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Study of the influence of electron beam irradiation on the photoelectric and electrophysical properties of silicon HJT solar cells

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Received September 11, 2023
Revised October 26, 2023
Accepted October 26, 2023

In this work, HJT solar cells based on heterostructures *n*-Si:H/*c*-*n*-Si/*p*-Si:H were fabricated and studied, as well as the effect of electron irradiation on their photovoltaic properties. It has been shown that when irradiated by electrons with a fluence of $5 \cdot 10^{14}\,\text{cm}^{-2}$, a catastrophic drop in the quantum efficiency occurs at wavelengths greater than 600 nm, leading to a decrease in the short-circuit current from 33 mA/cm^2 to 22 mA/cm^2 and the open-circuit voltage from 0.7 V up to 0.52 V, and at a fluence of $1 \cdot 10^{15}\,\text{cm}^{-2}$ and 0.50 V. Admittance spectroscopy revealed a defect with an activation energy of 0.18 eV in irradiated structures, which could probably be responsible for degradation of photoelectrical properties, and its the concentration increases with increasing fluence.

Keywords: solar cell, admittance spectroscopy, radiation resistance.

DOI: 10.61011/TPL.2024.01.57838.19726

Heterojunction silicon solar cell (SC) technology, also known as HJT (heterojunction technology — heterojunction technology) solar cells, combines the advantages of crystalline and amorphous silicon and demonstrates the ability to achieve high solar energy conversion efficiency using less silicon and lower fabrication temperatures, not exceeding 200−250°C, compared to traditional diffusion [1] technologies. The first HJT solar cells with 12% efficiency were developed in the 1990s by Sanyo [2]. After years of research, this technology has achieved an efficiency of over 26%, which is a record for single junction silicon solar cells [3].

Highly efficient SCs based on HJT technology, which are actively used on Earth, are of interest for space applications, in particular in low-Earth orbits (500−2000 km). However, the degradation of silicon SCs due to the presence of radiation in space, which can adversely affect the photovoltaic performance of the SCs, is the main limiting factor for their use in space. At present, the most common and used for space are multijunction (three or more subcells) SCs based on A_3B_5 materials, mainly based on GaAs and semiconductors similar to it in terms of lattice constant, but the cost of their creation is many times higher than for silicon SCs. Silicon SC HJTs can be used for space missions where high power consumption is not needed, and the ease of industrial creation and the cost of SCs are more important factors than the efficiency [4]. In addition, they do not require rare elements for their production, as in CIGS [5] based thin-film SCs.

By today there are very few studies of the effect of cosmic radiation on silicon SC HJTs and the mechanisms of defect formation in them. Nevertheless, there are works that study the effect of electron flow on the structure of HJT. For example, the [6] results revealed that when a heterostructured SC on an *n*-type silicon substrate is irradiated, the peak quantum efficiency decreases by 60%, and the short-circuit current and fill factor decrease by about 2 fold. This is presumably due to an increase in the activation energy of doped layers of amorphous hydrogenated silicon. In addition, thin-film solar cells based on hydrogenated nanocrystalline silicon show absorption deterioration after proton irradiation [7].

In the present work, photoelectric properties and defect formation in the structure of HJT were investigated to study the effect of electron irradiation on the properties of the HJT structure.

In work, SCs grown on substrates *n*-Si ($n = 3 \cdot 10^{15}\,\text{cm}^{-3}$) by plasma-chemical deposition are considered. More information about growth technology can be found in [8]. Fig. 1 shows the schematic structure of the solar cell. To passivate surface defects, nanolayers of native amorphous hydrogenated silicon (*i*-*a*-Si:H) are deposited on the front and back sides of the substrate. To create an ohmic contact on the back side and a potential barrier on the front side, doped layers of *n*-*a*-Si:H and

Figure 1. Investigated SC structures on *n*-Si substrates.

p-*a*-Si:H, respectively, are deposited on top of *i*-*a*-Si. The doped layers of amorphous silicon are coated with layers of conductive transparent ITO (indium tin oxide — indium tin oxide) material on the back and front sides, which also acts as an anti-reflection coating. The metal contacts were formed by screen printing silver paste.

