Highly coercive L1₀-FePd thin films grown on MgO single crystal substrates

M. Carbucicchio and R. Ciprian
Department of Physics, University of Parma, Parma, Italy
E-mail: massimo.carbucicchio@fis.unipr.it

Abstract. L1₀-ordered systems are of great interest from both the technological and research point of view since their high magnetocrystalline anisotropy makes them suitable candidates for future high density recording media. FePd and FePt are isostructural alloys that in their ordered phase show very different magnetic behaviour. In this work ultra-thin films of FePd and FePt films have been grown showing very hard magnetic properties. The coercivity of FePd films grown at 700°C reaches values well above 10 kOe much greater than that obtained in FePt films grown in the same conditions.

1. Introduction
In the last decades great attention has been given to the study of systems whose high temperature ordered phase is characterized by a tetragonal-L1₀ structure. A few examples are the FePt, CoPt and FePd alloys. During the ordering there is a lowering of symmetry resulting in an increase of the lattice periodicity along the slip direction and the establishing of a strong uniaxial anisotropy along the contracted c-axis [1]. A peculiarity of these systems in the form of thin films is the possibility to induce a strong perpendicular anisotropy by means of an epitaxial growth with the c-axis oriented along the perpendicular to the film plane [2]. Moreover by adjusting the growing parameter [3,4], by using suitable bufferlayers and by varying the thickness of the films [5], it is possible to tailor the magnetic properties of the systems allowing to satisfy different technological demands in the field of recording media, permanent magnets and micro-electromechanical systems.

Compared to FePt, the FePd system is characterized by a higher saturation magnetization, a lower order-disorder transition temperature, a lower perpendicular anisotropy (Kₚ ~ 2 × 3 × 10⁶ erg/cm³). Moreover, in the literature coercivities of a few hundreds of Oe are reported for FePd films [6,7], values which are much lower than those reported for FePt. The hysteresis loops generally show jumps of the magnetization which are to be ascribed to the competition between a strong demagnetizing field and the perpendicular anisotropy [8,9].

The comprehension of the causes of such different magnetic behaviour in systems that are very similar from the structural point of view is very important also in view of possible technological applications. With this aim, in the present work FePd thin films were epitaxially grown on monocry staline substrates at different temperatures. For comparison, FePt films with comparable thickness were also grown under the same conditions. The magnetic properties and morphology of the samples were analyzed by magneto-optical Kerr effect magnetometry and atomic force microscopy.
2. Experimental

Ultra-thin films of FePd and FePt were grown on MgO-(100) monocrystalline substrates in UHV using a molecular beam epitaxy system equipped with four e-beam evaporation guns. The high miscibility of the metals allows the growth of the alloys to be carried out by alternating the deposition of single elemental layers, and adjusting the relative thickness to obtain the desired composition. The formation of FePd and FePt alloys was confirmed by conversion electron Mössbauer spectroscopy.

The FePd thin films, 4.5 nm thick with 50 at.% Fe, were grown at room temperature, 300, 540 and 700°C. In the following these samples were indicated as RT-FePd, 3FePd, 5FePd, 7FePd respectively. The FePt films, 4.8 nm thick, were grown at 500 and 700°C, and indicated as 5FePt and 7FePt respectively. The growth rate was for all elements 0.4 nm/min. The thickness was measured in-situ by a quartz microbalance.

The magnetic properties were measured by a magneto-optical Kerr effect magnetometer (MOKE) using a s-polarized 633 nm laser light. The morphology of the samples was analyzed by means of an ultra-high vacuum atomic force microscopy system (AFM).

3. Results and Discussions

The hysteresis loops measured in polar geometry for the FePd films grown at room temperature and at 300°C are reported in figure 1. The RT-FePd sample shows magnetic properties typical of a soft ferromagnetic phase [figure 1(a)]. The low field necessary to reach the complete saturation indicates a tilting of the magnetic moments out of the film plane, suggesting the presence of a perpendicular contribution to the anisotropy. The tilting can be ascribed to the formation of a small amount of ordered L1₀-FePd compound, which can be due to the high interdiffusivity promoted by both the low thicknesses of the elemental layers and the low growth rates.

By increasing the growing temperature to 300°C, 3FePd film [figure 1(b)], both the coercivity and the demagnetizing field increase, the last lowering the perpendicular component of the anisotropy. The growing temperature induces an increase of the volume fraction of the FePd ordered phase giving rise to an increase of the hardness of the film. On the other hand the annealing temperature is not sufficient to induce a good (001) orientation of the c-axis.

For both RT-FePd and 3FePd samples, the x-ray diffraction patterns show a very broad peak which can be ascribed to the superposition of a main contribution from the (200) reflection of the disordered phase and a minor contribution from the (002) reflection of the L1₀ phase. By increasing the growing temperature, the contribution from the disordered phase disappears and a broad (001) superstructure peak appears. The broadening may well be connected to the very low thickness of the films.

The FePd film grown at 540°C, [figure 2(a)], shows a strong perpendicular anisotropy, a coercive field of about 2.2 kOe and a remanence to saturation ratio of about 90%. It is to be noted that the effects due to the demagnetizing fields are practically absent. This result is quite surprising considering that in the literature the FePd films are reported to show very low values of both coercivity and remanence. Moreover, the competition between perpendicular anisotropy and demagnetizing field gives rise to sharp jumps of magnetization at given applied fields [6-9].
By growing the FePd films at 700°C [figure 2(b)] a further enhancement of the magnetic hardness occurs. In effect for maximum applied fields of 15 kOe, only a minor loop can be measured. The coercive field reaches a value of 10.4 kOe and the squareness of the loop a value of 98%.

