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Magnetocrystalline anisotropy of $L1_0$-ordered FePt thin films studied by Fe L-edge magnetic field angle-dependent x-ray magnetic circular dichroicsm

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1 Introduction

Recently, magnetic recording media with higher recording density have been required, and materials with strong perpendicular magnetic anisotropy (PMA) have been studied intensively. $L1_0$-ordered FePt is well known as a candidate material because of its large magnetic anisotropy energy (MAE) of about to 7×10^7 erg/cc. For $L1_0$-ordered FePt, the MAE can be modified by changing the degree of long-range chemical order S. Seki *et al.* have shown that this S can be controlled by deposition and annealing temperatures [1]. Despite its importance, the origin of the PMA of $L1_0$-ordered FePt is still not understood.

Bruno [2] has derived a simple relationship that the MAE is proportional to the difference of the orbital magnetic moments between the magnetic hard and easy axis by perturbation theory with respect to spin-orbit coupling within the tight-binding approximation. Beside this calculation, van der Laan [3] has derived another term that has been ignored by Bruno. This term is proportional to the anisotropy of spin-density distribution, namely, the magnetic dipole term. In the following, we refer to the first term, which has been discovered by Bruno, the spin-conservation term, and the second term, which has been pointed out by van der Laan, the spin-flip term after the spin direction of virtual states in perturbation theory. From the first-principles calculation study of the MAE of $L1_0$-ordered FePt, Solovyev *et al.* have indicated that not only the Fe 3*d* orbitals but also the Pt 5*d* orbitals contribute to the MAE [4]. Their calculation has shown that the relationship between the orbital magnetic moment anisotropy and the MAE contradicts the Bruno's relationship both at the Fe and Pt sites. To resolve this issue, we have investigated the spin-conservation term at the Fe and Pt sites, and concluded that the spin-conservation term cannot be the origin of its large PMA [5], consistent with the Solovyev's study. Then, our next purpose is to clarify the role of the spin-flip term and attempt to understand the origin of the MAE of $L1_0$-ordered FePt.

In this work, we have performed magnetic field angle-dependent x-ray magnetic circular dichroism (XMCD) measurements of FePt thin films at the Fe $L_{2,3}$-edge to obtain the magnetic dipole term experimentally and to evaluate the contribution of the spin-flip term to the MAE.

2 Experiment

FePt thin films were grown on MgO (100) substrates by the ultrahigh vacuum magnetron sputtering method. The structure of the sample was MgO subs./Fe (1nm)/Au (30nm)/FePt (20nm)/Au (2nm). The deposition temperature (T_S) and annealing temperature (T_A) ranged from room temperature (R.T.) to 500 ºC (see Table 1).

Magnetic field angle-dependent XMCD measurement is an XMCD measurement with changing the magnetic field direction while fixing the x-ray incident direction. From magnetic field angle-dependent XMCD measurement, one can obtain the uniaxial MAE K_u as well as the magnetic dipole term (Q_{zz}) [6]. In this study, we have performed this measurement in order to deduce the magnetic dipole term of the Fe sites in $L1_0$-ordered FePt samples with various degrees of long-range chemical order S. For this measurement, we have employed a vector XMCD apparatus at KEK-PF BL-16A2.

Table 1: Sample preparation conditions and the degree of long-range chemical order S of each sample.

T_S (ºC)	T_A (ºC)	S
R.T.	-	0
300	350	0.3
300	500	0.4

3 Results and Discussion

Figure 1 shows that the magnetic field angle-dependent XMCD spectra of the sample with S=0.4. Here, we defined θ_H as the angle measured from the sample normal to the magnetic-field angle and the magnitude of magnetic field were below 1T. The incident x-ray direction was 30 degree. One can observe that the XMCD spectrum changes its sign with the magnetic-field angle. Figure 2 shows that the magnetic field angle dependence of the effective spin magnetic moments at the Fe site for various S. Dashed line is the fitting of the magnetic field angle dependence of the effective spin magnetic moment assuming the Stoner-Wohlfarth model. From this fit, one can deduce the magnetic dipole term of each sample. Figure 3 shows the deduced quadrupole Q_{zz} comprising

