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Recovery of soft magnetic properties of FeNiSm films by Ta interlayer

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ABSTRACT

The magnetic properties of FeNiSm thin films with different thicknesses, different Ta interlayer thicknesses and different numbers of Ta interlayers were investigated. The single layer FeNiSm shows in-plane uniaxial anisotropy at a thickness below critical value, but shows weak perpendicular anisotropy with a stripe domain structure at thickness above the critical value. Experiments indicate that one or more Ta interlayers inserted into thick FeNiSm films with weak perpendicular anisotropy were effective not only in canceling the perpendicular anisotropy, but also in recovering the in-plane uniaxial anisotropy. Blocking of the columnar growth of FeNi grains by the Ta interlayer is considered to be responsible for this spin reorientation phenomenon. Moreover, the magnetization reversal mechanism in FeNiSm films with uniaxial anisotropy can be ascribed to coherent rotation when the applied field is close to the hard axis and to domain-wall unpinning when the applied field is close to the easy axis. The dynamic magnetic properties of FeNiSm films with uniaxial anisotropy were investigated in the frequency range 0.1–5 GHz. The degradation of the soft magnetic properties of magnetic thin films due to the growth of columnar grains can be avoided by insertion of a Ta interlayer.

1. Introduction

Soft magnetic materials are widely used in electronic devices and magnetic sensors [1]. With the miniaturization and integration of electromagnetic devices the requirements for high frequency soft magnetic thin films are more demanding, which means the magnetic thin films must have low coercive field (H_c), high magnetic permeability, high anisotropy field (H_k) and high saturation magnetization ($4\pi M_s$). In order to use magnetic thin films in the high frequency region, the samples should have a large anisotropy field according to the formula [2] $f_r=(\gamma/2\pi)\sqrt{H_k(4\pi M_s+H_k)}$, where γ is the gyromagnetic ratio. Several methods, including stress [3–5], annealing under magnetic field [6–8], micro-strip patterning [9,10], exchange bias [11] and element/compound additions [12], have been used to adjust the anisotropy field of magnetic thin films, which is one of the key factors that determines the cut-off frequency. Recently, rare-earth element doped amorphous 3d-transition metal films have been shown to exhibit very large in-plane uniaxial anisotropy field when the film thickness is below a critical value [13]. Above this thickness value, the magnetic thin films exhibit weak perpendicular anisotropy. This may result in the degradation of soft magnetic properties and can be explained by structural short-range order as in CoTi amorphous films [14–16], or by columnar growth of grains [13].

In this work, we report a thickness dependence of a spin reorientation transition (SRT) phenomenon in FeNiSm films. As thickness increases to a critical value (about 170 nm), the in-plane uniaxial anisotropy disappears and the film exhibits a weak perpendicular anisotropy with stripe domain structure. However when one or more Ta interlayers were introduced into the thick FeNiSm film, the in-plane uniaxial anisotropy appears again. The mechanism of SRT is due to interrupting the growth of FeNi columnar grains by the introduction of the Ta interlayer. Moreover, the magnetization reversal mechanism was investigated by analyzing the angular dependence of the remanence ratio and coercivity.

2. Experimental

FeNiSm films with and without Ta interlayers were fabricated by radio frequency (RF) magnetron co-sputtering onto Si (1 1 1) substrates with background pressure below 3×10^{-5} Pa and sputtering Ar pressure of 0.2 Pa. The sputter guns with 3 in. Sm and $Fe_{25}Ni_{75}$ (at%) alloy targets were tilted with respect to the substrate for co-sputtering. The power for sputtering the FeNi and Sm targets was selected as 170 and 30 W, respectively, to achieve good soft magnetic properties. The Sm content in the FeNiSm films was measured by energy dispersive spectroscopy to be around 12 at%. A Ta target was used on another RF gun in the chamber to produce a 5 nm seed layer, a 5 nm protective overcoat and the interlayers. The thickness of each layer was controlled by

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the deposition time and rate, which were calibrated by measuring the thickness of a calibration sample using a surface profilometer. The water cooled substrate holder was rotated at 1.7 rad/s during deposition in order to obtain a homogenous film. A magnetic field of 40 Oe was applied in the sample plane during deposition in order to induce a well-defined easy axis. The substrate was held at room temperature during the deposition.

The crystal structure of the films were examined by X-ray diffraction (XRD) with Cu-Kα radiation. The static magnetic properties of FeNiSm films were measured using a vibrating sample magnetometer (VSM). The domain structures at the surface of the FeNiSm films were studied using magnetic force microscopy (MFM) with soft magnetic tips that were magnetized perpendicular to the sample plane. The cross-section microstructures of the FeNiSm films were studied using a Hitachi S-4800 scanning electron microscope. The permeability spectra of the samples were obtained by a shorted microstrip transmission line perturbation method, from 100 MHz to 5 GHz.

3. Results and discussion

The structure of the FeNiSm films was investigated by XRD as shown in Fig. 1 for a 200 nm FeNiSm film and a 200 nm FeNiSm film with one 6 nm Ta interlayer. It can be seen that a broad peak appears around 44.5°, which can be identified as the (1 1 1) diffraction peak of the nano-crystalline FeNi grains. Similar XRD patterns were obtained for other FeNiSm films with different thicknesses of FeNiSm layers and of Ta interlayers, indicating that the films consist of FeNi nano-grains. Comparing the patterns of Fig. 1(a) and (b) it is easy to understand that the Ta diffraction intensity becomes stronger in Fig. 1(b), as this sample contains a thick Ta layer.

