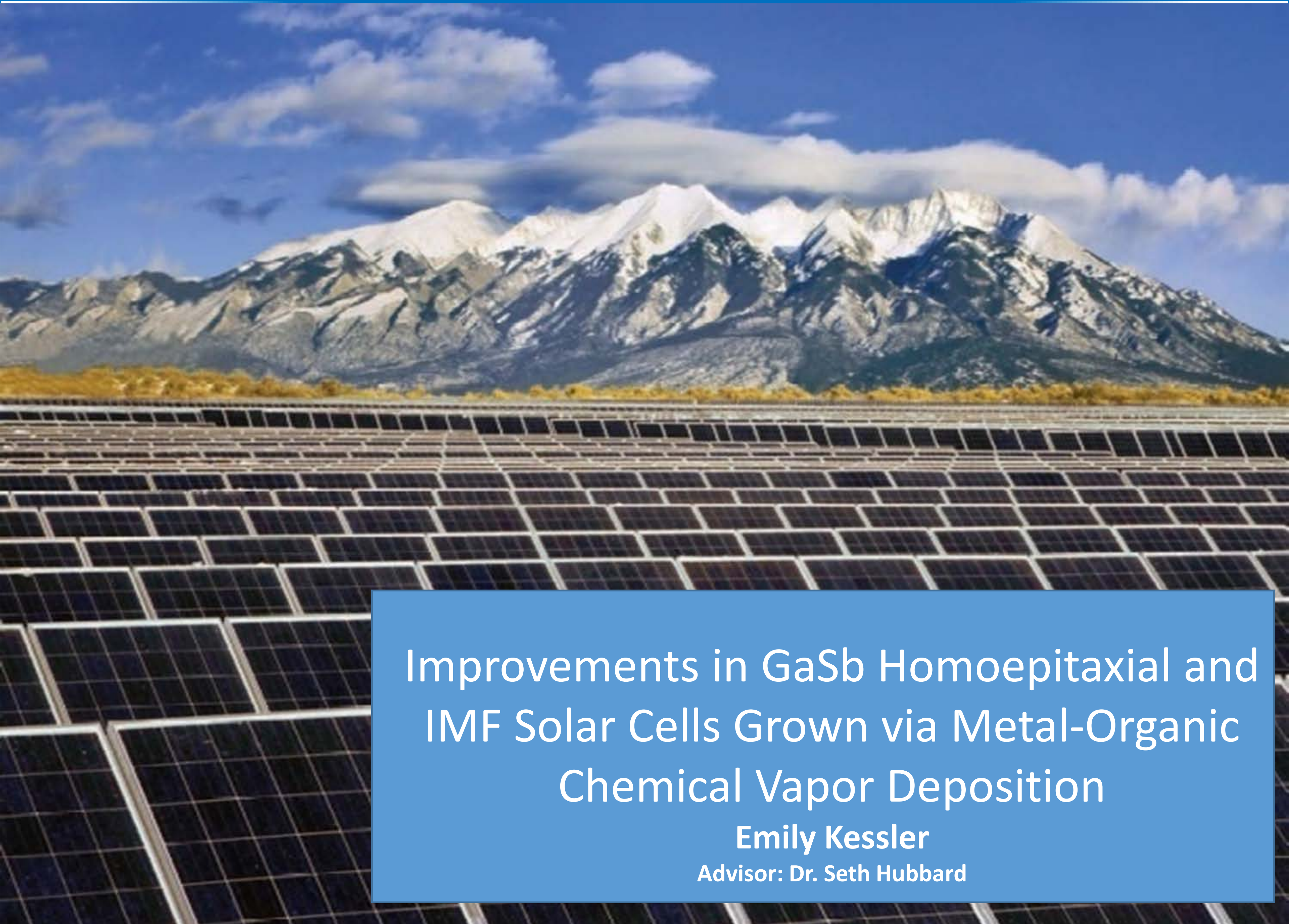

Improvements in GaSb Homoepitaxial and IMF Solar Cells Grown via Metal-Organic Chemical Vapor Deposition

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Advisor: Dr. Seth Hubbard

Applications of GaSb

The narrow band gap (0.72 eV) of GaSb makes it a useful material for several applications

