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Studies on high-moment soft magnetic FeCo/Co thin films

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The dependences of soft magnetic properties and microstructures of the sputtered FeCo (=$Fe_{65}Co_{35}$) films on Co underlayer thickness t_{Co}, FeCo thickness t_{FeCo}, substrate temperature T_s and target-substrate spacing d_{T-S} are studied. FeCo single layer generally shows a high coercivity with no obvious magnetic anisotropy. Excellent soft magnetic properties with saturation magnetization $\mu_0 M_s$ of 2.35 T and hard axis coercivity H_{ch} of 0.25 kA/m in FeCo films can be achieved by introducing a Co underlayer. It is shown that sandwiching a Co underlayer causes a change in orientation and reduction in grain size from 70 nm to about 10 nm in the FeCo layer. The magnetic softness can be explained by the Hoffmann's ripple theory due to the effect of grain size. The magnetic anisotropy can be controlled by changing d_{T-S}, and a maximum of 14.3 kA/m for anisotropic field H_k is obtained with d_{T-S}=18.0 cm.

Keywords: FeCo film, sputtering conditions, high saturation magnetization, soft magnetic properties
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1. Introduction

The continuous increase in magnetic recording density beyond 100 Gb/in^2 can bring about two major impacts on heads and media. One is the demand for higher medium coercivity to overcome the transition to self-demagnetizing field and to maintain the thermal stability of the recorded information. The other is that the increase in the data rate will substantially reduce the write head field duration, which makes the dynamic writing coercivity of the media even higher. Both require an increasingly high writing head field, which is primarily restricted by the saturation magnetization $\mu_0 M_s$ of the head material. The development of high $\mu_0 M_s$ head materials (with $\mu_0 M_s$ being higher than that of pure Fe) is therefore indispensable to meeting the requirements for high medium coercivity and high data rate. In addition to the requirement for high $\mu_0 M_s$ a head material is also required to have small coercivity (i.e. high permeability), well-defined uniaxial anisotropy, and good thermal stability. The challenge for developing a good head material is to find such a material that its properties can meet all the requirements for ultrahigh-density recording. Since the highest saturation flux density of $\mu_0 M_s \geq 2.4$T can be achieved in bulk $Fe_{1-x}Co_x (0.3 < x < 0.4)$ alloy,[1] it is a potential candidate for write-head material as future high coercivity recording media if the microstructure can be optimized to reduce the coercivity. Some promising approaches have been proposed to try to control the microstructure of the FeCo film by optimizing deposition process,[2,3] laminating an amorphous layer,[4] adding a third element,[5−7] and implementing a suitable buffer layer.[8−10] In the present work, the double-layered FeCo/Co films are prepared by sputtering and the effects of sputtering conditions on soft magnetic properties and microstructures are studied.

2. Experiment

The films were deposited on glass substrates by facing targets sputtering (FTS), in which two FeCo composite targets were symmetrically placed facing each other and the substrates held orthogonal to the target surfaces. The background pressure was below 1.33×10^{-4} Pa. For the FeCo/Co film, the Co layer

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was deposited at a power of 50 W in an Ar pressure of 0.40 Pa. The FeCo layer was deposited at 100 W in 0.27 Pa with the thickness ranging from 50 nm to 800 nm. The film composition was confirmed by electron probe microanalyser (EPMA). The magnetic properties were measured with a vibrating sample magnetometer (VSM). The film thickness is measured by the Surfcom 900B step. X-ray diffraction (XRD) measurements were performed to characterize film crystallographic properties. Cross sectional transmission electron microscope (TEM) analysis was used to characterize the grain size and the morphological changes.

3. Results and discussion

FeCo single layer films were prepared to optimize the soft magnetic properties, as well as for reference. The FeCo single layer generally shows high coercivity with no obvious magnetic anisotropy (as shown in Fig.1(a)). Dramatically different soft magnetic properties of FeCo films can be obtained by sandwiching a thin Co underlayer between the film and the glass substrate. FeCo/Co films show well-defined uniaxial hysteresis loops with a remarkable reduction in coercivity. The typical magnetic hysteresis loop of FeCo (200 nm)/Co (5 nm) is shown in Fig.1(b). Varying

