Advances in Science and Technology Vol. 74 (2010) pp 211-218
© (2010) Trans Tech Publications, Switzerland
doi:10.4028/www.scientific.net/AST.74.211

CPV Modules Based On Lens Panels

V.D. Rumyantsev, Yu.V. Ashcheulov, N.Yu. Davidyuk, E.A. Ionova, P.V. Pokrovskiy, N.A. Sadchikov, V.M. Andreev

Ioffe Physical Technical Institute, 26 Polytechnicheskaya str., St.-Petersburg 194021, Russia

email: rumyan@scell.ioffe.rssi.ru

Keywords: III-V solar cell; Fresnel lens, Module design; Thermal regime; Cell characterization.

Abstract. A work on development of the high concentration photovoltaic (HCPV) modules with Fresnel lens panels and III-V multijunction cells is presented. A composite structure of the small-aperture area 40x40 (or 60x60) mm^2 Fresnel lenses, united in a panel, was realized. A silicate glass sheet (front side of a module) serves as a superstrate for transparent microprisms formed in silicone. Small averaged thickness of the prisms ensures low IR absorption of sunlight in comparison with acrylic Fresnel lenses. Temperature dependences of the optical properties in such a type of the solar concentrators and PV properties of the cells in passive heat dissipation conditions are under consideration.

The solar cells are the triple-junction InGaP/(In)GaAs/Ge cells with designated illumination area 1.7-2.3 mm in diameter.

A HCPV module consists of the 144 (or 64) sub-modules in 12x12 (or 8x8) configuration. Solar cells are protected from environment in different ways: by side walls of a module body, or by a rear glass sheet at integrated sealing the cells in a back-side module panel. Module design includes refractive smooth-surface secondary lenses. The cell strings are glued to the rear glass surface of the module body using lamination process. Proper quality of the solar cells in a multistage module assembling procedure is ensured owing to specially developed contactless test method, based on analyzing the electroluminescent signals at local photoexitation.

For arrangement of the HCPV modules in a solar installation, a number of the solar trackers have been developed and realized for 1-3-5 kWp of the installed power.

Introduction

HCPV modules with small aperture area glass-silicone Fresnel lenses and multijunction III-V solar cells are being developed at the Ioffe Physical Technical Institute over the last years [1-3]. For 40x40mm2 or 60x60mm2 Fresnel lenses and solar cells 1.7 or 2.3 mm in diameter mounted on passive copper heat spreaders, a high concentration and proper thermal regimes can be realized in a very simple design with low consumption of the materials involved in fabrication of all parts of the modules. Proper choice of the optical parameters of the Fresnel lenses and structural features of the heat spreaders was among the aims of the conducted work.

The use of the secondary optical elements decreases the accuracy requirements on assembly, alignment, and tracking technology for the high-concentration photovoltaic modules [4,5]. In the case of the secondary lenses, it is possible to increase significantly the sun concentration ratio, keeping constant the above parameters, what leads to the more effective use of the semiconductor materials. Disadvantage of the lens-type secondary elements is the inherent optical losses due to reflection from the air-glass interface. Positive feature of them is possibility to be arranged without a mechanical contact with the cell surface, so that the thermal expansion difference problem, as well as that of the long-term stability of the optical lens-cell contact, is totally eliminated. Another aim consisted in conceptual design and practical realization of the solar concentrator modules

demonstrating capabilities of work for a long time under various environmental conditions. Composite silicone-on-glass Fresnel lenses are characterized by excellent environmental stability, but for them there exists such an insufficiently explored feature as influence of thermal regimes on optical efficiency at solar energy concentration. Assembling the modules consisting of a great number of the lenses and cells required elaboration of a special technique for precision positioning of all the elements in a module, as well as all the modules in a power installation. Proper quality of the solar cells in a multistage module assembling procedure was ensured owing to specially developed contactless test method, based on analyzing the electroluminescent signals at local photoexitation. Final part of the work was devoted to development of the solar trackers for 1-3-5 kWp of the installed power.
An overview of the corresponding activity is contained in a present article.

Design of the solar concentrator modules

Fig. 1 shows design of the small-aperture area HCPV sub-modules under investigation.