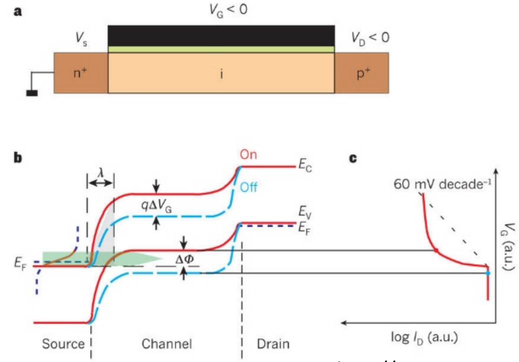
Infrared Detectors

https://dir.indiamart.com/impcat/infrared-detector.html

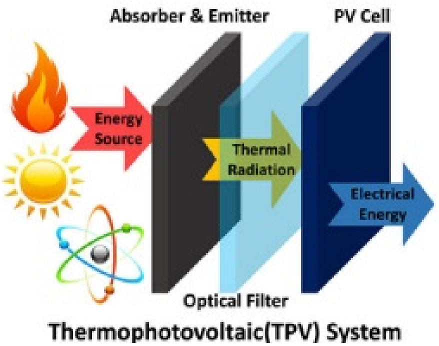
Infrared LEDs

https://storify.com/compactlighting/what-is-led-bulbs-and

High Frequency Transistors

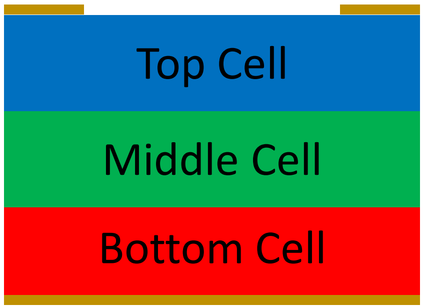


http://www.nature.com/nature/journal/v479/n7373/full/nature10679.html



http://mel.khu.ac.kr/research1.html

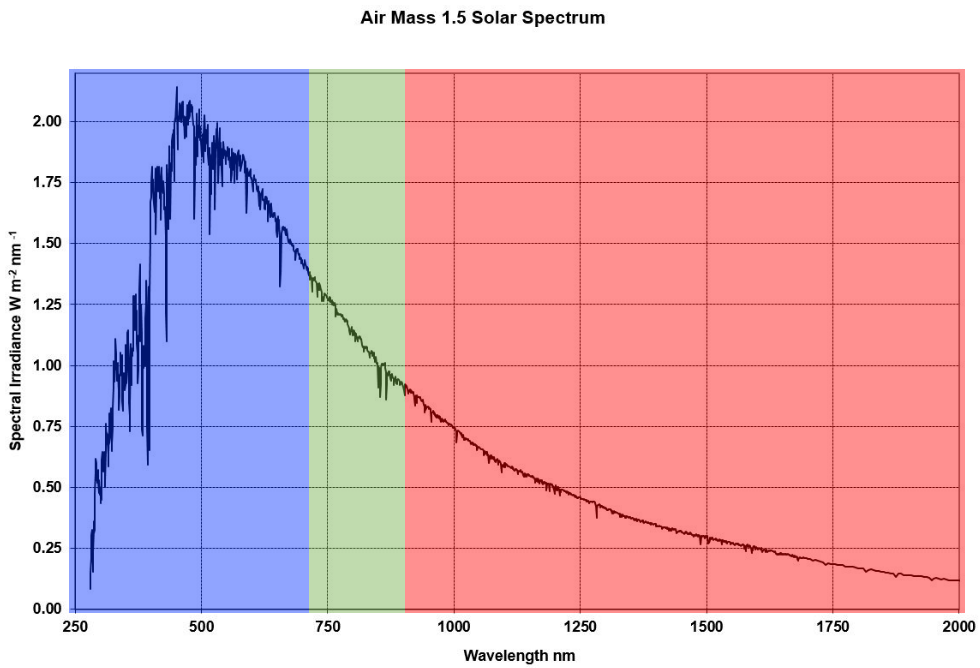
Thermophotovoltaics

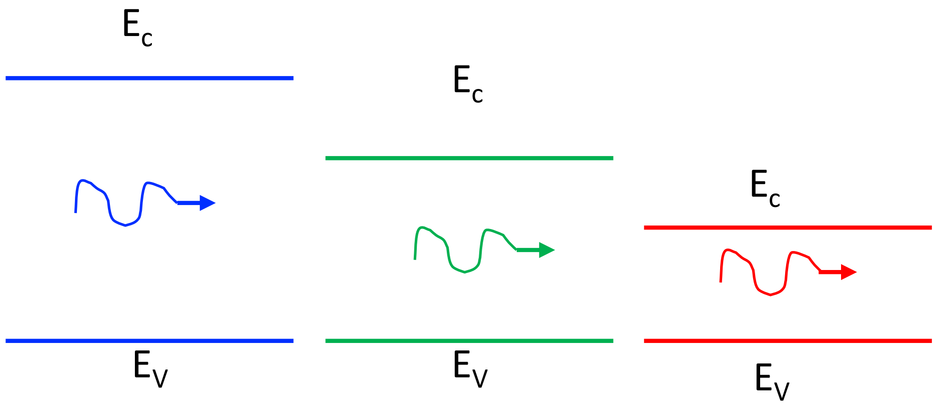


Multi-junction Solar Cells

Multijunction Solar Cells

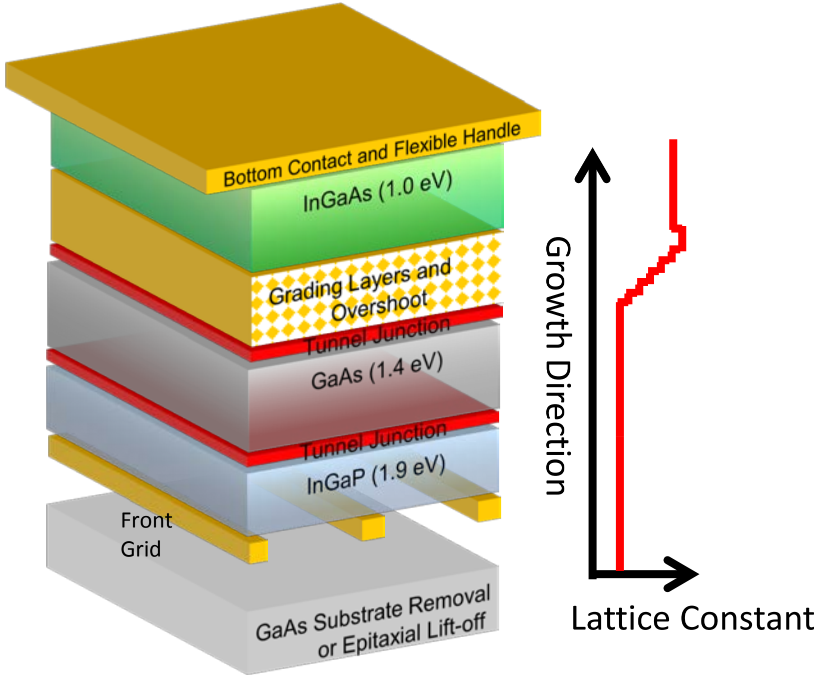
- **Single junction** solar cells are limited in percent of the solar spectrum they can absorb
    - GaAs (E_g=1.42 eV, λ=873 nm) collects light most efficiently between ~700 and 885 nm
    - The two biggest loss mechanisms are **transmission below the bandgap** and **thermalization**
- **Multijunction** solar cells stack materials of varying bandgaps in order to collect more of the solar spectrum

