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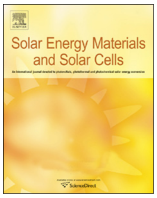

Open circuit voltage increase of GaSb/GaAs quantum ring solar cells under high hydrostatic pressure

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ABSTRACT

Hydrostatic pressure can be used as a powerful diagnostic tool to enable the study of lattice dynamics, defects, impurities and recombination processes in a variety of semiconductor materials and devices. Here we report on intermediate band GaAs solar cells containing GaSb quantum rings which exhibit a 15% increase in open-circuit voltage under application of 8 kbar hydrostatic pressure at room temperature. The pressure coefficients of the respective optical transitions for the GaSb quantum rings, the wetting layer and the GaAs bulk, were each measured to be ~10.5 ± 0.5 meV/kbar. A comparison of the pressure induced and temperature induced bandgap changes highlights the significance of the thermal energy of carriers in intermediate band solar cells.

1. Introduction

Intermediate band solar cells (IBSC) have the potential to achieve a high power conversion efficiency of 63% compared with 41% for a single junction solar cell under maximum solar concentration [1,2]. However, implementing effective two photon absorption and photocarrier generation ideally requires effective de-coupling of a partially filled intermediate band from the conduction and valence bands [3,4]. With this aim, GaSb/GaAs quantum ring solar cells (QR SC) have been realized, where the type-II band alignment provides longer carrier lifetime which enhances the extracted photocurrent [5], so that larger short-circuit current density can be obtained compared with the type I-InAs/GaAs system [6]. However, due to reduced electron–hole overlap, the absorption of type-II structures is somewhat lower. Although IBSC are expected to lead the third generation of solar cells, as yet there is no experimental evidence of high efficiency in such devices based upon quantum dots, primarily because the introduction of quantum dots into the depletion region of the solar cell has been found to result in a degradation of the open-circuit voltage [5–10]. Extensive research is underway to improve both the growth of the quantum dot arrays and also in developing and designing new characterization set-ups for understanding the limitations of these solar cells [11–15]. Two photon photocurrent and photovoltage measurements have been performed at low temperatures, and bias light power dependence experiments have explored the effect of intermediate band (IB) photo-filling [13]. Complete recovery of the open-circuit voltage, to that in the host material, can be achieved using a combination of high solar concentration and low temperatures [14,15]. Under these conditions the rate of optical excitation of holes exceeds the rate of thermal escape of holes from the quantum rings which is necessary to achieve effective two photon operation of the intermediate band [16].

Hydrostatic pressure has been extensively used in the literature for studying lattice dynamics, defects, impurities and recombination processes in a variety of semiconductor materials and devices including lasers, LEDs and photodetectors [17–22]. Hydrostatic pressure increases the bandgap of a semiconductor material at a fixed temperature, so that a single device can be tuned under pressure to operate at different wavelengths in a reversible and non-destructive manner. This saves fabricating new devices for each particular study and avoids any issues associated with growth-related changes in material quality. In this work, we present an investigation of GaSb/GaAs QR SC under hydrostatic pressure, where the transition energies increase with application of pressure without modifying the thermal distribution of the carriers. These results are compared with the effect of changing the cell temperature over the same photon energy range, from 1.42 to 1.51 eV. By measuring the spectral response we obtain the pressure coefficients for each of the main absorption edges corresponding to the different layers used in the QR SCs: bulk GaAs, GaSb wetting layer (WL) and GaSb quantum ring. We observed an increase in the open-circuit voltage and a decrease in the dark current as the applied pressure increases.

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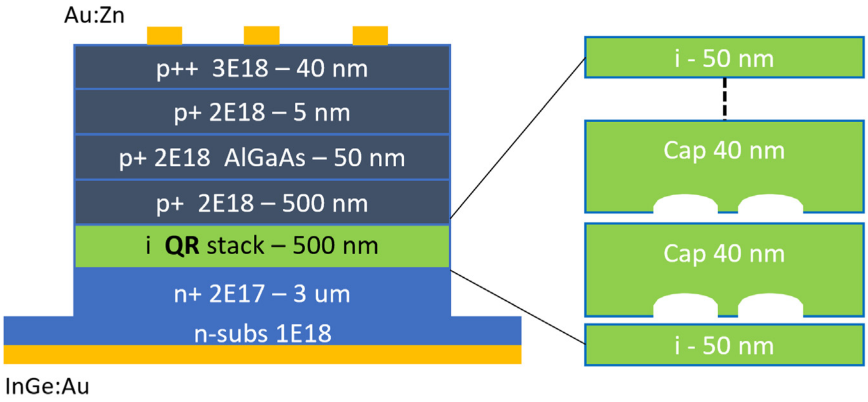

Fig. 1. Structure of the GaAs based QRSC with 10 layers of GaSb QR spaced by 40 nm in the active region.

