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Angular modulation of the GMR at the 2nd AFM

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Abstract

In order to study the effect of the magnetic anisotropy on the giant magnetoresistance (GMR), the angle dependent magnetoresistance (MR) was measured. The experimental results show that the maximum MR ratio depends on the angle between the direction of the applied field and that of 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. The typical property of MR loops at 2^{nd} antiferromangtic maximum (AFM) such as two maxima was discussed in relation with the magnetic anisotropy (MA). The simulated results under an assumption of the two in-plane easy axes, which exist in the sample, were compared with the experiments.

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 GMR maximum with decreasing amplitude [2]. In spite of the extensive studies, the problem that has been poorly understood is an irreversible decrease in GMR maximum after an as-grown specimen has been subjected to a magnetic field [3-9]. The next interesting point is that the magnetoresistance curve at the 1st AFM shows single maximum (usually at 0 field) while it shows 2 maxima (at ± coercive field) at the 2nd AFM. The third one is the role of magnetic anisotropy (MA). The alignment of magnetization vectors, which directly affects GMR, is determined by the competition among the magnetic anisotropy, exchange coupling, and magnetic field, after assuming the coherent rotation.

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 two maxima by treating multilayers as assemblies of grains with random orientations of magnetic easy axis. Borchers, *et al* [8]. suggested a model of breaking antiparallel correlation of Co domains across Cu spacer in a weakly coupled Co/Cu multilayers for the irrevesible decrease of GMR maximum.

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

Experiments

We have prepared [Co (15 Å)/ Cu (20 Å)]$_{30}$ on Si (100) substrate with a natural oxide using UHV dc magnetron getter-sputtering system which has been described elsewhere [10]. All measurements were carried out at the 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. The standard four point spring-loaded probe was used for MR. Magneto Optic Kerr Effect (MOKE) was used to measure magnetic hysteresis loops. For MOKE measurements the 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 are *s*-polarized in order to measure the magnetization component parallel to the scattering plane.

Results

Fig. 1 shows the typical MR (H) curve and the hysteresis loop on Si/[Co/Cu]$_{30}$ at the second AFM such that the ratio, $MR_b\,(0)$, is 31 % before applying 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 difference. Fig. 2(b) shows the angular modulation of GMR maximum ($MR_{max}\,(\alpha)$). $MR_{max}\,(\alpha)$ shows four maxima at -90° (CH),

-25° (E1), 25° (E2) and 90° (CH) and a dip at 0° (CE) and minima at -65° (H2) and 65° (H1). The width of 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 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.

