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Improvement in Effective Optical Absorbency for the Bottom Cells of Mechanical Stacked Multi-Junction Solar Cells

Masahiko Hasumi[1], Yoshihiro Ogawa[1], Kousuke Oshinari[1], and Toshiyuki Sameshima[1]
[1] Tokyo Univ. of Agri. and Tech.
2-24-16 Naka-cho, Koganei, Tokyo 184-8588, Japan
Phone: +81-42-388-7109 E-mail: tsamesim@cc.tuat.ac.jp

Abstract

Reduction of optical reflection loss at intermediate region of mechanical stacked samples is discussed in the case of top GaP and bottom Si substrates bonded with epoxy adhesive. Transparent and conductive Indium gallium zinc oxide (IGZO) layers with thicknesses of 102 nm were formed on the bottom surface of GaP and the top surface of Si substrates. The insertion of IGZO layers reduced the optical reflectivity of the stacked sample. It successfully gave high effective optical absorbency for bottom substrates, A_{eff} of 0.93 for wavelength regions for light in which top GaP substrate was transparent and bottom Si substrate was opaque. High A_{eff} values were maintained by changing the light incident angle from 0 to 50°.

1. Introduction

We have proposed mechanically stacked-type multi-junction solar cells with transparent conductive adhesive layers [1,2]. The epoxy adhesive layer dispersed with 20-μm-sized Indium tin oxide (ITO) conductive particles has achieved the connecting resistivity lower than 0.5 Ωcm^2. It was low enough to fabricate multi-junction solar cells with efficiency higher than 30%. On the other hand, large difference in refractive indexes of semiconductor materials and adhesive causes high optical reflection, which reduces transmittance of light into the bottom cell. We propose conductive and transparent IGZO layers formed between the semiconductor substrates and intermediate adhesive to reduce optical reflection loss [3]. In this paper, we report calculation and experimental demonstration of reduction in optical reflection loss with different incident angles of light. We report values of A_{eff} higher than 0.9 when the IGZO anti-reflection layers with appropriate film thicknesses are formed.

2. Calculation of A_{eff}

A numerical calculation program of optical reflectivity spectra for the structure of top substrate/IGZO/adhesive/IGZO/bottom substrate was developed to analyze experimental reflectivity spectra and A_{eff}. The top and bottom substrates were thick enough to ignore the optical interference effect of incident light. The intermediate adhesive layer has a thickness of 20 μm. We also assumed that no optical interference effect occurred between the top and bottom adhesive surfaces. The Fresnel-type optical interference effect was calculated for the IGZO layer under the assumption of simple plain wave model. The optical phase coupling results in an interface with a new reflectivity coefficient depending on IGZO film thickness for both surface cases of the intermediate adhesive layer. The four individual optical interfaces are therefore formed by five optical media of air, top substrate, intermediate adhesive layer, bottom substrate, and air, as shown in Fig. 1, while the real sample has six material interfaces. A calculation system of multiple reflections and transmission was made between the four interfaces to obtain the optical reflectivity. When the wavelength is located between the top substrate is transparent and the bottom substrate is opaque, the optical reflectivity of sample is given by multiple reflection components between the three top interfaces as well as a component given by the top surface, as shown in Fig. 1. The reflectivity at second and third interfaces given by IGZO is therefore important to reduce the total reflectivity.

To estimate optical reflection loss, the effective optical absorbency for bottom substrate, A_{eff} was defined as

$$A_{eff} = \int_{\lambda_1}^{\lambda_2} (1 - R(\lambda)) d\lambda \Big/ \int_{\lambda_1}^{\lambda_2} (1 - r_{top}(\lambda)) d\lambda \quad , (1)$$

where $R(\lambda)$ is the optical reflectivity of sample at the wavelength λ and $r_{top}(\lambda)$ is the reflectivity at the top surface of an individual top substrate. λ_1 and λ_2 are the shortest and longest wavelength for conditions with transparent top and opaque bottom substrates. The denominator is the integration of light incidence ratio into the top substrate between λ_1 and λ_2 because the top substrate was transparent at wavelength longer than λ_1. The numerator is the integration of optical absorption ratio of sample between λ_1 and λ_2. Because the bottom substrate was opaque at wavelength shorter than λ_2, the numerator of eq. (1) depends on the reflectivity at the interface adhesive layer. A_{eff} therefore gives the effective optical absorbency for the bottom substrate of incident light at the top substrate. Figure 2 shows calculated A_{eff} with normal incident as a function of IGZO thickness for the stacked samples with top Si and bottom Ge, top GaAs and bottom Si, and top GaP and bottom Si substrates A_{eff} increased as the IGZO thickness increased for every sample. It had peaks at the IGZO thicknesses of 183, 130, and 102 nm, respectively, in the cases of stacking Si and Ge, GaAs and Si, and GaP and Si. The peak values of A_{eff} were higher than 0.9 in the all sample cases. Zero thickness of IGZO gave the lowest value in each A_{eff}. It means that the samples with no IGZO layers had the highest optical reflection loss at the intermediate adhesive layer.

