GaSb/GaAs type II quantum dot solar cells for enhanced infrared spectral response

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The authors report an enhanced infrared spectral response of GaAs-based solar cells that incorporate type II GaSb quantum dots (QDs) formed using interfacial misfit array growth mode. The material and devices, grown by molecular beam epitaxy, are characterized by current-voltage and spectral response characteristics. From 0.9 to 1.36 μm, these solar cells show significantly more infrared response compared to reference GaAs cells and previously reported InAs QD solar cells. The short circuit current density and open circuit voltages of solar cells with and without dots measured under identical conditions are 1.29 mA/cm^2, 0.37 V and 1.17 mA/cm^2, 0.6 V, respectively. © *2007 American Institute of Physics*. [DOI: 10.1063/1.2734492]

Recently quantum dots (QDs) on GaAs have been used in the intrinsic region of *p*-*i*-*n* junction solar cells to increase the spectral response and efficiency in the near infrared spectral regime. The use of QDs with appropriate band alignment has a potential to increase the efficiency over 63% as proposed by Luque and Marti[1] by the intermediate band effect. This is much higher than the efficiency proposed by Shockley and Queisser[2] in the case of a single junction solar cell. The single junction solar cells lack either in long wavelength response or efficiency or both. In single junction solar cells, photons with energies smaller than the band gap are not absorbed but rather transmitted through the device. Thus, low band gap materials compared to GaAs, Si, and Ge are required for longer wavelength photon absorption. The QDs can be incorporated into existing multijunction cells either as a means to increase the current or efficiency by using low band gap nanoscale materials. However, the device design and growth must be carefully planned to reduce defect formation due to strain accumulation. The QD solar cells can produce additional photocurrent by absorbing photons with energies less than the GaAs band gap. An extended spectral response in InAs/GaAs (Ref. 3) and InGaAs/GaAs (Ref. 4) QD solar cells compared to GaAs solar cells has already been reported. However, several issues exist that may ultimately limit the QD utility in solar cell devices including reduced open circuit voltage, increased leakage current, carrier transport, and sufficient absorption cross section.

In this letter we discuss the growth and characterization of GaSb QD ensembles in solar cell devices grown by molecular beam epitaxy. These QDs are unique compared to already reported InAs QDs by the Stranski-Krastanov (SK) growth mode. First, the GaSb QDs have a type II band alignment in GaAs that provides hole confinement (450 meV) but no electron confinement[5] which may improve carrier extraction. Second, the GaSb QDs are formed using interfacial misfit (IMF) array growth mode.[6,7] The introduction of IMF at the GaSb/GaAs interface relieves the strain associated with lattice mismatch in a localized manner.[8] This strain-free growth mode enables a large number of closely spaced QD stacks for significantly enhanced photon absorption. The number of QD stacks that can be grown is not limited by the accumulated strain energy that is present in conventional SK strained QD layers.

Two types of solar cells are studied here. These two cells are identical in all aspects except that one sample contains ten layers of GaSb QDs in the unintentionally doped GaAs intrinsic region and the other does not. Figure 1(a) shows the structure of a solar cell with ten stack GaSb QDs in the *i* region of the *p*-*i*-*n* heterojunction. Growth of this structure is initiated by a 300 nm smoothing layer of *p*-GaAs with a doping density of 10^{17} cm^{-3} on a p^+-GaAs substrate, which is then followed by *i* and *n* layers, respectively. A 95.35 nm undoped GaAs barrier layer is grown on both sides of a ten stack GaSb QD *i* region. The QD stacks are separated by a 15 nm spacer, as shown in the figure. The GaSb QDs are formed at 510 °C with a growth rate of 0.32 ML/s with a V/III ratio of 2:1 using the IMF growth mode. A 250 nm *n*-GaAs with a doping density of 10^{18} cm^{-3} is formed on the top barrier followed by a 30 nm $Al_{0.6}Ga_{0.4}As$ window layer to reduce surface recombination. A 50 nm *n*-GaAs is the top contact layer with a doping density of more than 10^{18} cm^{-3}.

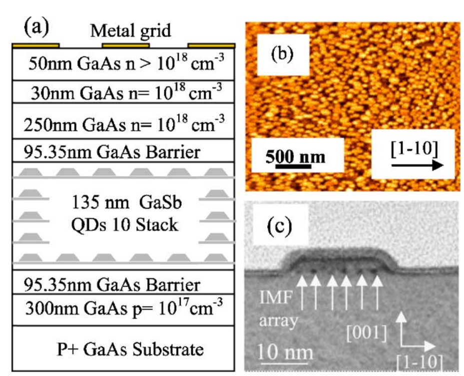

FIG. 1. (Color online) (a) Schematic diagram of ten stack GaSb QD solar cell. The doping levels and layer thicknesses are also shown in the figure. (b) Atomic force microscope image of GaSb quantum dots grown on GaAs. (c) Cross sectional high resolution transmission electron microscope (HRTEM) image of QD IMF.

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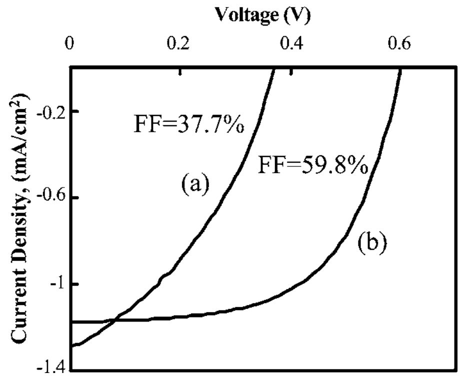

FIG. 2. Current and voltage (I-V) characteristics of cells with (line a) and without (line b) GaSb QDs. Fill factors corresponding to both the cells are also shown.

