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The Effect Of Concentration On The Performance Of Quantum Dot Intermediate-Band Solar Cells

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Abstract. Implementation of a high-efficiency quantum dot intermediate-band solar cell (QD-IBSC) must accompany a sufficient photocurrent generation via IB states. The demonstration of a QD-IBSC is presently undergoing two stages. The first is to develop a technology to fabricate high-density QD stacks or a superlattice of low defect density placed within the active region of a *p-i-n* SC, and the second is to realize half-filled IB states to maximize the photocurrent generation by two-step absorption of sub-bandgap photons. For this, we have investigated the effect of light concentration on the characteristics of QDSCs comprised of multi-layer stacks of self-organized InAs/GaNAs QDs grown *with* and *without* impurity doping in molecular beam epitaxy.

Keywords: quantum dot solar cell, intermediate-band solar cell, concentration, self-consistent device simulation.
PACS: 73.20.Hb, 73.21.La, 88.40.fh, 88.40.H-

INTRODUCTION

Proposed implementation of a high-efficiency quantum dot intermediate-band solar cell (QD-IBSC) [1] must accompany a sufficient photocurrent generation via IB states. The demonstration of a QD-IBSC is presently undergoing two stages. The first is to develop a technology to fabricate high-density QD stacks or a superlattice of low defect density placed within the active region of a *p-i-n* SC, and the second is to realize half-filled IB states to maximize the photocurrent generation by two-step absorption of sub-bandgap photons.

For the former requirement, we have developed a strain-compensation or strain-balanced technique to grow multi-stacks of InAs QDs in GaNAs matrix on GaAs(001) substrate.[2-4] For the latter, the detailed balance model has shown that a sufficient population of photogenerated carriers and hence a production of additive photocurrent can be sustained in a QD-IBSC if the cell were operated under concentration, typically in the range of 100 ~ 1000 suns.[5] In this work, we have investigated the effect of light concentration on the characteristics of QDSCs comprised of multi-layer stacks of InAs/GaNAs strain-compensated QDs on GaAs substrate grown *with* and *without* impurity doping in molecular beam epitaxy.

EFFECT OF CONCENTRATIONATION ON THE PERFORMANCE OF QD-IBSC

We have investigated the effect of concentration on the characteristics of QDSCs. First, the effect of increasing the number of multi-layer stacks of InAs/GaNAs strain-compensated QDs was studied. Second, *P-V* characteristics under concentration was compared for samples grown with doped and non-doped InAs QDs. The doping of IB states should result in an improved pumping of electrons by providing both empty states to receive electrons being photo-excited from the valence band (VB), and filled states to promote electrons to the conduction band (CB) via absorption of second sub-bandgap photons. This is a prerequisite for a high-efficiency IBSC operation.[6]

Effect Of Increasing The QD Density By Multiple Stacking Of QD Layers

We have fabricated up to 50 stacked layers of InAs/GaNAs strain-compensated QDs (non-doped) which have been introduced into the i-layer of GaAs p-i-n cell. All SCs were grown by atomic hydrogen-assisted molecular beam epitaxy (H-MBE) with a radio frequency plasma cell as the nitrogen source. Four SC samples were grown on n+-GaAs (001) substrate as shown in Fig. 1. These samples were identical in the structure except for the i-layer region. Three QDSCs were grown with 20, 30 and 50

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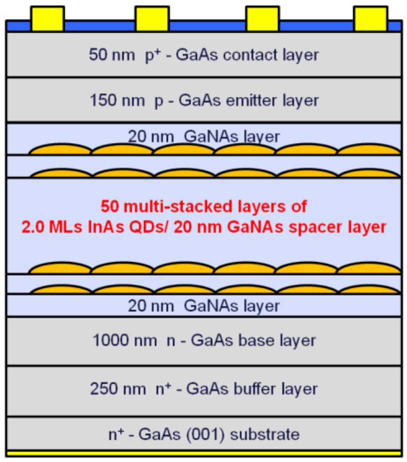

FIGURE 1. Schematic structure of QDSC with multi-stacked layers of InAs/GaNAs strain-compensated QDs.

