InAs/GaAs$_{1-x}$Sb$_x$ quantum dots for applications in intermediate band solar cells

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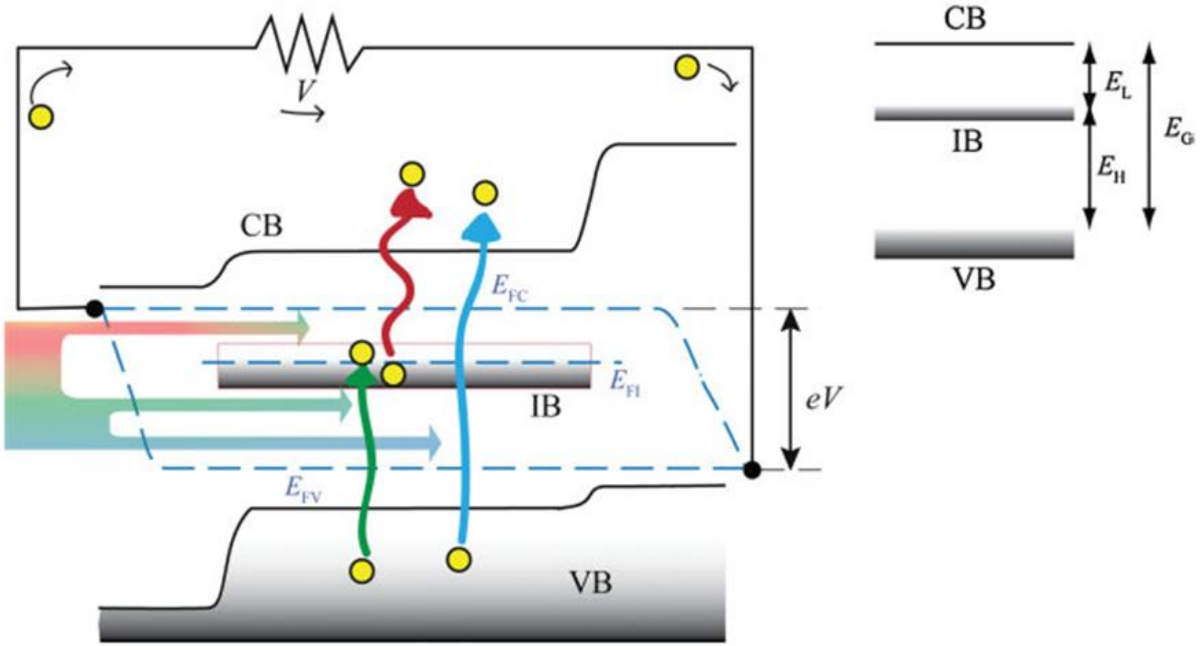
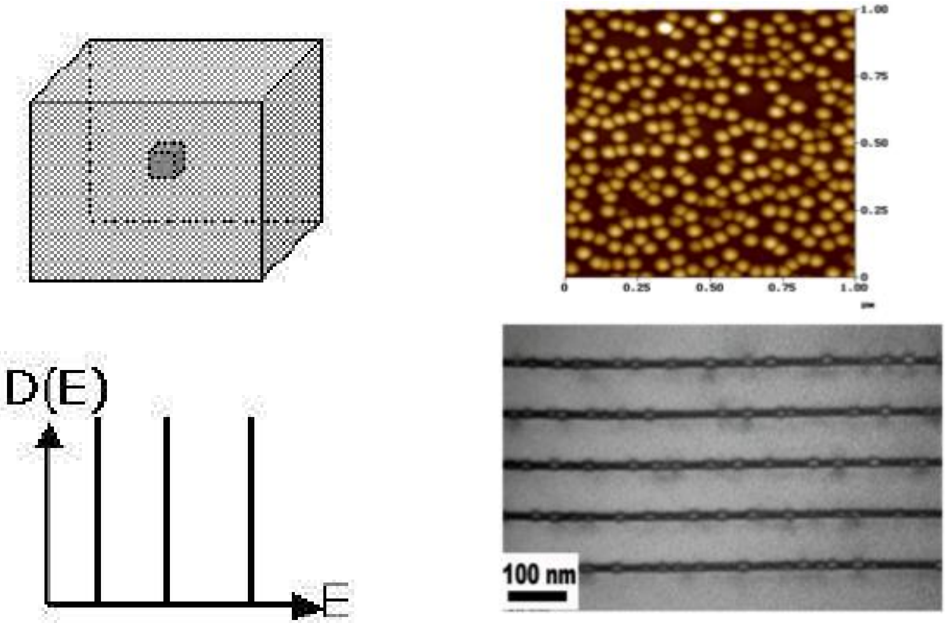
Intermediate Band Solar Cells



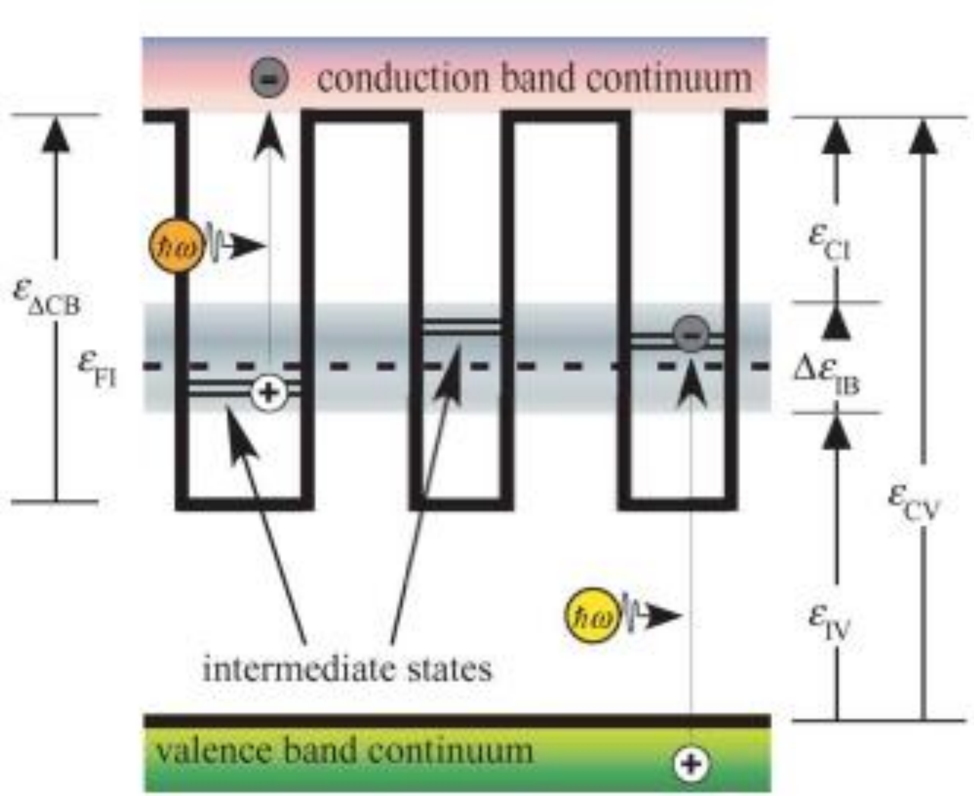
*A. Luque and A. Martí, Advanced Materials, **22**: 160–174. (2010)*



