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Coercivity of ledge-type $L1_0$-FePt/Fe nanocomposites with perpendicular magnetization

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Exchange-coupled ledge-type $L1_0$-FePt/Fe composite systems with out-of-plane anisotropy composed of nanostructured $L1_0$-FePt films covered by Fe are prepared to analyze the influence of the soft magnetic layer thickness on the magnetic properties. By the soft magnetic layer thickness d_{Fe} the coercivity can be tailored according to a $1/d_{Fe}^{1.38}$ relation. This result can be used to realize recording media with coercivities in the range which are afforded by conventional write heads. © *2009 American Institute of Physics*. [DOI: 10.1063/1.3078286]

Perpendicular magnetic recording based on exchange-coupled composite (ECC) elements currently seems to be most straightforward for realizing ultrahigh recording densities of several Tbit/in.[2].[1] ECC elements are composed of a hard magnetic part (storage layer) and a soft magnetic part (nucleation layer) which are coupled by exchange interaction through the common interface.[2] The phase boundary between the two materials can be sharp or graded.[3,4] Whereas in conventional ECC elements the cross-sectional shape for the hard and the soft parts is the same, in ledge-type ECC elements the soft sections are more extended in the recording direction.[5] The composite system guarantees high thermal stability of the stored information due to the hard magnetic part and moderate switching fields which can be afforded by conventional write heads due to the soft magnetic part.

So far, extensive theoretical work has been carried out to investigate the reversal mechanism in composite films,[2,6–9] switching characteristics,[10,11] and thermal stability[10,12] of very small ECC prototypes. Experimental work has been performed to realize hard/soft bilayers, e.g., epitaxial SmCo/(Fe,Co) with in-plane anisotropy,[8,13] granular CoCrPt–SiO_2 based ECC media,[14] granular $L1_0$-CoPt/Co with ⟨111⟩ anisotropy,[15] and epitaxial $L1_0$-FePt/Fe with perpendicular anisotropy.[4,16] In particular Goto *et al.*[17] and Fullerton *et al.*[8] showed for in-plane anisotropy that the coercivity decreases with increasing thickness of the magnetically soft layer. This behavior is also predicted by computational micromagnetism by Fullerton *et al.*[8] and Asti *et al.*[18]

In the present work we take $L1_0$-FePt as hard magnetic component due to its large magnetocrystalline anisotropy constant, its large corrosion resistance, and its perpendicular easy-axis magnetization when grown on single-crystalline MgO(100). Also we choose Fe as soft magnetic component which due to its large spontaneous magnetic polarization leads to a significant enhancement of the remanence for the exchange-coupled hard/soft magnetic bilayer.

In this paper the influence of the thickness of the soft magnetic layer on the characteristic magnetic properties of ECC nanoparticles is systematically studied by preparing different $L1_0$-FePt/Fe nanocomposites to enable tailoring of the coercivity. Furthermore, it is shown that at least the hard magnetic part of epitaxially grown ECC films has to be nanostructured to obtain large coercivities.

In the first step nanostructured $L1_0$-FePt films of different nominal layer thicknesses have been prepared on single crystalline MgO(100) substrates heated to 800 °C by magnetron cosputtering of Fe and Pt. After the deposition the temperature was held for 1 h. The composition of the deposited films has been determined to be $Fe_{50}Pt_{50}$ by wavelength dispersive x-ray analysis. The morphology of the $L1_0$-FePt films directly grown on heated substrates is controlled by the nominal layer thickness d.[19] For small nominal thicknesses of $d=5$ nm the films show an island-type nanostructure of isolated $L1_0$-FePt particles with out-of-plane texture. According to Fig. 1(a) the size of the isolated $L1_0$-FePt nanoparticles varies between 15 and 50 nm (with height of ~10 nm). Therefore, the nanoparticles are single-domain particles separated by 10–15 nm from each other. For nominal layer thicknesses up to 20 nm the sizes of the nanoparticles continuously increase. For $d \geq 20$ nm the nanoparticles start to interconnect forming a networklike structure. For nominal layer thicknesses larger than 60 nm the films are

