Magnetic-moment enhancement and sharp positive magnetoresistance in Co/Ru multilayers

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Structure, magnetization, and magnetoresistance of (Co t_{Co} nm/Ru 9.6 nm) multilayers, prepared by vapor deposition, have been studied as a function of Co layer thickness (t_{Co}), from 1.1 to 6.6 nm. The experimental results indicate that an expansion of average atomic volume would enhance the magnetic moment of Co to $2.11\mu_B$ with decreasing t_{Co} to 3.3 nm, and then would be reduced by nonmagnetic element alloying. Furthermore, we observe two distinct modes of positive magneto-resistance (PMR) in the Co/Ru series: In mode 1 the PMR shows consistent variation with the magnetization, producing a narrow full width at half maximum (FWHM), accompanied by ferromagnetic coupling. In mode 2 the FWHM of PMR is wide with a high saturation field, in accordance with antiferromagnetic coupling. The mechanisms responsible for the magnetic-moment enhancement and positive magnetoresistance are discussed in terms of the metastable atomic configuration of Co atoms formed in the films and interface spin-dependent scattering, respectively.

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I. INTRODUCTION

The origin of ferromagnetism has interested researchers since the exchange interaction model proposed by Heisenberg in 1928 (Ref. 1) and the free electronic model developed by Bloch in 1929.[2] The topic has attracted renewed interest because studying magnetic multilayers not only raises some novel magnetic properties, such as perpendicular magnetic anisotropy (PMA), and giant magnetoresistance (GMR),[3,4] but also provides an opportunity to clarify the origin of the magnetization of the materials.[5,6] In the Co-based multilayers, metastable fcc Co, bcc Co, and rhombohederal Co were obtained in Co/noble-metal,[7–9] Co/Mo,[10] Co/Bi system,[11] respectively. The observation of these metastable Co phases provides a way to explore the origin of the magnetization of the multilayers, i.e., magnetic moment per Co was enhanced to $2.84\mu_B$ with the formation of metastable fcc Co in Co/Ag.[9] However, the magnetic-moment enhancement arising from the structural transition (e.g., change from hcp Co to fcc Co) or the atomic-volume variation is ambiguous because these two factors coexist in these systems. Very recently, employing *ab initio* calculations, Kong *et al.*[12,13] suggested that an expansion of average atomic volume would enhance the magnetic moment of Co and metastable fcc Fe.

It is hence of vital importance to clarify the magnetic property of hcp Co phases with various atomic volume in Co/hcp system, that is, the space of Co can be expanded or shrank (something similar to a balloon) with variation of the layer thickness, accompanied by the amplitude or reduction of magnetic moment. This is of help for a better understanding of the origin of the magnetic property of the matter. Co and Ru have been selected as constituents of multilayers in this work for two reasons. First, bulk Ru is a 4*d* element with hcp structure. Second, among the ferromagnetic/nonmagnetic multilayers, much attention has been drawn to Co/Ru system, which is a system showing peculiar properties, such as strong interlayer antiferromagnetic coupling[14–19] and perpendicular magnetic anisotropy.[18,19] Yet the coupling appears to be very sensitive to the preparation conditions and the GMR is always quite small. Moreover, Co/Ru system was commonly found to show negative GMR,[4,14–16] but positive GMR was reported by Rahmuni[17] *et al.* in (Co 3.2 nm/Ru 1.4 nm/Co 3.2 nm) and doped $Co/Ru/Co_{0.92}Ru_{0.08}$ sandwiches. Up to now, the magnetization and magnetoresistance of Co/Ru films remain open questions.

In this paper, we report the experimental results of magnetic-moment enhancement and two different modes of positive magnetoresistance observed in Co/Ru multilayers prepared by electrogun vapor deposition, and discuss the possible mechanism responsible for the observed magnetic properties.

II. EXPERIMENT

A series of Co/Ru multilayer films were prepared by alternately depositing pure Co (99.99%) and pure Ru (99.99%) onto NaCl single-crystal chips and glass substrates in an electron-gun evaporation system. The background vaccum level was 6×10^{-8} Torr, and the vacuum during deposition was better than 8.5×10^{-7} Torr. The depositing rate was controlled at 0.02–0.03 nm/s and during deposition, no special cooling was provided to the sample holders. The first layer on the substrate was Ru and the top layer was Co. The total thickness of each multilayer film which was controlled by an *in situ* quartz monitor was approximately 80 nm with a constant 9.6 nm Ru layer thickness (t_{Ru}) and a Co layer thickness (t_{Co}) ranging from 1.1 to 6.6 nm, i.e., t_{Co}=1.1, 1.7, 2.2, 3.3, 5.0, and 6.6 nm.

