Temperature dependence of tunneling magnetoresistance in manganite tunnel junctions

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The mechanism of temperature-dependent tunneling magnetoresistance (TMR) is proposed for manganite tunnel junctions. Using the transfer Hamiltonian method, we show that the variation of the electronic spin polarization and the collective excitations of local spins at the interfaces between the insulator and the manganite electrodes are responsible for the drop of the maximum TMR ratio with increasing temperature. The theoretical result can reproduce the main characteristic feature of the experimental data in the trilayer junction structure, $La_{0.67}Sr_{0.33}MnO_3/SrTiO_3/La_{0.67}Sr_{0.33}MnO_3$. [S0163-1829(99)09229-2]

I. INTRODUCTION

The mixed-valence manganese oxides $La_{1-x}A_xMnO_3$ (A = Sr, Ca, Ba, etc.) have been extensively studied in recent years due to their colossal magnetoresistance (CMR) effect.[1–5] In the interesting doping range $0.2 \lesssim x \lesssim 0.5$, $La_{1-x}A_xMnO_3$ is a metallic ferromagnet below the Curie temperature T_C. The coexistence of ferromagnetism and metallic behavior is usually explained by the double-exchange mechanism.[6–8] An important feature in the manganites is the strong Hund coupling between the Mn t_{2g} local spin ($S=3/2$) and the Mn e_g itinerant electron, which dominates the basic physics of this system. The e_g electron spin combines with the local spin to form two configurations of the total spin, $S+\frac{1}{2}$ and $S-\frac{1}{2}$, respectively. As a result of the strong Hund coupling, the $S-\frac{1}{2}$ configuration and the doubly occupied state are forbidden, so that there exists only the $S+\frac{1}{2}$ configuration. At temperatures well below T_C, the relatively narrow majority carrier conduction band (bandwidth about 1.5 eV) is completely separated from the minority band by the large Hund coupling energy, as well as the exchange energy ($\Delta_{ex} \simeq 2.5$ eV), which leads to a nearly complete spin polarization of the electrons.[9–12] The conduction band of such a half-metallic ferromagnet is substantially different from those of ordinary itinerant ferromagnets such as Fe, Co, Ni, and their alloys.[13] Also, the optical conductivity spectra measurements indicate that there is a large variation of the electronic structure for $La_{1-x}A_xMnO_3$ with temperature.[9] With increasing temperature from $T=0$, the exchange-split energy Δ_{ex} will be gradually reduced. As the temperature is increased beyond a certain temperature T_0 ($T_0 \ll T_C$), the density of states (DOS) for the majority band begins to decrease while the nonzero DOS for the minority band appears and increases with further increasing T. Thus the system undergoes a crossover from a half-metallic state to an ordinary metallic state at T_0. For $T \geqslant T_C$, the electron occupations of the majority and minority bands are equal and no spin polarization exists. It is obvious that the electron-spin polarization is sensitively dependent on the variation of the electronic structure in the manganites.

The manganese perovskites $La_{1-x}A_xMnO_3$ exhibit CMR effect when subjected to a high magnetic field of the order of Tesla. In order to reduce the field scale in the magnetotransport of manganites, the $La_{0.67}Sr_{0.33}MnO_3/SrTiO_3/La_{0.67}Sr_{0.33}MnO_3$ trilayer structure was proposed and investigated.[14–16] Large tunneling magnetoresistance (TMR) was observed as high as 83% in this tunnel junction at low magnetic fields of only tens of Oe at 4.2 K, and the temperature dependence of the maximum TMR ratio was also obtained.[14] Below 90 K, the maximum TMR ratio decreases slowly with increasing temperature. The drop in the maximum TMR ratio accelerates above 90 K and the magnetoresistance effect vanishes at about 200 K, which is much lower than $T_C \approx 347$ K for $La_{0.67}Sr_{0.33}MnO_3$. This temperature dependence of the TMR is very interesting, but is short on theoretical explanations. As a result, it is highly desirable to develop a theoretical model to account for this experimental result.