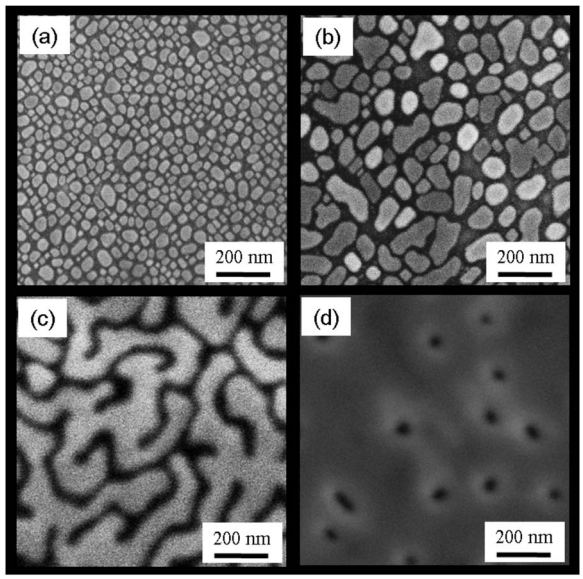

FIG. 1. Scanning electron microscope images of $L1_0$-FePt films with out-of-plane texture for varying nominal film thicknesses: (a) 5, (b) 10, (c) 20, and (d) 50 nm. The samples have been prepared by cosputtering Fe and Pt on MgO(100) heated to 800 °C.

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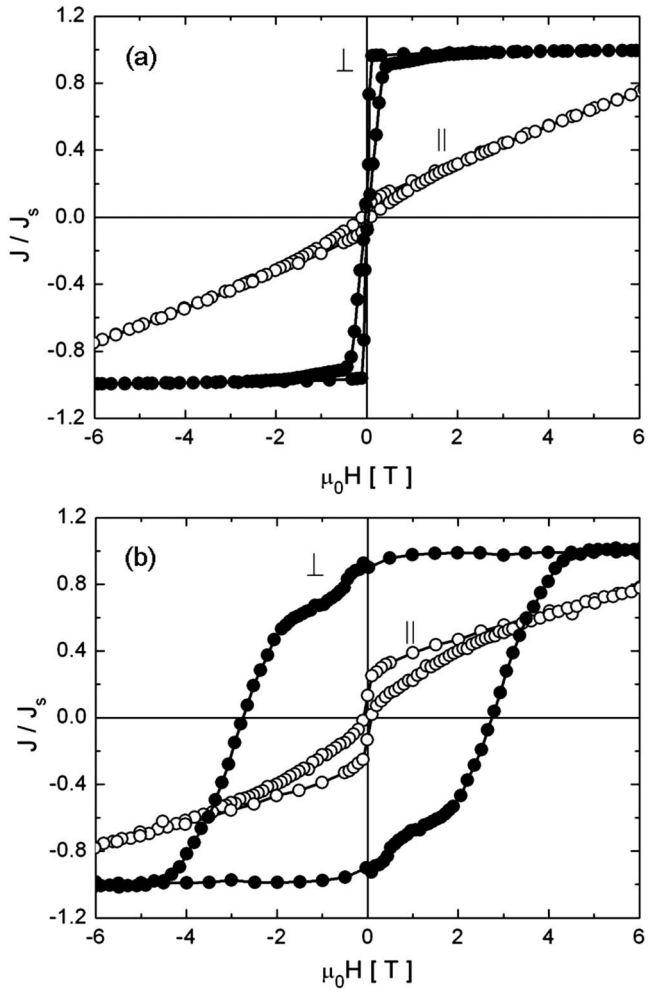

FIG. 2. RT out-of-plane and in-plane hysteresis loops of (a) a continuous $L1_0$-FePt film of nominal layer thickness 60 nm and (b) the island-type nanostructure of isolated hard magnetic $L1_0$-FePt particles shown in Fig. 1(a).

