Empirical *J-V* modelling of CIGS solar cells

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Abstract

Chalcopyrite based solar modules combine the advantages of thin film module technology with the stability of crystalline silicon cells. Therefore chalcopyrite based modules can potentially take up a large part of the PV market. Today the efficiency of lab scale devices is close to 20 %, comparable to the best multicrystalline silicon cells. Physical insight in the electronic device structure is essential to develop devices with even higher efficiencies.

To analyse the cells we measure *J-V* curves, both dark and light different light intensities, J_{sc} -V_{oc} curves, spectral response measurements $QE(\lambda)$ and capacitance measurements. The diode parameters saturation current J_0, ideality factor n, series resistance R_s and shunt conductance G_{sh} are extracted form the dark, light and J_{sc}-V_{oc} curves.

We investigated the light dependence of these parameters at room temperature for different CIGS cells. In this article we will introduce new interpretation schemes: a comparison of the shape of the *J-V* curves measured over 4 decades of illumination intensity with simulations based on a one diode model, and a study of the fill factor loss calculated ideal FF_0 minus measured FF as a function of J_{sc}/V_{oc} or V_{oc}/J_{sc}, obtained by varying the illumination intensity. The interpretations proposed here can help solar cell developers in finding causes for a too low fill factor FF.

1. Introduction

Chalcopyrite based solar modules combine the advantages of thin film module technology with the stability of crystalline silicon cells. Therefore chalcopyrite based modules can potentially take up a large part of the PV market. Today the efficiency of lab scale devices is close to 20 %, comparable to the best multicrystalline silicon cells [1]. Physical insight in the electronic device structure is essential to develop devices with even higher efficiencies.

In this article we will introduce an empirical modelling scheme, i.e. a model not based on physical parameters such as band gap, thickness of the layers, etc. The use of this model is to gain a first indication of the non-idealities of a solar cell.

2. Non-idealities of a solar cell

The ideal solar cell equation is:

$$J\left(V\right)=J_s\left[\exp\left(\frac{qV}{kT}\right)-1\right]-J_L \tag{1}$$

where the symbols have their usual meaning: J_s is the dark saturation current and J_L the light current.

Standard non-idealities are a series resistance R_s, a shunt conductance G_{sh}, a diode ideality factor $n>1$ and voltage dependent collection $QE(V)<1$ for $V>0$. If we include all these non-idealities in Eq, 1 we get:

$$J(V_j)=J_s\left[\exp\left(\frac{qV_j}{nkT}\right)-1\right]+G_{sh}V_j-QE\left(V_j\right)J_L$$

with (2)

$$V_j=V-R_sJ$$

2.1 About voltage depend collection

Two symptoms commonly encountered in thin film solar cells are often described as 'voltage dependent collection':

1. The forward *J-V* characteristic show a soft 'knee', which is not caused by a series resistance R_s, shunt conductance G_{sh} or an ideality factor $n>1$
2. or the quantum efficiency $QE(\lambda)$ decreases with forward bias V.

Voltage dependent collection can be caused by generation outside the space charge layer SCL in combination with a poor minority carrier diffusion length in the absorber, as is explained below.

In a typical thin film solar cell window/absorber structure Figure 1, a fraction $1-\exp\left(-\alpha W\right)$ of the incoming photons is absorbed in the space charge layer (SCL), where α is the absorption coefficient and W the depletion width. Due to the electric field $\mathcal{E}$ in the SCL, we can assume that all absorbed photons do contribute to the electric current:

$$1-\exp\left[-\alpha(\lambda)W(V)\right] \tag{3}$$

where we have explicitly written the dependence of the wavelength λ and the voltage V. This mechanism is indicated as 'gen 1' in Figure 1. In the neutral part of the absorber, a fraction $\exp\left(-\alpha W\right)$ of the incoming photons is absorbed. However, the generated free electron has to reach the edge of the

