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Effects of front InGaP layer thickness in InP/InGaP quantum dot solar cells

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Abstract

The influence of the front InGaP layer thickness on the solar cell characteristics is investigated in InP/InGaP quantum dot (QD) solar cells. To understand the cause of open-circuit voltage (V_{oc}) reduction compared to the reference InGaP solar cells with no InP QDs, current-volatge curves are measured for a wide temperature range from 100 to 300 K. In the InP/InGaP QD solar cells with the thick front InGaP layer, V_{oc} increases with decreasing temperature and the V_{oc} reduction to the reference cell decreases at low temperatures.

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, due to several problems to date, all the reported experimental efficiencies of QD solar cells have been lower than those of the best single-junction devices. The V_{oc} reduction has been mentioned as one of critical issues. As a solution to this problem, we have proposed the use of InP QDs in an InGaP host [5] and demonstrated the InGaP-host InP QD solar cells [6,7]. In addition, we have demonstrated the enhanced short-circuit current density (J_{sc}) in the device with thick front InGaP layer [8].

In this study, we performe current-voltage measurements for a wide temperature range and the temperatureare-dependent V_{oc} are discussed in the InP/InGaP QD solar cells with thick front InGaP layer.

2. Experimental procedure

We fabricated the InP QDs in an InGaP host using soid source molecular beam epitaxy. The multi-stacked InP QDs structures were inserted into a InGaP n-i-p junction. In addition, a front i-InGaP layer was incorporated at the top of QDs layer, as shown in Fig. 1(a). For comparison, we prepared the device with no front InGaP layer and the reference device with no InP QDs.

Figure 1(b) shows the energy diagram of the InGaP-based InP QD solar cell with the front InGaP layer. It was designed for the light with higher energy than InGaP bandgap energy to be absorbed by the front InGaP layer. After the growth, the front electrode was formed using photolithography and a lift-off technique. AuGeNi/Au and Ti/Au were used for the front and back electrodes, respectively. For current–voltage measurements at low temperatures, we used a Xe lamp with an AM1.5G optical filter for illumination. The low temperature measurements were performed in the temperature range from 300 to 100 K.

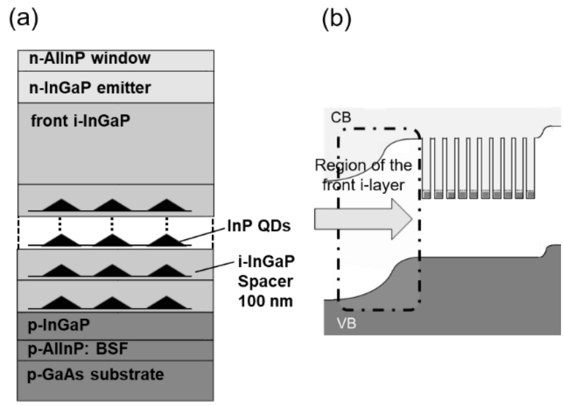

Fig. 1 (a) Schematic structure of InGaP-based InP QD solar cells. (b) Energy diagram of InGaP-based InP QD solar cell with the front i-InGaP layer.

3. Results and discussion

Figure 2 shows current-voltage curves in the device with the front InGaP layer measured at 220, 260, and 300 K. For comparison, the current-voltage curve in the device with no front InGaP layer is also shown. At 300 K, the device with the front InGaP layer shows larger J_{sc} compared to the device with no front InGaP layer. This can be attributed to the enhanced carrier collection efficiency in the device with the front InGaP layer [8]. In addition, the device with the front InGaP layer shows a slightly higher V_{oc}.

Next, in the device with the front InGaP layer, while J_{sc} decreases, V_{oc} increases with lowering temperature. To understand the influence of the front InGaP layer, we investigated the V_{oc} with varying temperature in the InP/InGaP QD solar cells with the front InGaP layer and compared with the device with no front InGaP layer and the reference InGaP solar cells with no InP QDs.

