Journal of Magnetism and Magnetic Materials 421 (2017) 418–421

Contents lists available at ScienceDirect

Journal of Magnetism and Magnetic Materials

journal homepage: www.elsevier.com/locate/jmmm

Thermopower in double planar tunnel junctions with ferromagnetic barriers and nonmagnetic electrodes

M. Wilczyński

Faculty of Physics, Warsaw University of Technology, Koszykowa 75, Warsaw 00-662, Poland

ARTICLE INFO

Article history:
Received 6 May 2016
Received in revised form
25 July 2016
Accepted 11 August 2016
Available online 12 August 2016

Keywords:
Tunnel junctions
Thermopower
Resonant tunneling

ABSTRACT

The Seebeck effect is investigated in double planar tunnel junctions consisting of nonmagnetic electrodes and the central layer separated by ferromagnetic barriers. Calculations are performed in the linear response theory using the free-electron model. The thermopower is analyzed as a function of the thickness of the central layer, temperature of the junctions and the relative orientation of magnetic moments of the barriers. It has been found that the thermopower can be significantly enhanced in the junction with special central layer thickness due to electron tunneling by resonant states. The thickness of the central layer for which the thermopower is enhanced depends not only on the temperature of the junction but also on the orientation of magnetic moments in the barriers.

1. Introduction

Recently the effects related to electron transport generated by the temperature gradient between the leads have attracted wider attention. Especially, in tunnel junctions one can observe the Seebeck effect (thermopower) related to the voltage drop generated by the temperature gradient. This effect has been experimentally [1–6] and theoretically [1,7–13] investigated in single junctions with ferromagnetic electrodes made of e.g. CoFe [1–9,12] or Co_2MnSi [13] and nonmagnetic barriers made of MgO [1–5] or Al_2O_3 [6,11]. It has been observed that the Seebeck effect in tunnel junctions can be quite large and usually increases with the increase of the thickness of the barrier and the average temperature of the junction. When the electrodes are ferromagnetic it additionally depends on the orientation of magnetic moments in the external ferromagnetic electrodes. According to theoretical papers, the Seebeck coefficient in such systems is usually of the order of several μV/K, however some papers indicate that this coefficient can be slightly higher in certain systems. It depends significantly on the structure of electron/barrier interfaces. When there are many oxygen vacancies at the interface [12] or when the average temperature of the junction is higher than room temperature [13] the magnitude of the Seebeck coefficient can reach even 160 μV/K. The experimental investigations confirm the appearance of the Seebeck effect at room temperature in the analyzed junctions of the same order of magnitude as predicted by the theoretical papers. However, some experimental papers may suggest that the Seebeck coefficient can be slightly higher in certain systems and at room temperature it can reach the values as large as 650 μV/K [3], 770 μV/K [5] or even 1 mV/K [6]. However, due to the difficulties in the exact determination of the temperature gradient across the junction the measured Seebeck coefficient has a high degree of uncertainty.

Many effects related to electron transport in tunnel junctions can be enhanced in systems in which single barrier is replaced by two barriers separated by a central layer due to the resonant tunneling through the system by resonant states. In the present paper we analyze the thermoelectric (Seebeck) effect in double planar tunnel junctions consisting of nonmagnetic external electrodes and the nonmagnetic central layer separated by the two magnetic barriers. In the low temperature range the barriers can be made of EuS [14–16] or EuO [17–19] whereas in the higher temperature range of $CoFe_2O_4$ [20,21], $MnFe_2O_4$ [22] or $NiFe_2O_4$ [23] which exhibit magnetic properties at temperatures much higher than the room temperature. Due to the magnetic character of the barriers it is possible to change the direction of magnetic moments in the barrier and consequently the height of the barriers for electrons of specified spin using the external magnetic field. In junctions with ferromagnetic barriers the polarization of electrons tunneling through the barrier can be very high (e.g. [14,17,20,23]), so they can be used as the effective spin filters. In double junctions the change of the height of the barriers leads to the change of resonant state positions which consequently depend on the relative orientation of magnetic moments in the barriers. This can lead to a significant tunnel magnetoresistance (TMR) in junctions with a special central electrode thickness [24]. This can

E-mail address: wilczyns@if.pw.edu.pl

http://dx.doi.org/10.1016/j.jmmm.2016.08.044
0304-8853/

also lead to dependence of the thermopower (Seebeck coefficient) on the magnetic configuration of the junction.

2. Model

The Seebeck coefficient has been calculated for double tunnel junctions consisting of nonmagnetic electrodes, a nonmagnetic central layer and two ferromagnetic barriers with different relative orientations of magnetic moments in the barriers.

It is assumed that the temperature difference between electrodes is so small that in the calculation of thermopower the linear response theory can be applied. It is also assumed that the electron spin σ, electron energy E and the component of the electron wave vector parallel to the electrode/barrier interface $k_{\parallel}$ are conserved during tunneling. As a result, the energy $\varepsilon_{\perp}$ corresponding to the electron motion in the direction perpendicular to the electrode/barrier interfaces is conserved and the transmission coefficient can be treated as a function of this energy.

Calculations are performed in the free-electron-like one-band model. The electronic structure of both electrodes and the central layer is modeled by parabolic band with the electron mass equal to the mass of the free electron m.

