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EFFECT OF THE ANNEALING TEMPERATURE ON THE ELECTRONIC AND ATOMIC STRUCTURES OF EXCHANGE-BIASED NiFe–FeMn BILAYERS

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In this study we measured the Fe, Mn, and Ni $L_{2,3}$ -edge X-ray absorption near-edge structure (XANES) and K -edge extended X-ray absorption fine structure (EXAFS) of the ferromagnetic (FM) NiFe and antiferromagnetic (AFM) FeMn bilayer films prepared with various annealing temperatures. The branching ratios of the white-line intensities in the Fe, Mn, and Ni $L_{2,3}$ -edges XANES spectra and consequently the magnetic properties of these exchange-biased FM NiFe – AFM FeMn bilayers are found to depend strongly on the annealing temperature. We find that the first peak in the Fe, Mn, and Ni K -edge EXAFS Fourier transform spectra are very similar, which suggests that the nearest-neighbor bond lengths among Fe, Mn, and Ni atoms are essentially the same in the NiFe–FeMn bilayers. However, the peaks at distances greater than ~ 3 Å appear to be sensitive to the annealing temperature especially for the Fe and Mn K -edge spectra, which suggests that annealing alters the atomic structures of the next-nearest-neighbor and more distant shells surrounding the Fe and Mn atoms in the NiFe–FeMn bilayers.

1. Introduction

The ferromagnetic (FM) NiFe and antiferromagnetic (AFM) FeMn layers with a high degree of exchange anisotropy have recently attracted extensive attention because of their potential application in high magnetic memory sensors and giant magnetoresistive (GMR) spin valve heads. These bilayers have a combination of a high exchange coupling strength and

a high blocking temperature T_b (the temperature at which the exchange field, H_{ex} , disappears).^{1–4} For memory applications, the high processing temperature requires that the exchange-biased FM–AFM bilayers have thermal stability. Previous investigations^{5,6} demonstrated that the annealing process strongly influences the thermal stability and substantially alters the magnetic properties of the exchange-biased FM–AFM bilayers. The exchange

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coupling and magnetic properties of the magnetic layers are generally believed to be strongly influenced by their electronic and atomic structures.⁷ The study of the electronic and atomic structures of these materials may elucidate the mechanism of the FM–AFM exchange interaction and the GMR properties. However, despite the various studies, which explored the exchange coupling and magnetic properties of FM NiFe – AFM FeMn bilayers (FeMn on top), the dependence of the local electronic and atomic structures in these materials on the annealing temperature, to our knowledge, has not been reported. Thus, we have carried out the measurements of the Fe, Mn, and Ni $L_{2,3}$ -edge X-ray absorption near-edge structure (XANES) and K -edge extended X-ray absorption fine structure (EXAFS) to investigate the effect of the annealing temperature on the electronic and atomic structures of the FM NiFe – AFM FeMn bilayers.

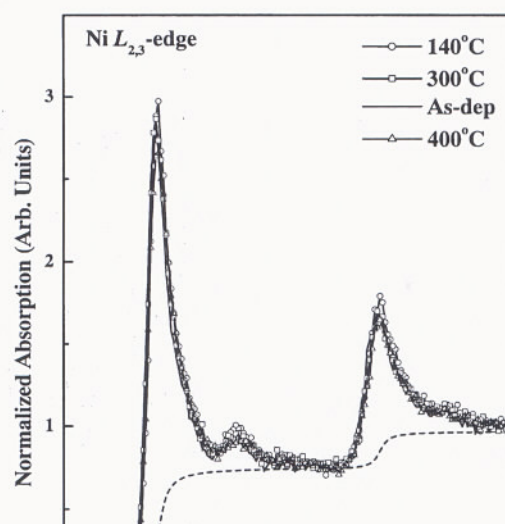
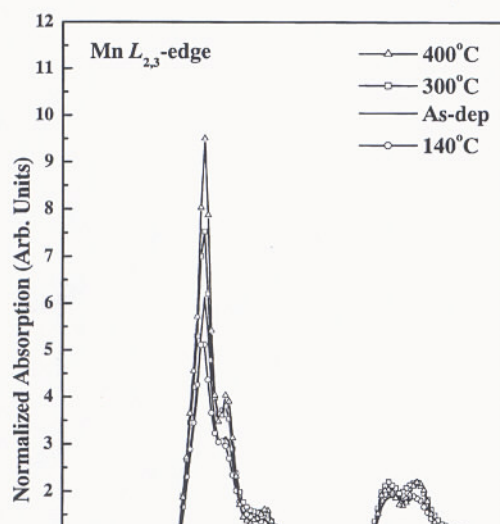
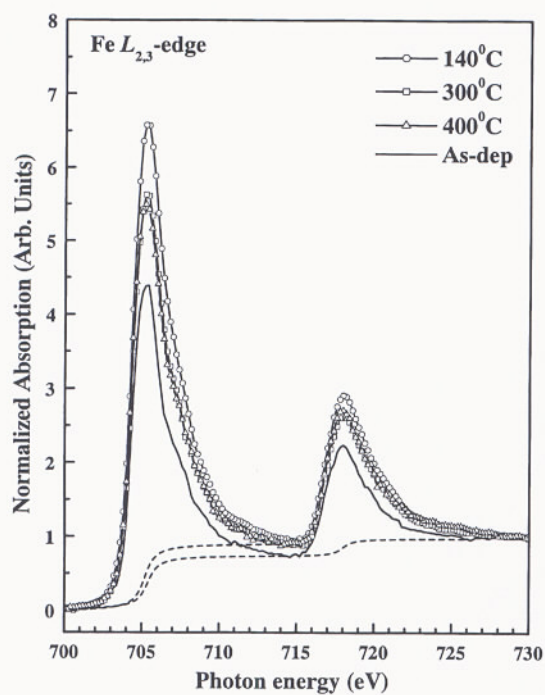
2. Experiment

