Tunneling magnetoresistance of double-barrier magnetic tunnel junctions in sequential and coherent regimes

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Taking into account the transport with coherent and sequential components, we study the conductance and tunneling magnetoresistance (TMR) in double F/I/F/I/F tunnel junctions with F the ferromagnet and I the thin insulating layer. It is found that the TMR ratio for the F/I/F/I/F junction in the sequential regime cannot go beyond the larger one between the TMR ratios of the two single F/I/F junctions forming the double junction. The coherent transport of electrons results in oscillations of the tunneling conductance and TMR with thickness L of the middle F layer, the sequential component leading to a decay of the oscillation amplitude with L.

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I. INTRODUCTION

Large tunneling magnetoresistance (TMR) observed in ferromagnet/insulating-layer/ferromagnet (F/I/F) magnetic tunnel junctions (MTJ)[1,2] has attracted much recent attention due to potential applications in sensors and magnetic access memories.[3] In addition to the single barrier MTJ (SBMTJ), both theoretical and experimental studies on F/I/M/I/F double barrier junctions with M the nonmagnetic metal[4–6] and F/I/F/I/F double barrier MTJ (DBMTJ)[7] are very interesting topics. The DBMTJ is very suitable for use as a magneto-electron tunneling injection device by using the top MTJ as a spin-polarized electron injector, while using the bottom MTJ as a spin detector.[8] With the highly spin-polarized currents easily realized, the DBMTJ can be designed as the spin-polarized current related devices for applications.

Recently, Lee *et al.* argued that the TMR ratio of a DBMTJ is expected to be two times larger than that of a SBMTJ.[9] Their argument arises from a TMR formula based on an extended Julliere model for the DBMTJ. However, this prediction has not been confirmed by experiment. Han *et al.*[10] reported that the TMR ratios measured for the DBMTJs are always lower than those for the corresponding SBMTJs, and certainly, far lower than those predicted by the Julliere's DBMTJ formula.[9] The discrepancy between the experiment and theory, together with lacking an explicit derivation, raises a serious query about the validity of the DBMTJ-TMR formula used in Refs. 9 and 10. In this work we reexamine the relation of the TMR ratios between the DBMTJ and the corresponding SBMTJ, and derive a correct Julliere's DBMTJ-TMR formula in the sequential regime. It is found that the TMR ratio for the F/I/F/I/F double junction in the sequential regime cannot go beyond the larger one between the TMR ratios of the two single F/I/F junctions forming the double junction. The present theoretical result can be used to interpret the experimental data of the DBMTJs.[9,10]

On the other hand, recent theoretical works[11,12] show that a DBMTJ may yield higher TMR ratio than the corresponding SBMTJ if the electron transport in the middle F layer is phase coherent. Zhang *et al.*[13] studied the spin-polarized resonant tunneling and quantum-size effect in DBMTJs subjected to an electric field. They showed that the TMR oscillates with the thickness of the middle F layer and can reach very large values under suitable conditions. The experimental study of Lee *et al.*[9] on DBMTJs revealed strong temperature dependence of TMR and an enhanced TMR effect at low temperatures. To get the enhanced TMR effect,[9,11–13] it is necessary to study the coherent tunneling case. In real case, when electrons pass coherently through the middle F layer, part of them may get scattered inside the well and lose phase memory. As a result, we consider the electron transport of the DBMTJs with coherent and sequential components and obtain the TMR ratio as a function of thickness L of the middle F layer. It is found that both the tunneling conductance and TMR ratio exhibit damped oscillations with increasing L. Under suitable L the coherent transport may make TMR ratio of the DBMTJ much greater than that of the corresponding SBMTJ. Since the phase-relaxation length decreases rapidly with increasing temperature, it provides an alterative interpretation for strong temperature dependence of TMR observed in DBMTJs.[9]

In Sec. II we study the conductance and TMR of the DBMTJs in the sequential regime. The relation of the TMR between the DBMTJ and SBMTJ is given in the sequential regime. In Sec. III we investigate a combination of the coherent and sequential tunneling components. A brief summary is given in Sec. IV.

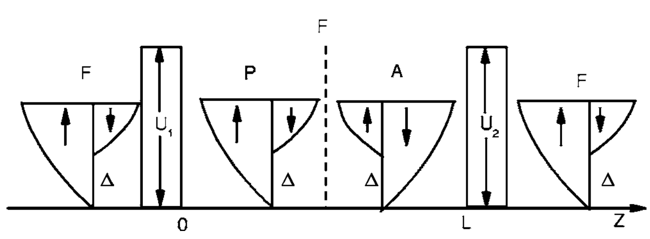

FIG. 1. Schematic representation of energy bands and potential profile in the P and A magnetization configuration in a F/I/F/I/F junction.

