Comparative analysis of some photovoltaic solar cells: an introduction to research methods to engineering students

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Abstract

The recent boom in the demand of photovoltaic solar cells might create a subject and technological demand for engineering education both in the under/graduate courses as well as a material shortage in the recent future. Engineering students take keen interest in the simulation and experimental work related to photovoltaic solar cell, as a new and advanced technology evolved for space and terrestrial use. In fact thin-film solar cells are becoming a promising choice in terms of device design, fabrication and cost effectiveness. Similarly thin film has the potential to revolution the present cost structure as it may replace the expensive silicon wafers modules which dominate above 50% the market share. This work deals with comparing thin-film CIGS solar cell with multilayer CIGS solar cells by using SCAPS a simulator free of cost available at educational institutions. Replacing the existing CIGS by multilayer will increase the efficiency by 40-50 % and will decrease the use of material by 30-40%. Simplicity of manufacturing and the cost per reliable watt are to be introduced to electrical engineering students interested in sustainable energy production. The analysis of simulation result so obtained from SCAPS is useful for understanding the fundamentals of PV devices as well as a feedback for designers and producers of high efficiency CIGS solar cells.

Keywords: *Electrical engineering education, lab practice for electrical engineering, photovoltaic solar cell, thin-film CIGS, Multi-layer, efficiency enhancement.*

1. Introduction

The increase in CO2 and other gases in the environment is the biggest problem for today human due to the use of fossil fuel. Engineering students should face this issue by performing some lab experience in order to avoid or at least decrease the use of fossil fuel by using renewable and environmental friendly sources. From undergraduate courses to advanced courses, students and researchers should perform practical experiments as will as theoretical simulations to achieve higher conversion efficiencies and in-depth physical analysis of the subject. One alternative solution is the use of renewable sources in which Photovoltaic (PV) energy is key to take advantage of solar energy. Solar energy and the use of photovoltaic is a well-developed technology in present and the future seems to be brighter. Different types and generations of solar cells have been developed to date.

In order to reach the 'green energy challenge' a large number of professionals and engineers in this field in our educational institutions are required. New laboratories and research centres should be developed and a large number of technical staff competent in solar cells and PV field is going to be needed.

On the other hand, before any practical work and manufacturing of solar cells professionals are required to simulate their work by using adequate software produces thus being crucial that lab practices

concerning this topic are developed at universities. In fact there is a number of such software available in market and its introduction and use is mentioned in the literature and specialized software [1], between we may mention the following:
- PC1D (One-dimensional semiconductor device simulator)
- AMPS (Analysis of Microelectronic and Photonic Structures)
- SCAPS (a Solar Cell Capacitance Simulator)
- ASA (Amorphous Semiconductor Analysis)
- AFORS-HET (Automat For Simulation of Heterostructures)
- SimWindows
- ADEPT-F
- ASPIN

Some of this software is dedicated to Si solar cells, some to thin film CIGS solar cells and other for both as well as general electronics and PV devices. In this work we present the results that can are obtained and can be performed as a lab session by interested students in solar energy. We use SCAPS for analysing our CIGS cells and the results obtained are mentioned. SCAPS is a useful tool for teaching the basics of PV devices particularly CIGS, CdTe and other thin film solar cells. It provides the students a better understanding of the role of the main parameters that control the behaviour of PV devices.

2. Insight into solar cells

In this lab work we review the third generation of solar cells with special focus on thin film technologies because it permits to save a considerable amount of raw material which also brings a lower price of energy and payback period. We will apply free software called Solar Cell Capacitance Simulator software (SCAPS) for simulating the behaviour of thin film solar cells based on Copper–Indium–Gallium–Diselenide (CIGS) absorbers. The band gap of CIGS materials can be tuned as a function of the Ga content and this has an effect on the External Quantum Efficiency (EQE) as well as on the main parameters of the PV device. The analysis of the outputs of the SCAPS model provides a better understanding of thin film PV solar cells.

The first (1st) Silicon solar cell was made in Bell Lab by Chapin, Fuller and Pearson in 1954. It was the first generation of solar cell and was used off-grid remote areas and in grid-connected applications. It consists of large-area, high-quality and single junction Si devices. Its efficiency reaches the theoretical limit of approximately 33%. [2] It is an expensive technology that requires high energy and labour input due to which its production cost is high. It has 5-7 years of production payback period.

