Study of thin film solar cells in high temperature condition

Mohamed Fathi\textsuperscript{a}*\textsuperscript{,*}, Mahfoud Abderrezek\textsuperscript{a}, Farid Djahli\textsuperscript{b}, Mohammed Ayada

\textsuperscript{a}Unité de Développement des Equipements Solaires, UDES/Centre de Développement des Energies Renouvelables, CDER, Bou Ismail, 42415, W. Tipaza, Algérie

\textsuperscript{b}L.I.S Laboratory, Department of Electronic, Faculty of Technology, University of Setif 1, 19000 Setif, Algeria

Abstract

In this paper, we study the effect of temperature on the Copper Indium Gallium Selenide (CIGS) thin film solar cells using the one dimensional solar cells simulator SCAPS-1D (Solar Cell Capacitance Simulator). The dependence of the CIGS solar cells characteristics on temperature was investigated from 25°C to 70°C at intervals of 5°C. We observed an apparent degradation in the open-circuit voltage and conversion efficiency with an increase of temperature from 25°C to 70°C, accompanied with degradation in the maximum power of the cell from 18.55 mW/cm\textsuperscript{2} (25°C) to 14.941 mW/cm\textsuperscript{2} (70°C). By the using of the luminescent downshifting approach, the conversion efficiency of the CIGS solar cell was enhanced under Standard Test Conditions (STC) at 25°C and in high ambient temperatures test conditions. The coefficient of the voltage variation to temperature $\Delta V_{oc}/\Delta T$ was reduced from -2 to $-1.8$ (mV/°C).

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1. Introduction

The use of solar simulators has become necessary in the design and analysis of solar cells due to the complexity of the physical mechanisms that govern these photovoltaic devices [1]. The objective searched in the simulation of solar cells, is to find a relationship between the properties of the materials and the performances of the solar cell. In addition, it permitted us to identify physical and technological parameters that affect the solar cell performances during their operating at high ambient temperature.

* Corresponding author. Tel.: +213-542-116-181; fax: +213-24-41-04-84.

E-mail address: dr_fathimohamed@yahoo.fr
In the present research study, a numerical simulation of CIGS thin film solar cells has been carried out by using SCAPS-1D, developed at ELIS laboratory (Electronics and Information Systems) in GENT University, Belgium [2]. It was realized by Marc Burgelman et al. in ELIS department for the simulation of heterojunctions polycrystalline solar cells. It was first designed and used for testing CdTe and GIGS solar cells.

Because of their low cost of production and their high conversion efficiency [3-4], solar cells based on CIGS materials have been the subject of much recent research [5-6]. During their operation in external conditions, high ambient temperature plays a vital role and affects the performance of solar cells. This study becomes of paramount importance if we want to understand the behavior of CIGS solar cells in high temperature conditions. To enhance the energy conversion of photovoltaic cells and their behavior under high temperatures, we introduced a new approach based on luminescent down shifting (LDS) materials.

### Nomenclature

| Abbreviation | Description                        |
|--------------|------------------------------------|
| SCAPS-1D     | Solar Cell Capacitance Simulator one Dimension |
| TCO          | Transparent Conductive Oxide       |
| AM           | Air Mass                           |
| QE           | Quantum Efficiency (%)             |
| J_{sc}       | short circuit current density (mA/cm²) |
| V_{oc}       | open circuit voltage (Volt)        |
| P_{max}      | maximum power (mW/cm²)             |
| FF           | Fill Factor (%)                    |
| D            | Conversion efficiency (%)          |
| LDS          | Luminescent Down Shifting          |
| PMMA         | PolyMethyl Methacrylate            |
| ASTM         | American society for testing and material |
| STC          | Standard Test Conditions           |

### 2. Studied structure

Figure 1 shows a schematic diagram of the CIGS solar cell studied with Transparent Conductive Oxide TCO layer. The heterojunction is composed from CdS buffer layer (N) type and CIGS absorber layer (P) type. The thickness and doping level for several layers used in this structure are the same as those used by M. Gloeckler et al [7].

![Fig. 1. The structure of the CIGS solar cell used for simulation with LDS (Left) and without LDS (Right).](image-url)
Table 1. Main material parameters of ZnO/CdS/CIGS solar cell used in the simulation [7].

| Semiconductor parameter's | ZnO | CdS | CIGS |
|---------------------------|-----|-----|------|
| Band gap (eV)             | 3.3 | 2.4 | 1.15 |
| Dielectric permittivity (relative) | 9   | 10  | 13.6 |
| Electron mobility (cm²/Vs) | 100 | 100 | 100  |
| Hole mobility (cm²/Vs)    | 25  | 25  | 25   |
| Nc effective density of states (1/cm³) | 2.2E18 | 2.2E18 | 2.2E18 |
| NV effective density of states (1/cm³) | 1.8E19 | 1.8E19 | 1.8E19 |
| Electron thermal velocity (cm/s) | 1E7 | 1E7 | 1E7  |
| Hole thermal velocity (cm/s) | 1E7 | 1E7 | 1E7  |
| Front surface recombination velocity (cm/s) | 1E7 |     |      |
| Back surface recombination velocity (cm/s) |     | 1E7 |      |
| Front Reflectivity         | 0.05|     |      |
| Back Reflectivity          |     | 0.8 |      |

The performance of the CIGS hetero-junction solar cell was simulated under the standard spectrum AM1.5G at 25°C. The obtained results were in accordance with those of the literature (Table 2) [8].

