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Quantitative study of solar cells based on Cu-In-S based absorber layers grown by the CISCuT-process

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CISCuT [CuInS$_2$ (CIS) on Cu tape] is a new fabrication technology for chalcogenide absorber layers for solar cells. In a roll-to-roll process, indium is electrochemically deposited on a copper tape, and subsequently sulphurised. It has been shown that various Cu-In-S phases are formed, depending on fabrication parameters. After completion with a Cu(O,S) window layer, the structure behaves as a photovoltaic p–n junction, the copper substrate being the n-side and the Cu(O,S) layer being the p-side. In this paper, evidence is given that the electronic p–n junction is located inside the CIS layer, and not at the Cu(O,S) interface.

Solar cells were prepared with a small area dot contact of Cu(O,S) of varying size and their I-V curves were analysed. Uniformly illuminated cells show too large a light current, and a low fill factor, due to pronounced shunt. The measured phenomena were explained quantitatively by a phenomenological model, which assumes that there is an internal p–n junction inside the absorber layer, and that this p-layer near the surface has a non-negligible lateral conductance. Fitting of measured and simulated I-V curves, as a function of the dot size, allowed estimating the sheet resistance of the p-type layer.

Keywords: solar cells, thin film, CIS, CISCuT.

1. Introduction

CISCuT – CIS (CuInS$_2$) on Cu tape is a new inexpensive and highly productive technology for the formation of copper indium chalcogenide absorber layers for CIS solar cells and modules, developed at IST (Institut für Solar Technologien, Frankfurt/Oder) [1,2]. In the CISCuT process, a metallurgical grade Cu tape is cleaned, and electrochemically coated with a thin indium layer in a continuous roll to roll process. Next, the tape is transported through a sulphurisation reactor where the CuInS$_2$ absorber is formed. Depending on fabrication parameters as transport speed and temperature profile of the reactor, different Cu-In-S phases are formed in the upper layer of the tape (Fig. 1), which has been identified by analytical and spectroscopic methods [3]. After removing the Cu$_{2-x}$ layer on top of the absorber layer with the KCN etch, the tape is completed with Cu(S,O) as window layer. This last step is carried out either at IST or at the partner's labs (University of Gent or ECN, Energy Research Foundation, the Netherlands).

Thin film CuInS$_2$ solar cells with the CISCuT technology show an electrical behaviour that differs from other CuInS$_2$ solar cells: the copper substrate is the n-side, and the Cu(O,S) contact is the p-side. This implies that at least part of the CuInS$_2$ layer structure must be n-type, which is uncommon. The question arises where the electrical pn-junction is located: is it a heterojunction between CuInS$_2$ and Cu(O,S), or is it an internal junction inside CuInS$_2$? It is the aim of this work to contribute to the answer of this question.

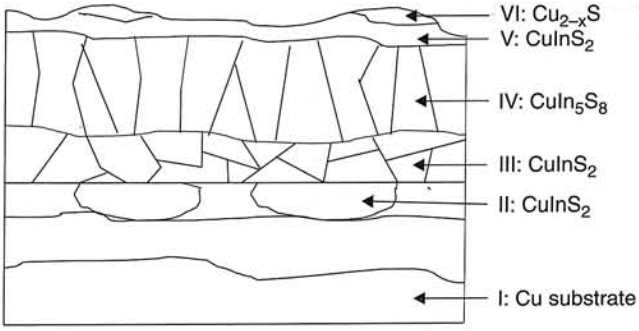

Fig. 1. Sketch of phase constitution of absorber layer of CISCuT solar cell (after Ref. 3).

2. Experimental

Solar cells based on the CISCuT technology were produced by completing the CIS layer with circular contact dots forming the window layer. This was done by spray pyrolysis and these contact dots had varying areas (2, 5 and 10 mm^2). Dark and illuminated (AM1.5G) I-V characteristics were measured with an Oriel solar simulator.

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3. Results and discussion

When the cell was illuminated uniformly (i.e., contact dot + surrounding area on the tape), the light current I_{sc} shows an unexpected high value and the light current density J_{sc} is dependent on the contact dot area (curve 5 in Fig. 2). When illumination is restricted to the dot area only, light current takes an acceptable value and the light current density is independent of the dot area (curve 4 in Fig. 2). Another remarkable result is that all cells show pronounced shunt behaviour. These observations imply that at least part of the collected light current was coming from outside the contact dot area. Hence, lateral conduction of current to the dot contact must be possible. We thus assume that the p–n-junction is situated inside the absorber layer instead of near the CIS-Cu(S,O) interface: that is, a p-type $CuInS_2$ layer must exist at the top of the CIS layer structure. In addition, we assume non-negligible lateral conductance in this layer. Doing so, we can explain all features of the I–V measurements quantitatively.

