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


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Intermediate Band Solar Cells

- 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

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

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


Growth and Analysis

- QD density (3.5×10^{11} \text{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 \textbf{119}, 114301 (2016)

PL, EQE, J-V measurements

Solar cell Structure

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.

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

Comparison of control and 3 Layer sample at 300K

**EQE**

- Wavelength (nm)
  - 400
  - 600
  - 800
  - 1000
  - 1200

- EQE (%)
  - 10^2
  - 10^1
  - 10^0
  - 10^-1
  - 10^-2

- Control
- 3 Layers

**Dark, Light J-V**

- Voltage (V)
  - -0.2
  - 0.0
  - 0.2
  - 0.4
  - 0.6

- J (mA/cm^2)
  - -10
  - -5
  - 0
  - 5

- Control
- 3 Layer
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

\[ J_{sc}\text{ (mA/cm}^2\text{)} \]

\[
\begin{array}{c|c|c|c}
\text{Temperature (K)} & \text{Control} & \text{3 Layer} & \text{5 Layer} & \text{7 Layer} \\
\hline
100 & 6.8 & & & \\
200 & 7.0 & & & \\
300 & 7.2 & & & \\
400 & 7.4 & & & \\
\end{array}
\]

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

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

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

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

Control

![Graph showing J vs Temperature for Control](a)

![Graph showing J vs Temperature for Control](b)

![Graph showing J vs Temperature for Control](c)

5 Layer

![Graph showing J vs Temperature for 5 Layer](d)

![Graph showing J vs Temperature for 5 Layer](e)

![Graph showing J vs Temperature for 5 Layer](f)
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.