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Bias-voltage controlled resistance in a magnetic tunneling junction with an inserted thin metallic layer

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ABSTRACT

We apply the spin-polarized free-electron model to study the resistance change in a ferromagnet/metal/insulator/ferromagnet magnetic tunneling junction, and find two types of resistance change. One type is varied by the magnetization configuration between two ferromagnetic layers, and the other type is controlled by the polarity of the bias-voltage. The former is the so-called tunneling magnetoresistance, and the latter is named the bias-voltage controlled resistance. Under suitable conditions, we show that both resistance changes resulting from the bias-voltage controlled resistance and the tunneling magnetoresistance are equal in magnitude, and are larger than the resistance change in a conventional ferromagnet/insulator/ferromagnet magnetic tunneling junction.

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1. Introduction

The topic of spin-dependent tunneling (SDT) in a magnetic tunneling junction (MTJ) continues to receive considerable attention, in regard both to its fundamental physics and its potential for highly functional device applications [1–5]. An MTJ consists of an $FM_1/I_3/FM_4$ structure, where FM_1 and FM_4 are ferromagnetic electrodes and I_3 is a thin insulator. SDT is characterized by the resistance of the $FM_1/I_3/FM_4$ MTJ. The change of SDT in the $FM_1/I_3/FM_4$ MTJ is measured by the tunneling magnetoresistance (TMR) ratio. In the $FM_1/I_3/FM_4$ MTJ, SDT is extremely sensitive to the interface structures between the insulator and each electrode. Thus, modulating one of the interfaces can change SDT. One way to achieve this is to insert a thin nonmagnetic (NM_2) layer between one of the ferromagnetic electrodes, FM_1 or FM_4, and the insulator I_3 [6–20]. The NM_2-inserted MTJ is the $FM_1/NM_2/I_3/FM_4$ structure. Although the geometry of the $FM_1/NM_2/I_3/FM_4$ MTJ is simply the $FM_1/I_3/FM_4$ MTJ with the inserted NM_2 layer, the inserted NM_2 layer leads to a severe alteration of the interface, thus resulting in a dramatic effect on SDT, the resistance, and the TMR ratio.

The excellent experimental work of Yuasa et al. shows how the TMR ratio is affected by the inserted Cu metal in a high-quality Co/Cu/Al_2O_3/NiFe MTJ [9]. A distinct attenuated oscillation of the TMR ratios with increasing the Cu thickness is observed at room temperature when the inserted Cu thickness is less than 29 Å [9]. This reveals that the phase coherence of the spin-polarized electron across the Cu layer is conserved after multiple reflections occur at the Co/Cu and the Cu/Al_2O_3 interfaces [15,20]. Thus, the phase factor of the electron across the NM_2 layer has a crucial influence on the TMR ratio, the resistance, and SDT in the $FM_1/NM_2/I_3/FM_4$ MTJ. Another noteworthy experimental effect from the inserted NM_2 layer is that the dependence of the applied bias voltage on the TMR effect in the $FM_1/NM_2/I_3/FM_4$ MTJ is much larger than that in the $FM_1/I_3/FM_4$ MTJ [9]. This implies that the phase factor of the electron across the NM_2 layer is sensitive to the bias voltage applied to the $FM_1/NM_2/I_3/FM_4$ MTJ. Consequently, it is important to investigate how the phase factor of an electron across the NM_2-inserted MTJ is affected by the applied bias voltage, in order to control SDT and the resistance change.

In this paper, we adopt the same spin-polarized free-electron model as that used in references [14–16], and extend our previous work in reference [17] to study the effect of the applied bias voltage on the phase factor, SDT, and the resistance change in the $FM_1/NM_2/I_3/FM_4$ MTJ. We consider only that electrons passing through the $FM_1/NM_2/I_3/FM_4$ MTJ are both spin-conserved and phase coherent. Our calculations show that the phase factors of an electron are different across the whole structure in the forward and backward tunneling processes due to the existence of the inserted NM_2 layer. This results in the asymmetry of the SDT effects, and then leads to different resistances. Since different tunneling processes correspond to different resistances of the $FM_1/NM_2/I_3/FM_4$ MTJ, the polarity of a negligible bias voltage can be exploited to switch the tunneling process and to change the resistance of the $FM_1/NM_2/I_3/FM_4$ MTJ. So, there exists a bias-voltage controlled resistance in a magnetic tunneling junction with an inserted thin metallic layer. Under suitable conditions, our calculations also show that the corresponding resistance change is sufficiently large for applications in spintronic devices.

