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TUNNEL SURFACE RECOMBINATION IN *p—n* JUNCTIONS

Current—voltage curves were measured on AlGaAs-GaAs laser double heterostructures at temperatures of 77...300 K. The exponential sections of I—V curves correspond to the ideality factor $n_t \leqslant 2$ at room temperature, which increases with lowering temperature. The I—V curves of surface recombination current were calculated under assumptions that: *a*) majority carriers tunneled to the surface and were captured to surface states; *b*) minority carriers were captured by surface states «classically»; *c*) the change in quasi Fermi level for minority carriers in surface depletion channel linearly depended on the surface barrier height. The obtained expression for I—V curves explains the features of measured current-voltage characteristics of laser heterostructures.

1. Introduction

Surface recombination reduces the performance parameters of diode lasers (DL) [1-3], bipolar transistors [4], photodiodes, solar cells and other devices on III—V semiconductors [5—6]. Surface recombination in a *p—n* junction results in forward current component [6]

$$I_S(V) = I_0 e^{\frac{qV}{n_t kT}}, \qquad (1)$$

where I_0 is constant; q is electron charge; V is bias voltage; k is Boltzmann's constant; T is temperature; n_t is ideality factor. Under some conditions $n_t \approx 2$ [6]. The most important of these conditions are the following:

a) surface states form deep levels in energy gap, which produce depletion channel at surface;

b) density of surface states is large, that usually occurs in III—V semiconductors such as GaAs, Al—GaAs, GaP, GaAsP, InP, InGaAsP;

c) quasi Fermi levels for electrons and holes are constant in surface depletion channels.

The purpose of this paper is to investigate the dependence $n_t(T)$ experimentally and theoretically.

2. Experimental results and model assumptions

The measurements were made on AlGaAs—GaAs laser double heterostructures (DHS) with stripe geometry, described in our previous papers [7 — 9]. The temperature of sample was varied in the range of 77...400 K. Fig. 1 represents the current—voltage characteristics of DHS, measured at various temperatures. It is seen that *I—V* curves plotted in semilogarithmic scale have linear sections corresponding to expression (1). The ideality factor was $n_t = 1{,}75...2{,}0$ (for various samples) at room temperature and 2,0...4,2 at 80 K. For each sample the value of nt increased with lowering temperature.

The calculations of forward current component in a *p—n* junction, due to surface recombination,

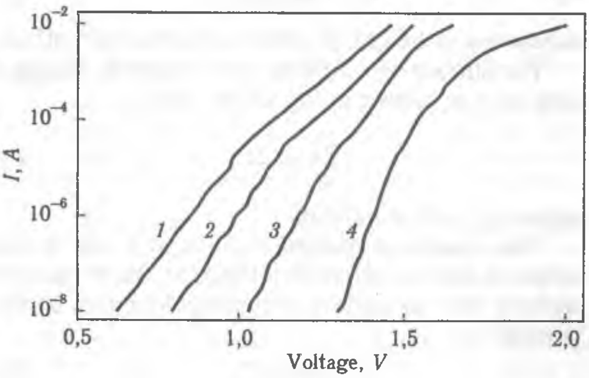

Fig. 1. *I—V* characteristics of laser heterostructure, measured at various temperatures:
1 — 293; *2* — 247; *3* — 183; *4* — 97 *K*

were performed under assumptions of [6], but quasi Fermi levels F_n, F_p were taken not constant in surface depletion channel. Surface recombination in *n* region occurs as shown in fig. 2: an electron tun-

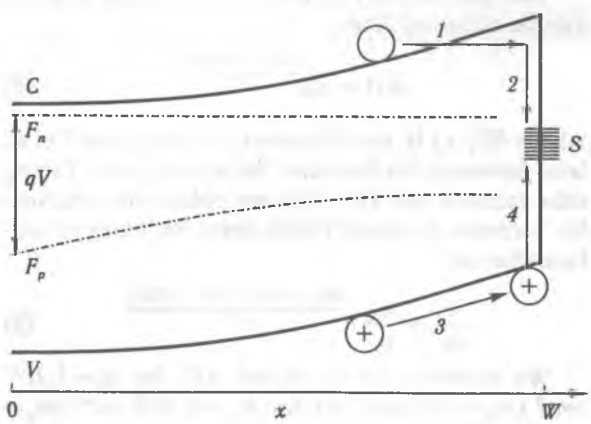

Fig. 2. Energy band diagram and electron and hole transitions in surface depletion channel

