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Oscillations in the Hall resistivity in Co(Fe)/Cu multilayers

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The Hall effect and magnetoresistance have been simultaneously measured for the field perpendicular to the plane on $Co_{90}Fe_{10}$/Cu multilayers for four Cu layer thicknesses corresponding to the first and second peaks and minima of the magnetoresistance oscillations. The magnetization has been measured also in the same geometry. We found that the extraordinary Hall coefficient oscillates as a function of the Cu layer thickness synchronously with the magnetoresistance oscillation, providing evidence for the dominance of a conduction-electron-scattering mechanism correlated with the giant magnetoresistance effect.

Much progress has been made to understand the giant magnetoresistance (GMR) effect both experimentally[1] and theoretically.[2] Recently quite a few experiments on various transport properties have been reported on magnetic multilayers and granular alloys to better understand the basic mechanism of the GMR effect. However, there still remain several controversial problems such as the field dependence of the extraordinary Hall coefficient.[3–11] The Hall resistivity of magnetic materials can be expressed as,[12]

$$\rho_H = R_0 H + R_S M, \tag{1}$$

where the first term represents the ordinary Hall effect due to the Lorenz force and the second is the extraordinary Hall resistivity ρ_H^M proportional to the magnetization M. A controversial point is whether R_S in GMR systems depends on field strength or not. For ordinary magnetic materials, R_S can be well described by a sum of the skew scattering component proportional to the resistivity ρ and the side-jump component proportional to ρ^2 as

$$R_S = a\rho + b\rho^2, \tag{2}$$

when ρ varies with measuring temperature or impurity concentration.[12] In GMR systems, we naturally expect R_S to be field dependent, since ρ depends largely on field strength.

A recent measurement of the Hall effect in a GMR system was reported by Song *et al.* on Fe/Cr multilayers.[4] They reported an anomalous bump in the field dependence of the Hall resistivity, though no clear explanation of its origin was provided. If R_S is field independent, ρ_H^M is expected to depend on H in the same manner as M as predicted from Eq. (1). Based upon our simultaneous measurements of ρ_H^M, ρ, and M in the same geomerty, we have pointed out that the

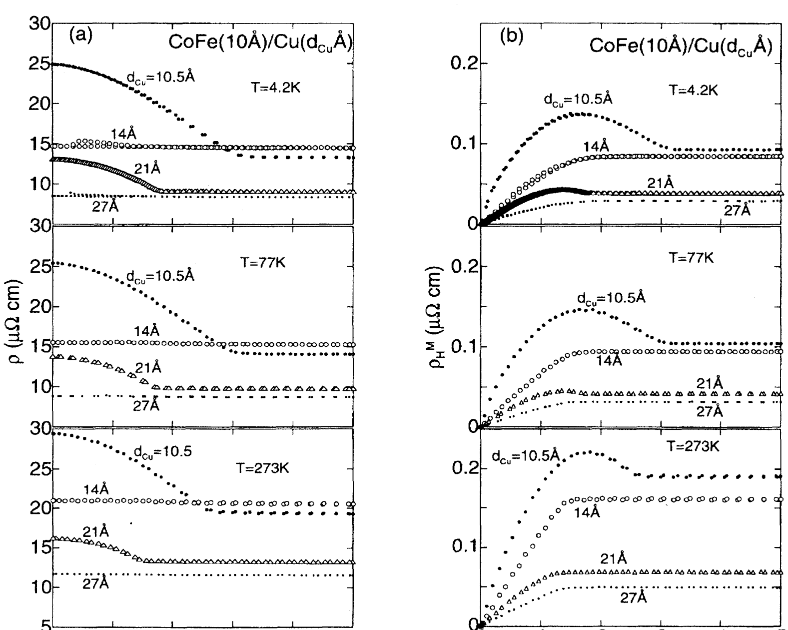

FIG. 1. (a) Field dependences of the magnetoresistivity at 4.2, 77, and 273 K, and (b) extraordinary Hall resistivity for $Co_{90}Fe_{10}$/Cu multilayers for Cu layer thicknesses of 10.5, 14, 21, and 27 Å.

bump originates from the field dependence of R_S and is a common feature to systems exhibiting the GMR effect, including multilayers and granular alloys.[10,11] However, many reports on the Hall effect in the GMR systems have ignored the field dependence and sometimes even emphasized that R_S is field independent. To settle the problem, we have measured the Cu layer thickness (d_{Cu}) dependence of ρ_H^M on Co(Fe)/Cu multilayers, which best suit the present purpose, since they exhibit a clear oscillation in the magnetoresistance (MR) ratio as a function of d_{Cu}.[13] We selected four values of d_{Cu}, at the first and second maxima and first and second minima of the MR oscillations to observe the oscillation most clearly.

