THE RECOMBINATION AND TUNNEL CURRENT IN GaAs-BASED SOLAR CELLS: EFFECT OF RADIATION.

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ABSTRACT

The space charge (depletion) region of photovoltaic and tunnel p-n junctions, as appeared, give an essential contribution to the characteristics of multi-cascade solar cells and to their radiation tolerance. In the present work the mechanisms of current passage in GaAs p-n junctions and their evolution under irradiation with 6.78 MeV protons, 1MeV electrons and gamma-rays from a Co^{60} source have been studied. The recombination component of the photovoltaic p^+-n junctions yields the carrier lifetimes in the SCR $\tau_w = (10^{-10}\div10^{-8})$s. Estimates of the damage coefficient in the SCR - $K_{\tau w}$, based on an analysis of the dependence of the carrier lifetime in the SCR on the irradiation fluences demonstrated that the damage coefficient is fluence dependent.

1 INTRODUCTION

Perfection of the design of a single-cascade GaAs-based solar cell [1,2] has allowed ensuring the minimum possible influence of the radiation induced degradation of its photovoltaic characteristics. The advent and development of multi-cascade solar cells (MSC) [3,4] resulted in a higher share of the space-charge (depletion) region (SCR) in the cells and, consequently, in its more important contribution to a higher solar cell efficiency and weaker radiation induced degradation of photovoltaic parameters of cascade solar cells. For example, the relative decrease in the photocurrent at the optimal load point is 0.96, and that in voltage, 0.88, in a three-cascade monolithic GaInP/GaAs/Ge solar cell irradiated with 1 MeV electrons at a fluence of $1\cdot10^{15}$ cm^{-2} [5]. At the same time, in a single-junction GaAs solar cell subjected to a similar irradiation, the relative decrease in the photocurrent and voltage is 0.83 and 0.9, respectively [6]. In a solar cell with an internal Bragg reflector the relative decrease in the short–circuit photocurrent and open-circuit voltage was 0.95 and 0.96, respectively, for irradiation with 3 MeV electrons at a fluence of $1\cdot10^{15}$ cm^{-2}, [7]. Thus it has been found that the radiation induced degradation of open circuit photovoltage in MSC is higher than that in the single-cascade solar cell (SC). Therefore, understanding and detailed study of recombination and tunnel processes within the space-charge region of the photovoltaic p^+-n junction and the tunnel p^{++}-n^{++} junction, and also their evolution under irradiation, become important. Available tool is the use of the dark forward current-voltage (I-V) characteristic, namely, those its parts, which are determined by the recombination of thermally injected carriers (electrons and holes) in a SCR [9,10], and also by the interband tunneling and the deffect-dependent tunneling [10,11] through the SCR. In this study, the shape and structure of dark I-V characteristics of GaAs p-n junctions and changes in these characteristics upon the irradiations were analyzed. This enabled, in particular, determination of the carrier lifetime within the SCR in relation to the irradiation fluence and the damage coefficient.

2 EXPERIMENTAL

The GaAs photovoltaic p^+-n junctions (PV) were fabricated by metal-organic chemical vapor deposition (MOCVD) and low-temperature liquid-phase epitaxy (LT LPE). The structures had the following design: a wide-gap AlGaAs window with thickness of about 0.1μm; 0.3-0.5 μm – thick p^+-GaAs emitter region doped with Mg (Zn) to a concentration $N_A=(10^{18}\div10^{19})$ cm^3; and n-type base region doped with Te (Si) to a donor concentration $N_D\sim(10^{16}\div10^{17})$ cm^{-3} and having thickness of 2-4 μm. The PV junction area was from 0.1 to 1.0 cm^2. The structure of GaAs tunnel p^{++}-n^{++} junction (TU) is formed during the LT LPE. The thickness of the heavily doped p^{++}- GaAs (Ge) and n^{++}- GaAs (Te) tunnel junction regions are chosen as thin as possible (5÷10 nm). Te and Ge atom concentration of about 10^{20} cm^{-3} have been measured by SIMS. The TU junctions area ranged from 0.0005 to 1.0cm^2.

