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Magnetoresistance Study in Co-Cr Superlattices and Films

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The magnetoresistance (MR) of $(Co/Cr)_{70}$ superlattice with *hcp*-Co layers and *bcc*-Cr layers on both MgO and Al_2O_3 substrates with Mo as a buffer layer, and the anisotropy magnetoresistance (AMR) of the single-crystal *hcp*-Co, fee-Co, as well as the CoCr alloy thin films have been studied at 10 K and 295 K, respectively. The MR of Co/Cr multilayers has been observed to increase by a factor of 3.8 with replacing its substract MgO(100) by $Al_2O_3(1\bar{1}02)$ only. The AMR of Co films has been found to decrease rapidly by the buffer layer as well as the alloying effect between Co and Cr.

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I. INTRODUCTION

The magnetoresistance (MR) in many metallic multilayer systems is currently attracting considerable attention. Giant magnetoresistance (GMR) was first realized in Fe/Cr superlattice [1]. In their original work, Baibich et al. found that the resistivity of Fe/Cr multilayers is reduced by almost 50% when an external field of $2T$ is applied. In a further study, Parkin et al. [2] reported oscillations in both the antiferromagnetic (AF) coupling strength and GMR with the Cr or Ru spacer-layer thickness of periods ranging from 12 Å in Co/Ru to 18-21 Å in the Fe/Cr and Co/Cr systems. The AF coupling between magnetic

layers is expected to play an essential role in the large magnetoresistance observed [3-5]. Similar MR behaviors have been reported in many transition-metal multilayers, such as Co/Cr, Co/Ru [2], Co/Cu [6], Co/Ag [7], Co/Au [8], and Co/Cu/Ni-Fe/Cu [9]. Among them, we pay special attention to the Co/Cr multilayer, because relatively quite small MR occurs in this system which is isomorphic with the Fe/Cr etc. multilayer system. The mechanism of GMR in superlattices has been qualitatively explained by Hesagawa [10]. It is well known that even the Co and Cr have almost the same atomic size, but they have very different bulk structures. The bulk Cr has a *bcc* structure with a = 2.88 A, and the bulk Co undergoes a structure transformation from *hcp* structure with a = 2.51 Å and c = 4.07 Å to *fcc* structure with a = 3.54 Å at about 400 °C. Therefore, it is worthwhile to study experimentally the MR behaviors in the Co/Cr system with different structure conditions.

In this paper, we report the experimental results of the MR of epitaxial $(Co/Cr)_{70}$ multilayers with *hcp-Co* layers and *bcc*-Cr layers on both MgO and Al_2O_3 substrates with Mo as a buffer layer; and the AMR of the single-crystal *hcp-Co, fee-Co,* as well as the epitaxial *hcp*-CoCr alloy thin films.

II. EXPERIMENTAL

Epitaxial $(Co/Cr)_{70}$ multilayers as well as single-crystal *hcp*-Co, *fee-Co,* and *hcp* CoCr alloy thin films have been grown on both MgO and Al_2O_3 substrates with Cr or Mo as a buffer layer by using an Eiko EL-10A molecular beam epitaxy (MBE) system with base pressure of 2×10^{-10} torr. It is extremely unlikely that residual gases played a role in determining the epilayer orientation and surface morphology. This MBE system is equipped with a 15 keV reflection high energy electron diffraction (RHEED) apparatus for in situ surface analysis. The incidence angle of the RHEED beam was adjusted to about 2° to 3°, and the diffraction patterns were photographed from the fluorescent screen during and after growth.

Pure elements (99.99%) of Co, Cr, and Mo were evaported from three independent e-beam evaporators. During deposition of the elements, the growth pressure were controlled at below 5×10^{-9} torr, and the deposition rates at ~ 0.1 Å/sec. To enable the growth of high-quality samples, polished and epitaxial grade MgO and Al_2O_3 substrates were chemically precleaned and rinsed in ultrasonic cleaner. For samples with Mo buffer layer, Mo was deposited on the substrates at about 900 °C. The substrate temperature during evaporting was kept between 300 and 350 °C. The structure of the films was examined by both RHEED and x-ray diffraction techniques.

