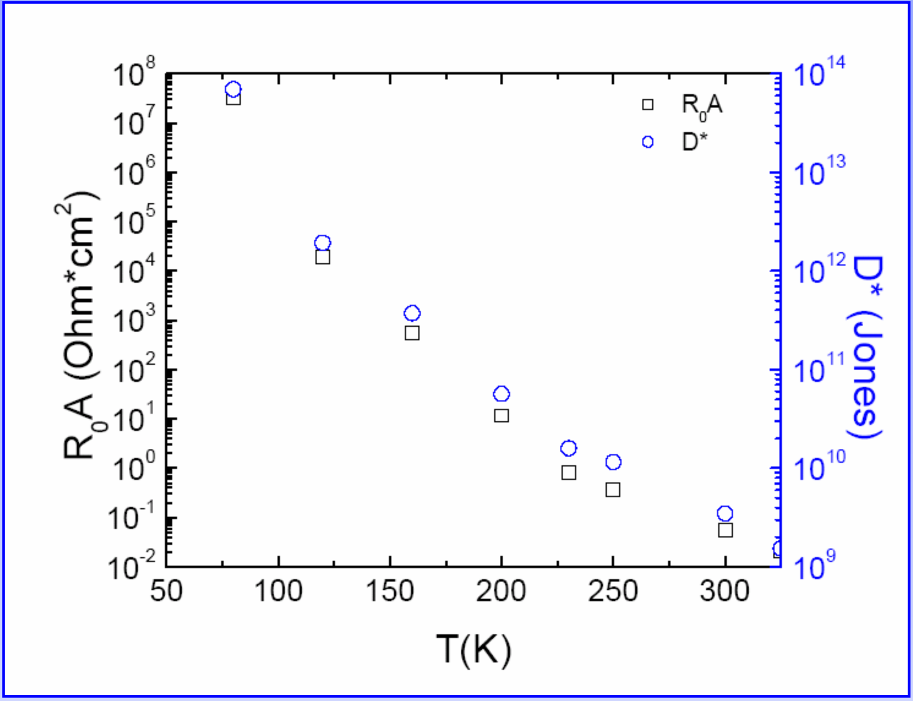
High Temperature 3.7µm Photodiodes





- We are also developing SL based MWIR detectors for FPA applications
- High QE devices - single pass, non-AR coated devices shown
- Current devices will likely make 1e11D* imaging arrays at ~200K for a 3.7µm cutoff