The irradiation of both GaAs p–n junction types was done with the following monochromatic flows: electrons with energy E_e = 1 MeV and fluences of $(3\cdot10^{14}\div 3\cdot10^{16})$ cm^{-2}, protons with energy E_p = 6.78 MeV and fluences of $(3\cdot10^{10}\div3\cdot10^{12})cm^{-2}$, and gamma quanta from a Co^{60} source with energies E_γ = (1.17÷1.33) MeV and doses of (1.7÷17)Mrad. Dark I-V characteristics of both types GaAs p-n junctions were measured at room temperature before irradiation and after every irradiation.

3. PHOTOVOLTAIC JUNCTIONS

3.1 Analysis of dark forward I-V characteristics.

The forward current consists of the components with exponential dependence on the voltage V_j across the SCR. Figure 1 shows a typical I-V characteristic. Such a qualitative description of a forward I-V characteristic of single cascade solar cells (SC) were studied [12,13,14]; however, no quantitative consideration has been made. An analytical description of the shape of a I-V characteristic should take into account the voltage IR_s across the ohmic series resistance of the p-n structure, with the result that the voltage V measured exceeds the voltage across the SCR (V_j), i.e., V_j = V- IR_s. Unity should be subtracted from each of the components to ensure zero current at zero voltage across the SCR. Taking into account all these factors, we have used the following two-component expression for fitting the forward dark current:

$$J=J_1+J_2=J_{01}\left(\exp\left(\frac{eV_j}{\varepsilon_1}\right)-1\right)+J_{02}\left(\exp\left(\frac{eV_j}{\varepsilon_2}\right)-1\right) \quad (1),$$

This functional dependence has five free parameters, namely: J_{01}, ε_1, J_{02}, ε_2, R_s, which were found from fitting. An illustration of the fitting (see Fig. 1) is presented.

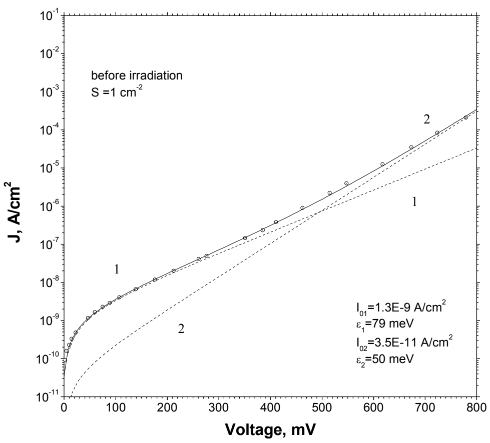

Fig. 1 The dark forward I–V characteristic of GaAs photovoltaic p^+-n junction of SC approximated by a sum of two exponential components: defect-dependent tunnel current (1) and usual recombination current (2).

The first component (see Fig.1), has ε_1=70÷200meV, which indicates the tunnel nature of the charge carrier transport. Furthermore, the relatively large SCR width suggests the so-called hopping tunneling along a dislocation line crossing the SCR [15]. This model allows estimation of the formal dislocation density ρ by means of the following expression:

$$J_{01} = e\rho\nu_D \exp\left(-\frac{eV_k}{\varepsilon_1}\right) \quad (2),$$

where ν_D = $7.5\cdot10^{12}$ s^{-1} is the Debye frequency corresponding to the Debye temperature Θ=360 K [16]. The ρ values calculated in this way for the PV junctions are within the range $\rho=(10^4\div10^5)$ cm^{-2} .

The second component (see Fig.1, 3) has practically the same ε_2~50meV, i.e., $2k_BT$, and the pre-exponential factor was in the range $J_{02} = (10^{-12}\div10^{-10})$ A/cm^2. Such ε_2 and J_{02} values enabled us to apply the model of single-valent recombination current [8] and, thereby, to estimate the lifetime (τ_w) of carriers in the SCR using the expression:

$$\tau_w = \frac{en_i l}{J_{02}} \quad (3),$$

where, n_i is the intrinsic carrier concentration in GaAs, $n_i=2.1\cdot10^6$ cm^{-3} [17]; $l = \left(\frac{k_BT}{eE}\right)$ is the characteristic width of the recombination zone within the SCR of a p-n junction; and E is the electric field inside the SCR, equal to ~$1\cdot10^5$ V/cm according to estimations based on capacitance–voltage measurements.

