Thin Solid Films 520 (2012) 2184–2189

Contents lists available at SciVerse ScienceDirect

Thin Solid Films

journal homepage: www.elsevier.com/locate/tsf

Tuning exchange spring effects in FePt/Fe(Co) magnetic bilayers

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ARTICLE INFO

Article history:
Received 1 March 2011
Received in revised form 20 October 2011
Accepted 21 October 2011
Available online 29 October 2011

Keywords:
Exchange spring
Soft/hard magnetic bilayers
FePt
Conversion Electron Mössbauer Spectroscopy
Magnetometry

ABSTRACT

Structural and magnetic properties of exchange spring magnets consisting of hard magnetic (FePt) and soft magnetic (Fe and Co) bilayers, prepared by ion beam sputtering method are studied via X-ray diffraction (XRD), magneto-optic Kerr effect (MOKE) and vibrating sample magnetometry (VSM). Thin tracer layers of ^{57}Fe were introduced in the soft layer in order to observe the Fe spin structure and interfacial diffusion by Conversion Electron Mössbauer Spectroscopy (CEMS). The observed in-plane exchange spring behavior extends also to the magnetic hard layer, whose switching field can be tuned in an unexpected manner via the top soft magnetic layer. To explain the observed phenomenon it is suggested that the increased switching field, found in the system with a Co/Fe bilayer acting as a single soft magnetic layer, is compatible with a peculiar behavior of the stiffness coefficient of the heterogeneous soft magnetic layer. According to this observation, possibilities to maximize the exchange spring effects via suitably chosen non-homogeneous soft magnetic layers are open.

1. Introduction

Nano-composite materials consisting of exchange coupled soft magnetic (SM) and hard magnetic (HM) phases, known as exchange spring magnets, are the focus of current research because of various technological applications, such as permanent magnets with high energy products [1] or nano-scale magnets for ultrahigh density recording [2]. For example, in the case of information storage, such composite systems combine the high thermal stability of the stored information due to the hard magnetic component with the moderate switching field due to the soft magnetic component.

Composite systems of type HM/SM, where the hard magnetic layer is $L1_0$–FePt and the soft magnetic layer is Fe, are being studied both theoretically and experimentally for their exchange spring behavior [3–8]. It may be noted that usually, the as-prepared equiatomic FePt alloy has chemically disordered face-centered-cubic (fcc) symmetry. Upon annealing at about 500–600 °C, it transforms into a face-centered-tetragonal (fct) structure, known as $L1_0$, with very high magnetocrystalline anisotropy [9]. In case of thin films, the fct structure can be grown, depending on the deposition conditions, either as an epitaxial phase with high perpendicular to plane anisotropy or as a polycrystalline phase with different textures. Hence, from the magnetic point of view, a soft magnetic film grown on a hard magnetic FePt layer of Ll_0 structure may develop an exchange spring structure with either out-of-plane or in-plane behavior.

Depending on the thickness of the soft magnetic layer, various magnetic regimes may occur in such composite systems. For a small thickness of the soft layer, the system behaves as a rigid magnet switching at a single field whereas for a higher thickness of the soft layer, the system behaves as an exchange spring magnet [4, 5]. Goto et al. [10] have also studied the magnetization reversal process in a SM film, ferromagnetically coupled to a HM layer with uniaxial in-plane anisotropy, under the assumption that the hard layer is perfectly rigid and the soft layer has no anisotropy. Upon decreasing the applied magnetic field from positive saturation, the spins of thick enough soft layers ($t > 50$ nm), exhibit continuous in-plane rotations, with the rotation angle increasing with distance from the hard layer. They always come back along the initial direction (positive magnetization) after releasing negative in-plane applied fields smaller than an exchange field, which is dependent on geometric and magnetic parameters of only the soft layer. For a much thinner soft layer (approaching the domain wall width in the hard layer), the soft layer is expected to be magnetically rigid coupled to the hard layer, switching together at a value of switching (or nucleation) field, which depends on the geometric and magnetic characteristics of both the soft and hard layer. In real situations, the soft layer may have a finite anisotropy and an intermediate thickness between the two situations described above and the hysteresis loop may show both the exchange and the switching (nucleation) fields [11]. Hence, the exchange field H_{ex} in the low-field range reflects the reversible magnetization reversal of the soft Fe layer, whereas the switching field H_{irr} in the high-field region is indicative for the irreversible switching of the hard layer. Larger are the exchange and switching fields, better are the exchange spring characteristics of

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0040-6090/$ – see front matter © 2011 Elsevier B.V. All rights reserved.
doi:10.1016/j.tsf.2011.10.143

the overall system. It is worth mentioning at this point the fundamental difficulty in assigning the exchange and the switching field in real systems presenting relatively thicker soft layers and finite anisotropy of the hard magnetic layer. It has been previously proved [12, 13] that the reversible twist of the spins in the soft layer is not pinned rigidly at the interface but rather propagate significantly into the hard magnetic layer. Therefore, the reversible magnetization is partially stored also in the hard magnetic layer and the usual procedure of using the magnetization reversal curves (hysteresis loops) for defining the exchange field (as related to the steeper decrease of the magnetization at low negative fields) and the switching field (as related to the steeper decrease of the magnetization at high negative fields), most probably fails. A distinction should be made between the exchange field (according to the above definition) and the field corresponding to the steeper decrease of the magnetization at low negative field, which will be called in the fallowing as the switching field of the soft magnetic layer. Accordingly, the last one can be seen as a sort of coercive field assigned to the soft layer (which is not free, but exchange coupled to the hard one). As physical meaning, it would correspond to a continuous rotation of the spins in the soft layer, as in a Bloch wall, with interfacial spins along the magnetization of the hard layer and the most far away spins, in the opposite direction (namely along the negative applied field). In such situations, it becomes very interesting to study both the exchange and the switching fields, with the mutual influence of the two interfacing layers one to each other, and especially the less expected influence of the soft magnetic layer on the hard magnetic one. However, the available classes of systems which may allow such a study is quite limited and request the possibility to tune the magnetic properties (e.g. magnetic hardness) of the both layers. In addition, the quality of the interface may also be decisive in establishing the magnetic properties of the bilayer structure. For example, it has been shown that diffused interface instead of sharp one between the hard magnetic (SmCo) and soft magnetic (Fe) phase improves the exchange spring behavior of the system [14].

