RADIATION DEGRADATION OF MULTIJUNCTION III-V SOLAR CELLS AND PREDICTION OF THEIR LIFETIME

V.M. Andreev, V.M. Emelyanov, O.I. Chesta, V.M. Lantratov, M.Z. Shvarts, N.Kh. Timoshina
Ioffe Physical-Technical Institute
26 Polytechnicheskaya str., St.-Petersburg, 194021, Russia
Tel.: +7(812) 292 7394; fax: +7(812) 297 1017; e-mail: resso2003@bk.ru

ABSTRACT: Degradation of multijunction GaInP/Ga(In)As/Ge solar cells under irradiation by 3 MeV electrons has been investigated. The dependencies of minority charge carrier life time on the 3 MeV electron fluence (up to $2 \cdot 10^{15}$ cm^{-2}) have been calculated from the spectral characteristics of GaInP and Ga(In)As subcells experimentally obtained in their base layers, and the damage coefficients have been determined. Comparison of the obtained coefficients with literature data for 1 MeV electrons has been performed. It has been shown that the increase of the damage coefficients with the electron energy cannot be explained only by the increasing number of created defects. An approach to describe the dependence of the damage coefficient of a material on the acting particle energy based on the Kinchin-Pease model and on the hypothesis on formation of defects of multiple types in the solar cell structure, the ratio of concentrations of which is proportional to the particle energy. An analysis of the effect of deviation of the radiation action from the rated one on the SC resource limited by the preset decrease of its efficiency has been done.
Keywords: III-V Semiconductors, Degradation, Multijunction Solar Cell, Radiation Damage, Simulation, Space

1 INTRODUCTION

Solar cells (SCs) are at present the main of primary power sources for spacecrafts. One of the basic operational characteristics of SCs is their radiation tolerance. The rise of the part of spacecrafts, on which III-V multijunction SCs with the efficiency greater than 30% [1] are used, makes the problems of SC degradation prediction in the conditions of space radiation to be actual.

In practice of predicting the radiation degradation of SCs, two main methods for simulating SC operation in the conditions of space radiation influence are used: the JPL Equivalent fluence method elaborated by the US Jet Propulsion Laboratory (California Institute of Technology) and the NRL Displacement Damage Dose Method elaborated by the US Naval Research Laboratory [2]. The main merit of the latter is the essential reduction of the amount of necessary radiation tests of SCs. However, in applying this method for multijunction SCs, the known problems of determining the damage coefficients with using the concept of “nonionizing energy loss” arise, since the SC structure contains different semiconductor materials, which have different radiation degradation rates. The dependences of the material degradation rates on type and energy of particles damaging the structure also differ [1, 3, 4].

In the present work, degradation of multijunction GaInP/Ga(In)As/Ge SCs under irradiation by high energy electrons has been investigated. Description of experimental dependencies of the damage coefficients of the photoactive layers materials on the particle energy has been attempted on the basis of the Kinchin-Pease model for the initial radiation defects [5]. At such an approach, there is a possibility to calculate the damage coefficients for main parameters of the SC I-V characteristic, to maximize the allowance for the effect of the SC structure parameters on the SC radiation degradation and in prospect, to allow for the effects of thermal and photo injection annealing of radiation defects.

2 DEGRADATION OF GaInP/Ga(In)As/Ge SCs UNDER ELECTRON IRRADIATION

2.1 Cell structures

Schematic of the structures of the investigated SCs is presented in Fig.1. The most valuable cause for the GaInP/Ga(In)As/Ge SCs efficiency drop at irradiation is the decrease of the value of the short circuit current, which is determined by the smallest photocurrent of the SC subcells:

$$J_{SC} = \min\left[J_{ph}^{\text{GaInP}}, J_{ph}^{\text{Ga(In)As}}, J_{ph}^{\text{Ge}}\right] \quad (1)$$

