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Enhancement of the nonlinear response of the semiconductor tunnel structures in the skin-effect regime

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Abstract. Nonlinear AC response of the semiconductor–barrier–semiconductor structures is considered. It is shown that in the vicinity of the barrier a low frequency plasma excitations–junction plasma polaritons (JPPs)—are excited on high frequencies. The excitation of JPPs has a substantial effect on the rectification properties of the structures in the skin-effect regime (on the frequency of 100 GHz and higher for the typical parameters of the structures). It leads to an essential increase in the rectified voltage. Its increase could be as large as one order of magnitude for the typical parameters of the structures.

Introduction

As a rule, when one considers the AC response of the semiconductor–barrier–semiconductor (SBS) structures, the distribution of the electro-magnetic field and the electric charges, induced close to the barrier, are supposed to be homogeneous in the barrier plane. The assumption ceases to be true when the frequencies are sufficiently high. On those frequencies the AC electric current does not flow homogeneously to the barrier, but it is grouped in the skin-layer in the vicinity of the lateral surface of the structure. The inhomogeneity of the electric current is responsible for the excitation of peculiar plasma excitations close to the barrier–junction plasma polaritons (JPP). JPPs are propagating along the barrier and they are characterized by low speed of propagation. That are low-frequency excitations. Their excitation makes the distribution of the voltage drop on the barrier and the electric charges in its vicinity inhomogeneous in the plane of the barrier. The results concerning spectrum of JPPs and their influence on the linear AC response of the SBS structures were presented in [1]. Here we present the results concerning the influence of JPP excitation on the nonlinear AC response of the barrier structures. The conductivity mechanism through the barrier is irrelevant, it could be both tunnel and thermo-ionic. What is important for the practical applications is the nonlinearity of the conductance, the more it is the better.

In Section 1 we shall briefly review the results concerning JPP spectrum and the influence of JPP excitation on the linear AC impedance of the SBS structures. In Section 2 we shall discuss the new results concerning the influence of JPP excitation on the value of the rectified voltage in the SBS structures.

1 JPP spectrum and linear AC impedance of the barrier structures

We have found the spectrum of JPPs in the SBS structure. To describe the dependence of the electric current on the electro-magnetic field and the gradient of electron concentration we used the hydro-dynamic approximation. The following dispersion equation for JPPs has been derived [1]:

$$(\omega + i\nu)(\omega + i\nu_{\Gamma})\kappa = \omega_p^2 \frac{d^*}{2} \left(\kappa^2 - \frac{\omega_p^2}{c^{*2}} \frac{\omega}{(\omega + i\nu)} - \frac{\omega(\omega + i\nu_{\Gamma})}{c^{*2}} \right), \text{Re}(\kappa) > 0, \quad (1)$$

here $\omega_p^2 = 4\pi n_0 e^2 / m^* \epsilon_l$ is the semiconductor bulk plasma frequency, $d^* = d + 2r_{\text{TF}}$ is the effective thickness of the barrier, r_{TF} is the Thomas-Fermi screening radius, $\nu_{\Gamma} = 4\pi G d^* / \epsilon_l$ is the reciprocal R_{TC} relaxation time due to the conductance of the barrier (G), ν is the reciprocal momentum relaxation time in the semiconductor; $\kappa^2 = q^2 - \epsilon_s \omega^2 / c^2$, q is the 2D JPP wavevector in the plane of the barrier, $\epsilon_s = \epsilon_l [1 - \omega_p^2 / \omega(\omega + i\nu)]$ is the dielectric function in the semiconductor allowing for the bulk plasma contribution, $c^* = c / \sqrt{\epsilon_l}$ is the effective light velocity in the barrier and ϵ_l is the lattice dielectric constant in the semiconductor and barrier (they are supposed to be the same). Eq. (1) have been derived in the low-frequency and long-wavelength approximations:

$$\max\{|\nu_{\Gamma}|, \omega, \nu\} \ll \omega_p, \quad q \ll \max\{1/d, 1/r_{\text{TF}}\}. \quad (2)$$

Further, we considered the linear response of the following structure: semiconductor with finite dimensions ($2W$ along x axis, ∞ along y axis, L along z axis)–barrier ($|z| < d/2$)–semiconductor ($2W \times \infty \times L$). The condition of the strong skin-effect is supposed to be fulfilled:

$$l_s(\omega) \ll W, L, \quad (3)$$

$l_s(\omega)$ is the skin-layer thickness. The following Eq. for the impedance of the pre-barrier region ($|z| < l_s(\omega) + d/2$) of the structure has been derived:

$$Z_j = \frac{i}{C(\omega + i\nu_{\Gamma})} \frac{qW}{\tan(qW)}, \quad (4)$$

C is the ordinary capacitance of the SBS structure. The first factor here is the ordinary impedance of the structure that one get if JPP excitation is not taken into account. The second factor appears due to JPP excitation by the current coming to the barrier region in the skin-layer along the lateral surface of the structure. In this case, the distribution of the current through the barrier ($j_{\Gamma}(x)$) has the form (we have been looking for a homogeneous solution in y direction):

$$j_{\Gamma}(x) = j_{\Gamma}(W) \frac{\cos(qx)}{\cos(qW)}. \quad (5)$$

Eq. (4) is valid if the penetration length of the JPPs along the barrier ($1/q''$) from the lateral surface of the structure is in comparison with the skin-layer thickness ($1/q'' \gg l_s$).