the magnetic dipole term plotted against S. The negative value of Q_{zz} indicates that the orbitals having spin magnetic moment are elongated along the z direction, and this tendency was enhanced with increasing S. We deduced the contributions of the spin-conservation term and the spin-flip term of the Fe site to the MAE and the summation of these two terms, as plotted against S in Fig.4. The contribution of the spin-flip term shows an opposite contribution to the PMA, and its magnitude is larger than spin-conservation term which favors the PMA. Totally, the contribution to the MAE from the Fe site is opposite to the PMA. This tendency is consistent with the first-principles calculation done by Solovyev *et al.*[4]. We, therefore, speculate that the the spin-flit term at the Pt site makes the dominant contribution to the PMA of $L1_0$-ordered FePt.

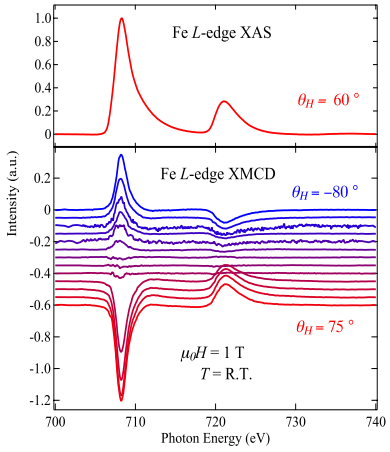

Fig. 1: Magnetic field-angle dependent x-ray magnetic circular dichroism spectra of $L1_0$-odered FePt at the Fe $L_{2,3}$ edge.

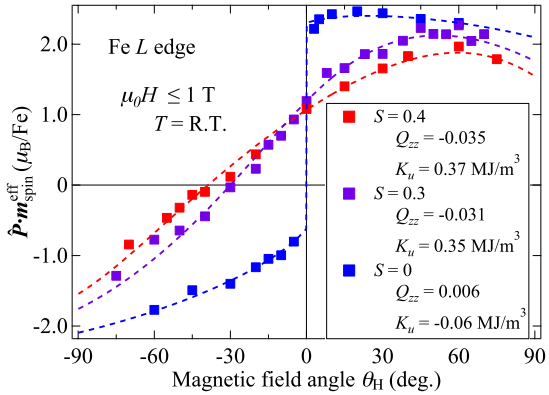

Fig. 2: Effective spin magnetic moment of Fe against the magnetic field angle θ_H. The samples with S=0.4 and 0.3 show the perpendicular magnetic anisotropy and S=0 shows in-plane magnetic easy axis originating from shape anisotropy.

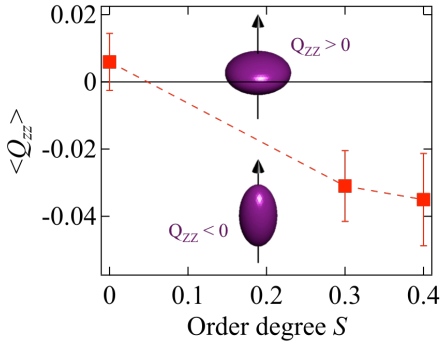

Fig. 3: Quadrupole Q_{zz} at the Fe site, which is proportional to the magnetic dipole, plotted against S. The Q_{zz} shows a negative value and its magnitude increases with the S.

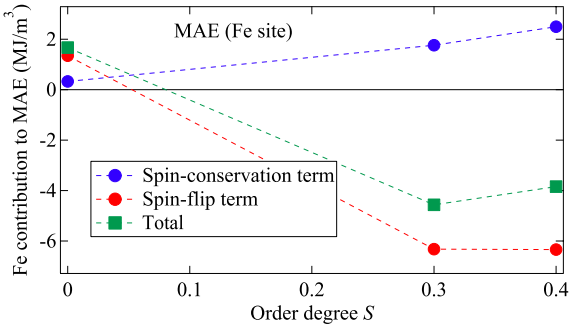

Fig. 4: Magnetic anisotropy energy of the Fe site, decomposed into the spin-conservation and spin–flip terms, and their summation, plotted against S. The total contribution shows a negative value mainly originating from the spin-flip term, indicating that the contribution of the Fe site is opposite to the perpendicular magnetic anisotropy.

References

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Research Achievements

1. JSR2018 students awards

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