SCL by diffusion, before it can be collected in the window layer and finally in the external contact. Due to minority carrier recombination in the absorber, the efficiency of this process is lower than unity, and the contribution to the current is given by:

$$\exp\left[-\alpha(\lambda)W(V)\right]\frac{\alpha(\lambda)L_n}{\alpha(\lambda)L_n+1} \tag{4}$$

with L_n the electron diffusion length in the *p*-type absorber. This mechanism is indicated as 'gen 2' in Figure 1. The overall quantum efficiency $QE(V,\lambda)$ is obtained by summing Eqs. (3) and (4). It obviously depends on voltage, via the depletion width $W(V)$, and on wavelength, via the absorption coefficient $\alpha(\lambda)$.

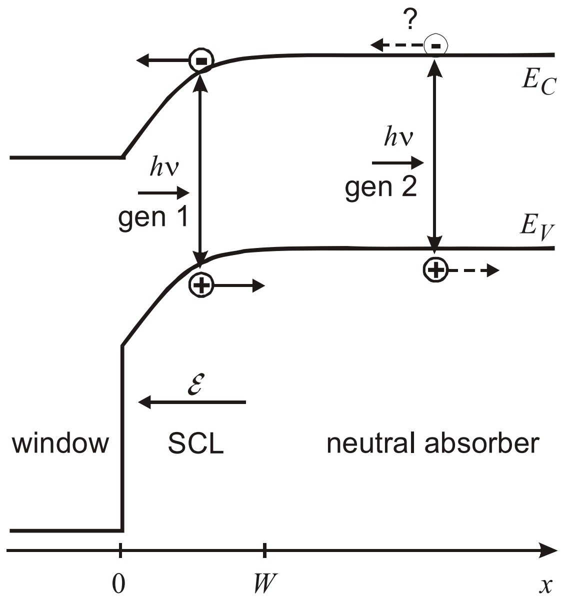

Figure 1 The generation of an electron-hole pair within the SCL ('gen1') and outside the SCL, in the neutral absorber ('gen2').

3. Non-idealities and the *J-V* curve

The four non-idealities considered here, this is: R_s, G_{sh}, $n>1$ and $QE(V)$, all influence the *J-V*, but in a slightly different way. To examine which mechanism is present, we investigate the *J-V* at different illumination intensities. To have a good overview of the light dependence all curves are normalised to their J_{sc} value, so they all pass through the a normalised short circuit current point $J_{sc}=-1$. This is shown in Figure 2, for an *I-V* measurement at 16 different light intensities of a CIS based thin film solar cell.

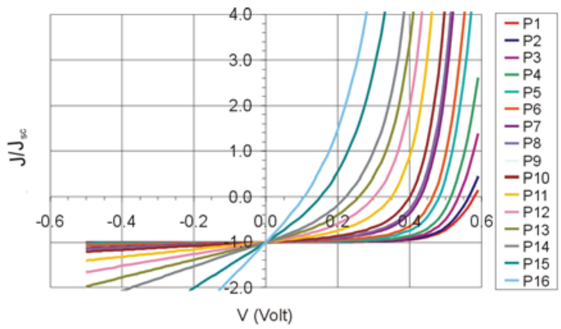

Figure 2 A J-V measurement at 16 different light intensities, all curves scaled to a normalised J_{sc} = -1

To investigate which mechanism is present, we compare the measured curves with simulations. Figure 3 (left) shows a simulation for cell with a high shunt conductance no series resistance, $n = 1$ and no voltage dependent collection. Figure 3 (right) shows a simulation with only a series resistance.