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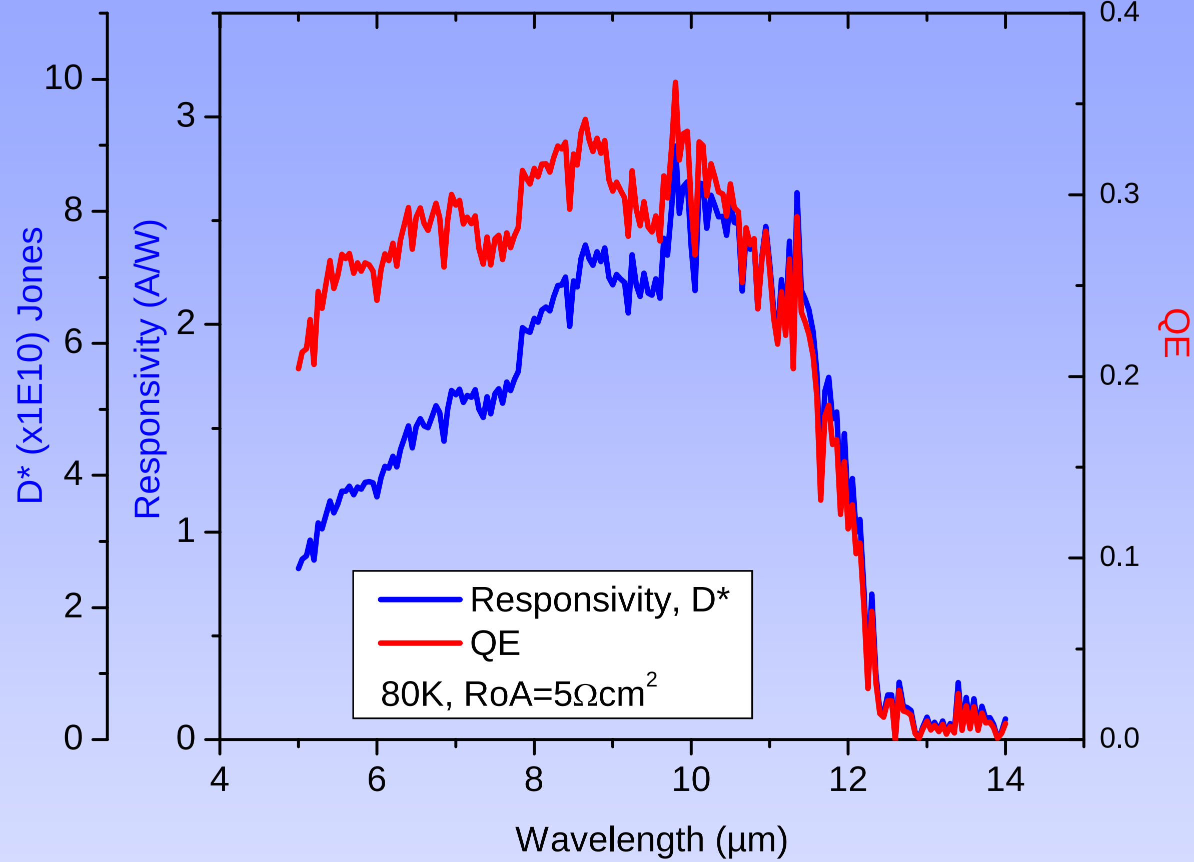
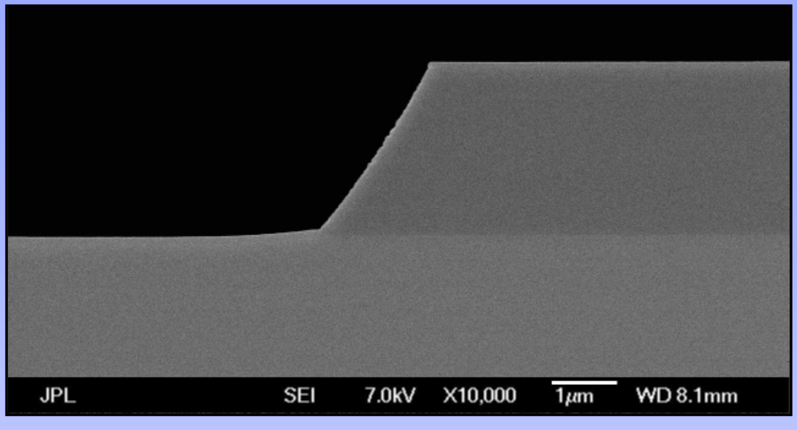
Single Device Performance

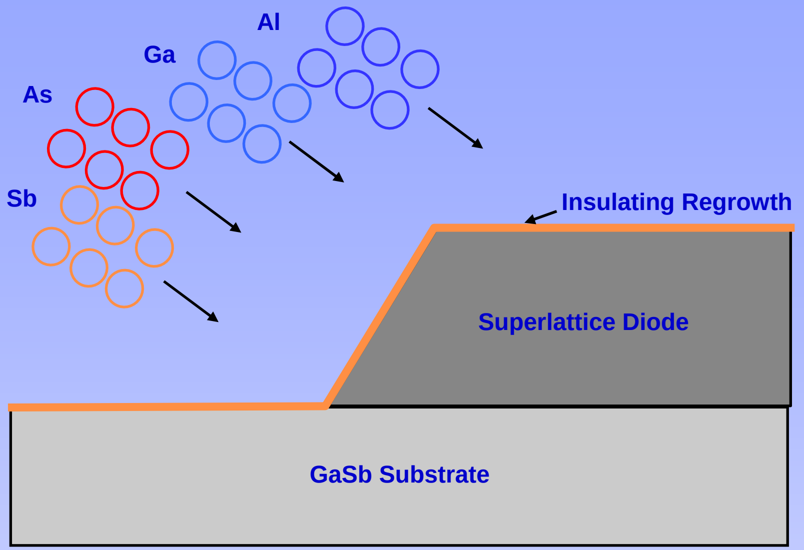


- **Current samples from JPL**
  - **12 micron (50%) cutoff, D* ~ 8×10^{10} Jones at 80K**
  - **Best RoA ~6.3 Ohmcm^2 @ 80K, typical values are ~5 Ohmcm^2**
    - **RA values increase to 12 Ohmcm^2 @ 30mV reverse bias**
  - **Front-side illuminated quantum efficiency of nearly 30%**