After the deposition, the samples were analyzed by x-ray diffraction (XRD) transmission electron microscope (TEM) with selected area electron diffraction (SAD) and bright field images. The magnetic properties were measured with a vibrating sample magnetometer (VSM), with a resolution of 5×10^{-6} emu. Background noise from the substrate and the sample holder was subtracted from the raw data. Consequently, the precision of the measured magnetization of the films was estimated to be better than 1%. Induced-coupled-

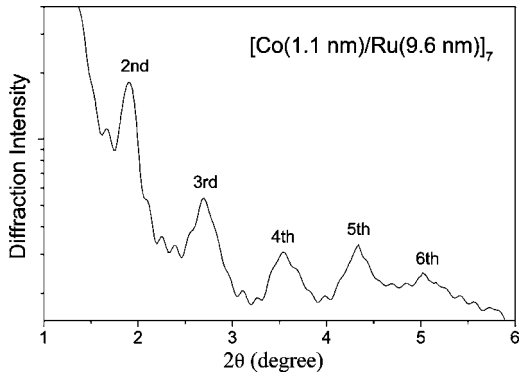

FIG. 1. Low-angle spectra of (Co 1.1 nm/Ru 9.6 nm)$_7$ multilayers.

plasma (ICP) measurement was used to determine the composition in the Co/Ru films after measuring the magnetic properties. The average magnetic moment per Co atom was then calculated. The error involved in the ICP measurement was about 5% and the total error for the magnetic moment was therefore around 6%. Magnetoresistance measurement was performed at room temperature using a standard dc four-probe method with a field up to 5 kOe applied parallel to the film plane. During the measurement process, the external field was parallel and perpendicular to the current direction, respectively. The MR ratio was calculated as $\mathrm{MR}\% = [R(H)\text{-}R(0)]/R(0)$.

III. RESULTS AND DISCUSSIONS

A. Periodicity and microstructure analysis

Low-angle XRD analyses are used to verify the periodicity of the Co/Ru multilayers. Typical low-angle XRD for the sample of (Co 1.1 nm/Ru 9.6 nm)$_7$ is shown in Fig. 1 in which the second- to sixth-order Bragg peaks with high intensity can be clearly seen. For the limiting experimental angle ($>1°$), the main peak has not been observed. According to the angle 2θ value of the diffraction peaks, the modulated periodicity is calculated to be 10.8 nm, which agrees well with the designed one. Though there are high-order peaks in Fig. 1, which may arise from the miscibility of Co and Ru. The lack of ordered finite size peaks (Kiessig fringes) implies a rough interface where Co and Ru atoms interdiffuse to some extent.

The microstructure of the films was investigated by TEM analysis. The experimental results revealed that the structure of Co/Ru multilayers varied strongly with the variation of the layer thickness of the constituent metals. Figure 2 presents two SAD of Co/Ru multilayers. In Fig. 2(a), there are two sets of hcp Ru and hcp Co rings in the SAD, shown as a representative sample for $t_{\mathrm{Co}} \geqslant 5.0$ nm. It demonstrates that the films consist of polycrystalline hcp Ru and hcp Co. The intensity of hcp Co rings becomes weaker with decreasing t_{Co}. When t_{Co} is reduced to 3.3 nm, the diffraction rings from hcp Co disappears in SAD. Similar observations are obtained for lower t_{Co}, such as the (Co 1.7 nm/Ru 9.6 nm) sample shown in Fig. 2(b), which means there is only one hcp phase

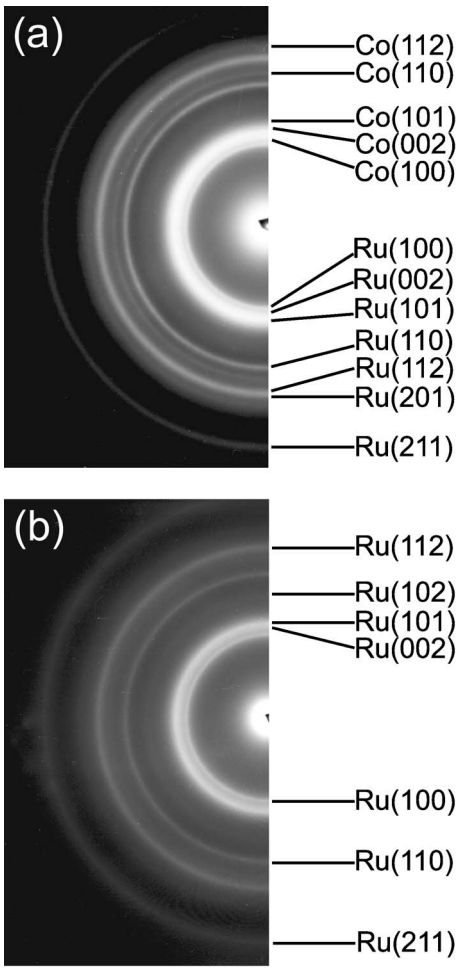

FIG. 2. TEM SAD pattern of the Co/Ru multilayered films: (a) (Co 6.6 nm/Ru 9.6 nm)$_5$ and (b) (Co 1.7 nm/Ru 9.6 nm)$_7$.

in the films, and its lattice parameters are determined to be $a = 0.267 \pm 0.005$ nm, $c = 0.428 \pm 0.005$ nm. This is very close to those of pure Ru. Moving this sample during the measurement process under TEM, we did not find strength variation of the diffraction lines and any hint of hcp Co structure.