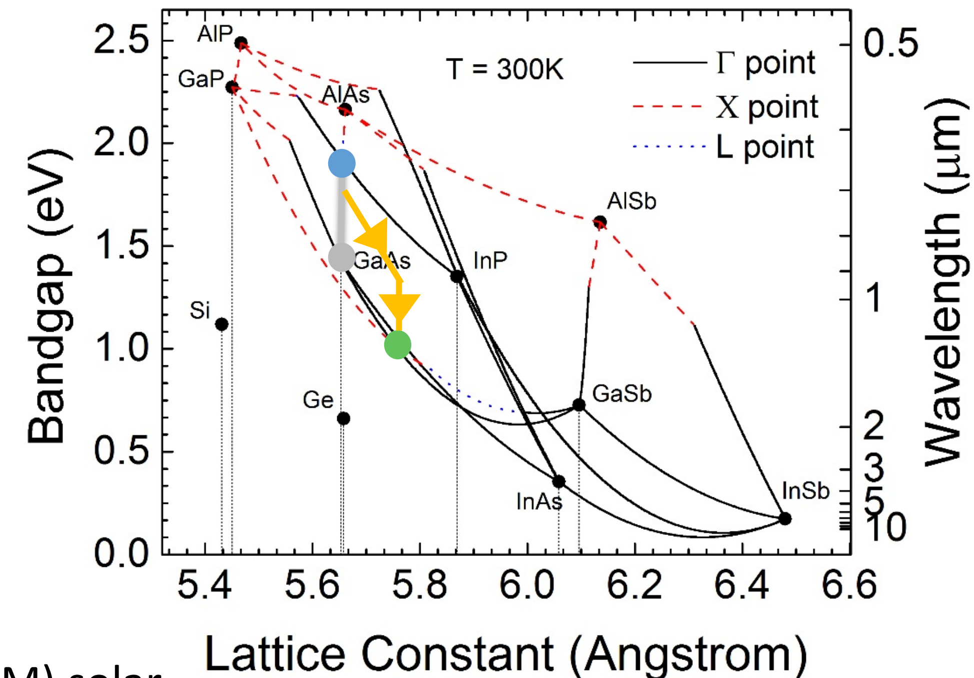




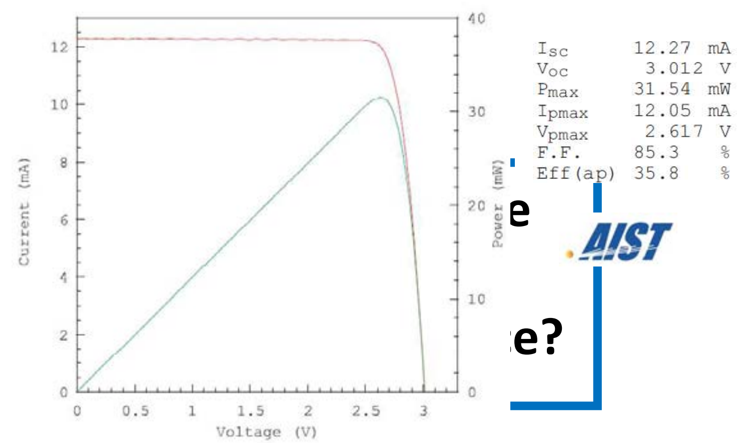
This greatly reduces loss due to transmission, mitigates thermalization loss, and **drastically increases efficiency**!

Current State of the Art Multijunction



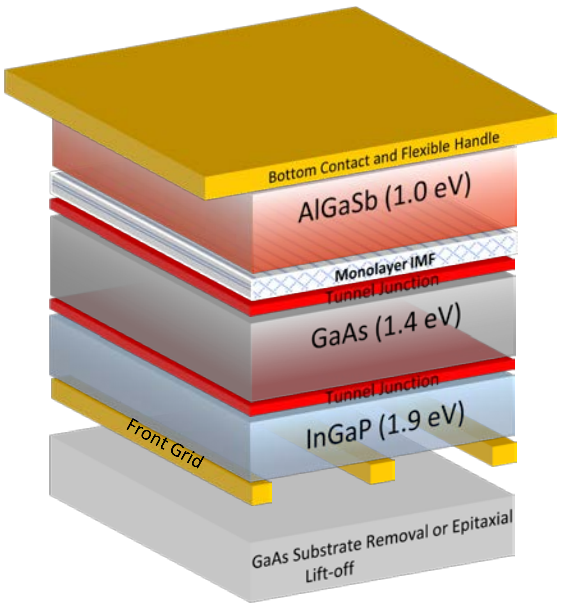


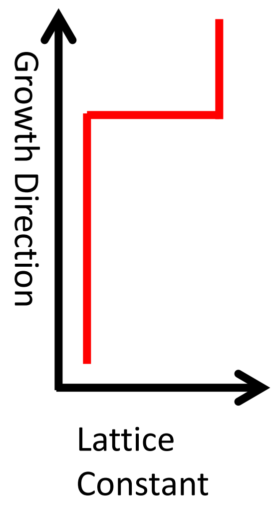
- **Inverted metamorphic multijunction** (IMM) solar cells have achieved efficiencies of 36%
- Requires several micron thick, growth intensive and expensive metamorphic buffer between GaAs and InGaAs
  - Buffer can have threading dislocation density on the order of 10^6 cm^{-2}, reducing minority carrier lifetimes
  - Attributes to **30%** of production cost

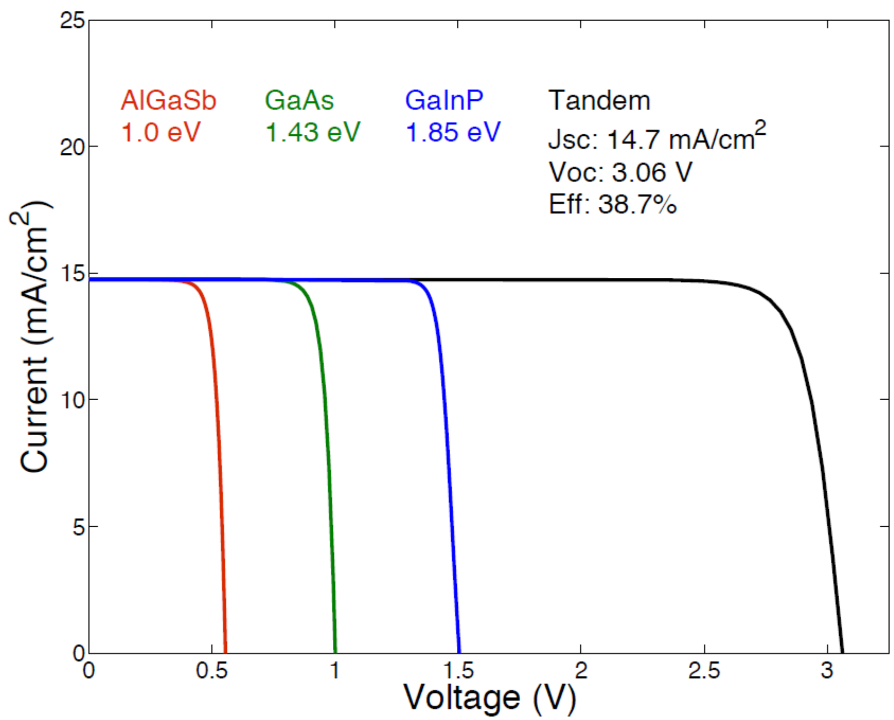


T. Takamoto et al. "World's highest efficiency triple-junction solar cells fabricated by inverted layers transfer process," in *2010 35th PVSC*, 2010.

