Study of lifetimes of nonequilibrium charge carriers by electroluminescence method in multijunction solar cells under irradiation with high-energy protons and electrons

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Triple-junction GaInP/Ga(In)As/Ge solar cells were studied by the electroluminescence method after irradiation with 2 and 4.5 MeV electrons and 10 MeV protons. The recombination current densities of $p-n$-junctions were determined and the dependences of the lifetimes of nonequilibrium charge carriers in GaInP and Ga(In)As layers were calculated depending on the fluences of damaging particles and the dose of structural damage, the damage coefficients for the considered materials and particles were calculated.

Keywords: electroluminescence, solar cell, radiation resistance, recombination current.

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Multijunction (MJ) solar cells (SC) are currently the main power source for spacecraft operating in various orbits around the Earth as well as for spacecraft designed for lunar and Mars missions. Exposure of semiconductor structures to high-energy particles, primarily, electrons and protons trapped by the Earth's magnetic field as well as carried by solar and galactic cosmic rays is a distinguishing feature of SC operation in space. Such particles cause radiation-induced damage of a structure leading to the occurrence of additional nonradiative recombination centers [1]. They cause reduction of carrier lifetimes in photoactive layers and, consequently, to:

– reduction of the external quantum efficiency (EQE) of photoconductive response and, accordingly, of SC photocurrent (in the case of MJ SC−photocurrents of SC subcells);

– increase in the dark current densities of the $p-n$-junctions leading to a decrease in the voltage and filling factor of the SC volt-ampere characteristic (VAC).

Traditional approaches to the analysis of SC radiation resistance include accelerated radiation tests and analysis of spectral and volt-ampere characteristics of devices after irradiation, however, for a monolithic MJ SC structure, it is particularly problematic to obtain VAC of SC subcells. This is an important problem because every subcell can demonstrate a different degree of degradation (due to differences in semiconductor designs, composition, thickness and doping levels of layers).

One of the methods to get information individually about every $p-n$-junction (apart from other subcells) is an electroluminescent examination method [2–5] based on the principle of reversibility of photovoltaic conversion and correlation between the photoconductive response EQE of the $p-n$-junction $EQE(\lambda)$ and its spectral dependence of electroluminescence (EL) M on the current through the $p-n$-junction J [6]:

$$M(\lambda, J) = EQE(\lambda)B(\lambda)\left[\exp\left(\frac{eV(J)}{kT}\right) - 1\right], \quad (1)$$

where e is the elementary charge, $V(J)$ is the $p-n$-junction VAC, λ is the radiation wavelength, k is the Boltzmann constant, B is the black-body spectrum at the given temperature T. The method is used to determine a subcell VAC according to the measured EL-current dependence with known photoconductive response EQE. It was successfully used by the authors before to explore the properties of MJ SC exposed to neutron irradiation [7].

Experimental findings for GaInP/Ga(In)As/Ge MJ SC samples (Table 1) exposed to 2 MeV and 4.5 MeV electron and 10 MeV proton irradiation are shown in Figure 1. From the measured VAC, densities of the diffusion current J_{01} and the recombination current J_{02} of the $p-n$-junctions of the GaInP and Ga(In)As subcells were calculated using the least-square method on the assumption that their VACs are described by a two-diode model [8,9]:

$$J(V) = J_{\text{ph}} - J_{01}\left(\exp\left(\frac{eV}{kT}\right) - 1\right) - J_{02}\left(\exp\left(\frac{eV}{2kT}\right) - 1\right), \quad (2)$$

where J_{ph} is the photocurrent density.

In [7], it was shown that the measured diffusion current density of the $p-n$-junction is impracticable for determining minority carrier (MC) lifetimes, therefore only the recombination current was further analyzed. Calculated J_{02} for GaInP and Ga(In)As is shown in Figures 2, a and 3, a, respectively. The measured dependences were scaled using the NIEL coefficient in accordance with the „displacement damage dose", DDD, model [10]. R_{ep} (defined as the ratio between DDD for electrons and DDD for protons) was assumed equal to 3.11 [11] because EL measurements of MJ SC subcells were performed in a near–no-load mode.

