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Angular Modulation of the Giant Magnetoresistance at the Second Antiferromagnetic Maximum in Co/Cu Multilayered System

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In order to study the effect of the magnetic anisotropy on the giant magnetoresistance in a Co/Cu multilayered system, the angle dependent magnetoresistance (MR) was measured. The experimental results showed that the maximum MR ratio depends on the angle between the direction of the applied field and the easy axis. The angular modulation of the MR ratio can be explained by the alignments of the two 'effective' magnetization vectors that are bound to their own easy axes. Two maxima observed in MR loops at the second antiferromagnetic maximum are discussed in relation to the magnetic anisotropy. The simulated results under the assumption of the existence of two in-plane easy axes in the sample are compared with the experiments.

1. Introduction

Magnetic multilayers that are composed of ferromagnetic and nonmagnetic metals have been widely studied for their giant magnetoresistance (GMR) effect [1], in which the resistance of the sample decreases when the magnetization vectors in the magnetic layers align parallel and increases when they align antiparallel. Increasing the thickness of the nonmagnetic layer leads to an oscillation of the GMR maximum with decreasing amplitude [2]. In spite of the extensive studies, a problem that remains poorly understood is the irreversible decrease in the GMR maximum after an as-grown specimen has been subjected to a magnetic field [3-9]. Another interesting point is that the magnetoresistance curve at the first antiferromagnetic maximum shows single maximum (usually at zero field), while it shows two maxima (at ± the coercive field) at the second antiferromagnetic maximum. A third qustion is the role of magnetic anisotropy (MA) on the GMR effect. The alignment of magnetization vectors, which directly affects GMR, is determined by the competition among the magnetic anisotropy, exchange coupling, and magnetic field, if we assume coherent rotation of the magnetization vectors.

Recently, Holloway and Kubinski [7] showed that the trapping of the magnetization vectors in local energy minima due to uniaxial anisotropy could explain the irreversible decrease and the two maxima, by treating multilayers as assemblies of grains with random orientations of the magnetic easy axis. Borchers *et al.* [8] suggested a model of breaking antiparallel correlation of Co domains across the Cu spacer in weakly coupled Co/Cu multilayers for the irreversible decrease of the GMR maximum.

In this paper we show how the MA affects the GMR maximum in the Si/[Co(15 Å)/Cu(20 Å)]$_{30}$ system in which the Cu thickness is chosen to correspond to the second antiferromagnetic maximum. We show, based on our results, that the angular modulation of the MR ratio can be explained by the alignment of the two effective magnetization vectors bound to their own easy axes, which are not perpendicular to each other. Simulated results were compared with the experiments.

2. Experiments

We have prepared [Co (15 Å)/ Cu (20 Å)]$_{30}$ films on a Si (100) substrate with a natural oxide using an UHV dc magnetron getter-sputtering system which has been described elsewhere [10]. All measurements were carried out at room temperature. The sample was rotated around the surface normal for the angle dependent measurements and the magnetic field was applied parallel to the sample surface. A standard four point spring-loaded probe was used for MR measurements. Magneto-Optic Kerr Effect (MOKE) was used to measure magnetic hysteresis loops. For MOKE measurements two lights were used and their scattering planes were perpendicular to each other. One of the scattering planes was parallel to the direction of the field. Both incident lights were *s*-polarized in order to measure the magnetization component parallel to the scattering plane.

3. Results

Fig. 1 shows the typical *MR* (*H*) curve and the hysteresis loop of Si/[Co/Cu]$_{30}$ at the second AFM such that the ratio,

