Fabrication of Stacked Quantum Dot Diodes and Related Nanostructures and Their Transport Properties

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Abstract:

One way to make a quantum dot intermediate band solar cell (QD-IBSC) is to embed indium arsenide (InAs) quantum dot stacks inside an ordinary solar cell. Embedded QD stacks serve as generation and recombination centers as well as scattering centers in the QD-IBSC, altering the photocarrier transport characteristics of the device. In our work, we studied the photocurrent induced by above-bandgap photons in a 5-period InAs/GaAs QD stack, InGaAs/GaAs superlattice, and undoped gallium arsenide (GaAs) system. Our measurements showed that the efficiency of photocurrent generation was not significantly reduced in the QD sample. We suggest that the influence of the quantum dots on transport was limited due to the relative thinness of the QD region and the de-localization of trapped holes and electrons in the intermediate band. A strain-free quantum dot diode with a thicker active region needs to be studied in the future to determine whether or not the effects of embedded QDs on photocarrier transport are in fact negligible.

Introduction:

The intermediate band solar cell (IBSC) has the potential to achieve higher energy conversion efficiency than many alternative photovoltaic conversion devices [1]. The IBSC is characterized by the presence of an allowed energy band within what would otherwise be the forbidden energy gap of a conventional semiconductor material. Sub-bandgap photons that normally pass through the material can then be absorbed in two transitions: valence band (VB) to intermediate band (IB) followed by IB to conduction band (CB). High-energy photons are absorbed as usual, by the VB to CB transition.

Engineering a device with the energy band structure proscribed by IBSC theory has proved challenging. One oft-studied possibility is the quantum dot intermediate band solar cell (QD-IBSC). In this structure, embedded quantum dots confine electrons such that discrete energy levels are attained below the CB of the bulk material. If the dots are stacked directly on top of one another, periodicity in the direction of stacking results in the formation of an IB.

One major advantage of the QD-IBSC is controllability. By manipulating the size and spacing of the quantum dots, one can adjust the position and bandwidth of the IB, respectively. Likewise, one can position the Fermi level as needed using modulated doping techniques. InAs/GaAs quantum dots have been the most widely studied for the QD-IBSC due to a desirable band structure and convenient growth methods [2].

As research on the QD-IBSC presses forward, we investigated effects of InAs/GaAs QD stacks on carrier transport. We were particularly interested in whether or not the scattering and/or trapping rates of carriers were increased as the result of embedded quantum dots. These effects suppress the photocurrent and solar efficiency of the device and can be used to address the limitations of the QD-IBSC as a model for the ideal IBSC.

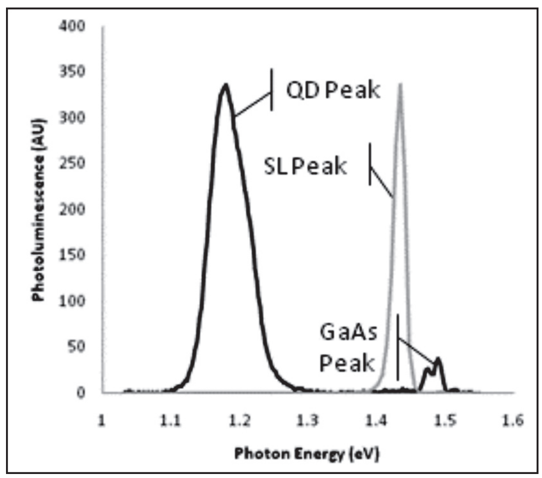

Figure 1: Photoluminescence spectra showing QD, SL, and GaAs ground state energies.

Experimental Procedure:

First, a wafer containing five periods of alternating InAs QD layers and ∂-doped GaAs capping layers was prepared by molecular beam epitaxy. The quantum dots were selfassembled by the Stranski-Krastanow method. Next, an InGaAs/GaAs SL sample was grown by incorporating the same amount of In as that for the QD wafer; note here that the strain in InGaAs is reduced so that its growth remains in layer-by-layer mode rather than forming QDs. Last, an undoped GaAs sample with the same dimensions as the QD and SL samples was prepared. The photoluminescence spectra for the three samples is shown in Figure 1.

