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Volt-Ampere Characteristics of Tunnel Junctions from Ferromagnetic Materials

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Abstract

The paper presents the model calculations of the volt-ampere characteristics of tunnel junctions with ferromagnetic plates. It is shown that their volt-ampere characteristics partially reflect the energy spectrum of ferromagnetic materials.

Keywords

Fermi energy; energy spectrum of the electrode; ferromagnetic materials; tunnel magnetoresistance; two-band insulator model.

Introduction

Tunnel magnetoresistance of ferromagnetic metal-insulator-ferromagnetic metal are interesting not only for their magnetoresistance properties, but also can be used as one of the key elements of electromagnetic high-frequency generators. In this case, when bias voltages at the junction exceed the Fermi energy of the conduction band of the starting electrode, the frequency of the generator radiation is associated in a certain way with the beginning of the region of negative resistance [1]. The applied use of new materials is limited since the materials themselves remain little explored. For example, only one work is known about the electronic spectrum of ferromagnetic materials [2], in which, based on the first-principle calculations of the electron iron spectrum, it is asserted that almost spherical *d*-bands with small Fermi energies take part in the tunneling, the largest of which has energy $E_F = 2.25$ eV.

In this research, it is assumed that tunneling can be used to study the spectra of these materials. As the investigated tunnel characteristic, the volt-ampere characteristic (**VAC**) is chosen. A significant advantage of the VAC is that its finding does not require modulation technology and, as shown in the paper, under certain conditions the interpretation of the VAC provides irrefutable information about the energy spectra of the materials under study.

Small values of the Fermi energies of the conduction bands of ferromagnetic electrodes indicate that such voltages are easily reached in the junctions, when the bottom of the conduction band is above the Fermi level of the entire tunnel junction so that a further increase in the voltage at the contact does not cause an increase in the number of electrons participating in the tunneling process. Thus, if the Fermi level is in the lower half of the band gap of the dielectric, then an increase in the bias voltage at the junction reduces the probability of tunneling, and a negative resistance can be observed. An experimental observation of the downward sections on the VACs would be a convincing proof of the results of [2].

Theoretical model

To calculate the tunneling current of tunnel junctions under the assumption that the tunneling process is elastic, an expression for the tunnel current used in [3–5] was obtained by the authors of [3]:

$$J(V) = \frac{4\pi m e^2 V}{h^3} \int_0^{E_F - eV} P(E_z, V)\, dE_z +$$

$$+\frac{4\pi m e}{h^3} \int_{E_F - eV}^{E_F} (E_F - E_z) P(E_z, V)\, dE_z,$$

where m and e are mass and charge of a free electron, respectively, h is Planck's constant.

However, in deriving the formula for the current, the authors of [3] used the approximation, when the barrier transparency $P(E_z)$ included in the relation is a function E_z only. In the present research, a formula for calculating the tunnel current is obtained; it takes into account the explicit dependence of the tunneling probability on the component of the quasimomentum of the electron $k_\perp$ parallel to the plane of the potential barrier. As an infinitesimal integration element, I consider a ring of infinitesimal thickness $dk_\perp$, of radius $k_\perp$ perpendicular to the z axis (tunneling direction) (Fig. 1). In the case of the two-band model, all the electrons whose energy states lie on this circle have the same group velocity $v_z = \frac{\hbar k_z}{m}$ and the probability of tunneling in them is the same, in the Wentzel, Kramers, and Brillouin (**WKB**) approximation is given by the expression [6]:

$$P(E_z, E_\perp, V) = \exp\left\{-2\int_0^d \left[-k_z^2(E_z, E_\perp, V)\right]^{1/2} dz\right\}, \quad (1)$$

where

$$k_z^2 = \frac{2m}{\hbar^2}\frac{(E-E_C)(E-E_V)}{(E_g)} - k_\perp^2;$$

$$k_\perp^2 = \left(2m/\hbar^2\right)E_\perp \quad \text{and} \quad E = E_z + E_\perp.$$

E_C determines the bottom of the conduction band of the insulator, and E_V determines the top of the valence band of the insulator, measured from the bottom of the conduction band of the initial electrode, $E_g = E_C - E_V$ is the width of the forbidden band of the dielectric, and d is the thickness of the tunnel potential barrier.