In the previous work,[17] we have derived an effective tunneling Hamiltonian for the manganite tunnel junctions by considering the strong Hund coupling and the spin-flip tunneling arising mainly from the impurity states of Mn ions in $SrTiO_3$ barrier to explain the large TMR ratio at 4.2 K. In this work, we focus our attention on the temperature dependence of TMR in the manganite tunnel junctions. In the next section, an inelastic-tunneling model including both the collective excitations of local spins at the interfaces and the spin-flip tunneling induced by the impurity states of Mn ions in $SrTiO_3$ barrier is presented for the manganite tunnel junctions. In Sec. III, the variation of the electronic spin polarization with temperature is obtained in the manganites. In Sec. IV, it is shown that the drop of the TMR ratio with increasing temperature is attributed to the variation of the electronic spin polarization and the collective excitations of the local spins at the interfaces. Finally, a brief summary is given in Sec. V.

II. INELASTIC-TUNNELING MODEL

The spin collective excitations localized at the interfaces between the insulating barrier and the ferromagnetic electrodes have been taken into account in the tunneling theory of the ordinary ferromagnet tunnel junctions, such as $Co/Al_2O_3/CoFe$ trilayers, to account for the *zero-bias anomaly* using the spin-wave approximation within the framework of the transfer Hamiltonian method.[18] It is neces-

sary to generalize this model to be suitable for the whole temperature range. For the collinear magnetization configurations, the system Hamiltonian of the manganite tunnel junctions is written as

$$H = H_{\mathrm{L}} + H_{\mathrm{R}} + H_{\mathrm{T}}, \tag{1}$$

$$H_{\mathrm{L}} = \sum_{\mathbf{p}\sigma} \varepsilon_{\mathbf{p}\sigma} c^{\dagger}_{\mathbf{p}\sigma} c_{\mathbf{p}\sigma} - J \sum_{i,j\in I} \mathbf{S}_{Li} \cdot \mathbf{S}_{Lj}, \tag{2}$$

$$H_{\mathrm{R}} = \sum_{\mathbf{k}\sigma} \varepsilon_{\mathbf{k}\sigma} d^{\dagger}_{\mathbf{k}\sigma} d_{\mathbf{k}\sigma} - J \sum_{i,j\in I} \mathbf{S}_{Ri} \cdot \mathbf{S}_{Rj}, \tag{3}$$

$$\begin{aligned} H_{\mathrm{T}} = {} & \sum_{\mathbf{kp}\sigma} (T^{0}_{\mathbf{kp}} d^{\dagger}_{\mathbf{k}\sigma} c_{\mathbf{p}\sigma} + \mathrm{H.c.}) + \sum_{\mathbf{kp}\sigma} (iT'_{\mathbf{kp}} d^{\dagger}_{\mathbf{k}\sigma} c_{\mathbf{p},-\sigma} + \mathrm{H.c.}) \\ & + \frac{1}{\sqrt{N_S}} \sum_{\mathbf{kpq}} \{T''_{\mathbf{kpq}} [S^{z}_{L}(\mathbf{q}) + S^{z}_{R}(\mathbf{q})] \\ & \times (d^{\dagger}_{\mathbf{k}\uparrow} c_{\mathbf{p}\uparrow} - d^{\dagger}_{\mathbf{k}\downarrow} c_{\mathbf{p}\downarrow}) + \mathrm{H.c.}\} \\ & + \frac{1}{\sqrt{N_S}} \sum_{\mathbf{kpq}} \{T''_{\mathbf{kpq}} [S^{+}_{L}(\mathbf{q}) + S^{+}_{R}(\mathbf{q})] \\ & \times (d^{\dagger}_{\mathbf{k}\downarrow} c_{\mathbf{p}\uparrow} + c^{\dagger}_{\mathbf{p}\downarrow} d_{\mathbf{k}\uparrow}) + \mathrm{H.c.}\}. \end{aligned} \tag{4}$$

Here H_{L} (H_{R}) is the Hamiltonian for freelike electrons plus the Heisenberg ferromagnetic coupling between the local spins at the interface in the left (right) electrode of the junction. $d_{\mathbf{k}\sigma}$ ($c_{\mathbf{p}\sigma}$) is the spin σ electron operator of the right (left) manganite electrode.

