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

T. Sidorova, A. Danilyuk*

Belarusian State University of Informatics and Radioelectronics, P. Browki 6, Minsk, Belarus

*e-mail: danilyuk@nano-center.org

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 determined that tunneling barrier, formed by the gap of wide-gap semiconductor, does not represent potential step, but the energy band gap. Its upper border is the bottom of the conduction band E_C, and the bottom part is the 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 a low barrier area. This shifting is the 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 appear at the current-voltage bias dependence at $qV> E_F$. Here areas of negative differential resistance should be expected at the voltage values higher than Fermi energy value of the emitting electrode for the zone electrons with the spin-up.

1. 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 using one-band insulator model.

In this article the charge carrier transport model in the ferromagnet/wide-gap semiconductor/ferromagnet based on two-band Franc-Keine model and phase function model is proposed [1]. It is taken into account that tunneling barrier with the width d, which was founded by the band gap, does not represent the potential step, but the energy band-gap. Its upper border is the bottom of the conduction band E_C, and the bottom part is the 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 the full electron energy, m_i is the electron effective mass, E_G is the band-gap width.

The current value is calculated taking into account the transverse component of

$$\frac{db_\sigma(z)}{dz} = \frac{U_{eff}(z)}{2k_\sigma}\left[\cos(2k_\sigma z) + 2a_\sigma + (a_\sigma^2 - b_\sigma^2)\cos(2k_\sigma z) - 2a_\sigma b_\sigma \sin(2k_\sigma z)\right]. \tag{8}$$

Using the system of equations (2), (6), (7), (8) current-voltage characteristics are calculated in dependence on the position of Fermi level. We considered the cases when Fermi level of nanostructure is located close to valence band maximum or conduction band minimum.

3. 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 a wide-gap semiconductor can appear. Current density of the main canal monotonically increases (Fig. 1). Current density of the additional canal changes monotonically for the applied voltage of 0 …3V (Fig. 2), but at the further increasing of the applied voltage up to 5 V the maximum appears, after which the tunneling current decreases.

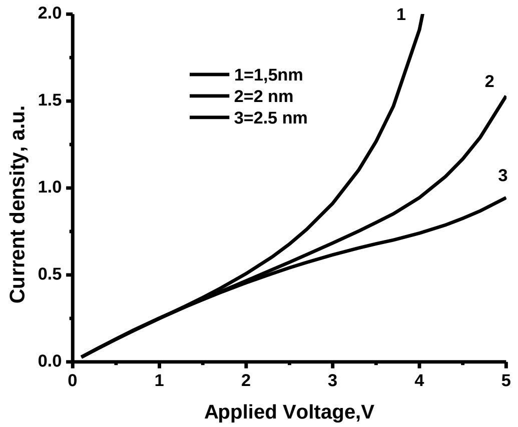

Fig. 1. Current–voltage characteristic of the main canal in dependence on the thickness of a wide-gap semiconductor for the case when E_F is situated below a midgap.

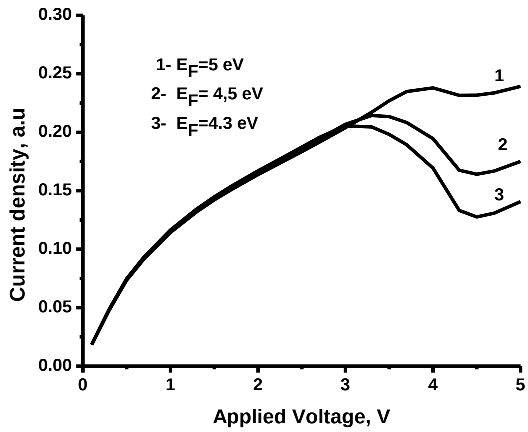

Fig. 2. Current-voltage characteristic of the additional canal in dependence on the Fermi level position for the case when E_F is situated below a midgap.

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 the effect of the negative differential resistance. Calculations show that in the case, when Fermi level E_F is situated below the midgap, current density monotonically increases at applied voltage changing from 0 to 3 V. Further growth of the applied voltage up to 5 V brings to significant changes in current-voltage characteristics behavior. These changes occur due to appearance of negative differential resistance.

Fermi level position influences on the value of the negative differential resistance; its value increases upon approximating Fermi level to the top of the valence band. Its value drops when Fermi level is comes closer to the midgap. Current-voltage characteristic of the main canal when Fermi level is situated above the midgap does not have the negative differential resistance region which is typical for the cases mentioned above. Thereby when Fermi level E_F of the nanostructure is situated below the midgap, on the dependence of the tunneling current on the applied V for the case when $qV > E_F$, the regions of the negative differential resistance appear. It can be explained by the appearance of an additional canal of the charge carrier transport through the valence band. [2].