*H. Y. Liu, I. R. Sellers et al., Appl. Phys. Lett. **85**, 704 (2004)*

- Allows harvesting photons with energy below band gap
- Retains V_{oc} while increasing J_{sc}
- QDs proposed as a candidate system: discrete DOS/artificial atoms
- InAs/GaAs QDs well developed system: QD lasers, LEDs, QDSCs

InAs/GaAsSb QD IBSCs



*M. Y. Levy, and C. Honsberg, IEEE Transactions on Electron Devices **55** 706-711 (2008)*

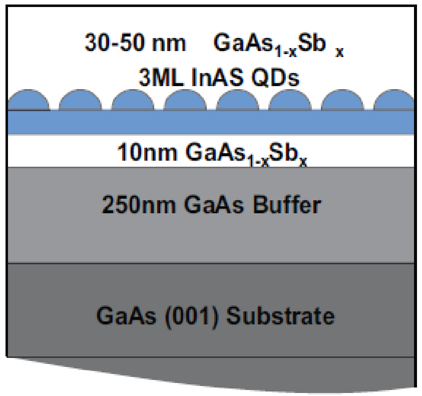
- Simple IB formation, improved hole extraction
- Increased carrier lifetime
- For the proposed system → increased QD density

- Less well-developed than InAs QDs
- Materials issues/still in development

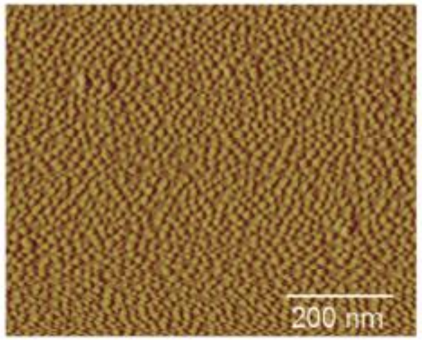
Chiu (2002), Chang (2008), Tomic (2013), Nishikawa (2012), Hatch (2014), Tang(2015), Yang (2016)

Growth and Analysis

Diagram of InAs/GaAsSb Structure



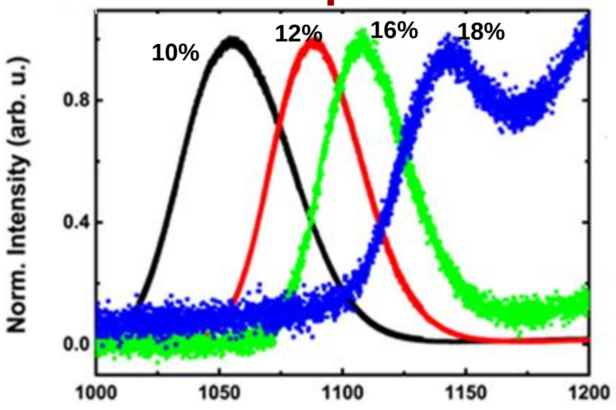
1 μm² AFM of InAs QDs (3 MLs) on GaAsSb



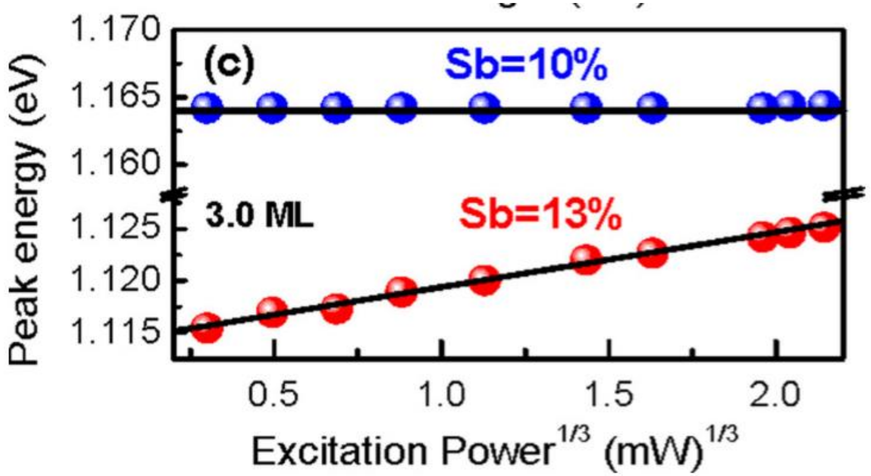
- QD density ($3.5\times10^{11} cm^{-2}$) has been achieved, one order of magnitude higher than InAs QDs on GaAs
- Band alignment transition from type-I to type-II is observed by varying Sb composition in the GaAsSb matrix.

*M. C. Debnath et al., Journal of Applied Physics **119**, 114301 (2016)*

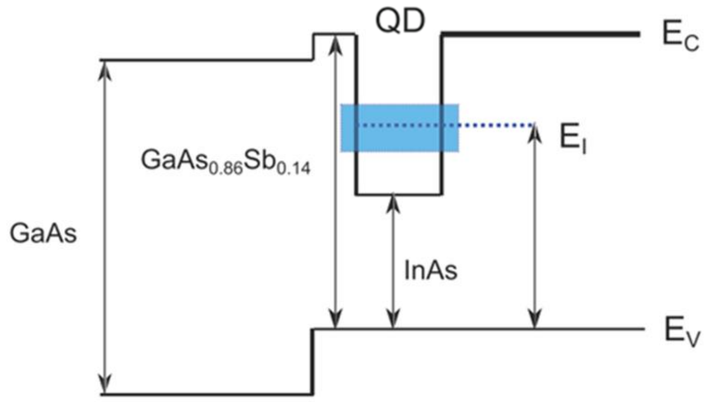
Normalized PL of Varying Sb Compositions