$$S^{z}_{\alpha}(\mathbf{q}) = (1/\sqrt{N_S}) \Sigma_{j\in I} S^{z}_{\alpha j} \exp(i\mathbf{q}\cdot\mathbf{R}_{\alpha j}),$$

$$S^{\pm}_{\alpha}(\mathbf{q}) = (1/\sqrt{N_S}) \Sigma_{j\in I} S^{\pm}_{\alpha j} \exp(\pm i\mathbf{q}\cdot\mathbf{R}_{\alpha j})$$

with $S^{\pm}_{\alpha j} = (S^{x}_{\alpha j} \pm i S^{y}_{\alpha j})/2$, $\alpha = L$ or R. N_S is the number of local spins at the interface and $\mathbf{q}$ is the two-dimensional wave vector parallel to the interface. The second term of Eq. (4) represents the spin-flip tunneling which has been introduced to the tunneling Hamiltonian for the ordinary ferromagnetic tunnel junctions in Ref. 19. For the manganite tunnel junctions this type of spin-flip tunneling arises from the impurity states of Mn ions inside $SrTiO_3$ barrier.[17] The imaginary i for the spin-flip tunneling matrix elements means the incoherence of the elastic spin-conserving and elastic spin-flip tunneling processes in any magnetization configurations. The last two terms of Eq. (4) denote the spin-conserving and spin-flip tunneling induced by the collective excitations of the local spins at interfaces. The electron tunneling involving the emission or absorption of the local spin collective excitations at the left and right interfaces is an inelastic-tunneling process. That the wave vector $\mathbf{k}$ is independent of $\mathbf{p}$ in Eq. (4) implies considering only the incoherent tunneling, which is appropriate for the defect-populated insulator and the rough interfaces.

The electrons that participate in the tunneling current have their energies very near the chemical potential on both sides of the tunnel junction. It is an adequate approximation to treat the transfer rates $|T^{0}_{\mathbf{kp}}|^2$, $|T'_{\mathbf{kp}}|^2$, and $|T''_{\mathbf{kpq}}|^2$ as their average values $|T^{0}|^2$, $|T'|^2$, and $|T''|^2$, respectively. Using the standard Green's-function techniques,[20] the tunneling current for the parallel magnetization configurations between the two electrodes is derived as

$$I_{\mathrm{P}} = I_{\mathrm{P1}} + I_{\mathrm{P2}} \tag{5}$$

with

$$\begin{aligned} I_{\mathrm{P1}} = {} & 2\pi e^2 V \left(|T^{0}|^2 + \sum_{\alpha} \langle S^{z}_{\alpha} \rangle^2 |T''|^2 \right) [\rho^{m}_{L}(\mu_L)\rho^{m}_{R}(\mu_R) + \rho^{M}_{L}(\mu_L)\rho^{M}_{R}(\mu_R)] \\ & + 2\pi e^2 V |T'|^2 [\rho^{m}_{L}(\mu_L)\rho^{M}_{R}(\mu_R) + \rho^{M}_{L}(\mu_L)\rho^{m}_{R}(\mu_R)], \end{aligned} \tag{6}$$

and

$$\begin{aligned} I_{\mathrm{P2}} = {} & \frac{2\pi e}{N_S} |T''|^2 \sum_{\mathbf{q}\alpha} [\langle S^{-}_{\alpha}(\mathbf{q}) S^{+}_{\alpha}(\mathbf{q}) \rangle (eV + E_{\mathbf{q}}) \theta(eV + E_{\mathbf{q}}) \rho^{m}_{L}(\mu_L) \rho^{M}_{R}(\mu_R) \\ & + \langle S^{-}_{\alpha}(\mathbf{q}) S^{+}_{\alpha}(\mathbf{q}) \rangle (eV - E_{\mathbf{q}}) \theta(E_{\mathbf{q}} - eV) \rho^{M}_{L}(\mu_L) \rho^{m}_{R}(\mu_R) \\ & + \langle S^{+}_{\alpha}(\mathbf{q}) S^{-}_{\alpha}(\mathbf{q}) \rangle (eV - E_{\mathbf{q}}) \theta(eV - E_{\mathbf{q}}) \rho^{M}_{L}(\mu_L) \rho^{m}_{R}(\mu_R) \\ & + \langle S^{+}_{\alpha}(\mathbf{q}) S^{-}_{\alpha}(\mathbf{q}) \rangle (eV + E_{\mathbf{q}}) \theta(-eV - E_{\mathbf{q}}) \rho^{m}_{L}(\mu_L) \rho^{M}_{R}(\mu_R)]. \end{aligned} \tag{7}$$