Proposed Multijunction







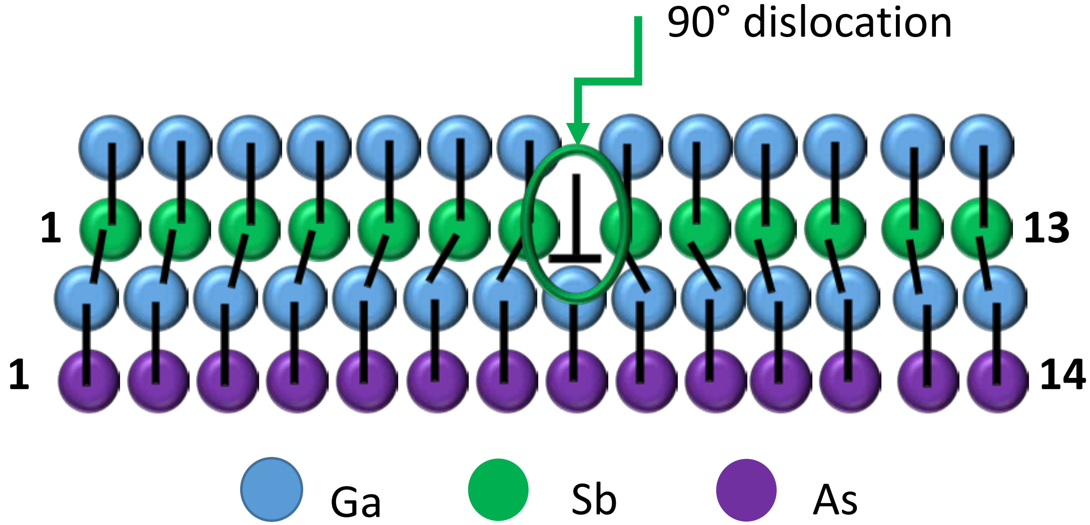
- AlGaSb (E_g=1.00 eV) is proposed in place of InGaAs
- Like the IMM solar cell, this design is current matched and capable of achieving high efficiencies

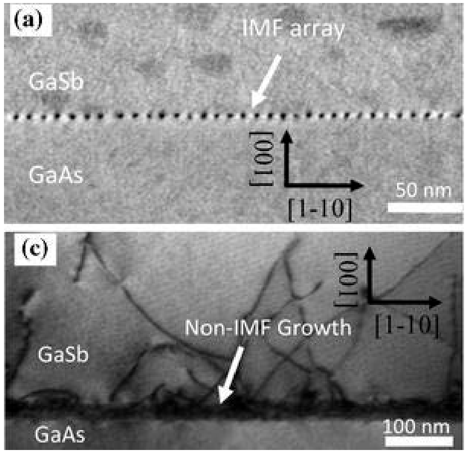
- There is a 7.5% lattice mismatch between AlGaSb and GaAs!

How can we grow Sb based materials on GaAs?

Interfacial Misfit Array (IMF)

- By manipulating growth conditions at the GaAs-GaSb interface dislocations can be preferentially occur at 90° with a periodicity of GaSb:GaAs 13:14
  - Unlike a 60° threading dislocation, a 90° dislocation, or **misfit** dislocation, will not propagate up into the active layers of the device



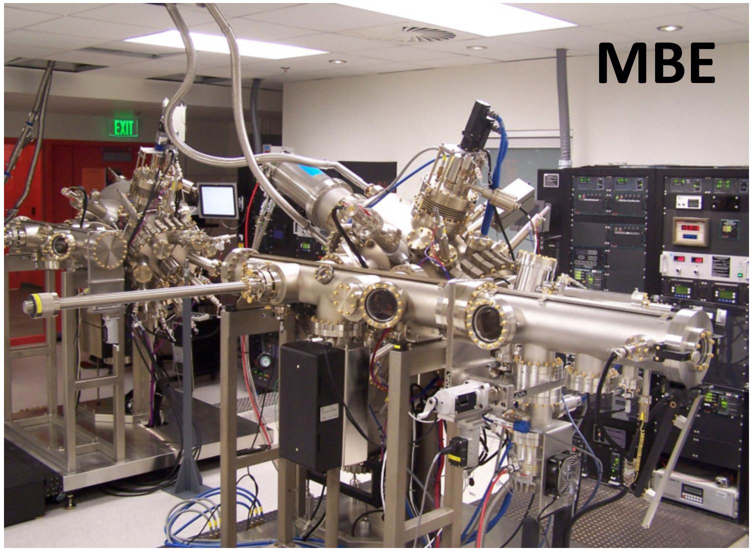


Jallipalli *et al.,* ", *Nanoscale Res Lett*, vol. 4, no. 12, pp. 1458-1462, 2009

- Without this interfacial misfit, or **IMF** array, threading dislocation density (TDD) can reach as high as 10^9 cm^{-2}
- High threading dislocation density has a strong impact on V_{OC} and minority carrier lifetime
- IMF has shown to be capable of TDD of 10^5 cm^{-2} and 98.5% relaxation

Metal Organic Chemical Vapor Deposition

- The majority of research on the IMF technique has been done via molecular beam epitaxy (MBE)
  - MBE is a **very slow growth process** that requires ultra-high vacuum (slow throughput, intensive maintenance costs)
  - **This is not compatible with production!**



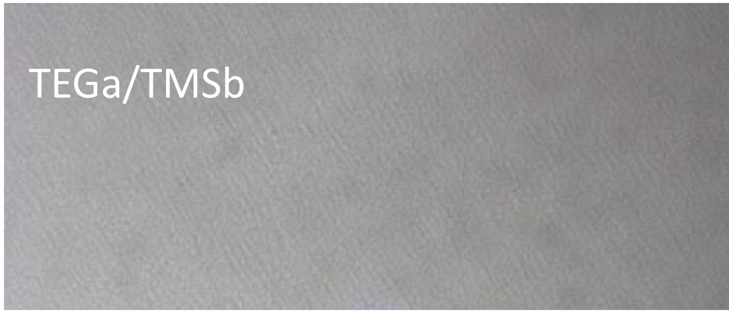
http://www.seas.ucla.edu/~huffaker/research_mbe.html

