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Spin-polarized current in asymmetric double-barrier magnetic tunnel junction

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Abstract. The spin-polarized current through a planar asymmetric double-barrier magnetic tunnel junction has been calculated using the quasi-classical model. In this nanostructure the magnetization of the middle ferromagnetic metal layer can be aligned parallel or antiparallel with respect to the fixed magnetizations of the top and bottom ferromagnetic electrodes. The transmission coefficients of an electron to pass through the barriers have been calculated in terms of the quantum theory. The dependences of spin-polarized currents on the applied voltage have been calculated under resonant conditions. In the framework of the developed physical model the resonant tunneling, enhanced spin filtering and spin-current diode effects can be explained.

Introduction

Spin-polarized current and tunnel magnetoresistance - two bright effects in layered nanostructures where various ferromagnetic layers are separated by insulators. If thickness of a layered nanostructure is comparable with the mean free path of conduction electrons, the conditions of the ballistic transport are satisfied, and mutual quantum-mechanical penetration of magnetism of the adjacent layers becomes important. As a result, mesoscopic ferromagnet-insulator heterostructures acquire unusual properties which can find useful practical applications [1]. One of the ways to get functionality in heterostructures is to manage transport properties by means of non-uniform magnetism or spin-polarized current. Our study is directed on building the consistent theory of spin-polarized transport and magnetoresistance in thin-film tunnel heterostructures switched by a current at presence or absence of an external magnetic field.

1. Model of asymmetrical double-barrier magnetic tunnel junction

In this work an asymmetrical double-barrier structure is investigated theoretically. As shown in Fig. 1, the double-barrier structure consists of three planar ferromagnetic layers of thicknesses t, m and b respectively, separated by two nonmagnetic insulators of thicknesses t_1 and t_2 of several angstroms. This gives three-dimensional model of the double-barrier magnetic tunnel junction $\mathrm{FM}^t/\mathrm{I}_1/\mathrm{FM}^m/\mathrm{I}_2$ $/\mathrm{FM}^b$. Typical examples for the constituents of the junction are Co, CoCr, CoFeB, Fe, and NiFe for ferromagnets, and Al_2O_3 and MgO for insulating nonmagnetic battiers. Note, that FM^m layer has lower coercivity as compared to the FM^t and FM^b layers.

If the voltage is applied to the nanostructure $\mathrm{FM}^t/\mathrm{I}_1$ $/\mathrm{FM}^m/\mathrm{I}_2/\mathrm{FM}^b$ the spin-polarized current is generated. This current is induced by the quantum tunneling through the barriers. It is very small and decays exponentially with increasing the thickness of the insulators. The FM^m layer can be considered as a quantum well. Then, the motion of electrons in the FM^m layer is quantized. For some parameters of the structure $\mathrm{FM}^t/\mathrm{I}_1/\mathrm{FM}^m/\mathrm{I}_2/\mathrm{FM}^b$, resonant conditions arise. The spin-polarized tunneling current will rapidly increase at specific values of the applied voltage. Since the magnetization direction of the FM^m layer can be easily changed (for example, in the case of a soft magnetic alloy), it takes either parallel (P) or antiparallel (AP) alignment with respect to the magnetization direction of the FM^t and FM^b electrodes. Now, if the system is transformed by an external magnetic field from the state with the P alignment of magnetizations of the layers FM^t, FM^b, and FM^m, into the state with the AP alignment of magnetizations, the electrical conductivity of the junction at a fixed dc bias is changed. For example, in an external magnetic field relative change of a current can reach 1000% (that is the current will change in 11 times) even at room temperatures [2].

