

## Perpendicular magnetization of $L1_0$ -ordered FePt films in the thinnest limit

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$L1_0$ -ordered FePt ultrathin films with thickness down to subnanometer range were fabricated by alternate monatomic layer (ML) deposition of Fe and Pt on Pt (001) substrate and were capped by Pt. Perpendicular Fe magnetic moment under magnetic field, together with that under remanence, was detected by soft x-ray magnetic circular dichroism. Pt/(Fe 1 ML/Pt 1 ML)<sub>3</sub>/Pt (001), whose FePt layer is  $\sim 1$  nm thick, showed perpendicular remanent magnetization at room temperature. At low temperatures, perpendicular remanent magnetization was found even at the thinnest end, i.e., 1 ML Fe sandwiched by Pt (001). © 2007 American Institute of Physics. [DOI: 10.1063/1.2717516]

Thin films of  $L1_0$ -ordered FePt have attracted much interest because the perpendicular magnetization is expected to open up such applications as ultrahigh-density magnetic storage media and spintronic device components.<sup>1–15</sup> In the course of such applications, it is crucial how thin the magnetic layer can be made keeping the room-temperature perpendicular magnetization. Since ferromagnetism is a collective phenomenon, it could be diminished when the thickness is reduced, leading to lower Curie temperatures and possibly to the disappearance of perpendicular magnetization even in the ferromagnetic phase.

In order to determine the thinnest limit for  $L1_0$ -ordered FePt films to have perpendicular magnetization, ultrathin films of FePt sandwiched by Pt were fabricated by alternate monatomic layer (ML) deposition of Fe and Pt. This deposition method has realized  $L1_0$ -ordered FePt films with the degree of long range chemical order of  $S=0.8\pm 0.1$ .<sup>8</sup> When the thickness of the magnetic layer is as thin as a few ML, it is extremely difficult to measure magnetization precisely by conventional techniques such as superconducting quantum interference device because of a large background due to substrate. Therefore, we have utilized soft x-ray magnetic circular dichroism<sup>16–18</sup> of the Fe  $2p \rightarrow 3d$  photoabsorption (Fe  $2p \rightarrow 3d$  XMCD), which can yield accurate Fe  $3d$  magnetic moment even for Fe coverage of below 1 ML.<sup>19</sup>

The samples, Pt/(Fe 1 ML/Pt 1 ML)<sub>*n*</sub>/Pt(001), were prepared by a UHV deposition system with two independent *e* guns.<sup>8,20</sup> The thickness *n* was varied between one and ten. An Fe seed layer of 1 nm was deposited on a MgO (001) substrate, and an epitaxial Pt (001) buffer layer of 40 nm was grown at 70 °C and was annealed at 230 °C. Monatomic layers of Fe (0.14 nm) and Pt (0.20 nm) were deposited alternately at a constant substrate temperature of 230 °C. Finally a Pt (001) cap layer of 1 nm was grown at 70 °C.

$L1_0$  order of the *n*=10 sample was confirmed by clear  $L1_0$ -FePt (001) and (003) peaks in x-ray diffraction, based on which the degree of chemical order was estimated as  $S=0.6\pm 0.1$ . The magnitude of the reflection high energy

electron diffraction oscillation during the sample growth was essentially constant in the thickness range of  $1 \leq n \leq 20$ , which suggests that, in all samples, *S* was maintained almost the same as the *n*=10 sample.

Fe  $2p \rightarrow 3d$  XMCD was measured in the Faraday configuration at BL25SU of SPring-8 (Ref. 21) by the total electron yield method. The magnetic field was applied perpendicularly to the sample films. The XMCD spectrum was measured, either under magnetic field or in the remanent magnetization condition, by switching the photon spin of the incident light between +1 and -1. XMCD spectrum is defined as  $I_+ - I_-$ , where  $I_+$  and  $I_-$  denote photoabsorption spectra (XAS) with the photon spin parallel and antiparallel to the magnetic field.

