05.6;07.2

Investigation of radiation resistance of heterostructure silicon solar cells

© V.S. Kalinovskii[1], E.I. Terukov[1,2], K.K. Prudchenko[1], A.A. Bazeley[2], E.V. Kontrosh[1], I.A. Tolkachev[1], A.A. Titov[2]

[1] Ioffe Institute, St. Petersburg, Russia
[2] R&D Center of Thin Film Technologies in Energetics under the Ioffe Institute LLC, St. Petersburg, Russia
E-mail: prudchenkokk@mail.ioffe.ru

Received March 31, 2023
Revised June 7, 2023
Accepted June 8, 2023

The radiation resistance of different types of heterostructural silicon solar cells under irradiation with 1 MeV electrons in the fluence range $2.5\cdot10^{14}-1\cdot10^{15}\,\mathrm{cm}^{-2}$ has been studied. Studies have shown that the smallest degradation of the „saturation" currents of the diffusion current flow mechanism from $J_{0d}\leqslant 5\cdot10^{-13}\,\mathrm{A/cm}^2$ to $J_{0d}\leqslant 3\cdot10^{-12}\,\mathrm{A/cm}^2$ and efficiency from 19.2 to 13.6% (AM0, $1367\,\mathrm{W/m}^2$) were n-α-Si:H/c-p(Ga)/p-α-Si:H and n-μc-Si:H/c-p(Ga)/p-α-Si:H. The results obtained make it possible to evaluate the prospects for the use of heterostructure silicon solar cells for low-orbit spacecraft.

Keywords: heterostructure silicon solar cells, saturation currents, efficiency, radiation resistance, 1 MeV electrons, low orbit satellite communication.

DOI: 10.61011/TPL.2023.08.56689.19573

A reliable high-speed broadband Internet connection may be established at any point within the country (in particular, at those sites where reliable communications are currently lacking) through the use of global low-orbit satellite communication (LOSC). LOSC spacecraft are fitted with solar cells that provide the needed electric power. The development of silicon solar cells (SCs) for space applications has ceased in the 1990s, and all the attention was shifted to A_3B_5 SCs. However, owing to their ready availability, relatively low cost, and sufficient performance capabilities, silicon SCs are gradually becoming competitive again (especially in the LOSC market). The efficiency of crystalline silicon solar cells was estimated theoretically at $\leqslant 26\%$ (AM0) [1]. Silicon SCs with a heterojunction (heterojunction technology solar cells, HJT SCs) have a considerable efficiency potential. Efficiencies in excess of 26% (AM1.5, $1000\,\mathrm{W/m}^2$) [2–4] have been reported for the best HJT SCs. The use of low temperatures for growth of passivating amorphous silicon layers translates into higher open-circuit voltages (up to 750 mV) and lower temperature coefficients ($< 0.3\%/^\circ$C) in HJT SCs, which are regarded as a major advantage over PERC (passivated emitter rear cell) and IBC (interdigitated back contact cells) silicon SCs [5–7].

Radiation defects (atomic displacements induced by irradiation) are the primary cause of degradation of space SCs. They exert a negative influence on photovoltaic parameters (short-circuit current I_{sc}, open-circuit voltage U_{oc}, and fill factor FF), electric power output $P_{\max}$, and the efficiency and useful lifetime of SCs in orbit. The issues of radiation resistance of HJT SCs remain understudied. The radiation resistance of n-type HJT SCs has been evaluated in [1,8]. The key to enhancing this resistance is the use of p-type silicon, since it offers a lower damage coefficient [9]. In order to find the most efficient and radiation-resistant structure, we have evaluated the resistance of six different types of HJT SCs to irradiation with electrons with an energy of 1 MeV within the $2.5\cdot10^{14}-1\cdot10^{15}\,\mathrm{cm}^{-2}$ fluence range, which is equivalent to the conditions in near-Earth orbits [10].

