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Numerical Modelling of Ultra Thin $Cu(In,Ga)Se_2$ Solar Cells

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Abstract

Various thicknesses of copper-indium-gallium-diselenide (CIGS) absorber layer are incorporated into numerical simulation by Solar Cell Capacitance Simulator (SCAPS) to investigate the performance of ultra thin CIGS solar cells. $CuIn_{1-x}Ga_xSe_2$ absorber layer thickness is varied from 0.3-1.0 µm. Results show that the performance of CIGS solar cells decreases as the absorber layer thickness is decreased. Conversion efficiencies of 10.74% and 14.36% are achieved for cells with 0.3 µm and 1.0 µm thick absorber layers, respectively. Incorporation of band gap grading or commonly known as back surface field in the ultra thin CIGS solar cells improves the performance of the cells. In this study, back surface field is incorporated in the numerical modelling of the ultrathin CIGS solar cells. For the graded cells, efficiencies of 12.38% and 17.26% are achieved for cells with 0.3 µm and 1.0 µm thick absorber layers. These improvements are attributed to the less recombination loss at the CIGS/Mo interface. This study shows ultra thin CIGS solar cells have comparable performance parameters with the conventional CIGS solar cells.

Keywords: Solar cells; ultra thin film; CIGS; SCAPS

1. Introduction

Copper-indium-gallium-diselenide (CIGS) thin film solar cell has achieved the highest conversion efficiency [1] compared to other Cu-chalcopyrite thin film solar cells as well as CdTe and amorphous Si

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thin film solar cells. The active layer of this thin film solar cell is the p-type $CuIn_{1-x}Ga_xSe_2$ polycrystalline semiconductor which acts as the absorber layer. $CuIn_{1-x}Ga_xSe_2$ has a variable band gap of 1.04 to 1.68 eV [2]. When x=0, the ternary system of CIS has a bandgap of 1.04 eV, while x=1 represents CGS which has a bandgap 1.68 eV. Currently, CIGS solar cells with x=0.3 which corresponds to a bandgap energy range of 1.1-1.2 eV yields the best efficiency both in laboratory and commercial modules. CIGS thin film solar modules exhibit good outdoor stability [3] and also radiation hardness [4].

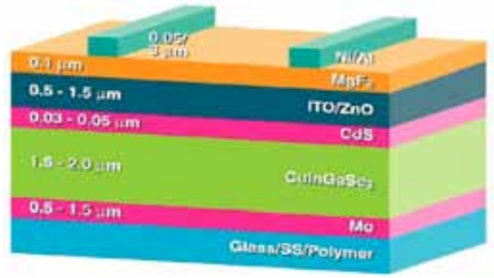

Fig. 1. Schematic view of CIGS solar cells

CdS layer as shown in Fig. 1 acts as the buffer layer between the highly conductive ZnO window layer and $CuIn_{1-x}Ga_xSe_2$ absorber layer. Since CdS is an n-type semiconductor, a p-n heterojunction is formed across the CdS/$CuIn_{1-x}Ga_xSe_2$ interface. Mo and Ni/Al structure act as the back and front electrode for the cell while MgF_2 layer acts as the anti-reflecting coating to minimise the reflection of incident photons. $CuIn_{1-x}Ga_xSe_2$ absorber layer is generally fabricated by co-evaporation of Cu, In, Ga and Se elements in vacuum condition. The currently best CIGS solar cell in terms of conversion efficiency is fabricated by a specially sequenced co-evaporation technique so-called *three-stage process* [5]. Apart from this technique, other fabrication method such as selenisation of metal precursors [6] and rapid thermal processing of stacked elemental layer [7] also produce absorber layers which have reasonable conversion efficiency. CdS is usually deposited by chemical bath deposition (CBD) technique [8] and ZnO window layer is grown by sputtering method. Practically, the thickness of $CuIn_{1-x}Ga_xSe_2$ absorber layer is around 1.5-2.5 µm thick. Optimum thickness of $CuIn_{1-x}Ga_xSe_2$ absorber layer determined by numerical simulation is around 3 µm [9]. Thicker absorber layer means more material usage as well as associated cost, particularly indium. Indium is an expensive material and its availability is estimated to diminish due to large indium consumption by flat panel display industry in the coming years [10]. Hence, lesser material usage leads to lesser overall cost of fabricating CIGS thin film solar cells a promising low-cost alternative for green energy application. In this study, numerical simulations of CIGS solar cells with ultra thin absorber layer are carried out to investigate the performance of ultra thin CIGS solar cells. Investigation on the effects of bandgap grading on the performance of the ultra thin CIGS solar cells are also carried out.

