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Non-Radiative Carrier Recombination and Carrier Transport Properties in the Multiple Quantum Well Solar Cell

量子井戸太陽電池におけるキャリアの非発光再結合損失および輸送特性

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1. Introduction

Recently, the solar cells have attracted much attention as one of the clean energy sources and their market increases year by year. Especially, the triple-junction solar cells composed of InGaP/InGaAs/Ge is expected because of its high conversion efficiency more than 40% under the concentration of about 300 suns. However triple-junction solar cell has the current mismatching issue caused by the difference of the bandgaps. Therefore, inserting multiple quantum wells (MQWs) into the absorption layer of the triple-junction solar cell has been proposed. This is because MQWs can extend the absorption to longer wavelength region and then enhance the short-circuit current. However, they act as recombination centers leading to the degradation of conversion efficiency. In order to improve the photovoltaic performance, structural parameters of MQWs such as well and barrier widths, barrier height, should be optimized under proper understanding of a carrier transport mechanism.

In this study, we investigated the non-radiative carrier recombination and carrier transport processes of photo-generated carriers of strain-balanced InGaAs/GaAsP MQWs embedded into GaAs *p-i-n* solar cells by using piezoelectric photo-thermal (PPT) measurements[1)]. This is because the PPT detects the non-radiative recombination signal and can control the detection depth from the surface/interface by changing the chopping frequency (f). Then we can discuss where the photo-generated carriers recombine non-radiatively and how they transport through an absorbing *i*-layer from the experimental results of the f-dependent PPT spectra.

2. Experimental procedures

The *p-i-n* GaAs solar cell structure sample with strain-balanced InGaAs/GaAsP MQW absorbing *i*-layer was prepared. Present MQW consisted of 10 stacks of 7.0-nm-thick $In_{0.25}GaAs_{0.75}$ well and 10.8-nm-thick $GaAs_{0.66}P_{0.34}$ barrier. All the layers were grown by metal-organic vapor phase epitaxy (MOVPE) on the 250-μm-thick GaAs substrate[2)]. For the PPT measurements, a disk-shaped PZT was directly attached to the *n*-type GaAs substrate surface. The probing light was irradiated from the *p*-type GaAs top layer side of the sample. The chopping frequency f was changed from 40 to 4000 Hz. All the measurements were carried out at room temperature.

3. Results and Discussion

Fig. 1 shows the f-dependent PPT spectra of the present sample. Two distinctive peaks were observed in the lower photon energy region below the band gap of GaAs (E_g, 1.42 eV at RT). As discussed in our previous paper[3)], they are considered to be signals caused by the intersubband transitions within the MQWs. In other words, both carrier generation and non-radiative recombination occurred in MQWs region. For higher photon energy region above E_g, PPT signal intensity showed an almost constant value up to 2.7 eV. In this region, carrier generations occur in the top *p*-type GaAs layer. Since generated carriers will transport to the *n*-type GaAs substrate through MQWs region, non-radiative recombinations occur both MQWs and GaAs regions.

In the photothermal methodology, we can control the thermal diffusion length (μ) by changing f of the probing light[1)]. The μ is defined as $\mu = (\kappa/\rho C\pi f)^{0.5}$, where κ is the thermal conductivity, ρ is the density, C is the specific heat. Therefore, μ decreases exponentially with increasing f. In Fig. 1, the PPT signal intensity decreases with increasing f in the entire photon energy region. This is because μ becomes short and results in the decrease of PPT signal intensity. It is noted that the signal decrease

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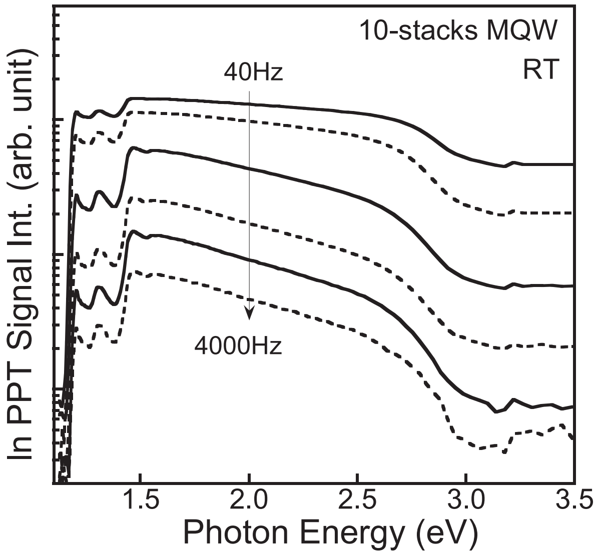

