Boosting solar-cell efficiency with quantum-dot-based nanotechnology

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Inserting indium arsenide quantum dots into crystalline III-V semiconductor-based photovoltaics results in both enhanced short-circuit current and improved efficiency.

Every hour, the sun radiates more energy onto the Earth’s surface than is consumed globally in one year. However, to best harness this vast source of power, efficient and cost-effective solar photovoltaic (PV) energy conversion is required. In particular, improving the efficiency of III-V-type semiconductor PV devices is a goal for both the space and terrestrial research communities. Current high-performance space technology relies on crystalline III-V materials to produce conversion efficiencies greater than 31%. High power-conversion efficiencies directly increase mass-specific power, thus lowering the costs associated with spacecraft deployment. Additionally, recent advances have demonstrated that III-V-based concentrator PVs can produce high efficiencies (>40%) and, therefore, reduce the cost of power generation.

Numerous approaches can increase both solar-cell efficiency and/or mass-specific power, including lightweight substrates, substrate removal, or bandgap engineering of multijunction solar cells (MJSCs) using quantum dots (QDs). Luque and Martí also proposed a novel extension of the bandgap engineering approach. It uses multiple QD superlattices to form an optically isolated intermediate band (IB) within the bandgap of a standard single-junction solar cell. Photons with energy below the host bandgap are absorbed from the host valence to the intermediate band, and from the intermediate to the host conduction band. As these lower-energy photons are normally lost to transmission in standard single-junction solar cells, the IB approach may result in a high limiting efficiency. Recently, several experiments have demonstrated the key operating principles of the IB solar cell using both indium arsenide (InAs) and gallium antimonide (GaSb) QDs in a gallium arsenide (GaAs) host.

Figure 1. (a) Quantum-dot (QD)-enhanced solar-cell design concept. (b) Current density-voltage curves for control and 5-20 layer enhanced cells under one sun global air mass 1.5 (AM1.5g) light. These cells did not have antireflective coating. InGaP: Indium gallium phosphide. GaAs: Gallium arsenide.

The Rochester Institute of Technology’s NanoPower Research Laboratories (NPRL) have made significant advances in this area by developing new nanomaterials and devices. We have engineered III-V-type solar cells to take advantage of the extended absorption spectrum of lower-bandgap heterostructures (such as QDs) inserted into the current-limiting junction of an MJSC. The larger absorption spectrum of the nanostructures enhances the overall short-circuit current and global efficiency of the cell. Models of an indium gallium phosphide (InGaP)/indium gallium arsenide (InGaAs)/germanium (Ge) triple-junction solar cell, in which QDs extend the middle junction’s absorption spectrum, indicate that we could raise the theoretical limiting efficiency to 47% under one sun illumination. These devices may also have additional benefits, such as enhanced radiation tolerance and temperature coefficients.
We demonstrated the feasibility of the QD tuning approach using strain-balanced InAs dots inserted in the intermediate (i) region of a GaAs p-i-n solar cell. The solar-cell structure (grown by organometallic vapor-phase epitaxy) is shown in Figure 1(a). Figure 1(b) shows the illuminated one sun global air mass 1.5 (AM1.5g) current density-voltage ($J-V$) curves for a control GaAs cell without quantum dots and for cells with 5–20 stacked layers of InAs QDs. We fabricated these cells using standard III-V processing technology and a concentrator grid designed with 20% metallization coverage. The control results were equal or close to the standard values for GaAs solar cells. Figure 1(a) clearly shows the enhancement in short-circuit current using QDs. This is a direct result of photo-generated current contributed by the nanoparticles. We expect the trend to continue with addition of QDs, because a greater portion of the sub-GaAs bandgap solar spectrum should be absorbed with increasing number (i.e., volume). Additionally, the strain-balancing technique employed for QD growth led to higher material quality in layers grown on top of the InAs nanoparticles. This has enabled short-circuit current enhancement and minimal open-circuit voltage degradation.

Measuring the cell’s external quantum efficiency (EQE) provided a spectroscopic means to study how QDs affect the device current-voltage characteristics. EQE measures the number of electrons or holes collected as photocurrent per incident photon at a particular wavelength. Figure 2 shows the EQE for the baseline and 5–20x QD samples. All three QD samples show an increased response at wavelengths greater than the GaAs band edge. This indicates that a portion of the short-circuit current of these cells is generated by QD-related absorption processes. Additionally, increasing the number of layers raises the EQE at all QD-related transitions. At 909nm (1.36eV) this amounted to increases from 2.5 to 9.2% by increasing the stacking from five to 20x (see Figure 3). This was clear evidence that raising the volume of the quantum-dot absorbers successively increases short-circuit current.

To assess the spectral enhancement of the QDs at higher concentration, we observed the control and 20-layer cells under high-intensity illumination. The trends seen at one sun continued, with the enhanced cells showing improved short-circuit currents (see Figure 3). All cells, including the baseline, show a slight superlinear trend in current, as has been observed in GaAs materials because of high-level injection effects. The 20-layer QD cell generated the largest short-circuit current (7.53A/cm$^2$) at 440suns. This represents an 11% increase compared to the control-cell current at the same concentration. The open-circuit voltage for all cells rose logarithmically with concentration. We calculated the efficiency for each type of cell under direct air mass 1.5 (AM1.5d) conditions (see Figure 3). Efficiency peaked near 400suns, consistent with our concentrator-grid design. The QD-enhanced cell showed almost 18% power efficiency at 400suns. This represented a ~1% absolute efficiency improvement compared to the control (a 6% relative improvement). Under high-illumination intensity, the reduced

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Figure 2. 5–20 layer QD-enhanced solar cells show a net increase in external quantum efficiency (EQE) at IR wavelengths compared to the baseline GaAs.

Figure 3. Direct air mass 1.5 (AM1.5d) efficiency and short-circuit current ($J_{SC}$) versus concentration for the baseline and QD cells. The enhanced cells show improved efficiency at higher concentration.

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(longer-wavelength) effective bandgap of the cell, as well as increased optical and thermal extraction of QD-generated carriers, leads to direct improvement in cell efficiency. This boost was due to higher short-circuit current combined with minimal open-circuit voltage loss.

Nanomaterial-based energy technologies have great promise for both terrestrial and extraterrestrial applications. Our experimental demonstration of current and efficiency enhancement in QD-based solar cells represents a milestone to breaking efficiency limits through using nanomaterials. Our next steps aim to increase the absorption cross section of the quantum dots by both increasing the number of QD layers and investigating new multilayer device designs. In addition, we are continuing our efforts to understand and model radiation and temperature effects in these solar cells.

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References