Conference materials
UDC 621.311.243
DOI: https://doi.org/10.18721/JPM173.126

Effect of light incidence angle on the characteristics of silicon solar cells with different texturing

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Abstract. The influence of the angle of incidence of the light flux on the photovoltaic performance of two types *a*-Si:H/*c*-Si heterojunction solar cells is investigated: KOH textured with a pyramidal surface, and black silicon with a nanostructured surface. Current-voltage characteristics and power depending on the angle of incidence of the solar flux – from 14 mW/cm^2 to 3 mW/cm^2 for pyramidal surface and from 9 mW/cm^2 to 2 mW/cm^2 for black silicon in the angle range 0–75° were obtained. Solar cell based on black silicon retains its characteristics 6% better as the angle of incidence of light increases to 75°.

Keywords: black silicon, amorphous silicon, heterojunction solar cell, current-voltage characteristic, angle of incidence

Funding: The research was supported by the RFBR research project No. 21-58-46001.

Citation: Yarchuk E.Y., Vyacheslavova E.A., Monastyrenko A.O., Gudovskikh A.S., Effect of light incidence angle on the characteristics of silicon solar cells with different texturing, St. Petersburg State Polytechnical University Journal. Physics and Mathematics. 17 (3.1) (2024) 134–137. DOI: https://doi.org/10.18721/JPM.173.126

Материалы конференции
УДК 621.311.243
DOI: https://doi.org/10.18721/JPM.173.126

Влияние угла падения света на характеристики кремниевых солнечных элементов с различным текстурированием

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Аннотация. Исследовано влияние угла падения светового потока на фотоэлектрические характеристики двух типов солнечных элементов с гетеропереходом *a*-Si:H/*c*-Si: текстурированного KOH с пирамидальной поверхностью и черного кремния с наноструктурированной поверхностью. Вольтамперные характеристики и мощность в зависимости от угла падения солнечного потока – от 14 мВт/см^2 до 3 мВт/см^2 для образца с пирамидальной поверхностью и от 9 мВт/см^2 до 2 мВт/см^2 для черного кремния в диапазоне углов 0–75°. Солнечный элемент на основе черного кремния сохраняет свои характеристики на 6% лучше при увеличении угла падения света до 75°.

Ключевые слова: черный кремний, аморфный кремний, гетеропереходный солнечный элемент, вольтамперная характеристика, угол падения

Финансирование: Проект РФФИ № 21-58-46001 «Разработка высокоэффективных двухсторонних гетероструктурных солнечных элементов на основе черного кремния».

Ссылка при цитировании: Ярчук Э.Я., Вячеславова Е.А., Монастыренко А.О., Гудовских А.С. Влияние угла падения света на характеристики кремниевых солнечных элементов с различным текстурированием // Научно-технические ведомости СПбГПУ. Физико-математические науки. 2024. Т. 17. № 3.1. С. 134–137. DOI: https://doi.org/10.18721/JPM.173.126

Introduction

One of the solutions to the issue of electricity availability is solar energy, which is actively developing now. It is estimated that the increase in electricity generation in this area will reach 260 GW by 2026 [1]. Understanding the dependence of the current-voltage characteristics (I-V curves) of a solar cell (SC) at different angles of its inclination relative to the incident light flux allows us to take conclusions about changes of electricity generation during daylight hours and evaluate its efficiency. Silicon solar cells dominate among photovoltaic cells, as they are relatively cheap, accessible and durable.

The most promising concept of silicon SC is heterojunction *a*-Si:H/*c*-Si (HJT) technology [2] with anti-reflection coatings and a pyramidal textured surface to reduce optical losses [3, 4]. Also promising is black silicon (*b*-Si), which has minimal reflection in a wide range of waves [5] and retains these properties at high angles of light incidence on it.

In this article the influence of the angle of incidence of the light flux on the silicon solar cells on their current-voltage characteristics is considered.

Materials and Methods

Figure 1 shows two types of heterojunction (HJT) silicon *a*-Si:H/*c*-Si solar cells with an area of 1 cm^2 taken for the research: HJT based on black silicon (*b*-Si) with a nanotextured surface (Fig. 1, *a*) and HJT with conventional pyramidal structure (*pyr*-Si) (Fig. 1, *b*).

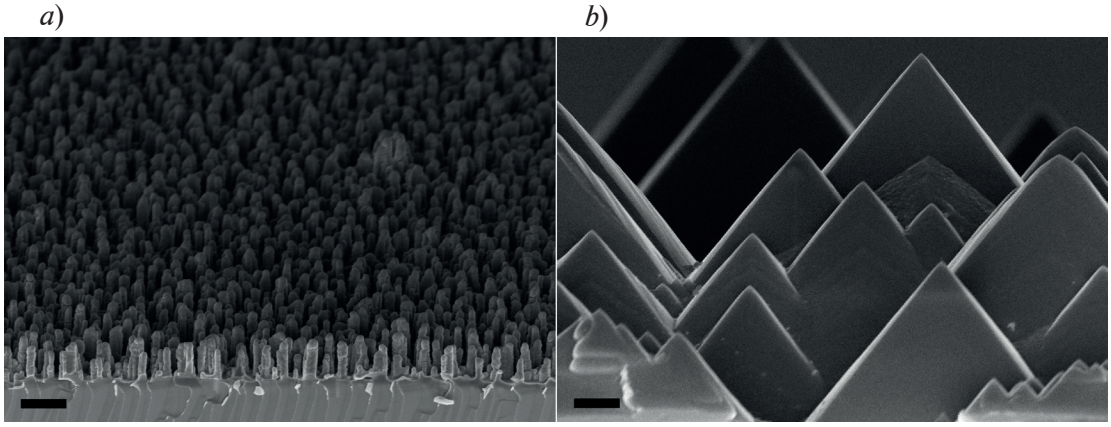

Fig. 1. SEM-images of the samples: *b*-Si (*a*), pyr-Si (*b*). The bare scale is 1000 nm

Comparison of the performance of *b*-Si and *pyr*-Si HJT allows us to evaluate the impact of different types of surface texturing on solar cell efficiency. This is important for determining the optimal type of structure for the development of more efficient photovoltaic devices.

