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RESEARCH ARTICLE

Influence of temperature and reverse bias on photocurrent spectrum and supra-bandgap spectral response of monolithic GaInP/GaAs double-junction solar cell

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Abstract In this paper, influence of temperature and reverse bias on photocurrent spectrum and spectral response of a monolithic GaInP/GaAs double-junction solar cell was investigated in detail. Two sharp spectral response offsets, corresponding to the bandedge photo absorption of the bottom GaAs and the top GaInP subcells, respectively, show the starting response points of individual subcells. More interestingly, the cell photocurrent was found to enhance significantly with increasing the temperature. In addition, the cell photocurrent also increases obviously as the reverse bias voltage increases. The integrated photocurrent intensity of the top GaInP subcell was particularly addressed. A theoretical model was proposed to simulate the reverse bias dependence of the integrated photocurrent of the GaInP subcell at different temperatures.

Keywords GaInP alloy, GaAs, solar cell, photocurrent

1 Introduction

Solar cells are one kind of optoelectronic devices converting clean solar energy into electric energy. Issues concerning energy conversion efficiency and cost effectiveness of solar cells have spurred endless research efforts over the past three decades. A main strategy for increasing solar cell efficiency is to develop so-called multi-junction (MJ) photovoltaic devices by utilizing several semiconductor materials with different energy bandgaps [1]. Two leading fabrication approaches have been developed for manufacturing MJ solar cells. One is mechanical stacking technique, while the other is monolithic growth method. In MJ solar cells prepared with the former technique, the subcells are mechanically stacked. In contrast to the case of mechanically stacked MJ solar cells, monolithic MJ solar cells are epitaxially grown on one substrate and the subcells are interconnected in series by tunnel junctions. Theoretically, the efficiency of such MJ solar cells could be more than 50% [2]. The present world-record efficiency is 44.7% for a 4-junction tandem cell measured at a concentration of 297 suns [3]. In the already demonstrated MJ solar cells with high efficiency, the $Ga_xIn_{1-x}P$/GaAs lattice-matched double-junction structure is a key element since its conversion efficiency has been demonstrated to be over 30% [4]. Therefore, the $Ga_xIn_{1-x}P$/GaAs lattice-matched double-junction tandem solar cells have been attracting a continuous research interest [4–9].

Depending on the degree of atomic ordering, the $Ga_xIn_{1-x}P$ (hereafter referred to as GaInP) top subcell has a bandgap value varying from 1.8 to 2.0 eV and is responsible for the red portion of the solar spectrum [5], whereas the GaAs bottom subcell with a typical bandgap of 1.4 eV is designed to absorb the longer wavelength near-infrared photons. Such an energy bandgap combination can lead to an efficient photo absorption in the visible and near-infrared spectral ranges of the solar spectrum. As argued earlier, how to increase energy conversion efficiency is a central issue in the study of all types of photovoltaic devices including the GaInP/GaAs double-junction tandem solar cells. To achieve the goal, an in-depth understanding of fundamental photophysical processes in individual subcell, including photoexcitation, transport, and mid-way recombination of charge carriers, is certainly required and highly desirable in addition to the development of measurement methods and analysis of performance of monolithic MJ solar cells [10,11]. Among

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various experimental techniques that have been employed to investigate the fundamental photophysical processes in the solar cells [5,8,9], photocurrent spectroscopy is uniquely appealing because it carries comprehensive information from electronic structures of involved materials to generation and transport of photogenerated carriers in complex optoelectronic device structures including MJ cell structure. In addition, photocurrent spectroscopy can be further examined as a function of other physical variables, such as temperature and bias voltage [12], which allows one to unveil the effects of these variables on the generation, diffusion, mid-way recombination and transport processes of photoexcited charge carriers, etc. Thus, applying photocurrent spectroscopic technique to the study of the GaInP/GaAs double-junction tandem photovoltaic structure is a very attractive topic in terms of the above justifications. Moreover, to the best of our knowledge, very few reports have been devoted to this topic.

In this paper, we present a detailed investigation on the influence of temperature and reverse bias voltage on photocurrent and spectral response mechanism of a monolithic GaInP/GaAs double-junction solar cell. It was found that both temperature and reverse bias voltage have significant influence on the photocurrent and spectral response of both the GaAs and GaInP subcells, especially, on the supra-bandgap response of the top GaInP subcell. A model was proposed to interpret the phenomenon.