Here I_{P1} is the contributions to the tunneling current from the first three terms in Eq. (4), while I_{P2} is the inelastic-tunneling current due to the emission or absorption of the local spin collective excitations at the interfaces. $\rho^{M}_{\alpha}(\mu_\alpha)$ and $\rho^{m}_{\alpha}(\mu_\alpha)$ are the majority and minority DOS at the chemical potential μ_α in the α electrode of the tunnel junction, respectively. V is the applied voltage across the junction with $eV = \mu_R - \mu_L$. It is well known[21] that the transverse correlation function is given by $\langle S^{-}_{\alpha}(\mathbf{q}) S^{+}_{\alpha}(\mathbf{q}) \rangle = 2\langle S^{z}_{\alpha} \rangle (e^{E_{\mathbf{q}}/k_B T} - 1)^{-1}$ and $\langle S^{+}_{\alpha}(\mathbf{q}) S^{-}_{\alpha}(\mathbf{q}) \rangle = 2\langle S^{z}_{\alpha} \rangle \exp(E_{\mathbf{q}}/k_B T)(e^{E_{\mathbf{q}}/k_B T} - 1)^{-1}$ with $E_{\mathbf{q}}$ representing the spin collective excitation spectrum at the interfaces. For the longitudinal correlation function, we have used the simple approximation $\langle S^{z}_{\alpha}(\mathbf{q}) S^{z}_{\alpha}(\mathbf{q}) \rangle \approx \langle S^{z}_{\alpha} \rangle^2$. For the same materials of the two electrodes, we have $\rho^{M}_{L}(\varepsilon) = \rho^{M}_{R}(\varepsilon) \equiv \rho^{M}(\varepsilon)$, $\rho^{m}_{L}(\varepsilon) = \rho^{m}_{R}(\varepsilon) \equiv \rho^{m}(\varepsilon)$, $\langle S^{-}_{L}(\mathbf{q}) S^{+}_{L}(\mathbf{q}) \rangle$

$=\langle S_R^-(\mathbf{q})S_R^+(\mathbf{q})\rangle \equiv \langle S^-(\mathbf{q})S^+(\mathbf{q})\rangle$, $\langle S_L^+(\mathbf{q})S_L^-(\mathbf{q})\rangle = \langle S_R^+(\mathbf{q})S_R^-(\mathbf{q})\rangle \equiv \langle S^+(\mathbf{q})S^-(\mathbf{q})\rangle$, and $\langle S_L^z\rangle = \langle S_R^z\rangle \equiv \langle S^z\rangle$. In deriving Eqs. (5)–(7), the crossed terms between the first and third terms of the tunneling Hamiltonian Eq. (4) are ignored as in Ref. 18 and the Fermi distribution function has been approximated to the unit step function, $\theta(x)=1$ for $x>0$ and $\theta(x)=0$ for $x<0$.

Then, the tunneling conductance at zero bias is obtained as

$$G_P = 2\pi e^2(|T^0|^2+2\langle S^z\rangle^2|T''|^2)[\rho_L^m(\mu)\rho_R^m(\mu) + \rho_L^M(\mu)\rho_R^M(\mu)] + 2\pi e^2\left(|T'|^2+\frac{2}{N_S}|T''|^2\sum_{\mathbf{q}}\langle S^-(\mathbf{q})S^+(\mathbf{q})\rangle\right) \times[\rho_L^m(\mu)\rho_R^M(\mu)+\rho_L^M(\mu)\rho_R^m(\mu)] \quad (8)$$

with $\mu_L=\mu_R\equiv\mu$ and the tunneling resistance given by $R_P=1/G_P$.