X-ray absorption spectra were measured using the facility at the Synchrotron Radiation Research Center (SRRC) in Hsinchu, Taiwan, operating with the electron energy of 1.5 GeV and a maximum stored current of 200 mA. The XANES spectra of all samples were obtained from the high-energy spherical grating monochromator beamline using the sample drain current method for Fe and Mn $L_{2,3}$ -edges and the fluorescence yield method for Ni $L_{2,3}$ -edge respectively, while the K -edge extended X-ray absorption fine structure (EXAFS) spectra were obtained from the wiggler beamline using the fluorescence yield method at room temperature. The exchange-biased NiFe–FeMn bilayers were deposited on the Si(100) substrate by DC magnetron sputtering. Ta layers deposited by RF magnetron sputtering served as the buffer and cap layers. The resultant film compositions were $\text{Ni}_{0.8}\text{Fe}_{0.2}$ and $\text{Fe}_{0.5}\text{Mn}_{0.5}$, respectively. The as-deposited Si/Ta(100 Å)/ $\text{Ni}_{0.8}\text{Fe}_{0.2}$ (150 Å)/ $\text{Fe}_{0.5}\text{Mn}_{0.5}$ (300 Å)/Ta(15 Å) film and the three annealed films with the same configuration are investigated. Annealing was performed in a magnetic field of about 500 Oe for 2 h at temperatures of 140, 300, and 400°C, respectively. The details of the preparation and characterization of these samples are given elsewhere.⁸

3. Results and Discussions

Figures 1(a)–1(c) display, respectively, the normalized Fe, Mn, and Ni $L_{2,3}$ -edge XANES spectra of the as-deposited and three annealed NiFe–FeMn bilayer films. According to the dipole-transition selection rule, the dominant transition is from Fe (Mn & Ni) $2p_{3/2}$ and $2p_{1/2}$ to the unoccupied Fe (Mn & Ni) $3d$ electron states. The area beneath the white-line feature in the Fe (Mn & Ni) $L_{2,3}$ -edge XANES spectra is predominantly a convolution of the absolute square of the transition matrix element and the unoccupied densities of states of the d character. The general line shapes in the Fe (Mn & Ni) $L_{2,3}$ -edge XANES spectra of the as-deposited and the three annealed NiFe–FeMn bilayers display similar features above the Fe (Mn & Ni) $L_{2,3}$ -edge, except for the intensity near the threshold of the Fe (Mn & Ni) $L_{2,3}$ -edge XANES spectra. Figures 1(a)–1(c) illustrate a systematic reduction in the intensity of the feature near the Fe and Ni $L_{2,3}$ -edge for the three annealed NiFe–FeMn bilayers with the increase of the annealing temperature. In contrast, the variation of the intensity in the Mn $L_{2,3}$ -edge XANES spectra shows exactly the opposite trend for the features of the three annealed NiFe–FeMn bilayers, which display increasing intensity of the Mn $L_{2,3}$ -edge XANES with the increase of the annealing temperature for the NiFe–FeMn bilayers, as presented in Fig. 1(b).