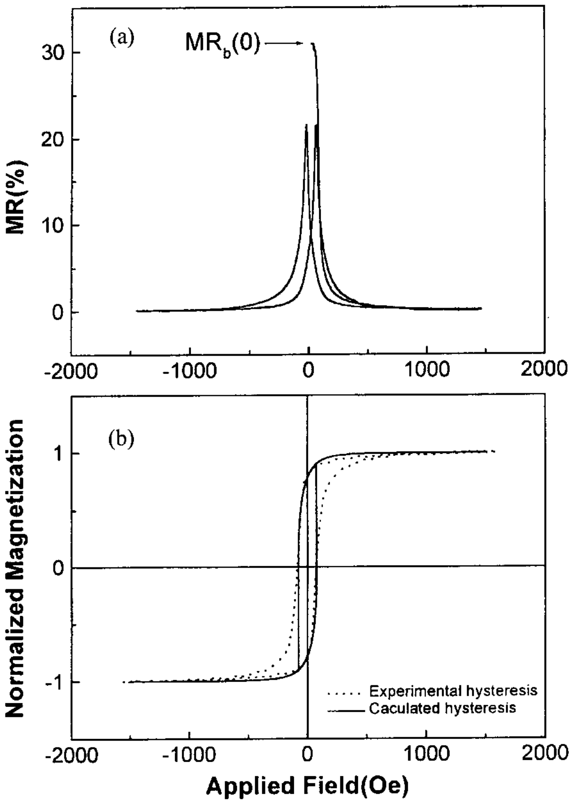

Fig. 1. (a) The typical magnetoresistance loop and (b) hysteresis loop of Si/[Co/Cu]$_{30}$. The solid line shows the calculated curve and the dotted line shows the experimental curve.

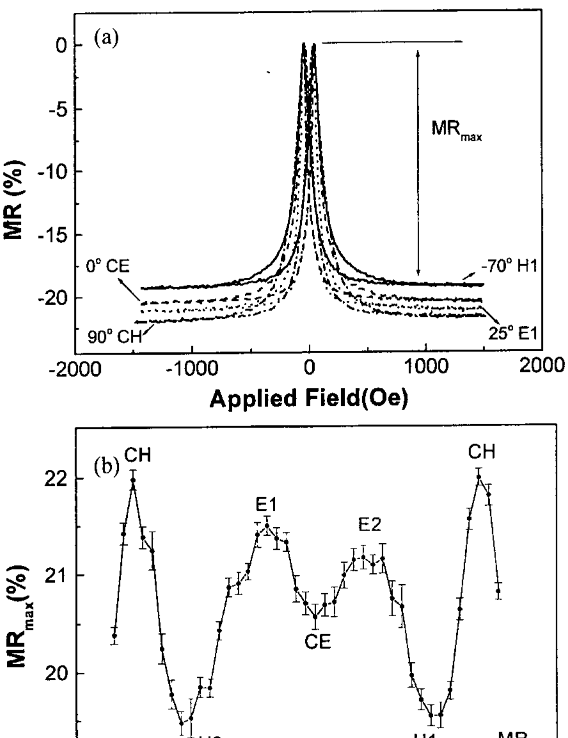

Fig. 2. (a) *MR* curves at various applied field directions. (b) Angular variation of GMR maximum ($MR_{max}(\alpha)$).

MR_b (0), is 31% before applying the field and after saturation the GMR maximum drops to 21%, which occurs at ± coercive field (H_c). After cycling the field, MR_b (0) is not repeated.

Fig. 2(a) shows *MR* (*H*) for various field directions (α), which are aligned to be the same level at their maximum to show the differences. Fig. 2(b) shows the angular variation of the GMR maximum (MR_{max} (α)). MR_{max} (α) shows four maxima at –90° (CH), –25° (E1), 25° (E2) and 90° (CH), a dip at 0° (CE), and minima at –65° (H2) and 65° (H1). The width of the peak at CH is much narrower than that at E1 and the width at E1 is almost the same as that at E2. This suggests that the peaks at E1 and E2 originate from a similar mechanism though their angular difference is ~50°, while the peak at CH comes from another origin. Moreover, the difference in angular positions of the peaks at the two CH is 180° and the angular difference between CH and CE is 90°. The difference between E1 (E2) and H1 (H2) is again 90°. These strongly suggest the existence of two 'effective' magnetic easy axes in this specimen.

MOKE measurements were used to find these effective easy directions. Fig. 3 shows the results. The *x*-component in Fig. 3(a) suggest that the easy direction of magnetization

