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The effect of the ferromagnetic metal layer on tunnelling conductance and magnetoresistance in double magnetic planar junctions*

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Based on the free-electron approximation, we investigate the effect of the ferromagnetic metal layer on the tunnelling magnetoresistance (TMR) and tunnelling conductance (TC) in the double magnetic tunnel junctions (DMTJs) of the structure NM/FM/I(S)/NM/I(S)/FM/NM, where FM, NM and I(S) represent the ferromagnetic metal, nonmagnetic metal and insulator (semiconductor), respectively. The FM, I(S) and inner NM layers are of finite thickness, while the thickness of the outer NM layer is infinite. The calculated results show that, due to the spin-dependent interfacial potential barriers caused by electronic band mismatch between the various magnetic and nonmagnetic layers, the dependences of the TMR and TC on the thicknesses of the FM layers exhibit oscillations, and a much higher TMR can be obtained for suitable thicknesses of FM layers.

Keywords: magnetic tunnelling junction, double-barrier magnetic junction, tunnelling magnetoresistance, tunnelling conductance

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1. Introduction

Spin-polarized tunnelling (SPT) and tunnelling magnetoresistance (TMR) in the magnetic tunnel junction (MTJ) have received considerable theoretical and experimental attention in recent years.[1−5] At first, TMR was studied just in the single magnetic tunnelling junction (SMTJ). The SMTJ is of the structure FM/I(S)/FM, where FM and I(S) represent the ferromagnetic metal and the insulator (semiconductor). In order to meet the requirements in research and application of magnetoresistance devices, a variety of complex structures have been developed from the SMTJ.[6−13] Among these, the double-barrier magnetic tunnelling junctions (DMTJs) structured as FM/I(S)/NM(FM)/I(S)/FM (here NM denotes nonmagnetic metal) have received special attention because they can combine the resonant tunnelling effect with the spin-polarized tunnelling effect, and with the Coulomb-blockade effect when the middle NM or FM layer is replaced by a small metallic grain with a similar material.[6,10−13] In this paper, we focus our attention on the structure FM/I(S)/NM/I(S)/FM in which the junction area is large enough to neglect the Coulomb-blockade effect. Such DMTJs have been studied by Zheng *et al*[11] and Wilczynski *et al.*[12] Based on Slonzwski's free-electron model,[14] Zheng *et al*[11] investigated the TMR and tunnelling conductance (TC) of the DMTJ at zero bias, taking a δ-type barrier to describe the I(S). Wilczynski *et al*[12] discussed the same problems at nonzero bias, taking the I(S) barrier as a trapezoid and adopting the Airy function technique for solving the Schrödinger equation. They all found that the TMR and TC oscillate periodically with the variation of thickness of the middle NM layer and, at some thickness, the TMR in the DMTJ could reach a value much higher than that in the SMTJ. It is expected that this oscillating behaviour and the strongly enhanced TMR effect will have potential applications in magnetoresistance devices. In the above-mentioned theoretical works, the thicknesses of the two FM layers were taken as infinite. However, in experiments and applications the thickness of each FM, NM or I(S) layer is always finite. What will happen when the finiteness of the

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FM layer thickness is taken into account? It could be expected that if the thicknesses of the FM layers are less than the electron mean free path, they should influence the TC and TMR significantly.[9,15–17] In this paper, choosing the NM/FM/I(S)/NM/I(S)/FM/NM structure as an example in which the two outer NM cap layers with infinite thickness represent the nonmagnetic metal electrodes, we investigate the effects of the thickness of FM layers on the TMR and TC in the DMTJ. For simplicity, we only consider the coherent tunnelling which can let us extend Slonzwski's free-electron model easily just as in Ref.[12].

This paper is organized as follows. In section 2, we describe briefly the theoretical model. In section 3, numerical results are presented. The summary and conclusions are in section 4.

