# Improved device performance of InAs/GaAs quantum dot solar cells with GaP strain compensation layers

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We report optical, electrical, and spectral response characteristics of three-stack InAs/GaAs quantum dot solar cells with and without GaP strain compensation (SC) layers. The short circuit current density, open circuit voltage, and external quantum efficiency of these cells under air mass 1.5 G at 290 $mW/cm^2$ illumination are presented and compared with a GaAs control cell. The cells with SC layers show superior device quality, confirmed by I-V and spectral response measurements. The quantum dot solar cells show an extended photoresponse compared to the GaAs control cell. The effect of the SC layer thickness on device performance is also presented. © *2007 American Institute of Physics*. [DOI: 10.1063/1.2816904]

For the past few years, self-organized quantum dots (QDs) have been investigated in photovoltaic (PV) devices to increase the sub-band-gap photon absorption and hence the energy conversion efficiency. More enticing is the possibility of very high single junction quantum efficiencies >63%, which can be achieved via an intermediate band gap available through appropriate QD band alignment.[1] The InGaAs/GaAs,[2] InAs/GaAs,[3,4] and GaSb/GaAs (Ref. 5) QD ensembles have previously demonstrated an extended photoresponse compared to a single junction GaAs solar cell. However, devices based on these materials are limited by the QD absorption cross section. While the QD absorption cross section can be increased by stacking the QD layers, the addition of multiple QD layers builds up excessive strain and leads to defect formation. These defects act as carrier traps and reduce the efficiency of solar cells. Even with the increased spacer thickness between the dot regions, these defects occur when many layers are stacked. The negative effects of stacking, driven by the cumulative compressive strain, can be reduced by introducing strain compensation (SC) layers. In our previous work, it has been observed that more than 35% compressive strain can be reduced with the GaP strain compensation layers.[7] The SC layers have already been shown to reduce overall strain in multistacked QD structures along with the reduced defect formation and improved QD uniformity in QD lasers.[6–9]

In this manuscript, we describe and contrast the solar cell performance for multistack InAs QD devices with and without SC layers. Previous work has introduced strain compensation as means of growing more quantum dot layers in GaAs-based solar cells.[10] The present work expands upon that approach by studying the effect of varying the GaP strain compensation layer thickness and number. Our solar cell structures contain various thicknesses (2, 4, and two 2 ML with 5 nm separation) of GaP between the QD layers. The current-voltage (*I-V*), photoresponse, and external quantum efficiency (EQE) measurements of these cells are described along with photoluminescence (PL). Figure 1 shows the QD solar cell device schematic. The epistructure is grown on a (001) *p*-type GaAs substrate in a Thomas Swan vertical flow metal organic chemical vapor deposition reactor at 60 torr using trimethylgallium, trimethylindium, trimethylaluminum, tertiarybutylphosphine, and tertiarybutylarsine. Carbon tetrachloride ($CCl_4$) and disiline ($Si_2H_6$) are used as dopant sources for *p* and *n* type, respectively. Before growth, the *p*-GaAs substrate is deoxidized at 760 °C for 5 min. A 300 nm *p*-GaAs buffer is grown at 750 °C with a doping density of $1\times10^{17}$ $cm^{-3}$ followed by a 110 nm undoped GaAs layer which is grown at the same temperature. The temperature is then lowered and stabilized to 550 °C for the active region growth. In both structures, the active region contains three periods of InAs QDs separated by a 29 nm GaAs spacer. To study the effect of the SC layer thickness on device parameters, three different samples are grown with 2, 4, and two 2 ML (separated by 5 nm GaAs) GaP layers. The QD and SC layer growth sequence is described in detail elsewhere.[11] The *p-i-n* structure is completed by a 250 nm *n*-GaAs and 30 nm *n*-$Al_{0.6}Ga_{0.4}As$ ($\sim1\times10^{18}$ $cm^{-3}$ for both layers) followed by a 50 nm *n*-GaAs contact layer (>5

