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The tunneling magnetic resistance in ferromagnetic junctions with spin-filter composite tunnel barriers

ZhengWei Xie [a,*], Houxiang Lv [a], Ling Li [a], Ming Xu [b]

[a] College of Physics and Electronic Engineering, Sichuan Normal University, Chengdu 610066, Sichuan, China
[b] College of Electrical Information Engineering Key Lab of Information Materials of Sichuan Province, Southwest University for Nationalities, Chengdu 610041, China

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ABSTRACT

Within the framework of the free-electron model, the tunneling magnetoresistance (TMR) in FM/I/SF/NM quasi-magnetic tunnel junctions (QMTJ) is investigated. FM, NM, I and SF represent the ferromagnetic metal, nonmagnetic metal, insulator and spin-filter barrier, respectively. Our results show that due to the spin-filtering effect in SF potential barriers, the FM/I/SF/NM can obtain relatively stabilized TMR in higher bias region when it has higher potential height and thicker SF barrier. And, for obtaining large TMR, the total thickness of the barrier region would be carefully selected as the influence of the supplementary I layer.

1. Introduction

The conventional magnetic tunnel junctions (MTJs) are trilayers composed of two layers ferromagnetic metal electrode (FM) separated by a thin insulating layer (I) acting as a tunnel barrier (FM/I/FM). The electrical resistance of these simple planar ferromagnetic junctions depends on their magnetic configuration which leads to the so-called tunnel magnetoresistance (TMR) effect [1–4]. Due to the potential applications in magnetoresistance random access memories and high-performance read heads of hard disk drives, the studies of MTJs have attracted much attention. But for the conventional FM/I/FM MTJs, the TMR consistently decreases with increasing applied voltage. Consequently, the operation of a practical MTJ device is limited to low bias for optimum TMR effect [1,4].

In order to overcome this limitation, recently, the use of spin filter (SF) tunnel barrier instead of ordinary insulating barrier in MTJs has been suggested [5–8,10,11,9,12,13,14–16]. Due to the exchange–split in the spin filter tunnel barriers, the electrons with minority spin face a higher barrier and are effectively filtered out as the spin of the electron is directly connected with its tunneling probability through the barrier. Due to the high efficiency of spin filter tunnel barriers, extremely large spin injection and tunnel magnetoresistance (TMR) are expected in MTJs with spin-filter tunnel barriers [17–19,9,14,15]. In addition to the large spin-polarization and TMR in the MTJs with spin-filter tunnel barriers, another characteristic of MTJs with spin-filter tunnel barriers is that the bias dependence of TMR is quite different from that of conventional FM/I/FM MTJ. For the spin filter tunnel junctions, when the applied bias voltage is comparable to the height of the energy barrier, the TMR begins to increase dramatically, and then decreases at high bias [6,12,9,14]. The reason for the TMR increasing with increasing bias voltage can be ascribed to the signature of Fowler–Nordheim tunneling [20,9,14]. Comparing with the monotonic decrease of TMR with bias in conventional MTJs, this non-monotonic bias dependence has great potential from the application's point of view, since the spin devices would work well at higher applied voltages.

The corresponding spin-filter materials are the europium chalcogenides (e.g. EuO, EuS and EuSe) and the ferrites (e.g. $CoFe_2O_4$, $NiFe_2O_4$ and Fe_3O_4) [17–19,21–24]. The europium chalcogenides can produce very large spin polarization in the tunneling currents and the ferrites are promising candidates for room temperature operations [24,25,17–19].

At present, the MTJs with spin-filter tunnel barriers can be divided into two types, one has a single spin filter barrier and the other one has double spin filter barriers [6–8,10–12,9,13–16]. Comparing with the double spin filter junctions which have no ferromagnetic electrode, a single spin filter tunnel barrier junctions still require a normal ferromagnetic electrode, but the corresponding fabricate requirements are not complicated than the former. The MTJ with single spin filter junctions can be simplified as the FM/SF/NM or FM/SF/FM structures and the works of

* Corresponding author.
E-mail address: zzwxie@aliyun.com (Z. Xie).

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Saffarzadeh, Jin et al. and Bzli et al. indicated that, due to the spin-filter effect, large and non-monotonous bias dependence can be obtained in MTJ with single spin-filter barriers [6,10,11].

Recently, the quasi-spin filter tunnel junctions, i.e. MTJs with hybrid single spin filter tunnel barriers, have been suggested by Refs. [9,16]. These junctions can be simplified as FM/I/SF/NM structure with hybrid nonmagnetic/magnetic tunnel barriers. Comparing with the FM/SF/NM structure suggested by Ref. [6], in quasi-spin filter tunnel junctions, the ferromagnetic electrode and spin-filter barrier are separated by a nonmagnetic barrier. The interlayer nonmagnetic barrier can eliminate the direct exchange coupling between the FM and SF layers. The experiments with respect to quasi-spin filter tunnel junctions were reported recently [9,16], but the relevant theoretical researches are few. Based on the quasi-spin filter tunnel junctions suggested by Refs. [9,16], in this paper, the TMR and its bias dependences at the various barrier thicknesses, barrier heights and molecular fields are investigated further. Our calculation results should be of concern for people who work on the research, manufacture and application of spin filter magnetoresistance devices. Our calculations are based on the Slonczewski free electron model, which can be regarded as an improvement of Julliere's tunneling probability method [26,27].

