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TUNNELING PROPERTIES OF HETEROSTRUCTURES WITH A DOUBLE MAGNETIC BARRIER

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Abstract: We consider the spin-dependent transport properties of an unpolarized electron beam through a multilayer system containing two magnetic barriers with different orientations of magnetizations. The dependences of the transmission coefficient and degree of polarization of transmitted electrons on the angle between the magnetization vectors of barriers and energy of electrons are calculated using transfer-matrix approach. It is found that at the resonance tunneling this dependence should manifest itself quite strongly.

1. In the world of spin-based-electronics or emerging field of "spintronics" one tries to use the electron spin and its sensitivity to carry the spin polarized current. The most prominent perspective in the "spintronics" is the quantum transport of spin-polarized carriers in nanosystems and nanostructures, as well as controlling the spin tunneling properties. This becomes very actual problem for the development of so-called spintronic devices, such as spin filters, fuel injectors, analyzers of the spin polarization, etc. controlled by spin polarization or an external magnetic field [1,2].

For example, in [3] it is shown that the most effective method of detection of spin-polarized electrons is a resonant tunneling of electrons through the double-barrier system. Several techniques were proposed to achieve spin filtering such as magnetic tunnel junctions comprised of half-metallic compounds. An alternative method consists in using spin-dependent resonant tunneling through magnetically active quantum wells. Recent advances in molecular beam epitaxial growth made it possible to fabricate exotic heterostructures comprised of magnetic films or buried layers (ErAs, $Ga_xMn_{1-x}As$) integrated with conventional semiconductors (GaAs) and to explore quantum transport in these heterostructures [4]. This increasing in interest spin-dependent resonant tunneling in double-barrier heterostructures stems from two major factors. First, there has been a lot of study of electronic and magnetic transport properties of semiconductor heterostructures greatly sensitive to electron spin. The second, the spin-dependent polarization in one-dimensional structures strongly depends on interfacial magnetic properties (multilayers) or number of magnetic barriers. However, often the various orientations of magnetization in barriers with the magnetic-barrier field have been overlooked [5,6]. Magnetic barriers are different from the potential barriers since the transmission depends not only on the energy of spatially quantized electrons but also the orientation on which electrons move toward barriers. current investigation is on electron tunneling through a system of two magnetized barriers with noncollinear magnetization vectors. The coefficients of transmission and spin polarization are obtained and dependences on the angle between magnetization vectors $\mathbf{M}_1$

and $\mathbf{M}_2$(noncollinearity angle) in the transmission characteristics are analyzed away from the resonances and exactly in the resonance as well. The proposed model for the quantum tunneling in the single and double-barrier systems is described in Section 2. The results of the transmission coefficient and polarization efficiency obtained by transfer matrix approach are presented in Sections 3 and 4. The conclusion is provided in Section 5.

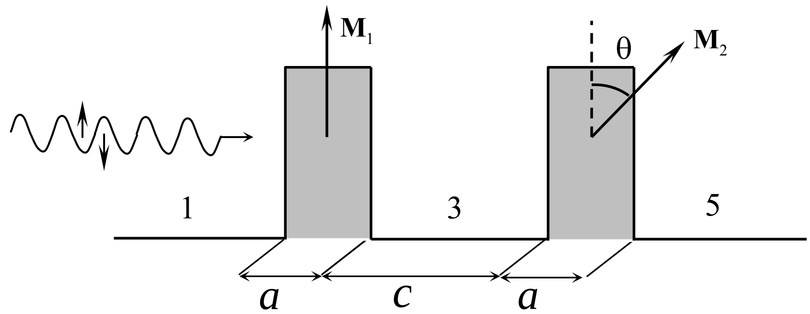

Fig. 1. Energy profile of two (magnetically) active layers 2 and 4 corresponding to barriers with magnetization $\mathbf{M}_1$ and $\mathbf{M}_2$ with angle θ between them.