Table 2. SCAPS1-D Simulation results of CIGS solar cell with experimental results.

| Parameters | CIGS (Experimental data) Ref [08] | CIGS SCAPS-1D Simulation |
|------------|-----------------------------------|--------------------------|
| Vₘ (Volt)  | 0.678                             | 0.666                    |
| J_sc (mA/cm²) | 35.22                           | 34.866                   |
| FF (%)     | 78.65                             | 79.88                    |
| η (%)      | 18.8%                             | 18.50                    |

2.1. CIGS Temperature effect simulation

After the calibration of the CIGS solar cell with reference [8], we explored the temperature effect on the CIGS solar cells performances by using the simulator SCAPS-1D.

Figures 2 (a) and (b) show the effect of ambient temperature on the Quantum Efficiency and the characteristics J (V) of CIGS solar cells. We observed a slight degradation of QE and short circuit current density J_sc, in comparison with the remarkable reduction of the open circuit voltage V_oc.

Fig. 2. Temperature dependence of the Quantum efficiency and the J(V) characteristics CIGS Solar cell.
Temperature effect on the CIGS solar cell performances (Jsc, Voc, η, FF and maximum power of the cell) are showing in figure 3 and 4. A degradation in the open circuit voltage of the cell accompany by a degradation in the conversion efficiency and power of the cell. A slight variation observed in the short-circuit current and for factor.

Fig. 3. Temperature dependence of P (V) and maximum power (Pmax) of CIGS Solar cell.

Fig. 4. Temperature dependence of Voc, Jsc, FF and η of CIGS Solar cell.

| Parameter’s          | Value  |
|----------------------|--------|
| ΔVoc/ΔT (mV/°C)      | -2     |
| ΔJsc/ΔT (mA/cm²/°C)  | -0.0162|
| ΔFF/ΔT (%/°C)        | -0.088 |
| Δη/ΔT (%/°C)         | -0.082 |
| ΔPmax/ΔT (mW/cm²/°C) | -0.078 |

3. Enhancement of the CIGS solar cell performances

In this part and in the aim to enhance the conversion efficiency of the CIGS solar cell, the photovoltaic (PV) glass encapsulation material is replaced with a polymer material of polymethyl methacrylate (PMMA) type, doped with several kinds of organic dyes [9, 10]. The organics dyes move the photons from ultraviolet and blue
region (where quantum efficiency of the cell is lower) to the visible region (where quantum efficiency of the cell is higher). This approach provides good adaptation between solar spectrum and spectral response of the solar cells; it also reduces the thermal losses in the solar cells [11].

We used, in this study, various samples of luminescent downshifting organics materials (LDS) formed by dyes mixed with PMMA. We will investigate the three fluorescent organic dyes (BASF Lumogen Violet 570 (V570), Yellow 083 (Y083), and Orange 240 (O240)) [13]. They are all made of naphthalomide and perylene molecules, manufactured by BASF (Ludwigshafen, Germany). In this section we replaced the spectrum input in SCAPS-1D, AM1.5G (ASTM G173) by the modified spectrum $\Phi_{\text{sae}}(\lambda)$; this last is calculated from the amount of photons absorbed and emitted by dyes using the following expression:

$$\Phi_{\text{sae}}(\lambda) = \Phi_{\text{s}}(\lambda) - \Phi_{\text{a}}(\lambda) + \Phi_{\text{e}}(\lambda)$$

Where: 
- $\Phi_{\text{s}}(\lambda)$ : is the incident solar spectrum
- $\Phi_{\text{a}}(\lambda)$ : the amount of photons absorbed by dyes introduced in PMMA layer
- $\Phi_{\text{e}}(\lambda)$ : the amount of photons emitted by dyes introduced in PMMA layer.

The amount of absorbed and emitted photons is calculated from the dyes absorption and emission Spectrum [10, 12]. Table 4 presents the different samples formed with organics dyes mixed with PMMA.

| Dyes Samples | Dyes                     | Absorption range (nm) | Emission range (nm) |
|--------------|--------------------------|------------------------|---------------------|
| S1           | PMMA doped Violet 570    | 300-410                | 395-500             |
| S2           | S1 + Yellow 083          | 300-490                | 470-585             |
| S3           | S2 + Orange240           | 300-530                | 510-625             |

Figure 5 shows the LDS effect on the AM1.5G solar spectrum; we can observe the substantial modification on the incident AM1.5G Spectrum.

