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Improved Method for Radiation Degradation Studying of Concentrated Solar Radiation Converter Subcells Based On AIIIBV/Ge Compounds

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Abstract. This paper presents the results of a study of the output electrical and spectral characteristics of subcells of concentrated solar radiation (CSR) converters based on semiconductor materials with the InGaP/InGaAs/Ge before and after electron irradiation with an energy of 7 MeV and a fluence 3×10^{12} cm^{-2}, 3×10^{13} cm^{-2} and 1×10^{15} cm^{-2}. The spectra of the external quantum efficiency (EQE) and electroluminescence (EL) spectra of the multi-junction CSR converters were analyzed. The degradation curves of the main electrical parameters of the CSR converters were obtained and analyzed: short-circuit current density J_{SC}, open-circuit voltage V_{OC}, maximum power P_{max} and efficiency. The change in the diffusion length of the minority charge carrier (CC) of the semiconductor materials of the CSR converter subcells due to electron irradiation was also considered. An improved method for calculating the open-circuit voltage for each subcell of the converter using the optoelectronic spectral reciprocity ratio was proposed and tested. It was shown that despite the greatest current degradation of the Ge subcell as a result of irradiation at a fluence of 1×10^{15} cm^{-2}, the InGaAs subcell makes the greatest contribution to the power degradation of the device in question.

INTRODUCTION

Nowadays, one of the reliable and well-proven primary power sources of the spacecrafts is solar panels (SP) based on solar cells (SC) with the InGaP/InGaAs/Ge structure [1]. The development of concentrator solar photoenergy is relevant for modern spacecraft. Due to the CSR the CS area can be less than 1 cm^2, which allows us to radically reduce the consumption of semiconductor materials per device. At the same time, the efficiency of the CSR converter can be higher than 40% compared to the most common SC with area ~ 30 cm^2 for which the efficiency value is (26 – 30) %. One of the converters advantages of this type is the effect of photo-injection annealing of the semiconductor structure, which can lead to decrease of the degradation of the output electrical characteristics [1 – 4]. In addition, smaller area of the device plays a role, as well as the shielding effect of the concentration system. The degradation of the characteristics of the SP and SC during their operation is mainly caused by the impact of ionizing radiation, the share of which is about 40 % [5] of all the factors of outer space. The uneven effect of radiation on the structure and, as a result, on the output characteristics of the device encourages the study of this effect also in order to optimize the elements of the concentration system. However, multi-junction converter structure causes difficulties in terms of research. To solve this problem, some researchers use specially designed elements similar to subcell converters, which requires additional costs [6, 7].

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The main purpose of this work is to analyze the degree of subcells degradation of CSR converters as a result of electron irradiation. So, an improved method for calculating the electrical parameters of converters was proposed based on well-known methods for studying the SC, using which there is no need to manufacture additional elements.

EXPERIMENTAL PROCEDURE

During the experiment CSR converters or SC with an area of (0.9 × 0.9) cm^2 with InGaP/InGaAs/Ge triple structure were studied. Three stages of experimental irradiation of the CSR converters at an electron accelerator with an energy of 7 MeV were carried out sequentially at fluences of 3×10^{12} cm^{-2}, 3×10^{13} cm^{-2} and 1×10^{15} cm^{-2}. Before and after irradiation, the I-V characteristic at 25X CSR (AM0, 25 °C) and spectral characteristics were studied: EQE (AM0, 25 °C), EL (25 °C). On the basis of the obtained data, the change in the electrical parameters of the converter subcells was calculated.

It is necessary to set the J_{SC} of the converter at 1X to measure the I-V characteristic of the CSR converter. In this work, the J_{SC} of the converter at 1X was obtained from the EQE spectra [8], while taking into account that the output current of the SC is the current from the subcell generating the minimum current.

