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Prospects of hybrid bifacial four-junction solar cell for concentrating photovoltaics

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Abstract. A hybrid monolithic four-junction solar cell composed of GaInP/Ga(In)As/Ge electricity-generating linear arrays arranged in an n-α-Si:H/(p)c-Si:(Ga)/p-a-Si:H bifacial photoactive heat-dissipating substrate was investigated as part of a concentrator photovoltaic module. The module provides a specific power output ≤ 500 W/m^2 (AM0, 1367 W/m^2) at the beginning of life, taking into account the converted the Earth albedo. The damage coefficient of effective diffusion length for minority charge carriers in the photoactive heat-dissipating substrate has been determined as $K_L = 1\cdot10^{-11}$ at 1 MeV electron fluence up to $1\cdot10^{15}$cm^{-2}. The anticipated lifespan of the monolithic hybrid four-junction solar cell in the module on geostationary orbit is projected to be ≤ 15 years. Accounting for the albedo effects, it does not only increase the generated electrical power but also reduces thermal stress on the spacecraft's solar panel.

Keywords: hybrid four-junction solar cell, concentrator photovoltaic module, albedo of the Earth, GaInP/Ga(In)As/Ge electricity-generating linear arrays, bifacial photoactive heat dissipating substrate, damage coefficient, geostationary orbit

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Перспективы двухстороннего четырехпереходного гибридного солнечного элемента для концентраторной фотовольтаики

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Аннотация. Монолитный гибридный четырехпереходный солнечный элемент на основе GaInP/Ga(In)As/Ge электрогенерирующих линеек и n-α-Si:H/(p)c-Si:(Ga)/p-α-Si:H двухстороннего фотоактивного теплоотводящего основания был исследован в составе концентраторного фотоэлектрического модуля. Концентраторный фотоэлектрический модуль для солнечных батарей нового поколения способен обеспечить в начале срока службы удельную мощность ≤ 500 Вт/м^2 (AM0, 1367 Вт/м^2) с учётом альбедо Земли. Определён «эффективный» коэффициент деградации диффузионной длины неосновных носителей заряда фотоактивного теплоотводящего основания $K_L = 1\cdot10^{-11}$. Ожидаемый срок службы гибридного четырехпереходного солнечного элемента в составе модуля составит ≤ 15 лет на геостационарной орбите. Учёт альбедо Земли позволяет не только увеличить вырабатываемую электрическую мощность, но и снизить тепловую нагрузку на солнечную батарею космического аппарата.

Ключевые слова: гибридный четырехпереходный солнечный элемент, концентраторный фотоэлектрический модуль, альбедо Земли, GaInP/Ga(In)As/Ge электрогенерирующие линейки, двухстороннее фотоактивное теплоотводящее основание, коэффициент деградации, геостационарная орбита

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Introduction

The presented research aims to enhance concentrated photovoltaic module (CPVM) based on three-junction GaInP/GaAs/Ge solar cells (SCs). An increase in specific electrical power in radiation-exposed environments could be achieved by employing a hybrid (concentrator-planar) four-junction (4-J) SC with bifacial photosensitivity. The development of a bifacial hybrid 4-J SC involves monolithic bonding a GaInP/Ga(In)As/Ge SC with a silicon heterojunction (SHJ) *n*-α-Si:H/(*p*)*c*-Si:(Ga)/*p*-α-Si:H SC, serving as a photoactive heat-dissipating substrate (PHDS), utilizing vacuum soldering techniques. It was motivated by two key factors: firstly, the exceptionally high conversion efficiencies achieved by SHJ SCs with gallium-doped *p*-type substrates, reaching over 26% under standard terrestrial sunlight conditions (1000 W/m², AM1.5) [1]; secondly, addressing the challenge posed by radiation-induced performance degradation of SHJ SCs, where efficiency loss remains below 30% (at a fluence of 1 MeV electrons of $1 \cdot 10^{15}$ cm^{-2}) under space environmental conditions (1367 W/m^2, AM0) [2]. Enhanced specific electrical power in bifacial hybrid 4-J SCs is achieved not only through improvements in the efficiency of GaInP/Ga(In)As/Ge SCs, but also by converting reflected scattered solar radiation into usable energy by the SHJ PHDS, including contributions from Earth's albedo [3, 4]. It should be noted that such hybrid systems maintain functionality even under conditions of misalignment relative to the Sun greater than ±2° [4].

To determine the operational lifetime of CPVM on geostationary Earth orbit (GEO), the degradation extent of a 4-J hybrid SC resulting from radiation exposure was assessed by evaluating the damage coefficient of minority carrier diffusion length. In 4-J hybrid SC, radiation hardness will be constrained by the silicon subcell due to lower absorption coefficient and electron/hole mobilities compared to III-V semiconductor materials. A fluence of 1 MeV electrons equivalent to $1 \cdot 10^{15}$ cm^{-2} corresponds to nonionizing radiation effects accumulated in GEO environment over a period of 15 years [5].

