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Combined radial Fresnel lens: controlling the distribution of solar irradiance and the profile of the generated photocurrent in a multi-junction solar cell

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A solution is proposed for a Fresnel lens with a variable pitch and focus, designed for use in ground-based concentrator modules with a high degree of solar radiation concentration. Compared to a Fresnel lens with a constant pitch and focus, this approach provided a reduction in the spatial and spectral inhomogeneities of the local concentration of solar radiation in a focal spot on the surface of an InGaP/GaAs/Ge multijunction solar cell (MJSC). This made it possible to form a distribution profile of the local photocurrent density with reduced peak values at the center of the SC and a minimum difference in the values of the local photocurrent density for three photosensitive $p-n$ junctions over the entire surface of the MJSC.

Keywords: concentrator photovoltaic modules, Fresnel lens, multijunction solar cells.

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Fresnel lenses (FLs) are the most common type of solar energy concentrators in concentrator photovoltaic modules (CPVMs). The development of silicon-on-glass (SoG) technology, which is used to fabricate FLs and provided an opportunity to construct a low-cost and commercially scalable type of optical solar energy concentrators with a high optoenergetic efficiency, was an important milestone in the advancement of concentrator photovoltaic energy systems [1–3]. This helped raise the efficiency of CPVMs based on an InGaP/GaAs/Ge multi-junction solar cell (MJSC) and an FL [3–5]. The record-high efficiency for MJSCs is 47.6% [4], and the record value for CPVMs with FLs is 38.9% [5].

When an MJSC is paired with a Fresnel lens forming a non-uniform irradiance distribution, the efficiency of this MJSC and a concentrator module is limited primarily, first, by resistive losses, which increase considerably as the local solar radiation concentration ratio grows, reaching 2500−3000 at the focal spot center, and, second, by the spectral and spatial inhomogeneity (attributable to chromatic aberration) of distribution of the solar radiation energy within the FL focal spot [6–10]. This spectral and spatial inhomogeneity of solar radiation translates into non-uniformity of the profile of distribution of the local photocurrent density over the entire MJSC surface, mismatching of photocurrents of individual $p-n$-junctions, and, consequently, reduction of the total photocurrent and efficiency of MJSCs and CPVMs [6–13]. Lateral currents emerging under this heterogeneous conditions offset partially the non-uniformity of the local photocurrent density profile [7–9], but the mechanism of resistive losses also applies to lateral currents at high irradiance levels [12].

The use of secondary optics elements is a possible solution to the problem [14], although this leads to an increase in the design complexity of CPVMs and their cost.

It is evident that new ways to redistribute concentrated solar energy over the MJSC surface without secondary optics are needed. This may be achieved by optimizing the FL profile. Various approaches to this problem have been proposed in [15–19]: a combination of different slope angles of microprisms [15,16,19], the use of curved refracting surfaces, and the use of composite FLs with two refraction profiles fabricated from materials with different refraction indices [17,18]. These solutions helped reduce the solar energy concentration ratio and the photocurrent density at the focal spot center.

Dependences of photovoltaic parameters of the MJSC with three InGaP/GaAs/Ge $p-n$-junctions and a photosensitive surface 3×3 mm in size on the concentration ratio varying within the 10−3300 range were measured in order to estimate the influence of high solar radiation concentration ratios and resistive losses on these parameters. The spectral photosensitivity of this MJSC was used in calculation of the photocurrent density distribution profile of a classical FL in [7–9] and the present study. A pulsed solar radiation simulator with the AM1.5D spectrum, which formed a uniform irradiance distribution on the MJSC surface, was used in measurements. Lateral currents were zero under uniform irradiance in the conditions of this experiment. The measurement data revealed that the MJSC efficiency reaches its maximum (above 42%) at concentration ratios of 380−890. The efficiency drops to 40% and 36% as the concentration ratio increases to 1500 and 3300 (see the table).

