Current-Voltage Characterization and Two-Step Photocurrent Generation in Lattice-Matched Quantum Dot Solar Cells

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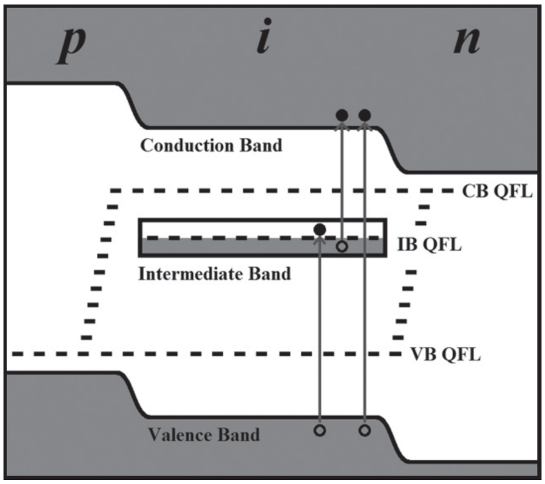

Figure 1: Ideal band diagram of the IBSC, with three distinct quasi-Fermi-levels (QFLs). Adapted from Luque [1].

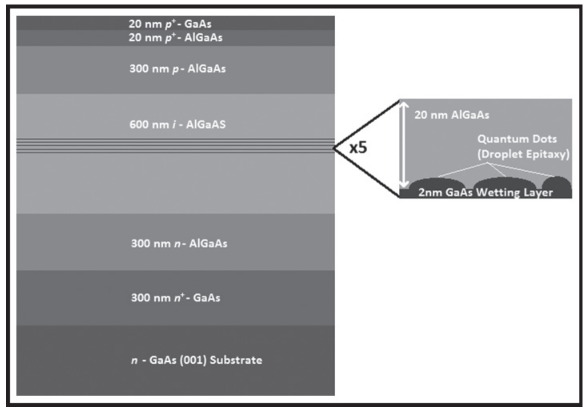

Figure 2: Fabricated QD-IBSC sample structure, grown by MBE.

Introduction and Motivation:

This research focused on studying the intermediate band solar cell (IBSC), which promises a great increase in photovoltaic conversion efficiency by extending the absorption range into the infrared while maintaining a high open circuit voltage. This is achieved by an intermediate band (IB) between the valence band (VB) and conduction band (CB), allowing the so called two-step photocurrent generation, wherein sub-bandgap photons produce a photocurrent by exciting the VB to IB, and IB to CB transitions in series (see Figure 1). The theoretical efficiency is 63% at maximum solar concentration, overcoming the Shockley-Queisser limit [1].

A widely used method of researching IBSCs employs embedded quantum dot (QD) layers. Many such efforts use lattice-mismatched materials because of the simplicity of dot formation. However, the resulting accumulated strain of many dot layers (which are necessary to absorb an appreciable amount of light) degrades the material quality, limiting the efficiency and masking intrinsic characteristics of the solar cell.

Here, we employed strain-free QDs fabricated in a lattice-matched system to eliminate strain related issues. To explore the viability of such a material system for realizing an IBSC, we studied fundamental properties of GaAs/AlGaAs QD solar cells with a focus on the two-step photocurrent generation process, a fundamental operating principle of the IBSC.

Fabrication of Quantum Dot Solar Cells:

A QD solar cell device was grown on n-type gallium arsenide (GaAs) <100> substrate by molecular beam epitaxy (MBE). As illustrated in Figure 2, the device was an aluminum gallium arsenide (AlGaAs) p-i-n structure with five layers of quantum dots embedded within the *i* layer. Each QD layer was separated by a 20 nm thick AlGaAs buffer layer, so adjacent electronic states were decoupled. The GaAs QDs (Figure 3) were fabricated by using droplet epitaxy, wherein metallic Ga droplets were formed on a GaAs wetting layer by supplying Ga in an As-depleted environment, and then As was supplied to crystalize the Ga droplets into GaAs QDs.