2. Let us consider an electron transmission through double-barrier heterostructure consisting of five layers, with magnetically active 2 and 4 interfaces, where the separation between the two adjacent magnetic barriers is c and the barrier width is *a*. Band gaps of the materials are selected such that the potential relief for the system contains two magnetic barriers of the same height shown schematically in Fig.1. The spin interaction of an electron with a barrier is described by the local spin-dependent term in the magnetic Hamiltonian

$$H_{\text{int}} = \left(V_0 - \gamma \mathbf{M}\boldsymbol{\sigma}\right)\varphi(y),$$

where V_0 is the height of the barrier, $\gamma = g\mu_B/2\mu_0$, g is the g-factor of the electron, μ_B is the Bohr magneton, μ_0 is the magnetic constant. Here we neglect the orbital effect which is well satisfied for the condition, $\Phi << \Phi_0/2\pi$ (Φ is the magnetic flux through the lateral edge of the magnetic layer whose width is Φ_0 is an elementary flux). We consider the magnetization of barriers of equal in amplitude that are in the plane of the interface forming an angle θ, i.e., $\left(\mathbf{M}_1 \cdot \mathbf{M}_2\right) = M^2 \cos\theta$.

The scattering wave function has the form

$$\begin{aligned} \psi_1 &= \frac{1}{\sqrt{2}}\left(\hat{I}e^{iky} + \hat{r}e^{-iky}\right), \quad y < 0 \\ \psi_5 &= \frac{1}{\sqrt{2}}\hat{t}e^{iky}, \qquad\qquad y > a, \end{aligned} \tag{1}$$

where $\hat{I}$, $\hat{r}$, $\hat{t}$ are the spinor amplitudes of the incident, reflected and transmitted waves, respectively, the factor $2^{-1/2}$ before $\hat{r}$ and $\hat{t}$ in (1) is introduced for convenience. The amplitude of the incident wave *I* we choose as

$$I = \begin{pmatrix} e^{i\omega} \\ 1 \end{pmatrix} \tag{2}$$

where ω is undefined phase, over which the final terms (the transmission coefficient, the spin polarization) should be averaged (over an ensemble of incident particles). This choice is dictated by the amplitude of the incident wave so that an average spin (polarization of the incident wave) in the states (2) after averaging over ω becomes zero. This is actually way how we define the polarity of the incident electron wave. First we consider the scattering of unpolarized electron wave by choosing a single rectangular barrier $\varphi(y) = \theta(y)\theta(a-y)$ for $\theta(x)$ is a step function, and the direction of magnetization **M** is taken as the quantization axis. Then we find

$$t_\ell = \frac{m_2}{m_1} \cdot \frac{4ikq_\ell e^{-2ika+i\omega}}{\left(q_\ell + i\frac{m_2}{m_1}k\right)^2 e^{-q_\ell a} - \left(q_\ell - i\frac{m_2}{m_1}k\right)^2 e^{q_\ell a}}, \tag{3a}$$

$$r_\ell = \frac{2\left(q_\ell^2 + \frac{m_2^2}{m_1^2}k^2\right) sh(q_\ell a)}{\left(q_\ell + i\frac{m_2}{m_1}k\right)^2 e^{-q_\ell a} - \left(q_\ell - i\frac{m_2}{m_1}k\right)^2 e^{q_\ell a}}, \tag{3b}$$

$$k = \frac{1}{\hbar}\sqrt{2m_1\left(E - \frac{\hbar^2 k_{\parallel}}{2m_1}\right)}, \quad q_\ell = \frac{1}{\hbar}\sqrt{2m_2\left(V_0 - E - \frac{\hbar^2 k_{\parallel}}{2m_2} \pm \gamma M\right)},$$

$k_{\parallel}$ is the wave-vector component parallel to interface, that is equal in all regions, $m_{1,2}$ is the effective masses of electrons in the nonmagnetic and magnetic layers, respectively. In the case where the scattering occurs on a system of two identical barriers (the same height and magnetization) the corresponding transmission amplitudes are [7]

$$T_{0\ell} = \frac{t_\ell^2 e^{i\omega_\ell}}{1 - r_\ell^2 \exp(2ikc)}, \tag{4}$$

where c is the distance between the barriers t_ℓ and r_ℓ defined in (3), and transmission coefficient is

$$D = \frac{1}{2}\hat{T}_0^+\hat{T}_0 = \frac{1}{2}\left(|T_{01}|^2 + |T_{02}|^2\right) = D_\uparrow + D_\downarrow \tag{5}$$

It follows from (4) and (5) that the averaging in this case over the phase ω a mere formality since the squares of modules $T_{0\ell}$ simply do not contain the ω-dependence. The reason is that non-polarized beam of electrons is a mixture of two beams of equal density with the polarizations parallel and opposite to **M** respectively.