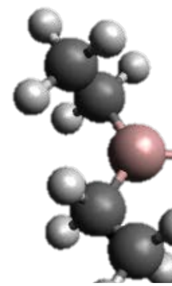
Aixtron 3x2” Close-Coupled Showerhead

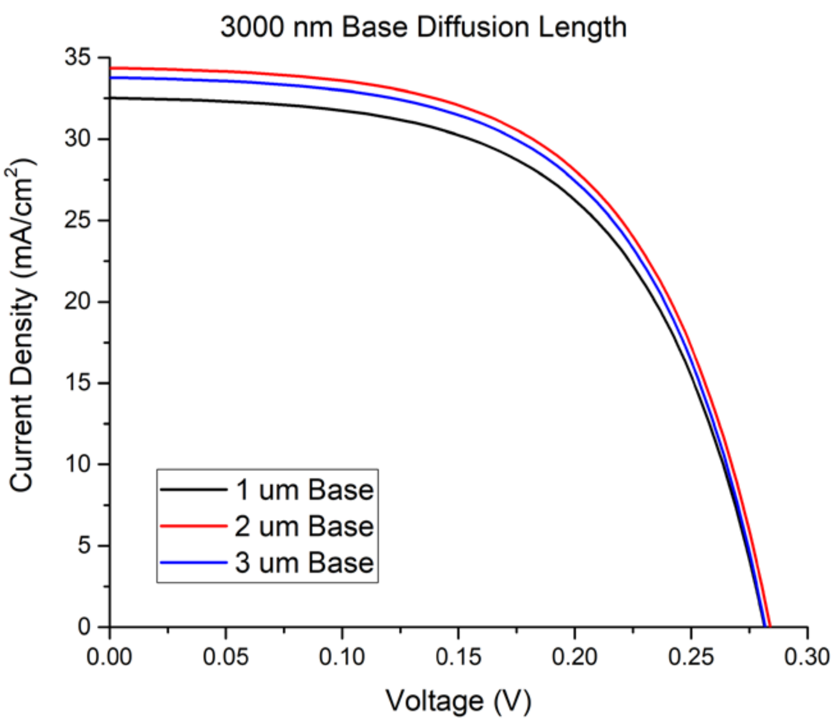
- Here at RIT we have a metal organic chemical vapor deposition (MOCVD) system
  - MOCVD is capable of much higher growth rates and does not require ultra-high vacuum, making it **much more attractive for production**
  - Limited literature on the IMF technique via MOCVD provides many areas of study

