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Local Measurements of Photothermal Signals on Polycrystalline Silicon Materials by Dual Sampling Method in Atomic Force Microscopy

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1. Introduction

A photothermal (PT) effect is an energy transfer phenomenon from photon to heat, and the nonradiative recombination process of photocarriers can be investigated from the PT measurements. For the PT spectroscopy, typically, thermal expansion [1] and/or acoustic wave emission [2] caused by light illumination with various wavelengths are observed at the sample surface, but the spatial resolution in conventional methods is not high enough to investigate the PT signal from individual micro/nano structures. If we apply atomic force microscopy (AFM) to the PT measurements, remarkable improvement in spatial resolution will be expected. To do so, sensitive detection of the thermal expansion by the light illumination at the sample surface should be realized by AFM. For such a purpose, we have proposed the dual sampling method in intermittent contact mode AFM (DS-AFM), by which the periodical thermal expansion produced by the intermittent light illumination is sensitively captured through sampling detection of the change in the cantilever oscillation [3-5], and have already confirmed its basic performance [6]. In this study, the PT signals on polycrystalline Si materials have been investigated by the DS-AFM, and the nonradiative recombination properties around a grain boundary have been discussed.

2. Experimental

Figure 1 shows our experimental setup for the PT spectroscopy based on a commercial AFM system (SII NT, SPA-300HV/SPI4000). Our AFM was operated in the intermittent contact mode in nitrogen gas (1 atom), and all measurements were performed at room temperature. To avoid the influence of stray light, a Si piezoresistive cantilever (SII NT, PRC-DF40P) was used. Its spring constant, resonant frequency, and quality factor at the resonance were typically 40 N/m, 500 kHz, and 600, respectively. The sample surface was illuminated by monochromatic light from a tunable Ti:Al_2O_3 laser in the continuous wave mode, whose intensity and spot diameter were about 50 mW/cm^2 and >1mm at the sample surface, respectively. This incident light was periodically modulated by an optical chopper with a duty ratio of 50%, and the modulation frequency was 810 Hz. The output of cantilever deflection sensor was sampled by 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.

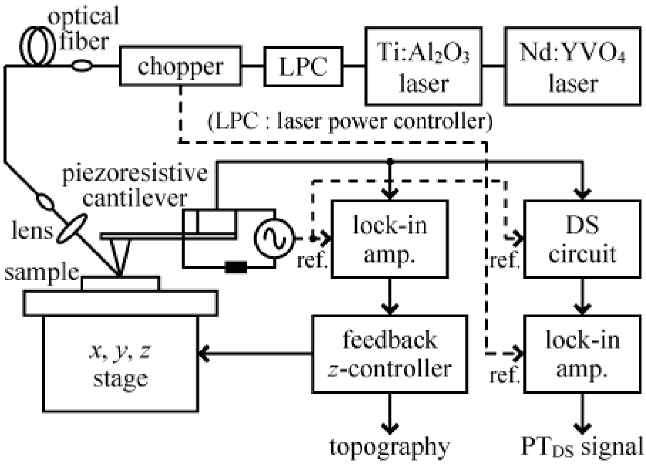

Fig. 1 Experimental setup for PT spectroscopy by DS-AFM.

The sample used in this study was a polycrystalline Si solar cell fabricated on a p-type substrate with an n-type surface layer (phosphorus doped) of approximately 500 nm in thickness. Its typical characteristics as the solar cell, such as photovoltage and minority carrier lifetime, were microscopically evaluated by photoassisted Kelvin probe force microscopy (P-KFM), details of which were described elsewhere [7, 8].

3. Results and discussion

Figure 2(a) shows a topographic line profile across a Σ3 boundary observed in the area indicated in an optical micrograph as an inset of this figure. In this paper, we named the (001) and (111) grains G1 and G2, respectively. The line profiles of the PT signals as an average taken over 64 line profile data are shown in Figs. 2(b) and 2(c), where the wavelengths of the incident light were 890 and 790 nm, respectively. As shown in these figures, the PT signal obtained on G1 was obviously higher than that on G2. Since the intensity of the PT signal is considered to be nearly proportional to the nonradiative recombination rate, we can conclude that the nonradiative recombination rate in G1 is higher than that in G2. In the Si material, the high nonradiative recombination rate simply results in the short minority carrier life time because Si is the indirect bandgap material. Therefore, the results shown in Fig. 2 indicate a fact that the minority carrier lifetime in G1 should be shorter than that in G2, which is very consistent with our previous results obtained by P-KFM [8].

