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Degradation of solar heterostructured cells under the influence of electron flow

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Abstract. In this work, we study the effect of irradiation as in low Earth orbits on heterojunction technology structures (*p*)*a*-Si:H/(*n*)*c*-Si. The samples were irradiated with an electron beam with an energy of 2 MeV and fluences of $3\cdot10^{13}$cm^{-2} to $3\cdot10^{15}$cm^{-2}. Solar cells performance deteriorate with increasing of fluence due to decrease of lifetime of charge carriers in bulk silicon. According to DLTS measurements, three defects with activation energies of 0.18 eV, 0.25 eV and 0.43 eV were detected, and their nature was identified. Further, the concentrations of the found defects were analyzed, during which it became clear that the concentration of defects decreases with increasing depth of the investigated structure. The correlation between fluence and concentration is also visible. The average values of concentrations vary from 10^{12} to 10^{14}.

Keywords: HJT solar cells, DLTS, defects, concentration, absorption cross-section

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Деградация солнечных гетероструктурных элементов под воздействием потока электронов

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Аннотация. В данной работе исследуется влияние облучения на низких околоземных орбитах, на структуры с гетеропереходом (*p*)*a*-Si:H/(*n*)*c*-Si. Образцы облучались электронным пучком с энергией 2 МэВ и флюенсами от $3\cdot10^{13}$ см$^{-2}$ до $3\cdot10^{15}$ см$^{-2}$. Производительность солнечных элементов ухудшается с увеличением флюенса из-за

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уменьшения времени жизни носителей заряда в объемном кремнии. По результатам DLTS-измерений были обнаружены три дефекта с энергиями активации 0,18 эВ, 0,25 эВ и 0,43 эВ, а также определена их природа. Далее был проведен анализ концентраций найденных дефектов, в ходе которого стало ясно, что концентрация дефектов уменьшается с увеличением глубины исследуемой структуры. Также прослеживается корреляция между флюенсом и концентрацией. Средние значения концентраций варьируются от 10^{12} до 10^{14}.

Ключевые слова: солнечные элементы HJT,DLTS, дефекты, концентрация, сечение поглощения

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Introduction

The technology behind silicon solar cells with a heterojunction, also referred to as HJT solar cells (Heterojunction technology), combines the benefits of both crystalline and amorphous silicon. This approach shows potential for achieving high solar energy conversion efficiency while using less silicon and operating at lower manufacturing temperatures, not exceeding 200–250 °C, compared to traditional diffusion technologies [1]. These characteristics make such solar cells particularly interesting for space applications. In previous work, we studied the impact of electron irradiation with an energy of 1 MeV, similar to the values encountered in near-Earth orbits, on the photoelectrical and defect properties of HJT [2].

In this study, we will investigate the photoelectrical properties of HJT solar cells subjected to higher electron irradiation with an energy of 2 MeV. Additionally, we will use deep-level transient spectroscopy to examine defect formation in HJT samples.

Materials and Methods

This paper focuses on HJT solar cells based on anisotype heterojunction *p*-*a*-Si/*i*-*a*-Si/*n*-*c*-Si, formed on specially prepared *n*-Si ($n = 3\cdot10^{15}$ cm^{-3}) substrates using plasma-enhanced chemical vapor deposition at low temperatures. The rear contact was created on the developed *n*-Si surface by depositing a passivating *i*-*a*-Si layer followed by *n*-*a*-Si. Subsequently, transparent conducting ITO layers were sputtered using a BOC Edwards Auto500 setup, and a metallic contact was formed with silver paste, followed by annealing. Capacitance DLTS measurements were carried out with an automated system based on a Boonton-7200B capacitance bridge in the temperature range of 80–360 K in a Janis VPF-100 nitrogen vacuum cryostat. These structures were subjected to electron irradiation with an energy of 2 MeV at fluences ranging from $1\cdot10^{13}$ cm^{-2} to $3\cdot10^{15}$ cm^{-2}.

Results and Discussion

Fig. 1 shows the current–voltage characteristics measured under illumination of AM1.5G. In [2], a catastrophic drop in the current-voltage characteristic and quantum efficiency was observed after irradiation of samples with a flow of electrons with an energy of 1 MeV. During this work, a drop in performance is also observed, for example the short circuit current decreases from 26.55 mA/cm^2 to 15.7 mA/cm^2 and the open-circuit voltage from 530 mV to 430 mV. Influence of irradiation also is confirmed by spectrum of external quantum efficiency (EQE) (Fig. 2). Obviously, EQE strongly drop in long-wavelength region with increase of fluence. It means decrease of lifetime of charge carriers in bulk silicon after irradiation. Perhaps, it is explained by defect formation in depth of substrate so method of deep-level transient spectroscopy (DLTS) was applied to explore defect in HJT.