Fig. 2 shows the in-plane magnetic hysteresis loops of FeNiSm films of various thicknesses without a Ta interlayer. From Fig. 2(a), one can see that the sample with thickness $t_1 = 50$ nm has in-plane uniaxial anisotropy with the easy axis parallel to the applied magnetic field during deposition. The easy axis coercive field (H_{ce}), hard axis coercive force (H_{ch}) and the anisotropy field (H_k) are about 9.8, 4.0 and 90 Oe, respectively, for this sample. For the FeNiSm film with $t_1 = 100$ nm, H_{ce} and H_{ch} decrease slightly to 7.2 and 3.2 Oe, respectively, and H_k is still about 90 Oe as shown in Fig. 2(b). Compared to pure FeNi films, where the anisotropy field is only about 4.5 Oe [17], FeNiSm films have a large anisotropy field, which may result from the strong interaction between the 3d and 4f electrons of the transition metals and the rare-earth elements [18]. As t_1 increases to 200 nm, the hysteresis loop, as shown in Fig. 1(c), changes to the characteristic loop of a film with weak perpendicular anisotropy and stripe domain structure [19]. It is noted that the saturation field increases to 150 Oe, which is about 17 times larger than the easy axis saturation field of FeNiSm films with in-plane uniaxial anisotropy, and the coercivity increases to 40 Oe. Thus the degradation of the soft magnetic properties and the spin reorientation transition are observed due to the increase of the FeNiSm film thickness above the critical value. The measured saturation magnetization ($4\pi M_s$) of FeNiSm films is about 4500 Gs, compared to about 8000 Gs for pure $Fe_{25}Ni_{75}$.

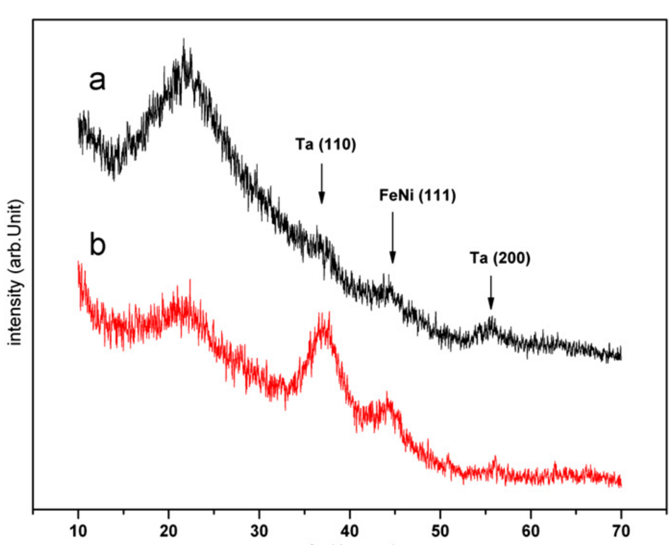

Fig. 1. XRD patterns of 200 nm FeNiSm films without Ta interlayer (a) and with one 6 nm thick Ta interlayer (b).

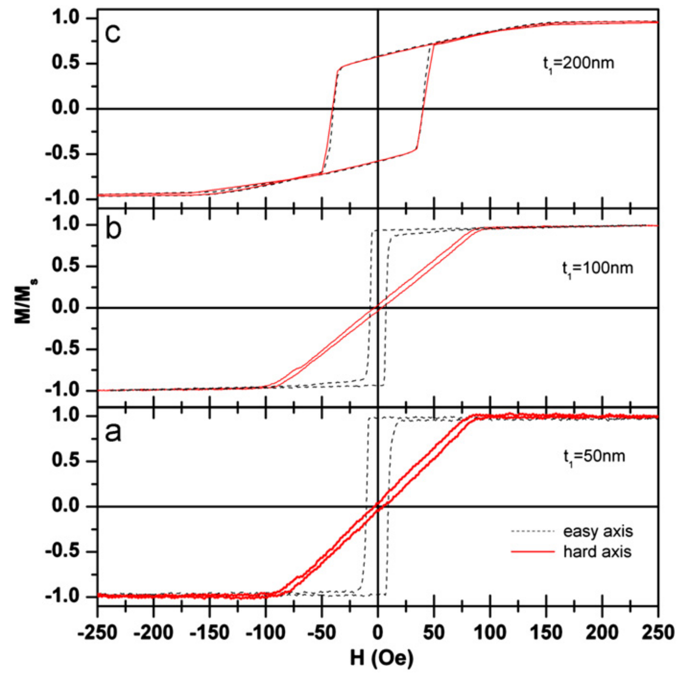

Fig. 2. Hysteresis loops of FeNiSm films with thickness of 50 nm (a), 100 nm (b) and 200 nm (c).

The zero-field MFM images of FeNiSm films with different thicknesses are shown in Fig. 3. One can see that the surface domain structure is quite different for FeNiSm films with different thicknesses. The film with $t_1 = 100$ nm shows no magnetic structure, while the sample with $t_1 = 200$ nm shows obvious alternate dark and light stripes, indicating that there is an alternating structure of magnetic moments. As the magnetic MFM tip is sensitive to the stray field of magnetization perpendicular to film surface, the alternate dark and light stripes can be understood as the result of domains magnetized alternately upward and downward perpendicular to the film surface. The SEM images (not shown) of the cross-section of the FeNiSm films show a columnar structure with columns perpendicular to the film plane, as in FeCoNd films [13]. This structure is responsible for the appearance of the perpendicular anisotropy. Thus, the thicker the FeNiSm films, the longer the columns and a higher perpendicular anisotropy will be observed. Therefore, FeNiSm films with thickness over the critical value show weak perpendicular anisotropy instead of completely in-plane anisotropy.

For practical applications, relatively thick films are needed to obtain sufficient magnetic signal. Considering that the degradation