II. SEQUENTIAL TUNNELING

We first consider a F/I/F/I/F double junction, whose potential profile is shown in Fig. 1. For simplicity, we assume the two F electrodes and the middle F layer to have the same exchange energy Δ. For such a double junction, if the thickness of the middle F layer is longer than the phase-relaxation length but much shorter than the spin diffusion length, the transport is in the sequential regime and satisfies the two spin-channel current model. For each spin channel, the transmission probability of the electron is obtained by summing the probabilities for all possible transmission processes, yielding[6,14]

$$T^s = \bar{T}_R T_L + \bar{T}_R \bar{R}_L \bar{R}_R T_L + \bar{T}_R \bar{R}_L \bar{R}_R \bar{R}_L \bar{R}_R T_L + \cdots, \qquad (1)$$

where $T_L(T_R)$ and $R_L(R_R)$ are the transmission and reflection probabilities, respectively, in the left (right) tunnel junction. The successive terms in this series have clear physical meaning. The first term is the probability for transmission through the two insulating barriers without any reflection, the second term for transmission with two reflections, the third term for transmission with four reflections, and so on. In the sequential regime, the electron in the middle F layer undergoes scattering by impurities and so its momentum does not conserve. For this reason, in Eq. (1) we have introduced the averaged reflection and transmission probabilities

$$\bar{T}_i = \frac{\int T_i(k_\parallel) d^2 k_\parallel}{\int d^2 k_\parallel} \qquad (2)$$

and $\bar{R}_i = 1 - \bar{T}_i$ with $i = L$ and R. Both T_i and R_i are functions of parallel momentum $k_\parallel$. From Eq. (1), the average of the transmission probability is obtained as

$$\bar{T}^s = \frac{\bar{T}_L \bar{T}_R}{1 - \bar{R}_L \bar{R}_R}. \qquad (3)$$

In the case of either $\bar{T}_L \ll 1$ or $\bar{T}_R \ll 1$, Eq. (3) is approximately equal to

$$\frac{1}{\bar{T}^s} = \frac{1}{\bar{T}_L} + \frac{1}{\bar{T}_R}. \qquad (4)$$

In the two-channel current model, Eqs. (1)–(4) hold for each spin channel, in which the spin indices are omitted for simplicity of writing. The transmission and reflection coefficients are spin dependent and depend on the magnetization configuration of the three F regions. For example, the transmission coefficient of the left F/I/F junction for the σ-spin channel is given by[15]

$$T_{L\sigma\sigma'} = \frac{16 k_{1\sigma} k_{2\sigma'} \kappa_L^2 \exp(2\kappa_L d_L)}{\{\kappa_L (k_{1\sigma} + k_{2\sigma'})[1 + \exp(2\kappa_L d_L)]\}^2 + \{(\kappa_L^2 - k_{1\sigma} k_{2\sigma'})[1 - \exp(2\kappa_L d_L)]\}^2}, \qquad (5)$$

with $\sigma = \uparrow$ or $\downarrow$. Here $k_{i\uparrow} = \sqrt{2mE_F - k_\parallel^2}$ and $k_{i\downarrow} = \sqrt{2m(E_F - \Delta) - k_\parallel^2}$ are the perpendicular components of the Fermi wavevectors for the majority- and minority-spin bands in the ith F region ($i = 1$ for the left F and $i = 2$ for the middle F), respectively. $\kappa_L = \sqrt{2m(U_L - E_F) + k_\parallel^2}$ is the decaying wavevector within the left barrier where U_L is the barrier height and d_L the barrier width. Correspondingly, the conductance of the left F/I/F junction for the σ-spin channel is given by

$$G_{\sigma\sigma'}^L = \frac{e^2}{4\pi^2} \int T_{L\sigma\sigma'} d^2 k_\parallel = \frac{\mathrm{e}^2 k_{\mathrm{Fmin}}^2}{4\pi} \bar{T}_{L\sigma\sigma'}. \qquad (6)$$

The upper limit of the above integral is taken as the maximum of $k_\parallel$ to guarantee all the wavevectors appearing in the integral to be real, and k_{Fmin} is the Fermi wavevector of the minority-spin band. From Eqs. (4) and (6), the conductance for the σ-spin channel of the F/I/F/I/F double junction is obtained as

$$\frac{1}{G_{\sigma\sigma}} = \frac{1}{G_{\sigma\sigma'}^L} + \frac{1}{G_{\sigma'\sigma}^R}, \qquad (7)$$

where we have assumed the magnetization directions of the two F electrodes are always the same. Let us consider two magnetization configurations: Parallel (P) with $\sigma = \sigma'$ and antiparallel (A) with σ and σ' having the opposite directions. In the present two-channel current model, the total conductance is the sum of those in the two spin channels and depends on the magnetization configuration of the F regions. For the P configuration, the tunneling conductance is given by