Recombination current density of the $p-n$-junction is defined by the carrier recombination through deep centers in the subcell's space charge region. Function of MC recombination through deep centers is written as [8,9]

$$R(n,p) = \frac{pn - n_i^2}{\tau_p(n + n_1) + \tau_n(p + p_1)}, \tag{3}$$

where $\tau_p = (\gamma_p N_r)^{-0.5}$, $\tau_n = (\gamma_n N_r)^{-0.5}$ are MC lifetimes in the n and p layers, respectively; γ_n, γ_p are the deep center trapping coefficients for electrons and holes; N_r is the number of deep centers; n, p are electron and hole

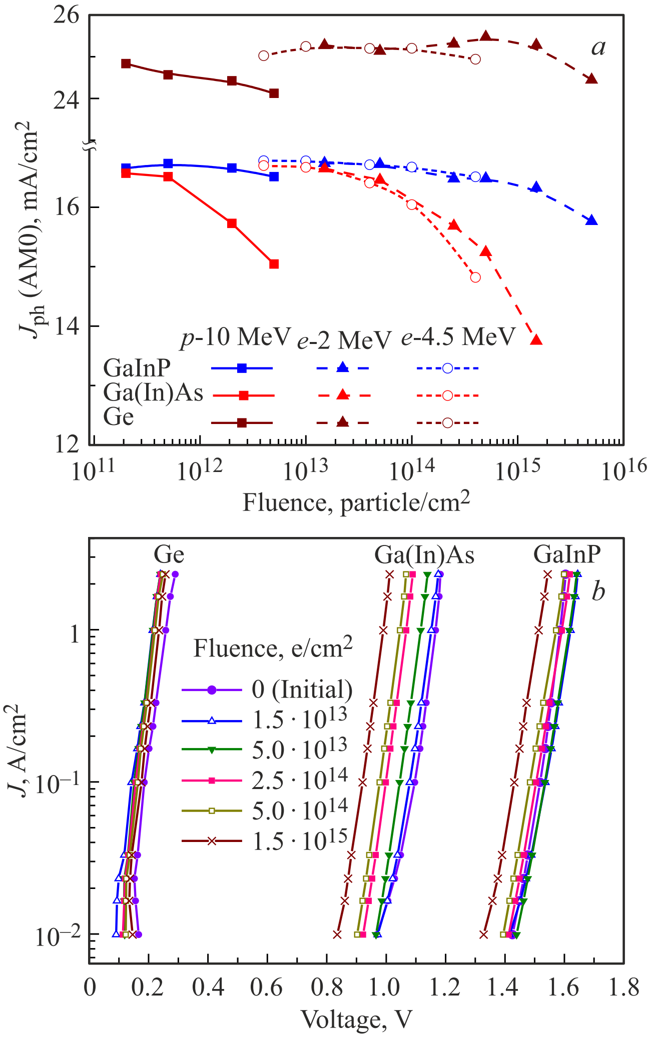

Figure 1. Degradation dependences for photocurrent densities of subcells of the studied GaInP/Ga(In)As MJ SCs (*a*) before and after exposure to the 2 MeV and 4.5 MeV electron irradiation and 10 MeV proton irradiation, and „voltage–current" dependences for subcells measured by the electroluminescent examination method with 2 MeV electron irradiation (*b*). „Voltage–current" dependences with 4.5 MeV electron irradiation and 10 MeV proton irradiation are identical to those shown in Figure *b* and are available on request.

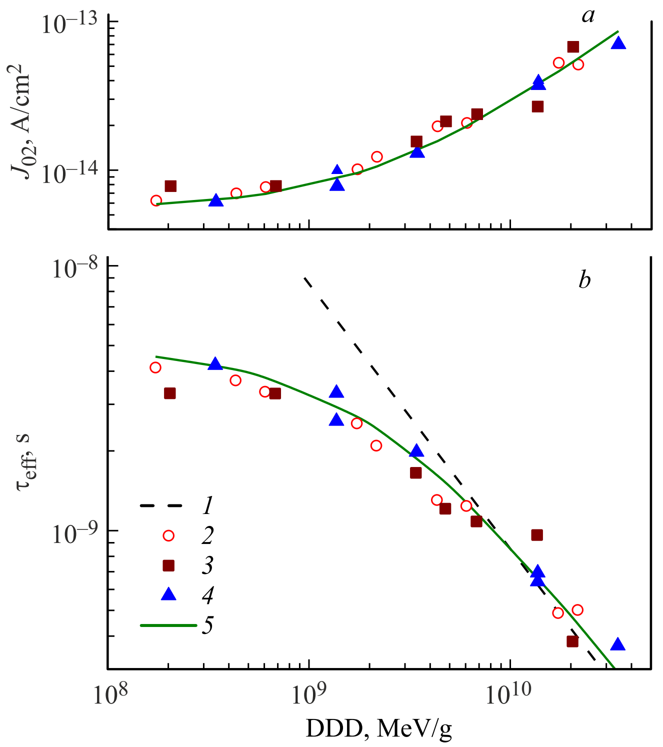

Figure 2. Dependences of the recombination current density (*a*) and nonequilibrium carrier lifetimes in SCR (*b*) for the GaInP subcells on the displacement damage dose (DDD) scaled in accordance with non-ionizing energy loss (NIEL): *1* — literature data for 1 MeV electron irradiation [11]; *2* — 2 MeV electron irradiation; *3* — 4.5 MeV electron irradiation; *4* — 10 MeV proton irradiation; *5* — approximation of dependences *2* and *3*.