2 Experimental

The solar cell sample investigated in this work was a GaInP/GaAs double-junction tandem monolithic structure grown by metalorganic chemical vapor deposition (MOCVD). The structural and growth details of the device have been reported elsewhere previously [8,9]. The top GaInP subcell consists of a 670 nm GaInP base layer with *p*-type doping density of 6×10^{16} cm^{-3} and a 70 nm GaInP emitter layer with *n*-type doping density of $4 \times 10^{17} - 4 \times 10^{18}$ cm^{-3}. The bottom GaAs subcell was grown with a *p*-type base layer with thickness of 2900 nm and an *n*-type emitter layer with thickness of 100 nm, and the doping density of both layers are 1×10^{17} cm^{-3} and $6 \times 10^{17} - 2 \times 10^{18}$ cm^{-3}, respectively. The two subcells are coupled in series by the AlGaAs/GaAs/GaInP double-heterostructure tunnel junction. The whole device structure was grown on a p^+-GaAs substrate, with a misorientation angle of 2° off (100) toward (111)B. For the convenience of discussion, the sample will be denoted as “Sample 2°” hereafter.

For the measurement of the photocurrent spectra, the white light emitted from a *Newport Quartz Tungsten Halogen* lamp (rated power: 250 W) was dispersed by an *Acton SpectraPro 300i* monochromator and employed as the excitation light source. The solar cell sample was mounted onto the cold finger of a *Janis CCS150* closed cycle cryostat system whose temperature can be varied from 8 to 300 K. The sample was connected in series with a *Aim-TTi TSX3510P* DC power supply where bias voltage was controlled in the range of 0 to –4 V, together with a 0.24 MΩ sampling resistor to acquire the photocurrent signal. A *Stanford Research SR830* lock-in amplifier combined with an optical chopper was utilized to increase the signal-to-noise ratio. The spectral characteristic effect of the lamp was removed by taking the ratio between the photocurrent recorded from the solar cell sample and from a calibrated reference Si detector.

3 Results and discussion

Figure 1 shows the photocurrent spectra recorded from Sample 2° at different temperatures without the application of external bias. Several spectral features can be clearly observed. The first is sharp increase in the photocurrent intensity at about 1.430 eV for the cell at room temperature of 300 K, suggesting occurrence of extremely efficient photoexcitation of charge carriers starting from this particular photon energy. Actually, this photon energy just corresponds to the bandgap value of GaAs at 300 K. From the photocurrent spectra in Fig. 1, we can also determine the bandgap value of GaAs at 10 K: E_{GaAs} = 1.516 eV. Temperature dependence of E_{GaAs} evaluated from the photocurrent spectra in Fig. 1 exhibits the bandgap shrinking behavior described by Varshni empirical formula [13]. The second feature observed from Fig. 1 is an obvious photocurrent peak at 1.950 eV at 10 K. As shown in Fig. 2, this peak (solid squares) gradually redshifts with increasing the temperature, which follows the tendency (solid line) predicted by Varshni empirical formula. It was located at 1.862 eV for T = 300 K. Understandably, this peak, denoted by E_{GaInP}, corresponds

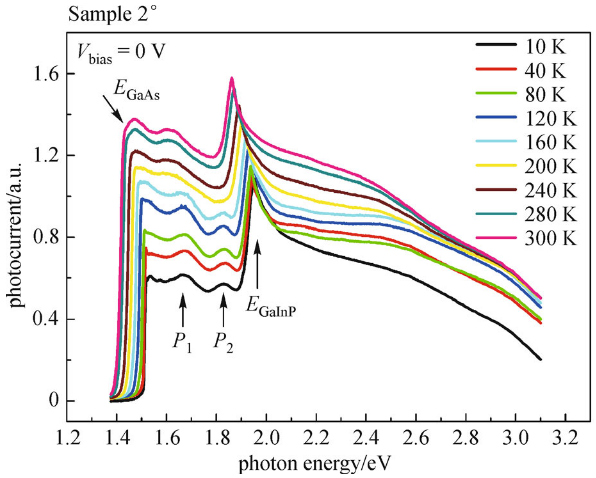

Fig. 1 Photocurrent spectra recorded from Sample 2° at different temperatures without the application of external bias voltage. Several spectral features are indicated by arrows and labels

