INDOOR CHARACTERIZATION OF THE MULTIJUNCTION III-V SOLAR CELLS AND CONCENTRATOR MODULES

M.Z.Shvarts, A.E.Chalov, E.A.Ionova, V.R.Larionov, D.A. Malevskiy, V.D.Rumyantsev, S.S.Titkov
Ioffe Physico-Technical Institute, 26 Polytechnicheskaya, 194021 St.Petersburg, Russia,
e-mail: shvarts@scell.ioffe.rssi.ru

ABSTRACT: This paper presents methods and set-ups for indoor characterization of the multijunction concentrator solar cells (SC) and small-size concentrator sub-modules intended for space and terrestrial application in concentrator PV arrays. Test procedures and setups allows to investigate the spectral characeristics of multijunction SC such as quantum efficiency, reflectance and transmittance and I-V curves at different illumination levels and spectrum contents of irradiance. In measuring the parameters of concentrator sub-modules the angular divergence of solar radiation is simulated by means of a collimating optical system with a xenon flash lamp as a light source. Measurements of I-V curves of concentrator SCs are carried out at a non-uniform distribution of the irradiance corresponding to real one (under the lens), so that chromatic aberrations are taken into account. The electroluminescent technique has been employed for determination of internal resistance components in the dual-junction SC in order to estimate their ability to operate at nonuniform illumination.
Keywords: Multijunction Solar Cell, Concentrator Cell, Characterization

1. INTRODUCTION

The team of the Ioffe Institute is involved in the development of space and terrestrial concentrator modules based on the following concepts: multijunction III-V solar cells; small-aperture area and short focal length Fresnel lens concentrators; smooth-surface secondary mini-lenses; “all-glass” module design (for terrestrial modules) [1, 2]. Photoelectrical performance measurements of multijunction solar cells and small-aperture area concentrator sub-modules with such cells have imposed specific requirements on solar simulating equipment and relevant testing methods. For the accurate indoor measurements, the following procedures and computerized equipment have been developed:

First, spectral response curves in absolute units are recorded for a cell under steady-state colour and modulated monochromatic illumination.

Second, illuminated I-V curves are obtained from measurements in a multi-zone flash solar simulator with adjustable spectrum [2]. To check a tunnel diode ability to work in concentrator cell the I-V curves at non-uniform illumination of SCs were investigated.

Third, after mounting the cell on a heat sink and placing it in a sub-module with small-aperture area concentrator, the illuminated I-V curve is recorded in a flash solar simulator, reproducing spectrum, intensity and angle-size of the sun.

A procedure for determination of the solar cell internal resistance components is presented as well.

2. SPECTRAL RESPONSE MEASUREMENTS

A compact spectral instrument has been developed on the basis of a standard grating monochromator (Fig. 1). Monochromatic light is modulated by a chopper with frequency of 75 Hz. Electrical signals from tested and reference cells are registered in selective amplifier and digital system. Each point in the spectral response curve is obtained by comparing the signals, when light is directed to corresponding cell.

Special transformer-type input of the amplifier ensures introduction of the voltage biases to both tested

