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Improvement of radiation resistance of Multijunction GaInP/Ga(In)As/Ge solar cells with application of Bragg reflectors

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Abstract. Feasibility to increase the radiation resistance of multijunction solar cells in using Bragg reflectors has been shown. Two designs of Bragg reflectors for multijunction solar cells, which allow ensuring in the Ga(In)As subcell base an effective collection of minority charge carriers at the decrease of their diffusion length caused by radiation treatment, have been investigated. Influence of subcells' thicknesses of *n-p* GaInP/Ga(In)As/Ge solar cell under 1 MeV electron irradiation with fluences up to $3 \cdot 10^{15}$ cm^{-2} on short circuit current was considered. Optimal thicknesses of GaInP and GaInAs subcells with Bragg reflectors, depending on the rated operation period on the geostationary orbit, were estimated. It has been shown that such an optimization allows to achieve efficiency at long operation of solar cells on the orbit noticeably higher than that of non-optimized cells.

Introduction

At present, solar cells (SCs) are the main power sources for spacecrafts. One of the most important characteristics of such SCs is the resistance to radiation damages caused by high-energy particles of the near-Earth space (protons, electrons, etc.). These damages form additional centers of nonradiative recombination, which results in reduction of the minority charge carrier (MCC) diffusion length and in degradation of the SC photocurrent and open circuit voltage.

There exist different ways for increasing the SC structure radiation resistance: the use of low doped active layers [1-5], the application of drain fields [6], embedding Bragg reflectors (BR) [7-9], etc. A merit of applying a BR is that diminishing the negative effect of the MCC diffusion length reduction is achieved by decreasing the thickness of a layer, from which the carrier collection by the p-n junction takes place. Here, in comparison with the other methods, embedding a BR in a SC does not lead to the increase of the cell series resistance and to the decrease of the potential barrier on the cell photoactive p-n junction. The BR also plays a role of the back surface field (BSF), ensuring better MCC collection from the base. For this reason, the use of a BR in the cell structure allows obtaining radiation tolerant high efficient SCs.

The goal of the current work was estimation of feasibilities for increasing the radiation resistance of GaInP/Ga(In)As/Ge multijunction solar cells (MJSC) at application of built-in BR and selection of the SC structure optimum parameters and a reflector design.

Analysis of degradation of a MJSC in the space

The efficiency of a solar cell is determined by its short circuit current, the open circuit voltage and the fill factor of the cell current-voltage characteristic. The short circuit current I_{SC} of a monolithic MJSC is determined by the smallest photocurrent of its subcells:

$$I_{SC} = \min[I_{ph}^{(1)}, I_{ph}^{(2)} \ldots I_{ph}^{(N)}], \quad (1)$$

where $I_{ph}^{(j)}$ is the photocurrent of the *j*-th subcell, *N* is the number of subcells. Thus, a reduction of the cell smallest photocurrent results in the decrease of I_{SC} of the whole SC and its efficiency.

The open circuit voltage is a sum of open circuit voltages of the subcells $V_{OC}^{(j)}$ of a MJSC:

$$V_{OC} = \sum_{k=1}^{N} V_{OC}^{(j)} . \tag{2}$$

The decrease of the open circuit voltages of the subcells leads to the equivalent decrease of the open circuit voltage and the efficiency of the whole MJSC. It was shown in [10,11], that the top GaInP and the bottom Ge subcells in the *n-p* GaInP/Ga(In)As/Ge MJSC are in less degree subjected to radiation degradation. For this reason, to increase the radiation resistance of GaInP/Ga(In)As/Ge MJSCs, it is necessary, first of all, to improve the radiation hardness of Ga(In)As subcells.

Diffusion length reduction at radiation treatment can be described with by the following formula [12-15]:

$$\frac{1}{L^2} = \frac{1}{L_0^2} + \frac{1}{L_\phi^2}, \quad L_\phi = \sqrt{D / K\phi}, \tag{3}$$

where L is the MCC diffusion length in the material; K is the material damage coefficient; ϕ is the particle fluence; L_0 is the MCC diffusion length before irradiation; D is the MCC diffusion coefficient.