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2. Calculation

We consider the $FM_1/NM_2/I_3/FM_4$ MTJ as shown in Fig. 1, in which two semi-infinite ferromagnetic leads [FM_1 and FM_4] are connected by an insulating layer (I_3) of width d_I and a nonmagnetic metal layer (NM_2) of width d_M. The structure reduces to a conventional $FM_1/I_3/FM_4$ MTJ when $d_M = 0$. The magnetizations of the FM_1 and the FM_4 layers are denoted by $\vec{m}_1$ and $\vec{m}_4$, respectively. The spin indices $\sigma = \uparrow$ and $\sigma = \downarrow$ are for the majority- and the minority-spin bands with respect to the quantization axis z in the FM_1 layer, respectively, and $\sigma' = \uparrow$ and $\sigma' = \downarrow$ with respect to the quantization axis z' in the FM_4 layer, respectively. Without loss of generality, the z-axis is fixed and along the magnetization direction in the FM_1 layer, while the z'-axis is along the magnetization direction in the FM_4 layer and different from the z-axis by an angle θ. The relative angle $\theta = 0$ represents the parallel magnetization configuration between the FM_1 and the FM_4 layers, and $\theta = \pi$ indicates the antiparallel magnetization configuration. The potential barrier height of the I_3 insulator is U. The applied bias voltage across the I_3 insulator is V_0. The positive polarity of $V_0 > 0$ corresponds to the backward tunneling process for the current from the FM_4 layer to the FM_1 layer, while the negative polarity of $V_0 < 0$ corresponds to the forward tunneling process. Since the bias voltage is applied to switch the tunneling process, the strength is assumed to be negligible compared with U; i.e., $U >> |V_0| \approx 0$. The other corresponding physical quantities for the wave function of a single electron are dependent on the out-of-plane energy E_ξ across the $FM_1/NM_2/I_3/FM_4$ MTJ, and are defined as follows. The wave vectors $k_{1\uparrow}$ ($k_{4\uparrow}$) and $k_{1\downarrow}$ ($k_{4\downarrow}$) are for the majority- and minority-spin bands in the FM_1(FM_4) layer, respectively. The wave vector in the NM_2 layer is k_2. The imaginary wave vector within the I_3 insulator is defined as κ_3. For simplicity, we adopt three assumptions for an electron [14–17]: (i) the effective mass m is the same in all regions, (ii) the in-plane wave vector remains unchanged due to the semi-infinite flat surface normal to the tunneling direction, and (iii) the total energy is conserved so that the sum of the out-of-plane energy E_ξ and the in-plane energy must be just the Fermi energy E_F.