Power Dependence of Peak PL



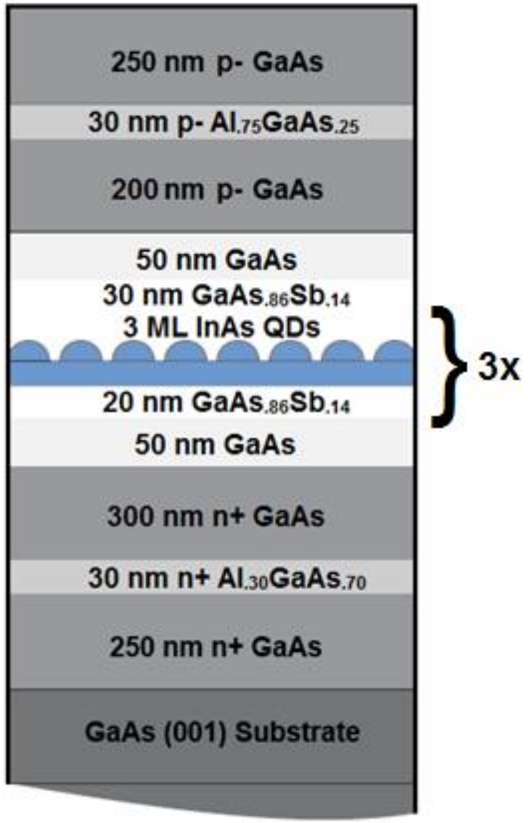
Band Diagram of InAs/GaAsSb Structure

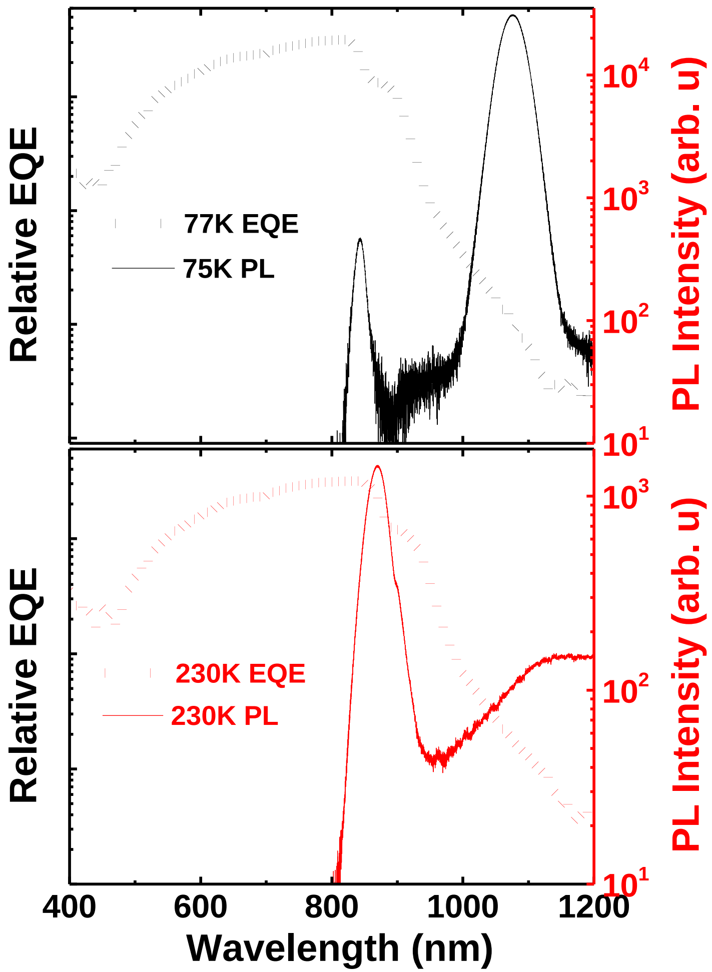


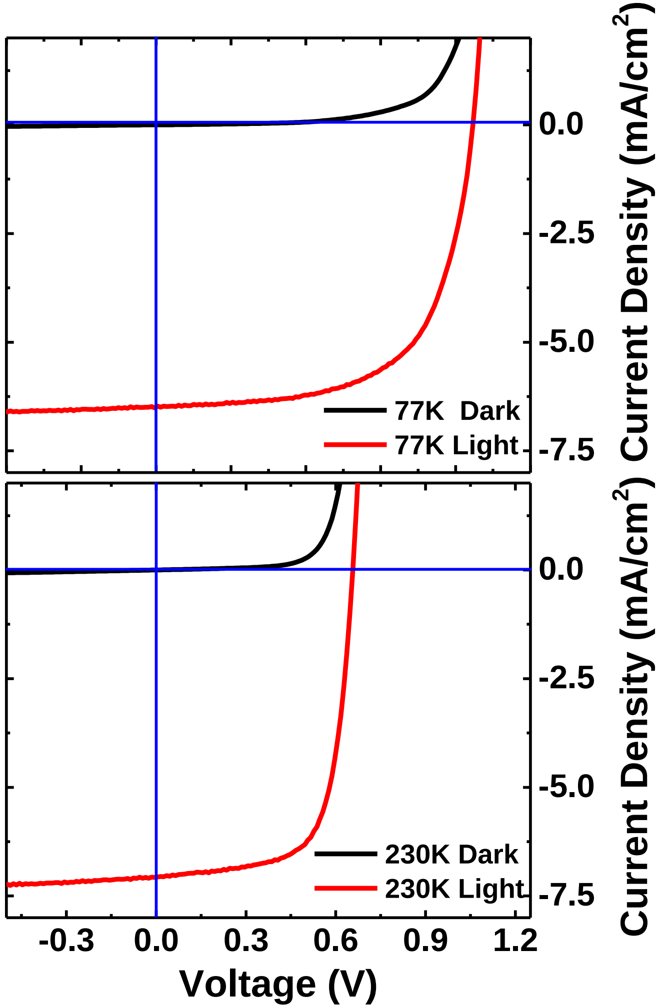
*Y. Cheng et al., Solar Energy Materials and Solar Cells **147** 94 (2016)*

