Study of the possibility to increase annual electricity production using silicon solar cells with a nanostructured surface

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The results of a study of the angular dependence of the reflectivity of black silicon structures with conical and filamentary nanowires, and a silicon surface with a textured pyramidal surface coated with an ITO layer are presented. The possibility to increase the annual electricity generation for solar cells based on black silicon has been demonstrated due to the weak angle dependence of the total reflectance. Compared to the textured pyramidal surface, the increase is 7.34% and 6.33% for the solar cells based on black silicon with conical and filamentary nanowires, respectively.

Keywords: Solar energy, black silicon, total reflection, power generation.

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The development of solar energy requires reducing the cost of electricity, increasing the efficiency of photovoltaic converters and increasing the energy generated. The current record efficiency value of a silicon solar cell is 26.7% [1], which is close to the theoretical Shockley–Quisser limit 30% [2]. Further development is possible by reducing the amount of reflected light over a wide range of angles and by capturing reflected and scattered light. More recently, a more efficient way to reduce optical loss by forming a developed silicon surface known as „black silicon“ has been proposed. It effective over a wide spectral range as well as at different angles of incidence. Thus, black silicon effectively absorbs solar radiation over a wide wavelength range $\lambda = 250{-}1200$ nm. A solar cell (SC) based on a structure with interdigitated back contact (IBC) and a black silicon front surface has already achieved an efficiency of 22.1% [3]. However, to date, little information is available on the real gain of black silicon-based SC compared to the classical textured-surface SC design. In this work, based on experimental data on the angular dependence of the reflectance, the average annual power generation for black silicon-based SCs and heterostructured SCs with a textured surface was calculated.

To perform the calculation, the angular dependence of the reflectance spectra for two black silicon (*b*-Si) samples differing in silicon fiber geometry and substrate backside structure were obtained. Both samples were obtained by cryogenic dry etching of *n*-type ($10^{15}\,\mathrm{cm}^{-3}$) silicon wafers and orientation (100). The process was carried out in an inductively coupled plasma in an SF_6/O_2 gas mixture at a temperature -150°C [4]. The first sample was fabricated with cone-shaped silicon fibers on only one side of the substrate (Figure 1, *a*) by using our developed process with the addition of argon [4], and the second sample was formed with the characteristic *b*-Si geometry — with silicon fibers of different diameters obtained on both sides of the substrate (Figure 1, *b*). A sample based on a *a*-Si:H/*c*-Si-heterajunction with a textured silicon surface with an ITO layer deposited was taken for comparative analysis (Figure 1, *c*).

A dual CAS 140B Array Spectrometer was used to receive the received radiation for the entire spectral range, and to measure the total reflectance $R(\lambda)$ — an integrating sphere UPB-150-ART, for which a sample holder was fabricated that allowed the angle of incidence of the input light beam to be varied over a range from 0–90°.

To estimate the annual energy production of the SC, it is necessary to calculate the power output for each silicon SC, taking into account the daily and annual variation of illumination — insolation, as well as the angular dependence of the position of the Sun relative to the surface SC. Such a calculation requires data on the position of the Sun at a particular time with the necessary discreteness, as well as insolation data for the selected region — the city of St. Petersburg, Russia. The solar orientation of the SC, i.e., the angle of incidence of the sun's rays on the SC, is determined by the solar azimuth γ_s and its height above the horizon α_s in spherical coordinates and is determined by the formula from [5] when the SC is oriented strictly to the south:

$$\cos\theta = |\cos\theta_z \cos\beta + \sin\theta_z \sin\beta \cos\gamma_s|, \qquad (1)$$

where $\theta_z = 90-\alpha_s$, β — the angle of inclination of the SC to the surface.

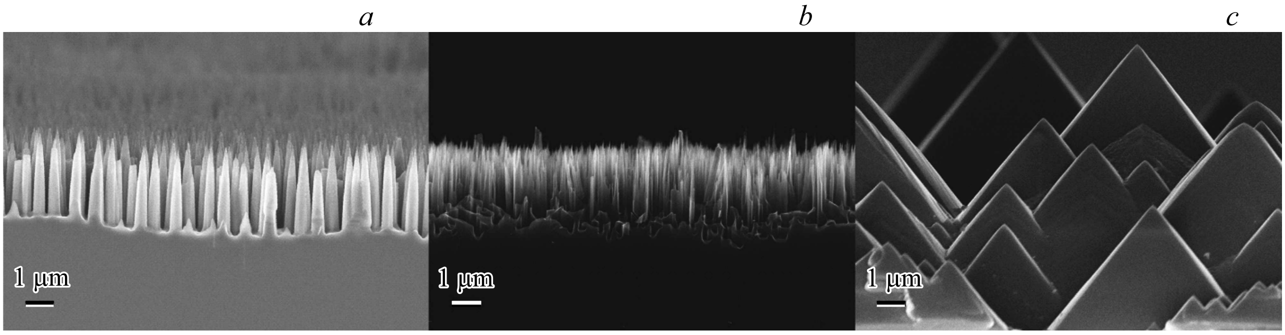

Figure 1. SEM images of the structures: *a* — a unilateral black silicon sample with cone-shaped nanofibers, *b* — a bilateral black silicon sample with filamentary nanofibers, *c* — a silicon sample based on *a*-Si : H/*c*-Si-heterojunction with textured surface.

