ELECTRICAL PROPERTIES OF CIGS CELLS

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ABSTRACT: Cells from AVANCIS were transferred to UGent for electrical characterisation and analysis. The cells under study differ on open circuit voltage V_{oc}, but not so much in their 'optical' properties (light current J_{sc}, quantum efficiency $QE(\lambda)$). On the other hand, they do differ in their 'electrical' properties, both empirical (apparent shunt conductance G_{sh}, fill factor *FF*) and physical (diode ideality *n*, diode saturation current J_0 and built-in potential). We investigated the illumination dependence of these parameters at room temperature, introducing new interpretation schemes. The new interpretation schemes are: a comparison of the shape of the *J-V* curves measured over 4 decades of illumination intensity with simulations based on a 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 the inverse), obtained by varying the illumination intensity. Both methods point to the same conclusion: the cell behaviour is determined by the larger than unity *n* value, and to a minor extend, by shunt conductance; series resistance hardly has any influence. A relation between *n* value and V_{oc} was observed, and also a relation between the light dependence of *n* and the cross-over of light and dark *J-V* curves.
Keywords: characterisation, chalcopyrite, modelling

1 INTRODUCTION

$Cu(In,Ga)(S,Se)_2$ or CIGS-based thin film module technology has all opportunities to compete with crystalline silicon. The total module output power and the efficiency are now meeting the requirements for the power market. Since 1998 a first generation of CIGS modules is being commercialized by Siemens Solar (later Shell Solar and now AVANCIS). Over the past years AVANCIS has also been developing a second-generation CIS process for large-area CIGS thin film modules at the AVANCIS R&D Centre in München, Germany[1-4].

The purpose of this work is to deepen the physical insight in CIGS cells of AVANCIS. We will therefore present an extensive set of electrical measurements of these cells, together with simulation- based interpretation.

2 EXPERIMENTAL

The samples used were prepared at AVANCIS (D). The key features of the process are: controlled sodium doping, deposition of a Cu-In-Ga-Se elemental precursor stack, rapid thermal processing (RTP) in a sulphur-containing ambient, sputter deposition of a ZnO window layer [1-4].

Our approach will be based on the illumination dependence of the solar cell characteristics (see next section).

We therefore carried out *J-V* measurements in dark and under varying illumination intensity, J_{sc}-V_{oc} measurements, external quantum efficiency measurements $EQE(\lambda)$, *C-V* and *C-f* measurements. As a numerical simulation tool we use SCAPS [5] and *J-V* curve fitting based on a standard algorithm. Here we will start the electrical characterisation with a careful study of the illumination dependence of room temperature *J-V* measurements. To interpret room temperature, illumination dependent *J-V* measurements, we introduce two new schemes in the next section.

3 INTERPRETATION

We measured the illumination dependent *J-V* curves with a constant light source dimmed by neutral density filters, ranging from $ND = 0$ to $ND = 3.7$. In this way, the illumination intensity was varied over almost 4 decades, with 4 points/decade. At each intensity, the full *J-V* curve was recorded. The main properties J_{sc}, V_{oc} and *FF* were directly determined, whilst other parameters from the one-diode model of Eq. (1) were obtained by curve fitting: ideality *n*, saturation current J_0, series resistance R_s and shunt conductance G_{sh}.

$$J(V) = J_0\left(\exp\left(\frac{q(V - R_s.I)}{n.k.T}\right) - 1\right) + G_{sh}.V - J_L \qquad (1)$$

In the dark, some of these parameters can also be deduced from the log*J-V* curve (this is the case for *n* and J_0) or from the log*J*-log*V* curve (for G_{sh}). Under illumination we also used *n* and J_0 values from the logJ_{sc}-V_{oc} curve, and compared these to the curve-fitted values.
We present here two original ways to asses the influence of the non-idealities ($n > 1$, series, shunt) on the cell performance. One is to compare the shape of the measured illumination dependent *J-V* curves with simulations with Eq. (1). To this purpose, either all *J-V* curves are scaled to the same short circuit current, or they are shifted to the origin (see next section, results). We show that this allows to conclude which of the non-idealities are dominant. Another way is to study the fill factor loss ΔFF as a function of J_{sc}/V_{oc} (or the inverse). Here $\Delta FF = FF_0 - FF$, where FF_0 is 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 $G_{sh} = 0$ (see next section, results) [6].

