Magnetoresistance and magnetic properties of Co/Ir multilayers on MgO(110) substrates

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A Co(12 Å)/Ir(16 Å) multilayer deposited on MgO(110) is found to have a strong uniaxial anisotropy, comparable to bulk hcp-Co. Experimental results suggests the crystallographic relation of (100)[001]Co/(110)[001]Ir/(110)[001]MgO. A remarkable difference is seen between easy and hard axis magnetization processes, due to competition between the in-plane anisotropy and the exchange coupling. Considering the characteristics of the MH loops and magnetoresistance curves, we simulate the magnetization and magnetoresistance processes numerically. The results of our simulation indicate the existence of biquadratic coupling in Co/Ir(110). © *1997 American Institute of Physics.* [S0021-8979(97)71208-8]

I. INTRODUCTION

Magnetic multilayers (MLs) have been attractive because of their enormous potential for applications. Various magnetic characteristics have been reported in magnetic ML systems having both magnetic anisotropy and magnetic coupling between layers.[1,2] Of particular significance is the appearance of giant magnetoresistance (GMR) in ML systems, which is associated with the antiparallel configuration of magnetization between adjacent layers. Such configurations are most readily realized by an antiferromagnetic coupling between adjacent layers. In recent years, the existence of $\pi/2$ (biquadratic) interlayer coupling has been reported both experimentally[3] and theoretically.[4] The presence of strong biquadratic interactions could lead to a greater variety of magnetization configurations, and consequently, to a large variety of magnetoresistance (MR) curves.

In this article, we report strong in-plane magnetic uniaxial anisotropy, comparable to that of bulk hcp-Co ($K_u = 4.6\times10^6$ erg/cc), in Co/Ir MLs grown on MgO(110). Using a model taking account of exchange energy up to a biquadratic term, the model can reproduce the magnetic-field dependence of the magnetization and MR, and hence supports the existence of a biquadratic term in the Co/Ir(110) ML.

II. EXPERIMENT

A Co/Ir ML was deposited with a magnetron sputtering system onto Fe(5 Å)/Pt(50 Å)/Ir(50 Å) as a buffer layer deposited on a MgO(110) single-crystal substrate. We chose a Co layer thickness of 12 Å and Ir layer thickness of 16 Å corresponding to the second maximum of antiferromagnetic coupling.[5] The ML is composed of 100 repeats of Co(12 Å)/Ir(16 Å), with a 34 Å Ir cap layer deposited to prevent oxidation. The ML structure was confirmed by medium-angle x-ray diffraction with Co K_α radiation ($\lambda = 1.79$ Å). Magnetization curves (MH loops) were measured with a SQUID magnetometer. MR measurements were carried out using a conventional dc four-contact method. The sample for MR measurements was cut into a strip shape along MgO[001]. Magnetic fields up to 15 kOe were applied along MgO[001] and MgO[110] directions. Both MH measurements and MR measurements were performed at 10 K and room temperature. In-plane magnetic torque measurements were carried out with an automatic torque magnetometer at room temperature in a magnetic field of 14 kOe. The torque-measurement sample was cut into a rectangle (2.9×2.2 mm^2) in order to reduce demagnetization effects; the same sample was used for MH measurements.

III. RESULTS AND DISCUSSION

An x-ray diffraction pattern of the Co/Ir ML was obtained in reflection geometry with the scattering vector normal to the surface. Peaks due to an artificial structure were observed around the hcp-Co(100) and the fcc-Ir(220) Bragg peaks; however, there was no peak around the angle corresponding to the Bragg peak of the fcc-Co(111). The result supports the crystallographic relation of (100)hcp-Co/(110)Ir/(110)MgO.

