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Long-range exchange bias through a metal spacer

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Abstract

We have theoretically analyzed the long-range exchange bias between a ferromagnet and an antiferromagnet separated by a nonmagnetic metal spacer. The Fermi–Dirac distribution was included in the Ruderman–Kittel–Kasuya–Yosida interaction to study the thermal effects of the conduction electrons, and thus to study the temperature effects and thickness dependence in the trilayer structure. The experimentally observed oscillatory exchange bias through the metal spacer is in good agreement with the calculated results. © 2002 Elsevier Science B.V. All rights reserved.

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The hysteresis loop displacement was first discovered in 1956 by Meiklejohn and Bean [1,2], when they were studying fine particles of cobalt (ferromagnet) with the cobaltous oxide (antiferromagnet) shell. This displacement was known as the exchange bias (H_E), and the origin of the H_E is a consequence of the interaction between a ferromagnetic (FM) and antiferromagnetic (AFM) layer at interface. On the other hand, the long-range magnetic coupling between two FM layers across a nonmagnetic conduction metal (M) has attracted a lot of attention in the past decade [3–7]. The interlayer exchange coupling between two FM layers behaves oscillatory with the thickness of the metal spacer, and this oscillatory behavior has been explained successfully based on the Ruderman–Kittel–Kasuya–Yosida (RKKY) model [6,7]. The FM/M/AFM trilayer system was first studied by Gökemeijer et al. in 1997 [8]; in their results, the H_E can be measured, too. But the interlayer exchange coupling decays exponentially with increasing thickness of the metal spacer, instead of an oscillatory coupling as in the FM/M/FM trilayer system. Recently, several experiments showed that the oscillation of the long-range H_E was observed [9–11], e.g., in NiFe/Cu/

NiO structures. Fig. 1 shows the H_E in NiFe(100 Å)/Cu/NiO(250 Å) as a function of Cu thickness at different measured temperatures. One finds that the long-range H_E oscillates with Cu thickness, and the interlayer exchange coupling strongly depends on the temperature [11].

Here, we theoretically analyze this oscillation of the H_E in NiFe(100 Å)/Cu/NiO(250 Å) in detail. The RKKY interaction and the dipolar interaction are used to calculate the temperature effects and thickness dependence of the H_E in this trilayer system. In our model the interfacial spin in the AFM layer is assumed to be uncompensated, therefore there is a net magnetic moment ($\vec{m}_{AF}$) in the AFM at the interfaces. For simplicity, we assumed that the FM anisotropy axis, AFM anisotropy axis, and the applied field are in the same direction, but the $\vec{m}_{AF}$ and the cooling field are along the opposite direction. The energy per unit area in the FM/M/AFM system can then be written as (Fig. 2)

$$\varepsilon(t) = K_F t_F \sin^2 \theta - H M_F t_F \cos \theta + \varepsilon_{\text{dip}}(t) + \varepsilon_{\text{RKKY}}(t), \quad (1)$$

where t is the thickness of metal, K_F is the anisotropy of the FM layer, t_F is the thickness of the FM layer, H is the applied field, and θ is the angle between $\vec{M}_F$ and the

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Fig. 1. The H_E values in NiFe(100 Å)/Cu/NiO(250 Å) as a function of Cu thickness at different measured temperature of 70, 145, 200, and 275 K.

Fig. 2. Schematic diagram of the structure of FM/M/AFM trilayer system.

anisotropy axis. The first term in Eq. (1) accounts for the effect of the FM anisotropy, the second term is the effect of the applied field on the FM layer,

$$\varepsilon_{\text{dip}}(t) = \frac{\vec{M}_F \cdot \vec{m}_{\text{AF}} - 3(\vec{M}_F \cdot \hat{n})(\vec{m}_{\text{AF}} \cdot \hat{n})}{t^3} t_F$$

$$\approx -\frac{1}{t^3} M_F m_{\text{AF}} t_F \cos \theta \quad (2)$$

is the dipolar interaction between $\vec{M}_F$ and $\vec{m}_{\text{AF}}$. The indirect exchange coupling (RKKY interaction) between M_F and $\vec{m}_{\text{AF}}$ at zero temperature [12] is

$$\varepsilon(t) = \frac{4J^2 m^* k_f^4}{(2\pi)^3} \times \frac{2k_f t \cos 2k_f t - \sin 2k_f t}{(2k_f t)^4}$$

$$\times (-M_F m_{\text{AF}} t_F \cos \theta). \quad (3)$$

To obtain the exchange coupling between FM and AFM planes, we integrate over spins in the FM and AFM planes.