4 RESULTS

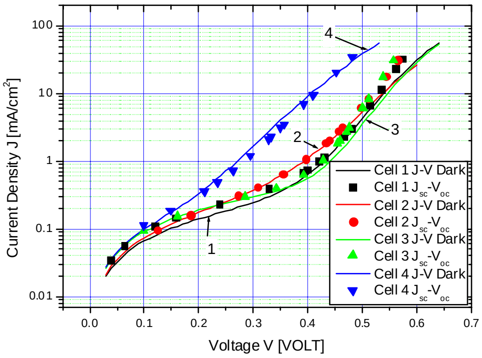

Figure 1: Lines: Dark *J-V* curves for 4 different AVANCIS CIGS cells. Symbols: J_{sc}-V_{oc} measurement for these 4 cells. Cells 2 and 4 are more sulphur-rich than cells 1 and 3.

The measurement programme was initiated with 4 samples from AVANCIS. The dark *J-V* measurements Figure 1 already hint to non-idealities: shunt (bent at low voltage), $n > 1$ (straight part not steep enough) and series resistance or illumination effects (a slightly difference between dark *J-V* and J_{sc}-V_{oc}).

The shape of the light dependent *J-V* curves (scaled Figure 2 and shifted Figure 3) was compared simulations based on Eq. (1): e.g. Figure 4 and Figure 5 (further simulations not shown here). From this we conclude that the dominant non-ideality is $n > 1$, with a minor influence of shunt conductance; series resistance hardly has any influence.

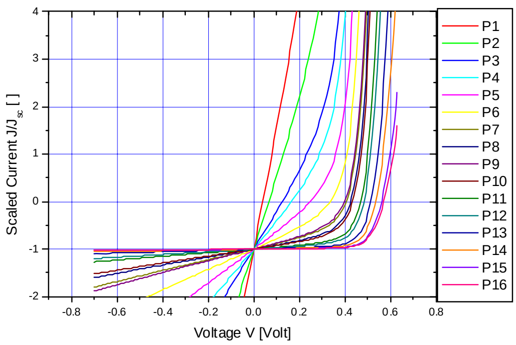

Figure 2 Scaled *J-V* curves of cell 1. The illumination intensity is varied over 4 decades. All curves are scaled to a normalised J_{sc} = -1.

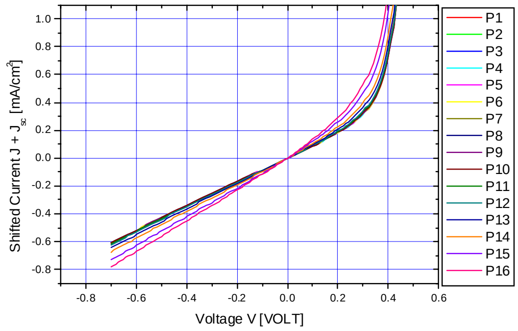

Figure 3: Shifted *J-V* curves of cell 1. The illumination intensity is varied over 4 decades. All curves are shifted upwards over J_{sc} .

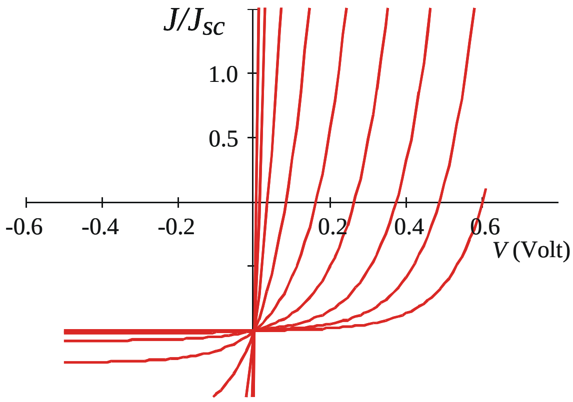

Figure 4: Simulated scaled *J-V* curves (Eq. (1)) of a cell with no other losses than $n > 1$ (here $n = 2$, $R_s = 0$ and $G_{sh} = 0$). Compare to the measurements of Figure 2.

