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Effects of temperature and electron effective mass on bias-dependent tunnelling magnetoresistance*

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In this paper, we study the effects of temperature and electron effective mass within the barrier on the bias dependence and sign-change behaviour of the tunnelling magnetoresistance (TMR) in ferromagnetic junctions. A significant decrease of the tunnelling magnetoresistance with increasing temperature is obtained, in accordance with the experiments. In addition to the height of barrier potential (ϕ) discussed in our previous papers, the electron effective mass ($m_{\rm B}$) within the barrier region is found to be another important factor that physically controls the sign-change behaviour of the TMR. The critical voltage ($V_{\rm c}$) at which TMR changes sign will increase with ϕ and decrease with $m_{\rm B}$. Furthermore, both the zero-bias TMR and $V_{\rm c}$ will decrease if the temperature rises. These results would be of practical use for experimental investigations.

Keywords: magnetotransport effects, quantum tunnelling
PACC: 7215G, 7335C

1. Introduction

Heterostructures consisting of two ferromagnetic electrodes (FM) and an insulating barrier (I) are called FM/I/FM junctions. Physically, they are characterized by a tunnelling magnetoresistance (TMR). Earlier experimental investigations are mainly focused on the TMR within a very small range of the applied voltage. Recently, the behaviour of TMR under large applied voltages has become particular interesting. In 1999, Sharma *et al*[1] reported that the TMR for the Ta_2O_5 barrier junction decreases quickly with the bias and changes its sign from positive to negative at a high enough applied voltage. In contrast, the junction with the same electrodes, but a different barrier (e.g., Al_2O_3), always exhibits a positive TMR decaying with the increase of the applied voltage. In addition to the strong bias-dependence, TMR is also found to be highly affected by temperature, it can be reduced significantly when the measuring temperature rises from 4.2K to room temperature.[2,3]

As to the theoretical part, the most widely used models to describe electron tunnelling in FM/I/FM junctions are the Jullière model[4] and Slonczewski model.[5] Both can explain the existence of TMR. However, the former neglects the quantum coherence among the barrier and the two electrodes, completely. The latter is confined only to the zero-bias case although it has taken into account the quantum coherence. Therefore, neither of them is suitable for the finite voltage case. Besides, Zhang *et al*[6] have calculated numerically the bias-dependence of TMR by employing Airy functions, and their results show a significant decrease of TMR with increasing voltage. Regrettably, the sign change behaviour is not achieved in this work.

In order to interpret the sign-change behaviour observed experimentally, we have developed an alternative theory for bias-dependent tunnelling[7,8] by extending the Slonczewski treatment[5] with a finite bias. The results show that the strong bias-dependence and sign-change behaviour of the TMR originate from the quantum coherence in the FM/I/FM system. However, in our previous papers,[7,8] we did not consider the effect of the variation of temperature and the influence of electron effective mass within the barrier region. Since all the experiments are performed at finite temperature, and the effective mass of the electrons

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in the barrier is generally different from those in the ferromagnetic electrodes, it is physically necessary to take into account the effect of temperature and the influence of the electron effective mass for the FM/I/FM system. This is the main task of the present paper. We shall prove that the quantum coherence among the barrier and the two ferromagnetic electrodes still exists at finite temperature, and remains to control the decreasing and sign-change behaviour of the TMR. In particular, we find that, apart from the barrier height as pointed out in Ref.[7], the effective mass of the electron in the barrier is another important factor responsible for the sign-change behaviour of the TMR.

2. Spintronic Hamiltonian and tunnelling magnetoresistance

As in Refs.[7] and [8], we still adopt the free electron model with parabolic bands for the three regions of the FM/I/FM system. Although this approximation cannot describe the details of the band structures in real FM metals, it does correctly include the quantum coherence in the junction, which has been proved to be most important in spin-dependent tunnelling.[9] Furthermore, we include the effect of temperature by employing the Stoner model,[10,11] and treat the insulating barrier as a simple spin-independent potential barrier. This leads to the following spintronic tunnelling model:[7]

$$H_{\mathrm{L}} = -\frac{\hbar^2}{2m_{\mathrm{L}}}\nabla^2 - \sigma_{\mathrm{L}}\Delta_{\mathrm{L}}(T), \tag{1}$$

$$H_{\mathrm{B}} = -\frac{\hbar^2}{2m_{\mathrm{B}}}\nabla^2 + \phi\,(x)\,, \tag{2}$$

$$H_{\mathrm{R}} = -\frac{\hbar^2}{2m_{\mathrm{R}}}\nabla^2 - \sigma_{\mathrm{R}}\Delta_{\mathrm{R}}(T) - eV \tag{3}$$

with

$$\phi\,(x) = \phi_{\mathrm{L}} + (\phi_{\mathrm{R}} - \phi_{\mathrm{L}} - eV)x/d. \tag{4}$$