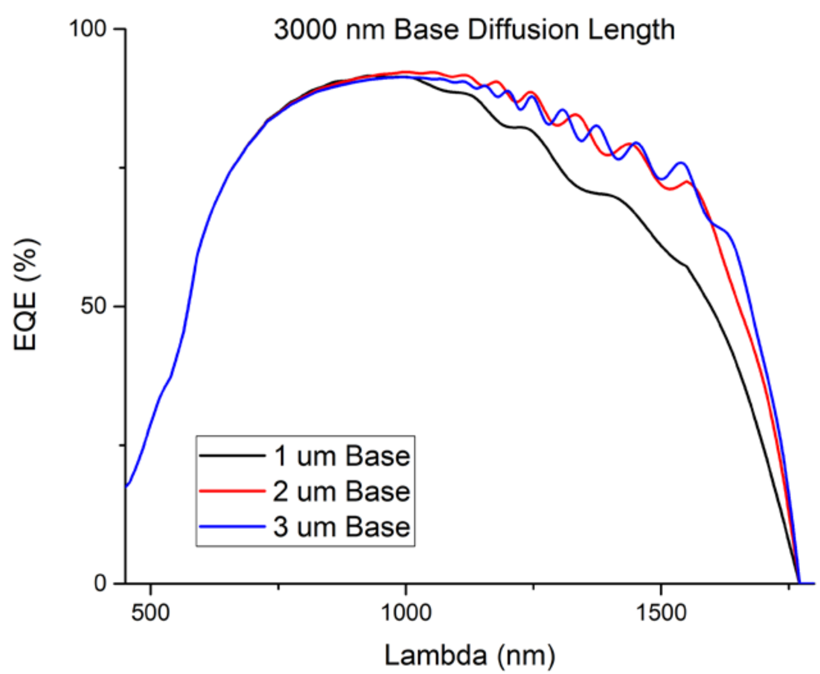
GaSb Solar Cell Growth

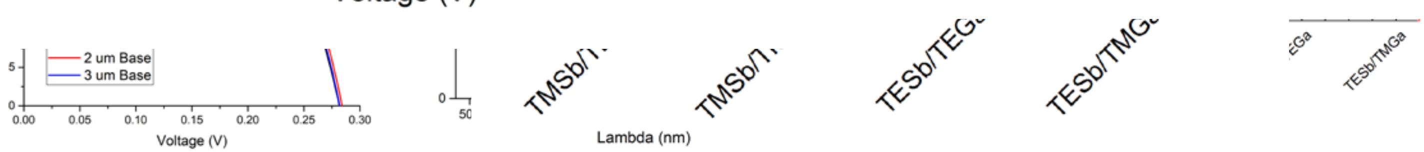
- gallium
  n
- oping
  oother





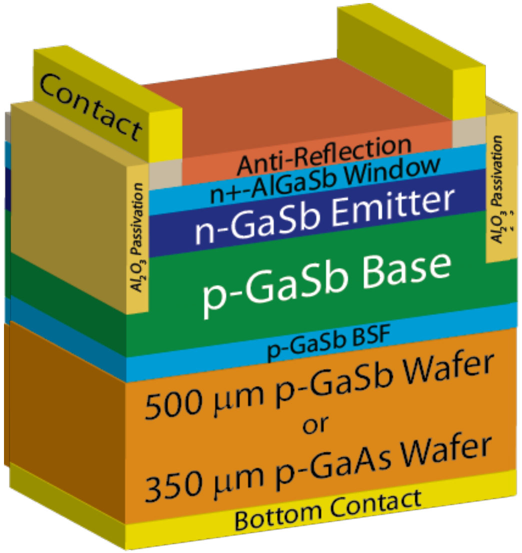


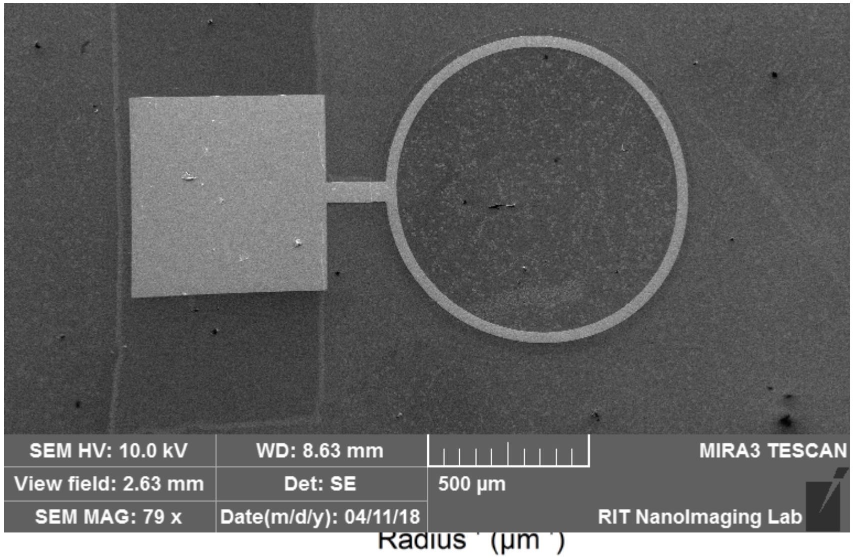




GaSb Solar Cell Fabrication

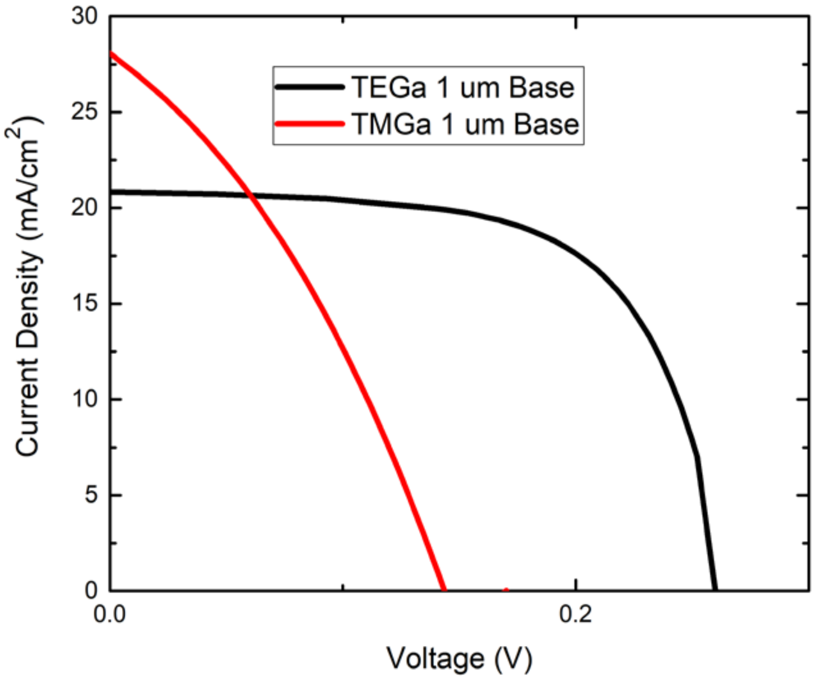
- All devices were fabricated here in the RIT Semiconductor and Microsystems Fabrication Laboratory (SMFL)
- All devices are n-i-p
  - N-type emitter (hole minority carrier), P-type base (electron minority carrier)
- Devices are first mesa isolated using a Citric:HF:H_2O_2 solution
- Device sidewalls are passivated using Al_2O_3 deposited via atomic layer deposition (ALD)
  - This is done to mitigate the effect the GaSb native oxide has on device performance
  - **The timing and execution of this step is vital and has been heavily studied at RIT**
- Ti/Pt/Au is evaporated for the back ohmic contact, Ti/Au is evaporated for the front ohmic contact