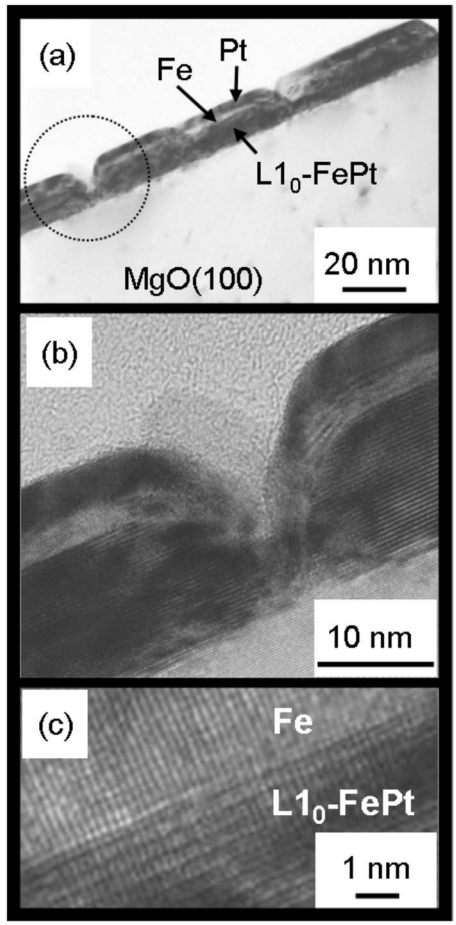

FIG. 3. Cross-sectional transmission electron microscope image of the island-type nanostructure of isolated hard magnetic $L1_0$-FePt particles shown in Fig. 1(a) covered by a 3 nm Fe layer and a 3 nm Pt protection layer: (a) overview, (b) the area marked by a circle in (a) in higher resolution, and (c) high-resolution image of the $L1_0$-FePt/Fe interface.

continuous and epitaxially grown. In Fig. 2 the room temperature (RT) out-of-plane and in-plane hysteresis loops (measured in a MPMS-XL superconducting quantum interference device magnetometer) of the island-type $L1_0$-FePt nanostructure of Fig. 1(a) are compared to the corresponding hysteresis loops of the continuous $L1_0$-FePt film. For both samples the out-of-plane texture is clearly visible. However, large coercivities of 2.74 T in out-of-plane direction are only obtained in the case of the nanostructured films due to the presence of $L1_0$-FePt single-domain nanoparticles. As soon as the nanoparticles start interconnecting the out-of-plane coercivity significantly decreases.

In the second step ledge-type $L1_0$-FePt/Fe nanocomposites have been prepared in the same magnetron sputtering system by depositing pure Fe at RT on the island-type $L1_0$-FePt nanostructure of Fig. 1(a). The nominal thickness of the Fe film d_{Fe} has been varied in the range between 0 and 15 nm. All ledge-type $L1_0$-FePt/Fe nanocomposites have been covered by a 3 nm thick Pt protection layer. By the additional deposition of Fe the spacing in the island-type $L1_0$-FePt nanostructure of Fig. 1(a) is gradually filled up with Fe and the $L1_0$-FePt nanoparticles are covered by Fe leading to a completely exchange-coupled $L1_0$-FePt/Fe nanostructure. However, as long as the nominal thickness of the Fe film is smaller than the height of the $L1_0$-FePt nanoparticles the Fe layer is not continuous. In Fig. 3(a) the cross section of the ledge-type $L1_0$-FePt/Fe nanostructure with d_{Fe}=3 nm observed in a transmission electron microscope (JEOL JEM-4000 FX) is presented. In Fig. 3(b) the spacing in between two $L1_0$-FePt nanoparticles is shown in higher resolution with the Fe layer being interrupted as its thickness remains below the height of the $L1_0$-FePt nanoparticles. According to Fig. 3(c), which shows the high-resolution image of the $L1_0$-FePt/Fe interface, both the $L1_0$-FePt nanoparticles and Fe grow epitaxially on the MgO(100) substrate resulting in the out-of-plane texture of the magnetization. The interface between the hard and the soft magnetic components is rather sharp.

