# Solar concentrator modules with silicone-on-glass Fresnel lens panels and multijunction cells

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**Abstract:** High-efficiency multijunction (MJ) solar cells, being very expensive to manufacture, should only be used in combination with solar concentrators in terrestrial applications. An essential cost reduction of electric power produced by photovoltaic (PV) installations with MJ cells, may be expected by the creation of highly-effective, but inexpensive, elements for optical concentration and sun tracking. This article is an overview of the corresponding approach under development at the Ioffe Physical Technical Institute. The approach to R&D of the solar PV modules is based on the concepts of sunlight concentration by small-aperture area Fresnel lenses and "all-glass" module design. The small-aperture area lenses are arranged as a panel with silicone-on-glass structure where the glass plate serves as the front surface of a module. In turn, high-efficiency InGaP/(In)GaAs/Ge cells are arranged on a rear module panel mounted on a glass plate which functions as a heat sink and integrated protective cover for the cells. The developed PV modules and sun trackers are characterized by simple design, and are regarded as the prototypes for further commercialization.



**OCIS codes:** (350.6050) Solar energy; (220.1770) Concentrators; (220.2740) Geometric optical design; (220.4840) Testing; (350.4600) Optical engineering.

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## 1. Introduction

The Photovoltaic (PV) Lab of the Ioffe Institute, from its inception in the 70s – 80s, benefited from extensive experience of pioneering investigations in the field of III-V semiconductor compound based optoelectronic heterostructure devices. Among these devices were the first AlGaAs/GaAs heteroface solar cells for space applications and the first InGaP/InGaAsP/GaAs heterostructures for visible spectrum lasers. From the initial stage, all the efforts had been headed for development of the whole set of the base elements and technologies for terrestrial concentrating photovoltaics: solar cells (SCs), optical concentrators, cooling systems, sun trackers, and various types of equipment for characterization and control of the cell chips and assembled modules [1]. Trends in those developments allowed us to propose in the late 80s a concept of small-aperture area high-concentration PV (HCPV) modules. This concept allowed a radical decrease in the concentrator and cell dimensions with retention of a high sunlight concentration ratio [2]. Consecutive optimization of all the construction parts of a module while taking into account specific features of operation of the "lens-cell" pairs resulted in the creation by the late 90s of the so-named "all-glass" photovoltaic modules with silicone-on-glass Fresnel lens panels and multijunction (MJ) cells [3].

Today, three-junction cells based on InGaP/(In)GaAs/Ge nanoheterostructures achieve efficiencies as high as 41.6% under concentrated solar illumination, and have the prospect of reaching even higher efficiencies with more-than-three-junction cells [4–6]. Being very expensive in production, the MJ solar cells in terrestrial applications should be used in combination with solar concentrators made of cheap materials. An essential cost reduction of electric power produced by making use of MJ cells may be expected only at the developments of high-effective, but not expensive, elements for optical concentration and sun tracking. This article is an overview of the corresponding approaches being under development at the Ioffe Institute.

## 2. Advantages of the small-aperture area HCPV modules

High concentration covers concentration ratios from above 100x to several thousands. Sophisticated Si cells may be used up to 250x, while III-V cells can be applied for higher (up to several thousands) concentration. However, the solar cell is only one aspect of the peak Watt performance of a concentration PV system. The module design should be kept deliberately simple to ensure low-cost manufacturing, high optical efficiency, and effective heat sinking. Also, long-term operation capabilities are of vital importance.

In Fig. 1, on the left, a comparison of the "large"- and "small"-aperture area HCPV module design is carried out. Incident solar power is characterized by low density being no more than 1000 Watts per square meter. Nevertheless, a black plate, exposed to the sun rays, appreciably overheats in comparison with ambient temperature, giving an estimation of temperature rise of a SC without any concentration. It is evident that a concentration ratio of, say 1000x requires an effective distribution of heat from the SC along a surface area equal to the area of the concentrator for adequate heat dissipation. In the case of smaller-in-size concentrators, effective heat distribution is realized with thinner heat sinking materials. Focal distance of such concentrators is shorter. Therefore, consumption of structural materials for heat spreading elements and for module walls is much lower. Regarding to cell mounting, at smaller cell dimensions there is no necessity in compensation of the thermal expansion difference between materials of a cell and a heat sink.

