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Investigation of the open-circuit voltage in the wide-bandgap InGaP-based InP quantum dot solar cells

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Abstract

To address the open-circuit voltage (V_{oc}) in intermediate-band solar cells, we investigated the current-voltage characteristics in wide-bandgap InGaP-based InP quantum dot (QD) solar cells. From the temperature dependence of the current-voltage curves, we show that the V_{oc} in InP QD solar cells increases with decreasing temperature. We use a simple diode model to extract V_{oc} at the zero-temperature limit, V_0, and the temperature coefficient, C, of the solar cells. Our results show that while the C value in the InP QD solar cells is slightly larger than that in the reference InGaP solar cells, the V_0 value is significantly reduced and coincides with the bandgap energy of the InP QDs rather than that of the InGaP host. This V_0 value indicates that the V_{oc} reduction in the InP QD solar cells is primarily caused by a breakdown of the Fermi-energy separation between the QDs and host InGaP solar cells.

1. Introduction

Intermediate-band (IB) solar cells have attracted attention as a method of overcoming the efficiency limit of single-junction solar cells.[1–3] Photons with energies below the bandgap energy of the host semiconductor are absorbed via new states called as IB, which generates additional photocurrent in the host solar cells.[4] The open-circuit voltage (V_{oc}) is determined by the quasi-Fermi level difference between the conduction band (CB) and valence band (VB) of the host semiconductor. Because of their ability to enhance the current while preserving the output voltage, a high conversion efficiency of over 60% has been predicted for IB solar cells.[4] However, to date, all the reported experimental efficiencies of QD solar cells have been lower than those of the best single-junction devices.

The primary issue is that V_{oc} decreases with respect to the reference cells without QDs, even though the short-circuit current density shows a small increase in the solar cells with QDs. Thermal excitation at room temperature can excite the carrier out of the QD,[5] which eliminates the quasi-Fermi energy separation between the IB of the QD and the VB (CB) of the host semiconductor. Therefore, wide-bandgap InGaP host semiconductors have been used to suppress thermal carrier extraction from the QDs.[6] In order to address the advantages of a wide-bandgap host and type-II QDs that confine electrons and holes into spatially-separated potentials, we have proposed the use of InP QDs in an InGaP host,[7] and demonstrated the extended optical absorption due to the InP QDs.[8]

In this paper, we investigate the V_{oc} in InGaP-based InP QD solar cells. From the temperature dependence of V_{oc}, we find that V_{oc} at the zero-temperature limit is significantly reduced and coincides with the bandgap energy of the InP QDs rather than that of the InGaP host. Our result indicates that the low V_{oc} in the InP QD solar cells is primarily caused by the breakdown of the Fermi energy separation between QDs and host semiconductors.

2. Experimental procedures

We fabricated the InP QDs in an InGaP host using solid source molecular beam epitaxy.[6,8] Figure 1 shows a schematic of the device structure, in which i-layer multi-stacked QD structures were inserted into an InGaP p-i-n junction. The i-layer region consists of ten stacked 4-monolayer InP QD structures with 100 nm InGaP spacer layers between the QDs. After 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.

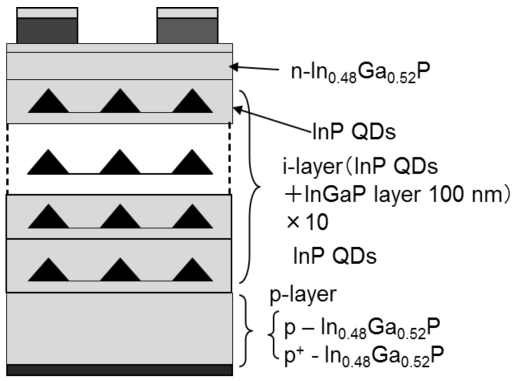

Fig.1 Schematic structure of the InGaP-based InP QD solar cells.

For current-voltage measurements at low temperatures, we used a Xe lamp with an AM1.5G optical filter for illumination. For photoluminescence (PL) measurements, a 405 nm diode laser was used as an excitation light source and PL signals were detected using a charge-coupled device.