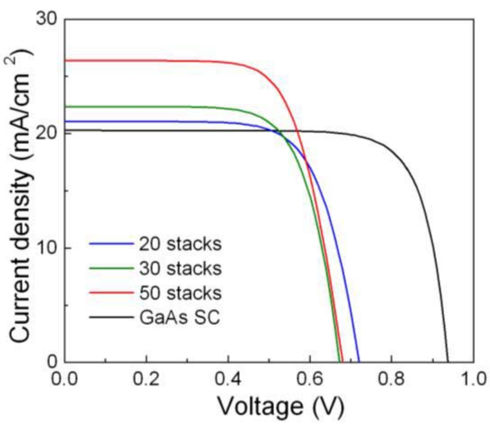

FIGURE 2. Current–voltage curves measured for QDSCs with 20, 30, and 50 stacks, and for GaAs reference cell at AM1.5 and 1sun, respectively.

stacked pairs of an InAs QD layer with 2.0 monolayers (MLs) thickness and a 20-nm-thick GaN0.01As0.99 strain-compensation spacer layer (SCL) in the center of i-region, respectively. This stacked configuration has been optimized as reported elsewhere,7 in which the lattice strain accommodated around QDs are near perfectly compensated by opposite strain induced by GaNAs SCLs. Because the total thickness of i-layer was set to 1.0 □m for each cell in order to make the built-in electric field to be constant at ~13.6 kV/cm, the thickness of intrinsic GaAs layer d was set to d = 300nm, 200nm, and 0nm for QDSC with 20, 30, and 50 QD stacks, respectively. Lastly, the fourth sample was a GaAs baseline cell with a 1.0-µm-thick i-GaAs layer used as a reference. The growth rates of InAs QDs and GaNAs layers were 0.09 and 1.0 µm/h, respectively. The growth temperature was set at 480 °C except in the growth of buffer and base layers, which were grown at 580 °C. The RF power during the growth of GaNAs spacer layers was kept

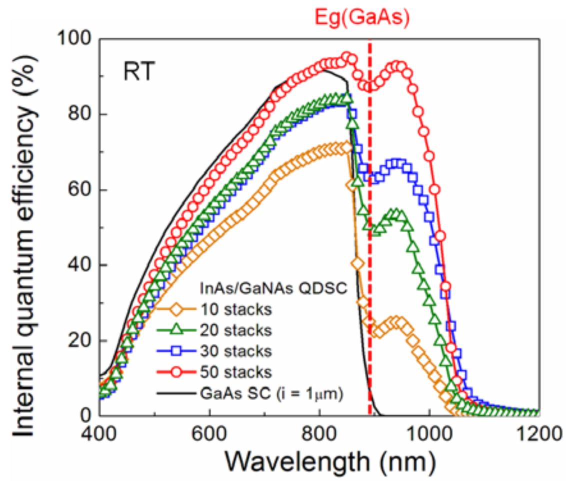

FIGURE 3. Internal QEs determined for QDSCs with 10, 20, 30, and 50 stacks, and for GaAs reference cell, respectively.

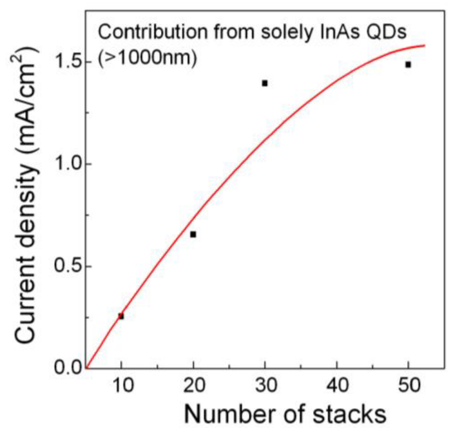

FIGURE 4. Current increase solely due to InAs QDs as a function of number of stacked QD layers.

at 50W. For solar cell characterization, Ti/Pt/Au alloy was used for the top contact and AuGeNi/Au for the bottom contact for 3×3mm2-sized cells, and SiO2 anti-reflection coating (ARC) was used.

Figure 2 show the P-V curves measured for QDSCs with 20, 30, and 50 stacks, and for GaAs reference cell. The short-circuit current Isc increases almost linearly from 21.0 to 26.4 mA/cm2 as the number of stacks is increased from 20 to 50 layers.