2. Model

We consider a NM/FM/I(S)/NM/I(S)/FM/NM structure which can be divided into seven regions, as shown in Fig.1, where x represents the coordinate perpendicular to the plane of the junction. d_2, d_6 (d_3, d_5) denote the thicknesses of the FM layers (insulator barriers), and $d_{\rm NM}$ is the thickness of the middle NM layer. The thicknesses of the outer two NM cap layers (i.e. the first and the seventh regions) can be regarded as infinite. The two ferromagnetic layers (i.e. the second and the sixth regions) are supposed to have different coercitivities so that the relative orientations of magnetizations can be controlled by applying an external magnetic field. In the spin-polarized free-electron approximation, the longitudinal part of the effective one-electron Hamiltonian of this structure is given by

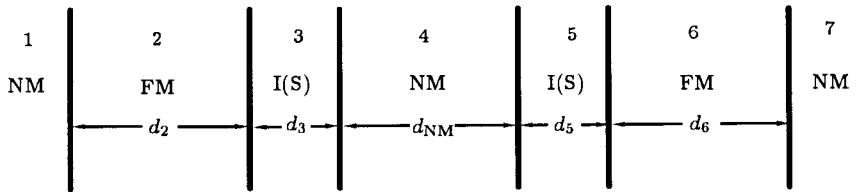


Fig.1. The schematic profile for the DMTJ with two NM cap layers.

$$H = -\frac{\hbar^2}{2m}\frac{\mathrm{d}^2}{\mathrm{d}x^2} + U(x) - \boldsymbol{h}(x)\cdot\boldsymbol{\sigma}, \qquad (1)$$

where $\hbar$ is the Planck constant, $\boldsymbol{\sigma}$ is the conventional Pauli spin operator, $\boldsymbol{h}(x)$ is the molecular field, m is the effective electron mass, and $U(x)$ represents the barrier potential. At zero bias, we assume that the barrier potential is of a rectangular shape and the barrier potential height is denoted by U_0. Thus, $U(x)$ is U_0 in the barrier region (i.e. $U_3 = U_5 = U_0$) and zero otherwise. For the molecular field, we assume that $|\boldsymbol{h}(x)| = h_0$ in each ferromagnetic metal layer and $|\boldsymbol{h}(x)|$=0 otherwise. Although the transverse momentum is omitted in Eq.(1), the summation over it will be carried out in the following calculation.

Based on Eq.(1), we can write out the electron wavefunctions in the seven regions from left to right as follows

$$\psi_{j\sigma} = A_{j\sigma}\mathrm{e}^{\mathrm{i}k_{j\sigma}x} + B_{j\sigma}\mathrm{e}^{-\mathrm{i}k_{j\sigma}x} \quad (j = 1,2,3,4,5,6,7), \qquad (2)$$

where $A_{j\sigma}$ and $B_{j\sigma}$ with $\sigma(=\uparrow,\downarrow)$ are the coefficients which can be determined by the boundary conditions. The normal components $k_{j\sigma}$ (j=1,2,3,4,5,6,7) of the spin-dependent electron wave vectors in all seven regions are given by the following formulae

$$k_{1\uparrow} = k_{1\downarrow} = k_{4\uparrow} = k_{4\downarrow} == k_{7\uparrow} = k_{7\downarrow} = \frac{\sqrt{2mE}}{\hbar}, \qquad (3)$$

$$k_{2\uparrow} = k_{6\uparrow} = \frac{\sqrt{2m(E+h_0)}}{\hbar}, \qquad (4)$$

$$k_{2\downarrow} = k_{6\downarrow} = \frac{\sqrt{2m(E-h_0)}}{\hbar}, \qquad (5)$$

$$k_{3\uparrow} = k_{3\downarrow} = k_{5\uparrow} = k_{5\downarrow} = \mathrm{i}\frac{\sqrt{2m(U_0-E)}}{\hbar}, \qquad (6)$$

where E is the longitudinal electronic energy. For simplicity, we assume that the band edge of the nonmagnetic metal coincides with the band edge of the ferromagnetic metal in the paramagnetic limit. Using the continuity conditions at the interfaces, along with the spinor transformation relation for every spin component of the wavefunction and its derivative with respect to x, we can gain the transfer matrix connecting the incidence and transmission amplitudes. Hence the transmission coefficient and TC can be found. When the bias V is very small, i.e., $V \approx 0$, the formula of TC for $\sigma(=\uparrow,\downarrow)$ electrons in the DMTJ is[12,18]

