NEW ANALYSIS METHOD FOR CRYSTALLINE SILICON CELLS

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ABSTRACT

Extensive research has been done in the past in order to fit the measured IV characteristics with reliable physical models such as the two diode model. Refined mathematical methods like non linear regression analysis and additional measurement procedures like dark I-V and variable illumination Jsc-Voc have been applied in order to find reliable estimates for the parameters [1], [2], [3]. We have developed a new measurement method which simplifies the basic fitting problem and does not require any additional measurement instruments or guessing the initial values for the parameters [4]. In this method in addition to the standard IV characteristics also the decay of the open circuit voltage decay is measured when the irradiance gradually decreases to less than 100 W/m2. Since the series resistance does not contribute to the open circuit voltage at all and the two diodes and the shunt resistance all have different voltage dependencies, it is easy to evaluate reliable estimates for these parameters. Thereafter the series resistance is the only component which is to be evaluated by fitting with the standard IV characteristics curve. We name the method Irradiance Decay Cell Analysis Method (IDCAM).

1. INTRODUCTION

Standard QuickSun solar simulators measure the IV characteristics by recording the voltage, current and irradiance signals during the falling tail of a Xenon flash pulse [see: www.endeas.fi]. The measurement is triggered typically at about 15 % above the target irradiance level, e.g. at 1150 W/m^2 and during the following two milliseconds the cell is swept from short circuit into open circuit. The cell voltage is increased linearly with a slope of about 300 mV/ms and altogether 4096 data points per each channel (voltage, current and irradiance) are sampled with 10 bit AD converters. The original data points are averaged in groups of eight and as a result the resolution of the final 512 data points is better than 0.05 % and in addition also the signal-to-noise ratio is better than with measurement systems of high resolution but low sampling rate. The cell temperature is measured with an accuracy of +/- 0.5 °C using a commercial IC temperature sensors, type LM35, from National Semiconductors. The IV characteristics curve e.g. at STC conditions (25 °C, 1000 W/m^2, AM1.5G) is thereafter evaluated by using the procedure described in the standard IEC 891. Since the measurement was triggered already at 1150 W/m^2, the irradiance correction is almost negligible at maximum power point. Due to the operation principle it is very easy to measure the IV characteristics at any irradiance level just by adjusting the triggering level.

2. IRRADIANCE DECAY CELL ANALYSIS METHOD (IDCAM)

2.1 Cell equivalent circuit

A well known and physically reliable model for crystalline silicon cells consists of five components which are i) ideal diode, ii) recombination diode, iii) shunt resistance, iv) series resistance and v) current source representing the irradiance stimulated current. This equivalent circuit has the well known mathematical form of equation (1). Our starting point was not to apply any diode ideality factors in order to work out physically meaningful parameters. Ideally the diode saturation currents are related to real material parameters as shown in equations (2) and (3) [5]. In general, the direct fitting of this model to the basic IV characteristics curve has turned out to be quite difficult. The problem is that the two measured signals, voltage and current, and in addition one unknown parameter, series resistance, are in the exponents of the terms which describe the diodes. This makes the fitting very sensitive e.g. to measurement noise.

$$I = I_{sun} - I_{diff}\left[e^{\frac{q}{kT}(V+IR_{ser})} - 1\right] - I_{rec}\left[e^{\frac{q}{2kT}(V+IR_{ser})} - 1\right] - \frac{V+IR_{ser}}{R_{shunt}}$$

(1)

$$I_{diff} = Aqn_i^2\left[\frac{1}{N_A}\left(\frac{D_n}{\tau_n}\right)^{1/2} + \frac{1}{N_D}\left(\frac{D_p}{\tau_p}\right)^{1/2}\right]$$

(2)

$$I_{rec} = \frac{Aqn_iW}{\sqrt{\tau_p\tau_n}}$$

(3)

2.2 Principle of Operation

In order to overcome the above described fitting problem we have modified the basic QuickSun measurement cycle. In addition to the standard IV curve measurement the recording of the open circuit voltage is continued during the falling tail of the flash pulse, Fig. 1. Since there is no current flowing through the series resistance, the equation (1) simplifies essentially. We also assume that the equivalent circuit current source is linearly proportional to the irradiance signal. This can be considered to be true within the irradiance range from 1000 to 100 W/m^2 which is enough for evaluating the important diode parameters. The diodes and the shunt resistance can be extracted from each other due to their different voltage dependencies. At high voltages the ideal diode behaviour dominates, at medium voltages depletion layer recombination current can be distinguished and at low voltages only the effect of the shunt resistance is observed. A simple least square fitting method can be applied. After this the only remaining unknown component, series resistance, is evaluated by fitting the initially measured voltage, current and irradiance signals. In order not to confuse the series