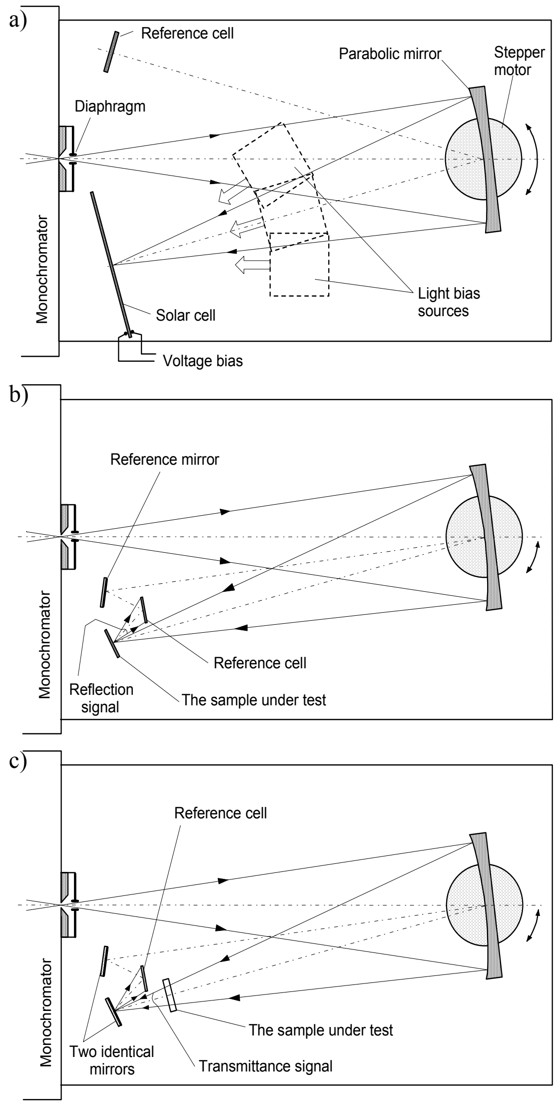

Figure 1: Optical layout of the instrument for measurements of the: a - SC external quantum efficiency spectrum; b - reflection spectrum; c - transmittance spectrum.

and reference cells, arrangement of a quasi-common load resistance for both cells (what is important, if some p-n junctions in a solar cell structure have a leakage) and similarity of gains in both channels along the whole spectral range (340-2100 nm in wavelength). The general block diagram of the Installation is shown in Fig. 2.

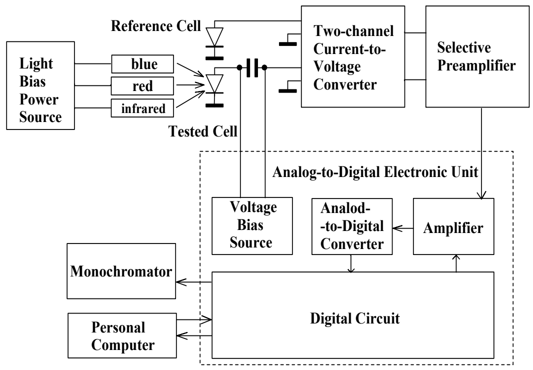

Figure 2: General block diagram of the Installation for spectral response measurements

Opto-insulation pairs perform the connection of the parts with external devices. The signals from both tested and reference cells are introduced into a current-to-voltage converter and selective amplifier. There is a variable voltage bias source providing the spectral response measurements of a tested cell under forward bias conditions (V=0÷3 V). A digital circuit ensures the Installation operation under PC-management.

A three-channel light source is built on the basis of high-intensive halogen lamps (20 or 35 watt each) supplied with reflectors, heat sinks and optical band filters. The filtering is carried out to provide an independent light bias of the subcells in a monolithic multijunction solar cell structure. Spectral transmittance of the filters is shown in Fig. 3. The intensity in each channel can be independently and gradually varied by means of the output voltage regulation in a stabilized three-channel power supply.

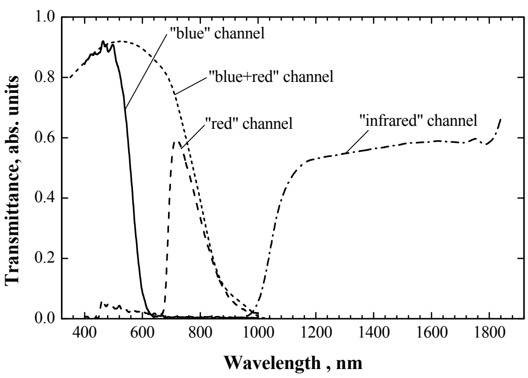

Figure 3: Spectral transmittance of the optical filters in the light bias source.