There are two possible mechanisms for the formation of one hcp phase in Co/Ru multilayers, in which the Co layers are thinner than 3.3 nm. First, the Co atoms may grow in a metastable hcp structure (with lattice parameter of Ru) on Ru layers. Second, a hcp solid solution may be formed in the Co/Ru films. According to the low-angle x-ray diffraction results, the films have a good periodic structure along the normal to the films. In addition, the lattice parameters of the observed hcp phase are almost the same as that of pure Ru, so that the formation of a Co–Ru solid solution in the whole range is impossible. It could therefore be thought that, under our experiment conditions, the Co atoms grew in a metastable hcp structure on thick Ru layer, similarly to the metastable Co phases grew epitaxially in the Co-based multilayers, e.g., a fcc Co phase in Co/Ag superlattice,[9] and a bcc Co phase in Co/Mo multilayers.[10] In addition, although the lattice parameter mismatch of Co and Ru is about 8%, in Co/Ru system, the formation of metastable hcp structured Co phase on the thick Ru layer is possible. The dependence

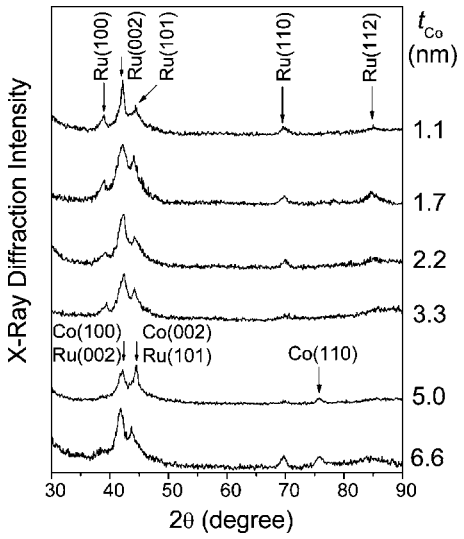

FIG. 3. High-angle XRD spectra of the Co (t_{Co} nm)/Ru (9.6 nm) (t_{Co}=1.1, 1.7, 2.2, 3.3, 5.0, 6.6 nm) multilayered films.

of formation of metastable hcp phase on adjusting the distance between the atoms in the crystal cell instead of atom sites transformation is due to both bulk Co and Ru are hcp structure.

Figure 3 shows high-angle XRD profiles of Co/Ru multilayers. When t_{Co} increases from 1.1 to 3.3 nm, in general, all of the diffraction peaks correspond to the hcp structure of Ru, which shift towards the higher angle side with increasing t_{Co}, i.e., Ru(100) peaks locate at 38.96 and 39.46 in (Co 1.1 nm/Ru 9.6 nm) and (Co 3.3 nm/Ru 9.6 nm) films, respectively. Nevertheless as t_{Co} increases to 5.0 nm, in addition of the diffraction peaks from hcp Ru phase, a hcp Co(110) peak and overlapping Co(100), Co(002) peaks emerge as shown in Fig. 3, indicating that the stable hcp Co is formed in the films, i.e., the films consists of hcp Ru and hcp Co. This structure transition is in good agreement with the SAD analyses. Consequently, the average atomic volume is obtained, and the t_{Co} dependence of atomic volume is plotted in Fig. 4. The metastable hcp phase (observed in the $t_{Co} \leqslant 3.3$ nm samples) separate into two constituent phases,

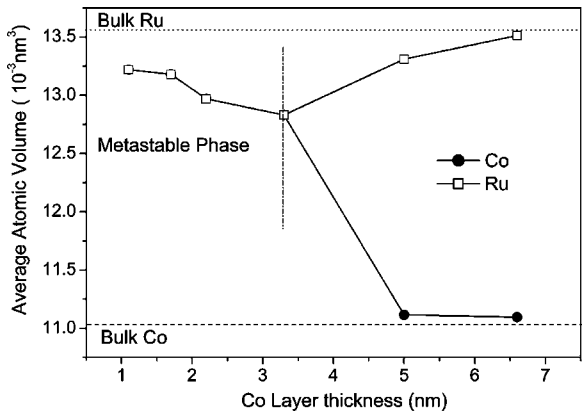

FIG. 4. Dependence of the average atomic volume of Co (solid circles) and Ru (open squares) on Co layer thickness in Co/Ru multilayers (t_{Ru}=9.6 nm).

