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Deep-level transient spectroscopy of solar cells based on HJT architecture under influence of electron irradiation

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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. To compare the photoelectric properties, three samples were created: the original (without electron irradiation) and two irradiated ones with the fluence of irradiation of $5\cdot10^{14}$ cm^{-2} and $1\cdot10^{15}$ cm^{-2}. Catastrophic deterioration of photoelectrical properties were observed for this irradiation: short-circuit current falls almost by two times, and open-circuit voltage drops by 150–200 mV. By measurements of deep-level transient spectroscopy, formation of A-center (V-O, vacancy-oxygen) with 0.16–0.17 eV in silicon wafer in bulk material were shown, and its concentration increases with growth of irradiation dose. Its arising leads to degradation of solar cells.

Keywords: solar cells, heterojunction, irradiation, defects

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Нестационарная спектроскопия глубоких уровней в солнечных элементах HJT архитектуры под действием облучения электронами

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Аннотация. В данной работе проводится исследование влияния сходного с космическим излучения на околоземных орбитах на дефектообразование в СЭ на подложках кремния *n*-типа с технологией гетероперехода, выращенных методом плазмохимического осаждения. Для сравнения фотоэлектрических свойств были созданы три образца: исходный (без электронного облучения) и два облученных с флюенсом облучения $5\cdot10^{14}$ cm^{-2} и $1\cdot10^{15}$ cm^{-2}. Продемонстрировано катастрофическое падение параметров солнечных элементов: ток короткого замыкания падает почти в два раза, а напряжение холостого хода на 180–200 мВ. Измерения методом нестационарной спектроскопии глубоких уровней продемонстрировали формирование А-центров (V-O, комплекс вакансия-кислород) с энергией активации 0.16–0.17 эВ во всем объеме подложки кремния, а их концентрация растет с увеличением дозы облучения. Таким образом, их формирование ответственно за ухудшение фотоэлектрических свойств рассматриваемых солнечных элементов на *n*-Si.

Ключевые слова: солнечные элементы, гетеропереход, космическое излучение, дефекты

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Introduction

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

Solar elements based on HJT technology, actively used on Earth, are of interest for space applications. However, due to the presence of radiation in outer space, which can negatively impact the electro-optical characteristics of solar elements, research is needed to study the influence of space radiation on HJT structure. Currently, there is much less research in this area compared to A3B5 elements. Nevertheless, there are articles investigating the impact of electron flux on HJT structure. For example, according to the results of the article [4], it was found that when irradiating the heterostructure of the solar element on an n-type silicon substrate, the peak quantum efficiency decreases by 60%, and the short-circuit current and fill factor decrease by approximately two times. Presumably, this is due to the increase in energy required for minimum electrical conductivity of doped layers of amorphous hydrogenated silicon. Additionally, deterioration of absorption in silicon-based heterostructure solar elements after proton irradiation has been demonstrated [5]. In our previous work, we explored irradiated by electros HJT by admittance spectroscopy. Admittance spectroscopy revealed a defect with a conductivity activation energy of 0.18 eV in irradiated structures, which could probably be responsible for degradation of photoelectrical properties, and its concentration increases with increasing fluence [6]. However, this method is mostly sensitive to interface states and defect located near to heterojunction in space charge region of silicon wafer, so it is complicated to obtain information about bulk properties of silicon wafer.

Therefore, in this study deep-level transient spectroscopy will be applied to HJT samples to profile silicon wafer far from heterojunction *a*-Si:H/*c*-Si.

Materials and Methods

The paper discusses solar cells grown on *n*-Si ($n = 3\cdot10^{15}$ cm^{-3}) substrates using plasma-enhanced chemical vapor deposition. To passivate surface defects on the front and rear sides of the substrate, layers of intrinsic amorphous hydrogenated silicon (*i*-*a*-Si:H) are applied. To create ohmic contact on the rear side and a heterojunction on the front side, layers of doped *n*- and *p*-*a*-Si:H are deposited on the intrinsic layers. Layers of conducting transparent material ITO (indium tin oxide) were applied onto the doped amorphous silicon layers on the rear and front sides, serving also as an anti-reflective coating. Metallic contacts were formed using the screen-printing method with silver paste.

These structures were affected by electron irradiation with an energy of 1 MeV at fluences of $5 \cdot 10^{14}$ cm^{-2}, $1 \cdot 10^{15}$ cm^{-2}. The chosen irradiation parameters were selected due to the resulting equivalent fluence ($1 \cdot 10^{13} - 3 \cdot 10^{15}$ cm^{-2}) corresponds to the exposure of the investigated silicon photovoltaic converters in low Earth orbits, significantly lower than the corresponding value in radiation-hazardous orbits (> 2000 km). The *I*–*V* curves under AM1.5G (100 mW/cm^2) were measured using Abet Technology SunLite simulator and Keithley 2400 source-meter.