The EL spectra were recorded as follows: direct current was applied to the SC in the forward direction in the range from (0.03 – 0.54) A in increments of 0.03 A, while the voltage at the power source did not exceed 3.2 V. In this case, the SC operated in the LED mode. The spectrum was recorded using the Ocean Optics "USB 2000+" spectrometer in the range from (200 – 1100) nm, which captures the radiation spectra of only the two upper subcells – InGaP and InGaAs.

RESEARCH METHODS

Based on the measured characteristics of the CSR converter described above, the electrical parameters of the subcells before irradiation were calculated. The V_{OC} of the converter subcells was calculated using the expression (1) derived from the spectral reciprocity ratio [9 – 11], which relates the spectra of EQE and EL:

$$V_i(J_{EL}) = \frac{kT}{q}\ln\left[\varphi_{EL\,i}(J_{EL})\right] + \frac{E_{max\,i}}{q} - 2\frac{kT}{q}\ln(E_{max\,i}) - \frac{kT}{q}\ln(\varphi_{EQE\,i}) - \delta V = V_i^*(J_{EL}) - \delta V, \qquad (1)$$

where k is the Boltzmann constant, eV/K; T is the temperature, K; q is the elementary electric charge, C; $\varphi_{EL\,i}\,(J_{EL})$ is the intensity of the EL peak signal of the subcell i at a given injection current density, relative units; J_{EL} is the injection current density when shooting the EL subcell spectrum, mA/cm^2; $E_{max\,i}$ is the energy at the maximum EL intensity corresponding to the subcell i of the SC, eV; $\varphi_{EQE\,i}$ is the EQE for the subcell i of the SC, relative units; δV is the voltage offset, V.

The data of the EL spectrum of the Ge subcell of the unirradiated CSR converter were taken from [9].

The voltage offset is expressed by the following formula:

$$\delta V = \frac{1}{3}\left[\sum_{i=1}^{3} V_i^*(J_{EL\,i} = J_{Photo\,i}) - V_{OC}^{SC}\right], \qquad (2)$$

where $J_{Photo\,i}$ is the photocurrent density obtained from the spectra of the EQE, mA/cm^2; V_{OC}^{SC} is the open-circuit voltage obtained from the measurements of the I-V characteristic of the SC, V.

The calculation of the V_{OC} of the subcells after irradiation was carried out in the same way, but it is necessary to determine the degradation coefficient of the diffusion length of the minor CC K_L to calculate the Ge subcell. The data required for the calculation were taken from the energy dependence of non-ionizing energy loss (*NIEL*) from the work [12]. From the dependence graph for the corresponding energy value, the value *NIEL* was selected, and then, according to the found value, the corresponding K_L was selected according to the dependence $K_L(NIEL)$ from the data of the work [13]. Then the diffusion length of the minor CC after irradiation was calculated using the formula [12, 14]:

$$\frac{1}{L^2} = \frac{1}{L_0^2} + K_L \Phi \tag{3}$$,

where L is the diffusion length of the minor CC after irradiation in material, cm; L_0 is the diffusion length of the minor CC before irradiation in material, cm; K_L is the material damage coefficient, relative units; Φ is the fluence of the damaging particles, cm^{-2}.

To calculate the Ge subcell voltage after irradiation, it is necessary to apply the formula (4), which uses the data before irradiation, as well as the change in the diffusion length of the minor CC [15]:

$$V_{OC}^{Ge} = V_{OC0}^{Ge} - \frac{2kT}{q} \ln\left(\frac{L_{n0}^{Ge} L_{p0}^{Ge}}{L_n^{Ge} L_p^{Ge}} \right) \tag{4}$$,

where V_{OC0}^{Ge} – the open-circuit voltage of the Ge subcell before irradiation, V; L_{n0}^{Ge}, L_{p0}^{Ge} – the diffusion length of the electrons and holes before irradiation, respectively, cm; L_n^{Ge}, L_p^{Ge} – the diffusion length of the electrons and holes after irradiation, respectively, cm.

