Spin-filter tunneling magnetoresistance in a magnetic tunnel junction

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A systematic study is carried out on the spin-filter (SF) tunneling magnetoresistance (TMR) occurring in a ferromagnetic metal/ferromagnetic insulator/ferromagnetic metal (FM/FI/FM) tunnel junction. The theoretical investigation gives a unified and compact description on the SF and TMR effects in this structure, and qualitatively explains the relevant experiments in this area. Specifically, due to the strong SF effect, the TMR can be separately controlled by the extended Slonczewski's polarization factors, leading to both the barrier-height and bias-voltage induced sign-change behavior. It is also proved that this structure can provide a positively or negatively large and stable TMR, which does not vary appreciably with increasing the bias. These features are very prominent compared with an FM/I/FM conventional magnetic tunnel junction and are believed to be of practical use in designing spintronic devices.

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The spin-filter (SF) tunneling magnetoresistance (TMR) in a ferromagnetic metal/ferromagnetic insulator/ferromagnetic metal (FM/FI/FM) tunnel junction is actually a combination of the TMR effect in conventional magnetic tunnel junctions and the SF effect in simple spin-filter junctions. The TMR effect is concerned with the electrode-controlled different currents under different magnetizations, while the SF effect is usually the spacer-controlled different currents with different spins. Compared with a well-known ferromagnetic metal/insulator/ferromagnetic metal (FM/I/FM) junction,[1–4] the FI spacer in a FM/FI/FM junction provides two spin-dependent barriers.[5] An electron with its spin parallel or antiparallel to the direction of magnetization in the FI spacer will tunnel through a lower or higher barrier. Even for a small exchange splitting between the two magnetic subbands of the FI spacer, the tunneling process through the higher barrier is negligible compared with that through the lower barrier.[6,7] Our theoretical work proves that the absence of the higher-barrier spin-channels due to the strong SF effect gives rise to the barrier-height induced sign-change behavior for TMR in this junction, which generalizes Slonczewski's result in FM/I/FM non-SF junctions.[2] This result qualitatively explains the experiment by Nowak and Rauluszkiewicz.[8] We also find that the TMR in the FM/FI/FM junction can be maintained in a stably high value with increasing the bias, if only the barrier-height is sufficiently high or low. This feature suggests the possibility to develop new kinds of spintronic devices.[9,10]

We consider a general spintronic tunneling model for an FM/FI/FM tunnel junction in which the two FM electrodes are assumed to be different, shown in Fig. 1. μ_L and μ_R are the Fermi energies of the left and right electrodes measured from the centers of their exchange splittings Δ_L and Δ_R. ϕ_L and ϕ_R are the work functions at the two interfaces measured from the Fermi level μ of the system to the center of barrier exchange splitting Δ_B. $\delta\mu=\mu_L-\mu_R$ and $\delta\phi=\phi_L-\phi_R$ stand for the differences of the Fermi energies and work functions between the left and right regions. Both the applied bias-voltage eV and the built-in bias-voltage $\delta\phi$ contribute to the difference of the interfacial barrier-heights $\delta U=U_L-U_R=\delta\phi+eV$, where $U_L=\mu+\phi_L$, $U_R=\mu+\phi_R-eV$. d denotes the barrier width, and m_L, m_B, and m_R are the effective masses in three regions.

Choosing the energy zero of the system so that $\mu=\mu_L$, the model Hamiltonian is given by

$$\hat{\mathcal{H}}_\sigma=-\frac{\hbar^2}{2m_\nu}\nabla^2+U(x)-\sigma_\nu\Delta_\nu,\quad(\nu=L,B\text{ or }R),\tag{1}$$

with the x-dependent potential

$$U(x)=\begin{cases}0, & x<0,\\ U_L-(\delta U/d)x, & 0\leqslant x\leqslant d,\\ \delta\mu-eV, & x>d,\end{cases}\tag{2}$$