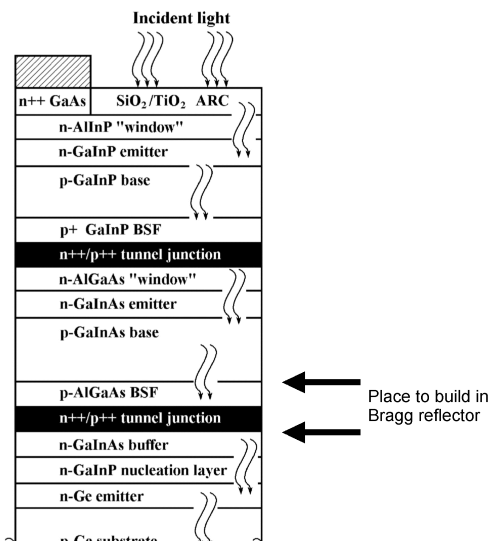

Figure 1: Typical structure of a space GaInP/Ga(In)As/Ge SC

High energy electrons are the main type damaging particles on the geosynchronous orbits. In multijunction SCs based on GaInP/Ga(In)As/Ge structure, the Ga(In)As subcell degrades faster under such type of radiation treatment. For this reason, to raise the radiation tolerance, SCs as these have usually the Ga(In)As subcell photocurrent greater than that of other subcells, and their short circuit current at the early spacecraft flight period is confined by the GaInP subcell photocurrent. The Ge subcell photocurrent does not confine the SC short circuit current during the whole operation period, since its degradation rate is essentially lower than that of the Ga(In)As subcell, and, at the beginning of its operation, there exists its significant reserve. For these reasons, in investigating the degradation, the processes of the radiation damage of GaInP and Ga(In)As subcells are of prime interest.

To increase the radiation tolerance of the Ga(In)As subcell, either light doping of its base layer can be performed or creation of a sweeping field in it. Also, to decrease degradation, a Bragg reflector (BR) can be integrated in the structure allowing reducing essentially the subcell thickness and decreasing the life time of photogenerated carriers necessary for their collection in the p-n junction [6]. Probable regions of the structure, in which a BR can be integrated, are shown in Fig.1. However, in all cases, degradation of the Ga(In)As subcell will occur faster than that of the GaInP and Ge subcells.

2.2 Radiation treatment

Radiation tests were carried out by irradiating the test specimens by a 3 MeV electron stream. For the tests, a structure obtained by the MOCVD technique without built-in fields in the Ga(In)As subcell base and without a BR has been used. The thicknesses of the subcells were optimized for the beginning of their life in correspondence with the procedure described in [7].

The spectral characteristics of GaInP and Ga(In)As subcells before and after irradiation by 3 MeV electrons of different fluences are presented in Fig. 2. The results of simulation of the spectral characteristics obtained with application of the model described in [8] are also presented in the figure. In simulating, the photogenerated carrier life time was being varied to ensure the best fitting of the rated and experimental characteristics. Some discrepancy between the plots in the range of 700-750nm results, apparently, from imperfection of the formation of the antireflection coating, The nonequilibrium charge carrier (NCC) parameters used at simulation are presented in Table 1. The values of rates of the surface charge carrier recombination on the “window-emitter” and “base - back surface field layer” (BSF) interfaces were considered as not greater than 100 cm/s. The refraction indices and the absorption coefficients of the semiconductor materials for calculations were taken from [9-10].

Due to that conditions for collecting NCCs from the bases of the GaInP and Ga(In)As subcells, it is convenient to carry out the determination of the damage coefficients of these materials by varying the NCC life time in the bases. Values of the latter ensuring the best fitting of the rated and experimental spectral characteristics for different electron fluences are presented in Fig. 3. The dependencies obtained were approximated by the classical formula [11]:

$$\frac{1}{\tau} = \frac{1}{\tau_0} + K\phi, \qquad (2)$$

where τ is the NCC life time in the material after irradiation with the electron fluence ϕ; τ_0 is the NCC life time before irradiation; K is the coefficient of damage of the material by a given type of particles; ϕ is the fluence of damaging particles.

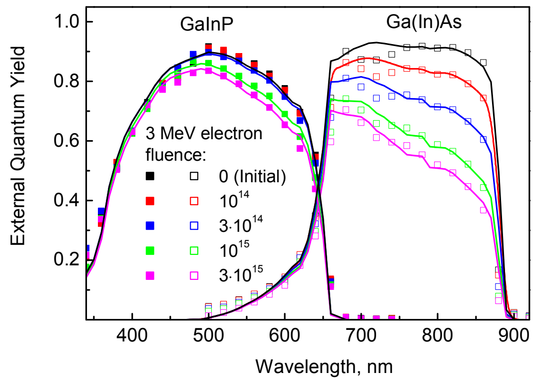

Figure 2: External quantum yield of two top subcells of the investigated GaInP/Ga(In)As/Ge SC before and after irradiation by 3 MeV electrons. Lines – the simulation results, symbols – the experimental data.

