Magnetic anisotropy of bcc Co on $FeCu_3$(001)

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Single crystalline body-centered-cubic (bcc) Co films were achieved on $FeCu_3$ buffer layer by molecular-beam epitaxy. Fourfold symmetric magnetic hysteresis loops for bcc Co were obtained unambiguously with the easy axes along Co⟨110⟩. The in-plane uniaxial anisotropy is significantly reduced by $FeCu_3$ buffer layer. The magnetocrystalline anisotropy constant of bcc Co was further determined to be -1.0×10^5 erg/cm^3 by rotational-magneto-optical Kerr effect. Hexagonal-close-packed Co, which would contribute an effective positive K_1, appeared on top of bcc Co when the film thickness was beyond 0.9 nm. As a result, the magnetocrystalline anisotropy constant of the whole system switched from negative to positive with increasing film thickness.

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Magnetocrystalline anisotropy corresponding to different crystallographic structures in 3*d* transition metals is a long-standing issue.[1,2] The epitaxial growth of thin films has made it possible to prepare these metals into crystalline phases which does not occur naturally. Extensive interest was thus generated to investigate the magnetic properties of these metastable materials, e.g., body-centered-cubic (bcc) Ni, bcc Co, and face-centered-cubic (fcc) Fe.[3–6] Among them, single crystalline bcc Co, in particular, has provoked increasing interest recently due to its potential application of giant tunneling magnetoresistance.[7–10] However, so far, the evolution of magnetocrystalline anisotropy for bcc Co is still controversial.

Bcc Co, which does not exist in nature, was stabilized on GaAs(110) epitaxially by Prinz.[3] The magnetocrystalline anisotropy constant, K_1, was proposed to have a negative value, superimposed by a strong in-plane uniaxial anisotropy. For the (001) thin film, a negative K_1 denoted that the easy axes of fourfold anisotropy were parallel to bcc Co⟨110⟩ directions. Contrary to this, Blundell *et al.*[11] later pointed out a positive K_1 for 4 nm Co/GaAs(001), with the easy axes of the fourfold magnetic hysteresis loops along Co⟨100⟩ directions. This positive K_1, however, was believed to originate from two-domain hexagonal-close-packed (hcp) Co on GaAs(001).[12] Later, Wu *et al.*[13] and Mangan *et al.*[14] presented clear pictures of the epitaxial growth of Co on GaAs(001). A positive K_1 for 2 nm bcc Co was also estimated from the fourfold magnetic loops.[13] However, this positive K_1 could hardly explain the negative magenetocrystalline anisotropy of single crystalline Fe_xCo_{1-x} alloys at the Co rich end.[15] In our recent work, a negative K_1 was obtained for bcc Co/GaAs(001) by the torque method after excluding the contribution from the hcp phase.[16] Hence, a negative K_1 seems rather convincing for bcc Co on GaAs(001).

However, the interface effect for 3*d* transition metals epitaxially grown on GaAs(001) could not be neglected, particularly at low film thicknesses. The planar uniaxial anisotropy in these thin films, which was not present in their corresponding cubic bulk materials, was generally believed to be induced by the interface effect.[17–19] Moreover, the interface effect could reverse the sign of fourfold magnetic anisotropy at low film thicknesses, e.g., in Fe/GaAs(001).[18] Wu *et al.*[13] also mentioned in their paper that the interface effect was a possible explanation for the positive K_1. Therefore, the sign of K_1 is hard to be determined if the interface effect is not eliminated. In addition, the chemical interdiffusion between Co and GaAs substrate would further complicate the characterization of magnetic properties for bcc Co.[20,21]

In this work, we exhibit a system of single crystalline bcc Co in which the uniaxial anisotropy is suppressed remarkably by epitaxially grown on nonmagnetic $FeCu_3$(001) sublayer. Fourfold magnetic hysteresis loops are thus obtained, from which the magnetocrystalline anisotropy can be unambiguously determined to be negative. The magnetocrystalline anisotropy of Co/$FeCu_3$ is also investigated as a function of Co thickness.