2. Numerical simulation methodology

In this study, numerical modelling of CIGS thin film solar cell has been carried out by SCAPS-1D, version 2.8.02 computer software to investigate the effects on absorber band gap grading on the overall CIGS solar cell device performance. SCAPS-1D is a one-dimensional computer software developed at the University of Ghent under Marc Burgelman [11]. It is developed especially to simulate the AC and DC characteristics of heterojunction thin film solar cells, especially CIGS and CdTe solar cells. The special feature of SCAPS-1D version 2.8.02 can analyse the solar cell with graded band gap [12]. In this numerical study, $CuIn_{1-x}Ga_xSe_2$ absorber layer thickness is varied from 0.3-1.0 µm. A base case simulation with 2.5 µm thick $CuIn_{1-x}Ga_xSe_2$ is also carried for comparison purposes.

Output such as current voltage characteristics in the dark and under illumination can be obtained from the solution provided by an SCAPS simulation. For solar cell and detector structures, collection efficiencies as a function of voltage, light bias, and temperature can also be obtained. In addition, important information such as energy band diagram of the overall cell, occupation probability of deep defects, carrier generation-recombination profiles, and individual carrier current densities as a function of position can be extracted from the SCAPS program.

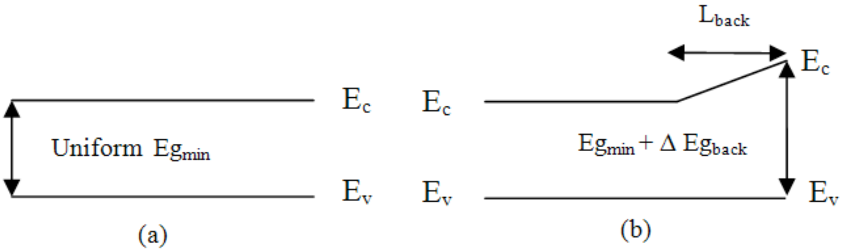

Fig. 2. Energy band diagrams. (a) Uniform band gap; (b) back surface graded band gap

Figure 2 above shows the energy band diagrams of CIGS absorber layer that have been numerical modelled in this study. By incorporating the various material parameters into SCAPS for all of the analysis aspects, changes in the values for efficiency, V_{oc}, J_{sc} and FF are obtained and recorded. Finally, the performances of the solar cell are analysed via its J-V characteristics and spectral response. Hence, numerical simulation enables researchers to perform theoretical studies on the overall characteristics and performance of solar cells. Although the final output of the numerically modelled solar cell and the real fabricated solar cell is the overall efficiency, there will be definitely some marginal differences between both results. This is due to the complexity of fabrication process which may induce many other physical electronic processes in which the numerical modelling cannot replicate or take into account during the simulation. However, numerical modelling offers a great opportunity to the scientific community to understand and explore the working principles of various photovoltaic devices prior to the practical cell fabrication and characterisation.