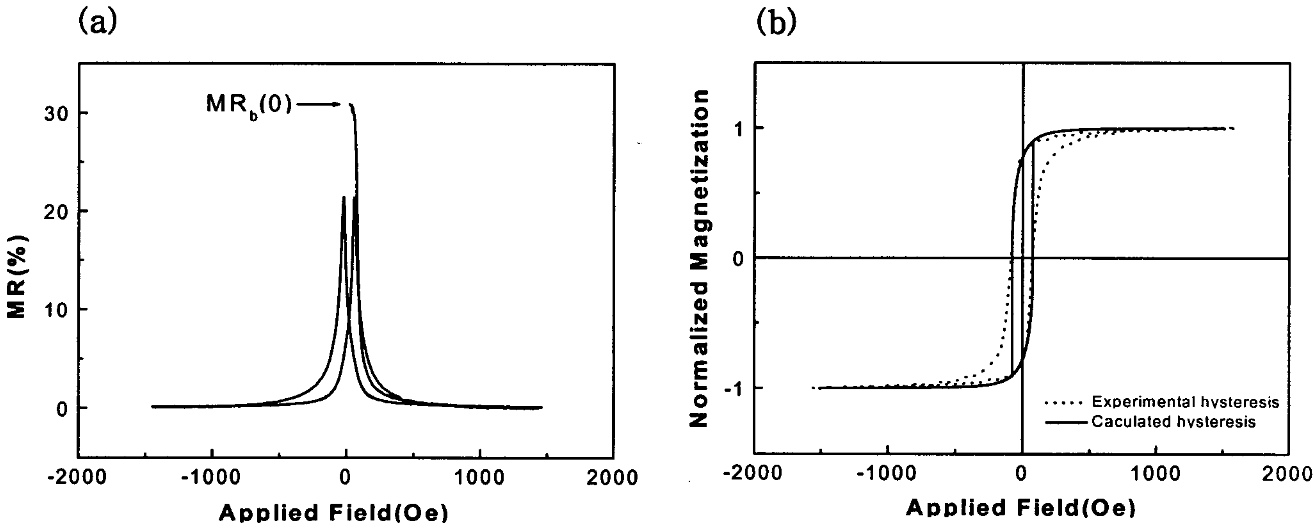

Fig. 1. (a) The typical magnetoresistance loop and (b) hysteresis loop on the Si/$[Co/Cu]_{30}$. The solid line shows the calculated curve and the dotted line shows the experimental curve.

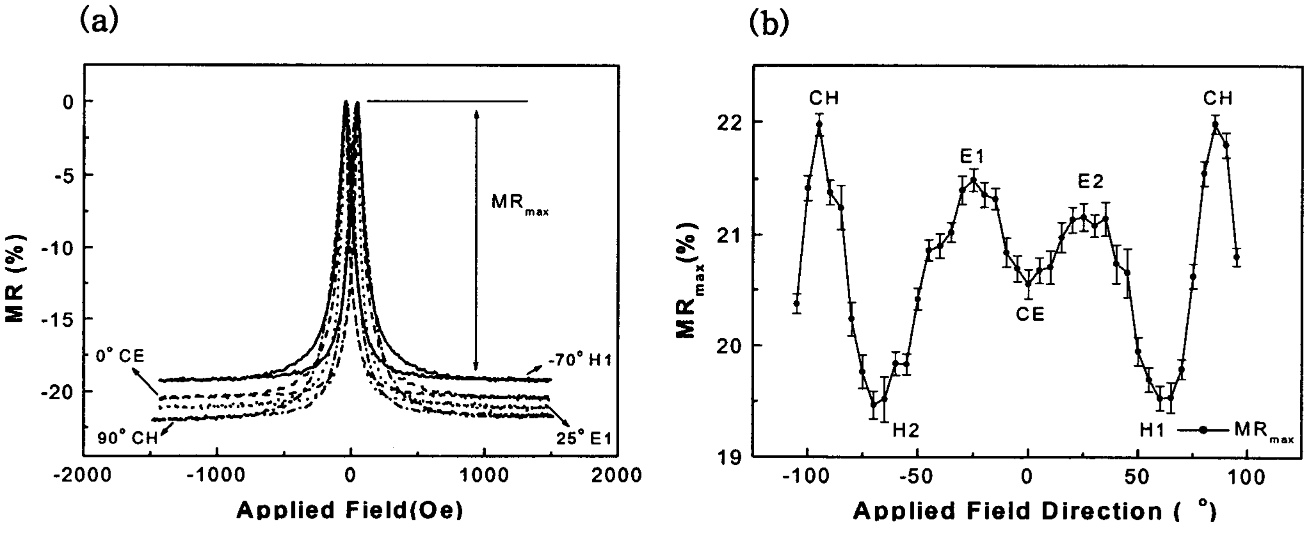

Fig. 2. (a) *MR* curves at various applied field directions. (b) Angular modulation of GMR maximum ($MR_{max}(\alpha)$).

MOKE measurements were used to find out these effective easy directions. Fig. 3 shows the results. The x-component in Fig. 3(a) suggests that the easy direction of magnetization is around $\alpha=0°$ and the hard direction at $\alpha=90°$. But the y-component shows 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 of -95°~ 5°. $M_y(\alpha)$ shows maximum at H2 and minimum at CH and CE, and this is not uniaxial property. 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.

