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Local Characterization of Multicrystalline Silicon Solar Cells through Photothermal and Potential Measurements by Scanning Probe Microscopy

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1. Introduction

Solar cells have been attracting a great deal of attention as a countermeasure of global environmental problems. In solar cell materials, carrier recombination is one of the most important properties because it causes an internal loss of photocarriers. Especially in multicrystalline Si materials, the recombination at a grain boundary is the serious problem which deteriorates conversion efficiency. The recombination property around the grain boundary was investigated by, for instance, the photoluminescence (PL) method[1] and the electron beam induced current (EBIC) method[2]. In those methods, activeness of the grain boundary as a recombination center was represented by reductions in the PL intensity and in the EBIC signal. Because the recombination at the grain boundary is mostly considered to be nonradiative and also because those nonradiative recombination generates heat, we can expect that the nonradiative recombination property of the photocarriers will be investigated through a precise measurement of the heat generated. To measure the heat generation under periodic light illumination, the lock-in thermography using infrared camera has been reported[3]. We, on the other hand, chose usage of atomic force microscopy (AFM) because AFM is expected to have high resolution enough to realize the precise detection of thermal expansion induced by the light illumination. We have already proposed the local measurement method of photothermal (PT) signals by AFM. In this method, the periodic photothermal expansion produced by the intermittent light illumination is detected through a change in the motion of AFM cantilever, and combined it with dual sampling (DS) method to improve its sensitivity, which we refer to as DS-AFM[4]. By DS-AFM, we have observed the fundamental features of the PT signal on the multicrystalline Si solar cell[5]. In this study, the PT signals around various grain boundaries in the multicrystalline Si solar cell have been carefully investigated by DS-AFM. In addition, we have observed surface potential distributions by Kelvin probe force microscopy (KFM)[6] and compared those results to examine the nonradiative recombination property around the grain boundaries.

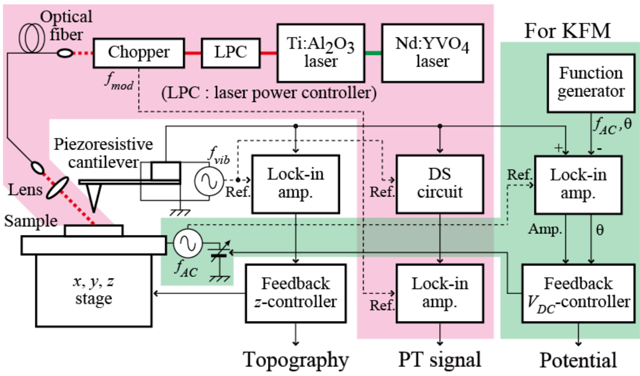

Fig.1 Experimental setup for the PT measurements by DS-AFM and the surface potential measurements by KFM. The sample bias was set to be zero for the PT measurements and the surface potential measurements were done in darkness.

2. Experimental

Figure 1 shows our experimental setup based on a commercial AFM system (SII NT, SPA-300HV/SPI4000). Our AFM was operated in the intermittent contact mode, and all measurements were performed at room temperature. In the PT measurements, a Si piezoresistive cantilever (SII NT, PRC-DF40P) was used to avoid an influence of stray light. Its spring constant and resonant frequency were typically 40 N/m and 450 kHz, respectively. The sample surface was illuminated by monochromatic light from a tunable $Ti:Al_2O_3$ laser in the continuous wave mode. Intensity and spot diameter of the incident light were about 100 mW/cm^2 and >1mm at the sample surface, respectively, and this light was periodically modulated by an optical chopper at a frequency of 540 Hz with a duty ratio of 50%. The output of cantilever deflection sensor was sampled by the DS circuit, and the PT signal was acquired as the periodical change in the DS circuit output at the modulation frequency extracted by the lock-in amplifier[4]. The surface potential measurements were performed in darkness by KFM with a conductive Si piezoresistive cantilever (SII NT, PRC400) to exclude a photovoltaic effect. The spring constant and resonant frequency of this cantilever were typically 3 N/m and 77 kHz, respectively. The amplitude and frequency of AC bias were set to be 0.3 V_{pp} and 79 kHz, respectively, and the homemade system for potential feedback, suited to the surface potential measurements by KFM with the piezoresistive cantilever, was used[5].