In our model light current is not only collected from underneath the dot area but also from some additional area outside the dot area. In order to test this model, a numerical program was written.

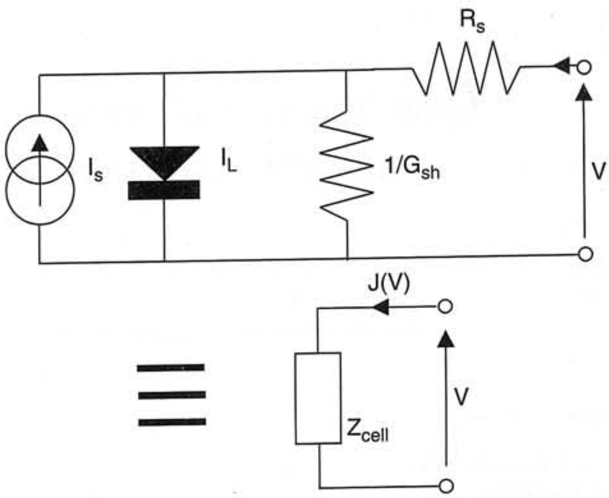

Fig. 3. Electrical circuit of phenomenological model of an elemental (small area) solar cell.

4. Numerical model

We start from a phenomenological description of the I-V characteristic of an elemental (small area) solar cell (Fig. 3) based on the following equation

$$J(V) - \frac{G_{sh}}{A}[V - R_s AJ(V)] = J_s\left[\exp\left(\frac{V - R_s AJ(V)}{akT/q}\right) - 1\right] - J_L, \tag{1}$$

where G_{sh} is the shunt conductance and R_s the series resistance of this elemental solar cell, the other parameters having their usual meaning. A two dimensional model is used to simulate the behaviour of a circular contact dot on a large solar cell area. Light current generated under the contact dot is directly collected to the contacts. Light current generated outside the contact dot experiences the sheet resistance R_{sq} of the upper p-type layer before being collected by the contact dot. This is the problem of a graded resistance in a circular geometry (Fig. 4). Our program solves this problem by finding a solution for the two-dimensional Poisson equation with two boundary conditions

$$\nabla^2 V(r,\phi) = -R_{sq} J(r,\phi) \qquad V(R_{dot},\phi) = V_{dot}, \quad V(\infty,\phi) = V_\infty \tag{2}$$

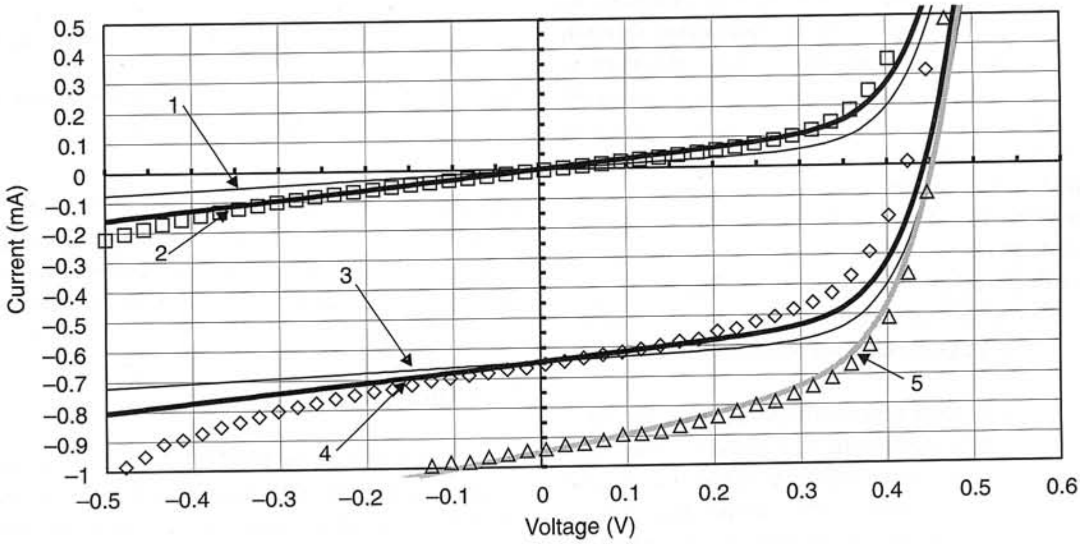

Fig. 2. Simulated and measured I-V curves of cell with 5 mm^2 area. Curve 1: dark, dot current; curve 2: dark, total current; curve 3: restricted illumination, dot current; curve 4: restricted illumination, total current; curve 5: full illumination, total current; (□) dark measurement; (◇) light measurement, restricted illumination; (Δ) light measurement, total illumination.

