Non-Radiative Carrier Recombination in the Strain-Balanced InGaAs/GaAsP Multiple Quantum Wells for Solar Cell Application

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1. Introduction

The quantum structure has a potential to extend the absorption region towards the infrared and enhance the collection of photo-generated carriers. Therefore, the inserting a quantum structure could be a promising candidate to solve the current matching issue in a multi-junction solar cells [1, 2]. We have attempted to insert multiple quantum wells (MQWs) into the intrinsic region of a GaAs solar cells and reported an enhancement of short-circuit current (Isc) [3]. However, MQWs also act as recombination centers leading to degradation in both open-circuit voltage (Voc) and fill factor (FF). That is, there is a trade-off between Isc and Voc in an optimization of MQWs solar cells.

In this study, we investigate escape and recombination mechanisms of photo-generated carriers in the strain-balanced InGaAs/GaAsP MQWs inserted into GaAs p-i-n solar cell structure to improve the photovoltaic performance. We then evaluated escape, radiative and non-radiative recombination processes of photo-generated carriers by using the surface photovoltage (SPV), photoluminescence (PL), and piezoelectric photothermal (PPT) spectroscopies, respectively. We have obtained the excitonic and two-dimensional step-like subband absorptions up to 3rd order in the GaAs/AlAs MQWs grown on the semi-insulating (SI) GaAs substrate by SPV and PPT [4].

2. Experimental Procedures

A strain-balanced InGaAs/GaAsP MQWs absorbing layer that inserted in to GaAs p-i-n junction was composed of 10 stacks of 7.4-nm-thick InGaAs well and 10.8-nm-thick GaAsP barrier. All the layers were grown by metal-organic vapor phase epitaxy (MOVPE) on the GaAs substrate. By monitoring the see-saw-like oscillation of wafer curvature, a strain balancing in a period of well/barrier was successfully achieved [5].

For the PL measurements, An Ar⁺ laser of 488 nm was used as the excitation light source and a PL signal was detected by a Si photodiode. For the PPT measurements, a disk-shaped PZT was directly attached to the GaAs substrate surface. The probing light was illuminated from the MQWs layer side of the sample. A heat and elastic waves generated by the non-radiative recombination of photo-generated carriers were detected as the PPT signal. Details of PPT method have been reported elsewhere [6]. For SPV measurements, an indium tin oxide (ITO) films as a transparent front electrode was placed on the sample with 0.5-mm-thick vacuum layer. A voltage between ITO and back electrode generated by photoinduced changes in surface potential was detected as the SPV signal.

3. Results and Discussion

Figure 1 shows the PL and PPT spectra at room temperature. The distinctive peaks at 1.24 eV were observed at the same photon energies below the bandgap of GaAs substrate (1.42 eV). At first, we calculated the energy shifts by the strain due to the difference of the lattice constants [7]. In this case, a bandgap energy of InGaAs shows a blue shift by a compressive strain, whereas that of GaAsP represents a red shift by an extensional strain. After that, by considering the difference in effective mass between well and barrier, the energies of subbands were calculated. A and B-peaks were then concluded to the excitonic transition associated with the subband transition between first electron (e1) and heavy-hole (hh1) subbands in MQWs. In addition, the second order subband transition was also observed in the PPT spectrum. On the contrary, the PL spectrum showed a band to band radiative transition of GaAs.

![Fig. 1 PL and PPT spectra of sample at room temperature](image-url)
substrate in the higher photon energy region.

When the temperature decreased, PL signal intensity of A-peak increased. This experimental result reflects the fact that a ratio of carrier escape from the QW increases at higher temperature. Based on the van Roosbroeck-Shockley treatment, radiative recombination efficiency can be defined as $\eta = 1/(1 + \tau_r/\tau_a)$, where $\tau_r$ and $\tau_a$ are the lifetime of radiative recombination and thermal escape, respectively. The temperature dependence of PL signal intensity can be fitted with the equation [8],

$$I_{PL}^{T}(T) = \frac{I_{PL}^{0}}{1 + A \cdot T^{-1/3} \exp(-\Delta E_{PL}/kT)}$$  \hspace{1cm} (1)

where $I_{PL}^{0}$ is the PL signal intensity at 0 K. This equation can be fitted to the experimental data reasonably and the value of $\Delta E_{PL}$ were estimated to be 186 meV. This value coincided well with a calculated value of 210 meV, a difference between $\tau_1$ and a top of potential barrier.

Figure 2 shows the temperature dependence of PPT spectrum. As in the case for PL, signal intensity of B-peak also increased with decreasing the temperature. It is noted that the probing light intensities of PPT measurement were three orders of magnitude smaller than the excitation light intensity of PL. It was ascertained that a PL signal was not observed with such low excitation condition. Therefore, we can consider only two processes of carrier escape and non-radiative carrier recombination. As a result, the temperature dependence of PPT signal intensity can be fitted with above eq. (1), where $I_{PL}^{0}$ and $\Delta E_{PL}$ were replaced with $I_{PPT}^{0}$ and $\Delta E_{PPT}$, respectively. The fitting result was shown in Fig. 3 and $\Delta E_{PPT}$ was estimated to be 62 meV. This value was considerably smaller than $\Delta E_{PL}$ (= 186 meV) and the calculated potential barrier height of 210 meV.

The SPV spectrum at room temperature also showed the distinctive C-peak at the same photon energy of A- and B-peaks. In contrast to A- and B-peaks, the SPV signal intensity of C-peak decreased with decreasing the temperature. This is understood in terms of that the SPV detects the sample surface accumulation of thermally escaped carriers from QW. As shown in Fig. 3, the intensity of C-peak decreased exponentially, its activation energy $\Delta E_{SPV}$ was then estimated to be 3 meV by using an Arrhenius equation. The reason of this extremely low value is not clear yet.

3. Conclusions

In the present study, escape from QW, radiative and non-radiative recombination processes of photo-generated carriers in the strain-balanced InGaAs/GaAs QMWs inserted into GaAs p-i-n solar cell structure by using SPV, PL, and PPT spectroscopies, respectively. $\Delta E_{PPT}$ and $\Delta E_{SPV}$ showed very smaller values than the calculated barrier height. The reexamination of carrier escape and recombination processes within QWs considering the internal electric field of p-i-n junction is necessary.

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References