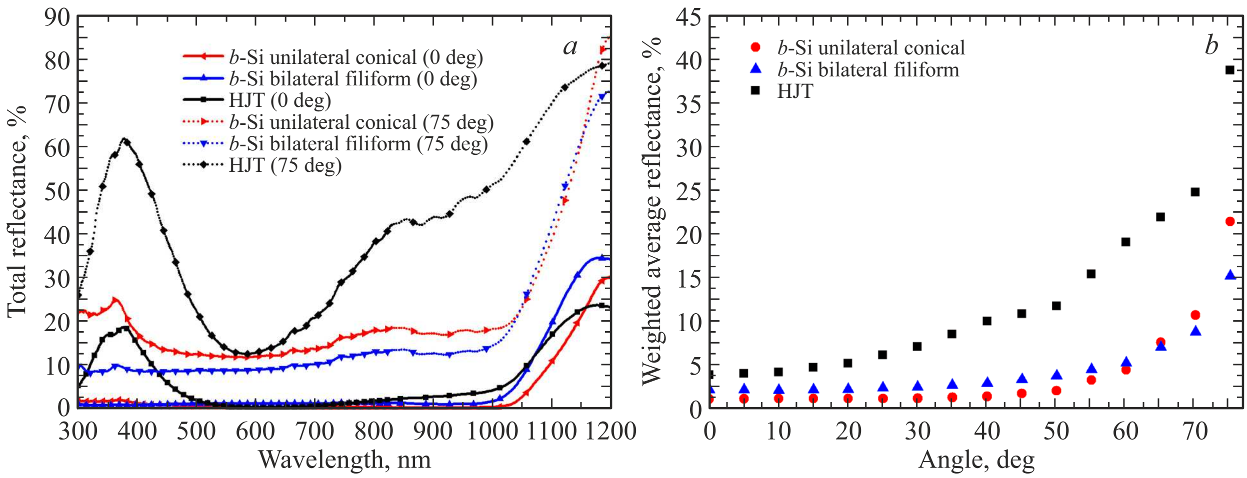

Figure 2. Spectral dependences of total reflection at sample tilt angles 0 and 75° (*a*), dependence of the weighted average reflectance for *b*-Si and HJT on the angle of incidence of radiation (*b*). (The colored version of the figure is available on-line).

NASA Power Data Access Viewer [6] databases were used to obtain insolation data. For calculations, we took data on insolation under clear skies for every fifth day in 2021 year for the geographical region of Saint-Petersburg. The data on the sun's position was obtained using an online resource for automating such calculations [7]. To account for the angular and spectral dependence of the total reflectance, the Weighted Average Reflectance (WAR) calculated by the formula [8] should be used in the calculation of the output power.

$$\mathrm{WAR} = \frac{\int_{\lambda_0}^{\lambda_i} \Phi R d\lambda}{\int_{\lambda_0}^{\lambda_i} \Phi d\lambda}, \tag{2}$$

where the flux Φ is calculated from the standard AM1.5G [9] solar radiation spectrum:

$$\Phi = \frac{E_0}{1240e}\lambda, \tag{3}$$

E_0 — spectrum intensity density distribution AM1.5G.

Calculation of output power of solar cells taking into account their spectral dependence of total reflectance was carried out by the following formula:

$$P = P_r I_R \left(1 - \frac{\mathrm{WAR}}{100}\right)\cos\theta, \tag{4}$$

where $\cos(\theta)$ — cosine of the angle of incidence of sunlight, P_r — rated power for standard lighting conditions (1000 W/m^2), I_R — insolation value.

To estimate the absolute values of energy produced by modules with different surface morphologies, the same power rating for standard lighting conditions (P_r) was used in calculations. The technical characteristics of Hevel heterostructured solar panels (HJT) with $P_r = 400$ W [10] were taken as the basis. Factors that reduce the efficiency of the SC, such as heating or snowing, are not considered in this paper. Thus, only the difference in the angular dependence of the reflectance was taken into account in the calculations.

The spectral dependences of the total reflectance R for the HJT sample and the investigated *b*-Si samples, measured in the 300–1200 nm wavelength range over the available range of light incidence angles on the samples, are shown in Figure 2, *a*. For the control sample HJT, the total

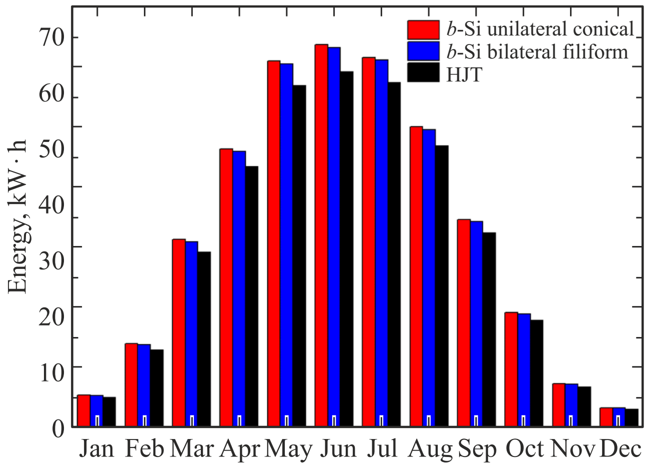

Figure 3. Distribution of electricity generation during the year for the region of St. Petersburg.