$$G_P = \frac{G_{\uparrow\uparrow}^L G_{\uparrow\uparrow}^R}{G_{\uparrow\uparrow}^L + G_{\uparrow\uparrow}^R} + \frac{G_{\downarrow\downarrow}^L G_{\downarrow\downarrow}^R}{G_{\downarrow\downarrow}^L + G_{\downarrow\downarrow}^R}, \qquad (8)$$

where $G_{\sigma\sigma}^L$ ($G_{\sigma\sigma}^R$) is the tunneling conductance of the spin-σ electrons through the left (right) junction. For the A configuration, similarly, we have

$$G_A = \frac{G_{\uparrow\downarrow}^L G_{\downarrow\uparrow}^R}{G_{\uparrow\downarrow}^L + G_{\downarrow\uparrow}^R} + \frac{G_{\downarrow\uparrow}^L G_{\uparrow\downarrow}^R}{G_{\downarrow\uparrow}^L + G_{\uparrow\downarrow}^R}. \qquad (9)$$

The TMR ratio of the F/I/F/I/F structure is defined as

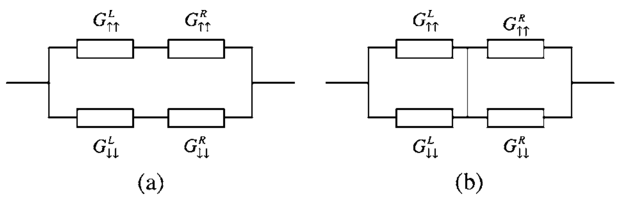

FIG. 2. Equivalent circuits in the two spin-channel current model for G_P (a) and G_M (b) defined in text.

$\alpha_D=(G_P-G_A)/G_A$. According to the same definition, the TMR ratio α_L (α_R) of the left (right) single tunnel junction is given by

$$\alpha_L = \frac{G^L_{\uparrow\uparrow}+G^L_{\downarrow\downarrow}}{G^L_{\uparrow\downarrow}+G^L_{\downarrow\uparrow}} - 1 \tag{10}$$

and

$$\alpha_R = \frac{G^R_{\uparrow\uparrow}+G^R_{\downarrow\downarrow}}{G^R_{\uparrow\downarrow}+G^R_{\downarrow\uparrow}} - 1. \tag{11}$$

The relation of the TMR ratio between the DBMTJ and those of the two single tunnel junctions is easily obtained as

$$1+\alpha_D = \beta_L(1+\alpha_L)+\beta_R(1+\alpha_R), \tag{12}$$

with $\beta_L=G_P/(G^L_{\uparrow\uparrow}+G^L_{\downarrow\downarrow})$ and $\beta_R=G_P/(G^R_{\uparrow\uparrow}+G^R_{\downarrow\downarrow})$, where we have used symmetry relations $G^L_{\downarrow\uparrow}=G^L_{\uparrow\downarrow}$ and $G^R_{\downarrow\uparrow}=G^R_{\uparrow\downarrow}$. We first discuss two special cases. If the two barriers are identical, we have $\alpha_L=\alpha_R$ and $\beta_L=\beta_R=1/2$ so that $\alpha_D=\alpha_L=\alpha_R$. If there is a big difference in the barrier height or/and width between the two barriers, e.g., $(G^L_{\uparrow\uparrow}+G^L_{\downarrow\downarrow})\ll(G^R_{\uparrow\uparrow}+G^R_{\downarrow\downarrow})$, we have $\beta_L\approx 1$ and $\beta_R\ll 1$. In this case, $\alpha_D\approx\alpha_L$ is determined by the TMR ratio of the single tunnel junction with higher or/and wider barrier, but independent of the TMR ratio of another single tunnel junction. In general cases, the situation is somewhat complicated. It can be shown that α_D is always not greater than, at most equal to, the larger one between α_L or α_R. For sake of definition, we discuss the case of $\alpha_L \leqslant \alpha_R$. From Eq. (12), we have

$$\alpha_D \leqslant \alpha_R-(\alpha_R+1)(1-\beta_L-\beta_R). \tag{13}$$

It is easy to verify that $(\beta_L+\beta_R)$ is always less than 1, so that the TMR ratio of the double tunnel junction cannot go beyond the larger one between α_L and α_R of the single tunnel junctions. In reality, $(\beta_L+\beta_R)$ can be rewritten as G_P/G_M where G_P given by Eq. (8) is the conductance of the two-channel current model shown in Fig. 2(a), while G_M is the conductance of the circuit shown in Fig. 2(b) with $1/G_M=1/(G^L_{\uparrow\uparrow}+G^L_{\downarrow\downarrow})+1/(G^R_{\uparrow\uparrow}+G^R_{\downarrow\downarrow})$. Evidently, from Fig. 2, it follows that $(\beta_L+\beta_R)=G_P/G_M\leqslant 1$. In conclusion, it is impossible to enhance the TMR ratio by replacing the single tunnel junction by the double tunnel junction in the sequential regime.