The carrier lifetime τ_w in the SCR of the junctions calculated for different doping levels of the n–GaAs base region are in the range $\tau_w = (10^{-10}\div10^{-8})$ s.

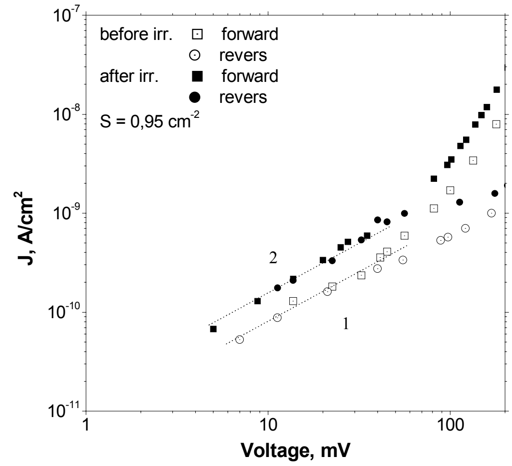

Fig. 2. Forward and reverse dark I-V characteristics of GaAs photovoltaic p^+-n junctions of SC before (1) and after (2) 6,78 MeV proton irradiation at a fluence of $3\cdot10^{12}$ p/cm^2.

In addition to these two components, some structures show indications of the presence of a third component at voltages of (0.7÷0.8)V. In this case, fitting based on the two-component expression (1) gave ε_2 < $2k_BT$, (ε_2 =35÷40 meV). At the moment we consider two versions of interpretation of this case. First, it may be a contribution of so called multivalent recombination component, which is determined by the recombination through multivalent centers of electrons and holes thermally injected into the space charge region of the p-n junction [9]. This component was previously observed in GaAs-based p-n junctions and has $\varepsilon_3 = (5/4)\ k_BT$ [18], i.e. 1<n<2, where $n = \varepsilon_3/k_BT$. Second, it may be a modest contribution of the diffusion component. As a rule, this third component is observed at high current densities of J > 10^{-4} A/cm^2. The three-component expression for fitting the forward dark current is:

$$J=J_1+J_2+J_3=J_{01}\left(\exp\left(\frac{eV_j}{\varepsilon_1}\right)-1\right)+J_{02}\left(\exp\left(\frac{eV_j}{2kT}\right)-1\right)$$
$$+J_{03}\left(\exp\left(\frac{eV_j}{\varepsilon_3}\right)-1\right) \quad (4)$$

In some cases, the third component can be masked at higher currents by the effect of the series resistance R_s.

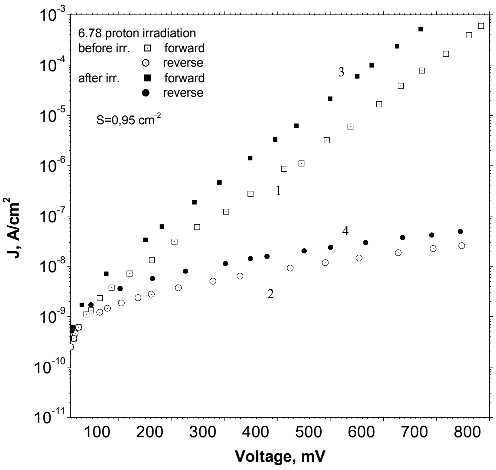

Fig. 3. Forward dark I-V characteristics of GaAs photovoltaic p^+-n junctions of SC: before (1,2) and after (3,4) 6,78 MeV proton irradiation at a fluence of $3\cdot10^{12}$ p/cm^2.