The structures were further irradiated with 1 MeV electrons with fluxes $5 \cdot 10^{14}$ and $1 \cdot 10^{15}$ cm^{-2}. The irradiation parameters used were chosen because the equivalent fluence ($1 \cdot 10^{13}$–$1 \cdot 10^{15}$ cm^{-2}) corresponds to the stay of the studied silicon photovoltaic converters in low-Earth orbits, which is significantly lower than the corresponding value in radiation-hazardous orbits (> 2000 km).

Fig. 2 shows, for the three solar cells investigated, the current-voltage curve (CVC) measured under standard conditions at AM1.5G irradiation spectrum and 25°C temperature, and the quantum efficiency spectra measured at room temperature. The CVCs of the fabricated SCs were measured on an Abet Technologies Model 11002 SunLite solar simulator using a Keithley 2400 source-meter. The measured results show that the CVC is significantly dependent on the irradiation dose and the photoelectric properties deteriorate sharply after irradiation of the original sample. At an irradiation fluence of $5 \cdot 10^{14}$ cm^{-2}, the no-load voltage and short-circuit current decreased by about 30%: from 0.7 to 0.52 V and from 33 to 22 mA/cm^2, respectively. Further increasing the fluence to $1 \cdot 10^{15}$ cm^{-2} results in a further degradation of the photoelectric properties, but not as significant. The short-circuit current drop is also confirmed by external quantum efficiency spectra measured in the range of 300– 1200 nm at an in-house facility based on the M266-IV monochromator. The graphs show that the irradiated samples show a significant drop in quantum efficiency at wavelengths of 600 nm and longer. This behavior may indicate a deterioration of the lifetime of non-basic charge carriers in the silicon substrate volume due to the influence of radiation defects.

The possible difference in the photoelectric properties is explained by the formation of defects due to electron irradiation, so at the next stage of work the structures were studied by total conduction spectroscopy. Measurements were performed using an Agilent Keysight E4980-001 (former HP) precision ICR meter over the frequency range of 20 Hz to 2 MHz with a test signal of 50 mV at various DC bias voltages in a JANIS CCS-400H/204 helium cryostat and temperatures from 30 to 300 K. The method of total conductivity spectroscopy consists in carrying out measurements of the dependences of capacitance and conductivity on temperature and frequency. Total conduction spectroscopy is widely used to determine the electronic properties of structures with heterojunctions based on crystalline and amorphous hydrogenated silicon [9,10].

In structures based on the Schottky barrier or *p*–*n*-transition, when an AC signal is applied, the position of the Fermi level in the space charge region oscillates with frequency equal to the AC signal. Thus, the modulation

