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# *Numerical Characterization of Cu(In,Ga)$Se_2$ Solar Cells Using Capacitance-Voltage and Capacitance-Frequency Characteristics.*

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***Abstract* – The paper presents the effects of buffer layer thickness, operating temperature, and series resistances on the capacitance-voltage and capacitance-frequency (C-f) characteristics of the standard ZnO/CdS/OVC/Cu(In,Ga)Se2/Mo thin film solar cells.**
**The numerical simulation tool used is a one dimensional program: Solar Cell Capacitance Simulator (SCAPS). We found that, the junction capacitance value increases when the recombination rate of carrier becomes important resulting in an increasing of electrical field intensity. Series resistances (Rs) are factors limiting the solar cells performance. This paper proposes a theoretical model where the effects of Rs onto the solar cell are minimized. For a better optimization of solar cell model performance we get a value of Rs ≤1 Ω*cm², Rsh≥1000 Ω*cm² and the operating temperature to the order of 260 to 380 K.**

***Keywords* – Buffer Layer; Operating Temperature; Rs; Recombination Rate; Electrical Field Intensity; Capacitance Value.**

## *I. Introduction*

Numerical characterization of copper indium gallium diselenide (CIGS) solar cells is an effective tool for understanding and solving very complex phenomena. It permits to increase considerably the efficiency of conversion and the stability of solar cells. Cu(In,Ga)Se2 (CIGS) is a promising candidate for high efficiency thin-film solar cells.

The current challenge is low cost, high conversion efficiency, good stability, mass production and accessibility for all. CIGS solar cells exhibit remarkable conversion efficiency up to $\eta$ = 20.8% [1] and CIGS absorber today has a typical thickness of about 1-2 µm [2].

Solar cells performance more dependents on properties of the space charge region (SCR), but also the properties at the interface layers.

In the literature several studies on the solar cells characterization focus on two techniques, Current-density (J-V) and quantum efficacy (QE) [3]. J-V characteristics and QE permit to detect the losses of current by reflection and incomplete collection of carrier density. But very often, CIGS solar cells performances are severely affected by recombination inside the SCR and in the bulk of layers. This limits the electronic transport at the interface CdS/CIGS and reducing the open-circuit voltage [4, 5, 6, 7, 8].

Capacitance knowledge of the solar cells as function of voltage or frequency can used to determine the interface layers quality, but also to estimate the SCR width and carrier density in the solar cell [2, 7, 9]. In this paper we characterize the solar cell using C-f en C-V techniques with SCAPS-1D.

In order to improve the performance of CIGS solar cells a reduction of the recombination rate, and get good values for series resistance is necessary. Thus, in the present work, our goal is to develop a theoretical model of CIGS solar cell where energetic performances are optimized. In this paper we investigate the effect of the buffer layer thickness, operating temperature and series resistances onto C-V and C-f characteristics.

## *II. Materials/Methods*

### *2.1. Cell structure*

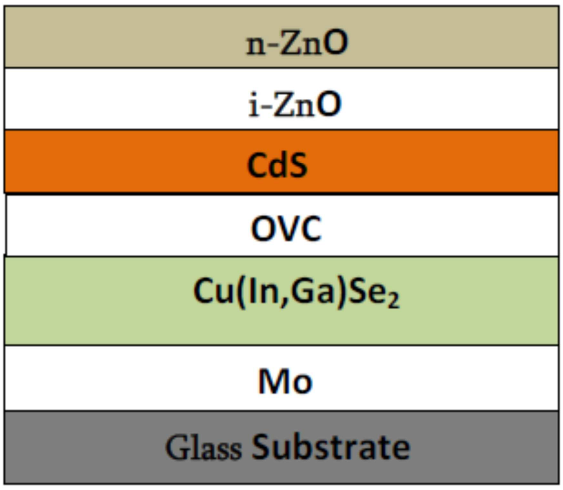


Figure 1. A Schematic Structure Of Typical CIGS Solar Cell.