The magnetic properties of all the samples were studied by using a SQUID magnetometer. The MR and AMR measurements were carried out by conventional four probe technique in a magnetic field up to 2T and with temperatures at 10 K and 295 K, respec-

tively.

III. RESULTS AND DISCUSSION

Since the crystal structures of thin films or multilayers are considerably affected by the choice of buffer layers, substrates, and their orientations. In this study, we selected MgO(100), $Al_2O_3(11\bar{2}0)$, & $Al_2O_3(1\bar{1}02)$ as substrates, and Cr or Mo as the buffer layers to study the variation of MR and AMR for Co-Cr system. In general, for Co grown on MgO(100) substrate without a buffer layer, a fee-Co films with (100) planes epitaxial growth can be formed for Co thickness of roughly larger than 60 A. Fig. l(a) shows the x-ray diffraction peak of a 200 Å thick *fcc*-Co(100) film which was grown on a MgO(100) substrate without any buffer layers. However, if we grow a thin buffer layer of Cr(lOO) about 20 Å or Mo(100) about 100 Å on either MgO(100) or $Al_2O_3(11\bar{2}0)$, then x-ray diffraction studies, as shown in Figs. l(b) and l(c), confirm both *hcp*-Co and *hcp*-CoCr alloy films with $(1\bar{1}01)$ plane epitaxially on the (110) surface of Cr or Mo buffer layers. Detail analyses of the structures have been reported before [11].

Before discussing the experimental data of MR and AMR in the Co-Cr system, we have to clarify their definition.

The MR (or GMR) in multilayers is defined as $[R_{AF} - R_S]/R_S$, where R_S is the electrical resistance at saturated high magnetic field; and the spins in Co layers aligh in the field direction. R_{AF} is the electrical resistance when the field is removed, the Co layers adjacent to the Cr layer in-between exhibit antiferromagnetic coupling.

The AMR in ferromagnetic films is defined by $(R_{//} - R_{\perp})/R_o$, where R_o is the averaged electrical resistance, and $R_{//}$ and $R_{\perp}$ are the saturated longitudinal and transverse magnetoresistances, respectively.

Figure 2 presents the normalized electrical resistance between magnetic field and zero field as function of the magnetic field at room temperature for 3 thin film samples: (a) a *fcc*-Co(100) film with 200 Å thick grown on MgO(100), (b) a *hcp*-Co$(11\bar{2}0)$ film with 200 Å thick grown on Cr(lOO) which is about 20 Å and on MgO(100), and (c) a *hcp*-CoCr$(1\bar{1}01)$ alloy film with 40 Å thick grown on Mo(110) as a buffer layer on the Al_2O_3(1120) substrate.

It is obvious that the AMR of the fee-Co films without any buffer layer is the largest (roughly 1%); and the value of the AMRs of the Co film with Cr as a buffer layer, and the *hcp*-CoCr alloy film with Mo as a buffer layer is roughly 0.1%, and 0.02%, respectively. This means that the effect to the AMR for Co films with different structure is negligible, if it is compared with the variation due to the addition of a buffer layer of Cr and Mo, as well as the alloying effect between Co and Cr.

For $(Co/Cr)_{70}$ multilayer samples, we selected MgO(100) and $Al_2O_3(1\bar{1}02)$ as the

