Anisotropy effect of magnetoresistance in spin polarized tunneling

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Abstract - We calculate the influence of single-ion anisotropy in spin polarized tunneling and conclude that the tunneling magnetoresistance ratio increases for lower barrier height with the increasing anisotropy parameter. In particular, the optimal alignment of the ferromagnetic layers, yielding the largest TMR ratio is proposed.

I. INTRODUCTION

Large magnetoresistance(MR) observed in ferromagnet-insulator-ferromagnet (FM/I/FM) tunneling junctions[1-2] has attracted considerable attention for its potential applications in sensors and magnetic random access memory[3]. The resistance of a FM/I/FM tunneling junction is usually much higher than that of ferromagnetic multilayers. However, its magnetoresistance ratio is still comparable to the giant magnetoresistance (GMR) of multilayers[4]. For high resistance tunneling junctions, the power consumption is much less than in multilayers, which attract attention not only for fundamental studies but also for application of the junction as an electronic device. If two ferromagnetic electrodes are separated by a nonmagnetic tunneling barrier, then the spin polarized tunneling conductance depends on a number of parameters, e.g., relative angle between the magnetizations of two ferromagnetic electrodes, the applied field, the bias voltage and the temperature. The observed magnetoresistance is attributed to the polarized electron tunneling across the insulating barrier for the negligible contribution of ferromagnetic electrodes, and it is called tunneling magnetoresistance (TMR).

An early work reported[5] that the tunneling conductance of an Fe/Ge/Co junction has an MR ratio up to 14% at 4.2 K under zero bias voltage. Julliere qualitatively analyzed TMR ratio, $\Delta G/G$, using Tedrow and Meservey's theory [6] and found that it could be expressed as

$$\frac{\Delta G}{G} = \frac{G_p - G_{ap}}{G_p} = \frac{2P_1 P_3}{(1 + P_1 P_3)}, \quad (1)$$

where G_p and G_{ap} stand for the conductance of two ferromagnetic electrodes with parallel and antiparallel magnetizations, respectively. P_1 (or P_3) are the polarizations

of the two ferromagnets. The upper bound of the experimental data for TMR ratio is roughly proportional to the product of the spin polarizations of both ferromagnets, but the spread of those data is very broad[7]. Based on the free electron model, Slonczewski suggested that TMR ratio depends on the spin polarization of conduction electrons [8]. However, spin polarization decreases fast with the increase of the barrier height in Slonczewski's theory and the predicted value of the TMR ratio is much smaller than experimental values[2].

Here we study the effect of single-ion anisotropy[9,10] of tunneling electrons on the tunneling junction. The spin and charge transmission coefficients are calculated from a proposed spin Hamiltonian and the TMR then follows. Fe/I/Fe junction is chosen to demonstrate the anisotropy effect of the ferromagnetic electrodes and the optimal alignment of the ferromagnetic layers, yielding the largest TMR ratio is proposed.

II. THEORY

Our analysis is based on the plane wave approximation of the spin-polarized conduction electrons within the three junction regions: two ferromagnetic electrodes and a rectangular barrier(Fig. 1). The transmission of a single electron transversing a rectangular barrier from the left into the right ferromagnetic electrode can be characterized by the longitudinal part of the spin Hamiltonian

$$H_{\xi,i} = -\frac{\hbar^2}{2\mu} \left(\frac{d}{d\xi} \right)_i^2 + U_i(\xi) - h_i(\xi) \sigma_i + D_i (\sin \theta_i)^2. \quad (2)$$

Figure 1: Schematic diagram for a FM/I/FM tunneling junction. Easy axis of each ferromagnetic layer deviates θ_i from their spin quantization axis. The molecular field h_i is along the spin quantization axis z_i and the angle between z_1 and z_3 is ϕ .

Manuscript received February 25, 1999.

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This work was supported in part by Taiwan Economics Minister under Grant No. 88S12-J3.

Subscripts i ($= 1, 2, 3$) represent the ferromagnetic layer F_1 , the barrier, and the right ferromagnetic layer F_3 , respectively. The kinetic energy term is $-\hbar^2/2\mu(d/d\xi)^2$, U is the potential term, μ is the effective mass and $\hbar$ is the Planck constant. The internal exchange energy of the i -th ferromagnetic layer is $-h_i(\xi)\sigma_i$, where h_i is the molecular field and σ_i is the Pauli spin operator. We also included the single-ion anisotropic term [9,10], $D_i(\sin\theta_i)^2$, where D_i is the anisotropy parameter [9,10] and θ_i is the angle between the spin quantization axis and the easy axis in the i -th layer. Since the ferromagnetic materials in electrodes can be different, h_i does not necessary equal h_3 . The spin quantization axes z_1 and z_3 span an angle ϕ and we assume the directions of h_1 and h_3 to be parallel with the corresponding spin quantization axes z_1 and z_3 (Fig. 1).

