Studies of anisotropic and giant magnetoresistance in Co/Cu(111) epitaxial multilayers

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Co/Cu(111) multilayers, [Co(17 Å)/Cu(8 Å<\(t_{Cu}\)<14 Å)]\(_{30}\), have been prepared on Co(70 Å) buffer layers on \(\text{Al}_2\text{O}_3\)(0001) substrates by molecular beam epitaxy. From the longitudinal and transverse magnetoresistance (MR) measurements, it is observed that MRs consist of two components with a small anisotropic MR (<2%) component at low field sitting on top of the giant MR (up to 22%) component at higher field. The AMR effect strongly correlates with the abundance of hcp stacking of Co, which tends to decrease with the increasing of Cu spacer thickness. The AMR saturation fields (1–3 kOe) coincides with those of the magnetization. It is suggested that the observed AMR effect is due to scattering from the hcp-phase Co layers in the multilayers. This together with the large saturation field (30–40 kOe) obtained from the entire MR curves indicate that the observed GMR effect may result from the Co-Cu interfacial spin-dependent scattering.

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I. INTRODUCTION

Anisotropic MR (AMR£5%) has commonly been observed in pure ferromagnetic materials for many years. Recently, the giant magnetoresistance (GMR) in magnetic multilayers has become the subject of considerable interest both from scientific and advanced technological point of view. Note that GMR is quite different from AMR. AMR is basically an effect due to the spin-orbital interaction, while GMR effect is related to the spin configuration change of neighboring ferromagnetic layers from the antiferromagnetic (AF) coupling state to the ferromagnetic (F) coupling state. Further, GMR is isotropic with respect to the relative direction between the field \(H\) and current \(I\), while AMR depends strongly on relative direction of \(H\) and \(I\).

Giant MR (GMR) was first realized in the Fe/Cr multilayers. Accompanied with the GMR effect, oscillatory exchange coupling phenomena were discovered in many magnetic multilayers. Particularly, Co/Cu multilayers have attracted much attention because of the giant MR values. In addition, Co/Cu is a suitable system to verify the mechanism of oscillatory exchange coupling because of the relatively simple nature of the Cu Fermi surface. Although GMR effect is widely explained in correlation with the spin configuration change of the successive ferromagnetic layers, increasing evidences were shown, however, that scattering from interfacial states between the ferromagnetic and nonferromagnetic layers could be more important for GMR effect in some multilayer systems.

In this investigation, we report the structural and magnetic characterizations of Co/Cu(111) multilayers prepared by MBE. The effect of structure upon magnetic and magnetotransport properties has been systematically studied.

II. EXPERIMENTAL PROCEDURES

The epitaxial Co/Cu(111) multilayers presented here were grown on Co buffer layers (70 Å) on \(\text{Al}_2\text{O}_3\)(0001) substrates by molecular beam epitaxy (Vacuum Product model MBE-930) system. Pure elements (99.99%) of Co, Cu were evaporated from an \(e\)-beam evaporator and a Knudsen cell, respectively. The base pressure of the system before deposition was less than \(4\times10^{-10}\) Torr. To enable the growth of high-quality samples, polished and epitaxial grade \(\text{Al}_2\text{O}_3\) substrates were chemically precleaned and rinsed in an ultrasonic cleaner. They were then outgassed at 1000 °C for 1 h under ultra-high-vacuum condition in the MBE chamber. Buffer layers of 70 Å Co were deposited on substrates at about 400 °C to initiate the multilayer growth. The deposition rates for Co and Cu were controlled at about 0.1 Å/s. A series of [Co(17 Å)/Cu(\(t_{Cu}\)Å)]\(_{30}\) (with the Cu spacer layer thickness \(t_{Cu}\) designed to be 8, 10, 12, and 14 Å) multilayers were then prepared at about 150 °C.

The surface structures of the films were in situ examined by reflection-high-energy electron-diffraction (RHEED). The bulk structures and the superlattice period were determined by x-ray diffraction (XRD). The magnetic properties and MRs of all the samples were studied by using a commercial (quantum design) SQUID magnetometer in a magnetic field up to 50 kOe with measuring temperature at 10 K. MR measurements were carried out by standard dc four-point probe technique with \(I\) and \(H\) in the plane of the layers. Transverse and longitudinal MRs were measured with \(I\perp H\) and \(I\parallel H\), respectively.

III. RESULTS AND DISCUSSIONS

Figure 1 shows a typical RHEED pattern of fresh Cu(111) surface during the growth of Co/Cu multilayers. Similar RHEED feature was observed on the growing surface of Co. As can be seen from the RHEED pattern, the crystal surface was rather smooth and nice indicating high-quality epitaxial multilayers. Figures 2(a)–2(d) show the high-angle XRD spectra for the Co/Cu(111) multilayers for a fixed Co thickness of 17 Å and variable Cu layer thickness \(t_{Cu}\) (in one bilayer). To avoid the enormous \(\text{Al}_2\text{O}_3\)(0001) substrate peak at \(2\theta\approx41°\), the range of x-ray spectra is limited to above 42.5°. The large peaks located at about \(2\theta\approx43.7°\), indexed as fcc(111), lie in between the positions of bulk fcc Cu(111) and bulk fcc Co(111), as illustrated in the inset of Fig. 2. The fcc(111) peaks are likely due to the strain effect between the Cu and Co layers with close lattice parameters.

of 2.087 and 2.051 Å. Similar strain effect was also found in sputtered Co/Cu multilayers in the other work. The fcc(111) peak slightly shifts toward the bulk fcc Cu(111) positions as \( t_{\text{Cu}} \) increased (see Fig. 2). By average each shift corresponds to an increase of the interatomic spacing of about \( 2.2 \times 10^{-3} \) Å. This is quite reasonable since the lattice parameter of fcc Cu is slightly larger than that of the fcc Co.

