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Influence of the phenomena occurring at the interface between $L1_0$-ordered-FePt and Fe on the coercivity behavior

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Abstract $L1_0$-ordered FePt/Fe thin bi-layers were grown using a molecular beam epitaxy onto (100)-MgO substrates changing the soft Fe layer thickness. The study of the intermixing phenomena occurring at the hard/soft interfaces was carried out using surface Mössbauer spectroscopy. The magnetic properties of the samples were analyzed with a magneto-optical Kerr effect magnetometer. The surface morphology and the magnetic domains were analyzed with an UHV atomic and magnetic force microscopy in tapping and lift mode respectively.The present work clearly demonstrates that the degree of interface intermixing and reactions is the responsible for the coercivity behavior in exchange-spring magnets.

Keywords Exchange-spring magnets · Perpendicular anisotropy · $L1_0$ -ordered systems · Interface phenomena · Mössbauer spectroscopy

1 Introduction

Last generation of magnetic recording devices require materials characterized by large values of the maximum energy product $(BH)_{max}$, a parameter which represents the density of information that can be stored in a magnet. Moreover, the continuous reduction of the

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device sizes requires a fine control of the properties which arise due to surface and interface phenomena.

Suitable candidates as recording media are the exchange spring magnets i.e. nanocomposites constituted by a hard phase characterized by a large uniaxial anisotropy and a soft phase having a very large saturation magnetization. If a strong exchange coupling establishes at the interface between the different phases, the system can behave as a single-phase hard magnet [1–3]. This can be obtained by finely adjusting the growth parameters in order to preserve a good crystallographic coherence and adhesion between the different phases.

While from theoretical works, a decrease of coercivity has been normally predicted by increasing the soft layer thickness [2, 3], experimentally an initial slight increase in coercivity has been often found [4, 5]. In a recent work on exchange-spring magnets based on the fct-ordered FePd alloy [5] grown at different temperatures, the phenomena occurring at the hard/soft interfaces have been demonstrated to be responsible for this peculiar coercivity behavior.

In this work exchange-spring magnets based on FePt/Fe thin bi-layers were grown using a molecular beam epitaxy onto (100)-MgO substrates changing the soft Fe layer thickness. The study was carried out in order to analyze the phenomena influencing the coercivity behavior in a system characterized by a larger perpendicular anisotropy and magnetic hardness in comparison with that of FePd-based magnets. The study of the intermixing phenomena occurring at the hard/soft interfaces was carried out using surface Mössbauer spectroscopy (CEMS). For increasing the CEMS sensitivity to the compounds that eventually form at the interfaces, the FePt films were grown using natural iron, while iron highly enriched with ^{57}Fe isotope was used for the growth of soft layers.

2 Experimental

Almost equiatomic FePt thin films, 15 and 20 nm thick, were grown by means of a molecular beam epitaxy equipped with electron guns onto MgO-(100) monocrystalline substrates at 550°C. The growth proceeds alternating very thin layers of Fe and Pt, about 0.2 nm thick. The thickness was measured by means of an oscillating quartz microbalance. Energy dispersive x-rays spectroscopy indicates a mean composition of about 52at. % of Fe (± 2at. %), while x-ray diffraction measurements confirm the epitaxial growth of the ordered $L1_0$-FePt films with c-axis well oriented along the perpendicular to the film plane. In the following these samples were labeled as FePt(t) where t is the total film thickness in nm. On the top of these samples thin layers 7, 10 and 14 nm thick of Fe highly enriched with ^{57}Fe Mössbauer isotope have been grown at room temperature.

The phenomena occurring at the soft/hard interface have been studied using conversion electron Mössbauer spectroscopy (CEMS). A 50mCi ^{57}Co(Rh) source was used with the γ-rays incident at an angle of 7°from the normal to the sample surface. A least squares minimization routine with a combination of linear and non-linear regressions was used to fit the spectra as a superposition of Lorentzian lines. The isomer shifts were referred to α-Fe. The use of ^{57}Fe for the growth of the soft layer allows to increase the Mössbauer sensitivity to only the soft layer and to those compounds that eventually form at the Fe/FePt interface. The magnetic properties of the samples were analyzed with a magneto-optical Kerr effect (MOKE) magnetometer using a 635 nm He-Ne laser-light and the modulation-polarization technique. The surface morphology and the magnetic domains were analyzed with an UHV atomic and magnetic force microscopy (AFM/MFM) in tapping and lift mode respectively. For the MFM measurements the tip to sample distance was fixed at 30 nm.

3 Results and discussion

The magnetic properties of the FePt films 15 and 20 nm thick are typical of hard magnets characterized by a large perpendicular anisotropy (Fig. 1a and d black lines). The FePt(15) shows a squared-shaped out-of-plane hysteresis loop (Fig. 1a), and a dot-like morphology (Fig. 1b). The increase in the film thickness up to 20 nm determines a decrease of both the loop squareness and coercivity (Fig. 1d).