Consider an incident plane wave of a spin-up electron with unit flux in the F_1 layer ($\xi < 0$ as shown in Fig. 1): by matching boundary conditions at the interfaces $\xi = 0$ and $\xi = t$, we can determine the wave function in three regions. In our calculations, we assume a rectangular barrier for $0 < \xi < t$, and $h_2 = 0$ inside the barrier (Fig. 1). After some algebraic manipulations and spinor transformation, the transmission probability ($T_{\sigma\sigma'}$) of tunneling electrons from the spin- σ state in the F_1 layer to the spin- σ' state in the F_3 layer become

$$T_{\uparrow\uparrow} = 8 \frac{k_{\uparrow} k_{\uparrow} \kappa^2 e^{-2\kappa t}}{(\kappa^2 + k_{\uparrow}^2)(\kappa^2 + k_{\uparrow}^2)} (1 + \cos\phi), \quad (3-a)$$

$$T_{\downarrow\downarrow} = 8 \frac{k_{\downarrow} k_{\downarrow} \kappa^2 e^{-2\kappa t}}{(\kappa^2 + k_{\downarrow}^2)(\kappa^2 + k_{\downarrow}^2)} (1 - \cos\phi). \quad (3-b)$$

Since $\kappa \gg 1$, and thus for brevity, we only keep the terms up to $e^{-2\kappa t}$. The wave vector inside the ferromagnetic layers is k_{σ} and the imaginary wave vector inside the insulating barrier is $i\kappa$. The values of $T_{\downarrow\downarrow}(\phi)$ and $T_{\uparrow\uparrow}(\phi)$ follow by symmetry. Since the anisotropy term in the spin Hamiltonian only depends on the angle θ , the contribution to the potential energy by either spin-up or spin-down electrons is the same. Therefore, even if considering the single-ion anisotropy, the energy splitting of the spin-up and spin-down electrons remains the same as they are isotropic. However, the kinetic term (i.e., wave vector, k_{σ}) becomes a function of D and θ for the changing of potential energy from single-ion anisotropy effect. In order to simplify the resultant expression for tunneling conductance, we introduce the following notation:

$$n_1(\theta_1, d_1; p_1) = \frac{k_{\downarrow}(\theta_1, d_1; p_1)}{k_{\uparrow}(\theta_1, d_1; p_1)} = \frac{\sqrt{(1+p_1^2) - (1-p_1^2)(1+d_1 \sin^2 \theta_1)}}{\sqrt{(1+p_1^2) + (1-p_1^2)(1-d_1 \sin^2 \theta_1)}}, \quad (4)$$

$$q_1(\theta_1, d_1; p_1, m_1) = \frac{\kappa}{k_{\uparrow}(\theta_1, d_1; p_1)} = m_1 \sqrt{\frac{2}{(1+p_1^2) + (1-p_1^2)(1-d_1 \sin^2 \theta_1)}}, \quad (5)$$

where $p_i (= k_{\downarrow}/k_{\uparrow})$ and $m_i (= \kappa/k_{\uparrow})$ are isotropy ratios, i.e., $D_i = 0$. We let $d_i = D_i/h_i|\sigma_{iz}|$, and $d_3 = D_3/h_3|\sigma_{3z}|$. If $D_1 = D_3$, we have

$$d_3 = \frac{h_1}{h_3} d_1 = \frac{(1-p_1^2)(1+p_3^2)}{(1+p_1^2)(1-p_3^2)} d_1$$

Similar expressions for n_3 and q_3 can also be given. Using the usual techniques [8], we sum the charge transmission over E_{ξ} and $k_{\parallel}$ for all occupied states near the Fermi energy (E_F) at 0K, and obtain the tunneling conductance at vanishing external voltage [8,11]. In the following calculation of tunneling conductance, κ and k_{σ} therefore are only derived from E_F . For a $F_1/I/F_3$ junction, the tunneling conductance depends on the angle ϕ between the two magnetizations, and we can write it as

$$G(\phi) = \frac{e^2 \kappa}{\pi^2 \hbar t} e^{-2\kappa t} \frac{(q_1^2 + n_1)(1+n_1)q_1(q_3^2 + n_3)(1+n_3)q_3}{(q_1^2 + 1)(q_1^2 + n_1^2)(q_3^2 + 1)(q_3^2 + n_3^2)} \left[1 + \frac{(1-n_1)(q_1^2 - n_1)(1-n_3)(q_3^2 - n_3)}{(1+n_1)(q_1^2 + n_1)(1+n_3)(q_3^2 + n_3)} \cos\phi \right], \quad (6)$$

The angular dependence of the tunneling conductance $G(\phi)$ has predominantly cosine dependence [8] apart from modifications due to k_{σ} .