Diffusion length reduction in layers of the j-th subcell leads to a lack of MCC collection by the photoactive *p-n* junction and decrease of the subcell photocurrent. Also, it causes the reduction of the subcell open circuit voltage:

$$V_{oc0}^{(j)} = \frac{2kT}{q} \ln\left(\frac{I_{ph}^{(j)}}{I_r^{(j)}}\right), \tag{4}$$

where k is the Bolzmann constant; T is the absolute temperature; q is the electron charge; $I_{PH}^{(j)}$ is the photocurrent density; $I_r^{(j)}$ is the recombination current density of the photoactive *p-n* junction calculated as:

$$I_r^{(j)} = \frac{kT}{\varphi'} \frac{n_i \sqrt{D_n^{(j)} D_p^{(j)}}}{L_n^{(j)} L_p^{(j)}} = I_{r0}^{(j)} \frac{L_{n0}^{(j)} L_{p0}^{(j)}}{L_n^{(j)} L_p^{(j)}}, \tag{5}$$

where $L_n^{(j)}, L_P^{(j)}$ are the diffusion lengths of electrons and holes in the space charge region of the j-th subcell; $D_n^{(j)}$, $D_P^{(j)}$ are the carrier diffusion coefficients; n_i is the intrinsic charge carrier concentration; φ' is the average gradient of the potential in the *p-n* junction; $L_{n0}^{(j)}$, $L_{P0}^{(j)}$ and $I_{r0}^{(j)}$ are the charge carrier diffusion lengths and the recombination current density in the *p-n* junction before irradiation. Diffusion length reduction increases the recombination current density and decreases the open circuit voltage.

Influence of the Ga(In)As subcell thickness on the solar cell characteristics

The subcell photocurrent is determined by the number of photons absorbed in the photoactive layers and by the collection coefficient of photogenerated charge carriers by the p-n junction. For GaAs and $Ga_{0.99}In_{0.01}As$, a valuable increase of the number of absorbed photons is observed at layer thicknesses increase up to 3–3.5 µm. The effect of the MCC diffusion length values in different layers of GaInP/Ga(In)As/Ge MJSCs on the carrier collection probability by the p-n junction has been studied in [16]. It has been established that, in the case of Ga(In)As emitters, the carrier collection at the level of 95% is achieved when the diffusion length exceeds the layer thickness in three times, and similar collection in the case of the base layers when it exceeds in two times.

The cell structure radiation damages cause the MCC diffusion length reduction, which results in the photocurrent degradation. Improvement of the carrier collection in the base can be fulfilled by its thinning to compensate electron diffusion length reduction in it. To determine the effect of Ga(In)As subcell base thickness on the short circuit current and the efficiency of the GaInP/Ga(In)As/Ge MJSC the simulation of current and efficiency values under irradiation has been simulated with the use of the method presented in [16]. As damaging particles, 1 MeV electrons have been chosen, which are the main affecting factor on geostationary orbits.

Using Eq.3, the MCC diffusion lengths in the emitter and base layers of the GaInP, GaInAs and Ge subcells of the GaInP/GaInAs/Ge MJSC for 1 MeV electron fluences up to $3\cdot10^{15}\,cm^{-2}$ were calculated (which correspond to 18 years existence on the orbit). Data on material damage coefficients for the Ga(In)As layers were taken from [17], and values of the MCC diffusion lengths before irradiation – from [16]. Simulation results presented in Fig. 1 show the degradation dependencies of the short-circuit current and the efficiency for three values of the Ga(In)As base thickness.