Here H_{L}, H_{R} and H_{B} are, respectively, the Hamiltonians for the left electrode, the right electrode and the barrier, $\phi\,(x)$ is the potential in the barrier region as shown in Fig.1, d is the barrier width, V is the applied voltage, ϕ_{L} and ϕ_{R} are the barrier potentials at the left and right barrier/electrode interfaces respectively. For simplicity, we introduce three different effective masses m_{L}, m_{R} and m_{B} to describe the electronic structures in the three regions. The $\sigma_{\mathrm{L(R)}} = \pm 1$ is used to denote, respectively, the up and down spin states of the electron with respect to the local spin-quantization axis of the left (right) ferromagnetic electrode. We have $\sigma_{\mathrm{L}} = \sigma_{\mathrm{R}}$ if the magnetization orientations of the two FM electrodes are parallel, and $\sigma_{\mathrm{L}} = -\sigma_{\mathrm{R}}$ if antiparallel.

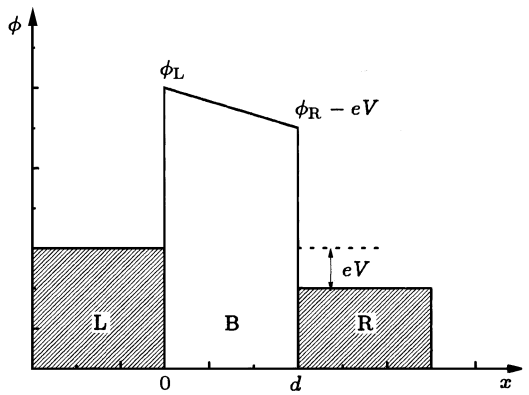


Fig.1. A schematic potential for the FM/I/FM junction under the bias $V > 0$.

The mean field $\Delta_{\mathrm{L(R)}}(T)$ represents one half of the exchange splitting between the two spin bands of the left (right) ferromagnetic electrode.[8] As usual, it can be determined by the Stoner model,[10,11] the result is shown in Fig.2. Obviously, it is a monotonically decreasing function of temperature T. We will see that this temperature dependence of $\Delta_{\mathrm{L(R)}}(T)$ can impose a strong influence on the spintronic tunnelling at finite temperature.

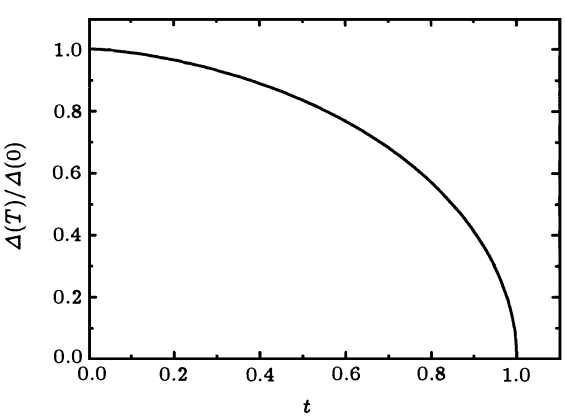


Fig.2. The order parameter $\Delta(T)/\Delta(0)$ versus the reduced temperature $t \equiv T/T_{\mathrm{C}}$, where $E_{F\uparrow} = 10.0eV$, $k_{F\downarrow}/k_{F\uparrow} = 0.15$, T_{C} is the Curie temperature of the FM electrodes.

