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Tuning magnetic anisotropy of amorphous CoFeB film by depositing on convex flexible substrates

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We have investigated the magnetic properties of amorphous $Co_{40}Fe_{40}B_{20}$ (CoFeB) thin films grown on flexible polyimide (PI) substrates, which were fixed on convex molds with different curvatures during the magnetron sputtering deposition. When the flexible substrates were changed from convex to flat state after fabrication, a uniaxial magnetic anisotropy was induced in the CoFeB film due to magnetostrictive effect. Furthermore, the anisotropy also depends on the thicknesses of the film and substrate. Our results demonstrate a convenient method to tune the anisotropy of magnetic thin films grown on flexible substrates.
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I. INTRODUCTION

Magnetic anisotropy, which determines the magnetization easy axis, is essential for many devices such as magnetic recording, magnetic sensors, microwave devices, and so on.[1–3] Materials with different magnetic anisotropy are needed for various applications.[4–7] Therefore, tuning the anisotropy of magnetic materials is of vital importance and has attracted a lot of attention. Various methods, including oblique deposition,[8] annealing in magnetic field,[9] cluster beam deposition,[10] and bending the substrate during film deposition,[11,12] have been investigated. Recently, we studied the magnetic properties of amorphous $Co_{40}Fe_{40}B_{20}$ (CoFeB) thin films on flexible substrates, which show that the anisotropy can be effectively tuned by strain partially due to the negligible magnetocrystalline anisotropy.[13,14]

We have fabricated amorphous CoFeB thin films on pre-bent flexible polyimide (PI) substrates, which have excellent thermal stability, good mechanical, optical, electrical, and chemical properties.[15] Due to magnetostrictive effect, the uniaxial magnetic anisotropy of amorphous CoFeB can be enhanced by increasing the pre-strain of the flexible substrates during film growth. Combined with the roll-to-roll technique,[16,17] we propose a method to grow flexible magnetic films with controllable magnetic anisotropy.

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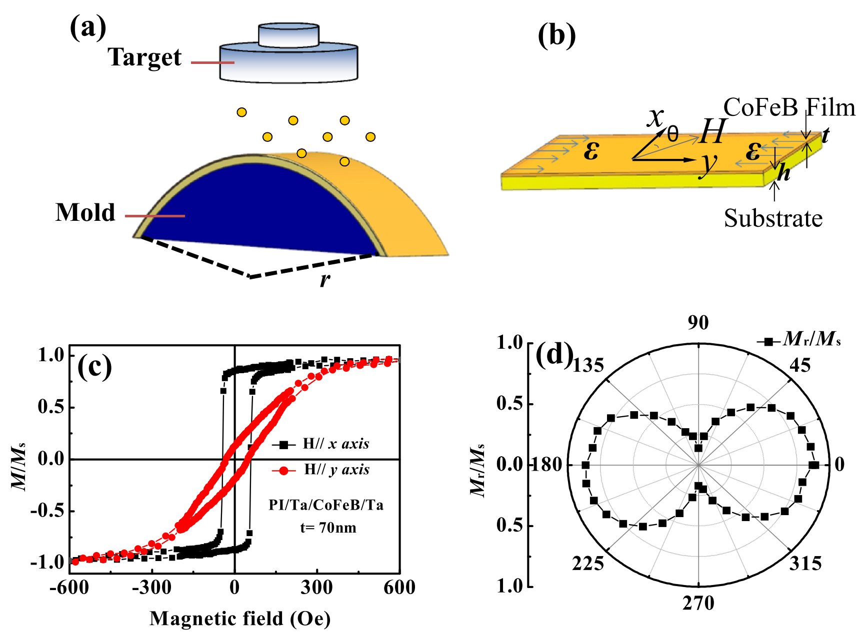

FIG. 1. (a) An illustrative drawing of the experimental set-up for sample fabrication, (b) diagram of the flatten state of magnetic film, (c) hysteresis loops of 70 nm CoFeB along x and y direction, (d) angular dependence of normalized M_r/M_s of 70nm CoFeB film.

