Research paper

Improvement the Efficiency of CIGS Thin Film Solar Cells by Changing the Doping of the Absorbent Layer and Adding the InAsP Layer

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Article Info	Extended Abstract
	Background and Objectives: In this article, the functionality of solar cells structure based on $CuIn_{1-x}Ga_xSe_2$ is investigated. This type of solar cell consists of different layers, namely, ZnO (TCO layer), Cd_S (Buffer layer), CIGS (Absorbent layer), and MO (Substrate layer). Two layers, Cd_S and CIGS, form a PN Junction. **Methods:** CIGS thin film solar cell is simulated using SILVACO software. The absorbent layer doping was originally changed. Later doping was kept constant and P-type layer of InAsP was added. Their effect on cell function was observed and examined. It was observed that after doping some parameters of the solar cell have improved whilst some others have decreased. It was also concluded that examined increase or decrease in the amount of dopant would reduce our efficiencies of solar cell. **Results:** Added the InAsP layer leads to increased open circuit voltage, short circuit current and the solar cell power, consequently gives the efficiency about 33.2%, which is an acceptable efficiency. **Conclusion:** It was clear that extreme increase or decrease in the amount of dopant in the absorbent layer can change solar cell parameters, and can improve cell functionality. The amount of dopants can also alter some other solar cell parameters which are not desirable, the added InAsP layer leads to increased open circuit voltage, and short circuit current and the solar cell power, consequently gives the about 33.2%, efficiency which is an acceptable efficiencies.

Introduction

Nowadays, one of the major problems of today is the limited availability of fossil fuels and hydrocarbons and the consequences of increasing consumption on the environment, quality of life, and human health. For these reasons, it is imperative to shift to other energy sources. Renewable energy is one answer to this problem, and one of the most prevalent forms is solar. Through photovoltaic (PV) technology, solar energy becomes available and widely exploitable.

Today PV technology is experiencing significant growth and development and, as a source of electric energy, is considered sufficiently reliable. The operation and maintenance of PV power plants has a very low cost, and the operation of these systems is silent since they have no moving parts. Most important, PV technology does not produce air pollution. These plants can be installed quickly and adjusted easily to direct the power supply to the necessary points without the need for transmission lines.

There are many applications in various installations already, often supplying energy in places where it would be impossible to provide power otherwise. The social, economic and environmental benefits are evident for a number of local communities [1].

Thin Film Solar Cells

The need for new, advanced materials and systems having new properties led to thin-film technology. The process and the mechanisms of molecule deposition from the gas phase to the surface of the solid material is the basis of this technology.

This new technology is coming to replace the conventional one as more efficient and more cost effective. Thin-film solar cells are the latest development in the field of photovoltaic cells, and there is considerable hope for wide spread use in the production of electricity [2].

The thin-film is the microstructure created by the individual layers of a material objective on the surface of a solid (bulk) material, where one dimension is orders of magnitude smaller than the other two. Thin-films, with thicknesses ranging from a few nanometers (nm) up to a few microns (μm), have properties that are significantly different from those of solid materials and surfaces.

Alterations are especially important when the thickness is very small or in the early stages of development. These differences are mainly due to microstructure and the creation of incorporations that are generated during the course of the transformation of the free atoms of a gas phase directly into a solid phase. In most deposition techniques, thin-films are deposited on the surface of a material at temperatures much lower than the melting temperature of the given material, and the growth of the film takes place under non-equilibrium thermodynamic conditions [3].

These conditions are responsible for forming various metastable phases of unformed and nanostructured materials. The development of single-layered or multi-layered thin-film structures gives to the overall system the desired physical and chemical properties required for the specific use as well as new, exceptional properties to extend their scope of application and lifetime duration.

In general, construction consists of depositing a semiconductor that absorbs light onto a substrate, which may be coated glass, metal, or plastic. These semiconductor materials are not required to be thick, because they absorb light very efficiently, resulting in generated solar cells that are very thin, lightweight, durable, and easy to use.

Regardless of the applied deposition technique in thin-films, there is a set of fundamental parameters to control, the most significant of which are the substrate temperature, deposition rate, pressure of the ambient gas within the deposition chamber, and the energy of the flow of deposited particles.

In thermal deposition, the contribution of the energy of the flow of deposited particles to the dynamics of the surface energy is insignificant, considering the fact that it is one to two sizes smaller than the bond forces of the surface components.

