

Direct Bonding using a-Si:H Thin Films for the Fabrication of Chalcopyrite Tandem Solar Cells

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1. Introduction

Tandem solar cells have potential to enhance the conversion efficiency and have been researched with many kind of photovoltaic material [1-2]. Chalcopyrite semiconductors such as $\text{Cu}(\text{In}_{1-x}\text{Ga}_x)\text{Se}_2$ (CIGS) are one of the most promising materials for tandem solar cells, because the bandgap is controllable from 1.05 to 1.68 eV by varying the composition and the best conversion efficiency of over 20% has been reported [3]. While CIGS has good characteristics for tandem solar cells, there is a critical problem for fabrication of tandem solar cells. Typical tandem solar cells such as $\text{GaInP}/\text{GaAs}/\text{GaInAs}$ is fabricated by sequential deposition. However, the electrical characteristics of CIGS solar cells fabricated by a sequential method will degrade due to high temperature ($\sim 550^\circ\text{C}$) during the deposition of the second CIGS absorber [4]. Therefore, it is necessary to develop the fabrication technique of CIGS tandem solar cell structure at low temperature.

Surface activated bonding is one of the promising techniques to bond two CIGS solar cells at low temperature, although in order to succeed in the bonding by surface activated method, the root-mean-square (RMS) of the surface roughness should be lower than 1 nm [5].

In previous our work [6], we proposed surface activated bonding for fabrication of chalcopyrite tandem solar cells. As a material used for bonding, it is desirable to use $\text{ZnO}:\text{Al}$ (AZO), since AZO is the most major transparent conductive oxide for CIGS solar cells. However, the adhesion force between $\text{ZnO}:\text{Al}$ (AZO) thin films was weaker than that between Si substrates and was not enough to apply to tandem solar cell structure. In this paper, we focused on an hydrogenated amorphous silicon (a-Si:H) thin film. Since a-Si:H has short-range order, it is possible to obtain the similar strength of adhesion with a Si wafer. Moreover, a-Si:H has a bandgap of about 1.7 eV which is almost same as the bandgap of a top cell, suggesting that the a-Si:H adhesion layer does not influence the performance of a bottom cell. Therefore, we tried surface activated bonding of a-Si:H thin films.

2. Experimental

AZO and a-Si:H thin film were deposited onto Corning Eagle XG glass substrates. The sample structure was shown in Fig. 1(a). The substrate size was $20\text{ mm} \times 20\text{ mm} \times 0.7\text{ mm}$ and the substrates were cleaned by acetone and ethanol

solutions before the deposition.

30nm-thick AZO was deposited by radio frequency (RF) magnetron sputtering system. Ar was used as a process gas. Ar gas pressure, the plasma power density, deposition time and substrate temperature were 0.4 Pa, $1\text{ W}/\text{cm}^2$, 30 minutes and 200°C , respectively.

After the deposition of AZO films, 30 nm-thick a-Si:H thin films were continuously deposited by plasma-enhanced chemical vapor deposition (CVD) system without air exposure. The flow rate of SiH_4 , H_2 , the plasma power density, deposition time and substrate temperature were 5 sccm, 10 sccm, $6.5\text{ mW}/\text{cm}^2$, 3 minutes and 200°C , respectively.

After the AZO/a-Si:H deposition, the RMS of surface roughness was measured by scanning probe microscopy (SPM) with SHIMADZU SPM-9600. The RMS of surface roughness of two selected samples was 0.3 nm, and these samples were set in a vacuum chamber ($10^{-4}\sim 10^{-5}\text{ Pa}$) facing each other. And then, the surfaces of the two thin films were exposed by O_2 plasma to activate the surface [7]. O_2 gas pressure, plasma power density and activated time were 30 Pa, $1\text{ W}/\text{cm}^2$ and 30 seconds, respectively. Subsequently, the two samples were pressed against each other under the pressure of 1 MPa in the vacuum chamber. During the pressing, two samples were annealed at 200°C for 2 hours. After the annealing, the samples were kept under the pressure for 24 hours.

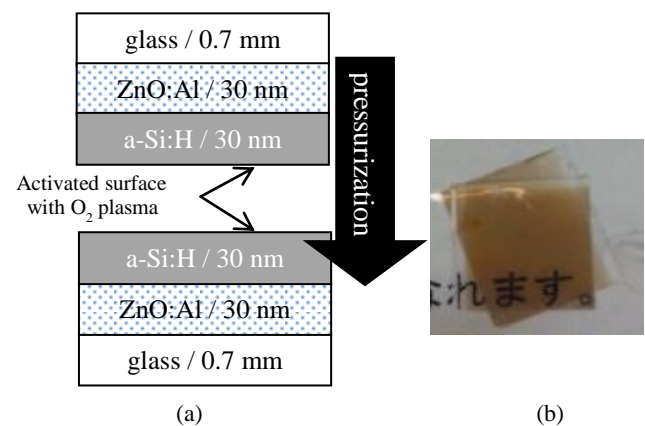


Fig. 1 (a) Schematic of surface activate bonding and the sample structure (b) Picture of bonded a-Si:H/AZO thin films by surface activated bonding