Table 1: Simulation parameters for the subcells of the investigated GaInP/Ga(In)As/Ge SC

	GaInP	Ga(In)As
NCC lifetime before radiation treatment in emitter layer, s	$1.6{\cdot}10^{-10}$	$8.2{\cdot}10^{-11}$
NCC lifetime before radiation treatment in base layer, s	$5.7{\cdot}10^{-10}$	$4.9{\cdot}10^{-9}$
Hole diffusion coefficient, cm^2/s	1	4
Electron diffusion coefficient, cm^2/s	25	100

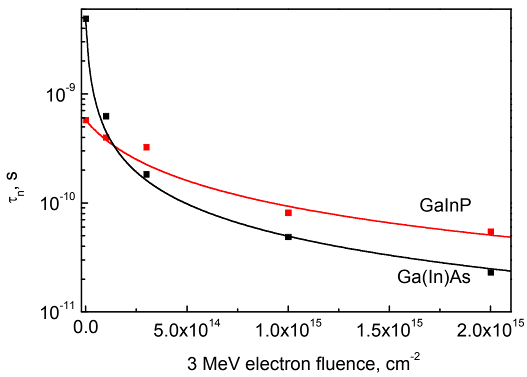

Figure 3: NCC life time in the bases of the GaInP and Ga(In)As subcells vs 3 MeV electron fluence.

The coefficients were being selected to ensure the best fitting of the rated and the experimental dependencies. The obtained values are presented in Table 2. It is clear that they allow obtaining a good quality of approximation. The Table 2 presents also damage coefficients for 1 MeV electrons from [3].

Table 2: Damage coefficients for different particles, cm^2/s

	GaInP	Ga(In)As
1 MeV electrons [3]	$3.6\cdot10^{-7}$	$1.2\cdot10^{-6}$
3 MeV electrons	$9\cdot10^{-6}$	$2\cdot10^{-5}$

3 THEORETICAL APPROACH TO OBTAIN THE DAMAGE COEFFICIENTS

3.1 Concentration of the radiation-induced defects

The Kinchin-Pease model for initial radiation defects [5] has been applied for simulating values of the damage coefficients of the materials of two top subcells of the GaInP/Ga(In)As/Ge SC.

The mean concentration of radiation defects in the SC structure was calculated in the frames of the classical theory of elastic collisions of particles with nuclei by the following formula:

$$N_r = \phi\cdot\sigma\cdot n\cdot w, \qquad (3)$$

where σ is the cross-section of the particle interaction resulting in transferring energy to an atom sufficient for its shifting from a crystalline lattice site; n is concentration of atoms; w is the average number of shifter atoms per one initially knocked out atom

To determine concentration of the initial shifts at action of electrons, the results of calculation of the atom shift cross-section performed by Mott in the form of the formula for approximation of McKinly-Feshbach, which ensures a calculation accuracy reasonable (up to 10%) for such estimations:

$$\sigma = \pi\left(\frac{Zq_e^2\gamma}{m_e c^2(\gamma^2-1)}\right)^2\left(\left(\frac{T_m}{T_d}-1\right)-\frac{\gamma^2-1}{\gamma^2}\ln\frac{T_m}{T_d}+\right.$$
$$\left.+\alpha\pi Z\sqrt{\frac{\gamma^2-1}{\gamma^2}}\left(2\sqrt{\frac{T_m}{T_d}}-2-\ln\frac{T_m}{T_d}\right)\right), \qquad (4)$$

where Z is the atomic number; q_e is the electron charge; m_e is the electron mass; $\gamma=\left(1-(v/c)^2\right)^{-1/2}$ is the relativistic correction; v is the electron velocity; c is the velocity of light in vacuum; T_m is the maximum energy, that could be transferred to atom by an electron; T_d is the threshold energy for atom shifting from a crystalline lattice site; α.=1/137 is the fine structure constant.