2. Experimental details

The samples investigated in this study were p-i-n GaAs based solar cells, containing GaSb quantum rings in the intrinsic region to form the intermediate band, and were grown by molecular beam epitaxy (MBE) on n + GaAs substrates following our earlier design [4] as shown in Fig. 1. The reference solar cell is a p-i-n junction based on GaAs. The structure consists of a 3 µm thick n- type 10^{17} cm^{-3} base layer, followed by a 500 nm thick intrinsic region and a 500 nm thick p-type (10^{18} cm^{-3}) emitter layer. In order to improve the device performance, a 50 nm thick, p-type (10^{18} cm^{-3}) $Al_{0.8}Ga_{0.2}As$ window layer was used, capped with 5 nm of p-type GaAs followed by a contact layer of 50 nm thick, heavily doped, p-type (10^{19} cm^{-3}) GaAs. The quantum ring solar cell (QR SC) is of similar construction but contains 10 layers of GaSb quantum rings (QR) capped by 40 nm of GaAs grown within the intrinsic region of the device. The QRs are grown by the Stranski-Krastanov technique, where the large mismatch of 7% between GaSb and GaAs initially results in the formation of a thin wetting layer followed by GaSb quantum dots with a density of $\sim 10^{10}$ cm^{-2}. Following the subsequent deposition of the GaAs capping layer the As-Sb exchange mechanism modifies their shape into QRs [23]. The resulting structures were fabricated into 1 mm diameter mesa-etched solar cells using standard GaAs processing technology. Metallization for the top p-type contact layer was Au/Zn/Au (10/10/200 nm) and the bottom n-type was InGe/Au (20/200 nm) to provide good ohmic contacts.

Hydrostatic pressure measurements were carried out at room temperature using a Unipress He-gas compressor system capable of generating pressures of up to 10 kbar in a pressure cell where the solar cells were inserted. Electrical access is provided from one side of the pressure cell and the light is incident through a sapphire window from the other side. Further details of the set-up are given in Ref. [24]. For this experiment dark and illuminated I-V curves were performed under a maximum applied He pressure of 8 kbar. The spectral response was measured from 400 to 1300 nm by using a Bentham quartz-halogen (QH) lamp connected to a Bentham TMC-300 grating monochromator. A Ge reference detector was used to obtain the spectral flux dependence of the source. The electrical characterization was performed using a Keithley 2635 source-measure unit, both in the dark and under illuminated conditions, using the QH lamp to simulate solar illumination.

3. Results and discussion

Fig. 2(a) shows the square of the normalized photovoltage versus photon energy for the QR SC. Three main absorption features can be identified corresponding to transitions: GaAs valence band to conduction band (~ 1.4 eV), GaSb wetting layer (WL) valence band to GaAs conduction band (~ 1.25 eV), and GaSb QR valence band to GaAs conduction band (~ 1.0 eV). The pressure dependence of each of these transitions is shown in Fig. 2(b). Using a linear fit of the data, the pressure coefficients (*PC*) were obtained as 10.5 ± 0.5 meV/kbar for the GaAs bulk layer feature, which is in agreement with literature values, which lie in the range 8.5–12.6 meV/kbar [25] and 10.5 ± 0.5 meV/kbar for both the GaSb WL and QR transitions.

Using the measured pressure coefficients (*PC*) for each transition

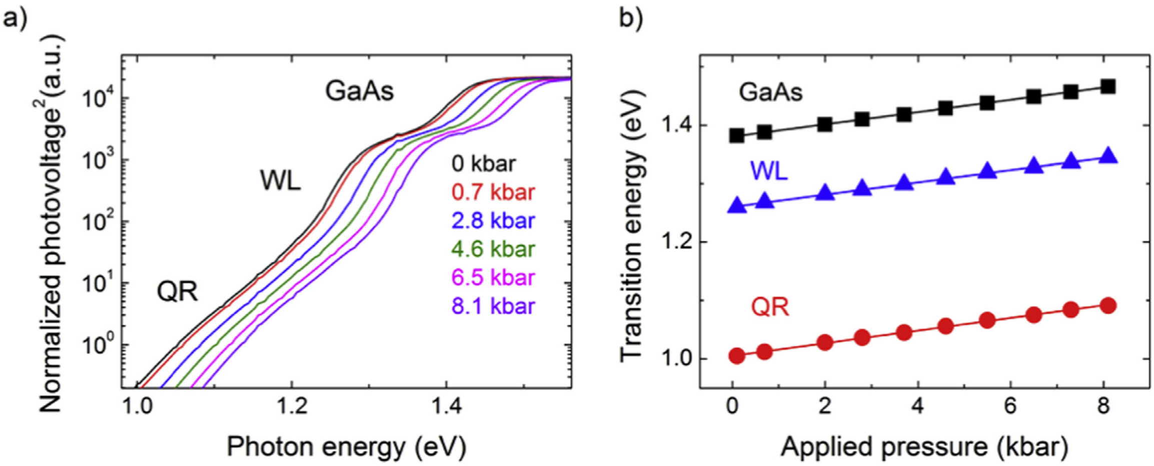

Fig. 2. (a) Square of the normalized photovoltage versus incident photon energy for the GaSb/GaAs QRSC for different applied pressures measured at 300 K. Three absorption features can be identified corresponding to: GaAs bulk layer, GaSb wetting layer (WL) and GaSb quantum ring (QR). (b) Transition energy versus applied pressure for the GaAs bulk layer (black squares), GaSb WL (blue triangles) and QR (red circles). The pressure coefficients are obtained from the linear fits (solid lines). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)