To study the angular dependences of the current-voltage characteristics, a rotating sample holder was made and shown in Figure 2.

It is a tilt-adjustable platform that allows the solar cell to be precisely positioned relative to the beam of the solar simulator. The design of the stand eliminates the appearance of shadows, which ensures accurate measurement of the I-V curves at different angles of light incidence.

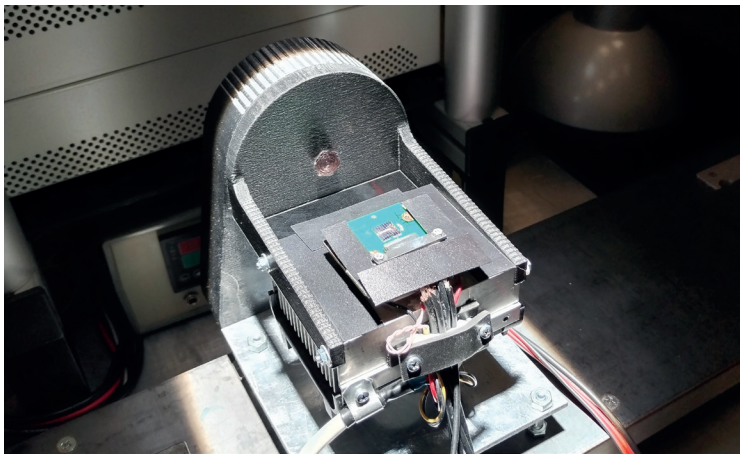

Fig. 2. Rotating sample holder designed for the research

Using a rotating stand allows us to study with high accuracy the effect of the angle of incidence of light on the efficiency of a solar battery. This allows to optimize the placement of solar panels to achieve maximum energy production throughout the day. Unlike standard methods for measuring current-voltage characteristics, which are often limited to several fixed angles, the use of a rotating stand allows to obtain a complete picture of the angular dependences of the current-voltage characteristics, which is especially important for assessing the performance of solar panels under conditions of changing insolation during the day.

Results and Discussion

The dependences of the I-V curves for these samples at angles of light incidence on them from 0° to 75°, the short circuit current and their power characteristics are shown in Figure 3.

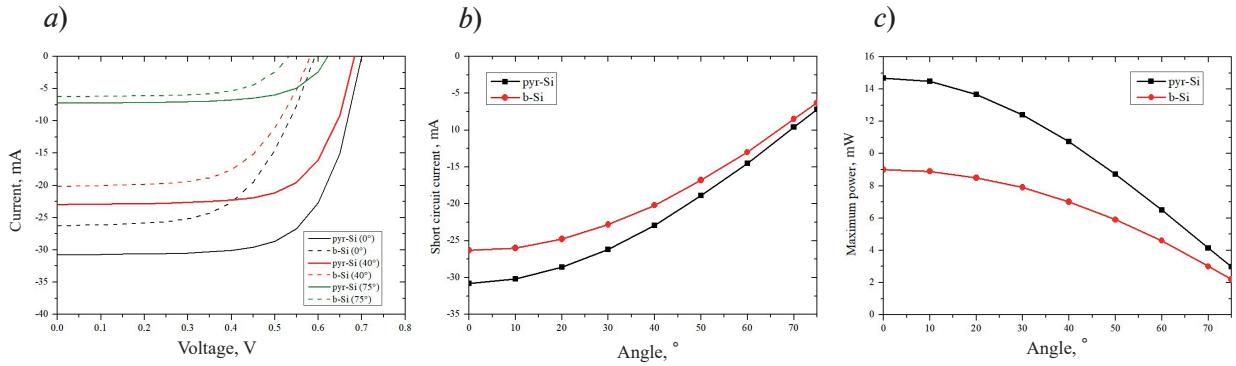

Fig. 3. I-V curves for samples *pyr*-Si (solid lines) and *b*-Si (dashed lines) for angles of 0° (black lines), 40° (red) and 75° (green) (*a*), angular dependences of short circuit current (*b*) and points of maximum power (*c*) for samples *pyr*-Si (black lines) and *b*-Si (red)

The maximum power is observed at light incidence angles of 0–20° and decreases with increasing angle. The *pyr*-Si demonstrates better perfomance (from 14.4 mW/cm^2 to 3 mW/cm^2, weakening is 79.2%), but at the same time characteristics more strongly decrease with increasing light incidence angle than the *b*-Si sample, which at more modest absolute values (from 9 mW/cm^2 to 2.3 mW/cm^2, weakening is 74.5%, 6% better), remains more stable at large angles, which explained by the structure of its surface.

Conclusion

The influence of the angle of incidence of the light flux on the current-voltage characteristics of heterostructure solar cells with different surfaces was studied. As the angle of incidence of light increases, the characteristics of solar cells deteriorate by reflection losses, but the nature of these changes is different. Thus, the *b*-Si shows more stability, while *pyr*-Si significantly loses its

effective power with increasing angle. This shows the potential of black silicon research, and the need to improve black silicon production technologies.

Acknowledgments

The research was supported by the RFBR research project No. 21-58-46001.

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Received 28.07.2024. Approved after reviewing 05.08.2024. Accepted 09.08.2024.