3. CHARACTERIZATION OF CONCENTRATOR MULTI JUNCTION CELLS AND SUB-MODULES

The shape of a concentrator SC I-V curve depends essentially on the irradiance distribution on the SC surface. Earlier we have proposed a technique for obtaining the illuminated I-V curves at non-uniform distribution of irradiance without a concentrator [3]. To create a non-uniform irradiance the set of the aperture shadowing a part of the SC surface is used. For multijunction cells this technique appeared to be a very useful in the investigations of tunnel diode properties. It was found that the tunnel diode peak current is very sensitive to irradiance distribution over the cell surface.

Fig. 4 presents an example of realization of the procedure proposed. As it is seen from comparison of the I-V curves presented, the procedure reveals the problems with tunnel diode to operate in the concentrator SC at the non-uniformity of illumination.

Indoor characterization of the concentrator sub-modules includes recording the illuminated I-V curves in the conditions of non-uniform illumination and off-normal position, which may take place under natural sun illumination. Such conditions are simulated by an optical system with a collimator developed for a flash tester. The optical system includes: flash Xe-lamp (1); aperture (2); collimator housing (3) with lens (4); and steady-state lamp (5) for initial adjustment of the measurement system (Fig. 5).

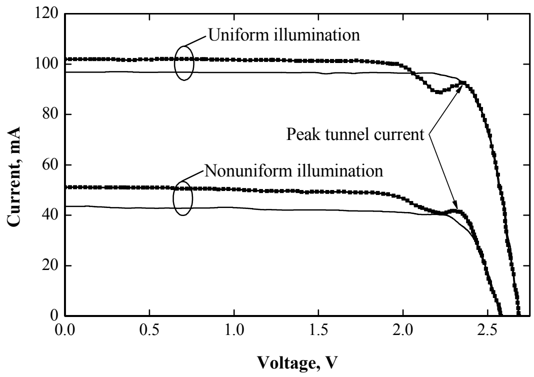

Figure 4: I-V curves of multijunction solar cell at uniform and non-uniform illumination.

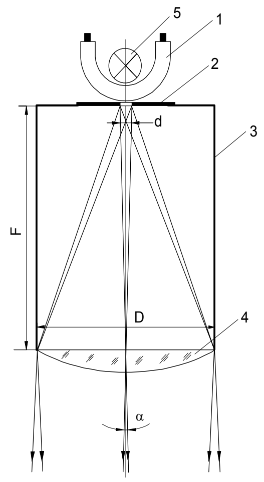

Figure 5: Optical scheme of the illuminating system with collimator: F=230 mm, D=100 mm, d=2.2mm.

Divergence of the rays is 32 ±2 min. of arc, whereas illumination non-uniformity across the 95 mm in diameter working area is better than 5%. An external view of the solar tester reproducing spectrum, intensity, and angle-size of the sun is shown on Fig. 6.

Figure 6: Photograph of the solar simulator reproducing spectrum, intensity, and angle-size of the sun (three-channel illuminating head is shown as well as an optional part of the simulator, see [2]).

4. PROCEDURE FOR DETERMINATION OF THE SOLAR CELL INTERNAL RESISTANCE COMPONENTS

The internal resistance of concentrator SCs has because of nonuniform irradiance distribution on their surface a stronger effect on SC characteristics compared to that in the case of homogeneously illuminated SCs. For this reason, investigation of the SC internal resistance is of a prime importance. Determination of the load I-V characteristic and calculation of the fill factor allow to reveal an integral effect of the cell internal resistance on the generated power. However, the internal resistance is multi-component one and is comprised of:

1) In the case of single-junction (SJ) SCs: the frontal region layer resistance, the contact resistance and the longitudinal resistance of the metallic contact grids.

2) In the case of dual-junction (DJ) SCs: the upper cell frontal region layer resistance, the contact resistance, the contact grid longitudinal resistance and the tunnel junction resistance.

To reduce the negative effect of the internal resistance in creating and improving SCs converting concentrated sunlight it is necessary to have an information on its each component.