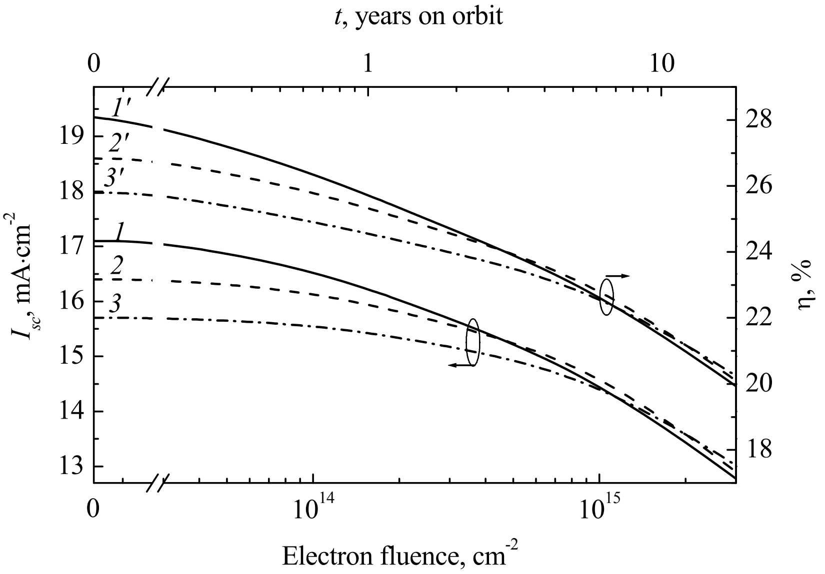

Fig. 1. Dependence of the short circuit current density I_{SC} (*1*,*2*,*3*) and efficiency η (*1'*,*2'*,*3'*) of GaInP/Ga(In)As/Ge MJSC on 1 MeV electron fluence and time on geostationary orbit. The Ga(In)As base thickness, μm: *1,1'* – 3.5; *2,2'* – 2; *3,3'* – 1.5. The Ga(In)As emitter thickness is 0.1 μm.

It is evident that although before radiation treatment the photocurrent and the efficiency initial values appear to be proportional to the subcell base thickness, this dependence disappear after electron fluences about $1\cdot10^{15}\,cm^{-2}$. So, in spite of the photocurrent of the thinnest cell has the degradation rate lower than that of the thicker one, its lower initial value does not permit to use this merit.

Ga(In)As subcell with Bragg reflector

Thinning the Ga(In)As subcell base allows reducing degradation of the photocurrent. However, this results in a drop of its initial value due to incomplete light absorption. In Ga(In)As subcells with 2 μm base thickness, it is valuable from the wavelength about 800 nm. In the subcells with 1.5 μm base thickness – from 720-730 nm.

Ensuring of the complete absorption of longwavelength photons in such subcells is possible by embedding into the subcell the BR structure, as proposed in [8,9]. Spectral dependencies of the reflection coefficient for the BRs are depicted in Fig.2.

A single BR containing 15 pairs of GaAs/AlAs layers (BR1*) or 20 pairs of $Al_{0.1}Ga_{0.9}As$/AlAs layers (BR1) (both are centered at 860 nm) ensures effective reflection for wavelengths of 800-900 nm in the SC structure with the Ga(In)As subcell base thickness of 2 μm.

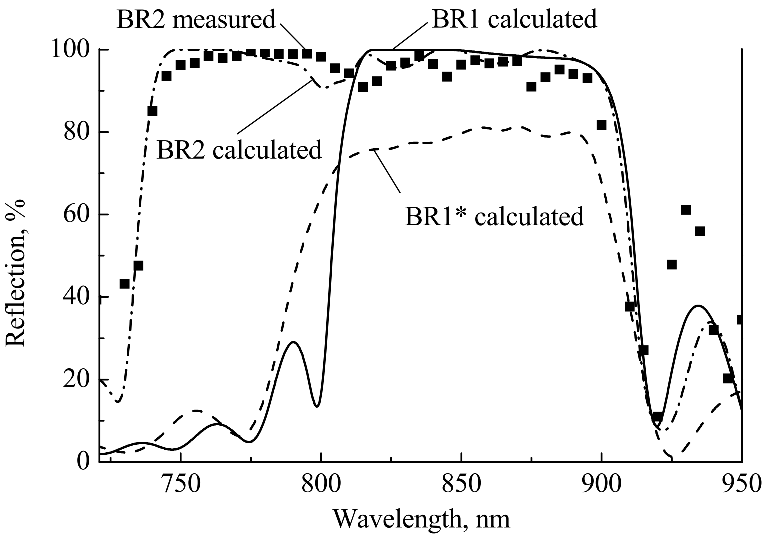

Fig. 2. Reflection of different BR:

A doubled BR, containing 20 pairs of $Al_{0.2}Ga_{0.8}As$/AlAs layers centered at 770 nm and 20 pairs of $Al_{0.1}Ga_{0.9}As$/AlAs layers centered at 860 nm (BR2) reflects light in the wavelength range of 750-900 nm. It allows thinning the Ga(In)As subcell base to 1.5 µm. It is clear that a good fit of calculated spectral characteristics to experimental ones was obtained for this BR.

