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Thickness dependence of magnetic anisotropic properties of FeCoNd films

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ABSTRACT

The magnetic FeCoNd films with thickness (*t*) from 50 to 166 nm were fabricated by RF magnetron co-sputtering at ambient condition. The amorphous structures of all of the films were investigated by X-ray diffraction and transmission electron microscopy. A spin reorientation transition from in-plane single domain state to out-of-plane stripe domain state was observed as a function of *t*. When *t* is below a critical thickness, magnetic moments lie in the film plane corresponding to in-plane single domain state because of the strong demagnetization energy. However, when *t* is increased, out-of-plane stripe domain structure was developed due to a dominated perpendicular magnetic anisotropy. Scanning electron microscopy data indicate that the perpendicular anisotropy, which is responsible for the formation of stripe domains, may result from the shape effect of the columnar growth of the FeCo grains.

1. Introduction

With the discovery of perpendicular magnetic anisotropy in rare earth-transition metal (RE-TM) alloys in the 1970s [1], research and development for high performance magnetic materials have mainly concentrated on rare earth and transition metal element based compounds [2–4]. In thin film systems, if the perpendicular anisotropy constant is large enough, it can overcome the demagnetization energy and force the magnetic moments to lie perpendicular to the film plane. This phenomenon consisting of the transition from out-of-plane to in-plane magnetization has been called spin reorientation transition (SRT) [5]. Experimentally, the SRT phenomenon has been investigated in several ultra-thin films (such as in permalloy [6–8], Fe [9,10], Co [11], LSMO [12], and FeSiB [13] thin films) with changing film thickness. The magnetization vector lies in the film plane, and favorable soft magnetic properties can be obtained. However, by increasing the film thickness to a certain value, the magnetization vector is perpendicular to the film plane, and the corresponding stripe domain structure can be detected. The equilibrium domain structure results from the competition between the exchange, dipolar, applied field, and anisotropy energies. At the SRT point, where the spins switch from perpendicular to in-plane directions of the film, the in-plane magnetic shape anisotropy cancels out the perpendicular magnetic anisotropy.

In this paper, we report the change of magnetic properties of FeCoNd films as a function of film thickness. We have found that there exists a critical thickness, above which the in-plane domain configuration was suddenly transformed into the closure domain configuration. The emphasis is placed on the effect of thickness on magnetic properties and domain structures. In addition, the reason for this phenomenon is also investigated.

2. Experimental

The magnetic FeCoNd films in this work were deposited by radio frequency (RF) magnetron co-sputtering onto Si (1 1 1) substrates with common base pressure below 3×10^{-5} Pa and processing Ar pressure of 0.2 Pa. The sputter guns with Nd and $Fe_{10}Co_{90}$ (at%) alloy targets were tilted to the substrates to achieve co-sputtering. Thus, the $(Fe_{10}Co_{90})_{17}Nd_2$(at%) films were obtained by adjusting the sputtering power of Nd and $Fe_{10}Co_{90}$ targets. A Ta target was also used on another RF gun in the chamber to produce a 9 nm seed layer and 6 nm protective overcoats for all of the magnetic FeCoNd films. The substrate holder was rotated with an angular speed of 1.7 rad/s during deposition in order to obtain a uniform film. The thickness of the films determined by the surface profilometer measurements was within the range from 50 to 166 nm.

The microstructures of the films were examined using FEI Tacnai G2 F30S transmission electron microscopy (TEM) and X-ray diffraction (XRD) with Cu-K_α radiation. Energy dispersive spectroscopy (EDS) was used to determine the composition of the films. The static magnetic properties of FeCoNd films were measured by a vibrating sample magnetometer (VSM). Surface

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topographies were characterized with an atomic force microscope (AFM), and the domain structures at the surface were studied using magnetic force microscopy (MFM) with soft magnetic tips magnetized perpendicular to the sample plane. The cross-section microstructures of the films were studied through Hitachi S-4800 scanning electron microscopy (SEM).

3. Results and discussion

The microstructure of FeCoNd thin film with the thickness of 50 nm was examined by TEM. As shown in the high resolution TEM image of Fig. 1(a), a large amount of amorphous phase and the growth of $(Fe_{10}Co_{90})_{17}Nd_2$ grains are observed. It is worthy to note that the parallel lines separated by 0.3 nm, as shown in the inset of Fig. 1(a), correspond to the *d* spacing of $(Fe_{10}Co_{90})_{17}Nd_2$ (113) planes of the nano-crystallites. Fig. 1(b) shows the electron diffraction pattern. One can see a halo ring, indicating the amorphous feature of the thin films. The presence of very fine $(Fe_{10}Co_{90})_{17}Nd_2$ crystals embedded in the amorphous matrix was also identified by the XRD measurements (not shown).

