High Efficiency Flexible Chalcopyrite Solar Cells with Narrow-Gap Absorber for Tandem Applications

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Abstract: In this study, light-weight and flexible chalcopyrite $Cu(In, Ga)(Se, S)_2$ solar cells with narrow-gap absorber were newly developed for suitable bottom cells of high efficiency double-junction tandem solar cells. Efficiency of 19.2% at the bandgap-energy of 1.01 eV for the flexible $Cu(In, Ga)(Se, S)_2$ solar cells on thin Ti foils was confirmed, which was considered to be comparable level with the rigid chalcopyrite solar cells on the glass substrates. We believe these results are one of big steps for achieving light-weight and flexible tandem solar cells applicable to building integrated photovoltaics, vehicle integrated photovoltaics and aerospace photovoltaics.

1. Introduction

Light-weight and flexible thin-film solar cells have been taken a great attention for the applications in emerging markets, such as building integrated photovoltaics (BIPV), vehicle integrated photovoltaics (VIPV) and aerospace PV. Various technologies for the light-weight and flexible thin-film solar cells have been developed for more than 50 years, for instance, amorphous-Si, CdTe, chalcopyrite, organic and perovskite solar cells. Among these technologies, the chalcopyrite solar cells have a relatively high efficiency (Eff) above 20% and long outdoor durability over 20 years as well as a large volume mass-production experience (annually GW-scale). Recently, the world record Eff of 22.2% for the flexible chalcopyrite solar cells by using polyimide films has been reported [1]. However, metal foils are more desirable for the substrate of the flexible chalcopyrite solar cells than the polymer films, taking into account their high moisture barrier property and easier fabrication of high Eff large-area cells due to their high electrical conductivity and high-temperature tolerance. So far, the cell Eff of 20.6% [2] and large-area module Eff of 18.6% [3] for the flexible chalcopyrite solar cells by using stainless steel foils have been reported. The typical aperture-area Eff of commercial flexible chalcopyrite modules is around 16%, which is considered to be the highest Eff among the currently available all kind of flexible solar modules.

In addition, the chalcopyrite solar cells are also getting attention for the application in high Eff double-junction tandem solar cells because of their bandgap-energy (E_g) tunability from 1.0 to 2.4 eV, while that of crystalline Si solar cells is fixed at 1.1 eV. As the bottom cell of the tandem solar cells, the theoretically optimal E_g has been estimated to be ranging from 0.9 to 1.0 eV [4,5]. Therefore, the narrow-gap chalcopyrite bottom cells should be more suitable for the tandem applications than the crystalline Si bottom cells. So far, the Eff of 21.5% at the E_g of 1.02 eV [5] and the Eff of 18.7% at the E_g of 1.01 eV [6] for the chalcopyrite solar cells on the rigid glass substrate have been reported, respectively. The purpose of this paper is to realize the high Eff flexible chalcopyrite solar cells with narrow-gap absorber for tandem applications.

2. Results and Discussion

The chalcopyrite $Cu(In, Ga)(Se, S)_2$ (CIGSS) solar cells used for this study were specially developed for the severe environments, such as the VIPV and the aerospace PV applications. Not only the high temperature tolerance but also the radiation hardness, the thermal cycle tolerance and the mechanical vibration tolerance were much improved than the conventional CIGSS solar cells [7, 8]. The CIGSS solar cells were fabricated by highly productive sputtering-based process. The basic structure was anti-reflective coating/Ag grid electrode/transparent conductive oxide/electron transport layers/narrow-gap CIGSS absorber/Mo back electrode on the flexible Ti foil. The thickness of the CIGSS device layer and the Ti substrate was about 3 um and 50 um, respectively. The weight of the CIGSS solar cells were about 250 g/m^2. After the cell fabrication, all samples were pre-stabilized by the light soaking at 200C30min in N_2 box. The current–voltage characteristics were measured by a class A solar simulator (XI-05A1V2-L, SERIC Ltd., Japan) with AM 1.5 and 100 mW/cm^2 illumination at room temperature. External quantum efficiency (EQE) curves ranging from wavelength of 300 nm to 1300 nm were measured by a spectral response measurement system (CEP25-MLT, Bunkoukeiki Co., Ltd., Japan) at room temperature without any bias.