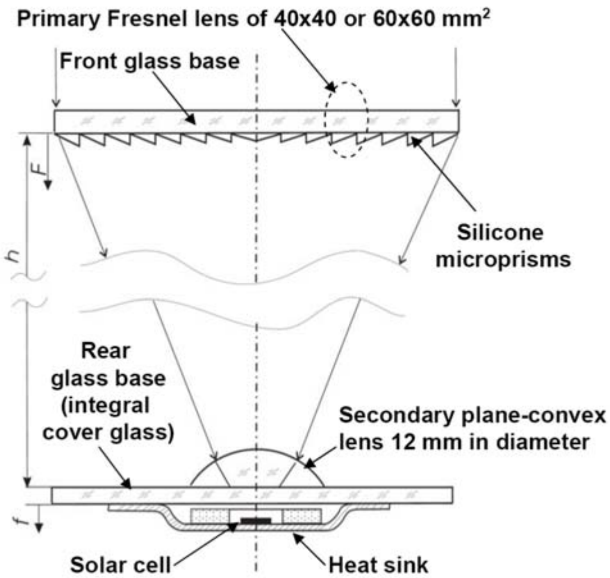


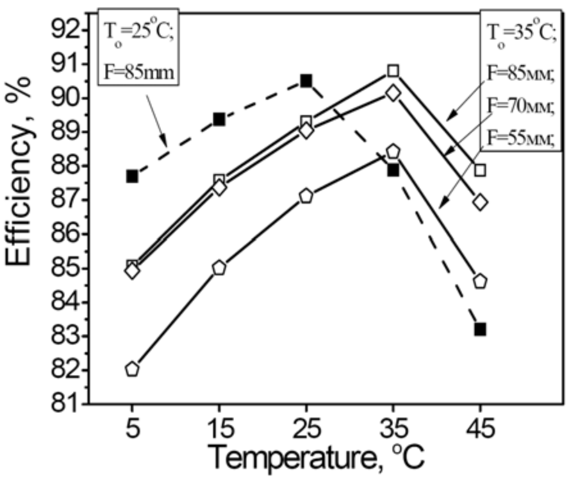
Figure 1. Optical scheme of an individual solar concentrator submodule. Shown are the planes from which the focal distances *F* and *f* are measured. A full-size module contains a panel of the primary lenses (144 lenses in arrangement of 12x12 for 40x40 mm lenses) and a panel of the cells with secondary optical elements.

The concentrator module is made in a form of a front lens panel connected with a rear energy-generating panel by aluminum walls. Each lens focuses solar radiation onto an underlying SC with a photosensitive surface area diameter of 1.7 or 2.3 mm. The heat-distributing plates are glued to the outer surface of the rear module plate, which is made of silicate glass. The heat is removed from the cells by spreading along the copper plates and glass base. The heat sink plates are protected from environment by a laminating film on the rear side of the module.
An ordinary convex lens as a secondary element can distinctly improve the misorientation curve of a module, having such an advantage that it may be placed without a direct contact with the cell surface. Also, the rear glass plate may serve as a common base for these lenses and at the same time as protective cover for all the cells in a module. It should be noted that in the case of illumination with increased local sun concentration ratio the cells must have certainly improved parameters

regarding to the low internal ohmic resistance and the high enough peak current in the built-in tunnel junctions. Fortunately, this is realized in commercially available triple-junction cells.
To reduce losses due to reflections, an antireflection coatings (ARC) may be applied, so that residual losses for two lens sides could be achieved at a level of 2÷3%. Contribution of an ARC deposition process to the cost of the lenses may be of the same "weight" as that of highly reflective coatings in the case of the reflective pyramids. Operation capabilities of cells at a very high local concentration were confirmed for practical structures of the high efficiency triple-junction cells. Indeed, the I-V curve fill factors *FF* were in the range of 85÷86% at local concentration ratios of about 5000x (see below).

