POSTRADIATION LIGHT EXPOSURE FOR PHOTOINJECTION ANNEALING AT SOLAR CELL IRRADIATION TESTS

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ABSTRACT: The present work generalizes results of our own experimental investigations of the effect of the postradiation light exposure on the efficiency restoration of single- and multijunction SC photovoltaic parameters. Presented are the data on irradiation of SCs by 1-3 MeV electrons and 6.3 MeV protons with allowing for photoinjection annealing on a simulator of high-intensity light flux (up to 360 X) in the temperature range up to 100 °C. It has been determined that, after photoinjection annealing, I-V characteristic parameters of all SCs were improved. However, for SCs irradiated by protons, restoration of the properties occurs essentially in less extent compared to SCs irradiated by electrons. So, the recovery of the short circuit current occurs in greater extent compared to that of the open circuit voltage. A comparative analysis of different ways of the illumination simulation has been carried out. On the base of studying the effect of intensity and exposure duration of the light flux on the effectiveness of annealing of radiation defects, with allowing for estimation of the semiconductor structure tolerance to irradiation, recommendations for conditions of postradiation light exposure of SCs have been proposed.
Keywords: Concentrator Cells, Radiation Damage, Photoinjection Annealing

1 INTRODUCTION

The radiation tolerance is one of the main operational properties of SCs intended for space-craft solar arrays functioning on the radiation dangerous orbits. For this reason, considerable attention is given to estimating the indices of the SC radiation resistance. Such estimations are obtained, as a rule, on the bases of testing SCs under action of monoenergetic electrons and protons, as the main component of space radiation environment on the near-earth orbits. Requirements to the procedure for such tests are determined by ISO/WS 23038. In accordance with these requirements, taking account of possible effects of thermal annealing of radiation defects should be done by holding a SC after irradiation in conditions of the operation temperature during the time ensuring stabilization of the output electrical characteristics of a SC.

In known designs of solar arrays for spacecrafts based on modules with sunlight concentrators, SCs on the basis of $A^{III}B^{V}$ semiconductors are used [1-3]. The real operation temperature of concentrator module SCs does not, as a rule, exceed 100°C, which is much lower than the threshold of thermal annealing of radiation defects in these semiconductors [4, 5]. However, considerable amount of experimental data indicating the effect of the charge carrier concentration in semiconductors on the effectiveness of annealing of radiation defects is known. For this reason, at high level of illuminance of concentrator SCs, annealing of some types of radiation defects may take place also at temperatures lower than the thermal annealing threshold.

In known works, the influence of luminance on the radiation degradation of different SCs was being established experimentally, and the effect of SC photovoltaic parameters recovery depending on the irradiation fluence, type and energy of particles, annealing temperature and semiconductor material.

In [6], SCs based on AlGaAs-GaAs heterostructure were irradiated on air by 20.6 MeV protons and 1 MeV electrons. SC current-voltage characteristics were determined before and after irradiation in illuminating by a AM0 solar simulator at 25°C. Three types of conditions were set up at irradiation: room temperature and absence of illumination; temperature of 150°C and illumination corresponding to the 4X concentration; temperature of 180°C and illumination corresponding to the 5X concentration. It has been established that in the whole range of the proton integral flux density (up to $1.5\cdot10^{12}$ cm^{-2}) and that of electrons (up to $7.5\cdot10^{14}$ cm^{-2}) the degradation degree of the short circuit current and the maximum power decreases and the open circuit voltage does not practically change with illumination and temperature. After irradiation, an additional annealing of SCs was carried out. To determine the effect of illuminance on the defect annealing process, two regimes of thermal treating were used: with illumination of specimens and without it. As a result, it has been established that thermal treating of SCs at temperatures and illuminances corresponding to the irradiation conditions does not result in restoration of parameters of the specimens irradiated by protons, but improves essentially parameters of the SCs irradiated by electrons. It has been shown on the bases of studying the experimental dependence of the degree of I_{sc} restoration in SCs irradiated by electrons on the annealing duration that it obeys the logarithmic law. It has been found that, after 20 hours of annealing, further restoration of SC photovoltaic parameters does not occur.