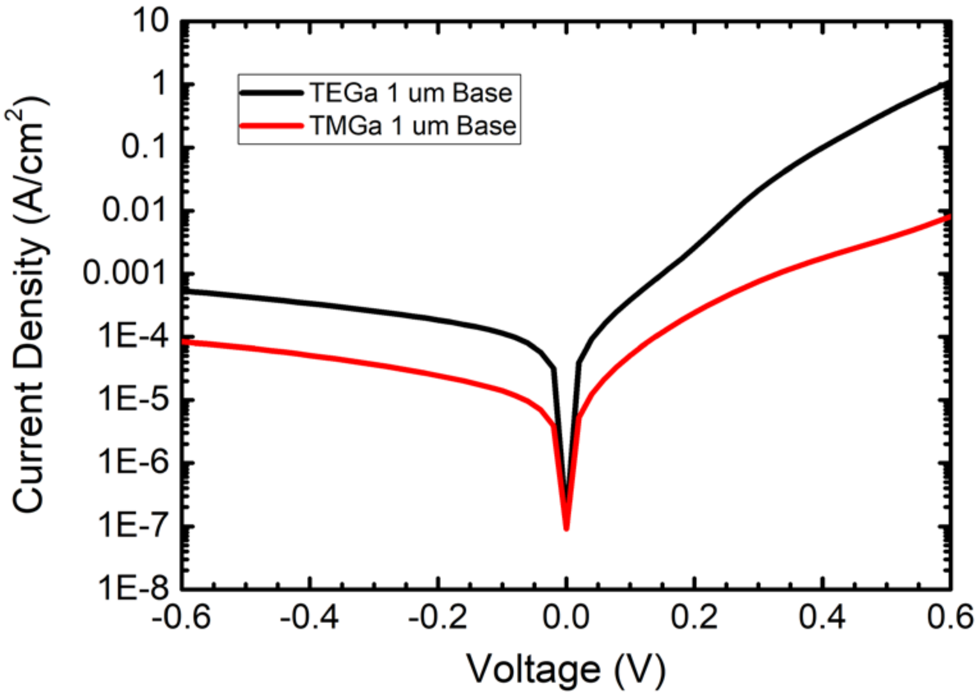


Homoepitaxial 1-sun and Dark IV

AM1.5 Illuminated IV



Dark IV

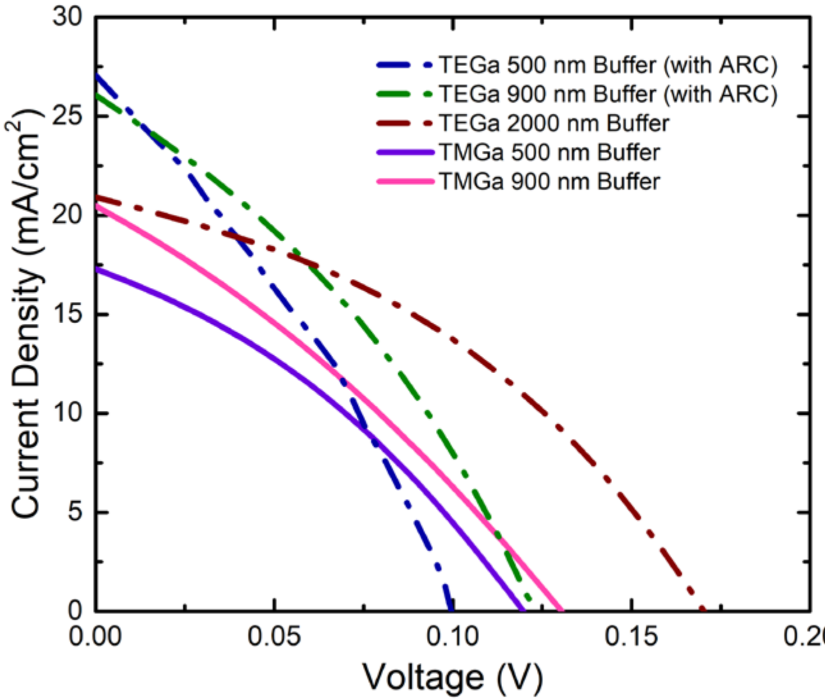


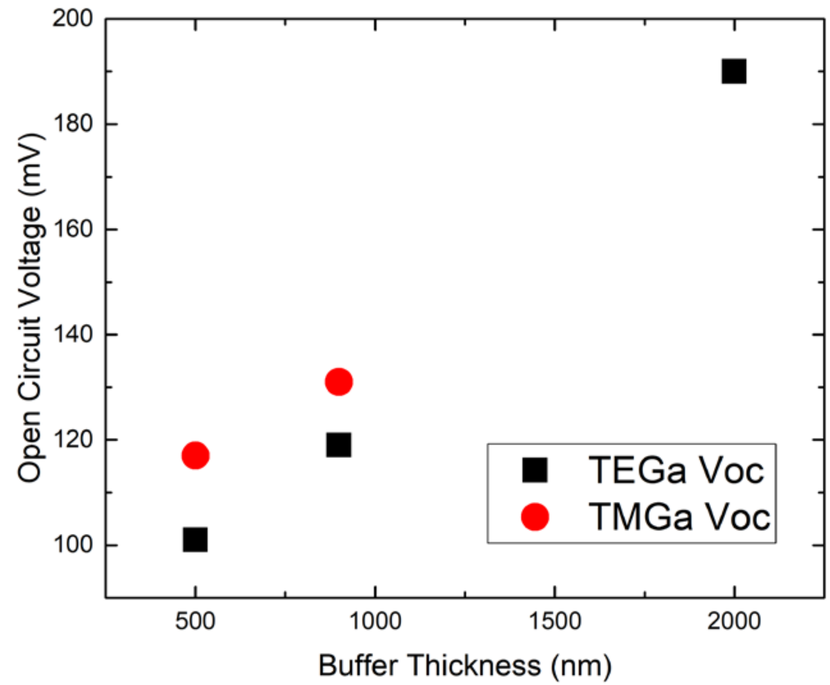
- For a triple junction solar cell with a GaSb bottom junction, target V_{OC}=360 mV
    - TEGa V_{OC}=269 mV
    - TMGa V_{OC}=145 mV
- Light IV measurements show heavy shunting in TMGa device
    - This is likely due to issues that occurred during fabrication

- Dark IV shows poor rectification of TMGa cell and a combination of poor series and shunt resistance
- Poor series resistance seen in fill factor (FF) of illuminated IV
    - TEGa FF=53%
    - TMGa FF=34%

IMF 1-sun and Dark IV

AM1.5 Illuminated IV





- Light IV measurements show improved open circuit voltage (V_{OC}) in TMGa devices for equivalent buffer thickness

- Dark IV shows that possibly better shunt resistance for TMGa, but much worse series resistance in TMGa devices

TMGa shows better open circuit voltage but worse series resistance in IMF devices

Quantum Efficiency Fitting

$$j_p(\lambda) = qF_0(\lambda)\left\{\frac{L_pF_1(\lambda) + \frac{S_pL_p}{D_p}F_2(\lambda) - F_3(\lambda)\left(\sinh\frac{d_1}{L_p} + \frac{S_pL_p}{D_p}\cosh\frac{d_1}{L_p}\right)}{\left(\cosh\frac{d_1}{L_p} + \frac{S_pL_p}{D_p}\sinh\frac{d_1}{L_p}\right)} - L_pF_4(\lambda)\right\}$$

$$F_0(\lambda) = \frac{L_p(1-R_1)\alpha\varphi_0}{(1-\alpha^2L_p^2)}, F_1(\lambda) = \alpha, F_2(\lambda) = 1, F_3(\lambda) = e^{-\alpha d_1}, F_4(\lambda) = \alpha e^{-\alpha d_1}$$

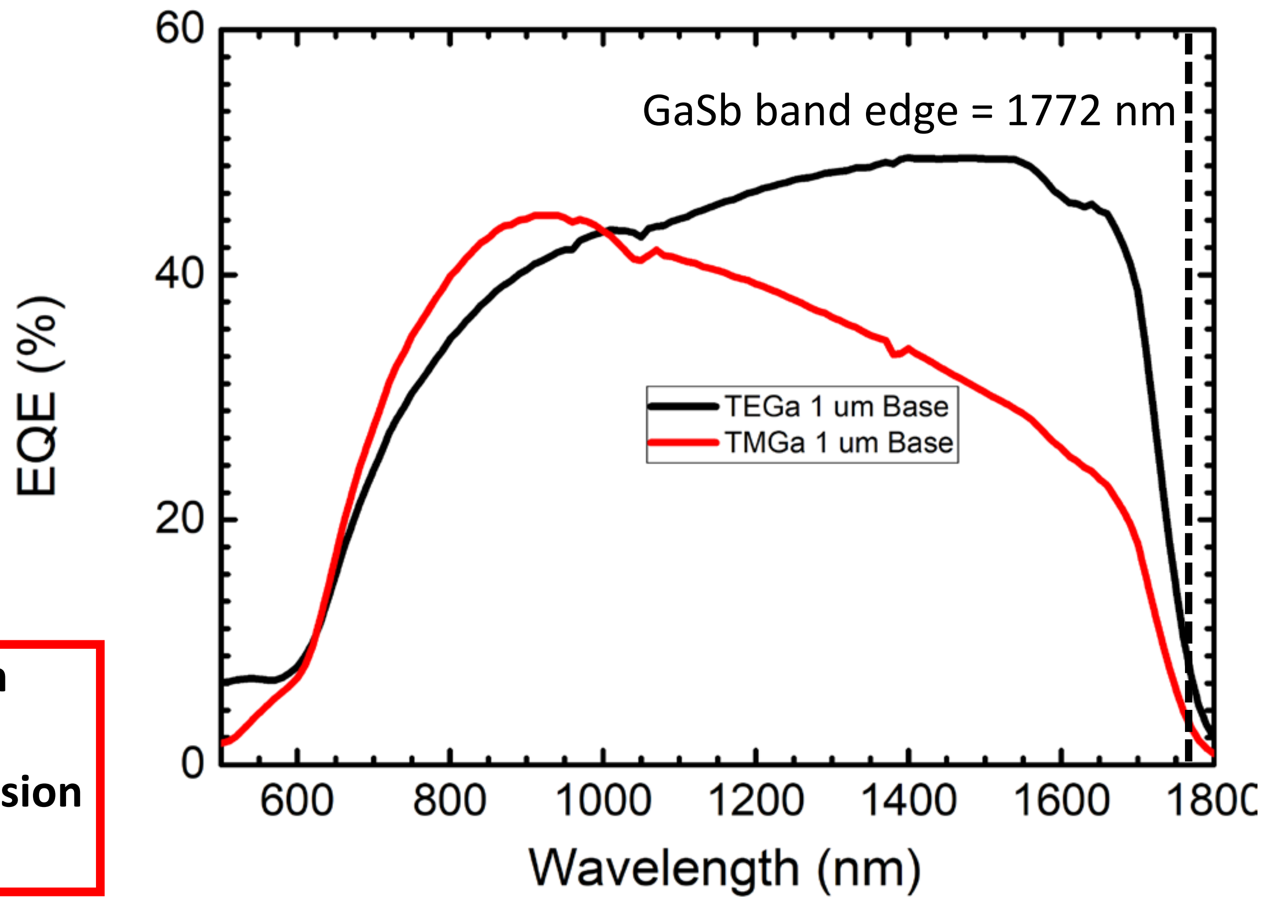
- Using an analytical drift-diffusion model (Hovel Model) for quantum efficiency the minority carrier diffusion lengths can be extracted
  - Above equation is for holes, by symmetry the equation for electrons is similar