The expression for the maximum energy, which can be transferred by a particle to an atom, is the following:

$$T_m = 2\frac{m_e}{M}E\left(2+\frac{E}{m_e c^2}\right), \qquad (5)$$

where E is the electron energy.

Calculation of concentration of the secondary defects caused by interaction of the initially knocked out atoms with atoms of a semiconductor is carried out on the base of estimation of the average number of shifts occurred using the Kinchin-Pease cascade model [5]. In accordance with this, the average number of atomic shifts at allowance of the Coulomb potential is determined as:

$$w=\frac{1}{2}\ln\left(\frac{T_m}{2T_d}\right). \qquad (6)$$

Values of the threshold energies of the atomic shifts T_d for GaInP and Ga(In)As at calculations were taken equal to 7–11 eV.

The rated dependencies of the number of defects created by one electron penetrated into the structure on its energy are presented in Fig. 4.

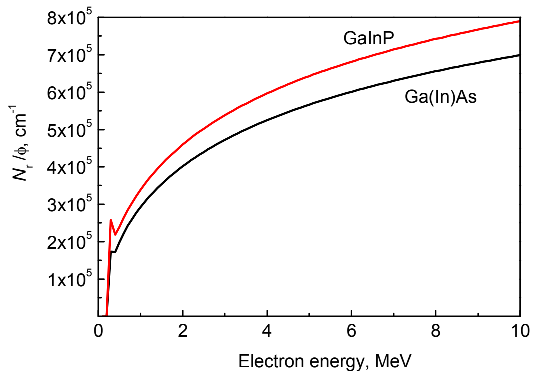

Figure 4: Rated dependencies of the amount of defects generated by one electron on its energy.

3.2 Model with two types of defects

It is seen from Table 2 that the increase of the electron energy from 1 to 3 MeV leads to the rise of the material damage coefficient more than by an order of magnitude. At the same time, Fig.5 shows that the amount of radiation defects increases approximately in two times. Comparison of these results allows concluding that the induced defects change not only quantitatively but also qualitatively with increasing the energy of particles penetrating the structure.

One can try to describe this phenomenon by means of a model with multiple versions of defects. Suppose for an example that defects appearing in the materials of each subcell are of two types, and their concentrations are N_1 and N_2, and:

$$N_1 + N_2 = N_r. \qquad (7)$$

In such a case, for every preset electron fluence ϕ of energy E, valid is:

$$K(E)\phi = N_1\beta_1 + N_2\beta_2, \qquad (8)$$

where $K(E)$ is the semiconductor damage coefficient for an electron of energy E; $\beta_{1,2}$ are the coefficients of NCC capture by recombination centers corresponding to defects of the first and the second types.

Suppose that there exists some minimum energy E_0, before achieving which electrons create defects only of the first type, but at higher energies the probability to generate defects of the second type is proportional to the electron energy, that is:

$$\begin{cases} N_2 = 0, \quad E < E_0; \\ N_2 / N_1 = \eta E, \quad E > E_0, \end{cases} \qquad (9)$$

where η is the proportionality coefficient.

This will result in the following expression for the damage coefficient:

$$K(E) = \frac{1}{\phi} N_r \beta_1 \frac{1}{1+\eta(E-E_0)\theta(E-E_0)} + \\ + \frac{1}{\phi} N_r \beta_2 \frac{\eta(E-E_0)}{1+\eta(E-E_0)} \theta(E-E_0), \qquad (10)$$

where $\theta(x)$ is Heaviside's function.

A substantial change of the damage coefficient on the short portion is probable only when $\beta_2 >> \beta_1$ and $N_2 << N_1$. In this case ,on the portion of the intensive rise, one can neglect the first term in the formula (10), which will lead to the expression:

$$K(E) = \frac{N_r}{\phi} k(E), \\ k(E) \approx (E-E_0)\xi\theta(E-E_0), \quad \xi \leftrightarrow \beta_2 \eta, \qquad (11)$$

where $k(E)$ is the specific coefficient of radiation damage of a material for an electron with energy E.

The results of calculation of the damage coefficient by formula (11) compared with the experimental data from Table 2 are presented in Fig. 5. The values of the proportionality coefficient and of the threshold energy used at calculation are presented in Table 3.

