DARK *J–V* CHARACTERISTICS MODEL OF CHALCOPYRITE-BASED SOLAR CELLS

Ľubomír Škvarenina
Doctoral Degree Programme (4), FEEC BUT
E-mail: skvarenina@phd.feec.vutbr.cz

Supervised by: Robert Macků
E-mail: macku@feec.vutbr.cz

Abstract: An equivalent circuit model of the current parasitic pathways is proposed to describe a behaviour of dark current density–voltage characteristics of chalcopyrite-based solar cells in order to understand a shunting behaviour between the ZnO:Al/*i*-ZnO/CdS/$Cu(In,Ga)Se_2$/$MoSe_2$/Mo/Ti/TiN layers. The model fitting with a parameter extraction is evaluated for the sample before and after an appearance of a permanent breakdown to prove an accurate response of the proposed model to an ohmic and non-ohmic component shift.

Keywords: dark *J–V* characteristics, parasitic current pathways, heterojunction, CIGS, solar cell, thin-film, equivalent electrical model, parameters extraction

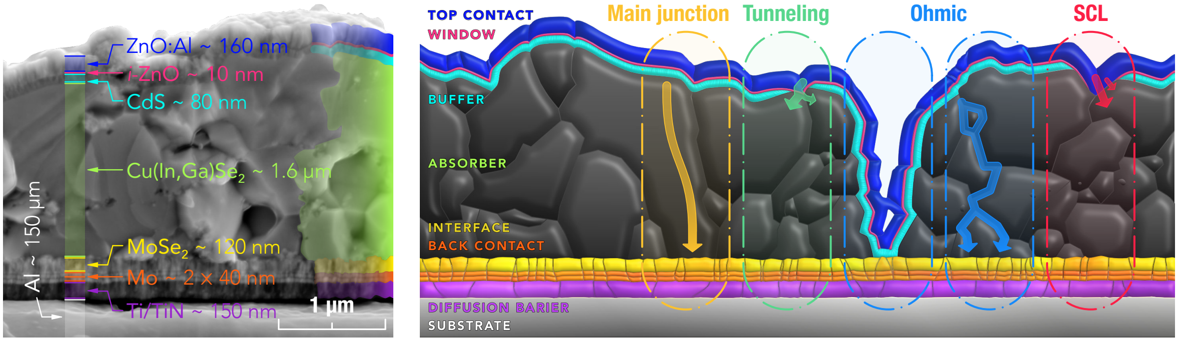
1 INTRODUCTION

A chalcopyrite-based solar cell is a rather complex system, consisting of several layers of various materials. Non-uniformities in these solar cell type may be manifested in the thickness of all layers as well as in the electronic parameters such as band gap, carrier density and carrier lifetime. In addition, the voids and pinholes often appear in different layers of CIGS solar cells under certain growth conditions [1]. These non-uniformities have a strong influence on a current density–voltage (*J–V*) characteristics and they may lead to a creation of a permanent breakdown. The impact of permanent breakdown on device performance can be analysed by modelling and fitting of dark *J–V* characteristics with parameters extraction, accompanied by an examination of particular components participating on charge carrier transport mechanisms [2].

2 THEORY

2.1 PARASITIC CURRENT PATHWAYS

The real structure of examined CIGS solar cell samples by a scanning electron microscopy (SEM) is shown in Fig. 1a. The *p–n* junction of these solar cells is based on *p*-type chalcopyrite $Cu(In,Ga)Se_2$ absorption layer in combination with a *n*-type CdS buffer layer. Accordingly to the real structure in the Fig. 1a, which is examined by SEM, is shown in Fig. 1b an illustrated model with a parasitic current pathways. The main junction in Fig. 1b (marked in yellow) represents a proper pathway for a current flow. The tunnelling (marked in green) represent parasitic current pathway via high densities of mid-gap defect states in the depletion region of the *p–n* junction. The ohmic leakage current (marked in blue) is caused by pinholes in the absorber layer or by low-resistance paths along the grain boundaries. The space-charge limited current (marked in red) is present due to a metal/semiconductor/metal-like regions which may caused a metal diffusion from the highly doped ZnO:Al front contact (or busbars Al grid) through a pinholes in an intrinsic window *i*-ZnO and buffer CdS layer [3]. It should be noted that the current flow is not likely to be produced by just one specific type of current pathway in a certain area (as illustrated in Fig. 1b), but rather by a combination of the these current conductions.



a) b)

Figure 1: a) Real cross-section of deposited layer stack, SE detector, beam accelerating voltage 6 kV, magnification 72,500×. b) Illustration with possible current pathways in CIGS solar cells.

