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# Minority carriers' diffusion length determination in thin films CuInSe2 solar cells electro deposited on flexible substrate in Kapton

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**Abstract**

In this work, we have characterized thin films of the chalcopyrite compound CuInSe2 that were elaborated by electrodeposition. The elaboration was made on a flexible substrate in polyimide of Kapton. The Scanning Electronic Microscopy (SEM) and the X-Ray Diffraction (XRD) reveled good morphologic and structural properties of the achieved films. The films enabled the achievement of solar cells in the form of left contact (front)/ITO/n-CdS/p-CIS/Ni/Kapton/right contact (back). This allowed us to carry out optical and electrical measures. We determined the diffusion length of carriers in the CuInSe2 with the photocourant-capacitance method (P-C) and the differential photocourant-capacitance method (DPC). In view of the gap among the results of these two methods we propose a simplified method that allows most exact results.

The CIS-ED flexible solar cell modeling with the Solar Cell Capacitance Simulator (SCAPS) allow us to evaluate the good quality of the cells electrodeposited on Kapton. The J-V characteristic and the electrical parameters such as the open circuit tension Voc, the short circuit current density Jsc, the form factor FF and the efficiency are discussed.

***Keywords:*** *CuInSe2, flexible substrate, Kapton, photocourant-capacitance method (PC), differential photocourant-capacitance method (DPC), simplified method of DPC*

## 1. Introduction

CuInSe2 semiconductor is one of the most promising materials for the fabrication of solar cells in thin films. This chalcopyrite is elaborated on rigid substrates because of his excellent properties like his direct gap (about 1.2eV), his optical absorption coefficient (>105cm-1), his cost and his stability.

Then to satisfy an architectural aesthetics worry and a widening of the scopes of applications, we propose flexible substrates use aiming at flexible photovoltaic solar cells. In this paper, the supple substrate used is the Kapton wish is a polyimide synthesized by the polymerization of a dianhydre with an aromatic diamine.

The films elaboration is carried out by electrodeposition, a successful method. In fact, the research showed that thin films electrodeposited had good structural, optical, electric and morphological properties. [1]

We have deepened this research carrying our work on a most technical aspect: The determination of the diffusion length of the carriers. We carried out photocourant and capacitance measures at different wave-lengths.

Then we have performed the modeling of the CIS-ED solar cell, elaborated on a flexible substrate of Kapton, using the SCAPS. This modeling allowed us to extract and discuss the J-V characteristic of the solar cell and its electrical parameters such as the Voc, the Jsc, the FF and the efficiency η

## 2. Experimental process

The used flexible substrate is the Kapton wish is a polyimide with excellent physical, electrical and mechanical characteristics in a large range of temperature. It's of HN type and it's used with success for applications involving temperature falls about -261°C or temperature rise of 400°C. It can be laminated, metallic, printed, or covered with an adhesive layer. His thickness is about 7.5µm. [2]

The films are deposited by electrodeposition method. This method is an important technique comparative to traditional methods of physical vapor deposition. This is due to the fact that it has many advantages like his low cost, his great predictability and his low temperature process that allow altering the substrate. [1]

CIS thin films have been prepared by one-step electrodeposition process from aqueous solution containing $CuSO_4*5H_2O$, $In_2(SO_4)_3$, $H_2SeO_2$ and gluconic acid as complexing agent. [3]

The characterization of thin films $CuInSe_2$-ED on flexible substrate of Kapton was carried out by SEM and XRD. The results of these characterizations are presented in the results and morphological and structural properties are discussed.

First our work was facing the determination of the diffusion length of the minority carriers. The method was based on incident monochromatic lights with wavelengths of 1.15µm, 1.20µm and 1.25µm. The choice of these wavelengths was due to the fact that they corresponded to energies near of the gap of the $CuInSe_2$ *(1.2eV)*. The

diffusion length was determinate by free methods based on photocurrent and capacitance measures.
Secondly we carry on the characterization using the SCAPS. SCAPS is a numerical simulation program under windows developed at the University of Gent [2].
SCAPS is used for modeling a solar cell and extract its various characteristics. The figure 1 shows the solar cell configuration based on CIS-ED deposited on flexible substrate of Kapton.

