3rd Nordic PV Conference
18-19 May 2009 Tallinn, Estonia

HIGH-CONCENTRATION APROACH TO DEVELOPMENT OF THE SOLAR PV INSTALLATIONS WITH III-V MULTIJUNCTION CELLS

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ABSTRACT

Research activity and results in the field of cost-effective terrestrial modules and installations realizing the concept of very high solar concentration by use of the composite glass-silicone Fresnel lenses and multijunction III-V cells are described. At the Ioffe Institute, main components for a high-concentration PV (HCPV) concept have been developed: panels of the small-aperture area Fresnel lenses; reflective and refractive secondary optical elements; triple-junction cell strings with passive heat spreaders; “tower”-type tracking mechanisms in the range of 1-3-5 kWp of installed power. For concentrator modules of size 0.5x0.5 m^2, overall conversion efficiency is in the range of 24÷26% at cell efficiency near to 33%. The concentrator modules are arranged on two-ax sun trackers with programmable/analog sun positioning mechanism. Experimental set-ups are equipped with electrical accumulators and invertors. Organizing the serial production of the high-efficient solar concentrator PV installations is in progress, being aimed to reduction in the installed “solar“ electric power cost down to 1.8 USD for 1 Wp.

INTRODUCTION

Pioneered works on the III-V materials and heterostructures conducted at the Ioffe Institute in connection with PV and CPV applications are generally recognized. Among them are AlGaAs/GaAs and InGaAs/InGaAsP/GaAs heterostructures for photoconverters and optoelectronic devices, as well as the various approaches to design of the concentrator modules and installations [1-3]. Basic components of the HCPV facilities are under development: 3-junction solar cells, panels of the small-aperture area Fresnel lenses; reflective and refractive secondary optical elements; cell strings with passive heat spreaders; sun tracking systems of different design for installed power in the range of 1-3-5 kWp. This report is devoted to recent results in this field.

A high concentration covers the concentration ratios above 100x and can reach several thousands. Sophisticated Si cells may be used in the range up to 250x, while III-V solar cells can be applied for much higher concentrations. HCPV is an alternative solution to the application of solar PV as a dependable energy resource. However, the solar cells are only one aspect to the peak Watt performance of a concentrator system. The module design should be kept deliberately simple to ensure low-cost manufacturing at high optical efficiency of the concentrators and effective heat sinking. Also, long-term operation abilities are of vital importance.

The advantages of the concentrator PV modules with small-aperture area sub-modules are the following:

- low ohmic losses in the small in area (sizing of 1-2 mm^2) solar cells;
- no necessity in compensation of the thermal expansion difference between materials of a cell and a heat sink;
- reduced (down to several cm) thickness of modules;
- reduced detrimental effect of chromatic aberrations (for the case of the refractive concentrators) on cell operation;

- low consumption of module housing and heat sink materials;
- possibility to apply for PV module manufacturing the high-productive mounting methods developed for production of electronic components.

In the case of the small-aperture area sub-modules, a very stable and cheap silicate glass may be used as a heat-dissipating material in stack with relatively thin heat-spreading metal (copper or steel). In spite of poor thermo-conductive properties of glass, waste heat can be dissipated to ambient air, as it is in regular flat-plate modules without concentrators. Superior insulating properties of glass allow connecting the cells in electric circuit of any configuration ensuring electrical safety of a module as a whole. Even walls of module housing may be made of glass justifying this approach as “all-glass” module design [4].

HCPV MODULE DESIGN

Ioffe’s research team is directed on a composite structure of the small-aperture area (40x40 mm^2) Fresnel lenses, where a silicate glass sheet (front side of a module) serves as a superstrate for transparent silicone with microprisms [5]. Advantages of this approach are based on a high UV stability of silicone, excellent resistance to thermal shocks and high/low temperatures, good adhesive properties in a stack with silicate glass. Small averaged thickness of the prisms ensures low IR absorption of sunlight in comparison with acrylic Fresnel lenses. A full-scale module consists of 144 sub-modules of Fig. 1 in 12x12 configuration.