and the spin indices

$$\sigma_\nu=\theta_\nu\sigma\quad(\nu=L,B\text{ or }R).\tag{3}$$

σ is the conserved spin orientation in three regions. $\sigma=+1(\uparrow)$ or $-1(\downarrow)$ means up-spin or down-spin with respect to the positive z direction. $\theta_\nu=+1(\Uparrow)$ or $-1(\Downarrow)$ denotes the magnetization direction in the ν region, parallel or antiparallel to the positive z direction. Then $\sigma_\nu=+1(\uparrow)$ or $-1(\downarrow)$ is the relative spin orientation, parallel or antiparallel to the given magnetization in the ν region. Without loss of generality, we fix $\theta_B=+1(\Uparrow)$, i.e., $\sigma_B=\sigma$, and let θ_L and θ_R vary. Referring to Fig. 1, the tunneling electrons with $\sigma=+1(\uparrow)$ experience the lower barrier connected by $U_{L\uparrow}$ and $U_{R\uparrow}$, while those with $\sigma=-1(\downarrow)$ experience the higher barrier connected by $U_{L\downarrow}$ and $U_{R\downarrow}$. In addition, we shall employ some useful energy relationships: $U_{L\sigma_B}=U_L-\sigma_B\Delta_B$, $U_{R\sigma_B}=U_R-\sigma_B\Delta_B$, $\phi_{L\sigma_B}=\phi_L-\sigma_B\Delta_B$, $\phi_{R\sigma_B}=\phi_R-\sigma_B\Delta_B$, $\mu_{L\sigma_L}=\mu_L+\sigma_L\Delta_L$, $\mu_{R\sigma_R}=\mu_R+\sigma_R\Delta_R$.

The eigenenergy $\mathcal{E}$ and the transverse momentum $\hbar\boldsymbol{q}$ are conserved in this structure, then the longitudinal energies in three regions can be expressed by

$$E_\nu=\mathcal{E}-\hbar^2q^2/2m_\nu\quad(\nu=L,B\text{ or }R).\tag{4}$$

Since $U_{L\sigma_B}$ and $U_{R\sigma_B}$ are normally larger than E_B, the asymptotic expansion of Airy's functions[11,12] gives an approximated but highly precise formula for the transmission

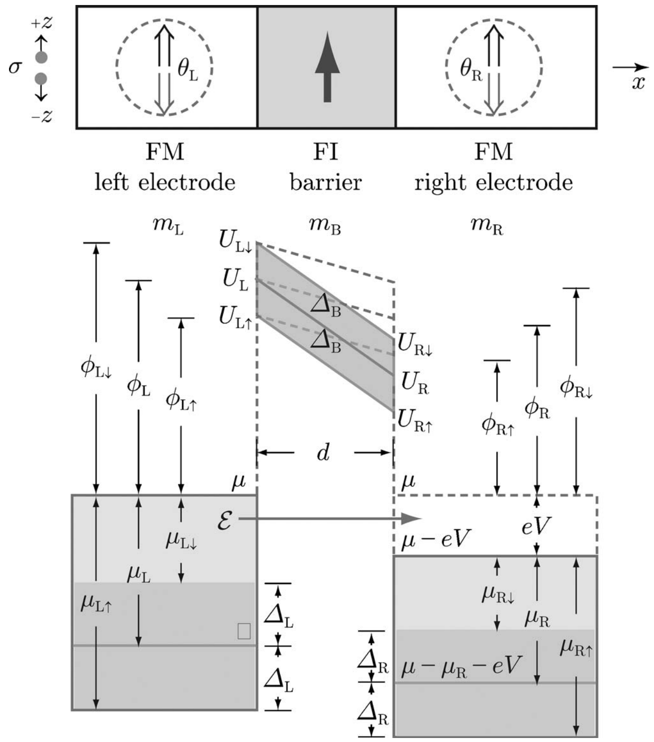

FIG. 1. Schematic diagram of a FM/FI/FM tunnel junction with spin-dependent potential, energy relationships, and magnetization configurations.