In non-thermal deposition techniques, however, the energy of the flow of deposited particles strongly influences the film's properties. Of course, there are other factors, such as the thermodynamic properties of the system, the crystallinity, the orientation, the chemical properties, and the substrate lattice constants to influence the film's properties. These properties are not independent and optimizing one affects the others. The interdependence of these parameters contributes to the selection of the most suitable deposition technique [4].

Fabrication Materials for Solar Cells and Panels

Literature surveys show that the 2006 solar cell market includes 55 percent of poly crystal, 30 percent of single-crystal silicon, 6 percent of amorphous silicon (also known as a-Si), 5.8 percent of a-Si on Czochralski single-crystal, and 3.5 percent of ribbon-silicon. Cadmium telluride was used first to fabricate solar cells in 1960, but it was stopped due to its extremely low absorption capability [5].

It is indicated that high light absorption capability is the critical requirement for solar cell materials. High absorption capability is possible with thin films of group III-V compound semiconductor materials, such as GaAs, InP, CIS, CIGS, and CdTe. The use of CdTe material for fabrication of solar cells cannot be justified due to its poor absorption capability.

Solar cells fabricated with thin films of CIS and CIGS demonstrate conversion efficiencies better than 20 percent under laboratory conditions, which will be reduced to 18 percent or so. These solar cells are currently available in small quantities, but at higher procurement costs due to limited production. Moreover, multi junction solar cells with V-groove configurations and using thin films of CIS and CIGS can boost the conversion efficiency better than 30 percent in the near future [6].

Research on concentrated solar cells or PV cells can extend the efficiency close to 40 percent under laboratory conditions. Hence, the roof-mounted multi junction solar cells will be able to generate electricity in the tens of kilowatt range with grid-connected power supply system with acceptable cost.

Research and development activities by Stanford University professors and other industry scientists on solar cells show achievements on light-weight, flexible, thin films of organic materials. However, reliable data on

manufacturing yield and efficiency are not available at the present moment.

Three basic types of solar cells include crystalline silicon cells with conversion efficiencies ranging from 15 to 22 percent, multi junction GaAs solar cells with efficiencies ranging from 26 to 29 percent, and various kinds of thin-film solar cells with conversion efficiencies in the range of 32 to 38 percent.

It should be noted that the multi junction GaAs-based solar cells are fabricated using metal organic chemical vapor deposition techniques on mono crystal wafers with maximum theoretical conversion efficiency approaching 40 percent approximately. Therefore, these multi junction cells are very expensive to manufacture and are limited to applications where cost is not an issue or where small areas are involved, such as satellites or solar concentrators [7].

CIGS Solar Cells Structure

CIGS solar cell consists of 4 layers, namely ZnO (TCO layer), Cd_S (Buffer layer), CIGS (Absorbent layer), and MO (Substrate layer). The second and third ones, Cd_S and CIGS layers, form a PN Junction [4].

CIGS (Copper-Indium-Gallium-Selenium) solar cell is a semiconductor I-IIIVI2 with a direct band gap and high absorption coefficient [8].

The standard thickness of the CIGS absorber layer in CIGS thin-film solar cells is presently 1.5–2μm [9].

The preceding is an alloy between CIS and CGS which is described by the chemical formula $CuIn_{1-x}Ga_xSe_2$, where x is the ratio Ga/(Ga+In). By changing x, the Gallium and Indium values will change that alter the band gap. The value of band gap change from 1.04ev for x= 0 for the CIS to 1.68ev for x=1, for the CGS, maximized for a Ga content with a value roughly 0.3, resulted in absorber energy band gap values of roughly 1.1–1.2 eV [10].

As shown in Fig. 1, CIGS solar cell is composed of 6 layers. In these cells, the lowest conduction band has been put against the maximum capacity of the tape and has the highest efficiency compared to other solar cells [8].

Cu(In,Ga)(Se,S)2 alloys from the I–III–VI group of the periodic table are used as absorber layers that crystallize in the quadratic structure of chalcopyrite. This system of $Cu(In,Ga)(Se,S)_2$ type chalcopyrites includes a wide range of band gaps. CuInSe2 has a relatively low band gap of 1.04 eV but can be adjusted better to the solar spectrum by replacing part of In with Ga and part of Se with S. Chemical and percentage composition of the chalcopyrite can vary the band gap from 1.04 eV for $CuInSe_2$ to 1.53 eV for $CuInS_2$ to 1.7 eV for CuGaSe2 (CGS), up to 2.5 eV for $CuGaS_2$ [11].