- $L_{p/n}$=Diffusion length
- $S_{p/n}$=Recombination velocity
- d=Thickness of the Quasi Neutral Region
- $D_{p/n}$=Minority carrier diffusivity
- R=Reflectance
- α=Absorption coefficient
- Φ=Photon flux

Homoepitaxial Quantum Efficiency

- External quantum efficiency (EQE) of TMGa cell is degraded compared to TEGa cell at λ > 1000 nm
  - Indicative of degraded material quality in the base region
- Electrons not fully collected in TMGa base

TEGa-Better base diffusion length
TMGa-Better emitter diffusion length



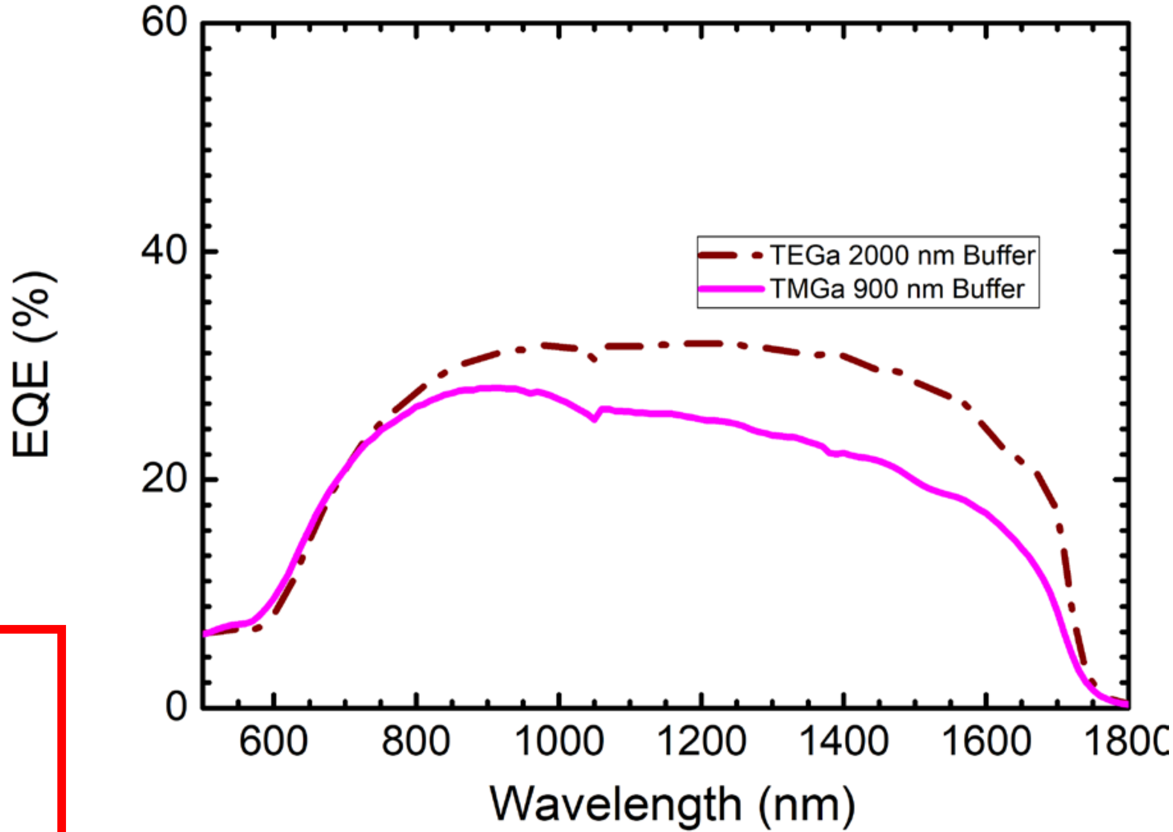
	L_E (nm)	L_B (nm)	S_E (cm/s)	S_B (cm/s)
TEGa	75	>>3x base thickness	$>>10^6$	$<<10^6$
TMGa	196	600	$>>10^6$	$<<10^6$

Emitter thickness=125 nm, n-type Base thickness=1000 nm, p-type

IMF Quantum Efficiency

- External quantum efficiency (EQE) of TMGa cell is degraded compared to TEGa cell in the same region as homoepitaxial cells, although they deviate a little earlier (800 nm)
- Rear recombination velocity (S_B) set higher
  - Likely due to graded defect density from GaAs/GaSb interface

TEGa-Better minority carrier diffusion lenghts



	L_E (nm)	L_B (nm)	S_E (cm/s)	S_B (cm/s)
TEGa 2000 nm Buffer	20	693	>>10^6	>>10^6
TMGa 900 nm Buffer	14	310	>>10^6	>>10^6

Emitter thickness=125 nm, n-type   Base thickness=1000 nm, p-type

Conclusions

- GaSb solar cells were grown via MOCVD, fabricated, and tested all at RIT
- Homoepitaxial cell demonstrating V_{OC}=269 mV, approaching goal of 360 mV
- IMF cell demonstrating V_{OC}=180 mV, becoming viable for a triple junction
- TEGa appears to be the optimal precursor
- IMF TMGa Illuminated IV does not present a clear story
- High S_B in IMF devices likely due to a graded defect density

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