In order to compare the present result with that used in Refs. 9 and 10, we use the extended Julliere model to calculate the tunneling conductance G_P and G_A. Just at the moment of this small paragraph, for ease of comparison, the middle F layer and the both F electrodes are assumed to have different spin polarizations, but the left and right barriers to be identical to each other. In the Julliere model, we have $G^L_{\uparrow\uparrow}=CN_1^{\uparrow}N_2^{\uparrow}$, $G^R_{\uparrow\uparrow}=CN_2^{\uparrow}N_3^{\uparrow}$, $G^L_{\downarrow\downarrow}=CN_1^{\downarrow}N_2^{\downarrow}$, and $G^R_{\downarrow\downarrow}=CN_2^{\downarrow}N_3^{\downarrow}$ with $N_i^{\uparrow(\downarrow)}$ is the density of state for the majority-spin (minority-spin) bands in the ith F region (i=1,2,3) and C is constant. Substituting them into Eq. (8), the tunneling conductance for the P configuration is obtained as $G_P=CN_1^{\uparrow}N_2^{\uparrow}N_3^{\uparrow}/(N_1^{\uparrow}+N_3^{\uparrow})+CN_1^{\downarrow}N_2^{\downarrow}N_3^{\downarrow}/(N_1^{\downarrow}+N_3^{\downarrow})$. For the A configuration, similarly, we have $G_A=CN_1^{\uparrow}N_2^{\downarrow}N_3^{\uparrow}/(N_1^{\uparrow}+N_3^{\uparrow})+CN_1^{\downarrow}N_2^{\uparrow}N_3^{\downarrow}/(N_1^{\downarrow}+N_3^{\downarrow})$. It then follows

$$\alpha_D = \frac{2P_2(P_1+P_3)(1-P_1P_3)}{(1-P_1^2)(1-P_2P_3)+(1-P_3^2)(1-P_1P_2)}, \tag{14}$$

with $P_i=(N_i^{\uparrow}-N_i^{\downarrow})/(N_i^{\uparrow}+N_i^{\downarrow})$ as the spin polarization of the ith F layer. If $P_1=P_3$, one gets the TMR ratio of the double tunnel junction as

$$\alpha_D = \frac{2P_1P_2}{1-P_1P_2}, \tag{15}$$

which is just equal to the TMR ratio of the single tunnel junction. This deduction is in good agreement with the experimental result of Han *et al.*,[10] that the TMR ratios for both the SBMTJ and DBMTJ are almost equal to each other in a wide temperature range from 4.2 to 300 K. In their DBMTJ, the thickness of the middle $Co_{75}Fe_{25}$ layer is about 8 nm, greater than the phase-relaxation length in it, so that the electron transport must be in the sequential regime. It is worthy of pointing out that Eq. (14) obtained here is quite different from that used in Refs. 9 and 10. The latter was given by

$$\alpha_D' = \frac{2P_2(P_1+P_3)}{1+P_2P_3-P_2(P_1+P_3)}, \tag{16}$$

from which it follows that α_D' with $P_1=P_3$ for the DBMTJ is greater than that for the SBMTJ by a factor of 2. The validity of Eq. (16) is questionable, and its source without derivation is not clear while it was used in Refs. 9 and 10 to be compared with experimental results. Figure 3 shows the TMR ratios as functions of P_3/P_1 for the DBMTJ and two SBMTJs. In the present calculation, since $P_1=P_2=0.5$ is

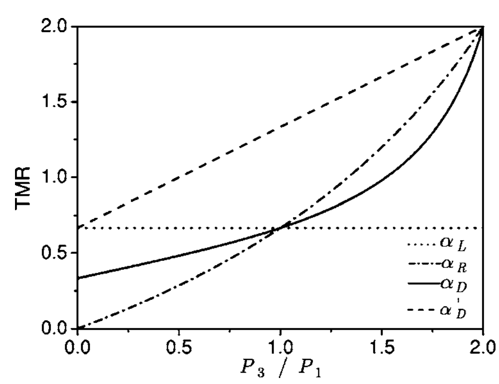

FIG. 3. TMR ratios α_D for the DBMTJ and α_L (α_R) for the left (right) SBMTJ as functions of P_3 with $P_1=P_2=0.5$. α_D' is obtained from Eq. (16).

fixed, the TMR ratio α_L of the left SBMTJ is constant and α_R of the right SBMTJ increases with P_3, as shown by the dotted and dash-dotted lines, respectively. The present result for α_D (solid line) calculated from Eq. (14) is always between the TMR ratios of the two SBMTJs, as has been discussed above. The dashed line for α'_D calculated from Eq. (16), which always lies above the other lines, is questionable. For example, if the right F electrode is replaced with a normal-metallic one ($P_3=0$ and $\alpha_R=0$), we have $G^R_{\uparrow\uparrow}=G^R_{\uparrow\downarrow}$ and $G^R_{\downarrow\downarrow}=G^R_{\downarrow\uparrow}$ in the two-channel circuit of Fig. 2(a). In this case, α_D should be smaller than α_L due to the presence of the right tunnel junction, as shown in Fig. 3. Evidently, $\alpha'_D=\alpha_L$ at $P_3=0$ is an incorrect result.