CIGS solar cells structure is constituted of layers: glass substrate (Na), molybdenum (Mo), absorber (CIGS), ordered vacancy compound (OVC), buffer layer (CdS), intrinsic transparent conductive oxide (i-ZnO) and doped transparent conductive oxide (n-ZnO). CIGS absorber is the main layer of solar cells and the most important. It is the place where the photons are efficiently converted into electron-hole pairs. n-CdS layer is deposited by chemical bath deposition (CBD), it is the buffer layer and its presence induces a best performance and good stability [10]. In addition, it protects absorber layer during the sputter of the transparent conductor oxide (TCO) layer. Therefore, the diffusion of Cd atom in the CIGS has good effects [11]. n-ZnO (TCO) window layer plays a very important role in CIGS solar cell functioning. With a large band gap of 3.3 eV, it mobilizes the maximum photon of sunlight toward the absorber layer. In order to improve the cell performance, we consider the presence of a thin layer of ordered vacancy compound (OVC), also referred to some literatures as surface defect layer (SDL). An OVC layer is presumably present at the surface region of CIGS thin film, since a copper (Cu) poor film composition was found at the surface of the CIGS layer [12, 13, 14]. OVC layer permits to detect the defects which exist at CdS/CIGS interface and also reduce the recombination rate. It has been reported in literature that the inverted surface layer is considered to be beneficial to the performance of CIGS cells [15, 16, 17, 18]. We also add an intrinsic layer of TOC (i-ZnO) between the n-ZnO and n-CdS layers. i-ZnO layer which can be considered as an additional buffer layer. It is usually employed in order to make the p-n junction less sensitive to shunts material fluctuations of the absorber. It protects equally the buffer and absorber layer against sputter damage by energetic ions [19]. An interesting explanation for the need of an intrinsic buffer layer in CIGS would result from defect chemicals rather than from electronic considerations [20].

### *2.2 Material parameters*

The computer simulation tool SCAPS (Solar Cell Capacitance Simulator) is an one dimensional computer software to simulate the AC and DC electrical characteristics of thin film heterojunction solar cells. It is developed especially for CdTe and CIGS solar cells [21, 22]. The program is being extended with transient analysis so that different values like current and capacitance can be calculated in function of applied bias voltage and illumination intensity. SCAPS is able to calculate the relevant electro-optical measurements commonly carried out on thin film solar cells. These are not only the J(V) characteristics, but also spectral response QE(λ) and the capacitance measurements C(V) and C(f), all these as a function of temperature. Optical conditions can be specified by a user defined spectrum [23]. SCAPS calculates solutions of basic semiconductor equation in one dimension and in steady state conditions. These are the Poisson equation for the electrostatic potential ϕ, and the continuity equations for electrons and holes, together with the appropriate boundary conditions.

All simulation uses Fermi-Dirac statistics given by equation (1) [24]. The energy distribution in the different layers and interface is Gaussian.

$$f(E) = \frac{1}{1+\exp[(E-E_F)/kT]} \quad (1)$$

In order to model an effective recombination center, a deep level defect is placed in the middle of the band gap of the CdS layer, the inverted surface layer, and the SCR of the CIGS absorber [15, 16], there is the same for the other layers.

## *III. Results And Discussion*

### *3.1 Buffer layer effect.*

#### *3.1.1 Capacitance voltage characteristic*

Figure 2 presents C-V characteristic as function of the CdS thickness.

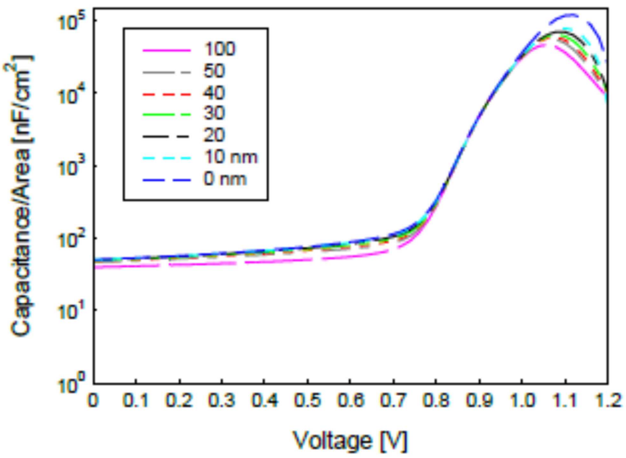


Figure 2. C-V Characteristic as Function of Cds Thickness.

From Figure 2 we can observe that the different C-V curves have the same appearance. Each C-V curve presents three distinct parties which determine three states of the p-n junction capacity behavior.

i) In the range of 0-0.8 V of the applied voltage, the capacitance value slightly increases and the curves stay almost constant (Figure 2). This may correspond to the loss of capacity of the junction; the recombination of pair electron-hole inside the space charge region is important.

ii) In the range of 0.8-1.1 V, the capacitance value considerably increases and reaches its maximal value (Figure 2). This can explain the fact that many electrons are trapped inside the SCR and represent a negative space charge. The electron-hole pair recombination is minimized therefore the electric field intensity inside the SCR increases.

iii) For an applied voltage higher than 1.1 V, the value of the capacitance drops freely; this can be explained by an inversion of the junction space charge of the solar cell. Due to the electrons traps conversion in hole traps and the recombination of electron-hole pair in the space charge region. According to Marc Burgelman and al., a quantitative analysis of the defect densities reveals that the decrease of the density of electron traps is equivalent to the increase of the density of hole traps and this implies that electron traps are converted into hole traps [6].

