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Evaluation Of The Solar Cell Internal Resistance In I-V Measurements Under Flash Illumination

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Abstract. At fabrication of the concentrator SCs one of the central problems is radical reduction of the internal ohmic losses. To distinguish the presence of the internal resistance components in an *I-V* curve, uncertainty due to the shape of the p-n junction(s) *I-V* curve should be eliminated. In this connection, it is more adequate to analyze the shape of the "resistance curve", which can be constructed by subtraction of the voltage coordinates of the illuminated or dark *I-V* curve of a SC from those of the p-n junction at the same current magnitudes. In turn, the p-n junction *I-V* curve of a real SC can be constructed as a dependence of photocurrent I_{ph} on open circuit voltage V_{oc} in varying the illumination level from low up to the level producing I_{ph} of a required magnitude. In the simplest case of a SC model with series resistance, the "resistance curve" is a straight line. In a general case, not only one, but several components of the “distributed” resistance may be present, so that the shape of the "resistance curve" may indicate this. In the present work, both hard- and software have been created for constructing the "resistance curves" in *I-V* measurements of the cells with using a flash solar tester.

Keywords: Solar cells, Internal resistance, Indoor testing, Flash tester.
PACS: 88.40.F-88.40.ff, 88.40.H-88.40.hj, 88.40.jp.

INTRODUCTION

Internal ohmic losses are among the limiting factors at development of highly effective concentrator solar cells (SCs). For any SC, the “illuminated” *I-V* curve (as well as that in the dark) may be represented as an *I-V* characteristic of a *p-n* junction (or junctions in the case of a multijunction SC) deformed by the voltage drop across the internal “lumped” and “distributed” resistance components [1]. To reveal action of the internal resistance components from *I-V* measurements, uncertainty associated with an unknown *p-n* junction curve configuration should be eliminated. In this respect, it is more correct to analyze the shape of certain "resistance curve", which can be constructed by subtraction of the voltage coordinates of the illuminated or dark *I-V* curve of a SC from those of the *p-n* junction at equal current magnitudes. As to the *p-n* junction *I-V* curve itself, so it can be constructed as a dependence of the photocurrent I_{ph} on the open circuit voltage V_{oc} in varying the SC’s illumination level– from a given value up to that being quite low.

In the simplest model of a SC with “lumped” (series) resistance, the "resistance curve" is a straight line. In a “classical” model of a rectangular SC with regular contact fingers on the front side, the "resistance curve" may have a certain curvature. In this case, tilt angle of the curve chord corresponds to the sum of the “lumped” resistance component and one half of the “distributed” component. Also, two tangents to this curve have definite tilts, which depend on illumination level [1]. In a general case, more than one component of the “distributed” resistance may take place. Configuration of the "resistance curve" may reveal this situation, giving important information for SC optimization.

Flash solar testers are the convenient instruments for indoor characterization of the concentrator SCs and assembled modules [2-5]. In the present work, both hard- and software have been created for construction of the "resistance curves" in *I-V* measurements of the cells by means of a flash solar tester. The described methodology was applied to *I-V* recordings in single- and triple-junction SCs based on AlGaAs/GaAs and InGaP/GaAs/Ge heterostructures. The features and limitations for the proposed approach are discussed.

METHODOLOGY OF MEASUREMENTS

During last decade, flash solar testers of different design have been elaborated at the PV Lab of the Ioffe Institute, intended for indoor characterization of the III-V solar cells and concentrator modules [2-3, 5]. In all instruments, light pulse is formed as a plateau, during which illuminated *I-V* curve is recorded, and a “tail”, where light intensity decreases gradually. An idea how the "resistance curves" can be constructed consists in possibility to use light “tail” after *I-V* measurements. For this, the load circuit of a tested cell should be disconnected for V_{oc} measurements at

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decreasing light intensity. In turn, light intensity is regarded as that producing the proportional amount of photocurrent, whereas photocurrent calibration with respect to light intensity took place during *I-V* recording within the light plateau. Subtraction (at equal current magnitudes) of the voltage coordinates of the illuminated or dark *I-V* curve of a SC from those of a *p-n* junction (the latter is the dependence of I_{ph} on V_{oc} in varying SC's illumination level) is carried out by software.