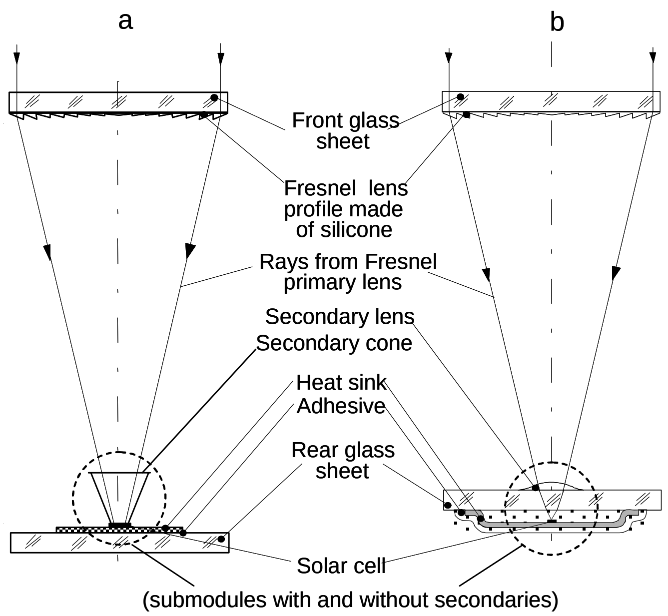

Fig. 1. Variants of optical diagrams of the HCPV sub-modules under development: a – with/without reflective Al- or glass-based kaleidoscopes as the secondaries; b – with/without refractive smooth-surface secondary lens.

In variant “a” of Fig.1, a solar cell is protected from environment by side walls of a module body. Three designs are under development: design without secondaries as the simplest one for module manufacturing; that with secondary reflective Al- or glass-based kaleidoscopes for advanced modules. In variant “b”, each solar cell is protected being hermetically sealed by metallic heat spreader and rear glass sheet of the module body [6]. Possible for use secondary element is a refractive smooth-surface lens.

Full-size HCPV modules are shown in photograph Fig.2. At current stage of work our full-size modules are made in accordance with optical diagram “a” of Fig.1 and contain no secondary elements. The triple-junction InGaP/(In)GaAs/Ge cells with designated illumination area of 1.7-2.3 mm in diameter are used. Cell circuit consists of 12 series connected strings, and in turn each string consists of 12 parallel connected cells with one protective diode.

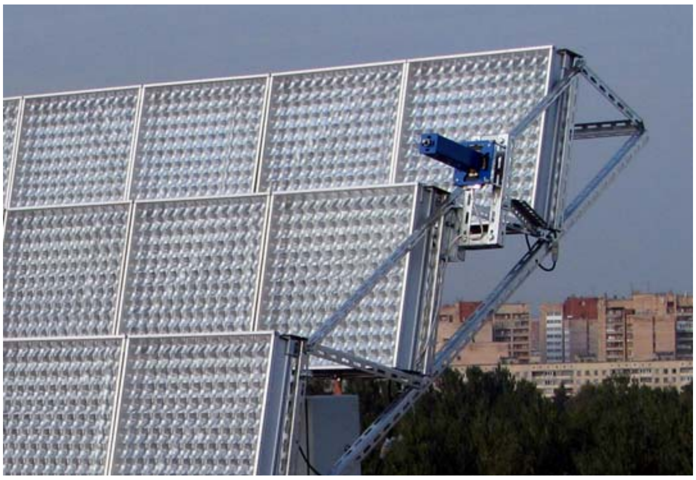

Fig. 2. Photograph of the full-size HCPV modules on a sun tracker (the roof of the Ioffe Institute).

