TUNNEL GaAs AND GaSb p-n JUNCTIONS - THE CARRIER TRANSPORT AND THE EFFECT OF IRRADIATIONS

V.S.Kalinovsky, V.M.Andreev, V.V.Evstropov, V.P.Khvostikov
Ioffe Physico-Technical Institute, 26 Politekhnicheskaya str., St.-Petersburg, 194021, Russia,

ABSTRACT: The effect of proton, electron and gamma irradiations on GaAs and GaSb tunnel p+-n+ junctions utilized as connecting elements in multilayer cascade solar cells was investigated. Tunnel junction structures were grown by the low-temperature liquid phase epitaxy technique. As a result of irradiations the peak current decreases, and the excess one rises. The excess current rise is interpreted as an increase in more than 5 times of the dislocation density (at the initial density of about $10^7 cm^{-2}$) piercing the space charge region (SCR) of the tunnel junction. The “peak” current decrease at practically invariable “peak’’ voltage is interpreted as widening of SCR by approximately 1 nm. It is supposed that this widening is caused by the radiationally stimulated impurity diffusion. For a multicascade solar cell (MSC) such a widening is a negative effect.. Evolution of SCR parameters and tunnel current mechanisms found experimentally and shown in calculations are similar to those of GaAs and GaSb tunnel p+-n+ junctions under the irradiations.
Keywords: Radiation Damage, Degradation, Tunnel Junction.

1. INTRODUCTION

At present an interest to tunnel p-n junctions (TJ) is associated with their utilizations in monolithic cascade solar cells (SCs) [1,2]. Study of such TJs shows an important role of the diffusion of electrically active impurities [3,4]. One of the most actual directions of investigation is the effect of irradiation on p-n junction properties. As has been already pointed out before [5,6] comparison shows principal differences in regularities of radiational degradation of single-cascade and monolithic multi-cascade SCs. The photocurrent (short circuit current) degradation in single-cascade SC is going on faster than degradation of the open circuit voltage, whereas in monolithic MSC – vise versa. An apparent difference between mechanically stacked cascades and monolithic MSCs is the presence in the latters of tunnel connecting diodes. For this reason it is advisable to study the tunnel current mechanism and the effect of irradiation on tunnel p+-n+ junction characteristics. In the present work the dark current-voltage characteristics (DI-V) of GaAs and GaSb tunnel p+-n+ junctions and the effect of proton, electron and gamma ray irradiations on them were analyzed.

2. INVESTIGATION OBJECTS

GaAs and GaSb tunnel p+-n+ junction structures were obtained by the low temperature liquid phase epitaxy technique (LT LPE).

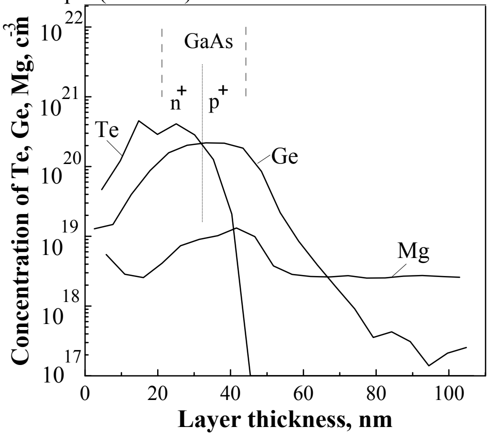

Fig. 1 SIMS profiles of doping elements across the GaAs tunnel junction grown by LT LPE.

We intended to make the tunnel junction SCRs with characteristics similar to those of the tunnel junctions in MSCs [1,2]. Concentration of Te and Ge atoms as impurities in GaAs tunnel p+-n+ junction were of the order of 10^{20} cm^{-3}, (Fig.1)

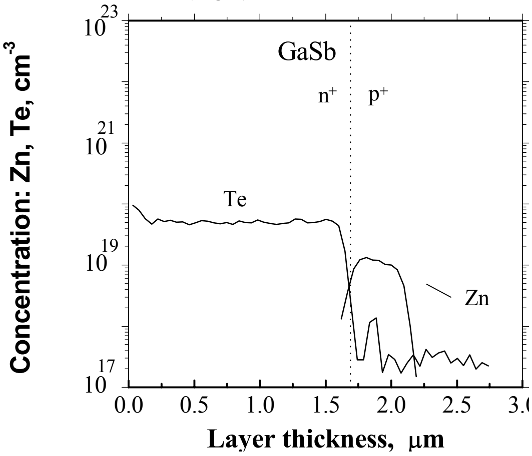

Fig. 2 SIMS profiles of doping elements across the GaSb tunnel junction grown by LT LPE.

