Journal of
Applied Sciences

Promises of Cu (In, Ga)Se$_2$ Thin Film Solar Cells from the Perspective of Material Properties, Fabrication Methods and Current Research Challenges

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Abstract: Solar Photovoltaic (PV) technologies are undoubtedly going to merge with mainstream energy harvesting technologies for mankind around the globe in near future. The promises that various photovoltaic options provide to date include high conversion efficiency with low manufacturing cost. Solar manufacturing industries are in the midst of an argument over which material to dominate the future for harvesting sunlight. Solar panels based on silicon currently account for more than 90% of the production with some limitations. However, much attention has been paid to alternatives like thin film semiconductor materials such as amorphous silicon, cadmium telluride and copper-indium-gallium-diselenide based solar cells due to the promises in cost efficiency. Attributed to some recent breakthrough in copper-indium-gallium-diselenide (CIS, thereafter) based solar cell efficiency, commercialization has got momentum around the world. Here, progresses in Cu (In, Ga) Se$_2$ thin film solar cells technologies are discussed here in regard to material properties of the Cu (In, Ga) Se$_2$ absorber layer, fabrication method of the complete device and the current CIGS research challenges. The scope of this review aims to elucidate the basics of CIGS solar cells fabricated by co-evaporation method which yields the highest conversion efficiency so far.

Key words: Solar cells, Cu(In,Ga)Se$_2$ Thin film, material properties, cell fabrication

INTRODUCTION

Among all other thin film solar cells, Cu(In,Ga)Se$_2$ solar cells have emerged as one of the most promising solar cells in terms cost-effective photovoltaic technologies. The main advantage of Cu(In,Ga)Se$_2$ thin film solar cells over the popular bulk monocrystalline silicon solar cells is the lesser material and thermal energy usage during the fabrication process. Lesser material and thermal energy usage directly results in overall lower production cost. The most important aspect of all, Cu(In,Ga)Se$_2$ solar cells have demonstrated high efficiencies in both cell and the module levels. Currently at the time of writing this article, the highest cell efficiency is 20.1% with 0.5 cm^2 total area fabricated by ZSW (Centre for Solar Energy and Hydrogen Research, Germany, 2010). As for module efficiency, National Renewable Energy Laboratory (NREL) of United States of America has attained highest efficiency of 13.8%. Cu(In,Ga)Se flexible thin film solar cells have also shown promising conversion efficiency of 17.6%. Moreover, Cu(In,Ga)Se$_2$ thin film modules show good outdoor stability (Ullal *et al.*, 1997) and higher radiation resistance, compared to crystalline silicon solar cells (Jasenek *et al.*, 2001). The latter cell property makes Cu(In,Ga)Se$_2$ solar cells a promising candidate as power generator for space application. Cu(In,Ga)Se$_2$ solar cells can be regarded as a complex structure from electronics point of view. As can be observed in Fig. 1, there are 6 main layers excluding the front electrode (not shown). This physically means there are 5 heterointerfaces in the overall structure. When two dissimilar semiconductors make a metallurgical junction, a heterojunction is said to be formed. The inter-diffusion of chemical elements from these two semiconductor layers forms a new thin layer in between these two layers. This new layer is known as the heterointerface layer. Interestingly, in Cu(In,Ga)Se$_2$ solar cells the properties of heterojunction and heterointerfaces play a major role in the performance of solar cells.

This review aims to elucidate a few key points pertaining the Cu(In,Ga)Se$_2$ solar cells. The primary key points emphasized here are: (1) material properties of Cu(In,Ga)Se$_2$ absorber layer, (2) fabrication method of complete Cu(In,Ga)Se$_2$ solar cells with greater emphasize

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Transparent
front contact

ZnO:Al (0.3-0.4 μm)
ZnO (~0.1 μm)
CdS (~0.05 μm)

Cu(In, Ga)Se₂
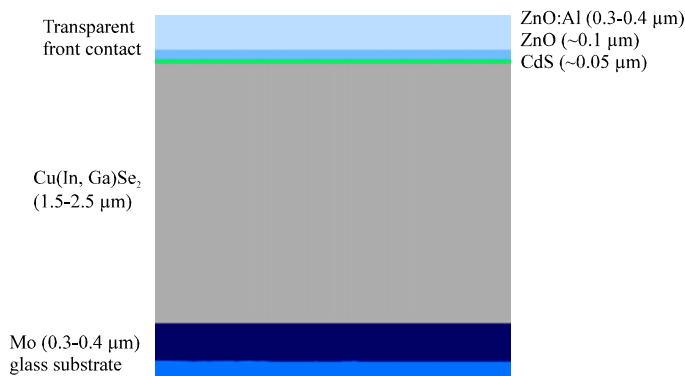(1.5-2.5 μm)

Mo (0.3-0.4 μm)
glass substrate

Fig. 1: Schematic structure of conventional Cu(In,Ga)Se₂ solar cell

given on various deposition method of Cu(In,Ga)Se₂ absorber layer and (3) current research challenges in Cu(In,Ga)Se₂ solar cells.