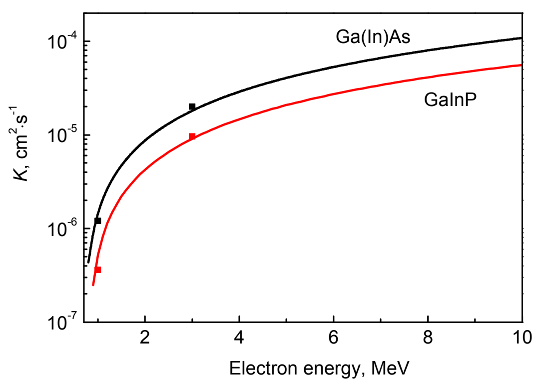

Figure 5: Dependencies of the material damage coefficients on the electron energy. Lines – calculation results; dots – experimental data (1 MeV – [3], 3Mev – this work).

It should be noticed that the model with only types of defects is the simplest. Accurate fitting of experimental dependencies of the damage coefficients with considerable number of measured values could demand three or more types of defects. The most probable model should be selected from further investigations.

The ratio of the damage coefficients for GaInP and Ga(In)As for electrons of different energies calculated by formula (11) is presented in Fig. 6. It is clear that the relative rate of degradation for the given materials can vary practically in two times in dependence on the energy of particles causing it.

Table 3: Parameters to calculate the damage coefficients

	GaInP	Ga(In)As
ξ, $cm^3/(s \cdot MeV)$	$7.69 \cdot 10^{-12}$	$1.67 \cdot 10^{-11}$
E_0, MeV	0.8	0.7

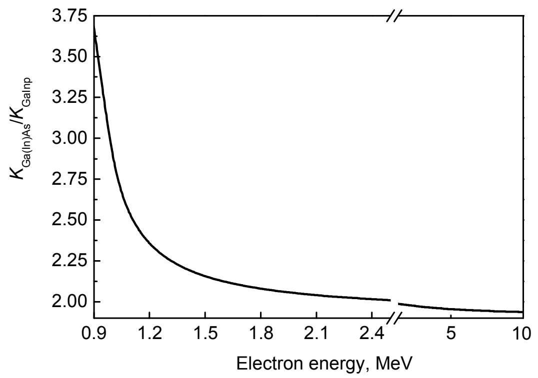

Figure 6: Ratio of the coefficients of damage of Ga(In)As and GaInP for different electron energies.

4 CORRECTION OF THE PREDICTED LIFETIME

Power fluctuations and content of space radiation affecting a SC may result in reduction of its life time compared with predicted one. Furthermore, differences in damaging properties of different particles lead to that the run of degradation of a multijunction SC will not correspond to rated one due to the difference between the assumed and real spectra of radiation affecting aSC.

Monitoring of the current state of a structure during operation allows correcting the prediction of its life expectancy and reacting correspondingly on this life expectancy changes. The monitoring can be performed by means of periodic variation of some photovoltaic characteristics of a test structure (for example, its current and voltage) being in the same conditions as a SC of a spacecraft solar array.

For investigating the possibility to realize such a monitoring, degradation of a multijunction GaInP/Ga(In)As/Ge SC with a built-in dual BR has been simulated. The SC structure corresponded to Fig. 1. The BR consisted of 20 pairs of $Al_{0.1}Ga_{0.9}As$/ layers ensuring the maximum reflection at wavelength of 860 nm and 20 pairs of $Al_{0.2}Ga_{0.8}As$/AlAs layers ensuring the maximum reflection at wavelength of 770nm. The subcell thicknesses were optimized for the life expectancy at operation on the geosynchronous orbit of 6 years in correspondence with the procedure described in [7].

In the case of more intense compared to the rated one action of space radiation on a SC during some time, its service, when the efficiency will be no less than the preset η_{min}, will be reducing. Figure 7 presents the dependencies of a GaInP/Ga(In)As/Ge SC parameters an duration of SC operation on an orbit in the case, when, in the time interval between t_1 and t_2, faster degradation of the Ga(In)As subcell compared to the rated one takes place.