In contrast to widely used InAs/GaAs QDs grown by the Stranski-Krastanov growth, these QDs were strain-free (GaAs

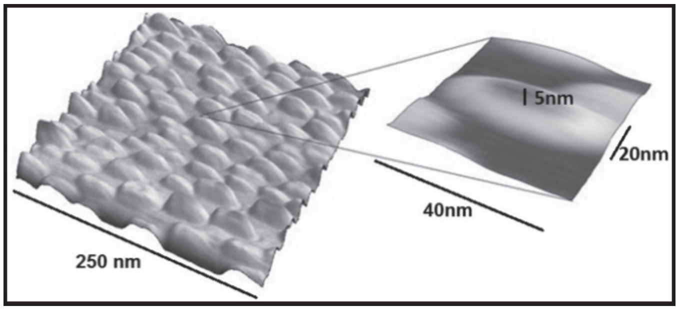

Figure 3: Visualization of QDs (inset to scale).

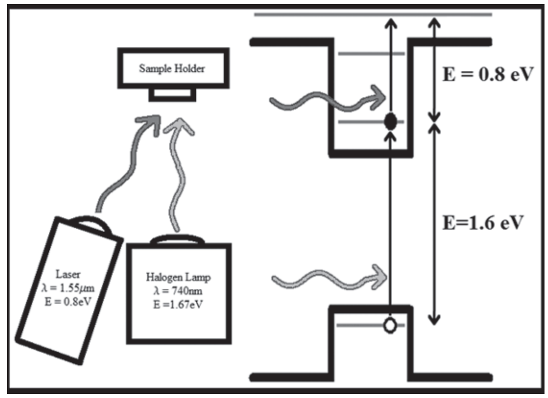

Figure 4: Experimental setup for two-step photocurrent measurements using 740 nm Halogen light.

and AlGaAs have nearly identical lattice constants), and the two-dimensional GaAs quantum well (QW) layer embedded underneath the QDs was controllable during growth. Here, the 2 nm thick QW layer was introduced to increase the confinement energy, aiming for suppression of thermal escape of carriers from the QDs and improved homogeneity of the QDs. The QW layer was doped n-type with Si, and the supplied electrons relax into the QDs.

Device Characterization:

As determined by atomic force microscopy (AFM), the resulting QD heights were 4.8 ± 0.8 nm, and each layer had an area density of 6.7×10^{10} /cm^2. Photoluminescence measurements at 20 K revealed nanostructure transitions with peaks at 1.6 eV and 1.67 eV, corresponding to the QDs and the wetting layer. This indicated that the barrier heights for electrons and holes are on the order of 100 meV, which is sufficiently high (compared to thermal energy, 26 meV, at room temperature) to limit thermal escape.

Photocurrent measurements at room temperature (using a Halogen lamp and a monochromator) demonstrated the absorption of photons with energies below the bandgap (1.8 eV) of AlGaAs. A reduction in photocurrent was observed, starting from negative bias and strengthening at higher biases (up to the open-circuit voltage). These current-voltage characteristics depended on the wavelength (λ) of light, and were explained in terms of the wavelength dependence of the absorption coefficient and the bias dependence of trapping efficiencies of electrons and holes by QDs.

To observe two-step absorption of sub-bandgap photons, we used the Halogen lamp and a 1.55 μm (0.8 eV) laser (see Figure 4). The λ of the Halogen lamp was set at 740 nm (1.68 eV), generating carriers only in the QDs. Upon illumination of the sample with the laser, we observed an increase in photocurrent (ΔI), i.e., two-step photocurrent generation, and found that it depended largely on V. The increase in photocurrent was also observed for shorter wavelengths (450 and 600 nm), where carriers were generated mostly in AlGaAs and then became trapped in the QDs. ΔI was at its maximum at -0.5-0.0 V, followed by a gradual reduction. This dependence of ΔI on V was qualitatively explained by the number of trapped carriers in QDs, and re-trapping of photoexcited carriers by the QDs.

Conclusions and Future Work:

We successfully fabricated lattice-matched GaAs/AlGaAs QD solar cells with five QD layers. A 2 nm thick GaAs wetting layer was embedded underneath each QD layer to suppress thermal escape of carriers generated in the QDs. Current-voltage characteristics were analyzed by comparison to the bias dependence of carrier trapping and absorption coefficients. We observed two-step photocurrent generation due to absorption of sub-bandgap photons, which is necessary for the operation of IBSCs. These results demonstrate the potential of GaAs/AlGaAs QD SCs.

Future work is needed to fully understand the dependences of the two-step process on voltage and incident energy, and will focus on identifying and tuning the necessary parameters to optimize the IB to CB transition.

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References:

[1] A. Luque, et al. Nature Photonics 6, 146-152 (2012).