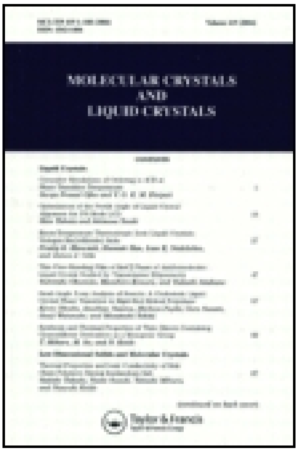

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Effect of ZnO Layer Thickness on Efficiency of $Cu(In,Ga)Se_2$ Thin-film Solar Cells

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The effect of intrinsic ZnO(i-ZnO) layer thickness on the efficiency of $Cu(In,Ga)Se_2$ (CIGS) thin film solar cells was investigated using ITO/ZnO/CdS/CIGS/Mo structures. CIGS thin films were deposited on Mo-coated soda-lime glass using co-evaporation. CdS buffer layers of about 50nm thickness were then grown by chemical bath deposition on the top of CIGS layer. Finally, the ZnO and ITO layers were deposited using rf-magnetron sputtering, resulting in solar cells with ITO/ZnO/CdS/CIGS/Mo structure. From the optical and electrical characteristics of the solar cells, we found a close relationship between the transmittance of the ZnO layer and the efficiency of the solar cells. Several characteristics improved for solar cells with a 50 nm thick ZnO layer relative to those with both 90 nm thick and no ZnO layer. Therefore, we conclude that the optimum ZnO thickness for CIGS-based solar cells is around 50 nm.

Keywords Co-evaporation; $Cu(In Ga)Se_2$; Efficiency; i-ZnO; Solar cell

Introduction

$Cu(In,Ga)Se_2$ (CIGS) thin film solar cells have attracted great attention owing to their high efficiency, with values reported to be as high as 19.9% [1] and 20.3% [2]. While the fabrication process for CIGS solar cells is well established [3–4], the thickness of the intrinsic ZnO layer for these reported high-efficiency solar cells found to vary between 50 and 100 nm [2] or fixed at 90nm [1,3]. The intrinsic ZnO layer prevents the leakage current between the buffer layers and the transparent conductive oxide (TCO) layer of CIGS solar cell. In this study, we explored the relationship between the thickness of the intrinsic ZnO layer and efficiency of CIGS solar cells.

We measured the external quantum efficiency and J-V characteristics of the prepared solar cells as a function of the ZnO layer thickness and performed the same measurements for solar cells without a ZnO layer. In order to systematically study the effect of ZnO

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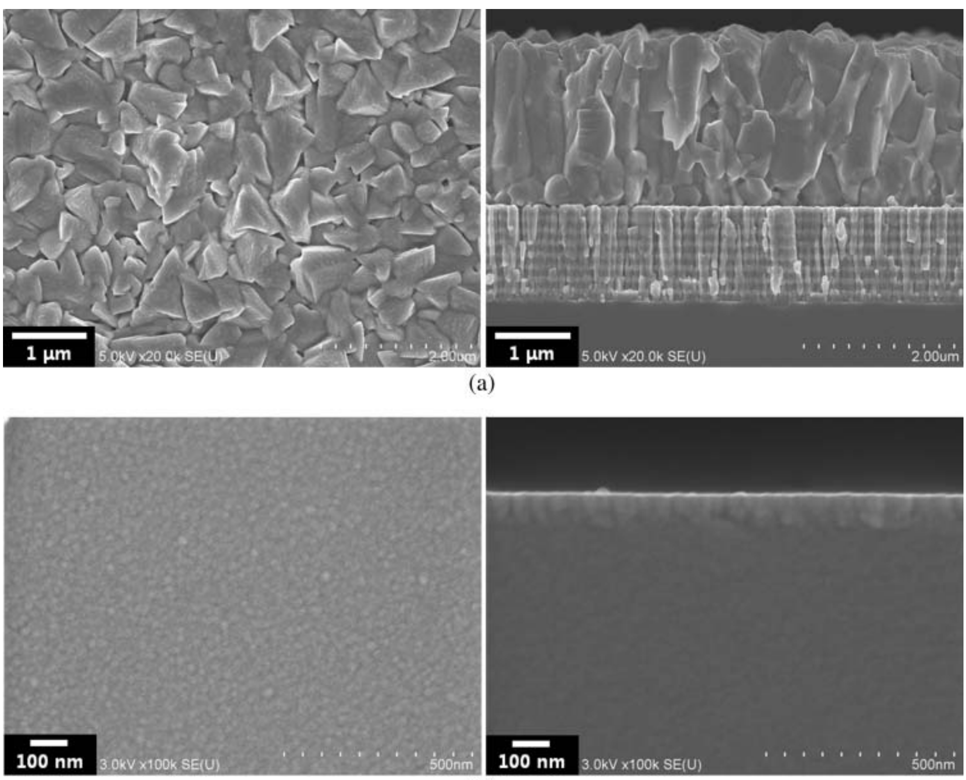
thickness on the solar cell, we avoid certain processing steps that are known to affect solar cell efficiency, such as post-CdS growth annealing [5] and heating the substrate during window layer deposition [6].