Passivation



Etched Mesa



- Passivation is the key to a high performance FPA
  - As in MCT, the mesas the sidewalls are leaky after etching
  - Experience has shown that simply encapsulating the mesa in a dielectric (e.g. SiN_x) does not improve the performance
  - Very good results shown with plasma-deposited SiO_2 from NWU (Thin Solid Films, Vol. 447-448, (2004))
- Currently a lot of active research in epitaxial regrowth
  - Similar to approaches used in MCT and other LWIR materials
  - After forming the detector mesa the detector wafer is re-introduced into vacuum and an insulating, lattice matched layer is grown on the top and sides of the mesa
  - Minimizes the leakage paths on the superlattice sidewalls
  - Most promising results to date come from IAF using AlGaAsSb for the regrowth material (Appl. Phys. Lett., 86, 173501, (2005))

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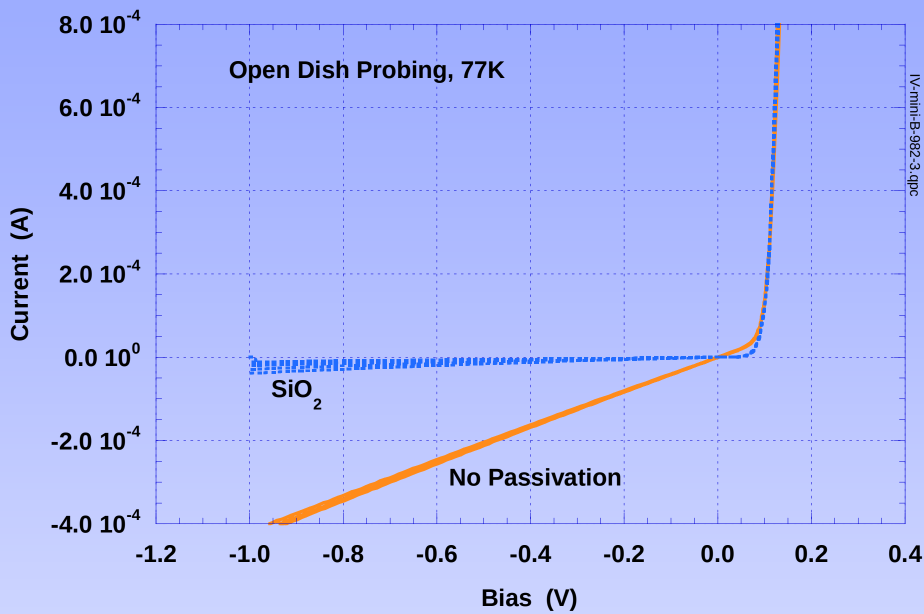
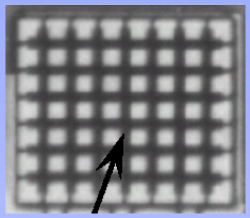
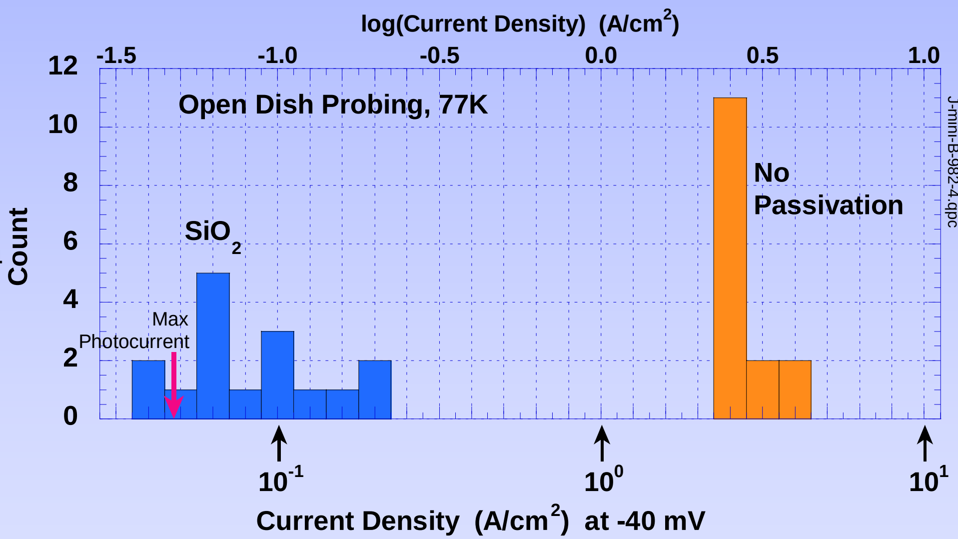
SiO_2 Passivation on SLS