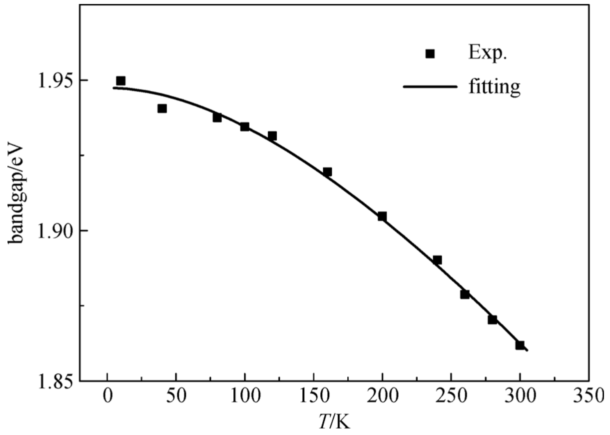

Fig. 2 Temperature dependence (solid squares) of the photocurrent sharp peak due to the bandedge absorption of GaInP in the top subcell. Solid line is the fitting curve with the Varshni empirical formula

to the bandedge absorption of GaInP in the top GaInP subcell [8]. It is interestingly noted that the cell photocurrent signal decays relatively slowly for photon energy $> E_{\mathrm{GaInP}}$, and still preserves even for the photon energy of ~1 eV above E_{GaInP}. This suggests that the cell photoresponse is still quite efficient for the incident photons with energy above the top GaInP subcell bandgap (supra-bandgap). The last spectral features observed from Fig. 1 are the two undulation structures occur between 1.6 and 1.9 eV, as indicated by P_1 and P_2 in Fig. 1. Separate photocurrent measurements have been performed on another GaInP/GaAs double-junction tandem solar cell sample grown with nominally identical conditions but a larger substrate misorientation angle of 7° off (100) toward (111)B. Two undulation structures located at the same energetic position as P_1 and P_2 were also seen in the temperature-dependent photocurrent spectra of this sample (data are not shown in here). These evidences suggest that these in-between structures might be irrelevant to the atomic microstructure variation in the top GaInP subcell due to the difference in substrate misorientation [14]. Instead, they might stem from optical interference in the GaInP and GaAs thin layers [11].

In addition to the above argued spectral features, the most significant phenomenon seen in Fig. 1 is that the cell photocurrent remarkably increases with increasing the temperature. Furthermore, the cell photocurrent also exhibits reverse-bias voltage dependence as shown in Fig. 3 where the photocurrent spectra measured at different temperatures were depicted for several reverse bias voltages. As seen from Fig. 3, at each temperature, the cell photocurrent rises significantly with increasing the reverse bias voltage. Due to different spectral response of separate junctions in a MJ cell [11], the photocurrent of the top GaInP subcell was particularly addressed in the present study. Integrated photocurrent intensity of the GaInP subcell was evaluated at each temperature for the supra-bandgap absorption $\geqslant E_{\mathrm{GaInP}}$, and the results (open symbols) are shown in Fig. 4. The integration range is from the value of E_{GaInP} at that applied bias to the upper measurement limit, i.e., 3.1 eV. Evidently, the integrated photocurrent intensity of the GaInP subcell for the supra-bandgap absorption increases with increasing the reverse bias.

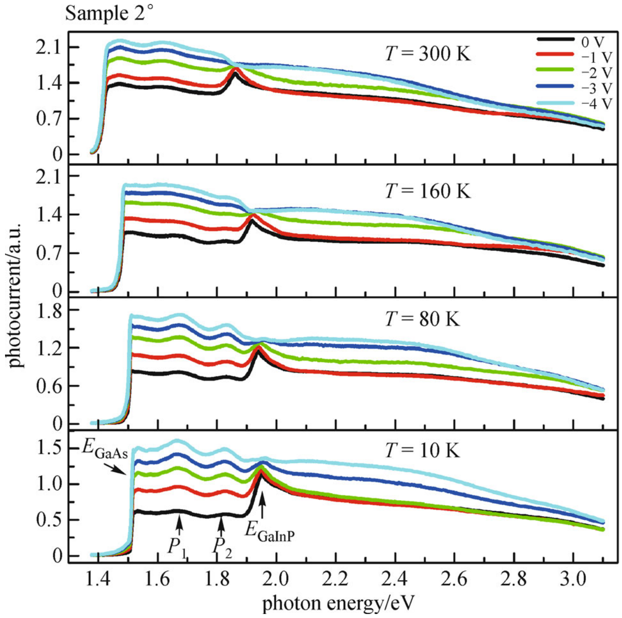

Fig. 3 Photocurrent spectra measured from Sample 2° at 10, 80, 160 and 300 K for different reverse bias voltages. The reverse bias voltage increases from 0 to –4 V. Several spectral features are marked by arrows and labels in the bottom figure

