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Photovoltaic characteristics of each subcell evaluated in situ in a triple-junction solar cell

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ABSTRACT

New manufacturing processes were proposed to evaluate important photovoltaic properties of each subcell in an InGaP/InGaAs/Ge triple-junction solar cell. In addition to the triple-junction cell, an InGaAs/Ge double-junction cell and a Ge single-junction cell were also fabricated and employed for evaluation. The key merit of the double-junction cell is that semiconductor layers of forming InGaP top subcell are retained as a dummy top subcell. Thus, the InGaAs middle subcells in both triple- and double-junction cells will receive the same light spectrum. Similarly, the Ge single-junction cell is fabricated with dummy top and middle subcells as light filters. Open-circuit voltage, short-circuit current, conversion efficiency, and current mismatched ratio were measured for evaluating and optimizing each subcell. It is found that Open-circuit voltages are 1.295, 0.967, and 0.212 V for the InGaP, InGaAs, and Ge subcells with temperature coefficients of −2.5, −1.99, and −1.87 mV/°C. Thus the Ge subcell no longer acts a real solar cell at temperature over ∼140 °C. Besides, effect of ambient temperature on short circuit currents of all as-fabricated solar cells is not relevant. The current mismatched ratios are 18.6–20% at temperature ranged from 25 °C to 80 °C. A low efficiency of ∼18.7% is due partly to the poor current match. However, the processing concept proposed is useful as a method of matching currents among the subcells.

1. Introduction

Solar cells used to convert solar energy into electric power were reported by Bell laboratory in 1954. Then solar cells have become ones of the most important energy sources in past several decades [1–3]. In previous development stage, most work has involved using silicon-based solar cells [4–6]. As a result, silicon-based (solar) cells are currently used in a number of commercial and consumer-oriented applications. On the other hand, many researchers are engaged in exploiting solar cells fabricated by using various compound semiconductors. These compounds, for example, include II–VI (CdS, CdTe, and $CuInSe_2$) [7,8] and III–V (GaAs- and InP-based) [9–13] related materials. However, cells with improved power and conversion efficiency have been highly demanded due to other important applications such as satellites used in mobile and telephone communications. The energy conversion characteristic of the cells depends mainly on effective utilization of the available solar spectrum. Thus, multijunction cells have recently attracted increasing attention for their super-high conversion efficiencies [14–22]. This is because that these multijunction cells use multiple subcell band gaps to divide the broad solar spectrum into smaller sections, each of which can be converted to electricity more efficiently. However, an overall short-circuit current of such the multijunction cell is limited by the minimal short-circuit current among subcells. Besides, an individual solar cell with the same structure as the subcell in the multijunction cell was usually grown on a substrate for evaluation [23]. Accordingly, the individual cell fabricated on the substrate will receive different solar spectrum from that of the subcell in the multijunction cell. Thus, photovoltaic properties evaluated for the individual cell contribute little to optimize the multijunction cell.

In this work, a double-junction cell (composed of a middle and a bottom subcells) and a single-junction cell (only composed of the bottom subcell) were fabricated using the same overall epitaxial structure as that employed to fabricate a triple-junction cell. A key feature of fabricating the double-junction cell is that semiconductor layers grown for a top subcell still remain atop the double-junction cell. Thus, the double-junction cell will receive the same light spectrum as those of the middle and the bottom subcells in

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the triple-junction cell. Similarly, those layers for the top and the middle subcells also remain atop the single-junction cell. Photovoltaic properties in our single-junction cell are considered to be equivalent to those extracted from the triple-junction cell. Furthermore, temperature dependences of principal photovoltaic parameters of individual subcells are investigated based on current-voltage measurements of as-fabricated triple-, double- and single-junction cells. Experiments and measurements about the newly proposed double- and single-junction cells are described in following section. In Section 3, we addressed photovoltaic properties of each subcell based on experimental results obtained from our double- and single-junction cells with a so-called light filter. Finally, a conclusion was made.

