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Cross-section Profile of Carrier Recombination Properties in the Multiple Junction Solar Cell Using Piezoelectric Photo Thermal Spectroscopy

圧電素子光熱分光法による多接合太陽電池に於けるキャリ再結合断面プロファイル

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1. Introduction

Multi-junction solar cells composed of multi-layers of single-junction solar cells with different bandgap energies have a wide wavelength sensitivity for the photovoltaic conversion efficiency. For estimating the efficiency of such solar cells, a spectral sensitivity measurement under a solar simulator is commonly used. However, it was difficult to identify in which cell or boundary performance degraded. Then, it is important to investigate the carrier generation and recombination mechanisms along the depth direction of the solar cell structures.

In this study, we investigated the sample depth profile of the non-radiative recombination process of photo-generated carriers in multi-junction solar cell by using a piezoelectric photo-thermal (PPT) measurements[1)]. This is because the PPT detects the non-radiative recombination signal and at the same time we can control the detection depth from the surface/interface by changing the modulation frequency of the probing light (*f*). Theoretical calculations for the frequency-dependent PPT signal intensity and phase were also carried out for comparing with the experimental results.

2. Experimental procedures

As shown in **Fig. 1**, the triple-junction solar cell structure sample composed of InGaP top, InGaAs middle, and Ge bottom cells was prepared by metal organic chemical vapor deposition. The tunnel junctions between each subcell and buffer layer on the Ge bottom cell were prepared. For the PPT measurements, a transparent piezoelectric transducer ($LiNbO_3$) was placed on the cap-GaAs top layer. The probing light was irradiated from the cap-GaAs top layer of the sample. The modulation frequency *f* was changed from 5 to 4000 Hz. All the measurements were carried out at room temperature.

3. Results and Discussion

Figure 2 shows PPT spectra of the present

Thickness (μm)	
0.40	cap-GaAs
1.65	InGaP top cell (1.88eV)
0.05	tunnel-juncton
3.40	InGaAs middle cell (1.41eV)
0.05	tunnel-juncton
1.40	buffer-layer
177	Ge bottom cell (0.66eV)

Fig. 1 Sample structure

sample. The arrows in the figure show the corresponding band gap energies of Ge, InGaAs and InGaP, respectively. Here, the composition of the III –V elements were also taken into account for estimating their band gaps. We could observe the drastic increases of the PPT signal at the critical energies corresponding to the energy gap of Ge and InGaAs cells. When the modulation frequency increases, the signal at higher energy region more than the band gap of InGaAs drastically decreases. This may be due to the decrease of the thermal diffusion length of the sample as discussed in the followings. Additional spike around 1.1 eV, labelled

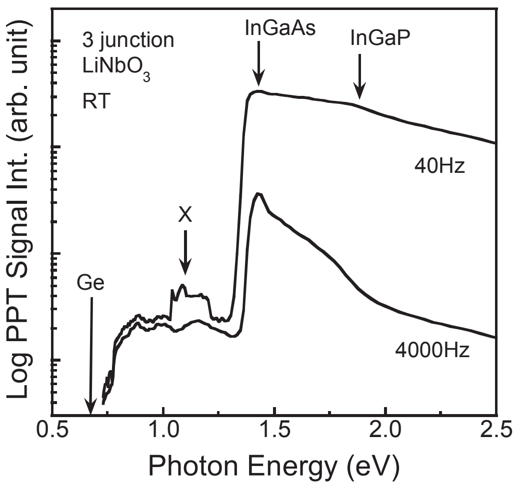

Fig. 2 PPT spectrum at room temperature

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as X, was observed in the spectrum of low modulation frequency. The origin is not clear at present.

To discuss the details of the non-radiative recombination process of the photo-generated carriers in each subcell, we carried out the theoretical calculation based on the pyroelectric photo-thermal signal generation model proposed by Horita *et al*[2]. This theoretical calculation consists of three layers where the finite air gap is inserted between the detector and a single layer sample. Although the present sample had a complicated multi-layers structure, we use this three layer model for simplicity. Since the In content of the InGaAs middle cell is small as 0.01, it is reasonable to consider the thermal diffusion length is almost the same as that of GaAs. Furthermore, InGaP has larger thermal diffusion length than that of GaAs. Therefore, thermal property could not be changed by the present modulation frequency region up to 4000 Hz. We, then, considered the three layer model composed of $LiNbO_3$(1.5 mm), GaAs(6 μm) and Ge layers (180 μm) and fixed the incident photon energy at 0.78 and 0.97 eV, corresponding to the low and high absorption region. The light penetration length is calculated as 90 and 1 μm at 0.78 and 0.97 eV, respectively.

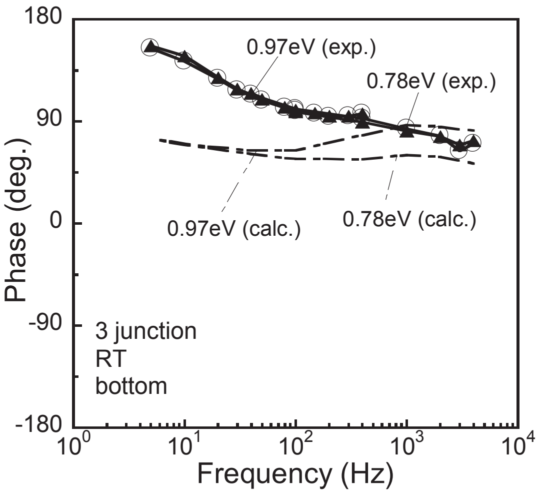

Fig. 3 The theoretical and experimental phases as a function of modulation frequency

Figure 3 shows the experimental and calculated results for the PPT signal phases as a function of *f* at incident photon energies of 0.78 and 0.97 eV. The observed phase decrease with increasing the frequency and there was no difference for the incident photon energy. However, we could find the difference between the two calculated results. This is due to the change of the light penetration length with modulation frequency. For the incident photon energy of 0.97 eV, almost of the light absorbed within a thin layer of Ge around 1 μm. Heat source is localized near the interface between the Ge bottom cell and the transparent region. The phase may not change with frequency. However, for hν of 0.78 eV, distance of the gravity of the heat source and the detector changes with frequency. This may cause the advance of the signal phase at higher modulation frequency as shown in the figure. The reason why the experimental results could not be explained by the calculated curve may be that we could not consider the effect of carrier transportation within the cell. Since the many kinds of electric field exists in this structure, for example, at *p-n* junction or tunnel junction interfaces, carrier easily drifts and non-radiative recombination occurs at the distance from the carrier generation point where the photons are absorbed.

To conclude, we investigated the sample depth profile of the non-radiative recombination process of photo-generated carriers in multi-junction solar cell from the *f*-dependent PPT spectra. It was found that photo-generated carriers in the bottom cell drift to hetero-junction interface. In order to discuss in more detail the carriers recombination process of multi-layers structure sample, it is required to formulate a new model which takes into account the diffusion and drift of the photo generated carriers as well as surface and interface carrier recombination.

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