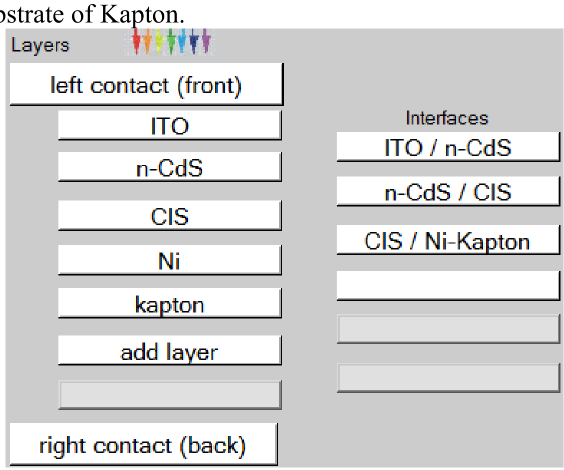


Fig. 1: SCAPS configuration of the CIS-ED solar cell deposited on flexible substrate of Kapton

The SCAPS give us many results such as the I-V, C-V, C-f and QE characteristics. In this paper we keep our comment to the J-V characteristics and we raise the Voc, the Jsc, the FF and the η parameters.

## 3. Diffusion Length Determination Method and the SCAPS Modeling Of The Solar Cell

### 3.1 Photocurrent-Capacitance Method (PC)

The PC method is based on the photocurrent *(Iph)* increasing wish result from the widening of the width depletion area *(W)*. This widening is due to the inverse bias increasing in the solar cell illuminated with an incident monochromatic light. Meanwhile the width depletion area must be negligible in relation to the optical penetration depth $\left( 1/\alpha \right)$:

$$1/\alpha \succ\succ W \qquad (1)$$

$$\alpha W \prec\prec 1 \qquad (2)$$

If the depletion approximation is applied, the heterojunction capacitance is given by:

$$C_p = \frac{\varepsilon_0 \varepsilon_r A}{W} \qquad (3)$$

Where $\varepsilon_0$ is the vacuum permittivity, $\varepsilon_r$ is the relative permittivity of $CuInSe_2$ and A the cell thickness. [3]

The photocurrent Iph is expressed:

$$Iph = qI_0 AT(1-R)(1-\frac{\exp^{-\alpha W}}{1+\alpha Ln}) \qquad (4)$$

Where $q$ is the carrier charge, $Io$ is the incident light intensity, $A$ the area of the solar cell, $T$ the transmission coefficient of the window layer, $R$ the reflection coefficient, α the absorption coefficient, $W$ the depletion width and $Ln$ the diffusion length.
From capacitance-voltage and photocurrent-voltage measures we obtain the photocurrent-capacitance curved. [4]

$$\alpha W \prec\prec 1 \qquad \exp^{-\alpha W} \approx 1-\alpha W \qquad (5)$$

$$Iph = \alpha qIoAT\frac{(1-R)}{1+\alpha Ln}(Ln+W) \qquad (6)$$

$$W = \frac{\varepsilon_0 \varepsilon_r A}{C_p} \qquad (7)$$

$$Iph = \alpha qIoAT\frac{(1-R)}{1+\alpha Ln}(Ln+\frac{\varepsilon_0 \varepsilon_r A}{C_p}) \qquad (8)$$

$$Iph = K(\frac{1}{C_p}+\frac{Ln}{\varepsilon_0 \varepsilon_r A}) \qquad (9)$$

$$K = \alpha q\varepsilon_0 \varepsilon_r IoA^2 T\frac{(1-R)}{(1+\alpha Ln)} \qquad (10)$$

K is a constant independent of the reverse bias.
We traced the plot of the photocurrent against the inverse of the capacitance (1/C). The extrapolation of the curve at Iph=0 give an intersection point at a value of (1/C) wish depend on the wavelength λ of the incident monochromatic light.

$$Iph=0 \qquad (11)$$

$$\left(\frac{1}{C}+\frac{Ln}{\varepsilon_0 \varepsilon_r A}\right) = 0 \qquad (12)$$

Then

$$Ln = -\frac{\varepsilon_0 \varepsilon_r A}{C_p} \qquad (13)$$

This method is used in many works whose results are established and exploited. [5]-[6]

### 3.2 Differential Photocurrent-Capacitance Method (DPC)

When the applied reverse bias is modified form ΔV, the depletion area width varied of ΔW and the photocurrent of ΔIph.

