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Indium-tin-oxide/GaAs Schottky barrier solar cells with embedded InAs quantum dots

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ABSTRACT

We report the electrical and optical characteristics of indium-tin-oxide (ITO)/GaAs Schottky barrier solar cells (SBSCs) with embedded InAs quantum dots (QDs). Twenty layers of self-assembled InAs QDs are inserted into the SBSCs so as to increase the potential barrier height at the ITO/GaAs junctions and to create additional photo-generated electrons in the quantum confined states of the QDs. After analyzing the current density–voltage characteristics, the photoluminescence, and the external quantum efficiency of the fabricated SBSCs, it was found that the incorporation of InAs QDs into the ITO/GaAs SBSCs results in an increase of both of the open-circuit voltage and the short-circuit current density compared to SBSCs without InAs QDs.

1. Introduction

Schottky barrier solar cells (SBSCs) have long been extensively studied due to their potential for low-cost mass production and their relatively easy fabrication process. However, the efficiency of SBSCs remains limited in comparison to that of conventional p–n junction cells, as the barrier height of the Schottky barrier junction is much lower than that of general homojunction and heterojunction structures, which results in a higher thermionic emission dark current [1–3]. To overcome this deficit, increasing the metal-semiconductor barrier height has been the main solution used to reduce the dark current. With regard to the performance parameters of solar cells, the increased barrier height directly indicates an enhanced open-circuit voltage (V_{OC}) of SBSCs, as both factors are inversely proportional to the dark current. In addition, the increased barrier height can lead to the maximum value of the short-circuit current which the materials of SBSCs can generate due to the lower dark current. Barrier height enhancements using various methods, such as the insertion of a native insulating layer between the metal and the semiconductor [4], the use of surface defects [5], surface treatments with different chemicals [6], and the use of organic materials such as polymer layers which serve as an electron blocking layer [7,8], have been reported in the literature. However, these works mainly concentrated on increasing the barrier height, and the materials used to modify the barrier height cannot be used for a photoabsorption layer in optoelectronic conversion applications. To increase the efficiency of SBSCs further, it is necessary to use different light-absorbing materials and to increase the barrier height simultaneously.

Nanostructures such as quantum dots (QDs) are a promising solution to enhance the performance of SBSCs. QDs behave as potential wells near the semiconductor surface, leading to an increase in the barrier height [9]. Moreover, embedding QDs into a semiconductor creates discrete energy states in QDs, leading to light absorbance given the energy difference between the ground state and the excited states. Recently, Nripendra et al. reported Au/p-Si SBSCs with InP QDs which were deposited onto p-Si wafer surfaces in direct contact with Au [10]. However, their study did not show photocurrent generation at InP QDs beyond the Si absorption spectra. Here, we demonstrate the insertion of InAs QDs into GaAs-based SBSCs which increases the barrier height and generates additional photocurrent.

In this work, the electrical and optical characteristics of indium-tin-oxide (ITO)/n-GaAs SBSCs with embedded InAs QDs are demonstrated. ITO film, transparent from the visible to the near-infrared region corresponding to the wavelength of the absorption spectra of GaAs and InAs QD, is used here. Comparative studies of the current density–voltage (*J*–*V*) characteristics of SBSCs with and without InAs QDs are conducted in dark and light conditions. The photoluminescence (PL) spectra and the

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external quantum efficiency (EQE) results are also presented to investigate the effects of InAs QDs with regard to the optical performance levels of SBSCs.

2. Experiment

The SBSC samples were prepared with and without QDs by molecular beam epitaxy. A control sample without QDs was prepared by growing an undoped GaAs buffer layer on an N–GaAs substrate with a thickness of 1 μm. For the SBSC sample with QDs (QD-SBSC), InAs QDs were grown by the Stranski–Krastanov growth mode and then capped with a GaAs layer of 50 nm. This process was repeated 20 times to have a total epitaxial thickness of 1 μm. A schematic of the QD-SBSC is depicted in Fig. 1(a) The average height and width of the QDs were 7 nm and 40 nm, respectively. The density of InAs QDs was 5×10^{10} cm^{-2}.

For the fabrication of the SBSC, n-type electrodes were formed on the bottom side of the prepared samples with Ni/Ge/Au (5/17/300 nm) using e-beam evaporation. Rapid thermal annealing for the ohmic contact was carried out at 385 °C in a nitrogen ambient environment for 1 min. Wet-chemical etching with a NH_4OH–H_2O (10:1) solution was conducted to remove the native oxide layer before the formation of the Schottky contact with ITO. An ITO (90%In2O3 + 10%SnO2) was deposited on the front side of SBSC samples by the RF sputtering. The RF power was 100 W and the Ar pressure used was 0.4 Pa. The thickness of the ITO film samples was approximately 80 nm in all cases so as to form an antireflection coating. The transparency of ITO film is usually greater than 80% in visible and near-infrared regions of light, indicating that near-infrared light can be absorbed by the ITO/GaAs SBSC with QDs. A contact layer was deposited onto the ITO films with Ti/Au through standard photolithography and a lift-off technique.

