TECHNISCHE FAKULTÄT DER CHRISTIAN-ALBRECHTS-UNIVERSITÄT ZU KIEL	ADVANCE LAB COURSE **Functional Materials**
Temperature Dependence of Solar Cell Parameters	FM-No.: **8**

Aims: Measurement and simulation of strongly temperature dependent U_{oc} curves of solar cells which are a good example for large surface diodes

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1. Introduction

Solar cells typically are large-area devices (usually around 10cm x 10cm) characterized by some "global" numbers referring to electrical properties of the whole cell, e.g. the maximum current density or voltage delivered under standard illumination. One possibility to gather more information on the properties of a solar cell are local measurement, e.g. LBIC (light beam induced currents) which allows to determine the lateral distribution of the diffusion length. A second possibility are temperature dependent measurements; they allow a detailed analysis of individual defects and/or average parameters like the quality of the pn-junction. For such experiments the temperature of the solar cell must be controlled which is quite complicated, especially if the solar cell is illuminated strongly.

2. Basic Physical Concepts

We will discuss briefly the

- description of solar cells by a two diode model
- the *IU* characteristics
- the *U*(*Illumination intensity*) curve

2.1 The two diode model

As illustrated in Fig. 1 the solar cell may be described as an illuminated diode (= p-n-junction). We can describe a solar cell as an illuminated diode (I_{cell}: solar cell current)

$$I_{cell} = \widehat{I}_1\left(\exp\left(\frac{qU_{eff}}{n_1 kT}\right)-1\right)+\widehat{I}_2\left(\exp\left(\frac{qU_{eff}}{n_2 kT}\right)-1\right)+\frac{U_{eff}}{R_{Shunt}}-I_{Ph} \qquad (1)$$

and

$$U_{eff} = U - R_{ser} I_{cell} \quad . \qquad (2)$$

Applying a small positive potential, we will measure a negative current if the photo generated current I_{Ph} (represented as a current source in the equivalent circuit.) is large enough. This is how a solar cell generates power. The corresponding *IU*-curve is plotted in Fig. 2. At a specific working point (U_a, I_a) the solar cell generates maximum power since the product U_a*I_a has its largest value at this point. Other important parameters for a solar cell are the short circuit current I_{sc}, and the open circuit potential U_{oc} as shown in Fig. 2. The short circuit current is given by the percentage of photo-generated carriers that are collected at the junction and thus depends mainly on the minority carrier life time τ or diffusion length L of the (Si) material since carriers generated in the bulk of the Si which recombine before reaching the junction will not contribute to the photo current. The serial resistance R_{ser} in the equivalent circuit diagram of Fig. 1 describes unavoidable resistors in the circuit; it contains the resistivity of the solar cell materials, the contact resistivity of the contacts (always a grid on the front side) and thus mirrors the ohmic losses which may be large e.g. due to "bad" grid finger or a bad emitter of the diode. Its influence on measured parameters is most pronounced for potentials in the range of U_{oc}.