We found a close relationship among the thickness of the ZnO layer, the transmittance of the ZnO layer, and the efficiency of our solar cells. Several solar cell characteristics improved for samples with a 50 nm thick ZnO layer relative to those with both a 90 nm thick ZnO layer and no ZnO layer. From these observations we conclude that the optimum ZnO thickness is around 50 nm for CIGS-based thin-film solar cells.

Experimental

$Cu(In,Ga)Se_2$ (CIGS) thin films were deposited on Mo coated soda-lime glass (SLG) using the co-evaporation method. The evaporation rate of each element was measured by using a quartz crystal microbalance (QCM) sensor and controlled by the power to the effusion cell. During evaporation, the substrate temperature was maintained at 570°C. A 50 nm buffer layer of CdS was grown on the CIGS thin film using chemical bath deposition (CBD). The CBD process was performed by dipping the CIGS film into a mixed solution of $CdSO_4$, thiourea(CH_4N_2S), and NH_4OH for 10 min at 50°C. The ZnO and ITO-window layer were then deposited using rf-magnetron sputtering at 5mTorr argon gas pressure with an rf power



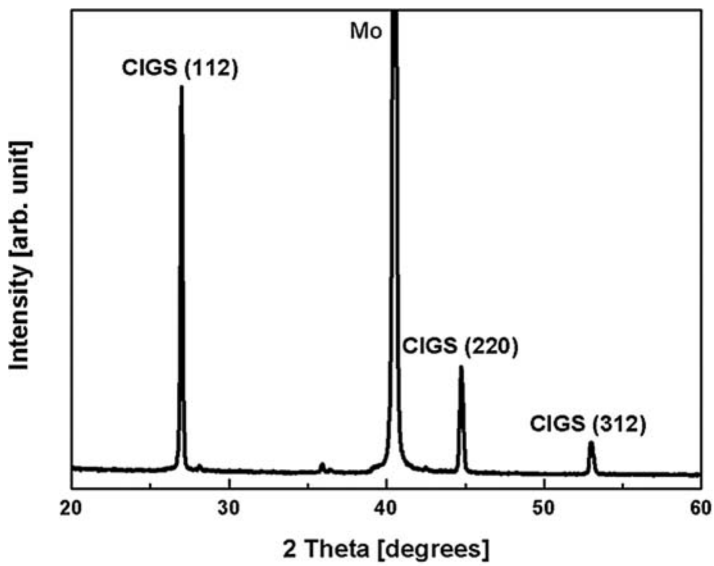
(a)

(b)

Figure 1. Surface (left) and cut-view (right) secondary electron contrast SEM images of the CIGS (a) and ZnO (50 nm) (b) films.

of 300W. The substrate was not heated during this process. The thickness of the ZnO layer was controlled by tuning the deposition time. We deposited a 150 nm thick layer of ITO as an electrode. For efficiency measurements, a patterned aluminum layer was then deposited using a thermal evaporator with a shadow mask. By this fabrication process, we obtained eight solar cell samples each with a particular ZnO layer thickness.

The morphology of the grown films was analyzed by X-ray diffraction (XRD, PANalytical X'pert Pro-MPD) and field emission scanning electron microscopy (FE-SEM, Hitachi S-4800). The atomic composition of the CIGS films was measured by inductively coupled