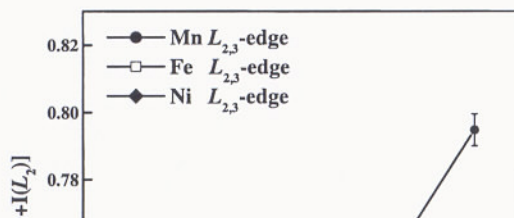
Generally, the lower the intensities of the features near the threshold in the Fe (Mn & Ni) $L_{2,3}$ -edge XANES spectrum, the fewer the unoccupied Fe (Mn & Ni) $3d$ states the material has. The line shape of the $L_{2,3}$ -edge white-line absorption spectra of $3d$ transition-metal ions depends strongly on the crystal-field symmetry and ligand-field splitting parameter $10D_q$.⁹ In a study of how the Fe (Mn & Ni) $3d$ electronic structure and the magnetic property of the NiFe–FeMn bilayers change with the annealing temperature, Thole and van der Lann noted that¹⁰ the branching ratio of the white-line intensity $I(L_3)/[I(L_3) + I(L_2)]$ is highly sensitive to the spin states of the $3d$ transition-metal ions. They found that the high-spin states have a relatively large white-line branching ratio. Thus, in this study we have investigated the branching ratio to understand the spin states and the magnetic properties of the NiFe–FeMn bilayers. An arctangent function

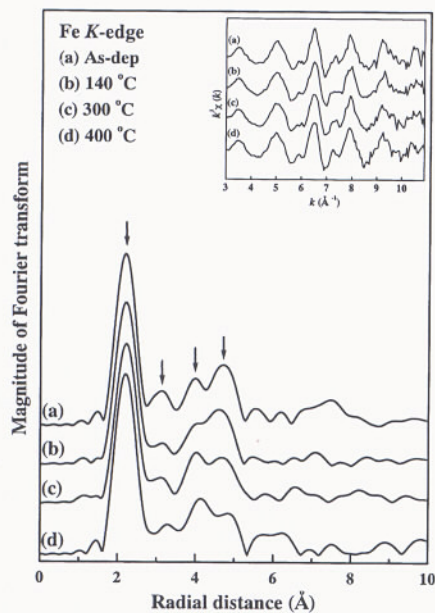


representing the background intensity, as displayed by dashed lines in Figs. 1(a)–1(c) was first subtracted from the intensities $I(L_3)$ and $I(L_2)$. Then $I(L_3)$ (between 700.0 and 714.2 eV for Fe, 634.2 and 646.2 eV for Mn, 847.0 and 863.0 eV for Ni) and $I(L_2)$ (between 714.2 and 730.0 eV for Fe, 646.2 and 654.0 eV for Mn, 863.0 and 878.0 eV for Ni) were integrated separately for the as-deposited and the annealed films. Figure 2 shows the results of the branching ratio $I(L_3)/[I(L_3)+I(L_2)]$ as a function of the annealing temperature. The trend of the branching ratio $I(L_3)/[I(L_3)+I(L_2)]$ in the Fe $L_{2,3}$ -edge spectra is very different from those in the Mn and Ni $L_{2,3}$ -edge spectra. First, the Fe $L_{2,3}$ -edge branching ratio $I(L_3)/[I(L_3)+I(L_2)]$ remains constant up to the annealing temperature of about 140°C, then decreases with the increase of the annealing temperature. In an opposite trend, the Mn and Ni $L_{2,3}$ -edge branching ratios increase with the increase of the annealing temperature above 140°C. These trends suggest that the spin moments of the Fe, Mn, and Ni 3d states are not affected by the annealing treatment up to 140°C. However, the spin moments of the Fe (Mn & Ni) 3d states are significantly reduced

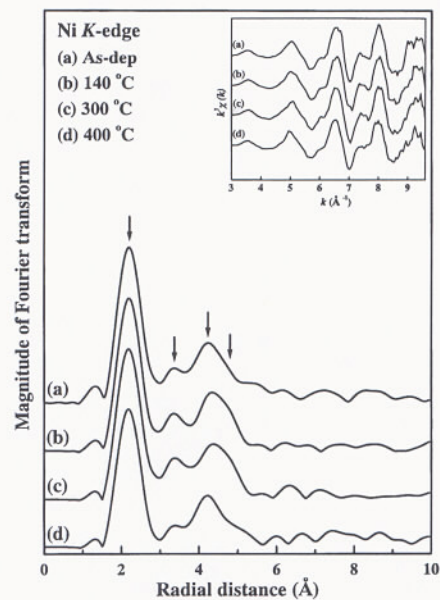
(enhanced) when the annealing temperature of the NiFe–FeMn bilayers exceeds 140°C. The substantial decrease in the spin moment of the Fe 3d states is most likely caused by the formation of bcc Fe in the top fcc FeMn layer.⁶ This result suggests that the Fe ions approach the low-spin state, while Mn & Ni ions approach the high-spin state when the annealing temperature exceeds 140°C. The major contribution to the desirable magnetic properties of the NiFe–FeMn bilayers is primarily from the significant change of the Fe, Mn, and Ni 3d spin states in the NiFe and FeMn layers following annealing. The critical annealing temperature of around 140°C, below which the spin moments of the Fe, Mn, and Ni atoms remain unaffected, is close to the observed blocking temperature T_b , at which H_{ex} disappears, of $\sim 150^\circ\text{C}$ in the NiFe–FeMn films.^{2,3,11} This critical annealing temperature for the spin moments of the Fe, Mn, and Ni atoms may be closely related to the lowering of the Néel temperature from that of the bulk FeMn of $\sim 220^\circ\text{C}$.³ Since the existence of H_{ex} is caused by a unidirectional anisotropy arising from the nearest-neighbor exchange coupling, which is proportional to the spin moments,¹ H_{ex} will roughly follow the dependence of the overall spin moments of the Fe, Mn, and Ni 3d atoms on the annealing temperature.