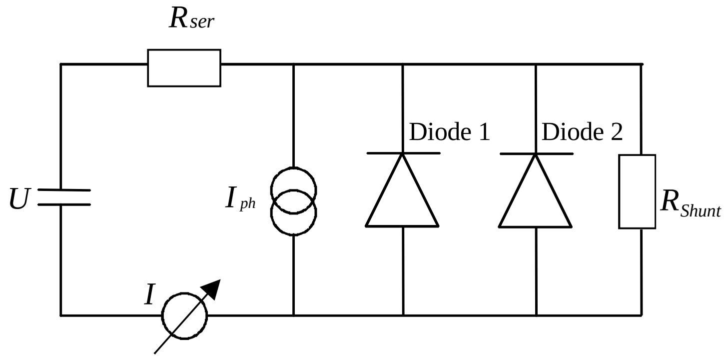

Fig. 1: Equivalent circuit of a solar cell

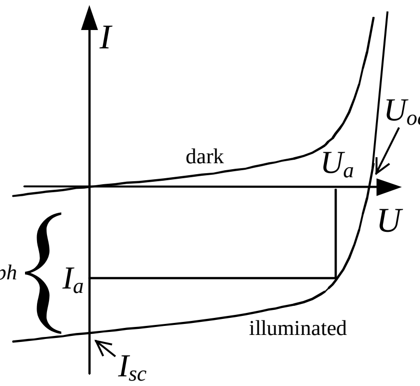

Fig. 2: Principle *IU*-curve of a solar cell

The parallel resistance R_{Shunt} describes imperfections in the p-n-junction e.g. local short circuits, it is most heavily felt for currents in the range of I_{sc}.
The pn-junction itself can be described by two diodes:

- The first diode corresponds to minority and majority currents through the space charge region. In a simple approximation it is described by

$$\widehat{I}_1 = \left(\frac{eD_e}{\tau_e} \frac{n_i^2}{N_A} + \frac{eD_p}{\tau_p} \frac{n_i^2}{N_D} \right) \tag{3}$$

and $$n_1 = 1 \tag{4}$$

De, p are the diffusion coefficients in the n and p region of the solar cell, $\tau_{e,p}$ are the life times of minority carriers in the corresponding regions, $N_{A,D}$ are the doping concentrations, and $n_i = n_{i,0} \exp\left(-\frac{E_g}{2kT} \right)$ is the intrinsic carrier concentration for a semiconductor with band gap E_g. The factor $n_1 \neq 1$ in Eq. (1) is called non ideality factor.

- The second diode corresponds to recombination and generation processes in the space charge region of the pn-junction. In a simple approximation it is described by

$$\widehat{I}_2 = \left(en_i \frac{W}{\tau} \right) \tag{5}$$

and $$n_2 = 2 \tag{6}$$

W denotes the width of the space charge region and τ an effective life time of minority carriers within the space charge region.

The photo current is proportional to the illumination intensity *Int* and depends on the life time $\tau_{e,p}$ of the minority carriers. Since most recombination processes are temperature dependent, $\tau_{e,p}(T)$ might be a quite complicated function of the temperature.

2.2 The IU-characteristics

As already implied by Eq. (1) a typical and mostly applied measurement to characterize a solar cell is the current-voltage-curve for fixed illumination intensity and temperature. Measuring a large number of pairs (I_i, U_i) one can calculate all parameters in Eq. (1) by a least square fit as described later. Directly from the *IU*-curve one can calculate I_{sc}, U_{oc}, I_a and U_a. *IU* measurements need quite a long time since for each measured point one must wait for steady state. Especially the charging of the large capacitance of the pn-junction is a time consuming process.

Since for the complete time of the measurement the solar cell is illuminated strongly a heating of the solar cell occurs. In order to get reproducible results the temperature of the solar cell must be controlled. This is not necessary if we perform *U*(*Int*)-measurements.

2.3 U(Int)-measurements

Using a very stable current source one can fix the current coming out of the solar cell, independent of the illumination intensity *Int*. The potential *U* is measured and interpreted according to Eq. (7)

$$\begin{aligned} I_{cell,fixed} = \quad & \hat{I}_1\left(\exp\left(\frac{q\left[U(Int)-R_{ser}I_{cell,fixed}\right]}{n_1 kT}\right)-1\right) \\ & +\hat{I}_2\left(\exp\left(\frac{q\left[U(Int)-R_{ser}I_{cell,fixed}\right]}{n_2 kT}\right)-1\right) \\ & +\frac{\left[U(Int)-R_{ser}I_{cell,fixed}\right]}{R_{Shunt}}-I_{Ph}(Int) \end{aligned} \tag{7}$$

Solving this equation for *U* can only be done numerically but is no principle problem.