Second (2nd) generation PV was developed in RCA Laboratories by Carlson and Wronski, who made the first amorphous silicon Photovoltaic cell in 1976. To reduce the production cost of the solar cells, new materials and technologies were used. These materials were cadmium telluride (CdTe), copper indium gallium selenide (CIS, CIGS), amorphous and micro-morphous silicon. [3] Alternative manufacturing techniques vapour deposition and electro-plating were used, too. [2] Its efficiency is much reduced compared to 1st generation. It can be deposited like thin film on substrates such as glass or ceramics that may reduce the overall cast and material mass. Its commercialization is low but increases day by day. CIGS-CIS and CdTe thin film solar cells offer significantly cheaper production cost and higher conversion efficiencies. However its efficiency is lower than the first generation solar cells and also toxic.

Third (3rd) generation PV was developed by Konarka's flexible, thin film PV technology in 2001. Konarka is the first to offer a truly green solar solution. [4] [5] Nowadays the 3rd generation approaches including organic photovoltaic, tandem cells, dye-sensitized titania solar cells as well as materials that generate multiple electron-hole pairs.

Basically the advancement of 2nd generation solar cells (thin-film technologies) addresses the gain of better electrical performance. To increase the efficiency from 30-60% while retaining low cost materials and manufacturing techniques (the theoretical solar conversion efficiency limit for a single energy threshold material, calculated by Shockley and Queisser as 31 % under 1-Sun illumination in 1961). [6] Different approaches are used to achieve these high efficiencies.
1) Multi-junction photovoltaic cells (multiple energy threshold devices).

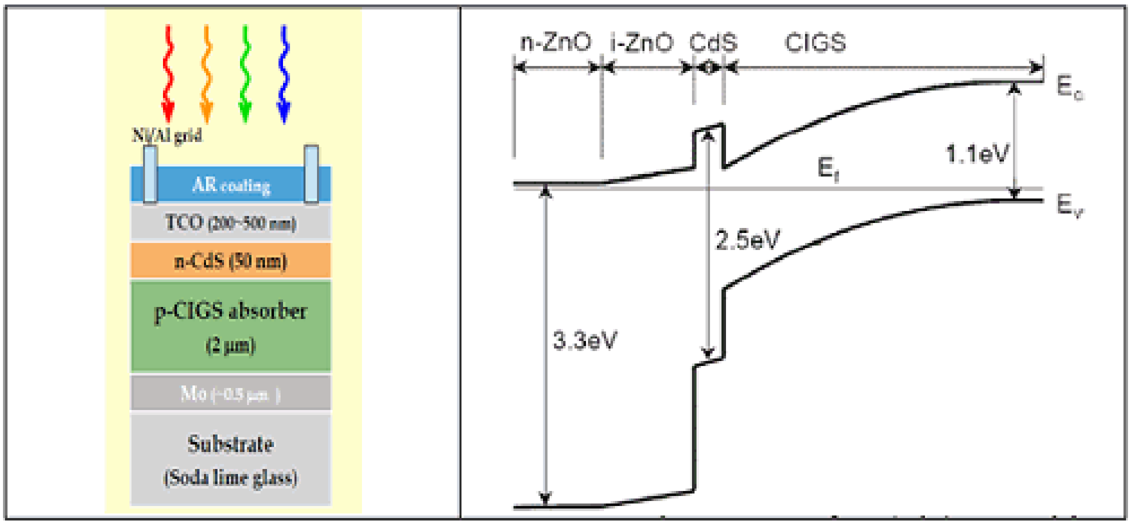
2) Modifying incident spectrum (surface Plasmon's, concentration).
3) Use of excess thermal generation (caused by ultraviolet UV light) to enhance voltages or carrier collections.
4) Use of infrared spectrum to produce electricity at night

The study of thin-film solar cells and modules is an important goal for the photovoltaic industry. Record-efficiency devices provide a proof of concept for developing products. Dedicated simulation software offer a suitable tool for exploring new concepts. The use of several absorber layers (tandem-concept) in a solar cell allows harnessing/absorbing a higher amount of photons and hence the conversion efficiency increases. In order to describe and demonstrate the physical behaviour of photovoltaic devices theoretically, different type of numerical modelling software is used. [1]