2.2 Two-diode extended model

The proposed extended model consist of four main parallel components which representing the specific current pathways illustrated in Fig. 1b. These current pathways can be modelled by two diodes (different ideality factor) with a shunt resistor extended by a space-charge limited component. Then the illustrated current pathways in Fig. 1b can be redraw into an equivalent circuit which is shown in Fig. 2. These parallel components are coupled to a series resistor that represents the resistance

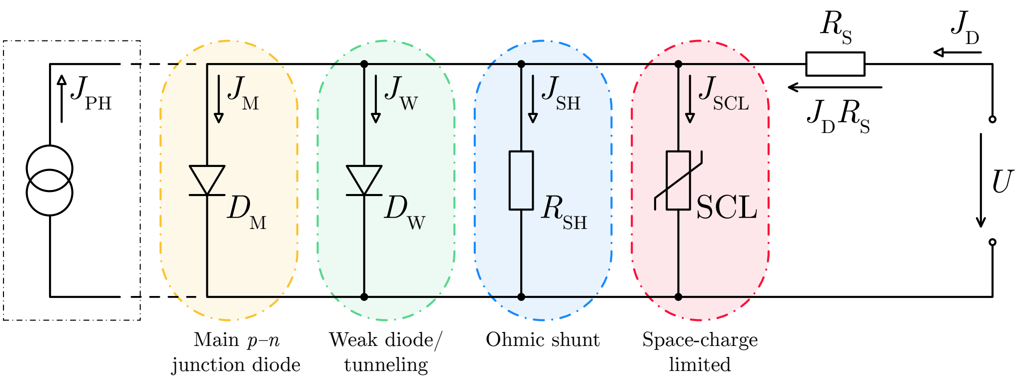


Figure 2: Equivalent circuit of two-diode (D_M, D_W) model with parasitc shunt (R_{SH}), series (R_S) resistances and space-charge limited (SCL) component for thin-film chalcopyrite-based solar cell.

for a current path along the deposited layers (see Fig. 1b). Therefore, it is possible to express a total dark current density (J_D) according to the Kirchhoff's current law from the Fig. 2 as a sum of these individual current components [4]. The total J_D is then expressed by the following equation

$$
\begin{aligned}
J_D = & \underbrace{J_{0M}\left\{\exp\left[\frac{q\,(U - J_D R_S)}{n_M k_B T}\right] - 1\right\}}_{\text{Main } p\text{–}n \text{ junction diode}} + \underbrace{J_{0W}\left\{\exp\left[\frac{q\,(U - J_D R_S)}{n_W k_B T}\right] - 1\right\}}_{\text{Weak diode / tunneling}} \\
& + \underbrace{\frac{(U - J_D R_S)}{R_{SH}}}_{\text{Ohmic shunt}} + \underbrace{k\,(U - J_D R_S)^m}_{\text{Space-charge limited}} \,,
\end{aligned}
\tag{1}
$$

where J_{0M}, J_{0W} are a saturation current of the main p–n junction, respectively a saturation current of the weak diode/tunnelling, q is the electron charge, n_M, n_W are diodes ideality factors, k_B is the

Boltzmann's constant, T is an absolute temperature of the *p–n* junction, R_{SH} is a shunt resistance, R_S a series resistance, k is a coefficient of the space-charge limited current component and m is its power factor. Alternatively, it is possible to use in two diode components a more robust single exponential parameter A according to the relation $A = q/nk_BT$.

3 EXPERIMENTAL

The preparation of thin-film chalcopyrite-based solar cells requires a high accuracy in dividing the sheet into smaller samples. Despite that, the many non-uniformities are created between layers ZnO:Al/*i*-ZnO/CdS/$Cu(In,Ga)Se_2$/$MoSe_2$/Mo/Ti/TiN after a sheet dividing along the entire cut edges. Therefore it is necessary to perform an edge deletion by a fine grinding/polishing on a metallographic machine. Finally, the samples are electrically contacted by two precise positioners with gold-plated pogo pins. Then, the dark *J–V* characteristics are measured by a high precision source meter Keithley 2420. Modelling with fitting of the dark *J–V* characteristics with Eq. 1 is implemented in MATLAB® by using symbolic (returns exact solutions) or numeric (returns approximated symbolic solutions) solver in Symbolic Math Toolbox™. The transcendental Lambert *W*-function $f(W) = We^W$ is necessary to use to solve the corresponding dark current density (J_D) from the Eq. 1.