The internal quantum efficiencies (IQE) are shown in Fig. 3. The QE measurements were performed under a constant photon irradiation of 10^{16}/cm^2. It can be observed that in addition to a photoabsorption peak originating from GaNAs spacer layer at around 980 nm, the absorption edge extends from 880 nm for GaAs reference cell up to ~1200 nm for each QDSC. This is due to the photoabsorption from InAs QDs and wetting layer. The filtered I_{sc} above the GaAs bandedge of 880nm for 50-stacked QDSC is

6.3 mA/cm[2,] and the contribution solely from InAs QDs, *i.e.* above the wavelength of 1000nm, is 1.5mA/cm^2 as shown in Fig. 4.

On the other, the open-circuit voltage V_{oc} drops by incorporating QDs. This is predominantly due to an increased dark current by using GaNAs as a barrier layer, which has a narrower bandgap compared to GaAs. In addition, there is a mismatch between the transition rates from VB to QD-IB and from QD-IB to CB, resulting in increased radiative recombination losses in our present QDSC structure. We have reported previously that the optical pumping rate from QD-IB to CB is quite small at present, and the ratio of this QD-IB to CB optical generation rate to that of thermal and/or field-assisted extraction at room temperature is ~ 1:20[4].

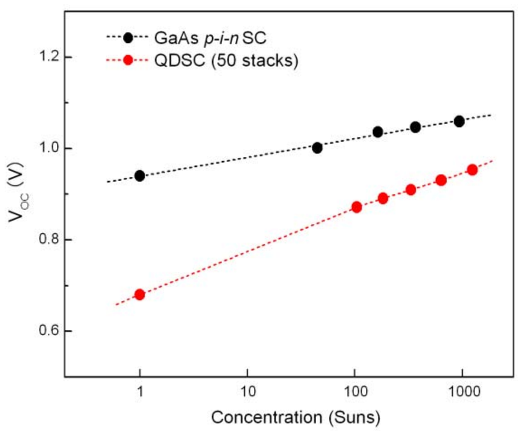

FIGURE 5. Measured V_{oc} as a function of concentration. A rapid initial recovery in V_{oc} is observed up to ~100 suns for 50-layer stacked InAs/GaNAs strain-compensated QDSC.

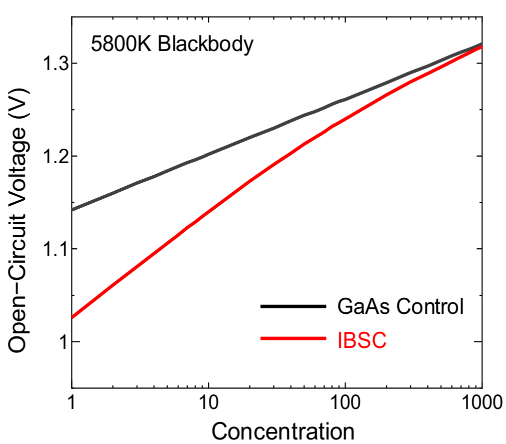

FIGURE 6. Calculated V_{oc} as a function of concentration. The concentration increases the generation rate and hence sufficient carriers are populated in IB, which in turn rapidly increases the photocurrent production in IBSC.

However, it can be observed that V_{oc} initially recovers rapidly up to ~100 suns for the 50-layer QDSC as shown in Fig. 5. Then V_{oc} further increases but at a smaller rate towards but not reach V_{oc} of GaAs *p-i-n* reference cell. Figure 6 show the calculated plots of V_{oc} for both IBSC and GaAs reference cells as a function of concentration ratio. The calculation is performed by using self-consistent device simulation tool developed by our group.[8] The *general features* observed for the calculation and measured data show a fair qualitative agreement. The results indicate that the concentration increases the generation rate and hence sufficient carriers are populated in IB, which in turn drastically changes the band structure thereby rapidly increasing the photocurrent production in IBSC. This mechanism can explain the characteristics observed in Fig. 5.

The QD-IBSCs which commonly suffer from small absorption by QDs leading to low V_{oc} and efficiencies are thus expected to recover fast and perform better under concentration operation.[9] In a well-developed cell, a 50-layer stacked InAs/GaNAs QDSC results in an efficiency of ~20.3% at 100 suns and ~ 21.2% at 1,000 suns, respectively.