nels to surface (arrow *1*) and is then captured to surface states (arrow *2*). Minority carrier (a hole) moves to surface (arrow *3*) and is then «classically» captured by the surface states (arrow *4*). At the crossing of bulk- and surface depletion regions both electrons and holes tunnel to surface and are captured by surface states. In case of tunneling electrons, the electron current density at the edge of surface depletion channel is determined by [2]

$$j_t = j_{t_0} e^{-\frac{e\varphi}{n_{t_0} kT}}, \tag{2}$$

where j_{t_0} is constant; the coefficient n_{t_0} is determined by

$$n_{t_0} = \frac{1}{1 - \frac{\hbar^2}{6 m_t W_t^2 (kT)^2}}, \tag{3}$$

where m_t is «tunnel» effective mass of charge carriers; W_t is the coefficient in the expression for barrier width in surface depletion channel

$$W = W_t (q\varphi)^{1/2}, \tag{4}$$

where $q\varphi$ is height of potential barrier at surface.

For surface recombination in n region, taking x axis as it is shown in fig. 2, we have

$$\frac{dF_p}{dx} = \frac{j_p}{\mu_p p}, \tag{5}$$

where μ_p is hole mobility.

The maximum change in F_p is at $x \approx 0$, at the edge of surface depletion channel. Hole current density due to surface recombination can be expressed as

$$j_p = q p_s S_0, \tag{6}$$

where S_0 is velocity of surface recombination. Hole density at surface can be written as

$$p_s = p_b e^{\frac{q\varphi_s - \Delta F_p}{kT}}, \tag{7}$$

where p_b is density of holes at $x = 0$; $q\varphi_s$ is surface band bending; ΔF_p is the change in F_p in surface channel.

The hole density at point x in surface channel can be obtained from

$$p(x) = p_b e^{\frac{q\varphi(x) - \delta F_p(x)}{kT}}, \tag{8}$$

where $\delta F_p(x)$ is the difference in hole quasi Fermi level between the bulk and the actual point. Taking into account eqs. (6)—(8), we obtain the equation for increase in quasi Fermi level for holes in surface channel

$$\frac{dF_p}{dx} = \frac{qS_0}{\mu_p} e^{\frac{q[\varphi_s - \varphi(x)] - [\Delta F_p - \delta F_p(x)]}{kT}}. \tag{9}$$

We numerically calculated ΔF_p for $n_b = 1{,}10^{17}$ cm^{-3} ($m_p = 260\ cm^2/Vs$) and $n_b = 1{,}10^{18}$ cm^{-3} ($m_p = 170\ cm^2/Vs$), as well as ΔF_n in p region for $p_b = 1{,}10^{17}$ cm^{-3} ($\mu_n = 4800\ cm^2/Vs$) and $p_b = 1{,}1018$ cm^{-3} ($\mu_n = 2800\ cm^2/Vs$), taken $S_0 = 4{,}10^5$ cm/s. The results are shown in fig. 3. It is seen that over wide range of surface barrier heights, the change

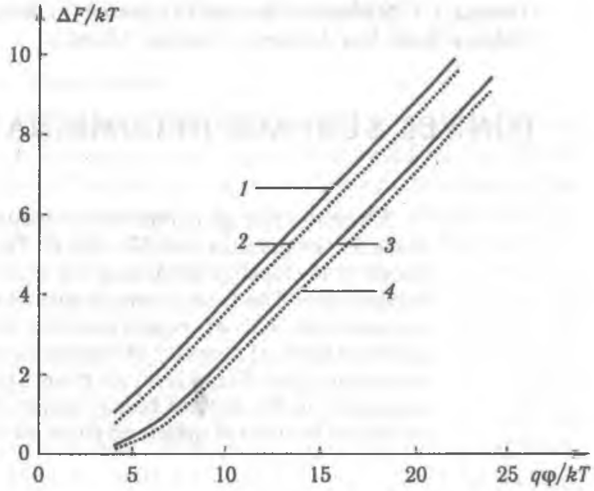

Fig. 3. The change in quasi Fermi level for minority carriers in surface depletion channel:

1 — for holes in n region at $n_b = 1{,}10^{17}$ cm^{-3}, *2* — for holes in n region at $n_b = 1{,}10^{18}$ cm^{-3}; *3* — for electrons in p region at $p_b = 1{,}10^{17}$ cm^{-3}, *4* — for electrons in p region at $p_b = 1{,}10^{18}$ cm^{-3}

in quasi Fermi level for minority carriers in surface depletion channel can be approximated as

$$\frac{\Delta F_n}{kT} = a\frac{q\varphi_s}{kT} - b, \tag{10}$$

where coefficients a and b depend on the sign and concentration of majority carriers.