We have at the *(4)*: $Iph = qI_0 AT(1-R)(1-\frac{\exp^{-\alpha W}}{1+\alpha Ln})$

We traced the plot of Iph versus $\exp^{-(\alpha W)}$.

The extrapolation to $\exp^{-(\alpha W)} = 1$ *(14)*
Gives:

$$Iph\big|_{W=0} = \alpha qIoAT\frac{(1-R)}{(1+\alpha Ln)}\times Ln \quad (15)$$

We set:

$$\Gamma = \alpha qAIoT\frac{(1-R)}{(1+\alpha Ln)} \quad (16)$$

$$Iph\big|_{W=0} = \Gamma\times Ln \quad (17)$$

$$\frac{\Delta Iph}{\Delta W} = \alpha qIoAT\frac{(1-R)}{(1+\alpha Ln)}\times\exp^{-\alpha W} \quad (18)$$

$$\frac{\Delta Iph}{\Delta W} = \Gamma\times\exp^{-\alpha W} \quad (19)$$

$$\ln\left(\frac{\Delta Iph}{\Delta W}\right) = -\alpha W + \ln\Gamma \quad (20)$$

We traced the plot of $\ln\left(\frac{\Delta Iph}{\Delta W}\right)$ versus the depletion width W. The extrapolation to W=0 gives:

$$\ln\left(\frac{\Delta Iph}{\Delta W}\right)\bigg|_{W=0} = \ln\Gamma \quad (21)$$

$$\frac{\Delta Iph}{\Delta W}\bigg|_{W=0} = \Gamma \quad (22)$$

We obtain finally the diffusion length doing the ratio:

$$Ln = \frac{Iph\big|_{W=0}}{\frac{\Delta Iph}{\Delta W}\big|_{W=0}} \quad (23)$$

This method is established and used in many works. [7]

### 3.3 Simplified Differential Photocurrent- Capacitance Method

We have précised to *(19)*: $\frac{\Delta Iph}{\Delta W} = \Gamma\times\exp^{-\alpha W}$

We traced the plot of $\frac{\Delta Iph}{\Delta W}$ versus $\exp^{-\alpha W}$

The extrapolation of $\frac{\Delta Iph}{\Delta W}$ to $\exp^{-(\alpha W)} = 1$ allowed writing:

$$\frac{\Delta Iph}{\Delta W}\bigg|_{W=0} = \Gamma \quad (24)$$

We found again the diffusion length doing directly the ratio of *(23)*:

$$Ln = \frac{Iph\big|_{W=0}}{\frac{\Delta Iph}{\Delta W}\big|_{W=0}}$$

This method allowed finding results nearest of the repotted value because we didn't use the logarithmic function wish implied important roundness.

### 3.4 Solar cell modeling with SCAPS

The CIS-ED solar cell modeling with SCAPS is presented in the figure 1. The defects of the materials are taken to account. The n-ZnO/n-CdS interface, the n-CdS/CIS interface and the CIS/Kapton interface are well fixed. at these interfaces, the type of charge, the carrier concentration and the energy distribution are determined. The modeling is set under Standard Spectrum AM_1.5G 1sun.spe whose incident light power is $1000 W.m^{-2}$.

## 4. Results and Discussion

### 4.1 SEM and XRD results

The fig. 2 shows a dense visible distribution on the surface of $CuInSe_2$ films. We notice flexible films with good morphological properties.
The characterization by XRD (Fig. 3) showed a preferential peak (220) corresponding to the chalcopyrite structure of $CuInSe_2$ thin films and good structural properties of flexible films.