The experiments have also shown that thermal treating of the SCs irradiated by electrons without illumination does not lead to restoration of their parameters, if the annealing temperature does not exceed temperature, at which irradiation of SCs took place. This indicates the effect of illuminance on annealing of the defect induced by electrons.

The light exposure effect on annealing of the defects induced by protons was analyzed by comparing the degree of I_{sc} restoration for SCs irradiated at 25°C without illumination resulted from their thermal treating during 10 hours at 180°C in dark and with illumination corresponding the 5X of the AM0 sunlight. It has been found that the annealing effectiveness decreases with the particle integral flux density increase, and, at illumination, more complete restoration of SC parameters occur. The results obtained by the authors of [6] agree well with the data of [7], where an additional restoration of photovoltaic parameters of alike SCs after photoinjection was also observed.

The work [8] presents results of study of radiation effects of the InP-CdS heterophotoconverters irradiated by 5MeV electrons in dark and in illuminating with a density of 320 mW/cm². Specimen temperature at irradiation was held on the level of room temperature in all cases. It has been established that the rate of degradation of main photovoltaic parameters of heterophotoconverters irradiated at illumination is much less in the whole range of electron irradiation fluencies.

The great number of works on investigation of the electro injection (passing the forward current through the p-n junction) effect on the radiation degradation of SCs is available [7, 9-12].

So, [7] presents results of study of the injection annealing of SCs based on GaAs irradiated by 1 MeV electrons at room temperature. The SC power, after irradiating up to the fluence of 10^{16}cm^{-2}, reduced by 50 %. The isothermal annealing at 200°C was carried out up to the moment when restoration of the SC output power was terminated. Such thermal annealing allowed rising the SC power up to 76 %. Then, annealing at 200°C together with passing the 125 mA/cm² forward current was carried out. The injection annealing during about 80 hours has resulted in restoration the output power up to 90 %.

The authors of [9] studied the processes of the injection annealing of radiation defects induced in irradiating by Co^{60} γ-quanta and electrons in the GaAs diffusion p-n junctions. The injection annealing was applied after radiation impact by passing the forward current pulses of 2 msec in duration at the temperature range of 77−300 K. The pulse repetition rate was varied from 5 to 500 Hz, and the current density in a pulse - up to $2.2\cdot10^4$ A/cm². The portion of unannealed defects was determined by restoration of the electroluminescence integral intensity. It has been found that, at room temperature and pulse repetition rate of 5 Hz the annealing of defects was not observed at the current density up to 10^2 A/cm². Further increase of the current density results in reduction of the portion of unannealed defects up to 10 % after 60 sec at the current density of $2.2\cdot10^4$ A/cm².

The injection annealing at lower temperature was studied by the authors of [10]. GaAs based SCs were irradiated by 1 MeV electrons and then annealed at 330 K in passing the forward current of 1.3 A/cm². Concentration of the E3 and E5 radiation centers was determined by the DLTS method. It has been found that the dependence of N_d centers' concentration on the annealing duration t obeys the $N_d = N_{d0} \exp(-At)$ law. In this case, the values A for the E3 and E5 centers were $1.4\cdot10^{-4}$ and $1.9\cdot10^{-4}$ sec^{-1}, correspondingly.

Paper [11] presents results of investigation of the degradation of SCs based on AlGaAs –GaAs structures in irradiating them by the 6.7 MeV proton flux at room temperature and in passing the forward current (for the indicator-specimens – without passing the forward current). The radiation damage of the structures was estimated by the dependence of the collection coefficient of charge carriers generated at illumination by focused light of He–Ne laser on the proton irradiation fluence. It has been shown that the structures, through which a forward current of 1 A/cm² density is passed during irradiation, degrade slower compared to those without the injection current. The effectiveness of the injection current action decreases with radiation fluence.