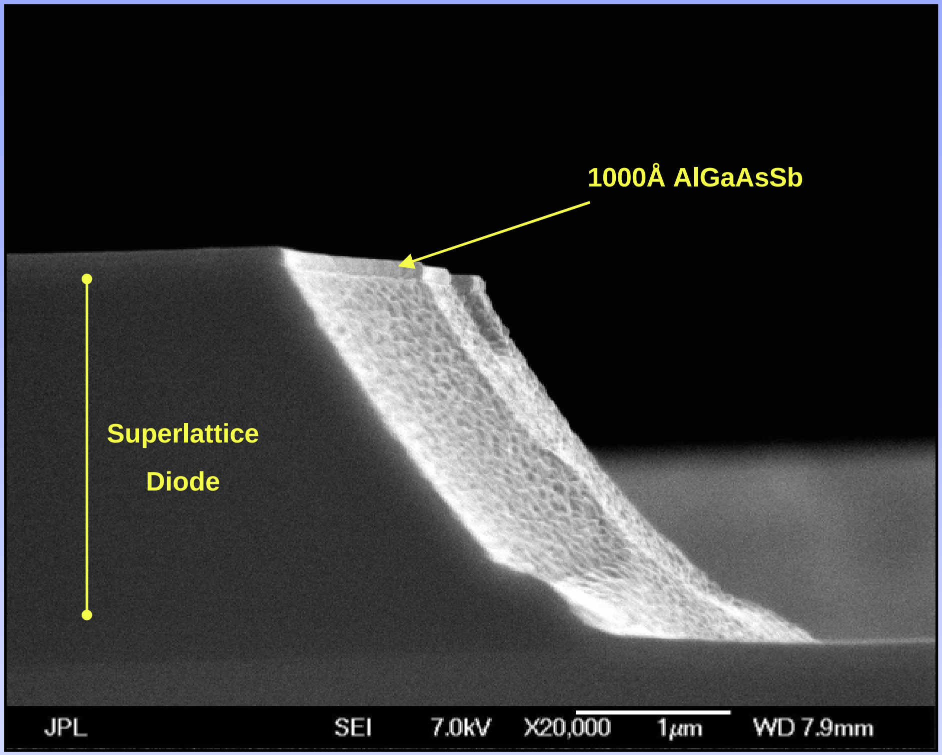




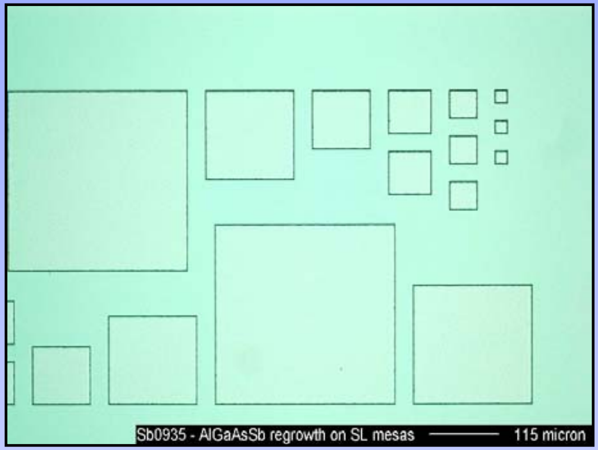


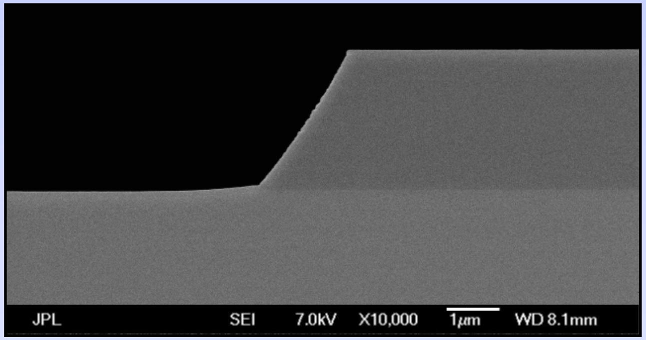
- SiO2 passivation performed at Raytheon on superlattice diodes
- Show open dish probing (300K background) on a 30 µm mini-Array
- Test devices have a cutoff wavelength ~10.5µm