Most important for the measurement is the simple relation between the photo current and the illumination intensity

$$I_{ph} = \psi(\tau,T) * Int \quad , \tag{8}$$

i.e. there exists just a scaling factor between the illumination intensity and the photo current. This is not generally true; e.g. recombination processes may depend explicitly on the concentration of carriers (injection level dependence). But for each solar cell this relation can easily be checked measuring simultaneously the illumination intensity with a diode and the short circuit current for different intensities. Typically this will give a constant scaling factor $\psi(\tau,T)$ for fixed temperature. Once knowing this factor one can measure

$$U(I_{ph}) = U(\psi(\tau,T) * Int) = U(Int) \tag{9}$$

by measuring simultaneously the illumination intensity with a photo diode and *U* galvano-

statically.
Since the current I_{cell} is hold constant the capacitance of the space charge region must not be recharged. Therefore a very fast measurement is possible, even a flash light can be taken to change the illumination intensity.
This procedure minimizes the time for illuminating the solar cell and therefore heating up of the solar cell. Since it is very fast, changes of the temperature may be neglected within one measurement. So it is an easy tool to monitor temperature dependent parameters.

3. Fitting of data

For fitting of data normally a least square algorithm is used. Taking the measured data (I_i, U_i), and model function $I_m(x_n, U)$ with fitting parameters x_n a function

$$\mathrm{X}^2(x_n) = \sum_i \left(I_i - I_m(x_n, U_i)\right)^2 \quad . \tag{10}$$

which calculates the distances between the measures and the theoretically expected values. Minimizing $\mathrm{X}^2(x_n)$ with respect to the fitting parameters x_n one gets the best result for the chosen model. The square function in Eq. (10) is taken because one gets the only function which can be differentiated at all values. This is quite important since many minimization algorithms need the gradient of $\mathrm{X}^2(x_n)$ to find the optimal parameters.

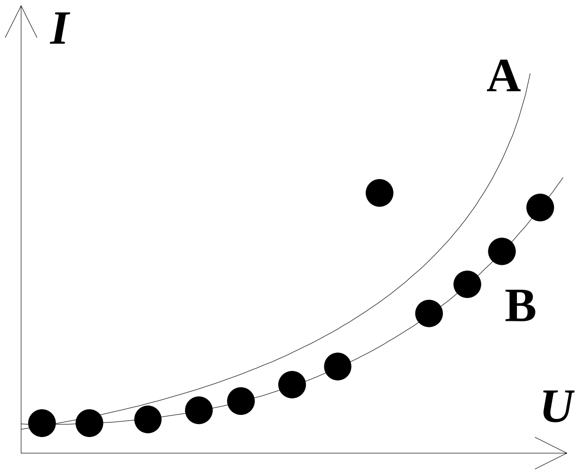

Fig. 3: Schematic plot of two fitted curves for a set of measured data.

For many measured data sets $\mathrm{X}^2(x_n)$ may not be an adequate minimization function; e.g. Fig 3 shows a curve which may be well fitted by function B. But when performing a least square fit, always curve A is generated as the best fitting result. The reason is one "bad" measured value. Since the square function is most sensitive to the largest value of $\left(I_i - I_m(x_n, U_i)\right)^2$ the curve A try's to minimize this value although this is obviously not a good fit for the curve. A more robust fitting function is

$$F(x_n) = \sum_i \left(abs\left(I_i - I_m(x_n, U_i)\right)\right)^\alpha \quad , \tag{11}$$

with α smaller than 2 (typically 0.5-1.0). $F(x_n)$ searches for the largest number of measured data points, which fit to the theoretical curve. Minimizing this function the fitted curve B is found.

For minimization in several dimensions only $\mathrm{X}^2(x_n)$ can be used because of the computational problems which would occur if the gradient $\mathrm{X}^2(x_n)$ does not exist. Just optimizing one parameter, one may find a great improvement when using a minimization function like in Eq. (11). This improvement can only be checked by the eye, because we change the numerical function which quantifies the minimization rule.

4. The experiment

4.1 Devices / Samples

One small solar cell (about 1.5cm x 1.5cm)

4.2 Hard and Software

The sample is connected with four electrodes (working, counter and two reference electrodes). Directly in front of the solar cell a LED-array is placed. This is connected to a large capacitor C in series with a resistor $R_{discharge}$. With a time constant $t = R_{discharge}C$ the capacitor can be discharged. The discharging current operates the LED-array, illuminating the solar cell with an exponentially decaying intensity. The discharging of the capacitor as well as the measuring of data is triggered by a PC-program. Measured are the illumination intensity $Int(t)$ with a photo diode simultaneously with the current $I_{cell}(t)$ respectively potential $U(t)$ of the solar cell. From this two data sets $U(Int)$ is calculated and stored on the PC.