Figure 1 shows magnetization curves at RT and at 10 K after subtraction of the substrate diamagnetic background. With the magnetic field applied along MgO[001], a staircase-like open hysteresis loop was obtained. On the other hand, when the field was applied along the MgO[110] direction, there was little hysteresis and the magnetization changed monotonically with a saturation field of ≈19 kOe (≈22 kOe at 10 K). The in-plane torque profile suggests that the anisotropy of this sample is uniaxial in the film plane; the easy and

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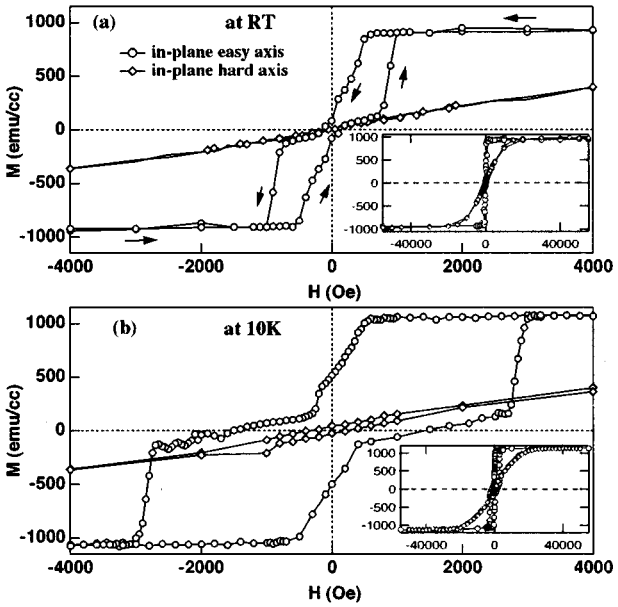

FIG. 1. Magnetization vs applied field along the in-plane two directions: MgO[001] (circles) and MgO[110] (diamonds). (a) RT, (b) 10 K. The inset shows *MH* curves up to 55 kOe at each temperature.

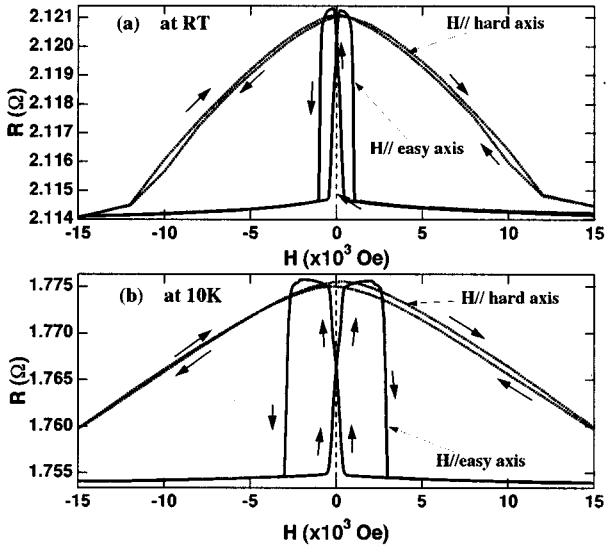

FIG. 2. Magnetoresistance vs applied field along MgO[001] (circles) and MgO[110] (diamonds). (a) and (b) are measured at RT and 10 K, respectively. The field is applied up to 15 kOe.

hard axes correspond to MgO[001] and $[\bar{1}10]$ directions, respectively. The torque curves were dependent on the external fields, but saturated above an external field of 13 kOe. We estimated the uniaxial anisotropy (K_u) as $\approx 5\times 10^6$ erg/cc from the amplitude of torque. The value is close to that of hcp-Co ($K_u = 4.6\times 10^6$ erg/cc) and we presume that the hcp-Co[001] lies along the MgO[001]. Supposing that only Co atoms are responsible for the magnetic moments of the ML, we find the magnetization (M) to be 940 emu/cc at RT, and 1110 emu/cc at 10 K. This distinctly lower value of M compared with bulk hcp-Co (1440 emu/cc) suggests mixing or alloying at interfaces between Co and Ir layers.