$$G_\sigma(\theta) = \frac{e^2 m}{4\pi^2\hbar^3}\int_0^{E_F} T_\sigma(\theta)\mathrm{d}E, \tag{7}$$

where $T_\sigma(\theta)$ denotes the transmission coefficient of the σ electron when the angle subtended by the magnetizations in the two FMs is θ, e is the electron charge and E_F is the Fermi energy in the NM electrodes. The total conductance for the parallel alignment (θ=0) and antiparallel alignment (θ=0) of the magnetizations in the two ferromagnetic layers are, respectively,

$$G_P = G_\uparrow(0) + G_\downarrow(0), \tag{8}$$

$$G_{AP} = G_\uparrow(\pi) + G_\downarrow(\pi)$$

and

$$R_{TM} = \frac{G_P - G_{AP}}{G_{AP}}, \tag{9}$$

can be obtained finally.

3. Numerical results and discussion

In our numerical calculations, the Fermi energy E_F is taken to be 2.62eV, the molecular field h_0 is 1.96eV, the barrier height U_3=U_5=U_0=0.75eV (calculated from the Fermi energy), the thickness d_3 = d_5=0.5nm and the effective mass of the electron m is the free-electron mass. These parameters have been used in Ref.[12]. For convenience of comparison, here we use them again in our calculation.

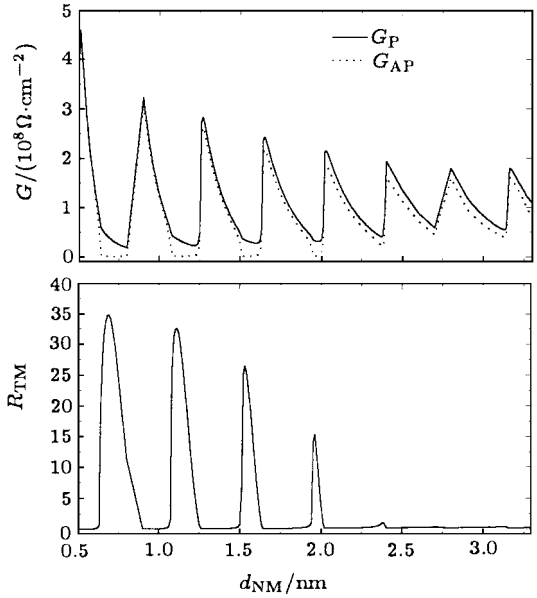


Fig.2. TC and TMR as functions of the thickness of the middle layer NM (d_{NM}) for the FM/I(S)/NM/I(S)/FM structure.

Firstly, we consider a DMTJ without cap layers, i.e. as a FM/I(S)/NM/I(S)/FM structure, and we assume that the FM layers have infinite thicknesses. For this structure, variations of G_P, G_{AP} and R_{TM} with the thickness of the middle layer NM (d_{NM}) at zero bias ($V \approx 0$) are calculated, and the results are shown in Fig.2.

From Fig.2, we can see that variations of G_P, G_{AP} and R_{TM} with d_{NM} are periodic, and the maximum in R_{TM} corresponds roughly to the minimums in G_P and G_{AP}. These results are similar to those obtained in Ref.[12] at V=20mV. Since 20mV can be regarded as a very low bias, the difference between the result at $V \approx 0$ and that at V=20mV should be small. Then we consider the DMTJ with NM cap layers outside the two FM layers, i.e. the structure NM/FM/I(S)/NM/I(S)/FM/NM shown in Fig.1, and we assume that the two FM layers have same finite thickness ($d_2 = d_6$). For this structure, the dependences of G_P, G_{AP} and R_{TM} on d_{NM} are shown in Fig.3.