III. COHERENT TUNNELING

In order to get an enhanced TMR effect,[9,11–13] let us turn to the coherent tunneling case. In the coherent regime, it is easy to calculate the coherent transmission probability and reflection probability by using the scattering matrix approach.[6,14]

$$T^c_{\sigma_1\sigma_2\sigma_3}=\frac{T_{L\sigma_1\sigma_2}T_{R\sigma_2\sigma_3}}{1+R_{L\sigma_1\sigma_2}R_{R\sigma_2\sigma_3}-2\sqrt{R_{L\sigma_1\sigma_2}R_{R\sigma_2\sigma_3}}\cos\theta}, \quad (17)$$

$$R^c_{\sigma_1\sigma_2\sigma_3}=\frac{R_{L\sigma_1\sigma_2}+R_{R\sigma_2\sigma_3}-2\sqrt{R_{L\sigma_1\sigma_2}R_{R\sigma_2\sigma_3}}\cos\theta}{1+R_{L\sigma_1\sigma_2}R_{R\sigma_2\sigma_3}-2\sqrt{R_{L\sigma_1\sigma_2}R_{R\sigma_2\sigma_3}}\cos\theta} \quad (18)$$

with $\theta=2k_{F\sigma_2}L$ where $k_{F\sigma_2}$ is the perpendicular component of the Fermi wavevector for the spin-σ band in the middle F layer and L is its thickness. $\sigma_i=\uparrow$ or $\downarrow$ ($i=1,2,3$) stands for the majority- or minority-spin band with respect to the quantization axis of the ith F region. In the presence of scattering processes in the middle F layer, only a fraction of electrons transmit coherently, while the remainder get scattered inside the well with losing phase memory and effectively leak out of the coherent stream as shown in Fig. 4. As a result, one needs to consider a combination of the coherent and the sequential transport. Introducing the phase-relaxation length l_p in the middle F layer and taking care to insert a factor $\exp(-L/l_p)$, we obtain[6,14]

$$T^c_{\sigma_1\sigma_2\sigma_3}=\frac{T_{L\sigma_1\sigma_2}T_{R\sigma_2\sigma_3}\exp(-2L/l_p)}{1+R_{L\sigma_1\sigma_2}R_{R\sigma_2\sigma_3}\exp(-4L/l_p)-2\sqrt{R_{L\sigma_1\sigma_2}R_{R\sigma_2\sigma_3}}\exp(-2L/l_p)\cos\theta}, \quad (19)$$

$$R^c_{\sigma_1\sigma_2\sigma_3}=\frac{R_{L\sigma_1\sigma_2}+R_{R\sigma_2\sigma_3}\exp(-4L/l_p)-2\sqrt{R_{L\sigma_1\sigma_2}R_{R\sigma_2\sigma_3}}\exp(-2L/l_p)\cos\theta}{1+R_{L\sigma_1\sigma_2}R_{R\sigma_2\sigma_3}\exp(-4L/l_p)-2\sqrt{R_{L\sigma_1\sigma_2}R_{R\sigma_2\sigma_3}}\exp(-2L/l_p)\cos\theta}. \quad (20)$$

In this case, $T^c+R^c<1$, so that $T^s_L=1-T^c-R^c$ is the scattering probability in the middle F region. As shown in the upper part of Fig. 4, T^s_L is just the sequential transport part of arriving at the right F/F interface. Evidently, T^s_L increases with L. In the large L limit, $T^c=0$, $R^c=R_L$, and $T^s_L=1-R_L$, corresponding to a completely sequential case. The scattered electrons tunnel partially through the right barrier with transmission probability T^s and partially through the left barrier with reflection probability R^s, as shown in the lower part of Fig. 4. It then follows that the sequential transport part of the whole double-barrier structure is given by $T^s=T^s_L\bar{T}_R/(1-\bar{R}_L\bar{R}_R)$. The total tunneling probability is the sum of the coherent andsequential components, yielding

$$T_{\sigma_1\sigma_2\sigma_3}=T^c_{\sigma_1\sigma_2\sigma_3}+\frac{(1-T^c_{\sigma_1\sigma_2\sigma_3}-R^c_{\sigma_1\sigma_2\sigma_3})\bar{T}_{R\sigma_2\sigma_3}}{1-\bar{R}_{L\sigma_1\sigma_2}\bar{R}_{R\sigma_2\sigma_3}}. \quad (21)$$