HJT SC samples (Fig. 1) were fabricated on Czochralski-grown n- or p-type crystalline silicon (c-Si) substrates with a thickness of $\sim 125\,\mu$m doped with phosphorus, gallium, or boron with a carrier density $\leqslant 10^{16}\,\mathrm{cm}^{-3}$. Layers of undoped amorphous silicon (i-α-Si:H) with a thickness up to 10 nm, n-α (or n-μc) and p-α- layers with a thickness of 10–20 nm, and 100-nm-thick indium tin oxide (ITO) layers were deposited on both sides of substrates. A p–n-junction was formed on the front side for p-type c-Si and on the rear side („rear emitter" configuration) [5] for n-type c-Si. Silver contact buses $40\,\mu$m in width were deposited with a pitch of 1.2 mm by screen printing. The studied HJT SC structures had different dopants added to c-Si and

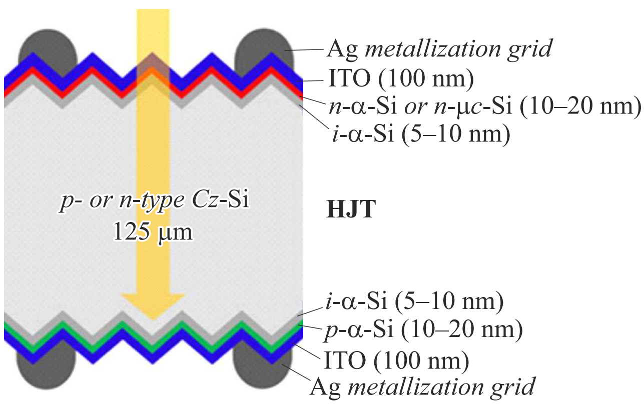

Figure 1. Structure of HJT SC samples with n- or p-type bases.

