THE NEGATIVE DIFFERENTIAL RESISTANCE IN FERROMAGNET/ WIDE-GAP SEMICONDUCTOR/ FERROMAGNET NANOSTRUCTURE

T. Sidorova, A. Danilyuk
Belarusian State University of Informatics and Radioelectronics, Minsk, Belarus

Abstract – The model of charge carrier transport in ferromagnet/wide-gap semiconductor/ ferromagnet nanostructure based on two-band Franc-Keine model and phase function method was proposed. It is calculated, that tunneling barrier, formed by the wide-gap semiconductor band-gap, does not represent potential step, but the energy band-gap. Their upper border is the bottom of the conduction band E_C, and the bottom part is top of the valence band E_V. Inside this zone wave vector of the electron is an imaginary value. According to the dispersion law states located in the midgap sustain the largest attenuation. That is why when the Fermi level of the analyzed structure lies in the bottom part of the band-gap, bias voltage V shifts levels of the tunneling electrons to the low barrier area. This shifting is a reason of the tunneling current reduction and leads to the negative differential resistance effect. It is shown that areas of the negative differential resistance effect appears at the current-voltage bias dependence in case of $qV > E_F$. Here areas of negative differential resistance should be expected at the voltage values bigger than Fermi energy value of the emitting electrode for the electrons zone with the spin-up.

I. INTRODUCTION

Ferromagnet /wide-gap semiconductor/ ferromagnet nanostructures attract a great interest during the last decade regarding their prospects for creating information-processing devices, including spintronic devices. Previously, the tunneling magnetoresistance (TMR) in such nanostructures was calculated generally using one-band insulator model.

In this article the charge carrier transport model in the ferromagnet / wide-gap semiconductor/ feromagnet based on two-band Franc-Keine model and phase function model is proposed [1]. It is taken into account, than tunneling barrier with the width d, which was founded by the band gap, does not represent potential step, but the energy band-gap. Their upper border is the bottom of the conduction band E_C, and the bottom part is top of the valence band E_V. Inside this area the wave vector of the electron is an imaginary value. According to the Franc-Keine law it is defined as [2]

$$k_Z^2 = \frac{2m_i}{h^2}\frac{(E - Ec)(E - E_V)}{E_G} - k_p^2, \tag{1}$$

where k_z, k_p – are wave vector components which are perpendicular and parallel to the barrier, correspondingly, E – is a full electron energy, m_i – the electron effective mass, E_G - is the band-gap width.

The current value is calculated taking into account the transverse component of the tuning electron energy based on the transport equation:

$$I(V) = \frac{4\pi \cdot m_i q}{h^3}\int_0^\infty dE[f_L(E) - f_R(E,V)] \int_0^{(m/m_i)E} dE_p P(E, E_p, V), \tag{2}$$

where E_p – is an electron energy component which is parallel to the tunneling barrier surface, m and m_i – are the electron effective masses in electrode and in the wide-gap semiconductor correspondingly, q – is an electron charge, h – is the Planck constant, $f_L(E)$, $f_S(E)$ – are the Fermi-Dirac distribution functions for left and right electrodes, $P(E, E_p, V)$ – tunnel transparency of the barrier.

II. MODEL

To find the transmission coefficients we develop a model on the basis of phase functions. The model accounts for the barrier parameters, the image force potential and allows include the potential relief at the interfaces and in the volume of the wide-gap semiconductor. The main feature of the phase function is possibility to obtain the transmission coefficients. For In the phase function method not a wave function, but only its changes as a result of potential actions are calculated.