coefficient of each spin channel σ under a certain magnetization $\theta_L\theta_R$,

$$T_\sigma^{\theta_L\theta_R}(\mathcal{E},q) = \frac{16 k_{L\sigma_L} k_{R\sigma_R} \kappa_{L\sigma_B} \kappa_{R\sigma_B} e^{-2\xi_{\sigma_B} d}}{(k_{L\sigma_L}^2 + \kappa_{L\sigma_B}^2)(k_{R\sigma_R}^2 + \kappa_{R\sigma_B}^2)}, \tag{5}$$

where the reduced wave vectors are

$$k_{L\sigma_L} = \lambda_L (E_L + \sigma_L \Delta_L)^{1/2}, \tag{6a}$$

$$k_{R\sigma_R} = \lambda_R (E_R - \delta\mu + eV + \sigma_R \Delta_R)^{1/2}, \tag{6b}$$

$$\kappa_{L\sigma_B} = \lambda_B (U_{L\sigma_B} - E_B)^{1/2}, \tag{6c}$$

$$\kappa_{R\sigma_B} = \lambda_B (U_{R\sigma_B} - E_B)^{1/2}, \tag{6d}$$

and the decaying WKB wave vector is

$$\xi_{\sigma_B} = \frac{2}{3} \frac{\lambda_B}{|\delta U|} \left| (U_{L\sigma_B} - E_B)^{3/2} - (U_{R\sigma_B} - E_B)^{3/2} \right|. \tag{7}$$

Here $\lambda_\nu = \sqrt{2m_e^2/m_\nu \hbar^2}$ ($\nu = L$, B or R) with m_e the free-electron mass. The above result is an extension to Gundlach's work in normal metal/insulator/normal metal (NM/I/NM) nonmagnetic tunnel junctions, exhibiting the regular tunneling (RT) effect.[12] It also applies to the square-barrier case,[5] where $U_{L\sigma_B} = U_{R\sigma_B} = U_{\sigma_B}$ and $\lim_{\delta U \to 0} \xi_{\sigma_B} = \lambda_B (U_{\sigma_B} - E_B)^{1/2} = \kappa_{\sigma_B}$. Although Eq. (5) is a function of the bias-voltage eV, it is valid only in the small-bias case. As the bias goes very high, a new transmission formula can be obtained to describe the oscillatory behavior.[4,12] To our knowledge, no experiments for this case in FM/FI/FM junctions have been reported so far. We thus confine our discussion within the small-bias case, which is preferred by most experimentalists.

When the applied bias-voltage eV is small and the barrier-width d is large, the transmission at the Fermi level μ with $q=0$ contributes predominantly. Following the conventional treatment,[2,13,14] we obtain the zero-temperature conductance as

$$G_\sigma^{\theta_L\theta_R} = \frac{J_\sigma^{\theta_L\theta_R}}{V} = \frac{e^2}{8\pi^2\hbar} \frac{\xi_{\sigma_B}}{d} T_\sigma^{\theta_L\theta_R}(\mu,0). \tag{8}$$

Hereafter, we assume all the wave vectors take their values at the Fermi level. For a given magnetization configuration, the total conductance is given by summing over both the up-spin and down-spin channels

$$G^{\theta_L\theta_R} = G_\uparrow^{\theta_L\theta_R} + G_\downarrow^{\theta_L\theta_R}. \tag{9}$$

Conventionally, the TMR ratio between $G^{\Uparrow\Uparrow}$ and a given conductance $G^{\theta_L\theta_R}$ is defined as[15,16]

$$\eta^{\theta_L\theta_R} = (G^{\Uparrow\Uparrow} - G^{\theta_L\theta_R})/(G^{\Uparrow\Uparrow} + G^{\theta_L\theta_R}). \tag{10}$$