The first magnetization curves of 5FePd and 7FePd indicate that the coercivity of the samples is mainly controlled by the domain wall pinning mechanism. By increasing the growing temperature, this mechanism significantly strengthens as can be deduced by the well defined kink in the first magnetization curve of 7FePd sample. In effect, the magnetization remains practically zero until the applied field reaches the value of the coercive field, above which abruptly increases. To our knowledge, no data are reported in literature about coercive fields reaching so high values (> 10 kOe) for FePd samples, with the anisotropy field well overcoming the demagnetizing one.

The measurement of the minor loops obtained by recording the hysteresis loop for increasing maximum applied fields, can be helpful for evidencing the eventual presence in the sample of phases showing different magnetic hardness. The absence of kinks at low applied fields in the minor loops of both 5FePd and 7FePd samples [figure 2(c)] suggests that these films are magnetically homogeneous and constituted by only the hard L1₀ phase. This fact is also supported by the absence of magnetization recovery in the recoil curves, indicating that the moment reversal occurs only through irreversible switching of the magnetization.

Figure 2. Polar hysteresis loops of (a) 5FePd, and (b) 7FePd. (c) Minor loops of 7FePd sample.

Figure 3(a) shows the hysteresis loop measured for the FePt film grown at 500°C, 5FePt film. The sample shows a good perpendicular anisotropy, a high remanence to saturation ratio in spite of a very low coercive field of about 500 Oe. To be noted that at the same temperature of growth, a stronger perpendicular anisotropy and a better hardness \( H_c = 2.2 \text{ kOe} \) developed in 5FePd sample.

For the FePt films grown at 700°C [figure 3(b)], only a minor loop can be measured applying a maximum field of 15 kOe, as in the case of 7FePd sample. The coercive field is 9.5 kOe.

Figure 3. Polar hysteresis loops of (a) 5FePt and (b) 7FePt. (c) Minor loops of 7FePt.

The minor loops performed for 7FePt [figure 3(c)] show that coercivity linearly increases by increasing the maximum applied field and the normalized remanence is for each loop lower than 100%. This behaviour is different from that of 7FePd sample [figure 2(c)] where, applying an increasing external field, the coercivity remains constant up to ~ 5 kOe, and than, abruptly increases. The normalized remanence is 100% for each minor loop. These facts suggest that, for growing
temperature of 700°C, the domain wall pinning mechanism is stronger in FePd films (7FePd) than in the FePt samples (7FePt). This result is also evidenced by the comparison between their first magnetization curves [figures 2(b) and 3(b)].

Figure 4 reports the AFM images obtained for 7FePt, 5FePd and 7FePd samples. The FePt film grown at 700°C is constituted by very small particles [figure 4(a)] which are at the origin of its very hard magnetic properties.

![AFM images](image)

**Figure 4.** AFM images (500 × 500 nm) recorded for (a) 7FePt, (b) 5FePd and (c) 7FePd samples.

The FePd film grown at lower temperature, 5FePd sample, is characterized by a morphology constituted by nanometric islands intercalated by small droplets. By increasing the growing temperature to 700°C, the small droplets coalesce into islands elongated in shape showing a very regular pattern. For the FePd films, the increase of the magnetic hardness can be linked to the formation of well separated and regularly distributed islands that favour a decrease of the strength of the interparticle interactions.

4. Conclusions

FePd thin films, 4.5 nm thick, were grown on MgO monocrystalline substrates at different temperatures. By increasing the growing temperature to 700°C, the coercivity of the films increases reaching values well above 10 kOe. This is due to a strengthening of the domain wall pinning mechanism that controls the coercivity. The hardness and the loop squareness are comparable or greater than those of FePt thin films grown in the same conditions. In effect the domain wall pinning mechanism controlling the coercivity of both systems is stronger in the FePd films.

It is to be noted that while in the FePt films the increase of the growing temperature induces a morphology constituted by small particles, in FePd systems the growing temperature induces the coalescence of small droplets into elongated islands having a very regular configuration. The good separation among these islands can decrease the interparticle interactions increasing the coercivity.

References

[1] Gehanno V, Auric P, Marty A and Gilles B 1998 J. Magn. Magn. Mater. 188 310-8
[2] Cebollada A, Weller D, Sticht J, Harp G R, Farrow R F C, Marks R F, Savoy R and Scott J C 1994 Phys. Rev. B 50 3419-22
[3] Barmak K, Kim J, Lewis L H, Coffey K R, Toney M F, Kellock A J, and Thiele J U 2005 J. Appl. Phys. 98 33904(1-10)
[4] Spada F E, Parker F T, Platt C L and Howard J K 2003 J. Appl. Phys. 94 5123-34
[5] Ciprian R, Carbucicchio M and Turilli G 2009 Hyper. Inter. 191 33-40
[6] Sato K and Hirotsu Y 2003 J. Appl. Phys. 93 6291-8
[7] Pan F, Yang T, Zhang J and Liu B X 1993 J. Phys.: Condens. Matter 5 L507-14
[8] Ravelosa D, Cebollada A, Briones F, Diaz-Paniagua C, Hidalgo M A and Batallan F 1999 Phys. Rev. B 59 4322-26
[9] Klein O, Samson Y, Marty A, Guillou S, Viret M, Fermon C and Alloul H 2001 J. Appl. Phys. 89 6781-3