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Interpretation of the Giant Magnetoresistance Oscillation with the Thickness of Ferromagnetic Layer in Magnetic Multilayers*

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In virtue of Mott mechanism, we calculate the giant magnetoresistance(GMR) in Fe/Cr superlattices. Our results show that the GMR oscillations with the thickness of the ferromagnetic layer is due to the finite size effect of magnetic itinerant holes. The calculation is consistent with the experimental observation.

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Much attentions have been paid to the giant magnetoresistance(GMR) in magnetic multilayers since it was discovered in Fe/Cr superlattices by Baibich *et al.*[1] It is shown that the oscillation of the exchange coupling with the nonmagnetic spacer thickness is always accompanied by the oscillations of magnetoresistance.[2] Recently, the experiments also showed that the GMR oscillates as a function of the ferromagnetic thickness. Since the first report on this phenomenon in Fe/Cr superlattices,[3] evidences were also found in Fe/Mo and Fe/Ag systems.[4] This is a rather surprising result and no theoretical elucidation has been given by now.

In this letter, we develope a theory to account for the phenomenon. Our treatment is based on the Mott mechanism (or *s-d* scattering mechanism),[5] and the resistor network model proposed by Edwards *et al.*[6] For a periodic two-component superlattice with layer thicknesses denoted by a, b and by σ_a, σ_b the corresponding conductivities, from the classical transport theory Edwards *et al.*[6] obtained the total conductivity σ as follows

$$\sigma = \frac{a\sigma_a + b\sigma_b}{a+b} - \frac{3(\lambda_a - \lambda_b)(\sigma_a - \sigma_b)}{a+b} \int_1^\infty \frac{(x^2-1)dx}{x^5\{\coth(ax/2\lambda_a) + \coth(bx/2\lambda_b)\}} , \qquad (1)$$

where λ_a and λ_b are the corresponding mean-free paths. For $a, b \gg \lambda$, it is a simple parallel problem because the second term in Eq. (1) diminishes off. In the opposite limit $a, b \ll \lambda$ which is the case we concern, it is easy to check that the following approximation holds

$$\rho \approx \frac{a\rho_a + b\rho_b}{a+b} , \qquad (2)$$

where ρ, ρ_a and ρ_b are the corresponding resistivities.

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Now, let us consider a superlattice with alternating magnetic and nonmagnetic layers, in which the coupling between the magnetic layers is antiferromagnetic. The magnetoresistance (MR) coefficient is defined as $MR = (R_{\uparrow\downarrow} - R_{\uparrow\uparrow})/R_{\uparrow\uparrow}$, where $R_{\uparrow\downarrow}$ is the resistivity under zero external magnetic field and $R_{\uparrow\uparrow}$ corresponds to field-induced ferromagnetic configuration. Following Ref. 6, there exist three different resistivities in each period of superlattice. The resistivity $\rho_{\rm N}$ of the nonmagnetic spacer layer has the same value for both spin orientations of conduction electrons, whereas the high $\rho_{\rm M}^{\rm H}$ and low $\rho_{\rm M}^{\rm L}$ represent the resistivities corresponding to the two different spin orientations in the ferromagnetic layer. In virtue of Eq. (2) we can obtain the MR of the superlattice

$$MR = \frac{(\eta_\uparrow - \eta_\downarrow)^2}{4\,(\eta_\uparrow + t_{\rm N}/t_{\rm M})\,(\eta_\downarrow + t_{\rm N}/t_{\rm M})}\ , \tag{3}$$

where $\eta_\uparrow = \rho_{\rm M}^{\rm H}/\rho_{\rm N}$, $\eta_\downarrow = \rho_{\rm M}^{\rm L}/\rho_{\rm N}$, while $t_{\rm M}$ and $t_{\rm N}$ are the thicknesses of the magnetic and nonmagnetic layers, respectively.

The $\eta_\uparrow$ and $\eta_\downarrow$ are usually taken as constant parameters.[6,7] However, a more precise consideration should be taken if the layer thicknesses are very thin. In fact, according to Mott[5] the resistivity of a transitional metal can be given as

$$\rho_\sigma = A_{ss} N_\sigma^s(E_{\rm f}) + B_{sd} N_\sigma^d(E_{\rm f})\ , \tag{4}$$

where the first term is the contribution of s-s scattering, and the second s-d scattering. σ represents the spin channel (up or down), A_{ss} and B_{sd} are parameters corresponding to the scattering matrix, and $N_\sigma^s(E_{\rm f})$, $N_\sigma^d(E_{\rm f})$ are the state densities per unit volume at the Fermi energy $E_{\rm f}$ for s-electrons and d-holes, respectively. A_{ss} and B_{sd} are independent on the spin channel and $\rho_{\rm M}^{\rm H}$ and $\rho_{\rm M}^{\rm L}$ only depends on the densities of s-electron and d-hole numbers at the Fermi surface.

For conduction s-electrons, they can move freely and its finite size effect can be neglected. However, the itinerant d-holes are confined in the ferromagnetic layer, the energy band should be changed by varing the thickness of the ferromagnetic layer if the ferromagnetic layer is thin enough. As a simple consideration, we also take d-holes as free particles but with larger effective mass, and are confined in respective ferromagnetic layers by infinite walls. Thus, the state density of holes for each spin channel in such a thin film system can be expressed as

$$D_\sigma(\epsilon) = D_0 \sum_{k=1}^{K_\sigma} \theta(\Delta_\sigma - E_k - \epsilon)\ , \tag{5}$$

in which Fermi level is chosen to be zero and the difference between effective hole-masses of up and down channels is neglected. $D_0 = (m_{\rm d} S)/(2\pi\hbar^2)$ is the 2D state density of the holes in the layer plane, where S is the area of each layer plate and $m_{\rm d}$ the effective hole-mass.