As for historical background, the research group in Bell Laboratories grew a number of ternary chalcopyrite compounds and characterized their electrical and optical properties in the early 1970s (Tell *et al.*, 1971, 1972). CuInSe₂ ternary compound synthesis and characterization started even earlier around 1953 by Hahn *et al.* (1953). Apart from the ternary chalcopyrite compounds, quaternary compounds were also intensively explored especially the CuGa$_x$In$_{1-x}$S₂ alloys (Shay *et al.*, 1974). The aforesaid works on ternary and quaternary compounds were mainly done on band structure characterization. The potential of CuInSe₂ as photovoltaic material was first demonstrated by Wagner *et al.* (1974) when the first CuInSe₂ solar cells were made by evaporating n-type CDs onto p-type single crystals of CuInSe₂ (Wagner *et al.*, 1974). Since then, CuInSe₂ compound has steadily stamped its mark as one of the interesting and promising photovoltaic material for terrestrial and space application as well.

MATERIAL PROPERTIES

Structural properties of Cu(In,Ga)Se₂: The quaternary compound of Cu(In,Ga)Se₂ is formed when Gallium atoms partially substitute Indium atoms in CuInSe₂ ternary system. Hence, the material properties of CuInSe₂ will be reviewed in this section as the basic to understand the properties of Cu(In,Ga)Se₂ compound. The ternary chalcopyrite CuInSe₂ crystallizes in tetragonal type space group 142 days as shown in Fig. 2.

The structure for Cu(In,Ga)Se₂ is similar to the structure shown in Fig 2. The tetragonal structure of the chalcopyrite compound can be regarded as a superlattice zincblende structure by doubling its unit cube along the
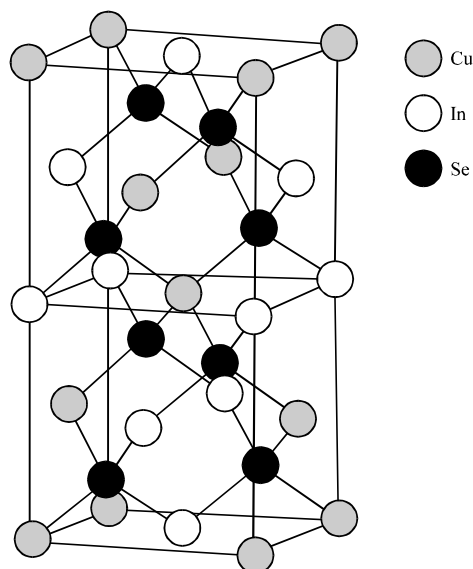

Cu
In
Se

Fig. 2: Unit cell of CuInSe₂ lattice structure

Table 1: Structural parameters a and c, c/a ratios for CuInSe₂ and CuGaSe₂ compounds

Compound	a (Angstrom)	c (Angstrom)	c/a ratio	Ref.
CuInSe₂	5.784	11.616	2.008	Spiess *et al.* (1974)
CuGaSe₂	5.614	11.030	1.965	Spiess *et al.* (1974)
CuGaSe₂	5.596	11.003	11.966	Abrahams and Bernstein (1974)

z-axis that becomes the c-axis of the chalcopyrite structure (Belhadj *et al.*, 2004). The lattice parameter of the tetragonal unit cell of a chalcopyrite structure is given in Table 1.

The ratio of c/a is called tetragonal deformation and the variations in the ratio values originate from the fact that the strength of the Cu-Se and the In-Se or Ga-Se bonds are different (Shafarman and Stolt, 2003). Smaller c/a ratio indicates the tetragonal unit cell is more closely packed.
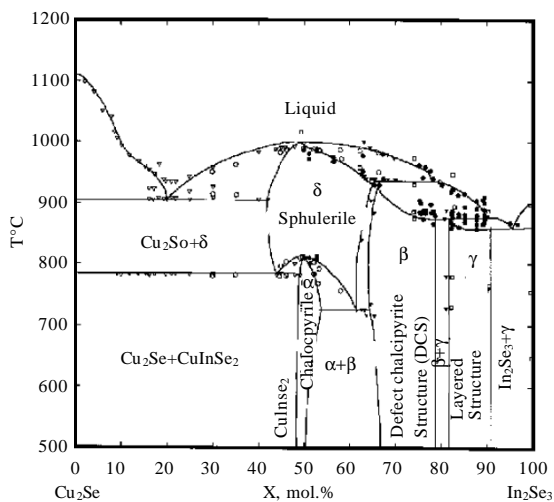
Fig. 3: Pseudo-binary In$_2$Se$_3$-Cu$_2$Se equilibrium phase diagram. (Chang *et al.*, 1996)