Current Regrowth Status at JPL



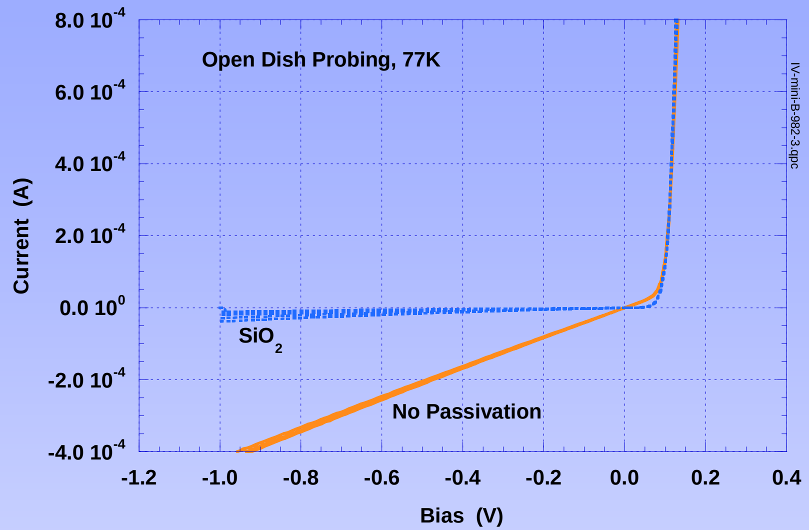
AlGaAsSb on SL

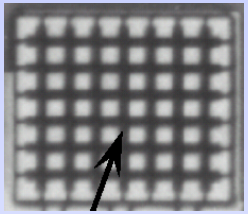




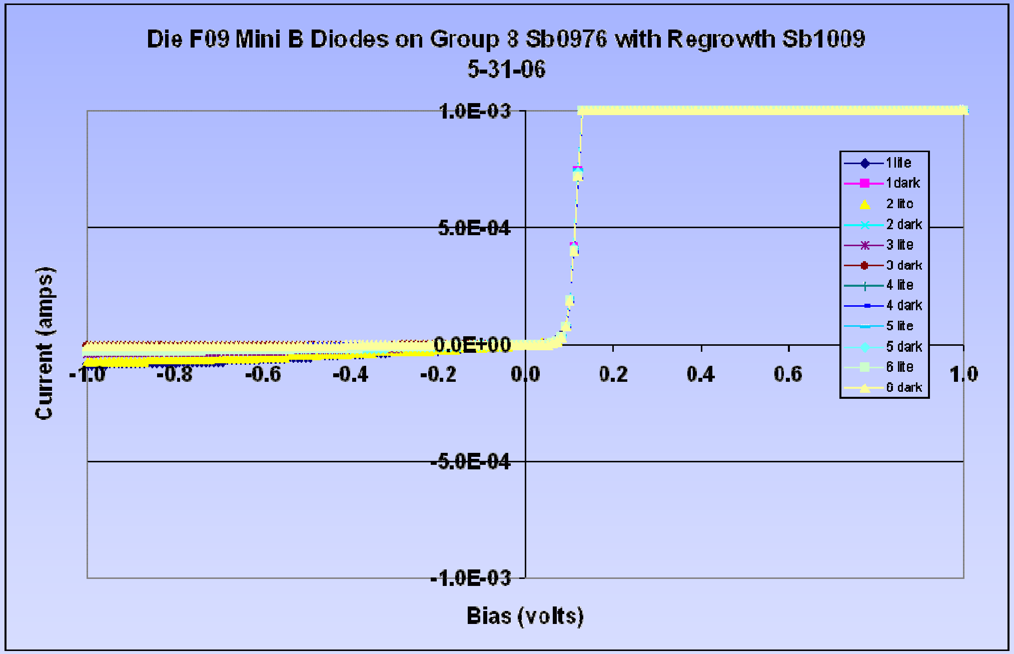
- We have achieved good material quality on the mesa tops
- Still some texture on the sidewalls, we have to perform additional investigation to see if this is from the etch technique or the regrowth process
- Still need some improvement in sidewall integrity