To evaluate the spin dependent transmission coefficient we solve the Schrödinger equation for each spin component:

$$\left[-\frac{\hbar^2}{2m_\sigma^*}\frac{\partial^2}{\partial z^2}+\frac{\hbar^2 k_{\mathrm{p}}^2}{2m_\sigma^*}+U_0-h_0\sigma-qV(z)-q\varphi(z)+V_{sc}(z)\right]\psi_\sigma(z)=E\,\psi_\sigma(z), \tag{3}$$

where z is a coordinate of the tunneling direction; σ – is the spin index (spin –up and spin-down); V_{sc} – is the scattering potential. Effective potential in this case is equal to:

$$U_{eff}=\left(2m_\sigma^*/\hbar^2\right)\left(U_0+k_\parallel^2-qV(z)-q\varphi(z)\pm V_{sc}(z)\right). \tag{4}$$

The tunneling transmission coefficient is:

$$T_\sigma=\exp\left[\frac{1}{k_\sigma}\int_0^d U_{eff}(z)\left[b_\sigma(z)\cos(2k_\sigma z)-a_\sigma(z)\sin(2k_\sigma z)\right]dz\right], \tag{5}$$

where a_σ and b_σ functions are defined by the equations based on the Phase function method:

$$\frac{da_\sigma(z)}{dz}=\frac{U_{eff}(z)}{2k_\sigma}\left[-\sin(2k_\sigma z)-2b_\sigma+(a_\sigma^2-b_\sigma^2)\sin(2k_\sigma z)-2a_\sigma b_\sigma\cos(2k_\sigma z)\right], \tag{6}$$

$$\frac{db_\sigma(z)}{dz}=\frac{U_{eff}(z)}{2k_\sigma}\left[\cos(2k_\sigma z)+2a_\sigma+(a_\sigma^2-b_\sigma^2)\cos(2k_\sigma z)-2a_\sigma b_\sigma\sin(2k_\sigma z)\right]. \tag{7}$$

Using system of equations (2), (5), (6), (7) current-voltage characteristics are calculated in dependence from position of Fermi level. We considered the cases when Fermi level of nanostructure is located close to valence band maximum or conduction band minimum.

III. Results and discussions

The dependence of tunneling current on the voltage applied to the transition for the case when E_F is located above the midgap is expected to be monotonically increasing function (Fig.1). But when E_F is situated below the midgap an additional canal through the valence band of the wide-gap semiconductor can appear. Current density of the main canal monotonically increases (Fig.1). Current density of the additional canal (Fig.2) for the applied voltage of 0.1 V…3 V increases monotonically, but at the further increasing of the applied voltage up to the 5 V the maximum appears, after which the tunneling current decreases. It means that the region of the negative differential resistance is formed. The smaller is the thickness of the wide-gap semiconductor d, the larger is effect of the negative differential resistance.

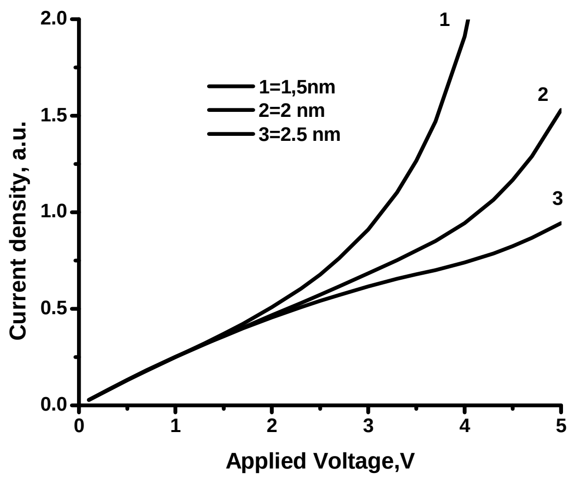

Figure 1 – Current –voltage characteristic of the main canal in dependence of the thickness of the wide-gap semiconductor for the case when E_F is situated below the midgap.

