

## 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 from 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:

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

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:

$$J(V_j) = J_s \left[ \exp\left(\frac{qV_j}{nkT}\right) - 1 \right] + G_{sh}V_j - QE(V_j)J_L \quad (2)$$

with

$$V_j = V - R_s J$$

### 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  $1 - \exp(-\alpha W)$  of the incoming photons is absorbed in the space charge layer (SCL), where  $\alpha$  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:

$$1 - \exp[-\alpha(\lambda)W(V)] \quad (3)$$

where we have explicitly written the dependence of the wavelength  $\lambda$  and the voltage  $V$ . This mechanism is indicated as ‘gen 1’ in Figure 1. In the neutral part of the absorber, a fraction  $\exp(-\alpha W)$  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:

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

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  $\alpha(\lambda)$ .

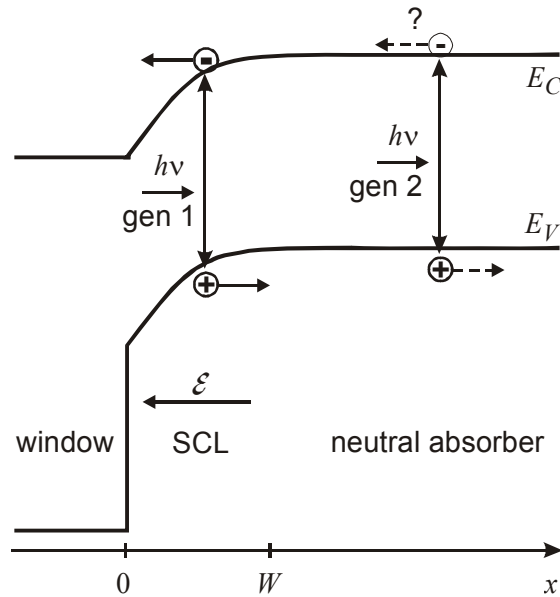


Figure 1 The generation of an electron-hole pair within the SCL ('gen1') and outside the SCL, in the neutral absorber ('gen2').

### 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.

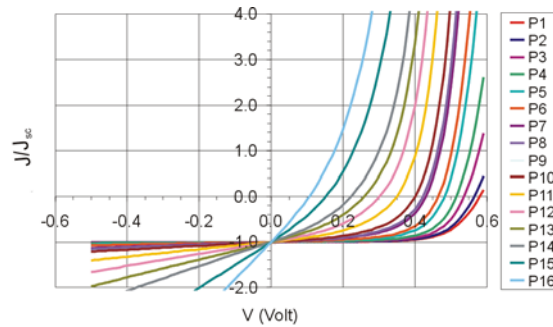


Figure 2 A J-V measurement at 16 different light intensities, all curves scaled to a normalised  $J_{sc} = -1$

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.

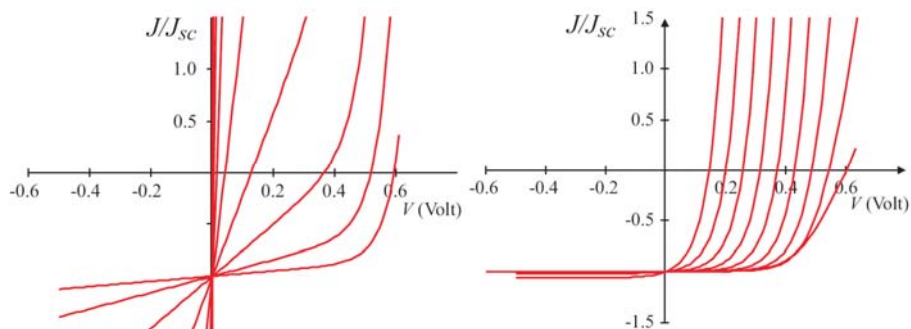


Figure 3 Left: a simulation with only shunt conductance present. Right: a simulation with only series resistance present.

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. From Figure 4 and Figure 2 we conclude that dominant non-ideality is a high ideality factor.