Numerous simulation and experimental work performed in the photovoltaic field to obtain high conversion efficiency and to increase the stability and durability of the technology. The evolution from 6% efficient crystalline silicon (c-Si) cell is reached to 25.0%. [7] The emergence of new materials, and the new concept that boost the efficiency up to 44.7 % for multi-junction (tandem four junction) solar cell. [8] For chalcopyrite thin-film solar cell, in CIGS the experimental and simulation results for different combination compared in a recent work. [9] The efficiency for CIGS has obtained an efficiency of 20.8 % for 1 sun but it is 22.8% for concentrated solar cells application. [10]

3. $CuInGaSe_2$ (CIGS) Solar cells

I-III-VI chalcopyrite materials have got very desirable properties for PV application. The band gap for $CuInSe_2$ is 1.53 eV, an Ideal material for PV purposes. Further, the band gap can be controlled by alloying with Ga, Al or S. [11] Moreover $Cu(In,Ga)Se_2$ has gained worthy reputation with high efficiency. The experimental results reported already give the efficiency above 20%. A higher value of 20.1% and 20.3% efficient CIGS solar cell for 1 sun is reported. [12] The basic schematic of a thin-film CIGS solar cell is elaborated in Figure 1. The efficiency for concentrated (multi sun) is 22.8% reported in the latest literature. The CIGS film is consist of a p-CIGS absorber layer with combination of n-CdS layer and ZnO window layer. The band gap here is a function of Gallium and can be varied from 1.0 – 1.72 eV, that would cause the effect in the variation of other solar cell parameters. [13] Simulation results giving efficiencies above 25% are also published. Though its efficiency is high but still it difficult to commercialize due to the availability of resources and particularly the rare metals Indium (In) and gallium (Ga), that adds to the cost of CIGS based technology. [14] CIGS solar cell and its band diagram are shown below.



Typical structure for a CIGS solar cell

CIGS solar cell band diagram

Figure 1. Schematic of a thin film CIGS solar cell and its band diagram.

The Gallium concentration was changed and the effect of different parameters had been observed in the CIGS thin film solar cell, the summary of results has demonstrated in Table 1. The open circuit voltage (Voc) increases as the gallium (Ga) content increases and the band gap of the CIGS layer also increase. The short circuit current represented by (Jtot) decreases as band gap increases due to the recombination of carriers, it has the reverse effect then Voc. Similarly the Fill-Factor (FF) increases upto an increase of 50%, moreover after increase in Ga contents beyond 50% causes decrease in FF, the same phenomenon also observed in the case of external quantum efficiency η (%). In the beginning eta increases up to 66% of Ga contents but further increase of Ga causes decrease in eta. [10] The results obtained by using SCAPS are given in Table 1.

Table. 1 Photovoltaic parameters for CIGS solar cells with different Ga content.

Ga content	V_{oc} (V)	J_{sc} (mA/cm^2)	FF (%)	eta (%)
0.00	0.5282	48.3933	79.75	20.38
0.31	0.6747	46.2690	82.37	25.71
0.45	0.7733	45.7018	83.43	29.48
0.66	0.8768	42.0037	84.04	30.0
1.00	0.8807	38.5823	83.59	28.40

4. Multi-layer CIS/CGS Solar cells

The aim of multi-junction solar cells is to exploit and convert all the incident photon from the sun into electricity. Because the major factor of energy loss is due to the gap between the photon energy and the band gap energy Eg of absorber material. A tandem (multi-junction) solar cell is the combination of two or more solar cells and an intervening buffer layer between two cells. Each cell absorbs the corresponding wavelength and the resultant efficiency increases. The highest efficiency with 44.7% is reported recently for a triple-junction III-V based solar cell under concentration of 297 suns. [8]

The same concept can be applied to CIGS based devices. Such a multi-layer CIS/CGS solar cell is based on the combination of two different absorbent layers with different band gaps. The CIS/CGS multi-layer cell used for simulation has two absorber layers, $CuGaSe_2$ of 0.5 μm and $CuInSe_2$ of 0.5 μm (optimum thickness), for obtaining best output values, the thickness of $CuInSe_2$ varied from 0.080 μm up to 0.50 μm. The thickness of n-CdS and i-ZnO layers are 0.050 μm each.