The results also indicate that the value of capacitance decreases with increasing the CdS layer thickness (Figure 2). The increase of the CdS layer thickness has the effect to increase the recombination of electron-hole pair, thereby the electrical field intensity decreases.

On the whole, the defects concentration is acceptable in the range of 10-30 nm, the recombination rate seems also to be minimized in the SCR.

*3.1.2 Capacitance-frequency characteristic*

In Figure 3, we meet three regimes which determine three situations for the capacity.

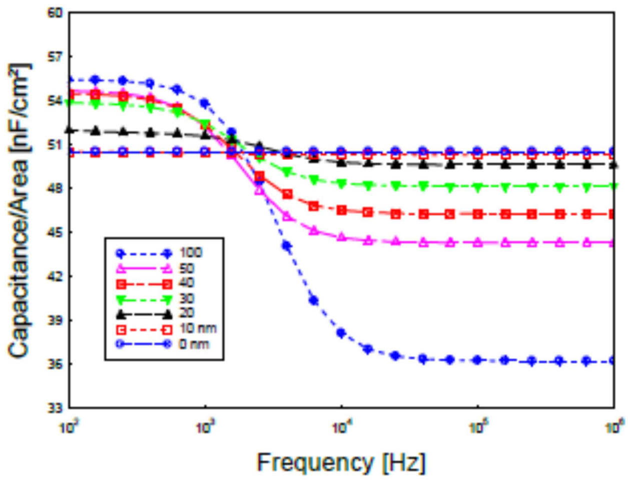


Figure 3. C-F Characteristic with Variable of Cds Thickness.

For low frequencies (≤103 Hz) the junction capacity reaches its maximum value and seems to be constant. This can indicate the well-known additional response of deep defects in the depletion region. When the frequency is between 103 and 104 Hz (103<Hz≤104), the junction capacity considerably decreases and especially for large thickness. It corresponds to the depletion capacity of the CIGS bulk junction in accordance with Eq.2 [7, 9, 25, 26],

$$Cd = \frac{\varepsilon A}{W} \quad (2)$$

Where ε is the dielectric constant of the material, *A* is the area of the sample, and *W* is the width of the SCR.

At high frequency than 104 Hz, the junction capacity reaches its minimum value and stays constant. This high frequency step reflects the dielectric relaxation time of the CIGS layer. In this high frequency regime, the CIGS absorber layer essentially behaves as an insulator with dielectric constant ≈ 12ε0 [7, 25, 26].

In addition, Figure 3 shows that for low frequencies, the capacity of the junction is very important. The thickness of 10 nm of CdS presents a linear curve whose capacitance value is in the order of 50 Hz. The frequency variation has a very low effect on the junction capacity for low buffer layer thickness.

Increasing of the CdS thickness has the effect in low frequency to increase the electron-hole pair's recombination. The effect of the same thickness is the opposite at high frequencies (>104 Hz) (Figure 3).

The range of 10-30 nm of CdS thickness shows a best performance for low frequency.

*3.2 Effects of operating temperature*

*3.2.1 C-V characteristic*

The variation of the capacitance-voltage characteristics of the Cu(In,Ga)Se2 solar cell according to the temperature is shown in Figure 4.

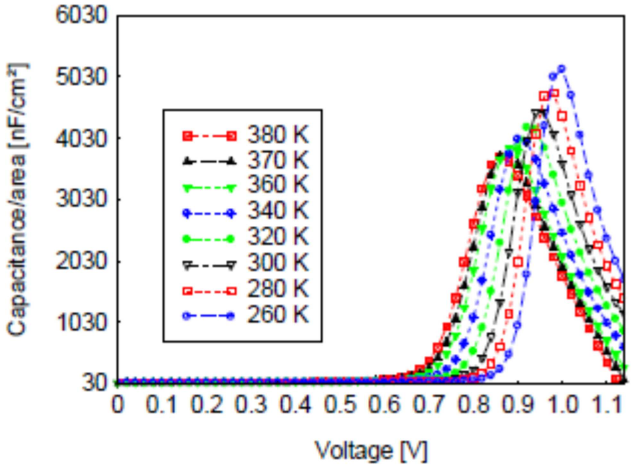


Figure 4. C-V Characteristic for Different Temperature.

In this section, the different curves of Figure 4 show three distinct parts as the C-V curves as function of the buffer layer of the previous preceding paragraph (Figure 2). More Temperature increases, the value of capacitance increases more (Figure 4).

At higher temperature, parameters such as the electron and hole mobility, carrier concentration and band gap of the materials would be affected. This causes recombination of the carriers and result in lower efficiency of the cell.

In addition, the space charge region width decreases and causes the decreasing of capacitance value (Figure 4).

