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The microscopic origin of the uncompensated antiferromagnetic (AFM) spins was investigated by means of the x-ray magnetic circular dichroism (XMCD) spectroscopy with transmission mode for Mn–Ir/ferromagnetic (FM) bilayers. As the AFM layer thickness increases, resonant absorption magnitude of Mn *L* edge naturally increases, but the XMCD magnitude does not change so much. When the FM layer material is modified, the XMCD signal of Mn *L* edge drastically changes not only in its magnitude but also in its sign. The XMCD signal vanishes without the FM layer. These facts clearly mean that the uncompensated Mn components are induced through the exchange interaction between the FM and the AFM layers and are localized at the very interface. Micromagnetic simulation within the framework of the classical Heisenberg model well supported the above conclusion. © *2007 American Institute of Physics*. [DOI: 10.1063/1.2710216]

Exchange anisotropy[1,2] of ferromagnetic (FM)/antiferromagnetic (AFM) bilayers is an indispensable physical phenomenon for the realization of high-density magnetic storage devices such as hard disk drives (HDDs) and magnetic random access memories (MRAMs). While the microscopic mechanism of the exchange anisotropy has been the subject of extensive studies, it is not yet fully understood. The lacking information to clarify the mechanism is the asymmetry of spin structure in the bilayer system, which is obviously needed to provide exchange anisotropy, against the reversal of the practical external magnetic field. As the only candidate that mediates the spin motion from the FM layer to the AFM layer under the magnetic field reversal, the uncompensated AFM spins might play a key role on the magnetization process of the AFM layer and likely be a clue to investigate the asymmetric spin structure formed in the AFM layer. X-ray magnetic circular dichroism (XMCD) is a powerful tool to detect the uncompensated AFM spins because of its element specifiability and excellent sensitivity.[3–6] We thus studied the microscopic origin of the uncompensated AFM spins by means of XMCD spectroscopy with transmission mode in Mn–Ir based exchange biased bilayers, which are widely used for the application of HDDs and MRAMs nowadays.

The specimens were deposited on 125-nm-thick Si–N membrane substrates held at room temperature (RT) with a substrate/Ta(4)/Ru(5)/$Mn_{73}Ir_{27}(d_{AF})$/FM(d_F)/Ru(1)/Ta(1) design (thickness units in nanometers) by magnetron sputtering. For the case of FM=$Co_{70}Fe_{30}$, d_F was fixed at 2.5 nm and d_{AF} was changed from 0.5 to 20 nm. With fixing d_{AF} =10 nm, the FM layer was modified as $Co_{70}Fe_{30}$ (d_F =2.5 nm), $Co_{90}Fe_{10}$ (d_F=2.5 nm), Fe (d_F=4 nm), and $Ni_{80}Fe_{20}$ (d_F=4 nm). For the purpose of structural characterization, identically structured films were also fabricated on thermally oxidized Si wafers. After breaking the vacuum, in order to induce exchange bias, the specimens were annealed at 250 °C for 1 h and were then cooled to RT under a vacuum pressure less than 5×10^{-6} Torr with an external magnetic field of 1 kOe. The microstructural characteristics of the specimens were studied by x-ray diffraction with a Cu $K\alpha$ radiation source and was found that the Mn–Ir layer has preferred fcc(111) orientation parallel to the film surface.

X-ray absorption spectra (XAS) were obtained by recording the x-ray intensity ratio of the transmission to the incidence as a function of x-ray energy. Compared to the generally used total electron yield method, the transmission method is less sensitive to artifacts owing to the magnetic field applied to specimens, and so is favorable for studying weak XMCD signals from uncompensated AFM spins. XMCD was obtained using a 1 Hz helicity switching technique with left and right circularly polarized x rays with a degree of circular polarization of $p=\pm0.96$ from the twin helical undulators at BL25SU of SPring-8.[7] The incident x-ray intensity I_0 and the transmitted intensity I were monitored as the total electron yield current of a 300-nm-thick Si–C membrane placed upstream of the x ray and as that of a gold thin film placed downstream of the x ray, respectively. The x ray was incident on the sample surface at an angle of 30° and a magnetic field of up to ±14 kOe was applied using