Co films were deposited at room temperature followed by epitaxial growth of $FeCu_3$ buffer layer on GaAs(001) substrate in an ultrahigh vacuum chamber. $FeCu_3$(001) is an appropriate buffer layer because it is not only nonmagnetic but also in bcc phase at low thickness.[22] The details of the growth conditions have been given in our previous works.[13,22] A 3 nm Au layer was finally capped to prevent the sample from oxidation. The epitaxial growth of the films was monitored by reflection high-energy electron diffraction (RHEED). Magnetic measurements were later conducted *ex situ* by magneto-optic Kerr-effect (MOKE) and rotational-magneto-optical Kerr-effect (ROTMOKE) techniques.

Figure 1 presented RHEED patterns of $FeCu_3$ and Co thin films with the high-energy electron incidence along the [110] direction of GaAs(001). We distinguish different crystal structures by their aspect ratios of the RHEED patterns. For instance, 1.4:1 and 1:1 correspond to bcc and fcc structures, respectively, in the experimental configuration we applied here.[23,24] Figure 1(a) shows the clean GaAs(001) surface, which was obtained using the treatment in Ref. 13. 1.0 nm $FeCu_3$ buffer layer was then deposited at room temperature on GaAs(001) substrate [Fig. 1(b)]. The aspect ratio of $FeCu_3$ is 1.35:1, indicating a body-centered-tetragonal structure, which is in accordance with the previous experiment.[22] Figure 1(c) shows bcc Co of 0.9 nm with the aspect ratio equaling to 1.4:1. When the thickness of Co is above 0.9 nm, extra spots appear which are emphasized by ellipses in Fig. 1(d). These spots are attributed to hcp Co twin domains,

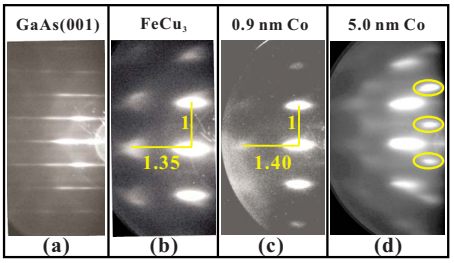

FIG. 1. (Color online) RHEED patterns of (a) GaAs(001) substrate; (b) 1.0 nm $FeCu_3$ film on GaAs(001); (c) 0.9 nm Co on (b); and (d) 5.0 nm Co on (b). The aspect ratios are shown in (b) and (c). The high-energy electron beam is incident along GaAs[110].

similar to Co/GaAs(001) system.[13] Therefore, according to the RHEED patterns, when the Co thickness is thinner than 0.9 nm, Co is in bcc phase. When the thickness is larger than 0.9 nm, bcc and hcp Co coexist. There is a close resemblance between the crystalline structure evolution of Co on $FeCu_3$(001) and that of Co on GaAs(001).

Then we investigated the magnetic properties of bcc Co/$FeCu_3$(001). Figure 2(a) shows the magnetic hysteresis loops of 0.9 nm bcc Co/1.0 nm $FeCu_3$ along different axes, which were measured using longitudinal MOKE. The 1.0 nm $FeCu_3$ underlayer was first confirmed to be nonmagnetic.