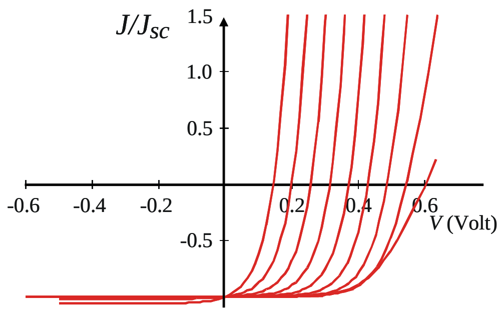

Figure 5: Simulated scaled *J-V* curves (Eq. (1)) of a cell with no other losses than series resistance (here $R_s = 5$ Ωcm^2, $n = 1$ and $G_{sh} = 0$). Compare to the measurements of Figure 2.

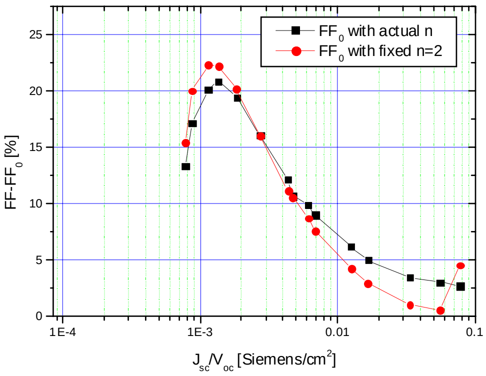

Figure 6: Fill factor loss of cell 4(*FF* measured, and FF_0 calculated, see text) as a function of J_{sc}/V_{oc} (each point is from a *J-V* curve at one illumination).

This conclusion is corroborated by studying the fill factor loss Δ*FF*, see Figure 6. In this curve, the influence of R_s would show as an increase of Δ*FF* at high values of the abscissa (hardly observed), the influence of G_{sh} as an increase at low values of the abscissa (observed), the decrease at values lower than 10^{-3} S/cm^2 cannot be explained. A minimum value of Δ*FF* > 0 would point to mechanisms not considered here (e.g. voltage dependent collection) hardly observed in Figure 6.

Cell 4 had V_{oc} about 80 mV lower than the other three. The reason is not found in the band gap: the sulphur-rich cells 2 and 4 have the same E_g, as deduced from EQE(λ), Figure 7. From the interference pattern we can make a estimation of the thickness of the layers. For all cells we find a thickness of approximately 1500 nm.

A first clue for the lower V_{oc} of cell 4 is given by the J_{sc}-V_{oc} measurement which points to an appreciable lower *n* value (thus another dominant current mechanism) for the higher V_{oc} cell (Figure 8).

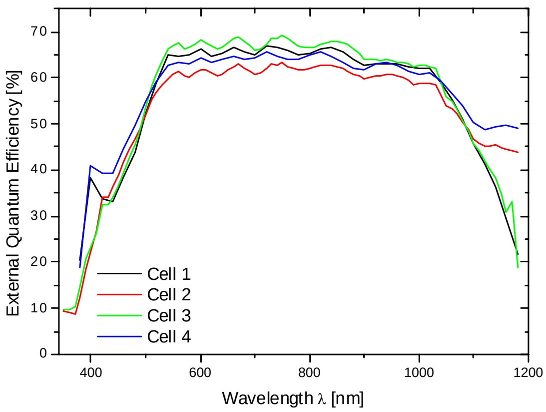

Figure 7: Measured external quantum efficiency of 4 cells with different V_{oc} (cell 2: 555 mV and cell 4: 477 mV). The sulphur rich cells have a larger bandgap.