In the two spin-channel model the tunneling conductance in the P configuration is given by $G_P=G_{\uparrow\uparrow\uparrow}+G_{\downarrow\downarrow\downarrow}$ where $G_{\uparrow\uparrow\uparrow}$ ($G_{\downarrow\downarrow\downarrow}$) indicates the conductance in the spin-up (spin-down) channel. In the A configuration with the magnetization of the middle F layer antiparallel to those of both F electrodes, the tunneling conductance is $G_A=G_{\uparrow\downarrow\uparrow}+G_{\downarrow\uparrow\downarrow}$ where $G_{\uparrow\downarrow\uparrow}$ ($G_{\downarrow\uparrow\downarrow}$) stands for the conductance in the spin-up (spin-down) channel. $G_{\sigma_1\sigma_2\sigma_3}$ can be easily obtained from $T_{\sigma_1\sigma_2\sigma_3}$ via Eqs. (6) and (17)–(21).

We calculate numerically the tunneling conductance and TMR as functions of thickness L of the middle F layer by making use of Eqs. (5), (6), and (19)–(21). In the present calculation the parameters are taken to be $E_F=3$ eV and $\Delta=0.8E_F$ for the F layers, $d_L=d_R=1.0$ nm and $U_L=U_R=5$ eV for the barriers, and $l_p=2.5$ nm for the middle F layer. Figure 5(a) shows L dependence of the tunneling conductances for

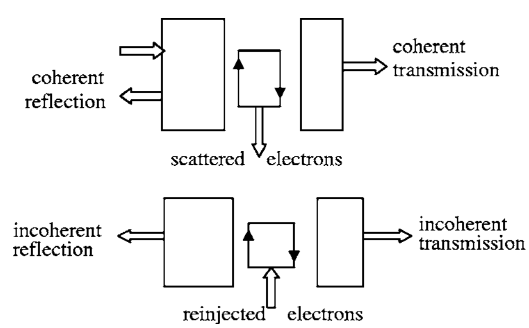

FIG. 4. Scattering processes in the middle F layer cause electrons to leak out of the coherent stream and result in the sequential components of transmission and reflection coefficients, taken from Datta (Ref. 14).

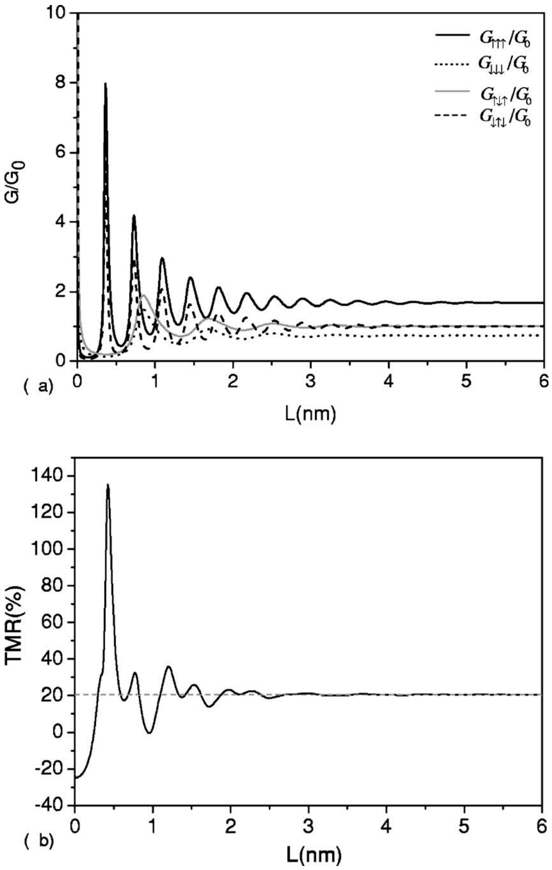

FIG. 5. Conductances (a) normalized by $G_0 = G_{\uparrow\downarrow\uparrow}$ in the sequential case and TMR (b) in the double F/I/F/I/F junctions as functions of the thickness of the middle F layer. The dashed line indicates constant TMR ratio α_D obtained from Eqs. (5)–(12) in the sequential case.