In Fig. 4 the RT hysteresis loops of the different ledge-type $L1_0$-FePt/Fe nanocomposites are shown with varying nominal thickness d_{Fe} of the soft magnetic Fe film. The magnetic field has been applied in out-of-plane direction. With increasing thickness of the Fe film the coercive field decreases continuously from 2.74 T for the pure $L1_0$-FePt film to 0.4 T for a 10 nm thick Fe film on top of the $L1_0$-FePt film. Additionally due to the large saturation polarization of Fe, with increasing thickness d_{Fe} the remanence is significantly enhanced as long as the coercive field is larger than half of the remanence, which has also been observed by Goll *et al.*[20] for nanocrystalline composite $Pr_2Fe_{14}B$/Fe melt-spun ribbons. The relation between the coercive field and the

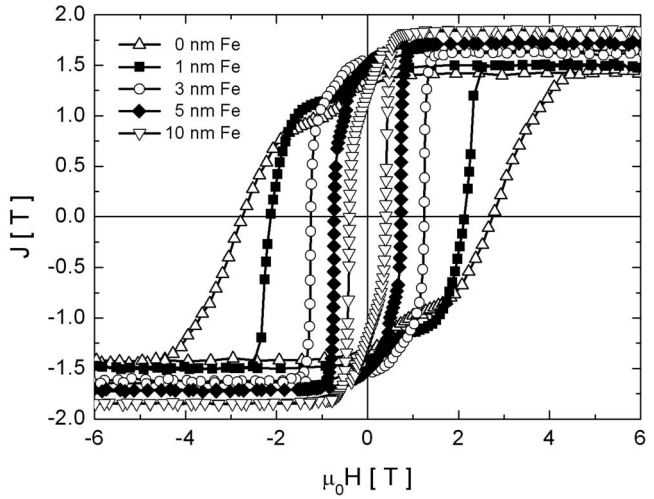

FIG. 4. RT out-of-plane hysteresis loops of $L1_0$-FePt/Fe bilayers composed of the island-type nanostructure of isolated hard magnetic $L1_0$-FePt particles shown in Fig. 1(a) and a soft magnetic Fe layer with nominal thickness varied between 0 and 10 nm. For all loops the magnetic polarization is normalized by the theoretical saturation polarization.

nominal thickness d_{Fe} of the soft magnetic Fe film is investigated in more details in Fig. 5. Accordingly, the measured values of the coercive fields are optimally fitted by a $1/d_{Fe}^{1.38}$ relation. At present no explicit analytical results of the thickness dependence of the coercivity exist. However, implicit analytical solutions of the micromagnetic equations for composite films lead to a power law of an exponent 3/2.[21] Here it should be noted that the results obtained previously by Kronmüller[22] for the thickness dependence of the nucleation field ($1/d$ and $1/d^2$) are not applicable for the depinning field considered here because in this case the magnetically soft film was embedded between hard films. Our experimental results as well as those of Fullerton *et al.*[8] clearly show that the coercive field decreases strongly by a factor of 3 or 4 for thicknesses up to 4 nm. In addition, it should be noted that the exponent may also be influenced by the specific microstructure of the system. Our relation given in Fig. 5 offers the possibility to tailor the coercivity of ledge-type $L1_0$-FePt/Fe nanocomposites by varying the thickness of the Fe layer.

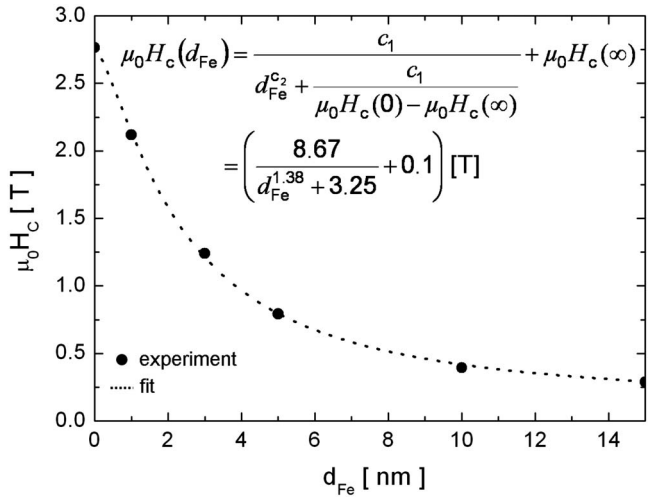

FIG. 5. Relation between the coercivity and the nominal thickness of the soft magnetic Fe layer d_{Fe} for the $L1_0$-FePt/Fe bilayers of Fig. 4. The relation used for fitting takes into account the boundary values obtained for pure $L1_0$-FePt $[\mu_0 H_c(0)]$ and expected for very thick Fe layers $[\mu_0 H_c(\infty)]$, where d_{Fe} is inserted in nanometers.

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