Materials and Methods

Investigations were carried out on a CPVM (Fig. 1), representing an elementary cell upon which the solar panel is built. The photovoltaic component of the CPVM is mounted onto a carbon fiber supporting frame. It ensures reduction of specific weight characteristics of the solar panel down to 2 kg/m^2. Moreover, it successfully passes all necessary ground tests simulating mechanical stresses encountered in outer space, such as thermal cycling, vibration, and shock impacts. On the front side of the assembly, a paired linear Fresnel lens concentrator (LC) with a focal distance of 32 mm, an optical area of 50 mm × 100 mm, and an efficiency of 90% is located. On the backside, a bifacial 4-J hybrid SC (Fig. 2, *a*) is positioned. Ohmic contacts for the 4-J SC were established by installing two electricity-generating linear arrays (EGLAs) with a size of 54 mm × 104 mm × 0.15 mm on the bifacial *n*-α-Si:H/(*p*)c-Si:(Ga)/*p*-a-Si:H

SHJ PHDS. These components were assembled using a specialized vacuum-brazing technique performed on the R200C (Savtech, Russia) machine [6]. Each EGLA consists of 18 thinned GaInP/Ga(In)As/Ge SCs with dimensions 5.6 mm × 6.4 mm, with thickness reduced to 80 μm. Additionally, the CPVM design includes an optical reflector system (indicated by 4 and 6 in Fig. 1, *a*) aimed at further improving the device performance.

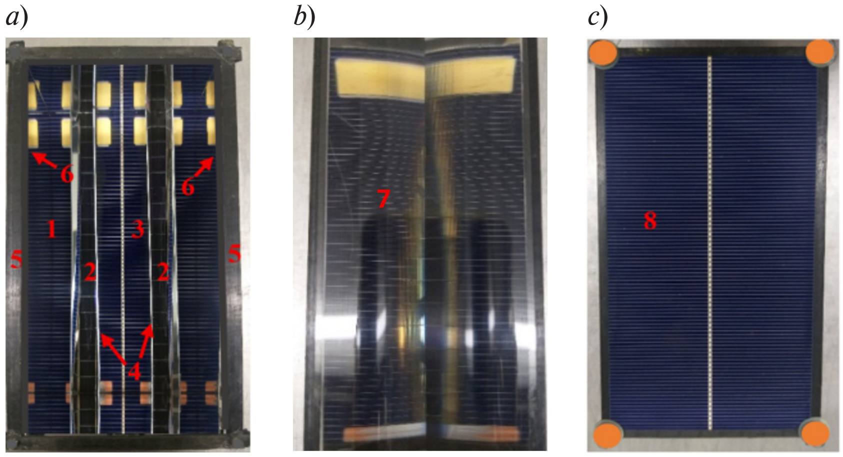

Fig. 1. Photographs of the CPVM with a bifacial 4-J hybrid SC: front side without LC (*a*), front side with LC (*b*), and rear side (*c*); (1) corresponds to bifacial 4-J hybrid SC, (2) to GaInP/Ga(In)As/Ge EGLA, (3) to SHJ PHDS, (4) to side reflectors, (5) to carbon fiber composite support frame, (6) to reflectors on frame walls, (7) to paired linear Fresnel LC, (8) to rear side of the hybrid SC in CPVM

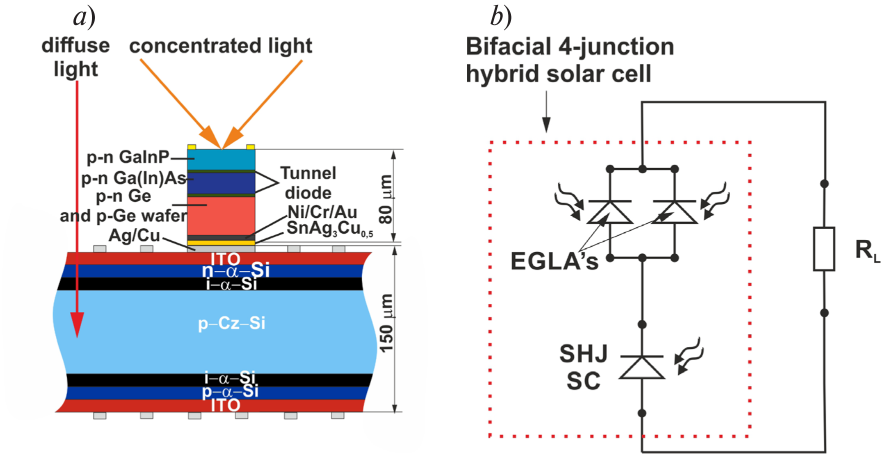

Fig. 2. Schematic representation of the bifacial 4-J hybrid SC structure (*a*) and schematic electric connection diagram of GaInP/Ga(In)As/Ge EGLAs with SHJ PHDS in CPVM (*b*), where R_L denotes the load resistance