concentrations, n_i is the intrinsic concentration of carriers. n_1 and p_1 having the concentration dimension correspond numerically to the number of carriers in such semiconductor where the Fermi level coincides with the recombination center level. If a field within the space charge region (SCR) with the thickness d is quite weak and electron and hole concentrations may be assumed to be virtually constant $n \approx p$, then the recombination current may be estimated as follows:

$$n = n_i\left(\exp\left(\frac{eV}{kT}\right) - 1\right), \quad J_{02} = \frac{en_i d}{\tau_{\text{eff}}}, \quad \tau_{\text{eff}} = \tau_n + \tau_p. \tag{4}$$

This may be observed when an undoped layer is embedded between the n and p regions and the Debye shielding length turns out to be smaller than the thickness of this layer d_i. For the $p-n$-junctions in GaInP and Ga(In)As, such situation may be observed in practice only at > 1 V and in the i-region with a size of $\sim 0.5\,\mu$m and more. However, the injection current, that grows faster due to twice as large exponent, usually dominates in this voltage range and the recombination current doesn't affect the shape of VAC any longer.

In the studied MJ SC subcells, the $p-n$-junction field is quite strong and the conduction band and valence band

Table 1. Structural parameters of the studied GaInP/Ga(In)As MJ SC

Layer	Material designation (sublayer description)	Layer thickness, nm
Upper subcell	n-$Al_{0.52}In_{0.48}P$ (wide-band window)	30
	n-$Ga_{0.51}In_{0.49}P$ (emitter)	50
	p-$Ga_{0.51}In_{0.49}P$ (base)	450
	p-$Ga_{0.51}In_{0.49}P$ (rear potential barrier (RPB))	100
Upper tunnel diode	p^{++}-$Al_{0.4}Ga_{0.6}As$ (p-layer)	15
	n^{++}-GaAs (n-layer)	15
Medium subcell	n-$Al_{0.8}Ga_{0.2}As$ (wide-band window)	30
	n-$Ga_{0.99}In_{0.01}As$ (emitter)	90
	$Ga_{0.99}In_{0.01}As$ (i-region)	0.1
	p-$Ga_{0.99}In_{0.01}As$ (base)	1800
	p-$Ga_{0.51}In_{0.49}P$ (RPB)	100
Lower tunnel diode	p-$(AlGa)_{0.5}In_{0.5}P$ (stop layer)	30
	p^{++}-$Al_{0.4}Ga_{0.6}As$ (p-layer)	30
	n^{++}-GaAs (n-layer)	30
	n-$Al_{0.5}In_{0.5}P$ (barrier layer)	100
15-period Bragg reflector	n-GaAs/n-$Al_{0.9}Ga_{0.1}As$	68/62
Buffer layer	n-$Ga_{0.99}In_{0.01}As$	300
Lower subcell	n-$Ga_{0.51}In_{0.49}P$ (wide-band window)	90
	n-Ge (emitter)	150
	p-Ge (substrate)	175000 ± 5000

