Measurement of Solar Cell Parameters with Dark Forward I-V Characteristics

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The grade of a solar cell depends mainly on the quality of the starting material. During the production of this material, many impurities are left in the bulk material and form defect levels in the band-gap, which act as generation-recombination centers or charge carrier traps. These levels influence the efficiency of solar cells. Therefore knowledge of the parameters of these levels, e.g., energy position, capture cross section and concentration, is very useful for solar cell engineering. In this paper emphasis is placed on a simple and fast method for obtaining these parameters, namely measurements of dark characteristics. Preliminary results are introduced, together with the difficulties and limits of this method.

Keywords: Solar cell, lattice imperfections, lifetime, dark I-V characteristics.

1 Solar cells

A solar cell, or photovoltaic cell, is a semiconductor device consisting of a large-area P-N junction diode, which in the presence of sunlight is capable of generating usable electrical energy. This conversion is called the photovoltaic effect. When light strikes the P-N junction of a semi-conductor the absorbed photon energy releases an electron from the P-type region and moves it to the N-type, creating a hole in the valence band and producing a current. The main criteria for the selected solar cell are efficiency and costs. These define the performance and availability, and they can vary greatly. This paper deals with problems of efficiency influenced by imperfections of crystal lattices, and the applicability of the basic diagnostic method used for determining such imperfections.

Free charge carriers generated by impacting light (known as excess carriers) move in all directions from their place of origin. An important quantity defining the range of a generated charge carrier is its lifetime, i.e., the time that passes before an electron meets a hole and recombines. However, as electrons and holes reach the boundary of the P-N junction, they are rapidly swept by the electric field of this junction, either to the P-side (in the case of holes) or to the N-side (in the case of electrons), generating voltage on the outer electrodes.

The basic means for lowering carrier lifetimes are lattice vibrations (phonons) and impurities or, generally speaking, lattice impurities. As lattice vibrations depend only on crystal structure and temperature, which are fixed for a specific semiconductor material and usage, we will be concerned here with lattice impurities and their effect on the lifetime of charge carriers.

2 Problems of carrier trapping and recombination

Every physical system attempts to achieve so-called thermal equilibrium as soon as possible, as do excess carriers. In the case of silicon, which is widely used in photovoltaic applications, the way to achieve thermal equilibrium, is either by Auger recombination or by capturing free charge carriers on energy levels that lie in the band that separates the conduction and valence band (the forbidden band, or the band gap).

These energy levels can originate either from an imperfection of the crystal lattice (e.g., dislocation) or from foreign atoms in some positions of the lattice, or even from complex crystal defects induced, for example, by radiation.

These imperfections strongly influence the electron and hole transport through the bulk of the semiconductor device. They can act either as a trap, where an electron or a hole is trapped on this level for a certain time, or as a generation-recombination (G-R) center, where one charge carrier annihilates with a carrier with the opposite charge.

3 Dark forward I-V characteristics of solar cells

When conducted under different temperatures, this method provides many parameters of a solar cell, e.g., the temperature dependence of the shunt resistance and diode factor, the energy and concentration of the dominant recombination center, the lifetime of the charge carriers.

The measuring apparatus works with a current source with a range of 0 to 100 mA. The temperature range is from approximately 20 °C to 150 °C. The process itself is controlled by a computer via a serial bus RS232, and the data (values of voltage and current) is stored on the hard drive.

The dark current of forward biased solar cell IDF can be expressed by the formula

$$I_{\mathrm{DF}} = A\,J_{01}\left[\exp\left(e\,\frac{V - R_{\mathrm{S}}I}{\eta_1 kT}\right)\right] + A\,J_{02}\left[\exp\left(e\,\frac{V - R_{\mathrm{S}}I}{\eta_2 kT}\right) - 1\right] + \frac{V - R_{\mathrm{S}}I}{R_{\mathrm{P}}}, \quad (1)$$

where A stands for the area of the sample, J_{01} is diffusion current density, J_{02} is generation-recombination current density, η_1 and η_2 are the diode factors, R_{S} is the series resistance, R_{P} is the shunt resistance, e is the electric charge, and k is the Bolzmann constant. The series resistance of large-area solar cells is small and can be negligible.

The plotted graph of I-V characteristics is divided into three regions:

1. in the range 0–40 mV, the influence of shunt resistance dominates and can be calculated; the current through the cell can be expressed by:

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$$I_{DF} \approx \frac{V}{R_P}. \tag{2}$$

2. in the range 40–300 mV, the generation-recombination compound of the total current predominates, so it can be expressed by:

$$I_{DF} \approx A\, J_{02}\left[\exp\left(\frac{e\,V}{\eta_2 kT}\right)-1\right]+\frac{V}{R_P}. \tag{3}$$

3. above 300 mV, the first term in the expression of the total current (diffusion compound) is dominant, so, by the curve fitting method, the diffusion saturation current and the diffusion diode factor can be extracted.

