MULTI-STACKED InAs/GaNAs QUANTUM DOTS WITH DIRECT Si DOPING FOR USE IN INTERMEDIATE BAND SOLAR CELL

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ABSTRACT

We investigated the effect of direct doping of quantum dots (QDs) with Si on the performance of QD solar cells (QDSCs). In order to control the Fermi level of intermediate band (IB) region, 25 layers of stacked InAs/GaNAs QDs were directly doped with Si impurity during the self-assembling stage of growth. A QDSC with Si doping shows an improved quantum efficiency (QE) in shorter wavelength region, which is from p-GaAs emitter layer. Further, the fact that applied external bias does not affect QE spectrum as well as photocurrent in QDSC with Si direct doping suggests that carrier collection has been enhanced in QD region as a result of reduction of recombination.

INTRODUCTION

An effciency enhancement exceeding the Shockley-Queisser limit [1] is possible in an intermediate band solar cell (IBSC) [2], which incorporates a 3-dimensional quantum dot (QD) superlattice in the active region [3]. The presence of IB leads to generation of a net electron-hole pair when two sub-bandgap photons are absorbed (Figure 1). One photon pumps an electron from the valence band (VB) to IB, while a second photon pumps an electron from the IB to conduction band (CB). These electron-hole pairs add to those produced by band-to-band transitions with photons above bandgap energy E_G that excite electrons directly from VB to CB. In IBSCs, the IB should ideally be half-filled with electrons [4], that is, the Fermi level should be located within the IB as shown in Fig. 1. If IB is not partially filled, pumping second electron will only occur at small rate and the voltage will be limited by the IB position rather than by the position of CB.

In this work, we propose a technique to fabricate a QDSC with directly Si doped InAs QDs in order to control the Fermi level of QD intrinsic region.

EXPERIMENTS

We have fabricated a *p-i-n* QDSC by atomic hydrogen-assisted RF-MBE on GaAs (001) substrate (Figure 2). 25 pairs of 2.0 monolayers (MLs) of InAs QD layer and a 20 nm-thick $GaN_{0.01}As_{0.99}$ spacer layer were incorporated into the *i*-layer region. The net average lattice strain was minimized by using *strain-compensation technique*, in which GaNAs dilute nitride was used as a strain-compensating layer (SCL) [5]. Each InAs QD layer was directly doped with Si impurity during the self-assembling stage of growth [6]. The sheet density of Si doping was set to be 5.0 × 10^{10} cm^{-2} per QD layer in order to dope approximately one Si atom per QD. In a separate

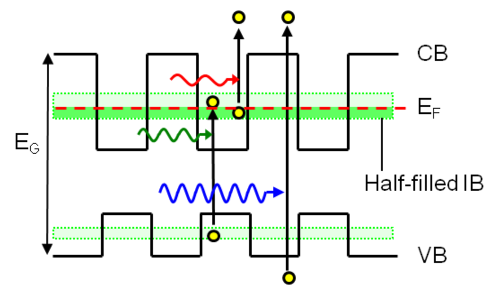

Figure 1 Basic operation of IBSC. The figure shows schematic band diagram with the absorption processes involved.

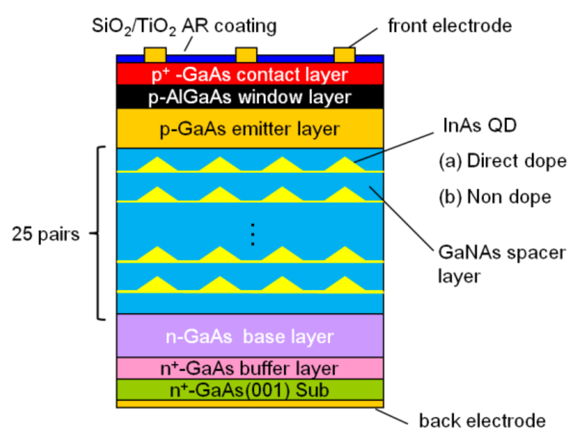

Figure 2 Schematic layer structure of QDSC fabricated in this work.

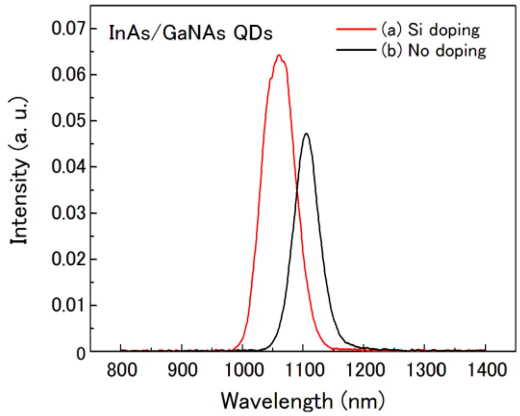

Figure 3 PL spectra at 77 K for 25 layers stacked InAs/GaNAs QDs with (a) direct Si-doping, and (b) no doping, respectively.