For the antiparallel magnetization configurations between the two electrodes, one can derive the conductance G_{AP} as

$$G_{AP} = 2\pi e^2(|T^0|^2+2\langle S^z\rangle^2|T''|^2)[\rho_L^m(\mu)\rho_R^M(\mu) + \rho_L^M(\mu)\rho_R^m(\mu)] + 2\pi e^2\left(|T'|^2+\frac{2}{N_S}|T''|^2\sum_{\mathbf{q}}\langle S^-(\mathbf{q})S^+(\mathbf{q})\rangle\right) \times[\rho_L^m(\mu)\rho_R^m(\mu)+\rho_L^M(\mu)\rho_R^M(\mu)]. \quad (9)$$

The corresponding resistance is given by $R_{AP}=1/G_{AP}$.

For the two-dimensional Heisenberg ferromagnet,[21] the collective excitation spectrum of the local spins is given by $E_q=D_Sq^2+E_0$, where D_S is the spin stiffness and E_0 is the spin gap due to anisotropy, with $D_S=D\langle S^z\rangle$ in the long-wavelength limit. At low temperatures, we have $\langle S^z\rangle=S$ and $D_S=DS$, with D taken close to its measured value of the bulk $La_{1-x}A_xMnO_3$.[22,23] In consideration of the above spin collective excitation spectrum, one can obtain

$$\frac{1}{N_S}\sum_{\mathbf{q}}\langle S^-(\mathbf{q})S^+(\mathbf{q})\rangle = -\frac{k_BT}{2\pi D}\ln(1-e^{-E_0/k_BT}). \quad (10)$$

According to its definition, $(\Delta R/R_p)_{max}=(R_{AP}-R_P)/R_P$, the maximum TMR ratio for $La_{1-x}A_xMnO_3$ tunnel junctions is given by

$$\left(\frac{\Delta R}{R_p}\right)_{max} = \frac{2(1-\tilde{\gamma})P^2}{(1-P^2)+\tilde{\gamma}(1+P^2)}, \quad (11)$$

with

$$\tilde{\gamma} = \gamma - \frac{\eta k_BT}{\pi D}\ln(1-e^{-E_0/k_BT}) \quad (12)$$

and

$$P = \frac{\rho^M(\mu)-\rho^m(\mu)}{\rho^M(\mu)+\rho^m(\mu)}, \quad (13)$$

where we have introduced the parameters $\gamma=|T'|^2/|\tilde{T}|^2$ and $\eta=|T''|^2/|\tilde{T}|^2$ with $|\tilde{T}|^2=|T^0|^2+2\langle S^z\rangle^2|T''|^2$ to characterize the spin-flip effects originating from the impurity states of Mn ions inside $SrTiO_3$ barrier and the collective excitations of the local spins at the interfaces, respectively. Since $|T^0|^2$ is one to two orders of magnitude larger than $|T''|^2$,[18] we have $|\tilde{T}|^2\simeq|T^0|^2$, $\gamma\simeq|T'|^2/|T^0|^2$, and $\eta\simeq|T''|^2/|T^0|^2$. P is the electronic spin polarization parameter which is temperature dependent in the manganites. In the absence of the spin-excitation-induced spin-flip tunneling, Eq. (11) is reduced to the corresponding result in Ref. 19. At very low temperatures, $P=100\%$ and so Eq. (11) becomes $(\Delta R/R_p)_{max}=1/\gamma-1$, which can also be obtained in the strong Hund coupling case.[17]

III. ELECTRON-SPIN POLARIZATION IN THE MANGANITES

In order to obtain the temperature dependence of the spin-polarization parameter P in the manganites, one needs to have the electron magnetization as a function of temperature. First, we assume that the electron normalized magnetization $m(T)=M/M_S$ can be described by

$$m(T) = \left[1-\left(\frac{T-T_0}{T_C-T_0}\right)^2\theta(T-T_0)\right]^{1/2} \quad (14)$$

with $T_0 \ll T_C$. This temperature dependence of the electron magnetization is shown in the inset of Fig. 1, which is very similar to the experimental data of the bulk magnetization in the manganese perovskite $La_{0.7}Sr_{0.3}MnO_3$ (Fig. 4 of Ref. 24). For $T<T_0$, we have $m(T)=1$ and so $P=100\%$, the system exhibiting the half-metallic feature.[9–12] For $T_0<T\leqslant T_C$, the behavior of the electronic normalized magnetization $m(T)$ is expected to be similar to that of the normalized ferromagnetic magnetization for a cubic Heisenberg ferromagnet since there exists only the $S+\frac{1}{2}$ configuration for the local spin and the itinerant electron due to the strong Hund coupling. When $T>T_C$, the electron spins become disordered and there is no electronic magnetization.