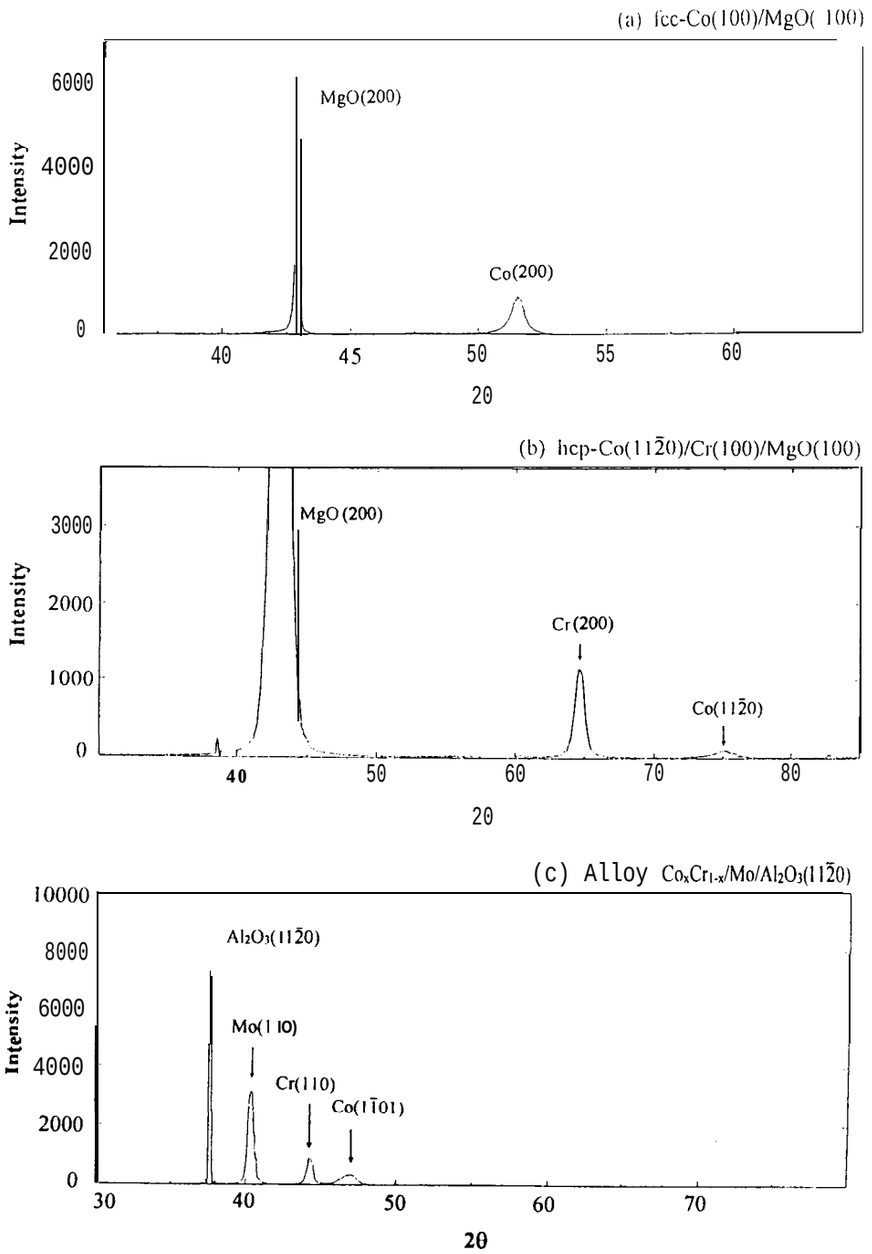

FIG. 1. X-ray diffraction patterns of (a) *fcc*-Co(100)/MgO(100), (b) *hcp*-Co(11$\bar{2}$0)/Cr(100)/MgO(100), and (c) *hcp*-CoCr alloy(1$\bar{1}$01)/Mo(110)/Al_2O_3(11$\bar{2}$0).