Silicone-on-glass Fresnel lens panels

For the lenses made of PMMA material, temperature effects are considered only from the point of view of a geometrical stability and long-term operational capabilities. For the lenses of a composite structure with silicone microprisms, two temperature-dependent issues are of significant importance– strong temperature dependence of the silicone refraction index and appreciable difference in thermal expansion coefficients of the glass base plate and silicone microprisms [6]. The effect of the Fresnel lens temperature on its optical efficiency is presented in Fig. 2. Computation of the tilt angles of the refracting facets was carried out for the refraction index *n* chosen for two cases: To = 35˚C and To = 25˚C. It is seen from the curves for the focal distance of *F*=85 mm that the choice of the rated temperature for determining *n* affects significantly the efficiency at lens operational temperature. As a result, it may be recommended to polymerize silicone in the lenses at temperature close to that at which lenses will really operate.
Right part of the Fig. 2 presents a table of the results on overheating measurements, ΔT, for a cell in dependence on position and surface treatment of the heat-distributing copper plate. In outdoor conditions overheating of the cells in a concentrator module is expected to be around 20 C [6].



Heat-distributing copper plate dimensions are 30 x 30 x 0.5 mm	ΔT, °C
Uncovered copper surface: no flow over the module, the surface is at 45° to the horizon	26.5
Flow over the module at a wind velocity of 1–2 m/s	10
Surface is covered by temperature-controlling paint: no flow over the module, the surface is at 45° to the horizon	22
Flow over the module at a wind velocity of 1–2 m/s	12

Figure 2. On the left- calculated dependences of the optical efficiency on operation temperature for lenses with different focal distances *F*. Lens area is 40x40mm^2, SC diameter is 1.7 mm. On the right- overheating of a cell, ΔT, in dependence on position and surface treatment of the heat-distributing copper plate.

Use of the secondary plane-convex lenses

In the investigations of the modules with secondary lenses, the maximum efficiency value of the photovoltaic conversion measured indoors by a solar simulator was the optimization criterion. It is known that the cell efficiency may increase due to better light collection at better focusing. Also, it can decrease due to too high local light concentration and, hence, decrease in the fill factor *FF* of the I-V curve. The fact that local light concentration is actually high, around 4000÷5000x, was confirmed by the result of scanning the focal spot in a PV system with primary and secondary lenses [5]. It should be noted that “sharp” focusing was not the criterion of optical adjustment, but that of the highest *FF* of the I-V curve.
At misorientation the submodule axis, a light spot of a smaller diameter can remain for a longer time on a SC surface. In Fig. 3, the results on misorientation angle measurements are presented for a concentrator sub-module with a primary Fresnel lens of 40x40 mm^2, solar cell 2,3 mm in diameter and secondary lenses of different focal distances *f*. The data are in the relative units for better comparison of the curves. Widening the contours of the module misorientation characteristics almost in three times was observed in the case of the shortest-focus secondary lenses. The similar results have been obtained for the test multilens modules in measurements under outdoor conditions [5] (see, also, a picture of such a module on the right side of the Fig. 3).

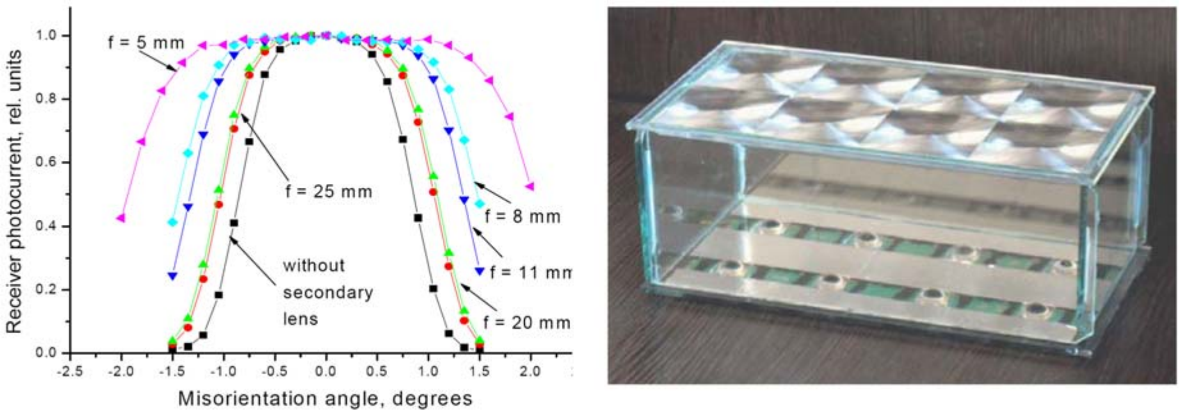


Figure 3. On the left- the results on misorientation angle measurements for a PV sub-module with a 40x40 mm^2 primary Fresnel lens, a solar cell 2.3 mm in diameter and secondary lenses of different focal distances *f*. On the right- a picture of the test module with secondary lenses.

