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Lift-off process for flexible Cu(In,Ga)Se_2 solar cells

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1. Introduction

Flexible solar cells are attractive for widening the application of thin-film solar cells. A chalcopyrite type compound semiconductor of Cu(In,Ga)Se_2 (CIGS) is promising candidate for high efficiency devices. On rigid soda-lime glass (SLG) substrates, a high efficiency of 20% was achieved [1]. There are reports on the growth of CIGS thin films on flexible substrate such as metal foil [2] and polymer film [3]. In terms of light weight, polymer films represented by polyimide (PI), plastic and fluoroplastic are attractive but their low melting points are a crucial problem on the crystal growth of CIGS requiring ~550^{o}C. Among them, PI has the highest thermal tolerance of ~450^{o}C and relatively high conversion efficiency (~14.7%) was reported on the device based on CIGS film grown on a PI film [3]. However with this approach, this level of performance can not be achieved on lower melting point materials. Another approach for flexible cells is a lift-off process, i.e., CIGS layer transfer from SLG to alternative substrates, realizing a freedom of substrate material choice. Some groups reported lift-off techniques [4,5], but a high efficiency was not obtained, i.e., only a 0.7% efficiency on a $CuGaSe_2$ solar cell. In our previous report, we developed a simple lift-off process without an intentional sacrificial layer between back contact and CIGS layers [6]. In this study, we report the fabrication of flexible CIGS solar cells on PI films using lift-off process.

2. Experimental

Fig. 1 shows the experimental flow of the lift-off process. First, a 2-μm thick CIGS layer was deposited on a SLG substrate sputter-coated with a 0.8 μm-thick Mo layer by three-stage evaporation [7]. Another Mo layer for a back contact of a lift-off cell was deposited by sputtering, and then an alternative substrate of 55 μm-thick PI film was attached onto the substrate with conductive epoxy. Then, the PI/exopy/Mo/CIGS stacked layer was detached from the primary substrate. Based on the stacked layer, a flexible CIGS solar cell was completed (see solar cell fabrication detail in [6]). Fig. 2 shows the photograph of the flexible CIGS solar cell fabricated in this study.

3. Results and discussion

Fig. 3 shows the current-voltage curves of CIGS solar cells fabricated with lift-off and standard processes. The lift-off cell severely suffered from high series-resistance (R_s). It was difficult to fit the curve to diode model but the R_s value was at least higher than 5 Ωcm^2, which was greatly higher than 0.8 Ωcm^2 for the standard cell. The high R_s value reduced short-circuit current density (J_{sc}) and fill factor (FF). In contrast, open-circuit voltage (V_{oc}) of the lift-off cell was higher than that of the standard cell. In the three-stage process, the bandgap (E_g) profile in depth direction of a CIGS film is controlled to be V-shaped profile, i.e., E_g values are higher toward back and front surfaces and the valley of E_g is positioned at near the front surface. The V-shaped E_g profile, so-called double-graded E_g structure, assists photo-generated carrier collection and also reduces the carrier recombination at a space charge region (SCR), resulting in high J_{sc} compatible with high V_{oc}. The CIGS film used in this study had a higher E_g at the back surface than that at the front surface. Then the Eg in the SCR of the lift-off cell was higher than that of the standard cell, resulting in the higher V_{oc} in the lift-off cell. However, this inverted double-graded E_g structure severely limited the J_{sc}. Consequently, the efficiency (Effi.) of the lift-off cell showed almost half value (3.96%) to that of standard cell (8.12%). Fig. 4 shows the quantum efficiency (QE) of the CIGS solar cells. Photo-generated carriers generated by long wavelength light, i.e., at the deeper part of the CIGS layer, became hard to be collected in the lift-off cell. To improve the carrier collection, the E_g profile in the CIGS layer has to be modified for the lift-off cell. Fig. 5 shows the QE spatial distribution of the CIGS solar cells. In contrast to the standard cell, the lift-off cell had inhomogeneous distribution like cracks originated by mechanical stress during the lift-off process. These cracks seem not to act as shunt pass as shown in a relatively high shunt resistance in Fig. 1; however, it may decrease J_{sc} by the reduction of available pn junction area.

4. Conclusions

A lift-off process which transfers a CIGS film grown on a SLG substrate to flexible alternative substrates (in this study a PI film) was developed. A flexible CIGS solar cell based on a lift-off CIGS film showed almost half of the efficiency compared to a CIGS solar cell with a standard process. Improvements in R_s and E_g profile and the reduction of mechanical damage on the CIGS film during lift-off will improve the device performance. This study indicated the possibility of lift-off process to realize flexible CIGS solar cells.