Phase diagram of Cu-In-Se system: The desired phase in Cu-In-Se system for a high efficiency Cu(In,Ga)Se$_2$ solar cells is the α-CuInSe$_2$ phase. Since there is numerous possible phases that can exist in the Cu-In-Se ternary system, the understanding of the phase diagram of the Cu-In-Se system is very crucial. Figure 3 shows the pseudo-binary In$_2$Se$_3$-Cu$_2$Se equilibrium phase diagram (Chang *et al.*, 1996).

From the pseudo-binary phase diagram, it can clearly be seen that the single phase α-CuInSe$_2$ only extends to a narrow region. However, the entire Cu$_2$Se + CuInSe$_2$ gives a direct chemical reaction path to a stoichiometric single phase CuInSe$_2$ (Kushia *et al.*, 1994). The binary compound of Cu$_2$Se is in liquid phase at growth temperature than 523°C (Chakrabarti and Laughlin, 1981). Hence, an oversupply of the group III elements (In or Ga) at temperature of 532°C or higher gives a reaction path to form a CIGS phase, which is assisted by the liquid phase of Cu$_2$Se. Although, single phase chalcopyrite compound is highly desired as the main absorber layer material in Cu(In,Ga)Se$_2$ solar cells, other phases inevitably are formed during the fabrication process. The slightly off-stoichiometric phases exist along the pseudo-binary Cu$_2$Se-In$_2$Se$_3$ tie line called the ordered defect compounds (ODC) which are generally Cu-poor compounds (Fearheiley, 1986). The occurrence of a number of Cu-poor phases e.g., CuIn$_3$Se$_5$ and CuIn$_5$Se$_8$ on the surface of the absorber layer plays an important role in the interface formation between the n-type CDs and p-type CIGS layer (Schmid *et al.*, 1993). More about phase diagram of Cu-In-Se ternary compounds can be found in other literature (Godecke *et al.*, 2000).

Defect physics of Cu(In,Ga)Se$_2$: The most special feature of Cu(In,Ga)Se$_2$ quaternary compound is its ability to tolerate a large number of off-stoichiometric compounds without degrading its electronic properties severely. To explain the aforesaid phenomena, the defect physics of Cu(In,Ga)Se$_2$ must be reviewed thoroughly. It is well known that CuInSe$_2$ compound does not need any external doping process to induce a specific type of conduction. CuInSe$_2$ is doped by its native defects, which means that the intrinsic defects that exist after the deposition process determine the conductivity type of the film. P-type CuInSe$_2$ can be grown if the material is overall Cu-poor and is annealed under high Se vapour pressure whereas an overall Cu-rich film with Se deficiency results in n-type film (Migliorato *et al.*, 1975; Noufi *et al.*, 1984). From the above facts, vacancy of Se, V$_{Se}$ (Se deficiency) is responsible as dominant donor in n-type material and the vacancy of Cu, V$_{Cu}$ (deficiency of Cu) is held responsible as the dominant acceptor in p-type film. The very efficient p-type self doping ability of CuInSe$_2$ is explained by the easy formation of the shallow Cu vacancies (Zhang *et al.*, 1998). The formation of V$_{Cu}$ intrinsic defect will induce an extra energy level close to the valence band (~30 meV above valence band) resembling the acceptor level in extrinsic semiconductor whereas the formation of V$_{Se}$ intrinsic defect will induce an extra energy level close to the conduction band resembling the donor level in extrinsic semiconductor. Apart from the V$_{se}$ which acts as donor level, there are a few other defects that can induce donor energy level such as In$_{Cu}$ (In at a Cu site). Hence, in order to fabricate a p-type Cu(In,Ga)Se$_2$ film, the intrinsic defect such as V$_{Se}$ and In$_{Cu}$ must be reduced.