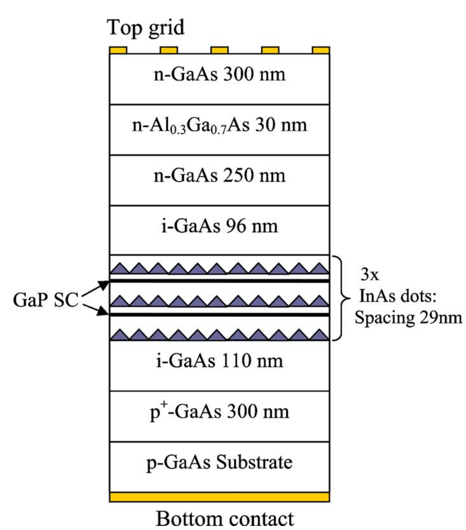


FIG. 1. (Color online) Schematic diagram of the QD solar cell containing three-stack InAs QDs.

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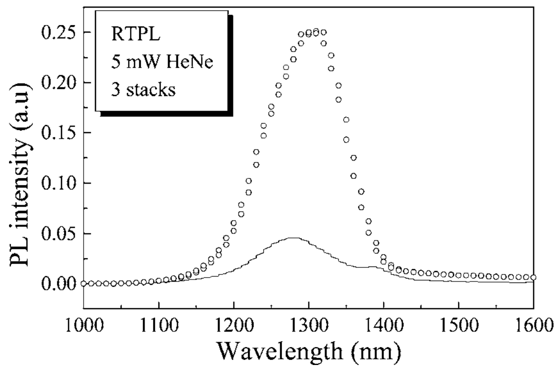


FIG. 2. Room temperature PL spectra from the test samples with (open circles) and without (solid line) SC layers.

TABLE I. Measured open circuit voltages ($V_{oc}$), short circuit current densities ($J_{sc}$), and fill factors (FFs) of GaAs control cells and InAs QD solar cells with and without SC layers under AM 1.5G at 290 mW/cm$^2$ light intensity.

| Sample | $V_{oc}$ (V) | $J_{sc}$ (mA/cm$^2$) | FF (%) |
|---|---|---|---|
| Control cell | 0.96 | 13.6 | 81.6 |
| 2 ML SC | 0.73 | 9.9 | 73.1 |
| 4 ML SC | 0.72 | 9.8 | 73.5 |
| Two 2 ML SC | 0.69 | 11.2 | 73.2 |
| No SC | 0.42 | 8.3 | 62.5 |

$\times 10^{18}$ cm$^{-3}$). A control cell has been grown with the same structure and doping except that it lacks QDs in the *i*-region. The *i*-region of the control cell contains undoped GaAs.

The samples are patterned into various cell dimensions ($2\times 2$, $3\times 3$, and $5\times 5$ mm$^2$). The *n*-metal contacts (Ge/Au/Ni/Au) and the back *p*-metal (Ti/Au) contacts are deposited by e-beam evaporation. A silicon nitride ($Si_3N_4$) antireflection coating is deposited on the top surfaces using plasma enhanced chemical vapor deposition system. These devices are isolated from each other using inductively coupled plasma reactive ion etching. The top metal grid design results in an estimated 20% shadowing to the incident light.

The PL measured from the test samples are shown in Fig. 2. These test samples, with and without (4 ML) SC layers, are grown under similar conditions to the solar cells. The PL measurements are performed with 5 mW and 1.5 mm He–Ne laser. The PL from the samples without SC layers exhibits a bimodal distribution, which indicates an increased dot size in the top QD layers due to accumulated strain from the inner layers. The first peak is observed at 1278 nm and the second at 1396 nm with a full width at half maxima (FWHM) of 79 and 39 meV, respectively. In contrast, the PL from the sample containing SC layers has a strong and narrow peak at 1295 nm with a FWHM of 78 meV indicating good material quality.