The sample used in this study was a multicrystalline Si solar cell fabricated on a p-type substrate of 300 μm in thickness with a phosphorus doped n-type surface layer of 0.5 μm in thickness.

3. Results and discussion

Figures 2(a) and (b) show the images of topography and corresponding PT signal taken under the light at a photon energy of 1.57 eV. In Fig. 2(a), three grain boundaries were recognized and we named them B1-B3. The result shown in Fig. 2(b) indicates that the PT signal was enhanced especially around grain boundary B1. Since the intensity of the PT signal is considered proportional to the generated heat due to the nonradiative recombination of photocarrier, we can deduce that the nonradiative recombination frequently occurred around B1, which implies that this area includes a lot of nonradiative recombination centers.

Figures 3(a) and (b), on the other hand, show the images of topography and corresponding surface potential in darkness on the area similar to Fig. 2. This result shows that surface potential was low especially around B1. Here, “potential” means electron potential and therefore the low potential area will easily attract the electron which is the minority carrier in the p-type substrate. Consequently, we can consider a possibility that this area with low potential around B1 is positively charged due to the segregation of donor-like impurities.

By comparing Figs. 2 and 3, we can recognize good correspondence between the areas where the PT signal was enhanced and where the surface potential was low. Therefore, we can deduce that the donor-like impurities segregated around B1 act as nonradiative recombination centers and the photocarriers frequently recombine via their impurity levels. To the contrary, less contrasts appeared around B2 and B3 in both images of the PT signal and the surface potential. The results suggest that those areas include fewer nonradiative recombination centers and consequently B2 and B3 become electrically inactive.

4. Conclusions

We have taken the images of photothermal (PT) signal and surface potential around grain boundaries in multicrystalline Si solar cell by dual sampling method in atomic force microscopy and Kelvin probe force microscopy, respectively. As a result, an enhancement of the PT signal and a lowering of the surface potential were observed around a particular grain boundary. We consider that donor-like impurities are segregated around there and the photocarriers frequently recombine via their impurity levels.

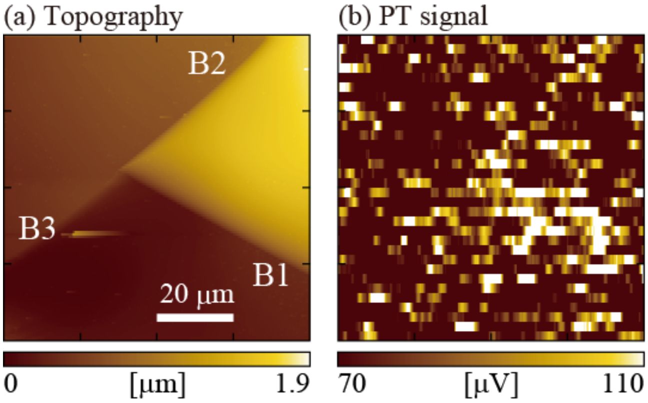

Fig.2 Images of (a) topography and (b) PT signal around grain boundaries in multicrystalline Si solar cell. The photon energy of incident light was 1.57 eV.

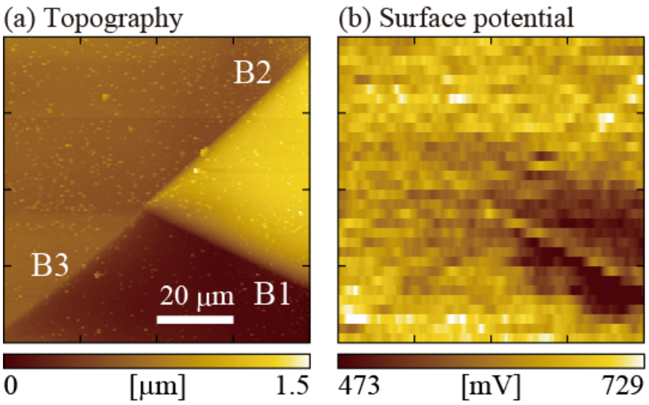

Fig.3 Images of (a) topography and (b) surface potential on the area similar to Fig. 2. Here, “potential” means electron potential.

Acknowledgements

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