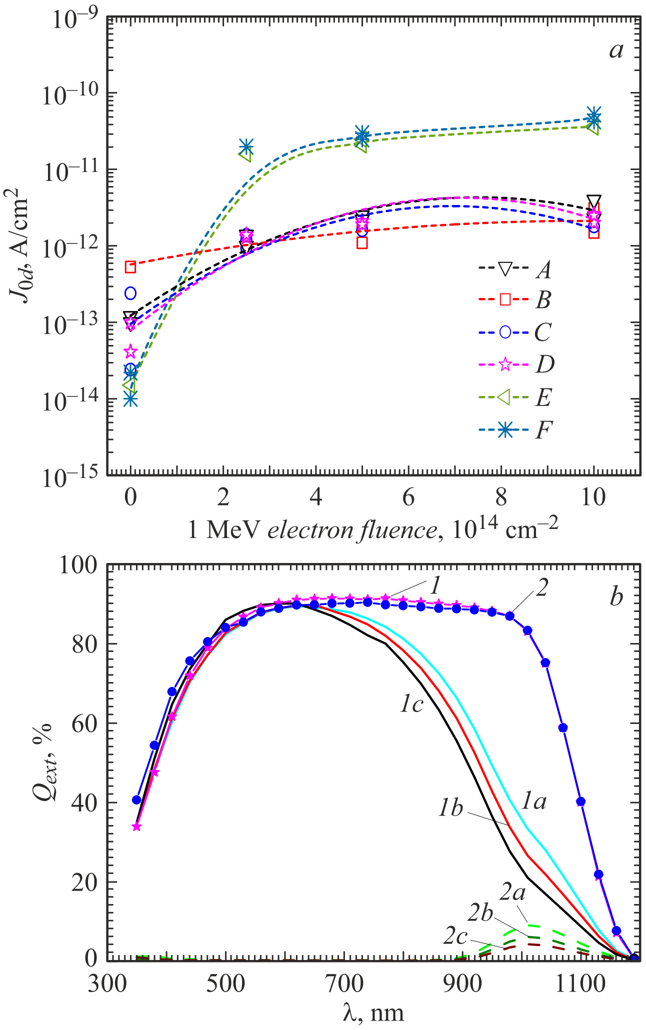

Figure 2. *a* — Dependences of saturation current J_{0d} of the diffusion current flow mechanism on the fluence of 1 MeV electrons, which was derived from experimental dark J–U, for HJT SC structures *A–F* (see the table); *b* — spectral characteristics of HJT SC structures *D* (curves *1*, *1a*, *1b*, and *1c*) and *E* (curves *2*, *2a*, *2b*, and *2c*)) under irradiation with fluences of 0 (*1*, *2*), $2.5 \cdot 10^{14}$ (*1a*, *2a*), $5 \cdot 10^{14}$ cm^{-2} (*1b*, *2b*), and $1 \cdot 10^{15}$ cm^{-2} (*1c*, *2c*).

amorphous or microcrystalline *n*-type front layers. Samples with an area of 1 cm^2 cut from HJT SCs 15.6 cm × 15.6 cm in size were examined without subsequent passivation of lateral surfaces.

The front side of samples was irradiated in air at room temperature in the process of two-coordinate scanning of SCs by an electron beam ($J_e = 12.5\,\mu$A/cm^2, $E_e = 1.0 \pm 0.1$ MeV) with fluences $F_e = 2.5 \cdot 10^{14}$, $5 \cdot 10^{14}$, and $1 \cdot 10^{15}$ cm^{-2} produced by an RTE-1V setup. The electron-beam current in the accelerator remained constant in the course of irradiation and was monitored with a GDM-8246 instrument. The electron flux, the intensity, and the exposure time were set so as to avoid thermal annealing of samples under irradiation. Current-voltage (J–U) and spectral characteristics were measured and analyzed before and after electron irradiation under darkroom conditions and under illumination in order to identify HJT SCs with the best parameters and radiation resistance. Dark J–U were measured using a high-precision sourcemeter within the 1 pA–1 A and 0–2 V current and voltage ranges. A collimated light flux produced by a pulsed simulator with the AM0 spectrum and an energy density of 1367 W/m^2 was used to measure I–U under illumination. Spectral characteristics were determined using a setup fitted with an M266 monochromator, a halogen lamp (300–2000 nm), and a silicon reference cell.

Experimental forward dark J–U of all types of HJT structures before and after irradiation were analyzed in accordance with the procedure outlined in [11]. This method consists in presenting a dark J–U as a combination of exponential sections that correspond to the following

