Investigation of InAs/GaAs$_{1-x}$Sb$_x$ Quantum Dots for Applications in Intermediate Band Solar Cells

60.4-MWp Solar Power Plant in Bulgaria. (PRNewsFoto/SunEdison)

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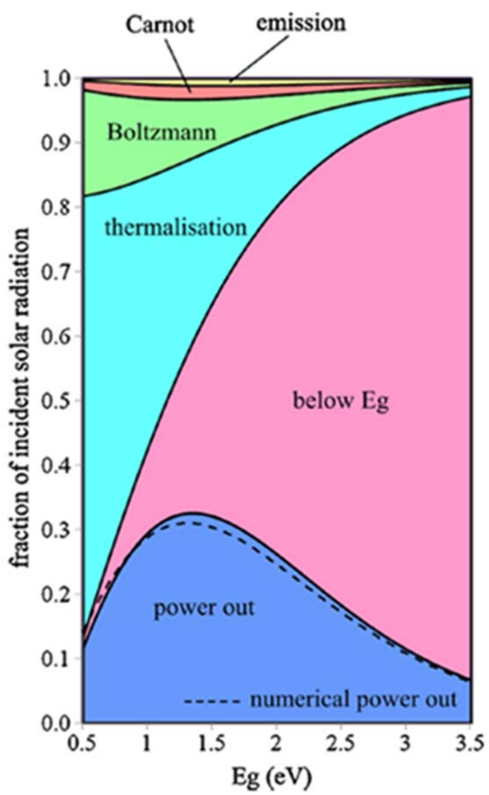
Third Generation Solar Cells

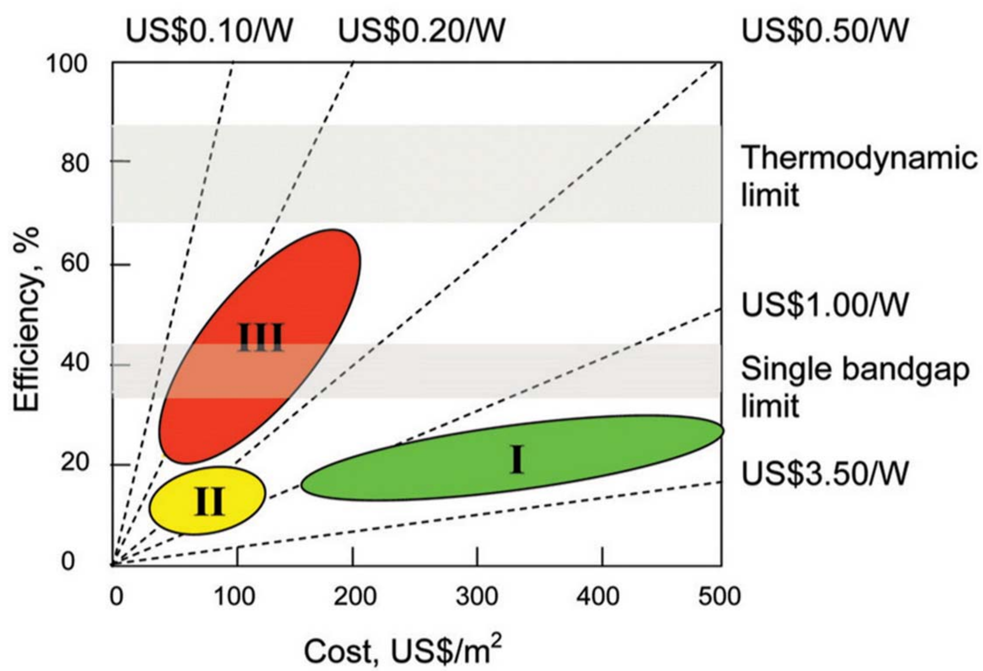
- Third generation has the potential to be cheaper than any other technology out there due to an increase in efficiency afforded by exceeding the Shockley-Queisser limit

Fundamental Losses in Solar Cells



Hirst, L.C. and N.J. Ekins-Daukes, Fundamental losses in solar cells. Progress in Photovoltaics: Research and Applications, 2011. 19(3): p. 286-293.

Costs of Generational Solar Cells

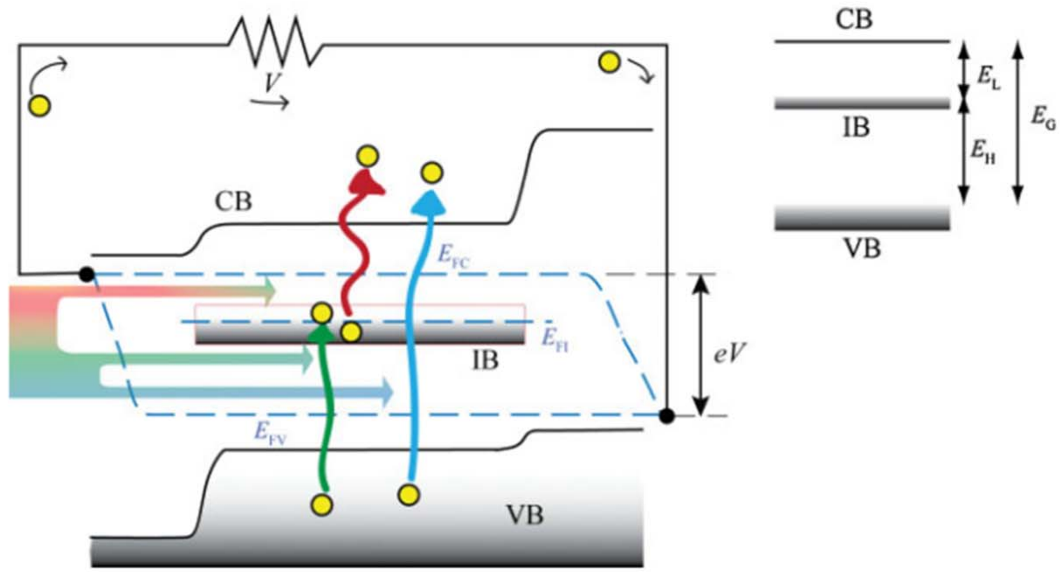


Conibeer, Gavin. "Third-Generation Photovoltaics". Materials Today 10.11 (2007): 42-50. Web. 5 Apr. 2016.