As an example, XAS and XMCD spectra of *n*=1, i.e., Pt/Fe 1ML/Pt(001), are shown in Fig. 1(a). Magnetic moments due to spin and orbital angular momenta,  $\mu_{\text{spin}}$  and  $\mu_{\text{orbital}}$  are estimated by applying the XMCD sum rules<sup>22,23</sup> to the spectra. The Fe  $3d$  total magnetic moment is defined by  $\mu_{\text{spin}} + \mu_{\text{orbital}}$ . In the sum rules,  $I_+$  and  $I_-$  are integrated over  $2p_{3/2} \rightarrow 3d$  and  $2p_{1/2} \rightarrow 3d$  absorption regions which are set from  $E_{3/2} - 5.0$  to  $E_{3/2} + 10.0$  eV and from  $E_{3/2} + 10.0$  to  $E_{3/2} + 31.4$  eV, respectively, where  $E_{3/2}$  represents the energy of the  $2p_{3/2} \rightarrow 3d$  peak of  $(I_+ + I_-)/2$ . The background for *n*=1 subtracted from  $I_+$  and  $I_-$  before integration is shown in Fig. 1(a) and similar backgrounds are assumed for all samples. The Fe  $3d$  electron number  $n_{3d}$  is assumed to be 6.61, the same as Fe metal.<sup>24</sup> The contribution to  $\mu_{\text{spin}}$  from the magnetic dipole term  $T_z$  (Ref. 23) is tentatively neglected.

In Fig. 2 is shown the temperature and thickness dependence of the perpendicular Fe  $3d$  magnetic moment in Pt/(Fe 1 ML/Pt 1 ML)<sub>*n*</sub>/Pt(100) under 1.4 T (a) and under remanent magnetization (b). In the latter, samples were first subjected to a magnetic field of 1.4 T and were measured without magnetic field. The drastic decrease from *n*=2 to 1 of the moment at room temperature (RT) under 1.4 T [see Fig. 2(a)] might suggest that the Curie temperature ( $T_C$ ) is above RT for  $n \geq 2$  and below RT for *n*=1. On the other hand, the perpendicular remanent magnetization at RT reaches zero already at *n*=2. Let us define the temperature under which perpendicular remanent magnetization drastically increases as  $T_{\text{rem}}$ .  $T_{\text{rem}}$  is between 250 and 300 K for *n*=2 and  $T_{\text{rem}} \sim 160$  K for *n*=1. These results, characterized

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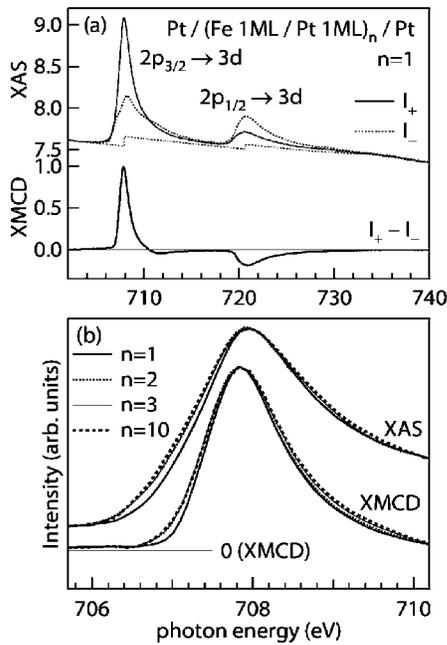


FIG. 1. Fe  $2p \rightarrow 3d$  XMCD spectra of Pt/(Fe 1 ML/Pt 1 ML) $_n$ /Pt (001). (a) That for  $n=1$ , i.e., Pt/Fe 1 ML/Pt (001), under 1.9 T at 25 K. In the top part, XAS with magnetization parallel and antiparallel to the photon spin,  $I_+$  and  $I_-$ , respectively, are shown. In the bottom part, the XMCD spectrum  $I_+ - I_-$  is shown. (b) Thickness  $n$  dependence of the averaged XAS  $(I_+ + I_-)/2$  and XMCD spectra around the  $2p_{3/2} \rightarrow 3d$  peak. The spectra were aligned with respect to photon energy at the peak position of XMCD. For closer comparison, XAS and XMCD intensities are arbitrarily scaled. From XAS, linear backgrounds are subtracted additionally. The data for  $n=1$  are from the same measurement as (a). Applied magnetic field and temperature were 1.4 T and 40 K, respectively, for  $n=2$  and 3, and 1.4 T and 300 K, respectively, for  $n=10$ .

by the lowering of both  $T_C$  and  $T_{\text{rem}}$  with the reduction of thickness  $n$ , agrees well to the expectation that ferromagnetism should be weakened as the thickness is reduced.

