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A Study of the Recombination Process at the *p-n* Junction Interface by the Photoexcited-Carrier-Concentration Controlled Piezoelectric Photothermal Method

光励起キャリア数を制御した圧電素子光熱変換分光法による半導体 *p-n* 接合界面の研究

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1. Introduction

The *p-n* junction is a vital component of the solar cells. At the *p-n* junction interface, there is a depletion region with built-in potential. In solar cells, the depletion region is used for generating electron-hole pairs and for their subsequent separation to free electrons and holes. When the cell is exposed to the solar spectrum, a photon with energy greater than E_g contributes to the cell output, and the excess E_g over is converted to heat through phonon interactions (thermodynamic energy loss, **Fig. 1**). Therefore, it is important to study carrier behavior at the *p-n* junction interface in more detail by examining factors such as carrier generation, separation by the built-in potential, and recombination.

We have already adopted the piezoelectric photothermal (PPT) and surface photovoltage (SPV) techniques to simple Si *p-n* junction samples.[1)] The former detects the phonon emitting non-radiative transition, the latter detects the surface potential change of the photo-excited carriers. It was found that SPV spectral shape coincided with that of open circuit voltage (V_{oc}) spectrum. On the contrary, as shown in **Fig. 2**, PPT spectra showed two peaks. The lower energy peak at 1.15 eV corresponded to SPV peak, in other words, the V_{oc} spectrum. The higher energy peak at 1.30 eV was considered to be a thermodynamic energy loss with phonon emitting.

In this study, we have investigated the PPT and SPV signal generation mechanisms in more quantitative by preparing the photoexcited-carrier-concentration controlled incident light.

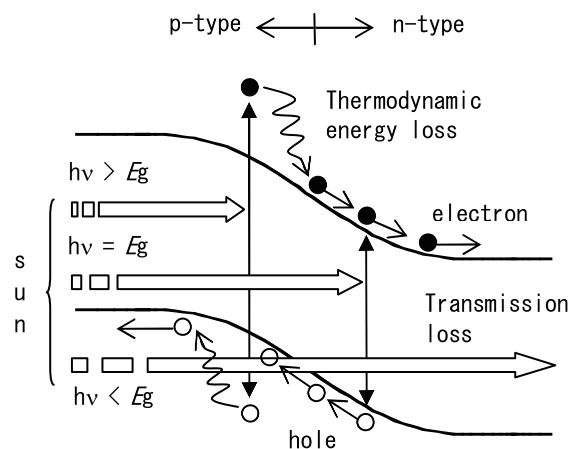

Fig. 1 Carrier behaviors at the *p-n* junction interface

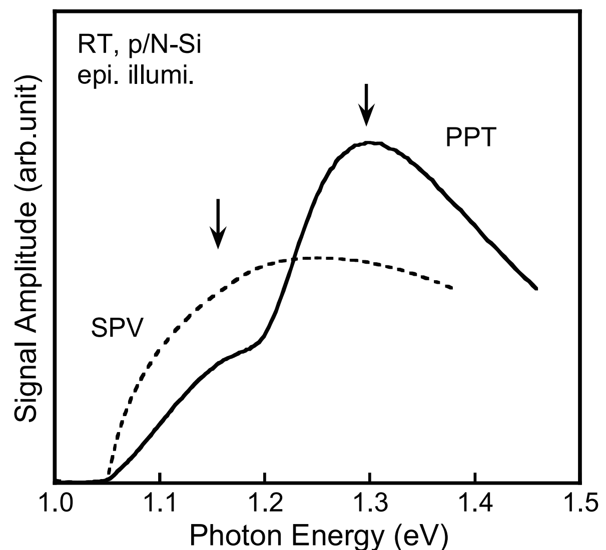

Fig. 2 SPV and PPT spectra at room temperature

2. Experimental Procedures

Two types of simple Si diode containing a *p-n* junction were prepared. One was a boron-doped *p*-type Si epitaxial layer (80 µm thickness) grown on a phosphorus-doped *n*-type CZ-grown Si substrate (the p/N sample). The other was a phosphorus-doped *n*-type Si epitaxial layer grown on a boron-doped *p*-type CZ-grown Si substrate

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(the n/P sample).