Regrowth Passivation on SLS



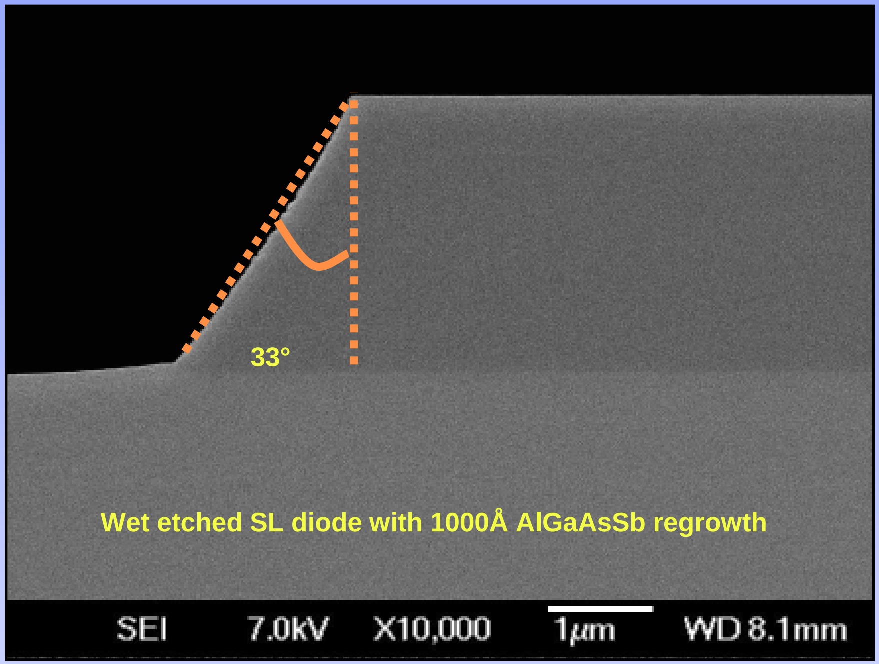


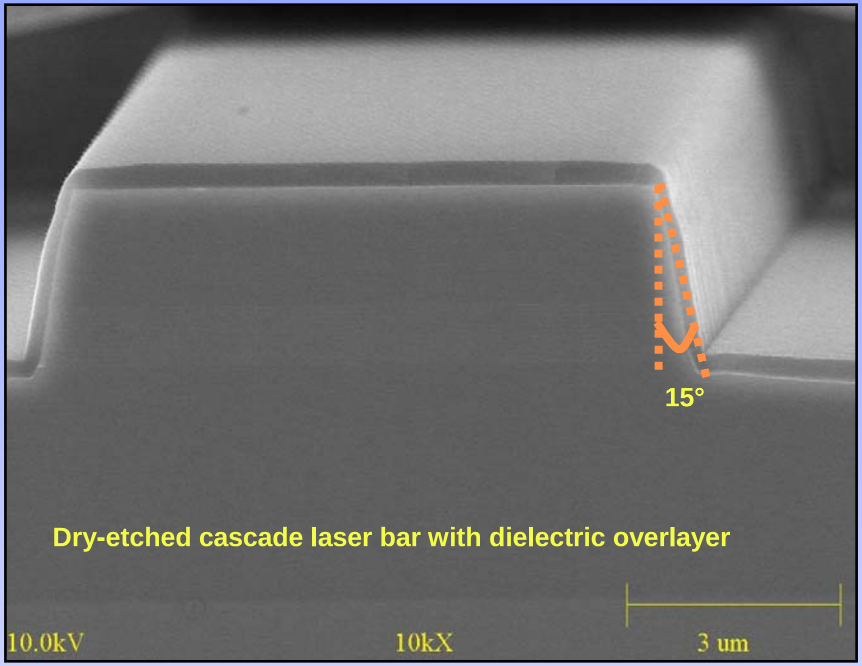
Diodes with MBE regrowth



- Regrowth passivation performed at JPL on superlattice diodes
- Show open dish probing (300K background) on a 30 µm mini-Array
- Test devices have a cutoff wavelength ~10.5µm

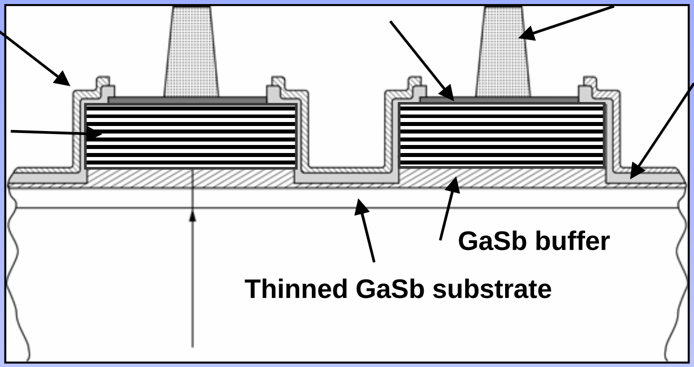
Sidewall Improvements with Dry Etching





- Many yield issues at JPL with the regrowth on wet-etched samples
- Developed an ICP-RIE etch technique that gives truly vertical sidewalls, and modified the fabrication process to give a 15° taper for better sidewall adhesion (originally developed for the NASA antimonide based interband cascade lasers for 2009 MSL mission)
- Currently working on optimizing the clean-up etch after regrowth to give as good of results as the wet-etched samples