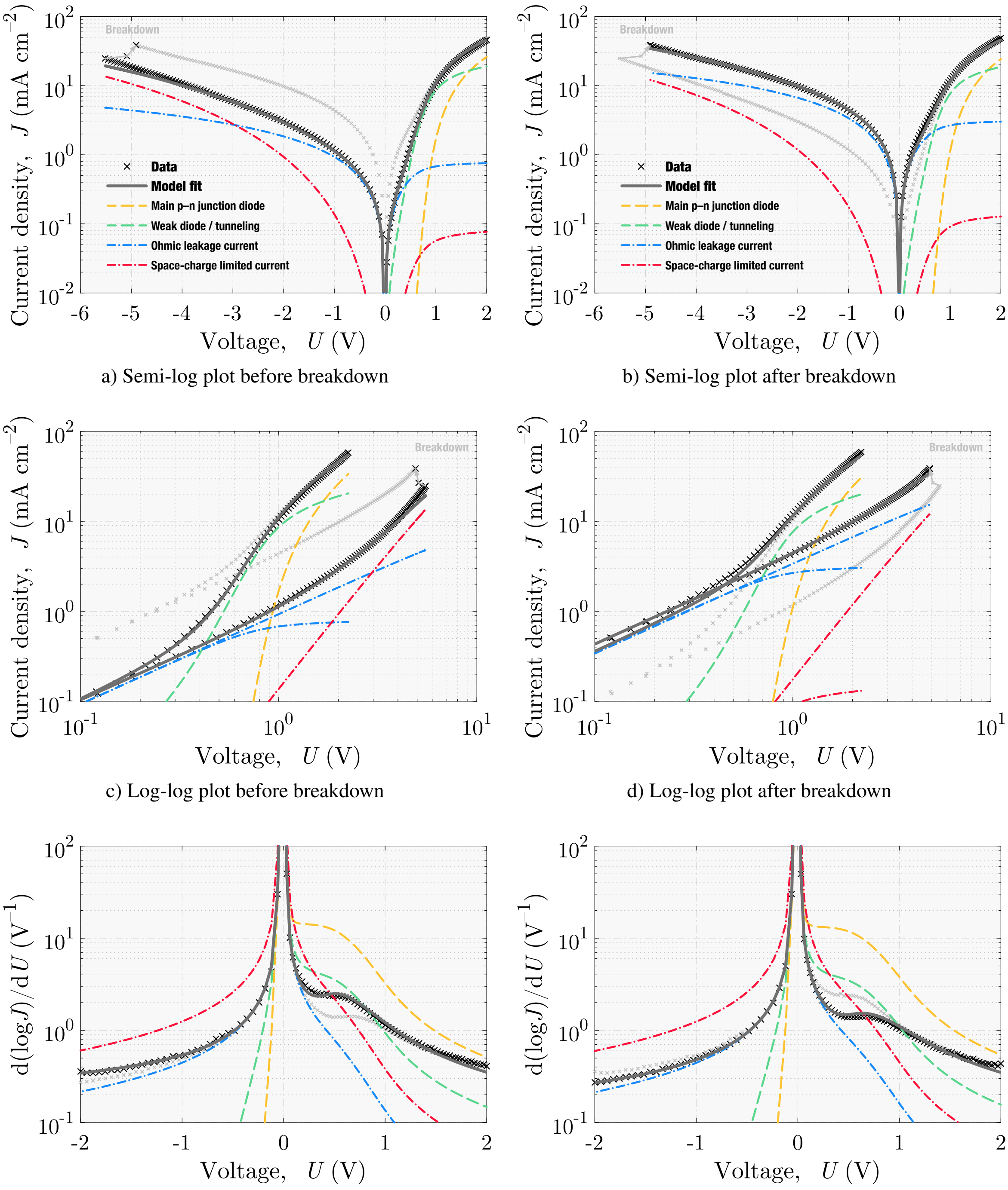
4 RESULTS

The superposition principle where the *J–V* characteristics under illumination (J_{IL}) is simply a summation of the dark current (J_D) and photocurrent (J_{PH}) is very often not valid ($J_{IL} \neq J_D + J_{PH}$) for thin-film solar cell, especially not for $Cu(In,Ga)Se_2$ solar cells [5]. The exact explanation is more exhausting and it is beyond the scope of this paper [6]. Therefore our investigation is focused only on a dark *J–V* characteristics. These dark *J–V* characteristics with a model fitting are shown in Fig. 3. The colors in Fig. 3 correlate with a coloured marking in Figs. 1b and 2 and Eq. 1. Moreover, the diodes are denoted by dashed lines and the ohmic and non-ohmic components are denoted by dashed dot lines. Very often the fitting by the model seems to be precise in semi-log plot but in log-log plot does not correspond with the measured data almost at all (or vice versa). Therefore, the three different data plots are showed as a proof of the high precise fit achieved by our proposed model. An excellent agreement between experimental and modelled data is achieved in Figs. 3a, 3c and 3e before breakdown as well as in Figs. 3b, 3d and 3f after breakdown. The corresponding extracted parameters from Eq. 1 are shown in Tab. 1. As can be seen in Tab. 1 the parameters of the main *p–n* junction diode and weak diode/tunnelling have not changed. After breakdown the change was observed mainly in change of shunt resistance, where decrease from 1.044 $k\Omega\,cm^2$ to 252 $\Omega\,cm^2$ (difference of $\Delta R_{SH} = 792\ \Omega$). The coefficient k which is related to the length and conductivity of the current path is 0.1493 $A\,V^{-m}$

Table 1: Extracted paramaters from dark *J–V* model fit of the sample $^{NS}CIGS_2$.

Model component	Variable	Before breakdown	After breakdown
Main *p–n* junction diode	J_{0M}	$5.8\overline{3} \times 10^{-11}$ mA cm^{-2}	$5.8\overline{3} \times 10^{-11}$ mA cm^{-2}
	n_M	1.1331 ($A_M = 34\ V^{-1}$)	1.1331 ($A_M = 34\ V^{-1}$)
Weak diode / tunneling	J_{0W}	8.3×10^{-3} mA cm^{-2}	8.3×10^{-3} mA cm^{-2}
	n_W	3.9311 ($A_W = 9.8\ V^{-1}$)	3.9311 ($A_W = 9.8\ V^{-1}$)
Ohmic shunt & series	R_{SH}	1.044 $k\Omega\,cm^2$	252 $\Omega\,cm^2$