resistance with the lateral voltage distribution effects present at high current levels the series resistance fitting was done when the current was less then half of the nominal short circuit reading. In addition, the temperature of the cell is measured and included in the analysis. The temperature dependence of the diode parameters will be used later for testing the reliability of the method.
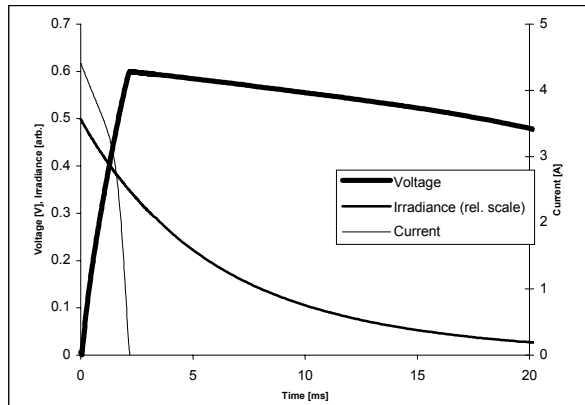
Fig. 1 Measurement principle of the Irradiance Decay Cell Analysis Method

3. TESTING OF THE METDOD

We have applied the method for full size cells from several recognized manufacturers and in most of the cases we found immediately an excellent fit between the measured IV characteristics and the simulated IV curve. This is a strong proof for the method since the important diode parameters evaluated from the voltage decay information prove to fit also when the cell is swept from short into open circuit. The two hardly distinguishable curves labelled as B in Fig. 2 demonstrate a typical fit. The curves are not temperature corrected and the cell temperature was 26.2 °C.
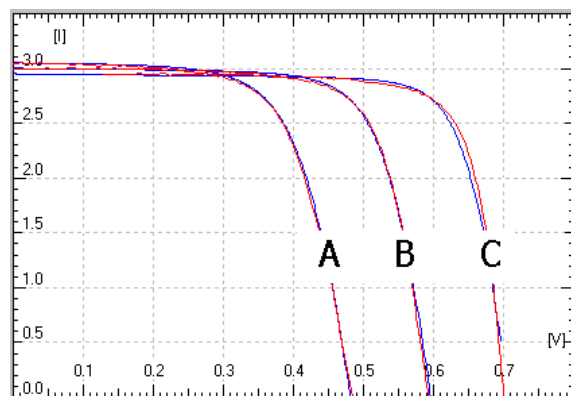

Fig. 2 Measured and calculated IV curves at 26.2 °C, graphs B. The same measurement data corrected to +75 °C and –25 °C; graphs A and C, respectively.

In addition, Fig. 2 demonstrates also the fit between the two curves when the same measurement data was corrected to 75 °C and to -25 °C applying the procedure of the standard IEC891 with the typical average temperature

correction coefficients and on the other hand the theoretical temperature dependence of the evaluated diode parameters for the simulated curve. We believe that the slight misfit at –25 °C is due to the limitations of the IEC891 procedure and particularly the non-physical voltage correction algorithm.
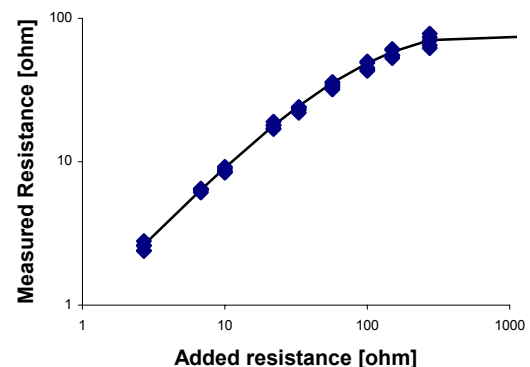
3.1 Series and shunt resistance