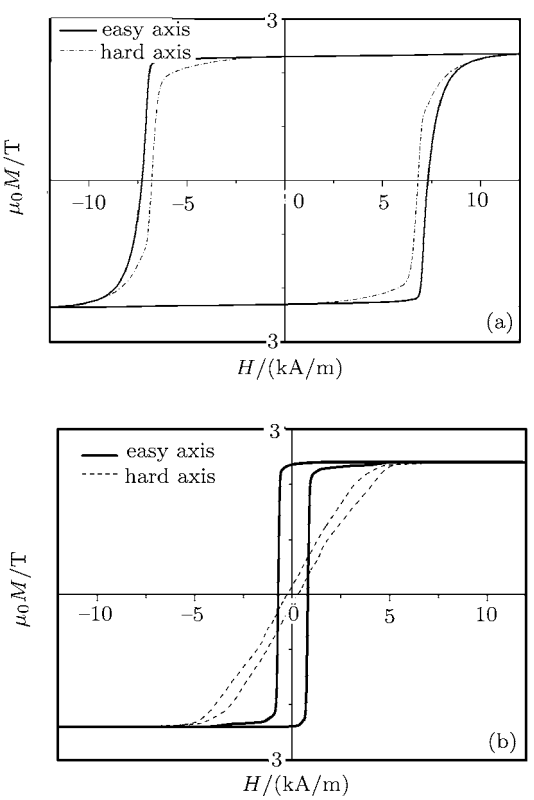


Fig.1. Typical hysteresis loops for (a) FeCo (200 nm) single layer and (b) FeCo (200 nm)/Co(5 nm) films.

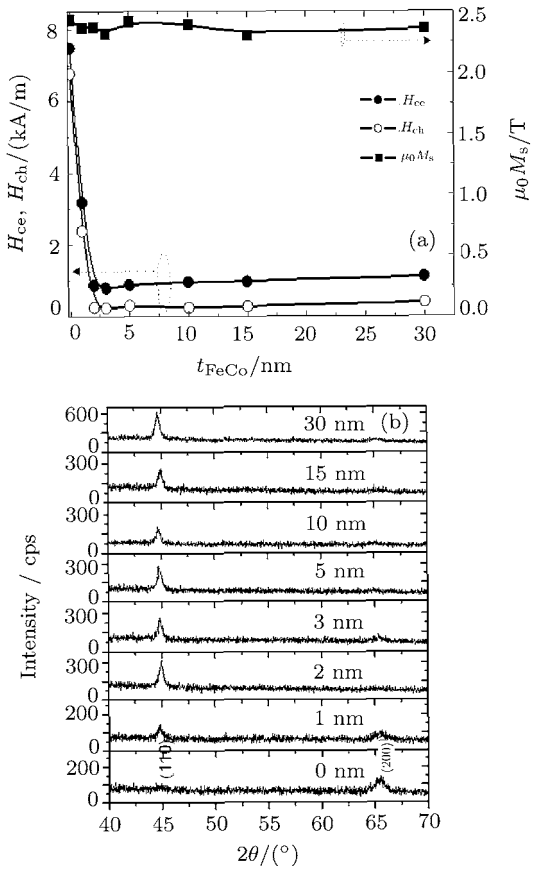


Fig.2. (a) Dependences of saturation magnetization $\mu_0 M_s$, easy axis coercivity H_{ce} and hard axis coercivity H_{ch} on Co underlayer thickness t_{Co} in FeCo (200 nm)/Co (t nm) film. (b) XRD patterns at different t_{Co}.

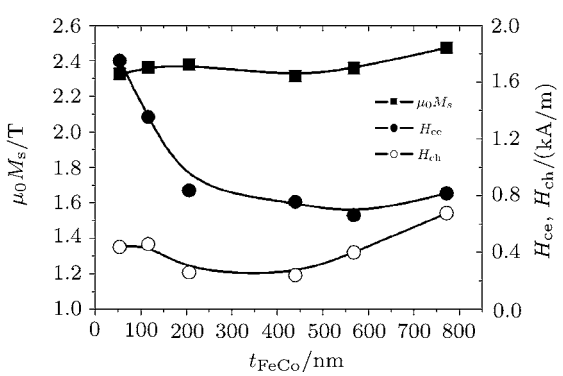


Fig.3. (a) Dependences of saturation magnetization $\mu_0 M_s$, easy axis coercivity H_{ce} and hard axis coercivity H_{ch} on t_{FeCo} in FeCo(t nm)/Co (5 nm) films.

the Co underlayer thickness t_{Co} may help one understand the effect of the Co better. The dependences of $\mu_0 M_s$, H_{ce} and H_{ch} of FeCo (200 nm) films on t_{Co} are shown in Fig. 2(a). It is clear that the easy and hard axis coercivities drop from 7.48 kA/m and 6.77 kA/m to 0.76 kA/m and 0.25 kA/m, respectively, when a 2-nm Co underlayer is located beneath the

FeCo film, and increase slightly when the Co underlayer goes up to 30 nm in thickness. The films show almost no dependence of $\mu_0 M_s \sim 2.35$T on t_{Co}. As seen in Fig.2(b), a very interesting phenomenon of texture change is observed. The Co underlayer tailors the preferred orientation from (200) in the FeCo without a Co underlayer to (110) in the FeCo with a Co underlayer. It indicates that the Co underlayer modifies the interface energy that determines the formation of crystallographic orientation during the initial growth of FeCo. Figure 3 shows the magnetic properties as a function of FeCo thickness for FeCo (t nm)/Co (5 nm). The film keeps good soft magnetic properties with t_{FeCo} ranging from 200 to 500 nm.