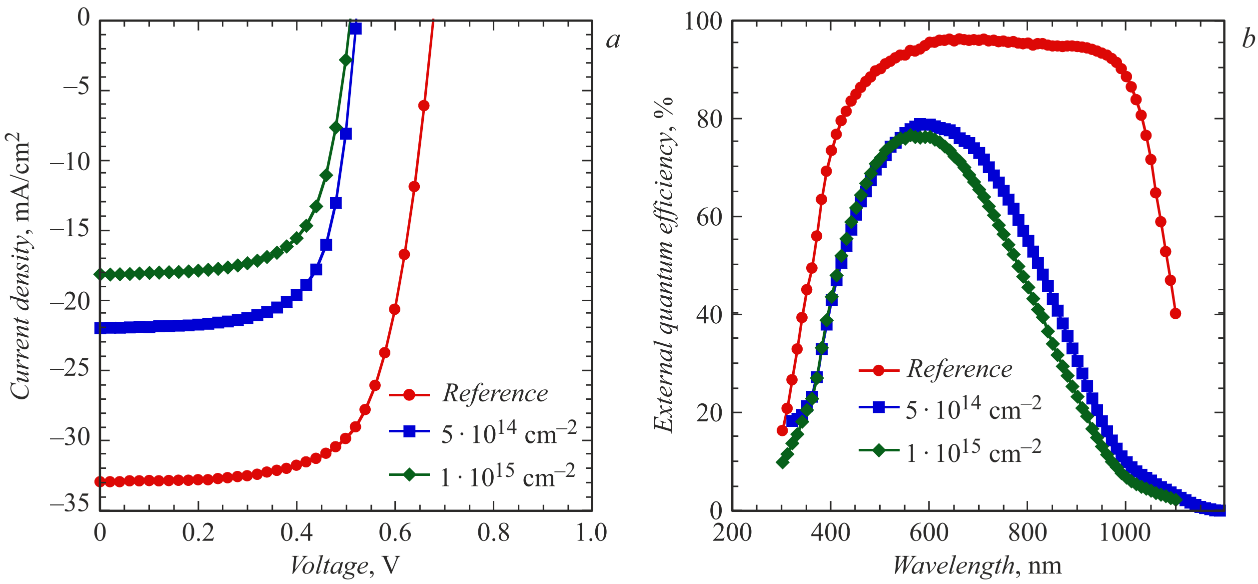

Figure 2. Current-voltage curve (*a*) and quantum efficiency (*b*) of samples with *n*-Si ($n = 3 \cdot 10^{15}$ cm^{-3}): initial and after irradiation with doses of $5 \cdot 10^{14}$ and $1 \cdot 10^{15}$ cm^{-2}.