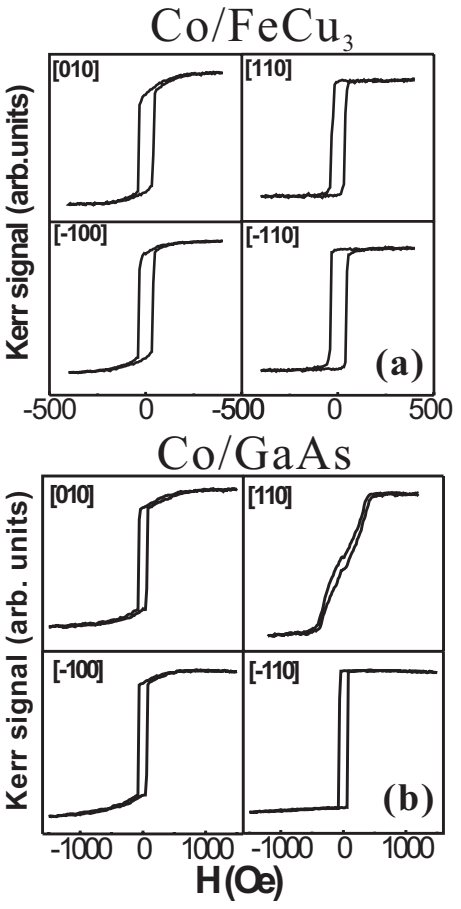

FIG. 2. Magnetic hysteresis loops of 0.9 nm Co on (a) 1.0 nm $FeCu_3$(001) and (b) GaAs(001) substrate (grown at 30 °C) with the magnetic field applied along different crystal directions.

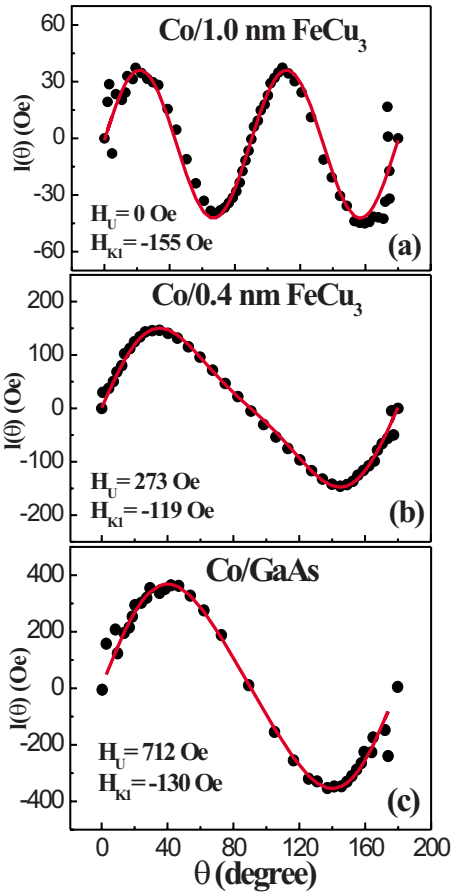

FIG. 3. (Color online) Torque measurement conducted by ROTMOKE determined the magnetic anisotropy field values in (a) 0.9 nm Co/1.0 nm $FeCu_3$; (b) 0.9 nm Co/0.4 nm $FeCu_3$; and (c) 0.9 nm Co/GaAs(001) (grown at 30 °C). The circles are the experimental data and the solid lines are the best fitting lines.

The magnetic hysteresis loops of bcc Co/$FeCu_3$(001) have a fourfold symmetry, with the easy axes along bcc Co[110] and $[\bar{1}10]$ directions and the hard axes parallel to bcc Co[010] and $[\bar{1}00]$ directions. Through the hysteresis loops alone, bcc Co/$FeCu_3$(001) is determined undoubtedly to have a negative K_1. By comparison, we deposited 0.9 nm Co directly on GaAs(001) at 30 °C and studied its magnetic properties which is shown in Fig. 2(b). A strong in-plane uniaxial anisotropy field is present along Co$[\bar{1}10]$ direction, which makes the magnetic easy axis parallel to Co$[\bar{1}10]$, hard axis along Co[110] and Co⟨100⟩ the intermediate. This uniaxial anisotropy is generally attributed to the Co/GaAs(001) interface, which conceals the fourfold anisotropy field of bcc Co.[18] By inserting the $FeCu_3$ layer, the uniaxial anisotropy from the Co/GaAs(001) interface is significant reduced.