Fig. 1 The chopping frequency dependence of the PPT spectra at room temperature

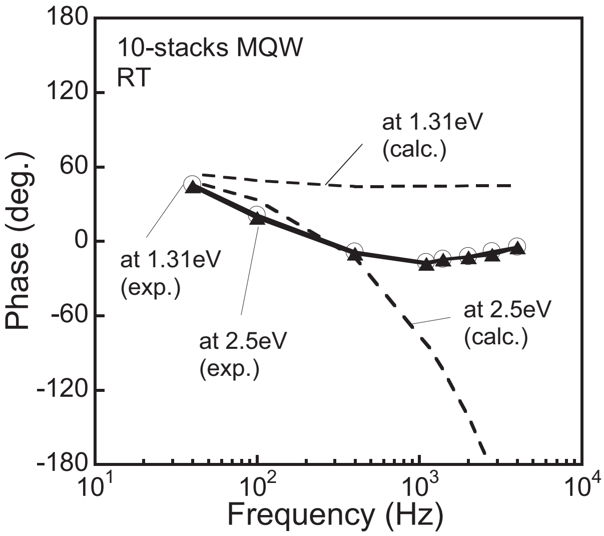

Fig. 2 The theoretical and experimental phase as a function of the chopping frequency

was remarkable in the higher photon energy. This arises from that carrier generation region moves away from the detector located at back surface of the sample by reducing the probing light penetration length (inverse of the optical absorption coefficient; $1/\alpha$) at higher photon energy.

The most important finding was that in the photon energy below E_g, PPT signals attributed to MQWs were clearly observed even at high f of 4000 Hz. When f varies from 40 to 4000 Hz, μ becomes 50 from 450 μm. Since MQWs were located in the sample surface and were away from PZT for about 250 μm, heat caused by the non-radiative recombination should not reach the PZT. A possible candidate is as follows. When carriers generated in MQWs region, part of carriers will thermally escape and drift to the *n*-type GaAs substrate because of an existence of internal electric field. Finally non-radiative recombinations occur in the *n*-type GaAs substrate. To discuss in more detail, we carried out the theoretical calculation based on the pyroelectric photo-thermal signal proposed by Horita *et al*.[4] In this calculation, since the total MQWs thickness of about 200 nm was thinner than that of GaAs substrate, we regarded as a single GaAs bulk and took the parameters of GaAs.

Fig. 2 shows the theoretical and experimental phases as a function of f. We picked up at the experimental phase signals of 1.31 and 2.5 eV, where they corresponded to MQWs and above E_g, respectively. It was found that both experimental phases showed the same values and same dependency. For the theoretical values, PPT phase at 1.31 eV was constant, whereas that at 2.5 eV decreased with increasing f. If the carrier photoexcited within MQWs did not thermally escape from well, the position of the signal source was fixed at the thin surface region. This situation almost corresponds to the phase at 2.5 eV of the GaAs bulk. The most likely explanation about f-dependency of the experimental phase at 1.31 eV is that thermally carrier escapes from the well occur and they can reach the *n*-type GaAs substrate. As a result, the PPT signal source moved to the neighborhood of rear surface.

To conclude, we investigated the non-radiative carrier recombination and carrier transport processes in strain-balanced InGaAs/GaAsP MQWs embedded into GaAs *p-i-n* solar cells from the f-dependent PPT spectra. It was found that carriers photoexcited within MQWs thermally escape from the quantum well and drift to *n*-type GaAs region. This may imply that the non-radiative carrier loss at MQWs region is a minor process.

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References

1. T. Ikari and Fukuyama: in *Progress in Photothermal and Photoacoustic Science and Technology*, ed. A. Mandelis and P. Hess (SPIE Press, Bellingham, WA, 2000), p. 145.
2. H. Fujii, K. Watanabe, M. Sugiyama, and Y. Nakano: Jpn. J. Appl. Phys. **51** (2012) 10ND04.
3. A. Fukuyama, Y. Nakano, T. Aihara, H. Fujii, M. Sugiyama, Y. Nakano, and T. Ikari: AIP Conf. Proc. **1477** (2012) 185.
4. S. Horita, H. Konishi, N. Miyabo, and T. Hata : Jpn. J. Appl. Phys. **33** (1994) 3238.