Multi-bandgap solar cells: opportunities and challenges

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Incorporating small bandgap materials is a practical way of increasing efficiency in solar cells.

As the importance of renewable energy sources grows, schemes for developing highly-efficient and cost-beneficial solar cells, such as concentrator solar systems, are increasingly receiving attention. Consisting of low-cost light reflectors and highly-efficient solar cells, they have a significant cost-benefit potential and are viewed as a promising approach to the development of solar plants. Light concentration factors of approximately 500 are achieved regularly in these systems. This reduces the cost of the system, and positions highly efficient solar cell technologies as ideal for use as solar concentrators.

One of the factors limiting the efficiency of single-bandgap solar cells is their ability to absorb photons with energies smaller than their bandgaps. Multi-bandgap solar cells have been proposed to address this limitation. These designs consist of layers of n-type and p-type materials with large bandgaps that sandwich layers of small bandgap materials. This allows the small bandgap materials to absorb longer wavelengths, enhancing the current generated by the solar cell. Both quantum wells (QWs) and quantum dots (QDs) can be used in multi-bandgap solar cells.

The crucial point for the success of a multi-bandgap solar cell is that the built-in potential and open circuit voltage ($V_{oc}$) are both determined by the Fermi levels of the materials with the larger bandgap. (The materials with smaller bandgaps should not have an adverse affect on the cell voltage.) Typically, the multi-bandgap solar cells that are investigated are of the p-i-n type: the p and n layers are made of the larger bandgap materials and the smaller bandgap materials are confined to the intrinsic (i) region. A schematic view of one of the QD solar cells that we studied is shown in Figure 1. We grew QDs with a self-assembled method that used the strain energy generated by depositing a semiconductor material—indium gallium arsenide (InGaAs)—onto a substrate material—gallium arsenide (GaAs)—with a smaller lattice constant. An atomic force microscopy image of a surface layer of QDs is shown in Figure 2. The resulting QDs had a size of 20nm wide and 5nm high with a density of about $4 \times 10^{10}$ cm$^{-2}$.

The spectral response curve of the QD device demonstrates that the incorporation of small bandgap nanostructures extends the wavelength range of the light absorbed by the device (see Figure 3). Moreover, it has been reported that the incorporation of either QDs or QWs produces an overall increase in the solar cell short-circuit photocurrent, proving that the use of nanostructures is a practical way of increasing solar-cell photocurrent. However, quality control of the semiconductor material and good design confinement energies are required to minimize carrier recombination, a phenomenon that can reduce the solar-cell photocurrent.

The greatest challenge facing QW and QD solar cells is controlling the impact that the small bandgap material has on the cell voltage. There is limited experimental evidence of an...

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enhanced $V_{oc}$ in QW solar cells, and the $V_{oc}$ of all reported QD solar cells (QDSCs) is smaller than the corresponding $V_{oc}$ of the GaAs reference cell. To study this problem, we performed a set of temperature-dependent measurements that show which mechanisms reduce the $V_{oc}$.\(^1\) In particular, we have shown that the built-in potential is not affected by the incorporation of the QD layers.

Our future work will focus on limiting the impact that QDs have on the $V_{oc}$, such as controlling the thermal relaxation of carriers migrating from barrier states to QD confined states. These carriers originate in the outmost contact layers of Figure 1, and have sufficient kinetic energy to reach the depletion region in the middle of the device. Essentially, what needs to be developed are new ways of controlling the time constants of these carriers. Growth technology should be improved to achieve QD layers with higher quality and density. In particular, novel approaches such as using nanoparticles for light scattering and trapping\(^3\) should be developed. This will enhance the absorbance of QDs in QDSCs and thus improve its short circuit current and efficiency.

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References


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