

# Quantum Dot Superlattice Hybrid Structures for Solar Cell Applications

**Rachel Lucas**

**Physics/Aerospace Engineering, Purdue University**

**NNIN iREU Site: National Institute for Materials Science (NIMS), Tsukuba, Ibaraki, Japan**

*NNIN iREU Principal Investigators: Dr. Takeshi Noda, High Efficiency Solar Cell Group, NIMS, Tsukuba, Ibaraki, Japan;*

*Professor Hiroyuki Sakaki, Toyota Technological Institute, Nagoya, Aichi, Japan*

*NNIN iREU Mentor: Dr. Martin Elborg, High Efficiency Solar Cell Group, NIMS, Tsukuba, Ibaraki, Japan*

*Contact: lucas27@purdue.edu, noda.takeshi@nims.go.jp, elborg.martin@nims.go.jp*

## Introduction:

Using quantum structures (QDs) in the absorption layer of a solar cell has been of great interest in potentially overcoming the Shockley-Queisser conversion efficiency limit of solar cells. QDs produce an intermediate band (IB) that allows absorption of sub-bandgap photons and thus increases photocurrent generation [1]. This process occurs in two steps wherein one photon excites a carrier from the valance band (VB) to the IB and a second photon excites this carrier from the IB to the conduction band (CB). This process is called two-step photocurrent generation (Figure 1) and it increases the number of carriers reaching the CB thus increasing the current created.

A hybrid quantum dot (QD) quantum well (QW) structure was proposed as a method to create intermediate energy states. This hybrid structure is expected to provide advantages of both QWs and QDs, surpassing the issues of using only one type of quantum structure. QDs afford a discrete density of states, but large absorption of light requires many layers of QDs, which is difficult to realize. QWs allow a relatively large absorption of photons however two-step photocurrent generation is less efficient when light is incident perpendicular to this structure. Using both structures is expected produce a combination of all desired traits.

A GaAs/AlGaAs superlattice (SL) structure and InAs QDs were grown and intermediate band solar cells (IBSC) were fabricated from them. In this work carrier transfer between the SL and QD structures was studied in addition to two-step photocurrent generation.

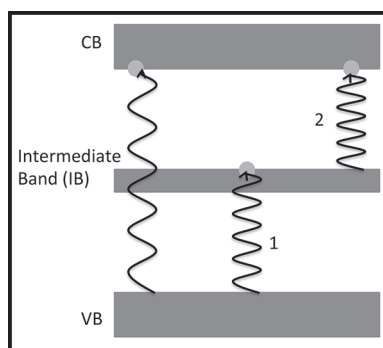
## Fabrication Procedure:

A superlattice structure of ten 4 nm thick GaAs wells separated by 3 nm thick AlGaAs barriers was grown beneath an InAs QD layer. The QDs were grown using the Stranski-Krastanov growth mode. In this growth mode, the initial growth proceeds layer-by-layer until a critical thickness is reached. A further deposition of the material causes the growth mode to change from two-dimensional to three-dimensional creating dots. This hybrid structure was grown between layers of AlGaAs on a p-type GaAs <100> substrate. All samples were grown using molecular beam epitaxy (MBE). Solar cells were fabricated using photolithography, sputtering, and chemical etching. The devices were then packaged and bonded for testing.

## Results:

Atomic force microscopy (AFM) was used to characterize the QDs. Approximate QD density was found to be  $6.6 \times 10^{10} \text{ cm}^{-2}$ , while approximate dot size was found to be 20 nm in diameter and 2 nm in height. Photoluminescence (PL) measurements performed at 10 K revealed that SL emission energy was 1.6 eV while QDs had a broad curve of emission energies peaking at 1.4 eV (Figure 2).

Through a comparison of the sample containing only the SL structure and the sample containing both SL and QD structures it is seen that the intensity of the SL peak decreases with the addition of QDs to the sample structure. This indicates that carriers are being transferred out of the SL and into the QDs in the hybrid structure.



