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Morphological and microstructural study of $L1_0$-ordered FePt and $L1_0$-FePt/Fe ultrathin films grown by UHV e-beam evaporation technique

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ABSTRACT

Ultrathin films of $L1_0$-ordered FePt alloy with different thickness were grown by UHV e-beam evaporation technique. In this ultrathin regime, the increase of the thickness induces a strong improvement of the magnetic properties followed by a decrease of the grain size. Starting from these hard layers, FePt/Fe/FePt trilayers with different thickness of the outermost layer have been grown. The samples show a single-phase magnetic behaviour and a strong perpendicular anisotropy thanks to the exchange-coupling that established at the soft/hard interfaces. By increasing the thickness of the outer layer, a strong reduction of the switching field distribution has been obtained with the appearance of a predominant exchange-type interaction among the magnetic grains. The morphology is characterized by well separated and elongated islands, while the magnetic pattern shows finely dispersed bubble domains.

1. Introduction

The structural and magnetic properties of thin $L1_0$-ordered FePt films have been intensively studied in the last few years. In effect in this ordered phase, FePt films can develop a strong perpendicular uniaxial magneto-crystalline anisotropy, making them promising candidate for future high-density magnetic storage media and permanent magnets [1–4]. In this regard, particular attention is addressed to the development of perpendicular exchange-spring magnets i.e. nanocomposites constituted by intercalated soft and hard magnetic phases, showing a single-phase magnetic behaviour, thanks to the exchange-coupling that establishes at the interface [5,6]. The combination of the high coercivity from the hard phase and the high saturation magnetization from the soft one allows high values of the maximum energy product to be obtained [7,8].

Despite the high number of works on this subject, many questions remain open in particular when the hard film is a few nanometers thick and the soft/hard thickness ratio is greater or equal to one. In effect, the ultrathin thickness of the hard phase can induce an improvement of the anisotropy strength, this way favouring the development of a good exchange-coupling with the soft phase.

The aim of the present work was (i) to study the effects on the magnetic properties of the thickness of $L1_0$–FePt ultrathin films and (ii) to investigate the possibility to realize ultrathin FePt/Fe perpendicular exchange-spring magnets. Both systems were obtained using an UHV e-beam evaporation technique, and studied by means of the X-ray diffraction (XRD), UHV atomic and magnetic force microscopy (AFM/MFM), and magneto-optical Kerr effect (MOKE) magnetometry.

2. Experimental

FePt films, 3.6 and 4.8 nm-thick [FePt(36) and FePt(48)], were e-beam evaporated in UHV (10^{-9} mbar) at 700 °C on MgO (1 0 0) monocrystalline substrates by alternating Fe and Pt layers 0.6 nm thick. The film thickness was measured "in situ" by an oscillating quartz microbalance.

Starting from the FePt(48), trilayers have been grown by depositing a 4.8 nm-thick Fe layer and an upper FePt layer 1.2 and 4.8 nm-thick [FePt(48)/Fe(48)/FePt(12) and FePt(48)/Fe(48)/FePt(48), respectively].

The morphology and the domain patterns were analyzed by UHV atomic and magnetic force microscopy in tapping mode, without breaking the vacuum, using cantilevers with non-magnetic and magnetic tips, respectively.

The X-ray diffraction patterns were recorded using a computer-controlled goniometer and CuKα radiation. The magnetic properties of the samples were measured using a magneto-optical Kerr effect magnetometer, with *s*-polarized 633 nm He–Ne laser light. In order to study the intergrain interactions, dc demagnetization (DCD) remanence and isothermal remanence (IRM) curves were

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collected. DCD remanence curves were recorded starting from a sample in the saturated state and then applying increasing negative fields. On the contrary for IRM remanence curves, the sample was initially demagnetized through successive minor loops and then subjected to increasing positive fields.

3. Results and discussion

Figs. 1(a) and (b) display the XRD patterns measured for FePt(36) and FePt(48), respectively. Both spectra show only the preferred (0 0 1) and (0 0 2) reflections typical of the $L1_0$-ordered FePt alloy epitaxially grown on (1 0 0)-MgO. It should be noted that by increasing the film thickness, the line width of both reflections decreases, indicating that an improvement in epitaxy occurred due to a lower dispersion of the contracted *c*-axis along the perpendicular to the film plane.

The very good structural order is proved by the high value of the order parameter which was evaluated to be 0.96 for both films. Moreover, the absence of significant difference in the peak positions in the XRD patterns of the films indicates that the tetragonal distortion of the lattice was unaffected by the film thickness.

The MOKE loops carried out in polar and longitudinal geometry for FePt(36) and FePt(48) films are reported in Figs. 2(a) and (b), respectively. The minor loops and the initial magnetization curves recorded in polar geometry are also reported.

In particular, the shape of the hysteresis loop measured for FePt(36) indicates that a strong perpendicular magneto-crystalline anisotropy developed as a consequence of a good epitaxial growth and chemical $L1_0$ order. The behaviour of the minor loops and the shape of the initial curve suggest that the domain wall pinning is the main mechanism controlling the coercivity. From the hysteresis loop obtained applying the maximum magnetic field of 15 kOe, a coercive field of 6.5 kOe was measured. The shape of this loop suggests that at 15 kOe the saturation magnetization is almost reached.