2. Method

The quasi-spin filter tunnel junctions suggested by Refs. [9,16] can be simplified as FM/I/SF/NM structure and are shown schematically in Fig. 1. From the point of view of mean field approximation, the local magnetic moments in the SF provide tunneling electrons with an effective magnetic field (molecular field) and this field makes the barrier height split via the Zeeman effect. Therefore, the barrier height experienced by a tunneling electron depends on its spin orientation. The spin-up electron will experience a lower barrier, while the spin-down electron will experience a higher one.

In a free-electron approximation of the spin-polarized conduction electrons, the longitudinal part of the effective one-electron Hamiltonian with exchange splitting energy in the ferromagnetic electrode and the barrier regions is given by

$$\hat{H} = -\frac{\hbar^2}{2m^*}\nabla^2 + U(x). \tag{1}$$

$$U(x) = \begin{cases} -h_{FM}\sigma_z, & x < 0, \\ U_I - \dfrac{evx}{d_I + d_{SF}}, & 0 < x < d_1, \\ U_{SF} - \dfrac{evx}{d_I + d_{SF}} - h_{SF}\sigma_z, & d_1 < x < d_2, \\ 0, & x > d_2, \end{cases} \tag{2}$$

where m^* is the electron effective mass, $\sigma_z (= \pm 1,$ corresponding to the $\uparrow, \downarrow$ spin electrons respectively) denotes the Pauli spin matrices, h_{FM} and h_{SF} are the exchange

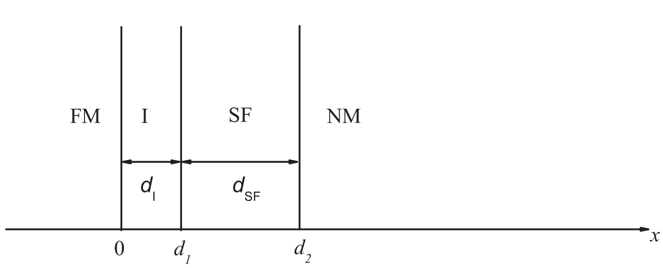

Fig. 1. A schematic diagram of FM/I/SF/NM quasi-spin filter tunnel junction.

splitting energy in the ferromagnetic electrode and the spin-filter barrier. U_I and U_{SF} are the potential in the I and spin-filter barrier regions, respectively.

To investigate the dependence of the TMR on the bias in the quasi-spin filter tunnel junctions, we utilize and generalize the multi-step rectangular approximation method for treating electron transportation in nonmagnetic tunnel junctions under an electric field [28]. If the shape of the barrier is trapezoid, the wave function in the barrier can also be expanded by Airy functions. To estimate the values of the transmission coefficient in a tunnel junction, the results obtained by Airy function expansion and multi-step rectangular approximation would not result in a large qualitative difference and the latter seems to be more convenient for the sake of numerical methods. Following the multi-step rectangular approximation method, first the magnetic barrier is divided into a number of adjacent thin rectangular subbarriers, then the continuity conditions at the interfaces between thin subbarriers are used along with the spinor transformation relation for every spin component of wave function and its derivative with respect to x. Thus the transfer matrix that connects incidence and transmission amplitudes can be found, and hence, the transmission coefficient, the tunneling conductance and the tunneling current as well. The formulas used to calculate tunneling current density for $\sigma(=\uparrow,\downarrow)$ electrons are [29]

$$J_\sigma(\theta) = \frac{em}{4\pi^2\hbar^3}\int_{-\lambda h_{FM}}^{E_F}(E_F - E)T_\sigma(\theta)\,dE, \quad eV > E_F, \tag{3}$$

and

$$J_\sigma(\theta) = \frac{em}{4\pi^2\hbar^3}\left[\int_{-\lambda h_{FM}}^{E_F}(E_F - E)T_\sigma(\theta)\,dE + \int_{E_F - eV}^{E_F}(E_F - E)T_\sigma(\theta)\,dE\right], \quad eV < E_F, \tag{4}$$

where $\lambda = \pm$ for $\sigma(=\uparrow,\downarrow)$ electrons respectively, $T_\sigma(\theta)$ denotes the transmission coefficient of $\sigma(=\uparrow,\downarrow)$ electrons when the angle subtended by magnetization in ferromagnetic electrode and spin-filter barrier is θ, and E_F the Fermi energy of nonmagnetic electrode.

From the total current density

$$J(\theta) = J_\uparrow(\theta) + J_\downarrow(\theta), \tag{5}$$

the average conductance and the TMR,

$$G(\theta) = \frac{J(\theta)}{V}, \tag{6}$$

and

$$\mathrm{TMR}(\theta) = \frac{G(0) - G(\theta)}{G(0)}. \tag{7}$$

respectively, can finally be obtained [26].

3. Results and discussion

In the following, according to Eqs. (3)–(6) the bias dependences of TMR in FM/I/SF/NM hybrid tunnel barrier junction on the thicknesses of the barrier, the barrier height and the molecular field in SF layer are calculated and the characteristics of this magnetic tunneling junction are investigated. In the calculation, the electron Fermi energy E_F in ferromagnetic electrodes is taken as 2.62 eV [26], the h_{FM} is taken as 1.9 eV, the effective mass of a tunneling electron as the mass of a free electron. For the sake of simplicity, the calculations are made only for $\theta = \pi$ and we abbreviate the TMR(π) as TMR.

First, for the different thicknesses of the I layer, the variations of TMR with the total thickness of hybrid tunnel barrier are