Dependence of photovoltaic parameters of the InGaP/GaAs/Ge MJSC on the solar energy concentration ratio

C, X	I_{sc}, mA	U_{oc}, V	I_{opt}, mA	U_{opt}, V	P, mW	FF, %	Eff, %
11.8	17.3	2.76	16.8	2.46	41.4	86.6	38.13
111.9	163.4	2.98	158.6	2.66	421.1	86.4	41.07
384.1	560.9	3.09	542.2	2.75	1490.1	86.1	42.35
659.0	962.1	3.13	935.8	2.73	2552.6	84.8	42.29
885.92	1293.5	3.15	1241.2	2.74	3409.5	83.7	42.01
1636.69	2389.6	3.18	2282.1	2.65	6064.5	79.7	40.45
2547.7	3719.8	3.20	3512.7	2.55	8954.4	75.2	38.37
3301.1	4819.7	3.20	4439.9	2.45	10888.8	70.6	36.01

Note. C — concentration ratio with respect to a power of 1000 W/cm^2, I_{sc} — short-circuit current, U_{oc} — open-circuit voltage, I_{opt} — current at the optimum load point, U_{opt} — voltage at the optimum load point, P — power, FF — current–voltage curve fill factor, and Eff — efficiency.

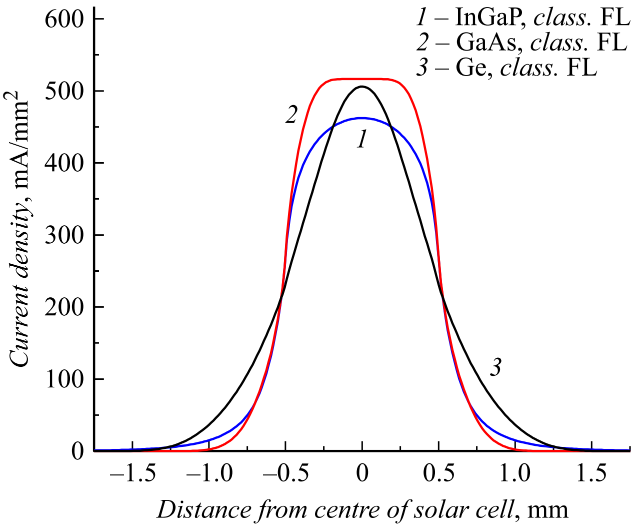

Figure 1. Distributions of the photocurrent density for three $p-n$-junctions (from the MJSC center to the edge) for a classical FL.

The MJSC efficiency reduction at radiation concentration ratios above 1000 is attributable to an increase in resistive losses at high photocurrent densities. In order to raise the efficiency of an MJSC paired with an FL, one needs to reduce the level of solar energy concentration at the focal spot center and make the distributions of solar energy and photocurrent density over the MJSC surface more uniform.

The results of engineering development of an SoG FL with an aperture of 60×60 mm and a „classical" refracting faces profile have been reported in [7–9]: a constant pitch of 0.25 mm, a design focal distance of 105 mm, and an MJSC photosensitive surface area of 3×3 mm. The output data are the profiles of photocurrent density distribution over the MJSC surface (Fig. 1). The focal spot diameter with a collecting efficiency of 90% is 1.91 mm.

It can be seen from Fig. 1 that the local photocurrent density profile is substantially non-uniform in three subranges over the entire MJSC surface if a classical FL is used.

In the present study, a „combined" FL with an aperture of 60×60 mm was designed in order to reduce the peak photocurrent values and make the profile of photocurrent density distribution over the entire MJSC surface more uniform: the lateral size of a refracting microprism in the central FL region was increased. An allowance for an insignificant (within 5–10%) enlargement of the focal spot was set as a criterion for choosing the new profile parameters. Distribution profiles of solar radiation and photocurrent density for the combined FL were calculated for each microprism. The size of the focal spot formed by each microprism and the minimization of differences between local photocurrent density values over the entire MJSC surface were set as the primary criteria shaping the parameters of the combined FL. The basic algorithm of passage of optic rays through refracting FL surfaces and the principle of formation of a photocurrent density distribution profile on the MJSC surface from [6–8] were used in shaping the combined FL profile.

The Fresnel profile was shaped in the direction from the center to the FL edge. The lateral size of an individual microprism was increased until the diameter of a spot formed by it became equal to the spot diameter for a classical FL with the same collecting efficiency (90%). The focal distance for each microprism was also varied within ± 1 mm from the design distance of 105 mm. The resulting profile of the combined FL with the lateral size of microprisms being equal to 1.8 mm in the central region and decreasing to 0.5 mm in the periphery was obtained.