Since there exist two spin-dependent barriers in the present structure, we introduce two sub-TMR ratios

$$\eta_\sigma^{\theta_L\theta_R} = (G_\sigma^{\Uparrow\Uparrow} - G_\sigma^{\theta_L\theta_R})/(G_\sigma^{\Uparrow\Uparrow} + G_\sigma^{\theta_L\theta_R}) \tag{11}$$

associated with the higher barrier ($\sigma = \downarrow$) and lower barrier ($\sigma = \uparrow$), respectively. We also define a SF ratio

$$\alpha^{\theta_L\theta_R} = (G_\downarrow^{\Uparrow\Uparrow} + G_\downarrow^{\theta_L\theta_R})/(G_\uparrow^{\Uparrow\Uparrow} + G_\uparrow^{\theta_L\theta_R}) \tag{12}$$

to represent the ratio between conductances through the higher and lower barriers. The less the $\alpha^{\theta_L\theta_R}$, the stronger the SF effect. Then the TMR can be reformulated as

$$\eta^{\theta_L\theta_R} = (\eta_\uparrow^{\theta_L\theta_R} + \alpha^{\theta_L\theta_R} \cdot \eta_\downarrow^{\theta_L\theta_R})/(1 + \alpha^{\theta_L\theta_R}). \tag{13}$$

This equation clearly shows that if the SF effect is very strong, $\alpha^{\theta_L\theta_R} \to 0$, then $\eta^{\theta_L\theta_R} \approx \eta_\uparrow^{\theta_L\theta_R}$, which means the down-spin channels are almost filtered and the TMR will only be dominated by the sub-TMR through the up-spin channels.

To begin our analytical analysis, we first notice that all the effective mass parameters can be renormalized into the energy parameters $\mu_{L\sigma_L}$, $\mu_{R\sigma_R}$, $\phi_{L\sigma_B}$, $\phi_{R\sigma_B}$ and eV according to Eq. (6), under the approximation leading to Eq. (8). Without loss of generality, we may simply set $m_L = m_B = m_R = m_e$, as we focus on the properties controlled by the energy parameters.[2,5] In addition, our model Hamiltonian is quite general, which applies to various tunnel junctions, as shown in Table I. This comparison improves our understanding on the physical mechanism of the SF and TMR effects in FM/FI/FM junctions.

For a simple SF junction NM/FI/NM, $k_{L\uparrow} = k_{L\downarrow} = k_L$, $k_{R\uparrow} = k_{R\downarrow} = k_R$. θ_L and θ_R are unnecessary, because there is no TMR effect in this junction, $\eta = 0$. However, the SF ratio

TABLE I. Comparison between various tunnel junctions.

Value	Junction type	Effect
$\Delta_L=0,\ \Delta_R=0$	NM/I/NM	
$\Delta_B=0$	nonmagnetic junction[a]	RT
$\Delta_L=0,\ \Delta_R=0$	NM/FI/NM	
$\Delta_B\neq 0$	simple spin-filter junction[b]	SF
$\Delta_L\neq 0,\ \Delta_B\neq 0$	FM/I/FM	
$\Delta_B=0$	conventional magnetic junction[c]	TMR
$\Delta_L\neq 0,\ \Delta_R=0$	FM/FI/NM	SF
$\Delta_B\neq 0$	partial magnetic junction[d]	TMR
$\Delta_L\neq 0,\ \Delta_R\neq 0$	FM/FI/FM	SF
$\Delta_B\neq 0$	full magnetic junction[e]	TMR

[a]Reference 12.
[b]Reference 17.
[c]References 2 and 3.
[d]Reference 10.
[e]References 5 and 8.

$$\alpha=\frac{\xi_\downarrow}{\xi_\uparrow}\frac{\kappa_{L\downarrow}\kappa_{R\downarrow}}{\kappa_{L\uparrow}\kappa_{R\uparrow}}\frac{(k_L^2+\kappa_{L\uparrow}^2)(k_R^2+\kappa_{R\uparrow}^2)}{(k_L^2+\kappa_{L\downarrow}^2)(k_R^2+\kappa_{R\downarrow}^2)}e^{-2(\xi_\downarrow-\xi_\uparrow)d} \tag{14}$$

plays its role, which is dominated by the product of Δ_B and d in $e^{-2(\xi_\downarrow-\xi_\uparrow)d}$. To increase Δ_B and d could largely strengthen the SF effect.