FPA Progress



- Standard vertical processing
  - Define individual detector mesas by etching
  - Deposit passivation layer
  - Encapsulate in dielectric
  - Make electrical contacts and indium bumps
  - Hybridize and thin
- Raytheon has done all of these steps individually
  - Next month we will start the first lot of imaging FPAs

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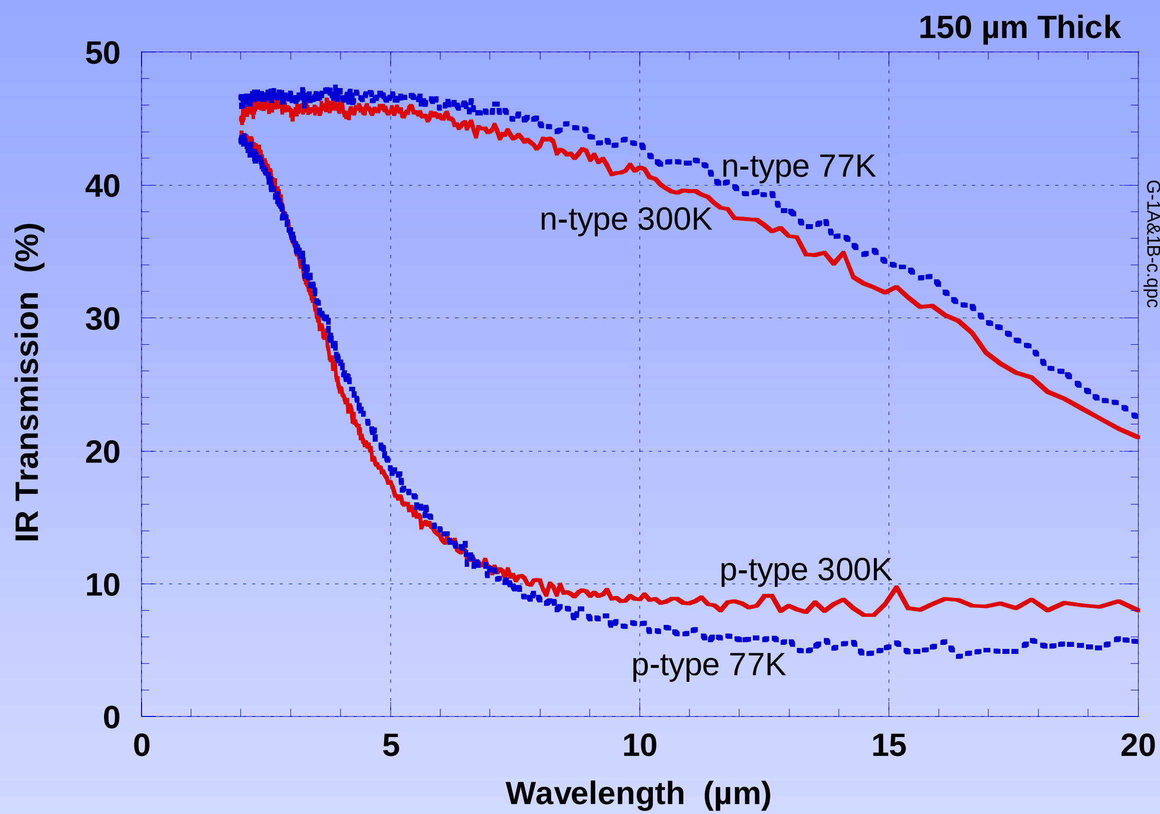
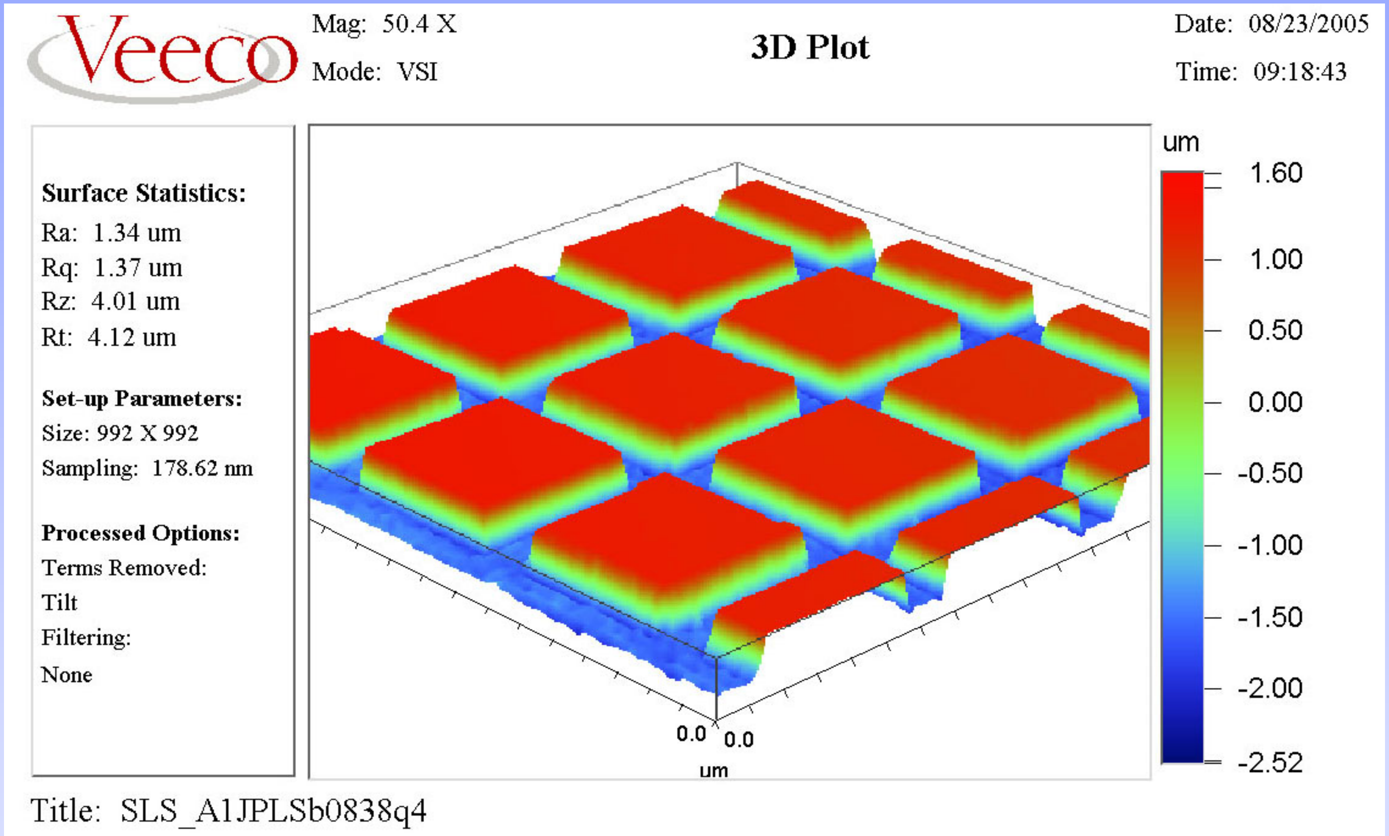
Issues for FPAs: Substrates



- Thick GaSb is opaque to the infrared wavelengths we wish to image
- Raytheon is applying their InSb FPA thinning technology to GaSb substrates
  - Concluded that they will have to thin to <150µm for n-type substrates, and < 20µm for pGaSb substrates
- We are trying to produce the newest wafers for Raytheon on n-type substrates to increase the mechanical stability and QE of the FPAs

Optical Profilometry to Measure Mesa Heights



- Mesas are uniform
- Stopped at intended depth

<u>Trench Depths (Mesa Heights)</u>

Average over wafer = 2.49 ± 0.06 µm

Span = 0.16 µm

Summary and Outlook

- We have very good device results on MWIR 3-5µm and LWIR 10 to 12 µm cutoff superlattice devices
- Mechanical FPA test runs are completed (unpassivated devices)
- Initial plasma passivation appears will provide a workable array, with MBE epitaxial regrowth now coming on-line as an additional passivation method
- Currently processing our next batch of LWIR FPAs