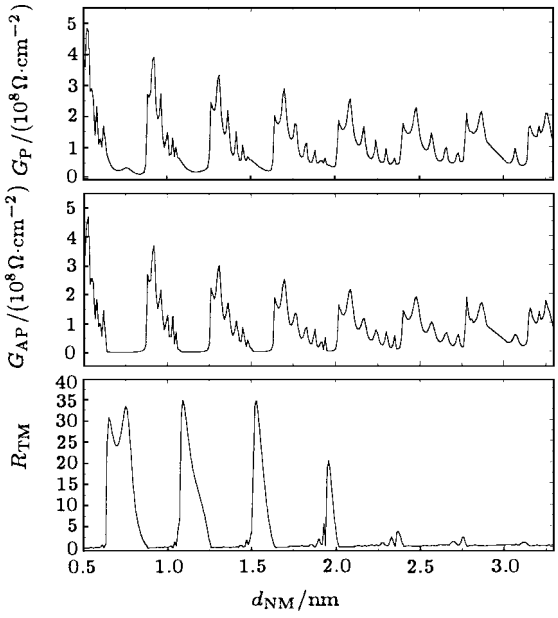


Fig.3. TC and TMR as functions of the thickness of the middle NM layer for the NM/FM/I(S)/NM/I(S)/FM/NM structure when the thickness of each FM layer is 5nm.

From Fig.3, we can see that variations of G_P and G_{AP} are periodic too but, in each period, additional oscillations appear. These additional oscillations also make the dependence of R_{TM} on the thickness a little different from that in the FM/I(S)/NM/I(S)/FM structure. In order to explain the above results, relevant transmission coefficients for both spin orientations and both magnetic configurations for the above two structures, i.e. with and without cap layers, are shown in Fig.4.