The ability of Cu(In,Ga)Se$_2$ quaternary compound to tolerate a large number of off-stoichiometric phases is due to the defect complex pairs of 2V$_{Cu}$ + In$_{Cu}$ (2 Cu vacancies with an In on Cu antisite defect) (Zhang *et al.*, 1998, 1997). High efficiency Cu(In,Ga)Se$_2$ solar cells are generally fabricated with slightly Cu-poor absorber film with the copper to indium ratio in between 0.9 to 0.98 (0.90<Cu/In<0.98) (Conteras and Noufi, 1997). Theoretical calculations using the first-principles electronic structure theory by Zhang *et al.* (1998) have shown that the defect complex pair of 2V$_{Cu}$ and In$_{Cu}$ has zero or negative formation enthalpy. This means that the defect pair of 2V$_{Cu}$ and In$_{Cu}$ exists spontaneously under equilibrium condition in abundance. The formation of this defect pair in the Cu-poor Cu(In,Ga)Se$_2$ films is the main reason that the film can afford large number of Ordered Defect Compounds (ODC) or also known as the Copper Poor Compounds (CPCs) such as Cu(In,Ga)$_3$Se$_5$ and Cu(In, Ga)$_5$Se$_8$. In addition, the defect complex pairs that
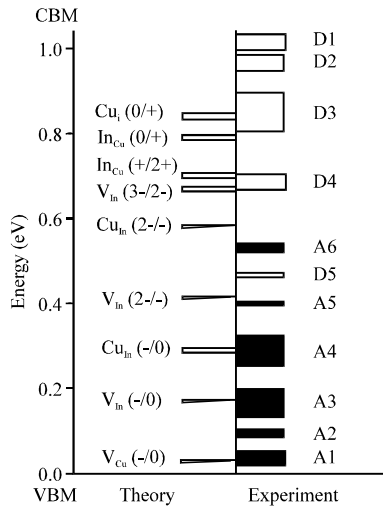
Fig. 4: Electronic levels of intrinsic defects in CuInSe$_2$. (Black histogram columns indicate acceptor type levels and white histogram columns indicate donor type level)
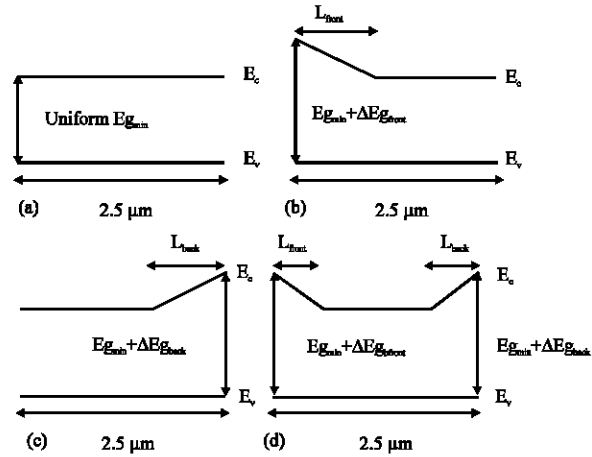

Fig. 5: Different types of absorber band gap profiles. (a) Uniform band gap. (b) Space charge region grading (front grading). (c) Back surface grading. (d) Double grading

are formed are electrically inactive due to the passivation of the In$_{Cu}^{2+}$ deep level by 2V$_{Cu}^-$. Without considering the incorporation of Ga or S into CuInSe$_2$ ternary system there are already 12 possible intrinsic defects that can take place in the film. The origin of defect states in chalcopyrite compounds can be found from literatures (Jaffe and Zunger, 1983a, b; Martins and Zunger, 1984). It is already becoming clear that the defect chemistry that is being involved is far more complicated than any other photovoltaic material. Figure 4 below shows a summary of theoretical and experimental value of electronic levels of intrinsic defects in respect to the Conduction Band Minimum (CBM) and Valence Band Maximum (VBM) of CuInSe$_2$ (Zhang *et al.*, 1997, 1998).

Optical property and band gap grading: Cu(In,Ga)Se$_2$ has a direct band gap which is a very desirable in photovoltaic material. More optimistically, the absorption coefficient of Cu(In,Ga)Se$_2$ is high around 10^5 cm^{-1} for a band gap of 1.4 eV (Neumann, 1986). The fact that the requirement for active material is less in Cu(In,Ga)Se$_2$ solar cell is due to the high absorption coefficient. A material with high absorption coefficient physically means that photons only have to travel a very short distance before being absorbed by the material.