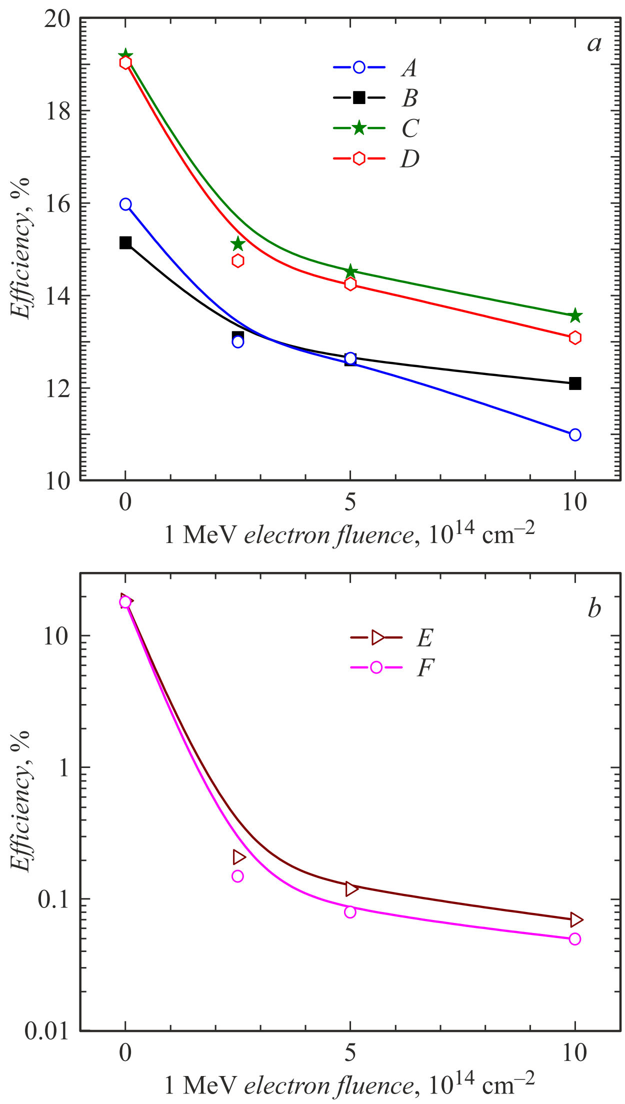

Figure 3. Dependences of the efficiency of HJT SC structures (see the table) on the fluence of irradiating 1 MeV electrons (AM0, 136 mW/cm^2, 300 K). *a* — Structures *A–D*; *b* — structures *E*, *F*.

Studied structures $A-F$ (Fig. 1)

Designation	Structure
A	n-α-Si:H/c-p(B)/p-α-Si:H
B	n-μc-Si:H/c-p(B)/p-α-Si:H
C	n-α-Si:H/c-p(Ga)/p-α-Si:H
D	n-μc-Si:H/c-p(Ga)/p-α-Si:H
E	n-α-Si:H/c-n(P)/p-α-Si:H
F	n-μc-Si:H/c-n(P)/p-α-Si:H

current flow mechanisms: tunnel-trap, „excess" with diode ideality factor $A_t > 2$ (Esaki), recombination with $A_r = 2$ (Sah−Noyce−Shockley), and diffusion with $A_d = 1$ (Shockley). The lowest „saturation" currents were found in n-type samples of structure E (the studied structures are listed in the table). Following irradiation with 1 MeV electrons with a fluence of $2.5 \cdot 10^{14}$, $5 \cdot 10^{14}$, and $1 \cdot 10^{15}\,\mathrm{cm}^{-2}$, the examined samples underwent degradation, and the saturation currents increased (see Fig. 2, a and the table). A similar pattern of degradation of n-type HJT SCs with predominant variation of the diffusion current component has been reported earlier in experiments on irradiation with 3.8 MeV electrons in [8]. The diffusion saturation current for n-Si samples after irradiation is, on average, more than an order of magnitude greater than the corresponding current for p-Si samples (Fig. 2, a).

The influence of irradiation with 1 MeV electrons on the spectral characteristics of HJT SC structures D and E is shown in Fig. 2, b. The degradation of the long-wave edge of external quantum efficiency of SC structure D with an increase in fluence is attributable to a reduction in the diffusion length of minority carriers. An almost complete degradation was observed in samples of structure E. This is attributable primarily to the rear positioning of a $p-n$-junction.

The results of measurements of I−U under illumination revealed that photovoltaic parameters degrade with increasing electron fluence in all the examined HJT SCs. Structures C and D (see Fig. 3 and the table) demonstrated the least significant (in absolute values) degradation of efficiency at the maximum fluence $F_e = 1 \cdot 10^{15}\,\mathrm{cm}^{-2}$.

The efficiency of structures A and B was lower than the one of structures C and D. This is likely attributable to the emergence and activation of bulk defects (boron–oxygen complexes) under illumination [12].