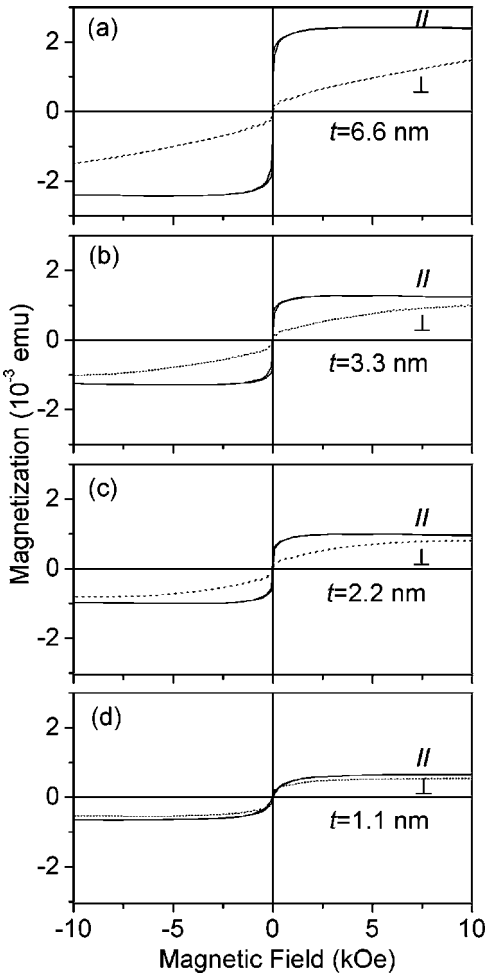

FIG. 5. VSM magnetic hysterisis loops at room temperature for the (Co t_{Co} nm/Ru 9.6 nm) multilayers (t_{Co}=6.6, 3.3, 2.2, and 1.1 nm, respectively). The magnetizing field was parallel (∥) and perpendicular (⊥) to the film plane.

which is described by the different atomic volume of Co and Ru. And the phase separation becomes identifiable at t_{Co} =3.3 nm. It is found that atomic volume of Co tends to decrease as t_{Co} increases, which may attribute to an intermixing at the interface for which it has been well established that interface alloying effect is likely to occur at the Co/Ru interfaces.[14,17] Some Co–Ru solid solutions form as transitional layers to release the strains at interfaces, which are also observed by the variation of the lattice parameter. The alloying at interfaces becomes so significant in the multilayers that it would influence both the structure and the subsequent magnetic behavior of the films.

B. Magnetic-moment enhancement

Magnetic hysteresis loops of the Co/Ru multilayers were measured at room temperature in a magnetic field (H) up to 10 kOe in parallel direction and 18 kOe in perpendicular direction to the film plane. Representative H dependences of the magnetization for t_{Co}=6.6, 3.3, 2.2, and 1.1 nm are presented in Fig. 5. From the figure, the saturation field, for the perpendicular case, depends on the thickness

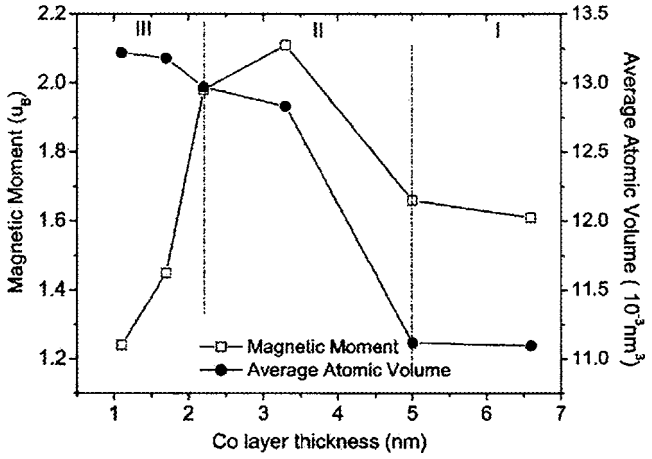

FIG. 6. The average magnetic moment per Co atom (open squares) in the Co/Ru multilayers as a function of Co layer thickness (t_{Ru}=9.6 nm). The dependence of average atomic volume (solid circles) on Co layer thickness is also plotted for comparison.

of the Co layer when t_{Ru}=9.6 nm. Saturating the (Co 1.1 nm/Ru 9.6 nm)$_7$ [shown in Fig. 5(d)] is much easier than saturating (Co 6.6 nm/Ru 9.6 nm)$_5$ [shown in Fig. 5(a)] ones, i.e., for higher t_{Co},(Co 6.6 nm/Ru 9.6 nm)$_5$ and (Co 3.3 nm/Ru 9.6 nm)$_5$ films, the saturation field are ~17 and ~14 kOe, respectively (not shown). This reveals that as the t_{Co} decreases, there is an increasing tendency for perpendicular magnetization in the Co/Ru multilayers, which is similar to those observed in Fe/Sb system.[5] Moreover, the results indicate that all the Co/Ru multilayers, either for the stable Co phases or the meatstable Co phases, exhibit soft ferromagnetic properties.

Figure 6 shows the average magnetic moment per Co atom in the Co/Ru multilayers as a function of t_{Co}. It seems that the moment depends strongly on t_{Co}. Some fluctuations appear with decreasing t_{Co} in Fig. 6, i.e., magnetic moment per Co atom is first significantly enhanced to the highest value of 2.11 μ_B with decreasing t_{Co} to 3.3 nm, and then reduces with decreasing t_{Co}. Interestingly, the moment changes with t_{Co} in a very similar way as in the Co-Ag multilayers, however, in which the magnetic moment is lower than that of bulk Co 1.71 μ_B.[20] The moment-t_{Co} curve can be divided into three regions (e.g., I, II, III) with different slopes indicated by vertical dash dotted lines.

In region I, that is, $t_{Co}>5.0$ nm, the magnetic moment is slightly lower than that of bulk Co, which can be explained as the ferromagnetic coupling between the nearest-neighboring ferromagnetic layers.[20,21] When nonmagnetic layers are thinner, in this series, that is, when the magnetic layers are thicker relatively (i.e., $t_{Co}>5.0$ nm), the coupling between the nearest-neighboring ferromagnetic layers is very strong, which makes their magnetization vectors tend to be parallel. Previous magnetization curves [Fig. 5(a)] have clearly indicated the coupling between the two cobalt layers is ferromagnetic. This leads to the atom magnetic moment be close to that of bulk Co.

