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Interpretation of Crossover in J-V Characteristics of $Cu(In,Ga)Se_2$ Solar Cell Using Lift-off Process

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1. Introduction

$Cu(In,Ga)Se_2$ (CIGS) chalcopyrite compound semiconductor is a promising absorber layer for high conversion efficiency solar cells [1]. Meanwhile, a lift-off process is an attractive method for expanding substrate choices [2,3]. Although the photo *J-V* characteristics of the CIGS thin film solar cells using the lift-off process were particular shape compared to those of the standard structure cells [4], this cause has not been interpreted yet. In this work, we therefore investigated the behavior of photocurrent in the CIGS solar cells. We report on the origin where photocurrent behaves particularly.

2. Experimental

The solar cells using the lift-off process were fabricated as follows. First, a 0.8-μm-thick Mo layer was deposited on a soda-lime glass (SLG) substrate without intentional substrate heating. Then, a 2-μm-thick CIGS layer was deposited on the Mo/SLG structure by using a three-stage evaporation process at the highest substrate temperature of approximately 550°C [5]. After CIGS surface cleaning by KCN solution, 0.2-μm-thick Au/1.6-μm-thick Mo stacked layers were deposited as a back electrode. After the electrode deposition, these samples were annealed at 250ºC for 30 min in nitrogen ambient. Then, an alternative SLG substrate was attached onto the electrode/CIGS/Mo/SLG structure with a conductive epoxy glue. Then, alternative-SLG/epoxy/electrode/CIGS stacked layers were detached from the primary Mo/SLG substrate by applying the tensile strain. After CdS deposition by chemical bath deposition, ZnO and ITO and NiCr-Al grid were deposited [4].

The standard solar cells, where the lift-off process was not used (Al-NiCr/ITO/ZnO/CdS/CIGS/Mo/SLG structures), were also prepared for comparison.

Current density-voltage (*J-V*) measurements were performed to characterize the fabricated solar cells under standard air mass 1.5 global conditions (100 mW/cm^2, 25°C). External quantum efficiency (EQE) measurements were performed under various bias conditions to investigate the behavior of photocurrent (I_{ph}).

3. Results and Discussion

Figures 1 and 2 show *J-V* characteristics obtained from the lift-off CIGS solar cell and the standard cell, respectively. The solar cell parameters obtained from these devices are summarized in Table I. The highest conversion efficiency was achieved compared to the previous reports of the lift-off CIGS solar cells [3,4,6]. However, this conversion efficiency is still lower than that of the standard cell. Crossover behavior is recognized for only the lift-off solar cell between the photo *J-V* and dark *J-V* characteristics from the comparison between Fig. 1 and Fig. 2. The origin of this crossover behavior will be discussed later.

Figures 3 and 4 show EQE spectra obtained from the lift-off solar cell and the standard cell, respectively. In the lift-off solar cell, EQE intensity decreases with increasing forward bias in the range from 0 V to 0.4 V. In particular, the EQE intensity decreases remarkably as wavelength becomes long. Moreover, The EQE values for the wavelength range from 1000 nm to 1050 nm are negative at the voltage of 0.5 V which slightly exceeds open-circuit voltage (V_{oc}). A negative value of EQE indicates that photocurrent flows from the back electrode to the surface grid (the forward bias direction) in the solar cell. On the other hand, the photocurrent which was generated by photons with wavelengths from 400 nm to 1000 nm flows from the surface grid to the back electrode (the reverse bias direction). It is found that the direction where the photocurrent flows depends on excitation wavelengths, suggesting that these directions depend on the depth where an electron-hole pair was generated. Moreover, the EQE values are negative in the range from 400 nm to 1200 nm at 0.6 V. The EQE values become further low at 0.7 V. It is therefore clarified that the directions where photocurrent flows depend on a bias voltage for the lift-off solar cell.

On the other hand, the EQE values also decrease with increasing bias voltage for the standard cell. However, even though the bias voltage exceeds V_{oc}, the EQE values are not negative. This result indicates that photocurrent flows toward only the reverse bias direction and the direction doesn't depend on these bias voltages.

Next, photocurrents calculated from these EQE spectra and the standard air mass 1.5 global conditions are plotted in the each *J-V* characteristic result. Both the photocurrent-voltage (I_{ph}-V) characteristics decrease with increasing forward bias voltage. The results of the dark J-V + I_{ph}-V characteristic are also plotted. Interestingly, the dark J-V + I_{ph}-V characteristics are in good agreement with photo *J-V* characteristics for not only the standard cell but also the lift-off solar cell. This indicates that the cause of this crossover behavior is attributed to the fact that the direction of the photocurrent changed from the reverse bias direction to the forward bias direction which is the same direction as the bias current due to the increase of the forward bias voltage.

