Element-specific magnetic properties of the epitaxial NiFe/Cr/NiFe trilayers

I. F. Lee, M. Y. Shen, Y. Y. Lay, J. C. Jan, J. W. Chiou, H. M. Tsai, and W. F. Pong[a)]
Department of Physics, Tamkang University, Tamsui, Taiwan 251, Republic of China

M.-H. Tsai
Department of Physics, National Sun Yat-Sen University, Kaohsiung, Taiwan 804, Republic of China

H. H. Hsieh, H.-J. Lin, and J. F. Lee
Synchrotron Radiation Research Center, Hsinchu, Taiwan 300, Republic of China

C. A. Ku and J. C. A. Huang
Department of Physics, National Cheng Kung University, Tainan, Taiwan 701, Republic of China

(Received 14 November 2002; accepted 28 January 2003)

Ni and Fe $L_{3,2}$-edge magnetic circular dichroism (MCD) and Cr K-edge x-ray absorption near-edge structure measurements have been performed for the Py/Cr(t_{Cr})/Py (Py=$Ni_{80}Fe_{20}$) trilayers with t_{Cr}=5, 10, 15, 20, and 25 Å. The MCD asymmetry ratios in the Ni and Fe L_3-edges spectra are found strongly affected by the thickness of the Cr layer. The moments of the Fe and Ni 3d states are found, respectively, to decrease and increase suddenly when t_{Cr} increases beyond 20 Å. The measured magneto-optical Kerr effect hysteresis loops show a ferromagnetic-to-antiferromagnetic phase transition at about the same Cr-layer thickness. The transition of the magnetic property is found to correlate with the structural transition of the Cr spacer layer from a pseudomorphic fcc-like structure to a bcc structure. © *2003 American Institute of Physics.* [DOI: 10.1063/1.1563743]

Trilayer structures with an antiferromagnetic (AFM) or nonmagnetic metal layer sandwiched between two ferromagnetic (FM) metal layers are known to exhibit oscillatory magnetic couplings, which diminish with the increase of the thickness of the interlayer. This phenomenon has drawn increasing interest.[1–3] The Fe/Cr/Fe trilayer has been extensively investigated[2–6] due to the potential technological applications of its giant magnetoresistive (GMR) effect. Permalloy (Py=$Ni_{80}Fe_{20}$)-related multilayers[7] and spin-valve heterostructure[8] have also attracted much attention in recent years because they exhibit a GMR effect at low saturation field. They also have potential applications as high magnetic memory sensors and spin-valve heads. Here, we have attempted to elucidate the effect of the Cr-layer thickness on the magnetic characteristics of the epitaxial Py/Cr/Py trilayers by Ni and Fe $L_{3,2}$-edges soft x-ray magnetic circular dichroism (MCD) and Cr, Ni, and Fe K-edge x-ray absorption near-edge structure (XANES) measurements.

MCD and XANES spectra were measured at the Synchrotron Radiation Research Center in Hsinchu, Taiwan. The MCD spectra of all samples were obtained from the Dragon beamline. Using the electron yield method for the Ni and Fe $L_{3,2}$-edges. An alternating magnetic field of 100 Oe was applied parallel to the surface of the sample, and the grazing angle of the incident light was fixed at 30° from the sample's surface. The Cr, Ni, and Fe K-edge XANES spectra were obtained from the Wiggler-C beamline, using the fluorescence yield method at room temperature. The molecular-beam-epitaxy-grown $Py(111)_{50\,Å}/Cr(110)/Py(111)_{50\,Å}$ trilayers structure with a stair-shaped Cr spacer layer was deposited at 150 °C on the Pt seeding layer on the Al_2O_3(1-102) substrate. The stair-shaped Cr layer has five 5-, 10-, 15-, 20-, and 25-Å-high (or thick) steps, which allows a detailed investigation of the dependence of the magnetic coupling on the thickness of the Cr layer under fixed sample preparation conditions. A thin capping Pt layer (~10 Å) was also deposited on the top of the sample to prevent oxidation problem. The details of the preparation and characterization of the samples have been presented elsewhere.[9]

