Wetting Layer Engineering for GaSb Quantum Dots

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Abstract:

Quantum dot intermediate band solar cells have the ability to absorb photons at three different wavelengths instead of just one, allowing them to surpass the Shockley-Queisser efficiency limit of 30% to a maximum theoretical efficiency of 63%. In depositing the quantum dots in the S-K growth mode, we used two different materials, indium arsenide (InAs) and gallium antimonide (GaSb), for the wetting layer to grow GaSb quantum dots. The change in wetting layer largely affected quantum dot geometry and optical properties. When fabricating solar cells, devices with the InAs wetting layer performed better than those with the GaSb wetting layer, suggesting that the InAs wetting layer allows for enhanced thermal excitation in the transition from the intermediate band to the conduction band.

Introduction:

Single band gap solar cells can only absorb photons at one energy level and have theoretical efficiency limit of 30% [1]. By introducing an intermediate band between the conduction and valence bands, solar cells can absorb photons to excite electrons at three different energy levels, allowing them to absorb sub-bandgap photons that were previously transmitted for a theoretical efficiency maximum of 63% [2]. One implementation of the intermediate band is through the usage of very small particles called quantum dots (QDs) [3-6]. QDs experience quantum confinement in all three dimensions, so they have discreet energy levels and can behave like quantum wells [7]. This allows for the intermediate band to be implemented in two different types of band structures as shown in Figure 1. We used GaSb QDs grown on GaAs because studies have shown that those materials form a type II structure where only the holes are confined, leading to less recombination [5,6].

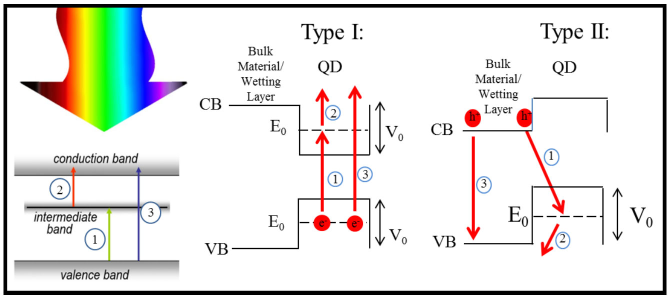


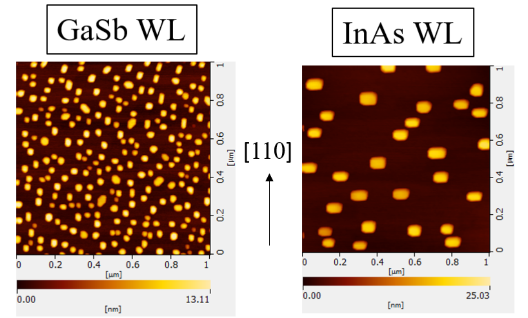
Figure 1: The three different photon excitations in the intermediate band solar cell and the corresponding types of band alignments.

We deposited QDs using the Stranski-Krastanov growth method, where a thin material called the wetting layer was first deposited onto GaAs. The slightly larger lattice constant of the wetting layer (0.6 nm) than the bulk GaAs (0.56 nm) leads to a compressive strain, and once 2-3 monolayers are deposited onto the sample, quantum dots begin to form [8,9]. The wetting layer is confined in one dimension and has a step function-like density of states, leading to a continuum above the ground state energy. It assists in the transition from the intermediate to the conduction band by thermal excitations. In this project, we studied the role of the wetting layer in the formation of different QD geometries and their effects on the performance of solar cell devices.

Experimental Methods:

We experimented with two different device structures. The first was a device with a 2.5 ML GaSb QD layer on top of a 1 ML GaSb wetting layer, and the other consisted of 2.5 ML GaSb deposited on a 1 ML InAs wetting layer. Both materials had almost equal lattice constants. We employed molecular beam epitaxy (MBE) to deposit smooth films of bulk GaAs before depositing our QD and wetting layers, and confirmed the deposition of our nanostructures using reflection high-energy electron diffraction (RHEED).

For solar cell device fabrication, we deposited 10 layers of the QD/wetting layer/GaAs structures on top of n-type GaAs. We then deposited n-type GaAs on top. For structural and optical characterizations, we used atomic force microscopy (AFM) and photoluminescence (PL) spectroscopy at 10K. IV characterizations to measure solar cell device performance were performed using a solar simulator at AM1.5G.



Height	Width	Density	Height	Width	Density
~11nm	~45nm	~220/µm²	~16nm	~85nm	~30/µm²

Figure 2: AFM imagery and statistics of the GaSb QDs grown using different wetting layers.

Results and Discussion:

AFM images show a sharp difference in the QD structures when using the two different wetting layers (Figure 2).

The InAs wetting layer sample had much larger and sparser QDs. PL spectra were also much different for the two samples (Figure 3). While both samples had a peak at around 1.25 eV, the peak for GaSb was not the ground state energy, and was instead around 1.05 eV. The PL data indicated that the device with the InAs wetting layer hade a shallower ground state energy level in the type II configuration. JV curves showed that the device with the InAs wetting layer had much better performance (Fig.4).

Differences in the size of dots and the density in the QD layer were due to diffusion in the S-K growth process when using different wetting layers. We expected the larger dots in the InAs wetting layer device to lead to a deeper well ground state energy, which would mean the PL peak should be at a lower energy. But instead, the GaSb wetting layer device had a lower PL peak. Further investigation into this anomaly is necessary.

The lower open circuit voltage in the GaSb wetting layer solar cell can be explained by the absorption peak at a lower photon energy. The shallower ground state energy level in the InAs wetting layer device led to easier thermal excitations and a more efficient solar cell. However, a two-step photocurrent measurement is still necessary to characterize the intermediate band solar cell implementation.

Acknowledgements:

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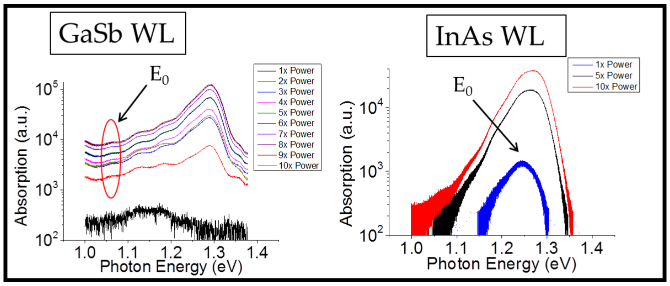
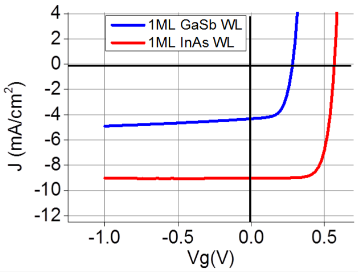


Figure 3: PL data for the samples.



Device	GaSb WL	InAs WL
V_{OC} (V)	0.28	0.52
J_{SC} (mA/cm²)	4.32	9.18
FF	60.3%	70.4%
Efficiency	0.73%	3.36%
n	1.165	1.471

Figure 4: IV characterization under AM1.5G illumination.