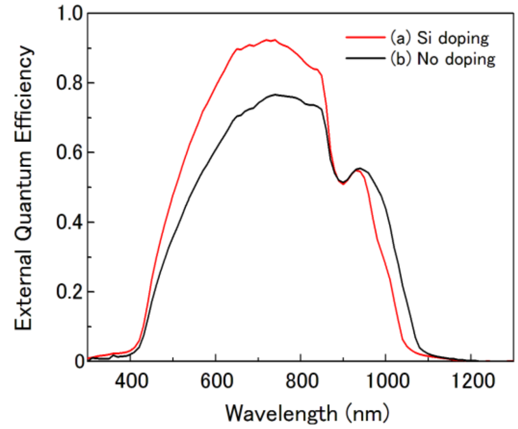

Figure 4 QE spectra measured for InAs/GaNAs QDSC with (a) direct Si-doping, and (b) no doping, respectively.

experiment, we determined the mean QD diameter, height, size uniformity in diameter, and sheet density to be 24.6 nm, 4.7 nm, 11.1 %, and 5.0 × 10^{10} cm^{-2}, respectively, from atomic force microscope (AFM) measurements.

For optical characterizations, photoluminescence (PL) measurements were performed using a 532 nm diode-pumped solid-state laser at an output power of 1 W/cm^2 and an electronically cooled PbS photodetector. For solar cell characterization, Ti/Pt/Au alloy was used for the top contact and AuGeNi/Au for the bottom for 3×3 mm^2-sized solar cells, and SiO_2/TiO_2 anti-reflection coating (ARC) was used. The quantum efficiency (QE) measurement was employed under a constant photon irradiation of 10^{16} $/cm^2$ at various applied bias voltage (V_{appl}) between -1.6 V (reverse) to 0 V in order to evaluate the effect of electric field on the carrier collection process.

RESULTS AND DISCUSSION

Figure 3 show PL spectra measured at 77K for 25 layers stacked InAs/GaNAs QDSC with (a) direct Si-doping, and (b) no doping, respectively. QD sample with Si doping shows a stronger PL intensity compared to the sample with no doping by a factor of 1.68. The observed enhancement of PL intensity indicates that the effect of doping on crystal quality of QDs is negligible, and free electrons in QD increase by doping. Further, PL peak blueshifts from 1105 nm to 1058 nm by Si doping, which likely due to state filling effect in the QD [7].

Figure 4 show QE spectra measured for QDSC with (a) direct Si-doping, and (b) no doping, respectively. QE response in shorter wavelength below 880 nm is contribution from GaAs layer, while the peak structure around 970 nm is contribution from GaNAs spacer layer. Further, QE response above 1000 nm is mainly from InAs QDs. It is particularly noted that Fig. 4 (a) shows a higher QE response than that for (b) in shorter wavelength range below 880 nm. This suggests that recombination process of carriers generated in p-GaAs emitter layer is effectively reduced in intrinsic QD region, because the electron state of QD is partially filled. On the other hand, QDSC with doping shows a decreased QE response than that for QDSC with no doping in the longer wavelength region above 1000 nm. This indicates that light absorption (VB-IB) of QDs become smaller as a result of partial filling. Further, we find that absorption edge is blueshifted by doping, which is in good agreement with PL result as of Fig.3.

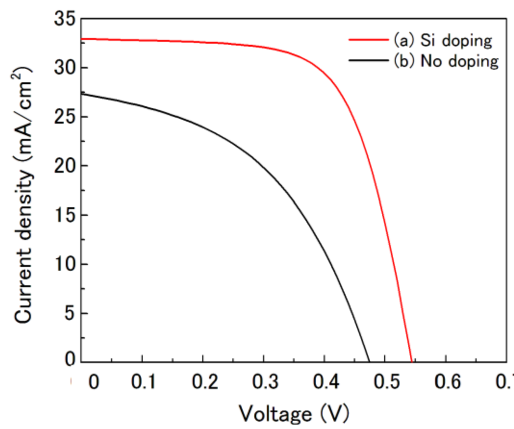

Figure 5 I-V curves of InAs/GaNAs QDSC with (a) direct Si-doping, and (b) no doping, respectively.

	No doping	Si doping
I_{sc} (mA/cm^2)	27.36	32.95
V_{oc} (V)	0.475	0.545
FF	0.458	0.659
Efficiency (%)	5.96	11.82

Table I Parameters of 25 stacked layers of InAs/GaNAs QDSC with direct Si-doping and no doping, respectively.