In the present work, we propose a study of the mutual influence of the interfacial layers in HM(FePt)/SM(Fe,Co/Fe) systems, with relatively thick soft magnetic layers, in order to induce the exchange spring behavior. The main advantage of the FePt HM layer consists in the possibility to tune its hardness via the processing conditions, as discussed in the following. In addition, the anisotropy of the SM component might be also tuned in the proposed system, while the Co layer presents a different anisotropy as compared to the Fe one. It is worth to mention the continuous change of the crystal structure of the equiatomic FePt phase via thermal treatments, from the chemically disordered A1 fcc phase to the chemically ordered Ll_0 fct phase, which can be monitored by the shift of the (111) peak and the evolution of the (001) and (110) peaks in the X-ray diffraction patterns (e.g. [15]). As expected, this evolution is accompanied by a change of the hardness of the FePt overall phase, which behaves magnetically as a single component with a coercive field, $\mu_0 H_C$, increasing from 0.02 T (for mostly chemically disordered fcc phase) to above 0.3 T (for a better formed chemically ordered fct phase) [15].

2. Experimental details

The studied thin films were prepared on Si(111) substrate by using an ion beam sputtering method. Firstly, the FePt film of 30 nm thickness was grown from a compound target. The compound target was obtained by placing Fe and Pt targets side by side. Relative areas of Fe and Pt targets exposed to the ion-beam were controlled in order to achieve equiatomic composition of the film. The film was in-situ post-deposition annealed at about 500 °C for one hour to induce the $L1_0$ phase formation. The obtained $L1_0$ ordered FePt film is used to prepare the multilayer structures [FePt(30 nm)/Fe(10 nm)/^{57}Fe(2 nm)/Fe(10 nm)/C(2 nm)] and [FePt (30 nm)/Co(10 nm)/^{57}Fe(2 nm)/ Fe(10 nm)/C(2 nm)], henceforth represented as FePt/Fe and FePt/Co/Fe respectively. While the hard magnetic FePt layer is identical for both structures, one may note that the single difference between the two samples is in terms of the soft magnetic layer which is directly coupled to the hard layer. In FePt/Fe sample, it is the Fe layer and in FePt/Co/Fe sample it is the Co layer which is expected to be coupled to the hard FePt layer. However, in the second sample, the Co/Fe bilayer is thought to act as a single soft magnetic layer. The total thickness of the soft magnetic layer is about 22 nm in both systems. A tracer layer of 2 nm ^{57}Fe is deposited in both samples in the middle of the soft layer in order to serve as a probe for ^{57}Fe Mössbauer measurements. X-ray reflectivity (XRR) and grazing incidence X-ray diffraction (GIXRD) measurements with an angle of incidence of 1° were carried out by using a Bruker D8-Discovery system with Cu K_α-radiation. The XRR patterns, analyzed via the Parratt formalism [16], indicates that the real thickness values of the metallic components in the multilayers, match closely the nominal thickness values, above mentioned.

Magnetic measurements at 300 K were carried out via a Quantum Design Physical Properties Measurement System, under the Vibrating Sample Magnetometry (VSM) mode, a high field measurement system (Cryogenic Limited) and a magneto-optic Kerr effect (MOKE) system. The magnetic field was applied parallel to the surface of the film, resulting therefore in-plane magnetization measurements. The MOKE system is equipped with a low field electromagnet (~0.12 T) and with a laser with 632 nm wavelength. The beam is incident on the sample at an angle of ~45°. Conversion electron Mössbauer spectra (CEM spectra) were recorded at 300 K, in perpendicular geometry, by using a conventional PC-based spectrometer with a home-made continuous $He+CH_4$ gas flow detector.

3. Results and discussion

Fig. 1 shows the GIXRD patterns of the two thin films. As expected from the processing procedure of the samples, they are quite similar with respect to the hard magnetic phase. One can clearly see various peaks corresponding to the ordered $L1_0$ FePt. It is worth mentioning

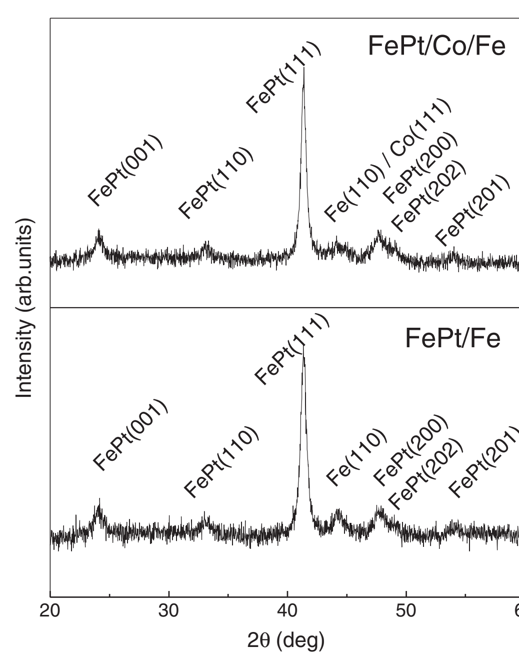

Fig. 1. GIXRD patterns of FePt/Fe and FePt/Co/Fe samples.