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Carriers transport properties in GaInP solar cells grown by molecular beam epitaxy

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ABSTRACT

The transport properties of carriers in GaInP solar cells grown by molecular beam epitaxy are investigated by temperature-dependent current–voltage (*I*–*V*) measurements. In contrast to GaInP/AlGaInP heterostructure, a long PL decay time is observed in GaInP/AlInP, which is ascribed to a lower interface recombination due to an improved carriers' confinement in the case of the high-energy barrier. However, the series resistance induced by the high potential barrier at GaInP/AlInP interface due to a big valence band offset prevents the improvement of solar cell's performance. An *S*-shape like *I*–*V* characteristic observed at low temperatures indicates that the transport of major carriers is limited by the barrier. A calculation based on the combination of a normal photovoltaic device with a barrier-affected thermal carriers transport explicitly explains this abnormal *I*–*V* characteristic. Our study demonstrates the critical role of the barrier-induced series resistance in the determination of solar cell's performance.

1. Introduction

The efficiencies of III–V compound semiconductor multi-junction solar cells (SCs) continue to rise with optimization of the device design and improvements in material quality [1–3]. The transport of majority carriers through potential barriers together with the recombination of minority carriers at the interfaces plays an important role in the determination of the SC's performance. An efficient back surface field (BSF) layer can confine the photo-generated minority carriers and at the same time, ensure the transportation of majority carriers to be efficiently collected [4–7]. Numerical simulations about the transport characteristics of majority carriers have been done [8,9], however, the experimental study of combination of the transportation of majority carriers and the recombination of minority carriers in the function of BSF is scarce. Especially, for low-temperature space application and for high-intensity concentrating photovoltaic application, the effect of the resistance resulting from the high potential barrier on the SC's performance will become more serious. Furthermore, the physical property of a heterostructure was greatly affected by different growth methods [10]. Metal-organic chemical vapor deposition (MOCVD) technique is generally used for the epitaxial growth for the SCs. As one of the most important epitaxial techniques, the research of SCs grown by molecular-beam-epitaxy (MBE) has not been extensively investigated. And the performance of the earlier GaAs SCs grown by MBE is worse than those obtained by MOCVD growth due to the low growth temperature and the presence of isolated defects [11,12]. However, a highly efficient MBE-grown GaInP/GaAs/GaInAsN triple-junction cell was recently reported by Solar Junction [13]. The experimental results of our group also demonstrated that MBE-grown phosphorus-containing III–V compound semiconductor solar cells are comparable to the case of MOCVD growth [14,15]. A comparative study of MBE-grown photovoltaic device is necessary to improve SC's efficiency as well as optimize the device's performance [16,17].

In this paper, we studied the effect of carriers' transport property with different BSF layers on the performance of the GaInP SC by using time-resolved photoluminescence (TRPL) and temperature-dependent current–voltage (*I*–*V*) measurements. It is found that a high-energy AlInP barrier could confine the photo-generated minority carriers effectively. However, in contrast to AlGaInP BSF, the high-energy barrier also results in a large series resistance in GaInP SC. An *S*-shape like *I*–*V* characteristic which is observed at low temperatures indicates that the limitation is induced by the barrier to the majority

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carriers' transport. A comparative study demonstrates the critical role of the barrier-induced series resistance in the SC's performance.

2. Experimental details

The growth was performed by Veeco GEN20A dual-chamber all solid-state MBE machine equipped with a valved phosphorous cracker cell and a valved arsenic cracker cell. The structures of GaInP SCs grown on p-type GaAs substrate are composed of a p-GaInP base layer, an n^+-GaInP emitter layer and an AlInP as the window layer to decrease the surface recombination. The investigated two SCs have the same doping densities of GaInP base layer of $5\times10^{16}\ \mathrm{cm}^{-3}$ and BSF layer of $2\times10^{18}\ \mathrm{cm}^{-3}$, respectively. The only variation of the structures lies in the BSF layer material. For the first cell (hereafter referred as A), the BSF layer was p^+-AlGaInP with the band gap energy of 2.08 eV and the second cell (hereafter referred as B) was p^+-AlInP layer. Fig. 1 presents the calculated energy band diagram at the BSF interface. The inset (left) shows the energy band diagram of the whole p–n junction. The inset in the right shows the PL spectrum of AlGaInP at room temperature (RT). The ΔE_c and ΔE_v between InGaP and AlInP used in the calculation are 0.25 eV and 0.13 eV, while in AlInGaP and InGaP are 0.134 eV and 0.066 eV, respectively [18,19]. The large conduction and valence band offsets are obviously observed in the case of AlInP/GaInP interface. The photovoltaic devices were processed following the standard III–V SC device art. The detailed growth and device fabrication art were all listed in our recent report [14]. In order to study the optical properties at the interface of GaInP base layer and BSF, two similar heterostructures of p-AlGaInP/p-GaInP/p-AlGaInP and p-AlInP/p-GaInP/p-AlInP which have the same doping density of respective layer as the corresponding layer within GaInP SCs were grown. The transient PL evolution was measured by using a synchroscan streak camera with a time resolution of 15 ps. The *I–V* characteristics were recorded using a voltage source and a current meter type (Keithley 2440) in a two-terminal configuration under the standard air mass 1.5 global (AM1.5G) illumination.