Figure 1 shows the field dependences of ρ_H^M and ρ at 4.2, 77, and 273 K. The normal part of the Hall resistivity is already subtracted using the higher field slope: this normal Hall coefficient monotonically varies from -13.8×10^{-11} m^3/C for d_{Cu} =10.5 Å to -7.7×10^{-11} m^3/C for d_{Cu}=27 Å at 4.2 K, all in the reasonable range between the reported values for Co(Fe) alloys[14] and for pure Cu. Above the saturation field, nothing related with the GMR effect has been observed; ρ_H^M increases monotonically with increasing ratio of Co(Fe) to Cu. However, below the saturation field, the field dependence of ρ_H^M clearly depends on the MR. For the small MR samples, ρ_H^M increases monotonically with increasing magnetic field and the field dependence mimics that of the magnetization M. The behavior is basically the same as was observed for ordinary single-layer ferromagnetic films, as predicted from the second term in Eq. (1) assuming a constant R_S. In contrast, for the large MR samples, a clear bump is observed except at 273 K for d_{Cu} =21 Å. Such a bump in ρ_H^M is hardly explained by a field-independent R_S. Rather, the close correlation of the field dependences of ρ_H^M and ρ in Fig. 1 demonstrates the field dependence of R_S. In other words, the bump is a direct consequence of the GMR effect. With increasing fields, ρ_H^M first increases due to the increasing contribution of M in Eq. (2). At a certain field, the decreasing contribution of R_S due to the reduction of conduction electron scattering overcomes the first contribution, leading to the bump in the field dependence. Similar bumps have been observed in many systems exhibiting the GMR effect, though no oscillation has previously been reported as a function of nonmagnetic layer thickness.[4–11] At higher fields, on the other hand, the scattering responsible for the GMR effect disappears and has no influence on ρ_H^M.

To obtain the field dependence of R_S experimentally, we need to determine M in the same geometry. To do that, we must subtract the contribution of the MgO substrate, which is the same order of magnitude as that of the sample. We first measured $M(H)$ of the sample along with substrate. After dissolving the sample with acid, we repeated the same measuring procedure on the substrate and determined the sample contribution by subtracting the substrate contribution. The determined $M(H)$ is shown in Fig. 2. For comparison, $M(H)$ for the field parallel to the in-plane easy axis are also shown.[13] The results for the in-plane hard axis (not shown) are similar to those in the perpendicular field direction, except for the difference in saturation field due to the shape anisotropy. Using the $\rho_H^M(H)$ in Fig. 1 and the $M(H)$ in Fig. 2, we determined the field dependence of R_S (Fig. 3). As