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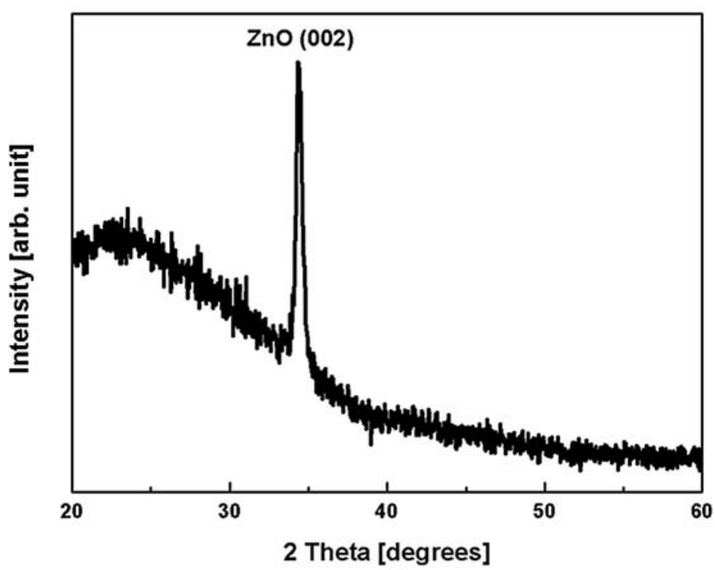

(b)

Figure 2. XRD patterns of the CIGS (a) and ZnO (b) films.

plasma-atomic emission spectroscopy (ICP-AES, Shimadzu, ICP-8100). The transmittance of the films was determined by UV-VIS-NIR spectroscopy (Perkin Elmer, Lambda 750). The J-V curves (obtained under AMI 1.5 global illumination) and the external quantum efficiency (EQE, Mc Science, IPCE K3100 measured in a wavelength range of 350∼1500 nm) of CIGS solar cells with different ZnO layer thicknesses were compared.

Results and Discussion

From ICP-AES data, we determined that the composition ratios of constituent elements in the CIGS film were Cu/(In+Ga) ∼ 0.95, Ga/(In+Ga) ∼ 0.3, and Se/(In+Ga) ∼ 2.0. Thus, the chemical composition of the CIGS film could be expressed as $Cu_{0.95}$ $(In_{0.7}$ $Ga_{0.3})$ Se_2. Figure 1 shows surface and cut-view SEM images of the CIGS and ZnO films. From these images, we observed large crystalline CIGS grains (Fig. 1-a). Figure 1-b shows the clear deposition edge and uniform surface of the ZnO film. Figure 2 shows representative XRD patterns of the CIGS and ZnO films. Figure 2-a shows typical XRD patterns of CIGS [7]. From Fig. 2-b, we found that ZnO has a hexagonal structure with c-axis of (002) orientation.

Eight different CIGS solar cell samples were prepared corresponding to each ZnO thickness in order to average the optical and electrical characteristics of solar cells. Figure 3 shows the optical transmittance of the ZnO films in the wavelength range of 360∼1,100 nm. The transmittance of the films was above 80% at greater than 420 nm for both 50 and 90 nm films. The 50 nm film was more transparent than the 90 nm film except in the range of 400 ∼ 500 nm

Figure 4 shows the J-V curves of CIGS solar cells with three different ZnO layer thicknesses. Both open circuit voltage (V_{oc}) and short circuit current density (J_{sc}) were found to be highest for the solar cell sample with a 50 nm ZnO layer. Figure 5 shows the EQE curves for CIGS solar cells with three different ZnO layer thicknesses. The solar cell sample with a 50 nm ZnO layer had the highest efficiency.

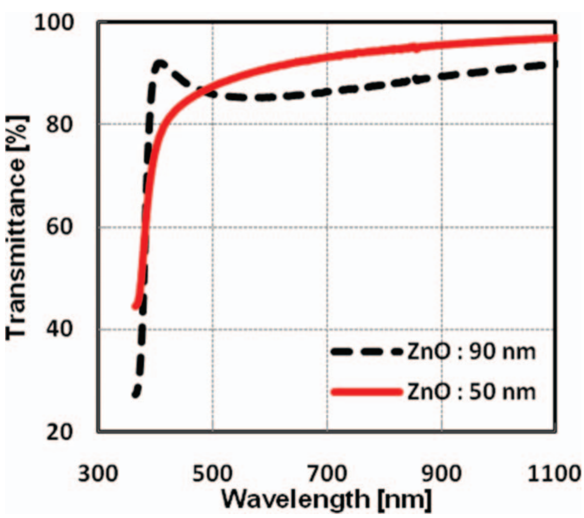

Figure 3. Optical transmittance of the 50 nm and 90 nm ZnO films.