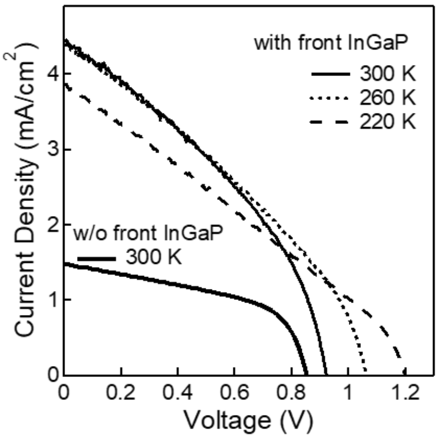

Fig. 2 Current-voltage curves of the InP/InGaP QD solar cells with the front InGaP layer measured at 220, 260, and 300 K and of the device with no front InGaP layer at 300K.

Figure 3 shows V_{oc} as a function of temperature. All the devices show a linear increase with decreasing temperature. This behabior reflects the fact that V_{oc} is determined by the bandgap energy E_g and dark current characteristics [8,9]. Next, we use a linear fit:

$$V_{oc}(T) = V_0 - C \cdot T, \quad (1)$$

where C is the temperature coefficient and reflects the dark current characteristics in the conventional single junction solar cells. V_0 is V_{oc} at the zero-temperature limit.

Here, we discuss V_{oc} at the zero-temperature limit V_0. The device with no front InGaP layer shows a lower V_0 value by ~0.2 V compared with the reference InGaP solar cell. The V_{oc} reduction at the zero-temperature limit compared to the reference solar cells with no QDs indicates that the V_{oc} reduction in the QD solar cells should be caused by the breakdown of the quasi-Fermi energy separation between the QDs and host [7,10]. Therefore, the large V_0 reduction in the device with no front InGaP layer means that the V_{oc} reducition compared to the reference InGaP solar cell is primarily caused by the breakdown of the quasi-Fermi energy separation between the conduction bands of InP QDs and InGaP host. In contrast, the V_0 in the device with the front InGaP layer shows almost the same V_0 value (~ 2.0 V) as the reference InGaP solar cell. This suggests that the V_{oc} reducition compared to the reference InGaP solar cell is not simply caused by the breakdown of the quasi-Fermi energy separation. This also indicates that thermal escape process from QDs, which is a primary cause of the breakdown of quasi-Fermi energy separation, should be suppressed in the device with the front InGaP layer. This is consistent with the fact that only weak built-in electric field is applied to QDs because of the thick i-InGaP layer. While the thermal escape from QDs may be suppressed, the photocarriers generated by two-step photon absorption cannot be extracted well under weak built-in electric field application. Optimization of the front InGaP layer thickness is required to preserve V_{oc} and increase J_{sc}.

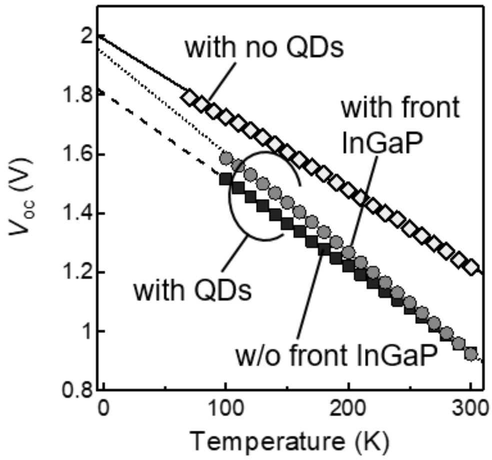

Fig. 3 V_{oc} as a function of temperature in InGaP-based InP QD solar cell with the front InGaP layer (circles), the device without front InGaP layer (squares) and the reference InGaP solar cells with no InP QDs (diamonds).

4. Conclusions

We investigated the impact of the front InGaP layer in InGaP-based InP QD solar cells. Our findings indicate that the insertion of the front InGaP layer can supresse the breakdown of the quasi-Fermi energy separation.

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