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Radiative recombination of carriers in the $Ga_xIn_{1-x}P$/GaAs double-junction tandem solar cells

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ABSTRACT

Radiative recombination of carriers in two kinds of $Ga_xIn_{1-x}P$/GaAs double-junction tandem solar cell structures was investigated by using room-temperature electroluminescence (EL) and photoluminescence (PL) techniques. Efficient radiative recombination was observed simultaneously in the top and the bottom subcells in both the samples. By studying the behavior of EL and PL spectra, the radiative recombination intensity Φ_{EL} was demonstrated to be reliant on the material-dependent radiative recombination coefficient, base layer doping concentration and thickness. Furthermore, dependence of Φ_{EL} on substrate misorientation in both the subcells was also evidenced, which was explained in terms of the growth-induced variations in microstructure for the GaInP top cell and in potential barrier profile across the *p*–*n* junction for the GaAs bottom cell. Based on these observations, the radiative recombination in the two base layers of the subcells was demonstrated to be the major carrier loss mechanism in the $Ga_xIn_{1-x}P$/GaAs double-junction tandem photovoltaic devices and should be suppressed.

1. Introduction

III–V compound multijunction (MJ) solar cells possess the potential for attaining solar energy conversion efficiency of over 40% and are promising candidates for the third generation space and terrestrial photovoltaic applications [1]. Among the miscellaneous MJ technologies already developed, monolithic two-junction tandem structure is the simplest configuration and has attracted extensive attention on further optimization of device performance [2–4]. One of the most trusted candidates is the $Ga_xIn_{1-x}P$/GaAs system with a band gap combination of 1.9 and 1.4 eV [2]. By utilizing $Ga_xIn_{1-x}P$ as the top cell material, many problems related to defects and crystal quality encountered in other possible alloy candidates such as $Al_{0.4}Ga_{0.6}As$ can be avoided [1]. As a result, many studies have been focused on characterizing the GaInP and GaAs material properties, especially the recombination dynamics of carriers in the active layers, by the photoluminescence (PL) techniques. For instance, surface recombination velocity of the GaInP base layer could be determined by the functional relation with the intensity of conventional PL [3]; effective lifetime of minority carriers within the GaInP (or GaAs) base layer could be estimated by time-resolved PL [5]. On the other hand, to our best knowledge, very little information have been reported on the characterization of carrier dynamics, in particular the loss of carriers through radiative process, using the electroluminescence (EL) technique. Despite the fact that it has been applied to model the irradiation-induced degradation of the MJ photovoltaic structures in space condition [6,7], it is believed that compared with the PL technique, the EL measurement is also competent in revealing the detailed kinetics associated with the recombination loss of charge carriers.

In this article, we investigate the radiative recombination of carriers by using the room-temperature EL technique, and demonstrate that the radiative recombination intensity is affected by intrinsic material parameters and the fabrication condition of the subcell material. Finally, based on the obtained results, we suggest that the radiative recombination in the base layer of subcells is the major loss mechanism of carriers in the $Ga_xIn_{1-x}P$/GaAs double-junction tandem photovoltaic structures.

2. Experimental details

The two $Ga_xIn_{1-x}P$/GaAs double-junction tandem solar cells investigated in this study were grown by low pressure metal-organic chemical vapor deposition (MOCVD). The only structural

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variation was the substrate misorientation on the Zn-doped GaAs substrate. For the first cell, growth was performed on the substrate oriented 2° off (100) toward [011] (hereafter referred to as "Sample 2°"), and for the second cell the misorientation angle was increased to 7° (hereafter referred to as "Sample 7°"). The GaAs bottom cell comprised a p^+-AlGaAs/p-GaAs back surface field (BSF) layer, a p-GaAs base layer, an n^+-GaAs emitter layer and an n^+-GaInP window layer. The GaInP top cell comprised a p^+-AlGaAs/p^+-AlGaInP/p-GaInP BSF layer, a p-GaInP base layer, an n^+-GaInP emitter layer, an n-AlInP window layer and an n^+-GaAs contact layer. The GaAs bottom cell and GaInP top cell are coupled electrically and optically by the GaAs tunnel junction. An MgF_2/ZnS anti-reflection coating was deposited under the front electrode to enhance the light absorption.

For the room temperature EL measurements, the cell module was glued by scotch tape on a standard optical mount where height adjustment was maneuverable. The EL light emitted from the cell was dispersed by a *SPEX 750M* monochromator and analyzed by a *Hamamatsu R928* photomultiplier tube in conjunction with a standard lock-in amplifier at a chopping frequency of 730 Hz so as to enhance the signal-to-noise ratio. For the room temperature PL measurements, the cell was excited by the 514.5 nm line of a coherent argon–krypton mixed gas laser, and by the 755 nm line of a self-mode-locked Ti: sapphire oscillator pumped by an 8 W array of laser diodes. The PL signal was analyzed by an *SP300i* monochromator and detected by the same system as described in the room temperature EL measurement. For the room temperature dark current–voltage (dark *I–V*) curve measurement, the cell module was thoroughly covered by a rectangular carton with black outer surfaces. External bias was applied on the cell using an *Aim-TTi* DC power supply and the current was recorded by a *Black Star* multimeter.