Figure 2 shows the profile of distribution of the photocurrent density over the MJSC surface formed by the combined FL.

The spot diameter for the combined lens was 2.39 mm (a collecting efficiency of 90%), which provides an allowance in positional displacement of the solar spot along the solar cell surface (an MJSC power reduction by no more than 10% of the maximum power) sufficient for an MJSC 3×3 mm in size (with a geometric concentration ratio of 400).

Figure 3 presents the comparison between local photocurrent densities of three subelements over the entire MJSC surface for classical and combined FLs.

It is evident that the combined FL provides a substantially higher spectral and spatial uniformity of the

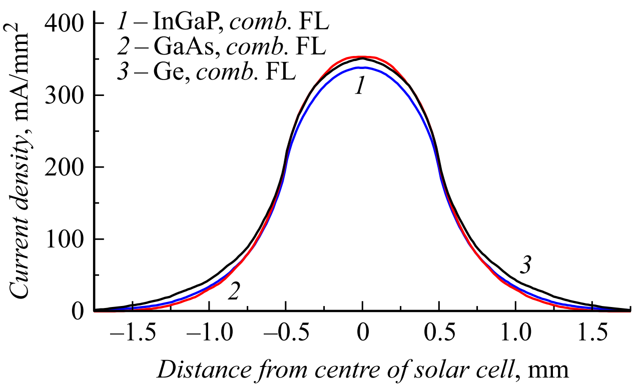

Figure 2. Distributions of the photocurrent density for three $p-n$-junctions (from the center of the solar cell to its edge) for the combined FL.

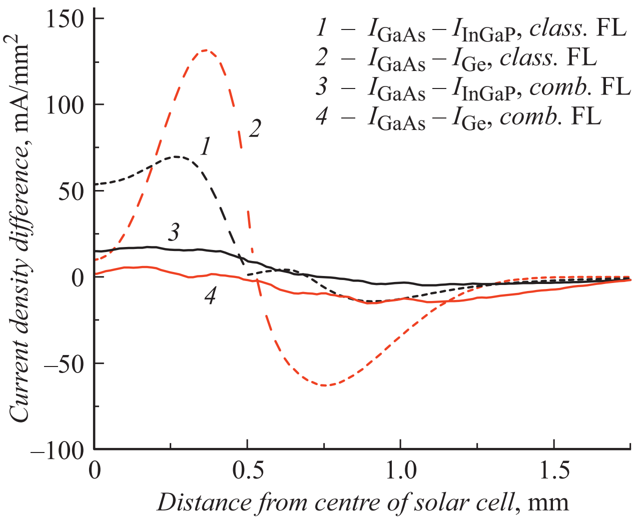

Figure 3. Differences between local photocurrent density values $I_{GaAs}-I_{InGaP}$ and $I_{GaAs}-I_{Ge}$ for three $p-n$-junctions of the MJSC for classical and combined FLs.

photocurrent density over the entire MJSC surface for three $p-n$-junctions (Fig. 2). The maximum photocurrent densities are 515 mA/mm^2 (Fig. 1) and 353 mA/mm^2 (GaAs $p-n$-junction) (Fig. 2) for classical and combined FLs, respectively. The maximum difference between the absolute photocurrent densities of GaAs and Ge subelements for a classical FL is 131 mA/mm^2 at a distance of 0.4 mm from the MJSC center, while the maximum difference between the photocurrent densities of GaAs and InGaP subelements for the combined FL is 16 mA/mm^2 at a distance of 0.2 mm from the MJSC center (Fig. 3). The difference between the photocurrent densities of all subelements is several times lower for the entire focal spot of the combined FL (this effect is especially pronounced in the central region where the bulk of solar energy is localized).

A further suppression of peak values and inhomogeneity of concentrated solar radiation and the photocurrent density may be achieved with the use of a more complex algorithm of variation of parameters of refracting surfaces of the combined FL (specifically, with the use of aspherical refracting surfaces).

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Conflict of interest

The authors declare that they have no conflict of interest.

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