the DBMTJs, exhibiting damped oscillations. The conductance oscillations arise from the coherent transport of electrons; while their amplitude decay comes from the scattering processes in the middle F layer, in which the phase coherence is partly broken. The oscillation periods are determined by the Fermi wavevectors of the middle F layer. The conduction electrons with wavevector **k** normal to the barrier ($k_{\parallel} = 0$) make the main contributions to the tunneling current in the double tunnel junctions.[5,6] Since the Fermi wavevectors of electrons in the majority-spin and minority-spin bands in the middle F layer are different, there are different oscillation periods for the conductances in different spin channels. This oscillation period is determined by the spin-dependent Fermi wavevector in the middle F layer, whether the magnetizations of the three F regions are in the P or A configuration. As shown in Fig. 5(a), there are two different conductance oscillation periods: One is for $G_{\uparrow\uparrow\uparrow}$ and $G_{\downarrow\uparrow\downarrow}$, while the other is for $G_{\downarrow\downarrow\downarrow}$ and $G_{\uparrow\downarrow\uparrow}$. This point is quite different from that in the F/I/N/I/F double tunnel junction, in which N denotes a normal-metallic layer without exchange splitting. For example, a single period of the tunneling conductance was observed by Yuasa *et al.*[5] in NiFe-Al_2O_3-Cu-Co junctions. Figure 5(b) shows the TMR ratio α_D as an oscillatory function of L, but there is no a single period. This can be understood

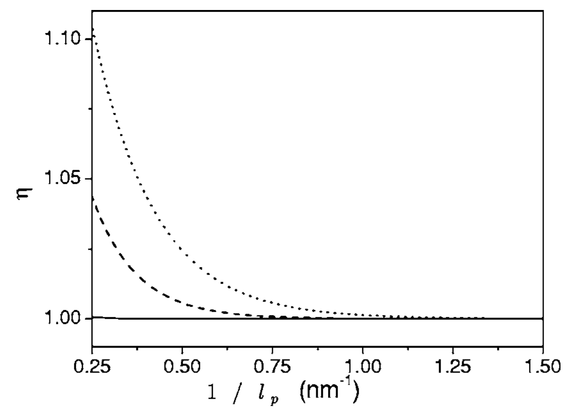

FIG. 6. α_D as a function of $1/l_p$ with $L=3$ nm (dotted line), 4 nm (dashed line), and 8 nm (solid line). Here $1/l_p$ increases with temperature.

from the two spin-channel current model. As mentioned above, $G_{\uparrow\uparrow\uparrow}$ and $G_{\downarrow\downarrow\downarrow}$ ($G_{\uparrow\downarrow\uparrow}$ and $G_{\downarrow\uparrow\downarrow}$) have different oscillation periods in the P (A) magnetization configuration. It then follows that neither G_P nor G_A oscillations have a single period, no more do the TMR oscillations. On the other hand, the TMR oscillations are around a constant value α_D (dashed line) in the sequential case. In a certain range of L, the TMR ratio in the coherent regime can be much greater than α_D in the sequential regime. The amplitude of the TMR oscillations decays with increasing L/l_p, tending towards constant α_D in the sequential case.

Figure 6 shows l_p dependence of the TMR ratio $\eta = \alpha_D$ for the DBMTJs. It is found that for $l_p \ll L$ the transport of the DBMTJ is in the sequential regime and η is constant. With increasing l_p, there is a crossover from sequential to coherent transport and η deviates gradually from the constant. Here we wish to connect the calculated result of η with the temperature dependence of α_D of the DBMTJ. Although the present calculations are performed at zero temperature, the phase-relaxation length l_p should be a function of temperature, decreasing rapidly with increasing temperature. Since the DBMTJ is composed of two SBMTJs separated by a F layer of thickness L, $\alpha_D(T) = [G_P(T) - G_A(T)]/G_A(T)$ is determined mainly by two factors: $\alpha_S(T)$ (S=L and R) and $L/l_p(T)$, with the former as the temperature-dependent TMR ratios of the two SBMTJs. The temperature dependence of $\alpha_S(T)$ usually arises from spin flip effects in the tunneling process,[16] which we do not want to study here. Instead, we assume η to be approximately proportional to $\alpha_D(T)/\alpha_S(T)$. Under this assumption, it follows that the TMR ratios of the DBMTJ and SBMTJ have almost same temperature dependence in the constant η region of $l_p(T) \ll L$, which is well consistent with the experimental data in Fig. 3 of Ref. 10. For $l_p(T) > L$, owing to the increase of η with lowering temperature as shown in Fig. 6, the TMR ratio of the DBMTJ increases more rapidly than that of the SBMTJ. This provides a qualitative explanation for the experimental result that the DBMTJ exhibits stronger temperature dependence of TMR than the SBMTJ.[9]

