Influence of Chromium in Co/Cr(100) Multilayers

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Abstract — Using magneto-optic Kerr effect on Co/Cr epitaxially grown multilayers, we observed an ordering transition of the Co layers with the variation of Cr thickness. Both the coercivity and the squareness show that ferromagnetic coupling exists at thick Cr layers and antiferromagnetic coupling at thin Cr layers. The ordering transition of Co appears around the 5–10 Å of Cr.

I. INTRODUCTION

Co/Cr systems attract attention for their fascinating magnetic properties and industrial applications[1]. In particular, a uniquely giant anisotropy magnetoresistance has been found [2] and it was shown that the thickness of both Co and Cr are important to the magnetic properties of the molecular beam epitaxy (MBE) grown film. Influence of the Cr thickness and the associated Co surface topology in bilayers has been well studied and the variation of anisotropy can be explained [3]. However, interlayer coupling between the magnetic layers has not been fully studied. The mechanism of interlayer coupling in magnetic-nonmagnetic multilayers is a topic of intense research. RKKY-type exchange coupling was observed through a nonmagnetic layer. For Fe/Cr system, it was suggested that the ordering of Cr layer is important for the interlayer coupling[4]. At the Néel temperature, $T_N=311\text{K}$, bulk Cr orders as an incommensurate spin density wave (I SDW) antiferromagnet along the (100) direction[5], the polarization changes from the transverse SDW phase above the spin-flip temperature ($T_{SF}=123\text{K}$) to longitudinal SDW phase below T_{SF} . In multilayers, recent studies concluded that Cr layers lose the Cr bulk magnetism and become paramagnetic, down to 4.2K, or even nonmagnetic for thickness below 6.0 nm[4], and this effect should influence the interlayer coupling between magnetic layers. Therefore, an understanding of the contribution of the Cr thickness on Co/Cr multilayers becomes necessary to fully understand of the multilayer magnetic properties and to optimize their applications.

The purpose of this paper is to study the influence of the Cr layer on the magnetic properties of the Co/Cr multilayer system. We use magneto-optic Kerr effect (MOKE) to study magnetic properties of Co/Cr epitaxially grown multilayers.

At constant thickness of Co layer, the coercivity and the squareness of the multilayers change abruptly around the 6Å thickness of Cr layer. Comparing with the coercivity of bilayer system, it suggests that ordering of Co layer changes at 6Å thickness of Cr.

II. FILM PREPARATION AND MEASUREMENTS

Co/Cr multilayers were grown on MgO substrate at the room temperature and crystal growth was carried out by a MBE system. During the deposition, the growth pressures were controlled at below 5×10^{-9} Torr, and the deposition rates were kept at 0.1 Å/s[5]. The quality of the multilayers was confirmed by reflection-high-energy-electron-diffraction (RHEED) and x-ray diffraction (XRD)[5]. We have grown 30 samples of the specific superlattices: $[\text{Co}(40\text{Å})/\text{Cr}(t_{\text{Cr}})]_{20}$, and repeated structures of multilayers are Co/Cr(100). All of the multilayers are grown on MgO substrates, with a 40Å Mo buffer layer and a 20Å Cr overlayer used to prevent Co layers oxidization. The magnetic properties were analyzed by magneto-optic Kerr effect (MOKE) technique. The LMOKE(magnetic field is parallel to the multilayers) measurements were carried out at room temperature in a magnetic field up to 2.2 kOe. The penetration depth of the He-Ne laser used in MOKE studies is around 200Å, and thus the measured magnetic properties are only surface behavior. However, the coupling between the Co layers should be manifested, at least for the top few layers. We have also measured the magnetoresistance (MR) changes of the multilayers at 10K by DC four-terminal method with up to 5.0 kOe applied magnetic fields.

III. RESULTS AND DISCUSSIONS

Previous studies of the magnetic properties of Co/Cr bilayer show their surface topology is important and it critically depends on the Cr thickness[3]. Nevertheless, atomic force microscopy (AFM) shows that the Cr thickness does not change the surface topology of the Co layer of multilayer system, at least for the top layer(not shown). This suggests that the origins of the variation of the magnetic properties in multilayer system, unlike in the bilayer system, are not associated with the surface topology and induced anisotropy. Since our MOKE penetration depth is around 200Å, only the magnetic properties of the top few layers were studied. Therefore, for a fixed thickness of Co, the variation of the magnetic properties of the multilayer system should mainly stem from the change in the interlayer coupling of the

