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Photovoltaic characteristics of HJT photo converters of laser radiation at a wavelength of 1064 nm

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Abstract. The possibility of efficient conversion of continual infrared laser radiation by heterojunction technology *a*-Si:H/*c*-Si photovoltaic converters is demonstrated. The photovoltaic characteristics of eight different types of heterojunction structures were investigated. The photovoltaic converters of the *n*-α-Si/*n*-*c*-Si/*p*-α-Si heterojunction structure with contact grid Ag turned out to be the best in terms of dark currents, external quantum efficiency, I-V characteristics, and conversion efficiency of laser radiation with 1064 nm wavelength at a power density up to 2 kW/m^2. The maximum efficiency ~ 24.5% of this structure was reached at power density of 1 kW/m^2.

Keywords: heterojunction technology solar cells, free space optics, high-power laser radiation converters, region of optical transparency of the atmosphere.

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Материалы конференции
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Фотовольтаические характеристики HJT фотопреобразователей лазерного излучения на длине волны 1064 нм

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Аннотация. Показана возможность эффективного преобразования постоянного лазерного излучения инфракрасного диапазона фотоэлектрическими преобразователями на основе гетеропереходных *a*-Si:H/*c*-Si структур. Исследованы фотовольтаические характеристики образцов из восьми различных типов гетеропереходных структур. Наилучшей по вольт-амперным характеристикам и параметрам темновых токов, внешней квантовой эффективности, эффективности преобразования лазерного излучения на длине волны 1064 нм с плотностью мощности до 2 кВт/м^2, оказалась *n*-α-Si/*n*-*c*-Si/*p*-α-Si гетеропереходная структура. Максимальный КПД данной структуры достигался при плотности мощности 1 кВт/м^2 и составил ~ 24.5%.

Ключевые слова: гетеропереходные солнечные элементы, атмосферные оптические линии связи, преобразователи мощного лазерного излучения, область оптической прозрачности атмосферы.

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Introduction

The best *a*–Si:H/*c*–Si photovoltaic converters (PVCs) made by heterojunction technology (HJT) have an efficiency of more than (25–26) % at solar radiation (AM1.5) [1–3]. In addition to solar energy conversion, HJT modules can find their application as high-power laser radiation converters, for example, in free space optics (FSO). Currently, FSO systems depend on reliable external power sources. For this reason, the HJT PVCs can be used as a power supply for the receiving and transmitting stations of FSO [4]. This makes it possible to significantly simplify and autonomize the operation of FSO systems, as well as expand the sphere of their application.

Taking into account the region of optical transparency of the atmosphere, it is important to evaluate the efficiency of the HJT PVCs when illuminated by high-power laser radiation in the near infrared range. In this work, a laser with a wavelength of 1064 nm was used, which has good spatial coherence, low beam divergence and a wavelength that coincides with the transparency window of the atmosphere in the near infrared range. To evaluate the maximum conversion efficiency of PVCs depending on the temperature and an incident laser radiation power, as well as stability and from the point of view of economic feasibility, all currently available HJT structures were used.

In total, eight different types of HJT PVCs structures were considered in this work (Table 1). To identify structures with the best parameters, the following dependences were measured and analyzed: direct dark current-voltage (*I*–*V*) characteristics in the voltage range from 0 to 1.0 V and characteristics of external quantum efficiency in the wavelength range (350–1200) nm. Further, studies of the PVCs characteristics were carried out on the basis of the selected most promising structure with the best characteristics. Load *I*–*V* characteristics in the power density range from 0.06 to 2 kW/m^2 with continuous laser radiation at a wavelength of 1064 nm, as well as load *I*–*V* characteristics in the temperature range from 25 °C to 80 °C at a power density of 1 kW/m^2 were measured.