With the above spintronic tunnelling model, the transmission coefficient can be solved similarly to Refs.[7] and [8] by matching both the wave functions and the probability current densities quantum mechanically at the two interfaces between the barrier and the ferromagnetic electrodes, which results in the

tunnelling currents,

$$J_{\mathrm{P(A)}}(V) = -\frac{em_{\mathrm{L}}}{4\pi^2\hbar^3}\int \mathrm{d}E_x^{\mathrm{L}}\int \mathrm{d}E_t^{\mathrm{L}} P_{\mathrm{P(A)}}(E_x^{\mathrm{L}}, E_t^{\mathrm{L}}, V) \times \mathrm{e}^{-2\eta}[f(E_x^{\mathrm{L}}+E_t^{\mathrm{L}}) - f(E_x^{\mathrm{L}}+E_t^{\mathrm{L}}-eV)], \quad (5)$$

where the subscripts P and A refer to the parallel and antiparallel alignments of the two FM electrodes, respectively. Here, the E_x^{L} and E_t^{L} represent the longitudinal and lateral energies of the electron in the left FM electrodes. The prefactor $P_{\mathrm{P(A)}}(E_x^{\mathrm{L}}, E_t^{\mathrm{L}}, V)$ can be expressed as

$$P_{\mathrm{P(A)}}(E_x^{\mathrm{L}}, E_t^{\mathrm{L}}, V) \equiv \frac{16\widetilde{k}_{\mathrm{L}\uparrow}\widetilde{k}_{\mathrm{R}\uparrow(\downarrow)}\widetilde{\kappa}_{\mathrm{L}}\widetilde{\kappa}_{\mathrm{R}}}{\left(\widetilde{\kappa}_{\mathrm{L}}^2+\widetilde{k}_{\mathrm{L}\uparrow}^2\right)\left(\widetilde{\kappa}_{\mathrm{R}}^2+\widetilde{k}_{\mathrm{R}\uparrow(\downarrow)}^2\right)} + \frac{16\widetilde{k}_{\mathrm{L}\downarrow}\widetilde{k}_{\mathrm{R}\downarrow(\uparrow)}\widetilde{\kappa}_{\mathrm{L}}\widetilde{\kappa}_{\mathrm{R}}}{\left(\widetilde{\kappa}_{\mathrm{L}}^2+\widetilde{k}_{\mathrm{L}\downarrow}^2\right)\left(\widetilde{\kappa}_{\mathrm{R}}^2+\widetilde{k}_{\mathrm{R}\downarrow(\uparrow)}^2\right)}, \quad (6)$$

and

$$\eta(E_x^{\mathrm{L}}, E_t^{\mathrm{L}}, V) = \left(\frac{2m_{\mathrm{B}}}{\hbar^2}\right)^{1/2}\int_0^d \kappa\left(E_x^{\mathrm{B}}, V, x\right)\mathrm{d}x, \quad (7)$$

$$\widetilde{k}_{\mathrm{L}\sigma_{\mathrm{L}}}(E_x^{\mathrm{L}}) = k_{\mathrm{L}\sigma_{\mathrm{L}}}(E_x^{\mathrm{L}})/m_{\mathrm{L}}, \quad (8)$$

$$\widetilde{k}_{\mathrm{R}\sigma_{\mathrm{R}}}(E_x^{\mathrm{L}}, E_t^{\mathrm{L}}, V) = k_{\mathrm{R}\sigma_{\mathrm{R}}}(E_x^{\mathrm{R}}, V)/m_{\mathrm{R}}, \quad (9)$$

$$\widetilde{\kappa}_{\mathrm{L}}(E_x^{\mathrm{L}}, E_t^{\mathrm{L}}) = \kappa\left(E_x^{\mathrm{B}}, V, 0\right)/m_{\mathrm{B}}, \quad (10)$$

$$\widetilde{\kappa}_{\mathrm{R}}(E_x^{\mathrm{L}}, E_t^{\mathrm{L}}, V) = \kappa\left(E_x^{\mathrm{B}}, V, d\right)/m_{\mathrm{B}} \quad (11)$$

with

$$k_{\mathrm{L}\sigma_{\mathrm{L}}}(E_x^{\mathrm{L}}) = \left(\frac{2m_{\mathrm{L}}}{\hbar^2}\right)^{1/2}\sqrt{E_x^{\mathrm{L}}+\sigma_{\mathrm{L}}\Delta_{\mathrm{L}}(T)}, \quad (12)$$

$$k_{\mathrm{R}\sigma_{\mathrm{R}}}(E_x^{\mathrm{R}}, V) = \left(\frac{2m_{\mathrm{R}}}{\hbar^2}\right)^{1/2}\sqrt{E_x^{\mathrm{R}}+eV+\sigma_{\mathrm{R}}\Delta_{\mathrm{R}}(T)}, \quad (13)$$

$$\kappa\left(E_x^{\mathrm{B}}, V, x\right) = \left(\frac{2m_{\mathrm{B}}}{\hbar^2}\right)^{1/2}\sqrt{\phi(x)-E_x^{\mathrm{B}}}. \quad (14)$$