The t_{Co} dependence of average atomic volume is also plotted in Fig. 6 for reference. It is surprising that magnetic moment changes with atomic volume in a totally same way in region II, and the latter one must strongly affect the magnetic moment per Co atom, i.e., the moment increases abruptly as atomic volume increases. The theoretical predictions by *ab initio* calculations have suggested that an expansion of average atomic volume would enhance the magnetic moment of Co, which, however, would be reduced by nonmagnetic element alloying.[12] Moreover, it is well known that for magnetic materials, an isolated magnetic atom has its highest magnetic moment, which would be reduced when its atomic volume is decreased, and vice versa.[6]

In region III, it is noted that the magnetic moment changes with atomic volume in a totally inverse way, i.e., the moment decreases as atomic volume increases. We attribute this inverse way to interface intermixing (i.e., alloying effect),[5,12,22] which cause the moment to decrease with decreasing t_{Co}. The interface intermixing have been indicated by our XRD results and Diana *et al.* have reported that alloying effect is likely to occur at the Co/Ru interfaces.[14,17] Namely, the moment per Co atom decreases with increasing the number of its nearest Ru neighbors in the interfacial metastable Co/Ru phases, in accordance with the mean field model proposed by Shan *et al.*[23] Thus, interface intermixing could be the controlling parameter in determining the magnetic moment in the Co/Ru system. The resultant magnetic moment is therefore attributed to a competitive effect of the two factors, i.e. the average atomic volume influence of Co phases and interface alloying effect.

C. Positive magnetoresistance

Magnetoresistance (MR) and the corresponding magnetization curves for (Co 5.0 nm/Ru 9.6 nm) and (Co 1.1 nm/Ru 9.6 nm) multilayers are shown in Figs. 7(a) and 7(b), respectively, in which positive magnetoresistance (PMR) are obtained both for t_{Co}=5.0 and t_{Co}=1.1 nm. From Fig. 7, one can see a significant feature: When t_{Co}=5.0 nm, the PMR varies consistently with magnetization showing a small saturation field. As t_{Co} decreases, PMR needs a much higher field to saturate, which is accompanied by the magnetization transition from mostly ferromagnetic coupling to antiferromagnetic coupling.

Concerning the details in Fig 7(a), the (Co 5.0 nm/Ru 9.6 nm) multilayers, has the two adjacent Co layers weakly or ferromagnetically coupled as expressed by a high remanence and a small saturation field. The most part of the magnetization (bulk part) has already switched at very small fields (below 50 Oe) and the remaining part (of about 10%) leads to the saturation field of 300 Oe corresponding mostly to the moments at the interfaces. Similar result was obtained in (Co 3.2 nm/Ru 1.4 nm/Co 3.2 nm) sandwich.[17] Interestingly, we found the MR is positive of about 0.1%. The MR curves decreases rapidly at low H below the coercive field (H_c) of the magnetization until reaching the minimum near H_c, and then saturates rapidly at the field of 300 Oe. It indicates that the MR varies consistently with the magnetization. The full width at half minimum (FWHM) of the PMR is 25–30 Oe approaching to the value reported by Hylton *et al.*[24] in the NiFe/Ag system. As well known, the PMR observed in many system is unsaturated even under very high

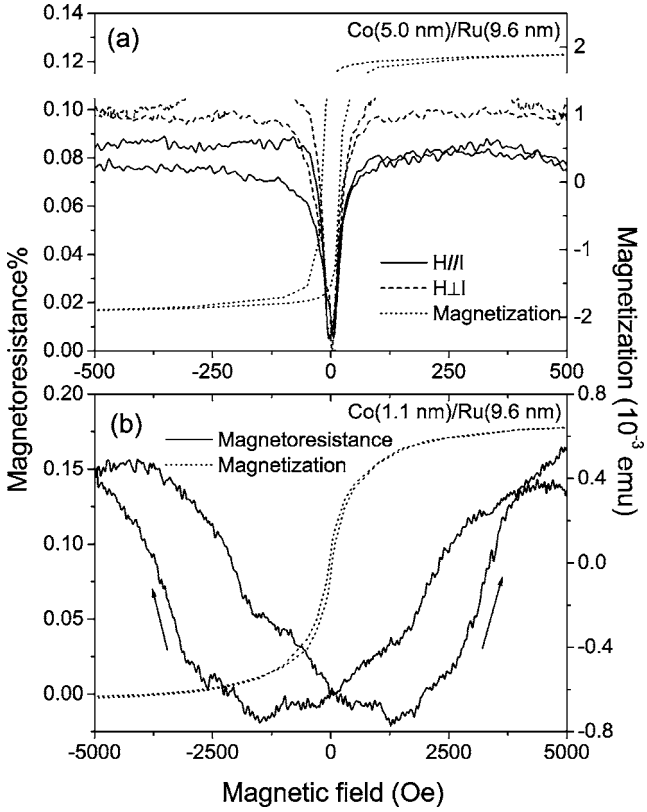

FIG. 7. Magnetoresistance and magnetization curves (dotted line) at room temperature with an in-plane field for (a) $(\text{Co } 5.0 \text{ nm}/\text{Ru } 9.6 \text{ nm})_5$ and (b) $(\text{Co } 1.1 \text{ nm}/\text{Ru } 9.6 \text{ nm})_7$ multilayers. For magnetoresistance curves the measurements have been performed with the magnetic field in the plane both parallel (solid) and perpendicular (dashed) to the current. Arrows indicate the direction of the swept field.

external field.[17,25–29] The FWHM in our sample is very narrow among these system[17,25–29] and worthy of technological consideration. We refer to this sharp PMR occurs under lower field and varies consistently with magnetization as mode 1.