The work [12] is devoted to investigating the injection annealing of radiation defects in $In_{0.5}Ga_{0.5}P$ SCs. Irradiation of specimens was carried out by 1 MeV electrons. The radiation defect characteristics were determined by the DLTS method. The radiation action with the fluence up to $3\cdot10^{16}$ cm² results in formation of two new hole capture centers H1 and H2 of concentration $6.8\cdot10^{14}$ and $2.8\cdot10^{15}$ cm^{-3} and three electron capture centers E1, E2 and E3 of concentration $3.1\cdot10^{15}$, $3.9\cdot10^{15}$ and $1.5\cdot10^{15}$ cm^{-3}, correspondingly. After irradiating the specimens, the forward current of J=0.1 A/cm² density was being passed during time t from 0.5 to 20 min (sample temperature was held at the level of 25°C), and defect concentration H2 was measured. It has been found that variation of the defect concentration is described by the dependence $N_d = N_{d0} \exp(-At)$, where N_{d0} and N_d are H2 center concentrations before and after electro injection, A is the annealing rate parameter. The dependence of the A parameter on the annealing conditions has also an exponential shape $A(J,T) = A_0(J)\exp(-\Delta E(J)/kT)$.

In this work, results of experimental investigations of the effects of postradiation light exposure of SCs based on $A^{III}B^{V}$ semiconductors are presented.

2 CHARACTERIZATION OF SCs AND METHODS FOR MEASURING THEIR PHOTOVOLTAIC PARAMETERS

The effect of the postradiation light action on concentrator SCs of two types - single-junction GaAs and dual-junction GaInP/GaAs - has been investigated. They were soldered on copper substrates for ensuring required heat removal. The SC structures were fabricated by the MOCVD technique [13].

The single-junction SCs were irradiated by 1-3 MeV electrons or by 6.3 MeV protons. The dual-junction SCs were irradiated by 3 MeV electrons. With the aim to increase the objectivity of results on the postradiation light action, a separate group of SCs of both types was not affected by radiation and carried a role of specimens-indicators.

To estimate the radiation degradation of SCs and the effectiveness of the postration light annealing, SC spectral and current-voltage characteristics before irradiation, after irradiation and after light exposure were recorded.

The procedure for obtaining the spectral dependence of the external quantum yield consists in comparison of electrical signals from an investigated spectrum and monitor one with a known $Q_{ext}^{mon}(\lambda)$ dependence in irradiating them by monochromatic light with preset wavelength [14]. From the $Q_{ext}(\lambda)$ obtained, the SC photocurrent for space sunlight spectrum $E(\lambda)$ was calculated:

$$J_{sc} = \int_{\lambda_2}^{\lambda_1} E(\lambda) \cdot Q_{ext}(\lambda) \cdot \lambda d\lambda \qquad (1)$$

Recording of the I-V characteristics was carried out on a pulsed sunlight simulator with a tunable spectral composition, which allowed us to come more adaptably to the procedure for accurate tailoring the radiation spectral composition in studying the degradation dependencies of multi-junction SCs [15].

The annealing effectiveness was estimated by the factor

$$F(x) = \frac{x_1 - x_2}{x_0 - x_1} \cdot 100\% \qquad (2)$$

where x_0, x_1 and x_2 are values of a measured photovoltaic parameter (I_{sc} or V_{oc}) before irradiation, after irradiation and after annealing, correspondingly.

3 INSTALLATION FOR POSTRADIATION LIGHT ACTION

To fulfill the postradiation light action, a concentrated light flux simulator was used. The simulator consists (see Fig. 1) of a power supply *1* with a remote control block *2* and an optics, which, in turn, consists of an elliptical mirror *3* of 0.6 m in diameter with an outer aluminum coating, a convergent mirror *4*, and a 10 kW xenon lamp *5*. The power efficiency of the simulator is increased essentially due to the use of secondary optical systems for concentrating radiation *6* (quartz lens or conically shaped reflective concentrator cooled by water). Location of cooled cupper substrates with mounted on them SCs *7* and of auxiliary units (additional optical elements, detectors, diaphragms, system elements for water and air cooling and others) is performed on a platform with a device for moving along three directions.