III. RESULTS AND CONCLUSIONS

We explore the tunneling conductance and the TMR ratio under different orientations of the ferromagnetic easy axes and of the applied field. For an $Fe/I/Fe$ junction, we study three geometric arrangements: (a) Perpendicular: The easy axes of both ferromagnetic layers are perpendicular to the z axis (Fig.2(a)). (b) Oblique: Both easy axes deviate from the applied field, e.g., the angle of easy axes are $\pm 60^\circ$ with the z axis (Fig.2(b)). (c) Orthogonal: The easy axes of two ferromagnetic layers are orthogonal to each other, and one of the axes is along the z -axis (Fig.2(c)). For an applied field along the z -axis, TMR ratio of the trilayer thin film shows a strong dependence on the easy axes orientation of two ferromagnetic layers. A large enhancement of the TMR value may be achieved by the proper alignment of the two ferromagnetic layers. Our calculations suggest that the perpendicular configuration always gives the largest TMR ratio for a lower barrier height. When applied field is perpendicular to the anisotropy axis, then the k_{σ} value for the demagnetized and saturated states significantly differ and huge TMR ratio can be observed. At lower barrier heights, TMR ratio is sensitive to the anisotropy parameter (Fig. 2), whose influence becomes insignificant at higher barrier heights. When the barrier heights increase, and then D/U_0 gradually decreases; therefore, the influence of single-ion anisotropy become insignificant as D/U_0 approaching zero. In other word, the orientations of two ferromagnetic electrodes will not affect the TMR ratio at higher barrier heights (Fig. 2).

Figure 2: TMR ratio versus barrier height of Fe/I/Fe junctions with three arrangements of their easy axes. (a) Perpendicular: The easy axes of both ferromagnetic layers are all perpendicular to the z axis. (b) Oblique: Both easy axes deviate from the applied field, e.g., the angle of easy axes are $\pm 60^\circ$ with the z axis. (c) Orthogonal: The easy axes of two ferromagnetic layers are orthogonal to each other, and one of the easy axis is along the z-axis. The wave vectors of Fe in calculation are $k_{\uparrow} = 1.09\text{\AA}^{-1}$, and $k_{\downarrow} = 0.43\text{\AA}^{-1}$ [8]. Anisotropy constant $d=D/\hbar|\sigma_z|$ and barrier heights m are used to be parameters. The graphs on the figures are $d_1=0.0$ (solid line), $d_1=0.025$ (long-dash line), $d_1=0.05$ (dash-dotted line) and $d_1=0.075$ (short-dash line) and $d_1=0.1$ (long-dash line), respectively

If the easy axes of the ferromagnetic layers both parallel to the applied field, it is the same results as isotropy (i.e., $D=0$ in Fig. 2) for $\theta=0$ now. Arbitrary anisotropy constants used in Fig. 2 are between the reported bulk values of transition metals and rare earth, in other words, TMR ratio is probably a little overestimated for the transition metal. However, the anisotropy constant of thin film is larger than its bulk value, and the anisotropy values in Fig. 2 are still much smaller than the values frequently used in theoretical modeling [10,11]. In particular, anisotropy constant of FePt is known to larger than the pure transition metal, and is about the same order used in Fig. 2. Therefore, the single-ion effect should be observable with the proper materials and orientation of easy axes. Indeed, our results qualitatively agree with the experimental data for NiFe/MgO/Co junctions [12]. Our calculation also indicated that the possible origins of the scattered data for TMR may be due to a distribution of the orientation of the easy axes and due to the variation of barrier heights. A further experimental study is required to clarify the contribution of the single-ion anisotropy in the TMR junction.

In summary, we have calculated that the influence of single-ion anisotropy on the tunneling magnetoresistance with different barrier heights. It shows that TMR ratio can be enhanced with the proper orientation of the easy axes of two ferromagnetic electrodes at lower barrier heights. We conclude that the TMR ratio in the perpendicular situation should be the largest among all possible arrangements.

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