INSTRUMENTATION FOR MEASUREMENTS

The picture of the elaborated solar tester is shown in Figure 1. The illumination system includes a flash Xe-lamp powered from a high-current pulse source. *LC*-circuits of the source allow producing light pulses with a plateau of 1 millisecond, or 3 milliseconds, in duration (light stability is ±2%) and a "tail" with gradually decreased intensity (see, also, Figure 2).

FIGURE 1. Picture of the elaborated solar tester (light protective housing is removed).

The measurement procedure consists of four steps (Figures 2 and 3). At first, the tested solar cell is connected (by an electronic switch) with a sweeping forward bias source. The dark *I-V* curve is recorded. At the second step, the cell is connected with a sweeping reverse bias source to arrange initial conditions for illuminated *I-V* curve registration. At the beginning of the third step, the light pulse is activated, and the cell is connected with a forward bias source to record the illuminated *I-V* curve. After this, at the fourth step, the cell is disconnected from the load circuit and the dependence of V_{oc} on I_{ph} in varying SC's illumination level is registrated during the light "tail".

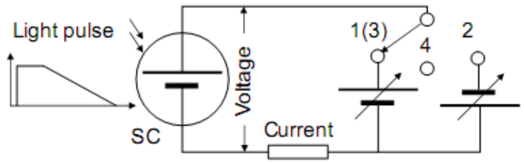

FIGURE 2. Simplified electric circuit of the *I-V* measurements (see text).

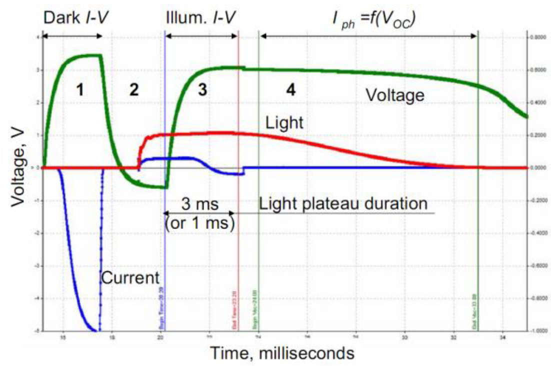

FIGURE 3. Oscillogram of light, voltage and current pulses at *I-V* measurements of the concentrator solar cells under flash illumination. The illuminated *I-V* curve is measured during a plateau on the light pulse (light stability is ±2%). The pulses corresponding to the light plateau of 3 ms in duration are shown. In the case of the 1 ms plateau, all pulses were proportionally shorter.

Computer treatment of the obtained data consists in the following (see Figure 4 for the case of a one-junction AlGaAs/GaAs solar cell): 1- representation of the dark and illuminated *I-V* curves; 2- construction of a curve corresponding to the dependence of photocurrent I_{ph} on open circuit voltage V_{oc}, where the I_{ph} magnitudes are calculated being proportional to light intensities in the flash tail with the initial value corresponding to the short circuit current measured before; 3- representation of the latter curve in as the *p-n* junction *I-V* one (for the conditions in the dark and under illumination); 4- construction of the dark and illuminated "resistance curves" by subtraction of the voltage coordinates of the real illuminated or dark *I-V* curve of the cell from those of the *p-n* junction at the same current magnitudes.

At a low current, the dark *I-V* curve coincides with the p-n junction curve (see Figure 4). It means that a simple comparison of the dark (instead of *p-n*) and illuminated *I-V* curves can give a likely method for the internal resistance evaluation close to the expected ideal position of the maximum power point, if there is no necessity to recognize detailed reasons for origin of the resistance.

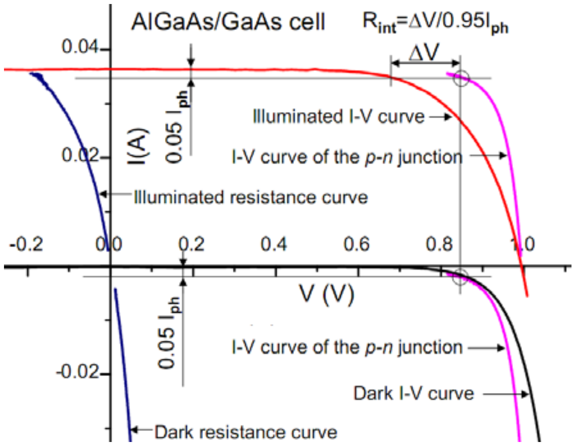

FIGURE 4. Set of the *I-V* curves obtained from one flash measurement procedure. A single-junction AlGaAs/GaAs solar cell was chosen for this experiment. "Classical" (non-linear) configuration of the illuminated resistance curves is realized in the case of presence of both lumped and distributed components of the internal resistance [1]. However, as a simple characterization parameter, R_{int} may be defined using the dark *I-V* curve at a low current (say, at 0.05 I_{ph} level).