For a conventional magnetic junction FM/I/FM, $\kappa_{L\uparrow}=\kappa_{L\downarrow}=\kappa_L$, $\kappa_{R\uparrow}=\kappa_{R\downarrow}=\kappa_R$ and $\xi_\uparrow=\xi_\downarrow=\xi$. There are only two effective configurations $\Uparrow\Uparrow$ and $\Uparrow\Downarrow$. No SF effect exists in this junction, $\alpha^{\Uparrow\Downarrow}=1$. But the TMR is[2,16]

$$\eta^{\Uparrow\Downarrow}=P_L\times P_R, \tag{15}$$

which is the product of Slonczewski's polarization factors

$$P_L=\frac{(k_{L\uparrow}-k_{L\downarrow})(\kappa_L^2-k_{L\uparrow}k_{L\downarrow})}{(k_{L\uparrow}+k_{L\downarrow})(\kappa_L^2+k_{L\uparrow}k_{L\downarrow})}, \tag{16}$$

$$P_R=\frac{(k_{R\uparrow}-k_{R\downarrow})(\kappa_R^2-k_{R\uparrow}k_{R\downarrow})}{(k_{R\uparrow}+k_{R\downarrow})(\kappa_R^2+k_{R\uparrow}k_{R\downarrow})}. \tag{17}$$

The terms $\kappa_L^2-k_{L\uparrow}k_{L\downarrow}$ and $\kappa_R^2-k_{R\uparrow}k_{R\downarrow}$, known as the Slonczewski's quantum-coherent factors, take the forms

$$\kappa_L^2-k_{L\uparrow}k_{L\downarrow}\propto\phi_L-\sqrt{\mu_L^2-\Delta_L^2}, \tag{18}$$

$$\kappa_R^2-k_{R\uparrow}k_{R\downarrow}\propto\phi_R-eV-\sqrt{(\mu_R+eV)^2-\Delta_R^2}. \tag{19}$$

They are linear functions of ϕ_L and ϕ_R, while the left work function ϕ_L is also called the barrier-height of the system measured from the Fermi level. Interestingly, for a symmetric junction ($\mu_L=\mu_R=\mu$, $\Delta_L=\Delta_R=\Delta$, $\phi_L=\phi_R=\phi$), at zero bias, $P_L=P_R$ and $\eta^{\Uparrow\Downarrow}=P_L^2$. Reducing the barrier-height ϕ gives rise to the simultaneous sign-change of P_L and P_R. Therefore, the sign-change of the quantum-coherent factors has no observable sign-change of the zero-bias TMR in symmetric FM/I/FM junctions due to the product form of the TMR in Eq. (15). To observe the sign-change behavior, one should apply a bias so that $P_R<0$ while the barrier-height ϕ keeps high so that $P_L>0$.[3,4] However, the situation will be significantly different in FM/FI/FM junctions, as can be seen in the following text.

Combining the functions of the NM/FI/NM and FM/I/FM junctions, we can get an FM/FI/FM tunnel junction, which exhibits both the SF effect and TMR effect. In contrast to the conventional magnetic tunnel junction, there are four effective magnetization configurations. The SF ratio can be extended to

$$\alpha^{\theta_L\theta_R}=\frac{\xi_\downarrow}{\xi_\uparrow}\frac{\kappa_{L\downarrow}\kappa_{R\downarrow}}{\kappa_{L\uparrow}\kappa_{R\uparrow}}A^{\theta_L\theta_R}e^{-2(\xi_\downarrow-\xi_\uparrow)d}, \tag{20}$$

which is still dominated by Δ_B and d in $e^{-2(\xi_\downarrow-\xi_\uparrow)d}$, as discussed in Eq. (14), but the factor $A^{\theta_L\theta_R}$ depends on the magnetization configuration. Owing to its lengthy form, we do not show it explicitly here. More importantly, we can find three sets of sub-TMR's,