PL, EQE, J-V measurements

Solar cell Structure

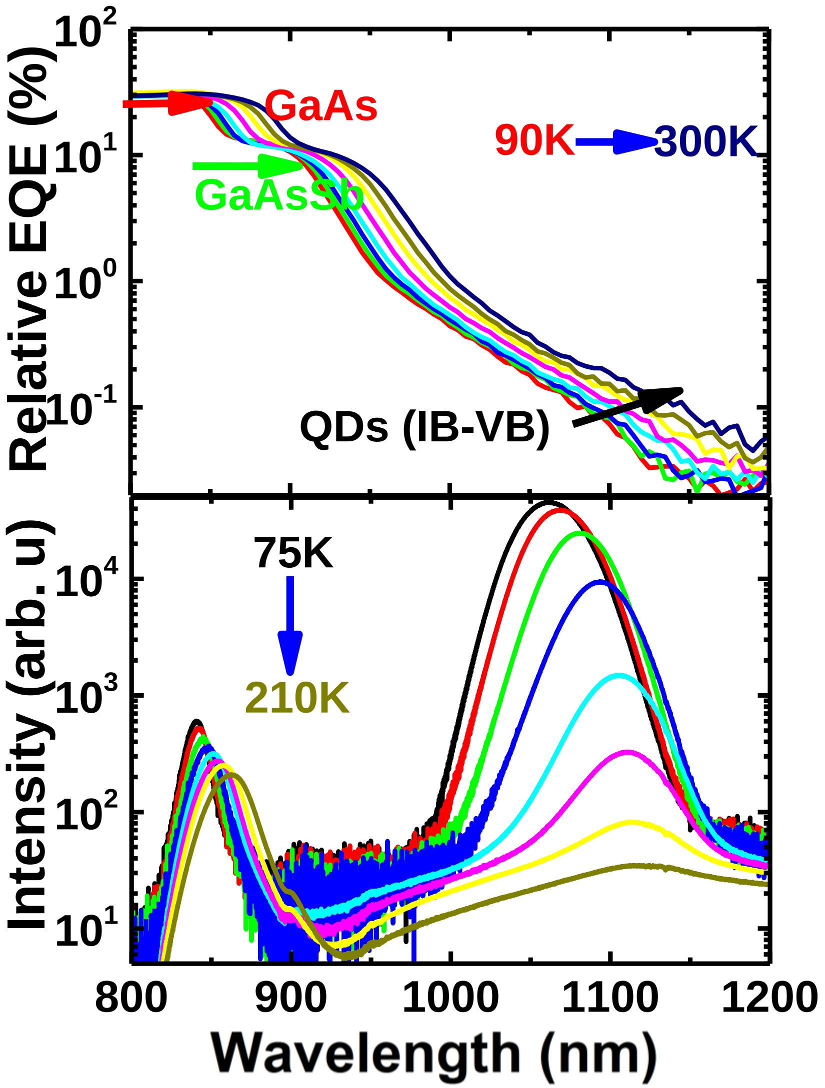






Y. Cheng et al., Solar Energy Materials and Solar Cells ***147*** *94 (2016)*

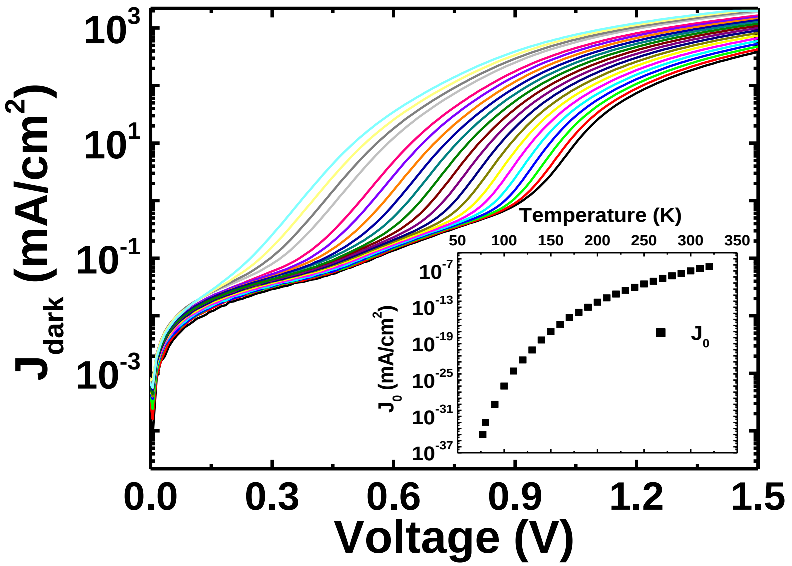
Temperature dependent PL and EQE measurements