In Fig. 1, on the right, operation of a "larger"- and a "smaller"-in-area SC of the same structure is analyzed assuming highly concentrated solar illumination at the same concentration level. It is important that the structural features of a SC, with layers in nanometer and few micrometer range and very thin contact grid, cannot be "adjusted" to various conditions of spatial light distribution. For "larger" cells, say, 1x1 $cm^2$, at concentration ratio of 1000x, absolute photocurrent is very high, being near to 12-15 A.

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Spatial distribution of the focused light is non-uniform as a whole and differs for different spectral bands, because any Fresnel lens is subject to chromatic aberrations, if no special secondary optics is applied. All the cascades of a MJ cells are connected in series. Current equalization conditions require the lateral photocurrent flowing through the thin layers in the structure. Negative influence of this type of non-uniform illumination cannot be compensated by use of more dense contact grid because lateral currents arise between sub-cells inside the cell structure. Smaller-in-area cells are preferable due to having lower ohmic losses at lower absolute currents flowing along shorter lateral paths.

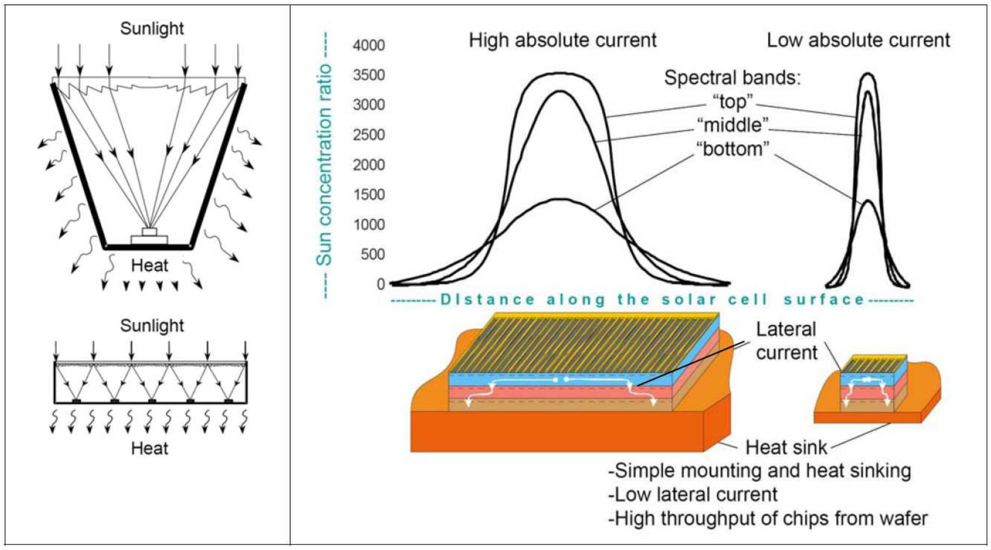


Fig. 1. On the left- comparison of the "large"- and "small"-aperture area approaches to HCPV module design. On the right- operation of "larger"- and "smaller"-in-area MJ SCs of the same structure under highly concentrated solar illumination of the same concentration ratio.

## 3. Silicone-on-glass Fresnel lens panels

The problem to be solved is the long-term stability of the sunlight concentrators. Ioffe's research team is directed to a composite structure of the Fresnel lenses, where a silicate glass sheet (front side of a module) is used as a superstrate for transparent silicone with Fresnel microprisms (see Fig. 2, on the left). In turn, the microprisms themselves are formed by polymerization of the silicone compound directly on the glass sheet with the use of a negatively profiled mould. 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 lower absorption of sunlight in comparison with acrylic Fresnel lenses of a "regular" thickness (see Fig. 2, on the right). Polymerization of silicone does not require high-temperature and high-pressure conditions. Corresponding approach was at first published in the work [7], and many years later, secondly, was introduced into practice with respect to panels of small-aperture area Fresnel lenses [8].