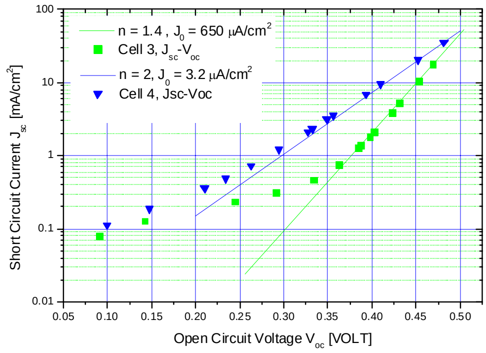

Figure 8: Measured J_{sc}-V_{oc} (each point is one light intensity) and fitted exponential law, for cells 3 and 4 (sulphur-rich) of Figure 7.

Another clue to the complexity of the current mechanisms playing, is the observed crossover of the dark and light *J-V* curves, and its variation between the cells (no illustration shown here). This can be linked to the observation that *n* evolves from about 2.3 in dark and at very low light intensity to about 1.8 at one sun intensity (Figure 9). To investigate these current mechanisms in further detail, room temperature measurements are not sufficient.

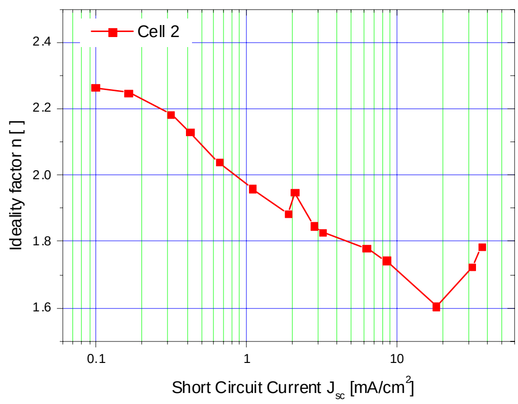

Figure 9: Diode ideality factor *n* of cell 2 at varying illumination, as obtained from curve-fitting the *J-V* curve.

Figure 10 Shows Mott-Schottky plots of the four samples taken from *C-V* measurements at room temperature on the four samples. For a uniform doping profile in the absorber this should give straight lines. The intercept of these lines with the voltage axis is equal to the built-in voltage V_{bi}. We find that the sulphur-rich cells 1 and 3 have a larger built-in voltage than the sulphur-poor cells 2 and 4, 1.37 V and 1.16 versus 0.79 V and 0.74 V respectively, but they have comparable apparent doping.

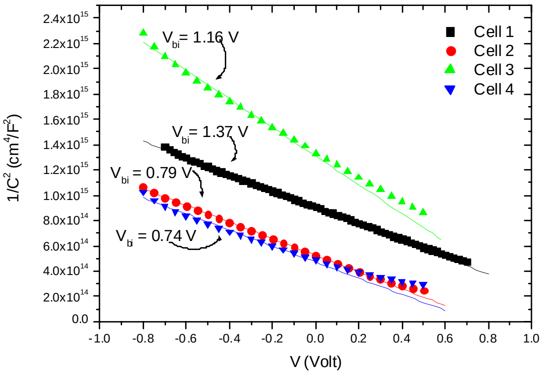

Figure 10: Mott-Schottky plots taken at room temperature of the 4 samples. The sulphur-rich samples 2 and 4 have a lower built-in voltage.

5 CONCLUSIONS

An extensive programme of electrical characterisation and analysis of AVANCIS CIGS solar cells has been started at the University of Gent.

The cells studied so far differ in V_{oc}, cross-over behaviour, in $QE(\lambda)$ behaviour and band gap E_g and in built-in voltages. An extensive room temperature study of these cells points to: no appreciable influence of series resistance, minor influence of shunt conductance, cell parameters determined by a rather high diode non-ideality factor n, no other non-idealities; the n factor seems to govern V_{oc}, and the dependency of n on the illumination intensity the cross-over behaviour.

6 ACKNOWLEDGEMENT

This work is part of the European ATHLET project (contract 019670). We thank AVANCIS for the CIGS samples.

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