Figures 1 and 2 display, respectively, the normalized Ni and Fe $L_{3,2}$-edges XANES and MCD (i.e., $I_+ - I_-$) spectra of the Py/Cr(t_{Cr})/Py trilayers with t_{Cr}=5, 10, 15, 20, and 25 Å. I_+(I_-) refers to the absorption spectrum obtained by projecting the spin of the incident photons parallel (antiparallel) to the spin direction of the Ni and Fe 3d majority-spin electrons. The two white-line regions, labeled L_3 and L_2 in Figs. 1 and 2, represent the electron transitions from the Ni and Fe 2$p_{3/2}$ and 2$p_{1/2}$ core levels to the Ni and Fe 3d unoccu-

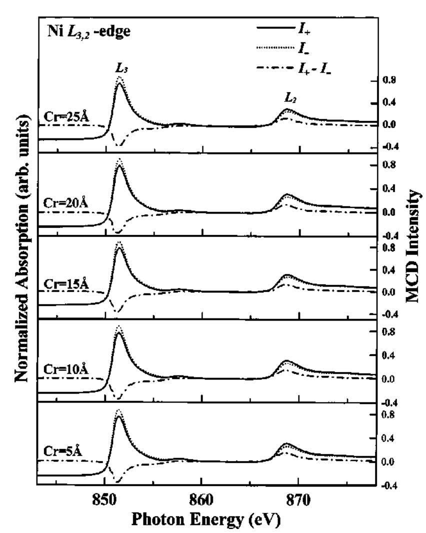

FIG. 1. Normalized Ni $L_{3,2}$-edge XANES and MCD spectra of the Py/Cr(t_{Cr})/Py trilayers with t_{Cr}=5, 10, 15, 20, and 25 Å.

[a)]Author to whom all correspondence should be addressed; electronic mail: wfpong@mail.tku.edu.tw

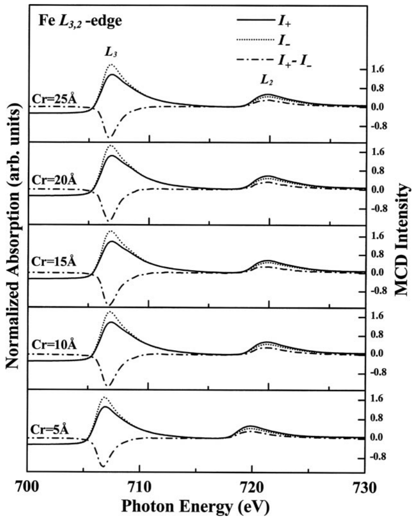

FIG. 2. Normalized Fe $L_{3,2}$-edge XANES and MCD spectra of the Py/Cr(t_{Cr})/Py trilayers with t_{Cr}=5, 10, 15, 20, and 25 Å.

pied states, respectively. The general line shapes of the Ni and Fe $L_{3,2}$-edges XANES and MCD spectra of the Py/Cr(t_{Cr})/Py trilayers are nearly identical regardless of the thickness of the Cr interlayer. They also exhibit a similar single-peak feature in the $L_{3,2}$ absorption white line of the corresponding Ni[10] and Fe[11] metals, respectively. The line shapes of the $L_{3,2}$-edge white-line absorption spectra of $3d$ transition-metal ions are known to depend strongly on the crystal-field symmetry and ligand-field splitting parameter $10D_q$.[12] Although the sum rule of the integrated intensities of the absorption and MCD spectra can be used to obtain quantitative information about the orbital[13] and spin[14] moments, difficulties with the background subtraction have limited its usefulness. Thus, we have not quantitatively extracted the spin and orbital moments of Ni and Fe atoms. Rather, we focus only on the dependence of their overall $3d$-state magnetic properties on the Cr-layer thickness.

Figure 3 shows the Ni and Fe L_3-edges MCD asymmetry ratios[15] (or MCD to XANES ratio[13,16]), $(I_+-I_-)/(I_++I_-)$ versus the thickness of the Cr layer. The MCD asymmetry ratios in the Ni and Fe L_3-edges spectra were integrated between 847 and 860 eV and between 700 and 716 eV, respectively. As shown in Fig. 3, the moment of the Fe $3d$ states exceeds that of Ni in the Py/Cr(t_{Cr})/Py trilayers except for t_{Cr}= 25 Å. This is because the Fe atom has a larger magnetic moment than the Ni atom. The variation of the MCD asymmetry ratio of the Fe L_3-edge spectra differs from that of the Ni L_3-edge spectra. The Fe L_3-edge MCD asymmetry ratio increases monotonically with the thickness of the Cr layer up to t_{Cr}= 15 Å. In contrast, the Ni L_3-edge MCD asymmetry ratio remains fairly constant within experimental uncertainties with a small oscillation for $t_{Cr} \leqq 20$ Å. Trilayer structures with a nonmagnetic metal layer sandwiched between two FM metal layers are known to exhibit oscillatory magnetic couplings. This oscillatory property is shown in Fig. 3 for Ni with a period of about 15 Å. For Fe, the increasing MCD asymmetry ratio from t_{Cr}= 5 to 15 Å seems to concave downward, which may just be one part of an oscillation with a much longer period.