3. Results and Discussions

Figures 2(a) shows the current-voltage curves for the InP QD solar cells. Compared to the current-voltage curve for the reference InGaP solar cells without InP QDs,[9] shown in Fig. 2(b), the V_{oc} at room temperature has been reduced. To clarify

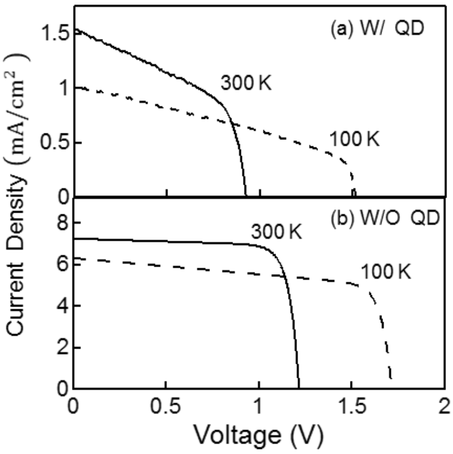

Fig.2 Current-voltage curves of the InGaP-based InP QD solar cells and (b) reference InGaP solar cells measured at 100 and 300 K.

the origin of this behavior, we investigated the temperature dependence of the current-voltage characteristics. In the QD solar cells, while the short-circuit current slightly decreases with decreasing temperature, the V_{oc} increases up to ~1.5 V at 100 K.

In conventional single-junction solar cells, V_{oc} decreases with increasing temperature, as determined by the bandgap energy of the host semiconductor, E_g, and the dark current characteristics,[10,11]

$$V_{oc} = E_g/q - C \cdot T, \quad (1)$$

where C is the temperature coefficient and reflects the dark current characteristics in the solar cells. In previously reported QD solar cells, the V_{oc} reduction is believed to be partially due to an increase in recombination caused by the quality of the QDs,[12] corresponding to an increased temperature coefficient, C. In addition, breakdown of the Fermi energy separation between the QDs and the host semiconductor may cause a reduced bandgap energy E_g.[11]

To obtain further insight, we investigate the temperature dependence of the temperature dependence of V_{oc}. Figure 3 shows temperature dependence of V_{oc} for QD solar cell and InGaP solar cell without QD. The V_{oc} value increases almost linearly with decreasing temperature in all the temperature region (T > 100 K). Next, we made use of a linear fit:

$$V_{oc}(T) = V_0 - C \cdot T. \quad (2)$$

From the fitted data shown in Fig. 3, we obtained V_0 = 1.8 V and $C = 2.9\times10^{-3}$ V/K for the InP QD solar cells and V_0 = 2.0 V and $C = 2.6\times10^{-3}$ V/K for the InGaP reference cells. The V_0 value is significantly reduced in the InP QD solar cells compared to the reference InGaP cells. On the other hand, C had the same value.

To discuss the origin of V_{oc} reduction in the QD solar cells, we investigated the bandgap energy of the InP/InGaP QD solar cells using PL measurements. We found that the PL peak positions are ~1.9 and ~1.75 eV for the InGaP host and InP QDs, respectively. The V_{oc} at the zero-temperature limit of the InP QD solar cells coincides with the bandgap energy of the InP QDs rather than that of the InGaP host. This means that

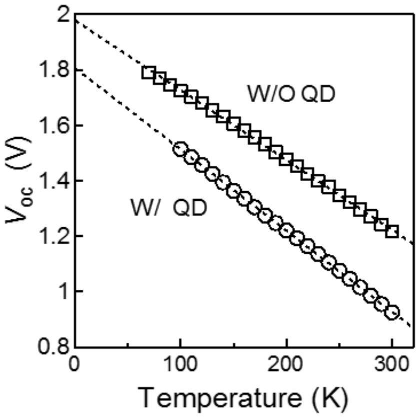

Fig.3 V_{oc} in the InGaP-based InP QD (circles) and InGaP (squares) solar cells. Broken lines indicate the fitting results using Eq. (2).

the large V_{oc} reduction in the InP/InGaP QD solar cells is primarily caused by the breakdown of the quasi-Fermi energy separation between the conduction of InP QDs and InGaP host.

4. Summary

We investigated the origin of V_{oc} reduction in InP QD solar cells. Our findings indicate that significant V_{oc} reduction at room temperature in the InP QDs solar cells is primarily caused by the breakdown of the quasi-Fermi energy separation between the QDs and host semiconductor.

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