The surface morphology appreciably changes with the establishment of major islands probably due to the small-grain coalescence (Fig. 1e). The magnetic morphology for both FePt films is characterized by irregular labyrinth-like domains (Figs. 1c and f).

The bilayers obtained covering these hard films with a soft ^{57}Fe layer 7 nm thick show magnetic behaviors typical of a single-phase hard magnet (Fig. 1a and d, blue lines). This suggests that a good exchange-coupling interaction establishes at the soft/hard interfaces.

However, for the two systems, the coercivity behavior is completely different. As expected, for the Fe(7)/FePt(15), Fe gives rise to a significant decrease of the coercivity with respect to that of the hard FePt(15) film. On the contrary in the case of the Fe(7)/FePt(20), Fe determines an increase of the hard film coercivity, while the complete magnetization saturation is reached only for very large applied magnetic fields (Fig. 1d). Only for an Fe layer thickness higher than 10 nm the coercivity starts to decrease. The behavior of the coercivity for the two systems as a function of the soft layer thickness is summarized in Fig. 1(g).

The Mössbuer spectra for the two Fe(7)/FePt(t) bilayers are reported in Fig. 2a and b. They are due to the superposition of many contributions:

- a singlet α_{I} due to Fe in the form of superparamagnetic small particles,
- a doublet δ and a series of sextet ν showing a broad distribution of hyperfine magnetic fields. These contributions can be interpreted as due to an Fe-rich FePt compound [6, 7] having a broad distribution of particle sizes down to the superparamagnetic limit (δ doublet).

  These compounds, as in the case of the FePd systems [5], are due to the reaction of the deposited Fe with the FePt superparamagnetic small particles which form on top of the hard films. These superparamagnetic FePt small particles has been found contributing to the Mössbauer spectra (not reported) measured for similar FePt hard films grown with ^{57}Fe isotope.
- a sextet α due to the ferromagnetic α-Fe which is the prevailing contribution in the spectra of the Fe(7)/FePt(15) bilayer (Fig. 2a). This contribution is completely absent in the Fe(7)/FePt(20) bilayer spectrum (Fig. 2b).

The increase in the Fe thickness gives rise in Fe(14)/FePt(15) (Fig. 2c) to a significant increase of the amount of both superparamagnetic (α_{I} singlet) and ferromagnetic (α sextet) Fe, while the contribution due to Fe-rich FePt superparamagnetic small particles (δ-doublet) completely disappears. These facts suggest that (i) a further reaction of Fe with FePt superparamagnetic small particles is hindered and (ii) due to the increased amount of deposited iron, the Fe-rich FePt particles increase in size allowing the establishment of ferromagnetic properties, as deduced by the increase in the relative area of ν-sextets.

For the Fe(14)/FePt(20) bilayers (Fig. 2d) the contribution due to α-Fe becomes the predominant one while the relative areas of the other contributions remain almost the same as in the case of Fe(7)/FePt(20) (Fig. 2b). This is probably due to the surface of the hard