Since the short circuit current of space GaInP/Ga(In)As/Ge SCs during the long period of their life is limited by the GaInP subcell photocurrent and then by the Ga(In)As subcell one, measurements of the short circuit current allow determining the photocurrent and the radiation degradation value of one of these subcells. The current state of the second one can be determined from the cell voltage drop.

The voltage drop of the GaInP/Ga(In)As/Ge SC between t_1 and t_2 is expressed by the formula:

$$\Delta U = -\frac{2kT}{q_e}\ln\left(\frac{J_{r2}^{\mathrm{Ga(In)As}}J_{ph1}^{\mathrm{Ga(In)As}}}{J_{r1}^{\mathrm{Ga(In)As}}J_{ph2}^{\mathrm{Ga(In)As}}}\right) - \frac{2kT}{q_e}\ln\left(\frac{J_{r2}^{\mathrm{GaInP}}J_{ph1}^{\mathrm{GaInP}}}{J_{r1}^{\mathrm{GaInP}}J_{ph2}^{\mathrm{GaInP}}}\right) - \frac{2kT}{q_e}\ln\left(\frac{J_{ph1}^{\mathrm{GaInP}}-J_{ph1}^{\mathrm{Ga(In)As}}}{J_{ph2}^{\mathrm{GaInP}}-J_{ph2}^{\mathrm{Ga(In)As}}}\right), \quad (12)$$

where J_{ph1}, J_{r1} are the photocurrent and recombination current densities of a *p-n* junction of a corresponding subcell at the moment t_1 and J_{ph2}, J_{r2} - at the moment t_2; k – Boltzmann constant; T – absolute temperature.

The first term in (12) reflects the drop of voltage due to degradation of the middle subcell, the second one – of the top subcell and the third one – of the bottom subcell due to variation of photocurrent mismatch of the subcells. The mathematical simulation of the processes of photocurrent generation in a multijunction subcell allows establishing the correlation between variations of the photocurrent and the recombination current for each subcell at their irradiation. Thus, the set of the expressions (1) and (12) contains only two independent parameters, and, hence, it may be unambiguously solved.

The consequence of accelerated degradation is reduction of the rated SC lifetime by the value Δt. The effective value of the fluence of high energy particles caused the SC accelerated degradation can be found from the rated dependence for voltage by means of the recurrent correlation:

$$t^* = U_{OC}^{-1}(U_{OC}(t_2) - \delta U^{(m)}),$$
$$\delta U^{(m+1)} = \Delta U + \frac{2kT}{q_e}\ln\left(\frac{J_{r2}^{\mathrm{GaInP}}J_{ph}^{*(m)\mathrm{GaInP}}}{J_{r}^{*(m)\mathrm{GaInP}}J_{ph2}^{\mathrm{GaInP}}}\right) + \frac{2kT}{q_e}\ln\left(\frac{J_{ph}^{*(m)\mathrm{GaInP}}-J_{ph}^{*(m)\mathrm{Ga(In)As}}}{J_{ph2}^{\mathrm{GaInP}}-J_{ph2}^{\mathrm{Ga(In)As}}}\right), \quad (13)$$

where $J_{ph}^{*(m)}, J_{ph}^{*(m)}$ are the photocurrent and recombination current densities of a *p-n* junction of a corresponding subcell after equivalent time t^*; $U_{OC} = U_{OC}(t)$ is the dependence of the SC open circuit voltage on time at stationary irradiation; $U_{OC}^{-1}(U)$ is a function inverse to the dependence of the open circuit voltage on the time on the orbit at stationary irradiation.

