Studies of the magnetic anisotropies of Co(1$\bar{1}$00)/Cr(211) and Co(1120)/Cr(100) multilayers

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Co(1$\bar{1}$00)/Cr(211) and Co(11$\bar{2}$0)/Cr(100) multilayers have been simultaneously prepared on MgO(110) and MgO(100) substrates, respectively, by molecular beam epitaxy. They show however distinct magnetic anisotropic behavior which coincides with their magneto–crystalline anisotropy. Magneto–optical Kerr effect shows the existence of a unique easy axis and strong in-plane uniaxial magnetic anisotropy in Co(1100)/Cr(211) multilayers, which is induced by the well-defined hexagonal crystalline of the Co(1100) layers. For Co(1120)/Cr(100) multilayers, on the other hand, an in-plane biaxial magnetic anisotropy is found due to the bicrystalline structure of the Co(1120) layers. [S0021-8979(96)51608-X]

I. INTRODUCTION

The magnetism of thin metallic films and multilayers has attracted much attention in recent years for both fundamental research and advanced technological applications. It is noted that magnetism in these systems can often be characterized by specific magnetic anisotropies. For example, the perpendicular surface (interface) anisotropy can exist in ultra thin magnetic films (multilayers) as a consequence of symmetry breaking in the surface (interface).[1] There also has been an increasing interest in understanding the relationship between the magnetic anisotropies and the crystal structures. It is found that the magnetic anisotropies of the thin films may depend strongly on the underlying templates (substrates or buffer layers).[2–5]

Co-related system is suitable for studying the correlation between structure and magnetism owing to the abundance of the its structural and magnetic properties. The bulk phase of Co is known as hexagonal close packed (hcp) at room temperature. It undergoes a Martinsitic structural transformation to face centered cubic (fcc) phase at ~400 °C.[6] In the form of thin films it can also be epitaxially stabilized as body centered cubic (bcc) structure.[7] Co/Cr multilayers are of our high interest because of the remarkable structural and magnetic properties, and possible applications in magnetic or magneto–optical recording. Previous studies[8–11] on Co/Cr multilayers have been, however, restricted to polycrystalline, textured, or semiepitaxial samples, making the understanding of the structural and magnetic properties and their interplay much difficult.

In this article we report the magneto-optical Kerr effect (MOKE) studies of the magnetic anisotropies of high-quality Co(1100)/Cr(211) and Co(1120)/Cr(100) multilayers grown by molecular beam epitaxy (MBE). Longitudinal and polar MOKE configurations were used to determine the magnetic easy and hard axes, and their connection with the crystal structures. We demonstrate here the novel control of the orientation and crystalline structure, and hence the magnetic anisotropies (uniaxial or biaxial) of Co layers by using proper crystal plane of the underlying Cr layers.

II. FILM PREPARATION AND MEASUREMENTS

We have indeed grown more than 30 samples of Co/Cr(211) and Co/Cr(100) multilayers. The results presented here mainly focus on the general and common features of these samples. The specific Co/Cr samples discussed here posses 17 bilayers periods with 40 Å Co and 20 Å Cr in each bilayer: $[\mathrm{Co}(40\ \text{Å})/\mathrm{Cr}(20\ \text{Å})]_{17}$. The Co/Cr(211) and Co/Cr(100) multilayers were simultaneously prepared on epitaxial grade MgO(110) and MgO(100) substrates, respectively. Details of the growth procedures were described elsewhere.[14]

The crystal structure and quality were characterized by reflection high-energy electron-diffraction (RHEED) and x-ray diffraction (XRD). The correlation between the structural and magnetic properties were investigated by MOKE technique. Polar (magnetization lies in the scattering plane and perpendicular to the film surface) and longitudinal (magnetization lies both in the scattering plane and the film surface) configurations of MOKE were employed to determine the out-of-plane and in-plane magnetization loops of the samples. The MOKE measurements were carried out at room temperature in a magnetic field H up to 2 kOe. Note that the penetration depth[12] of the (He–Ne) laser light for MOKE experiment is of ~150–200 Å, only top three Co/Cr bilayers (of the multilayers) can be probed by MOKE.