There are certain limitations in realizing the above procedure. First, ohmic losses may only be revealed at a relatively high illumination level specific for every cell design, when the "resistance curve" ceases to be merged into the current axis. Second, there exist "dead periods" for V_{oc} measurements: at the beginning of the tail, the electronic circuit spends some time for cell disconnection; at the end of the tail, uncertainties in measurements due to low light intensity take place. Third, at very high sunlight concentration ratios, heating effect may give rise to the increase in cell temperature during a light pulse. Fourth, in the case of the multijunction cells, uncertainty due to deformation of the illumination spectrum at the end of the tail may be essential producing a current mismatch in the sub-cells.

HEATING EFFECT

The elaborated solar simulator could operate in two modes: with 1 ms, or 3 ms, light plateaus. The 1 ms mode provided light intensities up to about 4500 suns at a minimal distance between the flash bulb and the tested cell, whereas in the 3 ms mode this intensity was no more than 1000 suns. There was not greater difference in the I-V curves configuration for the III-V solar cells available (such as 1-j AlGaAs/GaAs and GaSb, as well as 3-j InGaP/GaAs/Ge cells), which could result from some of the possible time-dependent cell properties. However, the 3 ms mode could bring-in more evident features concerning the heating effect of the tested cell under flash illumination.

In Figure 5, two dependences of V_{oc} on sunlight concentration ratio *C* are shown for a 3-j InGaP/GaAs/Ge cell. The solid curve was recorded "automatically" (as described above) during the light tail after 3 ms plateau. A number of quadratic points present results of the "manual" V_{oc} measurements at the beginning of the light plateau, when the flash illumination intensity is varied. A maximum difference in V_{oc} values took place after about 8 ms from the beginning of the light pulse corresponding to about 7° C cell overheating with respect to room temperature (bearing in mind 4,5 mV/C temperature coefficient). In the 1 ms mode of simulator operation, the maximum overheating was 2-3 times lower and could not be taken into account in corresponding measurements.

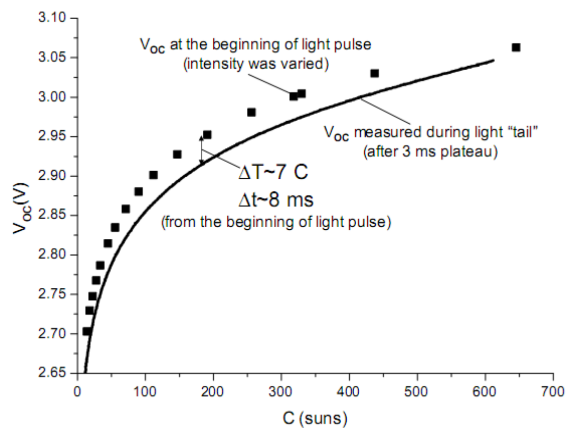

FIGURE 5. Dependences of V_{oc} on sun concentration ratio (*C*) for a 3-j InGaP/GaAs/Ge cell: solid curve– recorded "automatically" during the light tail after the 3 ms plateau; quadratic points– results of the "manual" V_{oc} measurements at the beginning of the light plateau, when the flash illumination intensity is varied.

CURRENT MISMATCH EFFECT

The photocurrent mismatch in a multijunction cell at an given illumination spectrum may lead to a situation, when the p-n junction curve is "worse" than the cell *I-V* curve. It occurs, if the internal ohmic losses are very low. For demonstration, a 2-junction cell has been modeled by two GaAs cells and three Schottky diodes (see Figure 6). The effect does not depend on the light intensity and on which sub-cell has greater photocurrent. Its nature is similar to that observed at cell investigations under forward current conditions [6].