$$\varepsilon_{\text{RKKY}}(t) \approx \frac{J^2 m k_f^2}{4\pi^2 \hbar^2} \left[\frac{2k_f t \cos 2k_f t - \sin 2k_f t}{(2k_f t)^2} - \int_{2k_f t}^{\infty} \frac{\sin y}{y} dy \right] \times (-M_F m_{\text{AF}} t_F \cos \theta), \quad (4)$$

is the indirect exchange coupling (RKKY interaction) between FM and AFM planes at zero temperature [13].

It should be noted that the unit of ε_{dip} and $\varepsilon_{\text{RKKY}}$ is the energy per unit area. In order to study the influence of temperature dependence in the long-range H_E , we include the Fermi–Dirac distribution in the RKKY interaction. For the low temperature limit,

$$\varepsilon_{\text{RKKY}}(t, T) \approx \varepsilon_{\text{RKKY}}(t)$$

$$+ \frac{J^2 m^3 k_B^2}{12 \hbar^6 k_f^2} \left(\int_{2k_f t}^{\infty} \frac{\sin x}{x} dx \right)$$

$$\times (-M_F m_{\text{AF}} t_F \cos \theta) T^2, \quad (5)$$

where k_B is Boltzmann's constant, and k_f is the Fermi wave vector. And we let

$$m_{\text{AF}}(T) = m_0(1 - bT^2) \quad (6)$$

to m_{AF} [14]. Therefore,

$$\varepsilon(t, T) = K_F t_F \sin^2 \theta - H M_F t_F \cos \theta$$

$$+ \varepsilon_{\text{dip}}(t, T) + \varepsilon_{\text{RKKY}}(t, T). \quad (7)$$

Minimizing the energy with respect to θ , the displacement of hysteresis loop is found to be

$$H_E = \frac{\varepsilon_{\text{dip}}(t, T) + \varepsilon_{\text{RKKY}}(t, T)}{M_F t_F \cos \theta}$$

$$= - \left\{ \frac{1}{t^3} + \frac{J^2 m k_f^2}{4\pi^2 \hbar^2} \left[\frac{2k_f t \cos 2k_f t - \sin 2k_f t}{(2k_f t)^2} - \int_{2k_f t}^{\infty} \frac{\sin y}{y} dy \right] + \frac{J^2 m^3 k_B^2}{12 \hbar^6 k_f^2} \left(\int_{2k_f t}^{\infty} \frac{\sin x}{x} dx \right) T^2 \right\}$$

$$\times m_0(1 - bT^2), \quad (8)$$

where m_0 and b are our fitting parameter. Fig. 3 exhibits results for Eq. (8) at different temperature, where m_0 is 6×10^{-19} emu, and b is $1 \times 10^{-5} \text{ K}^{-2}$. We have also analyzed experimental data with different thickness of NiO, and it shows m_0 is 6×10^{-20} , and b is 4×10^{-5} [15]. It means that there is about 60 bohr magneton at interfaces in AFM layer at zero temperature, and as the temperature increases, the $\vec{m}_{\text{AF}}$ rotates with AFM anisotropy. As the temperature increases the AFM layer

Fig. 3. Temperature dependence of the calculated H_E in FM/M/AFM for different thicknesses of the metal spacer. Here k_f is $\pi/10 \text{ Å}^{-1}$.

approaches the paramagnetic state, so the $\vec{m}_{\text{AF}}$ couples weakly with the neighbor spin within the AFM layer. We find that the RKKY interaction competes with the dipolar interaction, and the oscillation only becomes significant as the RKKY interaction dominates. As temperature increases, the H_E becomes oscillatory with variation of the film thickness, for the dominant contribution from the RKKY interaction.

In summary, we have analyzed the long-range oscillation H_E in FM/M/AFM trilayer system. The results show the interlayer exchange coupling is strongly dependent on the temperature, and the H_E oscillates with the thickness of the metal as temperature increases. The experimentally observed oscillatory H_E through the metal spacer is in good agreement with the calculated results. It needs to be pointed out that the uncompensated moment m_{AF} increases with the increase of the NiO thickness.

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