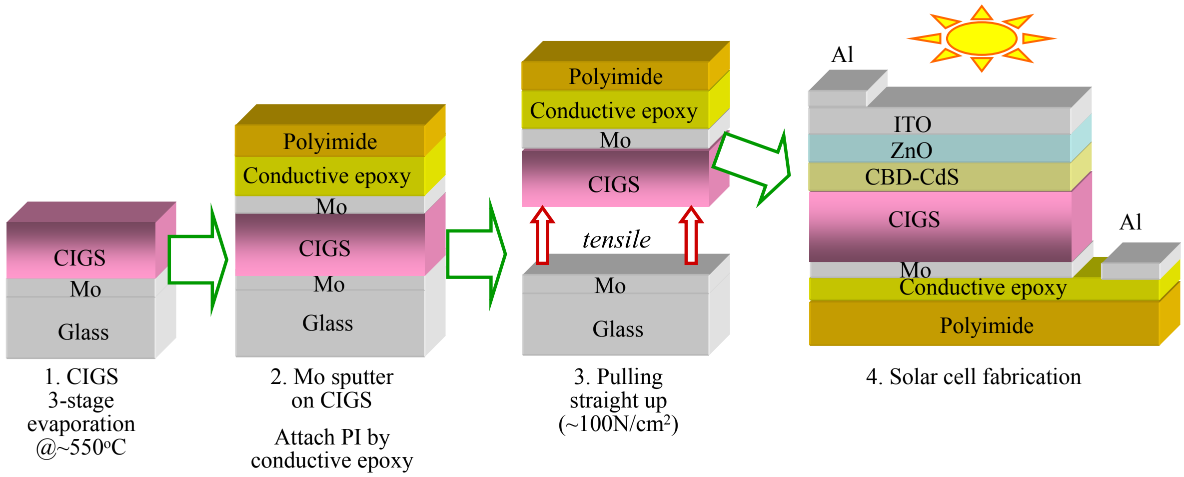

Fig.1 Schematics of lift-off process.

Fig. 2 Photograph of flexible lift-off CIGS solar cell.

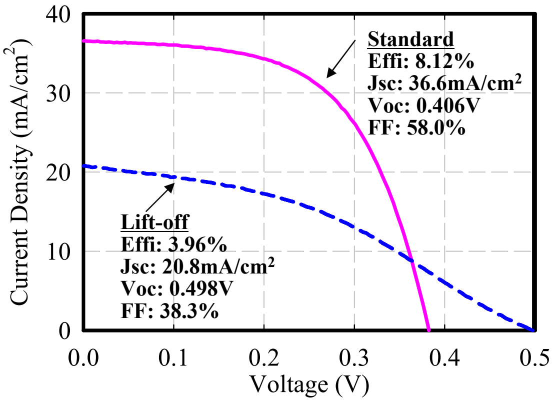

Fig. 3 Current-voltage curves of lift-off CIGS solar cell.

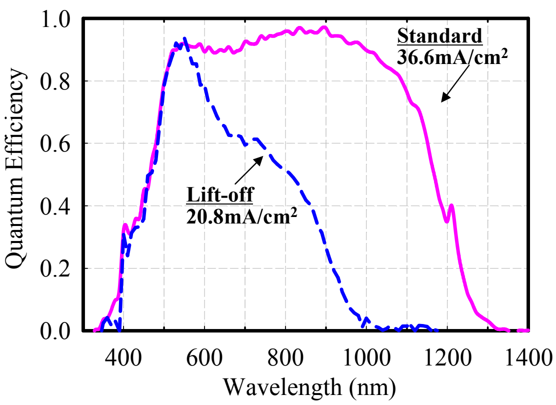

Fig. 4 QE of lift-off CIGS solar cell.

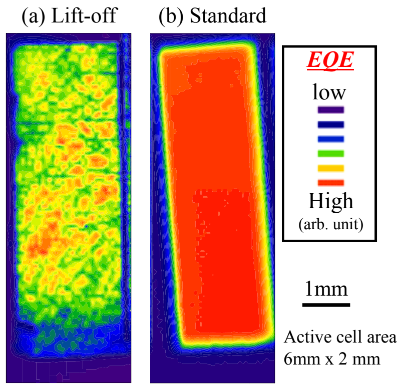

Fig. 5 QE spatial distributio n of lift-off CIGS solar cell.

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