THE MECHANISM OF A CURRENT FLOW IN THE SPACE CHARGE REGION OF ILLUMINATED AND NONILLUMINATED GaSb p-n JUNCTIONS.

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ABSTRACT: Current flow mechanism in the space charge region (SCR) of GaSb p-n junctions grown by the LPE technique and their photovoltaic properties have been investigated. Attention was payed to the analysis of the initial (dark resistance-free) current-voltage (I-V) characteristic obtained by means of a co-ordination of the dark and light characteristics. At current densities less than 10^{-3} A/cm^2 the tunnel-trap current was observed with the preexponential multiple – the “saturation” current density $J_{0t} \approx 5 \cdot 10^{-4}$ A/cm^2. Up to the current densities of 1.5 A/cm^2 the current flow mechanism is recombination one (Shockley-Noyce-Sah) with the diode coefficient A = 2. According to an estimation the electron-hole pair lifetime in SCR is ($10^{-9} \div 10^{-10}$) s, and the preexponential recombination (“saturation”) current density $J_{0r} = (5 \cdot 10^{-5} \div 5 \cdot 10^{-4})$ A/cm^2. In the case of the diffusion mechanism the diffusion preexponential (“saturation”) current density is $J_{0d} < (1 \cdot 10^{-8} \div 1 \cdot 10^{-7})$ A/cm^2. For semiconductor laser excitation (λ = 1.3 μm) equivalent to 30x sunlight (AM0) the maximum possible efficiency of GaSb p-n junctions under investigation, as calculation show, is about 30%. The proton irradiation (E_p = 6.78 MeV, $F_p = 3 \cdot 10^{10} \div 3 \cdot 10^{12}$ cm^{-2}) reduces the electron-hole pair lifetime in SCR more than by an order of magnitude. The average SCR lifetime damage coefficient of GaSb p-n junctions is equal to $2.5 \cdot 10^{-2}$ cm^2/s.
Keywords: III-V Semiconductors, Multijunction solar cells, Solar Cell Efficiencies, Lifetime

1 INTRODUCTION

At development of multijunction solar cells (MSC) the subject of interest is not only the load characteristic of MSC, but also such a fundamental p-n junction characteristic as the initial (dark resistance-free) I-V characteristic of an every separate p-n junction included into MSC. The latter allows to determine the current flow mechanisms (tunnel, recombination, diffusion) in the operational state of a solar cell (SC) p-n junction, and therefore to determine effectiveness of the sunlight conversion. Evaluation of the dark I-V characteristic allowed to study the effect of space irradiation on these mechanisms for prediction of the radiation tolerance of MSC.

The aim of the present work is: to obtain and to investigate by the example of a “narrow gap” GaSb p-n junction the initial I-V characteristic and its interplay with the light I-V characteristic, and also with other derived photovoltaic characteristics of SC; to determine the current flow mechanisms in the p-n junction and to estimate the maximum feasibilities of grown GaSb p-n structures and prospects of their application from the point of view of more complete conversion of solar energy into electrical one both as the lower cascade in mechanically stacked cascade SCs and in thermophotovoltaic converters.

The investigated GaSb structures were fabricated by using “bulk” wafers. The GaSb wafers were subjected to the initial zinc diffusion procedure by a “pseudo closed box” technique to form a shallow p-n junction in photoactive area of the cells. Zn-diffusion was performed in flow of hydrogen into “bulk” GaSb wafers from pure zinc source. Anodic oxidation and selective etching were used for precise thinning the diffused GaSb layers. Under the grid fingers a deep p-n junctions (1.3 ÷ 1.5 μm) were formed by the second diffusion process to avoid the current leakage.