	R_S	26.4 $\Omega\,cm^2$	26.4 $\Omega\,cm^2$
Space-charge limited	k	0.1493 $A\,V^{-m}$	0.25 $A\,V^{-m}$
	m	2.8	2.8

before breakdown and 0.25 $\mathrm{A\,V}^{-m}$ after breakdown (difference of $\Delta k = 0.1007\ \mathrm{A\,V}^{-m}$). The power factor m is in both cases 2.8. It is defined that the power factor in the case whereby shallow traps facilitate the current is ~ 2 and due to a high density of deep traps is > 2 [7]. However, this change of shunt resistance component which is dominated in dark current under reverse bias visibly influenced the dark current also in a forward-bias (where dominates the components of the two diodes).



a) Semi-log plot before breakdown

b) Semi-log plot after breakdown

c) Log-log plot before breakdown

d) Log-log plot after breakdown

e) Differential plot before breakdown

f) Differential plot after breakdown

Figure 3: Dark *J*–*V* characteristics of thin-film chalcopyrite-based solar cell with particular components of the model fitting a), c), e) before and b), d), f) after breakdown in various representations, sample $^{\mathrm{NS}}\mathrm{CIGS}_2$, area 129.4 mm^2, perimeter 45.3 mm, $T_{\mathrm{A}} = 301.22$ K.

5 SUMMARY

The parasitic current pathways with an equivalent circuit model has been developed to describe the dark *J–V* characteristics in thin-film chalcopyrite-based solar cells. The research effort was focused not only at modelling, fitting and parameters extraction, but also at verification of the model at permanent breakdown of the sample. The results confirmed the highly accurate response of the whole model (or individual components) to shunt resistance (R_{SH}) shift in forward as well as in reverse-bias. The shunt resistance R_{SH} after sample $^{NS}CIGS_2$ breakdown decrease from 1.044 $k\Omega\,cm^2$ to 252 $\Omega\,cm^2$ (the SCLC coefficient k increase from 0.1493 $A\,V^{-m}$ to 0.25 $A\,V^{-m}$, where $m = 2.8$). Future work will be focused on expanding the model for the response to a pre-breakdown voltage and also at an adaption of the model for possible application on other types of thin-film solar cell technologies such as CdTe, kesterite-based $Cu_2ZnSn(S,Se)_4$ or perovskite-based $CH_3NH_3PbI_3$.

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