INDOOR AND OUTDOOR MODULE EFFICIENCY MEASUREMENTS

It should be noted, that at PV Lab of the Ioffe Institute a complete set of the computerized characterization instruments have been developed which is necessary for HCPV research. Among them is spectral response machine for three-junction cells, as well as several modifications of the flash solar simulators to characterize indoors solar concentrators, cell chips, and assembled modules. In the case of the ready-made modules it is possible to use one and the same automatic measurement unit at both indoor (in-line, if at manufacturing) and outdoor I-V measurements. Applied voltage sweep is carried out during 1 millisecond, so that illuminated I-V curve is similarly obtained under flash and natural solar illumination. In Fig. 3, the I-V curve for one of the full-size modules is shown, measured outdoors at the Ioffe Institute. Also, “outdoor” (curve 2) and “indoor” (curve 3, measurement under flash illumination) I-V curves are shown for 8-lens test module to demonstrate overall module efficiency as high as 26.5% when standard cell temperature of 25C is ensured.

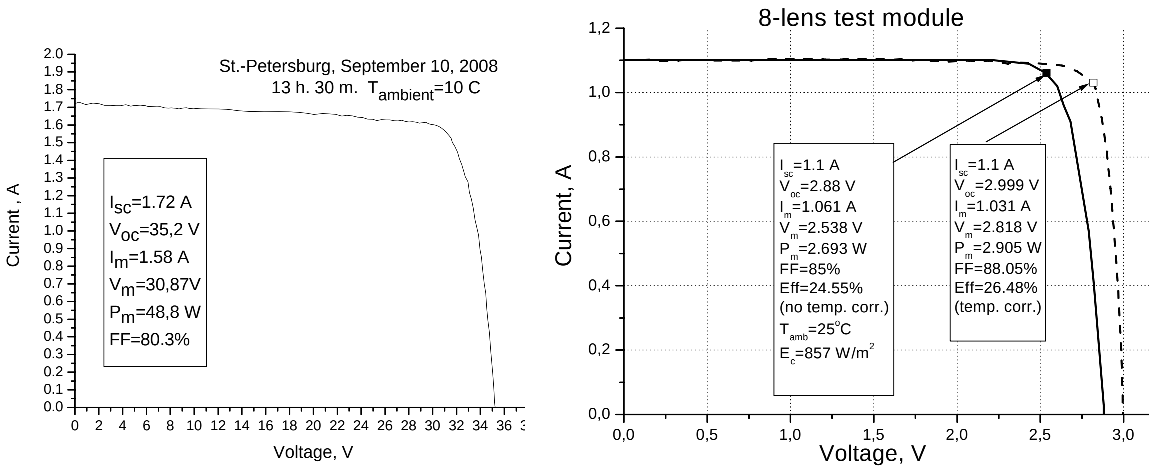

Fig. 3. On the left- illuminated I-V curve for one of the 144-lens module measured outdoors. No temperature corrected conversion efficiency was 24.3% at incident solar radiation density of 870 W/m^2. On the right- illuminated I-V curves measured on the 8-lens test module outdoors (ambient T=25C, solid line) and indoors by a flash solar tester (dashed line). Cell temperature is about 50C outdoors and 25C indoors.

SUN TRACKERS AND INSTALLATIONS

The concentrator modules are mounted on the sun trackers. Two types of trackers are under development – of "carrousel" design and of "tower" design (see photographs in Fig.4). A range of nominal output power of the solar installations is 1–3–5 kWp for "tower"-type trackers and 1.0 kWp for "carrousel" one. Each tracker is equipped with analog sun sensor for positioning the frame with modules in direction to the Sun with accuracy of about 0.1 degree of arc. Also, there exists a digital circuit for programmable rotation of the trackers from sunset to sunrise position and during cloudy periods.

The installation of Fig. 4, left side, contains 18 modules, which ensure appr. 1 kWp of output power. At present stage of work, the right-side installation of Fig. 4, being designed for 5 kWp (or slightly higher), is mainly equipped with flat silicon-based solar modules, and only in part with concentrator III-V modules. The modules are connected with a full-scale "controller-battery-inverter" system. Also, there is a computerized acquisition system, allowing for periodic measurements of the I-V curves in a representative set of the modules.