Polycrystalline Cu(In,Ga)Se$_2$ semiconductor has a tunable band gap that varies with the gallium content (Ga substitutes In in the chalcopyrite structure). The band gap for CuInSe$_2$ is around 1 eV (0.98-1.04 eV)

(Ramanathan *et al.*, 2003), whereas by adding Ga into the ternary system of CuInSe$_2$, the band gap energy of the CIGS quaternary system can be varied over the range of 1.04 to 1.68 eV (Huang, 2008). Currently, Cu(In,Ga)Se$_2$ solar cells with Ga/(In+Ga) ratio of 0.3 which corresponds to a band gap energy range of 1.1-1.2 eV yields the best efficiency both in laboratory and commercial modules. Spatial variation of Ga composition in the CIGS thin film determines the band gap profile of the CIGS absorber layer. Hence, by varying the Ga composition spatially within the CIGS absorber layer, various band gap profiles can be achieved as shown in Fig. 5.

Introduction of higher Ga/(In+Ga) ratio near the space charge region or near the back surface of the CIGS absorber layer will create a slight elevation in the band gap around the specified region. The increase in the band gap, ΔE_g will give rise to an additional electric field (Lundberg *et al.*, 2005) which is also known as quasi-electrical field (Kroemer, 2001). Ga incorporation at the Space Charge Region (SCR) and at the back surface will improve J$_{sc}$ performance parameter due to the additional electric force created that increases the carrier collection probability. Electron drift-diffusion length, L$_e$ is increased by the existence of the additional electric force which in turn results in a larger generated carrier collection at the junction with the corresponding increase of the illumination current density (Acevedo, 2009). The back surface grading also contributes in reducing the carrier recombination at the back contact, as CIGS/Mo interface is expected to have high recombination velocity (Lundberg *et al.*, 2005). The increase in quasi-electric field at the back contact is expected to compensate the

recombination at the back contact (Acevedo, 2009; Dullweber *et al.*, 2001). Generally, band gap grading is advantageous in Cu(In,Ga)Se$_2$ solar cell operation.

Deposition method of Cu(In,Ga)Se$_2$ absorber layer: There are wide ranges of deposition methods that can be employed to grow Cu(In,Ga)Se$_2$ film. Among all, only two specific deposition methods are able to produce high efficiency Cu(In,Ga)Se$_2$ solar cells which are co-evaporation of constituents elements method and selenization of metal precursor. All the previous champion cells and the current world record Cu(In,Ga)Se$_2$ cell are fabricated by the co-evaporation method (Ramanathan *et al.*, 2003; Contreras *et al.*, 1999). Hence, in this review only the co-evaporation method will be discussed. Literature materials on selenization of metal precursors method can be reviewed in (Dejene, 2009; Nishiwaki *et al.*, 2001) and rapid thermal processing of stacked elemental layers by Probst *et al.* (1996). Conventionally, Cu(In,Ga)Se$_2$ absorber layer is deposited on top Molybdenum (acts as back contact) coated soda lime glass. Simultaneous co-evaporation of constituent elements Cu, In, Ga, Se is done in a vacuum chamber as shown in the Fig. 6.

The elements of Cu, In, Ga and Se are loaded into the effusion cells and heated up to over 1300°C for Cu, 1100°C for In, 1200°C for Ga and 350°C for Se to produce respective molecular beams of the elements which are directed towards the heated rotating substrate. The greatest advantage of this method is the composition of the elements can be controlled by varying the effusion cell temperature which determines the element fluxes at any time during the deposition process. The conventional thickness of Cu(In,Ga)Se$_2$ absorber layer is around 2 μm
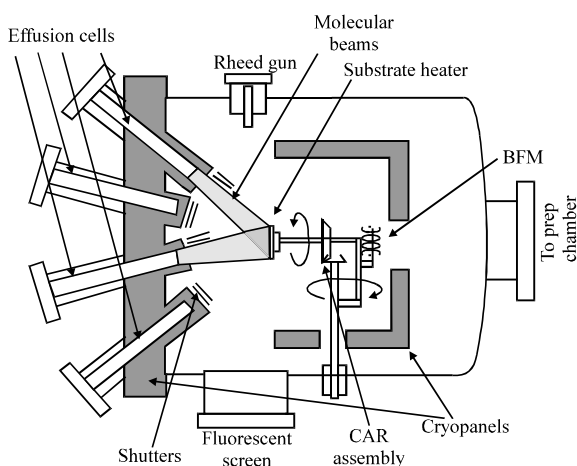
to 2.5 μm (Puvaneswaran *et al.*, 2010). Hence the time required to deposit a certain thickness of absorber layer depends on the deposition rate which has a linear relation with the effusion rate of each element.

