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.\(^5\) 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 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)/Pt (001), whose FePt layer is ~1 nm thick, showed perpendicular remanent magnetization at room temperature. At low temperatures, perpendicular remanent magnetization was found even at the thinnest limit, i.e., 1 ML Fe sandwiched by Pt (001). © 2007 American Institute of Physics. [DOI: 10.1063/1.2717516]
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 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 \( \text{Pt/Fe 1 ML/Pt} \) (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 \( \text{Pt/Fe 1 ML/Pt} \) (001). We therefore consider that the origin of the perpendicular magnetic anisotropy of \( L_{10} \) FePt depends essentially upon the electronic states of a single monatomic Fe layer sandwiched by Pt layers.

The observed Fe 3d magnetic moment of \( 2.6\mu_B \rightarrow 2.7\mu_B \) in low temperatures [see Fig. 2(a)] is very near to the reported Fe magnetic moment in the bulk \( L_{10} \)-ordered FePt of \( 2.8\mu_B \) obtained by neutron diffraction. Band structure calculation of \( L_{10} \)-ordered FePt predicts Fe magnetic moment of \( 3.0\mu_B \). The contribution of the orbital magnetic moment to the total moment, \( \mu_{\text{orbital}}/\mu_{\text{spin}} \), is found to be \( 5\pm1\% \) 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, \( L_{10} \)-ordered FePt thin films down to subnanometer thickness sandwiched by Pt (001) were fabricated and were found to show perpendicular remanent magnetization. \( \text{Pt/Fe 1 ML/Pt 1 ML}_{n} \) (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.

![FIG. 1. Fe 2p→3d XMCD spectra of Pt/(Fe 1 ML/Pt 1 ML)/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, \( I_\parallel \) and \( I_\perp \), respectively, are shown. In the bottom part, the XMCD spectrum \( I_\parallel - I_\perp \) is shown. (b) Thickness \( n \) dependence of the averaged XAS \( (I_\parallel + I_\perp)/2 \) 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 \( n=10 \).](image1)

![FIG. 2. Temperature and thickness dependence of the perpendicular Fe 3d magnetic moment per atom in Pt/(Fe 1 ML/Pt 1 ML)/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.](image2)

![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.](image3)
tropy of $L_1_0$ 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.

The authors would like to thank T. Muro and T. Nakamura of SPring-8/JASRI for their developing the XMCD measurement systems and for their support during the measurements. The authors are grateful to Y. Iguchi, T. Watanabe, and Y. Ishida for the assistance in the measurements and the analyses. This work is supported by Grant-in-Aids for COE Research (No. 10CE2004), for 21COE(G18) and for Scientific Research (No. 18360330) from MEXT and JSPS, Japan. Synchrotron radiation experiments at BL25SU, SPring-8 were performed with the approval of JASRI (Nos. 2002B0321, 2003A0673, and 2004A0450).