*Figure 1: Band diagram of two-step photocurrent generation where 1 marks the transition from VB to IB due to one photon and 2 marks the transition from IB to CB due to a second photon.*

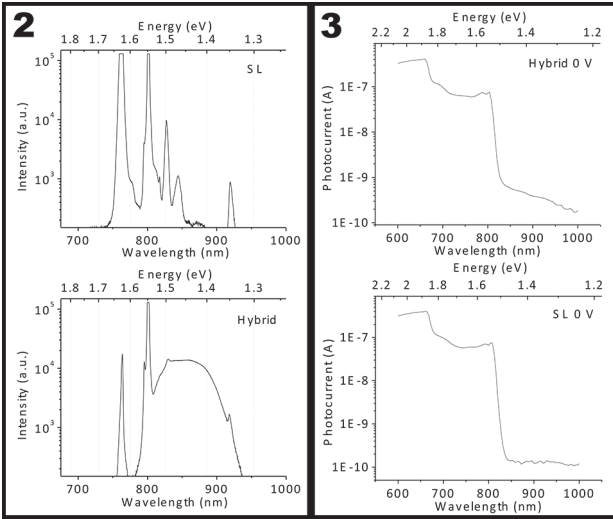


Figure 2, left: Photoluminescence data for superlattice and hybrid samples. Figure 3, right: Photocurrent data for superlattice and hybrid solar cell samples.

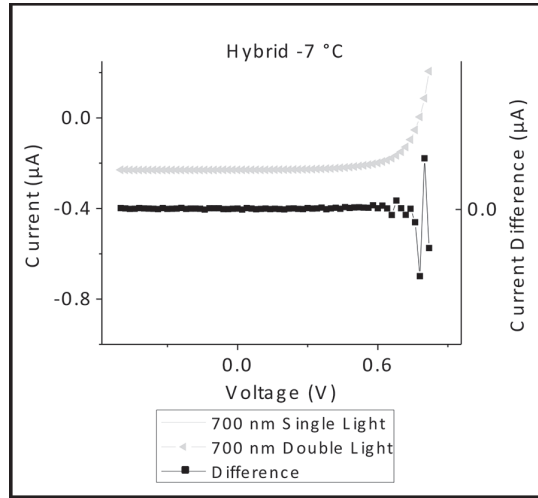


Figure 4: Room temperature two-step photocurrent generation for hybrid sample. Squares correspond to the right-hand y-axis while triangles correspond the left-hand axis.

Photocurrent measurements performed on the solar cell samples at room temperature (RT) reveal a step-like structure for each of the samples (Figure 3). These steps appear because of the sample's dependence of carrier generation on incident light energy. Light having energies greater than 1.9 eV can create carrier pairs throughout the entire solar cell sample. Therefore light with these energies produces the largest photocurrent. Between 1.9 eV and 1.5 eV light no longer has enough energy to create carrier pairs in AlGaAs causing a drop in photocurrent. A second, larger drop in photocurrent occurs at energies below 1.5 eV because carrier pairs can no longer be created in the SL structure. It is seen beyond this second drop in photocurrent that the addition of QDs to the structure causes a small increase in photocurrent by absorbing longer wavelengths.

A 1.55  $\mu\text{m}$  laser was used along with a 700 nm (1.77eV) monochromatic light source to investigate two-step photocurrent generation. The 700 nm light creates the carrier pairs while the laser is expected to excite these carriers from trapping in QDs to generate additional photocurrent. However, when the samples were lit with the laser there was no visible current difference than when only lit with the 700 nm light (Figure 4). In addition, saturated photocurrent flows until the voltage is close to the open circuit voltage. This indicates that the carriers escape trapping due, presumably, to thermal escape processes without the need for the laser. Therefore no two-step photocurrent generation is seen at RT.

### Conclusions and Future Work:

Growth of solar cell structures was successful as indicated by photocurrent spectra and current generation in current-voltage (IV) curves. Carrier transfer was confirmed from the SL to QD structures in PL data. In measurements at RT, however, two-step photocurrent generation was not observed in samples. This is explained by no or negligible carrier trapping at RT due to thermal escape processes. Low temperature measurements or adjusting the SL and QD hybrid structure are future works in order to prove the possibilities of our proposed structure.

### Acknowledgements:

Thanks to Dr. Takeshi Noda, Dr. Hiroyuki Sakaki, and Dr. Martin Elborg as well as the High Efficiency Solar Cell/Quantum Nanostructures Group. Thank you to the National Nanotechnology Infrastructure Network International Research Experience for Undergraduates and the NSF, Grant No. ECCS-0335765, for funding and thanks to NIMS.

### References:

- [1] Jo, M., Y. Ding, T. Noda, T. Mano, Y. Sakuma, K. Sakoda, L. Han, and H. Sakaki. "Impacts of Ambipolar Carrier Escape on Current-Voltage Characteristics in a Type-I Quantum Well Solar Cell." *Applied Physics Letters* 103,061118 (2013).