Having analyzed the spectral characteristics of HJT SC structures $A-F$ (see the table) and their J−U obtained under darkroom conditions and under illumination, we found that SC structure samples grown on p-type substrates are more resistant to irradiation with 1 MeV electrons within the $2.5 \cdot 10^{14}-1 \cdot 10^{15}\,\mathrm{cm}^{-2}$ fluence range. HJT SC structures C and D were the most resistant and had higher efficiencies before and after irradiation. Their saturation currents of the diffusion current flow mechanism changed the least (from $J_{0d} < 5 \cdot 10^{-13}\,\mathrm{A/cm^2}$ to $J_{0d} < 3 \cdot 10^{-12}\,\mathrm{A/cm^2}$) following irradiation with 1 MeV electrons with a fluence of $1 \cdot 10^{15}\,\mathrm{cm}^{-2}$. The reduction in external quantum efficiency, short-circuit current, and open-circuit voltage was < 25% ($\lambda = 0.35-1.2\,\mu$m), $I_{sc} < 16\%$, and $U_{oc} < 19\%$, respectively, while the efficiency dropped from $\leqslant 19.2$ to $\leqslant 13.6\%$.

Conflict of interest

The authors declare that they have no conflict of interest.

References

[1] M. Yamaguchi, K.-H. Lee, K. Araki, N. Kojima, Y. Okuno, M. Imaizumi, in *2019 IEEE 46th Photovoltaic Specialists Conf. (PVSC)* (IEEE, 2019), p. 2377. DOI: 10.1109/PVSC40753.2019.8981219

[2] Y. Liu, Y. Li, Y. Wu, G. Yang, L. Mazzarella, P. Procel-Moya, A.C. Tamboli, K. Weber, M. Boccard, O. Isabella, X. Yang, B. Sun, Mater. Sci. Eng. R, **142** 100579 (2020). DOI: 10.1016/j.mser.2020.100579

[3] W.M. Alkharasani, N. Amin, S.A. Shahahmadi, A.A. Alkahtani, I.S. Mohamad, P. Chelvanathan, T.S. Kiong, Materials, **15**, 3508 (2022). DOI: 10.3390/ma15103508

[4] W. Long, S. Yin, F. Peng, M. Yang, L. Fang, X. Ru, M. Qu, H. Lin, X. Xu, Solar Energy Mater. Solar Cells, **231**, 111291 (2021). DOI: 10.1016/j.solmat.2021.111291

[5] A.S. Abramov, D.A. Andronikov, S.N. Abolmasov, E.I. Terukov, in *High-efficient low-cost photovoltaics*. Springer Ser. in Optical Sciences (Springer, Cham, 2020), vol. 140, p. 113–132. DOI: 10.1007/978-3-030-22864-4_7

[6] M. Taguchi, ECS J. Solid State Sci. Technol., **10**, 025002 (2021). DOI: 10.1149/2162-8777/abdfb6

[7] V. Kanneboina, Microelectron. Eng., **265**, 111884 (2022). DOI: 10.1016/j.mee.2022.111884

[8] V.S. Kalinovskii, E.I. Terukov, E.V. Kontrosh, V.N. Verbitskii, A.S. Titov, Tech. Phys. Lett., **44**, 801 (2018). DOI: 10.1134/S1063785018090067.

[9] M. Yamaguchi, S.J. Taylor, S. Matsuda, O. Kawaki, Appl. Phys. Lett., **68**, 3141 (1996). DOI: 10.1063/1.115804

[10] A. Luque, S. Hegedus, *Handbook of photovoltaic science and engineering* (John Wiley & Sons, Ltd., 2003), p. 421.

[11] A.A. Andreev, V.M. Andreev, V.S. Kalinovsky, P.V. Pokrovsky, E.I. Terukov, Semiconductors, **46**, 929 (2012). DOI: 10.1134/S1063782612070044.

[12] B. Vicari Stefani, M. Kim, M. Wright, A. Soeriyadi, D. Andronikov, I. Nyapshaev, S. Abolmasov, K. Emtsev, A. Abramov, B. Hallam, Solar RRL, **5**, 2100406 (2021). DOI: 10.1002/solr.202100406

Translated by D.Safin