To investigate the bias-voltage controlled resistance in the $FM_1/NM_2/I_3/FM_4$ MTJ, we derive the transmission amplitudes, the transmission probabilities, the conductance, and then the resistance change in the $FM_1/NM_2/I_3/FM_4$ MTJ with the applied bias voltage. To derive the transmission amplitudes in the $FM_1/NM_2/I_3/FM_4$ MTJ, we first decompose the whole structure into the FM_1/NM_2 bilayer and the $NM_2/I_3/FM_4$ junction, and then reconstruct them together [14]. In the FM_1/NM_2 bilayer and the $NM_2/I_3/FM_4$ junction, the corresponding transmission and reflection amplitudes can be found in any standard textbook on quantum physics and are listed as follows. The transmission amplitude $t_{1\sigma\to2} = 2k_{1\sigma}/(k_{1\sigma} + k_2)$ and the reflection amplitude $r_{1\sigma\to2} = (k_{1\sigma} - k_2)/(k_{1\sigma} + k_2)$ are for the spin-σ electron transporting from the FM_1 layer to the NM_2 layer. Similarly, $t_{2\to1\sigma} = 2k_2/(k_2 + k_{1\sigma})$ and $r_{2\to1\sigma} = (k_2 - k_{1\sigma})/(k_2 + k_{1\sigma})$. The transmission and the reflection amplitudes are $t_{2\to4\sigma'}$ and $r_{2\to4\sigma'}$ for the spin-σ' electron from the NM_2 layer tunneling to the FM_4 layer. Under the approximation of the small barrier factor of $\exp(-2\kappa_3 d_I) << 1$, $t_{2\to4\sigma'} = -4ik_2\kappa_3\exp(-\kappa_3 d_I)/S[(\kappa_3 - ik_2)(\kappa_3 - ik_{4\sigma'})]$ and $r_{2\to4\sigma'} = (k_2 - i\kappa_3)/(k_2 + i\kappa_3)$. Similarly, $t_{4\sigma'\to2} = -4ik_{4\sigma'}\kappa_3\exp(-\kappa_3 d_I)/[(\kappa_3 - ik_{4\sigma'})(\kappa_3 - ik_2)]$ and $r_{4\sigma'\to2} = (k_{4\sigma'} - i\kappa_3)/(k_{4\sigma'} + i\kappa_3)$. Although the transmission amplitudes $t_{1\sigma\to2} \neq t_{2\to1\sigma}$ and $t_{2\to4\sigma'} \neq t_{4\sigma'\to2}$, the transmission probabilities $T_{1\sigma\to2} = T_{2\to1\sigma}$ and $T_{2\to4\sigma'} = T_{4\sigma'\to2}$, where $T_{1\sigma\to2} = \hbar k_2|t_{1\sigma\to2}|^2/\hbar k_{1\sigma}$, $T_{2\to1\sigma} = \hbar k_{1\sigma}|t_{2\to1\sigma}|^2/\hbar k_2$, $T_{2\to4\sigma'} = \hbar k_{4\sigma'}|t_{2\to4\sigma'}|^2/\hbar k_2$, and $T_{4\sigma'\to2} = \hbar k_2|t_{4\sigma'\to2}|^2/\hbar k_{4\sigma'}$. Thus, $T_{1\sigma\to2}T_{2\to4\sigma'} = T_{4\sigma'\to2}T_{2\to1\sigma}$, which will be used later.

By manipulating the above transmission and reflection amplitudes in the FM_1/NM_2 bilayer and the $NM_2/I_3/FM_4$ junction, the transmission amplitudes for the whole $FM_1/NM_2/I_3/FM_4$ structure can be expressed as an analytic form with clear physical interpretations [14]. In the $FM_1/NM_2/I_3/FM_4$ MTJ, $t^{\Rightarrow}_{1\sigma\to4\sigma'}$ represents the transmission amplitude for an electron from the spin-σ state of the FM_1 layer coherently tunneling to the spin-σ' state of the FM_4 layer. Due to the phase coherence of the spin-polarized electron across the NM_2 layer, the transmission amplitude $t^{\Rightarrow}_{1\sigma\to4\sigma'}$ stems from all coherent transmission processes, analyzed as follows. First, the transmission amplitude from the FM_1 layer to the FM_4 layer without any reflection within the NM_2 layer is $t^{\Rightarrow,0}_{1\sigma\to4\sigma'}$, which is $t^{\Rightarrow,0}_{1\sigma\to4\sigma'} = t_{1\sigma\to2} \times \exp(i\varphi^{\Rightarrow}/2) \times S_{\sigma,\sigma'} \times t_{2\to4\sigma'}$. The spinor transformation is $S_{\sigma,\sigma'} = \cos(\theta/2)$ if $\sigma = \sigma'$ but is $S_{\sigma,\sigma'} = i\sin(\theta/2)$ if $\sigma \neq \sigma'$ for the change in the quantization axis z and z'. The term $\varphi^{\Rightarrow}/2$ is the phase difference between the FM_1/NM_2 and the NM_2/I_3 interfaces for the electron in the forward tunneling process. Second, the transmission amplitude with two reflections within the NM_2 layer is $t^{\Rightarrow,2}_{1\sigma\to4\sigma'} = t_{1\sigma\to2} \times \exp(i\varphi^{\Rightarrow}/2) \times [r_{2\to1\sigma} \times r_{2\to4\sigma'} \times \exp(i\varphi^{\Rightarrow})] \times S_{\sigma,\sigma'} \times t_{2\to4\sigma'}$. Third, the transmission amplitude with four reflections within the NM_2 layer is $t^{\Rightarrow,4}_{1\sigma\to4\sigma'} = t_{1\sigma\to2} \times \exp(i\varphi^{\Rightarrow}/2) \times [r_{2\to1\sigma} \times r_{2\to4\sigma'} \times \exp(i\varphi^{\Rightarrow})]^2 \times S_{\sigma,\sigma'} \times t_{2\to4\sigma'}$. Finally, the transmission amplitude $t^{\Rightarrow}_{1\sigma\to4\sigma'}$ is the summation of the transmission amplitudes with zero reflection, with two reflections, with four reflections, etc.:

$$t^{\Rightarrow}_{1\sigma\to4\sigma'} = t_{1\sigma\to2}e^{i\varphi^{\Rightarrow}/2}\left\{\sum_{n=0}^{\infty}\left[r_{2\to1\sigma}r_{2\to4\sigma'}e^{i\varphi^{\Rightarrow}}\right]^n\right\}S_{\sigma,\sigma'}t_{2\to4\sigma'} = t_{1\sigma\to2}e^{i\varphi^{\Rightarrow}/2}\frac{1}{1-r_{2\to1\sigma}r_{2\to4\sigma'}e^{i\varphi^{\Rightarrow}}}S_{\sigma,\sigma'}t_{2\to4\sigma'}, \tag{1}$$

$$\varphi^{\Rightarrow} = +2k_2 d_M. \tag{2}$$

Similarly, the transmission amplitude $T^{\Leftarrow}_{1\sigma\to4\sigma'}(\theta)$ in the backward coherent tunneling process, from the FM_4 layer tunneling to the FM_1 layer, is

$$t^{\Leftarrow}_{1\sigma\leftarrow4\sigma'} = t_{4\sigma'\to2}e^{i\varphi^{\Leftarrow}/2}\frac{1}{1-r_{2\to1\sigma}r_{2\to4\sigma'}e^{i\varphi^{\Leftarrow}}}S_{\sigma',\sigma}t_{2\to1\sigma}, \tag{3}$$

$$\varphi^{\Leftarrow} = -2k_2 d_M, \tag{4}$$

where $S_{\sigma',\sigma} = S_{\sigma,\sigma'}$.

To derive the transmission probabilities in a clearer form, we replace the reflection amplitude $r_{2\to4\sigma'} = (k_2 - i\kappa_3)/(k_2 + i\kappa_3)$ in Eqs. (1) and (3) with

$$r_{2\to4\sigma'} = e^{i\varphi_0}, \tag{5}$$

which of the real and the imaginary parts are $\cos\varphi_0 = (k_2^2 - \kappa_3^2)/(k_2^2 + \kappa_3^2)$ and $\sin\varphi_0 = -2k_2\kappa_3/(k_2^2 + \kappa_3^2)$, respectively. The magnitude of 1 is due to the I_3 insulator, and the phase φ_0 is from the phase

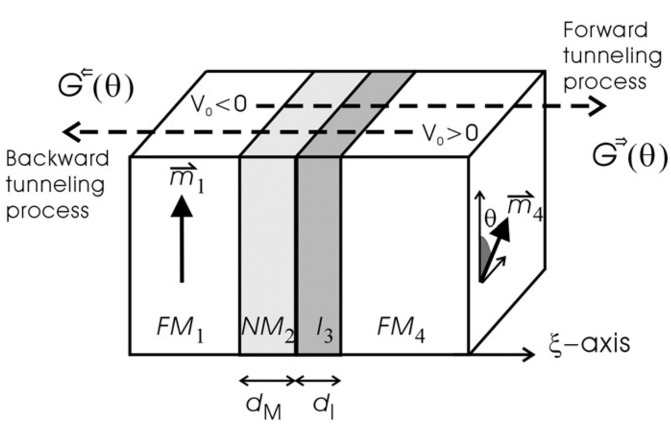

Fig. 1. Schematic diagram for a ferromagnet/metal/insulator/ferromagnet ($FM_1/NM_2/I_3/FM_4$) magnetic tunneling junction. The bias voltage of $V_0 < 0$ corresponds to the forward tunneling process for the current from the FM_1 layer to the FM_4 layer, while $V_0 > 0$ corresponds to the backward tunneling process. The conductance in the $FM_1/NM_2/I_3/FM_4$ MTJ is dependent not only on the relative angle θ in the magnetization configuration but also on the tunneling process. The forward and the backward tunneling conductances are $G^{\Rightarrow}(\theta)$ and $G^{\Leftarrow}(\theta)$, respectively.

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