The best current-voltage characteristic of the newly developed flexible CIGSS solar cells is shown in Fig 1(a). There are a variety of methods for estimating the E_g of solar cells [9], however, we used the $(E \cdot EQE)^2$ method and the derivative method for this study because our CIGSS absorbers had the double graded structures. Figure 1(b) shows the E_g determined by the $(E \cdot EQE)^2$ method and the derivative method from the experimental EQE curve of the CIGSS solar cell. The both methods indicated almost the same E_g of 1.01 eV. We confirmed the Eff of 19.2% at the E_g of 1.01 eV for the flexible CIGSS solar cell on the thin Ti foil, which was considered to be comparable level with the rigid chalcopyrite solar cells on the glass substrates. We believe these results are one of big steps for achieving light-weight and flexible tandem solar cells applicable to BIPV, VIPV and aerospace PV.

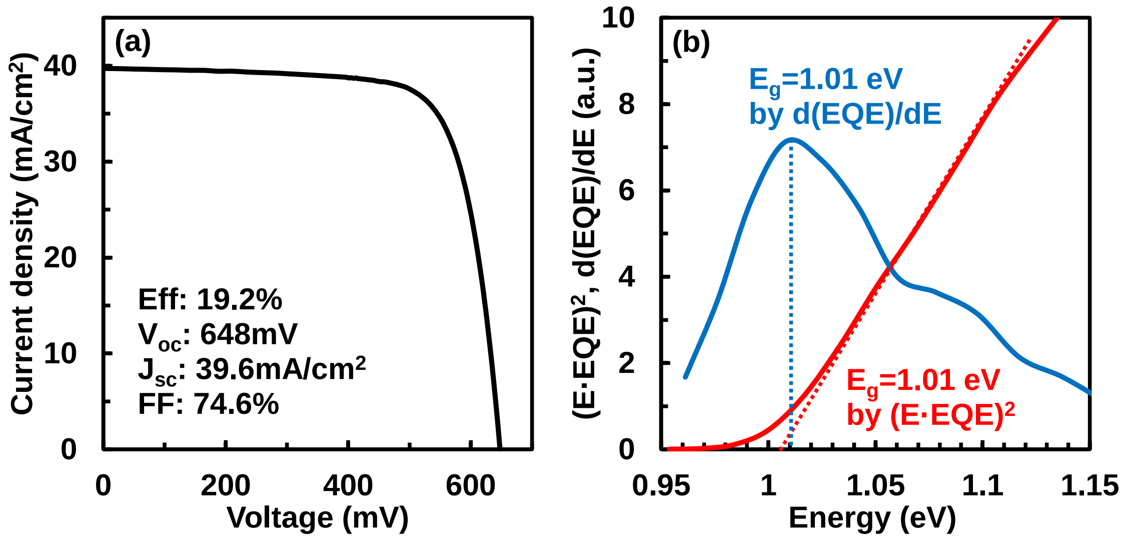

Fig. 1. (a) The best current-voltage characteristic of newly developed flexible CIGSS solar cells. (b) E_g determined by the $(E \cdot EQE)^2$ method (red line) and derivative method (blue line) from experimental EQE curve of the CIGSS solar cell.

3. Summary

Light-weight and flexible chalcopyrite CIGSS solar cells with narrow-gap absorber were developed for the suitable bottom cells of high efficiency double-junction tandem solar cells. The Eff of 19.2% at the E_g of 1.01 eV for the flexible CIGSS solar cells on thin Ti foils was confirmed, which was considered to be comparable level with the rigid chalcopyrite solar cells on the glass substrates. We believe these results are one of big steps for achieving light-weight and flexible tandem solar cells applicable to BIPV, VIPV and aerospace PV.

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