Intermediate Band Solar Cells

- IBSC absorbs below band gap photons via a mid gap state (IB)
- IB introduced through quantum dots (QD), impurities, or highly mismatched alloys
- InAs/GaAs QDs most studied; has poor absorption and spectral overlap
- InAs/GaAsSb QDs can have type-II band alignment and better QD density

Intermediate Band Solar Cell Band Diagram



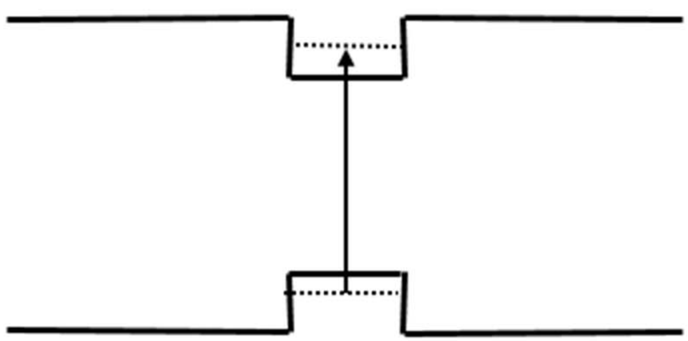
Luque, A. and Martí, A. (2010), The Intermediate Band Solar Cell: Progress Toward the Realization of an Attractive Concept. Adv. Mater., 22: 160–174.

v1

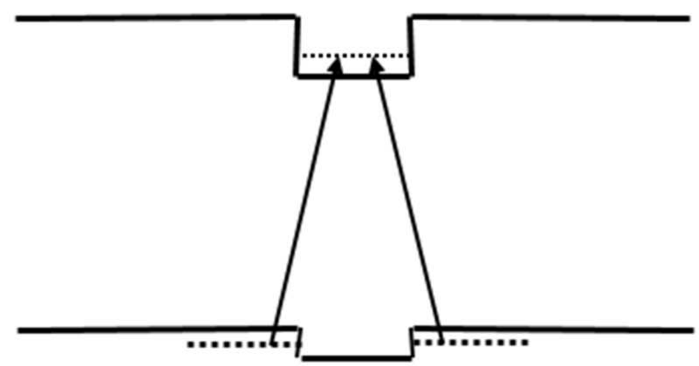
Transition from Type-I to Type-II Band Alignment

- Type-II band alignment is favorable in IBSC
- Has decreased photoluminescence (PL) due to spatially separated carriers
- Flat band condition (transition from type-I to type-II) has increased carrier (hole) transport through the valence band

Type-I Band Alignment



Type-II Band Alignment



Slide 4

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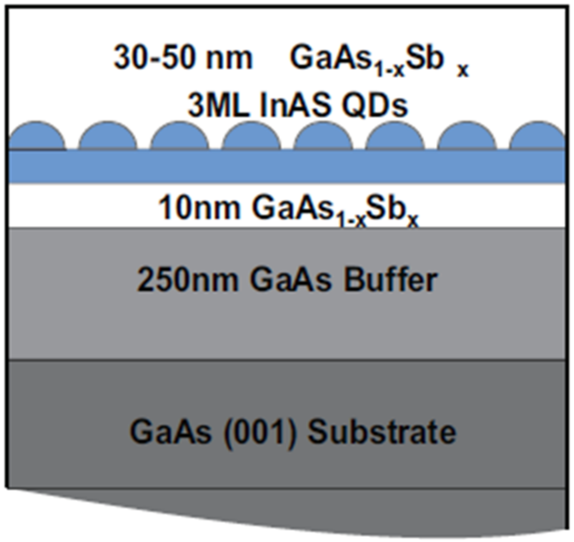
v1 utter nonsense
vrw, 4/15/2016

Growth and Analysis

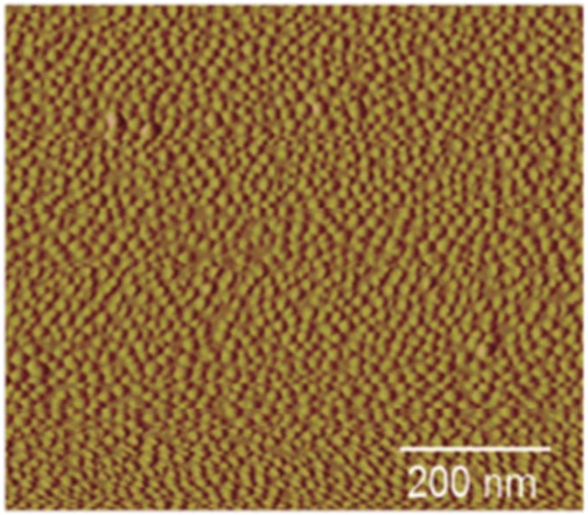
- QD density ($3.5*10^{11}$) an order of magnitude higher than InAs/GaAs
- Here, we varied the amount of antimony present in the structure
- Thickness of QDs grown previously determined to be 3 monolayers

Diagram of InAs/GaAsSb Structure



Cheng, Y. et al. "Investigation Of Inas/Gaas1−Xsbx Quantum Dots For Applications In Intermediate Band Solar Cells". Solar Energy Materials and Solar Cells 147 (2016): 94-100. Web. 5 Apr. 2016.

1 μm^2 AFM of InAs QDs (3 MLs) on GaAsSb

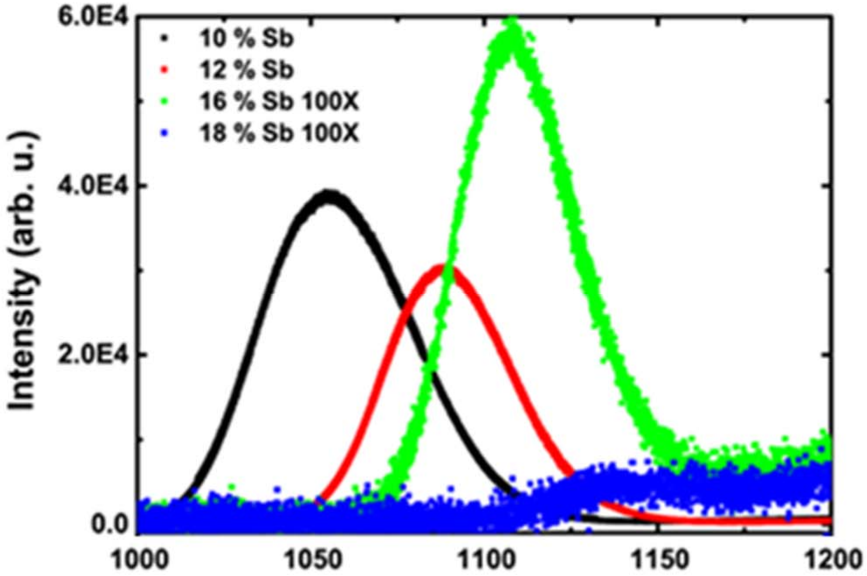


Cheng, Y. et al. "Investigation Of Inas/Gaas1−Xsbx Quantum Dots For Applications In Intermediate Band Solar Cells". Solar Energy Materials and Solar Cells 147 (2016): 94-100. Web. 5 Apr. 2016.