The dark and light *J–V* curves of the SBSCs were measured to investigate their performance capabilities using a parameter analyzer. The light *J–V* curves were measured with an air mass (AM) coefficient of 1.5 under 1 sun illumination. To examine the optical properties of QD structures in Schottky samples, the PL spectra of QDs and the EQE of Schottky samples were measured at room temperature (RT). The 532 nm diode-pumped solid-state laser with 60 mW together with nitrogen-cooled InGaAs detector was used in PL set up. In our EQE measurement, halogen lamp was used as white light source. Chopped light was passed through a monochromator. The photocurrent signals were collected and connected to a lock-in amplifier and a computer. The white light intensity is calibrated by a standard Silicon cell.

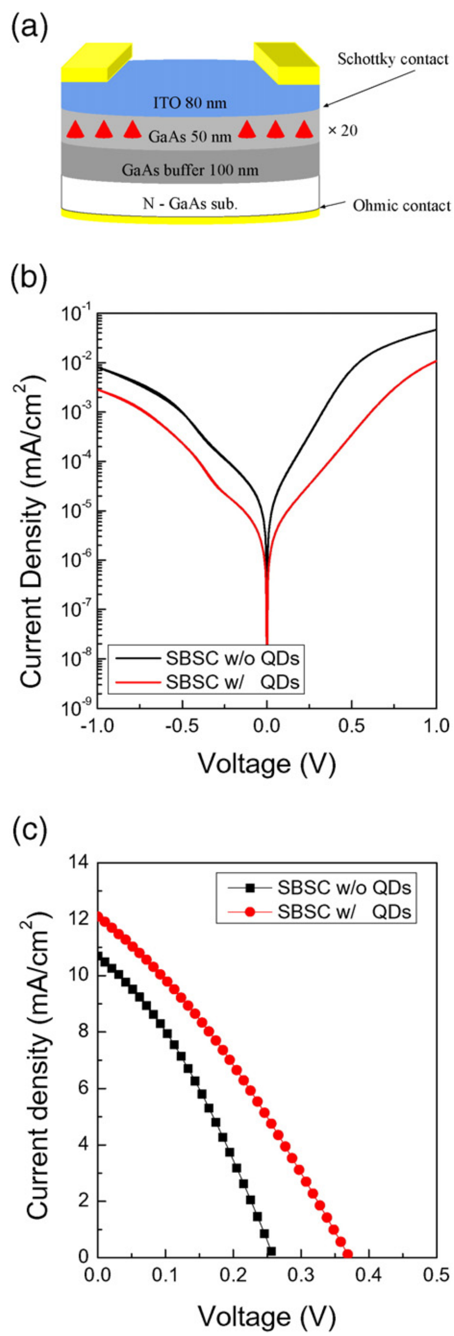

Fig. 1. (a) Schematic of a fabricated QD-SBSC, (b) the dark *J–V* curves of the QD-SBSC and the control SBSC without QDs, and (c) the light *J–V* curves of the QD-SBSC and the control SBSC without QDs under 1 sun illumination.

3. Results and discussion

Fig. 1 (b) and (c) presents the dark and light *J–V* characteristics of a QD-SBSC and a SBSC without QDs. The detailed SBSC parameters are depicted in the Table 1. The previous report of ITO/n-GaAs SBSCs, using the highly n-doped GaAs substrate, shows the higher values of V_{OC}, fill factor, and efficiency of SBSCs [5]. The doping concentration of a semiconductor is a crucial factor determining the built-in potential of SBSCs. In low doping concentration, thermionic emission current becomes dominant due to the low built-in potential. This thermionic emission current generates carrier recombination in the SBSC, resulting in the low barrier height of the SBSC. For these reasons, ITO/GaAs SBSCs formed on undoped GaAs layer show relatively lower performance than the ITO/n-GaAs SBSCs. To investigate how the QD itself affects the barrier height and photocurrent generation of the SBSCs, an undoped GaAs layer was used on the top of the epi-substrate as a Schottky contact layer for the QD-SBSC.

From the dark forward *J–V* curves, the barrier heights of the ITO/GaAs junctions can be calculated given by equations of below.

$$J = J_0 \, exp\left(\frac{qV}{nkT}\right), \tag{1}$$

$$\varphi_B = \frac{kT}{q} \ln\left(\frac{A^* T^2}{J_0}\right). \tag{2}$$

J is total current, n is the diode ideality factors, and J_0 is the reverse saturation currents. The other factors are standard symbols known as well. The calculated barrier heights of SBSCs with and without QDs are 0.678 eV and 0.641 eV, respectively. A higher barrier height of the QD-SBSC is observed due to quantum confinement in the QDs. The InAs QDs act as a potential well for electrons and capture the electrons which exist in the GaAs layer near the InAs QDs. From the view of the electrons in the QDs, the total potential barrier would be enhanced