3. Current component due to tunnel surface recombination

Let us consider the surface recombination in p region of p—n junction and in the adjacent section of depletion region, where $p_b \gg n_b$. For electrons, as minority carriers, the rate of «classical» capture by surface states can be written as

$$R_{sn} = C_n P_s n_s, \tag{11}$$

where P_s is density of empty surface states,

$$C_n = \sigma_n V_n, \tag{12}$$

where σ_n is the appropriate cross-section; V_n is thermal velocity of electrons. Electron density at surface is defined by

$$n_s = n_b e^{\frac{q\varphi_s - \Delta F_n}{kT}}, \tag{13}$$

where ΔF_n is the change in electronic quasi Fermi level in surface channel. We assume that relation (10) between ΔF_n and φ_s holds (with appropriate coefficients a and b), so

$$n_s = n_b e^b e^{(1-a)\frac{q\varphi_s}{kT}}. \tag{14}$$

For holes, as majority carriers, the change in quasi Fermi level is negligible [6], and their rate of tunnel capture to surface states can be described by

$$R_{sp} = C_p p_b N_s e^{-\frac{q\varphi_s}{n_t kT}}, \qquad (15)$$

where, similarly to eq. (12),

$$C_p = \sigma_p V_p, \qquad (16)$$

N_s is density of filled surface states; n_{t_0} is given by eq. (3).

Equating R_{sp} and R_{sn} in steady state we obtain for surface capture rate of electrons and holes

$$R_s = \left[(C_p N_s)^{(1-a)n_{t_0}} C_n P_s e^b\right]^{1/n_t} \times \\ \times \frac{n_i^{2/n_t}}{p_b^{(2-n_t)/n_t}} e^{\frac{F_{nb} - F_{pb}}{n_t}}, \qquad (17)$$

where F_{nb} and F_{pb} are bulk values of F_n and F_p,

$$n_t = 1 + (1-a) n_{t_0}. \qquad (18)$$

The expression for surface recombination current I_s can be obtained from

$$I_s = q L_s l_p R_s, \qquad (19)$$

where L_s is effective surface diffusion length [6]; l_p is the perimeter of p—n junction, under an assumption that

$$F_{nb} - F_{pb} = qV, \qquad (20)$$

where V is bias voltage.

Thus, for surface current component we obtain eq. (1),

$$I_0 = q L_s l_p \left[(C_p N_s)^{(1-a)n_{t_0}} C_n P_s e^b\right]^{1/n_t} \frac{n_i^{2/n_t}}{p_b^{(2-n_t)/n_t}}, \qquad (21)$$

n_t is defined from eq. (18).

4. Conclusions

The obtained expression for surface tunnel recombination current explains the features of I—V curves of AlGaAs—GaAs laser double heterostructures, measured at various temperatures. The ideality factor of 1,75...2,0 at room temperature, estimated for various samples, corresponds to the change in the quasi Fermi level of electrons in surface depletion channel, given by eq. (10), where $0 < a < 0{,}25$.

The temperature behavior of the ideality factor n_t, obtained from analysis of measured I—V curves, is described by eq. (3), where $W_1 = 60...220\ nm\ eV^{-1/2}$. The temperature dependence of pre-exponential factor in eq. (1) for the measured I—V curves can be approximated by

$$I_0(T) \sim (kT)^{1/2} e^{-\frac{\Delta E}{kT}}, \qquad (22)$$

where $\Delta E = 0{,}03...0{,}07\ eV$. This value is consistent with the estimation of coefficient a in eq. (10) for the change in quasi Fermi level for minority carriers in the surface depletion channel.

The results of our measurements on laser heterostructures, giving the ideality factor $n_t < 2$ at room temperature, provide evidence that the change in quasi Fermi level for minority carriers in surface depletion channel can be approximated by eq. (10).

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