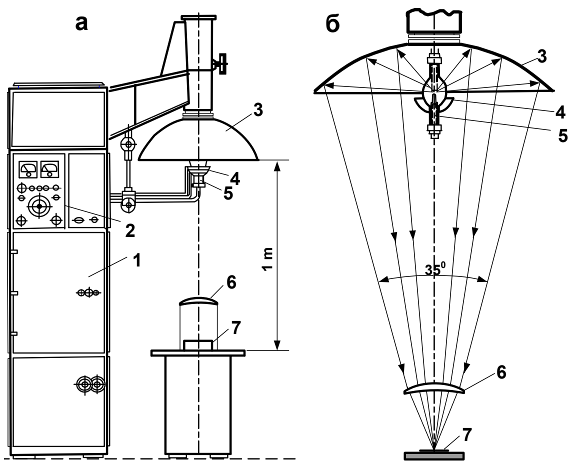


Figure 1: Simulator of highly concentrated light with a xenon lamp (a), scheme of a concentrating optics (b):
1 – power supply; 2 – remote control block; 3 – elliptical mirror; 4 – contrreflector; 5 – xenon lamp; 6 – additional optical element; 7 – SC on a cooled substrate with possibility to move along three directions.

The simulator has the following basic characteristics:

- distance between the first focus of the optical system, in which the lamp discharge interval is located, and the second one, where the distorted image of the discharge is formed, is 1000 mm;
- rays' convergency angle is 35°;
- radiation power in the focal spot can be varied gradually within 780 W – 2 kW by regulating the lamp current;
- light flux stability is not worse than ± 10% of the preset value;
- focal spot diameter is 30-60 mm depending on the mirror quality and focusing conditions.

4 RESULTS

4.1 Single-junction SCs.

Determination of the effectiveness of the SC postradiation light annealing on the exposure duration and power illuminance was performed in investigating single-junction SCs based on GaAs heterostructure with the AlGaAs wideband window irradiated predominantly by 1 MeV electrons or by 6.3 MeV protons.

Two SCs – investigated one and a nonirradiated specimen-indicator – were annealed simultaneously. Two power illumination levels were simulated: one equivalent to the sunlight (AM0) concentration ratio equal to 180X and another one – to 360X. Temperature of specimens was held at the level of 90-100°C. The total annealing time for each SC was 60 min.

As a result of the carried out experiments, it has been established that the specimens-indicators did not change their properties. For this reason, all observed variations of SC parameters may be related to the effects of the radiation defects' annealing. Table 1 presents dependence of the $F(x)$ value for the short circuit current (I_{sc}) and open circuit voltage (V_{oc})of SCs irradiated by electrons on duration and level of power illumination. Table 2 presents similar dependencies for SCs irradiated by protons. On Fig. 2 the plots of effectiveness parameter *for* I_{sc} and V_{oc} as a function of exposure duration are presented for two illumination levels It is seen, that after light exposure, I-V parameters of all SCs were improved. However, restoration of properties of SCs irradiated by protons occurs to a much lesser degree compared to those of SCs irradiated by electrons. A greater degree restoration of the I_{sc} occurs than that of the V_{oc}.

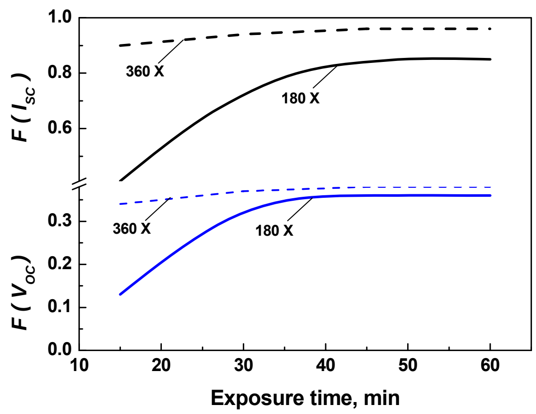
Table 1. Dependence of the annealing effectiveness parameter $F(x)$ of SCs irradiated by 1 MeV electrons on annealing duration and power illuminance.

Electrical parameters of SCs	Light illumination level, 180X			
	Annealing time, min			
	15	30	45	60
I_{sc}	0.41	0.72	0.84	0.85
V_{oc}	0.13	0.32	0.36	0.36
Electrical parameters of SCs	Light illumination level, 360X			
	Annealing time, min			
	15	30	45	60
I_{sc}	0.9	0.94	0.96	0.96
V_{oc}	0.34	0.37	0.38	0.38

Table 2. Dependence of the annealing effectiveness parameter $F(x)$ of SCs irradiated by 6.3 MeV protons on annealing duration and power illuminance.