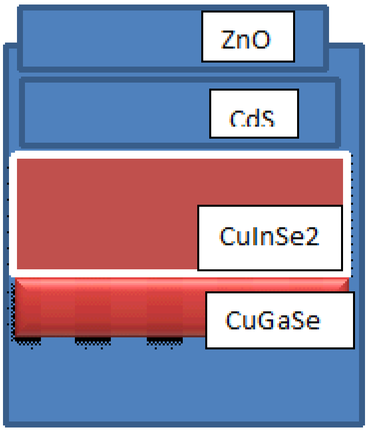


Figure 2. Schematic of CIS/CGS multi-layer solar cell.

Figure 3 displays the energy band diagram of a $CuInSe_2$/$CuGaSe_2$ multilayer solar cell. The Valence band of both absorbents are aligned and the higher $CuGaSe_2$ gap results in a step of about 0.8 eV in the Conduction bands.

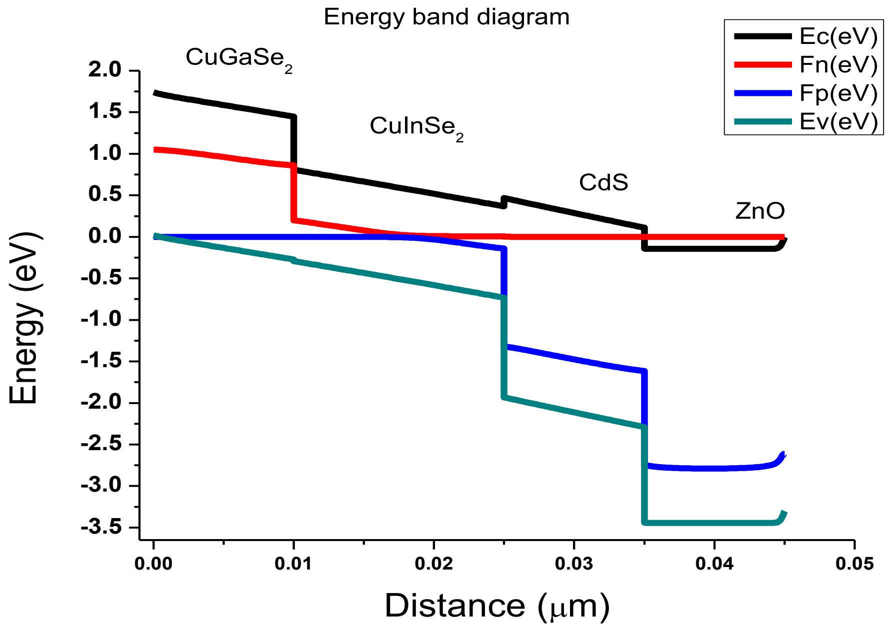


Figure 3. Band diagram of a CIS/CGS multi-layer solar cell.

5. Results and Discussion

The simulation results for both cells (CIGS single layer, and CIS/CGS multi-layer) were obtained from a chain of simulation experiments and tabulated. In Table 1, the simulated results are for the first case, giving maximum efficiency of 30.0% for Ga contents of 0.66, and a layer thickness of 2.5 μm. The experimental result giving maximum efficiency of above 20% and similar results that obtained from simulations in a recent work [9] Our simulation give better results.

The PV parameters of a CIS/CGS multi-layer solar cell are specified in detail in Figure 4. The values obtained here are eta 52.0%, FF 81.83 %, J_{SC} 0.04896 (A/cm^2) and open circuit voltage V_{OC} 1.298 (V). The high conversion efficiency of such a device is mainly due to the higher open circuit voltage (Voc) of such a PV device and the higher photon absorption related to the lower band gap absorber ($CuInSe_2$). Moreover, the material used in the multilayer combination is less (40%) than that of single layer CIGS thin-film, and the conversion efficiency obtained is more than 50% from that of experimental results and 30 % more that the simulated results.