Table 5 summarizes the effect of LDS layers formed with different organics dyes on the CIGS solar cell performances. An increase in short current density and conversion efficiency is observed with different samples used.

The gain in short-circuit current density and conversion efficiency is shown in table 6 and Figure 6, the
gain in conversion efficiency can be increased to 6.5% with LDS doped S3.

Table 5: Simulation results of the CIGS solar cell with and without LDS layer for different sample types.

|                  | CIGS (Experimental data) Ref [08] | CIGS SCAPS-1D Simulation | CIGS+LDS (S1) | CIGS+LDS (S2) | CIGS+LDS (S3) |
|------------------|-----------------------------------|--------------------------|----------------|----------------|----------------|
| \( V_{oc} \)     | 0.678                             | 0.666                    | 0.667          | 0.667          | 0.668          |
| \( J_{sc} \)     | 35.22                             | 34.866                   | 36.389         | 36.589         | 36.893         |
| FF               | 78.65                             | 79.88                    | 80.02          | 80.08          | 80.17          |
| \( \eta \)       | 18.8%                             | 18.50                    | 19.18          | 19.48          | 19.71          |

Fig. 6. Simulation results of the short circuit current density and conversion efficiency variation with number of dyes added.

Table 6. The Gain in short circuit current density and conversion efficiency of CIGS solar cells with the different samples used.

| Gain        | LDS-S1 | LDS-S2 | LDS-S3 |
|-------------|--------|--------|--------|
| \( J_{sc}(\%) \) | 4.368  | 4.941  | 5.813  |
| \( \eta(\%) \)    | 3.675  | 5.297  | 6.540  |

Simulation results of CIGS solar cell J(V) characteristics with and without LDS PMMA layer are presented in Figure 7. The Figure 8 shows the normalized power of simulated results of CIGS cells with and without LDS materials compared with typical multicrystalline silicon (mc-Si); CIGS thin films present higher power and improvement is added by LDS materials.
3.1. Temperature effect on CIGS Solar cell with LDS PMMA layer doped S3

In this section we study the behavior of the CIGS solar cell with LDS layer doped S3. Table 7 presents the variation of CIGS solar cell performances with the temperature increasing.

The obtained results are given in Table 7. They concern the voltage coefficient, the short circuit current density, the fill factor and the conversion efficiency variation to temperature. All these variations are lower than those of CIGS without LDS layer (Table 8). A good adaptation between the solar spectrum and solar cell spectral response is obtained; this permitted to enhance the electrical and thermal solar cell performance.

Table 7. Temperature dependence of CIGS Solar cell performances with LDS (S3).

| Temperature (°C) | Voc (V) | Jsc (mA/cm²) | FF (%) | η (%) |
|------------------|---------|--------------|--------|-------|
| 25               | 0.667   | 36.893       | 80.16  | 19.71 |
| 30               | 0.658   | 36.851       | 79.77  | 19.30 |
| 35               | 0.647   | 36.803       | 79.45  | 18.90 |
| 40               | 0.638   | 36.750       | 79.09  | 18.51 |
| 45               | 0.627   | 36.693       | 78.82  | 18.12 |
| 50               | 0.618   | 36.635       | 78.50  | 17.74 |
| 55               | 0.607   | 36.576       | 78.24  | 17.36 |
| 60               | 0.597   | 36.520       | 77.93  | 16.98 |
| 65               | 0.587   | 36.468       | 77.65  | 16.60 |
| 70               | 0.577   | 36.420       | 77.30  | 16.22 |

Table 8: The coefficient of Voc, Jsc, FF and η variation to temperature.

| Parameter’s          | CIGS without LDS | CIGS with LDS-S3 |
|----------------------|------------------|------------------|
| ΔVoc/ΔT (mV/°C)      | -2               | -1.8             |
| ΔJsc/ΔT (mA/cm²/°C)  | -0.0162          | -0.0116          |
| ΔFF/ΔT (%/°C)        | -0.088           | -0.064           |
| Δη/ΔT (%/°C)         | -0.082           | -0.076           |
| ΔPmax/ΔT (mW/cm²/°C) | -0.078           | -0.075           |
FIG. 8. Temperature dependence of Maximum Power (Pmax) of CIGS with and without LDS layer doped S3.

CONCLUSION

In this work, the CIGS solar cell performance was studied under high temperature conditions. The degradation was observed for the open voltage, conversion efficiency and power of the cell. By introducing the LDS layer on the top of CIGS solar cell, the electrical and thermal performances of the CIGS solar cell was improved in the standard and high temperature condition. The normalized power of CIGS cells with and without LDS materials shows better performances compared to conventional multicrystalline silicon cells.

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