Electron energy, corresponding to the resonance tunneling is determined from the equation

$$\delta_\ell + kc = \pi(n + 1/2), \tag{6}$$

where

$$\delta_\ell = \frac{\pi}{2} - 2ka + \arctan\left\{ \frac{2q_\ell k}{\left(m_2 k^2/m_1\right) - \left(m_1 q_\ell^2/m_2\right)} cth\left(q_\ell a\right) \right\}, \tag{7}$$

is a phase of transmission amplitudes for a single barrier.

3. We now consider the electron tunneling through a system of two magnetic barriers with noncollinear magnetizations. For this purpose we constructed the following transfer matrix [8]

$$S = \begin{pmatrix} U\alpha^* U^+ & -U\beta^* U^+ \\ -U\beta U^+ & U\alpha U^+ \end{pmatrix}, \qquad U = \begin{pmatrix} \cos(\theta/2) & -\sin(\theta/2) \\ \sin(\theta/2) & \cos(\theta/2) \end{pmatrix},$$
$$\alpha = \begin{pmatrix} 1/t_1 & 0 \\ 0 & 1/t_2 \end{pmatrix}, \qquad \beta = \begin{pmatrix} r_1/t_1 & 0 \\ 0 & r_2/t_2 \end{pmatrix}, \tag{8}$$

Then we introduce the following matrix equation:

$$\begin{pmatrix} T \\ R \end{pmatrix} = S(0)V(c)S(\theta)V^{-1}(c)\begin{pmatrix} T \\ 0 \end{pmatrix} \tag{9}$$

where T and R are amplitudes of transmitted and reflected waves, respectively,

$$V(c) = \begin{pmatrix} e^{-i\hat{k}c} & 0 \\ 0 & e^{i\hat{k}c} \end{pmatrix}, \qquad e^{-i\hat{k}c} = \begin{pmatrix} e^{ikc} & 0 \\ 0 & e^{-ikc} \end{pmatrix} \tag{10}$$

and the transmission coefficient for unpolarized wave in the approximation $\gamma M << V_0$ obtain

$$D = \left(D_\uparrow + D_\downarrow\right)\cos^2\frac{\theta}{2} + 2\sqrt{D_\uparrow D_\downarrow}\sin^2\frac{\theta}{2}, \tag{11a}$$

where $D_\uparrow$ and $D_\downarrow$ defined in (5), or, equivalently,

$$D = \frac{1}{2}\left(\left|T_{\uparrow\uparrow}\right|^2 + \left|T_{\uparrow\downarrow}\right|^2 + \left|T_{\downarrow\downarrow}\right|^2 + \left|T_{\downarrow\uparrow}\right|^2\right), \tag{11b}$$

where T_{ij} $\left(i, j = \uparrow, \downarrow\right)$ is the amplitudes of electron without and with the spin flip, and for $\theta = 0,\ \pi$ we find $T_{\uparrow\downarrow}, T_{\downarrow\uparrow} = 0,$ which implies that electron tunneling occurs without spin flip. On the other hand at any nonzero values of θ amplitudes $T_{\uparrow\uparrow}, T_{\downarrow\downarrow}$ not vanish.

Maximum *D* is achieved for collinear magnetization barriers $(\theta = 0)$: $D_{\max} = D_\uparrow + D_\downarrow$ and the minimum value $D_{\min} = 2\sqrt{D_\uparrow D_\downarrow}$ for anticollinear magnetization. We find that $D_{\min}$ is small even at resonance. At the non-resonant tunneling the dependence on θ is also rather weak (Fig. 2):

$$D \approx \left(D_\uparrow + D_\downarrow\right) - 2D_0\left(\frac{\gamma M}{V_0}\right)^2 \sin^2\frac{\theta}{2} \tag{12}$$

where D_0 is the transmission coefficient in the absence of magnetization $(M = 0)$.