3. Results and discussion

3.1. Cell performance with variable ultra thin $CuIn_{1-x}Ga_xSe_2$ absorber layer

Thickness of $CuIn_{1-x}Ga_xSe_2$ absorber layer is varied from 0.3 µm to 1.0 µm. The performances of the respective cells are shown in terms of V_{oc}, J_{sc}, FF and efficiency in Fig. 2. All the performance parameters in Fig. 3 show an increasing trend as the $CuIn_{1-x}Ga_xSe_2$ absorber layer is increased from 0.3 µm to 1.0 µm. Performance of conventional CIGS solar cell with 2.5 µm $CuIn_{1-x}Ga_xSe_2$ absorber layer simulated in this study yields an efficiency of 19.14% and has been used as a reference case. For a 0.3 µm thick $CuIn_{1-x}Ga_xSe_2$ absorber layer, the obtained efficiency is 10.74%. The highest efficiency obtained is 14.36% which corresponds to 1 µm thick $CuIn_{1-x}Ga_xSe_2$ absorber layer solar cell. The increase in the conversion efficiency is mainly due to the increase in the p-type $CuIn_{1-x}Ga_xSe_2$ absorber layer. As the p-type layer is increased more photons with longer wavelength can be collected in the absorber layer [9]. This eventually will contribute to more electron-hole pair (EHP) generation therefore increasing the open circuit voltage, V_{oc} and short circuit current, J_{sc}. An increase in J_{sc} and V_{oc} will collectively increase the conversion efficiency of the solar cell. Meanwhile, a very thin absorber layer physically means the back contact and the depletion region are very close to each other which enhances the capturing of electrons by the back contact. This form of recombination process is detrimental to the cell performance as it affects both V_{oc} and J_{sc}.

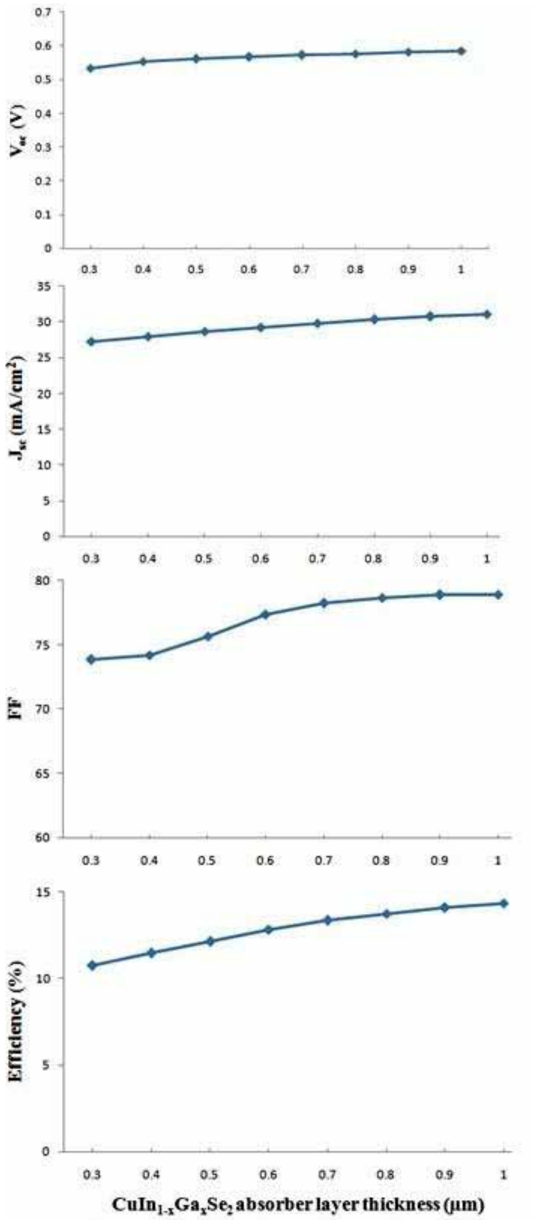

Fig. 3. Cell performance with variable $CuIn_{1-x}Ga_xSe_2$ absorber layer thickness