2 THE INITIAL I-V CHARACTERISTIC OF A p-n JUNCTION

The initial characteristic of p-n junctions of solar cells and of other semiconductor devices is the dark resistance-free I-V characteristic determining the dependence of the direct dark current density J through a p-n junction on the voltage V_j on the p-n junction space charge region (SCR) equals to the difference

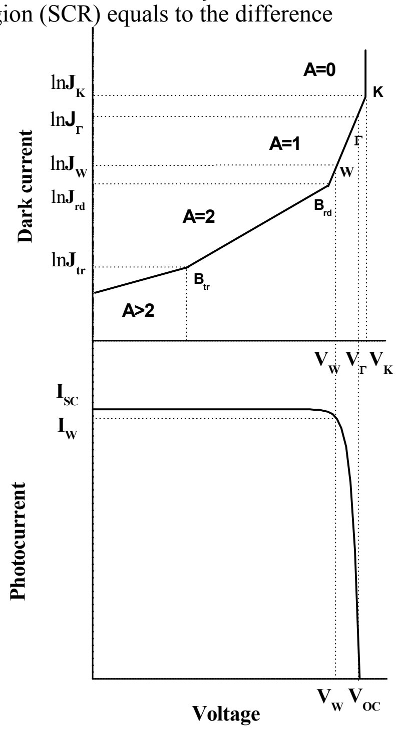

Figure 1: Schematic of the resistance-free dark and light I-V characteristics and their correlation. The operating point of the optimal load W is shown on the diffusion (A=1) portion of the dark I-V characteristic. $A=(q/kT)(\Delta V_j/\Delta \ln J)$ – dimensionless co-slope straight-line portion of the dark I-V characteristic.

between Fermi quasilevels (of holes and electrons) inside SCR, divided by q, $V_j = (F_p - F_n)/q$. Actually, all fundamental photovoltaic characteristics are derived from the initial one. For this reason, it is of particular interest.

In the ordinary shape the initial I-V characteristic has, as a rule, four exponential portions (Fig.1),

$$J = \sum_{i=1}^{4} J_{0i}\left(\exp\frac{qV_j}{A_i kT} - 1\right) \quad (1)$$

where J_{0i} – preexponential ("saturation") current density,
q – electron charge,
k – Boltzman constant,
T – absolute temperature
A_i – diode coefficient (the dimensionless co-slope of the I-V curve in a semi logarithmic scale).

The diode coefficient (A), or a so-called quality factor of a p-n junction is larger than 2 on the tunnel portion, equal to 2 on the middle, recombination, one and equal to 1 on the upper, diffusion one. On the uppest practically barrierless portion one may put formally mathematically A = 0.

The solar cell efficiency is characterized by the fill factor value (FF). Fill factor at given I_{SC} and V_{OC} increases with decreasing A. Therefore, for solar cells at a low level of illumination the most promising operating portion of the I-V characteristic is the diffusion one.

3 PHOTOVOLTAIC PROPERTIES OF OBTAINED GaSb p-n JUNCTIONS

3.1 Dark I-V characteristics

Experimental dark I-V characteristics of GaSb p-n junctions were obtained from measurements at room temperature in the current density range of $(1{\cdot}10^{-6} \div 1{\cdot}10^{-1})$ A/cm^2 (Fig.2). At fitting the experimental characteristics were presented by the sum of two exponential components with allowing for the series resistance.

$$J = \sum_{i=1}^{2} J_{0i}(\exp\frac{q(V - JR_S)}{A_i kT} - 1) \quad (2)$$

where R_S, J_{0i}, A_i (i = 1,2) – free parameters. Two components were observed experimentally: tunnel trap (excessive, $A \approx 6$, i.e. $A > 2$) and recombination (Shockley-Noyce-Sah, A = 2), (Fig.2). The diffusion component (Shockley, A = 1 must be present at higher current densities. The preexponential tunnel current density $J_{0t} = 5{\cdot}10^{-4}$ A/cm^2 and the preexponential recombination one $J_{0r} = (5{\cdot}10^{-5} \div 5{\cdot}10^{-4})$ A/cm^2. The e-h pair lifetime in SCR $\tau_w = (10^{-9} \div 10^{-10})$ sec. The boundary current density between tunnel and recombination ones for GaSb p-n junctions is $J_{tr} \approx 10^{-3}$ A/cm^2.