III. RESULTS AND DISCUSSIONS

For Co/Cr multilayers on grown Mo buffer layers on MgO(110) substrates studied here, we have determined the following orientational relationships (ORs):

Co(1$\bar{1}$00)‖Cr(211)‖Mo(211)‖MgO(110),

Co[11$\bar{2}$0]‖Cr[$\bar{1}$11]‖Mo[$\bar{1}$11]‖MgO[$\bar{1}$10],

Co[0001]‖Cr[0$\bar{1}$1]‖Mo[0$\bar{1}$1]‖MgO[001];

while on MgO(100) substrates the ORs are:

Co(11$\bar{2}$0)‖Cr(100)‖Mo(100)‖MgO(100),

Co[$\bar{1}$100]‖Cr[011]‖Mo[011]‖MgO[010],

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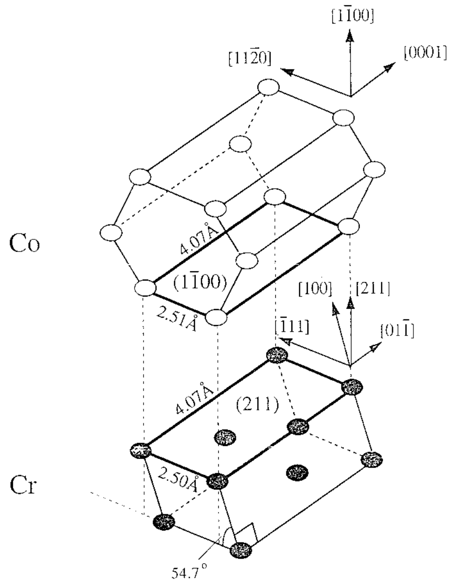

FIG. 1. Schematic diagrams showing the geometry, unit cell (indicated by bold lines) and epitaxial relationship of the hcp Co(1100) and bcc Cr(211).

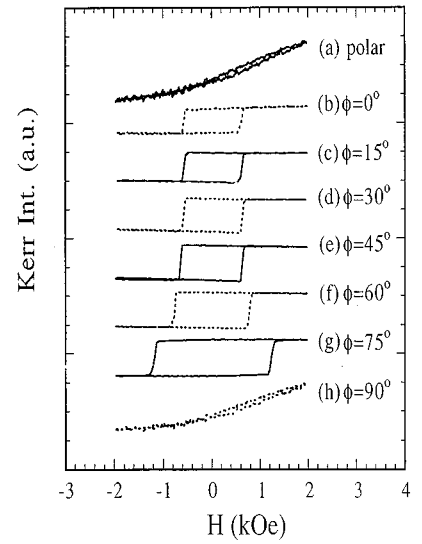

FIG. 3. The MOKE hysteresis loops for the Co(1$\bar{1}$00)/Cr(211) multilayer: (a) polar Kerr loop; (b)–(h) longitudinal Kerr loops as a function of the azimuthal angle ϕ.

$$\text{Co}[0001]\|\text{Cr}[0\bar{1}\bar{1}]\|\text{Mo}[0\bar{1}\bar{1}]\|\text{MgO}[001]$$

(or

$$\text{Co}[0001]\|\text{Cr}[011]\|\text{Mo}[011]\|\text{MgO}[010],$$

and

$$\text{Co}[1\bar{1}00]\|\text{Cr}[0\bar{1}1]\|\text{Mo}[0\bar{1}1]\|\text{MgO}[001]$$

due to the bicrystalline structure, as discussed below). The epitaxial relationships were confirmed by RHEED and XRD studies. Part of the structural analysis related to these multilayers were or to be published elsewhere.[13–15] We present here mainly about their magnetic properties and the effect of crystal structure upon magnetic anisotropies, as investigated by MOKE.

Figure 1 and Fig. 2 display the schematic diagrams of the geometry and the unit cells of Co(1100)/Cr(211) and Co(1120)/Cr(100) multilayers, respectively. Although Co (hcp) and Cr (bcc) possess distinct bulk structures, Co(1100) and Cr(211) planes match extremely well in lattice parameters and symmetry (both are twofold). As illustrated in Fig. 1, the unit cell of Co(1100), 4.07 Å×2.51 Å, matches perfectly with that of Cr(211), 4.07 Å×2.50 Å. This provides us an opportunity to synthesize high-quality heterostructural superlattices. For Co(1120)/Cr(100) system, on the other hand, the unit cell of Co(1120), 4.07 Å×4.34 Å, match poorly in

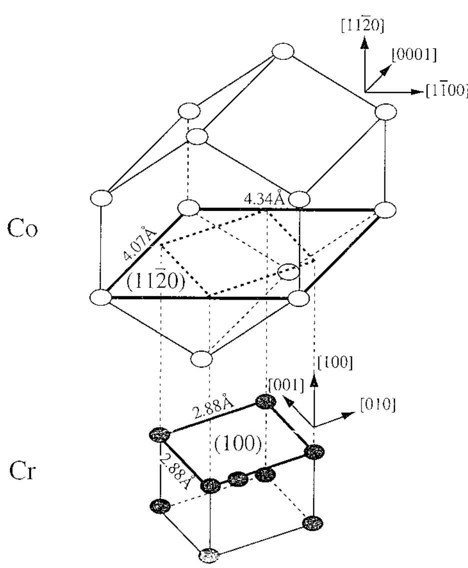

FIG. 2. Schematic diagrams showing the geometry, unit cell (indicated by bold lines) and epitaxial relationship of the hcp Co(1120) and bcc Cr(100).