In the case of resonant tunneling (i.e., $D_\uparrow = 1/2$ reaches maximum and) $D_\downarrow$ becomes exponentially small) dependence on θ becomes significant (Fig.2)

$$D_{rez} = \sqrt{2D_\downarrow} + \frac{1}{2}\cos^2\frac{\theta}{2}. \tag{13}$$

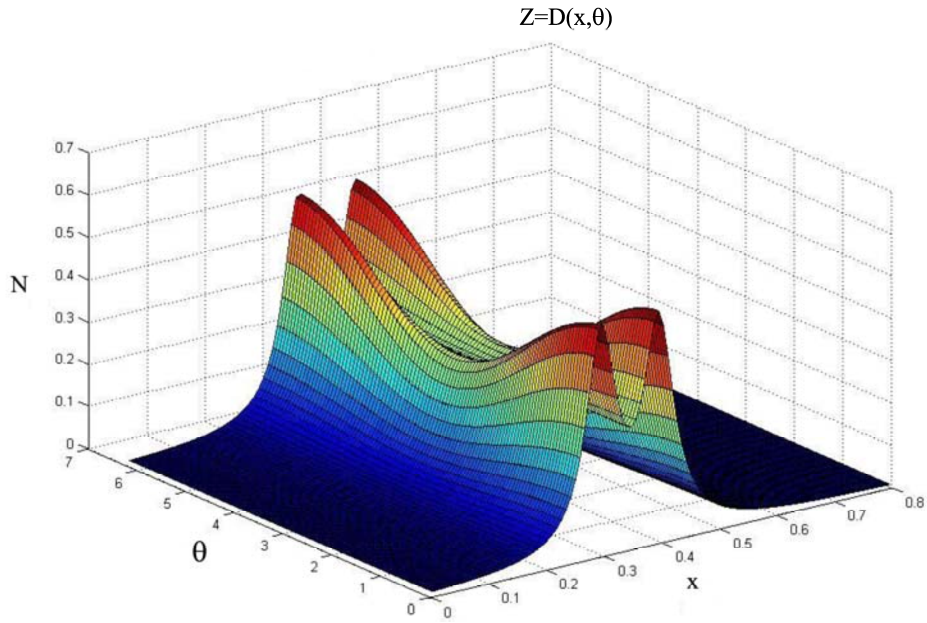

Fig. 2. Dependence of the transmission coefficient on the dimensionless electron energy *x* and orientation angle θ.

The maximum of the transmission coefficient D_{rez} as a function of the energy parameter $x = E/V_0$, is due to the presence of two groups of resonance transmission – for the spin up and spin down Note that the dependence on the angle θ in the transmission coefficient and conductance is the same. Thus, Fig. 2 describes the transmission coefficient *D* (spin-dependent conductance) for electron tunneling through double barrier system as a function of an angle θ for magnetization between two magnetic barriers and energy parameter *x* of transmitted electrons. It is evident that the spin-dependent tunneling in the absence of magnetic field exhibits (double peak) symmetric structure as a function of E/V_0 and an angle *q*. The spin transport is significantly suppressed for anticollinear orientation of magnetizations in barriers.

4. Knowing the amplitude transmission one can calculate the vector of spin polarization of electrons, tunneled through the double-barrier system:

$$\mathbf{P}\overline{\langle \hat{\psi}_5^+ \hat{\psi}_5 \rangle} = \overline{\langle \hat{\psi}_5^+ \hat{\boldsymbol{\sigma}} \hat{\psi}_5 \rangle} \tag{14}$$

where **P** is the polarization, brackets correspond to the quantum mechanical averaging, and the horizontal line – over an ensemble of incident electrons (in phase ω, see Eq. (2)), and the degree of polarization $P(\theta) = \sqrt{P_x^2 + P_y^2 + P_z^2}$ [9].

We will not give the exact expressions for $P_i\left(i = x, y, z\right)$ obtained from (14), but give only the results of their research. The simplest form of P_i one can get in the case of parallel magnetization $\left(\theta = 0\right)$:

$$P_x = P_y = 0,\ P_z = \frac{D_\uparrow - D_\downarrow}{D_\uparrow + D_\downarrow}. \qquad (15)$$

Thus, the spin polarization efficiency P_z determines the difference of transparency for the spin states with up and down through the barrier. Far from the resonance transmission we have $P_z \approx \gamma M / V_0 << 1$ and unity with an accuracy up to exponentially small terms in the resonance transmission.