In contrast, Fig. 7(b) shows that the (Co 1.1 nm/Ru 9.6 nm) film exhibits an antiferromagnetic (AF) configuration of the nearest-neighboring ferromagnetic layers as expressed by a linear like variation of the magnetization until the saturation at 5.0 kOe. This AF coupling has been reported by Rahmouni *et al.*[17] in (Co 3.2 nm/Ru 1.0 nm/Co 3.2 nm) sandwiches. Such a coupling is accompanied by the gradual increase of PMR, saturated at a field as high as 5.0 kOe with a value of about 0.15%. The FWHM is up to 5.0 kOe as well. We refer to this PMR with wide FWHM as mode 2, which occurs under higher field. It is well known that the presence of a plateau in the magnetoresistance curve is a good indication that the AF coupling is almost perfect and homogeneous on the whole surface of the sample.[15] As a consequence of its small surface roughness, the AF exchange coupling strength of this sample is much higher than the (Co 5.0 nm/Ru 9.6 nm) multilayers.[15] The strength of AF coupling J_{AF} of this sample is calculated to be approximately -0.79 erg/cm^2.

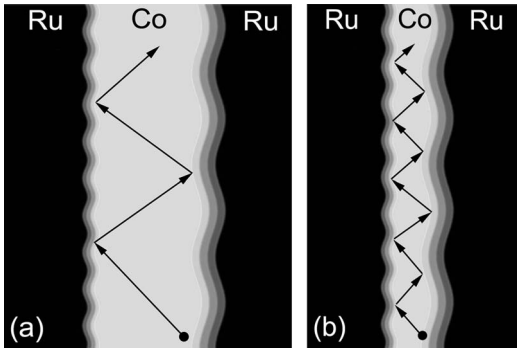

FIG. 8. Compared influence of t_{Co} on the transmission of electrons. The difference in roughness between the neighboring Co/Ru interfaces is also shown. (a) $(\text{Co } 5.0 \text{ nm}/\text{Ru } 9.6 \text{ nm})_5$ and (b) $(\text{Co } 1.7 \text{ nm}/\text{Ru } 9.6 \text{ nm})_7$.

Considering that the MR ratio is small in Co/Ru multilayers, especially in (Co 5.0 nm/Ru 9.6 nm) sample (e.g., MR% = 0.1%), it may come from an interplay of many contributions, such as the ordinary magnetoresistance (OMR) induced by the Lorentz force, the anisotropic magnetoresistance (AMR) and the spin-dependent scattering in the interface between the magnetic and the non magnetic layers.[28] On the one hand, the OMR is always positive and proportional to $(eB_{\perp}\tau/m^*)^2$ because the Lorentz force elongates the electron mean free path.[28] Since the MR ratio in Fig. 7(a) is not in proportion with the external field when H is higher than 50 Oe, the positive MR of this sample arising from OMR is impossible. A small contribution to this PMR is due to the AMR, which is confirmed from the small difference in total signals of both PMR curves measured with an in plane external applied magnetic field parallel and perpendicular to the current direction in Co/Ru system [Fig 7(a)]. The positive total signal variations of both curves at least four times of the AMR signal itself, suggests that there is another source which contributes to the PMR.

The observation of positive MR for all the Co/Ru multilayers probably has an interface spin-dependent scattering origin. In the case of symmetrical interfaces moments with the same chemical composition and the same CoRu alloy at both interfaces, the spin-dependent scattering ratios $\alpha(\alpha = \rho\downarrow/\rho\uparrow)$ are the same at both interfaces. However, using tight-binding calculations, Stoeffer and Gautier[30] have shown that Co layers wet the Ru layers due to their surfaces energies, while Ru layers do not wet a Co surface due to the elastic strains. This suggests that the interfacial properties of the first Co/Ru interface where Ru is deposited on Co are different from the second Co/Ru interface where Co is deposited on the Ru spacer. This is in agreement with the RHEED analysis reported by Ounadjela *et al.*[19] In addition, recalling that no Kiessig fringes exist in low-angle XRD profiles, indicating that interface mixing (i.e., CoRu alloying) exist at the Co/Ru interface to some extent, in which asymmetry is possible. A schematic explanation of this effect is given by the two different adjacent Co/Ru interfaces in Fig. 8. Such asymmetry can induce different α, respectively, lower and larger than one at each side of the Ru spacer layer. This is further supported by Itoh calculations[31] of the density

of states at the Fermi level including potentials at interfaces and *ab initio* calculations by Rahmouni *et al.*[17]