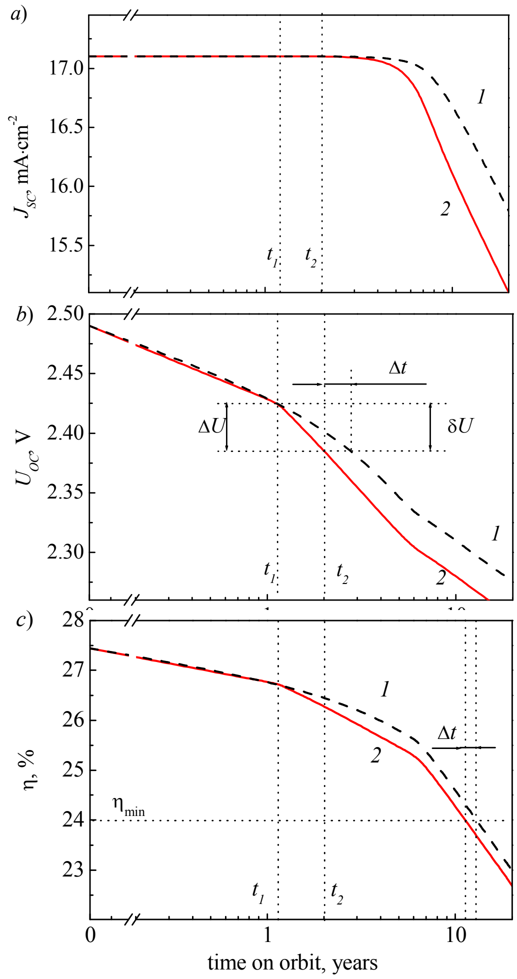

Figure 7: Short-circuit current (*a*), open-circuit voltage (*b*) and efficiency (*c*) of a triple-junction GaInP/GaInAs/Ge SC with faster than expected degradation of the middle subcell between t_1 and t_2: *1* – expected values; *2* – observed values.

In the zero approximation, $\delta U^{(0)} = \Delta U$. In the case, when the subcell damage was caused by only fast protons and electrons generating defects within the whole structure depth, the zero approximation gives a precise result.

The value of reduction of SC lifetime due to the accelerated degradation of its middle subcell is the different between the expected and the equivalent times:

$$\Delta t = t^* - t_2. \quad (14)$$

If the top subcell is selectively damaged, the decrease of the SC short circuit current on the portion, where it is determined by the GaInP subcell photocurrent, and the drop of the operating voltage on the portion confined by the GaInAs subcell photocurrent is observed (Fig. 8).

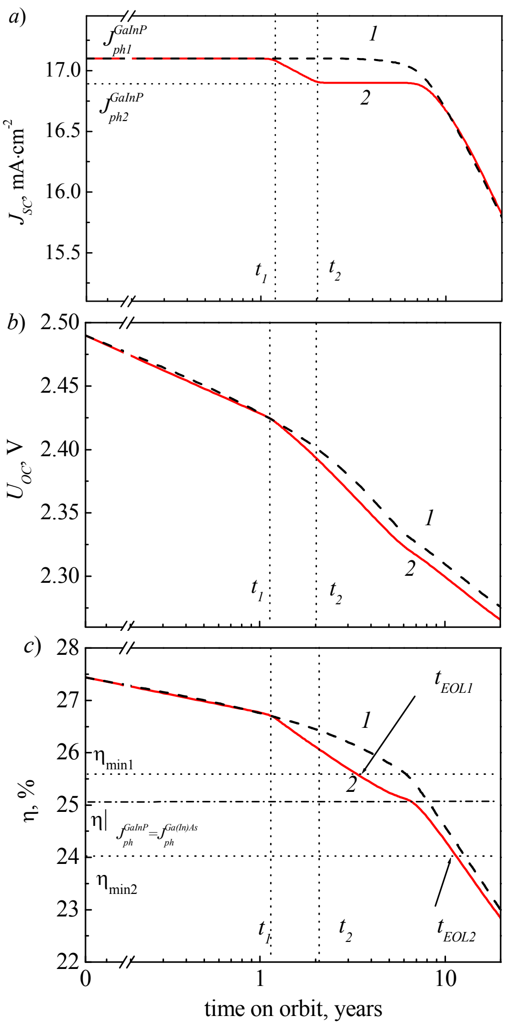

Figure 8: Short-circuit current (*a*), open-circuit voltage (*b*) and efficiency (*c*) of a triple-junction GaInP/GaInAs/Ge SC with faster than expected degradation of the top subcell between t_1 and t_2: *1* – expected values; *2* – observed values.