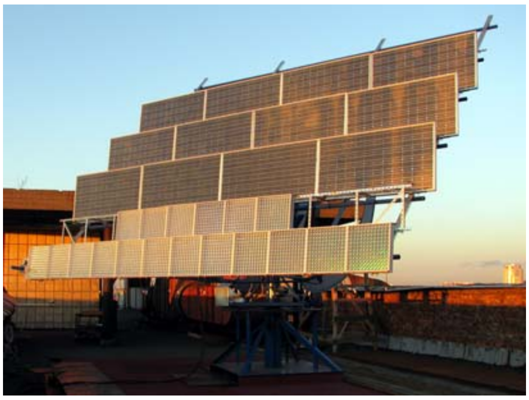

Fig. 4. On the left: PV installation with "carrousel"-type tracker and concentrator modules for 1 kWp of output power. On the right: PV installation with "tower"-type tracker, which will ensure appr. 5 kWp of output power (two lower rows – the concentrator modules; three upper rows – commercially available Si-based flat-plate modules).

SECONDARY OPTICAL ELEMENTS

Optical secondaries ensure certain increase in module acceptance angle, or increase in average concentration ratio. As it was mentioned above, reflective Al- or glass-based secondary kaleidoscopes, as well as refractive smooth-surface lenses are regarded for the use in advanced modules. In Fig. 5, the kaleidoscope-type secondaries are shown, as well as smooth-surface lenses. Typical input aperture dimensions are in the range of 10÷12 mm.

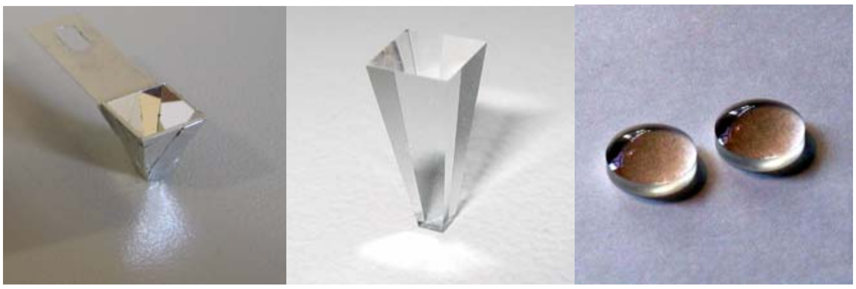

Fig. 5. Photographs of the kaleidoscope-type and lens secondaries (from left to right):
an element made of high-reflective aluminium foil; an element made of silicate glass; conventional glass lenses.

In Fig. 6, the dependences of the averaged sun concentration ratio on misorientation angle are shown for a concentrator sub-module of variant "a" and "b" (see Fig. 1) under flash illumination. Flash tester could simulate 1 sun intensity, AM 1,5d spectrum, and 32 minutes of arc divergence of the rays by aberrationless mirror-type optics. The curves have been recorded for the cases of without and with Al-, or glass-type kaleidoscopes, fitting every time an optimum "primary lens – cell" distance *D* for the maximum signal at normal sub-module position. There were two optimum distances for glass kaleidoscope – at *D*=74.5 and 78 mm. It should be noted, that output hole of both kaleidoscopes was 1.46x1.46 mm^2, and a shadowing screen with a square hole of corresponding dimensions was placed on the surface of the receiver cell. An ordinary convex lens as a secondary element can distinctly improve mentioned above module parameters having such an advantage that it may be placed without direct contact with cell surface.