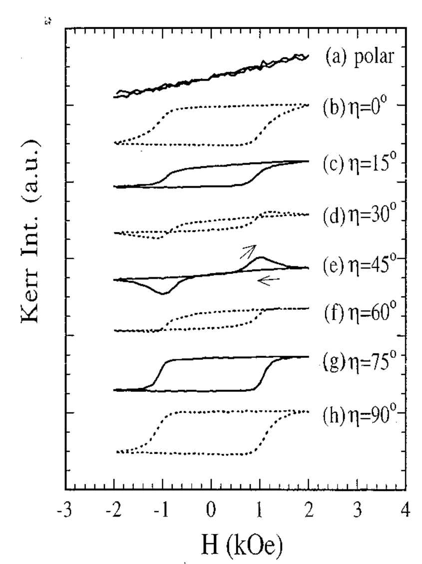

FIG. 4. The MOKE hysteresis loops for the Co(11$\bar{2}$0)/Cr(100) multilayer: (a) polar Kerr loop; (b)–(h) longitudinal Kerr loops as a function of the azimuthal angle η.

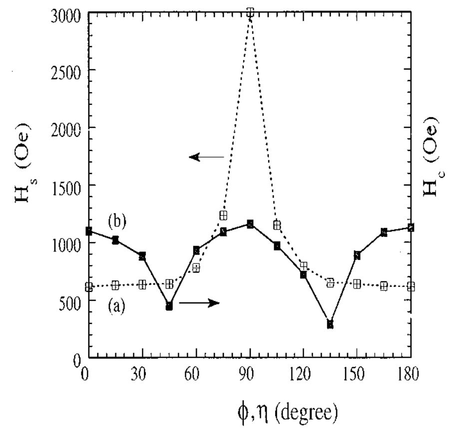

FIG. 5. (a) Saturation field H_s is shown as a function of the azimuthal angle ϕ for the Co(1100)/Cr(211) multilayer. (b) Coercive field H_c is plotted as a function of the azimuthal angle η for the Co(1120)/Cr(100) multilayer.

one direction (Co[1100]) with the rotated cell of Cr(100), 4.07 Å×4.07 Å, where 4.07 Å($=\sqrt{2}\times 2.88$ Å) is the diagonal spacing of the original cell. Indeed, Cr(100) possesses fourfold crystal symmetry while Co(1120) has only twofold symmetry. The symmetry and lattice-spacing mismatches between Co(1120) and Cr(100) cells result in the bicrystalline structure of the Co(1120) layers. That is, the Co[0001] axis can be either parallel to the Cr[011] or Cr[011].

Shown in Figs. 3(a) and 4(a) are the polar MOKE hysteresis loops of the Co/Cr(211) and Co/Cr(100) multilayers, respectively. It is clear that both multilayers are hard to be magnetized along the out-of-plane directions. For Co/Cr(211) sample, Figures 3(b)–3(h) show a series of in-plane magnetization loops as a function of the azimuthal angle ϕ, where ϕ is defined as the angle between the MgO[110](‖Cr[011]‖Co[0001]) axis (see Fig. 1) and the direction of the applied field. Similar measuring procedures of the MOKE hysteresis loops for Co/Cr(100) multilayers are displayed in Figs. 4(b)–4(h), where in this case the azimuthal angle η is the angle between the in-plane MgO[001](‖Cr[011]) axis (see Fig. 2) and the direction of the field.

Although both multilayers are difficult to be magnetized along the out-of-plane directions, they show however quite distinct in-plane azimuthal anisotropies. For Co/Cr(211) sample, square hysteresis loops were observed from $\phi=0°$ (H‖Co[0001]) to 75° with gradual increase of the saturation field as the angle ϕ is turned (experimentally done by in-plane rotation of the sample with the field direction fixed). While continuously varying magnetization curves were observed for field along $\phi=90°$ (H‖Co[1120]), as shown in Figs. 3(b)–3(h). The saturation field H_s here is defined as the field when the magnetization is 90% saturated during magnetization reversal process. It is obvious that the magnetic hard axis lies in the (in-plane) Co[1120] direction perpendicular to the easy axis Co[0001] (see Figs. 1 and 3). Very similar hysteresis loops and saturation fields were found for field directed along the azimuthal angles ϕ and $(180-\phi)$ [as well as $(\phi+180)$ and $-\phi$], suggesting the existence of a uniaxial magnetic anisotropy for the Co/Cr(211) sample. This can be clearly seen by plotting H_s as a function of the azimuthal angle ϕ, as shown in Fig. 5(a). The relatively large saturation fields of >500 Oe in the easy direction is likely resulted from the Cr spacer layers.[16]