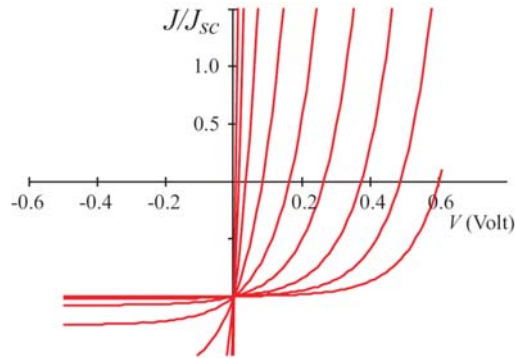


Figure 4 A simulation for a high ideality factor with no series resistance and no shunt conductance.

#### 4. Study of the fill factor loss $\Delta FF$

An other way to study non-idealities is to study the fill factor losses  $\Delta FF$ . 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  $n$ :

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

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  $\log P_{in}$ . 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.

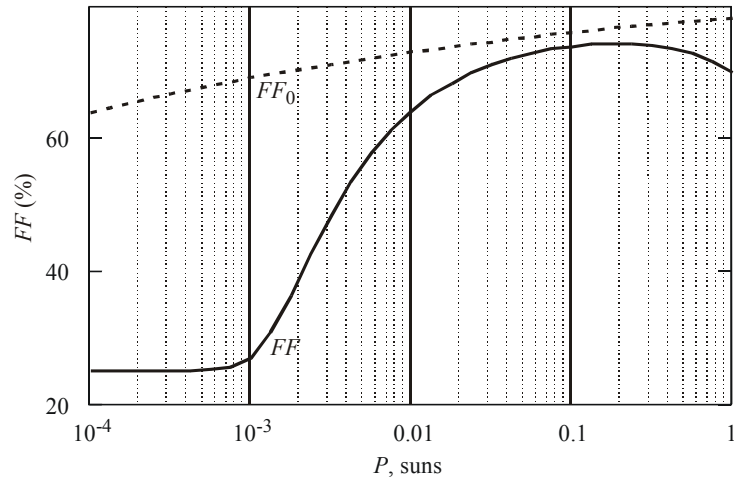


Figure 5 In solid line: fill factor  $FF$  versus illumination intensity  $P_{in}$  logarithmic scale, arbitrary units.  $FF$  decreases towards low  $P_{in}$  due to shunt, and it also decreases towards high  $P_{in}$  due to shunt. In dashed line: the calculated ideal  $FF$  series and shunt neglected,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

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

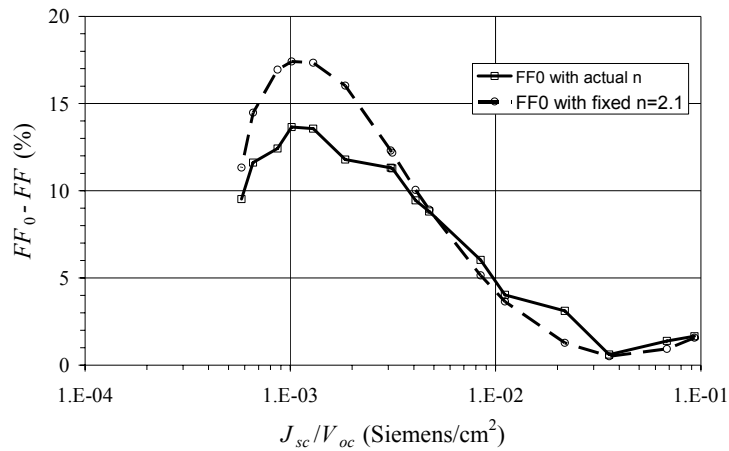


Figure 6 Fill factor loss  $\Delta FF$  vs.  $J_{sc}/V_{oc}$ . In the dashed curve is  $FF_0$  calculated with a fixed  $n = 2.1$ ; in the solid curve is  $FF_0$  calculated with ideality factor obtained from curve fitting.

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 an 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  $\Delta FF$  as a function of  $J_{sc}/V_{oc}$ .

## References

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