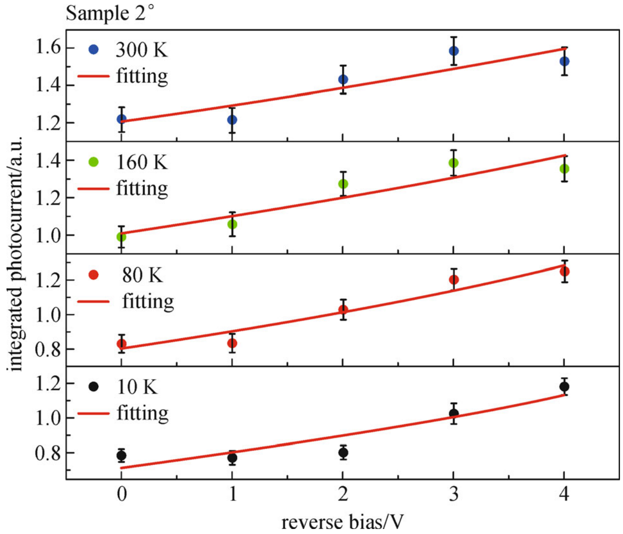

Fig. 4 Dependences of the integrated intensity of photocurrent with energy$\geqslant E_{\mathrm{GaInP}}$ on the reverse bias voltage at different temperatures excerpted from Fig. 3. Theoretical fitting curves with Eq. (9) are also shown by the solid curves at each temperature

For temperature-induced photocurrent enhancement, it was previously observed in other III-V semiconductor device structures, such as the GaInP compressively-strained single quantum well and the InGaAs/AlGaAs multiple quantum well diodes [12,15]. There are several possible physical origins for temperature-induced photocurrent enhancement. The first could be the exponential increase of dissociation rate of excitons formed after the photoexcitation with temperature [16]. The second could be the significant increase of tunneling rate of dissociated carriers with temperature through the tunnel junction connecting the top GaInP subcell and the bottom GaAs subcell [17]. The third could be temperature dependence of the diffusion coefficient of carriers, $D = \mu \cdot (k_{\mathrm{B}}T)/q$, where μ is the carrier mobility, k_{B} is the Boltzmann constant and q is the electron charge. It is obvious that increasing temperature could facilitate the diffusion process of carriers, especially those being photoexcited within one diffusion length from the depletion region where carriers could readily drift through the region with the assistance of the strong built-in electric field [17].

4 Theoretical consideration and simulation

To make a more detailed explication on the reverse bias voltage dependence of the photocurrent of the GaInP subcell at different temperatures, we propose a theoretical model on the basis of impacts of external electric field on generation and transport mechanism of photoexcited carriers in a *p-n* junction. When a *p-n* junction is under the illumination of light, the total current, I_{t}, will be described by [17]

$$I_{\mathrm{t}} = -I_{\mathrm{r}}\left(\mathrm{e}^{\frac{qV}{k_{\mathrm{B}}T}} - 1\right) + I_{\mathrm{ph}}, \tag{1}$$

where I_{r} is the reverse saturation current, q the electronic charge, V the applied bias, $k_{\mathrm{B}}T$ the Boltzmann's thermal energy, and I_{ph} the photocurrent due to drafting of photo absorption induced charge carriers. The first term on the right hand side of Eq. (1) is essentially the diode current under dark conditions. The photocurrent, I_{ph}, is proportional to the concentration of minority carrier photoexcited in the base, emitter and depletion region, which can be formulated as

$$I_{\mathrm{ph}} \propto [(N_p)_n + (N_n)_p + (N_{p,n})_w], \tag{2}$$

where $(N_p)_n$, $(N_n)_p$, and $(N_{p,n})_w$ denote the concentration of minority hole in the *n*-type emitter, minority electron in the *p*-type base, and both carriers in the depletion region w respectively. When the subcell is reversely biased, the diode current is mainly contributed by the reverse saturation current which is usually very small. Moreover, in the *p*-type (or *n*-type) region of the light-illuminated *p-n* junction, available theoretical estimation shows that the change of majority carrier concentration is usually subtle, while that of the minority carrier can increase by a factor of ~10^7 [17]. Considering that efficient photoexcitation of carriers mainly occurs in the thickest GaInP base layer in the subcell, we can approximate that the photocurrent of GaInP subcell originates from change of minority electrons in the *p*-type base layer due to the photo absorption. Therefore, the subcell photocurrent is described by

$$I_{\mathrm{ph}} \propto (N_n)_p. \tag{3}$$

The minority electron concentration in the *p*-type GaInP base layer can be calculated by using

$$\begin{aligned}(N_n)_p &= \int f(E)\cdot g(E)\mathrm{d}E \\ &= \int \left(\frac{1}{1+\mathrm{e}^{\frac{(E-E_{\mathrm{Fn}})}{k_{\mathrm{B}}T}}}\right)\cdot g(E)\mathrm{d}E,\end{aligned} \tag{4}$$