In order to form an ohmic contact between a metal and semiconductor, a higher work function for metal with respect to that of the semiconductor is needed. Mo is usually used as a back contact in chalcopyrite devices since it is highly anticorrosive and creates a contact with the absorber due to the MoSe2 interlayer formed during its deposition [12].
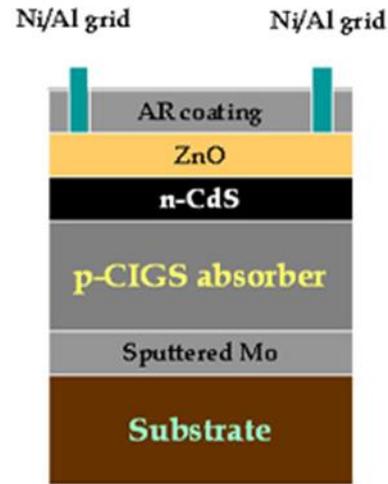

Fig. 1: CIGS structure.

The back-contract thickness depends on the resistance requirements of each solar cell. The properties of the Mo layer and the selection of the glass substrate play important roles on the quality of the cell. It is due of the role of Na, which diffuses from the glass substrate to the growing layer of the absorber through the Mo layer. This trend has been found to improve crystallographic properties and doping in CIGS thin-films. By depositing various compounds prior to the deposition of the absorber, the diffusion of Na is controlled and homogeneous, allowing the use of other types of substrates as a back contact without any significant change in the cell's performance, given that a sufficient amount of Na is provided [13].

One major advantage for absorbers in this category is the fact that they exhibit non-toxicity, in contrast with CdTe absorbers (which makes them unacceptable).

Moreover, they exhibit excellent stability in electrical properties in all stoichiometric ratios in which they are manufactured. However, the use of rare materials such as In and Ga increases the production cost of the entire device [14].

Simulation

The construction of experimental specimens is the process followed by most research centers and manufacturers of PV cells. Although it is the most reliable procedure for evaluating the performance of a cell, it is still costly and time consuming. On the other hand, modeling using software provides a fast, consistent, and relatively inexpensive way to design solar

cells.

Modeling and simulation allowed for thousands of combinations to be investigated before the fabrication of actual examples.

The use of Silvaco ATLASTM simulation software to model a tandem CIGS cell and evaluate the performance for different variations of cell parameters is the focus of this paper.

Design optimization was accomplished by separately altering the thickness and Ga ratio of both CIGS layers of the tandem cell. Simulation of a PV cell in ATLASTM is made through a text input deck called   Deck Build, a run-time environment in which many different parameters of cell structure and composition must be defined.

The structure definition comprises a cornerstone for the simulation since it not only bears the physical dimensions and thicknesses of the different layers constituting the cell but also builds a mesh for the cell through its fine division. Its significance is that at the grid points, called nodes, a set of differential equations are solved with a view to simulating the transport of the cell's carriers and enabling a study of the behavior of the cell.

The composition definition is also important since ATLASTM is a physically-based device simulator. Once the physical structures are specified, composition and bias conditions statements lead ATLASTM to make predictions of the electrical characteristics of the cell.

The buildup consists of a well-defined mesh on which the cell is constructed. The simulation's resolution is determined by the density of the mesh's numerous triangles and designates the time needed for program iterations and the accuracy of cell representation.

This triangular meshing is then divided into regions, and different materials are assigned in each of those regions.

Then, the electrodes to obtain the electrical characteristics for the device or for any region required are assigned. Next, every defined material must be associated with a doping, and, as much as possible, material properties must be declared for the most accurate simulation.

The next step for the user is to choose among different models, finding that which is most the suitable for evaluating the structure, and achieving a better outline for the specific cell simulation.

A specification of a light beam illuminates the cell as in real conditions, simulating different regions of the solar spectrum, depending on the beam chosen. Also, the selection of a method, among the different offered by the ATLASTM library, is needed for solving the differential equations through which the cell's operating characteristics arise.