According to Ref.[12], the longitudinal energies E_x^{R} in Eq.(13) and E_x^{B} in Eq.(14) can be determined by the energy conservation and the conservation of the lateral momentum, which gives rise to

$$E_x^{\mathrm{B(R)}} = E_x^{\mathrm{L}} + E_t^{\mathrm{L}}\left(1-\frac{m_{\mathrm{L}}}{m_{\mathrm{B(R)}}}\right). \quad (15)$$

Finally, the TMR can be obtained according to the following definitions:

$$G_{\mathrm{P(A)}}(V) = \frac{J_{\mathrm{P(A)}}(V)}{V}, \quad (16)$$

$$\mathrm{TMR}(V) = \frac{G_{\mathrm{P}}(V)-G_{\mathrm{A}}(V)}{G_{\mathrm{P}}(V)} = \frac{\Delta J(V)}{J_{\mathrm{P}}(V)}, \quad (17)$$

where $G_{\mathrm{P(A)}}(V)$ is the tunnelling current for parallel (antiparallel) alignment, and $\Delta J(V)$ the difference between $J_{\mathrm{P}}(V)$ and $J_{\mathrm{A}}(V)$. It is worthy to emphasize that the above derivations are all formulated under a finite bias V, a finite temperature T, and different electron effective masses m_{L}, m_{R} and m_{B}. Therefore, the influences of these physical factors on the TMR and its sign-change behaviour can be investigated systematically.

3. Numerical results and discussions

Now, the numerical calculation of the TMR can be performed by using Eqs.(5)–(17). For simplicity, we will discuss the symmetric junction with $m_{\mathrm{L}} = m_{\mathrm{R}} \equiv m$, $\phi_{\mathrm{L}} = \phi_{\mathrm{R}} \equiv \phi$ and $\Delta_{\mathrm{L}}(T) = \Delta_{\mathrm{R}}(T) \equiv \Delta(T)$. The following physical parameters are needed in numerical calculation: $E_{F\uparrow}$, $\kappa_F^2/k_{F\uparrow}^2$, $k_{F\downarrow}/k_{F\uparrow}$, d, m, m_{B}, t ($t \equiv T/T_{\mathrm{C}}$) and T_{C}, where $E_{F\uparrow}$ represents the Fermi energy of the spin-up electrons in the ferromagnetic electrodes, the $\kappa_F^2/k_{F\uparrow}^2 = [\phi-\mu(0)]/E_{F\uparrow}$ denotes the relative barrier height with $\mu(0)$ the chemical potential of the electrode at zero temperature, $k_{F\downarrow}/k_{F\uparrow}$ is the ratio of the Fermi wave numbers for different spin bands, d the barrier width, m and m_{B} are the electron effective masses in the FM electrodes and the barrier respectively, $t \equiv T/T_{\mathrm{C}}$ is the reduced temperature of the system, and T_{C} the Curie temperature of the FM electrodes.

First, we study the effect of temperature on TMR and its sign change behaviour. The results are shown in Fig.3 where we have simplified the calculation by assuming $m_{\mathrm{L}} = m_{\mathrm{R}} = m_{\mathrm{B}} = m$. Obviously, at a given temperature, the TMR decreases rapidly when the applied voltage increases, it will change from positive to negative at a critical voltage V_{c}. Moreover, with the increase of temperature, the zero-bias TMR($V=0$) drops significantly while the critical voltage V_{c} reduces slightly. The reason why the TMR can decrease and change sign at a finite temperature as the applied voltage increases, has been interpreted in Ref.[8]. The decreasing behaviours of the zero-bias TMR and the critical voltage V_{c} when temperature rises can be explained theoretically as follows.