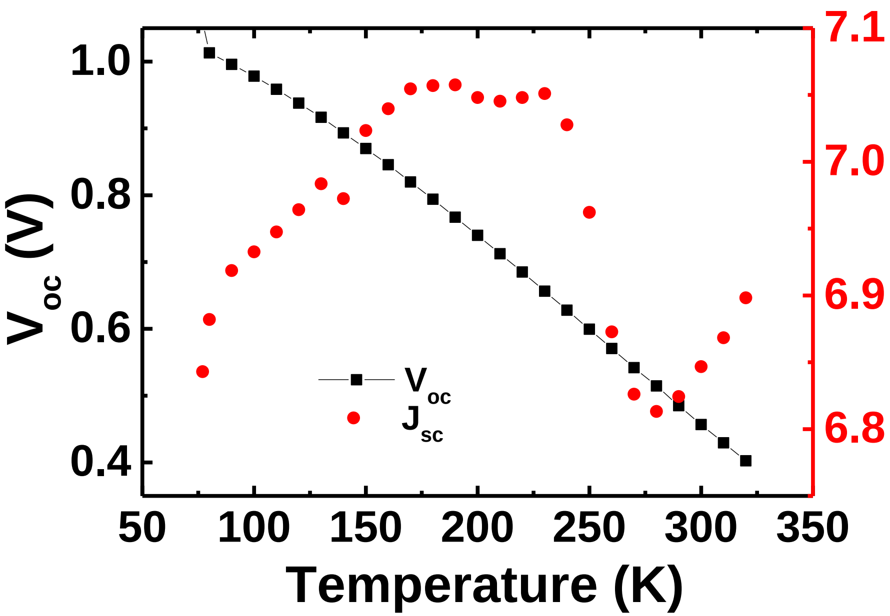


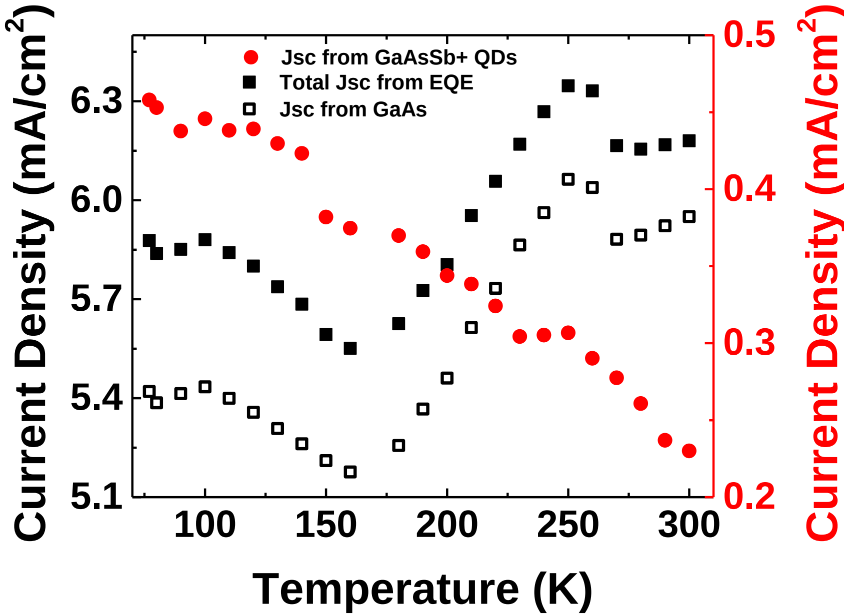
- GaAs (red arrow) EQE peak shifts horizontally.
- $GaA_{0.86}Sb_{0.14}$ (green arrow) EQE peak shifts to the longer wavelength but also becomes shallower.
- EQE related to the InAs QDs also has a red shift, but with an additional enhancement.
- At low temperature, the EQE related to QDs seems to be dominated by radiative recombination.
- Reduction of the radiative recombination (PL) results in the EQE enhancement.

Y. Cheng et al., Solar Energy Materials and Solar Cells ***147*** *94 (2016)*

Temperature dependent J-V measurements





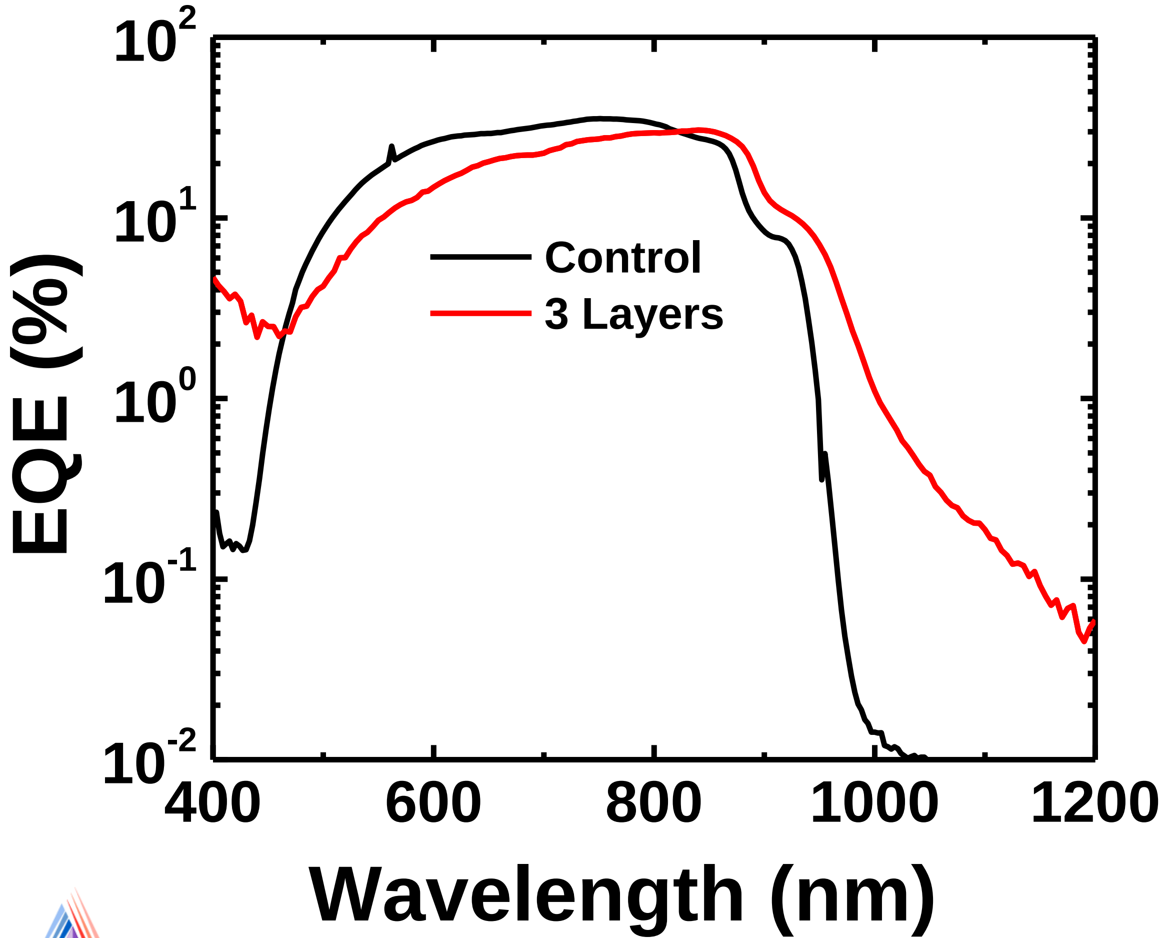


- Large V_{oc} drop observed coupled with rising dark saturation current
- Temperature dependent J_{dark} shows a barrier to transport that decreases with increasing temperature
- "S-shaped" J_{sc} behavior from non-radiative recombination due to defects