The MR curves at RT and 10 K are shown in Fig. 2. The MR ratio $[\Delta R/R(H_s)]$ is only 0.3% at room temperature and 1.2% even at 10 K. Parabolic MR curves with little hysteresis are obtained when the field is applied along hard axis. Along the easy axis, however, the MR curves exhibit squared plateaus and large hysteresis of several kOe. The MR processes are quite consistent with the MH curves at every temperature, indicating that the resistance mechanism is strongly dependent on the magnetization. When $H=15$ kOe at RT, there is little difference between hard- and easy-axis MR, and this implies that each magnetic configuration is equivalent and saturated to a nearly parallel configuration. The saturated torque curves will be given by the same mechanism.

Here, in order to investigate the origin of these peculiar curves of MH and MR, we consider the free energy (E) using a model[6,7] containing in-plane uniaxial anisotropy (K_u), first-order (bilinear) exchange (J_1), second-order (biquadratic) exchange[4] (J_2), and magnetostatic energy. The Co/Ir MLs have out-of-plane anisotropy as strong as the uniaxial anisotropy of hcp-Co due to the interface anisotropy;[8] however, we ignore this in order to simplify the model. Assuming a coherent rotation model of the magnetization process, without domain motion or pinning effect, we can find the in-plane configuration of magnetic moments by minimizing the reduced energy ($\epsilon \equiv 2E/M$),[6]

$$\epsilon(\xi,\eta) = H_k\left[\sin^2\left(\frac{\xi}{2}\right)\cos^2\ \eta + \cos^2\left(\frac{\xi}{2}\right)\sin^2\ \eta\right] + \frac{H_1}{2} \times \cos\ \xi + \frac{H_2}{2}\cos^2\ \xi - 2H\ \cos\left(\frac{\xi}{2}\right)\cos(\psi-\eta), \quad (1)$$

where ξ is an angle between the magnetic moments of Co adjacent layers, η and ψ are the angles of the net magnetization and applied magnetic field measured from the easy axis, and t is the Co layer thickness. The energy terms are expressed as fields; that is, $H_k \equiv 2K_u/M$, $H_1 \equiv 4J_1/tM$, $H_2 \equiv 4J_2/tM$. Because the above configurations cannot be solved analytically, in general, we use an iterative calculation.[9] The net magnetization parallel to the field is proportional to $\cos(\xi/2)\cos(\psi-\eta)$, and in the simplest MR picture, $\Delta R(H)$ is similarly proportional to $\cos(\xi)$. We regard 100 bilayers as infinite repeats of bilayers,[7,10] and neglect coupling-energy differences that depend on layer numbers.

Some special magnetic characteristics, such as saturation fields and remanence, can be expressed analytically using the transformed fields above. The saturation fields along easy and hard axes are $H_{s,e} = H_1 + 2H_2 - H_k$, and $H_{s,h} = H_1 + 2H_2 + H_k$, respectively. The condition for finite remanence along the easy axis is $2H_2 \geqslant H_k - H_1 > 0$. When the easy axis MH curve possesses a finite remanence, the configuration is given by $\xi = \cos^{-1}[(H_k - H_1)/2H_2]$, $\eta = 0$. Similarly, the condition for no remanence along the hard axis is

$$2H_2 \leqslant H_k + H_1. \quad (2)$$

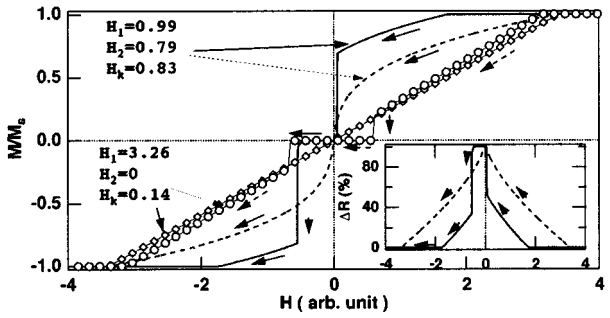

FIG. 3. *MH* curves obtained by iterative simulation for two cases. The solid line and dotted line are *MH* curves for easy and hard axes, respectively, obtained for case II: $H_1=0.99$, $H_2=0.79$, and $H_k=0.83$. The circles and diamonds are obtained for case I: $H_1=3.26$, $H_2=0$, and $H_k=0.14$. These values are determined from the relations, that is, $H_{s,h}/H_{sw}\approx 5$ and Eq. (2). The inset shows MR curves for case II.