3.2 Effect of irradiations.

Irradiation of a single cascade solar cell with protons, electrons and gamma rays resulted in qualitatively identical changes in dark I-V characteristics. As seen from fig. 2, 3 forward and reverse currents grow upon irradiation. The dark forward I-V characteristic can still be approximated by the expression (1) after irradiation. The slope of the second (usual recombination) component remains unchanged (ε_2~50 meV), and the pre-exponential factor J_{02} grows. The increase in J_{02} means that the concentration of recombination centers in the SCR becomes higher and, correspondingly, the carrier lifetime decreases ($J_{02} \sim N_r \sim \tau_w^{-1}$).

The increments in the inverse lifetime $\Delta(1/\tau_w) = (1/\tau_w) - (1/\tau_w)^{initial}$, depend on the fluence sublinearly for three types of irradiation (see Fig.4 and Table 1), [19]. In spite of this fact, let us introduce the damage coefficient by inverse carrie lifetime in SCR - $K_{\tau w}$ similarly [13] for each of the types of irradiation:

$$\Delta\left(\frac{1}{\tau_w}\right) = K_{\tau w}\cdot F \qquad (5),$$

where F is the irradiation fluence.

As is seen from the Fig.4 and Table.1, $K_{\tau w}$ values depend on the irradiation fluence. It is seen from Fig.4 that approximately the same effect $\Delta(1/\tau_w) \approx (4\div6)ns^{-1}$ is yelded by the following proton, electron and gamma irradiations: $F_p=3\cdot10^{11}$ p/cm^2, $F_e=3\cdot10^{15}$e/cm^2 and F_γ=17 MRad. For these values of F_p, F_e and F_γ one may compare the damage coefficients – $K_{\tau w}$ (see Table 1) with K_τ, where K_τ is a damage coefficient expressed through inverse lifetime in bulk. The interralation between coefficients K_τ and K_L is $K_\tau=DK_L$, where D is diffusion coefficient of minority carriers in bulk and K_L is a damage coefficient expressed through square inverse diffusion length.

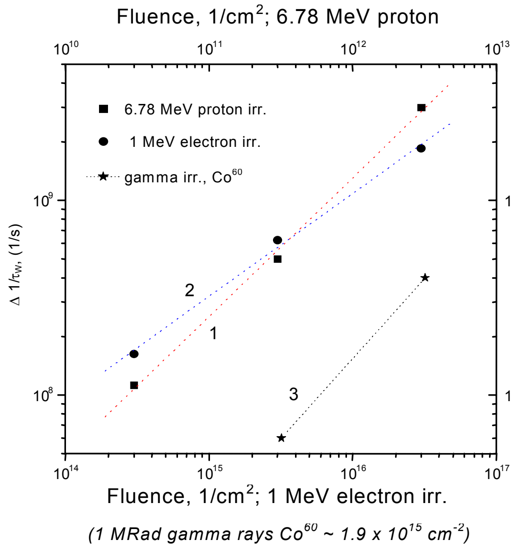

Fig. 4. Increment of the inverse carrier lifetime in the SCR of GaAs photovoltaic p^+-n junctions of SC under irradiation with protons (1), electrons (2) and gamma rays (3).

Using the literature data for K_L of GaAs bulk [13,20,21] and for D_p=10cm^2/s [17] one may obtain that: 1) for the electron irradiation $K_{\tau w}$ has the same order of magnitude as $K_{\tau p}$, $K_{\tau w} \approx K_{\tau p}$,; 2) for the proton irradiation $K_{\tau w} > K_{\tau p}$ approximately by one order of magnitude, where $K_{\tau p}$ is the damage coefficient expressed through inverse hole lifetime in n-GaAs.

Table 1.

Fluence, (1/cm^2)	$\Delta(1/\tau_w)$, (1/s)	$K_{\tau w}=\Delta(1/\tau_w)/F_i$, (s$^{-1}\cdot$cm^2)
Protons, E_p= 6.78 MeV		
$3\cdot10^{10}$	$1.0\cdot10^8$	$4.0\cdot10^{-3}$
$3\cdot10^{11}$	$5.0\cdot10^8$	$1.5\cdot10^{-3}$
$3\cdot10^{12}$	$3\cdot10^9$	$1.0\cdot10^{-3}$
Electrons, E_e = 1 MeV		
$3\cdot10^{14}$	$1.5\cdot10^8$	$6\cdot10^{-7}$
$3\cdot10^{15}$	$6.0\cdot10^8$	$2.5\cdot10^{-7}$
$3\cdot10^{16}$	$2.0\cdot10^9$	$8.0\cdot10^{-8}$
Gamma rays, Co^{60} MRad		
1.7 MRad	$6.0\cdot10^7$	$2.0\cdot10^{-8}$
17 MRad	$4.0\cdot10^8$	$1.5\cdot10^{-8}$