The presence of interface asymmetry is sufficient to explain the PMR, it is, however, not sufficient to explain the natural difference of modes 1 and 2. Note that the conductivity of the Co layers ($\rho_{Co}=6.24\times10^{-6}\ \Omega$ cm) is unusually large, a possible explanation for this difference can be found invoking a mechanism similar to the one proposed by Tsui[32] for the low-temperature PMR of Dy/Sc superlattices. Here the Co layers are low-resistance layers with a mean free path many times greater than their thickness. Under these circumstances the electrons reflect many times from the interfaces before scattering indicated by the arrows in Figs. 8(a) and 8(b) for (Co 5.0 nm/Ru 9.6 nm) and (Co 1.1 nm/Ru 9.6 nm) respectively. Also this enhances the sensitivity of resistance to momentum loss upon reflection. The extra resistance is[33]

$$R \sim \frac{1-p}{1+p} \sim \frac{1-p_0}{1+p_0}\left[1-\frac{2\Delta p}{1-p_0^2}\right] \tag{1}$$

with $p=1$ for specular reflection, $p=0$ when all parallel momentum is lost. Here $p_0(0<p_0<1)$ is close to 1 revealing the high conductivity of Co layer, similarly to $p_0=0.9$ corresponds to the high conductivity of Sc layer.[32] The last term shows how small changes Δp are enhanced when p_0 is close to 1. According to Ref. 32, electron reflection at the interface is reduced upon its magnetization by the applied field, the total resistance of the film may increase due to an increase in the transmission of electrons into the Ru layers. Based on this idea, it may be imagined that the H dependence of the PMR should correlate with H dependence of the magnetization of the Co–Ru alloy interface, and the fractional interfacial alloy magnetization $\mu=M/M_{sat}$ must be the parameter relevant to the reflectance; p can depend only on μ^2, so that $p=p_0+\alpha\mu^2+\cdots$ and $\Delta p=\alpha\mu^2$ in Eq. (1), to the neglect of higher terms. Here, α may depend on orientation but not on μ. Thus, MR% is proportion to $(M/M_{sat})^2$, i.e., MR% $\sim(M/M_{sat})^2$. The linear dependence of MR% on $(M/M_{sat})^2$ was obtained by Spizzo *et al.*[34] in Co/Cu system, but with a negative slope as Co/Cu possessed negative magnetoresistance.

For mode 1, the sample has the two adjacent Co layers ferromagnetically coupled, saturating at a small field. It is noted that M/M_{sat} increases rapidly in the vicinity of $H=0$. Therefore, MR% changes abruptly with suddenly increasing $(M/M_{sat})^2$ in terms of MR% $\sim(M/M_{sat})^2$. The sharp PMR becomes a reality with the advent of rapid saturation of MR%, producing a narrow FWHM and a small saturation field. On the contrary, for mode 2, the film exhibits an antiferromagnetic configuration with a gradual increase of the magnetization until the saturation at 5.0 kOe, which leads to the gradual increase of M/M_{sat} to a much higher field. Taking into account of MR% $\sim(M/M_{sat})^2$, MR% shows small changes as applied field is enhanced. This leads to the PMR is wide with a high saturation field.

It is found that the different MR% value of two PMR modes can be explained by different interface spin-dependent scattering. For mode 1, part of momentum is lost for interface spin-dependent scattering upon its magnetization by the applied field, but the other part still remains for comparatively large t_{Co}, e.g., $t_{Co}=5.0$ nm, which to some extent reduces the probability of electrons transmit to interface, as illustrated in Fig. 8(a). In this case, an applied field only partly decrease the specular reflectance to cause a small MR%, i.e., MR% $=0.1\%$. When t_{Co} decreases to 1.1 nm, Fig. 8(b) reveals that the contribution of Co/Ru interface becomes more significant for relatively small t_{Co}, which enhances the probability of electron transmitting to the interface. This behavior would produce strong interface spin-dependent scattering and induces the most of momentum loss. Thus, the absolute value of the PMR is enhanced, e.g., MR% $=0.15\%$ for (Co 1.1 nm/Ru 9.6 nm) multilayers. In addition, the difference in PMR between the two different t_{Co} may arise from the different atomic volume and magnetic moment, which need further consideration.

IV. CONCLUSION

Co/Ru multilayers were prepared by electron beam evaporation. The magnetic moment of Co atom is enhanced to $2.11\mu_B$ as the formation of metastable hcp Co. The results seem to suggest that the variation of the magnetic moment of Co is governed by a combining effect of two competitive factors, i.e., an expansion of average atomic volume would enhance whereas nonmagnetic element alloying reduces the magnetic-moment of Co, which is in accordance with some theoretical calculations. Also, as t_{Co} decreases, there is an increasing tendency of perpendicular magnetization. Moreover, the (Co t_{Co} nm/Ru 9.6 nm) series show two distinct modes of positive magnetoresistance: For large t_{Co}, the sharp PMR varies consistently with the magnetization with a small saturation field, accompanied by ferromagnetic coupling. For small t_{Co}, the PMR is saturated at a high field, in accordance with antiferromagnetic coupling. The positive MR is attributed to the opposite interface spin-dependent scattering ratios at the two Co/Ru interfaces.