Procedures based on luminescence properties of direct-bandgap semiconductors for study of SC internal resistance components have been previously developed in the PV laboratory of the Ioffe Institute [4]. The basis for these procedures is visual observations of the electroluminescent radiation spatial distribution over the SC surface in passing the forward current through a p-n junction with simultaneous controlling the shape of dark I-V curve. For this purpose an electronic-optical converter of IR radiation into visual one was utilized. Nonuniformity of luminescence over the SC surface indicates the cause of the occurrence of a distributed resistance components such as longitudinal resistance of the metallic contact grid fingers, sheet resistance of frontal photoactive layer, existence of cracks and their onsets. Non-simultaneous "ignition" of the electroluminescence (EL) over the photosensitive area allows to detect localized leakages and to determine their nature. In smooth increasing the forward current through a p-n junction one can fix visually the current value, before reaching which the surface luminescence nonuniformity is absent, and, therefore, the distributed resistance can be neglected. However, the luminescence uniformity not always indicates the absence of resistive losses, since a voltage drop may take place on the contact resistance, the value of which is determined from the slope of the tangent line to the dark I-V curve. Together with visual observation of the EL picture of a sample one can make a qualitative estimation of the EL external quantum yield efficiency by means of EL intensity measurements [5].

It should be noted that the developed EL procedures and ways of their realization allow to study effectively the internal resistance of SJ SCs. However, at present monolithic DJ SCs, which production technology is being actively developed, are of prime interest. In such SCs both the top and bottom junction internal resistances affect the I-V curve shape. Therewith, it is impossible to determine from the I-V curve which of these cells limits the output power due to a higher resistance. A visual control of the EL spatial distribution for each of the p-n junctions of a dual junction SC is possible only when optical filter are used, since EL in this case is characterized by two spectral lines (fig. 7). For quantitative recording of the EL signal from each of the p-n junctions it is necessary together with a wide spectral sensitivity photodetector to choose narrowband filters, which is rather difficult, if the EL wavelengths of the separate p-n junctions are close to each other.

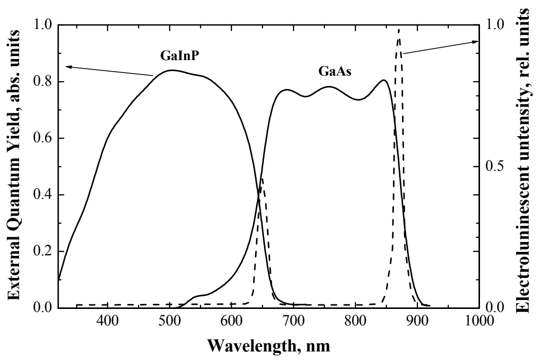

Figure 7: Quantum efficiency curves and electroluminescent spectrums of GaInP/GaAs DJ SC.

More effectively this problem can be solved, if a compact array spectrometer or polychromator with a photosensitivity in the wavelength range of 350-1100 nm is used (Fig.8). The key component in the spectrometer is a diode-array detector that captures individual spectral components of light reflected from the diffraction grating. The measurement setup for EL recording of SJ and DJ cells contains also: a rectangular pulse generator, a current pulse amplifier and a double-beam oscilloscope. The rectangular pulse generator and the current pulse amplifier allow to pass through SCs a strong forward current without heating SC. A SC under investigation is fixed in a special holder opposite to the spectrometer optical system, which excludes the entry of the external scattered light into the recording system.

The measurement procedure is the following. At every value of the forward current (*I*) passed through SC of area S_{SC} the EL intensity (E_{EL}) from one p-n junction (in the case of a SJ cell) or two p-n junctions (in the case of DJ cell) is registered. Simultaneously a voltage drop on SC is measured. As a result of the measurements the dependence $E_{EL}/J(J)$, where $J=I/S_{SC}$, is plotted (Fig. 9).

In the region of small forward current the EL intensity depends on current superlinearity and increases up to establishing the diffusion current flow mechanism through a p-n junction.