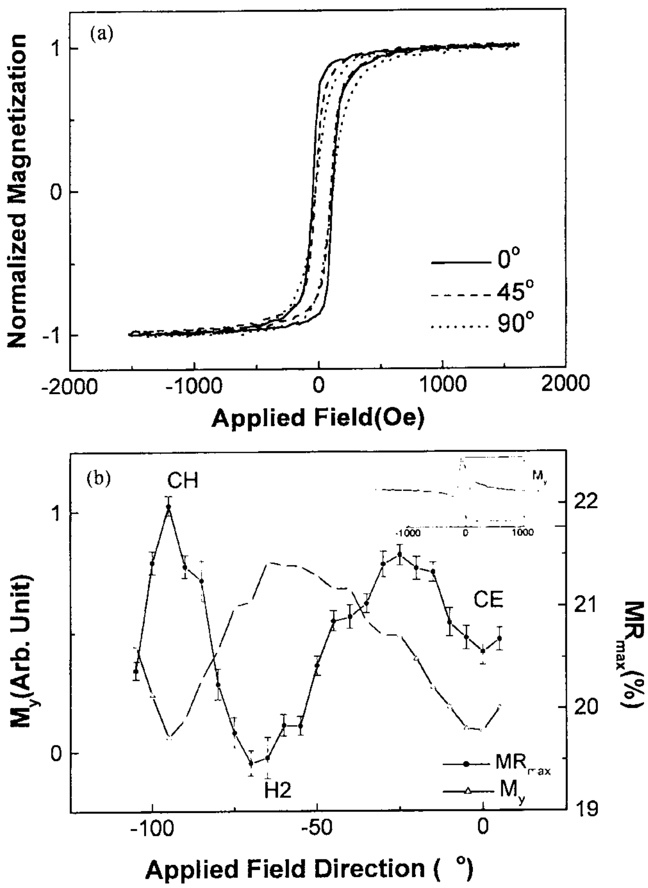

Fig. 3. (a) Normalized hysteresis loop of the *x*-component of magnetization at various field directions. (b) Angular modulation of $M_y(\alpha)$, which is normalized to the maximum value during the angular measurements, together with $MR_{max}(\alpha)$. Inset: definition of $M_y(\alpha)$.

is around α=0° and the hard direction at α=90°. But the y-component of magnetization shows a different behavior. The angular modulation of $M_y(\alpha)$, which is defined as $|M_y(H_c)-M_y(-H_c)|$ at α, is summarized in Fig. 3(b) together with $MR_{max}(\alpha)$ in the range −95°~5°. $M_y(\alpha)$ shows a maximum at H2 and minim at CH and CE, and this is not uniaxial behavior. Based on MOKE and MR measurements we conclude that there are two effective easy axes in this sample and the directions of E1 and E2 are the easy directions.

4. Discussion

The angular modulation of $MR_{max}(\alpha)$ is the direct results of the alignment of two magnetization vectors that are bound to their own easy axes. In the following discussion we assume coherent rotation of the magnetization.

We start by assuming that there exist two 'effective' magnetic easy axes, which separated by 50°, and that there exist two 'effective' magnetization vectors, which are bound to their own easy axes, in the Co/Cu multilayers. The direction of the center of easy axis (CE), which is the center of the two 'effective' magnetic easy axes, is taken to be the x-axis. The magnetization directions of the Co layers are θ_1 and θ_2, relative to the center of the easy axes, as shown in Fig. 4. The energy per unit area of mutilayers in the applied field H is

$$\begin{aligned} E_1 = & -mt_{Co}H\cos(\theta_1-\alpha)+K_a t_{Co}\sin^2(\theta_1-\beta) \\ & -mt_{Co}H\cos(\theta_2-\alpha)+K_a t_{Co}\sin^2(\theta_2+\beta) \\ & +2J_{af}\cos(\theta_1-\theta_2) \end{aligned} \quad (1)$$

where m is the saturation magnetization of Co layers with a thickness t_{Co}, K_a is an anisotropy constant, α is the angle between the applied field and the x-axis, β is the angle between the easy axis and the x-axis, and J_{af} is the AF coupling constant [11].

By applying Eq. (1), we can plot energy contours as a function of θ_1 and θ_2. We assume that the system is trapped in a local energy minimum. By looking for the position of the local minimum value in the energy contours for a range of applied fields, we can plot the hysteresis loops and the MR curve. By comparing the coercive field and remanence of the experimental hysteresis loop with the calculated hysteresis loop, we found that the anisotropy constant (K_a) is 1.24×10^5 erg/cm^3 and the antiferromagnetic coupling constant (J_{af}) is 0.0044 erg/cm^2. In Fig. 1(b) the solid line shows the calculated hysteresis and the dotted line shows the experimental hysteresis. The difference between experimental loop and calculated loop is due to the fact that the simulation assumes coherent rotation of magnetization while the experimental result has a contribution from domain wall motion. When H//CE direction (α=0°), both magnetization vectors (M_1 and M_2) point along the +x-direction at + saturation field ($+H_{sat}$). As H decreases, $M_1(M_2)$ starts to rotate toward its easy axis, E1 (E2), and the angle ($\Delta_H(0°)$) between M_1 and M_2 starts to increase. However at H=0, $M_1(M_2)$ does not lie in the E1 (E2) direction because of the antiferromagnetic exchange coupling, which prefers a larger angle between M_1 and M_2. From the calculation, the angle between $M_1(M_2)$ and CE is approximately 40° at $H=0$. As H becomes negative, $\Delta_H(0°)$ increases and then suddenly M_1 and M_2 switch to their easy axes at $H=-$