Then, using the formula (1), the voltages of the InGaP and InGaAs subcells were calculated. In this case, the voltage offset (formula (2)) will have the form:

$$\delta V = \frac{1}{3}\left[\sum_{i=1}^{3} V_i^*(\mathrm{J}_{EL\ i} = J_{Photo\ i}) + V_{OC}^{Ge} - V_{OC}^{SC} \right]. \tag{5}$$

Thus, with the help of the above calculations, the desired values of the degradation parameters of the CSR converters from the incident radiation were obtained.

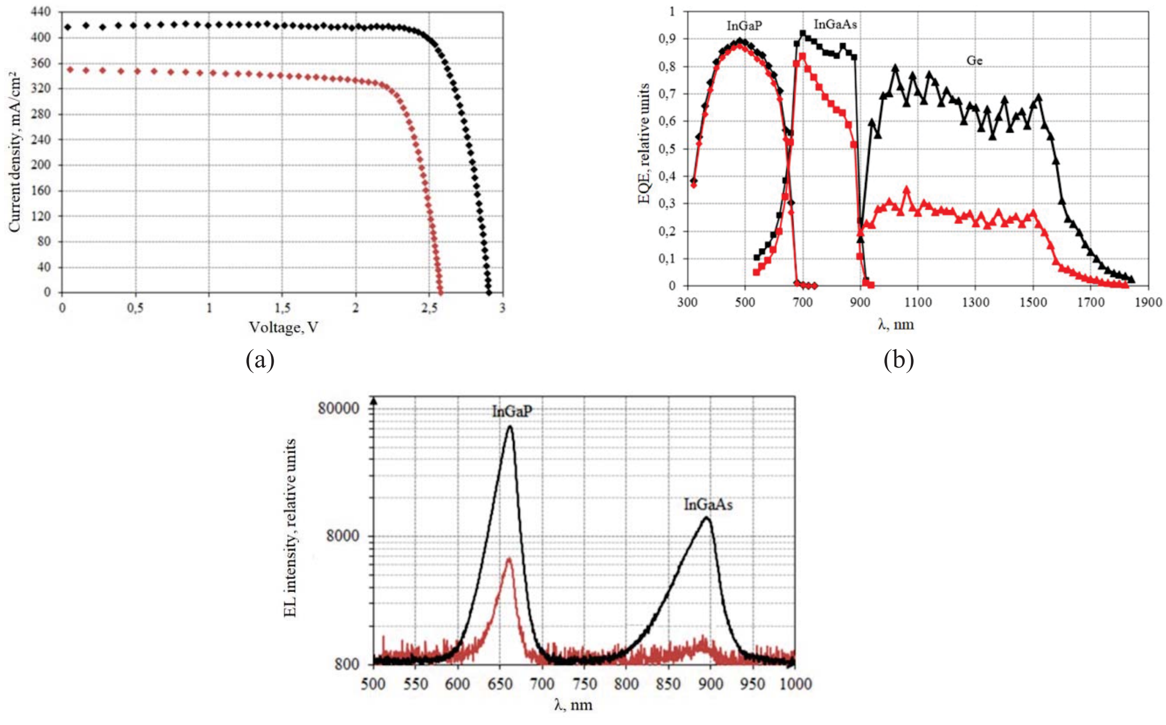
RESULTS AND DISCUSSION

Figure 1 shows the experimentally obtained averaged output characteristics of the CSR converters before and after irradiation with electrons with an energy of 7 MeV and a fluence of 1 × 10^{15} cm^{-2}: I-V characteristic, EQE, EL. For clarity, the results of irradiation with a fluence of 1 × 10^{15} cm^{-2} are analyzed, since the change in output characteristics was insignificant when irradiated with fluences of 3 × 10^{12} cm^{-2} and 3 × 10^{13} cm^{-2} with the same electron energy.

The degradation of the informative parameters, which represent the ratio of the electrical parameter after the n-th stage of irradiation to its initial value, was estimated on the basis of the obtained SC I-V characteristics (Fig. 1(a)). Figure 2 shows graphs of the dependence of the informative parameters of the converter on the electron fluence. The graphs were approximated by the least squares method according to the formula [16 – 18]:

$$f(\Phi_e) = 1 - C \cdot \lg\left(1 + \frac{\Phi_e}{\Phi_x}\right) \tag{6}$$

where C и Φ_x — approximation parameters.