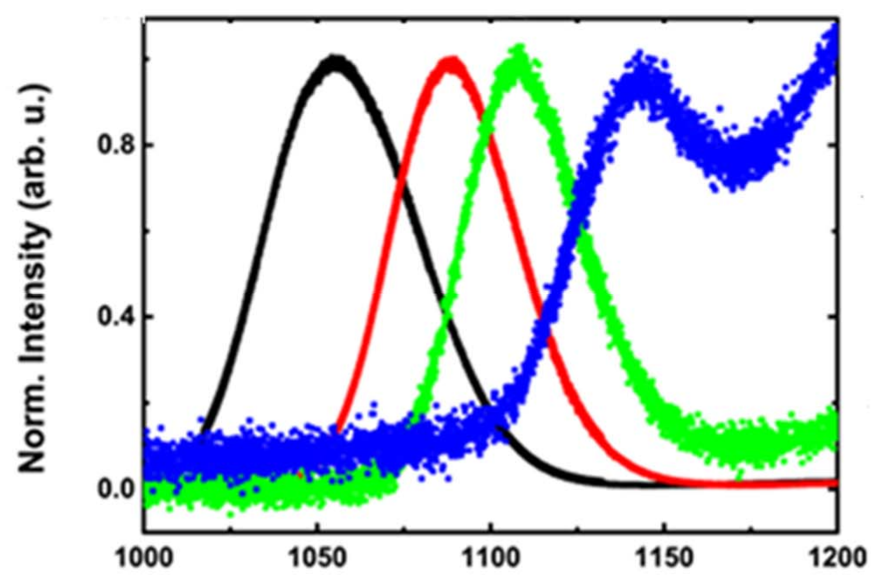
Experimental Data and Analysis

- A decrease in PL with increasing antimony is seen
- An increase in defects noted at 18% antimony

PL of Varying Sb Compositions



Normalized PL of Varying Sb Compositions

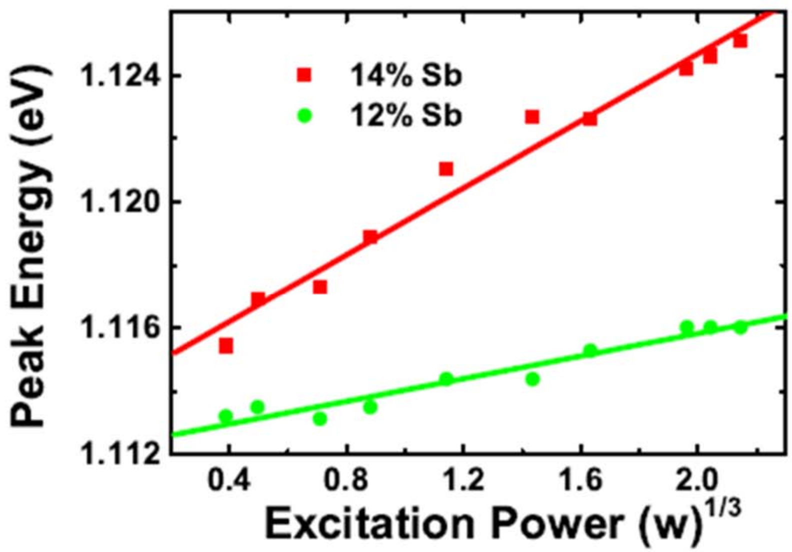


Cheng, Y. et al. "Investigation Of Inas/Gaas1–Xsbx Quantum Dots For Applications In Intermediate Band Solar Cells". Solar Energy Materials and Solar Cells 147 (2016): 94-100. Web. 5 Apr. 2016.

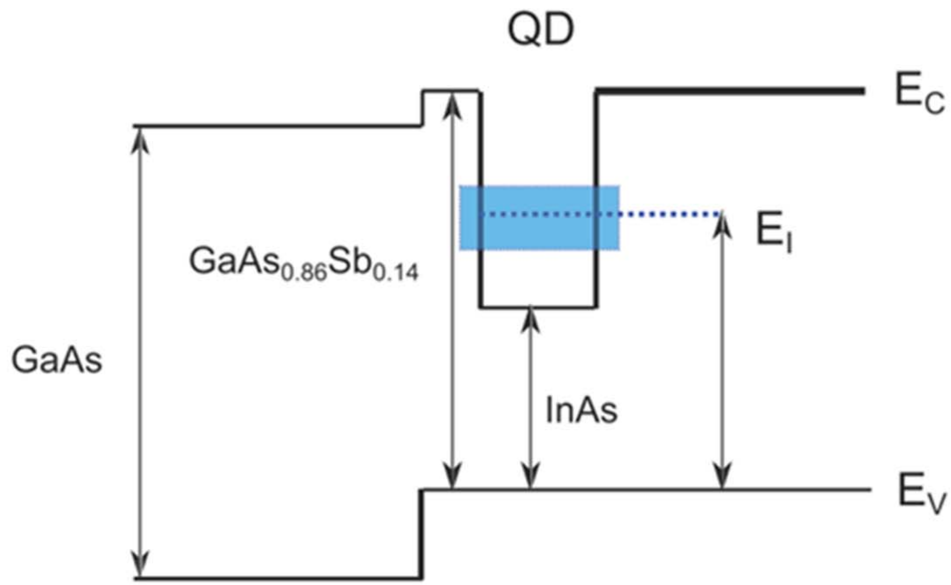
Experimental Data and Analysis

- Power dependent PL peak data shows clear band alignment shift
- Results in degenerate valence band and therefore band diagram shown