In the case of noncollinear magnetizations barriers in the non-resonant tunneling

$$P_x \sim \left(\gamma M / V_0\right)^2,\ \ P_{y,z} \sim \gamma M / V_0. \qquad (16)$$

At the resonant quantum tunneling the dependence of the degree of polarization on θ is quite weak, and near $\theta = \pi$ there is a failure to zero. This dependence is determined by the formula

$$P\left(\theta\right) \approx \left(\cos^2 \theta/2\right) / 2D_{rez}, \qquad (17)$$

where D_{rez} is defined by (13).

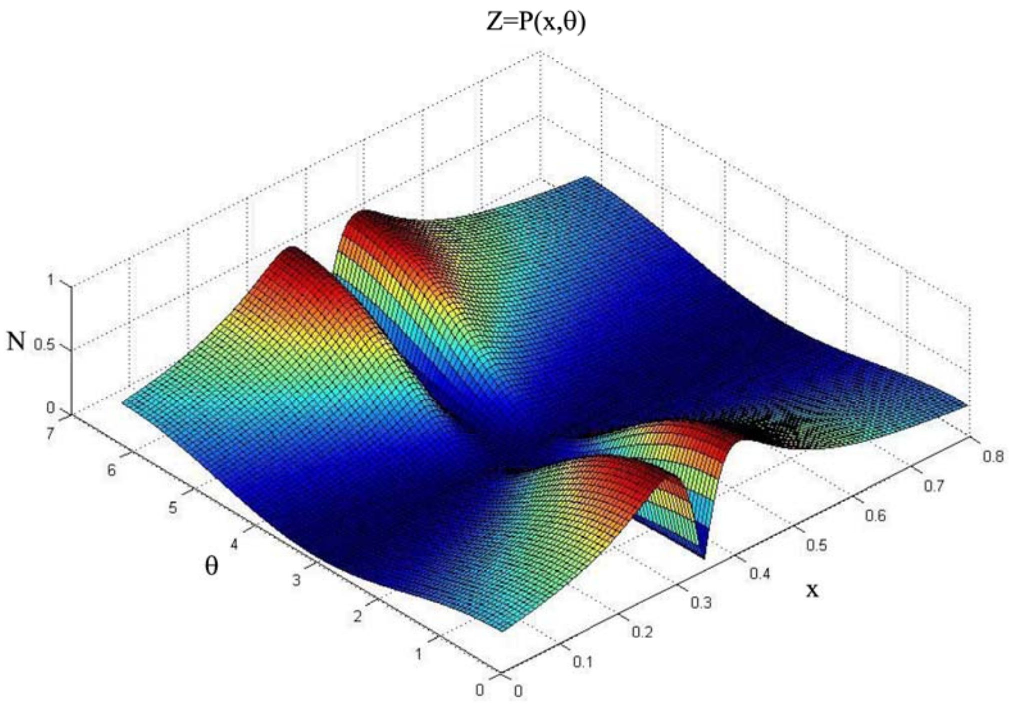

Fig. 3. Dependence of the degree of polarization of transmitted electron on the orientation θ and electron nergy parameter *x*.

The existence of two peaks under the variation of *x* as well as in the behavior $D = D\left(\theta, x\right)$ (Fig. 2) is due to the presence of two groups of resonance energies. Because of the smallness of the parameter $\gamma M/V_0$ the energies are located close enough to each other. On the other hand, the energies far from the resonant values there is a substantial drop in the degree of polarization.