4.3 Performing the experiment

1. The assistant will explain the hard- and software. Get used with the equipment by measuring $\psi(\tau,T)$, several $U(Int)$ curves at room temperature for different values of $R_{discharge}$. Choose an optimal intensity for the experiments and the correct discharging time.

2. The solar cell will be heated by a lamp up to about 60°C and cooled by exposing it to the air. While the solar cell is cooling down perform several series of measurements as specified later.

3. Evaluate the data by fitting.

4.4. Measurements at constant temperature

1. Measure $\psi(\tau,T)$
2. Measure $U(Int)$ curves for three values of $I_{cell,\,fixed}$: 2 mA, 5 mA, 9 mA
3. Save the data

Hint: You should try to measure as fast as possible, since the temperature may change when waiting to long.

5. Evaluation of the data

5.1. Room temperature

The solar cell is not temperature stabilized, so the only parameter set for which the temperature is well known is at room temperature. Use the three $U(Int)$ to fit all solar cell parameters to the measured data.
Take this set of parameters as a starting point for all following fits.

5.2. Evaluation at higher temperature

Following the results of Eq. (3) one expects

$$\frac{I_1(T_1)}{I_1(T_2)} = \frac{\exp\left(-\frac{E_g}{kT_1}\right)}{\exp\left(-\frac{E_g}{kT_2}\right)} \tag{12a}$$

$$\frac{I_2(T_1)}{I_2(T_2)} = \frac{\exp\left(-\frac{E_g}{2kT_1}\right)}{\exp\left(-\frac{E_g}{2kT_2}\right)} \tag{13a}$$

Since the non ideality factors in $\exp\left(\frac{qU_{eff}}{n_i kT}\right)$ just reflect more sophisticated effects at the pn-interface, the same effects may as well hold for the temperature dependence of I_1 and I_2, i.e. one may expect

$$\frac{I_1(T_1)}{I_1(T_2)} = \frac{\exp\left(-\frac{E_g}{n_1 kT_1}\right)}{\exp\left(-\frac{E_g}{n_1 kT_2}\right)} \tag{12b}$$

$$\frac{I_2(T_1)}{I_2(T_2)} = \frac{\exp\left(-\frac{E_g}{n_2 kT_1}\right)}{\exp\left(-\frac{E_g}{n_2 kT_2}\right)} \tag{13b}$$

Several fitting routines are implemented to fit the temperature at which the measurement was performed, when the fitting parameters at room temperature are know.

1. Check for the best fitting conditions with respect to the equations (12a), (13a), (12b) and (13b).

2. Check for the best fitting parameter α when changing the minimization function form Eq. (10) to Eq. (11).

3. Fit the temperature for all measured data sets.

5.3. Discussion and presentation of results

1. Compare the temperature values for the three $U(Int)$ curves at each temperature.

2. Plot the measured ψ at a function of the fitted temperature. Discuss the resulting curve.

3. Plot the cooling curve of the solar cell, i.e. plot the fitted temperature as a function of time of the measurement (this time is stored in each measurement data set). Discuss the resulting curve.

4. Do you think, the measured data are well described by the assumed model?

6. Questions

6.1 Why do we use a two diode model?

6.2 For which currents do the first and second diode account?

6.3 On which parameters does the recombination velocity of silicon depend and where do you find the temperature dependence?

6.4 How large is the energy gap of silicon?

6.5 How strong is the temperature dependence of E_g and on which parameter does it depend?

6.6 Why does a least square fit not always work?

7. Bibliography

- *Physics of Semiconductor Devises*, S.M. Sze, John Wiley & Sons, 1981

- Semiconductor and Solar Cell Text Books