The series resistance measurement reliability was tested by contacting additional milliohm size resistors in series with the cell and measuring the total series resistance. We used commercial 10 milliohm (+/- 1%) resistors connected in parallel resulting in 2, 3.3, 5 and 10 milliohm total resistances. The initial series resistance of the cell was measured to be 11.2 milliohm. As demonstrated in Fig. 3 the total measured series resistance follows very well the calculated series resistance. The measurement reproducibility was better than +/- 0.3 milliohms. It must be pointed out that the series resistance is always in practise a distributed parameter and therefore depends somewhat on the current level it is measured with.
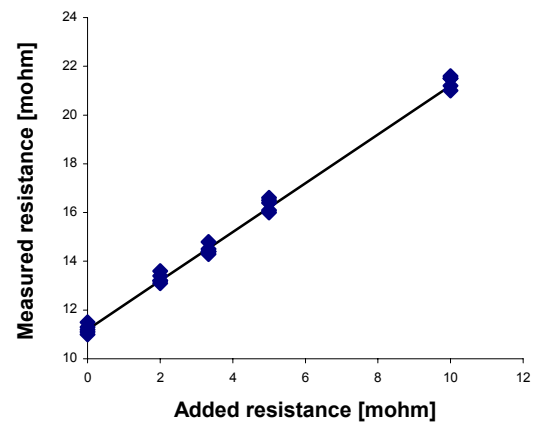
Fig. 3 Measured and calculated series resistance

The measurement reliability of shunt resistance was tested by adding extra shunt resistances in parallel with the cell. The original shunt resistance of the cell was 95 ohms as measured in dark. Fig. 4 demonstrates how the IDCAM system evaluated the total shunt resistance as a function of the added shunt resistance.

Fig. 4 Measured and calculated shunt resistance

The fit with the calculated resistance is good. The measurement uncertainty was less than 5 % below 10 ohms, less than 10 % below 30 ohms and less than 20 % below 70 ohms. The measurement reliability of high shunt resistance values is easily improved by using more sensitive instruments for irradiance measurement.

3.2 Diode saturation currents

The saturation current values of the ideal and recombination current diodes are not easy to identify and verify independently. We have worked out a qualitative test method relying on the theoretical temperature dependence of these parameters. Ideal diode saturation current is proportional to the square of the intrinsic carrier concentration and recombination diode saturation current is related linearly with the intrinsic carrier concentration, equations (2) and (3). The temperature dependence of the intrinsic carrier concentration is scientifically well formulated with great accuracy and reliability [5]. We measured the saturation current readings at several cell temperatures from 20 to 60 °C and plotted the values as a function of temperature, Fig. 5 and Fig. 6. In addition, we plotted also the corresponding theoretical saturation currents as a function of temperature. The measured ideal diode saturation current values fit excellently with the theory over two decades and the simultaneously measured recombination diode saturation current values fit equally well over one decade. The experiment proves with great confidence that the saturation current values measured with IDCAM are physically meaningful and therefore they can be used for estimation of more profound material parameters like minority carrier lifetimes and doping levels. This will be of great help not only in development laboratories but especially in controlling production processes of high volume.
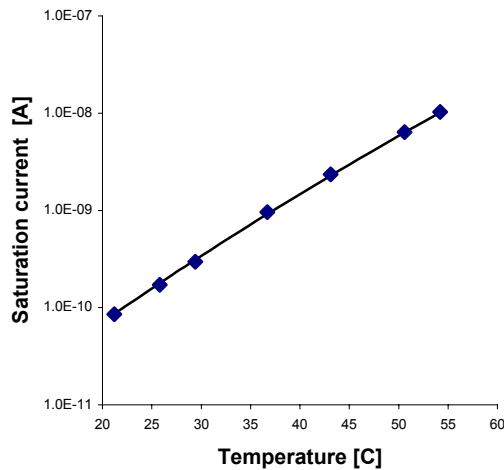
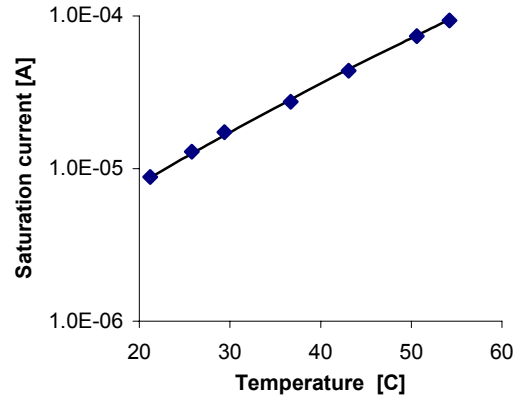**Fig. 5** Measured and calculated ideal diode saturation current