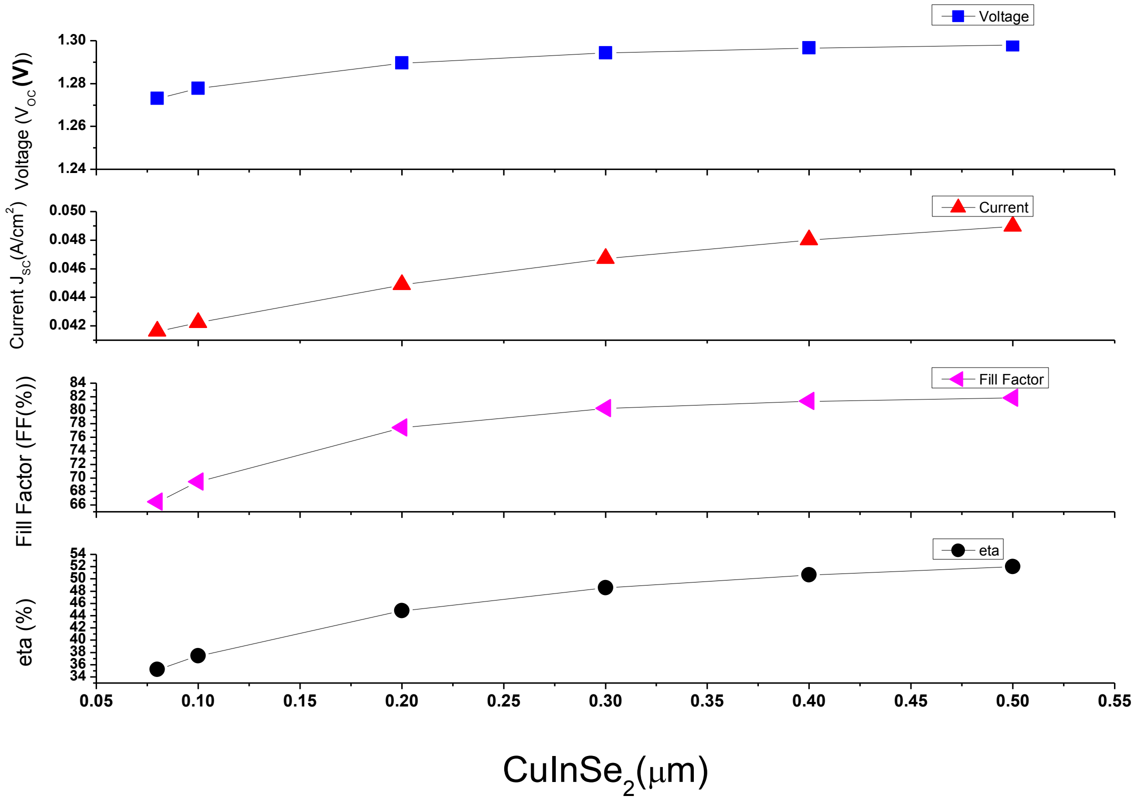


Figure 4. Photovoltaic parameters of CIS/CGS multi-layer solar cell.

6. Conclusions

The physical operation features of a thin-film solar cell structure are described by different software. Here for the basic understanding of solar cell behaviour we have performed analysis by using SCAPS.

The work developed is to be intended as a lab practice of electrical engineering or students interested in photovoltaic energy so that they can understand the details concerning the physical operation of a thin-film solar cell structure by means of its numerical simulation. In PV cell structure there are many parameters influencing the efficiency and performance. Only the I-V characteristic measure is not enough to fully describe a PV cell because of the physical mechanisms taken place inside. To get confidence in a solar cell model, the student must consider different characteristics as well as different possible conditions to be simulated and compared.

In this work the role of CIS/CGS and CIGS replacement for photovoltaic solar cell are discussed. To make the technology cheap and consumer friendly, bulk production and simple module of solar technology is now softening, and the technology capturing a high market share. Here we have compared thin-film CIGS solar cell and multilayer CIGS solar cells. Replacing the existing CIGS by multilayer increases the efficiency by 40-50 % and decreases the use of material by 30-40%. Simplicity of manufacturing and the cost per reliable watt are a result to be considered by future professionals. A conclusion of the work developed by making the experiments explained throughout this paper is that there are many parameters that influence the efficiency and performance in PV cell structure and in many simulation processes numerical modelling alone does not guarantee obtaining better photovoltaic solar cells.

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