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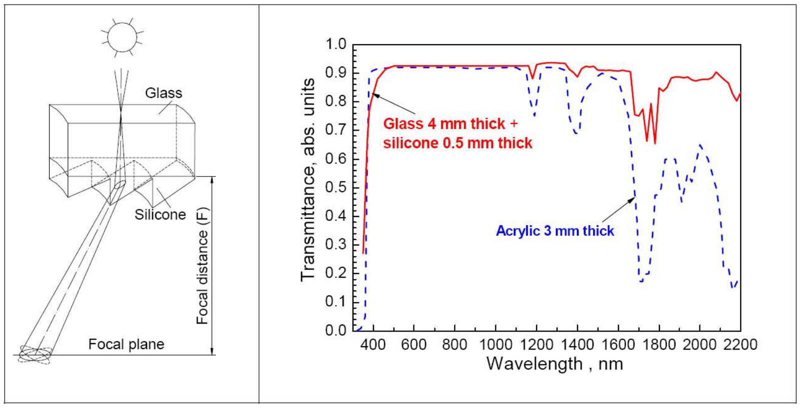


Fig. 2. On the left- a fragment of the "silicone-on-glass" composite Fresnel lens (front glass thickness is 4 mm, averaged thickness of the silicone microprisms is about 0.2 mm, focal distance is 70 mm). On the right- optical transmittance of a sample with "silicone-on-glass" structure, simulating a composite Fresnel lens, in comparison with that of a conventional acrylic Fresnel lens.

It is seen from the transmittance curve of the lens composite structure that the specific IR absorption in silicone need not be taken into account regarding the operation of the bottom Ge-based sub-cell in a triple-junction cell. Advantage of silicone-on –glass lenses is mainly directed on perspective more-than-three-junction cells, where splitting of solar spectrum should be more accurate with respect to equalization of the photogenerated currents in all the subcells. Indeed, any absorption of light by lens material in spectral region possible for PV conversion by materials of the subcells (including Ge) leads to considerable loss in final PV conversion efficiency. Fresnel lens profiles were optimized taking into account refraction index of silicone and its dependence on wavelength and temperature, focal distance (70 mm for 40x40 $mm^2$ lenses), receiver diameter (1.7 mm for above mentioned lenses), sun illumination spectrum, sensitivity spectra of the sub-cells in a triple-junction cell, and other technological aspects.

## 4. "All-glass" module design

"All-glass" module design implies an approach, in which main parts of a HCPV module are made from glass. Concentrator lens panels, having front surface of glass plates, are characterized by long-term stability and resistance to dirty and abrasive influences. Also, a very stable and cheap silicate glass is used as a base for rear panel of the SCs. The rear glass plate is in a stack with relatively thin heat sinking metallic plates made of copper or steel. In spite of low thermal conductivity of glass, in the case of the small-aperture area sub-modules waste heat can be dissipated to ambient air through bulk glass, just as in regular flat-plate modules without concentrators. Superior insulating properties of glass allow connecting the cells in electric circuits of any configuration ensuring electrical safety of a module as a whole.

In Fig. 3, optical diagrams of the concentrator sub-modules are shown, corresponding to the "all-glass" module design.

Module version "a" in Fig. 3 ensures the highest optical efficiency of the PV system owing to minimum reflection losses. This design implies hermetical sealing of the module housing, or special protection of the individual cell from environment. Heat dissipation is carried out through the bulk of a rear glass sheet. In the versions "b" and "c", the cells are mounted on the trough-like heat spreaders placed behind rear glass sheet. In this case, a rear glass sheet serves as a protective cover glass for all the cells in a module. A module housing itself may have the channels for external/internal air pressure equalization and escape of water condensation. In version "b", the rear glass sheet is a substrate for a panel of secondary lenses. The latter configuration is beneficial for further increase of the concentration ratio in a PV

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system, or for widening the off-track performance of a HCPV module (a situation, when module surface is not at right angle position with respect to the solar radiation).

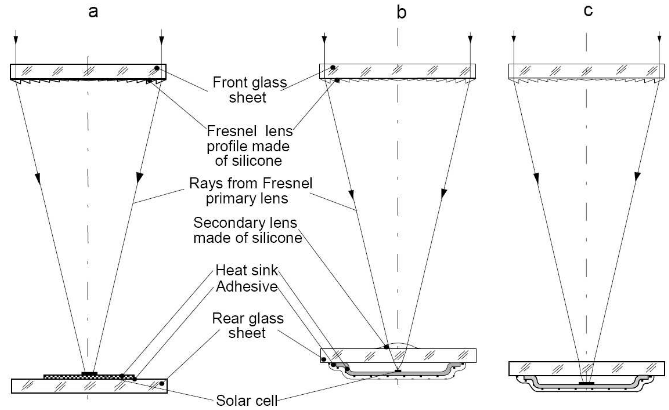


Fig. 3. Optical diagrams of the concentrator sub-modules corresponding to “all-glass” module design.