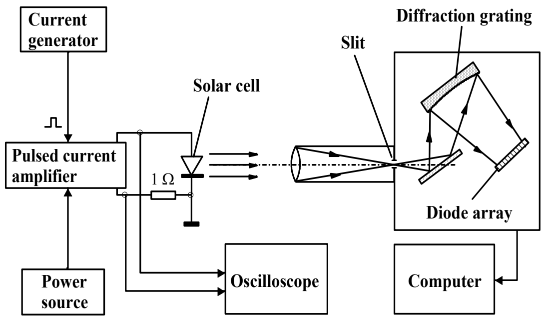

Figure 8: Measurement setup for EL recording of SJ and DJ cells

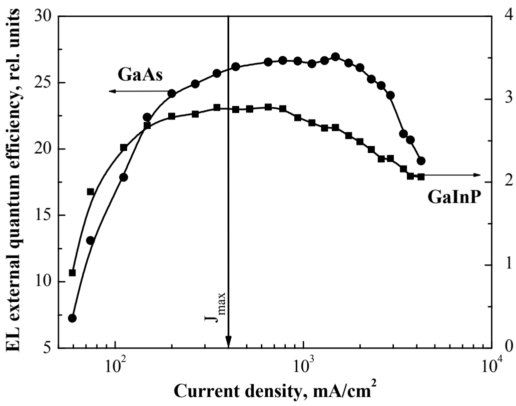

Figure 9: Dependences of the EL external efficiency on forward current density for GaInP/GaAs DJ SC.

At a further increase of the forward current the EL intensity rises linearly. The plateau on the $E_{EL}/J(J)$ dependence corresponds to this regime. At even larger values of the forward current the EL redistribution over the SC surface takes place due to the effect of the sheet and contact resistance. Current stops to flow over the front layer and the whole EL concentrates in the vicinity of the contacts and under them. Due to shadowing of a part of EL by the contacts a decent on the $E_{EL}/J(J)$ is observed.

The dependences obtained allow to determine the forward current density J_{max} up to which the layer resistance of both junctions can be neglected in estimating the total resistance losses of power. The value of J_{max} gives a possibility to estimate whether a definite SC is suitable for conversion of concentrated sunlight when irradiance is nonuniformly distributed over the cell photosensitive area. For this purpose it is necessary, using the lens optical–power characteristic (see [3]), to determine the maximum value of the local concentration K_{max} and to calculate the photocurrent density $J_{local}=J_{1Sun}\bullet K_{max}$ generated in the region of the maximum irradiance. Here, J_{1Sun} is the photocurrent density of DJ SC at its irradiation with light of intensity equal to one solar constant. It should be noted that the J_{1Sun} value measured for a DJ SC would characterize a p-n junction with the lower photocurrent density. Nevertheless as practice show the scatter in the value of the generated photocurrent between the junctions in a monolithic SC does not exceed 5-10%, which lies within an accuracy of J_{max} determined at the EL intensity measurements.

If $J_{local} \le J_{max}$, the layer resistance will not limit the DJ SC output power and a low fill-factor may result from the increased contact resistance, the value of which should be determined from the dark I-V characterictic. In the case of $J_{local}>J_{max}$ ways for improving the semiconductor structure and SC design with the aim of lowering down the layer resistance should be searched for.

Thus the developed procedure for the EL investigation of the internal resistance is valid for both SJ and DJ SCs and allows to estimate quantitatively the contribution of each of the internal resistance components into the total power losses. Besides, the use of spectrometer with a high resolution for EL recording allows to determine the luminescence wavelength, which is of practical importance in investigating SCs based on semiconductor compounds of different composition, i.e. with the different forbidden gaps.

5. CONCLUSION

The test procedures and necessary equipment for measurements of the main characteristics of concentrator multijunction cells have been developed and their abilities are presented. The electroluminescent properties of direct bandgap materials utilized for DJ cells give a possibility to employ the EL technique for identification of internal resistance components limiting cell output power.

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