Reduction of the SC lifetime, at which the SC efficiency will not drop lower than the $\eta_{\min}$, value, due to deviation of the degradation process from the rated one can be estimated by means of the following formula:

$$t_{EOL}=\begin{cases} t_{EOL1}, & \eta_{\min}\dfrac{J_{ph1}^{\mathrm{GaInP}}}{J_{ph2}^{\mathrm{GaInP}}}<\eta\Big|_{J_{ph}^{\mathrm{GaInP}}=J_{ph}^{\mathrm{Ga(In)As}}}; \\ t_{EOL2}, & \eta_{\min}\dfrac{J_{ph1}^{\mathrm{GaInP}}}{J_{ph2}^{\mathrm{GaInP}}}>\eta\Big|_{J_{ph}^{\mathrm{GaInP}}=J_{ph}^{\mathrm{Ga(In)As}}}; \end{cases}$$

$$t_{EOL1}=\eta^{-1}\left(\eta_{\min}\frac{J_{ph1}^{\mathrm{GaInP}}}{J_{ph2}^{\mathrm{GaInP}}}\right)-\Delta t,$$

$$t_{EOL2}=\eta^{-1}\left(\eta_{\min}\left(1-\frac{2kT}{q_eU_{OC}^{EOL}}\ln\left(\frac{J_{ph1}^{\mathrm{GaInP}}}{J_{ph2}^{\mathrm{GaInP}}}\right)\right)^{-1}\right)-\Delta t. \quad (15)$$

where $\eta^{-1}(\eta)$ - is the function inverse to the rated dependence of the efficiency on the lifetime; U_{OC}^{EOL} is the SC open circuit voltage at the end of the SC lifetime at the rated degradation regime.

5 CONCLUSIONS

In the present work, the effect of irradiation by 3 MeV electrons on the life time of GaInP and Ga(In)As subcells of a triplejunction SC has been investigated. The coefficients of damage of GaInP and Ga(In)As by particles of this type have been determined.

By means of the Kinchin-Pease model, dependencies of the amount of defects created by one electron on its energy have been calculated. Comparison of the data on the coefficients of damage of GaInP and Ga(In)As by 1 and 3 MeV electrons has allowed establishing that the particle energy increase results not only in quantitative but also qualitative change of the defect content in the structure. To describe this process, a model with two types of defects has been proposed.

Analysis of deviation of the radiation degradation run from the rated one for GaInP/Ga(In)As/Ge SCs for the life expectancy of their operation was carried out. An analytical approach to correction of predicted operation life expectations based on a monitoring of SC parameters has been proposed.

ACKNOWLEDGMENTS

The authors would like to thank N.A. Kalyuzhnyy and S.A. Mintairov for the helpful discussions.

This work was supported by Russian Foundation of Basic Research (Grants 12-08-01019-a, 12-08-01034-a and 11-08-12031-ofi-m-2011).

REFERENCES

[1] Meusel M., Baur C., Guter W. et. al. // Proc. 20th EPSEC (Barcelona, Spain, 2005), p. 20–25.
[2] S.R. Messenger et al. // Prog. Photovolt.:Res. Appl.. 9, 2001, pp. 103-121.
[3] M. Yamaguchi, T. Sasaki, H.S. Lee et. al. // Proc.of the 33rd IEEE PVSC (San Diego, USA, 2008), 10.1109/PVSC.2008.4922716.
[4] M. Imaizumi, T. Takamoto, T. Oshima et. al. // Proc. 29th IEEE PVSC (New Orleans, Louisiana, USA, 2002), pp. 990-993.
[5] J. Bourgoin and M. Lannoo, Point Defects in Semiconductors, I. Theoretical Aspects (Springer-Verlag, Berlin, 1981), 265 p.
[6] V. Emelyanov et al. // Proceedings of SPIE (SPIE, Bellingham, WA 2010), v. 7521, 75210D.
[7] V.M. Emelyanov et al. Semiconductors, 44, 1600 (2010).
[8] Andreev V.M. et al. // Proc.of the 23rd EPSEC (Valencia, Spain, 2008), p. 375-381.
[9] D.E. Aspnes, S.M. Kelso, R.A. Logan, R. Bhat. J. Appl. Phys., 60, 754 (1986).
[10] S.S. Adachi. Optical Constants of Crystalline and Amorphous Semiconductors: Numerical Data and Graphical Information (Kluwer Academic, Boston, 1999).
[11] W. Rosenzweig, F.M. Smits, W.L. Brown. J. Appl. Phys., 35, 2707 (1964).