For Co/Cr(100) sample, on the other hand, the in-plane magnetization loops are more complicated. As shown in Fig. 4(b), squarelike hysteresis loops were observed for $\eta=0°$. By turning the azimuthal angle η from 0° to 45°, the hysteresis loops shift from one type to another with gradual decrease of the coercive field. Similar hysteresis loops and coercive fields were found for field directed along the azimuthal angles η and $(90-\eta)$. The MOKE patterns in Figs. 4(b)–4(h) repeat for η from 90° to 180° (and every other 90°). Figure 5(b) shows the coercive field H_c as a function of the azimuthal angle η. As can be determined from Fig. 5(b) and Figs. 4(b)–4(h), the easy axes are along $\eta=0°$ (‖Cr[011]) and $\eta=90°$ (‖Cr[011]), and the hard axis along $\eta=45°$ (‖Cr[010]) and $\eta=135°$ (‖Cr[001]), indicating the existence of a biaxial magnetic anisotropy for the Co/Cr(100) sample. Note that the two magnetic easy axes (along Cr[011] and Cr[011]) coincide with the Co[0001] axes of the bicrystalline Co layers, as discussed above.

Similar magnetic anisotropic properties mentioned above have been detected in single bilayer films of Co/Cr(100) and Co/Cr(211). Furthermore, we have observed relatively strong (weak) anisotropic effect in magnetoresistance measurements for the latter (former) case.[15] It appears that the anisotropic effect dominates in the Co/Cr(211) multilayers, in marked contrast to the other multilayer systems which show stronger coupling effect and isotropic (and giant) magnetoresistance effect. The mechanism of magnetization reversal processes, including the minor loop behaviors, of the Co/Cr(211) and Co/Cr(100) films will be published in the forthcoming articles.

[1] L. Neel, J. Phys. **15**, 225 (1954).
[2] J. J. Krebs, B. T. Jonker, and G. A. Prinz, J. Appl. Phys. **61**, 2596 (1986).
[3] J. M. Florczak and E. Dan Dahlberg, J. Appl. Phys. **67**, 7520 (1990).
[4] J. M. Florczak, E. Dan Dahlberg, J. N. Kuznia, A. M. Wowchak, and P. I. Cohen, J. Appl. Phys. **69**, 4997 (1991).
[5] N. Metoki, Th. Zeidler, A. Stierle, K. Brohl, and H. Zabel, J. Magn. Magn. Mater. **118**, 57 (1993).
[6] See, e.g., CRC *Handbook of Chemistry and Physics*, 69th ed., edited by R. C. Weast, M. J. Astle, and W. H. Beyer (Chemical Rubber, Boca Raton, Florida, 1988–1989).
[7] G. A. Prinz, Phys. Rev. Lett. **54**, 1051 (1985).
[8] D. Wang and D. J. Sellmyer, J. Appl. Phys. **69**, 4541 (1991).
[9] M. B. Sterns, C. H. Lee, and T. L. Groy, Phys. Rev. B **40**, 8256 (1989).
[10] M. B. Sterns, Y. Cheng, and C. H. Lee, J. Appl. Phys. **67**, 5925 (1990).
[11] Y. Henry, C. Meny, A. Dinia, and P. Panissod, Phys. Rev. B **47**, 15037 (1993).
[12] We have studied various Co/Cr bilayers with Cr(50–300 Å) grown on top of thick Co layers. The Kerr intensities were completely suppressed for Cr films thicker than 200 Å.
[13] J. C. A. Huang, Y. Liou, H. L. Liu, and Y. J. Wu, J. Cryst. Growth **139**, 363 (1994).
[14] Y. Liou, J. C. A. Huang, Y. D. Yao, C. H. Lee, K. T. Wu, C. L. Lu, S. Y. Liao, Y. Y. Chen, N. T. Liang, W. T. Yang, C. Y. Chen, and B. C. Hu, J. Appl. Phys. **76**, 6516 (1994).
[15] J. C. A. Huang, Y. Liou, Y. D. Yao, W. T. Yang, C. P. Chang, S. Y. Liao, and Y. M. Hu, Phys. Rev. B **52**, R13 110 (1995).
[16] We have observed a trend that H_s decreases with the decreasing of the Cr thickness for a fixed Co thickness in the multilayers. For pure Co films on MgO substrates, the measured saturation fields are of only ~50–100 Oe.