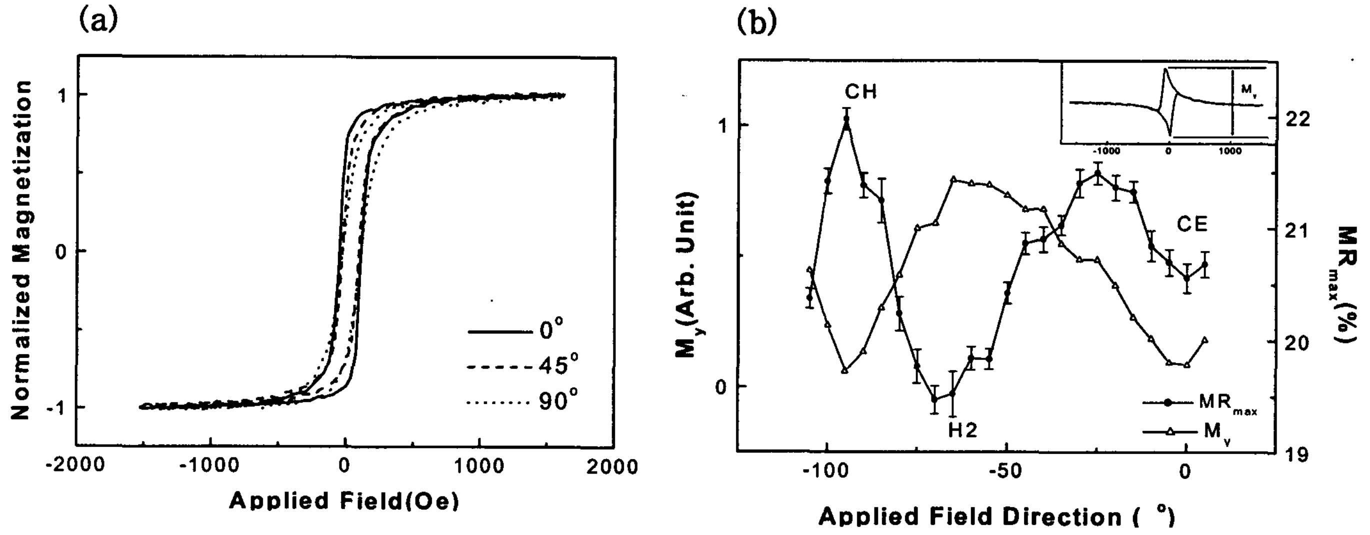

Fig. 3. (a) Normalized hysteresis loop of the x-component of magnetization at various field directions. (b) Angular modulation of $M_y(\alpha)$, which is normalized to the maximum value during the angular measurements, together with $MR_{max}(\alpha)$. Inset: definition of $M_y(\alpha)$.

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 the coherent rotation of magnetization.

We start by assuming there exist the two 'effective' magnetic easy axes, which separated by 50° each other and there exist the 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

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

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].

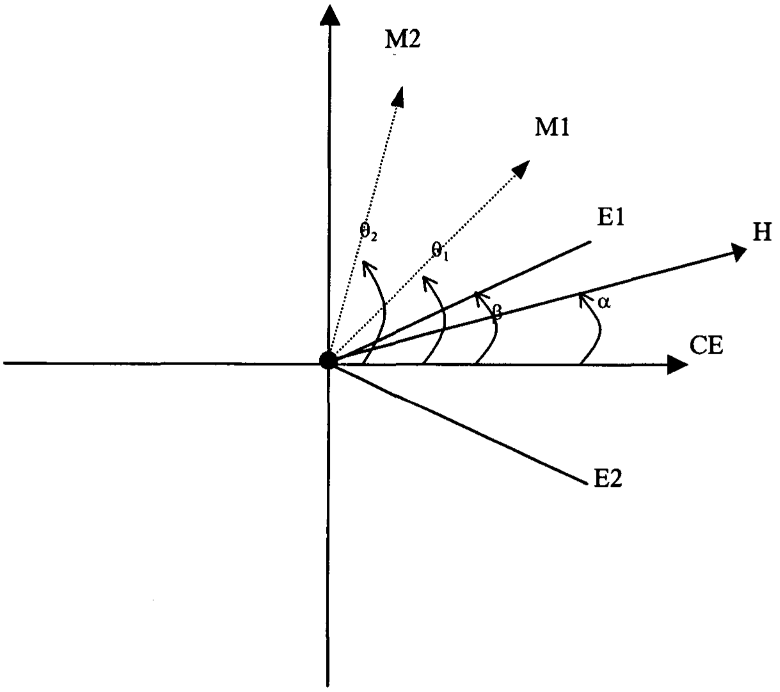

Fig. 4. Definition of θ_1, θ_2, α and β.