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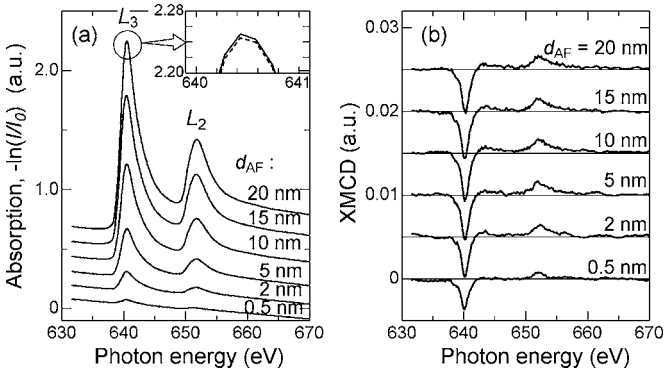

FIG. 1. (a) XAS and (b) XMCD spectra at the Mn $L_{2,3}$ edges in the Mn–Ir(d_{AF})/$Co_{70}Fe_{30}$(2.5 nm) bilayers. The spectra are vertically shifted to be distinguished from each other. The thin horizontal lines accompanied with the XMCD spectra indicate base (XMCD=0) lines.

an electromagnet along the axis rising 20° from the sample surface in the plane including the normal vector of the film surface and the exchange bias direction.[8] A near parallel configuration between the x-ray wave vector and the exchange bias direction was employed. All measurements were performed at RT.

Figure 1 shows (a) XAS and (b) XMCD spectra at the Mn $L_{2,3}$ edges measured for Mn–Ir(d_{AF})/$Co_{70}Fe_{30}$(2.5 nm) bilayers. Because of the small difference of x-ray absorption intensities (=XMCD), both the XAS for the respective helicity are superposed and hard to be distinguished from each other, though they are plotted in Fig. 1(a) with solid and broken lines. However, the difference certainly exists as shown in the inset of Fig. 1(a) and nonzero signals are obtained as XMCD spectra in Fig. 1(b) for the bilayers with the respective d_{AF}. It clearly indicates the existence of uncompensated AFM component in the present bilayers. As d_{AF} increases, resonant absorption magnitude at the respective L edge naturally increases in Fig. 1(a). On the other hand, the XMCD magnitude at the respective resonant peak does not change so much. This experimental fact implies that the uncompensated AFM components resulting in the XMCD signal are not homogeneously in the whole AFM layer and might be localized at the interface. In order to confirm this fact quantitatively, the XMCD magnitude at the L_3 edge was normalized by the resonant absorption magnitude at the same edge and plotted in Fig. 2 as a function of d_{AF}. Similarly, normalized Co XMCD magnitude at the L_3 edge was also plotted in the figure. In contrast to the almost constant magnitude of Co XMCD against d_{AF}, Mn XMCD magnitude shows a linear relation to the d_{AF} with a slope of −1 in the log-log plot. The important point to be noticed here is that even the specimen with d_{AF}=0.5 nm [2.3 ML (monolayer)] almost satisfies this linear relationship. It means that the uncompensated Mn component is localized at the very interface less than a few ML. Taking into account that the uncompensated Mn moment in the specimen with d_{AF}=10 nm is evaluated as $0.02\mu_B$ with applying magneto-optical sum rules,[8] we can convert the magnitude of Mn XMCD extrapolated to 1 ML in Fig. 2 as $0.9\mu_B$. It is about 40% of atomic moment of Mn in bulk $Mn_{75}Ir_{25}$ alloys ($2.5\mu_B$).[9]

Figure 3 shows (a) XAS and (b) XMCD spectra at the Mn $L_{2,3}$ edges measured for Mn–Ir(10 nm)/FM(d_F) bilay-