Power Dependence of Peak PL



Band Diagram of InAs/GaAsSb Structure

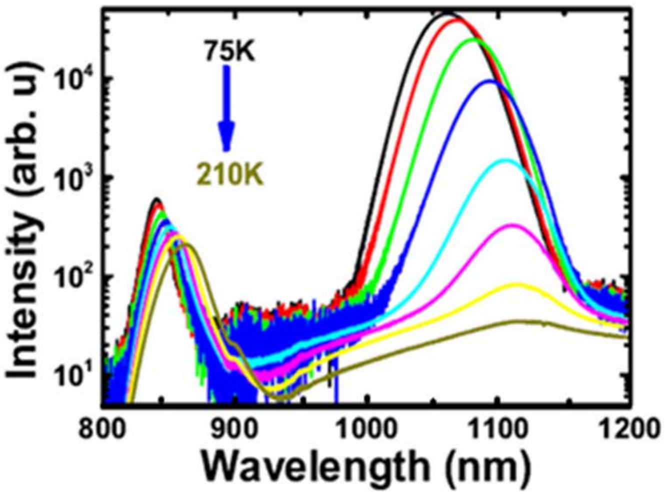


Cheng, Y. et al. "Investigation Of Inas/Gaas1−Xsbx Quantum Dots For Applications In Intermediate Band Solar Cells". Solar Energy Materials and Solar Cells 147 (2016): 94-100. Web. 5 Apr. 2016.

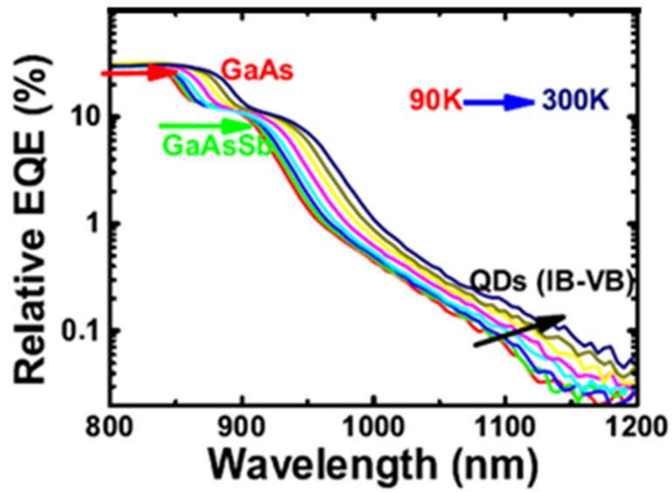
Experimental Data and Analysis

- Anti-correlation between QD PL and QD EQE
- This is due to increased carrier extraction from QDs with temperature

TD Photoluminescence



TD external quantum efficiency

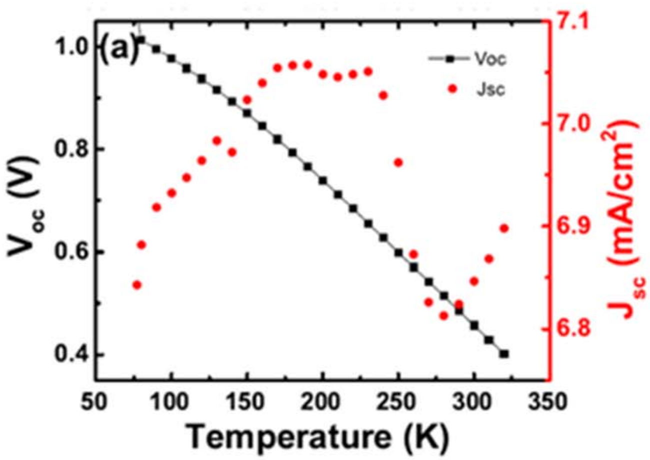


Cheng, Y. et al. "Investigation Of Inas/Gaas1−Xsbx Quantum Dots For Applications In Intermediate Band Solar Cells". Solar Energy Materials and Solar Cells 147 (2016): 94-100. Web. 5 Apr. 2016.

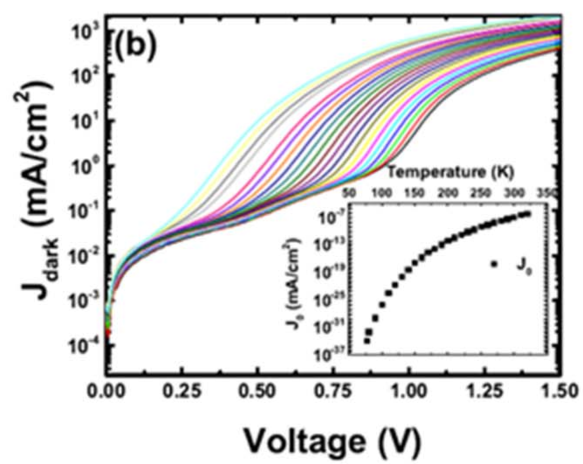
Experimental Data and Analysis

- Large V_{oc} drop observed coupled with rising dark saturation current
- TD J_{dark} shows a barrier to transport that decreases with increasing temp
- "S" shaped J_{sc} behavior due nonradiative recombination due to defects

TD V_{oc} and J_{sc}



TD Dark Saturation Current



Cheng, Y. et al. "Investigation Of Inas/Gaas1−Xsbx Quantum Dots For Applications In Intermediate Band Solar Cells". Solar Energy Materials and Solar Cells 147 (2016): 94-100. Web. 5 Apr. 2016.

New Samples: Determining the Reason for Lack of IB

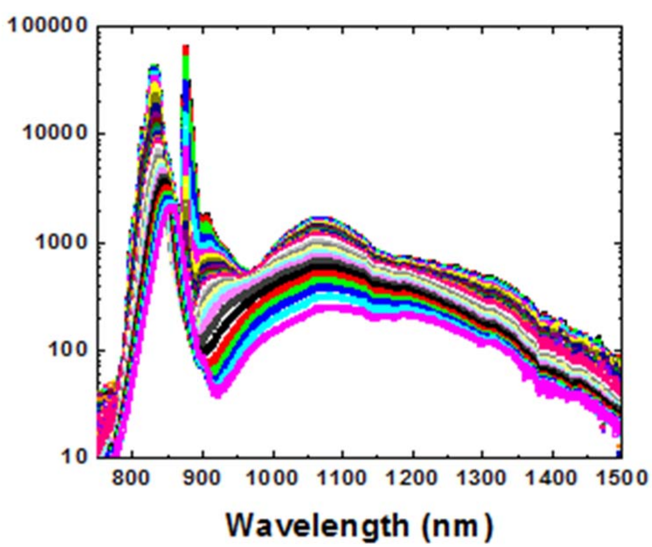
Next step: determine if the behavior is caused by the dots themselves