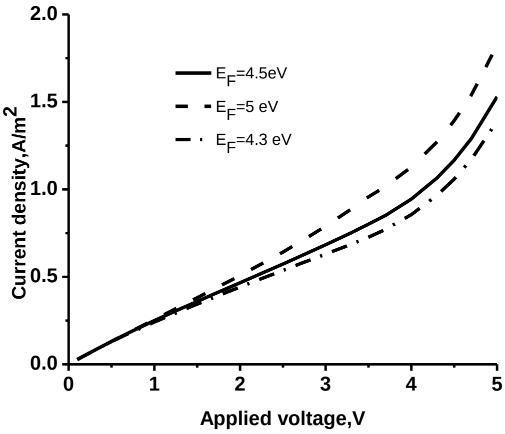

Fig. 3. Current-voltage characteristic of the main canal in dependence on the Fermi level position for the case when E_F is situated below a midgap.

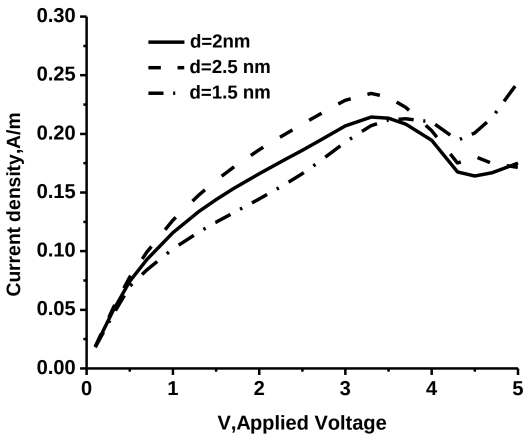

Fig. 4. Current-voltage characteristic of the additional canal in dependence on the thickness of the wide-gap semiconductor for the case when E_F is situated below a midgap.

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 the reason of the tunneling current decrease, which is, in its turn, the reason of the effect of the negative differential

conductivity.
We have calculated 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 a wide-gap semiconductor. TMR of the main canal monotonically decreases from 0.15 up to 0.03 (Fig. 5), but for the additional canal TMR changes insignificantly (Fig. 6).

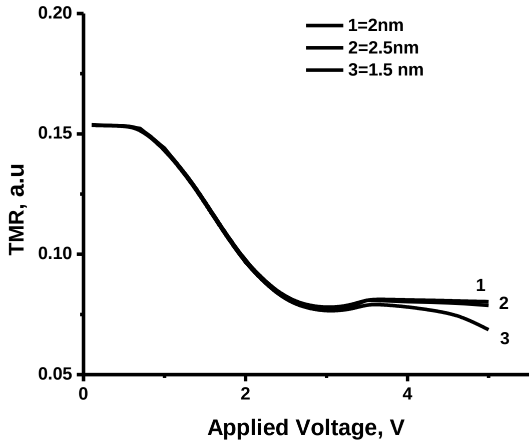

Fig. 5. TMR of the main canal in dependence on the wide-gap semiconductor thickness for the case when E_F is situated above a midgap.

For the wide-gap semiconductor thickness equal to 1.5 nm and 2.5 nm, TMR of the additional canal is almost constant. For the intermediate thickness equal to 2 nm, two extremes are observed at the TMR curve of the additional canal for the voltage bias equal to 1 V (TMR = 0.25) and 4 V – 4.3 V (TMR=0.1). These extremes 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 the thickness considered.

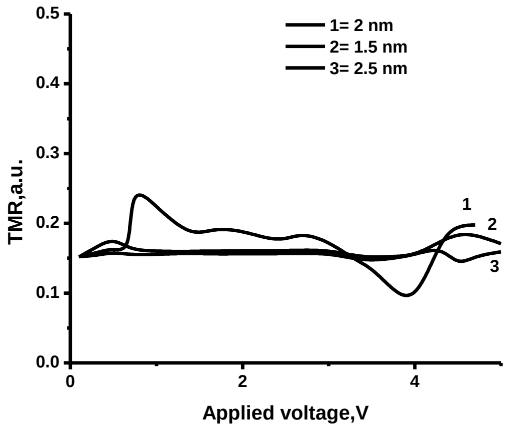

Fig. 6. TMR of the additional canal in dependence on the wide-gap semiconductor thickness for the case when E_F is situated above a midgap.

References

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[2] T.A. Kchachaturova, A.I. Kchachaturov // *Journal of Experimental and Theoretical Physics* **134(5)** (2008) 1006.