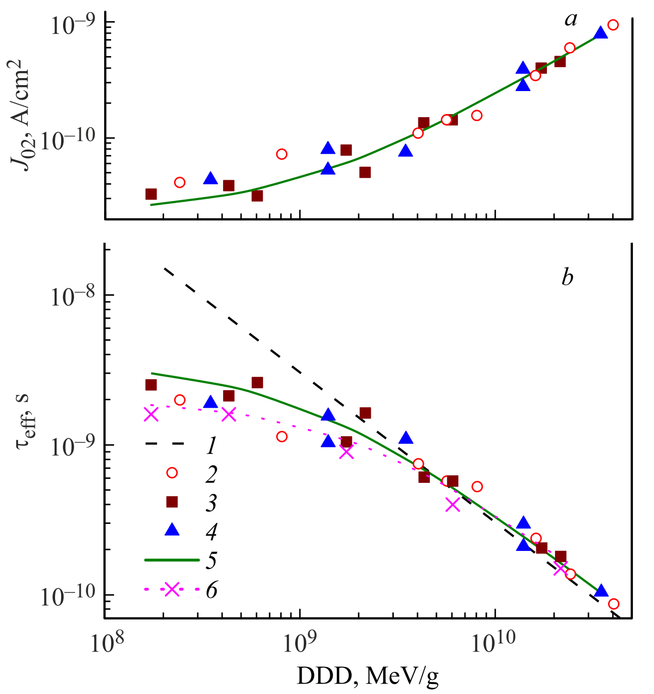

Figure 3. Dependences of the recombination current density (a) and nonequilibrium carrier lifetimes in SCR (b) for the GaInP subcells on the displacement damage dose (DDD) scaled in accordance with non-ionizing energy loss (NIEL): *1* — literature data for 1 MeV electron irradiation [11]; *2* — 2 MeV electron irradiation; *3* — 4.5 MeV electron irradiation; *4* — 10 MeV proton irradiation; *5* — approximation of dependences *2* and *3*; *6* — lifetimes during 4.5 MeV electron irradiation determined by the external quantum efficiency of photoconductive response.

boundaries vary smoothly from the n-doped to p-doped layers. The recombination current shall be found as the integral of expression (3) throughout the space charge region:

$$J_{02}\left[\exp\left(\frac{eV}{kT}\right)-1\right]=e$$

$$\times\int_0^d \frac{n_i^2\left(\exp\left(\frac{eV}{kT}\right)-1\right)dx}{\tau_n\left(p_1+p(d)\exp\left(\frac{e\varphi(x)}{kT}\right)\right)+ +\tau_p\left(n_1+n(0)\exp\left(\frac{e(\varphi(x)-V_0+V)}{kT}\right)\right)}, \quad (5)$$

where V_0 is the contact difference of potentials, φ is the electrostatic potential. It is assumed here that the n-region corresponds to $x<0$, and the p-region corresponds to $x>d$.

The approximated recombination current density from this integral may be found as

$$J_{02}=\frac{en_i d_{\rm eff}}{\tau_{\rm eff}},\quad \tau_{\rm eff}=\sqrt{\tau_n\tau_p},\quad d_{\rm eff}=\frac{kT}{e}\left(\frac{d\varphi}{dx}\right)\Big|_{\varphi=\varphi'}^{-1}$$

where

$$\exp\left(\frac{e\varphi'}{kT}\right)=\sqrt{\frac{\tau_n p(d)}{\tau_p n(0)}}\exp\left(\frac{e(V_0-V)}{2kT}\right). \quad (6)$$

Figures 2, b and 3, b show the dependences of the MC lifetimes calculated from the recombination current densities.

Table 2. Measured damage coefficients of the life time of the MC for GaInP and Ga(In)As materials under irradiation with high-energy particles

Material	Damage coefficient for particles, cm^2/s		
	2 MeV electrons	4.5 MeV electrons	10 MeV protons
GaInP	$(1.5 \pm 0.3) \cdot 10^{-6}$	$(4.0 \pm 0.6) \cdot 10^{-6}$	$(5.9 \pm 0.9) \cdot 10^{-4}$
Ga(In)As	$(4.6 \pm 0.6) \cdot 10^{-6}$	$(0.9 \pm 0.2) \cdot 10^{-5}$	$(1.6 \pm 0.3) \cdot 10^{-3}$

Dependences of the MC lifetimes on the fluence for 1 MeV electron irradiation are shown dashed [12].

The figures show that the obtained dependences of the MC lifetime on the damaging particle fluence agree well with the model described in this work. Figure 3, *b* also shows the dependence of the MC lifetime on the 4.5 MeV electron dose calculated by the external quantum efficiency (EQE) of photoconductive response for the Ga(In)A subcell [13]. It almost coincides with the EL examination data, except for the initial segment. This is due to the fact that, when the MC diffusion length exceeds manifold the subcell's *n*- and *p* layer thicknesses, photogenerated carriers are almost fully gathered in the $p-n$-junction, and determining the lifetimes by the photoconductive response EQE cannot provide valid results.

Thus, efficiency of the recombination current density of the $p-n$-junction measured using the electroluminescent method was demonstrated for finding the nonequilibrium carrier lifetimes during radiation testing of devices. Damage coefficients were determined for GaInP and Ga(In)As subcells of MJ SC exposed to 2 MeV and 4.5 MeV electron and 10 MeV proton irradiation (Table 2).

Conflict of interest

The authors declare no conflict of interest.

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