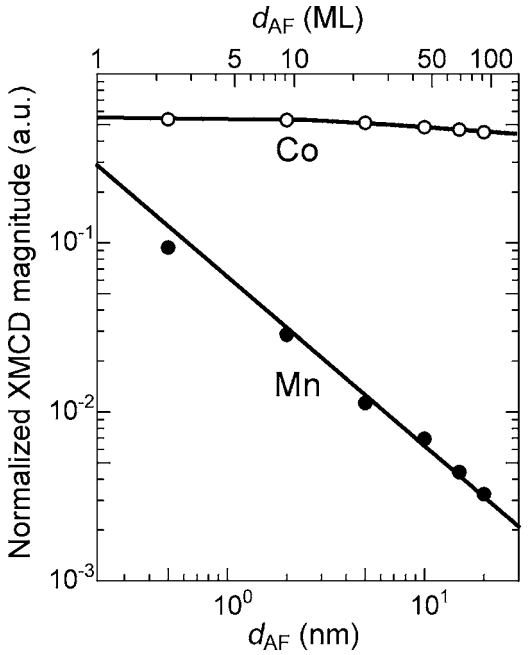

FIG. 2. XMCD magnitude normalized by absorption intensity at the respective L_3 edge of Mn and Co for Mn–Ir(d_{AF})/Co–Fe(2.5 nm) bilayers as a function of d_{AF}.

ers. While the XAS do not change so much as the FM layer material is modified, the XMCD spectrum drastically changes. In particular, for the case of "without FM," namely, the case of the Ru(1)/Ta(1) capping layer was directly deposited on the Mn–Ir layer, the XMCD signal is not observed at all. This fact means that the uncompensated Mn components are induced at the interface through the exchange interaction between the FM and the AFM layers. When the FM layers is modified, the XMCD signal is changed not only in its magnitude but also in its sign. For the case of FM=Fe, the sign of XMCD signal at the L_3 edge is reversed to be positive; this indicates that the uncompensated Mn moments are coupled antiparallel to the Fe moments at the interface. From the results in Fig. 3, we can say that the exchange interaction at the interface dominates the uncompensated AFM spins.

In order to give a theoretical interpretation to the depth dependence shown in Fig. 2, a micromagnetics simulation within the framework of the classical Heisenberg model was

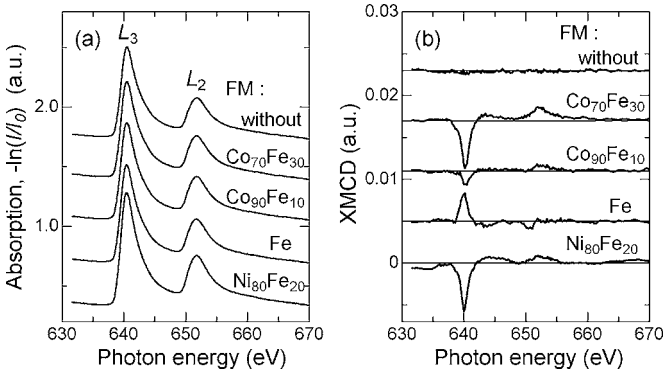

FIG. 3. (a) XAS and (b) XMCD spectra at the Mn $L_{2,3}$ edges in the Mn–Ir(10 nm)/FM (d_F) bilayers. d_F=2.5 nm for FM=$Co_{70}Fe_{30}$ and $Co_{90}Fe_{10}$. d_F=4 nm for FM=Fe and $Ni_{80}Fe_{20}$. The spectra are vertically shifted to be distinguished from each other. The thin horizontal lines accompanied with the XMCD spectra indicate base (XMCD=0) lines.

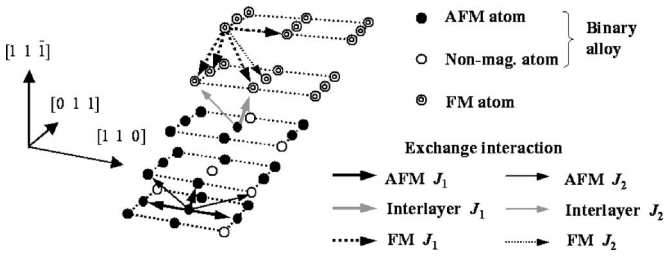

FIG. 4. The atomic configuration near the interface of the FM/AFM bilayer model.