To evaluate radiation hardness, *n*-α-Si:H/(*p*)c-Si:(Ga)/*p*-a-Si:H SHJ SCs with an area of 1 cm^2, and a resistivity ranging between (1.5–4.0) Ω·cm, were manufactured. Samples were irradiated by 1 MeV electrons with fluences ranging from $2.5 \cdot 10^{14}$ to $1 \cdot 10^{15}$ cm^{-2}. Details regarding the irradiation conditions are provided in Ref. [2]. Before and after electron irradiation, both dark and light current-voltage characteristics (*I–V* curves) were measured. Dark *I–V* curves of the SHJ SCs were acquired at room temperature using a high-precision source-measurement unit. Light *I–V* curves of the SHJ SCs with an active optical area of 0.9 cm^2, as well as those of the CPVM and individual circuit elements (Fig. 2, *b*), were recorded under collimated simulated solar illumination (AM0, 1367 W/m^2) at room temperature.

Results and Discussion

Figure 3 shows light *I–V* curves for the studied CPVM under normal incidence of collimated light beam (AM0, 1367 W/m^2), illustrating the interconnection layout (Fig. 2, *b*) optimized for photocurrent matching between EGLAs and the SHJ PHDS to maximize power output, considering the albedo effect. Further refinement of the CPVM design is needed for more precise alignment. Two parallel-connected EGLAs provide open-circuit voltage values of 2.84 V and generate a specific electrical power of 396 W/m^2 at an efficiency of 29% (Fig. 3, curves 1,1'). Meanwhile, the SHJ PHDS converts diffuse radiation, due to albedo, thus generating additional electrical power (Fig. 3, curves 3,3'). Thus, the bifacial 4-J hybrid SC integrated into the CPVM and matched in terms of photocurrent delivers a specific power output of 489 W/m^2 at an efficiency of 29.3% and an open-circuit voltage of 3.5 V (Fig. 3, curves 2,2'). The power increase of the CPVM equipped with bifacial 4-J hybrid SC amounts to 19% at the beginning of life without adding complexity, weight, and cost to the overall concentrator module structure. Accounting for the influence of albedo not only enhances the generated electrical power but also alleviates thermal loading on the satellite's solar panel.

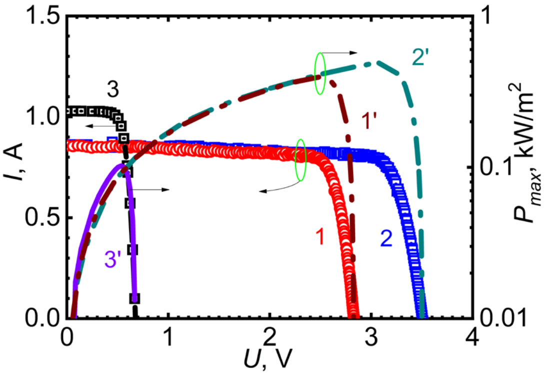

Fig. 3. Light I–V (curves 1–3) and calculated $P_{\max}$-V (curves 1′–3′) characteristics measured under simulated solar illumination (AM0, 1367 W/m^2) with LC efficiency of ~90%: 1, 1′ correspond to only parallel-connected GaInP/Ga(In)As/Ge EGLA; 2, 2′ to bifacial 4-J hybrid SC with parallel-connected EGLA with SHJ PHDS connected in series, accounting for albedo; 3, 3′ to SHJ Si PHDS with albedo

The evaluation of the CPVM's operational lifetime on GEO is based on determining its radiation hardness when exposed to 1 MeV electrons with fluences up to 1·10^{15} cm^{-2}. Since the limiting component of the CPVM structure is the SHJ PHDS, the analysis of radiation hardness focuses on this element. Given the substantial decrease in the external quantum efficiency into long-wave region [2], we assume that the crystalline silicon substrate degrades predominantly. Under electron fluences up to 1·10^{15} cm^{-2}, where processes related to the removal of majority charge carriers play a secondary role [7], the principal indicator of degradation is the reduction in minority carrier diffusion length due to defect introduction (recombination centers). This reduction is characterized by the damage coefficient of diffusion length, which is defined by Equation (1):