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[1] W. Heitsenberg, Z. Phys. **49**, 619 (1928).
[2] F. Bloch, Z. Phys. **57**, 545 (1929).
[3] P. F. Carcia, A. D. Meinhaldt, and A. Suna. Appl. Phys. Lett. **47**, 178 (1985).
[4] S. S. P. Parkin, N. More, and K. P. Roche, Phys. Rev. Lett. **64**, 2304 (1990).

[5] F. Pan, M. Zhang, M. Ding, B. X. Liu, Y. M. Zhou, and D. S. Wang, Phys. Rev. B **59**, 11 458 (1999).
[6] F. Pan and Z. S. Zhang, Physica B **293**, 237 (2001).
[7] J. Camarero, L. Spendeler, G. Schmidt, K. Heinz, J. J. de Miguel, and R. Miranda, Phys. Rev. Lett. **73**, 2448 (1994).
[8] U. Kohl, M. Dippel, G. Filleböck, K. Jacobs, B.-U. Runge, and G. Schatz, Surf. Sci. **407**, 104 (1998).
[9] Z. C. Li, D. P. Yu, and B. X. Liu, Phys. Rev. B **65**, 245403 (2002).
[10] G. H. Yang and F. Pan, J. Magn. Magn. Mater. **250**, 249 (2002).
[11] G. H. Yang, J. B. Chen, and F. Pan, J. Alloys Compd. **365**, 43 (2004).
[12] L. T. Kong, R. F. Zhang, Z. C. Li, and B. X. Liu, Phys. Rev. B **68**, 134446 (2003).
[13] L. T. Kong and B. X. Liu, Appl. Phys. Lett. **84**, 3627 (2004).
[14] A. Dinia and K. Ounadjela, J. Magn. Magn. Mater. **146**, 66 (1995)
[15] S. Colis, A. Dinia, D. Deck, G. Schmerber, and V. Da Costa, J. Appl. Phys. **88**, 1552 (2000)
[16] S. Zoll, A. Dinia, J. P. Jay, C. Mény, G. Z. Pan, A. Michel, L. El Chahal, V. Pierron-Bohnes, P. Panissod, and H. A. M. Van den Berg, Phys. Rev. B **57**, 4842 (1998).
[17] K. Rahmouni, A. Dinia, D. Stoeffler, K. Ounadjela, H. A. M. Van den Berg, and H. Rakoto, Phys. Rev. B **59**, 9475 (1999).
[18] K. Himi, K. Takanashi, S. Mitani, M. Yamaguchi, D. H. Ping, K. Hono, and H. Fujimori, Appl. Phys. Lett. **78**, 1436 (2001).
[19] K. Ounadjela, D. Muller, A. Dinia, A. Arbaoui, P. Panissod, and G. Suran, Phys. Rev. B **45**, 7768 (1992).
[20] G. H. Yang, J. B. Chen, and F. Pan, Phys. Status Solidi A **194**, 71 (2002).
[21] T. L. Hylton, K. R. Coffery, M. A. Parker, and J. K. Howard, J. Appl. Phys. **75**, 7058 (1994).
[22] L. H. Bennett, L. J. Swartzendruber, D. S. Lashmore, R. Oberle, U. Atzmony, M. P. Dariel, and R. E. Waston, Phys. Rev. B **40**, 4633 (1989).
[23] Z. S. Shan, P. He, C. Moore, J. Woollam, and D. J. Sellmyer, J. Appl. Phys. **73**, 6057 (1993).
[24] T. L. Hylton, K. R. Coffey, M. A. Parker, and J. K. Howard, Science **261**, 1021 (1993).
[25] J. M. George, L. G. Pereira, A. Barthélémy, F. Petroff, L. Steren, J. L. Duvail, A. Fert, R. Loloee, P. Holody, and P. A. Schroeder, Phys. Rev. Lett. **72**, 408 (1994).
[26] M. K. Chattopadhyay, S. B. Roy, S. Chaudhary, K. J. Singh, A. K. Nigam, Phys. Rev. B **66**, 174421 (2002).
[27] J. K. Tang, J. B. Dai, K. Y. Wang, W. L. Zhou, N. Ruzycki, and U. Diehold, J. Appl. Phys. **91**, 8411 (2002).
[28] R. P. van Gorkom, J. Caro, T. M. Klapwijk, and S. Radelaar, Phys. Rev. B **63**, 134432 (2001).
[29] T. He, Y. Gao, F. Zeng, and F. Pan, J. Phys. D **37**, 1 (2004).
[30] D. Stoeffler and F. Gautier, in *Structural and Phase Stability of Alloys*, edited by J. L. Moran-Lopez *et al.* (Plenum, New York, 1992).
[31] H. Itoh, J. Inoue, and S. Maekawa, Phys. Rev. B **47**, 5809 (1993).
[32] F. Tsui, C. Uher, and C. P. Flynn, Phys. Rev. Lett. **72**, 3084 (1994).
[33] J. M. Ziman, *Electrons and Phonons* (Oxford University Press, Oxford, 1960), Chaps. 11,12.
[34] F. Spizzo, E. Angeli, D. Bisero, P. Vavassori, and F. Ronconi, Appl. Phys. Lett. **79**, 3293 (2001).