By increasing the film thickness up to 4.8 nm, a strong improvement of the magnetic hardness occurs, and only minor loops are allowed to be measured (Fig. 2(b)). A coercive field of 9.5 kOe was measured applying in polar geometry the maximum magnetic field of 15 kOe. The saturation magnetization, evaluated from the Kerr rotation, was 520 in respect to that of 750 emu/cm^3 evaluated for the FePt(36). This lower value of M_s is in agreement with the fact that the complete saturation can be reached only at much higher values of applied fields.

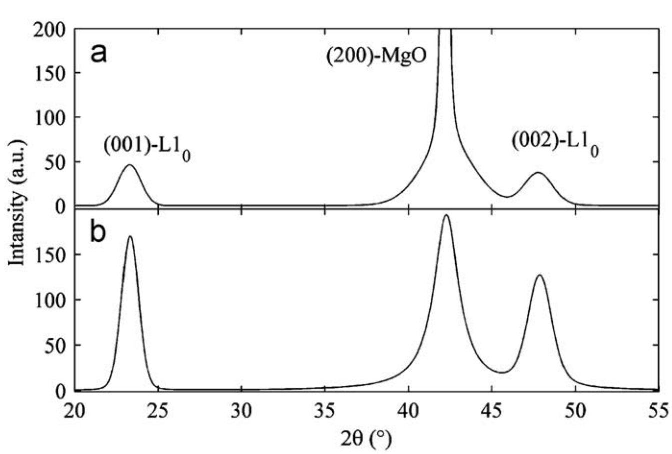

Fig. 1. The XRD patterns measured for (a) FePt(36) and (b) FePt(48).

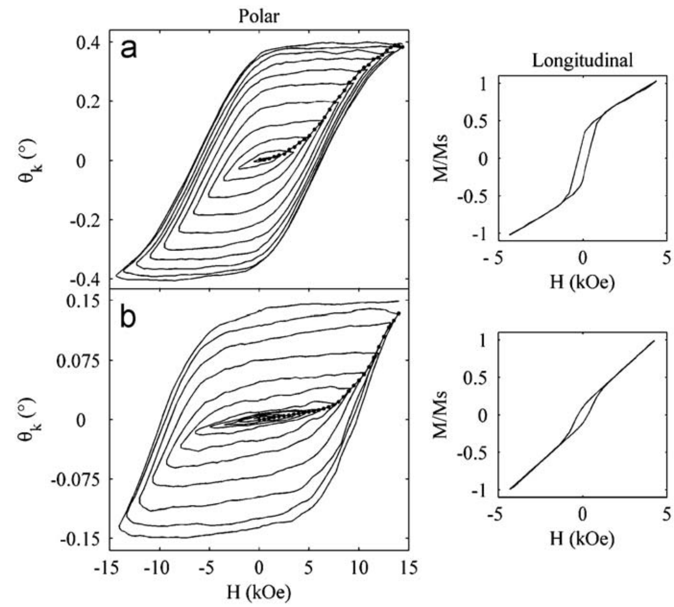

Fig. 2. The MOKE measurements in polar (—minor loops and ●●● initial magnetization curve) and longitudinal geometry for (a) FePt(36) and (b) FePt(48).

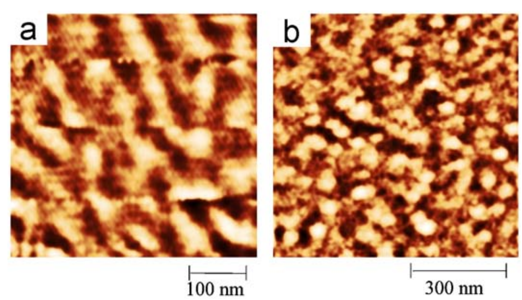

Fig. 3. The AFM images recorded for (a) FePt(36) and (b) FePt(48).

The first magnetization curve slowly rises with the applied magnetic field up to values closed to the coercive field, and then abruptly increases. This behaviour indicates that for the thicker film a relevant strengthening of the domain wall pinning occurred.

From the comparison between the longitudinal loops measured for FePt(36) and FePt(48), it follows that the last film grew with a better epitaxy and presents a very good orientation of the *c*-axis along the normal to the film surface.

The improvement of the magnetic hardness can be related to the film morphology. The AFM images for FePt(36) and FePt(48) films are reported in Figs. 3(a) and (b), respectively. Both films show an island-like pattern, but, contrary to what expected when increasing the film thickness, a reduction occurs of both the grain interconnection and the mean grain size. These facts may well cause the increase of coercivity of FePt(48) film.

Fig. 4 displays the MOKE measurements performed on FePt(48)/Fe(48)/FePt(12) trilayer. The minor loops and the initial magnetization curve, reported in Fig. 4(a), indicate that the trilayer is characterized by a strong perpendicular anisotropy and that, even for the maximum applied field of 15 kOe, no complete saturation was achieved. From the comparison with the measurements performed for the FePt(48) film (Fig. 2(b)), the trilayer shows a strong decrease of the squareness and of the coercive field (from 9.5 to 5.6 kOe) followed by an increase of the saturation magnetization (694 emu/cm^3 at 15 kOe applied field).