3.2 Light I-V characteristics

Experimental light characteristics of a GaSb p-n junction were obtained at its excitation by a semiconductor laser with a illumination up to 4.0 W/cm^2 ($\lambda = 1.3$ μm). The experimental load characteristics are presented in Fig.2. For fitting the experimental points the light I-V characteristic was presented by the recombination component (equation 3), since almost all experimental current density values were on the recombination portion,

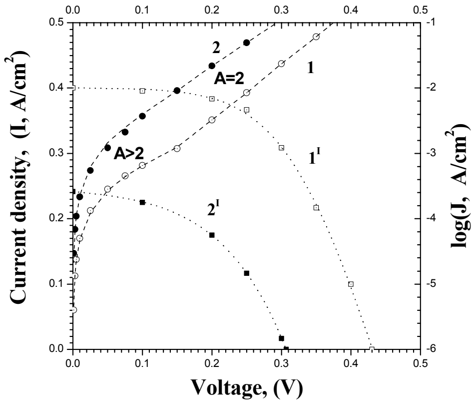

Figure 2: Experimental dark (1, 2) and light (1^I, 2^I) I-V characteristics of a GaSb p-n junction. Curves (1^I, 2^I) have been obtained in illuminating the structures of 2.5 W/cm^2, ($\lambda = 1.3$ μm). Curves ($2, 2^I$) have been obtained after proton irradiation, (E_p=6.78 MeV, $F_p=3{\cdot}10^{-12}$ cm^{-2}).

$$I = qG - J_{0r}(\exp\frac{q(V + IR_S)}{2kT} - 1) \quad (3)$$

where G – the generation rate of collectable electron-hole pairs. In an equivalent form we have,

$$I = I_{SC}\frac{\exp\frac{qV_{OC}}{2kT} - \exp\frac{q(V + IR_S)}{2kT}}{\exp\frac{qV_{OC}}{2kT} - \exp\frac{q(I_{SC}R_S)}{2kT}} \quad (4)$$

where I_{SC}, V_{OC}, R_S are free parameters. From the experiment we have $V_{OC} = 0.38 \div 0.43$ V, $I_{SC} = 0.38 \div 0.40$ A/cm^2. Using the expressions,

$$J_{0r} = \frac{I_{SC}}{\exp\frac{qV_{OC}}{2kT} - \exp\frac{qI_{SC}R_S}{2kT}} \quad (5)$$

we obtain $J_{0r} = (5{\cdot}10^{-5} \div 5{\cdot}10^{-4})$ A/cm^2. It means that the light I-V characteristics gave the same values of the preexponential recombination current density as the dark ones, and, consequently, the same lifetimes $\tau_w = (10^{-9} \div 10^{-10})$ s. Besides, from the expression

$$qG = I_{SC}\frac{\exp\frac{qV_{OC}}{2kT} - 1}{\exp\frac{qV_{OC}}{2kT} - \exp\frac{qI_{SC}R_S}{2kT}} \quad (6)$$

we obtain $J_\Gamma \equiv qG = 0.38 \div 0.4$ A/cm^2, i.e. $J_\Gamma \equiv qG \approx I_{SC}$. In this case the light I-V characteristics are resistance-free one.

3.3 The ($I_{SC} - V_{OC}$) and ($P - V_{OC}$) characteristics

The ($I_{SC} - V_{OC}$) characteristic (Fig.3) is approximated by one exponent,

$$I_{SC} = I_{SCo}(\exp\frac{qV_{OC}}{2kT} - 1) \qquad (7)$$

Experimental ($I_{SC} - V_{OC}$) characteristics coincide with the initial ones on the portion, where the series resistance does not yet influence. For this reason $J_{SC0} = J_{0r} = 5\cdot10^{-5} \div 5\cdot10^{-4}$ A/cm^2, i.e. the characteristics give the same preexponential recombination current density value as the light and dark I-Vs do, and, hence, the same value of the SCR e-h pair lifetime $\tau_w = 10^{-9} \div 10^{-10}$ s.