Checking the cells for module assembly

Assembling the concentrator modules consisting of a great number of the lenses and cells required elaboration of a special technique for checking and precision positioning all the elements in a module. It is evident that such an assembling should be realized by a cluster-type units. One of such units is a panel of the integrated primary lenses, formation of which is carried out in a negatively profiled mould with exact intercenter distances of the individual lenses. The other units are the strings of the parallel connected cells with exact intercenter distances along a string. The third unit may be a panel of the secondary lenses. The cell strings are glued to its rear surface using a presicion template, or positioning robot. After lamination process, the rear cell panel is fixed with respect to the front lens panel by means of an aluminium frame, which plays at the same time a protective role against environment.
Final success of a multistage module assembling procedure depends on proper quality of the solar cells. Indeed, one cell with current leakage may cause a shortening the cell string as a whole. On the other hand, dispersion of the photogenerated voltages in the cells within a string leads to reduction

in PV conversion efficiency. It means that preliminary testing the solar cells before their mounting is a very important issue.
There exists a traditional method for the concentrator solar cell testing and clustering consisting in measurements of the I-V curves under flash illumination. It should be noted that quantity of the cells in one epitaxial wafer is in the range of 1000÷3000 pieces, whereas quantity of the cells in a module may be up to several hundreds. Therefore, the I-V measurement procedure with electrical contacting to each cell and following flash illumination is too slow and expensive. Alternative method of a contactless cell characterization has been developed at the PV Lab of the Ioffe Institute. It is based on the fact that the triple-junction InGaP/GaAs/Ge cells are characterized by intensive photo- and electroluminescence (PL and EL) arising in both top and middle sub-cells under a local photoexitation [7]. In general, it is possible to estimate, or even to evaluate, the main PV parameters of a direct bandgap PV cell with a p-n junction by the contactless methods (collection efficiency, open circuit voltage, sheet resistance and others), by analyzing only PL- and EL- signals from a cell wafer under photoexitation [8]. Scanning the wafer with separated cells by a green laser beam and analizing the intensity of the EL signal from each cell is an effective tool for sorting the cells by photogenerated voltage.
In Fig. 4, on the left, the cross-section of a triple-junction cell is shown, and the conditions of the photoexitation and EL generation are presented.
Commercially available InGaP/GaAs/Ge cells with designated illumination area of 2.3 mm in diameter and dense contact grid were employed for sorting. The top InGaP-based sub-cell was subjected to local photoexitation by a green laser (λ=532 nm). Laser photons are completely absorbed in the top sub-cell material generating electron-hole pairs. A part of these pairs is not collected by p-n junction due to recombination losses, but may produce photoluminescence after radiative recombination. A source of the PL photons is located just within the laser spot. The main part of the photogenerated carriers are collected by the p-n junction. In open circuit conditions, electrons and holes flow along the n- and p-regions of the InGaP sub-cell and recombine producing red electroluminescence, in the same way, as it is in a conventional LED under forward-bias conditions. Owing to isotropic nature of the spontaneous radiation, many of the EL photons generated in the top sub-cell are absorbed in the GaAs-based sub-cell. Infrared EL radiation arises due to current generation and its flow through the GaAs-based p-n junction under open circuit conditions in the middle sub-cell.
The magnitude of the EL signal is proportional to injection component of the photogenerated current flowing through the p-n junction. On the other hand, at room temperature a tenfold increase in injection current is accompanied by 59 mV increase in photogenerated voltage [8]. It means that sorting the cells by EL signals is a very sensitive method for revealing the cells with current leakages and reduced voltage. Top sub-cell in an InGaP/GaAs/Ge cell structure is the most prone to defect formation and damages during epitaxial growth and post-growth treatment. That is why it is possible to analyze only “red” EL-signal from a ready-made cell under a short-wavelength photoexitation for evaluation of its working capability. Wafer map with a black/white cell classification is presented in the right part of the Fig. 4. Each circle represents one solar cell. The brighter the area, the stronger is the EL signal from the top InGaP-based sub-cell (at photoexitation it is named as PEL-signal). Intensity of the green excitation was chosen in the interval corresponding to the photocurrent density around 0.5 A/cm^2 generated in the top sub-cell. This choice was associated with real operational conditions of the triple-junction solar cells under high concentration. Indeed, at the photocurrent density of 5÷10 A/cm^2, 5÷10% of the current in the maximum power point of the I-V curve (depending on the quality of a p-n junction and internal ohmic losses) are injected through the p-n junction producing luminescence. Just this amount of luminescent photons can affect the PV parameters of a cell.