Effect Of Doping Of QDs On The Performance Of QD-IBSC

Next we have fabricated Si-doped and non-doped *p-i-n* QDSCs on GaAs (001) substrate.[3,4] The sample structure as shown in Fig. 7 was similar to Fig. 1 except for a 30nm-thick AlGaAs window layer was inserted this time. The QD region consisted of 25 pairs of a 2.0 monolayers of InAs QD layer and a 20 nm-thick $GaN_{0.01}As_{0.99}$ strain-compensating layer (SCL) whereby keeping the net average lattice strain to minimum as before. For doped-QD sample, InAs QD layers were directly doped with Si during the self-assembling stage of growth, which is an optimal timing for Si atoms to be doped evenly into QDs.[10] The sheet density of Si doping was 5.0×10^{10} cm^{-2} per each QD layer in order to dope approximately one Si atom per QD. In a separate experiment, we determined the mean QD diameter, height, size uniformity in diameter, and areal density to be 24.6 nm, 4.7 nm, 11.1%, and 5.0×10^{10} cm^{-2}, respectively. We did not observe any noticeable differences in the shape and size of QDs between direct Si-doped and non-doped QD samples as shown in Fig. 8. For SC characterization, Ti/Pt/Au alloy was used for the top contact and AuGeNi/Au for the bottom in 3×3 mm^2-sized cells, and no ARC layer was deposited.

We have previously reported on a method to simulate the characteristics of IBSCs[9] using a simple equivalent circuit model.[11] The dark *I-V* curves can be fitted by using the diode parameters which can then be used to simulate the expected characteristics and SC efficiencies as a function of concentration ratio. The diode parameters were extracted and used except for R_s, which was taken to be 0.01 Ω cm^2. Our present Si-doped InAs/GaNAs QDSC produces an additive current of 0.61mA/cm^2. The efficiency then reaches ~ 19.3% at ~ 100 suns compared to the non-doped QDSC which results in ~15%, though not shown. With a further optimization of processing of the wafer and adoption of a photon trapping technique, we should expect at least an order of increase in the current due to VB to QD-IB transition, J_{VI} and due to QD-IB to CB, J_{IC}. The simulated result for J_{VI} = J_{IC} = 8mA/cm^2 as compared to the present experiment of 0.61mA/cm^2 suggests that the efficiency can then outperform the GaAs reference cell at around 10 ~ 20 suns. Increasing the current by a factor of 10 by QD absorption remains as challenge.

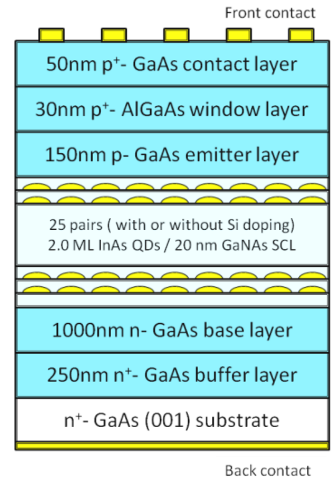

FIGURE 7. Schematic structure of QDSC with 25-stacked layers of Si-doped and non-doped InAs/GaNAs strain-compensated QDs.

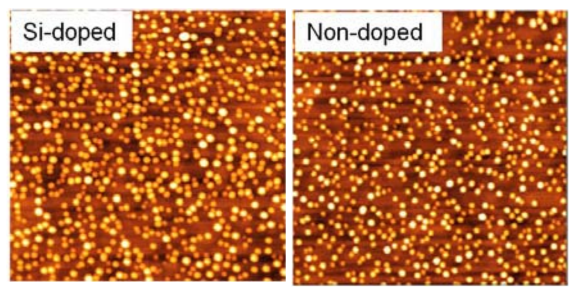

FIGURE 8. Noticeable differences in the shape and size of QDs were not observed between Si-doped and non-doped QDs. (Scale: 1µm×1µm).

SUMMARY

We have fabricated and studied the operation characteristics of InAs/GaNAs strain-compensated QD-IBSCs under concentration. We have shown that the concentration increases the generation rate and hence sufficient carriers are populated in IB, which in turn rapidly increases the photocurrent production via IB. The QD-IBSCs which commonly suffer from a small absorption by QDs leading to low V_{oc} and efficiencies are thus expected to recover fast and perform better under concentration operation. In the case of doped QDSCs, a fast recovery of V_{oc} was observed in a range of low concentration due to the effect of IB. Further, doped QDSC could outperform the GaAs reference SC if the IB current source were increased by an order of magnitude possibly by utilizing a photon trapping technique.

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