- 4 new samples grown each with a different amount of QD layers
- These samples are a 0, 3, 5 and 7 layer sample
- GaAsSb replaces QDs in the 0 layer (control) sample
- Each QD layer is 3 ML thick per previous data
- 14% Sb used per previous data

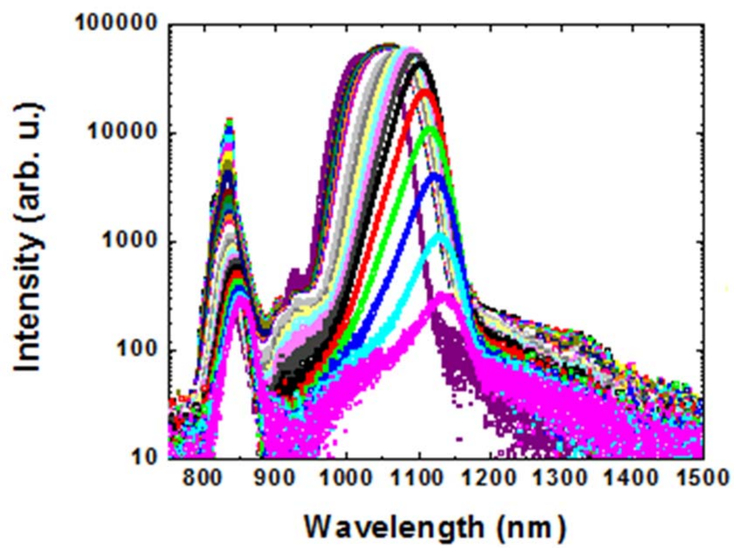
Experimental Data and Analysis

- 5 Layer sample has decreased PL from the QDs with increasing temperature
- This is consistent with previous data
- Control sample has defects due to 10% lattice mismatch between matrix/GaAs

Control TD PL



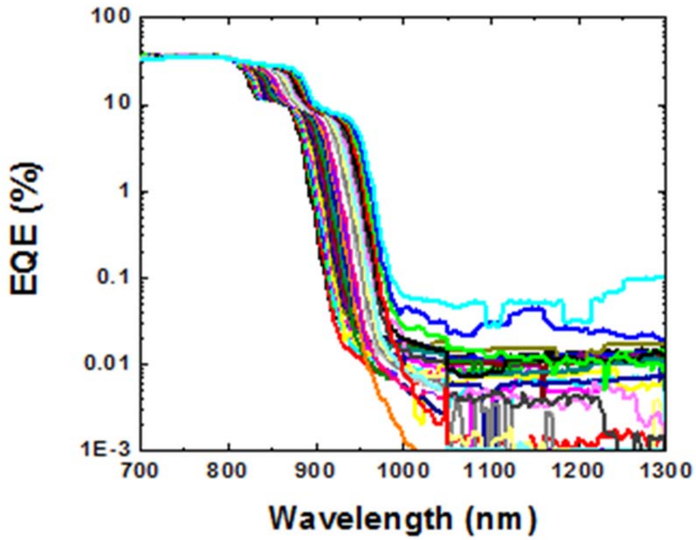
5 Layer TD PL



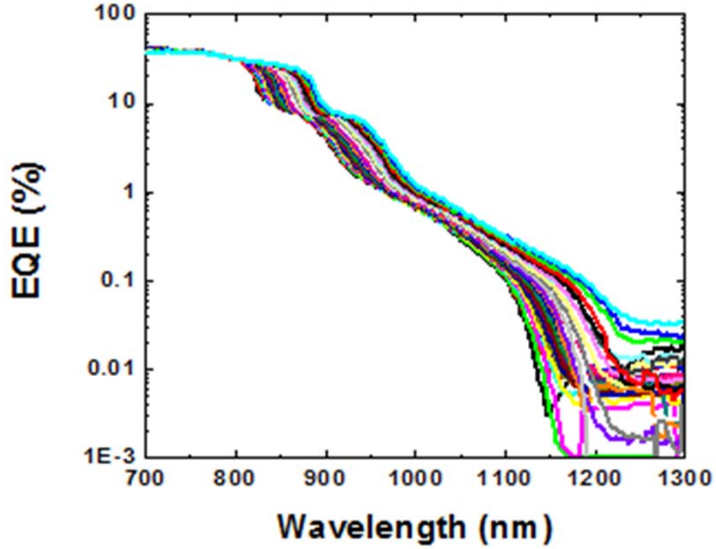
Experimental Data and Analysis

- 5 Layer sample has increased EQE from QDs anti-correlating with TD PL
- This is consistent with previous data
- Control sample has no EQE in that region

Control EQE



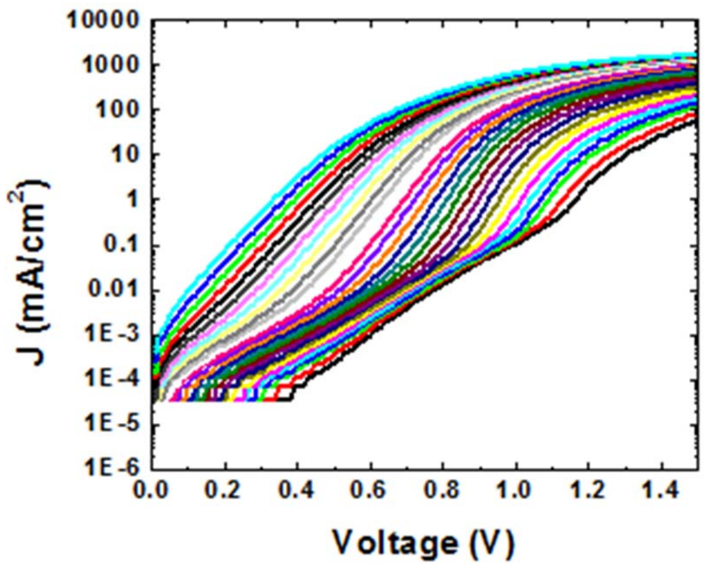
5 Layer EQE



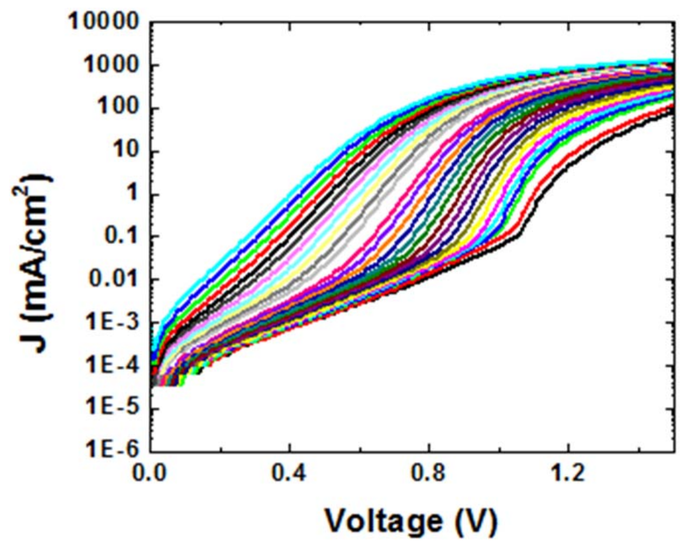
Experimental Data and Analysis

- Similar data as seen before
- Barrier lowering exists in control sample as well as 5 layer sample
- Fits using a two diode model have been performed
- One is the main junction diode and the other is a dominating tunneling diode