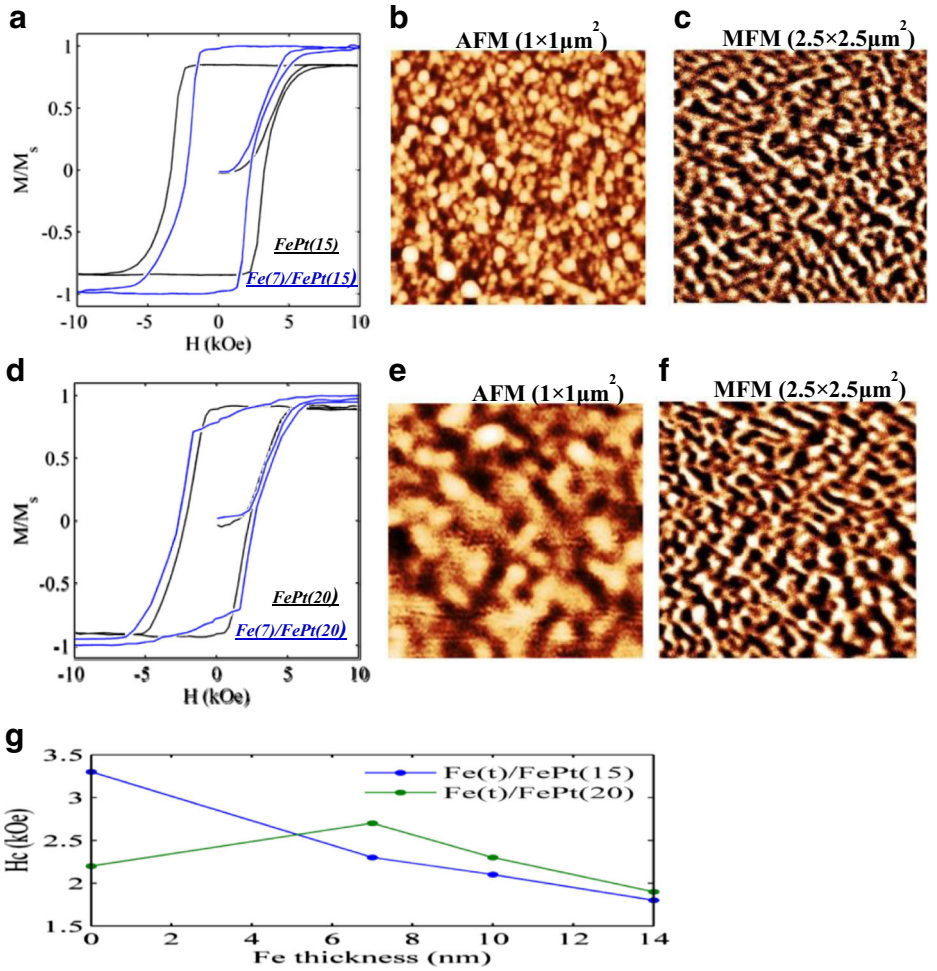

Fig. 1 Polar hysteresis loops for the (**a**) FePt(15) and Fe(7)/FePt(15) and (**d**) FePt(20) and Fe(7)/FePt(20). AFM ($1\times\ 1\mu m^2$) and MFM images ($2.5\times\ 2.5\mu m^2$) for (**b**,**c**) FePt(15) and (**e**,**f**) FePt(20). (**g**) Coercivity behavior as a function of the Fe layer thickness

FePt(20) films which is constituted by disconnected islands (Fig. 1e). Probably when Fe is deposited on top of the hard films, it diffuses and reacts at grain boundaries filling the voids between islands giving rise to an almost continuous surface. This allows the formation of a continuous and compact Fe layer on top of the systems. The establishment of this contribution due to pure α-Fe occurring for a Fe layer of about 10 nm determines a significant decrease of the bilayer coercivity (Fig. 1g).

Therefore it is possible to explain the different coercivity behavior of the two series of samples considering the different phenomena which occur at the Fe/FePt interface. In effect while the FePt(15) film is characterized by densely-packed small grains, the FePt(20) is constituted by well disconnected islands which largely favors the Fe diffusion at the grain boundaries and its reaction with FePt small particles present on top of the hard films.

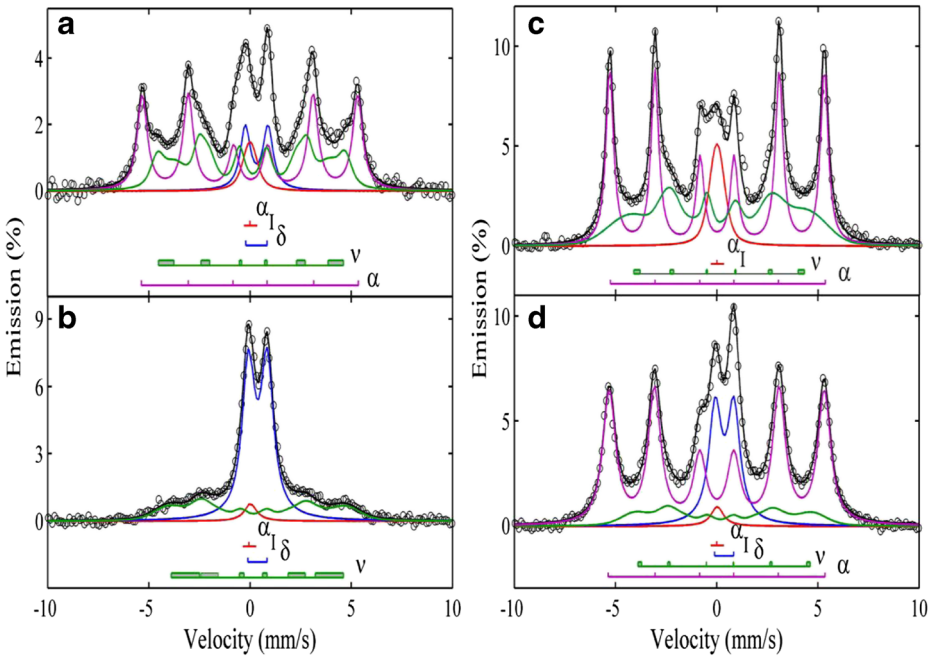

Fig. 2 CEMS spectra for (**a**) Fe(7)/FePt(15), (**b**) Fe(7)/FePt(20), (**c**) Fe(14)/FePt(15) and (**b**) Fe(14)/FePt(20)

In particular, in exchange spring magnets, the coercivity can increase after the growth of Fe if a complete intermixing occurs at the Fe/FePt interface, while the normally expected decrease in coercivity can only occur if the reaction between Fe and FePt is limited to a thin interfacial region.

While in the case of the FePd systems [5] these phenomena are due both (i) to the different Fe/FePd intermixing and (ii) to a change in the main mechanism controlling the coercivity, in the case of Fe/FePt systems the different coercivity behaviors are only due to the degree of intermixing and reaction between Fe and FePt. The larger hardness of FePt with respect to that of FePd determines a preferred rotation of the magnetic moments through the domain wall motion mechanism which remains unchanged increasing the hard FePt thickness.

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