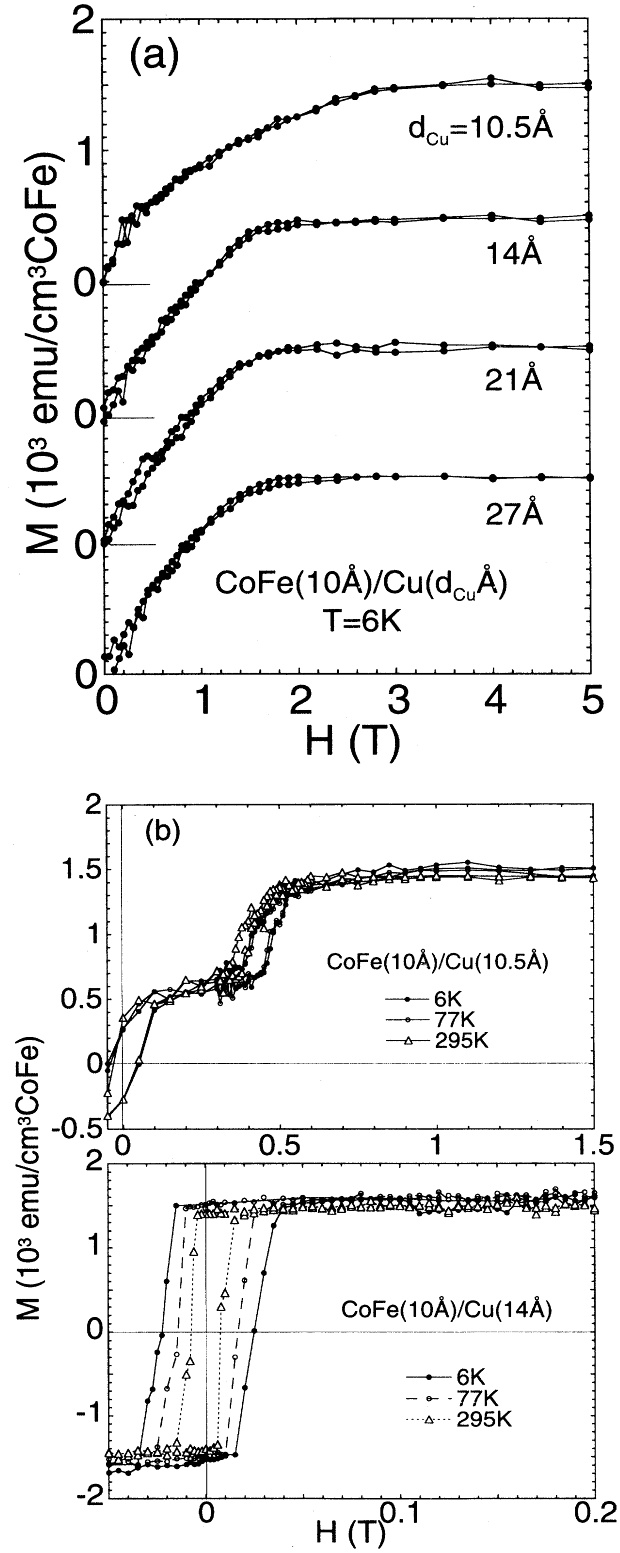

FIG. 2. Field dependences of the magnetization (a) in the same geometry as the Hall effect measurement; H perpendicular to the sample plane. (b) is for H parallel to the in-plane easy axis (H‖MgO[100]) for d_{Cu}=10.5 and 14 Å.

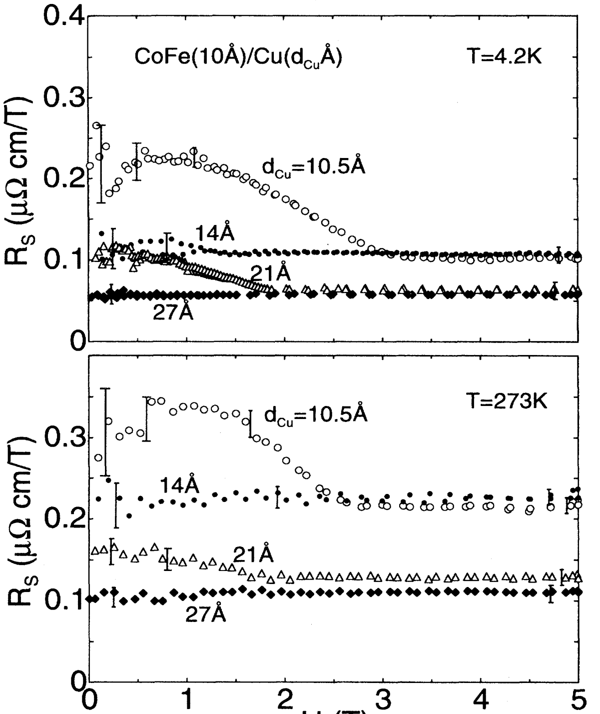

FIG. 3. Field dependence of the extraordinary Hall coefficient R_S.