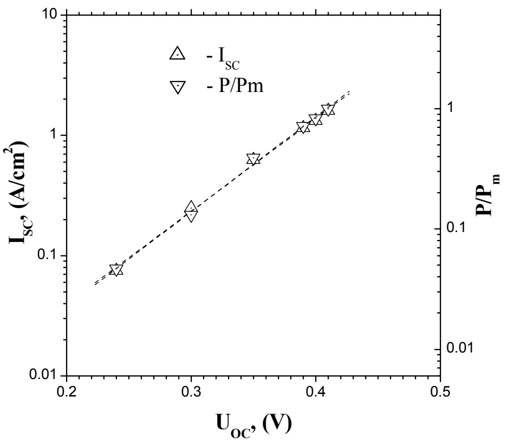

Figure 3: Experimental ($I_{SC} - V_{OC}$) and ($P - V_{OC}$) characteristics of a GaSb p-n junction were obtained at its excitation by a semiconductor laser with an illumination up to $P_m = 4.0$ W/cm^2, ($\lambda = 1.3$ μm).

The ($P–V_{OC}$) characteristic (Fig.3) is approximated by one exponent.

$$P = P_0(\exp\frac{qV_{OC}}{2kT} - 1) \qquad (8)$$

As is known, this characteristic coincides always with the sought-for initial (dark resistance-free) I-V characteristic, i.e. it is not affected by the series resistance of the structure. The recombination-diffusion current density boundary $J_{rd} > 1.5$ A/cm^2 is higher than the upper value of the used short circuit current density. Since $J_{rd} = \frac{J_{0r}^2}{J_{0d}}$, one can estimate the preexponential diffusion current density as $J_{0d} < 10^{-8} \div 10^{-7}$ A/cm^2.

3.4 The p-n junction efficiency

The SC efficiency is $\eta = \gamma_{out} \cdot \Theta$, where $\gamma_{out} = \frac{G}{P/h\nu}$ is the external quantum yield; $\Theta = \frac{qV_{OC}}{h\nu}FF$ - the p-n junction efficiency and fill factor FF is:

$$FF(U_W) = \frac{U_W^2}{(1 + U_W - \exp(-U_W))(U_W + \ln(1 + U_W))} \qquad (9)$$

where $U_W = \frac{V_W}{2kT}$, V_w is voltage in the operating point, and U_w is determinated from the transcendental equation

$$U_{OC}(U_W) = U_W + \ln(1 + U_W) \qquad (10)$$

where $U_{OC} = \frac{V_{OC}}{2kT}$. Taking $V_{OC} = 0.43$ V (Fig.2) and, correspondingly, $U_{OC} = 8.62$, we obtain $U_W = 6.595$ and the fill factor FF = 0.664, then $\Theta = 30\%$. In the case of the ideal external quantum yield ($\gamma_{out} = 1$) the maximum possible efficiency for the given GaSb SC could reach the value up to 30%.

4 THE EFFECT OF THE PROTON IRRADIATION ON GaSb p-n JUNCTION

4.1 Degradation of the dark I-V characteristic

The main effect at irradiation by protons of energy $E_p = 6.78$MeV and fluencies $F_p = (3\cdot10^{10} \div 3\cdot10^{12})$ cm^{-2} is the rise of the recombination component (Fig.2). The preexponential recombination current density J_{0r} increases and consequently the SCR e-h pair lifetime decreases. The proton SCR lifetime damage coefficient $K_{\tau w} = \Delta(1/\tau_w)/F_p$ proportional to the inverse e-h pair lifetime is a variable value and decreases (Table 1) with the fluence increase as in the "wide gap" GaAs p-n junctions [1,2].