One of the important parameters in thermal co-evaporation is the deposition profile which is the 'recipe' to fabricate high quality absorber layer. The deposition profile basically contains the information of variation of elemental fluxes (related to temperature) over time throughout the deposition process. In this study, three important deposition profiles which are constant rate deposition, Boeing process and three stage process will be discussed with the characteristics of consequent deposited Cu(In,Ga)Se$_2$ absorber films. The co-evaporation process with the constant rate deposition profile is shown (line 1) in Fig. 7 (Shafarman and Zhu, 2000). The effects of Cu-rich composition at the beginning (line 2) and in the middle (line 3) of deposition process are also investigated. The deposition profiles for (2) and (3) are famously known as the 'Boeing process' in which the film growth has a portion of Cu-rich profile at the beginning and later the fluxes are adjusted (In and Ga fluxes are deposited while Cu flux is terminated) to finish the overall composition of the film is Cu-poor (Mickelsen and Chen, 1980). In fact, the photovoltaic community began to give a substantial attention to CuInSe$_2$ solar cells when Mickelsen *et al* fabricated high efficiency 9.4% cells using the Boeing process. Apart from co-evaporation and selenization methods, there are few other methods to fabricate Cu(In,Ga)Se$_2$ absorber layer namely closed space sublimation, reactive sputtering and chemical bath deposition.

The overall Cu/III composition is maintained slightly below unity. Table 2 shows the performance of the solar cells with different Cu fluxes profiles and different substrate temperature, such as Tss of 400 and 550°C. From microstructural point of view, the grain size of film which is deposited with Cu-rich profile at any instant of
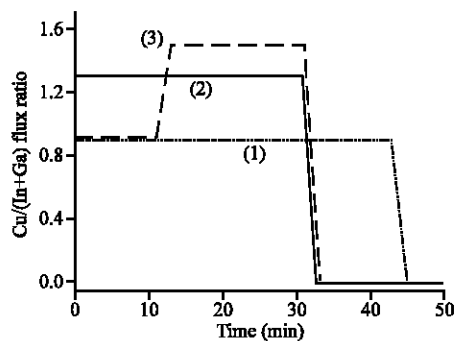

Fig. 6: Vacuum chamber used in co-evaporation process of Cu(In,Ga)Se$_2$ absorber layer

Fig. 7: Various deposition profiles used in CIGS film growth

Table 2: CuInSe₂ solar cell performance at various deposition profiles

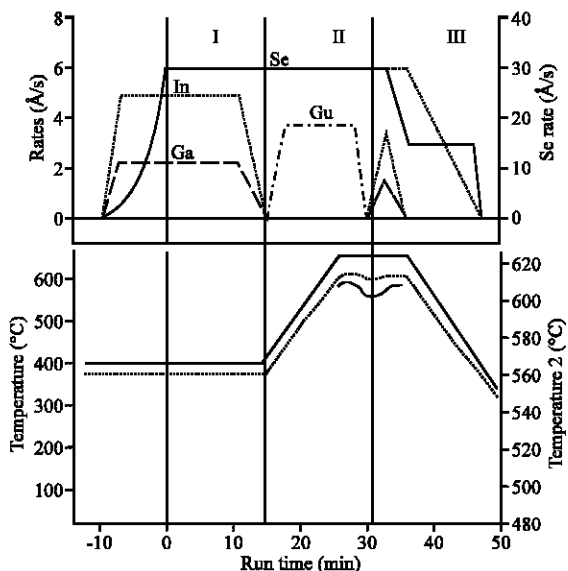| Tss (°C)	Process	V_{oc} (V)	J_{sc} (mA/cm²)	FF	ç (%)
400 (°C)	Uniform Cu flux	0.56	29	69	11.3
	Cu-rich at beginning	0.59	33	71	13.7
	Cu-rich in middle	0.60	33	71	13.8
550 (°C)	Uniform Cu flux	0.65	33	74	15.9
	Cu-rich at beginning	0.65	32	76	16.0
	Cu-rich in middle	0.65	32	75	15.5

Fig. 8: Three stage process deposition profile (Hasoon *et al.*, 2001)

deposition is larger than grain size in film deposited with uniform Cu flux. It is suggested that during Cu-rich composition, the binary phase of Cu$_x$Se is formed in the film and enhances the grain size (Yamaguchi, 1995; Klenk *et al.*, 1993).

Three-stage process is a sequential deposition process (Gabor *et al.*, 1994) and the deposition profile of a three-stage process is shown in the Fig. 8.