These characteristics from the simulation can be saved in a log file and used to create plots using TONYPLOT, the interactive graphics and analysis package included in the program.

Physical parameters used in the simulations have been identified in Table 1.

Table 1: Physical parameters used in the simulation [15]

Parameters	ZnO	CdS	CIGS
εr	9	10	13.6
χe (eV)	4	3.75	3.89
μn (cm2/Vs)	100	100	100
μp (cm2/Vs)	25	25	25
NA (1/cm3)	0	0	2e+16
ND (1/cm3)	1e+18	1e+18	0
NC (1/cm3)	2.2e+18	2.2e+18	2.2e+18
NV (1/cm3)	1.8e+19	1.8e+19	1.8e+19
Eg (eV)	3.3	2.4	1.15
Thickness (nm)	75	40	1700

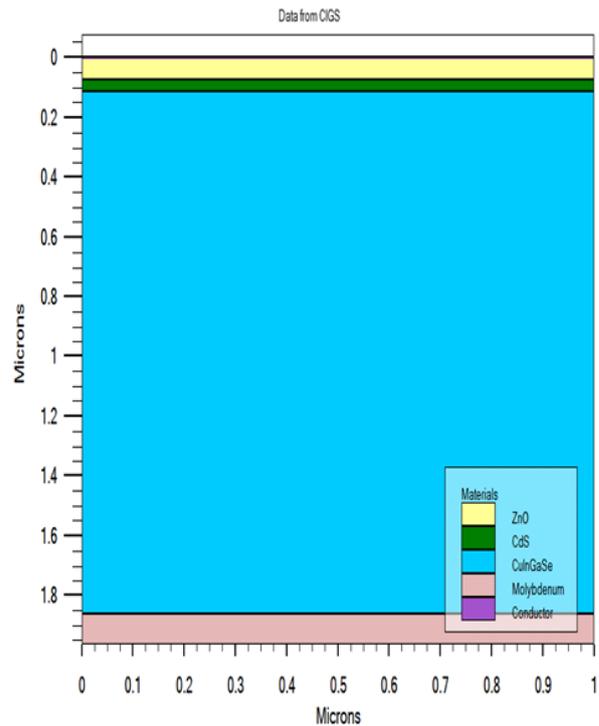Fig. 2 depicts the basic model structure for the simulated CIGS solar cells.

Fig. 2: Simulated CIGS Structure.

Changing the Doping Absorbent Layer

Simulation was also performed for CIGS layer fixed and equal to 1750nm but different amount of doping 1×1015(CIGS1), 1×1016(CIGS2) and 1×1017(CIGS3) were used. The results of I-V curve and efficiency are given in fig 3 and fig. 4 in respectively.
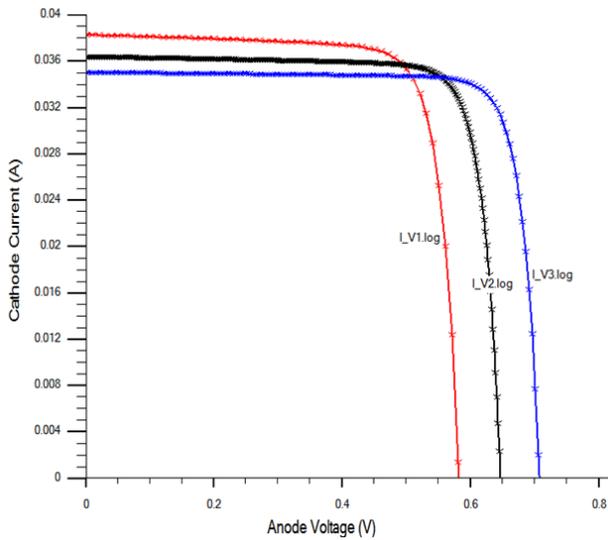
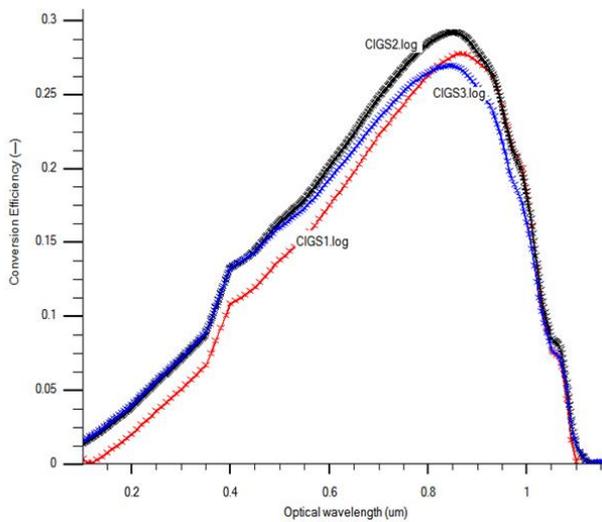Fig. 3: I-V curves for doping change of the absorbent layer.