The MCD asymmetry ratio of the Fe L_3-edge spectra has a sudden decrease from t_{Cr}= 15 to 20 Å, while the MCD asymmetry ratio of the Ni L_3-edge spectra increases suddenly from t_{Cr}= 20 to 25 Å. As indicated by the experimental error bars shown in Fig. 3, the sudden decrease of the Fe L_3-edge MCD asymmetry ratio, although small, is real, and is consistent with the Kerr intensity measurements to be stated later. These sudden changes suggest an occurrence of a transition of the magnetic property in the Py/Cr(t_{Cr})/Py trilayer around t_{Cr}= 20 Å, which indeed is confirmed by the magneto-optical Kerr effect (MOKE) hysteresis loops of the Py trilayers, as shown in the inset of Fig. 3.[17] These hysteresis loops are linear combinations of both Ni and Fe elemental hysteresis loops and represent the total magnetic moments of the Py/Cr(t_{Cr})/Py trilayers. The inset shows that the Py/Cr(t_{Cr})/Py trilayers with t_{Cr}= 5, 10, and 15 Å are clearly FM, while those with t_{Cr}= 20 and 25 Å are AFM. The MOKE and Ni and Fe L_3-edges MCD measurements consistently show the transition of the magnetic property of the Py/Cr(t_{Cr})/Py trilayer around t_{Cr}= 20 Å.

Atoms near the interfaces may diffuse across interfaces and pseudomorphism may occur in the Cr layer of the Py/Cr(t_{Cr})/Py trilayer and a strained thin Cr layer is expected to have the crystal structure of the substrate layer;[18] here, the Py layer. When the Cr layer is thick enough, one will expect that the Cr layer will transit to its thermodynamically stable crystal structure, that is, a bcc structure. Figure 4 displays the Cr K-edge XANES spectra obtained for the Py/Cr(t_{Cr})/Py trilayers and the reference Cr foil. Figure 4 also shows the Ni and Fe K-edge XANES spectra of the t_{Cr} = 5 Å Py/Cr(t_{Cr})/Py trilayer in the inset. The two small bumps in the region from around 0 to 10 eV above the threshold edge (labeled as $\mathbf{a}_1$ and $\mathbf{a}_2$) were attributed primarily to the Cr $1s$-to-$3d$ transition and the $p-d$ rehybridization, respectively. And the main feature (labeled as **b**) was attributed to the dipole $1s$-*to*-$4p$ transitions above the Fermi level E_F.[18,19] Figure 4 shows that the feature **b** becomes more and more similar to that of pure Cr as the thickness of the Cr layer increases from t_{Cr}= 5 to 25 Å. Feature **b** in the spectra of the trilayers with t_{Cr}= 20 and 25 Å already resemble that of pure Cr, which has a bcc structure. Feature **b** in the t_{Cr}= 5, 10, and 15 Å Cr K-edge XANES spectra are

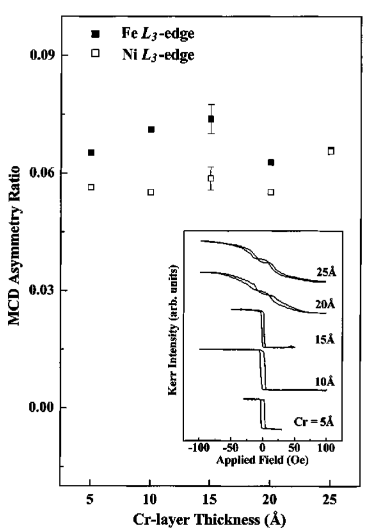

FIG. 3. Ni and Fe L_3-edges MCD asymmetry ratios versus the thickness of the Cr layer. The inset plots MOKE hysteresis loops.