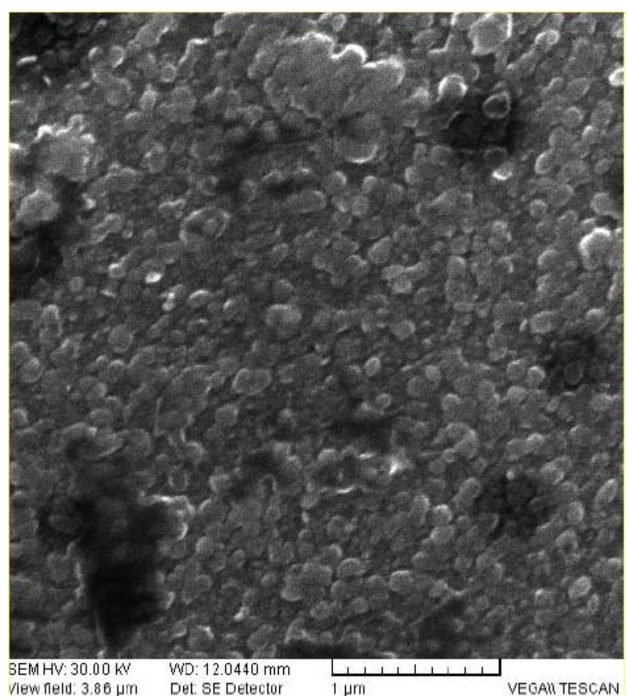

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Fig. 2: Microphotography by SEM of CuInSe2-ED on flexible substrate of Kapton

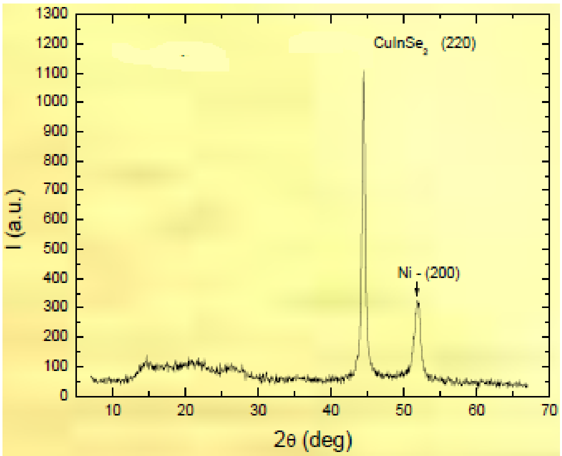


Fig. 3: XRD results of characterization of CuInSe2-ED on flexible substrate of Kapton

## 4.2. Results of the diffusion length determination

For all characteristics presented we were interested only by incident monochromatic light from wavelengths corresponding to energies near of the gap of the $CuInSe_2$. Measures were made with monochromatic light from wavelengths: $\lambda_1 = 1.15\mu m$ , $\lambda_2 = 1.20\mu m$ and $\lambda_3 = 1.25\mu m$

### 4.2.1. P-C method results

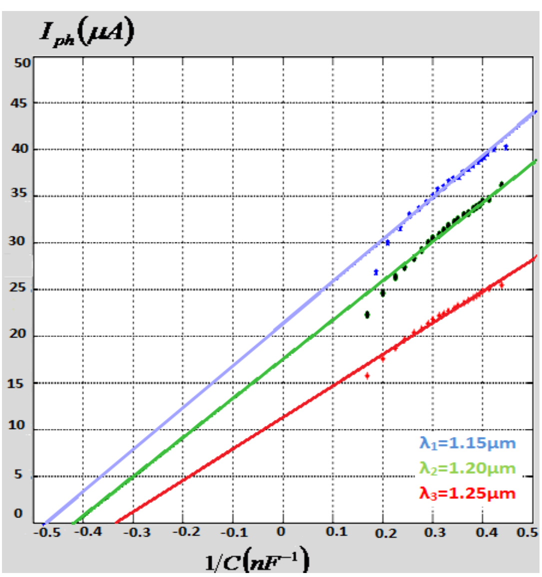


Fig. 4: Photocurrent versus reciprocal capacitance under monochromatic illumination at different wavelengths