In the simple case of $m_{\mathrm{L}} = m_{\mathrm{R}} = m_{\mathrm{B}} = m$, the parameters η, $\widetilde{k}_{\mathrm{L(R)}}$ and $\widetilde{\kappa}_{\mathrm{L(R)}}$ in Eqs.(7)–(11) become independent of the lateral energy E_t^{L}, so that the prefactors $P_{\mathrm{P}}(E_x^{\mathrm{L}}, E_t^{\mathrm{L}}, V)$ and $P_{\mathrm{A}}(E_x^{\mathrm{L}}, E_t^{\mathrm{L}}, V)$ do not depend on E_t^{L}. Therefore, the conductance difference

between parallel and antiparallel alignments at zero bias can be obtained

$$\Delta G(0) = \frac{e^2 m}{4\pi^2\hbar^3 k_{\rm B}T}\int {\rm d}E_x^{\rm L}\Delta P(E_x^{\rm L},0){\rm e}^{-2\eta}f\left(E_x^{\rm L}\right), \tag{18}$$

with $f\left(E_x^{\rm L}\right)$ being the Fermi distribution function and

$$\Delta P(E_x^{\rm L},0) = \left(\frac{\hbar^2}{2m}\right)^4\left[\frac{4\kappa_{\rm L}\left(k_{\rm L\uparrow}-k_{\rm L\downarrow}\right)\left(\kappa_{\rm L}^2-k_{\rm L\uparrow}k_{\rm L\downarrow}\right)}{\phi^2-\Delta^2(T)}\right]^2, \tag{19}$$

where we have used Eqs.(8)–(11). It should be pointed out that, in Eq.(19), both the $\kappa_{\rm L}$ and ϕ are independent of temperature, but $k_{\rm L\uparrow}$ and $k_{\rm L\downarrow}$ are temperature dependent through the FM order parameter $\Delta(T)$. As shown in Fig.2, the FM order parameter $\Delta(T)$ reduces monotonically as temperature rises. As a result, the $\Delta P(E_x^{\rm L},0)$ and $\Delta G(0)$ are both decreasing functions of T. Besides, $G_{\rm P}(0)$ will increase with elevating temperature due to the thermal activation. Therefore, the zero-bias TMR ($\equiv \Delta G/G_{\rm P}$) will drop significantly with increasing temperature, as shown in Fig.3. This analytical discussion indicates that, physically, the drop of zero-bias TMR is mainly due to the decrease of magnetization, i.e., order parameter $\Delta(T)$, in the FM electrodes with elevating temperature.

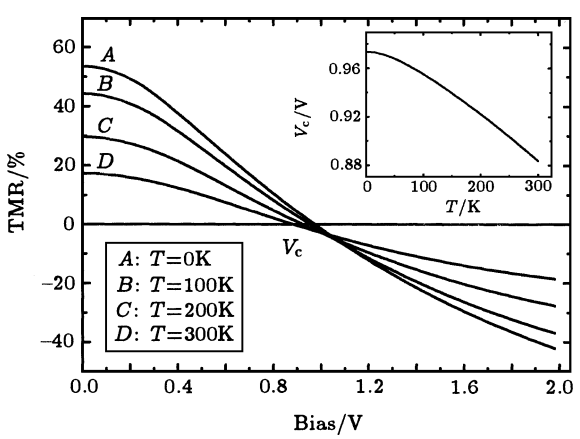


Fig.3. The curves of TMR versus the bias V, with $E_{F\uparrow}$=10.0eV, $k_{F\downarrow}/k_{F\uparrow}=0.15$, $\kappa_F^2/k_{F\uparrow}^2=0.3$ and d=1.5nm. Here and hereafter, we take $T_{\rm C}=1200$K as the Curie temperature of the FM electrodes. The curves A, B, C and D correspond to T=0, 100, 200 and 300K, respectively. The inset shows the curve of $V_{\rm c}$ vs T.

To understand the slight decrease of the critical voltage $V_{\rm c}$, one should notice that, at a finite temperature, the tunnelling current difference $\Delta J(V)$ can be formulated as

$$\Delta J(V) = \frac{em}{4\pi^2\hbar^3}\int {\rm d}E_x^{\rm L}A(E_x^{\rm L},V)D(E_x^{\rm L},V){\rm e}^{-2\eta} \times \ln\left(\frac{1+\exp\left(\beta\left(\mu-E_x^{\rm L}\right)\right)}{1+\exp\left(\beta\left(\mu-E_x^{\rm L}-eV\right)\right)}\right), \tag{20}$$

where $\beta=1/k_{\rm B}T$ with $k_{\rm B}$ being the Boltzmann constant. According to Ref.[7], the factor $A(E_x^{\rm L},V)$ keeps positive regardless of the strength of the applied voltage V. The quantum coherence factor $D(E_x^{\rm L},V)$ can be expressed as

$$D(E_x^{\rm L},V)=\kappa_{\rm R}^2(E_x^{\rm L},V)-k_{\rm R\uparrow}(E_x^{\rm L},V)k_{\rm R\downarrow}(E_x^{\rm L},V), \tag{21}$$

it will control the sign change of $\Delta J(V)$ with V. Actually, by solving $D(E_x^{\rm L},V=v_{\rm C})=0$, the zero-point voltage $v_{\rm C}\left(E_x^{\rm L}\right)$ for a given energy $E_x^{\rm L}$ can be obtained

$$ev_{\rm C}\left(E_x^{\rm L}\right)=\frac{1}{2}\phi+\frac{\Delta^2(T)}{2\phi}-E_x^{\rm L}. \tag{22}$$