reflectance has a well-defined minimum with a reflection of $< 2\%$ up to the angle 60° at a wavelength of 600 nm, which is due to the antireflection effect of the ITO layer. However, in the shortwave band, is $R \geq 17\%$ and grows to 60% with increasing incident radiation tilt angle, and also increases significantly with increasing tilt angle in the IR band.

The reflectance spectra for the *b*-Si samples (Figure 2, *a*) do not exceed 2% over a wide wavelength range (400–1000 nm) for normal incidence and are weakly dependent on the incident angle compared to the textured surface. For incidence angles $\geq 70^\circ$, the reflectance of the one-sided sample with tapered nanofibers becomes larger than that of the two-sided sample with filamentary nanofibers. The weighted average reflectance of the WAR was calculated from the reflectance data (Figure 2, *b*). The WAR for *b*-Si samples depends weakly on the incident angle and does not exceed 2% at angle $0-50^\circ$. The up to 60° WAR for the surface with tapered nanofibers is lower than that for filamentary ones. The WAR for the textured control sample (HJT) increases monotonically with increasing incidence angle, reaching 12% at 50°. With increasing angles of incidence of light, WAR increases. According to the received WAR by the formula (4), the average annual electricity generation for the year is calculated. The calculation of the optimum tilt angle demonstrates the fact that SCs based on *b*-Si can achieve higher power generation over the entire range of installation angles. The calculation of daily power generation proves that the *b*-Si-based structures are more efficient throughout the day, but most — during morning and evening hours, which is due to the weak angular dependence of R for *b*-Si.

The distribution of power generation by month (Figure 3) shows that the gain using these *b*-Si samples is 7–9% for the single-sided tapered fiber sample and 6–7.5% for the double-sided filament sample. At the same time, black silicon-based SCs allow to increase the output by $\sim 7\%$ over time. Thus, the total annual power generation at the southward orientation and at the optimum tilt angle 45° in the Saint-Petersburg city district for panels with $P_r = 400$ W is 369 kW · h for HJT-SC, for black silicon elements with conical nanofibers — 396 kW · h and for black silicon element with filamentary nanofibers ~ 392 kW · h. The gain using *b*-Si is 7.34 and 6.33% for *b*-Si with conical nanofibers and *b*-Si with filamentary nanofibers, which shows the promising application of silicon solar cells with nanostructured surface in ground-based solar energy.

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Conflict of interest

The authors declare that they have no conflict of interest.

References

[1] M.A. Green, Y. Hishikawa, E.D. Dunlop, D.H. Levi, J. Hohl-Ebinger, M. Yoshita, A.W.Y. Ho-Baillie. Progr. Photovolt.: Res. Appl., **27** (1), 3 (2019). DOI: 10.1002/pip.3102
[2] T. Tiedje, E. Yablonovitch, G.D. Cody, B. G. Brooks. IEEE Trans. Electron Dev., **31**, 711 (1984). DOI: 10.1109/t-ed.1984.21594
[3] H. Savin, P. Repo, G. von Gastrow, P. Ortega, E. Calle, M. Garín, R. Alcubilla. Nature Nanotechnol., **10**, 624 (2015). https://doi.org/10.1038/nnano.2015.89
[4] E.A. Vyacheslavova, I.A. Morozov, D.A. Kudryashov, A.V. Uvarov, A.I. Baranov, A.A. Maksimova, S.N. Abolmasov, A.S. Gudovskikh. ACS Omega, **7**, 6053 (2022). DOI: 10.1021/acsomega.1c06435
[5] M. Rosa-Clot, P. Rosa-Clot, P. Scandura, G.M. Tina. Proc. 24th Eur. Photovolt. Solar Energy Conf., PV Power Plants, Hamburg, 4162 (2009). DOI: 10.4229/24thEUPVSEC2009-5BV.2.41
[6] POWER. Data Access Viewer. URL: https://power.larc.nasa.gov/data-access-viewer/ (date of access: 12.02.2023).
[7] Online calculator: Azimuth and altitude of the sun above the horizon, PlanetCalc. URL: https://planetcalc.ru/320/ (date of access: 16.03.2023).
[8] G. Womack, P. Kaminski, A. Abbas, K. Isbilir, R. Gottschalg, J.M. Walls. J. Vac. Sci. Technol. A, **35** (2), 021201 (2017). DOI: 10.1116/1.4973909
[9] Th. Henriksen. *Solstråling, Sol-ozon-helse* (Gyldendal akademisk, 2002). ISBN13 9788205304062
[10] https://spb.hevelsolar.com/catalog/solnechnye-batarei/ (date of access: 23.04.2023).

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