Deep-level transient spectroscopy (DLTS) is the powerful method for exploration defect levels in semiconductor devices and heterojunction. The method is based on measurement of capacitance relaxation of the space charge region after filling it with a bias voltage pulse. The rate of capacitance relaxation is determined by the rate of charge carrier emission from possible deep levels within the semiconductor bandgap, which, in turn, depends on the temperature. Capacitance deep-level transient spectroscopy were done using an automated installation based on a Boonton-7200B capacitance bridge in the temperature range of 40–300 K in Janis CCS-400H/204 helium cryostat. The setup allows to apply bias voltage with different amplitude, all measurements were carried out in the LabView environment.

Results and Discussion

The current-voltage characteristics of the studied samples are presented in Fig. 1. Measurement results indicate that the *I*–*V* curves significantly depend on the irradiation dose, and the photoelectric properties sharply deteriorate after irradiating the reference. At an irradiation fluence of $5 \cdot 10^{14}$ cm^{-2}, the open-circuit voltage and short-circuit current dropped by approximately 30%, from 0.7 V to 0.52 V and from 33 mA/cm^2 to 22 mA/cm^2, respectively. Further increasing the fluence to $1 \cdot 10^{15}$ cm^{-2} leads to additional deterioration in the photoelectric properties, although not as significantly. Such behavior is explained by centers of non-radiative recombination in silicon wafer.

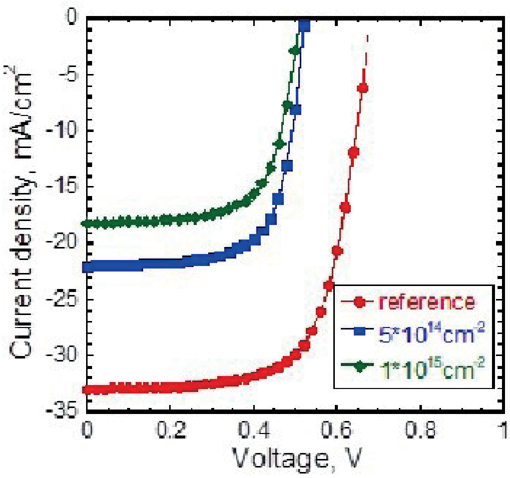

Fig. 1. Current-voltage characteristics under AM1.5G illumination at 25 °C of the studied samples

Further capacitance methods were applied to HJT solar cells. Firstly, capacitance-voltage characteristics for 1 MHz for initial sample is presented in Fig. 2, also dependence of depth on applied voltage is shown. As a result, electron concentration of $3 \cdot 10^{15}$ cm^{-3} is estimated which corresponds to doping of silicon wafer. *I*–*V* characteristics for irradiated samples are similar.

Secondly, DLTS measurements were done for two different modes: V_{init} = 0 V, V_{pulse} = + 2 V and V_{init} = - 8 V, V_{pulse} = + 5 V, pulse time is 50 ms, and relaxation was measured during 150 ms. Such two modes allow to detect defects in different space in silicon wafer: first one is near to heterojunction (not deeper than 550 nm, Fig. 2), and second one in bulk of wafer (in depth 1000° - 2000 nm, Fig. 2). DLTS spectra for rate window of 50 s^{-1} for three samples are presented in Fig. 3, *a* and 3, *b* for first mode and second one respectively. In the *S*(*T*) graph of the reference HJT the response with high amplitude in the range of 40–55 K is observed, and the similar response was obtained in two irradiated samples. For *a*-Si:H the position of the Fermi level weakly depends on temperature due to high density of states (DOS) in the mobility gap.

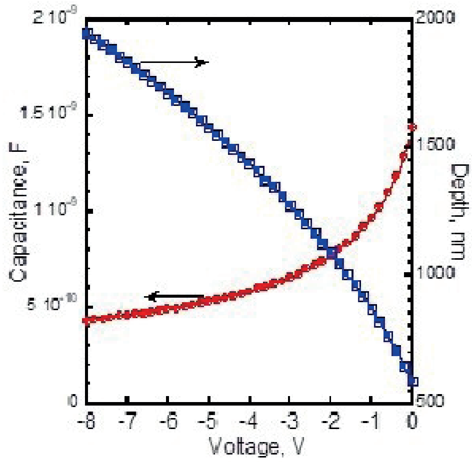

Fig. 2. Capacitance-voltage and depth-voltage characteristics for initial HJT solar cell

This effect is called pinning of the Fermi level. As a consequence electron (or hole for *p*-type) charge carrier density and conductivity has an exponential dependence on the temperature.