3. Results and discussion

The radiative recombinations of carriers in the two solar cell samples were investigated by measuring the EL spectra from the samples at room temperature as a function of forward bias, as shown in Fig. 1. The applied forward bias was increased from 2.5 V to 2.75 V at an increment of 0.05 V. The near-band-edge emissions originated from the GaInP top cells (hereafter referred to as "GaInP peak") are located in the red region of the visible spectrum and showed noticeable dependence on forward bias. For Sample 2°, the peak is located at 670.52 nm and shifted to 673.98 nm (1.8493–1.8398 eV) with a total shift of about 9.5 meV. For Sample 7°, the peak is located at 654.99 nm and shifted to 657.64 nm (1.8932–1.8855 eV) with a total shift of approximately 7.7 meV. On the other hand, the near-band-edge emissions stemmed from the GaAs bottom cells (hereafter referred to as "GaAs peak") in both samples are located in the infrared region, i.e., at about 835 nm (1.485 eV) and displayed very little dependence on forward bias. Careful examination on the EL behaviors of the two samples seemed not to support ascribing of the redshift observed in both the GaInP top cells to the temperature-induced band gap shrinkage as a consequence of heating effect [8,9]. Instead, these energy shifts were considered to be related to the reduction of $E_{e1} \rightarrow E_{hh1}$ exciton transition energy which was attributed to the Stark effect induced by the gradually increasing external electrical field applied in the spontaneously formed long-range ordered superlattice in the GaInP top cell material layer. While further study is needed to verify, the applicability of this proposal might seem to be supported by previous theoretical calculation [10,11] and optical experiments [12,13].

Fig. 2 shows the PL spectra measured from the two solar cell samples at room temperature with laser excitation at 514.5 nm and 755 nm. Selective absorption properties of the solar cell samples were pronounced, in which the 514.5 nm line reacted only with the GaInP top cell and was impervious to the GaAs bottom cell, while the 755.0 nm line was transparent to the GaInP top cell and reacted strongly to the GaAs bottom cell. It is known that in the configuration of homojunction shallow n^+–p subcell, the n^+-type emitter layer, the depletion region and the p-type base layer have distinct PL signatures in terms of peak position, linewidth and intensity [14]. Since the n^+-type emitter layer is very narrow and heavily doped, the PL response from the n^+-type layer is too weak to be detected at room temperature. The contribution to the PL response from the depletion region is thought to be negligible [15]. In all PL spectra shown in Fig. 2 only a single emission peak was identified. Therefore, the PL responses

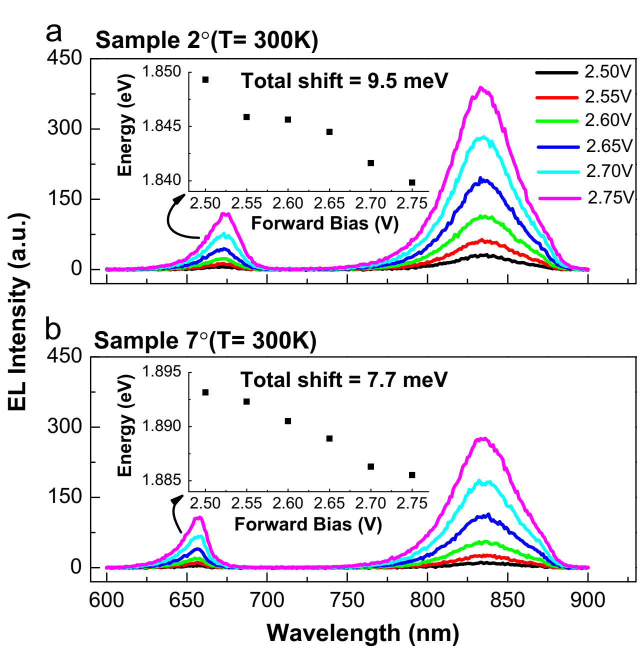

Fig. 1. Room temperature EL spectra recorded from the two solar cell samples at different forward biases. The insets show the dependence of emission energy from the GaInP top cell on the forward bias, with the total amount of energy shift indicated on the top.

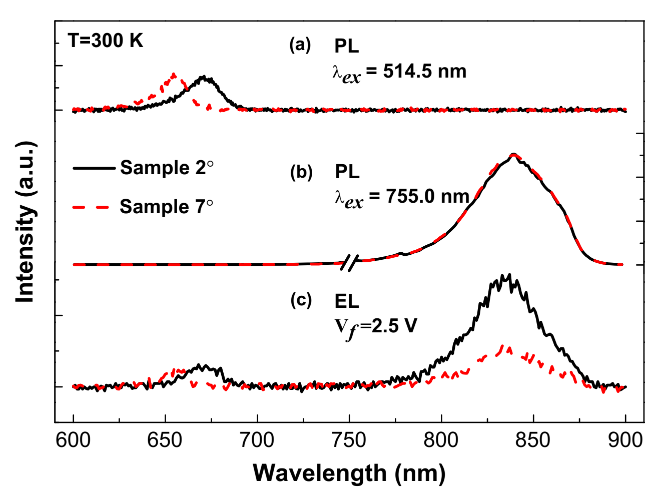

Fig. 2. Room temperature PL spectra recorded from the two solar cell samples with laser excitation at (a) 514.5 nm and (b) 755.0 nm. (In (b), the break of data points in the proximity of 750 nm is due to the effect of the laser line.) (c) Room temperature EL spectra recorded from the two solar cell samples at forward bias of 2.5 V.