Coercivity of the Co underlayer is about 4.0–2.4 kA/m with the thickness varying from 3 to 30 nm. A pure magnetostatic consideration would give a large average coercivity in FeCo/Co films. Therefore, the observed magnetic softness should be closely related to the microstructural alteration in FeCo/Co film. Cross sectional TEM is used to study the microstructural properties of the films with or without a Co underlayer. Figures 4(a) and (b) show the TEM micrographs of FeCo single layer and FeCo/Co (5 nm) films, respectively. Both FeCo and FeCo/Co films show the existence of columnar grains. For FeCo films directly deposited on glass, there are very coarse grains with the size ranging from 20 nm to 130 nm; the average grain size is about 70 nm. In contrast, the FeCo film with a Co underlayer shows the existence of much smaller grains, with the size ranging from 4 to 15 nm; the average grain size is about 10 nm. The interface and the surface of the films deposited on the Co underlayers are smoother than FeCo films on the glass substrates.

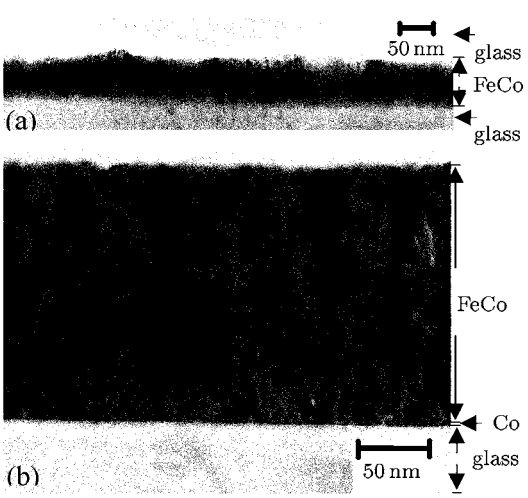


Fig.4. Cross-sectional TEM images for the FeCo single layer (a) and FeCo/Co (5 nm) film (b).

The soft magnetic properties in nanocrystalline ferromagnetic films are related to the sizes of their fine grains. In Hoffmann's ripple theory,[11] the wall coercivity of a thin polycrystalline film can be expressed as

$$H_C = \frac{\beta\sqrt{2}\sqrt{D}S}{L\pi\mu_0 M_S}\left(\frac{K_u}{A}\right)^{1/4},$$

where β is a fitting factor, L is the coupling length approximated by $(A/K_1)^{1/2}$, A is the exchange constant, K_1 is the magnetocrystalline anisotropic constant, D is the average grain size, S is the structure factor given by $K_{local}D/n^{1/2}$, K_{local} is the local anisotropy, n is the number of grains in the thickness, and K_u is the induced uniaxial anisotropy. Recently the expressions for the local anisotropy K_{local} have been conveniently given by Zou *et al*[12] as a function of the magnetocrystalline anisotropic constants K_1 and K_2, the magnetostriction constants λ_{100} and λ_{111}, and isotropic planar stress σ for different preferred orientations. In the present case, the fact that λ_S does not change for the two FeCo orientations with and without a Co underlayer, implies that $\lambda_{100} \cong \lambda_{111} \cong \lambda_S$. This means that in this alloy, K_{local} does not depend on σ. Assuming bulk values[1] of $K_1 = 7.3 \times 10^3$ J/m^3 and $K_2 = 2.5 \times 10^3$ J/m^3, $A = 2.0 \times 10^{-11}$ J/m, and $n = 1$, the ratio of the calculated coercivity in the (200) orientation without a Co underlayer to that in the (110) orientation with a Co underlayer (5 nm) using the measured values of D and K_u is 15.6. The measured ratio is 9.8. We demonstrate that the primary effect of the Co underlayer is to reduce the grain size, which causes a reduction in H_c. This is quantitatively consistent with ripple theory.

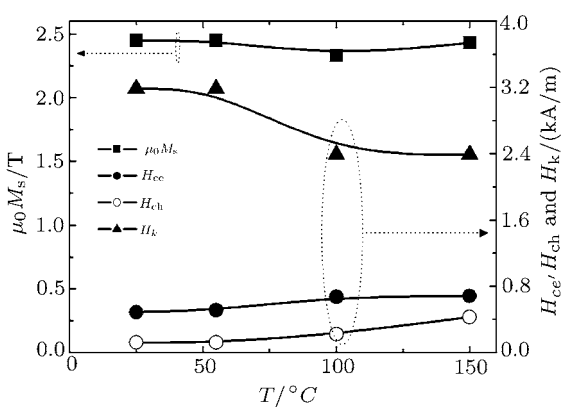


Fig.5. Saturation magnetization $\mu_0 M_s$, anisotropic field H_k, easy axis coercivity H_{ce} and hard axis coercivity H_{ch} as a function of substrate temperature T_S in FeCo(200 nm)/Co(5 nm) films.