2. Spin-polarized tunnel current

Original feature of the solved problem is the self-consistent treatment of dc bias on each barrier, depending on their thickness and width of a forbidden band of an insulator. The spin-polarized current through the double-barrier magnetic tunnel junction is calculated on the basis of the quasi-classical theory [3]. The coefficients of transmission of electron through the barriers are calculated in terms of the quantum theory. For solution of the problem with several layers a method of transfer-matrix was used, which essentially simplifies procedure of solution of combined equations, following from matching of the wave functions on each interfaces. The basic mathematical expressions and the cal-

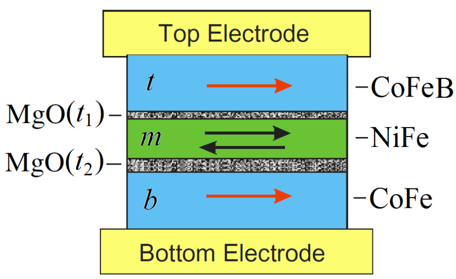

Fig. 1. Schematic drawing of the cross section of asymmetrical double-barrier magnetic tunnel junction. The top (t) and bottom (b) ferromagnetic layers are electrodes of the junction. Designations: m is the thickness of the middle ferromagnetic layer; t_1 is the thickness of the first barrier; t_2 is the thickness of the second barrier. Arrows indicate the magnetization of the electrodes and the middle ferromagnetic layer in the parallel and antiparallel alignments.

culation details can be found in article [2]. In this work the density of spin-polarized tunnel currents through the asymmetrical double-barrier magnetic tunnel junction was calculated by the formula

$$j_s^{\mathrm{P(AP)}} = \frac{e^2 \left(k_{F,s}^{t(b)}\right)^2 V_a}{4\pi^2\hbar} \times \left\langle \cos\theta_{t(b),s} D_{t(b),s}^{\mathrm{P(AP)}} \left(V_a, \cos\theta_{t(b),s}\right) \right\rangle ,$$

where $D_{t(b),s}^{\mathrm{P(AP)}}$ is the transmission coefficient of an electron through the asymmetrical double-barrier structure. The index t or b is selected by depending on polarity of the applied voltage V_a. The angular brackets denote averaging over the angles φ and $\theta_{t(b),s}$. The angle φ lies in the contact plane. The polar angle $\theta_{t(b),s}$ is defined by a trajectory of the motion of an electron in the top or bottom electrodes on the direction to the barrier. It is measured from the normal to the contact plane. The absolute value of the Fermi wave vectors $k_{F,s}^{t(b)}$ corresponds to the spin subbands of electrodes $\mathrm{FM}^{t(b)}$. The index $s =\uparrow, \downarrow$ denotes spin states of electrons in $\mathrm{FM}^{t(b)}$ and FM^m. The upward arrow indicates the spin-subband of the majority of electrons, and the downward arrow indicates the spin-subband of the minority of electrons. Furthermore, the index $s =\uparrow, \downarrow$ denotes the spin states of electrons in four spin conduction channels. For the P alignment of the magnetizations of the top and bottom ferromagnetic electrodes $\mathrm{FM}^{t(b)}$ and the middle layer FM^m, the electron moves in the following spin subbands: $s =\uparrow (\downarrow)$, $s' =\uparrow (\downarrow)$, $s =\uparrow (\downarrow)$. These are two spin-conduction channels. For the AP alignment of magnetizations of the ferromagnetic layers the electron moves in the spin subbands $s =\uparrow (\downarrow)$, $s' =\downarrow (\uparrow)$, $s =\uparrow (\downarrow)$. These are another two spin-channels. Note that