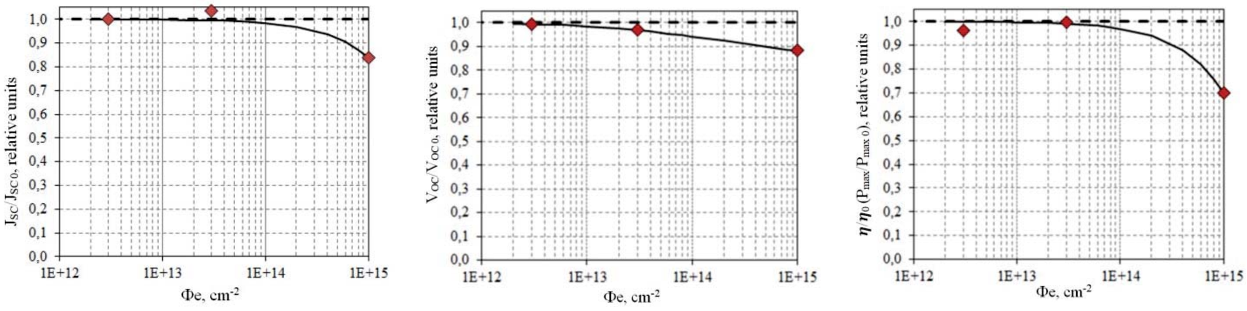


(a)

(b)

(c)

FIGURE 1. Output characteristics of the CSR converter before (black) and after (red) electron irradiation with a fluence of 1×10^{15} cm^{-2}: (a) – I-V characteristics, (b) – EQE, (c) – EL



(a)

(b)

(c)

FIGURE 2. Graphs of the dependence of the main electrical parameters of the CSR converters on the electron fluence: (a) – short-circuit current, (b) – open-circuit voltage, (c) – efficiency (maximum power)

As can be seen from Figure 2, the informative parameters remain almost unchanged until the fluence value is 3×10^{13} cm^{-2}. As a result of irradiation of the CSR converter with electrons with a fluence of 1×10^{15} cm^{-2}, the value of the J_{SC} SC fell from 417 mA/cm^2 to 350 mA/cm^2 (at 25X), the value of V_{OC} degraded by 12 % and became equal to 2.58 V. In addition, the efficiency value decreased by several percent and became equal to 21 %, and the power received from the SC (P_{max}) fell by 28 %.

To identify the contribution of defect formation in the subcell layers to the overall degradation of the SC, we refer to the results of measurements of the EQE spectra shown in Figure 1(b). No negative effect of electron radiation on the InGaP subcell was observed. This is due to its small thickness-about 0.5 μm [19]. A significant degradation of the spectrum is observed in the base area of the InGaAs subcell, since its thickness is several times greater than that of the InGaP subcell [19]. Besides, the electrons have a large penetration depth into the semiconductor structure, forming fields of disordering, mainly in the long-wavelength part of the spectrum, which explains the degradation of the Ge subcell [20].

Figure 1(c) shows the change in the EL spectra of the InGaP and InGaAs subcells. Since the EL is based on the radiative recombination of the minor CC of a semiconductor material, we can see from the obtained spectra that the luminescence intensity decreases with an increase in the electron fluence value. The fact is that in the semiconductor materials of the subcells, structural defects occur, which create allowed levels in the band gap of the semiconductor. Consequently, the probability of nonradiative recombination of CC – scattering on defects and phonons of the crystal lattice – increases [21]. At the same time, a pattern similar to the EQE spectra is observed – the electrons significantly affected the InGaAs subcell (the long-wave part of the spectrum). The peak intensity of the InGaAs subcell dropped almost to the level of the minimum signal discernible by the spectrometer. This may indicate that there are more defects in the structure of the InGaAs subcell than in the InGaP subcell.

