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Effect of Insertion of the Strain Relaxation Layer on the Carrier Transport Properties of InGaAs/GaAsP Superlattice Solar Cells Investigated by the Photo-Thermal Spectroscopy

光熱変換分光法による超格子太陽電池のキャリア輸送特性へ歪緩和層が与える影響評価

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1. Introduction

Inserting the superlattice (SL) structure with a GaAs strain relaxation layer between InGaAs well and GaAsP barrier layers into a GaAs-based solar cell has been proposed for the design of highly efficient quantum well (QW) solar cells.[1)] This structure enables a stacking of SL structure over 100 periods for sufficient absorption of sun light.[2)] At the same time, the miniband is formed at the second electron level in the conduction band (e2). The carriers are easily able to transport through this miniband. We had carried out the temperature-dependent photoluminescence (PL) measurements and analyzed the luminescence properties based on the rate equation considering all carrier relaxation processes. As a result, we concluded the carrier relaxation process, where the photo-excited electron to the first electron level in the conduction band (e1) pass through e2-miniband by tunneling after thermal excitation, is dominant around 300 K.[3)] However, it is difficult to analyze the PL properties above 300 K of the solar cells operation temperature. This is because the radiative recombination provability is very low at high temperatures. In this study, we carried out the temperature-dependent piezoelectric photo-thermal (PPT) measurements up to 340 K, and discussed the carrier transport properties of the SL solar cells with GaAs strain relaxation layer.

2. Experimental Procedure

Figure 1 shows a schematic of the samples. We prepared two types of solar-cell structure sample with 20 periods of SL embedded in the *i*-region of *p-i-n* GaAs. One is the b2.0-sample without strain relaxation layer, where the thickness of $In_{0.21}Ga_{0.79}As$ well and $GaAs_{0.58}P_{0.42}$ barrier layers were 5.1 and 2.0 nm, respectively. The other is the interlayer-sample with GaAs strain relaxation layer, where the thickness of well, barrier and GaAs strain relaxation layers were 3.8, 2.1, and 3.1 nm, respectively.

For the PPT measurements, a halogen lamp was used as an excitation light source. A heat generated by the non-radiative recombination of photo-excited carriers were detected by PZT transducer directly attached to the rear surface of sample. The PPT measurements were conducted at temperatures ranging from 100 to 340K.

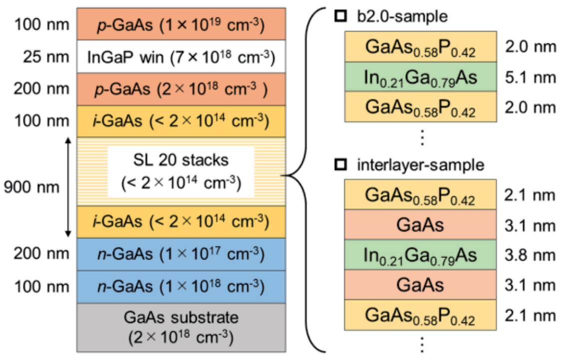

Fig. 1 Schematic structure of the sample

3. Results and discussion

For both samples, a distinct peak just below the bandgap of GaAs was observed in the PPT spectra at all temperatures measured. From the comparison with the theoretical calculation, this peak was identified as the PPT signal caused by the non-radiative recombination of photo-excited electrons from the first heavy hole level in the valence band to e1. **Figure 2** shows the temperature changes of the peak intensity. For b2.0-sample, the PPT peak signal intensity increased with increasing the temperature up to 280 K followed by the decrease above 280 K. On the other hand, for interlayer-sample, the PPT peak intensity simply decreased with increasing temperature.

We analyzed temperature dependences of the PPT peak signal intensity by using a rate equation for photo-excited electron in e1 assuming that three or four relaxation processes. For b2.0-samples,

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three relaxation processes, i.e., (i) radiative and (ii) non-radiative carrier recombination, and (iii) thermal escape from e1 to the barrier were assumed. On the other hand, an additional process, (iv) tunneling through e2-miniband after thermal excitation from e1 to e2, was also assumed for the interlayer-sample. From the fitting analyses, the thermal excitation energy to the barrier layer in the b2.0-sample and to the e2-miniband in the interlayer-samples were estimated to be 263 and 153 meV, respectively. They were consistent with the expected vale from the theoretical calculation. It was, then, confirmed that the thermal escaping energy for electrons in e1 decreased by the insertion of the relaxation layer.