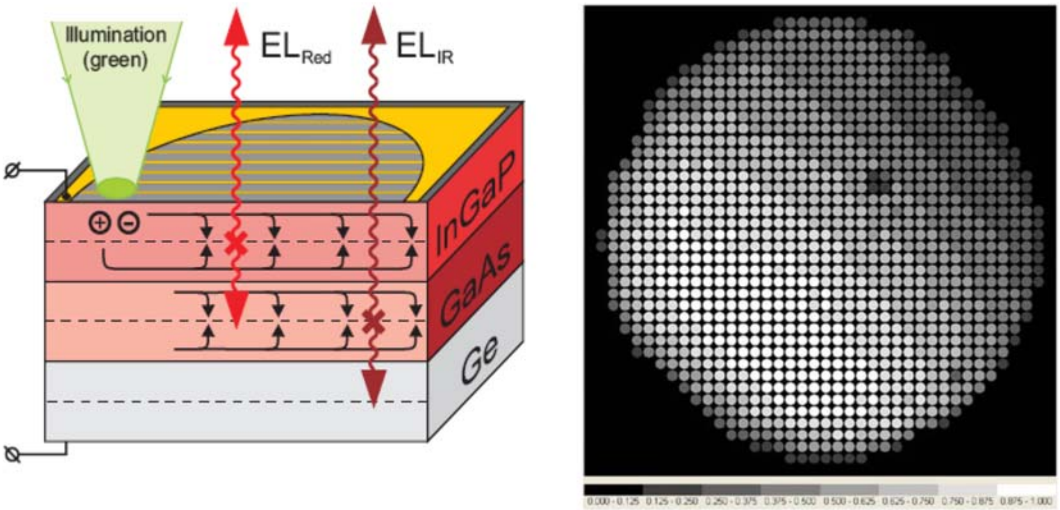


Figure 4. On the left- cross-section of a triple-junction cell and the conditions of the photoexitation and electroluminescent signals' generation. On the right- wafer map with a black/white cell classification. Each circle represents one solar cell. The brighter the area, the higher is the PEL-signal from the top InGaP-based sub-cell (gradation from black to white corresponds to EL intensities from 0 to 1 in arbitrary units).

In Fig. 5, a comparison of the I-V curves is carried out for the cells characterized by different PEL-intensities. In the left part of the Figure, this comparison is presented at photogenerated current equal to that at green photoexitation in recording the wafer map of Fig. 4. In the right part photocurrent corresponds to working conditions of the cells under solar concentration. Both I-V families were measured with the help of a flash solar simulator. One can see from the left part of the Fig. 5 that three-fold difference in PEL-intensity corresponds to about 30 mV difference in open circuit voltage, and this difference would characterize the maximum power points of these cells in operational conditions under concentrated solar illumination. What is more, this difference remains at the same level for open circuit voltage even at working photocurrent (see the curves in the right part of the Fig. 5).