performed. The atomic configuration of the calculation model is illustrated in Fig. 4. The bilayer is stacked to the fcc(111) orientation and the thicknesses of FM and AFM layers are 9 and 40 ML, respectively. The interface is atomically flat. The calculated region includes 24×24 atom in each ML and the periodic boundary condition is applied to the in-plane direction of the layered film. In the AFM layer, all the atomic sites are randomly occupied by 75% magnetic atoms and 25% nonmagnetic atoms. The following Hamiltonian is evaluated in the numerical calculations:

$$H = -\sum_{\langle i,j\rangle} J_{1ij}\boldsymbol{S}_i\cdot\boldsymbol{S}_j - \sum_{\langle i,k\rangle} J_{2ik}\boldsymbol{S}_i\cdot\boldsymbol{S}_k - \sum_i D_i(\boldsymbol{S}_i\cdot\boldsymbol{n})^2 - g\mu_B\sum_i \boldsymbol{S}_i\cdot\boldsymbol{H}, \quad (1)$$

where $\boldsymbol{S}_i$ is the unit vector of the spin at the ith magnetic atom, and the summation is carried out over all possible spin pairs by using exchange constants J_1 and J_2. The values of J_1 are assumed to be 20 meV in the FM layer and −20 meV in the AFM layer and at the interface. The value of J_2 is given by $|J_1|/2$. The third and fourth terms in Eq. (1) describe the magnetic anisotropy energy and the Zeeman energy, respectively. First, the spin structure was determined for single layered AFM by the Monte Carlo calculation. Then, the FM layer was attached on it, and the whole spin structure of the bilayer was determined by solving the Landau-Lifshitz motion equation under the external magnetic field of 10 kOe along the x ([−1,1,0]) direction. The detailed calculation procedure is described in Refs. 10 and 11.

The calculated spin component along the x direction, S_x, was averaged for each four equivalent atomic sites in each stacked plane. It is plotted as a depth profile in Fig. 5(a). Total spin vectors were summed up in the each stacked AFM plane and the resultant uncompensated AFM spin components along the x, y ([−1,−1,2]), and z ([1,1,1]) directions (s_x, s_y, and s_z, respectively) were determined. They are shown in Fig. 5(b). Near the bottom of the AFM layer (depth ~40 ML), where the interface without FM layer is simulated, the AFM spin direction in the each equivalent atomic site is uniform from the bottom to deep inside of the AFM layer. Every two AFM spins in different sites show the correlation angle of 90°–120° (not shown), which means the formation of noncollinear triple-Q spin structure expected in bulk $Mn_{75}Ir_{25}$ alloys.[12] Thus, the uncompensated component is almost zero at the every depth. On the other hand, near the interface (depth ~0 ML) between the FM layer and the AFM layer, AFM spin structure is modified as shown by bending S_x and a significant uncompensated component is induced in

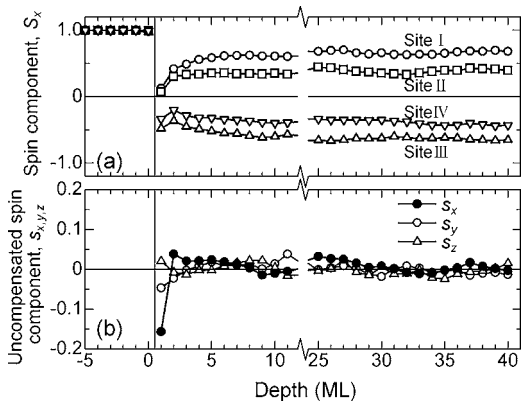

FIG. 5. Depth profiles of (a) spin component along the x ([−1,1,0]) direction, averaged over the equivalent atomic site (I-IV) in each stacked plane, and (b) uncompensated AFM spin components along the x, y, and z ([−1,1,0], [−1,−1,2], and [1,1,1]) directions, calculated for an AFM(40 ML)/FM(9 ML) bilayer. The depth from negative to 0 corresponds to the FM layer and positive corresponds to the AFM layer.

the opposite sign to the FM spin at the very interface (depth =1 ML). Since the atomically flat interface was assumed, this uncompensated spin inducement is purely an interfacial effect and not an alloying effect. The induced magnitude of the uncompensated spin component, s_x, at the interface is about 15% of the AFM spin. It well agrees with the experimental findings in Fig. 2 within an order of magnitude. If we assume other J_1 and J_2 values at the interface for the simulation, the variation of the magnitude and the sign of uncompensated spins, as observed in Fig. 3, might be explained.

From all the experimental and calculation results, we conclude that the uncompensated Mn components are induced through the exchange interaction between the FM and the AFM layers and are localized at the very interface.

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