MICROSTRUCTURAL DEFECTS OF SOLAR CELLS
INVESTIGATED BY A VARIETY DIAGNOSTIC METHODS

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Abstract: This paper discusses the application of a variety diagnostic methods applicable to the solar cells. More objective results about solar cells quality and reliability are possible to obtain by using a various methods. Diagnostic methods described in this paper are based on a dark and illuminated $J-V$ characteristics, a investigation of noise in a wide range of frequency and a radiation detection at a different spectral range, namely by an electroluminescence and a thermography method. These methods are primarily more appropriate for a detection or a localization of microstructure defects when a reverse-bias stress is applied. However, the analysis of a forward-bias conditions is included in an investigation of $J-V$ characteristics as well.

Keywords: Solar Cells, $J-V$ curve, Noise, Electroluminescence, Thermal Imaging, Defects

1. INTRODUCTION

Although the research and development nowadays are more directed to a thin-film solar cells the majority of a generating production today is still oriented on a silicon wafer-based photovoltaic technology. Despite this mass industrial production success, the manufacturing techniques are largely influenced by the requirements for a very low cost of solar cells that gives a space to creation of the microstructural defects caused by the technological imperfections. Our research is aimed precisely to a detection or a localization of the microstructural defects along with a investigation of their nature. These defects have a significant adverse impact at a required properties of the solar cells leading to a reduction of their durability and efficiency. The solar cell samples used in this investigation are not long term exposed to an ordinary operation, which can be responsible for an emergence of new microscopic cracks and fractures, so therefore the observed defects have the origin only in the process of their production. The solar cells are made from single-crystal silicon of dimensions $125 \times 125 \text{ mm}$ ($150 \text{ mm in diagonal}$ with a surface area of $150 \text{ cm}^2$) and a thickness of $220 \mu\text{m}$. The cells are designed for the solar panel fabrication. The samples are usually prepared from the monocrystalline silicon solar cell wafer by breaking the wafer into pieces. The discussion of results is performed for a selected interesting solar cell sample labelled as a ‘X’.

2. EXPERIMENTAL

2.1. CURRENT DENSITY-VOLTAGE CHARACTERISTICS

The dark current density-voltage ($J-V$) characteristics of the solar cells are measured under a reverse and a forward-bias conditions to provide the basic properties about the samples. The samples are an electrically stressed between two aluminium electrodes, where the bottom electrode is equipped with a thermoelectric cooler controlled by the source-meter Keithley 2510 TEC for a temperature stabilization. The $J-V$ characteristics are measured by the precision source-meter Keithley 2420 set to the voltage source with a current meter. The measurement of an illuminated $J-V$ characteristics is based
on a modular solution from the National Instruments company. The illuminated $J-V$ characteristics are measured by the programmable high-power source measure unit card PXI-4130 in the mode of a current sink and voltmeter. The illumination of the samples is realized by a halogen lamp controlled by the data acquisition card PXI-6224. Both of these cards are installed in the hybrid slots of the chassis PXIe-1073 with a integrated controller.

2.2. ELECTROLUMINESCENCE AND THERMAL IMAGING

A low-noise CCD camera is used for a sensing of radiation at the visible and near-infrared spectral range from $0.3\,\mu m$ to $1.5\,\mu m$ and a thermal imager is used for the detection of radiation at a far-infrared spectral range from $7\,\mu m$ to $13\,\mu m$. The CCD camera is equipped with a silicon chip with a resolution of $2184 \times 1472$ pixels cooled by a dual system of Peltier modules. The imaging system of the IR camera is based on an uncooled focal plane array detector with a resolution of $120 \times 160$ pixels. The samples are placed on the aluminium electrode with a thin finger contact equipped with a wrought silver in both of these measurements. The reverse-bias current is realized by the precision current source Keithley 6220 DC.