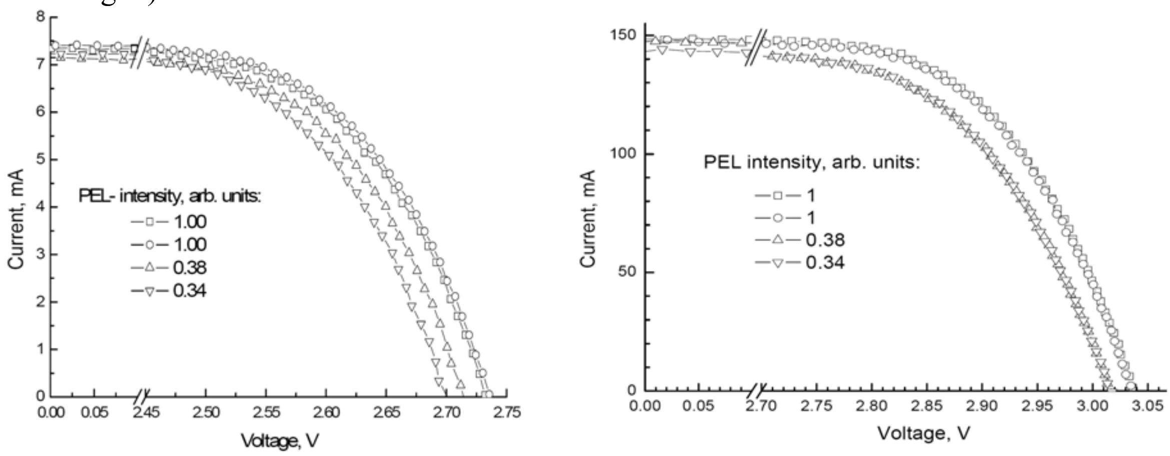


Figure 5. On the left- illuminated I-V curves of the InGaP/GaAs/Ge cells, PEL-intensities of which differ from 0.34 to 1.00 (in units presented in the right part of the Fig. 4). On the right- I-V curves for the same cells at photoexitation level corresponding to operation conditions of the concentrator solar cells. The curves were recorded with the help of a flash solar simulator.

PV installations with HCPV modules

High accuracy of module alignment to the sun is a specific feature of the concentrator installations. PV Lab of the Ioffe Institute has considerable experience in designing trackers for installed capacities of 1-3-5 kWp.

In Fig. 6, a stair-step principle of HCPV module arrangement on a solar tracker is shown. Advantage of such an arrangement is reduction of wind pressure on a frame with modules in different tracker positions during a day. Also, symmetry of two outermost positions of the frame (in directions to sunrise/sunset and to zenith) gives room to make this frame more rigid. The tracker is equipped with a digital circuit for programmable rotation in both daytime during cloudy periods and at night from sunset to sunrise position. Analog sun sensor is used for positioning the frame with modules in direction to the Sun with accuracy better than 0.1 degree of arc. In the right part of the Fig. 6, the I-V curve under illumination for one of the developed HCPV modules is shown, measured outdoors. Overall conversion efficiency of 24.3% is not temperature corrected value. If measured at standard cell temperature of 25 C, it would be 26.5%. Cell efficiency in the modules was on the level of 33%, so that one may expect strong increase in module efficiency if the cell efficiency approaches a level of 40%, the value characterizing today the best cells [9].

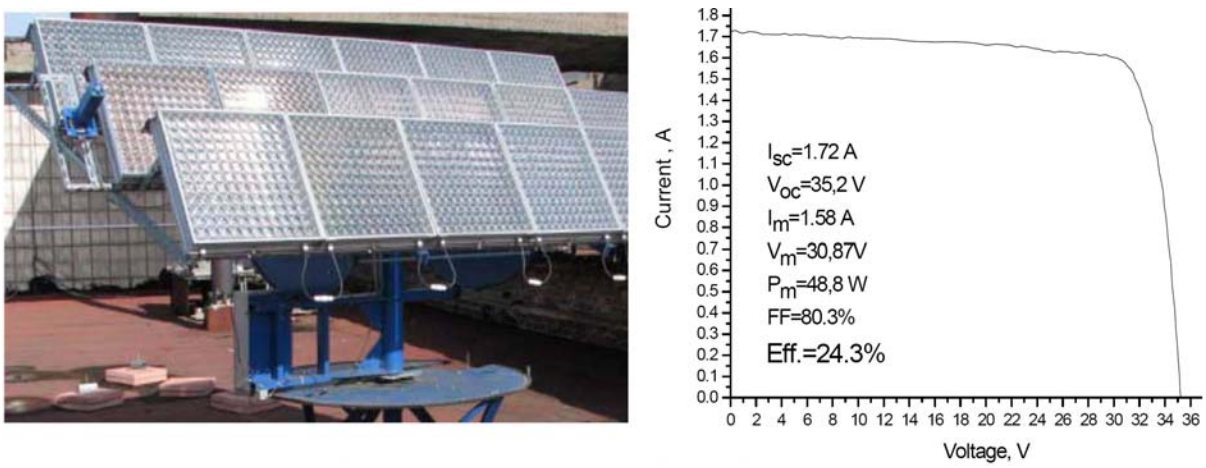


Figure 6. On the left- PV installation with concentrator modules for 1 kWp of output power on the roof of the Ioffe Institute. On the right- illuminated I-V curve for one of the full-size modules (50x50 cm^2) measured outdoors (Eff.=24.3%).