$E_k = (\pi^2\hbar^2k^2)/(2m_d t_M^2)$ $(k = 1,\ 2,\ 3,\ \cdots,\ K_\sigma)$ is the energy level in one-dimensional infinite well. The maximum occupied energy Δ_σ and the maximum quantum number K_σ of σ spin channel are determined by

$$\Gamma_\sigma S\ t_M = \int_0^{\Delta_\sigma} D_\sigma(\epsilon)d\epsilon\ , \tag{6}$$

where we have assumed that the multilayer is of simple cubic lattice for simplicity, and Γ_σ is the number density of d-holes with spin σ. Thus in the free electron approximation we get the hole number density of σ spin channel at Fermi surface

$$N_\sigma^d(E_f) = \frac{D_\sigma(E_f)}{S\ t_M} = \frac{m_d}{2\pi\hbar^2}\frac{K_\sigma}{t_M}\ . \tag{7}$$

Since we only wish to know the $N_\sigma^d(E_f)$ as a function of the thickness t_M and do not concern its absolute value, hereafter the constant factor in Eq. (7) will be chosen as unit and we will simply have $N_\sigma^d = K_\sigma/t_M$, with unit $Å^{-1}$. For Fe, it is known that $\Gamma_{\uparrow(\downarrow)} = 2.4(0.2)$ holes/atom for up(down) d-band. We choose the layer distance of the system to be 2.2Å. The hole number densities in Eq. (7) can be easily obtained and the results are shown in Fig. 1, both for up spin $N_\uparrow^d$ and down spin $N_\downarrow^d$. It can be seen that N_σ^d oscillates with the periods of about 1 Å(3 Å) for up(down) spin channel, and the oscillations become weaker as the thickness t_M increases.

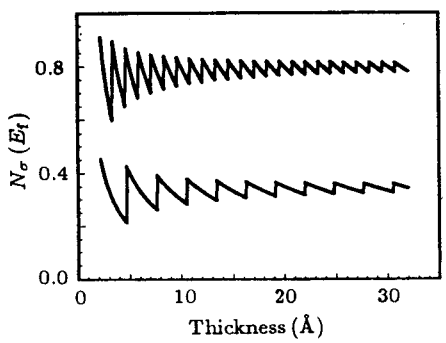

Fig. 1. Hole number densities via the thickness of ferromagnetic layer. The upper line represents $N_\uparrow^d(E_f)$ and the lower line $N_\downarrow^d(E_f)$.

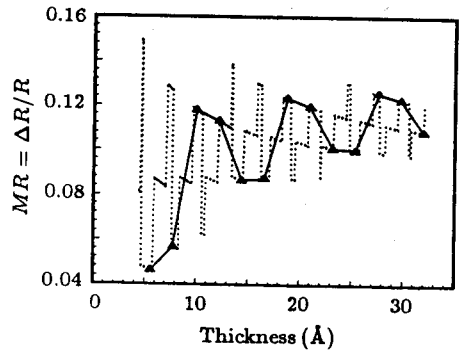

Fig. 2. MR ratio as a function of the ferromagnetic thickness. After sampled by the alaising effect, the long-period behavior (about 9 Å) appears.

Now, in virtue of Eq. (4) the two parameters $\eta_\uparrow$ and $\eta_\downarrow$ can be shown as

$$\eta_\sigma = \alpha + \beta K_\sigma/t_M\ , \tag{8}$$

where α (dimensionless) and β (with unit Å) are phenomenological parameters to be determined. Since the interface roughness plays an important role in GMR, the η_σ should not be simply chosen as the same value deduced from the ratio of pure iron and chromium, as pointed out in the improved treatment of the network model in Ref. 7. However, due to the introducing of many unknown phenomenological parameters, the things become significantly more complicated.[7]

Therefore, we will use an equivalent treatment by simply increasing the values of α and β, which means that each ferromagnetic layer includes the contributions of both Fe and Fe-Cr mixing parts. By setting $\alpha = 1$ and $\beta = 10$ Å, we get the MR ratio shown in Fig. 2, in which $t_N (= 12$ Å) and $t_M (= 5 - 35$ Å) are chosen directly from the experimental data.[3]

Quite similar to the theoretical calculation in interlayer coupling problem, our result also shows a short-period oscillation of MR as a function of ferromagnetic thickness. The period is among $1 - 3$ Å, the same as that of $N_\uparrow^d(E_f)$ and $N_\downarrow^d(E_f)$. However, a practical measurement is sampled at discrete points. This is called aliasing effect,[8] and it will shift the short-period oscillations to the long-period ones. In Fig. 2, we find that if the MR is sampled at the discrete set of the thickness (interval=2.2 Å), the long-period appears and it is as long as 9 Å or so. As the ferromagnetic thickness varies from about 5 to 30 Å, the MR ratio experiences three peaks. The result is consistent with the experimental data[3] from which one can observe a MR oscillation period of about 10 Å.

In summary, we have calculated the GMR in Fe/Cr superlattices in virtue of s-d scattering mechanism. Our results show that the observations of the GMR oscillation behavior via the thickness of ferromagnetic layer is due to the oscillation of the density of the d-holes at Fermi surface.

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