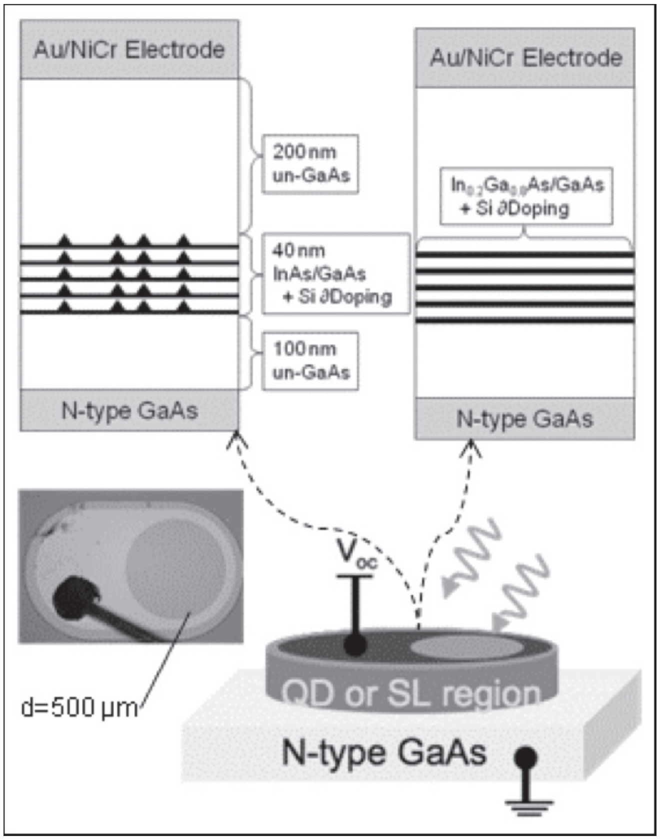

Figure 2: Comparison of QD and SL sample structure (top) and Schottky photodiode diagram (bottom).

These wafers were processed to make Schottky diodes, as shown in Figure 2. For this purpose, transparent Au/NiCr electrodes were patterned via metal liftoff and used as an etch mask for the diode structure. A thicker electrode, patterned to leave a transparent window, capped the device. Current-voltage characteristics of these three devices were measured at room temperature under dark conditions and under 808 nm, 635 nm, and 532 nm laser illumination. Photons with energies well above the GaAs bandgap energy were used for illumination because the generation of carriers by sub-bandgap excitation was negligible. Based on the current-voltage measurements, we evaluated the photocurrent efficiency of the device—the photocurrent per unit flux of incident photons.

Results and Conclusions:

The photocurrent efficiency results are shown in Figure 3. Our key finding was that the photocurrent efficiency was not lower in the QD sample than the SL and un-GaAs samples. This was contrary to our expectation; QD systems tend to reduce the mobility of photocarriers by disturbing the crystal periodicity and increase recombination by trapping electrons and holes in close proximity. To address the contradiction of our expectation, we suggest that: (1) the average mobility, taking into account the mobility and thickness of the intrinsic GaAs region, may not vary measurably between samples; and that (2) if the sub-band energy levels of the QD stacks are coupled and an electric field is present, electrons and holes drift to opposite ends of the stack where they have a low probability of recombining.

Future Work:

Future work should focus on determining the extent to which our surprising result can be generalized. The systematic measurement of photocurrent and radiative recombination under various bias voltages is important short-term work to assess whether or not recombination in the QD stacks is influenced by the magnitude of the built-in electric field. Fabricating and testing larger QD stacks, using strain-free systems, is a long-term goal.

Acknowledgements:

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References:

[1] A. Luque and A. Marti, "Increasing the Efficiency of Ideal Solar Cells by Photon Induced Transitions at Intermediate Levels," Phys. Rev. Letters, vol. 78, pp. 5014-5017, 1997.

[2] A. Marti et. al., "Novel Semiconductor Solar Cell Structures: The Quantum Dot Intermediate Band Solar Cell," Thin Solid Films, pp. 638-644, 2006.

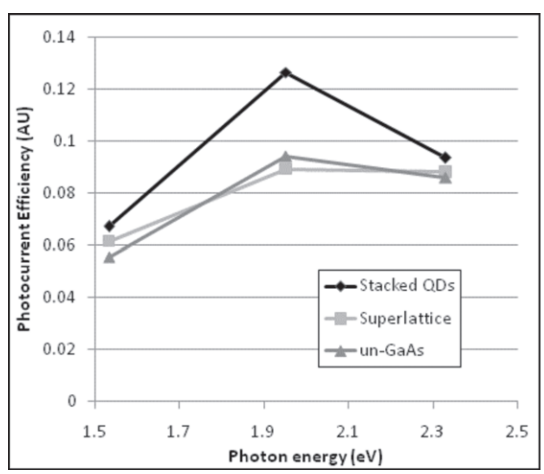

Figure 3: Photocurrent efficiency using 808 nm, 635 nm, and 532 nm laser excitation.