Summary

Research team of the Ioffe Physical Technical Institute (St.-Petersburg) has developed the basic components of the HCPV facilities: 3-junction cells, panels of the Fresnel lenses, concentrator modules; sun tracking systems and concentrator PV installations. Current stage of work assumes commercialization of the HCPV product in the near future. The Supervisory Council of the Russian Corporation of Nanotechnologies (RUSNANO) has signed a project aimed at production of nanoheterostructure solar cells with the efficiency reaching 37-45%. Solar modules and new generation power plants, equipped with Fresnel lenses and sun tracking system, will also be produced under the auspices of the project. It will commercialize the outcomes of research conducted at the Ioffe Institute in the field of fundamental scientific and technical principles and technological basis for constructing the main blocks of concentrator solar photovoltaic plants. It is expected that in 2015 the projected company's revenue will exceed 130 million Euros [10].

Acknowledgements

This work has been supported by the Russian Foundation for the Basic Research (Grant 09-08-00412-a and 09-08-12202).

References

[1] Zh. I. Alferov, V. M. Andreev, and V. D. Rumyantsev, “III-V heterostructures in photovoltaics” in: *Con centrator Photovoltaics,* edited by A. Luque, and V. Andreev, Springer Series in Optical Sciences, 130, 25-50 (2007).

[2] V. D. Rumyantsev, “Terrestrial concentrator PV systems,” in *Concentrator Photovoltaics*, edited by A. Luque, and V. Andreev, Springer Series in Optical Sciences, 130, 151-174 (2007).

[3] V.D.Rumyantsev “Solar concentrator modules with silicone-on-glass Fresnel lens panels and multijunction cells”, Optics Express, Vol. 18, Issue S1, pp. A17-A24, 2010

[4] V.D.Rumyantsev, O.I.Chosta, V.A.Grilikhes, N.A.Sadchikov, A.A.Soluyanov, M.Z.Shvarts, V.M.Andreev “Terrestrial and space concentrator PV modules with composite (glass-silicone) Fresnel lenses”, 29th IEEE PVSC, New Orleans, 2002, pp.1596-1599.

[5] V.D.Rumyantsev, N.Yu.Davidyuk, E.A.Ionova, D.A.Malevskiy, P.V.Pokrovskiy, N.A.Sadchikov HCPV Modules With Primary And Secondary Minilens Panels, M. Sturm Proc. of the 6th International Conference on Concentrating Photovoltaic Systems (6-11 April 2010, Freiburg, Germany).

[6] V.D.Rumyantsev, N.Yu.Davidyuk, E.A.Ionova, P.V.Pokrovskiy, N.A.Sadchikov, V.M.Andreev Thermal Regimes of Fresnel Lenses and Cells in ”All-Glass” HCPV Modules Proc. of the 6th International Conference on Concentrating Photovoltaic Systems (6-11 April 2010, Freiburg, Germany).

[7] V.D.Rumyantsev, N.I. Kozhuchov, D.A.Malevskiy, P.V.Pokrovskiy Transfer Of Power By Photons In HCPV Triple-Junction Cells Proc. of the 6th International Conference on Concentrating Photovoltaic Systems (6-11 April 2010, Freiburg, Germany).

[8] V. M. Andreev, V. A. Grilikhes, and V. D. Rumyantsev, *P hotovoltaic Conversion of Concentrated Sunlight*, John Wiley & Sons, Chichester, 1997, Chapter 4.

[9] Renewable energy world report, “Spectrolab Hits 41.6% PV Cell Efficiency record” (Renewable energy world, 2009). http://www.renewableenergyworld.com/rea/news/article/2009/08/spectrolab-sets-solar-cell-efficiency-record-at-41-6

[10] RUSNANO Press release, 30.04.2010, http://www.rusnano.com/Post.aspx/Show/26271 (in Russian).