2 Nonlinear AC response of the barrier structure

Let us consider the small-signal nonlinear response. The problem is to calculate the DC rectified voltage in the SBS structure when a high-frequency voltage is applied to it. We consider the same structure as that used in the impedance calculations. We

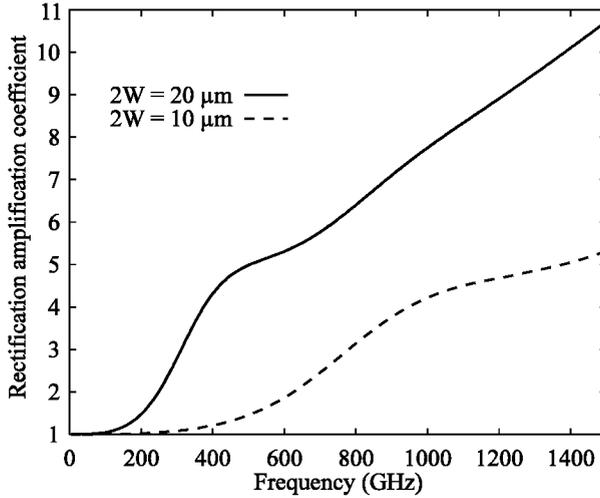


Fig 1. Rectification amplification coefficient at room temperature in the typical GaAs–barrier–GaAs structures with widths of 20 μm (upper curve) and 10 μm (lower curve).

suppose that the only nonlinear element in the structure is the barrier with nonlinear conductance. We suppose that the voltage drop on the barrier ($V(x)$) depends on the current through the barrier ($j_T(x)$) as follows:

$$V(x) = \frac{1}{G}Re [j_T(x)] + \alpha Re [j_T(x)]^2, \tag{6}$$

where α is the nonlinearity parameter. We suppose that the second term in (6) is small as compared to the first one. In the case the following approach is applicable: at first, we find the linear solution for the $j_T(x)$ (what in fact have been already made in the previous section), and further we are looking for a correction to $V(x)$ due to the nonlinearity, i.e. we substitute the linear solution for $j_T(x)$ in (6) and average $V(x)$ over x and t . In such a way we get the measurable rectified DC voltage $\langle V \rangle_{tx}$:

$$\langle V \rangle_{tx} = V_{rect}^{classic}(\omega)f(q(\omega)). \tag{7}$$

Here

$$V_{rect}^{classic}(\omega) = \frac{1}{2} \frac{\alpha}{(2W)^2} |I| \frac{1}{1 + (\omega C/2WG)^2} \tag{8}$$

is the ordinary Eq. for the rectified voltage, if JPP excitation is not taken into account, I is the net high-frequency current per unity of length in y direction.

$$f(q) = \left| \frac{qW}{\sin(qW)} \right|^2 \left[\frac{\sin(2q'W)}{4q'W} + \frac{\sinh(2q''W)}{4q''W} \right] \tag{9}$$

is the amplification coefficient of the rectified voltage due to JPP excitation, $q(\omega) = q' + iq''$ is the solution of Eq. (1).

As it follows from (9), the amplification coefficient $f(q)$ is close to unity when the frequency is sufficiently low ($|q|W \ll 1$). On higher frequencies ($|q|W > 1$) $f(q)$ can increase significantly. The applicability area of Eqs. (7) and (9) coincides with that of the impedance Eq. (4).

For example, we calculated the frequency dependence of the $f(\omega)$ for the two identical n -GaAs structures of different widths, $2W = 20 \mu\text{m}$ and $2W = 10 \mu\text{m}$ (see Fig. 1). The other parameters are the following: the electron effective mass is $m^* = 0.07m$, the electron concentration in the semiconductor is $n_0 = 3 \cdot 10^{18} \text{ cm}^{-3}$, the barrier thickness is 30 nm, the electron mobility is $\mu = 2 \cdot 10^3 \text{ cm}^2/\text{Vs}$, the dielectric lattice constants in the semiconductor and barrier are equal to $\epsilon_l = 13.5$. One can see from Fig. 1 that the rectification amplification coefficient could be as large as one order of magnitude. In the structures with higher mobility the $f(\omega)$ plots are oscillating more significantly due to the resonant JPP excitation.

Conclusions

We have shown that close to the barrier of the semiconductor–barrier (conducting, opaque, resonant tunneling one)–semiconductor structures low-frequency plasma excitations exist — junction plasma polaritons. They are excited by the high-frequency current coming to the barrier in the skin-layer along the lateral surface of the structures. JPP excitation leads to the build up of the AC voltage drop on the barrier or an effective change of the width of the barrier structure. Such effects are responsible for an amplification of the rectified voltage in the structures. The amplification becomes significant on the frequencies higher than 100 GHz for the typical parameters of the structures and it can be as large as one order of magnitude.

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References

- [1] Feiginov M. N. and Volkov V. A., *Proceedings of the 1997 International Semiconductor Device Research Symposium*, Charlottesville, USA, p. 155–158, 1997.