4. TUNNEL JUNCTIONS

The forward I-V characteristic of tunnel p^{++}-n^{++} junction has a usual shape [10,11] (see Fig.5.) and contains two tunnel components originating in the SCR. They have tunneling mechanism: interband and defect-dependent (excess). The characteristic can be written as:

$$J = J_p \frac{V_j}{V_p} \exp\left(1 - \frac{V_j}{V_p}\right) + J_0\left(\exp\left(\frac{eV_j}{\varepsilon}\right) - 1\right) \quad (6)$$

Where J_p is the peak value of the current density, V_p is the voltage corresponding to this value. All types of the irradiation used give qualitatively similar changes of the forward I-V characteristic shape, (see Fig.5): the peak current density J_p decreases, the corresponding voltage V_p being in the range of (0.1÷0.15) V; the defect-dependent (excess) current grows similar to that in photovoltaic p^+-n junctions; the series resistance of the tunnel structure R_s increases.

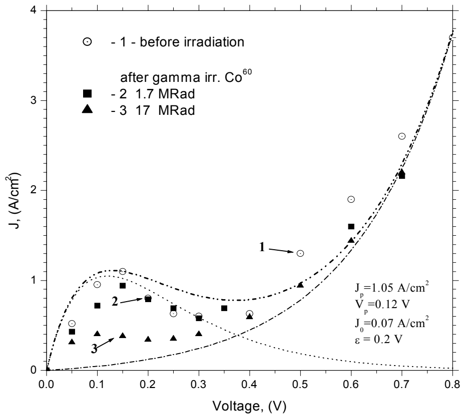

Fig. 5 The forward I-V characteristics of GaAs tunnel junction and their evolution under gamma irradiation Co^{60} at doses: zero MRad - (index 1), 1.7 MRad -(2), 17 Mrad-(3). The initial I-V characteristic (1) is approximated by the sum of two tunnel components: the interband and the defect dependent.

Such an important parameter for a MSC as the differential resistance in a zero point (I=0, V=0) R_0^{dif} = (dV/dJ) rises due to the decrease of the peak current J_p at almost unchangeable V_p, since $R_0^{dif}=(1/2.718)(V_p/J_p)$, where 2.718 is the base of natural logarithms. The peak current drops, probably, due to increasing the SCR width in decreasing the free carrier concentration in the neutral bulks of the tunnel p^{++}-n^{++} junction resulted from the compensation effect of radiation-induced defects at different used irradiations. The defect-dependent current in the tunnel junctions grows, as we believe, by the same reasons, which take place in photovoltaic p^+-n junctions, namely, due to increasing the dislocation density.

5. CONCLUSION

The forward dark current in GaAs PV junctions are determined by four mechanisms of carrier transport, associated with defect-assisted tunneling, single-valent (usual) recombination, multi-valent recombination and diffusion, at the same time in GaAs TU junctions are determined by two tunneling mechanisms: interband and defect-dependent (excess).

The electron, proton and gamma irradiations magnify both the forward dark current and the reverse current in the PV jnctuons. The defect-dependent tunnel component indicates that the formal dislocation density in the SCR increases with increasing the fluences.

The analysis of the recombination components yield the carrier lifetimes in the SCR and its dependence on the fluence of the irradiations. The increment of the inverse lifetimes in the SCR is not directly proportional to the irradiation fluences: $\Delta(1/\tau_w) \sim F^m$, $m < 1$. The damage coefficients decreases with increasing fluence of the irradiations.

For the tunnel jnctions it was observed that the differential resistance at zero point increases in 3 ÷ 5 times at maximum fluences of the irradiations.

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