Improvement of radiation resistance of Ga(In)As solar cells a BR

The degradation curves of the short circuit current and efficiency of GaInP/Ga(In)As/Ge MJSCs with and without a BR versus 1 MeV electron fluence are presented in Fig. 3. In the beginning of life (before irradiation) all cells have approximately alike photocurrents. At irradiation, the MJSC with the 1.5 µm Ga(In)As base and BR2 (MJSC3 in Fig. 3) ensures the short circuit current density greater by 1 mA·cm^{-2} and the cell with 2 µm Ga(In)As base with a BR1 (MJSC2) – by 0.5 mA·cm^{-2} compared with that for a cell with the 3.4 µm Ga(In)As base and without a BR (MJSC1). Gain in efficiency for the studied MJSCs with BRs was in the range of 2 and 1%, compared to the cell without BR.

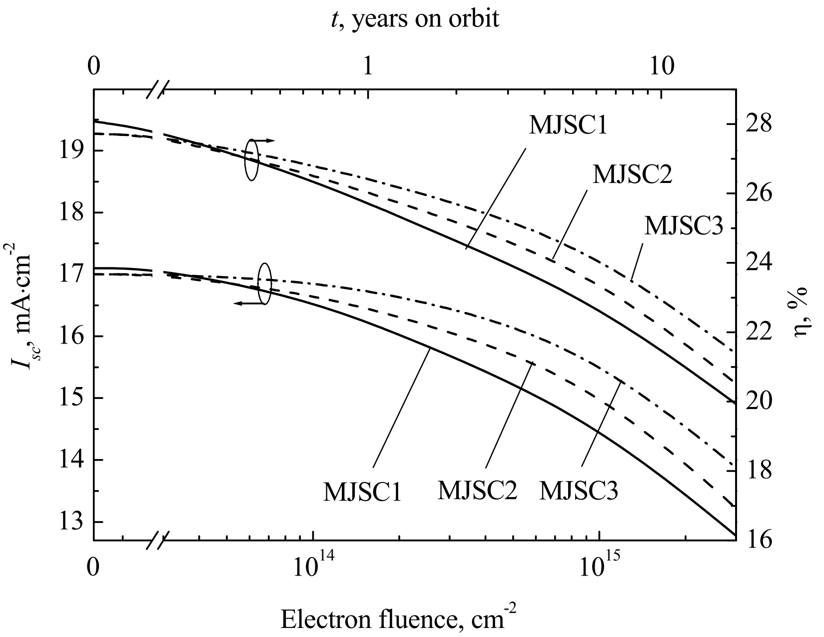

Fig. 3. Degradation of GaInP/Ga(In)As/Ge MJSCs with and without BR.

Application of the double BRs allows noticeably increasing the radiation tolerance of the GaInP/Ga(In)As/Ge MJSC. However, the short circuit current and, consequently, the efficiency of these MJSCs are still limited by the most rapidly degrading Ga(In)As subcell parameters. This effect can be reduced by structure optimization for the rated irradiation dose and should be touched upon GaInP and Ga(In)As subcells. Optimal values of subcells' thicknesses are shown in Fig. 4.

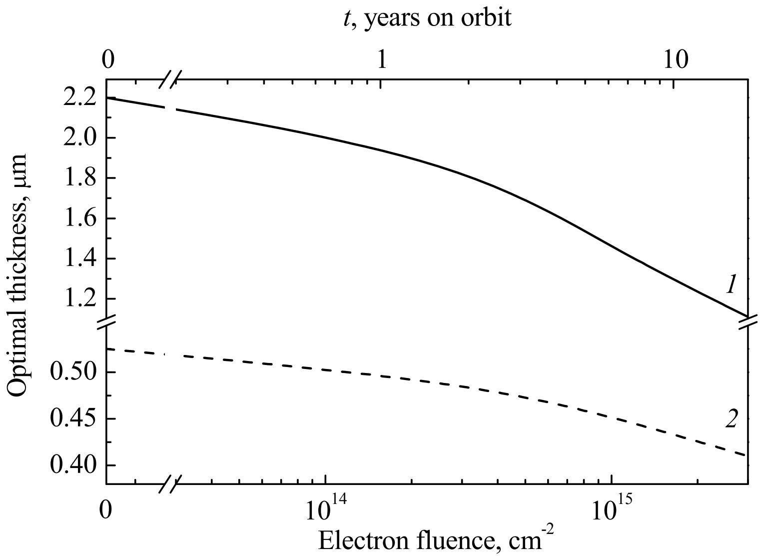

Fig. 4. Optimal thicknesses of Ga(In)As subcell base (*1*) and GaInP subcell (*2*) in a GaInP/Ga(In)As/Ge MJSC with BR2 on 1 MeV electron fluence and time on geostationary orbit.