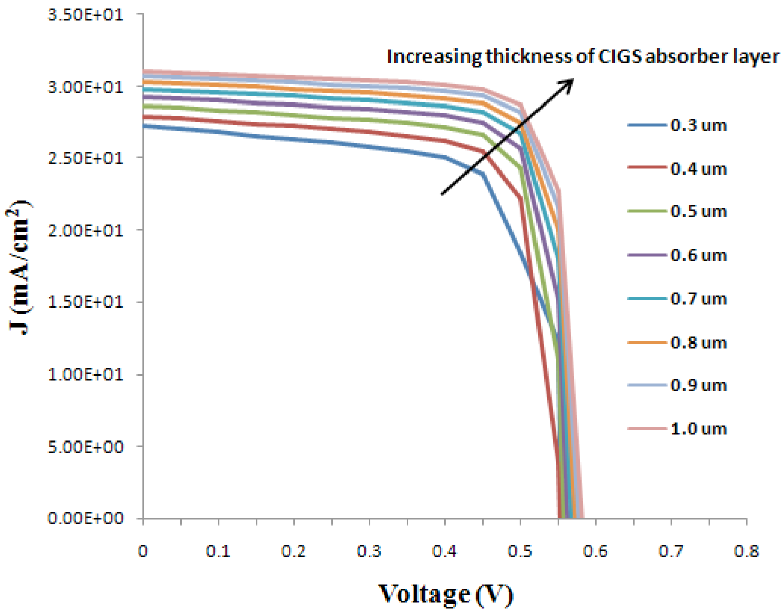

Fig. 4. J-V characteristics of solar cells with variable absorber layer thickness

Figure 5 shows the spectral response of the solar cell with variable absorber layer thickness. As mentioned earlier, when the p-type layer increases, more photons with longer wavelength can be collected in the absorber layer. This eventually will contribute to more electron-hole pair (EHP) generation and collection as the longer wavelength photons can be absorbed. The effect can clearly be observed in the spectral response of the solar cell. The quantum efficiency for a thicker absorber layer is much higher in the long wavelength portion as minority carrier diffusion length gains positively.

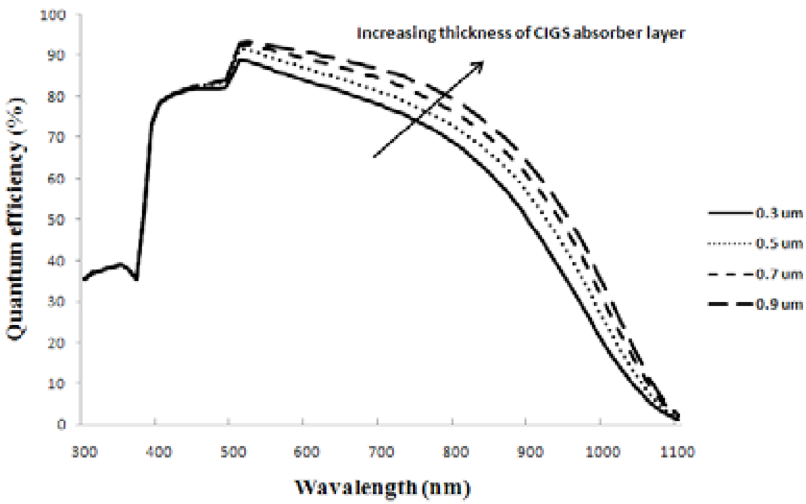

Fig. 5. Spectral response of solar cells with variable $CuIn_{1-x}Ga_xSe_2$ absorber layer thickness

3.2. Cell performance with variable ultra thin $CuIn_{1-x}Ga_xSe_2$ absorber layer

As mentioned earlier, recombination of electrons at the back contact is due to the depletion region being very close to the back contact. Furthermore, CIGS/Mo interface is expected to have high recombination velocity [13] which will enhance the electron capturing process during the cell operation. In order to increase the efficiency of the ultra thin CIGS solar cells, the carrier recombination at the back surface must be mitigated. One of the practical ways is to induce quasi-electric field towards the back contact by back surface band gap grading [14] or more commonly known as back surface field. Back surface field is created by increasing the level conduction band minimum by incorporating Ga at the back surface of $CuIn_{1-x}Ga_xSe_2$ absorber layer.

In this study, numerical study of ultra thin CIGS solar cells with back surface field is carried out. The band gap energy at the back surface is increased 0.1 eV. The physical structure of the CIGS solar cell is not altered for this simulation. By incorporating the back surface field, the efficiency of 0.3 µm thick $CuIn_{1-x}Ga_xSe_2$ absorber layer increases from aforesaid 10.74% to 12.38% while the efficiency of 1.0 µm thick $CuIn_{1-x}Ga_xSe_2$ absorber layer increases from 14.36% to 17.26%. To elucidate the effects of back surface field more clearly, numerical simulation has been applied to a 0.5 µm and 0.9 µm thick CIGS absorber layer solar cells. Figure 6 shows the J-V characteristics of graded and non graded ultra thin CIGS solar cells while Table 1 shows the efficiencies for all the respective J-V curves.