The fig.4 showed us that photocurrent increased with reciprocal capacitance and it's more important for $\lambda_1$=1.15µm than $\lambda_2$=1.20µm and $\lambda_3$=1.25µm.
The extrapolation of curves at *Iph=0* yields an intercept with the X-axis wish allows to obtain corresponding diffusion length:

$Ln_1=1.65\mu m$ for $\lambda_1=1.15\mu m$ (25)
$Ln_2=1.43\mu m$ for $\lambda_2=1.20\mu m$ (26)
$Ln_3=1.15\mu m$ for $\lambda_3=1.25\mu m$ (27)

### 4.2.2. DPC method results

We see in fig.5 the decreasing of the photocurrent with the increasing of the exponential term wish depends of the depletion width. The extrapolation of Iph at $exp^{-(\alpha W)}=0$ give flowing results:

$$Iph_1\big|_{W=0} = 7.41\mu A \quad \text{for } \lambda_1=1.15\mu m \quad (28)$$
$$Iph_2\big|_{W=0} = 4.44\mu A \quad \text{for } \lambda_2=1.20\mu m \quad (29)$$
$$Iph_3\big|_{W=0} = 0.37\mu A \quad \text{for } \lambda_3=1.25\mu m \quad (30)$$

Since the DPC method is based on the extrapolation of two characteristics, the fig.6 presents the variation of the logarithmic function of photocurrent in relation to the depletion width.

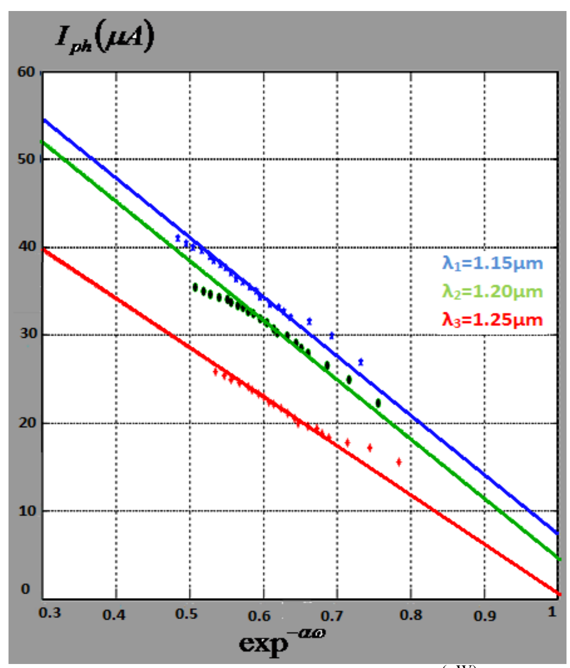


Fig. 5 Plot of photocurrent versus $exp^{-(\alpha W)}$ under monochromatic illumination at different wavelengths

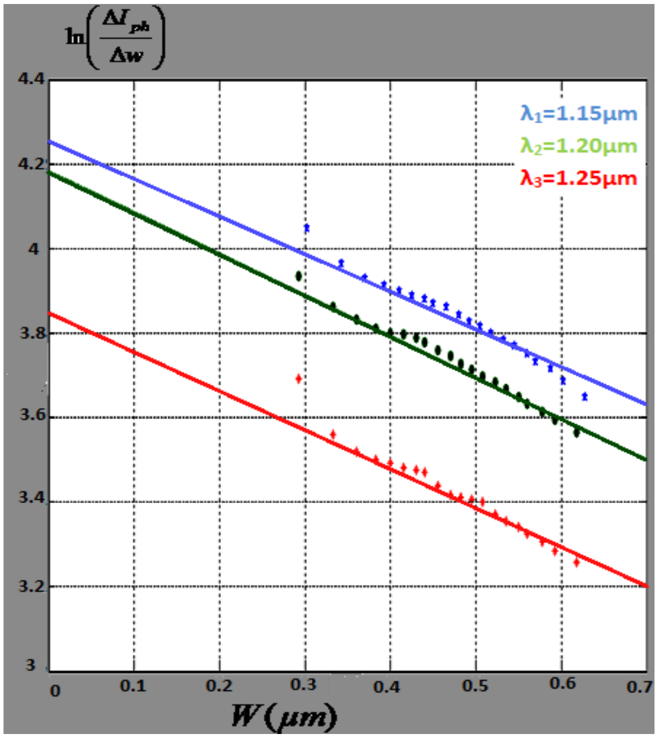


Fig. 6 plot of *ln(ΔIph/ΔW)* versus depletion width *W* under monochromatic illumination at different wavelengths