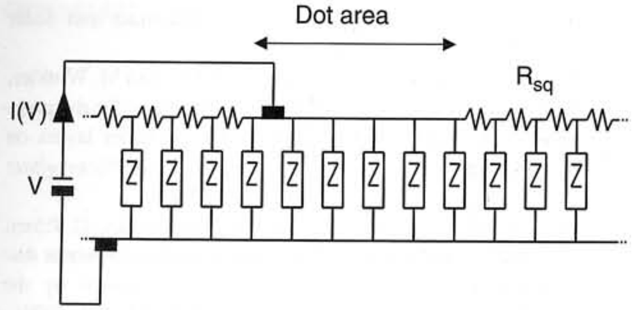

Fig. 4. Two-dimensional model of solar cell with internal junction and circular window layer as front contact.

where V_{dot} is the external imposed voltage and V_∞ is the voltage over the junction at large distance from the contact dot. If the surrounding area is illuminated, then V_∞ equals the open circuit voltage V_{oc}, and when illumination is confined to the dot area, $V_\infty = 0$. This two-dimensional boundary problem is solved by Newton-Raphson iteration. When V(r) is known, J(r) is calculated from Eq. 1, and integrated to the current. The phenomenological input parameters to the program are: J_s, J_L, R_s, G_{sh}, A, R_{sq}, diode ideality factor a, temperature, the contact dot radius R_{dot}, transmission of the window layer, the type of measurement (dark/illumination) and the type of illumination (full area/restricted area). The electrical input parameters are determined so that a fit between measured and simulated I-V characteristics is obtained, and this was done for many different solar cells.

5. Discussion

An example of a measured and simulated characteristic is shown in Fig. 2. An overview of the electrical properties of both is given in Table 1. In Fig. 2, we see five different simulated curves together with the three measured curves. Curve 1 shows the dark characteristic as if the solar cell only consists of the contact dot. In this case, there is no additional two-dimensional effect and the I-V curve has the same shape as the input characteristic of the elemental (small area) solar cell. Curve 2 shows the dark characteristic of the solar cell consisting of the contact dot together with the surrounding area in parallel. The major effect of this configuration is a strong amplification (by a factor 2 to 3) of the original shunt behaviour of the cell, given by G_{sh}. Curves 3 and 4 show the light characteristics of the cell with illumination of the contact dot only. The first curve shows again the characteristic as if the cell only consists of the dot itself, the second as if it is the contact dot with the surrounding (non-illuminated) area in parallel. Again, the major effect of the special geometry is an amplification of the shunt behaviour. Consequently, both V_{oc} and fill factor decrease strongly. The last curve shows the light characteristic of the cell when both dot and surrounding area are illuminated. This surrounding area supplies an extra contribution to the light current, depending on the value of the sheet resistance of the upper absorber layer.

In this example, simulated curves were fitted to the measured ones by changing sheet resistance R_{sq}, light current J_L, shunt conductance G_{sh}. This fitting resulted in a value for R_{sq} of 50 kΩ. For a dot area of 5 mm^2 and a sheet resistance of 50 kΩ, the extra area contributing to the light current is about 5 mm^2. This additional current shows very strong shunt behaviour, and this is independent from the initial value of G_{sh}.

6. Conclusions

I-V measurements of solar cells based on the CISCuT process with small circular contact dots cannot be interpreted directly, because of the contribution of area outside the contact dot to the cell current. To explain the measurements, we assume an internal p-n-junction between different phases of the CIS-layer. Consequently, due to a non-negligible lateral conductance light current is also collected from the area surrounding the contact dot, and this effect is calculated numerically. Quantitative agreement between measurement and simulation is obtained, giving evidence for the assumption of an internal junction.

Table 1. Overview of electrical parameters of the I-V curves of Fig. 2.

Parameter	Measurement or simulation	Dark	Restricted illumination	Full illumination
V_{oc} (mV)	Measurement Simulation	– –	423 430	450 440
I_{sc} (mA)	Measurement Simulation	– –	0.66 0.65	0.94 0.94
Fill factor (%)	Measurement Simulation	– –	57 55	55 52
G_{shunt} (mS)	Measurement Simulation	0.27 0.24	0.23 0.24	0.35 0.33

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