To describe the electron wave function in the specified barrier for electrons with spin σ and energy connected with the motion perpendicular to the interfaces $\varepsilon_{\perp} = E - \frac{\hbar^2 k_{\parallel}^2}{2m}$ the combination of the exponential functions is used

$$\psi_{\sigma} = C_{\sigma}\exp(\kappa x) + D_{\sigma}\exp(-\kappa x) \tag{1}$$

where $\kappa = \frac{\sqrt{2m(U - \Delta_b p_{\sigma} - \varepsilon_{\perp})}}{\hbar}$, U denotes the average barrier height, $2\Delta_b$ denotes the spin splitting of the barrier height, $p_{\sigma} = 1$ for $\sigma = \uparrow$ and $p_{\sigma} = -1$ for $\sigma = \downarrow$.

The z-axis of these local coordinate systems in the specified barrier is set by the direction of the net spin in this barrier. It is assumed that the net spins in both barriers are generally noncollinear and form the angle θ.

To describe the wave function of electrons in the left and right electrodes as well as in the central layer the combination of plane waves is used.

Transmission coefficients are calculated in the usual manner taking into account the continuity conditions of the electron wave function and their spatial derivatives at the electrode/barrier interfaces. Due to the fact that magnetic moments in the barriers form an arbitrary angle θ, in writing the matching conditions at the central layer/right barrier interface the appropriate spinor transformations have to be applied [25].

Having known the transmission coefficient one can calculate the charge current I. In the linear response theory it can be calculated using the expressions

$$I = eL_0\Delta E_F + \frac{e}{T}L_1\Delta T \tag{2}$$

where T denotes temperature, e positive electron charge, ΔT difference between the temperature of both electrons, ΔE_F difference between the position of Fermi levels in both electrodes which can be related to the bias voltage ΔV applied to the junction: $\Delta E_F = e\Delta V$.

In the Eq. (2) the quantity L_n $(n=0,1)$ can be calculated from the formula [10]:

$$L_n = -\frac{2\pi m}{h^3}\sum_{\sigma'}\int d\varepsilon_{\parallel}\int d\varepsilon_{\perp}(E - E_F)^n W_{\sigma'}(\varepsilon_{\perp})\frac{df(E)}{dE} \tag{3}$$

In the above formula $f(E)$ denotes the Fermi–Dirac distribution function of the electrons in electrodes obtained for the average temperature of the junction and energy $E = \varepsilon_{\perp} + \varepsilon_{\parallel}$; $W_{\sigma'}(\varepsilon_{\perp})$ stands for the transmission coefficient for the tunneling electron of energy $\varepsilon_{\perp}$ and spin σ' calculated for the specified orientation of magnetic moments in the barriers, whereas E_F denotes the Fermi energy. The integration is performed over the energy $\varepsilon_{\perp}$ connected with the movement in the direction perpendicular to the interfaces and over the energy $\varepsilon_{\parallel} = \frac{\hbar^2 k_{\parallel}^2}{2m}$, summation is done over two possible orientations of the electron spin in the left electrode.

The thermopower described by the Seebeck coefficient S was generally related to the voltage drop ΔV induced by the temperature difference ΔT under the condition that the charge current vanishes. This leads to the well-known formula for S

$$S = \lim_{\Delta T \to 0}\frac{\Delta V}{\Delta T} = -\frac{1}{eT}\frac{L_1}{L_0} \tag{4}$$

Using this formula one assumes that the Fermi levels in both electrodes are the same for both spin directions.

3. Results and conclusions

The schematic potential profile for electrons of both spin directions in the double tunnel junction with the parallel configuration of magnetic moments in the barriers is presented in Fig. 1. The numerical calculations of the Seebeck coefficient are performed mainly for the following parameters: the Fermi energy $E_F = 0.1$ eV, the average height of the ferromagnetic barriers U=1.1 eV and their spin splitting $2\Delta_b = 0.36$ eV, the thickness of the barrier d_b=0.6 nm. These parameters can roughly correspond to the EuS/PbS systems [15,16] and have been used in the previous publications concerning the investigations of tunnel magnetoresistance [24] and spin-transfer torque [26] in such junctions.

In Fig. 2(a) the Seebeck coefficient is presented for three different temperatures as a function of the central layer thickness when magnetic moments of both barriers are parallel. The results of similar calculations performed for the antiparallel orientation of magnetic moments are presented in Fig. 2(b). One can see that the magnitude of thermopower is significantly enhanced for the specified central layer thickness due to electron tunneling by resonant states. The maximal thermopower can be much higher than the thermopower obtained in single planar junctions consisting of typical ferromagnetic CoFe electrodes and nonmagnetic barrier especially in the low temperature limit. Results of the calculations performed within the free-electron model for single tunnel

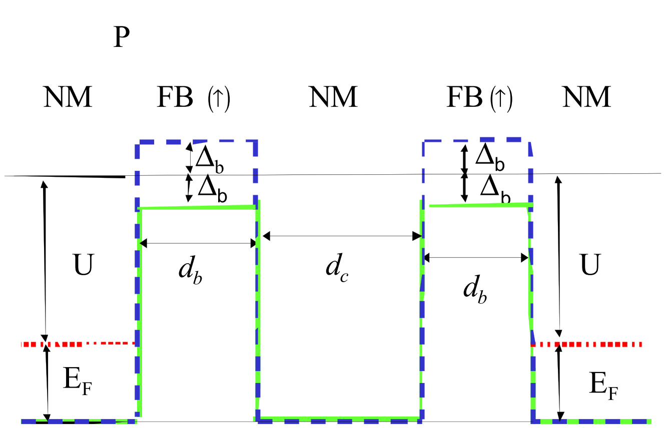

Fig. 1. The schematic potential profile for spin-up (green solid line) and spin-down (blue dashed line) electrons for the parallel configuration of the magnetic moments in the barriers. The red dotted line denotes the position of the Fermi energy in the electrodes in the limit of vanishing voltage drop across the junction. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)