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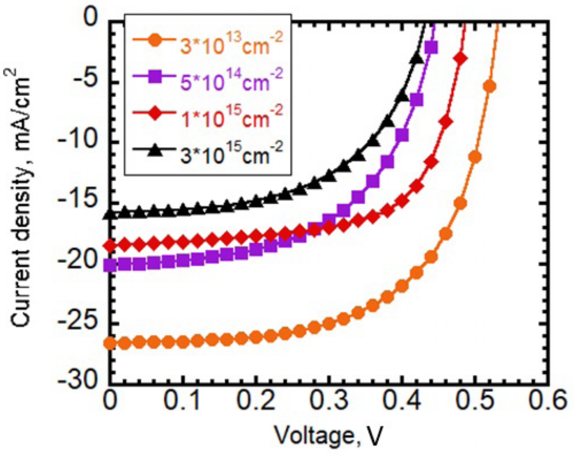

Fig. 1. Current—voltage characteristic for samples
with irradiation energy of 2 MeV and different fluence

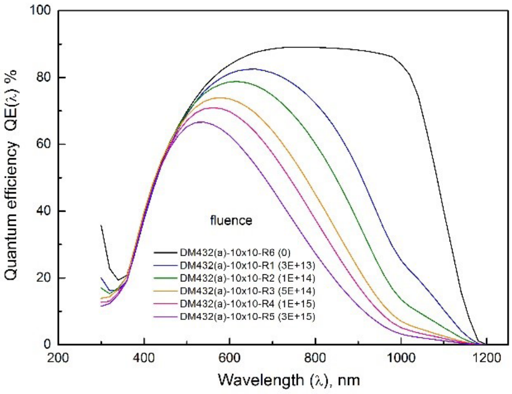

Fig. 2. External quantum efficiency of solar cells after different fluences

Thus, the mechanism of defect formation was studied using transient deep-level spectroscopy. The research process is demonstrated using a negative bias voltage of -3 V to 0 V.

When measuring a sample with a voltage U = -3—0 V, and a fluence of $3 \cdot 10^{13}$ cm^2, the graph looks non-standard due to the very high conductivity of the sample; in such cases, the values obtained by the device go beyond the measurement scale and the study cannot be carried out.

Two defects with E_a = 0.07 eV and E_a = 0.15 eV are observed in the plot with positive bias. The response with E_a = 0.07 eV in the range of 100-150 K is found in all samples close to the heterointerface in near-surface area (Fig. 3, *a*), in contrast to the bulk material (Fig. 3, *b*). However, its parameters are not critical for the photovoltaic properties due to the low capture cross section and E_a. Peak corresponding to the defect level with E_a = 0.15 eV, indicating deep defects. In addition, the amplitude of the appeared peaks increases by a factor of two with increasing irradiation dose, indicating a direct correlation between electron flux and defect appearance. Probably, the detected defect is an A-center (V—O, vacancy-oxygen) [3] arising due to the activation of oxygen atoms after electron irradiation. At negative bias voltage, new defects with activation energies E_a = 0.22 eV and E_a = 0.43 eV, in the temperature ranges of 110—180 K and 200—240 K, respectively, appeared. The defect with E_a = 0.22—0.23 eV can be explained by the appearance of an non-passivated dangling bond created by the N atom that replaces the Si vacancy [4], or perhaps this defect is associated with a V—V pair (vacancy-vacancy) [5]. This leads to the formation of unstable regions in the structure, which can affect the conductivity and recombination properties of the material. And the defect with E_a = 0.43 eV is probably an A-pair (V—H, vacancy—hydrogen) [6], which arises as a result of activation of hydrogen atoms after electron irradiation.