IV. SUMMARY

In summary we have presented a theoretical approach to the tunneling conductance and TMR in the DBMTJs with both coherent and sequential components. In the sequential regime, a correct DBMTJ-TMR formula is derived and the relation of the TMRs between the SBMTJ and DBMTJ is analytically obtained. It is shown that the sequential TMR ratio of the double junction cannot go beyond the larger one between the TMR ratios of the two single junctions. The present theoretical result is quite different from the previous one and provides a reasonable explanation for the recent experimental data. The coherent component results in the oscillations of the TMR, while the sequential component leads to their decay with the thickness of the middle F layer. There is no a single period of conductance and TMR oscillations, for there are different Fermi wave vectors for the majority-spin and minority-spin bands in the middle F layer. To get a larger TMR ratio, one needs to modulate the thickness of the middle F layer carefully in the coherent regime. There is a crossover from coherent to sequential tunneling with increasing temperature, which provides a qualitative explanation for the experimental result that the DBMTJ exhibits stronger temperature dependence of TMR than the SBMTJ.

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[1] T. Miyazaki, T. Yaoi, and S. Ishio, J. Magn. Magn. Mater. **98**, L7 (1991); T. Miyazaki and N. Tezuka, *ibid.* **139**, L231 (1995).
[2] J. S. Moodera, L. R. Kinder, T. M. Wong, and R. Meservey, Phys. Rev. Lett. **74**, 3273 (1995); J. S. Moodera and Lisa R. Kinder, J. Appl. Phys. **79**, 4724 (1996).
[3] J. L. Simonds, Phys. Today **48** (4), 26 (1995).
[4] Z. M. Zheng, Y. N. Qi, D. Y. Xing, and J. M. Dong, Phys. Rev. B **59**, 14505 (1999); M. Wilczynski and J. Barnas, J. Magn. Magn. Mater. **221**, 373 (2000); M. Chshiev, D. Stoeffler, A. Vedyayev, and K. Ounadjela, *ibid.* **240**, 146 (2002), Europhys. Lett. **58**, 257 (2002); H. Itoh, J. Inoue, A. Umerski, and J. Mathon, Phys. Rev. B **68**,174421 (2003).
[5] S. Yuasa, T. Nagahama, and Y. Suzuki, Science **297**, 234 (2002).
[6] J. Yang, J. Wang, Z. M. Zheng, D. Y. Xing, and C. R. Chang, Phys. Rev. B **71**, 214434 (2005).
[7] F. Montaigne, J. Nasser, A. Vaures, F. Nguyen Van Dau, F. Petroff, A. Schuhl, and A. Fert, Appl. Phys. Lett. **73**, 2829 (1998); J. Barnas and A. Fert, Phys. Rev. Lett. **80**, 1058(1998); H. Kubota, T. Watable, and T. Miyazaki, J. Magn. Magn. Mater. **198**,173 (1999); S. Tanoue and A. Yamasakib, J. Appl. Phys. **88**, 4764 (2000); X. Wang and M. B. A. Jail, *ibid.* **93**, 8056 (2003); M. Zeros, *ibid.* **94**, 1776 (2003); F. Giazotto *et al.*, Appl. Phys. Lett. **82**, 2449 (2003); S. Ladak and R. J. Hickena, J. Appl. Phys. **97**, 104512 (2005).
[8] S. Stein, R. Schmitz, and H. Kohlstedt, Solid State Commun. **117**, 599 (2001).
[9] J. H. Lee, I. W. Chang, S. J. Byun, T. K. Hong, K. Rhie, W. Y. Lee, K. H. Shin, C. Y. Hwang, S. S. Lee, and B. C. Lee, J. Magn. Magn. Mater. **240**, 137 (2002); J. H. Lee, K. I. Lee, W. L. Lee, K. H. Shin, J. S. Lee, K. Rhie, and B. C. Lee, J. Appl. Phys. **91**,7956 (2002).
[10] X. F. Han, S. F. Zhao, F. F. Li, T. Daibou, H. Kubota, Y. Ando, and T. Miyazaki, J. Magn. Magn. Mater. **282**, 225 (2004).
[11] L. Sheng, Y. Chen, H. Y. Teng, and C. S. Ting, Phys. Rev. B **B.59**, 480 (1999).
[12] X. Zhang, B. Z. Li, G. Sun, and F. C. Pu, Phys. Rev. B **56**, 5484 (1997).
[13] X. Zhang, B. Z. Li, G. Sun, and F. C. Pu, Phys. Lett. A **245**, 133 (1998).
[14] S. Datta, *Electronic Transport in Mesoscopic Systems* (Cambridge University Press, Cambridge, 1995), Chaps. 3 and 6.
[15] J. M. MacLaren, X. G. Zhang, and W. H. Butler, Phys. Rev. B **56**, 11827 (1997).
[16] For example, R. Y. Gu, D. Y. Xing, and J. M. Dong, J. Appl. Phys. **80**, 7163 (1996); P. Lyu, D. Y. Xing, and J. M. Dong, Phys. Rev. B **60**, 4235 (1999).