$$\eta_\sigma^{\Downarrow\Uparrow}=P_{L\sigma}=\frac{(k_{L\bar{\sigma}_L}-k_{L\sigma_L})(\kappa_{L\sigma_B}^2-k_{L\uparrow}k_{L\downarrow})}{(k_{L\bar{\sigma}_L}+k_{L\sigma_L})(\kappa_{L\sigma_B}^2+k_{L\uparrow}k_{L\downarrow})}, \tag{21}$$

$$\eta_\sigma^{\Uparrow\Downarrow}=P_{R\sigma}=\frac{(k_{R\bar{\sigma}_R}-k_{R\sigma_R})(\kappa_{R\sigma_B}^2-k_{R\uparrow}k_{R\downarrow})}{(k_{R\bar{\sigma}_R}+k_{R\sigma_R})(\kappa_{R\sigma_B}^2+k_{R\uparrow}k_{R\downarrow})}, \tag{22}$$

where $\bar{\sigma}_L=-\sigma_L$ and $\bar{\sigma}_R=-\sigma_R$, and particularly

$$\eta_\sigma^{\Downarrow\Downarrow}=\frac{P_{L\sigma}+P_{R\sigma}}{1+P_{L\sigma}P_{R\sigma}}\approx P_{L\sigma}+P_{R\sigma}. \tag{23}$$

The last step in Eq. (23) is reasonable because $P_{L\sigma}P_{R\sigma}$ is usually in the order of 10^{-2}. Also, numerical results prove that $\eta_\uparrow^{\theta_L\theta_R}$ and $\eta_\downarrow^{\theta_L\theta_R}$ are in the same order but $\alpha^{\theta_L\theta_R}\ll 1$, then refer to Eq. (13), we obtain the important result

$$\eta^{\Downarrow\Downarrow}\approx\eta_\uparrow^{\Downarrow\Downarrow}\approx P_{L\uparrow}+P_{R\uparrow}. \tag{24}$$

$\eta^{\Downarrow\Downarrow}$ is just the conventional definition of TMR in FM/FI/FM junctions.[8] Here, we find it is approximately equal to the sum of the two extended Slonczewski's polarization factors, in contrast to the product form of TMR in FM/I/FM junctions.

The extended Slonczewski's quantum-coherent factors in $P_{L\uparrow}$ and $P_{R\uparrow}$ take the forms

$$\kappa_{L\uparrow}^2-k_{L\uparrow}k_{L\downarrow}\propto\phi_{L\uparrow}-\sqrt{\mu_L^2-\Delta_L^2}, \tag{25}$$

$$\kappa_{R\uparrow}^2-k_{R\uparrow}k_{R\downarrow}\propto\phi_{R\uparrow}-eV-\sqrt{(\mu_R+eV)^2-\Delta_R^2}. \tag{26}$$

They are also the linear functions of the barrier height. Again, taking symmetric junction as an example, the zero-bias TMR can now be written as $\eta^{\Downarrow\Downarrow}\approx 2P_{L\uparrow}$ since $P_{R\uparrow}=P_{L\uparrow}$. This TMR exhibits an observable sign-change behavior as the barrier-height ϕ varies from high to low, which is completely different from that in FM/I/FM junctions. Although experimentally the two electrodes may not be symmetric, the above analysis is still approximately valid as long as $\delta\phi$, $\delta\mu$ and $\Delta_L-\Delta_R$ are not too large. Our theoretical result qualitatively explains the experiment by Nowak and Rauluszkiewicz.[8] For a relatively high barrier, the TMR is