The fig.6 shows that the function $\ln\left(\frac{\Delta Iph}{\Delta W}\right)$ decreases with the widening of the depletion width. The extrapolation of $\ln\left(\frac{\Delta Iph}{\Delta W}\right)$ at *W=0* gave following results:

$$\ln\left(\frac{\Delta Iph}{\Delta W}\right)_1\Bigg|_{W=0} = 4.25 \quad for\ \lambda_1=1.15\mu m \qquad (31)$$

$$\ln\left(\frac{\Delta Iph}{\Delta W}\right)_2\Bigg|_{W=0} = 4.18 \quad for\ \lambda_2=1.20\mu m \qquad (32)$$

$$\ln\left(\frac{\Delta Iph}{\Delta W}\right)_3\Bigg|_{W=0} = 3.84 \quad for\ \lambda_3=1.25\mu m \qquad (33)$$

To determine the diffusion length we calculate the ratio of the equation *(23)*:

$$Ln = \frac{Iph|_{W=0}}{\frac{\Delta Iph}{\Delta W}\Big|_{W=0}}$$

We obtained following results:

$Ln_1=0.105\mu m$ for $\lambda_1=1.15\mu m$ (34)
$Ln_2=0.068\mu m$ for $\lambda_2=1.20\mu m$ (35)
$Ln_3=0.008\mu m$ for $\lambda_3=1.25\mu m$ (36)

We notice a great gap on the results of PC and DPC methods. This is accented by the use of the logarithm function of the differential of photocurrent. Then we propose to go by the same values of differential of photocurrent without using the logarithm function.

### 4.3. Results of the simplified DPC method

The Fig.7 shows that the differential of photocourant decreases with the increase of the term $exp^{-(\alpha W)}$. The extrapolation of $\left(\frac{\Delta Iph}{\Delta W}\right)$ to $exp^{-(\alpha W)}=1$

Gave:

$$\left(\frac{\Delta Iph}{\Delta W}\right)_1\Bigg|_{W=0} = 3.32 \quad \text{for } \lambda_1=1.15\mu m \qquad (37)$$

$$\left(\frac{\Delta Iph}{\Delta W}\right)_2\Bigg|_{W=0} = 3.26 \quad \text{for } \lambda_2=1.20\mu m \qquad (38)$$

$$\left(\frac{\Delta Iph}{\Delta W}\right)_3\Bigg|_{W=0} = 2.99 \quad \text{for } \lambda_3=1.25\mu m \qquad (39)$$

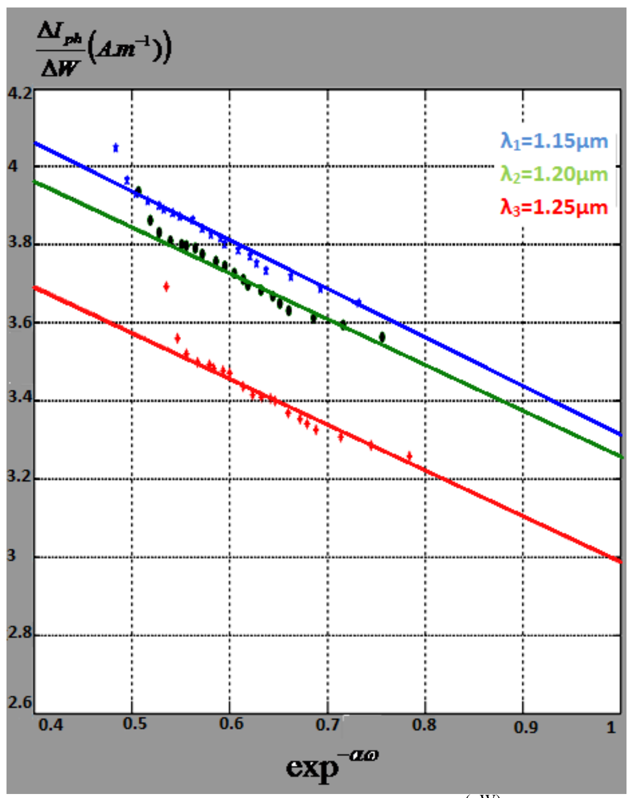


Fig.7 Plot of (ΔIph/ΔW) versus $\exp^{-(\alpha W)}$ under monochromatic illumination at different wavelengths