Electrical parameters of SCs	Light illumination level, 180X			
	Annealing time, min			
	15	30	45	60
I_{sc}	0.12	0.27	0.38	0.4
V_{oc}	0.017	0.034	0.05	0.05
Electrical parameters of SCs	Light illumination level, 360X			
	Annealing time, min			
	15	30	45	60
I_{sc}	0.2	0.37	0.45	0.46
V_{oc}	0.019	0.036	0.05	0.05

a)



b)

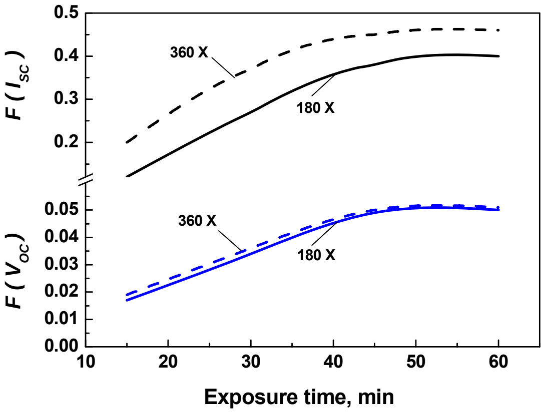


Fig. 2. Dependencies of the annealing effectiveness parameter F of SCs irradiated by 1 MeV electrons (a) and 6.3 MeV protons (b) on annealing duration and light intensity.

Effectiveness of radiation defect annealing depends on the level of the power illuminance. The quantitative indices of the annealing effectiveness (annealing rate and limiting value of restoration coefficients) rise with illuminance. The limiting value of the restoration degree depends on the initial degree of the radiation damage.

4.2 Dual-junction SCs

The dual-junction GaInP/GaAs SCs irradiated predominantly by 3 MeV electrons up to the fluence of $2 \cdot 10^{15}$ cm^{-2} were exposed to light during 5 hours. In all cases, the specimen temperature was held at the level of not higher than 50°C, which was ensured by intensive water cooling of the substrate with a SC soldered on it and by air-cooling.

At the action of the light flux of density proportional to 375X during 5 hours, the photocurrent was restored up to the level $F(I_{sc}) = 0.25$. Since the photocurrent of these SCs was limited by the current of the bottom GaAs subcell, the degree of restoration of this subcell photocurrent was also $F(I_{sc}) = 0.25$.

The top GaInP subcell has shown the higher degree of photocurrent restoration $F(I_{sc}) = 0.41$. Since the restoration process came to the saturation stage after about 3 hours, one may suppose that, at such conditions, complete annealing of one of types of radiation defects introduced in irradiating by 3 MeV electrons takes place, a concentration of these defects determining about 41% of the photocurrent degradation.

As a result of action on a separate GaAs SJ SC of the light flux equivalent to 150-200X during 5 hours, the photocurrent restoration occurs up to the level $F(I_{sc}) = 0.238$. Further light action does not result in restoration of the SC photovoltaic properties. It may be supposed that, at such conditions, complete annealing of one of the types of radiation defect introduced in irradiating by 3 MeV electrons occurs, these defects concentration determining about 24-25% of the photocurrent degradation. This confirms once more the conclusion made before about the limit of the photocurrent restoration in the GaAs structures after irradiating by 3 MeV electrons. Other defects have the higher energy of annealing activation, and, at the SC temperature up to 60ºC, photoinjection annealing does not occur.

5 SUMMARY

The results of the performed investigations indicate that, at postradiation light flux action on $A^{III}B^{V}$ concentrator SC, irradiated by electrons and protons, the considerable restoration of photovoltaic parameters is occurred. The effectiveness of such recovery is depending on joint action of the level of the power illuminance, duration of exposure and temperature at annealing. The quantitative indices of the annealing effectiveness (annealing rate and limiting value of restoration coefficients) rise with power illuminance. The limiting value of the restoration degree depends on the initial degree of the radiation damage.

It is evident from the obtained data that to raise the accuracy in estimating the indices of the radiation tolerance of SCs intended for operation in space solar arrays based on modules with sunlight concentrators, the standard procedure for radiation tests of SCs should be complemented by a stage of the postradiation light flux action with ensuring the operation temperature regime. The light action intensity should correspond to the operation regime by the level of the average concentration ratio, and the duration should be determined from the condition of saturation of observed photocurrent restoration.

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