where E is the electron energy, E_{Fn} is the electron quasi-Fermi level, and $g(E)$ is the density of states. For the minority electrons energy $E \gg E_{\mathrm{GaInP}}$, it is reasonable to make an assumption of $E \gg E_{\mathrm{Fn}} + k_{\mathrm{B}}T$. Therefore, $\mathrm{e}^{\frac{(E-E_{\mathrm{Fn}})}{k_{\mathrm{B}}T}} \gg 1$ could be valid. Equation (4) can thus be approximated as

$$(N_n)_p \approx \int \mathrm{e}^{\frac{-(E-E_{\mathrm{Fn}})}{k_{\mathrm{B}}T}}\cdot g(E)\mathrm{d}E. \tag{5}$$

Under the influence of an electric field which can be significantly enhanced by the applied reverse bias, the total energy of electrons would be increased by an amount which is directly proportional to its energy gain from the electric field. Mathematically, this can be written as

$$(E-E_{\mathrm{Fn}}) \propto \Delta E_{\mathrm{p}} = -q|V_{\mathrm{r}}|, \tag{6}$$

where E_{p} is the electron potential energy and V_{r} is the applied reverse bias. By substituting Eq. (6) into Eq. (5), we have

$$(N_n)_p \approx \int \mathrm{e}^{\frac{Cq|V_{\mathrm{r}}|}{k_{\mathrm{B}}T}}\cdot g(E)\mathrm{d}E. \tag{7}$$

Here factor C in the exponential term is the proportionality coefficient arisen from Eq. (6). Total contribution of the photoexcited electrons with energy $> E_{\mathrm{GaInP}}$ to the subcell photocurrent can now be estimated. By substituting Eq. (7) into Eq. (3), and then integrating from E_{GaInP} to the upper limit of measurement, i.e., 3.1 eV, we obtained expression of the subcell photocurrent:

$$I_{\mathrm{ph}} \propto (N_n)_p \approx \int_{E_{\mathrm{GaInP}}}^{3.1\ \mathrm{eV}} \mathrm{e}^{\frac{Cq|V_{\mathrm{r}}|}{k_{\mathrm{B}}T}}\cdot g(E)\mathrm{d}E. \tag{8}$$

Assume that the total number of supra-bandgap electronic states, $\int_{E_{\mathrm{GaInP}}}^{3.1\ \mathrm{eV}} g(E)\mathrm{d}E$, can be represented by a coefficient

G at each temperature. Furthermore, collection efficiency of the supra-bandgap electrons by the electrodes is denoted as P_c. The effects of these two coefficients on the total supra-bandgap photocurrent are grouped together by $P_t = G \cdot P_c$. Finally, the GaInP subcell photocurrent for the supra-bandgap electrons can be formulated as

$$I_{ph} \propto P_t \cdot e^{\frac{Cq|V_r|}{k_B T}}. \tag{9}$$

Theoretical fitting results with Eq. (9) are depicted in Fig. 4 by the solid curves. Good agreement between theory and experiment is obtained. At each temperature, the integrated supra-bandgap photocurrent intensity increases superlinearly with increasing reverse bias.

5 Conclusions

In conclusion, we carried out an in-depth investigation on photocurrent spectra of a GaInP/GaAs double-junction tandem solar cell at different temperatures and under different reverse-bias voltages. Under the constant illumination of monochromatic light, the cell photocurrent was found to significantly increase with increasing both the temperature and reverse bias. The integrated photocurrent of top GaInP subcell was particularly addressed in this present study. A theoretical model mainly taking into account contribution of photoexcited minority carriers (electrons) in the *p*-type GaInP base layer was proposed to interpret dependence of photocurrent of the top GaInP subcell on temperature and reverse bias. Good agreement between theory and experiment is achieved, which may lead to a deeper insight into complicated photoresponse mechanism in GaInP/GaAs double-junction tandem solar cell.

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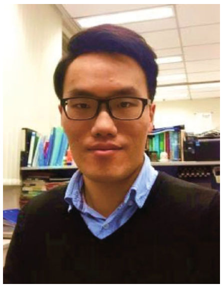

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Zheng Xing obtained his Master's degree in State Key Laboratory of High Power Semiconductor Laser from Changchun University of Science and Technology in 2008. Then he joined the Nano Fabrication Facility, Suzhou Institute of Nano-Tech and Nano-Bionics, Chinese Academy of Sciences. His main research interest and approach are related to the applications of thin film materials in semiconductor devices and nano-structures.