*3.2.2 C-f characteristic*

Contrary to the results obtained with buffer layer thickness (Figure 3), the value of capacitance increases with temperature increasing (Figure 5).

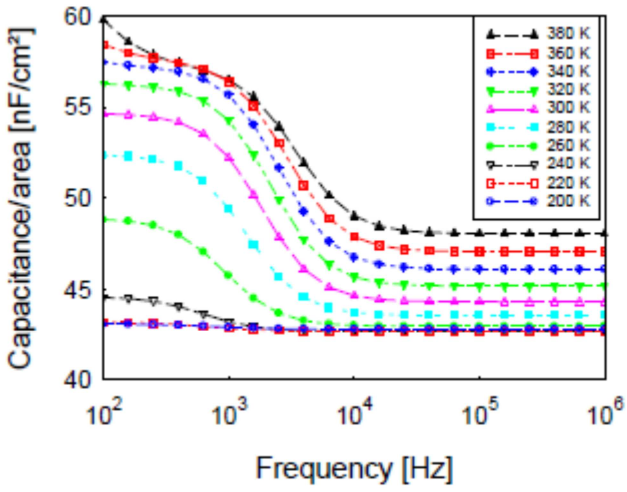


Figure 5. C-F Curves as Function of Temperature.

This result confirms once more the mobility reduction of carriers by temperature increasing. The electrical field intensity decreases. For a better functioning of the solar cell, we consider the range of 280-370 K of the temperature.

*3.3 Series resistance influence*

*3.3.1 C-V characteristic*

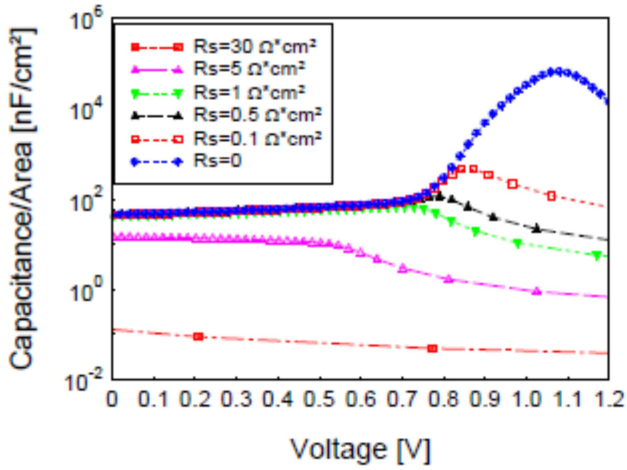


Figure 6. C-V Characteristic with Variable of Series Resistance.

The increase of Rs value induces a significant decrease of the capacitance value (Figure 6). A high value of Rs increases the potential barrier in the SCR and the electrical field intensity decreases. This can be explained by an important recombination rate at the layers interface.

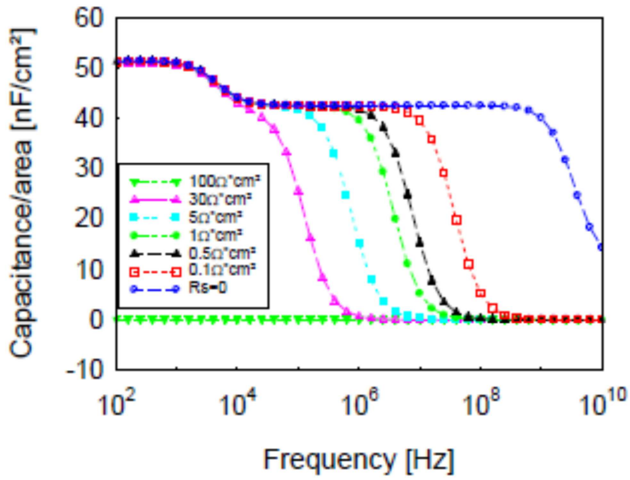


Figure 7. C-F Characteristic as Relation of Series Resistance.

Figure 7 shows a strong decrease in the capacitance value according to the increase of Rs value as in Figure 6. This confirms the Rs action on the carrier recombination. According to our results, the value of Rs≤1 Ω*cm2 is important for better performance of solar cell.

## IV. Conclusions

Numerical characterization in one dimension (1D) were used to characterize the Cu(In,Ga)Se2 solar cell with SCAPS. The effects of the buffer layer thickness, operating temperature and Rs on C-V and C-f characteristics are simulated. In this contribution, we have shown that the performance of the CIGS solar cell depends on all these parameters. The increase or decrease of the capacitance value is also bound to the importance of the applied voltage or the applied frequency. We found that our model has an acceptable performance for a 10-30 nm of the buffer layer thickness, the values of Rs≤1 Ω*cm² and an operating temperature range of 280 K to 370 K.

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