and Te and Zn in GaSb tunnel junctions – about 10^{19} cm^{-3} (Fig.2). All TJ specimens were irradiated at room temperature, at constant intensity of beam and without heating by monochromatic beam of 6.8 MeV protons in the fluence range of $3\cdot10^{10} \div 3\cdot10^{12}$ cm^{-2} and of 1 MeV electrons in the fluence range of $3\cdot10^{14} \div 3\cdot10^{16}$ cm^{-2}. Irradiation by Co^{60} gamma quanta was done at the same conditions in the dose range of 1.7 ÷ 17 MRad. Ohmic contacts to the GaAs and GaSb tunnel structures were formed, correspondingly, at 450 and 600^0C during minimum time.

2. ANALYSIS OF DARK I-V CHARACTERISTIC OF GaAs AND GaSb TUNNEL JUNCTIONS

3.1 Analytical expression for DI-V characteristics

The current passing through TJ consists of two tunnel components: interband (Esaki) and defect (“excess”) ones. For the interband component the analytical expression is [7]:

$$J = J_p \frac{V_j}{V_p} \exp(1 - \frac{V_j}{V_p}) \qquad (1)$$

The defect ("excess") component has the same voltage and temperature dependencies as the tunnel component in photovoltaic p-n junctions [5,6]:

$$J = J_0 (\exp \frac{qV_j}{\varepsilon} - 1) \qquad (2)$$

where J_p is the peak current, V_p is the voltage corresponding to the peak current ("peak" voltage), J_0 is the preexponent multiple ("saturation current"), q is the electron charge, ε is the diode characteristic energy, V_j is voltage on the p+-n+ tunnel junction, V_j=V-JR_s, R_s is the series resistance, V is voltage on the structure. Thus, for description of the experimental TJ DI-V we used the expression:

$$J = J_p \frac{V - JR_s}{V_p} \exp(1 - \frac{V - JR_s}{V_p}) + J_0 (\exp \frac{q(V - JR_s)}{\varepsilon} - 1) \qquad (3)$$

This expression contains 5 free parameters: J_p, V_p, J_0, ε, R_s which were determined by fitting to experimental curves correspondingly for GaAs and GaSb tunnel p+-n+ junctions before and after irradiation.

3.2 Peak current

In correspondence with a generally accepted conception, carriers tunnel through a barrier of height equal to the forbidden gap energy (E_g) and width equal to the SCR width (W). Transparency of the tunnel barrier is

$$T \approx e^{-\alpha \frac{W}{\lambda_t}} \qquad (4)$$

where α is the barrier shape coefficient, λ_t is the characteristic tunneling length, for GaAs it is equal approximately to 0.6 nm, and for GaSb – 0.3 nm. The peak current is proportional to the tunnel barrier transparency:

$$J_p \sim T \approx e^{-\alpha \frac{W}{\lambda_t}} \qquad (5)$$

We consider that in irradiating λ_t does not change, and therefore the peak current decrease is associated with SCR widening – ΔW. It follows from the expression (5) that ΔW is associated with the decrease of J_p from J_p' to J_p''.

$$\Delta W = \frac{1}{\alpha} \lambda_t \ln \frac{J_p^{'}}{J_p^{''}} \qquad (6)$$

For this reason the relative change of the peak current J_p'/J_p'' found experimentally allows to estimate the absolute ΔW of SCR according to the expression (6).

3.3 Excess current

Using for interpretation of the excess current the model of multi-hopping tunneling over dislocations piercing the p-junction one can estimate their density (ρ). Using the expression for the preexponential multiple of the tunnel excess current from [8] one can determine the dislocation density in SCR as

$$\rho = \frac{J_0}{q \nu_D \exp(-\frac{qV_K}{\varepsilon})}, \qquad (11)$$

where $\nu_D = \frac{k}{h}\Theta$ is the Debye frequency, Θ is the Debye temperature, k and h are Boltzmann's and Planck's constants.

4. THE EFFECT OF RADIATON ON GaAs AND GaSb TJs

4.1 GaAs p+-n+ tunnel junction

In initial GaAs p+-n+ tunnel structures the peak current density J_p≈1 A/cm^2 and corresponding voltage V_p≈ 0.07V. The calculated effective free charge carrier concentration at the SCR boundaries n_{eff} ≈ 3·10^{18} cm^{-3}, the contact potential difference is about 1.63 V, the SCR width is about 27 nm. The differential resistance in the zero point R_{diff} ≈ 0.025 Ohm cm^{-2}. For the excess component of the tunnel current the value of the characteristic energy appeared to be ε ≈ 0.19 eV, and the preexponential multiple J_0 ≈ 0.02 A/cm^2, which corresponds to the dislocation density ρ ~ 10^{-7} cm^{-2}.