Fig. 4: Efficiency curves for doping change of the absorbent layer.

Adding the InAsP Layer

The improved CIGS Solar Cell was designed using the added layer InAsP and doped P-type with and thickness 200nm. This was placed between the layers of the absorbent and MO.

In order not to change the thickness of the cell, the same thickness of 200nm has been reduced from the CIGS. You can see the specifications of physical parameters given in Table 2.

Table 2: Specifications of physical parameters of InAsP layer

NA (1/cm^3)	μp (cm^2/Vs)	μn (cm2/Vs)	χe (eV)	εr
2e+16	25	100	4.32	1.27
Thickness (nm)	Ban Gap (eV)	NV (1/cm^3)	NC (1/cm^3)	ND (1/cm^3)
200	1.27	8.54e+18	3.61e+17	0

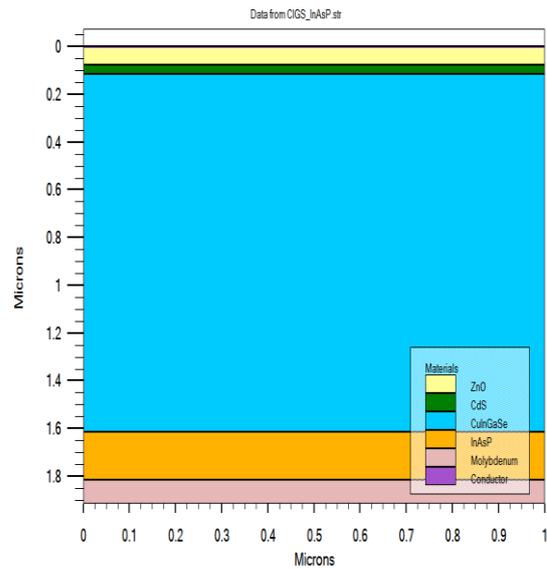The Changed model structures of simulated CIGS solar cells are shown in Fig. 5.

Fig. 5: The Changed model structures of simulated CIGS.

The efficiency of the changed solar cell is determined by its I-V characteristic, as shown in Fig. 6.
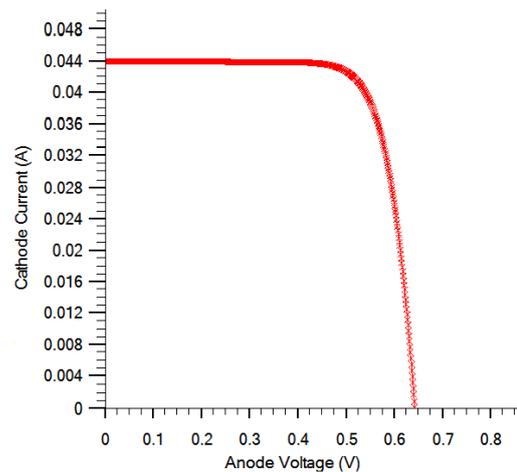

Fig. 6: I-V curves for adding the InAsP layer.

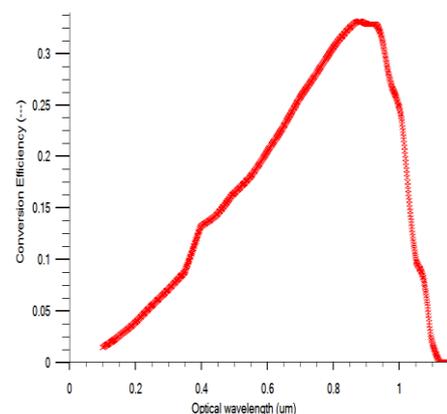Fig. 7 and Fig. 8 respectively show efficiency and power curves.