Obviously, $v_{\rm C}\left(E_x^{\rm L}\right)$ is a decreasing function of T due to the decreasing behaviour of $\Delta(T)$. Therefore, there will definitely exist a critical voltage $V_{\rm c}$ for $\Delta J(V)$ after performing the integration of Eq.(20), and $V_{\rm c}$ is also a decreasing function of temperature, as shown in the inset of Fig.3.

In the previous paper,[7] we have studied the relationship between the critical voltage and the barrier height at zero temperature. We found that the barrier height controls the sign change of TMR. For fairly high barrier potentials, the critical voltage increases linearly with the barrier height. Within the present tunnelling model, we can extend the study to finite temperatures, the results are shown in Fig.4. We find

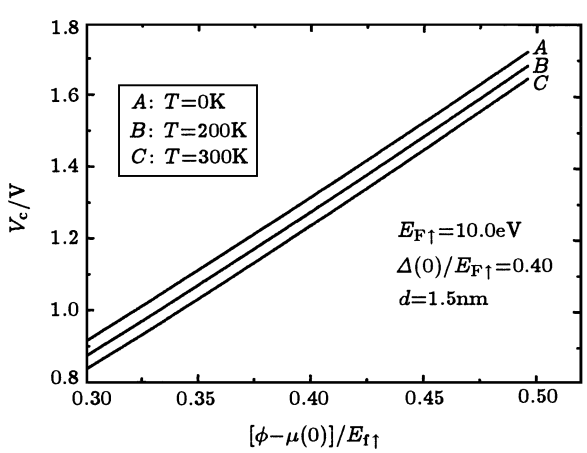


Fig.4. The curves of critical voltage $V_{\rm c}$ versus relative potential height $[\phi-\mu(0)]/E_{\rm F\uparrow}$ at different temperatures T=0, 200 and 300K.

that this linear relationship still exists at finite temperatures, which can also be easily understood from the relationship between $v_{\rm C}\left(E_x^{\rm L}\right)$ and ϕ as demonstrated in Eq.(22). The linear dependence between the critical voltage $V_{\rm c}$ and the barrier height ϕ indicates that, at finite temperatures, the barrier height remains an important factor responsible for the sign-change behaviour of the TMR.

Now, we turn to study the influence of the effective mass on the TMR and its sign-change behaviour. For simplicity, we will discuss the symmetric case with $m_{\rm L} = m_{\rm R} = m$, and adopt a different mass for the electron within the barrier region, $m_{\rm B} \neq m$. The numerical results are shown in Fig.5, where $m_{\rm B}/m$ ranges from 0.1 to 1.0. As an overview, the variation of $m_{\rm B}$ cannot change the monotonically decreasing behaviour of the TMR with the applied voltage, i.e. the TMR always decreases with increasing bias, irrespective of the magnitude of $m_{\rm B}/m$. This implies that the decreasing behaviour of the TMR with the bias does not depend on the effective mass $m_{\rm B}$, which is in agreement with the experiments.[1]

However, the variation of $m_{\rm B}$ can strongly affect both the zero-bias TMR and the critical voltage $V_{\rm c}$, as can be easily seen from Fig.5.

Physically, the decrease of the zero-bias TMR with $m_{\rm B}$ reflects the renormalization effect of the lateral energy on the height of barrier potential, which can be seen from the reformulated expression of Eq.(14),

$$\kappa\left(E_x^{\rm L}, E_t^{\rm L}, V, x\right) = \left(\frac{2m_{\rm B}}{\hbar^2}\right)^{1/2} \sqrt{\widetilde{\phi} + \frac{x}{d}(\phi_{\rm R} - \phi_{\rm L} - eV) - E_x^{\rm L}}, \quad (23)$$

where

$$\widetilde{\phi} = \phi + E_t^{\rm L}\left(\frac{m}{m_{\rm B}} - 1\right) \quad (24)$$

represents the renormalized potential. Obviously, $\widetilde{\phi}$ includes the influence of the lateral energy $E_t^{\rm L}$, it reduces to ϕ if $m_{\rm B} = m$. As is well known, the higher the barrier potential, the larger the tunnelling magnetoresistance. Since $\widetilde{\phi}$ increases as $m_{\rm B}$ gets lighter, the zero-bias TMR will increase with the decrease of $m_{\rm B}$, as shown in Fig.5.