2.3. POWER SPECTRAL DENSITY CHARACTERISTICS

The samples are placed in the dark environment between two conductive aluminium electrodes for the noise measurements. Two parallel capacitors (a ceramic $C_1 = 1\,\mu F$ and an electrolytic $C_2 = 470\,\mu F$) are on the input of the circuit. These capacitors are used for the voltage ripple stabilization and the excess noise elimination of a voltage source Agilent E3631A. The voltage source is set to the current control mode to keep the current density through material constant. The reverse current is set from the $0.5\,mA$ to $3\,mA$ in an increments of $0.5\,mA$. The noise of the samples is sensed on the output closed by a resistor ($R = 9.966\,\Omega$). The noise signal sensed on the resistor is amplified by a ultra low-noise amplifier Signal Recovery 5184 with a fixed voltage gain of $\times1000$ (60 dB). The noise is applied to an unbalanced Q input of a baseband analyser Rohde & Schwarz FMU36 with the selected input impedance of $1\,M\Omega$. The noise is finally investigated in the spectral range from $10Hz$ to $1MHz$.

3. RESULTS

The illuminated $J-V$ characteristics measurement under illumination provides the information for obtaining the basic external electrical parameters of the sample such as an operating point for a maximum power ($P_{\text{MAX}}$), a short-circuit current density ($J_{\text{SC}}$) and an open-circuit voltage ($V_{\text{OC}}$). These parameters are illustrated in the fig. 1a with the obtained maximum power point (MPP). This fourth quadrant of the $J-V$ dependence is also supplemented by a power density-voltage ($P-V$) dependence. The power density in this case refers to a power generated per unit area of the sample. The fill factor defined by a relation

$$FF = \frac{J_{\text{MP}} \cdot V_{\text{MP}}}{J_{\text{SC}} \cdot V_{\text{OC}}} = \frac{P_{\text{MAX}}}{J_{\text{SC}} \cdot V_{\text{OC}}},$$

where the $J_{\text{MP}}$ current density and the $V_{\text{MP}}$ voltage produce the maximal power, refers the ratio of the actual maximum obtained power to the open-circuit voltage and the shot-circuit current $V_{\text{OC}}$. The open-circuit voltage of $0.55\,V$ was measured at open-circuit conditions where the current is equal to a zero. Also the short-circuit current density of $9.15\,mA\,cm^{-2}$ was measured at the voltage equal to a zero. The reached fill factor is 0.51 for this obtained parameters by the eq. (1) including the maximum power density of $2.57\,mW\,cm^{-2}$. The typical fill factors of the contemporary solar cells are between 0.75 and 0.80 [1]. The inversion of obtained slopes in fig. 1a permits an easy determination of a shunt resistance ($R_{\text{SH}}$) and a series resistance ($R_S$). The origin of the series resistance can be in the current moving through the semiconductor base and an emitter of the $pn$ junction, in the top and rear metal contacts and in the interface between the metal contacts and the semiconductor material [2].
The series resistance estimated from the slope is about 22 Ω. The shunt resistance of the illuminated $J-V$ characteristics is estimated about 1.56 kΩ. It is caused by a microscopic defects which provides the alternative path for the generated photo-current crack through the semiconductor layers or a current path at the edges of the solar cell. To converge to the ideal illuminated $pn$ junction should be the shunt resistance large as possible and a series resistance small as possible. The theoretical derivation of these parameters based on the equivalent circuit is beyond the capacity of this paper. The forward-bias curve in the fig. 1b of dark $J-V$ characteristic shifted by the short-circuit photo-current is actually the illuminated $J-V$ characteristic in the fig. 1a [3]. The differences between their mutual fitting are probably caused by a heating produced by the halogen lamp [4] and much more robust fitting algorithm for fig. 1b. The dark reverse-bias $J-V$ characteristic in fig. 1b is more suitable for the detection of the microstructural defects. The estimated shunt resistance in fig. 1b is a nearly identical to the shunt resistance estimated in fig. 1a. The gradual change of the slope at 3V is caused by the electric field strength activation of a defect with estimated resistance ($R_{DEF}$) of 0.6 kΩ. The activated defect with a reduced resistance caused the increasing of the reverse current. Basically this may not be only one activated microstructural defect, but a whole range of some parallel microstructural defects activated at the similar time with the resistance of $R_{DEF}$. However, the electroluminescence investigation with the CCD camera below shows that the only one particular microstructure defect is responsible for the increasing of a reverse current in fig. 1b.