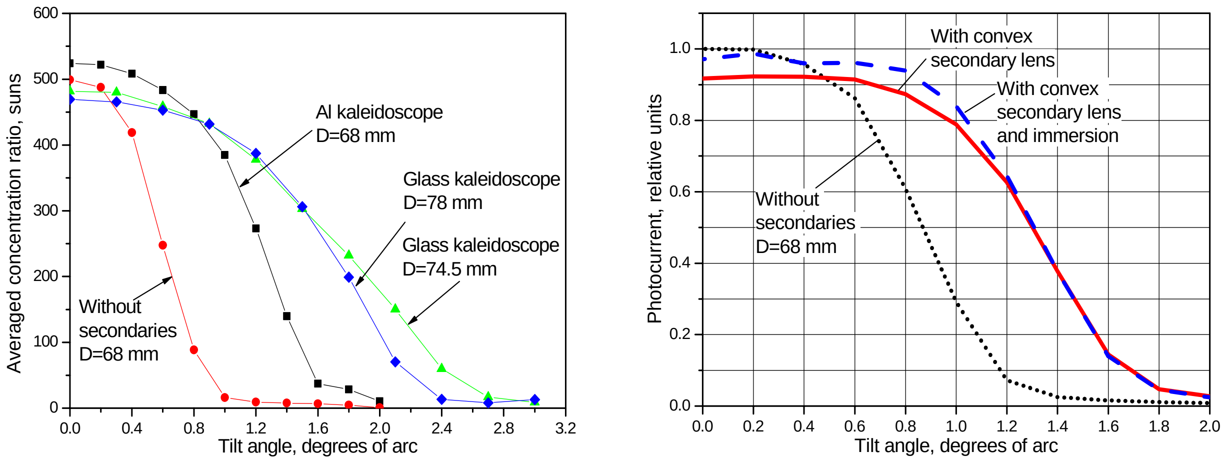

Fig. 6. Left graph: dependences of the averaged sun concentration ratio on misorientation angle for a concentrator sub-module of variant "a" without and with secondary kaleidoscopes. Right graph: the same for without and with secondary lens (the signal is in relative units).

ORGANIZING THE PRODUCTION OF SOLAR INSTALLATIONS WITH CONCENTRATORS

Original design and the fabrication methods of multi-junction heterostructures, SC chips, Fresnel lenses, secondary concentrators, photoreceiver plates, concentrator PV modules, sun trackers and PV systems are protected by 28 patents and applications for patents. Assumed technical parameters for industrial production are the following:

- Application of solar cells with the efficiency of up to 40% for concentrated sunlight conversion.
- Intermediate sunlight concentration up to 1000x by means of Fresnel lenses with optical efficiency as high as 90%, resulting in decrease of the solar cell area and its specific cost.
- Increasing the specific power output up to 300 W/m^2.
- Sun tracking by means of two-ax systems with an accuracy of ±0.1 angle degree continuously during a day
- Increasing the amount of electric power generated from the installation specific area in more than 2.5 times compared to the stationary silicon solar arrays.
- Predicted system lifetime is more than 25 years.

Production planning includes two stages:

- experimental stage with production of nanoheterostructures, solar cell chips, concentrator photovoltaic modules and installations for the total prescribed power of 10 MW/year;

- serial production of chips, modules and installations for the total power more than 140 MW/year.

Main cost parameter of the competition capability for serial production is 1.8 USD for 1W of the installed power, which will ensure the reduction in the “solar” electricity cost down to the level of the “grid parity” electric power cost.

Pool of expected investors: The Russian Corporation of Nanotechnologies RUSNANO (EUR 107m), Innolume, Onexim, potentially a strategic partner. The priority of RUSNANO is commercialization of nanotechnology projects with high business potential and/or social benefit. Its financial contribution in early-stage technology companies reduces risks of private investors. Corporation holds a minority share (under 50%) leaving the rest to founders and private capital in order to ensure that the project is realized with maximum efficiency.

CONCLUSION

Main R&D activity on HCPV with III-V-based solar cells is centered in the Ioffe Physico-Technical Institute (St.-Petersburg). Basic components of the HCPV facilities are under development: 3-junction cells, panels of the Fresnel lenses; reflective and refractive secondary optical elements; cell strings and modules; sun tracking systems and concentrator PV installations of different design for nominal power in the range of 1–3–5 kWp. Current stage of work assumes commercialization of the HCPV product in the near future.

ACKNOWLEDGEMENTS

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

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