The switching field is defined as the magnetic field along the easy axis at which the $\xi=\pi$ and $\eta=\pi/2$ configuration becomes unstable in an increasing field, and is given by

$$H_{sw}=\sqrt{H_k(H_k+H_1-2H_2)} \quad \text{for } H_k+H_1>2H_2. \qquad (3)$$

The above equations are necessary conditions because the changes of the submagnetization configurations are strongly dependent on the initial state.

Considering the hard axis *MH* curve, we conclude that the zero-field configuration must have $\xi(H=0)\simeq\pi$, because there is no remanence, and that η is always $\pi/2$. The maximum value of the easy axis MR is close to the zero-field MR value obtained along the hard direction so that the magnetic configuration of the plateaus on the easy axis MR curve must also have $\xi(H=0)\simeq\pi$. The plateau in the MR curves and the ratio of $H_{s,h}$ to H_{sw} (≈ 5 at 10 K) give us a key to determine appropriate values of the parameters. Figure 3 shows simulation results of *MH* for the two cases which satisfy the above relation ($H_{s,h}/H_{sw}\approx 5$) and Eq. (2). In case I we set $H_2=0$ while in case II we include a biquadratic term. We chose the fields so as to make $H_{s,h}=3.4$ in both cases. It is clear that we could not reproduce the experimental *MH* curves in case I ($H_1=3.26$ and $H_k=0.14$); however, quite similar *MH* curves to the experimental data are obtained in case II ($H_1=0.99$, $H_2=0.79$, and $H_k=0.83$). Each parameter should be optimized to obtain better agreement between experimental and simulation results.

In the hard axis magnetization process, there is no hysteresis and the relation $\eta=\pi/2$ is kept in any field. With the applied field along the easy axis, the MR curve (see the inset of Fig. 3) has a wide plateau with large staircaselike hysteresis similar to the experimental curves. Although there is disagreement between the simulated MR curve and the experimental data around zero field along the hard axis, most characteristics of the experimental results could be reproduced. Decreasing the easy axis field from saturation, the spins fan out from saturation ($\xi=0$, $\eta=0$) to ($\xi\neq 0$, $\eta=0$) and then make a discontinuous spin-flop transition at $H\gtrsim 0$ to zero net moment ($\xi=\pi, \eta=\pi/2$). The experimental *MH* loops, however, show a finite remanence. This AF configuration changes to $\xi\neq\pi$, $\eta\neq\pi/2$ in weak negative fields and then switches to negative M ($\xi\neq 0$, $\eta=\pi$) at the switching field. For $|H|>|H_{sw}|$, the magnetization process is reversible. From the above discussion, the H_2 term is seen to be necessary to reproduce the ratio of $H_{s,h}$ to H_{sw}, supporting the existence of the strong biquadratic coupling in this ML.

IV. CONCLUSION

We have found that Co(12 Å)/Ir(16 Å) MLs deposited on MgO(110) show strong anisotropy, comparable to bulk hcp-Co. Experimental results suggests the crystallographic relation of (100)[001] Co/(110)[001]Ir/(110)[001]MgO. Within the coherent rotation model, strong biquadratic coupling in Co/Ir(110) is required to reproduce the experimental MH and MR results.

ACKNOWLEDGMENTS

We are grateful to Professor A. Tasaki of University of Tsukuba. This research was partly supported by DOE Grant No. DEFG02-91-ER45439 at the University of Illinois.

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