II. EXPERIMENTAL

CoFeB thin films of different thickness were grown on PI substrates at room temperature (RT) using DC magnetron sputtering. The base pressure of the sputtering chamber is lower than $7.5*10^{-5}$ Pa. Before being placed into the sputtering chamber, the PI substrates were cleaned ultrasonically in ethanol for 15min, and then dried with nitrogen gas. The substrates were fixed on molds using double-sided tape with different curvatures, represented by the mold radii, as shown in Fig. 1(a). During deposition, the Ar flow was kept at 10.6 sccm and the pressure was set at 0.1 Pa. The deposition power and the distance between the target and the substrate were kept at 40 W and 50 mm, respectively. The deposition rate was 6 nm/min. Prior to be taken out of the chamber, 3 nm Ta layer was deposited on the CoFeB films to prevent oxidation. The hysteresis loops were measured using vibrating sample magnetometer (VSM, Lakeshore 7410) at room temperature.

III. RESULTS AND DISCUSSION

After deposition, once the samples are released from the convex molds and flattened, a compressive stress is induced to the film as shown in Fig. 1(b). Fig. 1(c) shows the magnetic hysteresis loops of a 70 nm CoFeB film on PI substrates with the magnetic field along x and y direction, respectively. Due to the positive magnetostriction of CoFeB, the compressive strain will induce a magnetic anisotropy in the film.[13] Fig. 1(d) shows the angular dependence of normalized remanent magnetization (M_r/M_s), which oscillates with 180° periodicity showing a uniaxial magnetic anisotropy in the CoFeB film. During the measurements, H is rotated within the xy plane with θ being the angle between H and x direction. It shows that the easy axis is along x direction and the hard axes along y direction, and M_r/M_s has a maximum value when H is parallel to the easy axis. Our results demonstrate that the magnetic anisotropy of amorphous CoFeB films can be effectively tuned by controlling the strain state of the substrate during film growth.

In the process of tuning magnetic anisotropy of CoFeB films as shown in Fig. 1(a)&1(b), several factors should be taken into consideration, such as the curvature of the substrate, the thicknesses of film and substrate *etc*. Figure 2 shows the hysteresis loops of 30 nm CoFeB films grown on substrates with different curvatures, which were measured along the x and y axis, respectively.

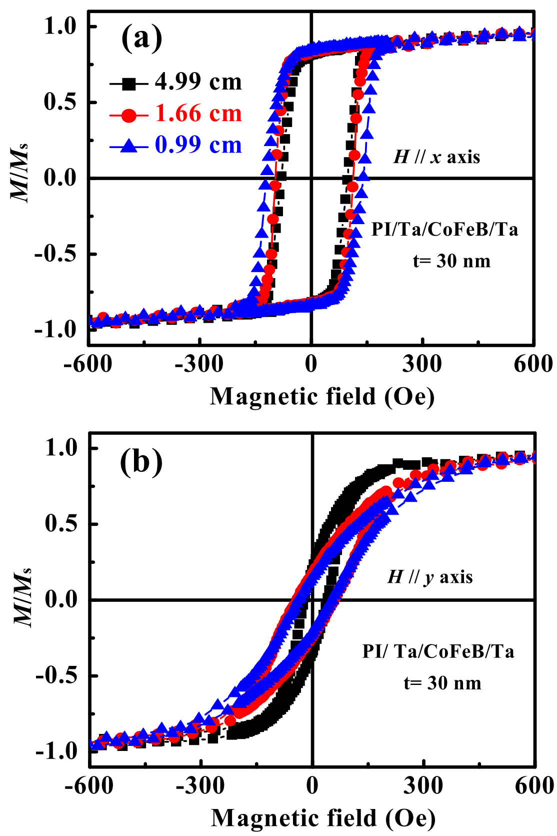

FIG. 2. Hysteresis loops of 30 nm CoFeB films grown under various curvature radii: (a) magnetic field parallel to the easy axis, (b) Magnetic field parallel to the hard axis.

With decreasing of curvature from 4.99 cm to 0.99 cm, the M_r/M_s along the $x(y)$ axis changes from 0.80 (0.23) to 0.90 (0.10). An anisotropy field (H_k) is introduced to describe the change of magnetic anisotropy quantitatively, which is defined as the difference in magnetic fields required to reach saturation magnetization along hard and easy axis, respectively [$H_k = H_{sat}$ (hard) – H_{sat} (easy)].[18–20] Here, we summarize the various factors that may influence the magnetic anisotropy. The compressive strain generated on the film will be increased when the curvature of the mold increases, which will give rise to a larger uniaxial magnetic anisotropy as shown in Fig. 3(a). Investigations on films with difference thicknesses show that the anisotropy field is enhanced with increasing CoFeB film thickness at a given mold curvature [Fig. 3(b)]. Thus, we can obtain the desired magnetic anisotropy by changing the thickness of the CoFeB film of the substrate mold curvature. Furthermore, the magnetic anisotropy also increases when the thickness of substrate is increased as shown in Fig. 3(c).