Figure 5 show I–V curves of QDSC with (a) direct Si-doping and (b) no doping, respectively. The parameters obtained from I-V curve for each QDSC are summarized in Table I. The short-circuit current density increases from I_{sc} = 27.4 to 32.9 mA/cm^2 by Si-doping, which is mainly due to increased QE in the shorter wavelength region. Further, we also observe an improvement in fill factor (FF) and V_{oc}, since recombination in QD intrinsic region is reduced as mentioned above. As a result, measured conversion efficiency is improved to 11.82 % as of (a) by direct doping compared to 5.96 % as of (b).

Figure 6 plot QE spectra measured under a short circuit condition for InAs/GaNAs QDSC with (a) Si direct doping, and (b) no doping, with V_{appl} = -1.6 V, -0.8V, 0V, respectively. The applied external reverse bias strongly affects the QE spectral shape as well as its intensity for (b), while those for (a) are almost identical in the entire range. We can see that QE response is improved by applying a stronger reverse bias voltage for (b). This suggests that the photogenerated carriers in *p*-GaAs emitter region recombine strongly in InAs QD region, in which non doped InAs QDs act as efficient recombination centers [8].

Figure 7 plot photocurrents as a function of applied reverse bias voltage for InAs/GaNAs QDSC with (a) Si direct doping, and (b) no doping, respectively. The photo current was calculated by taking the product of QE and AM 1.5 solar spectrum. The degree of increase with bias as difference of (a) is smaller than that for (b). This suggests that photogenerated carriers are extracted effectively for QDSC with Si direct doping.

CONCLUSION

We have characterized directly Si-doped InAs/GaNAs QDSCs fabricated by using strain compensation technique on GaAs (001) substrate. Each InAs QD layer was directly doped with Si impurity during the self-assembling process. QDSC with direct doping shows a higher QE response than that for no doped QDSC in the wavelength range below 880 nm. I_{sc} of Si doped QDSC is improved to 32.9 mA/cm^2 and we successfully obtained η = 11.82 %. The dependence of QE on reverse bias voltage indicates the QDSC with Si direct doping can extract carriers effectively due to the suppression of carrier recombination in QD region.

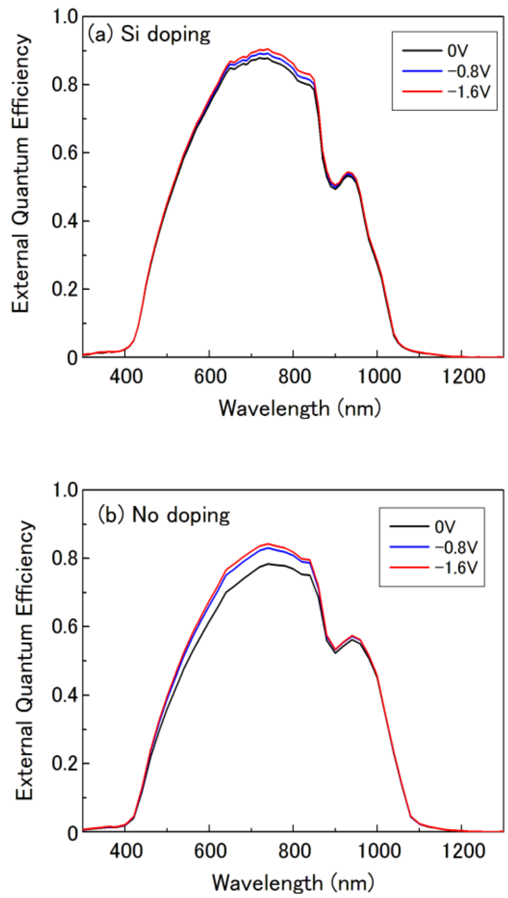

Figure 6 EQE spectra for InAs/GaNAs QDSC with (a) direct Si-doping, and (b) no doping, respectively.

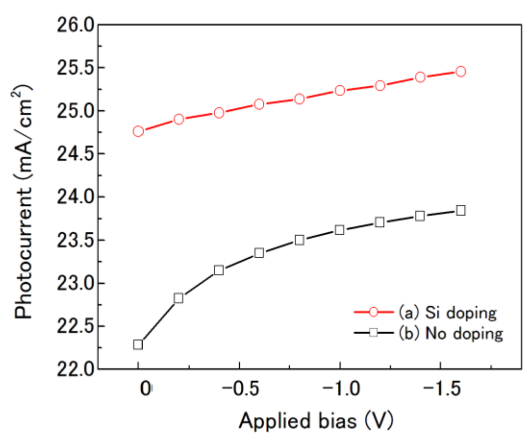

Figure 7 Photocurrent as a function of applied reverse bias.

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