Control Dark Saturated Current



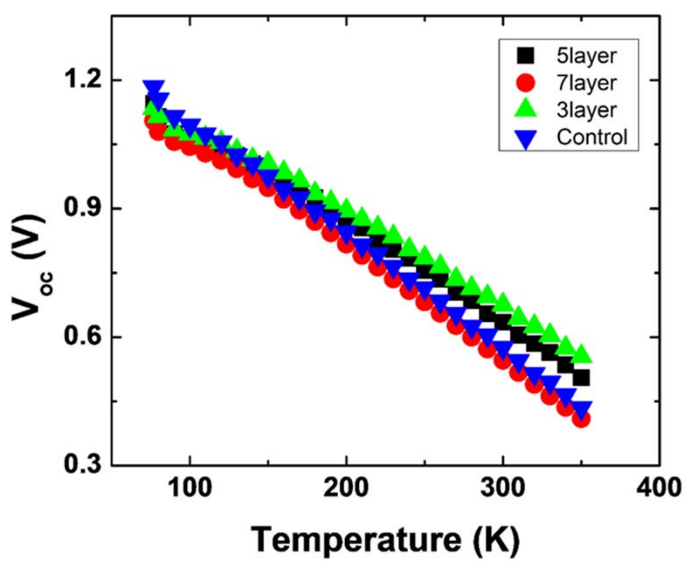
5 Layer Dark Saturated Current



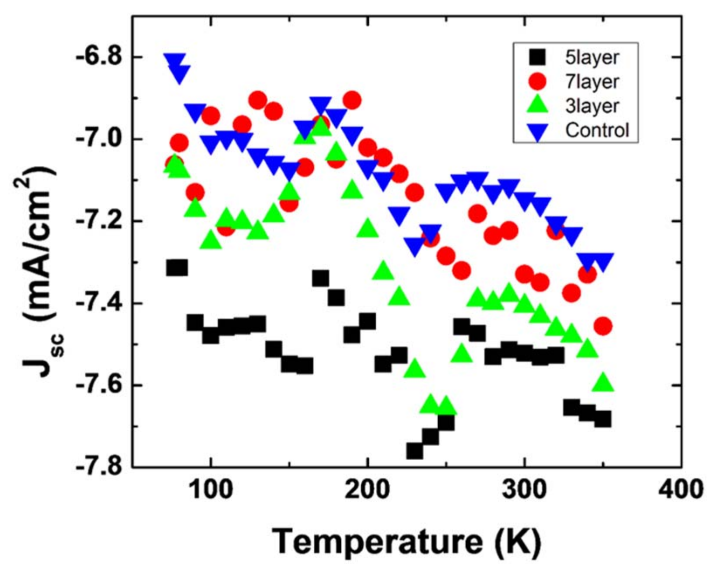
Experimental Data and Analysis

- Similar data as seen before
- Each sample, including control, shows "S" shaped J_{sc}
- Control sample also shows drastic loss in V_{oc} as well
- Therefore, lack of apparent IB due to defects in control and not the QDs

TD V_{oc}



TD J_{sc}



Future Goals

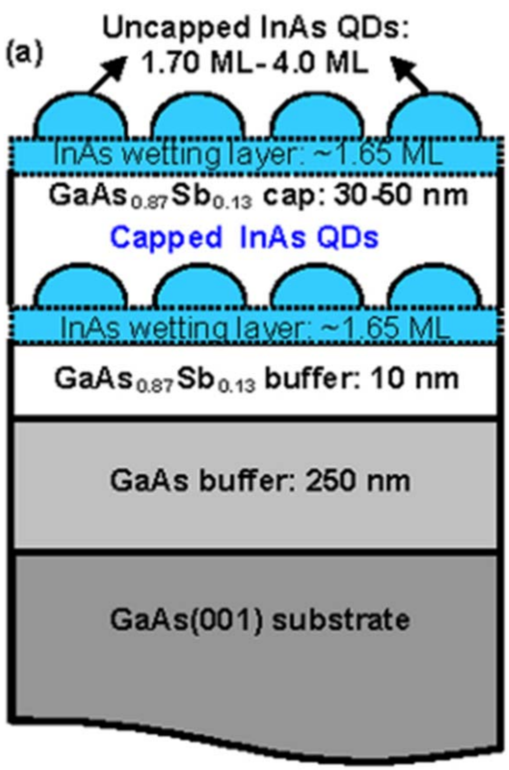
- Cross sectional TEM to physically determine the defects
- Test for sub band gap absorption since that has not been clearly shown in these experiments
- In the future, grow new samples perhaps without GaAs so as to not introduce lattice mismatch