Figure 2 also shows that the PT signal at the grain boundary was enhanced. This result is attributable to an enhanced nonradiative recombination rate at the grain boundary, which is also very consistent with the results of our P-KFM revealing the marked shortening of the minority carrier life time at the grain boundary [8]. Consequently, we can conclude that the grain boundary acts as a nonradiative recombination center. Moreover, we can confirm that the PT measurements by DS-AFM have a capability to analyze the distribution of the nonradiative recombination center.

When we compare Figs. 2(b) and 2(c), the intensity of the PT signal under the light with a short wavelength was enhanced. The light with the shorter wavelength has a shallower penetration depth, which means the distribution of the generated photocarriers is more concentrated near the surface. In general, the recombination rate at the surface should be much faster than that in bulk. Therefore, we can consider that the contribution of the surface recombination appeared as the enhanced PT signal in Fig. 2(c).

4. Conclusions

We have investigated the nonradiative recombination properties around a grain boundary in the polycrystalline silicon material through PT measurements by DS-AFM. The results indicate that the PT signals were enhanced in the grain having a short minority carrier lifetime as well as at the grain boundary and were also enhanced by the shallow generation of the photocarriers near the surface. Consequently, a capability of the PT measurements by DS-AFM to investigate the nonradiative recombination process has been confirmed.

Acknowledgements

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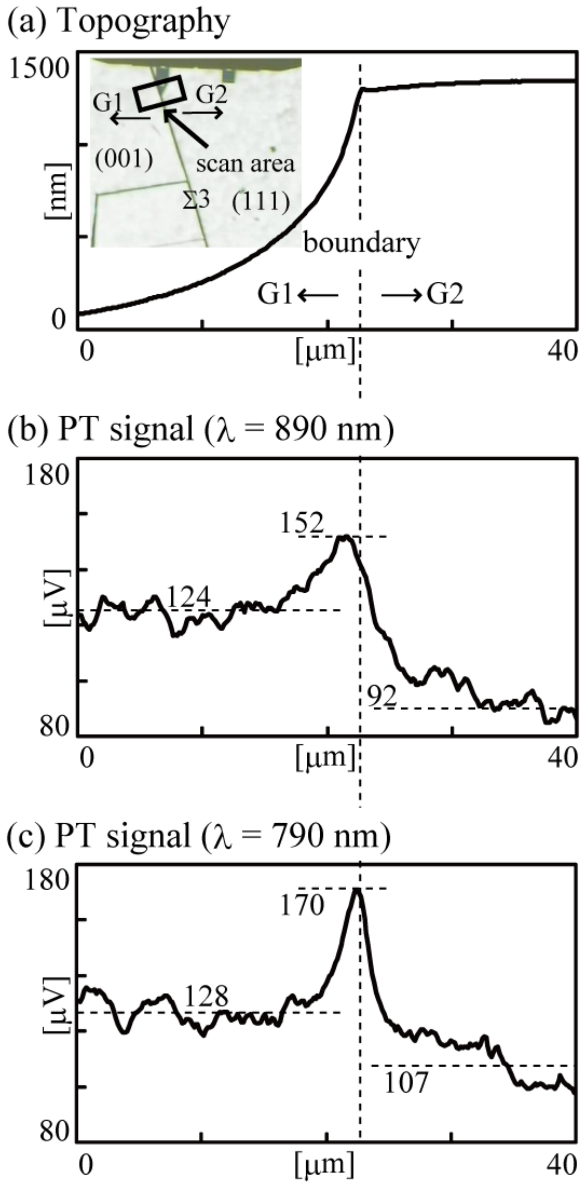

Fig. 2 Line profiles of (a) topography, (b) and (c) PT signal averaged over 64 data obtained under the light at the wavelengths of 890 and 790 nm, respectively. An inset in (a) is an optical micrograph of the sample surface including the scanned area. The (001) and (111) grains are named G1 and G2, respectively.

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