## 5. HCPV installations and module efficiency measurements

High accuracy of tracking to the sun is a specific feature of the HCPV installations. Technical and economical aspects concerned with system alignment are critical to determining the success of the HCPV concept. PV Lab of the Ioffe Institute has considerable experience in designing trackers for installed capacities of 1-3-5 kWp.

In Fig. 4, 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. Each tracker is equipped with a digital circuit for programmable rotation in the 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. External view of one of the developed HCPV installations is shown in photograph of Fig. 5.

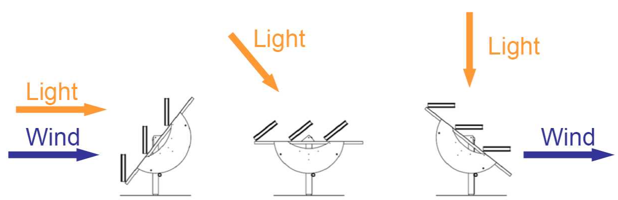


Fig. 4. Stair-step arrangement of the HCPV modules on a solar tracker and interaction of the module frame with light and wind fluxes during a day.

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Fig. 5. PV installation with concentrator modules for 1 kWp of output power on the roof of the Ioffe Institute.

In Fig. 6, the I-V curves under illumination for the developed HCPV modules are shown, measured outdoors, and, also, indoors by means of a solar simulator with collimated light flux. Overall conversion efficiency of test modules of the described design was 26.5% if measured at standard cell temperature of 25 C. Cell efficiency in the modules was on the level of 33%, so that one may expect large increase in module efficiency if the cell efficiency approaches a level of 40%. It should be noted, that, at assembling the concentrator modules – test ones with reduced number of the lenses, or full-size ones – they were supplied by triple-junction cells, fabricated in different technological processes. Some of the cells in these processes were characterized by higher photocurrent, and, also, by slighly reduced other PV parameters (for instance, fill factor). In the Fig. 6, the best results on overall PV conversion efficiency in the modules are shown, obtained during last period at the PV Lab of the Ioffe Institute.

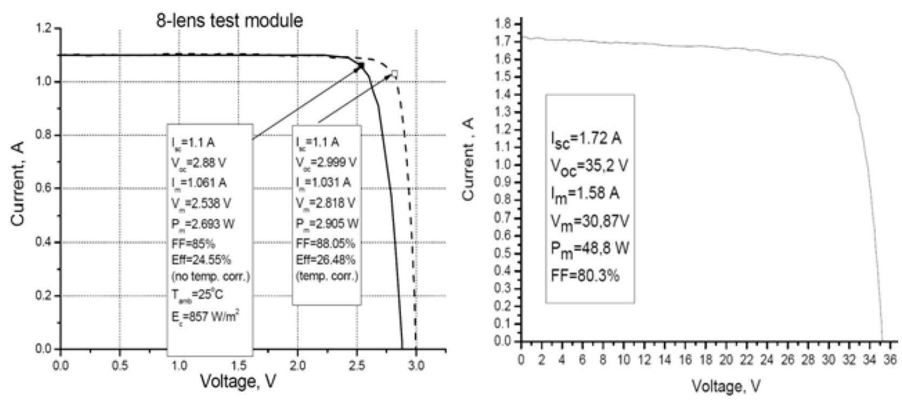


Fig. 6. On the left- I-V curves measured on an 8-lens test module outdoors (solid line, Eff. = 24.5%) and indoors by a flash solar tester (dashed line, Eff. = 26.48%). Cell temperature was about 50C outdoors and 25C indoors. On the right- illuminated I-V curve for one of the full-size modules measured outdoors (Eff. = 24.3%).