In order to further clarify the influence of $FeCu_3$ layer on the magnetic properties of bcc Co, we conducted the torque measurement based on ROTMOKE technique and obtained the K_1 value quantitatively for three 0.9 nm bcc Co films on different sublayers in Fig. 3.[16,22] In Fig. 3(a), the torque values of 0.9 Co/1.0 nm $FeCu_3$ (solid circles) show two periods in a 180° range, which also demonstrate a fourfold symmetry

for magnetic anisotropy. We could extract K_1, by fitting the experimental data according to the following equation in (001) thin film system:[22]

$$E/V = -M_s H\cos(\alpha-\phi) + K_u \sin^2\phi + K_1 \sin^2(\phi + \pi/4)\cos^2(\phi+\pi/4),$$

where E is the free energy, V is the volume of the thin film, M_s is the saturation magnetization, H is the applied magnetic field, and $\alpha(\phi)$ is the angle between the magnetic field (magnetization) and Co[110] direction. The best fit, shown as the solid line in the figure, determines $H_{K1}=2K_1/M_s=-155\mp2$ Oe and $H_u=2K_u/M_s=0\mp1$ Oe (95% confidence limits), which demonstrates a pure fourfold symmetry. The Chi square value is 9.4. By comparison, Fig. 3(c) shows the experimental data of 0.9 nm Co/GaAs grown at 30 °C. And the best fit gives $H_{K1}=-130\mp13$ Oe (95% confidence limits) and $H_u=712\mp7$ Oe (95% confidence limits). The corresponding Chi square value is 20.9 which still illustrates a good fit. However, the vanishment of in-plane uniaxial anisotropy in Co/$FeCu_3$ could not simply be explained by the substitution of Co/$FeCu_3$ interface for Co/GaAs interface. Figure 3(b) shows the ROTMOKE data of 0.9 Co/0.4 nm $FeCu_3$. Interestingly, an in-plane uniaxial anisotropy field is present as well. The best fit gives $H_{K1}=-119\mp3$ Oe and $H_u=273\mp1$ Oe (95% confidence limits). The Chi square value is 6.9. It appears that $FeCu_3$/GaAs interface would also transfer the uniaxial anisotropy to the upper Co thin films. In fact, there normally exists an in-plane uniaxial anisotropy field even though a thick metallic buffer layer is introduced on GaAs(001).

In Fig. 4(a), magnetic anisotropy fields of 0.9 nm bcc Co are plotted versus $FeCu_3$ film thicknesses. The uniaxial anisotropy fields decay sharply with $FeCu_3$ thicknesses. And surprisingly, the fourfold anisotropy fields nearly keep a constant value. The result is easier to understand if the uniaxial anisotropy is considered to strongly relate with the lattice mismatch.[25] The lattice mismatch between GaAs substrate (0.565 nm) and bcc Co (0.281 nm) is about 0.53%. Since the structure of $FeCu_3$/GaAs is gradually changing from bcc to thermodynamically stable fcc phase with the thicknesses,[22] the planar lattice constant is also gradually decreasing. As a result, the lattice mismatch between $FeCu_3$ and Co is decreasing with $FeCu_3$ thicknesses, which reduces the uniaxial anisotropy of bcc Co. It reaches the perfect match (0%) for bcc Co on 1.0 nm $FeCu_3$. In other words, only Co on 1.0 nm $FeCu_3$ is in a real bcc structure. This result suggests that the origin of in-plane uniaxial anisotropy of bcc Co on GaAs(001) might be mainly generated by the interface lattice shear.[26,27] On the other hand, the fourfold anisotropy seems insensitive to the tiny changes in lattice constant. And the negative sign of bcc Co is determined.