The in-plane hysteresis loops of FeCoNd thin films with different thicknesses are displayed in Fig. 2. It can be seen that the remanence magnetization (M_r) to the saturation magnetization (M_s) ratio (M_r/M_s) decreases, while the saturation field (H_s) increases with increase in film thickness (t). For the very thin film (t=50 nm), a square loop is observed along the easy axis (EA) with a coercive field (H_c) of 8.6 Oe whereas a tilted loop with a low value of remanence appears along the hard axis (HA). This hysteresis loop is typical for soft magnetic alloys with large in-plane uniaxial anisotropy. The in-plane uniaxial anisotropy field ($H_{k\parallel}$) estimated by the extrapolated hard axis loop to saturation was 91 Oe, which corresponds to an in-plane uniaxial anisotropy constant $K_\parallel = M_s H_{k\parallel}/2$. By assuming the saturation magnetization for the FeCoNd films to be equal to 10,414 Gs, the calculated value of $K_\parallel$ was found to be 4×10^4 erg/cm^3. For the film thickness t=100 nm, a weak in-plane anisotropy can also be found; however, an incline on the EA hysteresis loop near zero-field associated with a decrease of the remanence is seen. The EA and HA coercivities are both 54.6 Oe. When the film thickness t=163 nm, the shape of the hysteresis loop is shown to dramatically change, displaying a linear decrease of magnetization from its saturation value and a moderate remanence. This sample is typical of films with perpendicular magnetic anisotropy. The soft magnetic properties of the film deteriorate with a higher value of coercivity (H_c=102.7 Oe). The magnetic field $H_{k\perp}$ at which the sample reaches its saturation is 730 Oe. These hysteresis loops with a characteristic shape were called *transcritical*. The lower slope occurring before saturation

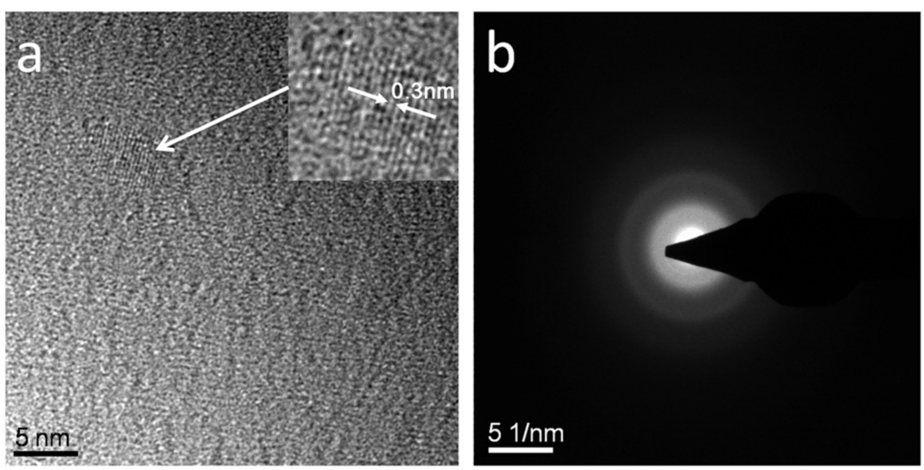

Fig. 1. High resolution TEM image (a) and electron diffraction pattern (b) of FeCoNd film with t=50 nm. The inset of (a) shows an enlargement of FeCoNd grain.

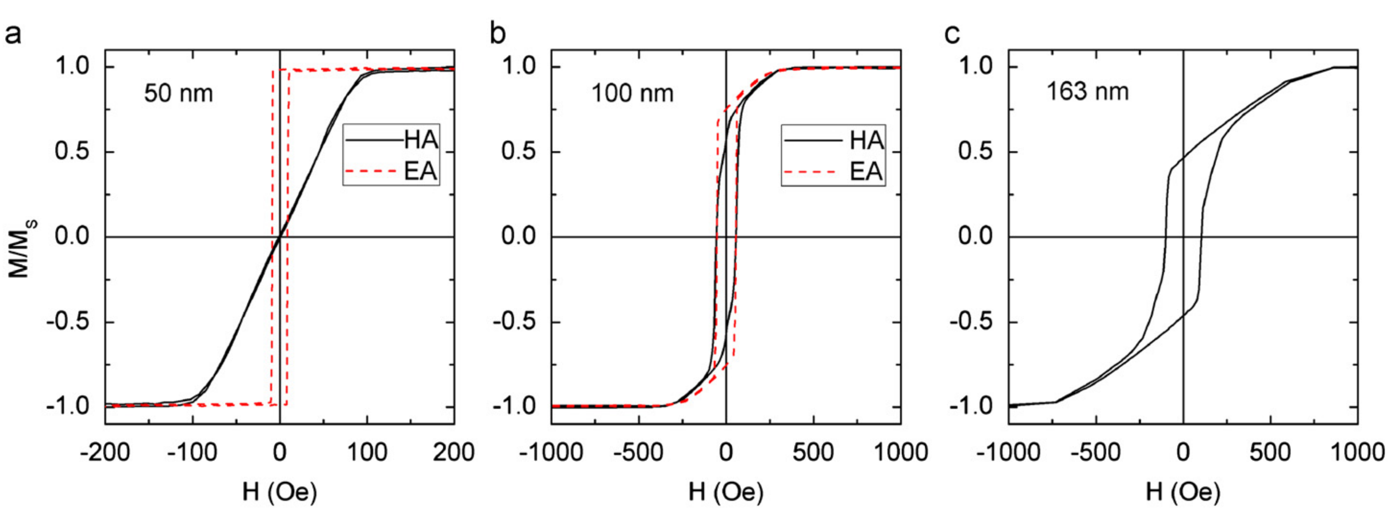

Fig. 2. Magnetic hysteresis loops of FeCoNd films with different film thicknesses.