3. Experimental Procedure

We prepared 2-inch crystalline GaP and 4-inch crystalline Si substrates. 102-nm-thick IGZO layers with a resistivity of 0.01 Ωcm were formed on the surfaces of GaP and Si substrates by radio frequency Ar plasma sputtering. The refractive index of the IGZO layers was 1.85. Transparent conductive adhesive with a refractive index of 1.47 was fabricated by dispersing 3.8 wt% ITO conductive particles in the Cemedine adhesive. Then it was pasted on the IGZO surfaces. They were stacked and kept in a pressure proof chamber with N_2 gas at 8.0×10^5 Pa for 2 h for solidifying the adhesive jell to make sample with a structure of GaP/102 nm-thick IGZO/adhesive/102nm-thick IGZO/Si. We also prepared a sample with a structure of GaP/adhesive/Si for comparison. Optical reflectivity spectra of the samples were measured with integrated sphere equipment with incident angles ranging from 0 to 20°. A home-made optical reflection measurement system with incident angle from 10 to 50° was also used, as shown in Fig. 3. Light of air mass 1.5 was slant irradiated to the sample. A crystalline GaP wafer was placed as optical filter which cut light with photon energy higher than GaP band gap. Reflection light was detected by a two dimensional Si photodetector. The angles of incident and reflectance lights were coincidentally changed from 10 to 50°. Consequently, reflectance light was detected for wavelength between 568 (λ_1) and 1020 nm (λ_2) given by the band gaps of GaP and Si.

4. Results and Discussion

Figure 4 shows experimental optical reflectivity spectra for the samples of GaP/102nm-IGZO/adhesive/102nm-IGZO/Si and GaP/adhesive/Si with incident angles of 0 and 20°. For each sample, similar reflectivity spectra were observed for incident angles of 0 and 20°. The sample of GaP/102nm-IGZO/adhesive/102nm-IGZO/Si had optical reflectivity ranging from 40 to 33% for wavelength between 568 and 1020 nm, where GaP was transparent and Si was opaque. On the other hand, high optical reflectivity ranging from 48 and 44% was observed for the sample of GaP/adhesive/Si. These results indicate that the 102-nm-thick IGZO layer give good anti-reflection condition.

Figure 5 shows experimentally obtained A_{eff} as a function of incident angle for the two samples measured by the system shown in Fig. 3. The calculated A_{eff} values with incident angle are also shown by dashed curves. The arrows at incident angle of 0° represent the experimental A_{eff} values obtained from the reflectivity spectra measured by the conventional spectrometer. High A_{eff} was observed for the sample of GaP/102nm-IGZO/adhesive/102nm-IGZO/Si structure. A_{eff} ranged from 0.91 to 0.94 for incident angles between 10 and 50°. On the other hand, A_{eff} ranged from 0.74 to 0.82 for the sample of GaP/adhesive/Si. The measurement results are consistent with the A_{eff} values of 0.93 and 0.79 obtained from the spectrometer, respectively for the samples of GaP/102nm-IGZO/adhesive/102nm-IGZO/Si and GaP/adhesive/Si. For each sample, calculated A_{eff} showed almost constant values for incident angles ranging from 0 to 50°. They showed good agreement with experimentally obtained values. High A_{eff} is simply achieved by the formation of single layer IGZO anti-reflection films with appropriate film thickness. We will present experimental results of samples with structures of GaAs/IGZO/adhesive/IGZO/Si and Si/IGZO/adhesive/IGZO/Ge at the conference. We will also discuss the optimum condition of low optical reflection loss with different incident angles.

5. Conclusions

We demonstrated reduction of optical reflection loss by IGZO anti-reflection layers at the intermediate adhesive layer for mechanical stacked multi-junction solar cells. Numerical analysis of reflectivity spectra gave the best IGZO thicknesses of 102 nm for GaP and Si stacked sample for the highest values of A_{eff}. GaP/102-nm-thick IGZO/adhesive/102-nm-thick IGZO/Si sample were fabricated by 3.8 wt% ITO particles dispersed epoxy adhesive and the sputtering method for IGZO formation. The insertion of IGZO layers reduced the optical reflectivity of the stacked sample for wavelength ranging from 568 to 1020 nm. It successfully gave high A_{eff} ranged from 0.91 to 0.94 for incident angles from 0 to 50°.

Acknowledgements

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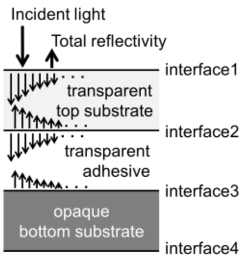


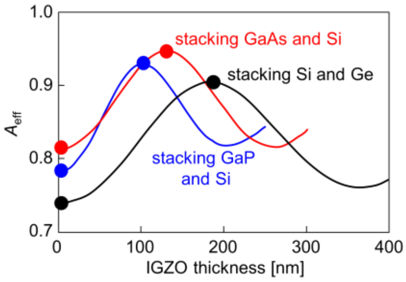
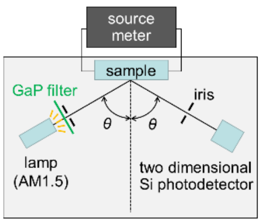


Fig. 1 Calculation image of multiple reflections and transmission in the case of wavelength between the top substrate is transparent and the bottom substrate is opaque.

Fig. 2 Calculated A_{eff} as a function of IGZO thickness for the samples with top Si and bottom Ge, top GaAs and bottom Si, and top GaP and bottom Si substrates.



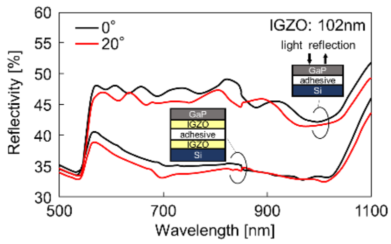


Fig. 3 Schematic image of optical reflection measurement system with incident angle.

Fig. 4 Experimental optical reflectivity spectra for the samples with incident angles of 0 and 20°.

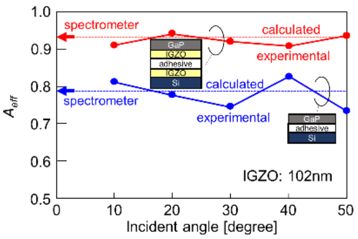


Fig. 5 Experimental and calculated A_{eff} as a function of incident angle. Arrows show the A_{eff} obtained from the reflectivity spectra.