Proton fluence F_p, (cm^{-2})	Inverse lifetime, $\Delta(1/\tau_w)$, (s^{-1})	Damage coefficient, $K_{\tau w}$, (cm^2/s)
$3\cdot10^{10}$	$0,13\cdot10^{10}$	$4.3\cdot10^{-2}$
$3\cdot10^{11}$	$1.05\cdot10^{10}$	$3.5\cdot10^{-2}$
$3\cdot10^{12}$	$2.09\cdot10^{10}$	$0.7\cdot10^{-2}$

Table I

4.2 Degradation of the light I-V characteristic

At the proton irradiation the open circuit voltage and the short circuit current values decrease (Fig.2) at retaining the diode coefficient A = 2. In correspondence with the expression (5) we have the rise of the preexponential recombination current density and, hence, the drop of the SCR e-h pair lifetime, as is also follows from the dark I-V characteristic degradation (paragraph 4.1). Besides, the preexponential recombination current densities obtained from the dark and light characteristics coincide within 10% at all used proton irradiation fluencies.

Therefore, the dark and light I-V characteristics degradations result from the rise of J_{0r} and correspondingly from the SCR e-h pair lifetime degradation (Table I). The current flow mechanism in p-n junctions is recombination one and does not change at the proton irradiation.

4.3 GaSb p-n junction efficiency degradation

From the experiment we have $V_{OC} = 0.307$ V (Fig.2). Using the speculation from the paragraph 3.4, when A = 2, we obtain $U_w = 4.35$ and FF = 0.59, then

Θ = 19%. In this case when the GaSb structures are irradiated by 6.78 MeV protons with the fluence $3{\cdot}10^{12}$ cm^{-2}, the SC maximum possible efficiency decreases down to 19%.

5 CONCLUSION

The dark and light characteristics of p-n junctions of the GaSb structures grown by the liquid phase epitaxy technique have been investigated. The initial (resistance-free dark) current-voltage characteristics in the current density range of $(1{\cdot}10^{-6} \div 1.5{\cdot}10^{0})$ A/cm^2 has been obtained and analyzed. The current flow mechanisms have been determined. At current densities higher than 10^{-3} A/cm^2 it is so called recombination current (Sah-Noyce-Shockley). At lower currents it is tunneling through traps – the tunnel trap current. The diffusion current flow mechanism must be at the values higher than 1.5 A/cm^2. The best preexponential recombination current density $J_{0r} = 5{\cdot}10^{-5}$ A/cm^2 and the e-h pair lifetime in SCR of the investigated structures $\tau_w = 10^{-9}$s. The preexponential diffusion ("saturation") current density $J_{0d} < 1{\cdot}10^{-8}$ A/cm^2.

According to the calculations made, in the case of structures illuminated by a semiconductor laser (λ = 1.3 μm), which is equivalent to the sunlight concentration rate up to 30 (AM0), the maximum possible efficiency of the investigated GaSb p-n junctions could reach 30%.

The proton irradiation (E = 6.78 MeV, $F_p = 3{\cdot}10^{10} \div 3{\cdot}10^{12}$ cm^2) of these structures caused the decrease of the SCR electron-hole pair lifetime in 15 times. The dependence of the inverse lifetime, which is proportional to the SCR nonradiative recombination center concentration, on the fluence has a sub linear character, as in the "wide gap" GaAs p-n junctions [1,2]. The average coefficient of the SCR lifetime damage for the used range of the proton irradiation fluencies is equal to $2.5{\cdot}10^{-2}$ cm^2/sec. Calculated efficiency of the GaSb p-n junction decreases down to 19% at the proton fluence $3{\cdot}10^{12}$ cm^{-2}.

The results of this work show that in bottom cells of MSC at a low light concentration rate the operating currents of generating electricity p-n junctions have, as a rule, the recombination (Sah-Noyce-Schockley) current flow mechanism.

6 ACKNOWLEDGEMENTS

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7 REFERENCES

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