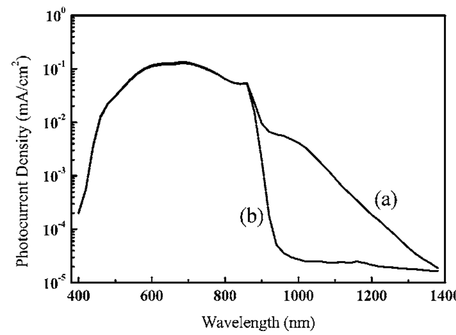

FIG. 3. Spectral response of cells with (line a) and without (line b) GaSb/GaAs type II QDs.

We utilize Be and GaTe for p- and n-type dopants, respectively.

The devices are fabricated with 2×2, 3×3, and 5×5 mm^2 patterns. After patterning, the samples are placed in an e-beam evaporator for top n-metal contact of Ge/Au/Ni/Au. After lift-off, the samples are placed back into the e-beam evaporator for the bottom p-metal contact of Ti/Au. A 90 nm thick Si_3N_4 antireflection coating is placed on the top surfaces using plasma enhanced chemical vapor depositor. The Si_3N_4 is removed from the bonding pads using another photolithography/etch process. The samples are cleaved into 2×2, 3×3, and 5×5 mm^2 pieces to reduce the leakage current along the edges.

The material characteristics of a test structure grown under similar conditions to QD solar cells are shown in Figs. 1(b) and 1(c). Figure 1(b) shows the atomic force microscopic image of the GaSb QDs. From the image, the base and height of the QDs are measured as 30 and 7 nm, respectively. The average dot density is calculated to be 6×10^{10} cm^{-2}. Figure 1(c) shows the cross sectional high resolution transmission electron microscope (HRTEM) image, which indicates that the strain at the GaSb/GaAs interface due to the lattice mismatch ($\sim 8\%$) has been relieved by the formation of IMF array. The strain-free nature of the IMF growth mode[9] enables the use of a thin GaAs spacer ($t \sim 15$ nm) without defect formation. The calculated areal density of IMF from TEM images is 3×10^{12} cm^{-2}. The photoluminescence measurements, performed on these samples containing ten stack QD, show an intense peak at 1310 nm with a full width at half maximum of 109 meV. Details of optical properties of ten stack GaSb/GaAs IMF QDs are described in Ref. 9.

A comparison between the current-voltage (I-V) characteristics of the p-i-n solar cell heterojunction with (line a) and without (line b) QDs is shown in Fig. 2. Measurements of I-V characteristics for both the diodes are performed using a tungsten halogen lamp under identical conditions. From the plot, short circuit current density and open circuit voltages of solar cells with and without dots are 1.29 mA/cm^2, 0.37 V and 1.17 mA/cm^2, 0.6 V, respectively. The reduction in the open circuit voltage is attributed to the introduction of narrow band gap QDs in the intrinsic region. The increased short circuit current is attributed to the absorption of long wavelength photons by the QDs. Experiments performed on other QD solar cells, cleaved from the same sample, indicate a reduced short circuit current compared to the cells without dots. This is presumably due to the nonuniformity across the wafer in either QD density or defect density. We expect that the device performance variation is linked with the temperature and deposition variations across the wafer during the growth. These variations are common in research reactors, but improve in production scale.[10,11]

The photoresponse of the QD solar cell, as well as the reference cell, is measured by using the tungsten halogen lamp filtered through a Spectra pro-275 monochromator. Photocurrent from the cell is measured between 400 and 1400 nm using a picoammeter. The measured spectral response of the cells with (line a) and without (line b) QDs, as a function of wavelength, is shown in Fig. 3. The cell with QDs shows an enhanced photoconversion at longer wavelengths over the cells without dots. The increased response at 1.3 μm is likely due to the ground state transition absorption while the response at 1.1 μm is likely due to the higher energy level transitions.[12] The response of QD solar cells is an order smaller than that of GaAs alone. The QD solar cell response can be improved by increasing the QD absorption volume without increasing leakage current. In order to optimize the maximum number of QD stacks that can be incorporated in the active region of solar cell, a detailed analysis of defect propagation, carrier transport, and extraction through the QDs is needed. Some of the QD solar cells with smaller short circuit currents are found to exhibit a poor photoresponse beyond 900 nm. This is possibly due to the variation of the QD density or defect density as mentioned earlier. While the band structure of the type II QDs is still under analysis, we expect the ground state absorption coefficient to be smaller than the higher energy level absorption due to the smaller density of states at the ground state compared to the excited states. We are working to understand the type II band structure and the relative absorption cross section as a function of wavelength.

In summary, we report GaAs-based solar cells that incorporate ten stacks of GaSb QDs. The GaSb QDs are unique compared to InAs SK QDs in two respects including type II band alignment and formation by IMF (strain-free) growth mode. The spectral response significantly increases with the inclusion of QDs in the intrinsic layer. These cells show an increased short circuit current and decreased open circuit voltage compared to the cells without QDs. The cell structure and growth conditions can be further optimized to produce higher short circuit current and open circuit voltages. The experiments to study the effect of QD stack number on cell performance and the carrier transport in QD region are in progress.

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