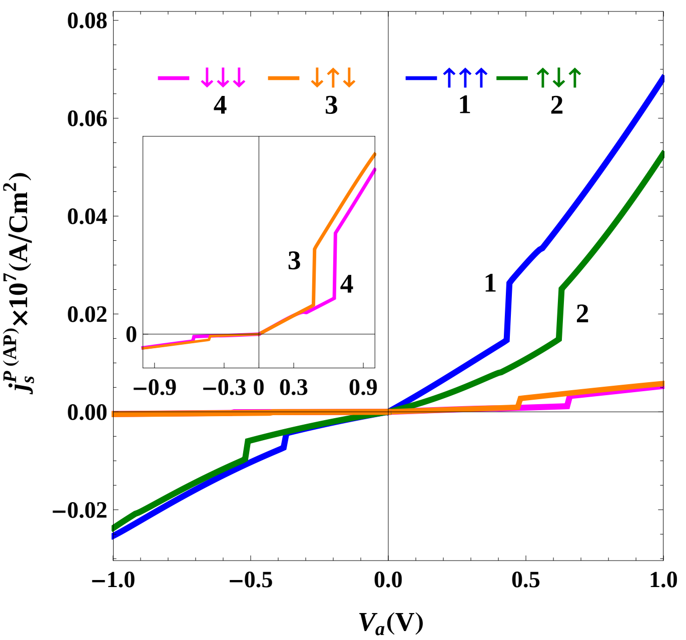

Fig. 2. Dependences of the tunneling spin currents vs applied bias across the asymmetrical double-barrier magnetic tunnel junction for four spin conduction channel (denoted by numerals and arrows).

during the tunnel and resonance the direction of the conduction electron spin is conserved.

In Fig. 2 dependences of the tunnel spin-polarized currents on the applied voltage V_a for the four spin channels of conductivity are shown. The curves were calculated with the following parameters of the structure. The values of the Fermi wave vectors for electrons of the spin subbands of FM layers were taken: $k_{F,\uparrow}^t$=0.8 Å^{-1}, $k_{F,\downarrow}^t$=0.6 Å^{-1}, $k_{F,\uparrow}^b$= 0.85 Å^{-1}, $k_{F,\downarrow}^b$=0.6 Å^{-1}, and $k_{F,\uparrow}^m$=1.03 Å^{-1}, $k_{F,\downarrow}^m$=0.9 Å^{-1}, respectively. The Fermi energy E_F was determined by the values of wave vectors of the medial FM^m layer. The effective masses of conduction electrons in the ferromagnetic layers corresponded to the free electron mass m_e. Two dielectric oxide layers had transverse sizes comparable to the mean free path of conduction electrons. The thicknesses were taken $t_1 = 9.5$ Å^{-1}, $t_2 = 12.0$ Å^{-1}, and heights of the energy potentials above the Fermi energy are $U_1 = 2.4$ eV, $U_2 = 2.0$ eV. The effective masses of electrons in the barriers were assumed to be $0.4m_e$. The thickness of the medial FM^m layer was taken 25.4 Å^{-1}.

3. Discussion

It can be seen from Fig. 2 that the tunnel currents of the spin channels ↑↑↑ and ↑↓↑ (curves 1 and 2) are eight times larger than the tunneling currents of the spin channels ↓↓↓, ↓↑↓ (curves 3 and 4). This illustrates the fact that some regimes of operation of the double-barrier magnetic tunnel junction can be used for the effect of spin filtering of currents. All dependences $j_s^{\mathrm{P(AP)}}(V_a)$ have single step at specific values of the applied voltage and at fixed parameters of the double-barrier magnetic tunnel junction. The current steps take place at such voltages at which energy of electrons in $\mathrm{FM}^{t(b)}$ layers coincides with the energies of quasi-stationary states in the FM^m layer. This fact can be qualitatively explained using the energy spectrum of the FM^m layer. It is a system of local quantum-well levels that can be considered as a system of spin-polarized conduction channels. General character of curves shows that the asymmetrical double-barrier magnetic tunnel junction at the given parameters possesses the diode effect.

In conclusion, we calculated the transmission coefficients and spin-polarized current versus bias voltage taking into account the spin degrees of freedom. It is shown that the spin-polarized conductance crucially depends on the middle layer thickness and the conduction band spin-polarizations in ferromagnetic layers. The theory can be used for explanation of the volt-ampere characteristics with the diode effect, and searching for condition of softening the requirements to magnitude of the current necessary for switching the tunnel magnetic structures between high and low resistive states.

Acknowledgement

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