4. Extracting the cell parameters

The generation-recombination current density J02 can be expressed by:

$$J_{02} = \frac{e\, n_i\, d}{\tau_{sc}}. \tag{4}$$

This means that the density J_{02} is inversely proportional to the lifetime of the charge carriers in the space charge region, for which in the case of a single trapping level the following formula can be obtained:

$$\tau_{sc} = \tau_{p0}\exp\left(-\frac{W_t + W_i}{kT}\right) + \tau_{n0}\exp\left(\frac{W_t + W_i}{kT}\right). \tag{5}$$

Here, τ_{p0} and τ_{n0} stand for the lifetime of the minority carriers in an N-type semiconductor or a P-type semi-conductor, respectively, W_t is the energy level of the G-R center (or trap), and W_i is the intrinsic Fermi level [1]. With the knowledge of these lifetimes and the capture cross sections the G-R center concentration N_t can also be extracted. Thus, to obtain the maximum parameters of the solar cell band gap structure, we are interested in the second region of the plotted graph.

Problems can arise from the fact that only a single recombination level can be extracted from this measurement. If there are, for example, two deep levels of approximately the same concentration, however, the standard extracting technique will lead to incorrect values of deep level energy.

To evaluate a large number of parameters, curve fitting is used. While linear dependence can be fitted without problems, fitting exponential dependence can be difficult, and the results may vary strongly with different initial conditions. These complex conditions may cause errors when simple fitting techniques are applied to them. For example, non-linear dependence of the diode factor on temperature is observed.

5 Parameters of G-R centers from I-V measurement

Monocrystalline silicon samples fabricated by the Czochralsky grown method were used in the measurements. The dimensions were 102×102 mm, and each sample represented one batch.

Figs. 1, 2 and 3 show the temperature dependence of shunt resistance R_p, diode factor η_2 and G-R current I_{02}, respectively.

For maximum efficiency of a solar cell, the highest shunt resistance is needed. The measured resistances are shown in Fig. 1. The values of the shunt resistance at the highest temperatures were always lower than at room temperature (RT), but some differences were found:

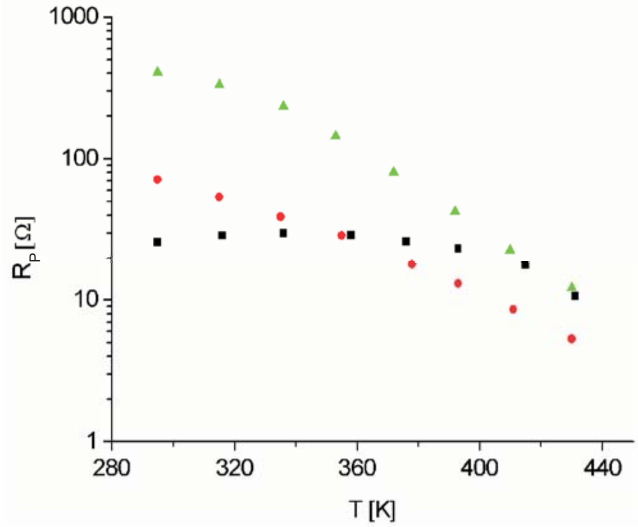

Fig: 1: Temperature dependence of shunt resistance R_P of samples #1942-02 (■), #20 (●) and LE2 (▲)

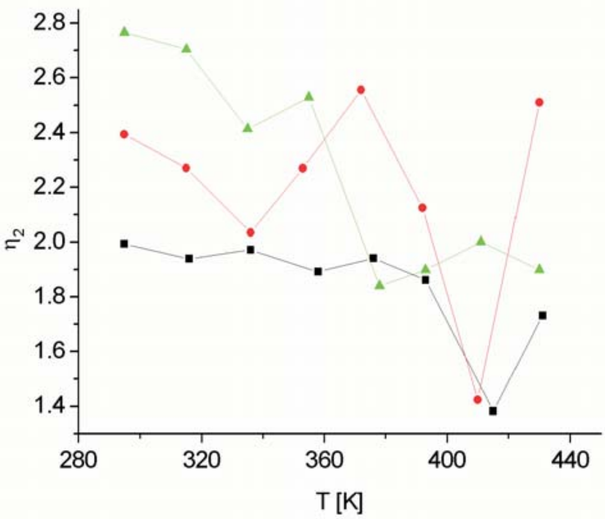

Fig. 2: Temperature dependence of diode factor η_2 of the samples #1942-02, #20 and LE2