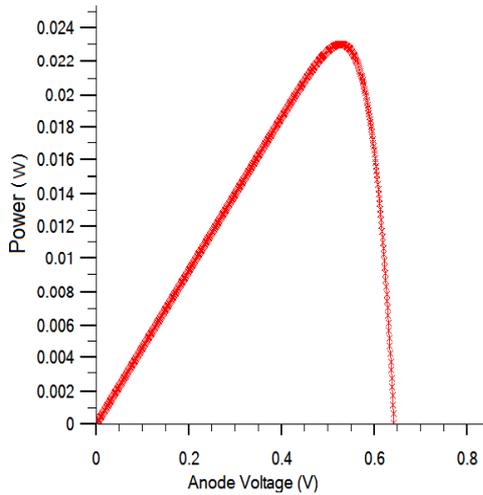Fig. 7: Efficiency curves for adding the InAsP layer.

Fig. 8: Power curves for adding the InAsP.

Results and Discussion

The results of efficiencies concerning "change the doping of absorbent layer" and "adding the InAsP layer" are given in Tables 3 and Table 4, respectively.

Table 3: Results of doping change of absorbent layer

Parameters	CIGS1	CIGS2	CIGS3
Doping absorbent layer	1×10^{15}	1×10^{16}	1×10^{17}
V_{oc} (V)	0.581	0.644	0.706
Isc (mA/cm^2)	38.5	36.5	34.5
P_{max} (mW/cm^2)	17.66	19.22	17.5
FF (%)	79.8	82.5	83.5
Efficiency (%)	27.8	29.2	26.9

Table 4: Results for adding the inasp layer

Parameters	value
V_{oc} (V)	0.625
I_{sc} (mA/cm^2)	44
P_{max} (mW/cm^2)	23.2
FF (%)	84.36
Efficiency (%)	33.2

According to the result obtained, as doping increases power and V_{OC} will be increased. This is due to increase in minority and majority carriers. It should be noted that increasing doping is the reason for decreasing the I_{sc}. This fact can be attributed to the existence of high number of minority and majority carriers which cause the recombination process of photons. Therefore, the recombined photons cannot contribute to the flow of current. It was concluded that extreme increase or decrease in doping can lead to reduce efficiencies.

Also, the added InAsP layer leads to increase open circuit voltage, short circuit current and solar cell power, consequently increase efficiency, because for absorbing lower energy photons that pass through the absorbing layer and are absorbed in the InAsP layer which produce electron and hole pairs. It is about 33.2% efficiency which is desirable.

Conclusion

In this study, the methods to increase the efficiency of thin film solar cells were investigated. Silvaco software was used to simulate and draw output diagrams in Deck Build environment. Two methods were simulated and analyzed. The absorbent layer doping was originally changed. Later doping was kept constant and P-type layer of InAsP was added. Their effect on cell function was observed and examined.

The factors of the solar cell that were examined included open circuit voltage (V_{oc}), short-circuit current (I_{sc}), power (P_{max}), Filling factor (FF), and efficiency.

In the first method, it was clear that extreme increase or decrease in the amount of dopant in the absorbent layer can change solar cell parameters, and can improve cell functionality.

The amount of dopants can also alter some other solar cell parameters which are not desirable, consequently gives the about 29.2%, efficiency.

In the second method, the added InAsP layer leads to increased open circuit voltage, and short circuit current and the solar cell power, consequently gives the about 33.2%, efficiency which is an acceptable efficiency with the previous efficiency which means 4-5 percent increase.

Author Contributions

H.firoozi designed and simulated experiments. H.firoozi collected the data. H.firoozi carried out the data analysis. H.firoozi and M.imanieh interpreted the results and wrote the manuscript.

Conflict of Interest

The author declares that there is no conflict of interests regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy have been completely observed by the authors.

Abbreviations

η	Efficiency
Cd_S	Cadmium - sulfide
CdTe	Cadmium- tellurium
CGS	Copper- Ingallium- Selenium
CIGS	Copper- Indium- Gallium- Selenium
CIS	Copper- Indium - Selenium
Cu	Copper
FF	Filling factor
Ga	Gallium

GaAs	Gallium Arsenic
In	Indium
I_{sc}	Short-circuit current
Mo	Molybdenum
P_{max}	Maximum power
Se	Selenium
Si	Silicon
TCO	Transparent Conductive Oxide
V_{oc}	Open circuit voltage
ZnO	Zinc Oxide

References

[1] M. Nagaich, S. Campbell, E. Aydil, "Wide band-gap CuIn1-xGaxSe2 based chalcopyrite absorbers for tandem cell application," presented at the 37th IEEE Photovoltaic Specialists Conf., Seattle, USA, 2011.