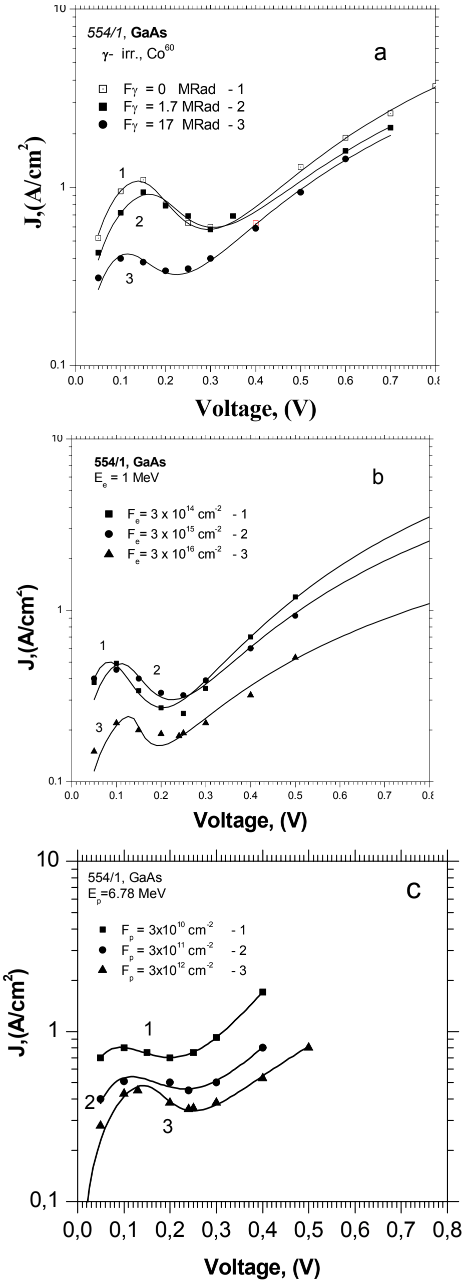

Fig.3 Degradation of the dark I-V characteristic of GaAs tunnel junctions at irradiation by: **a** - Co^{60} gamma rays of doses (MRad): 1 – 0; 2 – 1.7; 3 – 17; **b** – 1 MeV electrons at fluences (1/cm^2): 1 – 3·10^{14}, 2 – 3·10^{15}, 3 – 3·10^{16}; **c** - 6.8 MeV protons at fluences (1/cm^2): 1 – 3·10^{10}, 2 – 3·10^{11}, 3 – 3·10^{12}.

All three types of irradiations lead to the peak current decrease (Fig. 3a, b, c) and to the preexponential multiple increase. The peak voltage and the characteristic energy do not practically change. The rise of preexponential multiple (J_0) corresponds to the increase of the dislocation density (maximum in 5 times). For estimation and comparison it is useful to introduce the tunnel junction SCR degradation coefficient defined as the ratio of the preexponential multiple increment to the fluence value:

$$K_{J_0} = \frac{\Delta J_0}{F_i}, \quad \text{where} \quad \Delta J_0 = J_{0i} - J_0 \qquad (12)$$

In the case of proton irradiation the averaged SCR degradation coefficient of GaAs p+- n+ tunnel junction appeared to be $K_{Jo} \sim 1\cdot10^{-12}$ (A/p), for electrons $\sim 5\cdot10^{-17}$ (A/e) and for Co^{60} gamma rays $\sim 5\cdot10^{-18}$ (A/γ). The relative drop of the peak and the SCR widening at irradiations are presented in Fig. 5 and 6. It is seen that the maximum peak current drop and, correspondingly, SCR widening $\Delta W \approx 0.8$ nm for GaAs TJ take place at electron irradiation. At proton and gamma irradiations $\Delta W \approx 0.4$ nm. The maximum increase of the differential resistance (in zero point) in 5 times took place at electron irradiation. In the case of irradiation by protons and Co^{60} gamma quanta R_{diff} increased in two times.

4.2 GaSb p+-n+ tunnel junction

In initial GaSb tunnel p+-n+ structures the peak current J_p= 40 A/cm^2, and the corresponding to it "peak" voltage $V_p \approx 0.03$ V. The free carrier concentration calculated for the "n" – boundary of SCR TJ appeared to be $n \sim 5\cdot10^{17}$ cm^{-3}, the contact potential difference – 0.816 V, the SCR width ~ 50 nm. For the excess current the characteristic energy ε = 0.1 eV, the preexponential multiple $J_0 \approx 1$ A/cm^2, which corresponds to the dislocation density of $\sim 10^7$ cm^{-2}. At all three types of irradiation of the GaSb TJ variation of the characteristics qualitatively similar to that for GaAs TJ is observed with increasing the fluence (Fig. 4).