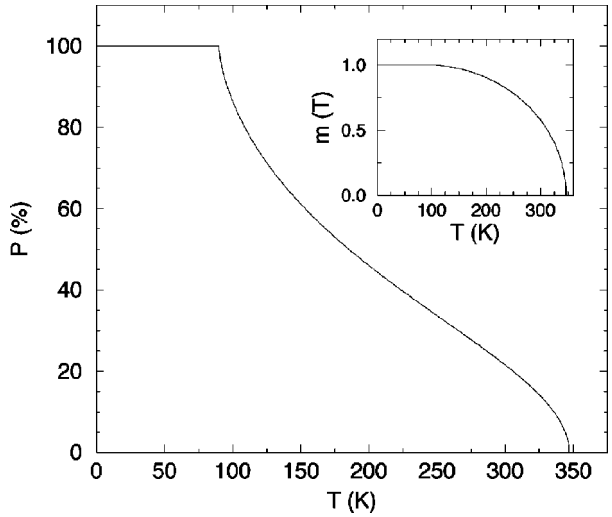

FIG. 1. Electronic spin polarization P versus temperature in the manganites. Electronic normalized magnetization $m(T)$ versus temperature is shown in the inset.

Next, we derive the relation between the spin polarization P and the electronic normalized magnetization $m(T)$. The spin-up and spin-down electron numbers are given by

$$N_{\uparrow}=\int_0^{\infty}\frac{\rho^M(\varepsilon)d\varepsilon}{\exp[(\varepsilon-\mu)/(k_BT)]+1}, \tag{15}$$

$$N_{\downarrow}=\int_{\Delta_{ex}}^{\infty}\frac{\rho^m(\varepsilon)d\varepsilon}{\exp[(\varepsilon-\mu)/(k_BT)]+1} \tag{16}$$

with

$$\rho^M(\varepsilon)=\frac{3}{2}\frac{(1-x)N}{\varepsilon_F^{3/2}}\sqrt{\varepsilon}, \tag{17}$$

$$\rho^m(\varepsilon)=\frac{3}{2}\frac{(1-x)N}{\varepsilon_F^{3/2}}\sqrt{\varepsilon-\Delta_{ex}}, \tag{18}$$

where ε_F is the chemical potential at $T=0$ and μ is temperature dependent. The majority and minority bands are separated by the exchange-split energy Δ_{ex}. For simplicity, $\rho^M(\varepsilon)$ and $\rho^m(\varepsilon)$ are selected as the DOS of freelike electrons per spin direction. For $T<T_0$, $\mu\simeq\varepsilon_F$ has very little variation with temperature, regardless of the temperature-induced decrease in Δ_{ex}. For $T_0<T<T_C$, however, the chemical potential μ, as well as $\rho^M(\mu)$ and $\rho^m(\mu)$, varies strongly with temperature due to the relative shift of the majority and minority bands in the manganites. Under the free-electron approximation, it follows from Eqs. (15) and (16) that

$$N_{\uparrow}\simeq(1-x)N\left(\frac{\mu}{\varepsilon_F}\right)^{3/2}, \tag{19}$$

$$N_{\downarrow}\simeq(1-x)N\left(\frac{\mu-\Delta_{ex}}{\varepsilon_F}\right)^{3/2}. \tag{20}$$

The relations between $N_{\uparrow}$, $N_{\downarrow}$, and $m(T)$ are given by

$$m(T)=\frac{N_{\uparrow}-N_{\downarrow}}{(1-x)N}, \quad (1-x)N=N_{\uparrow}+N_{\downarrow}. \tag{21}$$

From Eqs. (17)–(21) and Eq. (13), the spin polarization P can be expressed as

$$P=\frac{\sqrt[3]{1+m(T)}-\sqrt[3]{1-m(T)}}{\sqrt[3]{1+m(T)}+\sqrt[3]{1-m(T)}}. \tag{22}$$