[2] P. Reinhard, "Review of progress toward 20% efficiency flexible CIGS solar cells and manufacturing issues of solar modules," IEEE Journal Of Photovoltaics, 3(1): 42-44, 2013.

[3] D. K. Suri, K. C. Nagpal, G. K. Chadha, "X-ray study of CuGaxIn1-xSe2 solid solutions," Journal of Applied Crystallography, 22(6): 578-583, 1989.

[4] F. B. Dejene, V. Alberts, "Structural and optical properties of homogeneous Cu(In,Ga)Se2 thin films prepared by thermal reaction of InSe/Cu/GaSe alloys with elemental Se vapour," Journal of Physics D: Applied Physics, 38(1): 22, 2005.

[5] J. H. Scofield, A. Duda, D. Albin, B. L. Ballard, P. K. Predecki, "Sputtered molybdenum bilayer back contact for copper indium diselenide-based polycrystalline thin-film solar cells," Thin Solid Films, 260(1): 26-31, 1995.

[6] G. Gordillo, M. Grizález, L. C. Hernandez, "Structural and electrical properties of DC sputtered molybdenum films," Solar Energy Materials and Solar Cells, 51(3): 327-337, 1998.

[7] T. Nakada, A. Kunioka, "Direct evidence of Cd diffusion into Cu(In,Ga)Se2 thin films during chemical-bath deposition process of CdS films," Applied Physics Letters, 74(17): 2444-2446, 1999.

[8] A. Kylner, "The role of the CdS buffer layer in the Cu(In,Ga)Se2 thin film solar cell," Acta Universitatis Upsaliensis, 1998.

[9] A. R. Jeong, R. H. Shin, W. Jo, M. Song, S. Yoon, "Synthesis and physical properties of Cu(In,Ga)Se2 nanoparticles and CuGaSe2 thin-films for tandem cell photovoltaic applications," presented at the 35th IEEE Photovoltaic Specialists Conf., Honolulu, USA, 2010.

[10] P. Reinhard, "Review of progress toward 20% efficiency flexible CIGS solar cells and manufacturing issues of solar modules," IEEE Journal Of Photovoltaics, 3(1): 42-48, Oct 2013.

[11] Z. Beiley, A. Bowring, M. D. McGehee, "Modeling low-cost hybrid tandem Photo voltaic with power conversion efficiencies exceeding 20%," presented at the 38th IEEE Photovoltaic Specialists Conf., Austin, USA, 2012.

[12] A. Rohatgi, "High-throughput ion-implantation for low-cost high-efficiency silicon solar cells," Energy Procedia, 15: 10-19, 2013.

[13] Y. G. Xiao et al., "Modeling of CdZnTe nad CIGS and tandem solar cells," in Proc. 35th IEEE Photovoltaic Specialists Conf., Honolulu, USA: 20–25, 2010.

[14] L. Fraas, L. Partain, "Solar Cells and Their Applications, Second Edition," John Wiley & Sons, Inc., 2010.

[15] K. Ramanathan, M. A. Contreras, C. L. Perkins, S. Asher, F. S. Hasoon, J. Keane, D. Young, M. Romero, W. Metzger, R. Noufi, J. Ward, A Duda, "Properties of 19.2% efficiency ZnO/CdS/CuInGaSe2 thin film solar cells," Progress in Photovoltaics: Research and applications, 11(4): 225-230, 2003.

[16] H. Firoozi, M. Imanieh "Improvement performance CIGS thin film solar cells by changing the thickness Cd_S layer," UCT Journal of Research in Science, Engineering and Technology, vol5(2): 39-42, 2017.

Biographies

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Mohsen Imanieh was born in 1960 in Shiraz, Iran and holds a Ph.D. in Electronics from the University of Salford in England. He was also part of research group at the University in late 1990s. His research was involved on growing semiconductors such as CIS and CIGS. Currently, he is a faculty member of Islamic Azad University of Fasa in Iran and lecturers post-graduate student of Electronics department.