In the first stage, In, Ga and Se are evaporated to form (In, Ga)$_x$Se$_y$ compound, followed by the deposition of Cu and Se in the second stage. The Cu flux is supplied until the film is overall Cu-rich composition wise. This is indicated by the slight dip in the substrate temperature indicator towards the end of second stage. This slight dip in the temperature profile is the indication of excess Cu$_x$Se binary phase formation on the film surface. Cu$_x$Se has lesser thermal emissivity which causes the substrate temperature to drop. The main objective making the film Cu-rich is to enhance the grain size of the film. The substrate temperature is also ramped up to promote inter-diffusion of elements. The final stage of this process intends to make the film's final composition slightly Cu-poor by supplying In, Ga and Se fluxes.

Former champion Cu(In,Ga)Se₂ solar cell which recorded 19.9% efficiency was fabricated by using the three stage process but with slight modification by NREL researchers (Repins *et al.*, 2008). The modification was the termination of the 3 stage process without Ga for the last 100 Angstrom. Throughout the three stage process, the Se flux is always oversupplied. An investigation carried out by Islam *et al.* (2009) found out that deficiency of Se supply decreases the hole concentration and increases the resistivity of Cu(In,Ga)Se₂ film. Carrier concentration in Cu(In,Ga)Se₂ film fabricated by three stage process is around 10^{16}/cm³ to 10^{17}/cm³ (Mesa *et al.*, 2010). It can be considered that Se deficiency should generate anion vacancy, Vse, which would act as donor (Stanbery, 2002). The dependence of Se beam on defect states in CIGS based solar cells is described elsewhere (Sakurai *et al.*, 2010). Apart from co-evaporation and selenization methods, there are few other methods to fabricate Cu(In,Ga)Se₂ absorber layer namely close space sublimation (Guenoun *et al.*, 1998), reactive sputtering (Thornton *et al.*, 1988) and chemical bath deposition (Murali, 1988).

PN Heterojunction formation: cadmium sulphide (CDs) layer: A thin 50 nm of n-type CDs is deposited on top Cu(In,Ga)Se₂ absorber layer to form a pn heterojunction. Conventionally, CDs is deposited by Chemical Bath Deposition (CBD). Initially, CDs layer was 1-2 μm thick but it has been observed that blue photon loss occurs due to the absorption in the CDs layer. To overcome this problem, thick CDs layer is replaced by a thin layer of CDs and highly conductive ZnO layer (Potter, 1986). Thinner CDs minimizes photon loss in the layer [45]. The chemical constituents needed to perform CBD of CDs are cadmium salt (cadmium source e.g. CdSO₄, CdI₂), complexing agent (commonly ammonia, NH₃) and a sulphur precursor (sulphur source commonly thiourea, SC(NH₂)₂). These chemicals with a specific concentration are mixed to form an alkaline aqueous solution. The Cu(In,Ga)Se₂ film is immersed in a bath containing the solution at a temperature of 70°C. The reaction of the solution results in the growth of CDs on the Cu(In,Ga)Se₂ film. An elaborated CBD process of CDs on Cu(In,Ga)Se₂ film can be found in other literature (Hashimoto *et al.*, 1998).

Although CDs/Cu(In,Ga)Se₂ devices have achieved high conversion efficiency (Ramanathan *et al.*, 2003; Contreras *et al.*, 1999), a cadmium free buffer layer is preferred as the heterojunction partner of Cu(In,Ga)Se₂ due to environmental concerns. One of the promising alternative candidates to CDs is zinc sulphide (ZnS). ZnS/Cu(In,Ga)Se₂ devices have already demonstrated high efficiency of 18.8% (Nakada and Mizutani, 2002).

Another replacement for CDs buffer layer is the Zn_{1-x} Mg_xO. The best $Zn_{1-x}Mg_xO/ Cu(In,Ga)Se_2$ cell efficiency is 16.2% (active area) achieved by Matsushita Electric Industrial (Negami *et al.*, 2002). An excellent treatment of buffer layers for $Cu(In,Ga)Se_2$ solar cells application is given by Siebentritt (2004) and numerical modeling of $Cu(In,Ga)Se_2$ solar cells with various buffer layers can be found by Puvaneswaran *et al.* (2010).