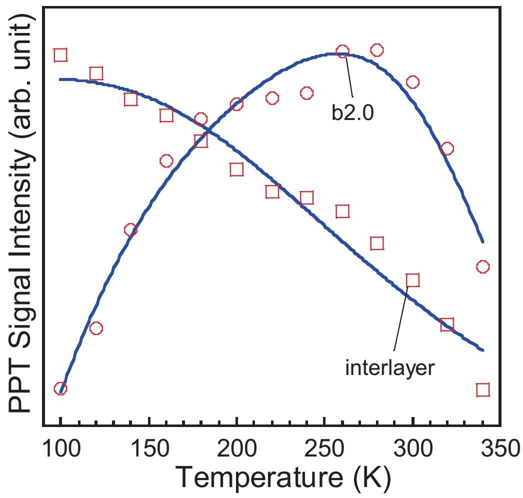

Fig. 2 Temperature dependence of PPT signal intensity

Next, to explain the temperature change of PPT peak signal intensity, we calculated lifetimes (τ) of each processes by substituting the best fit parameters. **Figures 3 and 4** show τ as a function of temperature for both samples. The $\tau_{(ii)}$ was the shortest for both samples. But, as shown in Fig. 3, the $\tau_{(iii)}$ approaches the $\tau_{(ii)}$ for the b2.0-sample. In other words, the effect of (ii) process is suppressed at 300 K or higher. Therefore, it is considered that

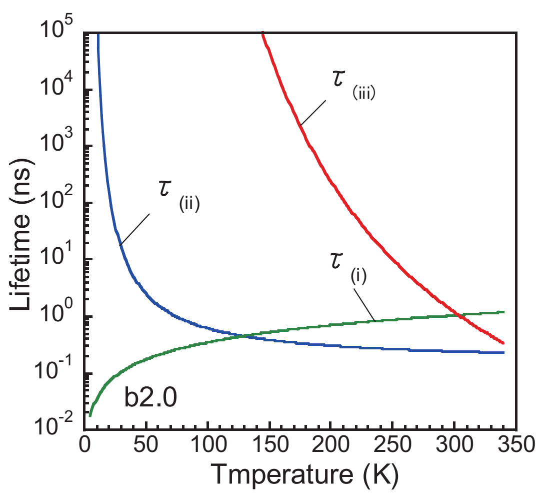

Fig. 3 Lifetime calculation result at the b2.0-sample

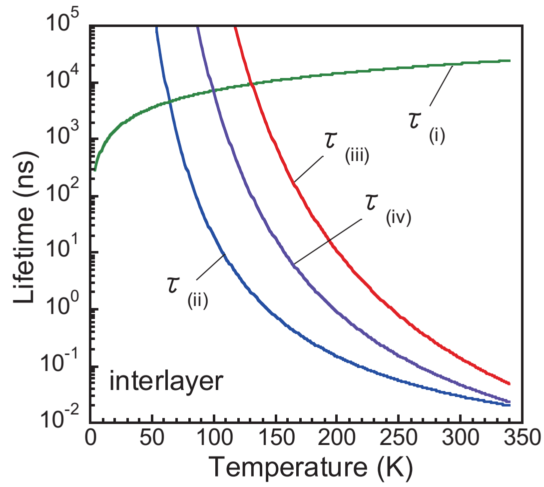

Fig. 4 Lifetime calculation result at the interlayer-sample

the PPT peak signal intensity in this temperature region decreased. The result also confirmed that in the interlayer-sample, the $\tau_{(iv)}$ became very close to the $\tau_{(ii)}$ compared to the $\tau_{(i)}$. The contribution of (iv) process was increased as temperature increased. In (iv) process, electrons are transported in the *i*-region by tunneling. Therefore, it was considered that the recombination loss was suppressed and the PPT peak signal intensity decreased.

4. Conclusion

By analyzing the temperature dependences of the PPT peak signal intensity, we confirmed that the thermal escaping energy for electrons from e1 decreased in the interlayer-sample. In addition, from the calculation of the lifetime of each processes, we concluded that the decrease in the PPT peak signal intensity in the interlayer-sample was due to that the recombination loss was suppressed by the (iv) process. Then, it can be expected that by inserting the strain relaxation layer, electrons were sufficiently transported by tunneling through the e2-miniband in the SL structure and recombination loss could be suppressed.

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