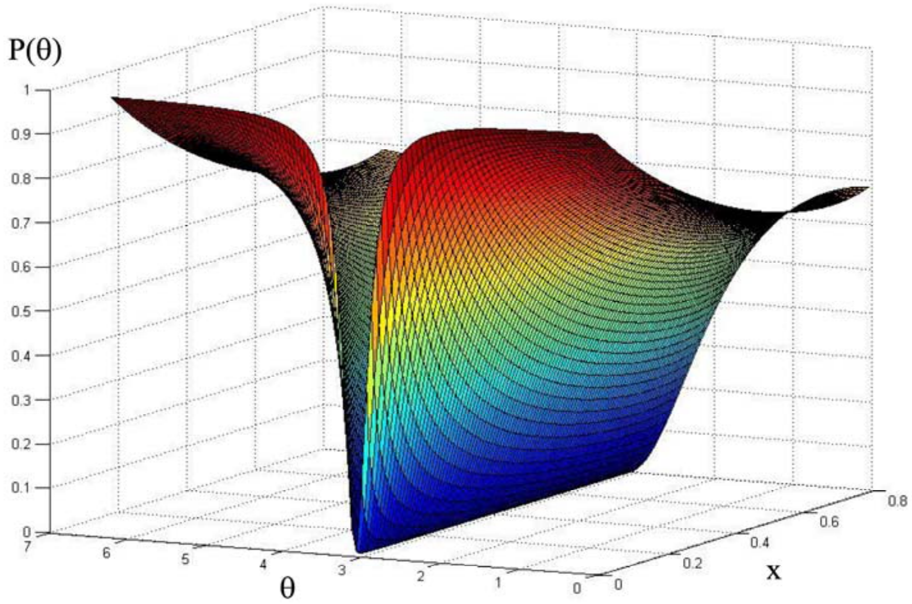

Fig. 4. Nearby the transmittance resonance at θ = π there is a peep dip in behavior P = P(θ).

Qualitatively, this behavior can be explained as follows: consider a unit (beam) stream of non-polarized electrons falls on the left barrier: $1 = I_\uparrow + I_\downarrow$, $I_\uparrow = I_\downarrow$ where $I_{\uparrow,\downarrow}$ are the fluxes of polarization along and against of the left barrier magnetization. In resonant tunneling, in the case when the barriers are having collinear magnetization, the flux through the system is $1/2$ up to exponentially small term. When rotating the magnetization of the right barrier at an angle θ, it makes the flux $(1/2)\cos^2(\theta/2)$. If $\theta = \pi$, the flux of electrons, tunneled through the right barrier with mutually opposite orientations of the polarization, decays exponentially, and hence the polarization of the transmitted flux is negligibly small. Fig. 3 presents the strong spin-dependent polarization for electron tunneling through the double magnetic barriers in the absence of the external magnetic field. The polarization is strongly dependent on the electron energy E. For some intermediate energy, the electrons exhibit a strong double peak behavior in spin polarization and transmittance, while for large and small electron energies, the spin polarization is weakened. The spin polarization also is strongly weakened for anticollinear orientation of magnetization in barriers. As it is evident from Figs. 2 and 3, there is a strong correlation in behavior of spin polarization and electron tunneling transport for general θ and x. Let us note that such dependence of polarization degree on the angle θ shows that there exist spin-valve effect in the subject system [10]. This effect manifests itself most clearly nearby the transmittance resonance (Fig. 4)

5. Our results imply strongly that the system consisting of two magnetized barriers can effectively work as a spin polarizer, only at the resonance transmission. At the same time and the transmission coefficient and the degree of polarization of the transmitted electron beam is strongly dependent on the angle of noncollinearity θ. Our calculations show a considerable influence of the angle of noncollinearity on spin-dependent polarization and the tunneling transmission characteristics. The double magnetic barrier structure can provide conditions for strong dependence of the tunneling transmission and spin-dependent polarization in the absence of magnetic field and this effect can be employed in the fabrication of spin filters on the base of heterostructures. These results can be also useful for understanding the spin-dependent transmission characteristics under the variation of the noncollinearity in the nanostructures consisting of realistic magnetic barriers produced by the deposition of ferromagnetic stripes on heterostructures or system containing diluted magnetic semiconductor layers [11]. These features also demonstrate that a much larger spin polarization or much better spin-filtering properties for magnetic barriers can be obtained by both using the proper electron energy parameter x and also by adjusting the angle θ between magnetization of ferromagnetic interfaces, which may be useful for control and fabrication of spin devices based on such magnetic barriers. This approach can be extended to calculate and understand the electron transport properties and polarization also in two dimensional structures or system with the number of periodic magnetic barriers or asymmetrical (magnetic) double barrier structures.

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