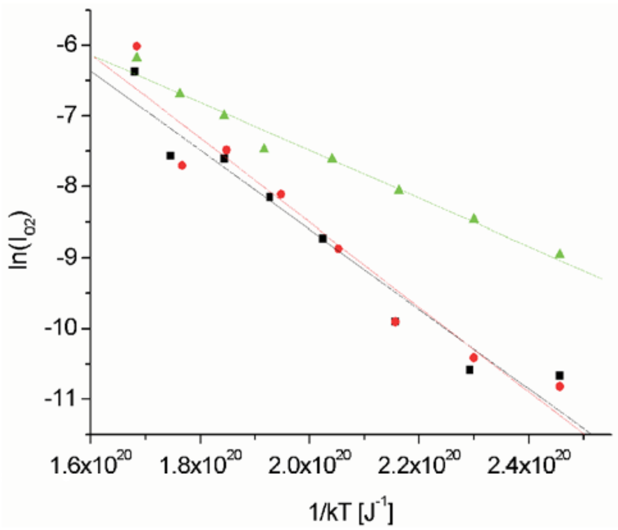

Fig. 3: Temperature dependence of G-R current I_{02} of samples #1942-02, #20 and LE2

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1. variation of more than one order between samples (e.g. #1942-02 and LE2) at RT.
2. samples such as #1942-02 showed a small initial increase in the shunt resistance before a final decrease.

Diode factor η_2 showed a decrease with temperature growth (Fig. 2). In some cases, however, this dependence was not very clearly confirmed (e.g., sample #20). Diode factors η_2 have to be extracted, so that the G-R current density I_{02} can be evaluated more precisely.

The hyperbolic logarithm of the G-R current density as a function of temperature is shown in Fig. 3. The dependence is almost linear. For the lowest trapping/generation effect, this dependence should be weak. This is shown in Fig. 3 for sample LE2, thus confirming its quality from the shunt resistance measurement.

The preceding extracted parameters and the obtained dependences were used for evaluating the energy levels of the G-R centers and their densities and the lifetime of the excess charge carriers in the space charge region. These parameters are shown in Tables 1 and 2 for each sample.

Table 1: Possible energy levels found in selected samples

sample#	ΔW_t [eV]	W_{t1} [eV]	W_{t2} [eV]
10	0.438	0.122	0.998
20	0.373	0.187	0.933
22	0.341	0.219	0.901
1942-02	0.351	0.209	0.911
1940-24	0.360	0.200	0.920
1x-0883	0.201	0.359	0.761
LE1	0.248	0.312	0.808
LE2	0.212	0.348	0.772
LE5	0.224	0.336	0.784

Comparing values of the deep energy levels with measured efficiencies, we can evaluate the influence of these levels. The samples of series LE# have almost the same levels and lifetimes, and also their efficiencies are similar. The same can be said about samples 1942-02 and 1940-24. Although the deep energy levels in these two batches are different, their influences are nearly identical. On the other hand, samples #10, 20 and 22 show some inhomogeneities in the deep level energy and the lifetime in the space-charge region. In sample 1x-0883 a very deep level was found and the lowest efficiency was measured. Other parameters of the measured solar cells, e.g., surface recombination velocity and series resistance, need to be determined for a more precise evaluation of the influence of deep level influence on efficiency.

Determining the formers of the deep levels, the most probable lattice imperfections creating deep levels in the range from 0.2 to 0.37 eV below the conduction band (or above the valence band), are bounded with boron, carbon and oxygen atoms, e.g. B_iC_s +0.29 eV, Bi −0.37 eV and B_iO_i −0.20 eV [2]. Here '+' means energy above the valence band and '–' means below the conduction band. The deep levels found in samples #10, 20 and 22 may have been caused by some special treatment of these samples, e.g. electron bombardment, which induces vacancy-related defects like VO −0.18 eV, or carbon related defects like C_iC_s −0.11 eV [1, 3].

Table 2: Lifetime of minority charge carriers in the space charge region. and the solar cell efficiencies of the measured sample

sample#	τ_{sc} (295 K) [s]	efficiency [%]
10	2.05×10^{-8}	14.29
20	8.00×10^{-8}	13.43
22	1.83×10^{-8}	14.11
1942-02	1.53×10^{-8}	14.27
1940-24	1.63×10^{-8}	14.15
1x-0883	2.90×10^{-8}	7.44
LE1	1.50×10^{-8}	14.58
LE2	1.10×10^{-8}	14.57
LE5	1.50×10^{-8}	15.03

Of course there may be some other explanation in each sample of electrical behavior, namely the inherence of two or more energy levels deep within the band gap. This simple technique cannot give the exact parameters of these centers, for reasons mentioned above.

6 Conclusion

A proper characterization of the charge carrier lifetime and the extracting parameters of G-R centers is very useful for solar cell utilization. and will play a key role in their future development. Although the method of dark forward characteristics has some limitations. as mentioned in the text, this method is very fast, non-destructive and simple, and can be used together with other methods as a diagnostic tool in the development and production of solar cells.

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