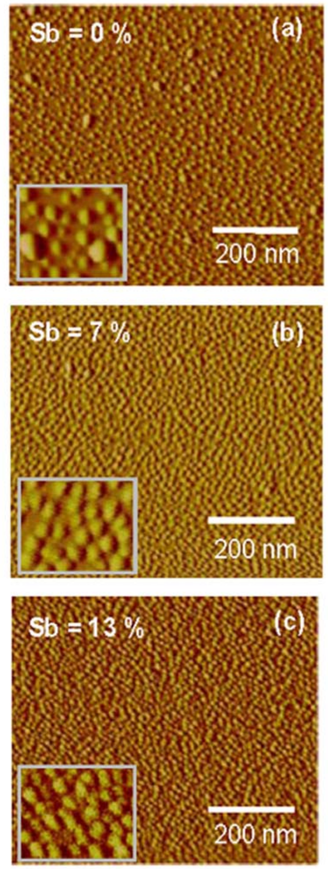
References

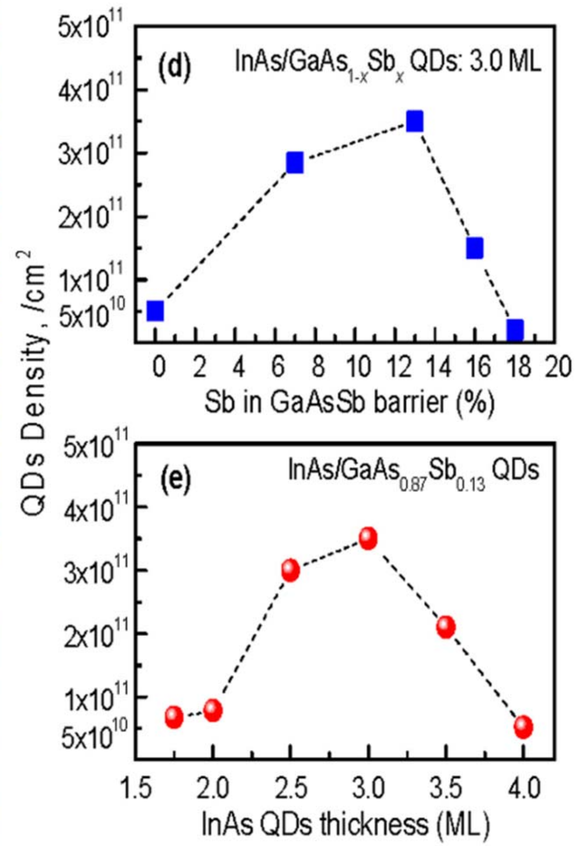
1. Hirst, L.C. and N.J. Ekins-Daukes, Fundamental losses in solar cells. Progress in Photovoltaics: Research and Applications, 2011. 19(3): p. 286-293.
2. Conibeer, Gavin. "Third-Generation Photovoltaics". Materials Today 10.11 (2007): 42-50. Web. 5 Apr. 2016.
3. Luque, A. and Martí, A. (2010), The Intermediate Band Solar Cell: Progress Toward the Realization of an Attractive Concept. Adv. Mater., 22: 160–174.
4. Debnath, M. C. et al. "High-Density Inas/Gaas1−Xsbx Quantum-Dot Structures Grown By Molecular Beam Epitaxy For Use In Intermediate Band Solar Cells". *J. Appl. Phys.* 119.11 (2016): 114301. Web. 16 Apr. 2016.
5. Cheng, Y. et al. "Investigation Of InAs/$GaAs_{1-X}$ Sb_x Quantum Dots For Applications In Intermediate Band Solar Cells". *Solar Energy Materials and Solar Cells* 147 (2016): 94-100. Web. 15 Apr. 2016.

Appendix

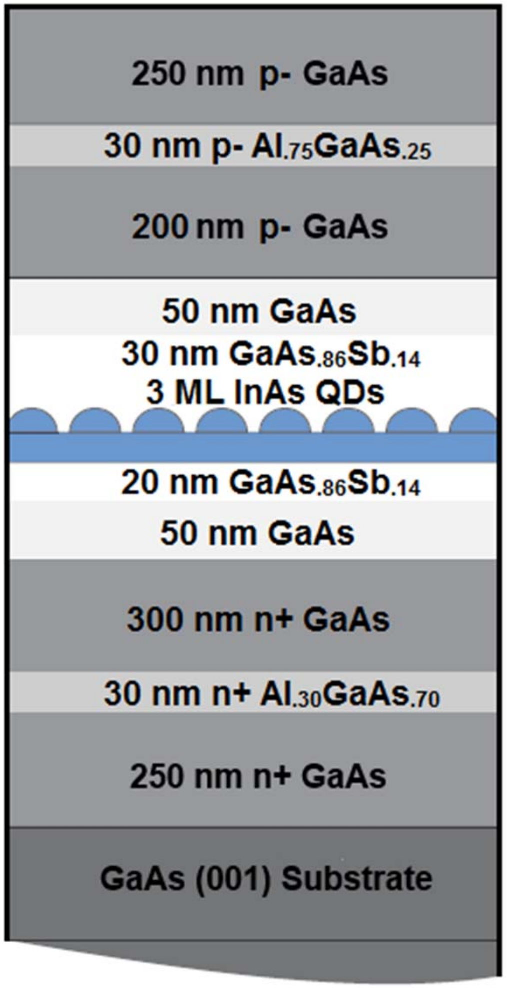
Both amount of Antimony and monolayer thickness varied to determine optimum composition for QDs







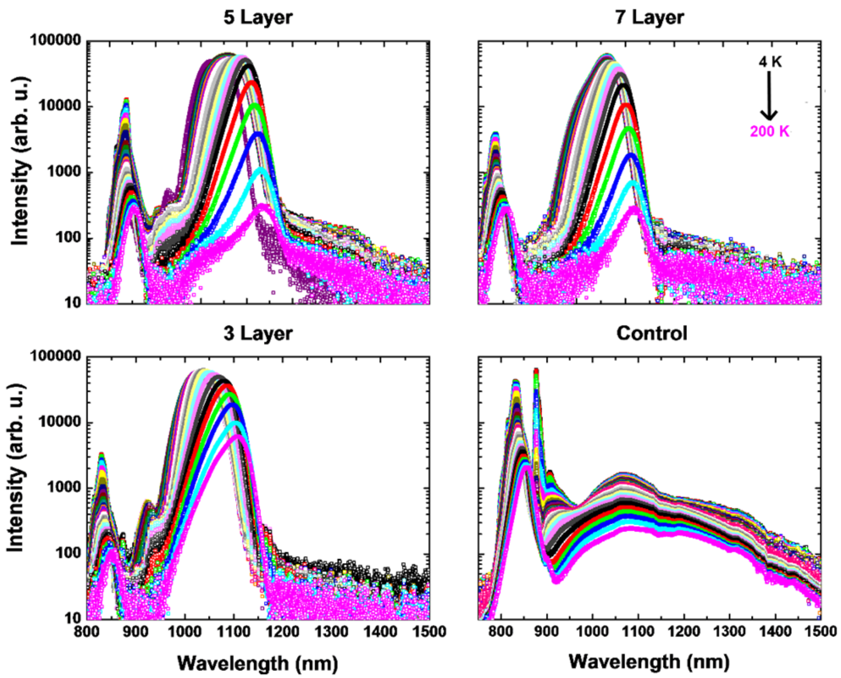
Determining the Reason for Apparent Lack of IB