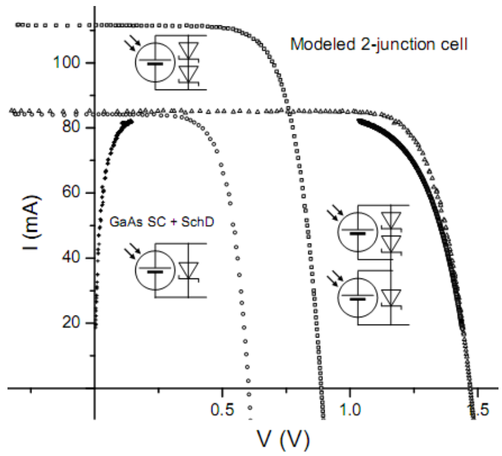

FIGURE 6. Two-junction cell modeling by means of two illuminated GaAs cells and three SchDs. A "narrow-gap" cell includes one SchD, whereas a "wide-gap" cell– two SchDs in series.

MEASUREMENTS UNDER FLASH ILLUMINATION SPECTRUM

The photocurrent mismatch in a multijunction cell may arise due to spectrum variation during a flash. To the end of the light "tail", increased contribution of IR light results in the rise of measured values of V_{oc}, because the current is limited by that generated in wider-in-gap sub-cells in both tested cell and monitor cell. In Figure 7, the normalized flash spectral curves are shown recorded at different time delays after the beginning of the 1 ms light plateau. It is seen that there is a long enough time interval, within which the spectral distribution is relatively stable, so that the current mismatch may occur only at a reasonably low illumination level.

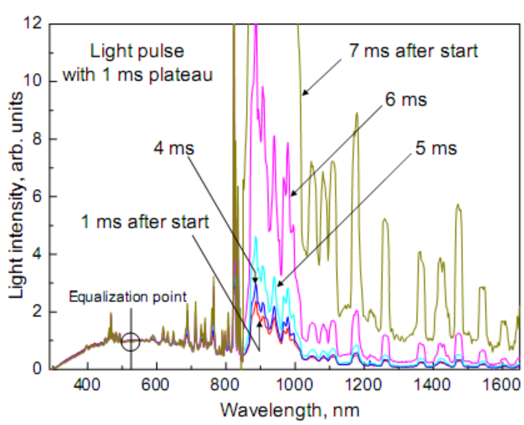

FIGURE 7. Flash illumination spectra in the 1 ms mode of simulator operation. The curves have been recorded at different time delays after the beginning of the 1 ms light plateau. The spectra have been normalized at the light wavelength of 520 nm.

In Figure 8, a family of the *I-V* curves is shown recorded for one of the small-in-area concentrator InGaP/GaAs/Ge solar cell at illumination intensities up to 3250 suns. Due to the photocurrent mismatch effect, the "resistance curve" is a vertical line with a small shoulder to the right at a low illumination level (see insert). At higher intensities the "resistance curves" demonstrate the existence of both series and distributed components. Configuration and slopes of the elements may bring useful information at cell optimization.

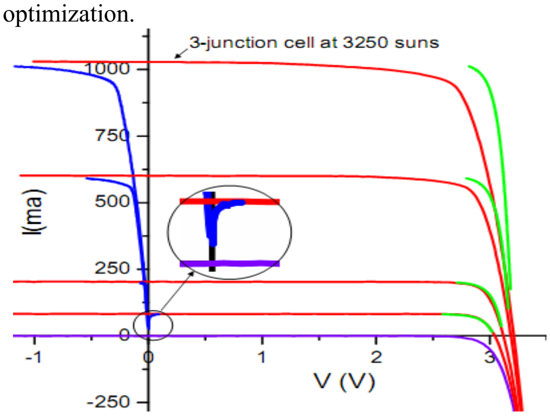

FIGURE 8. Family of the *I-V* curves, as well as "resistance curves", recorded for one of the small-in-area concentrator InGaP/GaAs/Ge solar cell.

CONCLUSION

At a low current, the dark *I-V* curve coincides with p-n junction curve, so that a simple comparison of the dark (instead of the *p-n*) and illuminated *I-V* curves may give a likely method for internal resistance evaluation as a simple characterization parameter. In multijunction cells, a great variety of distributed resistance components may exist (see, for instance, [7]). It means that at cell optimization a set of the complementary investigation methods should be applied, such as, for instance, electroluminescence, or local illumination. The shape of the "resistance curves" constructed by proposed in this paper method contains definite information about internal ohmic losses. It is important that this information is obtained under sun simulating conditions similar to the natural ones. Developed method of the time-dependent V_{oc} measurements could also be used to evaluate precisely the thermal resistivity of the cell to substrate interface by measuring the substrate temperature.

ACKNOWLEDGMENTS

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