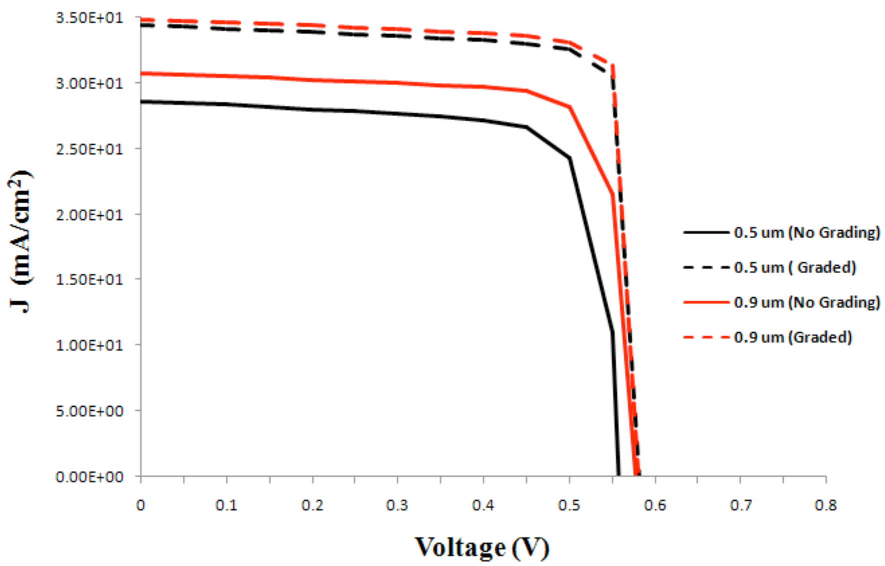

Fig. 6. J-V characteristics of graded and non-graded CIGS solar cells with various thicknesses

Table 1. Efficiency of graded and non graded cell with various CIGS layer thicknesses

CIGS Absorber Layer Thickness	Back surface field	Efficiency (%)
0.5 µm	No grading	12.15
0.5 µm	Graded	**16.21**
0.9 µm	No grading	14.09
0.9 µm	Graded	**17.24**

For non-graded cells, there is a comparable difference in the current density between thinner (0.5 µm) and thicker (0.9 µm) cell. There are 2 possible factors that contribute to the aforesaid phenomena. First, the recombination rate in the thinner cell is higher due to high recombination velocity which is caused by the proximity of p-n junction with the back contact. The second probable factor is the absorption of thinner cell is lower than the thicker cell which would lead to lower generation of EHPs and subsequently lower current density. However, the current densities of both thin and thick graded cells are almost equal. Hence, this fact suggests that the photocurrents of both cells are not limited by absorption. Back surface field in the graded cell mitigates the recombination mechanism which in turn increases the current density.

4. Conclusions

Efficiencies as high as 10.74% and 14.36% are achieved for CIGS cells with 0.3 and 1.0 µm thick absorber layers, respectively. Upon adopting grading at the back contacts, efficiencies of 12.38% and 17.26% are achieved for cells with 0.3 and 1.0 µm thick absorbers. Other the hand, back surface field increases the efficiency of solar cells with 0.5 and 0.9 µm thick CIGS absorber layer as much as 3%. Back surface field mitigates the recombination mechanism by repelling electrons away from the CIGS/Mo interface. Further investigation on the band gap grading in the ultra thin CIGS cells is recommended. Various band gap profiles such as double grading theoretically can improve the efficiency of the solar cells. However, when it comes to practical implementation ultra thin absorber film may need special fabrication technique to incorporate Ga in a unique way in order to create graded band gap profile. Optimisations of other layers are also recommended in practical implementation to further enhance the conversion efficiency.

Acknowledgements

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