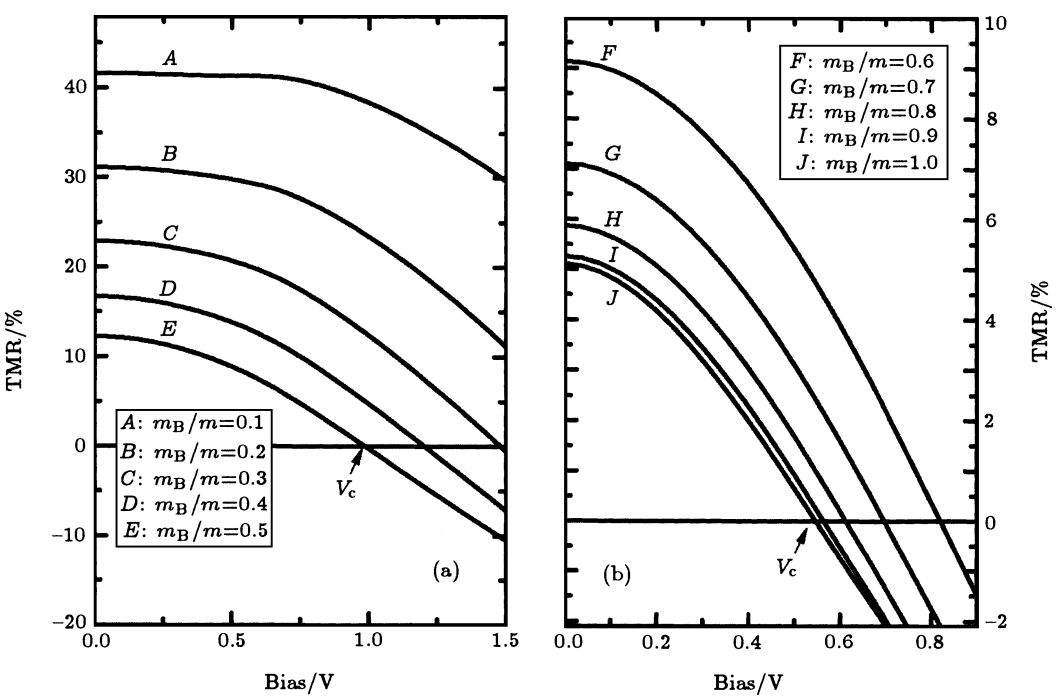


Fig.5. Curves of TMR versus the bias V for different effective mass $m_{\rm B}/m$ ranging from 0.1 to 1.0, with $E_{F\uparrow} = 10.0eV$, $k_{F\downarrow}/k_{F\uparrow} = 0.18$, $\kappa_F^2/k_{F\uparrow}^2 = 0.2$, d=1.5nm and T = 300K. (a) The curves for $m_{\rm B}/m$ = 0.1, 0.2, 0.3, 0.4 and 0.5. (b) The curves for $m_{\rm B}/m$ = 0.6, 0.7, 0.8, 0.9 and 1.0.

Figure 5 shows that, the lighter the effective mass $m_{\rm B}$, the larger the critical voltage $V_{\rm c}$ will be. This behaviour can also be understood analytically. After some algebraic manipulations, we can formulate the current difference $\Delta J(V)$ as

$$\begin{aligned}\Delta J(V) =& -\frac{em}{4\pi^2\hbar^3}\int {\rm d}E_x^{\rm L} \\ &\times \int {\rm d}E_t^{\rm L} A(E_x^{\rm L}, E_t^{\rm L}, V) D(E_x^{\rm L}, E_t^{\rm L}, V) {\rm e}^{-2\eta} \\ &\times \left[f(E_x^{\rm L} + E_t^{\rm L}) - f(E_x^{\rm L} + E_t^{\rm L} - eV) \right], \end{aligned} \quad (25)$$

where the factor $A(E_x^{\rm L}, E_t^{\rm L}, V)$ is positive for any V.[7] The quantum coherence factor $D(E_x^{\rm L}, E_t^{\rm L}, V)$ is

$$\begin{aligned} D(E_x^{\rm L}, E_t^{\rm L}, V) =& \widetilde{\kappa}_{\rm R}^2(E_x^{\rm L}, E_t^{\rm L}, V) \\ &- \widetilde{k}_{\rm R\uparrow}(E_x^{\rm L}, E_t^{\rm L}, V) \widetilde{k}_{\rm R\downarrow}(E_x^{\rm L}, E_t^{\rm L}, V). \end{aligned} \quad (26)$$