Experiment

The structures of HJT photo converters. The general scheme of the studied structures of the HJT PVCs is shown in Fig. 1. The studied samples (Table 1) were formed on textured *c*–Si *n*– or *p*–type substrates with a thickness of ~ 125 μm with a charge carrier concentration of ~ 10^{15} cm^{-3}. A layer of intrinsic amorphous silicon (*i*–α–Si:H) with a thickness of 5–10 nm was deposited on a c–Si substrate. Then, an amorphous or microcrystalline layer of n– or p–type silicon with a thickness of 10–20 nm and layers of indium-tin oxide (ITO) with a thickness of 100 nm were deposited on the front and back sides of the substrate. To create a contact grid on the surface of ITO layers, two manufacturing methods were used. The first is the production of silver (Ag) contact busbars with a width of 40 μm and a pitch of 1.2 mm by screen printing.

The second is the manufacture of copper (Cu) contact busbars by electroplating. The experiments used samples with an area of ~ 1 cm^2 with bilateral photosensitivity, which is an additional advantage in the presence of albedo. Samples with an area of 1 cm^2 were formed by laser cutting from the original full-size HJT photo converter with a size of 15.6 cm × 15.6 cm. The side surfaces of the cut samples were not subjected to special treatment and did not have additional passivating coatings.

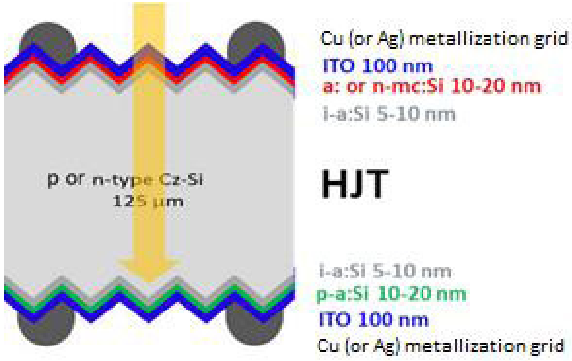

Fig. 1. A schematic sketch of the HJT PVCs on *n*- or *p*-type wafer

Dark *J*–*V* characteristics of structures (A-H). According to the method described in [5–6], the experimental direct “dark” *J*–*V* characteristics of the best samples of HJT structures (A-H) were measured and analyzed. The method is applicable to semiconductor *p*–*n* structures and consists in dividing the direct “dark” *J*–*V* characteristic into several exponential sections corresponding to different current flow mechanisms.

Table 1

The types of *n*– and *p*–type HJT photovoltaic converters structures with dimensions of 1 cm²

Structure	Wafer type	Configuration	Front n-layer	Fabrication of a contact grid
A	*n*	Rare (back) emitter [3]	Amorphous	Ag paste screen printed
B	*n*	Rare (back) emitter	Microcrystalline	Ag paste screen printed
C	*n*	Rare (back) emitter	Amorphous	Cu galvanic metallization grid
D	*n*	Rare (back) emitter	Microcrystalline	Cu galvanic metallization grid
E	*p* (Si doped with B)	–	Amorphous	Ag paste screen printed
F	*p* (Si doped with B)	–	Microcrystalline	Ag paste screen printed
G	*p* (Si doped with Ga)	–	Amorphous	Ag paste screen printed
H	*p* (Si doped with Ga)	–	Microcrystalline	Ag paste screen printed

There are tunnel-trap (excessive) with diode ideality coefficient $A_t > 2$ (Esaki), recombination with $A_r = 2$ (Sah-Noyce-Shockley) and diffusion with $A_d = 1$ (Shockley). Fig. 2 shows the experimental direct “dark” *J*–*V* characteristics of the best samples of HJT structures (A-H) – (*a*) and the values of “saturation” currents calculated from them – (*b*). According to the calculated experimental curves, all three current flow mechanisms with values of “saturation” currents – J_{0t}, J_{0r}, J_{0d} are extracted. The lower the “saturation” currents, the higher the efficiency of the laser radiation PVC.

Structure A in total has the lowest values of “saturation” currents, determined by the direct dark *J*–*V* characteristic, namely: $J_{0t} = 2.2\cdot10^{-7}$ A/cm²; $J_{0r} = 1.2\cdot10^{-10}$ A/cm²; $J_{0d} = 3.8\cdot10^{-14}$ A/cm².