Results

As shown in Fig. 1, the area of the ring is equal to $dS = 2\pi k_\perp dk_\perp$, the number of states belonging to this ring is found by dividing its area by the two-dimensional density of states $(2\pi)^2$: $dn = \frac{2\pi k_\perp dk_\perp}{(2\pi)^2}$, their contribution to the total electron flux incident on the barrier plane is equal to: $\frac{2\pi k_\perp dk_\perp}{(2\pi)^2}\frac{\hbar k_z}{m}$. Multiplying it by the tunneling probability $P(E_z, E_\perp, V)$, we obtain a contribution to the tunneling current from the ring under consideration. Further, carrying out a double integration and passing to the energy units, we find expression for the tunnel current:

$$J(V) = K\int_{E_F - eV}^{E_F}\int_0^{E_F - E_Z} P(E_Z, E_\perp, V)\,dE_\perp dE_Z + K\int_0^{E_F - eV}\int_{E_F - E_Z - eV}^{E_F - E_Z} P(E_Z, E_\perp, V)\,dE_\perp dE_Z. \quad (2)$$

Expression (2) is obtained for the case when the bias voltage applied to the conjunction is less than the Fermi energy of the largest of the bands $eV \le E_F$ and at zero temperature. We note that in the tunneling, those states that are located between two equipotential surfaces $E_F - eV$ and E_F are involved. In Fig. 2, they

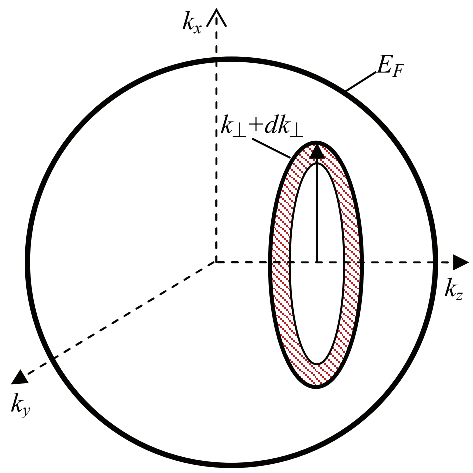

Fig. 1. The Fermi sphere of the starting electrode in the reciprocal space. With a bias voltage $eV > E_F$ all particles whose states lie inside the Fermi sphere can participate in the tunneling

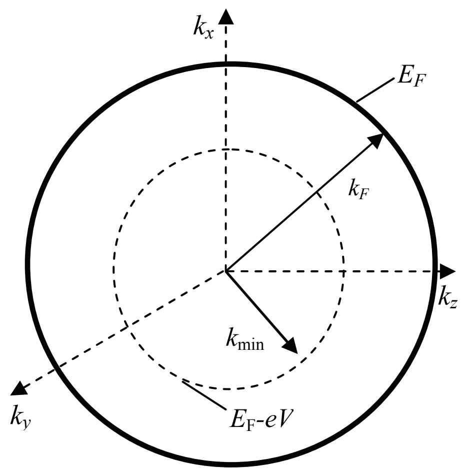

Fig. 2. With a bias voltage $eV > E_F$ particles whose states lie in a spherical layer between equipotential surfaces E_F and $E_F - eV$ can participate in the tunneling

are presented in the form of two concentric spheres with the corresponding radii $k_{\min}$ and k_F.

In the case when the bias voltage applied to the contact exceeds the Fermi energy of the conduction band of the starting electrode $eV > E_F$, all particles whose energy states lie inside the Fermi sphere can participate in the tunneling and the expression for the tunnel current takes the form:

$$J(V) = K \int_0^{E_F} \int_0^{E_F - E_Z} P(E_Z, E_\perp, V)\, dE_\perp dE_z, \qquad (3)$$

where coefficient $K = \frac{2\pi me}{h^3}$.

The fact that the number of tunneling particles remains constant is reflected in the fact that the limits of integration in formula (3) remain constant when $eV > E_F$, i.e., they do not depend on voltage.