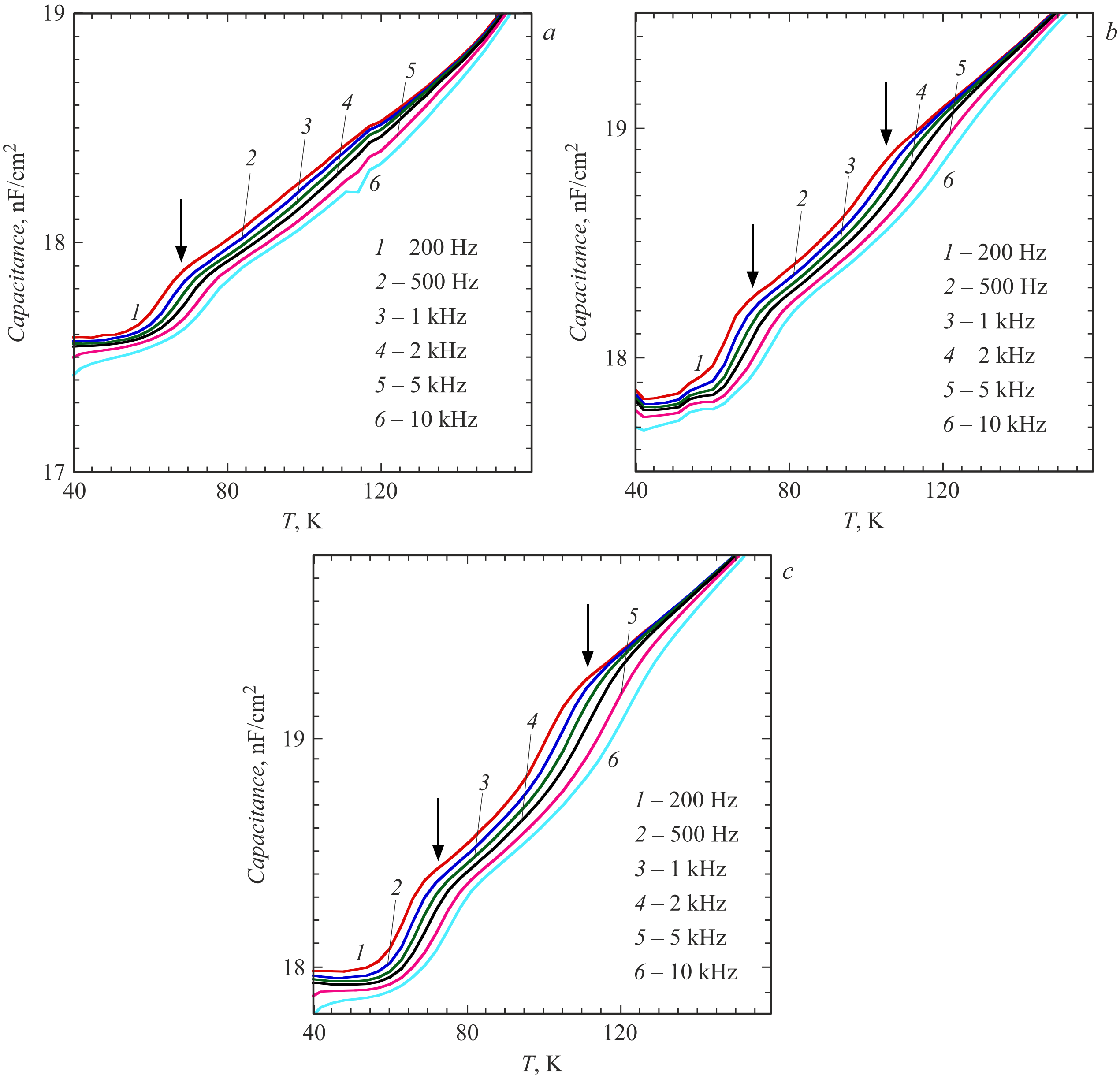

Figure 3. Dependences $C-T$ for the investigated samples with *n*-Si substrate: baseline (a) and after irradiation with doses $5 \cdot 10^{14}$ (b) and $1 \cdot 10^{15}\,\mathrm{cm}^{-2}$ (c).

of the concentration of free charge carriers in the depleted region is provided, which in turn leads to the variation of the population of states in the band gap. The population variation causes the processes of capture and emission of charge carriers on the states if the time constant of these processes is less than the period of the alternating signal. The change in charge associated with emission and trapping on states in the semiconductor, when an external voltage is applied, leads to an increase in the capacitance of the structure.

Fig. 3 shows the dependences of $C-T$ for three samples (initial, after irradiation with dose $5 \cdot 10^{14}\,\mathrm{cm}^{-2}$ and after irradiation with dose$1 \cdot 10^{15}\,\mathrm{cm}^{-2}$) at constant bias voltage 0 V. In Fig. 3, a, a series of capacitance steps in the range of 50–70 K are observed for the original sample, the position of which shifts towards higher temperatures with increasing frequency. The position of the capacitance steps for the same frequency is independent of the applied DC bias voltage. Similar capacitance behavior at low temperatures was observed previously for a-Si:H/c-Si-heterojunctions in [9] and was attributed to the conduction activation of the a-Si:H layer. The amplitude of the capacitance steps corresponds to the expected thickness of the undepleted layer a-Si:H (5–7 nm). In addition, similar series of peaks with identical amplitudes and the same step positions for the same frequencies are observed for the irradiated samples. Thus, the observed response corresponds to the thermal activation of the conduction of amorphous p-Si [10] with an activation energy equal to 0.13 eV. No other features were found in the curves for the original sample when the temperature was increased. However, in Fig. 3, b and c a second series of capacitance steps appears in the temperature range of 100−120 K, which is related to the formation of radiation defects under the influence of electron flow on the solar cell HJT. The activation energy of this defect is equal to $E_a = 0.18$ eV, and the amplitude of the response from this defect level is noticeably higher for the sample with a higher irradiation dose. Increasing amplitude indicates a higher concentration of defects. With further increase in temperature in all the samples, the capacitance curves for different frequencies almost coincide and no features are observed in the $C-T$ curves. The detected defect is probably an A-center (V−O, vacancy−oxygen) [11], which results from the activation of oxygen atoms after electron irradiation [12]. The response registration on the total conductivity spectra for the irradiated samples indicates the presence of a defect level within the space charge region, i.e. within less than 1 μm from the upper interface. Consequently, the formation of defect levels under the influence of electron flow occurs in the whole volume of the Si substrate of n conductivity type. However, in order to evaluate the uniformity of the Si thickness distribution, it is necessary to perform measurements by unsteady deep level spectroscopy at the substrate depth, which will be performed in the following experiments. Nevertheless, it is the detected formation of A-centers after irradiation that leads to a drop in the value of quantum efficiency and deterioration of photovoltaic properties. To identify ways to improve the radiation resistance of HJT solar cells, it is first necessary to consider structures formed on p-Si substrates.

Thus, in the present work, HJT solar cells on n-type silicon substrate were fabricated and studied, and the effect of electron irradiation on their photovoltaic properties was investigated. It is shown that irradiation with electrons with fluence $5 \cdot 10^{14}$ and $1 \cdot 10^{15}$ cm^{-2} results in a decrease of short-circuit current and no-load voltage. Using total conduction spectroscopy, a defect with an activation energy of 0.18 eV was detected in the irradiated structures, which could probably be responsible for this characteristic behavior.

Funding

This study was carried out under state assignment of the Ministry of Science and Higher Education of the Russian Federation (project No. 0791-2023-0007).

Conflict of interest

The authors declare that they have no conflict of interest.

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