A possible mechanism for the absence of remanent magnetization between  $T_{\text{rem}}$  and  $T_C$  is the formation of stripe

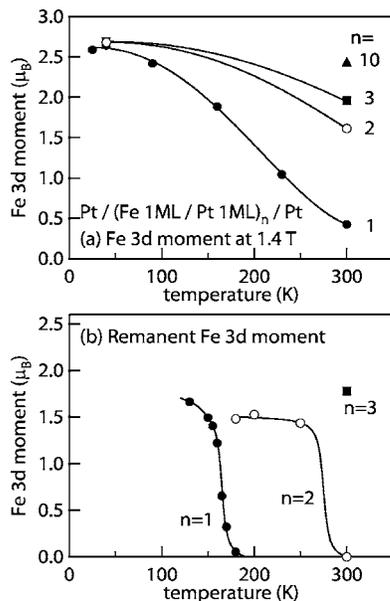


FIG. 2. Temperature and thickness dependence of the perpendicular Fe 3d magnetic moment per atom in Pt/(Fe 1 ML/Pt 1 ML) $_n$ /Pt(100) (a) under 1.4 T and (b) under remanent magnetization. Markers represent the measured values and the solid lines are guides for the eyes.

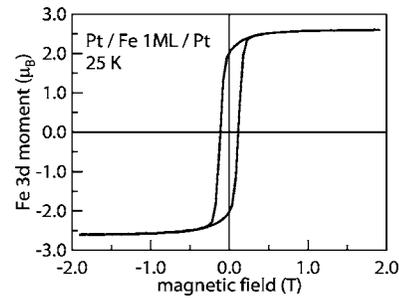


FIG. 3. Magnetization hysteresis loop of  $n=1$  sample, i.e., Pt/Fe 1 ML/Pt (001) at 25 K obtained by magnetic field dependence of the XMCD intensity at the  $2p_{3/2}$  peak.

domains characteristic of perpendicular magnetization. One cannot exclude other possibilities such as the spin reorientation transition to in-plane magnetization. In order to clarify the actual mechanism, it will be necessary to investigate magnetic domain structures by such methods as XMCD microscopy.

Perpendicular remanent magnetization of Pt/Fe 1 ML/Pt (001) in low temperatures is confirmed by the hysteresis loop at 25 K shown in Fig. 3, which is characterized by the perpendicular remanent magnetization of about 80% of the saturation and coercivity of about 0.1 T. This indicates that the perpendicular magnetic anisotropy remains significant even in Pt/Fe 1 ML/Pt (001). We therefore consider that the origin of the perpendicular magnetic anisotropy of  $L1_0$  FePt depends essentially upon the electronic states of a single monatomic Fe layer sandwiched by Pt layers.

The observed Fe 3d magnetic moment of  $2.6\mu_B - 2.7\mu_B$  in low temperatures [see Fig. 2(a)] is very near to the reported Fe magnetic moment in the bulk  $L1_0$ -ordered FePt of  $2.8\mu_B$  obtained by neutron diffraction.<sup>25</sup> Band structure calculation of  $L1_0$ -ordered FePt predicts Fe magnetic moment of  $3.0\mu_B$ .<sup>26</sup> The contribution of the orbital magnetic moment to the total moment,  $\mu_{\text{orbital}}/(\mu_{\text{spin}} + \mu_{\text{orbital}})$ , is found to be  $5 \pm 1\%$  for all studied  $n$ 's ( $n=1, 2, 3$ , and 10). This suggests that the Fe 3d electronic states do not depend strongly on  $n$ .

The XMCD spectra of intermetallic compounds usually reflect the spin polarization in the unoccupied Fe 3d electronic band structure.  $n$  dependence of both XAS and XMCD below  $T_C$  has been found to be very small. Detailed comparison of them in the  $2p_{3/2} \rightarrow 3d$  absorption region is shown in Fig. 1(b). Both XAS and XMCD become slightly wider from  $n=1$  to 10 but are essentially unchanged. Therefore, the Fe 3d band structure is essentially  $n$  independent.

In summary,  $L1_0$ -ordered FePt thin films down to subnanometer thickness sandwiched by Pt (001) were fabricated and were found to show perpendicular remanent magnetization. Pt/(Fe 1 ML/Pt 1 ML) $_3$ /Pt (001) was found to show perpendicular remanent magnetization at room temperature, which is expected to open up application in the field of magnetic storage and spintronics. Samples with thinner FePt layer showed perpendicular remanent magnetization in lower temperatures. Thickness dependence of perpendicular magnetization can be attributed to the lowering of  $T_C$  because ferromagnetism would be weakened due to the crossover from three dimensions to two dimensions. On the other hand, perpendicular magnetic anisotropy remains down to the thinnest end, as demonstrated by the hysteresis loop of Pt/Fe 1 ML/Pt(001). This indicates that the Fe 3d electronic states, which are the origin of the perpendicular magnetic anisotropy, are essentially  $n$  independent.

tropy of  $L1_0$  FePt, do not depend much on the thickness. Smallness of the thickness dependence of XMCD spectrum confirms the small thickness dependence of the Fe  $3d$  electronic states.

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