Figures 3–5 show the Fe, Mn, and Ni K -edge Fourier transform (FT) of the EXAFS oscillation $k^3\chi$ data for the as-deposited and the annealed NiFe–FeMn bilayers. The inset shows the corresponding Fe, Mn, and Ni K -edge EXAFS oscillation $k^3\chi$ data, respectively. The first peaks in the FT curves shown





data at the Fe K -edge from $k = 3.2$ to 11 \AA^{-1} for the as-deposited and three annealed NiFe-FeMn bilayers. The inset represents the Fe K -edge EXAFS oscillation $k^3\chi$ data.



data at the Ni K -edge from $k = 3.2$ to 9.7 \AA^{-1} for the as-deposited and three annealed NiFe-FeMn bilayers. The inset represents the Ni K -edge EXAFS oscillation $k^3\chi$ data.

the interface after extended annealing at $\sim 260^\circ\text{C}$ causing the formation of NiMnFe ternary alloys that display a strong antiferromagnetic order and are coupled to the NiFe to produce a much stronger exchange bias. The Auger composition analysis in conjunction with our Ni *K*-edge FT result seems to suggest that the atomic structure in the interface region and about 5 Å deep in the FeMn layer more or less has the fcc structure of the NiFe layer.

4. Conclusion

In summary, this study has investigated the electronic and atomic structures of the as-deposited and three annealed FM NiFe – AFM FeMn bilayers using

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References

1. M. F. Toney, C. Tsang and J. K. Howard, *J. Appl. Phys.* **70**, 6227 (1991).
2. T. Lin, D. Mauri, N. Staud, C. Hwang and G. L. Gorman, *Appl. Phys. Lett.* **65**, 1183 (1994).
3. G. Choe and S. Gupta, *Appl. Phys. Lett.* **70**, 1766 (1997).
4. Z. Qian, J. M. Sivertsen, J. H. Judy, B. A. Everitt, S. Mao and E. S. Murdock, *J. Appl. Phys.* **85**, 6106 (1999).

mgiondabout5AdeepMmFeMnlay...orelZiJ.芳,芳:ifi 品??叫 J K How 叫 i AWI
 or less has the fcc structure of the NiFe layer.2.T.Lin,D.Mallri,N.SMAId,c.Hwang and
 G.L.
 Goman,APPI-Phus.Lett.65,1183(1994).
 4.Conclusion 3.G.Choe and S.Gupta,APPL Phus.Lett.70,1766
 (1997).
 In summary,this study has investigated the
 elec-4.Z.Qian,J.h4.SivertseI1,J.H.Judy,B.A.Everith
 tronic and atomic structures of the as-deposited and S.Mao and E S.Murdock,i
 APPI-Phus.85,6106
 three amlealed FM NiFe-AFM FeMn bilayers using (1999).
 5.C.Loch.W.Maass,B.Ocker and k R 訓,i APPI-
 X-ray absorption spectroscopy and found substantial mus.泊,44ω(1999).
 variationofthe bramhi 時 ratioI(L3)/II(L3)+I(L2)]6.M.G.sama 此,J.Liining,J.st 他 r and
 S.S.P.
 for the Fe,MIU and Ni L23.edge at an annealing
 Parkin,APPI-Phus.Lett.76,3097(2000).
 temperature above MVC in the NEe-FeMn bilayers-7.G.A
 Prinz,mus.Reu-Lett.54,1051(1985);D.p.
 These results suggest that the spin moments of the pappahk.p.K&mper and H.Hopsten
 ibid.64,3179
 (1990);E E Fullerton D M Kelly,J.Guimpel and
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 the Ni and Mn atoms increase sigIliacantly with the 9.G.van der Laan and l
 W.Kirkman,i Phu8.J
 increase of the amlealing temperature-The EXAFS Condens-M α tteT4,4189(1992).
 10.B.T.Thole and G.van der Laan,Phus.Reu-B38,
 results show that annealing causes changes in
 3158(1988).
 the next-nearest-neighbor and higher-order shells 11.c.Tsang and
 K.Lee,J.APPI-Phus.53,260(1982).
 surrounding the Fe and Mn atoms in the NEe-FeMn ‘12.mble of Pe7iodic Pmpe7ties
 of the Elements
 bilayers-a (Sargent-Welch Sdentik Company,SKOkie,Illinois,
 1980).

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