## 6. Characterization equipment for HCPV approach

It should be noted that Ioffe's team has developed a full set of the computerized characterization instruments necessary for HCPV research and control. Among them are the

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spectral response machine, several modifications of the flash solar simulators to characterize indoors solar concentrators, cell chips, and assembled modules [9,10]. In the case of the ready-made modules it is possible to use the same automatic measurement unit at both indoor and outdoor I-V measurements. Solar testers based on flash lamps, light collimating systems and voltage sweep measuring units can be built-in in a production line for final inspection of the ready-made HCPV modules as relates to rated conversion efficiency.

It should be noted that in addition to a traditional approach on PV characterization (to illuminate and to measure photocurrent or I-V curve), there exists a "luminescent" approach, assuming generic similarity of the photo-voltaic and electro-luminescent devices (LEDs), based on semiconductor materials of a "direct" band structure. HCPV cells for small-aperture area modules have actually the same dimensions as LED chips– around 1-2 mm. Absolute levels of operational currents and amounts of dissipated heat are in the same ranges, implying similarities in mounting procedure and package design. Lighting technique is a field where application of semiconductor LEDs may become dominant, or extremely wide, in the nearest future. Of interest is to test LED packaging in the operation conditions of the concentrator PV modules to find suitable materials for reliable packaging of the latter (see photograph in Fig. 7, housing with LEDs). Such experiment may be regarded as a complementary event with respect to a widely used electroluminescent quality control of the MJ cells under forward bias conditions (see Fig. 7, PV module with triple-junction cells). More deep features may be revealed at the conditions when principle of energy reversibility is realized. In particular, it is possible to estimate, or even to evaluate, the main PV parameters of a direct bandgap PV cell with p-n junction by contactless methods (spectral curve, open circuit voltage, sheet resistance and others), by analyzing only photo- and electroluminescent signals from cell wafer under photoexcitation [11]. One of such methods allows us to qualify cell chips without contacting (see layout in Fig. 7, on the right). Being fixed on a common holder after wafer treatment, each chip is exposed for a short time under narrow light strip formed from a laser beam. Wavelength of photoexitation is adjsted to be absorbed in a top sub-cell of a MJ SC (it is InGaP-based sub-cell in the case of the InGaP/(In)GaAs/Ge triple-junction cell). Photocurrent, generated within the illuminated strip, is spread along the plane of the InGaP sub-cell, and, because of absence of an external load, injected in p-n junction, giving rise to electroluminescence (EL). High intensity of EL is a cumulative factor indicating both high value of external quantum efficiency at photocurrent generation and high value of voltage applied to p-n junction in open circuit conditions. With a high probability, good quality of the top sub-cell is an indicator of perfection of the beneath situated layers and p-n junctions in the MJ structure. Therefore, qualitative control of the cells may be organized in a high-productive way.

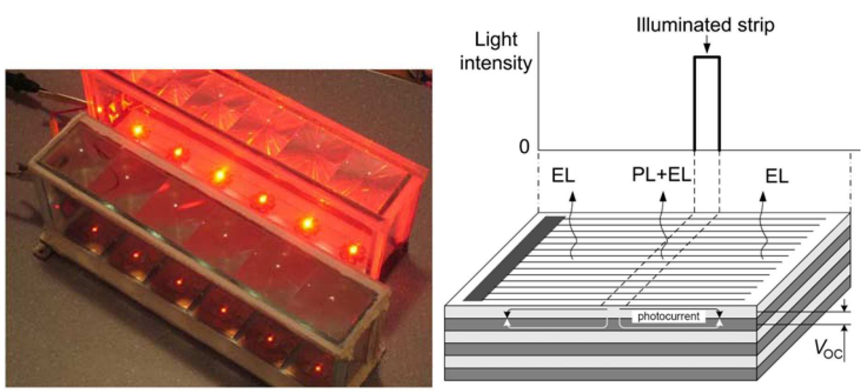


Fig. 7. On the left- concentrator PV module with triple-junction solar cells (in front) and similar housing with mounted red LEDs (behind), both emitting electroluminescence under forward bias conditions. On the right- layout of the cell qualitative control method with spatial separation of the photoluminescent (PL) and electroluminescent (EL) signals arising in turn at local photoexitation by green light (λ = 532 nm).

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## 7. Conclusions

In Russia, main R&D activity on solar HCPV with III-V-based solar cells is centered in the Ioffe Physical Technical Institute (St.-Petersburg). Basic components of the HCPV facilities are under development: 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) approved the 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 in 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 [12].

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