Figure 5 shows the effect of substrate temperature T_S on magnetic properties for FeCo (200 nm)/ Co (5 nm). H_c is found to increase with T_S increasing. It indicates that the soft magnetic properties cannot be improved by T_S. The anisotropy reduces with the increase of T_S. The hard axis loop of the films show large remanence at $T_S = 150°C$ even if the applied magnetic field is as high as 24 kA/m. This means that the in-plane uniaxial anisotropy is not just controlled by the field-induced anisotropy.

The hard axis loops at different d_{T-S} are shown in Fig. 6(a). The anisotropic field increases to a maximum of 14.3 kA/m when d_{T-S} changes from 16.5 cm to 18 cm. Further increasing d_{T-S}, the uniaxial anisotropy is found to decrease, accompanying with the increase of H_c. From the XRD pattern (Fig. 6(b)), the crystallographic orientation is not modified, but a slight shift towards the smaller angle of the (110) peak is observed at 44.9° for films at $d_{T-S} = 16.5$ cm and 44.7° for films at $d_{T-S} = 19.7$ cm. This can be explained by the change in film stress. The film has a large intrinsic tensile stress of 0.7 GPa at $d_{T-S} = 16.5$ cm and the stress reduces with d_{T-S}. As d_{T-S} increases, in-plane film becomes more compressive, resulting in a Poisson specific 'tension' in the d-spacings normal to the plane of the film which is measured by XRD. The mechanism of the anisotropy in FeCo/Co films, induced by changing d_{T-S}, results most likely from the modification of the short range order,[13] columnar growth morphology with different oblique angles,[14] and/or an anisotropic residual stress. The sputtering process in FTS is different from that in conventional sputtering. The film deposited on the substrate is mainly caused by the scattering that occurs when the sputtered atoms collide with the atoms of gas in the space between the target and substrate. The amount, energy and incident angle of Fe(Co) atoms arriving at the substrate will depend on d_{T-S}. In fact, the film thickness decreases with the increase of d_{T-S}. The columnar grain growth is also observed for the FeCo/Co film at normal d_{T-S}. The columnar grain of FeCo is tilted up to stand on the Co underlayer with the column diameter increasing towards the top surface (see Fig.4). Therefore, the film microstructure is a critical factor to control the uniaxial magnetic anisotropy.

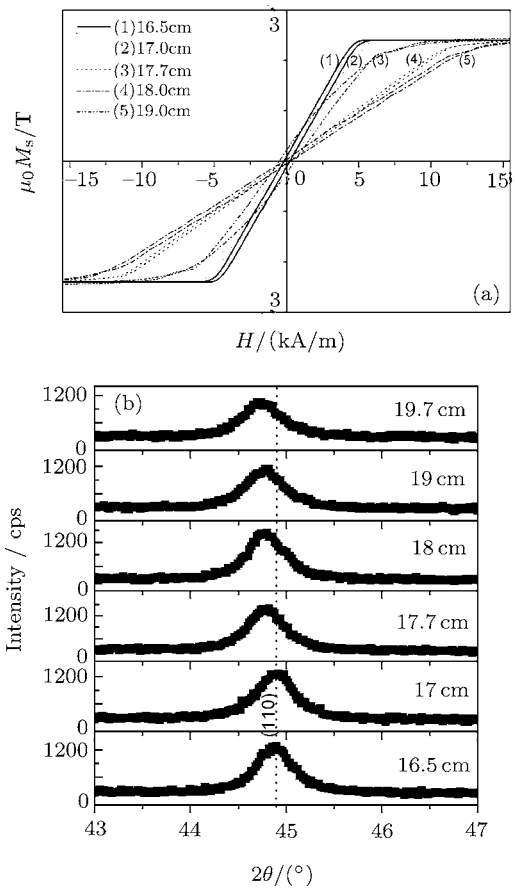


Fig.6. (a) The hard axis loops of FeCo/Co films at different d_{T-S}; (b) XRD patterns of FeCo/Co films at different d_{T-S}.

4. Conclusions

The soft magnetic properties of the sputtered FeCo films strongly depend on the underlayer and deposition conditions. These changes in properties are related to the microstructural evolution, especially a remarkable reduction in grain size. Samples show excellent soft magnetic properties with $\mu_0 M_s \sim 2.35$T, $H_c \sim 0.25$ kA/m and $H_K \sim 4.8$ kA/m for FeCo (200 nm)/ Co (5 nm). An anisotropic field as high as 14.3 kA/m is induced by controlling d_{T-S} and does not bring about any deterioration to the soft magnetic properties.

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