2. Experimental

Fig. 1(a) shows a schematic diagram of an original epitaxial structure used to fabricate triple-, double- and single-junction solar cells evaluated in this study. The typical structure was grown on a p-type Ge substrate using a metal-organic chemical vapor deposition (MOCVD) system. It consists of an InGaP top subcell, an InGaAs middle subcell, and a Ge bottom subcell with a band gap of E_{g1}, E_{g2}, and E_{g3}, respectively. A diffused Ge p-n junction acting as the bottom subcell was formed automatically during the MOCVD epitaxial growth. An InGaP layer is deposited as a diffusion barrier layer before growing the middle and the top subcells. The InGaAs middle subcell is connected to the Ge bottom subcell by a p^+-GaAs/n^+-GaAs tunnel diode (TD2). The InGaP top subcell is connected to the InGaAs middle subcell by a p^+-AlGaAs/n^+-InGaP tunnel diode (TD1). Finally, a highly doped n^+-InGaAs cap layer is deposited for making a low-resistance contact. After finishing the MOCVD epitaxial growth, both front and back electrodes were fabricated by depositing AuGeNi and AuZn, respectively, to implement the InGaP/InGaAs/Ge triple-junction solar cell with the band gap combination of E_{g1}, E_{g2}, and E_{g3}. A cell size of the triple-junction solar cell is 0.25 cm^2. Instead of complete removal, only 5% area of the semiconductor layers used to form the top subcell was chemically etched to form a patterned contact window. Then the front electrode upon the InGaAs middle subcell is deposited through the patterned contact window. Thus, the InGaAs/Ge double-junction solar cell having the same size of 0.25 cm^2 as that of the triple-junction cell also combines with the band gap of E_{g1}, E_{g2}, and E_{g3}, as shown in Fig. 1(b). However, the light absorption in the InGaP top subcell does not contribute an effective photocurrent to the present InGaAs/Ge double-junction cell. It is of importance that the light absorption of the InGaP top subcell is necessary so that our InGaAs/Ge double-junction cell can play equivalent behaviors done by the middle and the bottom subcells in the triple-junction cell. Similarly, a proposed Ge single-junction solar cell was fabricated by forming the front electrode atop the bottom subcell together with the back electrode. Fig. 1(c) clearly shows that original semiconductor layers with band gap combination of E_{g1} and E_{g2} remain upon the fabricated Ge single-junction cell. All as-fabricated cells were directly placed upon the temperature control stage (Intec STC200) for current-voltage (I-V) measurements. A thermocouple was used to monitor the actual temperature of the as-fabricated cells, which is confirmed to be very close to that preset. Temperature range employed is 25–80 °C responding to their possible operating temperature. The light from a solar simulator (model: XES-301S + EL-100, SAN-EI Electric Co., Ltd., Japan) with a 300 W Xe lamp (L2480, No. PA0323) was calibrated to 1-sun condition (AM 1.5G: 100 mW/cm^2) with a reference cell (ML-020 VM Si-pyranometer, EKO Instruments Co., Ltd., Japan). The exposing time for the I-V measurement (Keithley 2400 5A Source Meter) was shorter than 10 s (200 data points).

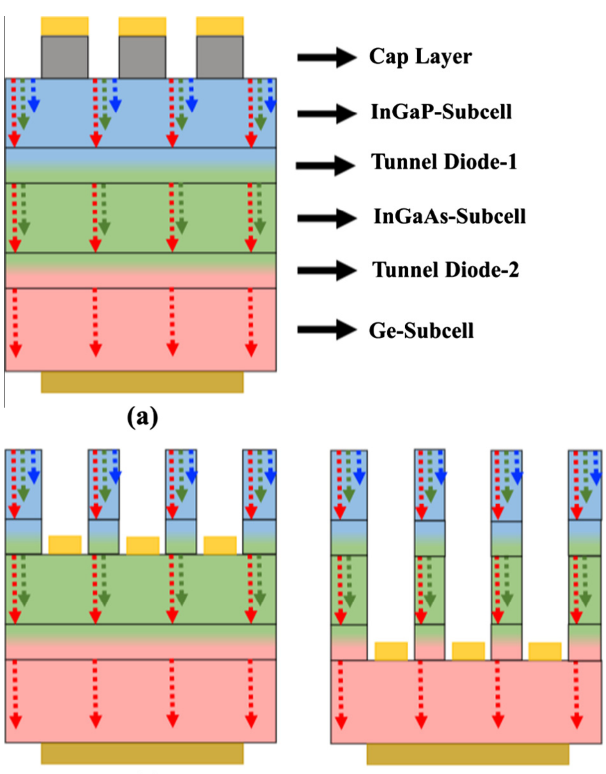

Fig. 1. Epitaxial structure used to fabricate all junction-type solar cells including (a) a triple-, (b) a double-, and (c) a single-junction cells.

3. Results and discussion

Fig. 2 shows the I-V curves of the triple-, double-, and single-junction cells under irradiation of a 100 mW/cm^2 light at various temperatures. It should be pointed out that three types of solar cells have the same band gap combination of E_{g1}, E_{g2}, and E_{g3}. Thus, the Ge bottom subcells in the triple-, double-, and single-junction cells will absorb the same solar spectrum. Similarly, the InGaAs middle subcells will also receive the same solar spectrum as they are in the triple-, double-, and single-junction cells. When the InGaP top subcell, the InGaAs middle subcell, and the Ge bottom subcell are connected in series, the overall short-circuit current

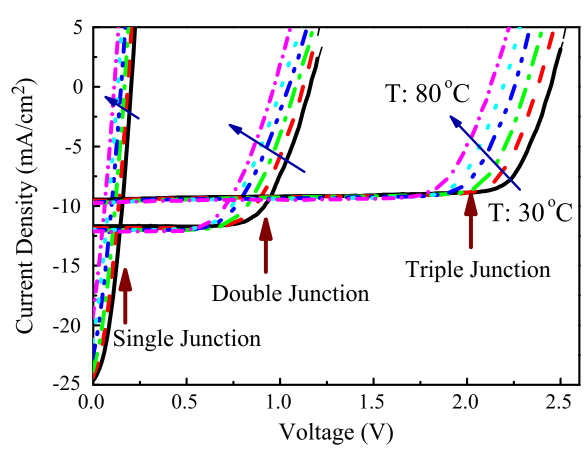

Fig. 2. Current-voltage characteristics of the junction-type solar cells at various temperatures.

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