Figure 3 shows the *I*-*V* characteristics of the InAs QD solar cells with and without SC layers, and the GaAs control cell under AM 1.5 G at 290 mW/cm$^2$ illumination. The incident light intensity from the Abet technologies solar simulator is measured using a Molectron thermopile, and the photocurrent generated in QD solar cell is measured with a Keithley picoammeter. The measured values of open circuit voltage ($V_{oc}$), short circuit current ($I_{sc}$), and fill factor (FF) are listed in Table I. All the cells with SC layers have higher fill factors (~73%) compared to the cells without SC layers (62.5%). The reduced $I_{sc}$ is due to the recombination of photogenerated electron hole pairs in the defects caused by the strain. The increased $I_{sc}$, $V_{oc}$, and enhanced FF in the cells with SC layers are clear indications of reduced strain and defects in the device. The experimental results indicate that the cell with two 2 ML GaP layers separated by 5 nm GaAs (a total of 4 ML of SC layer between two successive QD stacks) yields higher $I_{sc}$ and slightly reduced $V_{oc}$ compared to the cells with 2 and 4 ML SC layers. This is probably due to the optimized strain compensation and also better carrier transport through the thinner GaP layers. The exact reasons are under investigation.

The EQE, as shown in Fig. 4, is measured using an Acton 275 dual-grating monochromator, a Keithley picoammeter, and a Newport optical power meter. The solar cell's EQE is calculated using the following formula: $\text{EQE}=(I_{ph}\times 1240)/(P_{in}\lambda)$, where $I_{ph}$, $P_{in}$, and $\lambda$ are, respectively, the photocurrent collected (amperes), incident power (watts), and the wavelength of the incident light (nanometers). The QD solar cells show extended response up to 1100 nm due to the absorption of low energy photons by the QDs. In contrast, the response of GaAs control cell response drops sharply at 870 nm. Due to a smaller absorption volume of the three-stack QD InAs cells, the EQE from these QD solar cells is expected to be low as well. The EQE beyond 870 nm can be further increased by adding more QD stacks if the cumulative strain is controlled. The spectral response can be

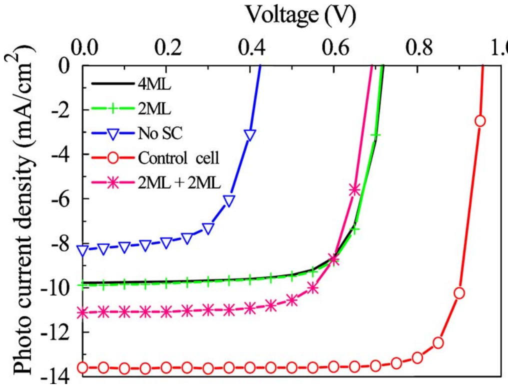


FIG. 3. (Color online) *I*-*V* characteristics of three-stack QD solar cells with and without SC layers and a GaAs control cell under AM 1.5 G at 290 mW/cm$^2$ illumination. For strain compensation 2, 4, and two 2 ML of GaP have been used between two successive QD stacks.

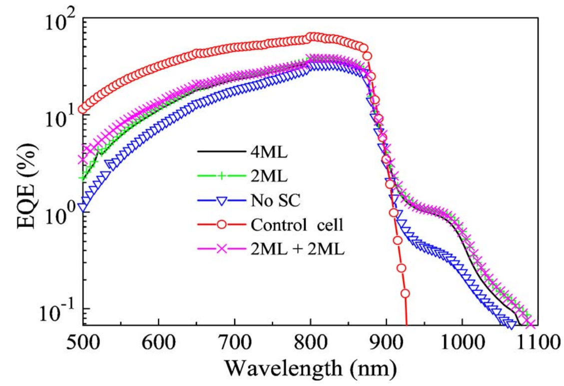


FIG. 4. (Color online) External quantum efficiency (EQE) measurements of three-stack QD solar cells with and without SC layers and a GaAs control cell.

extended to longer wavelengths by carefully designing the dot size and density.[12,13] Nonetheless, we have demonstrated the basic building block for a QD absorbing region that is scalable to larger volumes due to the proper use of the SC layers identified here.

In summary, we presented the comparative results of InAs QD solar cells with and without GaP SC layers. A reduction in $V_{oc}$ and $I_{sc}$ has been observed due to the insertion of QDs in *p*-*i*-*n* junction. This is due to the recombination of carriers in QDs. However, the cells with SC layers show improved device quality due to the reduced strain and defects. A longer wavelength response, compared to a GaAs control cell, has been observed in QD solar cells with and without SC layers due to the sub-band-gap photon absorption. A further reduction in defects and optimization of device parameters can lead to a better device performance.

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