To determine the effect of Ga(In)As and GaInP subcell thickness optimization degradation of the short circuit current and efficiency for three GaInP/Ga(In)As/Ge MJSCs with BR2 were simulated (Fig. 5). MJSC4 was optimized for the beginning of life, MJSC6 – for the ending of life (electron fluence of $3\cdot10^{15}$ cm^{-2}) and MJSC5 – at the electron fluence of $1\cdot10^{15}$ cm^{-2}. It is clear that the MJSC6 efficiency is maximal at the end of operation. At the same time, the MJSC5 efficiency is maximal up to 10 years operation period.

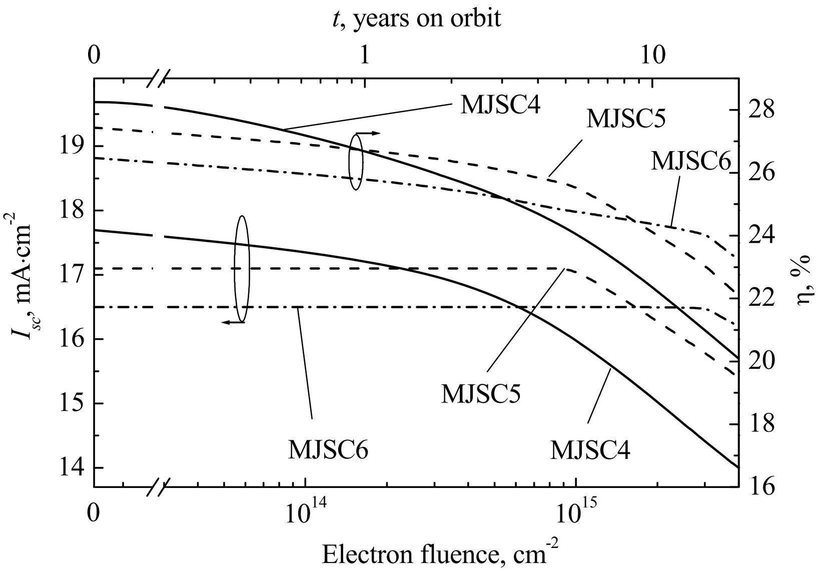

Fig. 5. Degradation of the short circuit current density I_{SC} and the efficiency η of GaInP/Ga(In)As/Ge MJSCs with BR2 optimized for different 1 MeV electron fluences.

Summary

In the present work, the feasibility for increasing the radiation resistance of GaInP/Ga(In)As/Ge MJSCs with the use of BRs has been studied with the use of the simulation method based on the main photovoltaic equations set analytical solution and determination of the electric field in the SC structure with the use of Abeles matrix method. Two configurations of BR designs – single and doubled – have been investigated. Obtained was a good fit between simulated and measured spectral dependencies of reflection for the BRs. It has been shown that application of the studied BR allows achieving efficiency of a MJSC after radiation treatment with 1 MeV electrons up to 2% higher, compared to a MJSC without a BR.

For a MJSC with a doubled BR, feasibility of the cell structure optimization to the rated radiation treatment has been considered. It has been shown that, although MJSCs optimized for higher electron fluences have lower initial values of the short circuit current and efficiency, compared to cells optimized on the beginning of life, to the end of operation, they could be considerable more efficient. Application of the MJSCs with doubled BR, optimized on the rated fluence of $1\cdot10^{15}$ см$^{-2}$ 1 MeV electrons, in arrays is preferable for the operation period on geostationary orbit up to 10 years. For longer operation periods, MJSCs with doubled BR optimized on rated fluences of $3\cdot10^{15}$ см$^{-2}$ and more than 1 MeV electrons are preferable. However, the application of such cells lead to reduction of the power of the solar array in the initial (before 10 years) period.

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