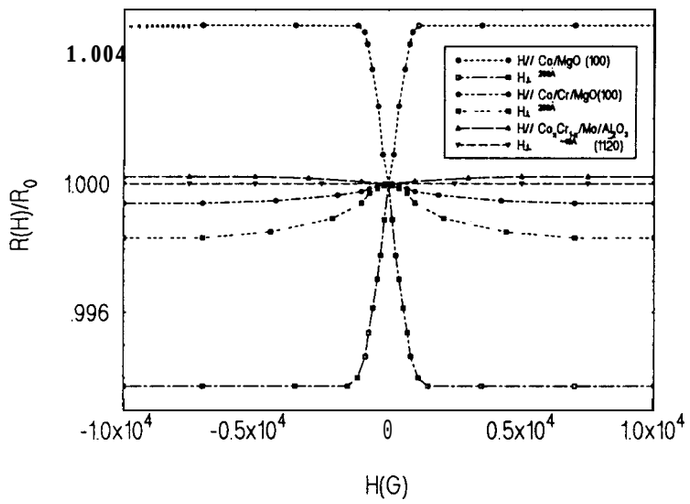

FIG. 2. The normalized electrical resistance between magnetic field and zero field as a function of magnetic field at room temperature for (a) *fcc*-Co(100)/MgO(100), (b) *hcp*-Co(11$\bar{2}$0)/Cr(100)/MgO(100), and (c) *hcp*-CoCr alloy(1$\bar{1}$01)/Mo(110)/Al_2O_3(11$\bar{2}$0).

substrates. The thickness of each layer is about 5 Å for Cr, and 40 Å for Co. We let Cr as the first layer to form the multilayer structures. For samples without Mo as a buffer layer, we found that the multilayers we made were always show polycrystal structure [12], if the thickness of the first Cr layer was less than 20 Å. Therefore, in this study, a buffer layer of Mo about 100 Å was evaporated on both MgO and Al_2O_3 substrates to study the epitaxial behavior of the Co/Cr multilayer system. From the XRD analysis, both *hcp*-Co and bee-Cr layers were identified for the two multilayer samples.

Since the $(Co/Cr)_{70}$ multilayer samples with either MgO or Al_2O_3 as substrate were epitaxially grown side by side under the same batch of crystal growth process. Any difference between this two samples should be due to the different substrate only, which will influence the roughness of the interface between the multilayer and substrate.

From both x-ray reflectivity measurement and mathematical analyses, we have reported that the interface roughness of the Co/Cr multilayer grown on MgO is much larger than that on Al_2O_3[12].

The normalized electrical resistance as a function of applied field at 10 K for the above two superlattice samples are shown in Fig. 3. The MR, i.e. $(R-R_S)/R_S$, is roughly about 3.43%, and 0.91% for $(Co/Cr)_{70}/Mo/MgO$ and $(Co/Cr)_{70}/Mo/Al_2O_3$, respectively.

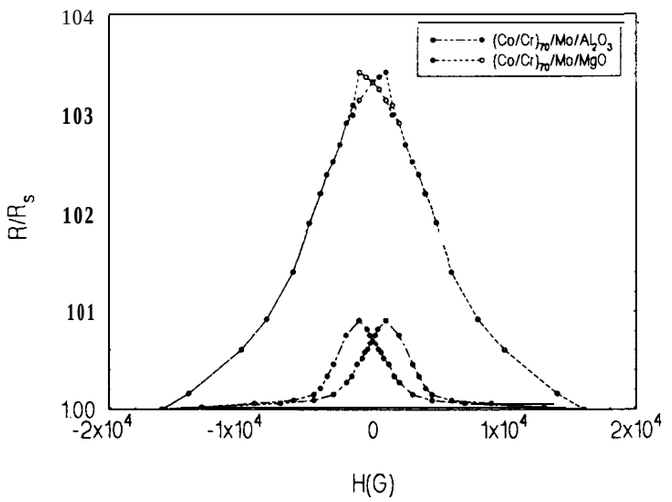

FIG. 3. The normalized resistivity as a function of applied magnetic field at 10 K for (a) $(Co/Cr)_{70}/Mo/Al_2O_3$, and (b) $(Co/Cr)_{70}/Mo/MgO$ superlattices.

This tell us that the MR in multilayers can be changed by varying its substrate. For the $(Co/Cr)_{70}$ multilayers, an enhancement of factor 3.8 ($\sim$ 4) has been observed with replacing the MgO substrate by the Al_2O_3 only.

Further quantitative analyses of our results are in progress and will be reported later.

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