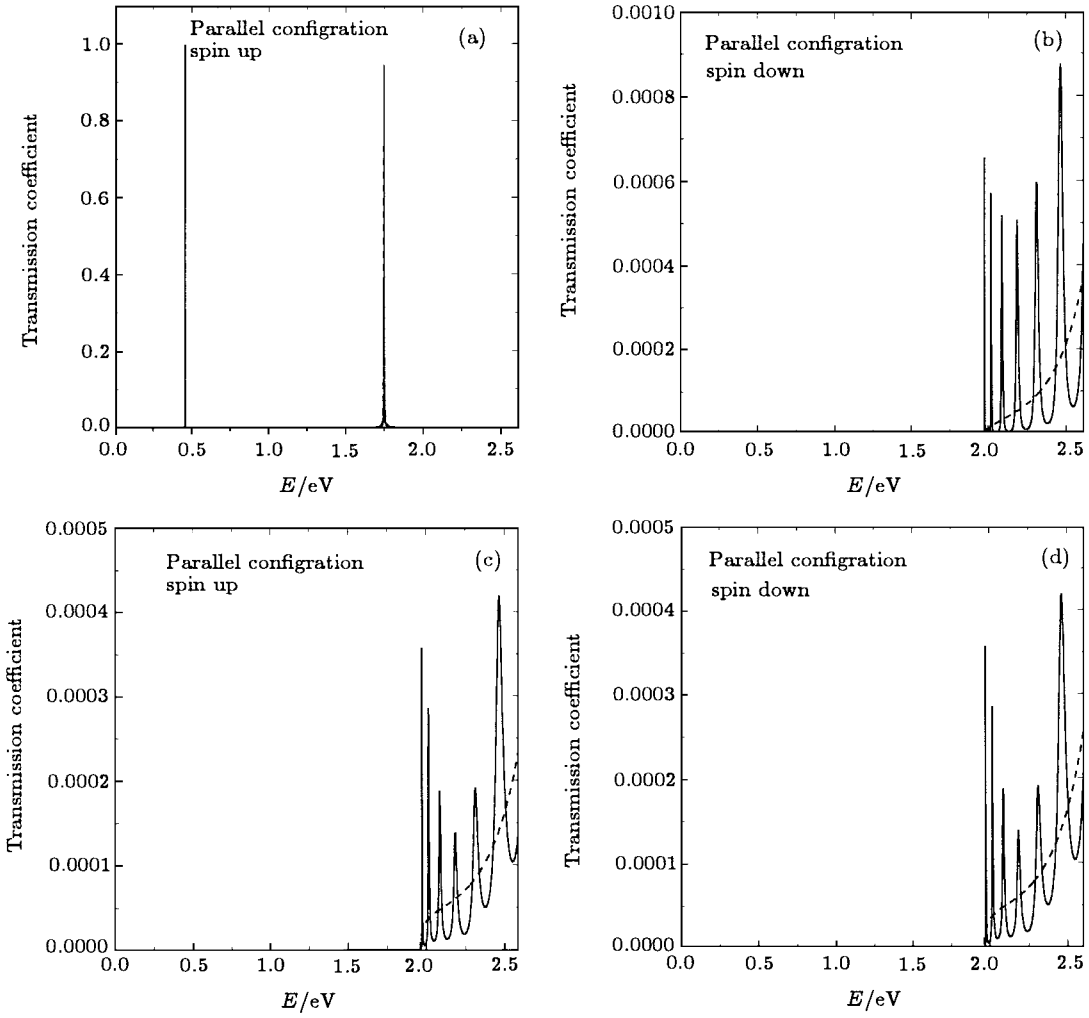


Fig.4. Transmission coefficients for the FM/I(S)/NM/I(S)/FM (dashed lines) and NM/FM/I(S)/NM/I(S)/FM/NM (solid lines) structures. Both middle layers NM have thicknesses d_{NM}=0.69nm.

From Fig.4(a), we find that the transmission coefficients for the spin-up electrons in the two structures all exhibit sharp resonance peaks and the same resonant states in parallel configuration. This result shows that the resonant states are determined mainly by the central NM layer and are slightly influenced by the thickness of the FM layer. Therefore, the periodic characteristics in the TC and TMR caused by the resonant tunnelling are similar in the two structures. But for other spins and configurations (Figs.4 (b)–4(d)), contrary to the rather smooth curves of the transmission coefficients in the structure without NM cap layers, there are large oscillations appearing in the structure with NM cap layers. This reflects that the effects of the FM layers can lead to oscillations in transmission coefficients, and hence to additional oscillations in the TMR and TC. The oscillations caused by the FM layer with a finite thickness (smaller than the electron mean free path) can be ascribed to the mismatch of the spin-dependent electron energy bands at the interface between the FM and NM layers. The FM layer can be regarded as a barrier to the tunnelling electron when its magnetization is antiparallel to the electron's spin moment, or as a quantum well when its magnetization is parallel to the electron's spin moment. Thus, the tunnelling electrons in the NM/FM/I(S)/NM/I(S)/FM/NM structure will experience more reflections at interfaces by these spin-dependent barriers and wells. These additional reflections can lead to the oscillations in the transmission coefficient, as well as in the TMR and TC.[7,8,19]

In the following, we consider how the TMR and TC vary with the thickness of the FM layers in the NM/FM/I(S)/NM/I(S)/FM/NM structure when the thickness of the middle layer NM is fixed. We choose d_{NM}=0.69nm as it corresponds to the first peak of the TMR in the FM/I(S)/NM/I(S)/NM/FM structure calculated above (see Fig.2). There are two cases

for the variations of the thickness of the FM layers and we discuss these separately. One is that both thicknesses of the two FM layers vary simultaneously (symmetric case); the other is that the thickness of one FM layer varies while that of the other is fixed (non-symmetric case). In the symmetric case, the dependences of the TMR and TC on the thickness of the FM layer are shown in Fig.5.