Two configurations of the sample and detector were employed for both PPT and SPV measurements, as in ref. 1. The incident light was irradiated on the sample from the epitaxial layer (the epi. illumination scheme) and from the substrate (the substrate illumination scheme), respectively. Details of the PPT and SPV methods have been reported elsewhere.[2, 3]

The photoexcited-carrier-concentration controlled incident light was prepared as follows. First, the coplanar electrodes were formed on the *p*-type bulk Si surface. A dc bias voltage of 9 V was applied between these electrodes. The number of photons was adjusted by the neutral density (ND) filter to keep constant the photocurrent of the sample when the photon energy of monochromatic incident light was varied. This is a method that used a principle of the constant photocurrent method (CPM).[4] As a result, the incident that kept constant the carrier concentration photoexcited in the sample over the measured photon energy range.

3. Results and Discussion

Figure 3 shows the PPT and SPV spectra by using the photoexcited-carrier-concentration controlled incident light at room temperature. When the photon energy ($h\nu$) was set at approximately 1.15 eV, the SPV spectrum showed a peak whereas the PPT spectrum indicated a dip. These results could be understood as follows. The optical penetration length (= inverse of optical absorption coefficient) at this $h\nu$ was almost equal to the sample thickness. Therefore, electron-hole pairs were photoexcited in the whole sample. Almost pairs will be separate by the built-in potentials existing at the *p-n* junction interface and the sample surface. If the recombination probability is low, separated carriers (electrons and holes) will accumulate the sample surface potential. This is the reason that the SPV and PPT showed a peak and a dip, respectively. This is a good illustration that carrier accumulation (SPV) and recombination (PPT) are complementary phenomena.

Next, we discuss the SPV and PPT signals at $h\nu$ = 1.30 eV in Fig. 3. As shown in the figure, both SPV and PPT showed the broad peaks. Based on the above discussion, one of the SPV and the PPT should show a dip. The most likely explanation is a thermodynamic energy loss. In this photon energy region, the penetration length was equal to a distance from the sample surface to the *p-n* junction interface, and $h\nu$ of the incident light was larger than that of E_g. Therefore, a number of carriers were photoexcited to the higher energy level in the conduction and the valence bands. These carriers relax to the bottom of the conduction band or top of the valence band with emitting phonon in a short

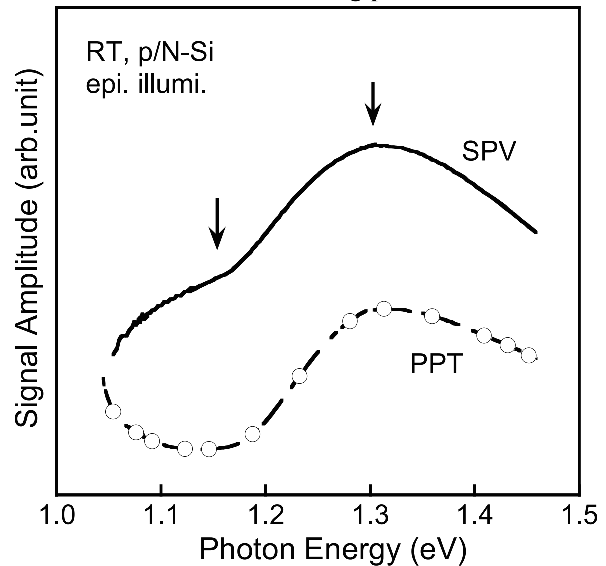

Fig. 3 PPT and SPV spectra by using the photoexcited-carrier-concentration controlled incident light

time. These emitted phonons were detected as PPT signal. We then concluded that a PPT peak at approximately 1.30 eV was due to a thermodynamic energy loss with phonon emitting. It is noted that almost relaxed carriers will accumulated to the surface without recombine.

To conclude, we have investigated the signal generation mechanisms of SPV and PPT by using the photoexcited-carrier-concentration controlled incident light. At $h\nu$ = 1.15 eV, since the carrier accumulation (SPV) and the recombination phenomenon (PPT) are complementary, SPV and PPT showed a peak and a dip, respectively. At $h\nu$ = 1.30 eV, both SPV and PPT showed peaks. This is because the PPT increased by a thermodynamic energy loss with phonon emitting.

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