These results lead to the diffusion lengths of carriers equal to:

$Ln_1=2\mu m$ for $\lambda_1=1.15\mu m$ (40)

$Ln_2=1.36\mu m$ for $\lambda_2=1.20\mu m$ (41)

$Ln_3=0.12\mu m$ for $\lambda_3=1.25\mu m$ (42)

We found again values near of those founded with the P-C method. Indeed this last method presents less mathematical roundness and is convenient for thin films characterizations.

### 4.4. Results of the solar cell modeling

The figure 8 presents the J-V characteristic of the solar cell based on CIS-ED on flexible substrate of Kapton. We have noticed the convergence of our result with the established applied results. We obtain an important Open Circuit Tension Voc=0.3633V. The Short Circuit Current Density of the solar cell is Jsc=35.87781mA.cm$^{-2}$. The Form Factor is given in percentage and FF=44.83%. This result certifies the quality of the cell elaborated on the flexible substrate. The modeling presents an efficiency of 5.84%. These results are satisfactory and encouraging for the use of flexible substrates.

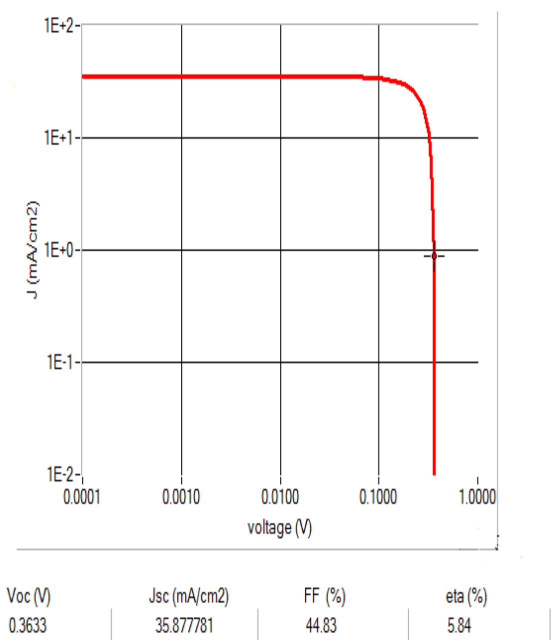


Fig. 8: results of the SCAPS modeling of the solar cell based on CIS electrodeposited on Kapton Substrate

## CONCLUSION

We characterized thin film solar cell based on CuInSe2 electrodeposited on a flexible substrate in Kapton. The characterization by MEB and XRD confirm good morphological and structural properties of thin films. The experimental methods of diffusion lengths determination of carriers give us good properties of films. We used the PC and the DPC methods and we propose, instead of the last one, a simplified method wish allow having results with less roundness, and then more exact. Based on one extrapolation and different of traditional PC and DPC methods, the used method in this paper gave a reliable diffusion length. We obtained:

$Ln_1=2\mu m$ for $\lambda_1=1.15\mu m$ (43)

$Ln_2=1.36\mu m$ for $\lambda_2=1.20\mu m$ (44)

$Ln_3=0.12\mu m$ for $\lambda_3=1.25\mu m$ (45)

The characterization is continued by he modeling of the solar cell using SCAPS. We have found that flexible cells have good electrical properties in particular the Form Factor FF of 44.83%, the open circuit voltage Voc=0.3633V, the short circuit current density Jsc=35.87781mA.cm$^{-2}$ and the efficiency of 5.84% to improve. These results certify the success of the flexible substrate use. The Research and Development about the flexible substrate use must be encouraged. This use offers a wide range of new applications to photovoltaic technology.

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