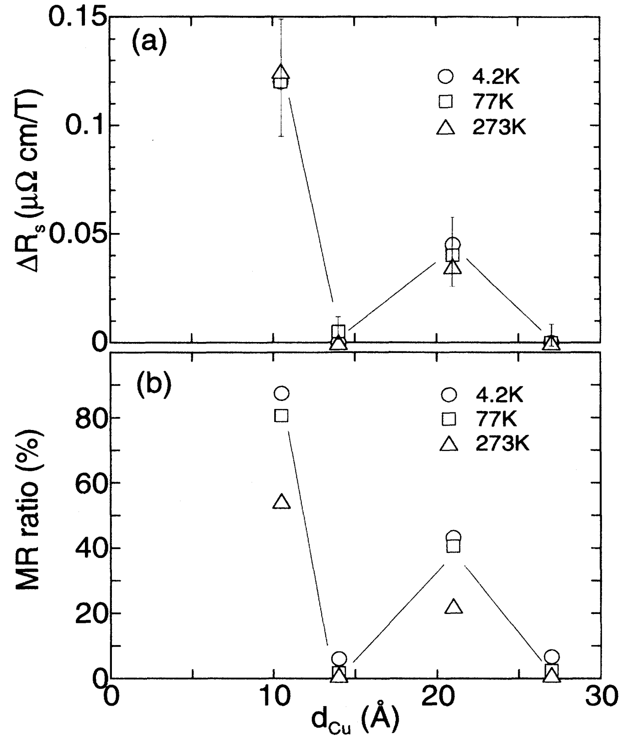

FIG. 4. Cu layer thickness dependences of (a) $\Delta R_S = R_S(0\ \mathrm{T}) - R_S(5\ \mathrm{T})$, and (b) magnetoresistance.

expected, for $d_{\mathrm{Cu}}=14$ and 27 Å, R_S is approximately field independent. In contrast, for $d_{\mathrm{Cu}}=10.5$ and 21 Å, R_S is greatly enhanced below the saturation field, though a large error mostly due to the M determination is unavoidable near zero field. The similarity of the field dependences between R_S (Fig. 3) and ρ (Fig. 1) is apparent. Figure 4 shows the field-dependent part $\Delta R_S = R_S(0\ \mathrm{T}) - R_S(5\ \mathrm{T})$ at 4.2 K as a function of d_{Cu} along with the MR ratio, where the ΔR_S oscillates synchronously with the oscillation in the MR ratio. This fact demonstrates that the same spin-dependent scattering mechanism responsible for the GMR effect contributes to the extraordinary Hall effect.

At high fields, the GMR-related contribution to ρ_H^M is small as described above. However, two experimental groups have reported extraordinary relations between R_S and ρ. They plotted $\ln(R_S)$ versus $\ln(\rho)$ to determine the slope; the exponent N in $R_S \sim \rho^N$. They argued that the exponent N should be between 1 (for skew scattering) and 2 (for the side-jump scattering) based on Eq. (2), since they implicitly assumed that a and b have the same sign. Song *et al.*[4] obtained the exponent $N \sim 2.6$ for the Fe/Cr multilayer from the temperature dependences of R_S and ρ on a single sample. For Co-Ag granular alloys, Xiong *et al.*[5] obtained $N \sim 3.7$ when R_S and ρ were varied by heat treatment. However, we must note that the constraint to the apparent N value is removed if a and b in Eq. (2) have opposite signs. In fact, both for Fe and Co it was reported that the b is positive and the a is negative.[12] For Fe/Cr multilayers, negative a and positive b values have been obtained from the field dependence of R_S and ρ.[6,10] The temperature-dependence measurement on a single sample for Co-Ag granular alloys also suggests negative a and positive b in Eq. (2). Then the slope for the $\ln(R_S)$ versus $\ln(\rho)$ plot diverges near $a + b\rho = 0$; i.e., N can take any values taking into account that N is experimentally estimated from the slope in a narraow range of ρ. Accordingly, we argue that there has been no experimental proof of the violation of the scaling relation in Eq. (2).

Theoretically, Zhang[15] recently calculated the extraordinary Hall effect in magnetic multilayers based on the Kubo formalism. He found that the commonly used scaling relation between ρ_H^M and ρ is not valid; the second term in Eq. (2) does not necessarily vary as ρ^2. For GMR systems, we believe that the Hall effect is most interesting at lower fields, where both the skew and side-jump components should be taken into account in any analysis. However, it might be better to start from the simplest case to compare with the theory. To do that, we measured the temperature dependence of ρ_H^M at 5 T for $d_{\mathrm{Cu}}=10.5$ and 14 Å.[15] Within the experimental accuracy, the experimental data, ρ_H^M plotted as ρ^2, lie approximately on straight lines passing nearly through the origin, which can be understood if the skew component is small and the side-jump component follows the ordinary square scaling relation. In Ref. 15, the square scaling relation was shown to be preserved in multilayer structures when the mean-free paths in the magnetic and nonmagnetic layers vary, with their ratios fixed. The present samples might satisfy this condition accidentally. To fully test Zhang's theory, further experiments over a wider range of experimental conditions are necessary.

To summarize, we found oscillations in the extraordinary

Hall coefficient as a function of Cu layer thickness in $Co_{90}Fe_{10}$/Cu multilayers at low fields, which proves a dominant role of the same spin-dependent scattering in the Hall resistivity as in the GMR effect.

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