Spectral characteristics of structures (A-H). In addition to the dark characteristics, the spectral characteristics were studied, which are the main ones for determining the photosensitivity of the investigated structures of the HJT PVCs. In particular, it can be seen from Fig. 3 that in the long-wavelength sensitivity edge of the HJT PVCs, the highest values of quantum efficiency are achieved in structures on an n-type substrate. The maximum value of the quantum efficiency Q_{ext} = 64% at a wavelength of 1064 nm had the structure A. At the same time, it should be noted that structures on p-type substrates doped with gallium also have relatively high quantum efficiency values. The *p*-type structures doped with boron had the lowest quantum efficiency values. The results obtained are a consequence of the formation of additional recombination centers effect associated with the formation of B-O bonds under the action of light in p-silicon doped with boron [7–8]. This, in turn, leads to a significant reduction in the lifetime of minority charge carriers.

In the long-wavelength region of the spectrum, the maximum difference in quantum efficiency between the structure F and the structure H was 20%. In this case, the higher the values of the external quantum efficiency at a wavelength of 1064 nm, the more preferable the structure is for creating the HJT PVC operating in photovoltaic mode at these wavelengths. The difference in quantum efficiency at a wavelength of 1064 nm between structure F and structure A was 24%.

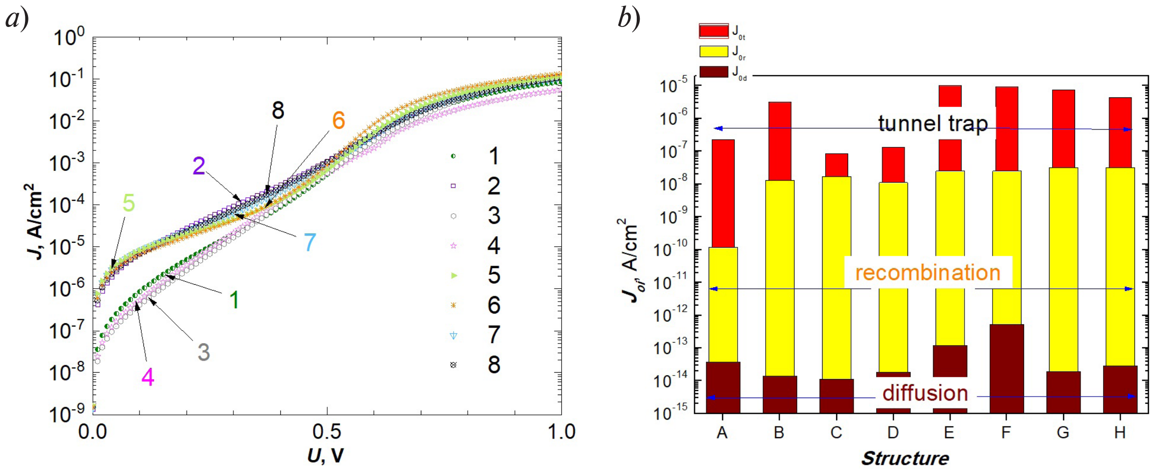

Fig. 2. Dark *J*–*V* characteristics (a) of HJT PVCs structures A (1), B (2), C (3), D (4), E (5), F (6), G (7), H (8) (Table 1) at *T* = 300 K, and the calculated values of “saturation” currents (*b*) for HJT structures of A–H types, J_{0t} , J_{0r} , and J_{0d} are tunnel-trap, recombination, and diffusion components of current flow mechanism, respectively