SOLAR CELL FABRICATION

Once the pn heterojunction is formed between CDs and $Cu(In,Ga)Se_2$ absorber layer, an undoped high resistivity ZnO (also known as i-ZnO) buffer layer is deposited by radio frequency (rf) magnetron sputtering before the sputter-deposition of Transparent Conducting Oxide (TCO) layer. Since the CDs layer is thin, formation of pinholes in the layer is quite imminent. Existence of pinholes in CDs will cause shunting of current if the TCO and $Cu(In,Ga)Se_2$ absorber layer comes to contact. To avoid this, a 50 nm thick undoped ZnO is sandwiched between CDs and TCO layer. Hence, the requirement of ZnO buffer layer depends on the quality and thickness of CDs layer (Rau and Schmidt, 2001). The common TCO material for $Cu(In,Ga)Se_2$ solar cell is Al doped ZnO. A 50 to 200 nm thick ZnO:Al is deposited by dc magnetron sputtering. The conductivity of the TCO depends on the amount of Al doped in ZnO and usually the conductivity is around $10^3 \ \Omega^{-1} \ cm^{-1}$. After the TCO deposition, a post deposition air annealing process at 200°C for one or two minutes is practiced to increase the efficiency of the cell (Tuttle *et al.*, 1996). Finally, a Ni or Al metal grid contact is deposited by thermal evaporation onto the TCO layer. An optimum metal grid area is needed to facilitate the maximum transmission of incident sunlight on to the cell.

CURRENT CHALLENGES IN CU(IN,GA)SE₂ SOLAR CELL RESEARCH AND DEVELOPMENT

The fact that $Cu(In,Ga)Se_2$ solar cells are being established as one of the most promising photovoltaic materials applies only for solar cells with low band gap in the range of 1.1 to 1.2 eV. The effort to replicate the high efficiency cells with higher band gap is so far futile. The increase in the performance of $Cu(In,Ga)Se_2$ thin film solar cells partially lies on the development of the solar cells with higher band gaps as the optimum band gap value for terrestrial single junction solar cells is 1.5 eV (Martin, 1982). In particular, $Cu(In,Ga)Se_2$ solar cell with high Ga content (Ga/(Ga+In) ~ 0.6, corresponds to band gap of 1.5 eV) yields much lower efficiency than anticipated. Higher

band gap material is expected to produce lower current densities but higher operating voltage which ultimately leads to lower resistive losses (I^2R losses) which is desirable in solar modules (Siebentritt, 2002).

So far, the open circuit voltage, V_{oc} of the wide band gap $Cu(In,Ga)Se_2$ solar cells is not proportional with the increase in band gap as one would expect. The failure in increasing the open circuit voltage is related to the leakage of Cu from the $Cu(In,Ga)Se_2$ grains which eventually creates defects that are known as N_1 and N_2 among the $Cu(In,Ga)Se_2$ researches (Van Vechten, 2005; Cahen and Noufi, 1989; Niki *et al.*, 2001). Comprehensive details on leakage phenomena of Cu from the grains and defect formation in chalcopyrite compound is given in (Van Vechten, 2005). Moreover, study shows that increase in Ga/(Ga+In) ratio more than 0.3 in $Cu(In,Ga)Se_2$ increases the bulk defect densities in the absorber layer by one magnitude which can degrade the performance of the solar cells (Hanna *et al.*, 2001). Defects in either bulk, interface or depletion region affects the electronic transport in $Cu(In,Ga)Se_2$ solar cells due to recombination mechanism (Rau and Schock, 1999). The idea of incorporation of atomic diffusion barrier in Cu-chalcopyrite by Van Vechten (2005) must be implemented practically to observe the viability of the solution. Since the $Cu(In,Ga)(S,Se)_2$ alloy system provides band gap over the range of 1 eV to 2.5 eV, high-efficiency Cu-chalcopyrite based tandem solar cells can be realized if the open circuit voltage for wide gap chalcopyrite can be increased beforehand. Hence, increasing the open circuit voltage of wide gap chalcopyrite is the most central issue in $Cu(In,Ga)Se_2$ solar cell research.

CONCLUSION

This review article has highlighted the basics of $Cu(In,Ga)Se_2$ solar cells in terms of its material properties, fabrication methods and also the primary challenges that if resolved may propel $Cu(In,Ga)Se_2$ solar cells into greater heights in photovoltaic applications in near future. The complex defect physics of $Cu(In,Ga)Se_2$ quaternary compound is one of the reasons that the overall understanding of the device physics has been vague initially. However, through vigorous research and theoretical prediction, the defect formation physics and its relevance to the $Cu(In,Ga)Se_2$ solar cells operation have been becoming clear over the period of time. The capability of $Cu(In,Ga)Se_2$ solar cells as one of the low cost, high efficiency photovoltaic material is proven up to certain extent primarily in laboratory scale. Yet, there is a huge potential in terms of $Cu(In,Ga)Se_2$ thin film solar module efficiency compared to the laboratory cells which

exhibits high conversion efficiency. Hence, the mechanism that is responsible for the inconsistency in terms of efficiency of solar cells and modules must be addressed with higher priority.

ACKNOWLEDGMENTS

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