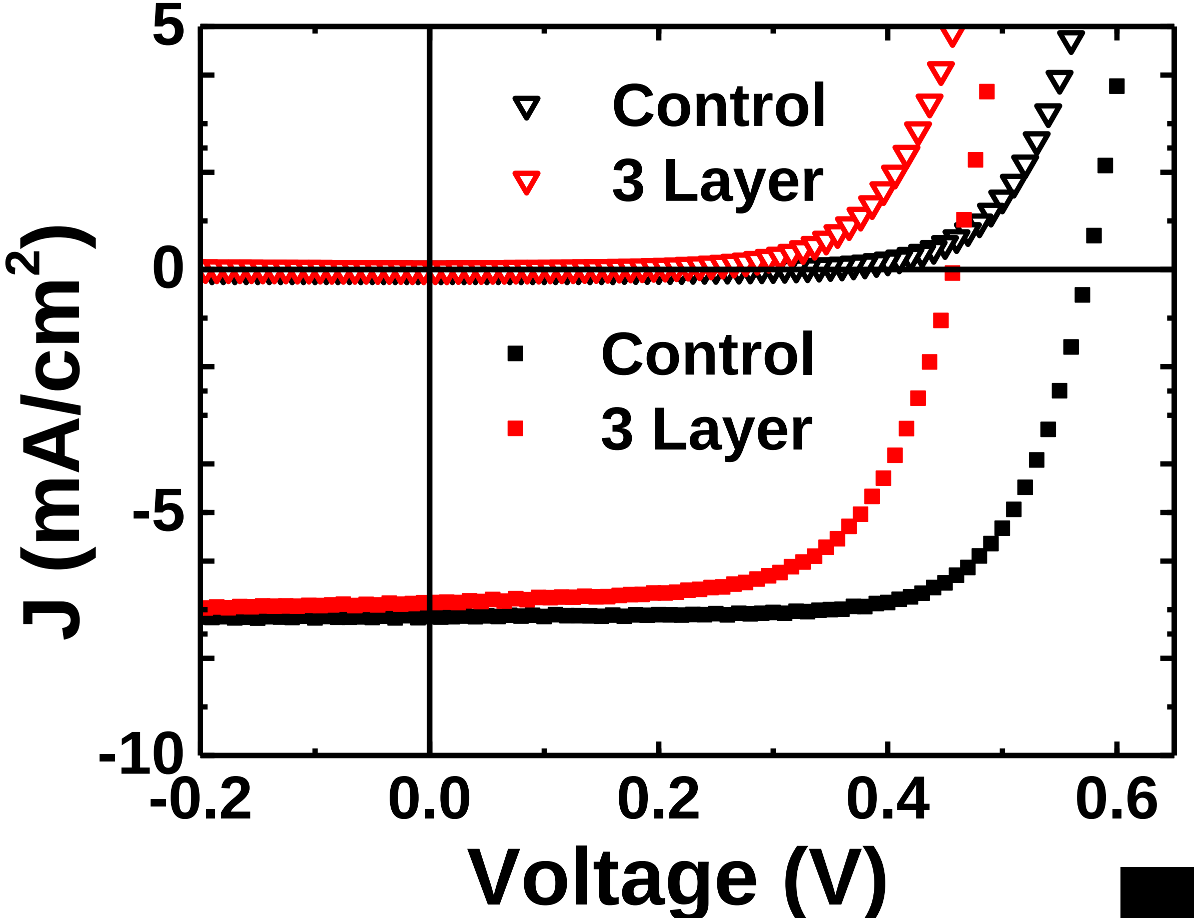
Y. Cheng et al., Solar Energy Materials and Solar Cells ***147*** *94 (2016)*