$$\frac{1}{L_{eff}^{\,2}} - \frac{1}{L_0^{\,2}} = K_L \phi, \tag{1}$$

where L_0 and L_{eff} are the the effective diffusion lengths of minority charge carriers before and after irradiation, Φ is the fluence of 1 MeV electrons, K_L is the damage coefficient of the diffusion length of minority charge carriers. Since the SHJ PHDS represents a p–i–n heterostructure consisting of amorphous/crystalline silicon, the pre-irradiation "effective" diffusion length for the PHDS was assumed to be approximately 1100 μm in calculations [8]. As demonstrated in Ref. [9], the damage coefficient K_L is correlated with saturation currents through Eqs. (2) and (3):

$$J_{0r\phi} = J_{0r0}(K_L L_0^{\,2}\phi + 1)\sqrt{\frac{p_0}{p_0 - R_c\phi}}, \tag{2}$$

$$J_{0d\phi} = J_{0d0}\sqrt{K_L L_0^{\,2}\phi + 1}\,\frac{p_0}{p_0 - R_c\phi}, \tag{3}$$

where J_{0r0}, $J_{0r\Phi}$ and J_{0d0}, $J_{0d\Phi}$ are the saturation currents for the recombination and diffusion mechanisms of dark current flow before and after irradiation, respectively, p_0 is the dopant concentration, R_c is the removal rate of the majority charge carriers from crystalline silicon doped with Ga, equal to 0.04 cm^{-1} [10]. Saturation currents corresponding to conduction mechanisms are derived from fitting experimental data of the forward branches of dark I–V curves, according to equation (4) [11]:

$$j_t = J_{0t}\left[\exp\left(\frac{U - jR_s}{A_t\varepsilon}\right) - 1\right] + J_{0r}\left[\exp\left(\frac{U - jR_s}{A_r\varepsilon}\right) - 1\right] + J_{0d}\left[\exp\left(\frac{U - jR_s}{A_d\varepsilon}\right) - 1\right], \qquad (4)$$

where J_{0t} (with $A_t > 2$), J_{0r} ($A_r = 2$), J_{0d} ($A_d = 1$) – the saturation currents for tunnel-trap, recombination, and diffusion current mechanisms, respectively, A_i is the diode ideality factors; U is the bias voltage; R_s is the series resistance of the cell structure, $\varepsilon = kT/q$ is the characteristic potential, k is the Boltzmann's constant, q is the electron charge, and T is the temperature.

By substituting the calculated saturation currents values (Table 1) into equations (2) and (3), the damage coefficient for the SHJ PHDS was determined as $K_L = 1\cdot10^{-11}$. For comparison, the coefficients K_L have been reported as follows: $6\cdot10^{-11}$ for boron-doped Back Surface Field (BSF) SCs and $4\cdot10^{-11}$ for gallium-doped BSF SCs [10, 12]. As for emerging Passivated Emitter Rear Cell (PERC) SCs, the value of K_L is estimated at $5\cdot10^{-11}$ [13].

Table 1

Parameters of the dark *I*–*V* curve fitting for SHJ solar cells using Equation (4)

Fluence, cm^{-2}	A_t	J_{0t}, A/cm^2	J_{0r}, A/cm^2	J_{0d}, A/cm^2	R_s, Ω·cm^2
0	3.17	$2.86\cdot10^{-6}$	$1\cdot10^{-9}$	$4.4\cdot10^{-14}$	2.71
$2.5\cdot10^{14}$	3.2	$3.86\cdot10^{-6}$	$3\cdot10^{-8}$	$1\cdot10^{-12}$	2.14
$5\cdot10^{14}$	3.79	$6.88\cdot10^{-6}$	$5.92\cdot10^{-8}$	$2\cdot10^{-12}$	2.61
$1\cdot10^{15}$	4	$9.09\cdot10^{-6}$	$1.19\cdot10^{-7}$	$2.47\cdot10^{-12}$	2.67

Conclusion

The possibility of using a bifacial hybrid four-junction solar cell in concentrated photovoltaic module has been explored. A hybrid four-junction solar cell composed of GaInP/Ga(In)As/Ge electricity-generating linear arrays and a photoactive heat-dissipating substrate made of *n*-α-Si:H/(*p*)c-Si:(Ga)/*p*-α-Si:H, incorporating Earth's albedo into the concentrated photovoltaic module, demonstrates the capability to deliver electrical power up to 500 W/m^2 with an efficiency of 29.3%. The operational lifetime of a concentrated photovoltaic module integrated into solar panels on geostationary Earth orbit is restricted by the radiation hardness of the silicon photoactive heat-dissipating substrate, characterized by a damage coefficient of minority carrier diffusion length, $K_L = 1\cdot10^{-11}$. This value is smaller than that found in state-of-the-art silicon solar cells used in space applications, such as Back Surface Field solar cells, as well as promising Passivated Emitter Rear Cell solar cells. We estimate that the service life of a solar panel based on concentrated photovoltaic module with a bifacial hybrid four-junction solar cell on geostationary Earth orbit may reach up to 15 years.

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