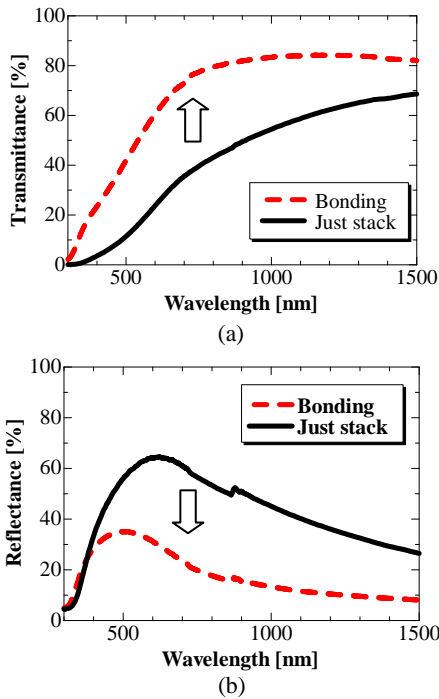


Fig. 2 Difference of optical properties between just stack and surface activated bonding substrates: (a) transmittance, (b) reflectance

3. Results and discussion

After the 24 hours pressurization, two a-Si:H/AZO thin films were successfully bonded. Fig. 1 (b) shows the picture of bonded two thin films on the glass substrates. There was no fringe pattern unlike in the case of AZO bonding [6], and it showed the all part of thin films was bonded completely.

In order to estimate the bonding, we measured the optical characteristics. Fig. 2 shows that surface activated bonding caused the increase of transmittance and the decrease of reflectance. The transmittance increase from 35.7 % to 73.0% and reflectance decrease 61.0 % to 23.6 % at 700 nm, respectively. This result was derived from whether there is the gap between the two samples or not, since the reflectance of interface between two layers with refractive index of n_1 and n_2 was determined by the following equation:

$$R = \left(\frac{n_1 - n_2}{n_1 + n_2} \right)^2 \quad (1)$$

Equation (1) shows the reflectance between 2 materials. And then, the refractive index of each material are $n_{\text{air}}=1$, $n_{\text{glass}}=1.5$, $n_{\text{ZnO}}=1.95$, $n_{\text{a-Si}}=3.92$, respectively. If an air gap exists between a-Si:H thin films, the reflectance is estimated at 59%. On the other hand, if a-Si:H /AZO thin films were bonded without any gap between the a-Si:H thin films, the reflectance will be 27%. This estimation is in good agreement with the experimental data. Therefore, surface activated bonding was successful without any air gap between the

samples.

Adhesion force between a-Si:H thin films was stronger than that of AZO, since the existence of hydrogen-terminated surface. Si-H groups are changed into silanol groups ($\equiv\text{Si-OH}$) by O_2 plasma and the silanol groups may form siloxane ($\equiv\text{Si-O-Si}\equiv$) bonds between the two surfaces accompanied by the release of water at temperature above 200 °C [8] as shown Fig. 3. a-Si:H has hydrogen terminated surface and this is why adhesion force was enhanced.

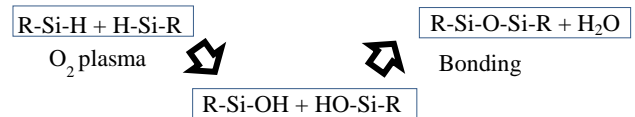


Fig. 3 Reaction process of surface activated bonding with O_2 plasma.

4. Conclusions

a-Si:H thin films were deposited on AZO-deposited glass substrates. The RMS of surface roughness was 0.3 nm. These samples were bonded by surface activated bonding. There was no fringe pattern and the whole of thin films was bonded completely. Measurement of transmittance and reflectance revealed that surface activated bonding was optically successful without any air gap between the samples. Adhesion force between a-Si:H thin films was stronger than that of AZO, since the existence of hydrogen-terminated surface. Therefore, direct bonding using a-Si:H thin films is a promising method for the fabrication of Chalcopyrite -based tandem solar cell structure.

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References

- [1] T. Agui, H. Juso, A. Yoshida, K. Nakaido, K. Sasaki, and T. Takamoto: Renewable Energy Proc. , Yokohama, O-Pv-5-4 (2010).
- [2] A. Banerjee, T. Su, D. Beglau, G. Pietka, F. Liu, G. DeMaggio, S. Almutawalli, B. Yan, G. Yue, J. Yang, and S. Guha: Proc. 37th IEEE PVSC, Seattle, June 2011.
- [3] M. A. Green, K. Emery, Y. Hishikawa, W. Warta: Prog.Photovolt.:Res. Appl,**19**(2011) 84-92.
- [4] S. Kijima and T. Nakada: Appl. Phys. Exp. **1**(2008) 075002.
- [5] H. Takagi, R. Maeda, T. R. Chung, N. Hosoda and T. Suga: Jpn. J. Appl. Phys, **37**(1998), 4197.
- [6] Y. Nakajima, Y. Kurokawa and A. Yamada: Tech. Dig. 21st Int. Photovoltaic Science & Engineering Conf. (PVSEC-21), PVSEC21, Fukuoka, 2D-3P-20.
- [7] H. Shinohara, J. Mizuno and S. Shoji: IEEJ Trans, **2** (2007) 301-306.
- [8] R. Stengl, T. Tan, and U. GoÈsele: Jpn. J. Appl. Phys. **28** (1989) 1735.