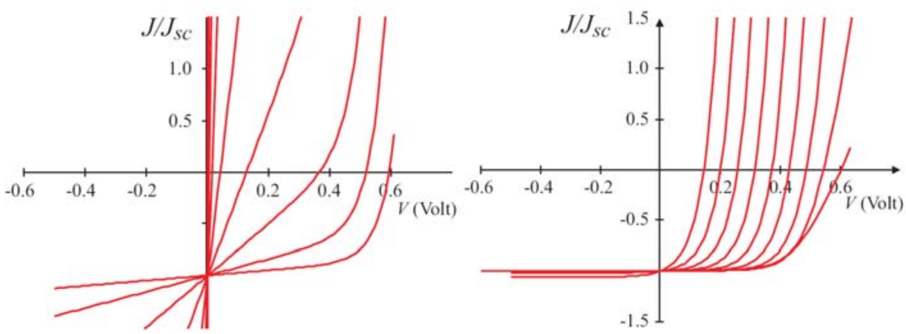

Figure 3 Left: a simulation with only shunt conductance present. Right: a simulation with only series resistance present.

Shunt conductance is manifesting itself at negative bias voltages. Thus we have to compare the negative bias characteristic of Figure 2 with Figure 3 (left). We conclude that there is a minor influence by shunt conductance.

Series resistance is manifesting itself at forward bias. If we compare the forward characteristic of Figure 2 with Figure 3 (right), we see that there is hardly any influence of series resistance.

Figure 4 shows a simulation for a cell with a high ideality factor, no series resistance and no shunt conductance. The ideality factor has an influence on the *knee* of the *J-V* characteristic. Form Figure 4 and Figure 2 we conclude that dominant non-ideality is a high ideality factor.

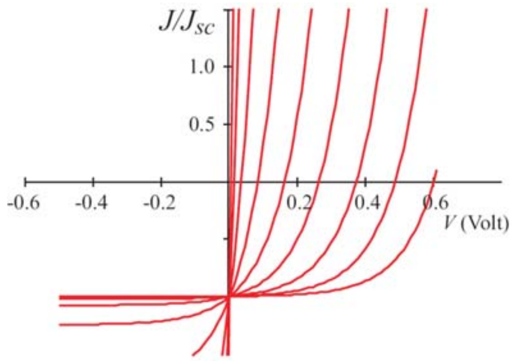

Figure 4 A simulation for a high ideality factor with no series resistance and no shunt conductance.

4. Study of the fill factor loss *ΔFF*

An other way to study non-idealities is to study the fill factor losses *ΔFF*. In [3], a formula is given for the fill factor as a function of the series resistance R_s, shunt conductance G_{sh} and ideality factor n:

$$FF\left(V_{oc},n,G_{sh},R_s\right)=FF_0\left(V_{oc},n\right)-C\left(V_{oc},n\right)R_s.A\frac{J_L}{V_{oc}}-D\left(V_{oc},n\right)\frac{G_{sh}}{A}.\frac{V_{oc}}{J_L} \quad (5)$$

with $FF_0(V_{oc},n)$ the calculated fill factor for a cell with the same V_{oc} measured and n fitted as the actual cell, but with $R_s = 0$ and $G_{sh} = 0$. The coefficients C and D are slowly varying with V_{oc} and n (in fact with qV_{oc}/nkT). For $qV_{oc}/nkT = 20$, which holds e.g. for $n = 1.2$ and $V_{oc} = 0.6$ V, these coefficients are $C \approx 0.9$ and $D \approx 0.7$, whilst $FF_0 \approx 0.8$. Eq. 5 holds when the fill factor loss FF_0-FF is not too large.

Eq. 5 suggests a straightforward way to interpret *J-V* measurements done under varying light intensity P_{in}. Normally one expects that J_L is proportional to P_{in}, and that V_{oc} increases with $\log P_{\text{in}}$. At high P_{in}, J_L/V_{oc} will be high, causing *FF*-loss by the series effect. At low P_{in}, V_{oc}/J_L will be high, causing *FF*-loss due to the shunt effect Figure 5.