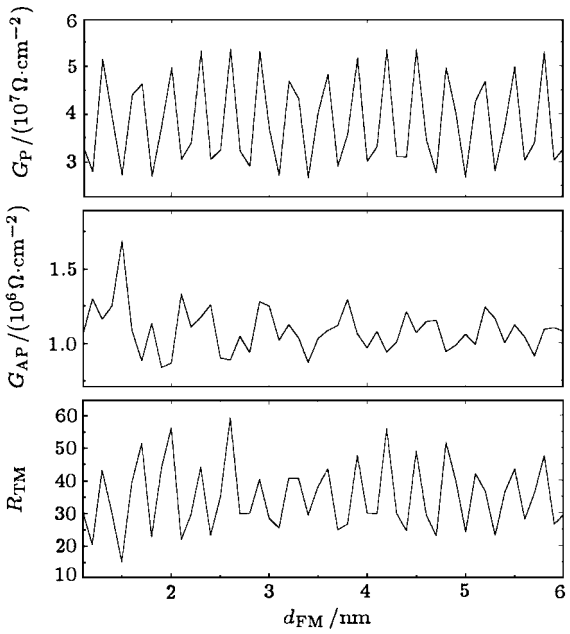


Fig.5. TC and TMR as functions of the thickness of the FM layer (d_{FM}) in the NM/FM/I(S)/NM/I(S)/FM/NM structure for the symmetric variation (d_2=d_6=d_{FM}). The middle layer NM has a thickness d_{NM}= 0.69nm.

We can find from Fig.5 that the variations of R_{TM}, G_P and G_{AP} exhibit oscillations and, when the thickness of the FM layers are suitable, we can obtain a much higher value of the TMR ($R_{TM} \approx 60$) than that ($R_{TM} \approx 35$) in the FM/I(S)/NM/I(S)/FM structure. This suggests an alternative way to obtain a large TMR by controlling the thicknesses of the FM layers in the DMTJ. Compared with the way of varying the thickness of the middle layer NM, this way is much easier. In addition, from Fig.5, we can see that, when R_{TM} reaches the maximum value, the corresponding G_P and G_{AP} reach the maximum and minimum values, respectively, and vice versa for the minimum R_{TM}. For the non-symmetric case, Fig.6, the results are similar to those of the symmetric case. The difference lies in that the oscillation amplitude of R_{TM} in the non-symmetric variation case is smaller than that in symmetric case.

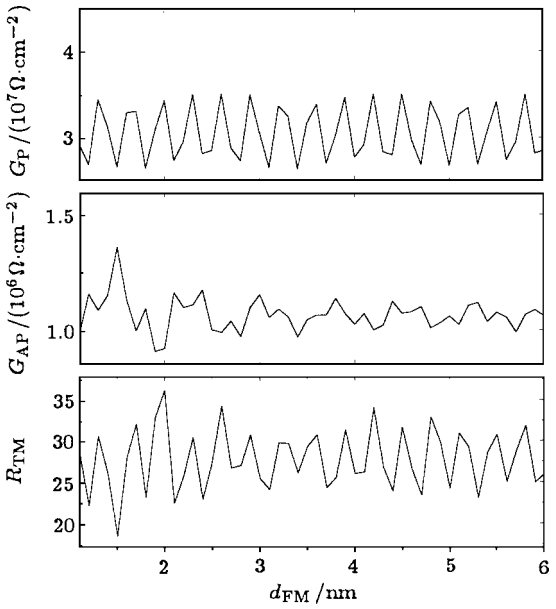


Fig.6. TC and TMR as functions of the thickness of the FM layer (d_{FM}) in the NM/FM/I(S)/NM/I(S)/FM/NM structure for the non-symmetric variation (d_2 is fixed at 5nm while d_6 is varied, d_{FM}=d_6). The middle NM layer has a thickness d_{NM}= 0.69nm.

According to the above results, we can see that, due to the spin-dependent interfacial potential barriers, the influences of the thicknesses of the FM layers on the TC and TMR in the DMTJ are significant and, when the thickness of the FM layer is suitably chosen, a large TMR can be obtained.

4. Summary

Based on the free-electron model, the dependences of the TC and TMR on the thicknesses of the FM layers and the middle layer NM in the DMTJ with NM cap layers are calculated and compared with those of the DMTJ without NM cap layers. The results show that the FM layers can superpose additional oscillations on the periodic variations of the TMR and TC with a middle layer NM. The dependences of the TMR and TC on the thicknesses of the FM layers exhibit oscillations and, when the thickness of the FM layers is suitably chosen, a much larger TMR can be obtained. This suggests another way to obtain a large TMR.

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