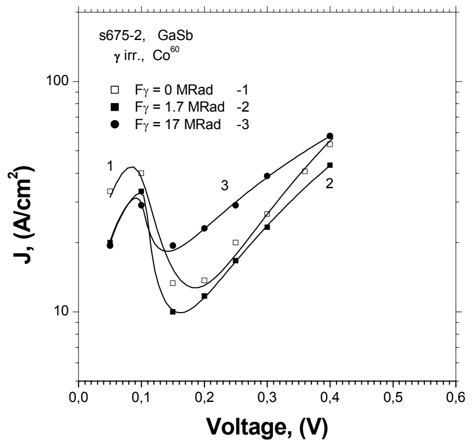

Fig. 4 Degradation of the dark I-V characteristic of GaSb tunnel junctions at irradiation by Co^{60} gamma rays of doses (MRad): 1 – 0; 2 – 1.7; 3 – 17.

The "peak" voltage and the characteristic energy do not practically change. The peak current drops (Fig. 4) and the preexponential multiple rises. Using the expression (12) we find that the excess current degradation coefficient averaged in the given fluence range $K_{Jp} \approx 1\cdot10^{-10}$(A/p) for protons, $1\cdot10^{-15}$ (e/cm^2) for electrons and $1\cdot 10^{-16}$ (A/γ) for Co^{60} gamma rays. The peak current drop (Fig.5) at irradiations indicates the increment of the GaSb TJ SCR width (Fig.6). So, in the case of irradiation by protons $\Delta W \approx 0.4$ nm, by electrons ~ 1.5 nm and practically did not change by Co^{60} gamma irradiation at doses 1.7 ; 17 MRad.

5. DISCUSSION

In the investigated GaAs and GaSb TJ (initial and irradiated), mainly two tunnel current components, interband and defect (excess), have been revealed. The peak current density in nonirradiated GaSb tunnel junction structures was essentially higher (approximately in 40 times) than that in GaAs TJ structures. An analysis of the experimental DI-V characteristic (Fig.3,4) has shown that the "peak" voltage corresponding to the peak current is lower in GaSb TJ than that in GaAs TJ. Correspondingly, the free charge carrier concentration at the SCR boundary in GaSb p+- n+ junction is lower, but the SCR width is larger than in GaAs tunnel junctions.

Using the excess current parameters (preexponential multiple - J_0 and characteristic energy – ε) one can estimate the dislocation density, if the multihopping tunneling model is applied [8]. The dislocation density in the space charge region in nonirradiated structures was approximately the same and of the order of 10^7 cm^{-2}.

As a result of proton, electron, and gamma irradiations the peak current (J_p) in all investigated structures dropped at practically constant "peak" voltage. The preexponential multiple (J_0) rose and the characteristic energy (ε) did not practically change. After proton and electron irradiation the degradations of J_p in GaSb TJ structures took place by the order of magnitude more intensively compared to GaAs structures (Fig,5).

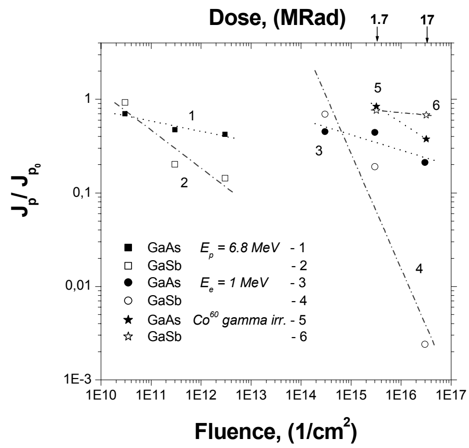

Fig. 5 Peak current drop at irradiation of GaAs and GaSb TJ by: 6.8 Mev protons – 1,2; 1 MeV electrons – 3,4; Co^{60} gamma rays – 5,6.

Gamma irradiations (Co^{60}) of GaSb tunnel structures change the peak current very weakly. In a number of specimens of GaAs TJ structures the irradiation resulted in some increase of another component – recombination one. The rise of preexponential multiples (J_0) in the investigated GaAs and GaSb TJs indicates the dislocation density increase. Estimations showed that the maximum increase was in 5 ÷ 10 times. Variation of the preexponential multiple for investigated structures may be characterized by the degradation coefficient $K_{Jo} = \Delta J_0/F_i$. Average values of the degradation coefficients determined from the experimental DI-V characteristic of the investigated tunnel p+-n+ junction structures are presented in Table 1.