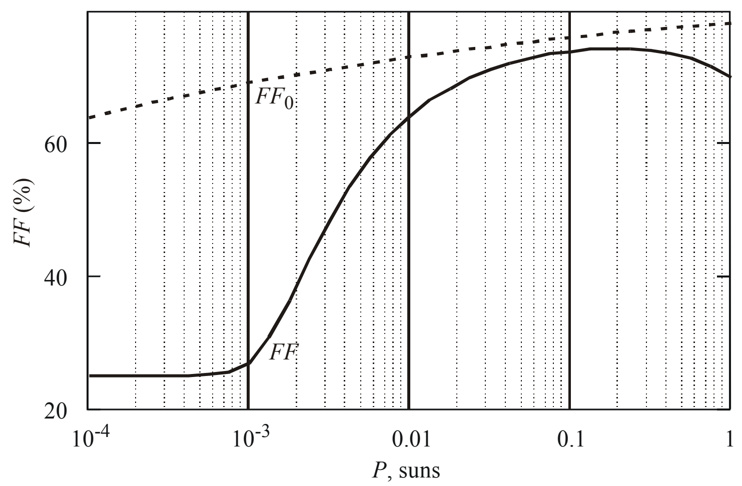

Figure 5 In solid line: fill factor *FF versus* illumination intensity P_{in} logarithmic scale, arbitrary units. *FF* decreases towards low P_{in} due to shunt, and it also decreases towards high P_{in} due to shunt. In dashed line: the calculated ideal *FF* series and shunt neglected, for varying P_{in} the calculation parameters are $n = 1$; at $P_{in} = 1$: $J_L = 20$ mA/cm^2, $J_0 = 1$ nA/cm^2 giving $V_{oc} = 0.420$ V

In Figure 6 we have plotted FF_0-FF as a function of J_{sc}/V_{oc}.

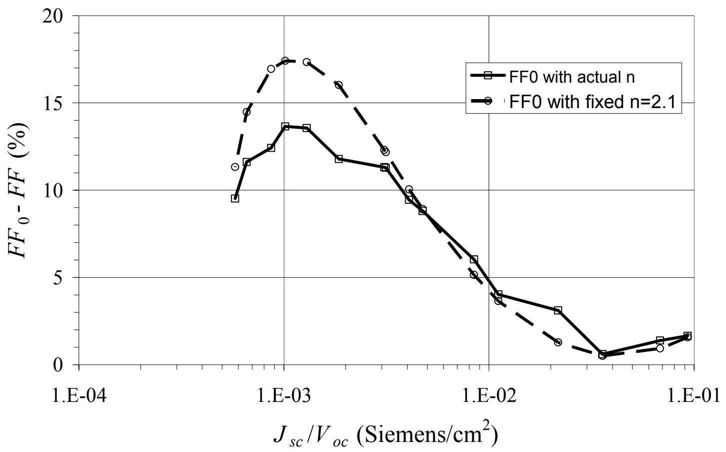

Figure 6 Fill factor loss ΔFF vs. J_{sc}/V_{oc}. In the dashed curve is FF_0 calculated with a fixed n = 2.1; in the solid curve is FF_0 calculated with ideality factor obtained from curve fitting.

There is very little loss of fill factor for high values of J_{sc}/V_{oc}, thus from series resistance. At low values of J_{sc}/V_{oc} there is a greater loss, thus shunt conductance is the dominant non-ideality.

5. Conclusion

We demonstrated a empirical model to study non-idealities of solar cells. We have shown two methods to study non-idealities from light dependent measurements. The first method is a comparison between measured and simulated *J-V* curves. In the second method we study the ΔFF as a function of J_{sc}/V_{oc}.

References

[1] R. Klenk and M-Ch. Lux-Steiner, "Chalcopyrite based solar cells", in *Thin Film Solar Cells: Fabrication, Characterization and Applications*, J. Poortmans and V. Arkhipov editors, J. Wiley & Sons, Chicester, Chapter 6, pp. 237-275, 2006.

[2] Markus Gloeckler, Device physics of CuIn,GaSe_2 thin-film solar cells, PhD. thesis, Colorado State University, Department of Physics 2005.

[3] M. Burgelman and A. Niemegeers, Calculation of CIS and CdTe module efficiencies, *Sol. Energy Mater. Sol. Cells*, **51**, 129-143 (1998).