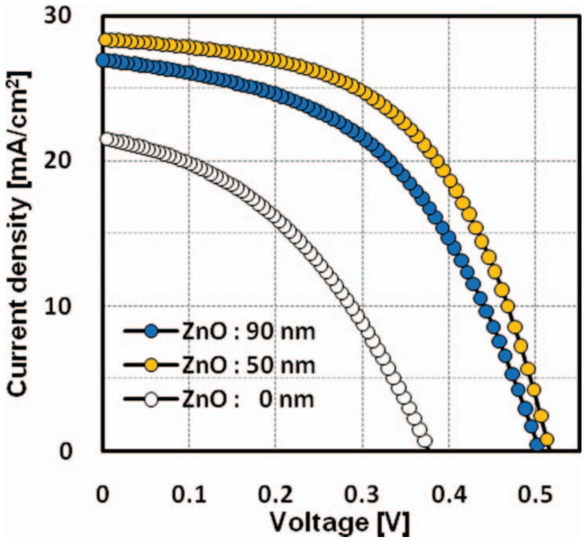

Figure 4. Dependence of J-V characteristics of the CIGS solar cells on ZnO thickness.

Electrical characteristics of each solar cell are summarized in Table 1. In this table, "Avg." and σ for each property represent the average value and standard deviation, respectively, for eight samples with the same ZnO layer thickness. "Max." denotes the largest value found among the eight samples with the same ZnO layer thickness. The solar cells with a 50 nm thick ZnO layer showed the largest values of all electrical characteristics. In particular, the 50 nm ZnO solar cell showed about a 1% higher efficiency than the 90 nm ZnO solar cell. Figures 3 and 5 also reveal a close relationship between the transmittance of the ZnO layer and the efficiency of the solar cells. A higher transmittance in the ZnO

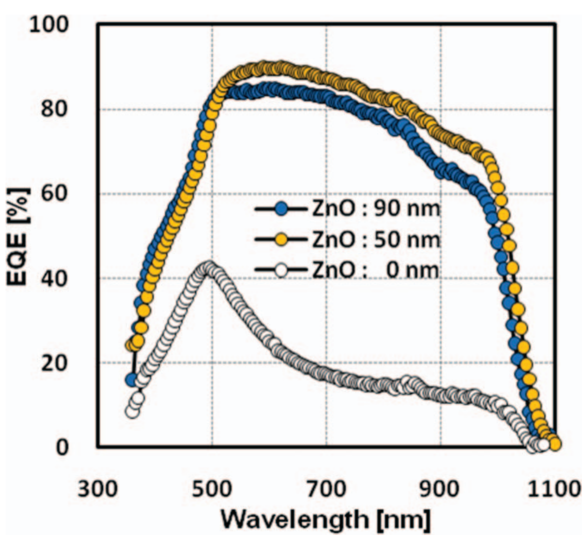

Figure 5. Dependence of external quantum efficiency of the CIGS solar cells on ZnO thickness.

Table 1. Properties extracted from the J-V curve of CIGS solar cells with different ZnO layer thicknesses.

	Efficiency [%]			V_{oc}[V]			J_{sc}[mA/cm^2]			Fill factor [%]			Series Resistance [Ω]			Shunt Resistance [Ω]		
ZnO Thickness	Max.	Avg.	σ	Max.	Avg.	σ	Max.	Avg.	σ	Max.	Avg.	σ	Max.	Avg.	σ	Max.	Avg.	σ
0 nm	3.29	2.78	0.40	0.380	0.363	0.020	22.63	21.54	0.76	40.4	35.4	2.9	43.5	40.3	3.8	366	228	87
50 nm	7.88	7.37	0.39	0.516	0.510	0.006	28.83	27.53	0.79	54.5	52.5	1.6	23.9	20.2	1.9	931	832	98
90 nm	6.63	6.43	0.22	0.505	0.500	0.004	28.17	27.13	0.62	48.7	47.4	1.4	29.0	25.3	1.8	624	548	47

layer results in a higher solar cell efficiency. The CIGS solar cell without a ZnO layer showed poorer electrical characteristics than the cells that had a ZnO layer. The solar cell characteristics improved by the addition of a ZnO layer, but deteriorated when the 90 nm ZnO layer was used. Thus, we can conclude that there exists an optimum thickness for the ZnO layer between 0 and 90 nm. From our observations, we found that this optimum ZnO layer thickness was about 50 nm.

Conclusions

CIGS [Cu(In,Ga)Se_2] solar cells were fabricated by depositing a sequence of CIGS, CdS, ZnO, and ITO films on Mo coated soda-lime glass. We measured several solar cell characteristics as a function of ZnO layer thickness.

We found that a higher transmittance of the ZnO layer resulted in a higher solar cell efficiency. The solar cell characteristics improved for the sample with a 50 nm thick ZnO layer relative to samples that had both a 90 nm ZnO layer and no ZnO layer. From these observations we found that the optimum ZnO thickness for CIGS-based solar cells is about 50 nm.

Acknowledgment

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