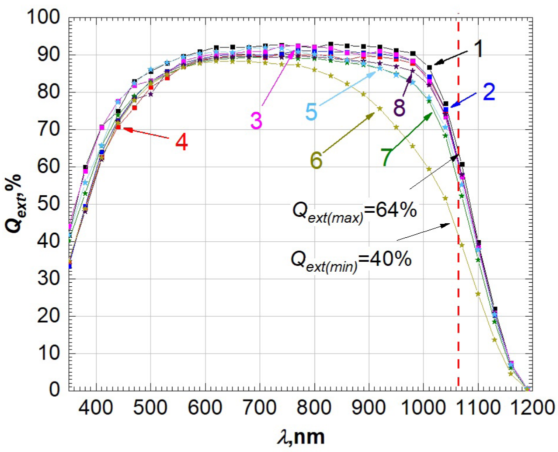

Fig. 3. Spectral characteristics of the external quantum efficiency of HJT PVC structures structures A (1), B (2), C (3), D (4), E (5), F (6), G (7), H (8) (Table 1) at *T* =300 K

Load *I*–*V* characteristics of structures (A–H). According to the results obtained, the structure A with the lowest dark losses and the highest quantum efficiency at a wavelength of 1064 nm can be chosen as the most preferred structure for an energy-informational PVC of FSO. The study of the effect of a not uniform illumination by radiation on the photovoltaic parameters of structure A was carried out. It has been established that at maximum shading, the fill factor and efficiency retain their original values with high accuracy.

The load *I*—*V* characteristics of the HJT PVC (structure A) were measured when it was exposed to laser radiation with a wavelength of 1064 nm, which has a relatively small beam divergence in the setup shown in Fig. 4. Fig. 5 shows the load *I*—*V* characteristics measured at laser radiation in the power density range up to 2 kW/m^2 and at a temperature of 300 K. The values of photovoltaic parameters and their dependences on the power of incident laser radiation were determined from the obtained curves. Fig. 6 shows the dependences of the fill factor and efficiency calculated values on the power density of the incident radiation.

Fig. 7 shows the load *I*—*V* characteristics of the n-α-Si/n-c-Si/p-α-Si:Ag HJT PVC (structure A), measured in the temperature range from 25 °C to 80 °C at a fixed power of continual laser radiation of 1 kW/m^2.

a) *b*)

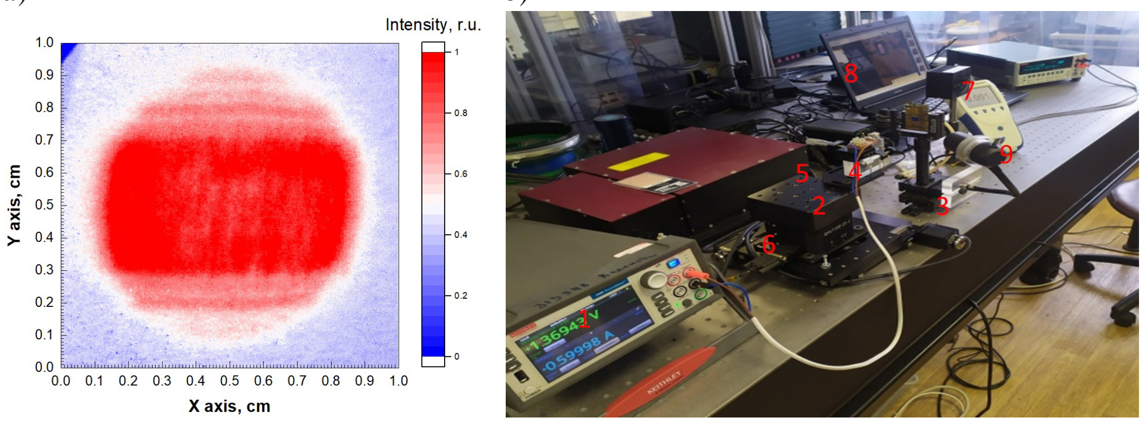

Fig. 4. Distribution of the laser radiation intensity (a) on the photosensitive 1 cm^2 surface of the HJT photo converter (structure A); Stand for measuring load I-V characteristics (*b*) of HJT PVC, 1 — source-meter Keithley 2460; 2 — laser (λ = 1064nm) with fiber optic radiation output; 3 — USB camera; 4 — the HJT PVC 1cm x 1cm; 5, 6 — precision three-axis motorized stage; 7 — source-meter Keithley 2430; 8 — PC; 9 — optical table “Standa”