By applying Eq. (1), we can plot the energy contours as a function of θ_1 and θ_2. We assume that the system trapped in a local energy minimum. By looking for the position of the local minimum value in the energy contours at the various applied field, we can plot the hysteresis loops and the MR curve. By comparing coercive field and remanence of the experimented hysteresis loop and 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. At Fig. 1.(b) the solid line shows the caculated hysteresis and the dotted line shows the experimental hysteresis. The difference between experimented loop and calculated loop is due to the fact that the simulation assumes coherent rotation of magnetization while the experimental results has a contribution from domain breaking. When H//CE direction (α=0°), both magnetization vectors (M_1 and M_2) points along +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 (Δ_H(0°)) between M_1 and M_2 starts to increase. However at H=0, M_1(M_2) does not point E1 (E2) direction because of the antiferromagnetic exchange coupling which prefers larger angle between M_1 and M_2. And from the calculation, the angle between M_1(M_2) and CE is 40° approximately at H=0. As H becomes negative, Δ_H(0°) increases and then suddenly M_1 and M_2 switch to their easy axes at -H_c. Just before switching, maximum Δ_{max}(0°) can be obtained as explained in Fig. 5(a), and MR_{max}(0°) is resulted 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 the switching occurs when $\theta_1 \cong 70°$ and $\theta_2 \cong -70°$. As H increase from $-H_{sat}$, the same process occurs and thereby two maxima appear in MR curve at ±H_c. When H//CH (α=90°), the same process also happens and the angle between M_1 and M_2 is larger than α=90°. This process also explains the reason for minimum M_y(0°) and M_y(-90°) in Fig. 3(b), because the y-components of the two magnetization vectors point in the opposite directions during coherent rotation.

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

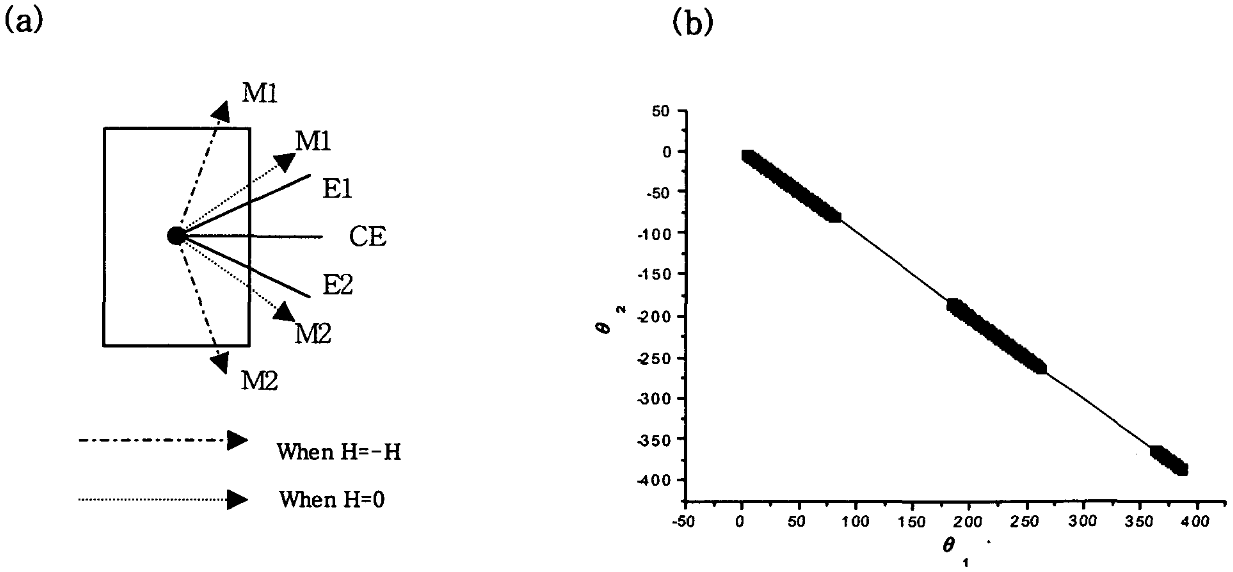

Fig.5. Coherent rotation of the two magnetization vectors when the field decreases from + H_{sat}. (a) H//CE (α=0°) (b) Simulated values of θ_1 and θ_2 It's shows that the switching occurs at θ=70°.

Summary

In conclusion, we have shown that the magnetic anisotropy together with antiferromagnetic coupling affect the maximum MR ratio and the existence of two maxima in MR curve can be explained by existence of the 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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