Fig. 6 Measured and calculated recombination diode saturation current

3.3 Lateral voltage distribution effect

With cells from some manufacturers there appears a gap between the measured and the simulated IV curves. This is demonstrated in the Fig. 7 where the measured IV curve at 1000 W/m^2 gives about 3 % less power at maximum power point compared with the simulated IV curve. It should be noticed that the gap starts to appear already at rather low voltages. In addition, when the cell is measured at reduced irradiance levels the fit improves as demonstrated in the same figure.
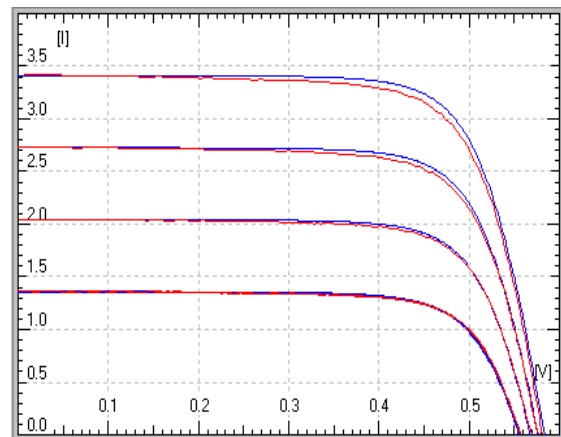
Fig. 7 Calculated and measured IV graphs at 1000, 800, 600 and 400 W/m^2.

In order to model this gap we have tested several modifications including diode ideality factors and also dynamic effects. The conclusion was that not a lumped component is able to explain the gap. Others have previously investigated also the effect of distributed series resistance which induces voltage distribution along the cell surface especially at high current levels [2], [6], [7], [8]. Accordingly, our lateral voltage measurements revealed that at high current levels at the end and between two fingers the voltage was even 100 mV higher than at the bus bars. Such voltage distribution does not only induce resistive losses but also premature current flow through the diodes of those high voltage areas. In order to test this phenomena we shadowed the cell in two ways while measuring at 1000 W/m^2 irradiance level, Fig. 8, Cases A and B.
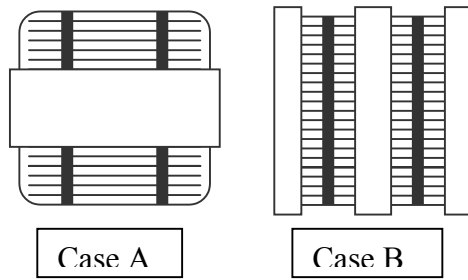
Fig. 8 Testing of shadow orientation on lateral voltage distribution loss

The misfit vanished only when the cell was shadowed as shown in the Case B. The conclusion is that due to limited lateral conductance a simple two diode model is not able to explain the cell behaviour but a distributed model should be used. The reliability of such a model would be a lot more case sensitive and require educated guesses on the exact origin of limited lateral conductance parameters. On the other hand, even the present IDCAM method gives true physical information of the real diode parameters avoiding the interference from the limited lateral conductance effects giving unprecedented information on the power loss due to lateral voltage distribution

4. SUMMARY

We have developed a new equivalent circuit analysis method for crystalline silicon cells. The method is called Irradiance Decay Cell Analysis Method (IDCAM) and it has been applied successfully for cells from several recognized industrial manufacturers. The method is simple to use and does not require any additional measurement instruments. It is an option to the standard cell solar simulator system and can be applied as easily in a development laboratory as in large volume production control applications.

For some cells the limited lateral conductance was found to cause, in addition to resistive losses, also premature current conduction through the equivalent circuit diodes. This is perhaps the first direct quantitative measurement of this loss phenomena and proves also not only the reliability of the method itself but the usefulness of refined cell analysis in general.

IDCAM method can routinely measure series resistance with better than one milliohm reliability and the result is completely undisturbed by the diode functions. In addition, also the shunt resistance values below 30 ohms can be measured with reliability better than 10 %. The measurement of shunt resistance does not require a darkened cell.

Physically the most important cell components are the diodes. We have found that the basic ideal diode and single level recombination diode models are adequate for describing cell operation. It is obvious that the ideal diode saturation current, Eqn. (2), should be modulated with the effects due to limited emitter and base lengths, back surface field and surface recombination but this is not affecting the fitting itself. Only when the ideal diode saturation current value is used for estimating the actual physical material parameters more refined model is necessary. But already today the recombination diode

saturation current reading with the equation (3) can be used as a qualitative measure for the effective lifetime.

A very practical consequence of the reliable two diode parameters is that the dominating voltage temperature correction to IV characteristics can be performed relying on real physical phenomena and parameters. This is a more accurate method than using a constant voltage temperature correction coefficient for all the IV curve data points.

In principle Irradiance Decay Cell Analysis Method can be applied with any solar cell technology if just physically reliable equivalent circuits and mathematical models are available. We hope that our preliminary work with crystalline silicon cells will stimulate other groups to work out these models and test the method accordingly.

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