Comparison of control and 3 Layer sample at 300K

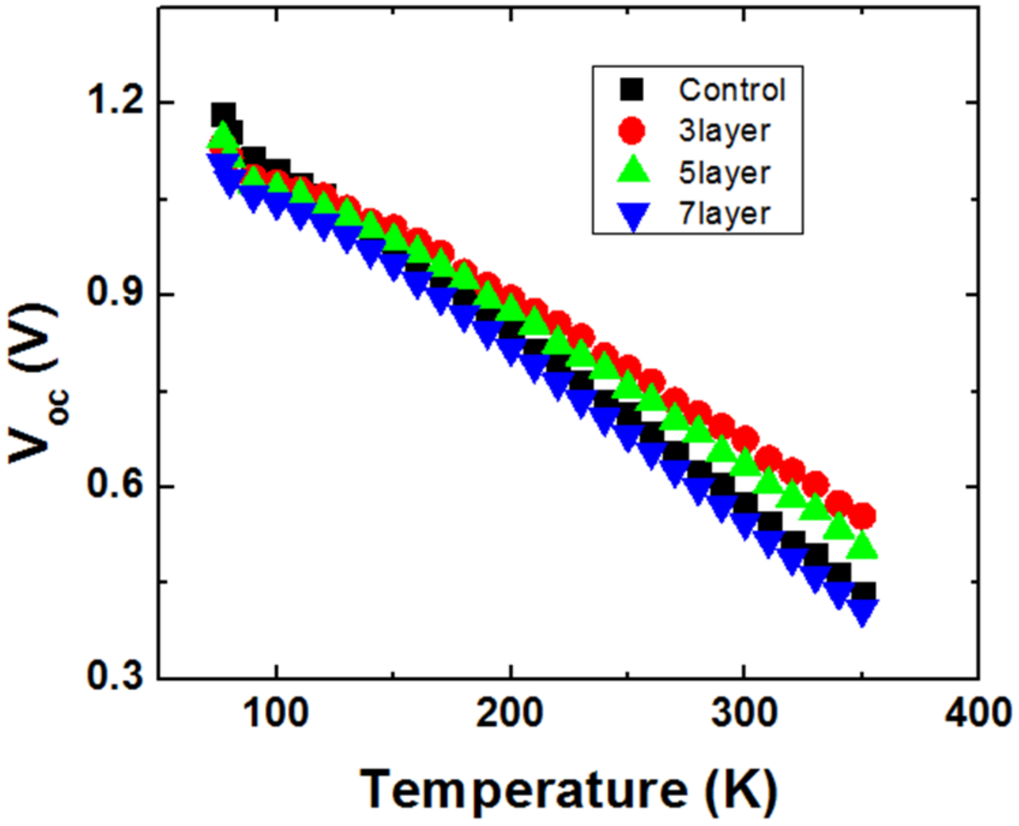
EQE

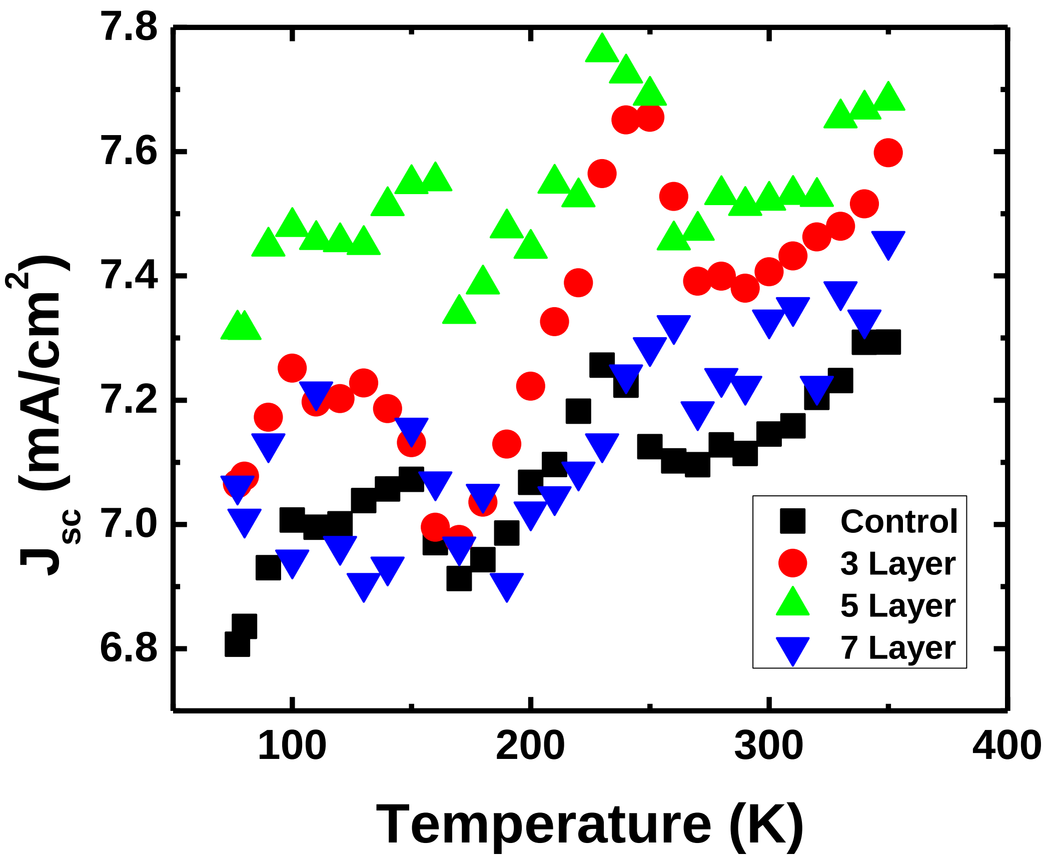


Dark, Light J-V



Comparison of multilayer QDSCs and control





- All samples show a large temperature dependence in open circuit voltage
- Above 130 K open circuit voltage of 3 and 5 QD samples larger than control
- *V_{oc} larger with decreasing QD layers*

- Non-conventional J_{SC} again evident in all samples

A. Meleco, Y. Cheng et al., in preparation (2016)

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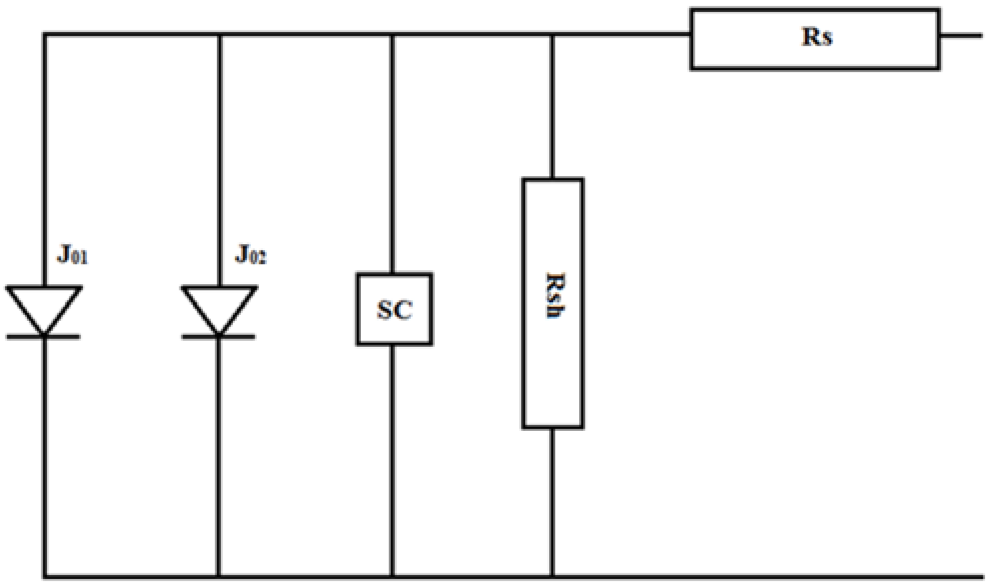
Equivalent Circuit of Model

Single diode model cannot fit dark *J-V*

1. J_{01} represents the main junction diode.
2. J_{02} represents the second diode to achieve a better fitting for the forward bias regime.
3. The third term represents the current due to ohmic shunt and series resistance.
4. the last term represents a non-ohmic (SCLC) leakage current.