IV. RESULTS AND DISCUSSIONS

According to Eqs. (14) and (22), the temperature dependence of the electronic normalized magnetization $m(T)$ and the spin polarization P in the manganites are shown in Fig. 1. The parameters in Eq. (14) are taken to be $T_0=90$ K and $T_C\approx347$ K, which agree with the experimental results.[11,14]

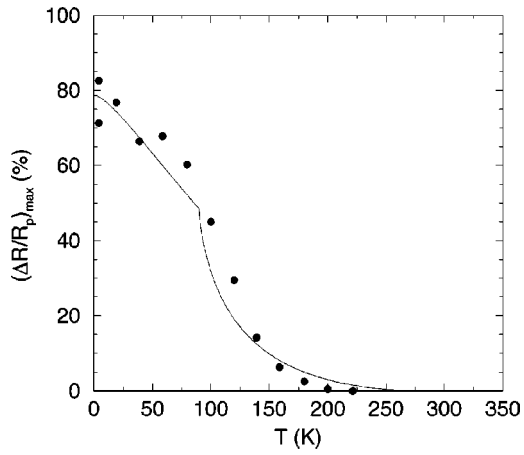

FIG. 2. Maximum TMR ratio versus temperature for the manganite tunnel junctions. The points are the experimental data taken from Ref. 14, and the solid line is the theoretical result calculated from Eqs. (11)–(13) using the parameters $D=5.0$ meV, $E_0=0.25$ meV, $\gamma=0.56$, and $\eta=1/15$.

In the range of $T_0<T\leqslant T_C$, the spin polarization decreases with increasing temperature, and there is no spin polarization for $T>T_C$. Figure 2 shows our theoretical result (solid line) calculated from Eqs. (11)–(13) and the experimental data[14] of the maximum TMR ratio for $La_{0.67}Sr_{0.33}MnO_3$ tunnel junctions. We have chosen $\gamma=0.56$ and $\eta=1/15$. The γ value suggests that the effective spin-diffusion length in the defect-populated $SrTiO_3$ barrier is much smaller than the width of the barrier,[17] and the η value has the same order of magnitude as that used for ordinary ferromagnet tunnel junctions.[18] The material parameters $D=5.0$ meV and $E_0=0.25$ meV used in numerical calculation are taken close to their bulk values. The theoretical result can reproduce the main characteristic feature of the experimental data.

At low temperatures, the experimental data are scattered due to the noise in data, which is a consequence of magnetic instabilities of the electrodes.[25] On the average, it is clear from these data that the TMR ratio decreases slowly as the temperature is raised. In the present model, this decrease in the TMR ratio is ascribed to the increasing statistical population of the spin excitations at the interfaces while the electron-spin polarization is unchanged. For $T>T_0$, both the further increasing statistical population of spin excitations and the steeply decreasing of the electronic spin polarization are simultaneously responsible for the accelerated drop of TMR ratio, and then the TMR ratio decreases steadily with the electronic spin polarization decreasing slower. The magnetoresistance effect vanishes at about $T\approx220$ K much lower than $T_C\approx347$ K of $La_{0.67}Sr_{0.33}MnO_3$. The factor $(1-\tilde{\gamma})$ in Eq. (11) indicates that this loss of the magnetoresistance is due to the joint effect of the collective excitations of local spins at the interfaces and the impurity states of Mn ions in $SrTiO_3$ barrier. Therefore, the temperature-dependent behavior of the maximum TMR ratio is dominated by the variation of the electronic spin polarization with temperature and the collective excitations of the local spins at the interfaces between the insulating barrier and the manganite electrodes.

V. SUMMARY

We have proposed the mechanism of the temperature-dependent tunneling magnetoresistance in $La_{1-x}A_xMnO_3$ tunnel junctions. Using the transfer Hamiltonian method, it has been found that the variation of the electronic spin polarization and the collective excitations of local spins at the interfaces between the insulator and the manganite electrodes are responsible for the drop of the maximum TMR ratio with increasing temperature. The theoretical result can reproduce the main characteristic feature of the experimental data in the trilayer junction structure, $La_{0.67}Sr_{0.33}MnO_3/SrTiO_3/La_{0.67}Sr_{0.33}MnO_3$.

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