Furthermore, we studied the magnetic anisotropy field of Co/1.0 nm $FeCu_3$ as a function of Co thicknesses, shown by the results in Fig. 4(b). H_{K1} values were determined by fitting the ROTMOKE data as shown in Fig. 3. When the Co thickness is thinner than 0.9 nm, H_{K1} is negative and the absolute

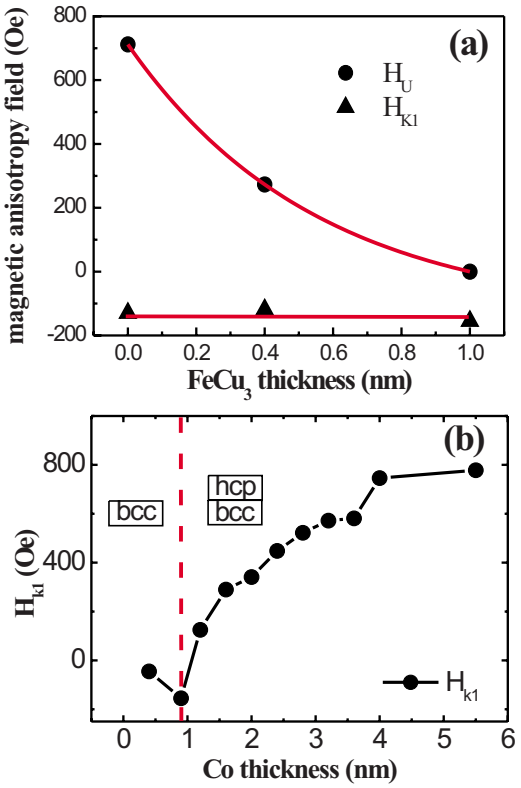

FIG. 4. (Color online) (a) The magnetic fields of 0.9 nm Co versus $FeCu_3$ thicknesses. The solid lines are guides to the eye. (b) The magnetic anisotropy fields H_{K1} of Co/1.0 nm $FeCu_3$ versus Co thicknesses. H_{K1} values were determined by ROTMOKE method shown in Fig. 3.

values increase with the increasing Co thickness. When the thickness is larger than 0.9 nm, H_{K1} turns to positive gradually. Meanwhile, RHEED patterns in Fig. 1(d) explicitly show that hcp Co domains appear on top of bcc Co when the thickness is above 0.9 nm.[28] These hcp Co domains will contribute an equivalent positive H_{K1},[12] which gradually overcomes the negative H_{K1} from bcc Co and results in a positive value finally when the thickness is above 1.1 nm. Although the values of lattice mismatch are different, the magnetic anisotropy fields of Co/$FeCu_3$(001) show similar dependence on the Co thickness to those of Co/GaAs(001).[16] It is quite clear that the $FeCu_3$ buffer layer could effectively reduce the uniaxial anisotropy as well as the interdiffusion between Co and GaAs(001), with limited influence on the fourfold anisotropy and Co growth process.

In summary, we achieved bcc Co by epitaxially growing Co on $FeCu_3$(001) buffer layer and studied its magnetic properties. The magnetic hysteresis loops showed fourfold symmetry with the easy axes along bcc Co⟨110⟩ directions. It demonstrated a negative magnetocrystalline anisotropy constant K_1, of about -1.0×10^5 erg/cm^3 for bcc Co, which was consistent with the negative K_1 value obtained from bcc Co on GaAs(001) by ROTMOKE method. Therefore, the magnetic uniaxial anisotropy was eliminated by introducing the $FeCu_3$ buffer layer. Hcp Co domains contributed a positive K_1, which competed with the negative K_1 from bcc Co when Co was thicker than 0.9 nm. Moreover, this method may be

applied to investigate the magnetic properties of 3*d* transition-metal films, e.g., bcc Ni/GaAs(001), bcc Fe/GaAs(001), especially when the interface effect plays a dominant role and conceals the magnetic properties of the magnetic films themselves.[6,19] This method also provides another possibility to study the origin of the in-plane uniaxial anisotropy existing in 3*d* transition-metal/semiconductor heterostructure, which has puzzled the researchers for decades.[17]

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