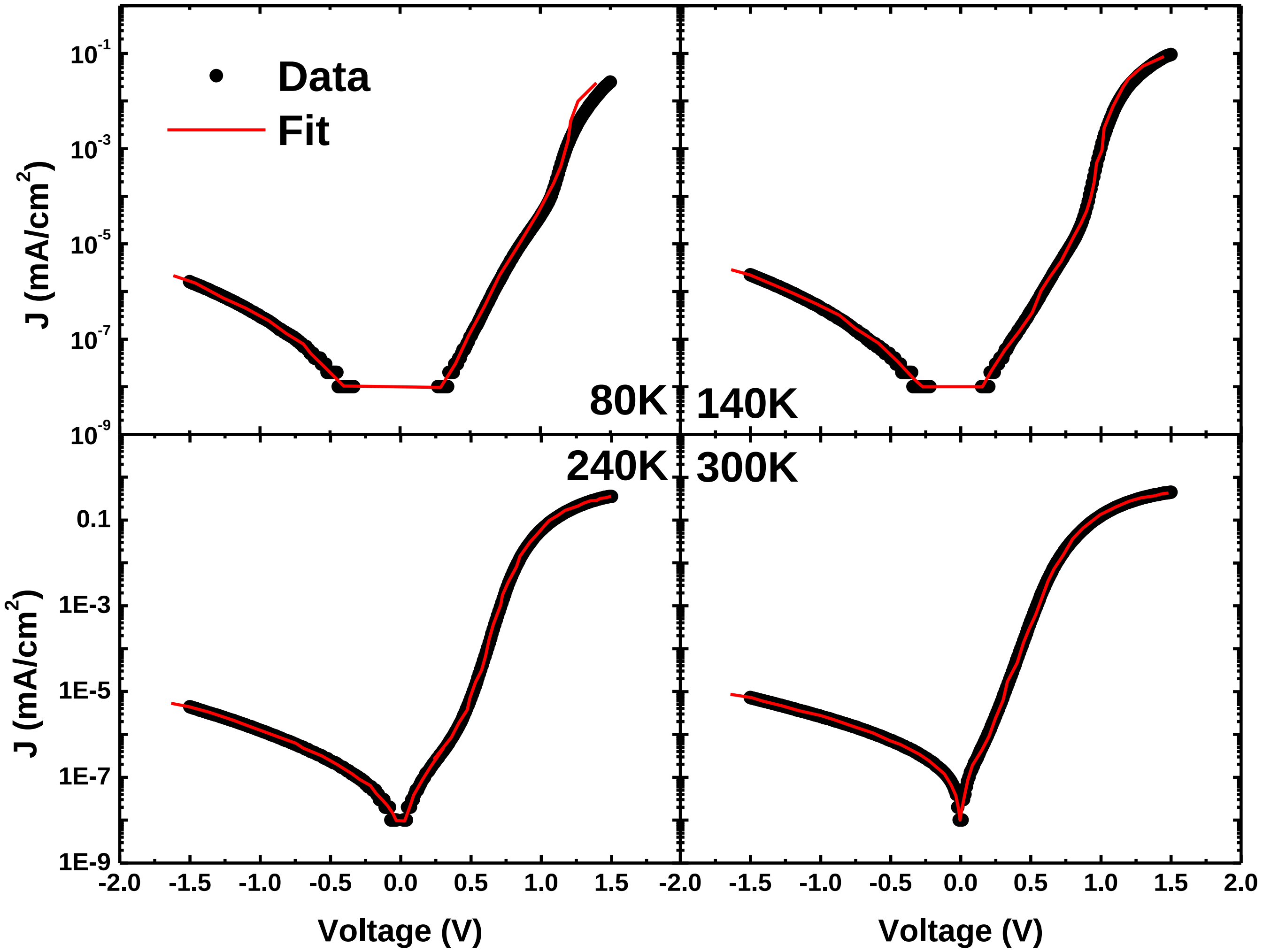
Equivalent Circuit



$$J_D(V) = J_{01}\left(e^{A_1(V-J_D R_S)} - 1\right) + J_{02}\left(e^{A_2(V-J_D R_S)} - 1\right) + \frac{V - J_D R_S}{R_{SH}} + k(V - J_D R_s)^m$$

B. L. Williams et al., Progress in Photovoltaics: Res. Appl. ***23****, 1516 (2015)*

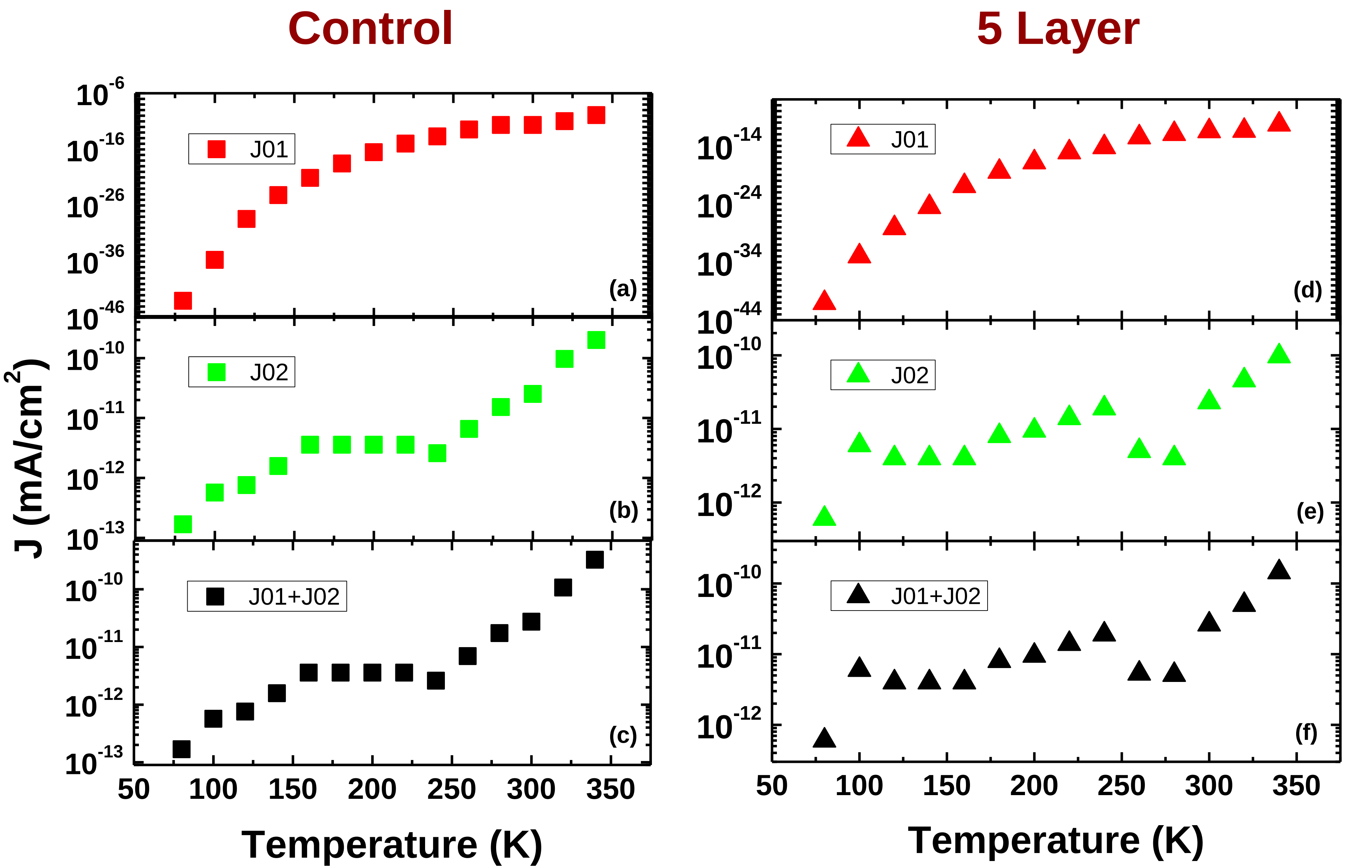
Dark Current Analysis/Fits



- Two-diode model produces good fits although they are less so a lower temperatures
- Non-ideality of system (inhomogeneities) also require large contribution from non-ohmic-space-charge type effects in reverse bias.
- At higher temperatures a single diode fit becomes dominant

A. Meleco, Y. Cheng et al., in preparation (2016)

Dark Saturation Coefficient



Conclusions/Future Work

- Growth conditions for InAs QDs on GaAsSb are optimized. Enhancement of QD density is achieved.
- A transition from type-I to type-II band alignment is observed through power dependent PL measurements.
- Lattice mismatch between GaAs and the matrix contributes to defect formation
- Those defects in the intrinsic region facilitate carrier escape process and dramatically decrease the V_{oc}.
- The escape of electrons compromises the formation of an isolated intermediate band even at low temperature in the present samples
- Phenomenological diode analysis now underway to further elucidate the unusual PV characteristics
- Cross-sectional TEM is important to validate our hypothesis for a defect mediated tunneling model.