Shown in Fig. 2 includes the satellite peaks (indexed as \( S \)) corresponding to the periodicity of the multilayers. In addition, for each XRD spectrum there is a very small yet broad peak around 2\( \theta \sim 51^\circ \), which corresponds to the position of the fcc(200) peak. Interestingly, one can also observe a rather strong peak near the fcc(111) for samples (a) and (b). This peak coincides with the position of bulk hcp Co(0002). The existence of hcp Co(0002) phase is likely due to a large concentration of stacking faults in the multilayers. Furthermore, the Co(0002) peak intensity decreases with the increasing of the Cu spacer layer thickness for the multilayers (see Fig. 2).

Figures 3(a)–3(c) show the magnetization, longitudinal and transverse MRs for the [Co(17 Å)/Cu(10 Å)]\(_{30}\) multilayer. Here MR is defined as \( [R(H) - R_{\text{min}}]/R_{\text{min}} \), as usual, where \( R_{\text{min}} \) is the minimum (at saturated field) of measured electrical resistance. Basically, both longitudinal and transverse MRs possess almost the same curves, saturation field (\( \sim 30 \) kOe) and GMR values (up to about 11%) for field larger than 3 kOe. For small magnetic field (\( \leq 3 \) kOe) the longitudinal MR curve exhibits a small dip (\( \sim 0.5\% \), negative), while the transverse MR curve displays a sharp spike (\( \sim 1\% \), positive). This low field anisotropic behavior together with the obvious hysteresis for both MR curves correlate strongly with the magnetization loops, as shown in the inset of Fig. 3. Note that this AMR phenomenon has a strong link with the hcp phase of Co in the multilayers, as discussed below. In addition, the distinct saturation fields for the magnetization (3 kOe) and the entire MR curves (30 kOe) point to the separate mechanisms between the observed GMR effect and the bulk scattering from the magnetic (Co) layers. The M-H loop shown in Fig. 3 indicates that the magnetic layers are largely ferromagnetically coupled, suggesting that the AF coupling between the magnetic layers may not be responsible for the observed GMR effect. Similar result was also observed by Barlett et al. in MBE grown Co/Cu(111) multilayers. It has been proposed that superparamagnetic states at the interface, for the Cu conduction electron band being partially polarized in proximity to the Co layers, are responsible for the high saturation field of GMR curves in MBE grown Co/Cu multilayers. We thus believe that interfacial spin-dependent scattering appears to be a dominant factor for the GMR effect in the Co/Cu(111) multilayers.

Shown in Figs. 4(a)–4(d) are the longitudinal MR curves for sample (a) to sample (d) with increasing \( t_{\text{Cu}} \). Note that similar features of longitudinal and transverse MRs in sample (b) also exist in sample (a). Compared to sample (b), sample (a) possesses larger GMR saturation field (\( \sim 40 \) kOe) and smaller AMR (and magnetization) saturation field (\( \sim 1 \) kOe), as shown in Figs. 4(a)–4(b). The AMR effect for sample (a) is slightly stronger than sample (b) with the longitudinal dip (see inset of Fig. 4) and transverse spike each of about 1%. On the other hand, the AMR effect completely disappears for sample (d) [see Fig. 4(d)], that is, the...
same longitudinal and transverse MRs at low or high field (isotropic GMR behavior) is found. For sample (c), the MR curve [Fig. 4(c)] appears to be an intermediate configuration between the typical pure GMR effect [like Fig. 4(d)] and the combination of the AMR and GMR effect [like Figs. 4(a) and 4(b)].

Finally we discuss the connection between the observed AMR effect and the hcp phase of Co in the multilayers. By comparison Figs. 4(a)–4(d) with the XRD spectra in Figs. 2(a)–2(d), it is quite easy to see a trend that the AMR effect decreases with the reducing of the hcp Co(0002) intensity. It is suggested that the observed AMR effect could be mainly due to scattering from the hcp Co layers of the multilayers. The strong correlation between the AMR and hcp phase of Co could be owing to the dominance of the anisotropic effect of the hcp phase (uniaxial anisotropy) over than that of the fcc phase. So far, however, we are not able to quantitatively determine the ratio of the fcc and hcp phase of Co in the multilayers.

In summary, we have presented the structural and magnetic characterizations of Co/Cu(111) epitaxial multilayers. A small AMR component at low field sitting on top of a large GMR component extended to higher field has been observed. The AMR effect strongly correlates with the abundance of hcp stacking in the Co layers, which tends to decrease with the increasing of Cu spacer layer thickness. The AMR saturation fields coincides exactly with those of the magnetization. It appears that the observed AMR effect is mainly due to the scattering from the hcp phase Co layers in the multilayers. This together with the large saturation field obtained from the entire MR curves indicate that the observed GMR effect may result from the Co-Cu interfacial spin-dependent scattering.

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