The average values of the electrical parameters of the CSR converters obtained from the calculations are presented in Table 1. The value of the diffusion length of the minor CC SC subcells before irradiation was taken from [15]. As a result of exposure to ionizing radiation, in particular electrons, structural defects appear in the semiconductor structure (mainly Frenkel pairs), which reduces the lifetime and diffusion length of the minor CC, which leads to the degradation of all the main electrical parameters of the SC [22]. As can be seen from Table 1, the diffusion length of the minor CC has been degraded in the p-areas of the subcells, which is consistent with the spectra of the EQE (Fig. 1(b)). Since the p-base is larger than the n-emitter in thickness, the probability of recombination centers increases accordingly.

TABLE 1. The values of the CSR converters parameters before and after irradiation with electrons with an energy of 7 MeV and a fluence of 1 × 10^{15} cm^{-2}.

SC area	**Before Irradiation**			**After Irradiation**		
	***L*, µm**	***J_{SC}*, mA/cm^2**	***V_{OC}*, V**	***L*, µm**	***J_{SC}*, mA/cm^2**	***V_{OC}*, V**
n-InGaP	0.05	17.70	1.55	0.05	16.97	1.51
p-InGaP	2.00			0.27		
n-InGaAs	0.30	17.74	1.06	0.30	13.94	0.76
p-InGaAs	7.00			5.31		
n-Ge	0.50	21.79	0.31	0.50	16.51	0.29
p-Ge	50.00			37.35		
SC (calculation)		17.70	2.91		13.94	2.56
SC (experiment)		19.16	2.91		16.13	2.56

Since the subcells are connected in series with each other, it is important to take into account the fact that the generated current is limited to the subcell that generates a current of the minimum value [19]. It can be noted that InGaP plays the role of the limiting subcell before irradiation, and InGaAs plays the role of the limiting subcell after irradiation. The greatest degradation in photocurrent is observed in the Ge subcell – 24.2 %, but its current reserve is still sufficient, so its degradation can be ignored. The InGaAs subcell is of the greatest interest, its J_{sc} decreases from the initial value of 17.74 mA/cm^2 to 13.94 mA/cm^2 (21.4 %). The J_{SC} value of the InGaP subcell fell by 4.1 %, which does not affect the output current of the SC.

The change in V_{OC} is caused by an increase in the dark current under the influence of a decrease in the diffusion length of CC, as well as an increase in the generation component in the space charge region [23]. The V_{OC} of the InGaP subcell fell by 2.6 %, the InGaAs subcell by 28.3 %, and the Ge subcell by 6.5 %.

According to the obtained data, it is possible to approximate the power degradation of each subcell: InGaP – 6.6 %, InGaAs – 43.7 %, Ge – 37.3 %, while the change in the P_{max} of the CSR converter obtained by measuring the I-V characteristic was 28.4 %. The degradation of the voltage of each of the subcells, as well as the change in the current of the limiting subcell, contributes to the degradation of the SC in terms of power.

The method considered in this paper is not limited to the size of the samples under study, but can also be used to assess the degradation of the SC as a result of proton irradiation.

CONCLUSION

As a result of irradiation of the CSR converter, its degradation in terms of J_{SC}, V_{OC}, and P_{max} (efficiency) was about 16 %, 12 %, and 28%, respectively. The change in the P_{max} of the SC was significantly affected by the greatest degradation in the power of the InGaAs subcell, which is caused by a decrease in the diffusion length of the minor CC in the p-base from 7 μm to 5.31 μm. The contribution of the deterioration of the electrical parameters of the remaining subcells to the degradation of the SC was insignificant due to the small thickness of the InGaP subcell, as well as the presence of a current reserve and a small contribution to the voltage of the Ge subcell. In the course of the conducted studies of the irradiated CSR converter, it is shown that the improved technique is applicable for the analysis of the electrical parameters of multi-junction SC, namely, the parameters of individual subcells during tests for the radiation resistance of the SP.

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