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Demonstration of InP/InGaP quantum dot solar cells

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Abstract

Wide-bandgap host intermediate-band solar cells have attracted attention to match solar irradiation spectrum. Here, we demonstrate the wide-bandgap InGaP-based InP quantum dot (QD) solar cells. InP QDs can form type-II confinement potential, in which a spatial separation between electrons and holes occurs and has advantages for efficient intermediate-band solar cells. We fabricated the InGaP-based InP QD solar cells using solid-source molecular beam epitaxy. Photoluminescence spectrum reveals a successful formation of multi-stacked InP QD layers in the InGaP solar cells. From current-voltage characteristics and spectral response measurements, we investigated the solar cell performances of InP/InGaP QD solar cells. Our findings indicate that further improvement of the optical transition using inter- and intra-band transitions of QDs is required for efficient intermediate-band solar cells.

1. Introduction

Intermediate-band (IB) solar cells using quantum dots (QDs) have attracted attention to overcome single-junction solar cells [1,2]. Lower energy photons below the bandgap energy of host semiconductors are absorbed through inter- and intra-band transitions of the QDs, which generate additional photocurrent in the host solar cells. The photocurrent generation has been demonstrated in InGaAs QDs and InAs QDs in the host GaAs solar cells [3,4].

Recently, in order to match the solar irradiation spectrum, wide-bandgap host semiconductors, such as InGaP, have attracted attention, in which the deep confinement potential is formed [5,6]. In addition, type-II QD solar cells have attracted attention for highly efficient intermediate band solar cell because type-II QDs exhibits a spatial separation between electrons and holes. Type-II QDs, such as GaSb/GaAs QDs [7] and Ge/Si QDs [8,9], have been investigated for use in IB solar cells. To address both advantages in the wide-bandgap host and type-II QDs, we proposed the use of type-II InP QDs in the InGaP host for wide-bandgap host IB solar cells [Fig. 1(a)] [10]. However, the detailed characteristics of the InP/InGaP QD solar cells have not been understood.

In this paper, we fabricated the InGaP-based InP QD solar cells using solid-source molecular beam epitaxy and investigated the solar cell performances. To understand the solar cell performance, we investigated photoluminescence (PL), current-voltage characteristics, and spectral response.

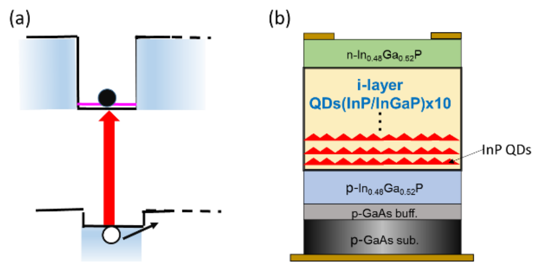

Fig.1 (a) Schematic illustration of energy diagram of InP/InGaP quantum dots and (b) device structures.

2. Experimental procedures

Figure 1(b) shows a schematic of device structure, in which i-layer multi-stacked QD structures were inserted in an InGaP p-i-n junction. The i-layer region consists of 10-stacked 4ML InP QD structures with 50nm InGaP spacer layers between the QDs. The QD layers were grown using solid-source monocular beam epitaxy on the GaAs substrate. After the growth, the front electrode was formed using photolithography and a lift-off technique. AuGe/Ni/Au and Ti/Au were used for the front and back electrodes, respectively.

For PL measurements, a GaN diode laser of 405 nm wavelength was used as an excitation light source and PL signals were detected using a charge-coupled device. Current-voltage characteristics of the solar cells were measured under 1 sun AM 1.5G illumination at 25 °C. External quantum efficiency (EQE) were measured under zero bias-voltage condition.

3. Results and Discussions

Figure 2 shows PL spectra measured at 140 and 300 K. Three PL peaks appear at 140 K. Peak A, B, and C are assigned to the emission from InGaP, InP QDs and GaAs substrate, respectively. This reveals a successful formation of multi-stacked InP QD layers in the InGaP solar cells.