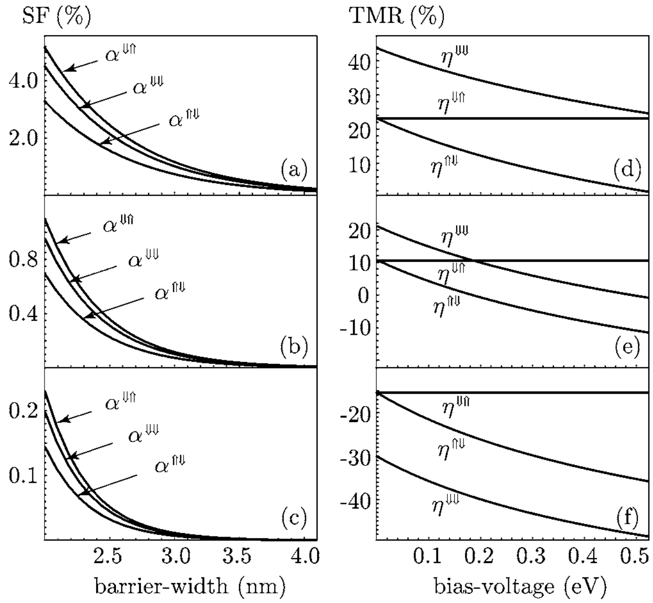

FIG. 2. Spin-filter and tunneling magnetoresistance ratios. $\mu_L = \mu_R = 2.5$ eV, $\Delta_L = \Delta_R = 2.2$ eV (Refs. 18 and 19). In the left panel, $\phi_L = 2.0$ eV, $eV = 0.5$ eV. (a) Weak barrier-splitting $\Delta_B = 0.2$ eV; (b) moderate barrier-splitting $\Delta_B = 0.3$ eV; (c) strong barrier-splitting $\Delta_B = 0.4$ eV. In the right panel, $\Delta_B = 0.3$ eV, $d = 3$ nm (Refs. 17 and 20); (d) high barrier-height $\phi_L = 3.0$ eV; (e) moderate barrier-height $\phi_L = 2.0$ eV; (f) low barrier-height $\phi_L = 1.0$ eV.

positive, corresponding to the case of Fig. 4 in Ref. 8. On the contrary, TMR will be negative for a relatively low barrier, which agrees with the case of Fig. 6 in Ref. 8. In a word, the barrier-height of the FI spacer can physically control the sign of the zero-bias TMR in FM/FI/FM junctions.

In our numerical calculation, we still employ the symmetric junction for simplicity. The left panel of Fig. 2 confirms that the SF ratio $\alpha^{\theta_L\theta_R}$ is very small and decreases rapidly with Δ_B and d, which lends itself to the validity of Eq. (24). In the right panel of Fig. 2, one can see that $\eta^{\Downarrow\Uparrow}$ only depends on the barrier-height and provides a TMR baseline, while $\eta^{\Uparrow\Downarrow}$ depends on both barrier-height and bias-voltage and exhibits the bias-induced variation from this baseline. $\eta^{\Downarrow\Downarrow}$ is the combination of the two, controlled by both barrier-height and bias-voltage through Eqs. (21) and (22) separately. Referring to our preceding analytical discussion, both barrier-height and bias-voltage induced sign-change behaviors can be clearly seen.

By investigating Fig. 2 in detail, one may notice that $\eta^{\Downarrow\Downarrow}$ can be maintained in a very wide range of applied bias without changing its sign, if only the barrier-height is sufficiently high or low. This is a natural result due to Eq. (24), because a large TMR baseline (positive or negative) is provided by the barrier height in $\eta^{\Downarrow\Uparrow}$. Also, we can see that the low barrier is more useful than the high barrier in practice, because it provides not only a large TMR (absolute value) but even gives an increasing TMR with increasing the bias, which does not exist in non-SF junctions. These features are of much practical use in designing spintronic devices.[9,10]

In summary, we have developed a single-electron theory for an FM/FI/FM tunnel junction. The SF effect as well as the TMR effect was systematically analyzed. Combining these two effects, it has been found that the total TMR is the sum, rather than the product, of the polarization factors on the two interfaces. As a result, the zero-bias TMR can change its sign as the barrier-height varies, which agrees well with the relevant experiment. In addition, a positively or negatively large TMR can be maintained in a wide range of applied bias. Our work is suggestive for developing new kinds of spintronic devices.

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