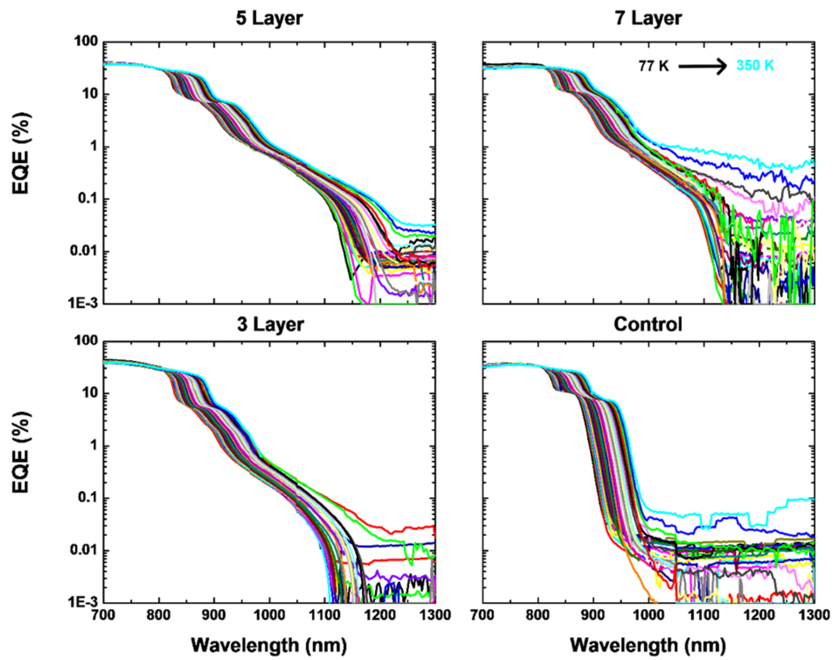


Next step: determine if the behavior is caused by the dots themselves

4 new samples grown
0, 3, 5, 7 QD layer samples
0 layer replaces QDs with GaAsSb
14% Sb, 3.0 ML used based on previous experiments

New Samples: IBSCs TD PL EQE data

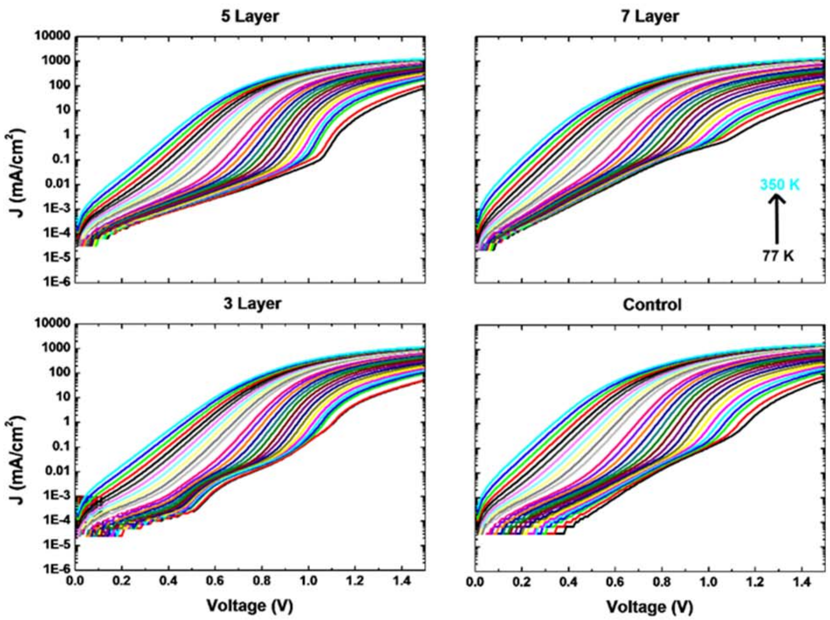


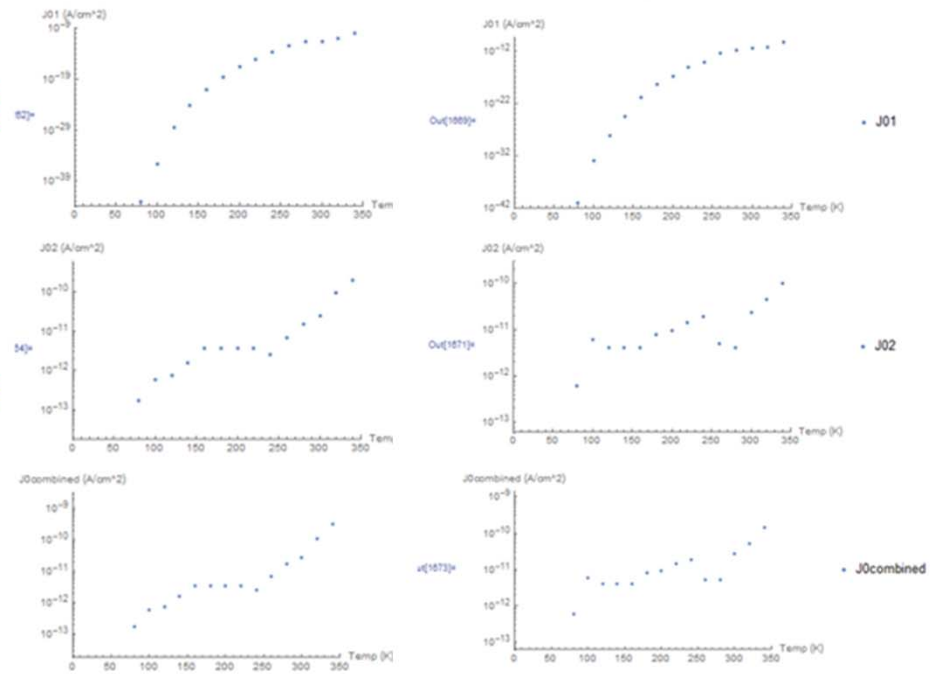


TD PL showing bimodal dot behavior.
Higher PL of 3 layer associated with higher activation energy seen in TD IV
Defects in control seen

TD EQE constant for GaAs/GaAsSb. Increased extraction from QDs associated with thermal assisted carrier escape. Agrees with PL quenching

IBSCs TD IV data and Fits





Two diode behavior observed at low temperature. Second diode thought to be a tunneling diode due to fits

Dark current dominated by second diode and not the main junction diode. Increasing dark current noted