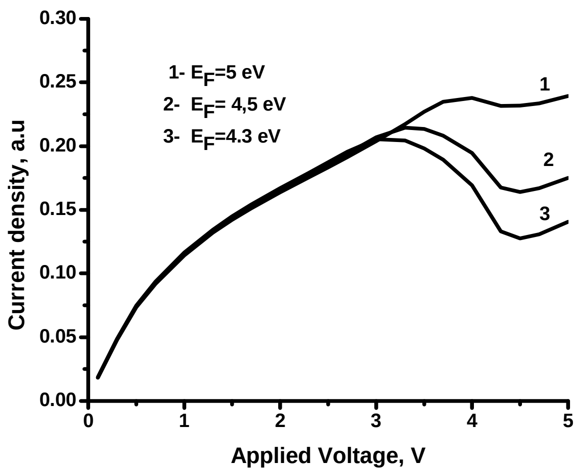

Figure 2 – Current –voltage characteristic of the additional canal in dependence of the Fermi level position, for the case when E_F is situated below the midgap

Thereby when Fermi level E_F of the nanostructure is situated below the midgap on the dependence of the tunneling current from the applied V for the case when $qV > E_F$, the regions of the negative differential resistance appear, that can be explained by the appearance of the additional canal of the charge carrier transport through the valence band. [2]. According to the dispersion law (1) states located in the midgap sustain the largest attenuation in the barrier. Therefore if Fermi level of the observed nanostructure is located near the bottom of the band-gap the bias voltage V shifts the levels of the tunneling electrons to the area of the lower barrier transparence. This shifting is a reason of the tunneling current decrease, which is the reason of the effect of the negative differential conductivity.

The tunneling magnetoresistance of the ferromagnet /wide-gap semiconductor/ ferromagnet nanostructures taking into account the appearance of the additional canal of the transport through the valence band of the wide-gap semiconductor was calculated. TMR of the main canal monotonically decrease from 0.15 up to 0.3 (Fig.3), but for the additional canal TMR changes insignificantly (Fig. 4).

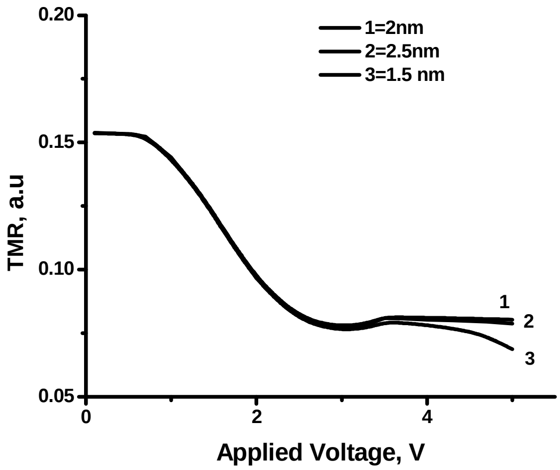

Figure 3: TMR of the main canal in dependence of the wide-gap semiconductor thickness for the case when E_F is situated above the midgap

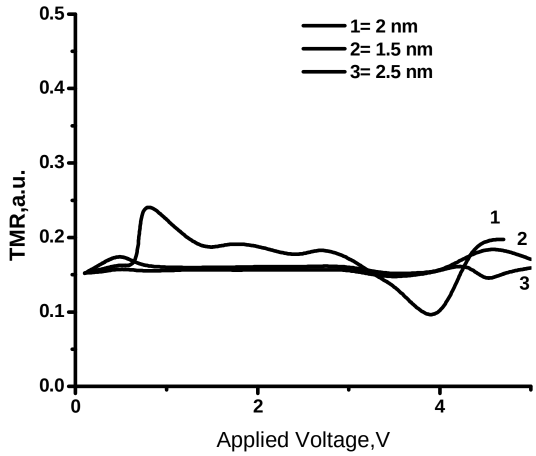

Figure 4. TMR of the additional canal in dependence of the wide-gap semiconductor thickness for the case when E_F is situated above the midgap

For the wide-gap semiconductor thickness equal to 1.5 nm and 2.5 nm the TMR of the additional canal is almost constant. For the intermediate thickness equal to 2 nm two extrema are observed at the TMR curve of the additional canal for the voltage bias equal to 1 V (0.25) and 4 V – 4.3 V (0.1). These extrema can be explained with the availability of the maximum correlation between minimal and maximal value on the current-voltage characteristic in the region of the negative differential resistance at this considered thickness.

REFERENCES

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[2] T. A. Kchachaturova, A. I. Kchachaturov, The negative differential resistance of metal/ insulator/ metal structure, JETF, 2008