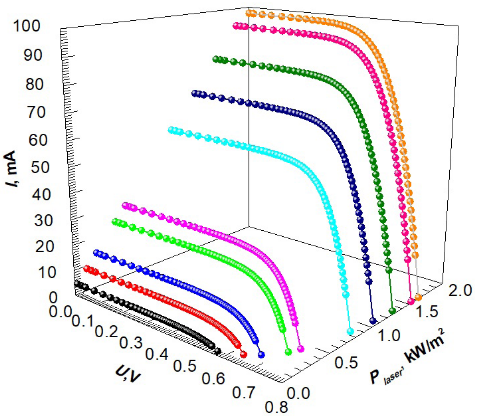

Fig. 5. Load I-V characteristics of HJT photo converter (structure A) in the range of laser radiation power densities 0.06—2 kW/m^2, *T* = 300 K

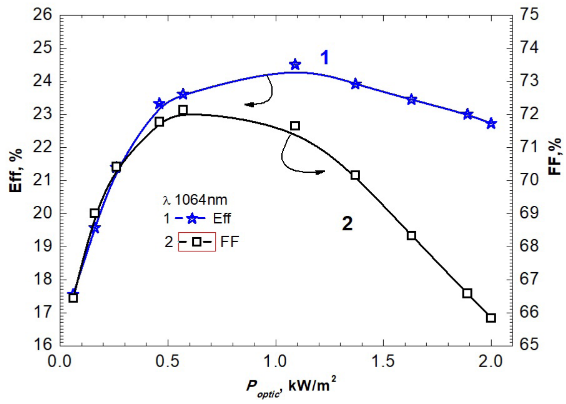

Fig. 6. Dependences of efficiency (1) and fill factor (2) of HJT photoconverter (structure A) on the power of laser radiation (λ = 1064 nm), *T* = 300 K

Fig. 8 shows the temperature dependences of the fill factor and efficiency, determined from the load *I*—*V* characteristics.

From the temperature dependences of the load *I*—*V* characteristics and photovoltaic parameters, it can be seen that heating the test sample to 80°C contributes to an almost linear decrease in the open-circuit voltage by 13% and the fill factor by 7%. The efficiency reached a maximum value of ~ 24.8% at temperature of about 50 °C. This is explained by an increase in the short-circuit current (Fig. 6) due to an increase in the quantum efficiency (Q_{ext}), caused by the shift of

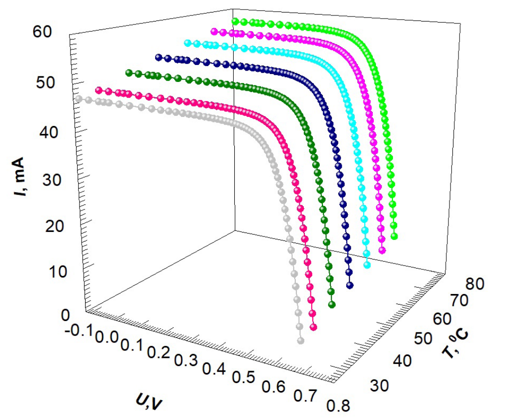

Fig. 7. Load I-V characteristics of HJT photo converter (structure A) in the temperature range from 250 ˚C to 800 ˚C, P_{laser} = 1 kW/m²