$$\frac{L}{L + \Delta L} = \frac{r + \frac{(t+h)}{2}}{r + t + h} \tag{1}$$

$$\varepsilon = \frac{\Delta L}{L} = \frac{h + t}{2r + h + t} = 1 - \frac{2r}{2r + h + t} \tag{2}$$

$$\delta = \varepsilon E_f/(1 - \gamma^2) \tag{3}$$

In order to understand how these factors affect the magnetic anisotropy, we propose a model as shown in Fig. 3(d). When the film/substrate is fixed on the convex mold, there is a tensile strain ΔL on the top surface and a compressive strain at the bottom. Assuming the original length of the substrates is L, $\Delta L/L$ is defined as the compressive strains ε that will be introduced to the CoFeB film when the sample is flattened. The value of ΔL can be obtained from equation (1), where r is the

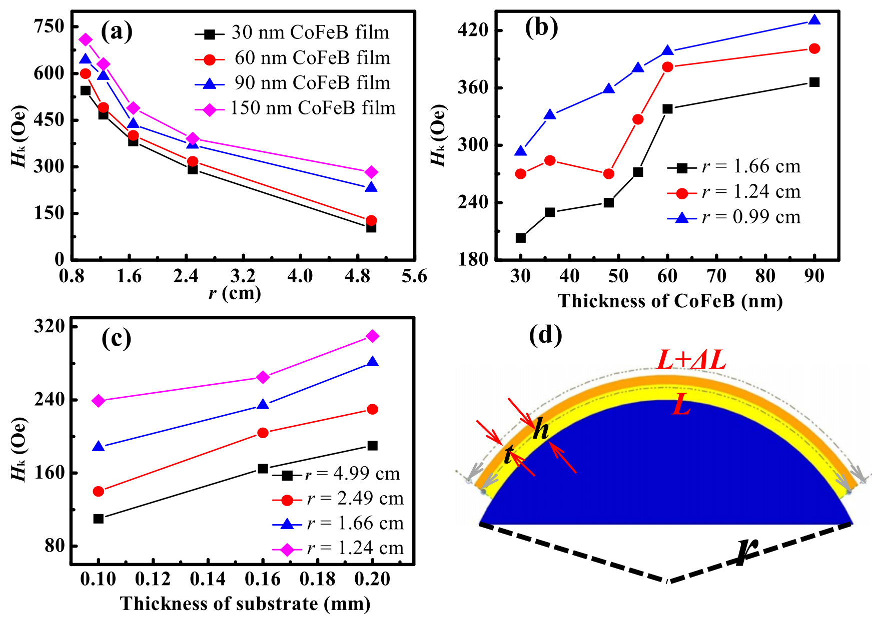

FIG. 3. (a) the curvature radii dependence of the anisotropy field (H_k) for CoFeB films with different thicknesses, (b) the thickness of film dependence of the anisotropy field (H_k) with different curvature radii, (c) the thickness of substrate dependence of the anisotropy field (H_k) for CoFeB films with different curvature radii, (d) the diagram of the sample for explain the relationship of influencing factor.

radii of the mold, h is the thickness of the substrate, and t the thicknesses of the CoFeB film. The corresponding stress δ in the film is represented by equation (3), where E_f is the Yong's modulus (E_f = 160 GPa for CoFeB), v is the Poisson ratio (v = 0.3 for metals).[21,22] From equation (2), we can clearly see that ε can be increases by reducing the substrate curvature, increasing the thicknesses of the film or substrate, resulting in larger compressive stress in the film when the sample is flattened.

IV. CONCLUSIONS

In summary, we have investigated the magnetic properties of amorphous CoFeB films deposited on flexible PI substrates fixed on convex molds. Uniaxial magnetic anisotropy is introduced to the CoFeB film due to magnetostrictive effect. The magnetic anisotropy strongly depends on the substrate curvature, the thicknesses of both the film and the substrate. Combined with the roll-to-roll deposition technique, it is possible to achieve large-scale preparation of flexible magnetic films with controllable magnetic anisotropy.

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