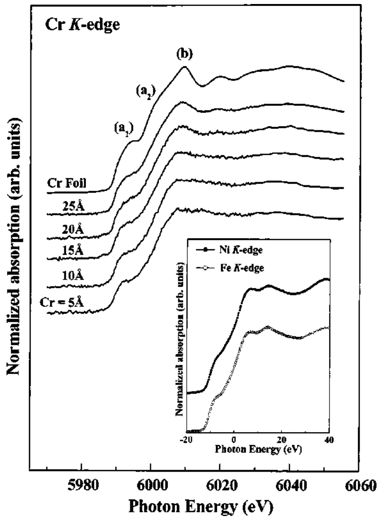

FIG. 4. Normalized Cr K-edge XANES spectra of the Py/Cr(t_{Cr})/Py trilayers with t_{Cr}=5, 10, 15, 20, 25 Å and pure Cr. The inset shows the Ni and Fe K-edge XANES spectra of the t_{Cr}=5 Å Py/Cr(t_{Cr})/Py trilayer, in which the zero energy is chosen at the inflection point.

much broader and appear to be much less resolved than those of t_{Cr}=20 and 25 Å Py/Cr(t_{Cr})/Py trilayers. This trend of the change of feature **b** suggests a structural transition in the Cr layer around t_{Cr}=20 Å. This finding also implies that the pseudomorphic Cr layer can be grown on a Py layer and can be constrained to a fcc-like structure when the thickness of the Cr layer is less than about 20 Å. This critical thickness, ~20 Å, for the structural transition as observed by the Cr K-edge XANES measurements is about the same as that of the FM–AFM transition observed by MOKE and Ni and Fe $L_{3,2}$-edges MCD measurements. Thus, we find a correlation between the structure of the Cr layer and the magnetic property of the Py/Cr(t_{Cr})/Py trilayer.

The magnetic properties of the magnetic multilayers are known to be strongly affected by the electronic and atomic structures of the interlayers.[20] The Cr layer can affect the magnetic property of the Py/Cr(t_{Cr})/Py trilayer in the following ways. One is the mediation of the magnetic coupling between the two FM layers through the Cr states, which include Cr 3d states, in the vicinity of E_F. Another is the modification of the magnetic moments in the FM layers through the shift of E_F, which alters the occupation of the majority-spin (↑-spin) and minority-spin (↓-spin) states. Since the coordination number of an atom in a bcc structure is less than that of the close-packed fcc structure and that the multidirectional d-orbital couplings, which determine the ferromagnetic coupling, favors a larger coordination number. The transition of the Cr layer from the pseudomorphic fcc-like structure to the bcc structure is expected to reduce the ferromagnetic coupling between the two FM layers. This may be the physical reason for the correlation between our observed structural and FM to AFM transitions. On the other hand, our observed sudden decrease and increase, respectively, of the Fe and Ni MCD asymmetry ratios seems to suggest that when the Cr layer transits to the bcc structure, E_F shifts downward in the FM layers. The Ni atom has an almost filled 3d shell. In the Py layers, the Ni ↑-spin 3d band will remain almost filled, while the leading edge of the ↑-spin 3d band will be empty, which gives rise to a net magnetic moment. Since the leading edge of the 3d band is steep, a slight decrease of E_F will cause a significant reduction of the number of ↑-spin 3d electrons and an increase of the magnetic moment of Ni. Thus, Ni has a sudden increase of the MCD asymmetry ratio accompanying the structural transition. In contrast, E_F lies inside both Fe ↑- and ↓-spin 3d bands. The numbers of both ↑- and ↓-spin 3d electrons are reduced by a downward shift of E_F, so that the net change of the magnetic moment of Fe due to the shift of E_F is much less significant. The sudden decrease of the MCD asymmetry ratio for Fe is due to the reduced Cr-layer-mediated magnetic coupling between the two FM layers, which outweighs the effect of the downward shift of E_F.

In summary, this work examined the dependence of the element-specific magnetic properties of the Py/Cr/Py trilayers on the thickness of the Cr layer. We found sudden changes in the Ni and Fe L_3-edge MCD asymmetry ratios when the Cr-layer thickness increases beyond about 20 Å. These results imply a magnetic transition at t_{Cr}~20 Å, which is also consistently shown by our MOKE hysteresis loops that show a FM-to-AFM transition at about the same thickness of the Cr layer.

This work was supported by the National Science Council of the Republic of China under Contract No. NSC 91-2112-M-032-015.

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