It can be rewritten as

$$\begin{aligned} D(E_x^{\rm L}, E_t^{\rm L}, V) =& \frac{2}{\hbar^2 m_{\rm B}} \left[\widetilde{\phi} - \left(eV + E_x^{\rm L} \right) \right] \\ &- \frac{2}{\hbar^2 m} \sqrt{\left(E_x^{\rm L} + eV \right)^2 - \Delta^2(T)}, \end{aligned} \quad (27)$$

where we have used Eqs.(9), (11), (13), (14), (15) and (24). We note that, the present quantum coherence factor $D(E_x^{\rm L}, E_t^{\rm L}, V)$ in Eq.(26) has included the influence of the electron effective mass inside the barrier, it is an extension of the one given in Ref.[7] where $m_{\rm B} = m$. Equation (27) indicates that $D(E_x^{\rm L}, E_t^{\rm L}, V)$ is a decreasing function of V for any $E_x^{\rm L}$ and $E_t^{\rm L}$, and it will change sign if V is large enough. This explains the fact that the critical voltage $V_{\rm c}$ for TMR still exists even if $m_{\rm B}/m < 1$. Furthermore, it can be found that, when $m_{\rm B}/m \ll 1$, $V_{\rm c}$ is mainly controlled by the first term on the right hand side of Eq.(27). As pointed out above, the renormalized potential $\widetilde{\phi}$ becomes larger when $m_{\rm B}$ decreases. Therefore, the decrease of $m_{\rm B}$ will result in a significant increase of the critical voltage $V_{\rm c}$, as shown in Fig.5.

On the other hand, it can be found from Fig.5 that the decreasing rate of the TMR with the applied voltage V becomes slow as $m_{\rm B}$ reduces, which demonstrates that the decreasing behaviour of the TMR with the applied voltage is strongly affected by the barrier parameters. This feature of the bias dependence of TMR is in accordance with the experimental fact that the $V_{1/2}$ at which ${\rm TMR}(V_{1/2}) = {\rm TMR}(0)/2$ is almost independent of the electrode material, but is mainly affected by the barrier parameters,[13] particularly, the barrier height and the effective mass inside the barrier.[9]

Finally, it is worth pointing out that, when the effective mass $m_{\rm B}$ is very small, the TMR will keep positive even if the applied voltage is considerably high, just like curves A and B in Fig.5. This property suggests that, within the experimental measurable range of the applied voltage, the TMR will not undergo any sign change in the junction with a very small effective mass $m_{\rm B}$. It indicates that, in addition to the height of the barrier potential, the effective mass of the electron within the barrier region is another factor that can strongly influence the sign-change behaviour of the TMR. In other words, the barrier height ϕ and the electron effective mass in the barrier $m_{\rm B}$ will cooperate to control the sign change of the TMR. As an example of this cooperation effect, we show that the junction with Al_2O_3 barrier always exhibits positive TMR without any sign change, that is because Al_2O_3 has a very small electron effective mass[14] and quite a large work function.[15]

4. Conclusion

In conclusion, the effects of temperature and electron effective mass within the barrier on the bias dependence and sign-change behaviour of the tunnelling magnetoresistance in FM/I/FM junctions have been studied, based on a microscopic bias-dependent model for spintronic tunnelling. The results show that the zero-bias TMR and the rate of change for the TMR versus the bias are depressed by the thermal fluctuations when temperature rises, but the TMR can also change its sign at finite temperatures with the critical voltage being just slightly reduced. On the other hand, the relationship between the barrier height and the critical voltage at a finite temperature indicates that it is also an important factor for the sign change of TMR. As to the influence of the electron effective mass within the barrier region, we find that it can impose strong influences on the sign change of TMR. It turns out that the barrier height and the effective mass are the two important factors which in effect control the sign-change behaviour of the TMR.

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