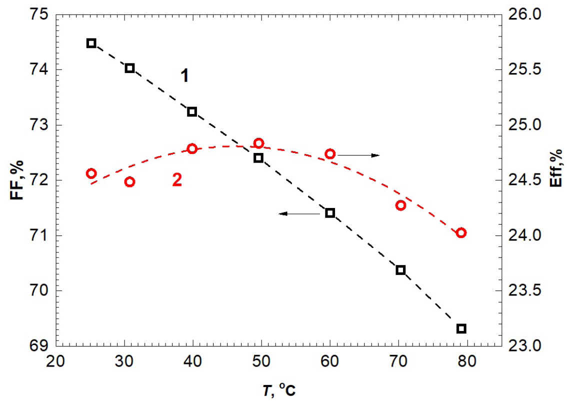

Fig. 8. Dependences of the fill factor (1) and efficiency (2) of HJT photo converter (structure A) on temperature when excited by laser radiation at λ = 1064 nm

the long-wavelength absorption edge to the infrared region when the HJT PVC is heated. Thus, the test sample (HJT, structure A) worked most efficiently at the power density of the incident laser radiation (λ =1064 nm) ~ 1.2 kW/m² with intensity distribution (Fig. 4, *a*) and the heating temperature ~ T = 50 ˚C (Fig. 6, 8).

Conclusion

Thus, the samples of the n-α-Si/n-c-Si/p-α-Si:Ag HJT PVC had the lowest "saturation" currents J_{0i} and the best external quantum efficiency Q_{ext} at the long wave edge. Therefore, this structure provided the maximum laser radiation conversion efficiency ~ 24.5% (λ = 1064 nm) at a power density ≤ 2 kW/m² in the atmospheric transparency window. The efficiency of the PVC at the laser radiation power density of ~ 1 kW/m² and when the temperature changed from 293 K to 353 K increased up to 24.8%. The HJT PVC had demonstrated good temperature stability in this range, and the efficiency varied within ± 4%.

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REFERENCES

1. **Masuko K., Shigematsu M., Hashiguchi T., Fujishima D., Kai M., Yoshimura N., Yamaguchi T., Ichihashi Y., Mishima T., Matsubara N., Yamanishi T., Takahama T., Taguchi M., Maruyama E., Okamoto S.,** Achievement of More Than 25% Conversion Efficiency With Crystalline Silicon Heterojunction Solar Cell, IEEE Journal of Photovoltaics 4 (6) (2014) 1433–35.

2. **Yoshikawa K., Kawasaki H., Yoshida W., Irie T., Konishi K., Nakano K., Uto T., Adachi D., Kanematsu M., Uzu H.I., Yamamoto K.,** Silicon heterojunction solar cell with interdigitated back contacts for a photoconversion efficiency over 26%, Nature Energy 2 (5) (2017) 17032.

3. **Abramov A.S., Andronikov D.A., Abolmasov S.N., Terukov E.I.,** Chapter 7. High-Efficient Low-Cost Photovoltaics, Silicon Heterojunction Technology: A Key to High Efficiency Solar Cells at Low Cost, Springer Series in Optical Sciences 140 (2020) 113–32.

4. **Kognovitsky S.O., Malevsky D.A., Kalinovsky V.S.,** RF Patent No. RU 2021137224, Photovoltaic receiver of an optical communication line, 2021.

5. **Andreev V.M., Evstropov V.V., Kalinovsky V.S., Lantratov V.M., Khvostikov V.P.,** Current Flow and Potential Efficiency of Solar Cells Based on GaAs and GaSb *p–n* Junctions, Semiconductors 43 (5) (2009) 671–78.

6. **Kalinovskii V.S., Terukov E.I., Kontrosh E.V., Verbitskii V.N., Titov A.S.,** Radiation Resistance of α-Si:H/Si Heterojunction Solar Cells with a Thin i-α-Si:H Inner Layer, Technical Physics Letters 44 (2018) 801–3.

7. **Bothe K., Schmidt J.,** Electronically activated boron-oxygen-related recombination centers in crystalline silicon, J. Appl. Phys. 99 (2006) 013701.

8. **Chen D., Kim M., Shi J., Vicari Stefani B., Yu Z. (J.), Liu S., Einhaus R., Wenham S., Holman Z., Hallam B.,** Defect engineering of p-type silicon heterojunction solar cells fabricated using commercial-grade low-lifetime silicon wafers, Prog. Photovolt. Res. Appl. 29 (11) (2021) 1165–79.

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