The results of the calculation using formulas (2) and (3) are shown in Fig. 3. We see that when $eV > E_F$, the obtained dependence $J(V)$ decreases with increasing voltage. The reason for this is that when $eV > E_F$, the further increase in voltage does not lead to an increase in the number of tunneling electrons, since the integration limits in formula (3) are independent of the voltage, and the tunneling probability, as shown in Fig. 4, decreases with increasing voltage. In this paper, a symmetric tunnel contact is considered, so the limitations imposed on specular tunneling associated with tunneling from a band of a larger radius to a band with a smaller one are absent [7].

Discussion

It is believed that the first derivative of the tunneling current with respect to the bias voltage $\frac{dJ(V)}{dV}$ is more sensitive to the parameters of the tunnel barrier, and also to the electronic spectrum of the tunnels of the tunnel junctions. The difficulties associated with measuring higher harmonics, i.e. first and second derivatives $\frac{d^2 J(V)}{dV^2}$, are completely compensated by the sensitivity of these characteristics to the spectrum of the conjunctions under study. However, there is no rule that unambiguously links the behavior of these derivatives to the spectrum of conjunction plates. Therefore, the observation of the downward section in the VAC is a reliable proof of the fact that tunneling occurs through the lower half of the bandgap of the insulating layer, so that a further increase in voltage will lead to a worse transparency. If the conduction band finishes, then the number of tunneling electrons does not increase, and the probability of tunneling decreases. The absence of such areas before the end of the band indicates the absence of gaps in the energy spectrum, which are possible due to hybridization of electronic bands [8].

Conclusions

The calculations of the dependence of the tunnel current on the voltage are carried out. It is shown that under certain conditions, namely, when tunneling

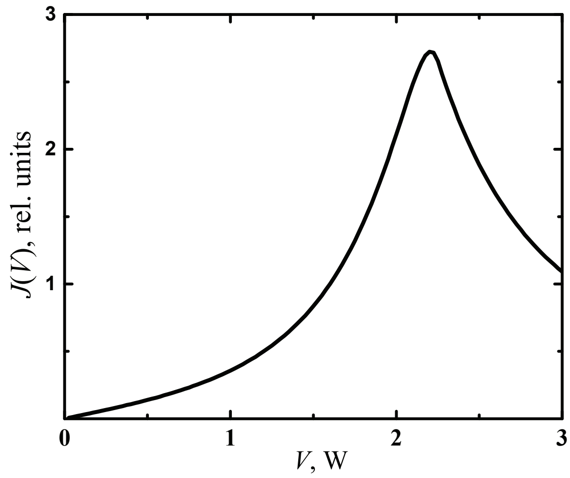

Fig. 3. The volt-ampere characteristic of the conjunction under study, the thickness of the tunnel barrier d = 15 nm, position of the Fermi level relative to the bottom of the conduction band of the insulator:
φ = 5.5 eV; band gap width E_g = 8 eV; the Fermi energy of the largest band Fe E_F = 2.25 eV

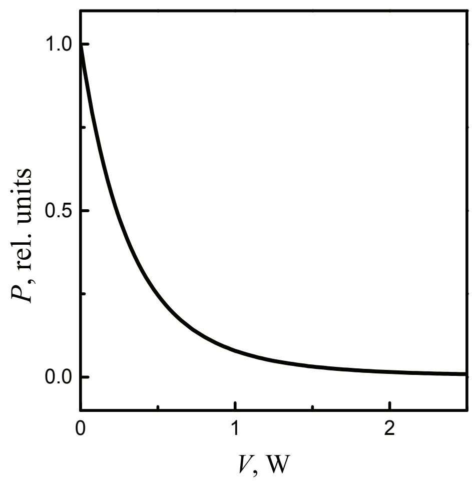

Fig. 4. Transparency of the tunnel barrier calculated by the formula (1). The calculated parameters of the band structure are equal to:
$E_\perp = 0$; $E_Z = E_F$; E_g = 8 eV; position of the Fermi level relative to the bottom of the conduction band of the insulator: φ = 5.5 eV; tunnel barrier thickness: d = 15 nm; variable parameter is the bias voltage

occurs through the lower half of the bandgap of the insulator, this characteristic can be used to determine the energy spectrum of the tunnels of the tunnel junction. A formula that allows calculating the dependence of the tunnel current on the bias voltage on the conjunction in the case of a two-gap insulator model is derived.

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