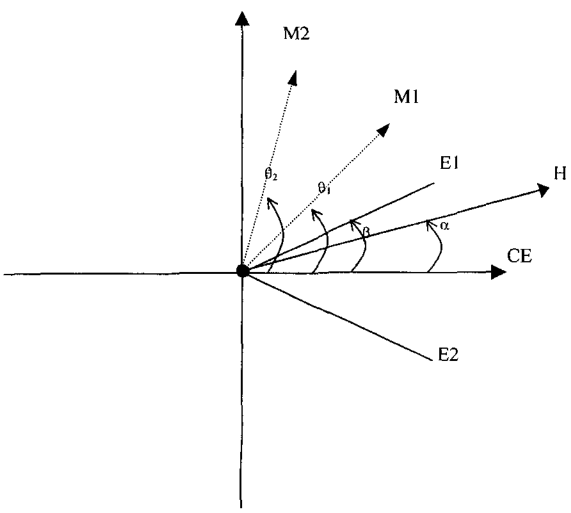

Fig. 4. Definition of θ_1, θ_2, α and β.

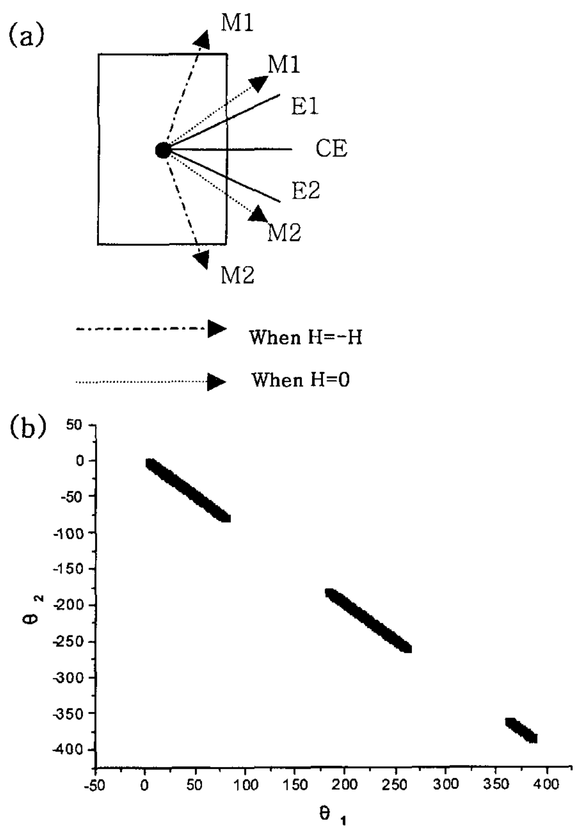

Fig. 5. Coherent rotation of the two magnetization vectors when the field decreases from $+H_{sat}$. (a) H//CE (α=0°) (b) Simulated values of θ_1 and θ_2, showing that the switching occurs at $\theta=70°$.

H_c. Just before switching, the maximum $\Delta_{max}(0^o)$ can be obtained as explained in Fig. 5(a), and $MR_{max}(0^o)$ results at $-H_c$. Fig. 5(b) shows the simulated θ_1, θ_2 by using Eq. (1) and confirms the above arguments. It shows that switching occurs when $\theta_1 \cong 70^o$ and $\theta_2 \cong -70^o$. As H increases from H_{sat}, the same process occurs and thereby two maxima appear in the MR curve at $\pm H_c$. When H//CH ($\alpha = 90^o$), the same process also happens and the angle between M_1 and M_2 is larger than $\alpha = 0^o$. This process also explains the minimum $M_y(0^o)$ and $M_y(-90^o)$ in Fig. 3(b), because the y-components of the two magnetization vectors point in opposite directions during coherent rotation.

It is also known from Fig. 5(b) that there exist two maxima in the GMR curve. By caculating $|\theta_1 - \theta_2|$ from the figure, we can obtain two maximum values near the $\pm$ coercive field, which means that there exist two maxima in the GMR.

Summary

In conclusion, we have shown that the magnetic anisotropy together with antiferromagnetic coupling affect the maximum MR ratio, and that the existence of two maxima in the MR curve can be explained by the existence of two easy axes. And from the simulated MR curve, we can determine the angle between M_1 and M_2.

Acknowledgments

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