Figure 3 shows the current-voltage characteristics of the sample. The obtained open-circuit voltage (V_{oc}) is 0.77 V. Compared to the InGaP solar cells, which shows the open-circuit voltage of 1.32 V [11], the V_{oc} in the InP/InGaP QDs solar cells exhibit lower V_{oc}, which may be

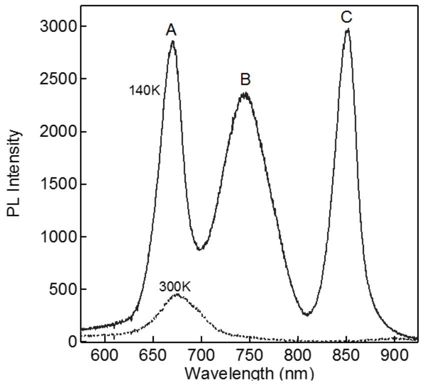

Fig.2 Photoluminescence spectra measured at 140 (solid) and 300K (dotted).

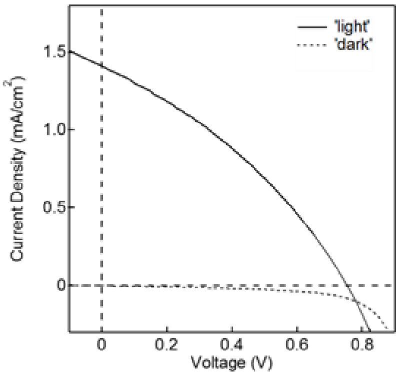

Fig.3 Current-voltage characteristics under light (solid) and dark (dotted) conditions.

caused by enhanced recombination current due to the InP QD insertion.

Figure 4 shows the EQE spectrum. The EQE is smaller compared with the InGaP solar cells without InP QDs [11]. This is partly because no anti-reflection coating at the front surface causes the larger reflectance of ~ 20% [Fig. 4]. A slight increase in the EQE spectrum around 700–800 nm indicate an additional photocurrent generation due to the InP QDs. Since the photocurrent generation requires the carrier extraction from QDs, thermal carrier escape may still exist even in the deep confinement potential of electrons in InP/InGaP QDs [3]. In addition, The EQE at shorter wavelength region (400–600 nm) shows a reduction compared to the InGaP solar cells without InP QDs [5]. This indicates that the generated carriers are not extracted from the solar cells. This may be related to the fact that the generated carriers at the incident surface may be captured at the QDs placed nearby the front surface and are not extracted efficiently from the solar cells, which is probably resulting in poor performance. To suppress the recombination of carrier in the QDs, efficient second optical excitation to the intra-band transition of QDs is also required. Then, the optimization of the device structures and QDs is a next step of this work.

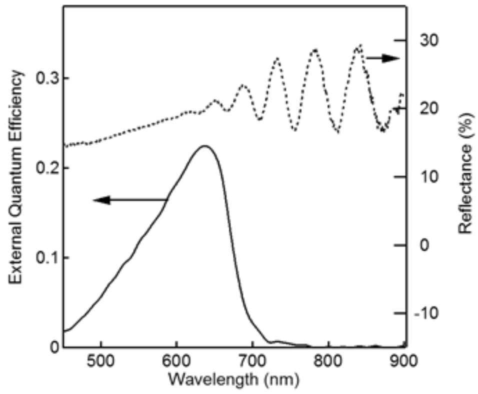

Fig.4 External quantum efficiency and reflectance.

4. Summary

We demonstrated the InP/InGaP QD solar cells and investigated the performance using PL and EQE measurements. PL spectra shows that the electronic states of InP QDs are formed in the bandgap of the InGaP host. EQE spectra indicate that a slight increase at longer wavelength region may be related to IB transitions. Toward efficient QD solar cells using two-step photon absorption, further understanding of the inter- and intra-band transitions of the QD will be required.

Acknowledgements

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