3. Results and discussion

Fig. 2 shows the PL decay curves of the two heterostructures. In the case of AlInP barrier, the PL decay time of 500 ps is obtained while the decay time of only 120 ps is observed for the case of AlGaInP barrier. Since the open voltage (V_{oc}) of a photovoltaic device is mainly determined by the recombination loss, therefore, a long PL decay time indicates that the AlInP barrier is more promising as the BSF for SCs as soon as only the recombination of minority carriers are concerned. Fig. 3 shows the current density–voltage (*J–V*) characteristics of two GaInP SCs (A and B) under AM1.5G at 1 sun. For sample A, an efficiency of 13.8% with the V_{oc} of 1.27 V, a short-circuit current (J_{sc}) of 12.9 mA/cm^2 and an fill factor (FF) of 84% is obtained. While for sample B, an efficiency of 13.5% with the V_{oc} of 1.29 V, a J_{sc} of 12.6 mA/cm^2, and an FF of 83% is obtained. As is expected, the open voltage of sample B with AlInP barrier is larger than that of sample A. V_{oc} is greatly affected by the recombination of minority carriers in the solar cell, the larger V_{oc} in sample B is attributed to the reduced surface-recombination. Considering the different band gap energies of AlGaInP and AlInP, a larger conduction band offset with respect to the GaInP base layer provides a potential barrier for minority electrons and increases the electrons confinement. The four times longer PL decay time due to reduced surface- recombination results in about 20 mV increase in open voltage.[20]

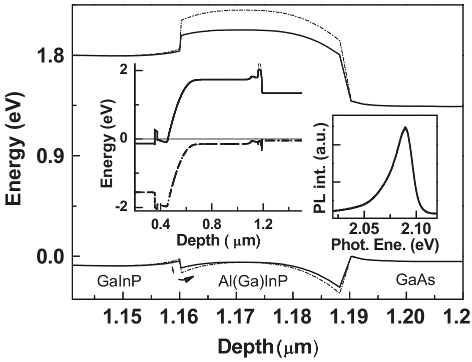

Fig. 1. Calculated energy band diagram at the BSF interface. The inset (left) shows the energy band diagram of the whole p–n junction, the right inset shows the PL spectrum of AlGaInP at room temperature.

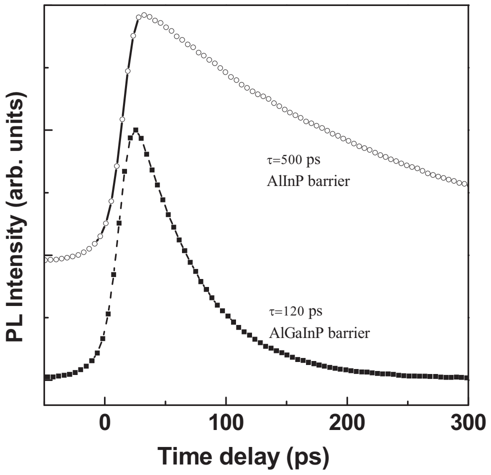

Fig. 2. PL decay curves of the two heterostructures.

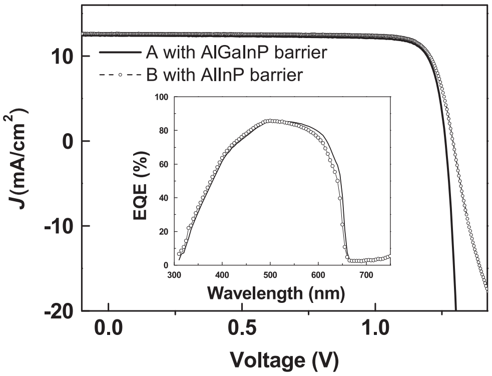

Fig. 3. The *J–V* characteristics of two GaInP SCs (A and B) under AM1.5G at 1 sun, inset shows the EQE of the two SCs.

However, because the operation of the photovoltaic device includes the process of photon absorption, carriers transport and collection, a high performance of a photovoltaic device relies on many parameters. As can be seen from Fig. 3, with increasing applied voltage, the series resistance (R_s) becomes larger for sample B. The calculated total R_s of sample A is 15.8 Ω, much smaller than sample B of 29.1 Ω. Because of the same device fabrication method, the difference can be regarded as from the intrinsic structures of the different devices. The long minority carriers related PL decay time in the case of the AlInP barrier results in large R_s, which prevents the improvement of J_{sc} and *FF* and therefore the conversion efficiency. The inset in Fig. 3 shows the external quantum efficiency (EQE) comparison between the