This temperature dependence is usually used to determine conductivity activation energy (being related to the position of the Fermi level) from Arrhenius plot (conductivity vs. $1/T$) [6]. It corresponds to the excitation energy of the impurity atom required to create the inactivation energy purity electrical conductivity of the *p*-*a*-Si:H semiconductor and is independent of irradiation, and is also detected using admittance spectroscopy [7]. Also, the response with $E_a = 0.07$ eV in the range of 100–150 K is detected in all samples, even in reference near to heterojunction (Fig. 3, *a*) unlike in bulk material (Fig. 3, *b*). But its parameters is not critical for photoelectric properties due to low capture cross section and E_a. However, in HJT solar cell irradiated by fluences of $5{\cdot}10^{14}$ cm^{-2} additional peak appears in 90 K corresponding to defect level with $E_a = 0.16$–0.17 eV, indicating the deep defects. Furthermore, these the amplitude of appeared peaks grows in two times with the increase in irradiation dose, suggesting a direct correlation between the electron fluence and the appearance of defects. The detected defect is probably an A-center (V-O, oxygen vacancy) [8], which arises as a result of the oxygen atom being displaced from a lattice site to the nearest interstitial site [9]. Furthermore, similar responses were detected in depth of silicon (Fig. 3, *b*), and estimated concentration (10^{12}–10^{13} cm^{-3}) is similar in both modes. It suggests arising of detected defects in the common silicon wafer, which leads to a deterioration in the photoelectric properties of the HJT of all solar cells of this series after irradiation. This result in

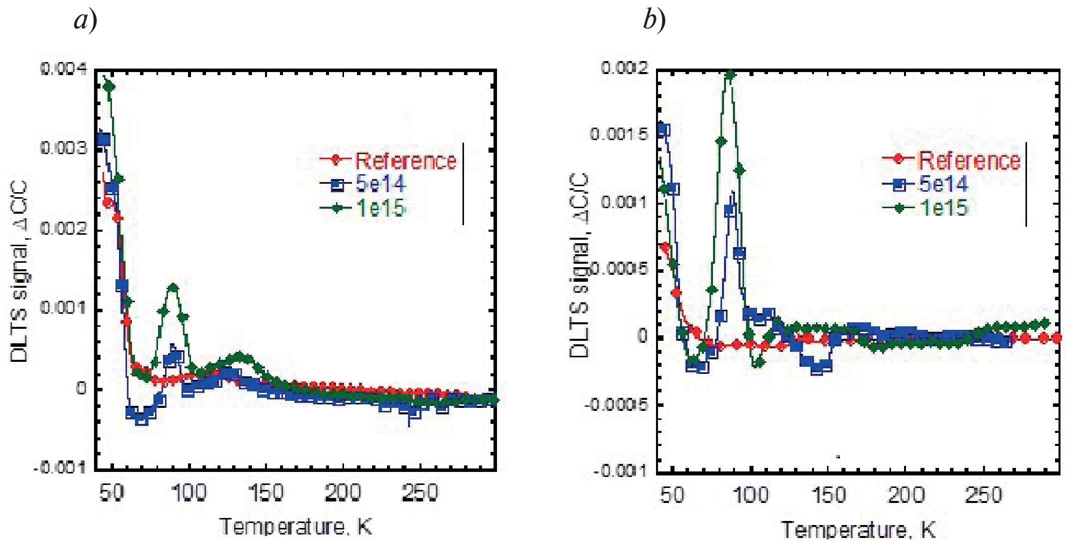

Fig. 3. DLTS spectra for rate window of 50 s^{-1} for all samples obtained under conditions $V_{init} = 0$ V, $V_{pulse} = +\,2$V (*a*) and $V_{init} = -\,8$V, Vpulse = + 5V (*b*)

good correlation with measurement of admittance spectroscopy, but here we prove formation of A-center in the entire volume of the silicon wafer.

Conclusion

In result, influence of irradiation as in low Earth orbits on properties of solar cells based on heterojunction (*p*)*a*-Si:H/(*n*)*c*-Si were studied. Catastrophic deterioration of photoelectrical properties were observed for this irradiation: short-circuit current falls almost in two times, and open-circuit voltage drops by 150–200 mv. By measurements of deep-level transient spectroscopy, formation of A-center (V-O, vacancy-oxygen) with 0.16–0.17 eV in silicon wafer in bulk material were shown, and its concentration increases with growth of irradiation dose. Its arising leads to degradation of solar cells.

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