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Co layers. For the variation of Cr thickness, coercivity of the Co/Cr multilayers seems to change abruptly around 5-10Å of Cr thickness(t_{Cr}). One may intuitively think the small coercivity for the Cr thickness less than 10Å results from the pinholes appearing between the Co layers and thus the coercivity approaches the bulk value of Co. However, the coercivity transition should not so abruptly as Fig. 1 shows, since there are still a lot of Cr pinning centers between the magnetic layers and the decreasing of the coercivity for the imperfect multilayers should smooth. Therefore, it suggests that the type of the interlayer coupling changes significantly for Cr spacer at this thickness. Comparing with the coercivity of Co/Cr bilayers, either grown with MBE [3] or RF sputtered[6], coercivities of Co/Cr multilayers are significantly different: The coercivities of bilayers are about 300-550 Oe, while the coercivity of multilayers becomes either 200 Oe($t_{Cr} \leq 5\text{\AA}$) or 950 Oe($t_{Cr} \geq 10\text{\AA}$) (Fig. 1). For a very thin Cr layer, the decrease of coercivity suggests that the interlayer coupling is of antiferromagnetic type; while for the thick Cr layer, the increasing coercivity suggests a ferromagnetic interlayer coupling. The squareness ($S = M_r/M(H = 2.2\text{kOe})$) data also indicate a coupling transition at Cr thickness around 10Å (Fig. 2). The gradual decay of coercivity and squareness for very thick Cr layer can be interpreted as the weakening of the interlayer coupling through increasing thick Cr layers separating the magnetic layers. It was observed that thin Cr layers lose their bulk magnetic properties and become paramagnetic, down to 4.2 K, or even nonmagnetic for thickness below 60Å [4]. Since the Cr thickness in our multilayers are well below 60Å, the interlayer coupling of Co layers should not be related to the

SDW of Cr itself. The observed ferromagnetic coupling can be explained via topological interaction effects for the Co layers[3]. Since the Cr is not very thick, surface growths of two adjacent magnetic layers are likely to be conformal and the interlayer coupling should be ferromagnetic type[7]. The

Fig. 2: Squareness dependence on the Cr thickness of $\text{Cr}_{20\text{\AA}}/(\text{Co}_{40\text{\AA}}/\text{Cr})_{20}\text{Mo}_{40\text{\AA}}/\text{MgO}(100)$ at the room temperature. The line only guided the eye.

Fig. 1: Coercivity dependence on the Cr thickness of $\text{Cr}_{20\text{\AA}}/(\text{Co}_{40\text{\AA}}/\text{Cr})_{20}\text{Mo}_{40\text{\AA}}/\text{MgO}(100)$ at the room temperature. The line only guides the eye and the arrow indicates bilayer coercivity in Ref. [3].

Fig. 3: Magnetoresistance ratio dependence on the Cr thickness of $\text{Cr}_{20\text{\AA}}/(\text{Co}_{40\text{\AA}}/\text{Cr})_{20}\text{Mo}_{40\text{\AA}}/\text{MgO}(100)$ at 10K. The line only guides the eye.

antiferromagnetic type coupling for thin Cr layers may be due to spins near the nonmagnetic layers staying as parallel as possible to "orange peel" surfaces and the magnetostatic interaction are no long significant[8].

Figure 3 shows the influence of the variation Cr thickness on the MR changes, the oscillatory periods are around 20Å. However, interlayer coupling above 10Å of Cr thickness is apparently ferromagnetic coupling type(Fig. 1); therefore, MR change is probably not from the spin-dependent scattering from the electrons' passages through the interfaces, but may be from the bicrystal structure of Co/Cr(100) multilayers[1]. The orthogonal easy axes make the demagnetization sates to be an alternating magnetization patterns[1] within the Co layer; therefore, the multi-domain boundaries may be the reason for the MR changes.

In summary, the influence of the thickness of Cr layer in Co/Cr(100) multilayers has been studied. Unlike the oscillatory RKKY-type coupling among the magnetic layers of Fe/Cr multilayers, antiferromagnetic coupling was observed for very thin Cr spacers; however, only ferromagnetic coupling exists at thicker Cr films. This implies that the coupling mechanisms in Fe/Cr[9] multilayers and Co/Cr is quite different. The origin of the disparate behavior still remains to be clarified. MR changes data indicate that the spin-dependent scattering may occur within the bicrystal Co layer instead of the interface of multilayer. Nevertheless, the influence of Cr thickness on the structure and the domain size of bicrystal Co layers are waited for further studies.

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