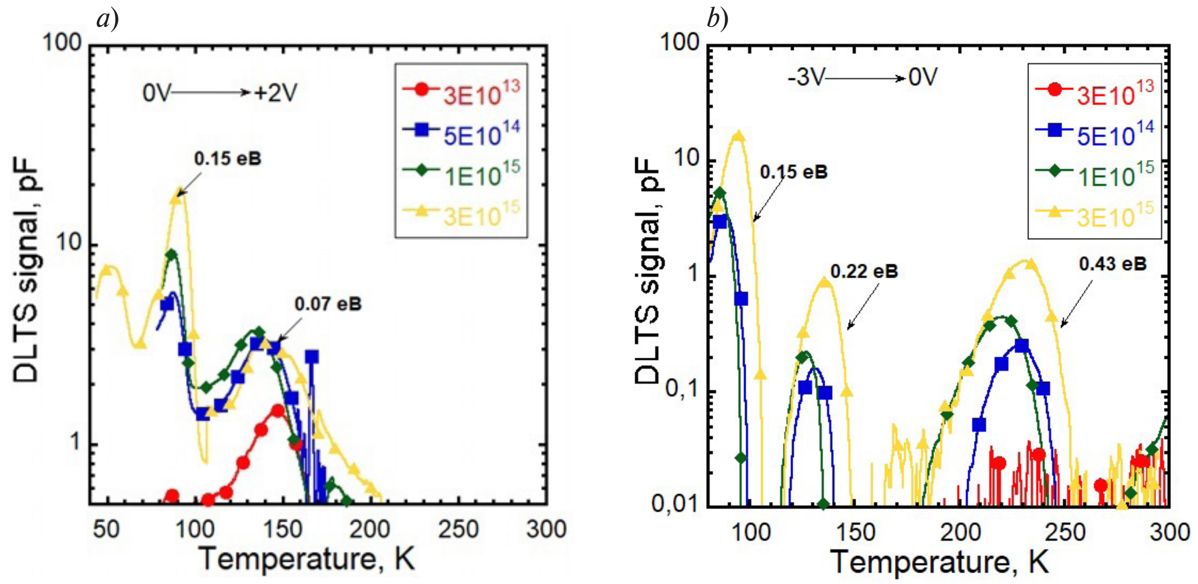

Fig. 3. DLTS signal graphs for the studied samples with fluences $3\cdot10^{13}$ cm^{-2}, $5\cdot10^{14}$ cm^{-2}, $1\cdot10^{15}$ cm^{-2} and $3\cdot10^{15}$ cm^{-2} and energy 2 MeV, at V_{init} = -3 V (*a*), V_{pulse} = +3 V and V_{init} = 0 V, V_{pulse} = +2V for emission rate of 200 s^{-1} (*b*)

Next, the values of defect concentrations were estimated. Analyzing the obtained values, it is possible to notice that with increasing depth of the investigated zone the concentration of defects decreases, for example, for a defect with activation energy 0.15 eV at a depth of about 500 nm (at positive displacement), the concentration is equal to 8.6E + 14, and with increasing depth 5.64E + 14.

Table

Main characteristics of defects

Activation energy E_a, eV	Capture cross section σ, cm^2	Concentration (V_{init} = 0 V, V_{pulse} = +2V)	Concentration (V_{init} = -3 V, V_{pulse} = 0 V)
0.07	$6\cdot10^{-21}$	1.86E + 13	–
0.15	$4.5\cdot10^{-15}$	8.6E + 14	5.64E + 14
0.22	$9\cdot10^{-15}$	1.13E + 13	1.65E + 13
0.43	$5\cdot10^{-15}$	–	9.46E + 13

Conclusion

HJT solar cells were studied after electron irradiation with an energy of 2 MeV at fluences from $1\cdot10^{13}$cm^{-2} to $3\cdot10^{15}$cm^{-2}. Quantum efficiency extremely drops with increasing of dose of electron irradiation in long-wavelength area of spectrum due to formation of defects in bulk silicon with activation energy of 0.15 eV, 0.22 eV and 0.43 eV detected by DLTS, and their concentration increases with growth of fluences.

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REFERENCES

1. **Green M.A., Dunlop E.D., Yoshita M., et. al.,** Solar cell efficiency tables (version 62), Prog. Photovoltaics Res. Appl. 31 (7) (2023) 651–663.

2. **Mikhaylov O.P., Baranov A.I., Gudovskikh A.S., Terukov E.I.,** Deep-level transient spectroscopy of solar cells based on HJT architecture under influence of electron irradiation, St. Petersburg State Polytechnical University Journal. Physics and Mathematics. 17 (1.1) (2024) 160–164.

3. **Losee D.L.**, Admittance spectroscopy of impurity levels in Schottky barriers, J. Appl. Phys. (46) (1975) 2204–2214.

4. **Masafumi Y., Kan-Hua L., Kenji A**., Analysis for Radiation Degradation of Advanced SiSpace Solar Cells, 46th Photovoltaic Specialists. 48 (2021) 3124.

5. **Zholdybayev N., Aimaganbetov K., Zhantuarov K., et. al.,** Development of Hetero-Junction Silicon Solar Cells with Intrinsic Thin Layer, A Review. Coatings. (15) (2023) 814.

6. **Hiller D., et. al.,** Kinetics of bulk lifetime degradation in float-zone silicon: fast activation and annihilation of grown-in defects and the role of hydrogen versus light, Physica Status Solidi. 217 (17) (2020) 2000436.

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