Table. 1

Irradiations	K_{J_0}, (A/particles)	
	GaAs	GaSb
6.8 MeV protons	$1\ 10^{-12}$ A/p	$1\ 10^{-10}$ A/p
1 MeV electrons	$5\ 10^{-17}$ A/e	$1\ 10^{-15}$ A/e
Gamma quanta, Co^{60}	$5\ 10^{-18}$ A/γ	$1\ 10^{-16}$ A/γ

It is seen from the table that the degradation coefficients for GaSb TJ are by 2 orders of magnitude higher than those for GaAs TJ. The peak current decrease corresponds to the SCR width increase. One may suppose that the SCR width increase takes place first of all as a result of radiation-stimulated diffusion of electrically active impurities of a tunnel junction. The value of SCR widening for GaAs TJ is essentially lower than for GaSb TJ (Fig.6) and in average was $\Delta W \approx 0.1 \div 0.7$ nm.

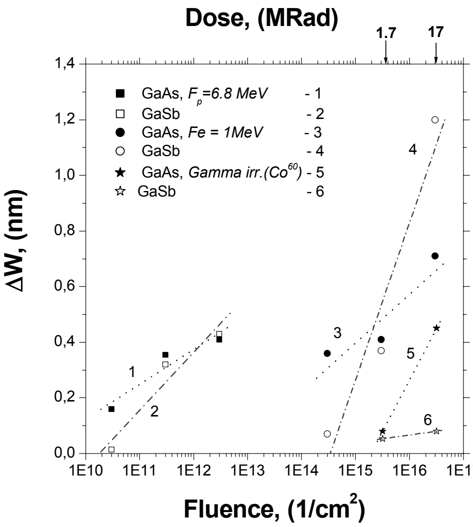

Fig. 6 Widening of SCR at irradiations of GaAs and GaSb TJ by: 6.8 MeV protons – 1,2; 1 MeV elctrons – 3,4; Co^{60} gamma rays – 5,6.

It should be noted that the SCR width increase at irradiation of TJ is extremely undesirable effect for multi-cascade monolithic solar cells. Actually, connecting TJ is located in electrically opposite direction to photovoltaic p-n junctions. For this reason an undesirable absorption of light in TJ lowers down the photovoltage of a multi-cascade SC. Radiation-stimulated widening of SCR increases the parasitic collection of electron-hole pairs, and, correspondingly increases opposing photovoltage lowering down the MSC open circuit voltage.

6. CONCLUSION

The dark I-V characteristic of tunnel p+-n+ junctions grown by the LT LPE technique on the base of "wide-band" GaAs and "narrow-band" GaSb were investigated from the point of view of parameters of these junctions as connecting elements in monolithic MSC. Studied was the effect of irradiation by: 6.8 MeV protons in the fluence range of
$3 \cdot 10^{10} \div 3 \cdot 10^{12}$ cm^{-2}, 1 MeV electrons at fluencies of $3 \cdot 10^{14} \div 3 \cdot 10^{16}$ cm^{-2} and Co^{60} gamma rays at doses of 1.7 ÷ 17 MRad, on the evolution of DI-V of GaAs and GaSb tunnel p+- n+ junctions. The most noticeable experimental result is the peak current drop, it being essentially stronger (by more than an order of magnitude) for GaSb tunnel p+-n+ junctions.
A principal physical result is widening of the tunnel p+-n+ junction SCR practically at all types of irradiation. We assume that the basic reason for this effect lies in the radiation-stimulated diffusion of electrically active impurities due to the increase of vacancy concentration after irradiation. For MSCs such a widening is undesirable effect, since it leads to a decrease of the photovoltage in MSCs: first, due to the tunnel junction differential resistance rise, second, due to the parasitic light absorption rise in the tunnel p+-n+ junction SCRs connected oppositely to the photovoltaic p-n junctions in MSCs. Investigation of degradation of characteristics of relatively wide (25÷50nm) GaAs and GaSb tunnel p+-n+ junctions has shown a noticeable effect of SCR widening at irradiations. This effect will be even more prononced with decreasing the SCR width due to the increase of the ratio ΔW/W.

ACKNOWLEDGEMENT

The authors would like to thanks G.M.Gusinsky for help in irradiation, S.A.Karandashov for technical assistance and O.V.Emel'yanenko, A.N.Imenkov and G.V.Il'menkov for useful discussion.

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