Finally, the cause where the photocurrent flows toward the same direction as the forward bias current is discussed. Figure 5 shows the band alignment of the lift-off solar cell under the forward bias condition. It is expected that our lift-off solar cell has an inverted graded bandgap structure because of the lift-off process as shown in Fig. 5. This assumption is in good agreement with the result where the lift-off solar cell shows higher V_{oc} than that of the standard cell. A normal graded bandgap structure of a CIGS layer enhances the diffusion length of the electrons generated near the back electrode toward the surface grid direction [7]. It is therefore expected that the inverted graded bandgap structure enables the electrons to diffuse toward the back electrode direction. We propose that the inverted graded bandgap structure plays an important role in the behavior of photocurrent.

4. Conclusions

The behavior of photocurrent in the lift-off CIGS solar cell was investigated in detail. We found that the cause of the crossover behavior in the *J-V* characteristics was due to the fact that the photocurrent flowed toward the same direction as the forward bias current. We concluded that this crossover *J-V* characteristic originated from the inverted graded bandgap structure in the lift-off CIGS solar cell.

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Table I Solar cell parameters

Structure	Eff. (%)	J_{sc} (mA/cm^2)	V_{oc} (V)	FF (%)
Lift-off	8.6	32.5	0.494	53.8
Standard	9.4	35.6	0.443	59.5

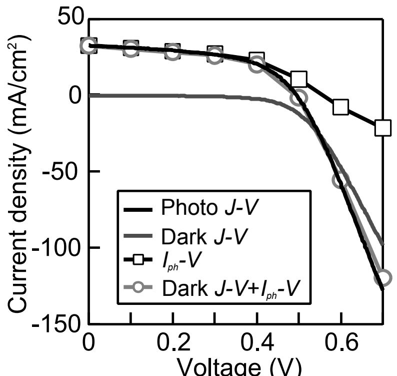

Fig. 1 *J-V* and I_{ph}-*V* characteristics of lift-off solar cell.

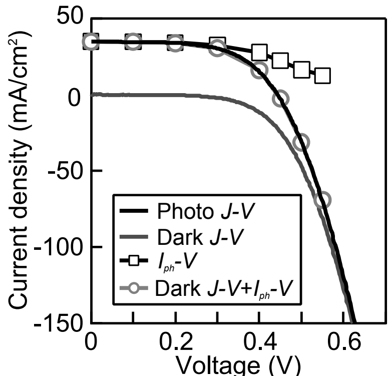

Fig. 2 *J-V* and I_{ph}-*V* characteritics of standard cell.

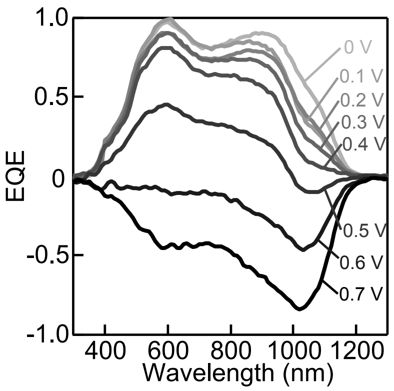

Fig. 3 EQE spectra of lift-off cell.

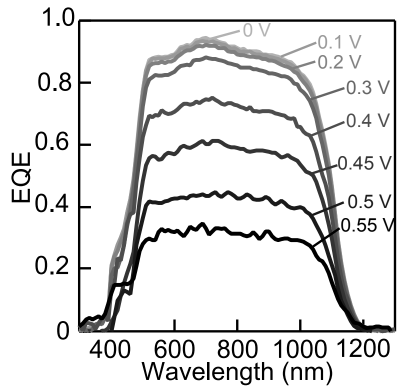

Fig. 4 EQE spectra of standard cell.

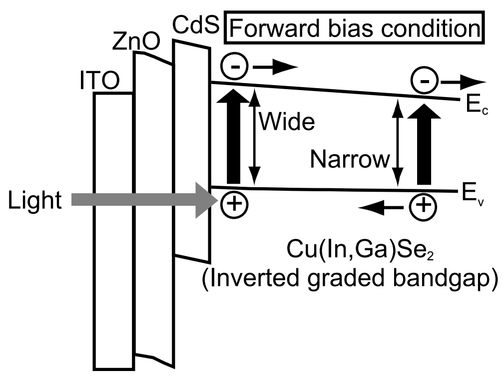

Fig. 5 Band alignment of lift-off solar cell.