The measurement of electroluminescence and the thermal radiation is provided for the different reverse-bias current of 1 mA, 3 mA and 6 mA. The investigation of the electroluminescence is based on a comparison of the obtained images at the different reverse-bias currents. The radiation intensity of the sample is expressed by a logarithm of photons per second (a photon flux $\Phi_q$). The intensity difference of the images at 3 mA and 1 mA shows a presence of the only one defect with a strong intensity near to the edge of sample. Thus, the defect at a lower reverse-bias current is not accompanied by the radiation. This microstructural defect is marked by the dashed-line circle in fig. 2a. We assume that, the resistance of this microstructural defect begin to decrease by a higher reverse-bias voltage and causes a steeper increase of the total reverse current (red line) in fig. 1b. The conductive channel is created and the difference of the resistances is almost 1 kΩ. The intensity difference of images at 6 mA and 3 mA shows emergence of two new microstructural defects marked by the dotted-line hexagons in fig. 2a. The negligibly small break disrupting the smoothness of the curve is in the dark $J-V$ characteristics in fig. 1b at the reverse-bias voltage of 18 V. This can be attributed to the
Figure 2:  
a) The electroluminescence of the solar cell fragment with light defect spots, exposure time 600 s, dark environment. b) The thermal activity of the solar cell fragment. Solar cell sample X, reverse-bias current $I_R = 6$ mA, ambient temperature $T = 25^\circ$C, area $126.33 \, \text{mm}^2$, perimeter $45 \, \text{mm}$.

extinction of an activated microstructural defect due to a small decrease of the reverse-bias current. This behaviour is also observed in fig 2a of the electroluminescence measurement as a decreasing the intensity of two microstructural defects marked by the cross-hairs. We assume these conductive channels caused by the microstructural defects on the left partially disappear and the total resistance of sample increased slightly. The investigation under a different reverse-bias current is also focused on the thermal imaging. The thermal radiation of the sample is shown in fig. 2b. The considerable overheating is observed on the left of the sample with the more significant defective area in the lower left corner comparing to the upper area. This thermal radiation on both cases can not be associated to an any particular light spot of the microstructural defects in fig. 2a. The emergence of the new defects or an extinction of already presented defects is not observed at different reverse-bias current and an increase of the reverse-bias current causes only the temperature increase of the overheating.

Figure 3: The noise power spectral densities of the current fluctuations for the different bias current, solar cell sample X, dark environment, night-time conditions.
The noise power spectral density (PSD) in fig. 3 shows the inversely proportional dependence on the frequency that correspond to the type of noise commonly know as a flicker noise. The $f^{-1}$ noise interpretation is given by Hooge’s formula in the principal form $S_I(f) = \frac{\alpha}{f^\beta}$. There is clearly defined that PSD is inversely proportional to frequency but there exists number of statements that have to be valid. Firstly, the $f^{-1}$ noise originates from fluctuation in the mobility. Secondly, it is believed that carriers provide mutual independent fluctuation. Parameter $N$ is preferable substituted by $nV$, where $n$ is carrier concentration and $V$ volume [5]. We expect that changes in the slope in fig. 3 could be given by defined statement infraction or voltage dependent changes in the equation parameters.

4. CONCLUSION

A variety of the diagnostic methods to obtain the information about the microstructural defects are described with a demonstration in figures. The illuminated $J$–$V$ characteristic provides the basic electrical parameters under the ordinary operation responsible for the behaviour of the solar cell. The qualitative information about the sample provides also the fill factor which is to a large extent influenced by the shunt and the series resistance. On the other hand, the dark $J$–$V$ characteristics provides the basis for the estimation of the microstructural defects, which can not be detected with the diagnostics under the normal operation, especially in the reverse-bias. The activated microstructural defect with the estimated resistance $R_{DEFF}$ began to affect the dark $J$–$V$ curve which consequently caused an increase of the reverse current. The measuring of the electroluminescence shows that the decrease of the resistance is mainly caused by the only one particular microstructure defect near to the edge of the sample. The radiation detection by the electroluminescence and the thermal imaging in the different spectral range shows that, the radiation of the microstructural defects in a visible and near infrared range is not also accompanied by the thermal overheating in these affected areas. The investigation of the power noise spectral density $S_I(f)$ shows dependence of $f^{-1}$ noise with changes in the slope. A precisely examination of this changes will be provided in the future. Future research will be focused on the use of these methods for an estimation quality of thin film solar cells, especially for evaluation of the microstructural defects in Cu(In, Ga)Se$_2$ solar cells. We have a lot of preliminary results now and it will be subject of the future publication.

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REFERENCES


