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Effect of magnetic layer thickness on magnetic properties of Ce-Fe-B thin films☆

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ABSTRACT

The $Ce_2Fe_{14}B$ thin films with a notable out-of-plane *c*-axis texture were prepared by DC magnetron sputtering on a Ta buffer layer. The morphological and magnetic properties were investigated. The thickness of the magnetic layer had a dramatic effect on the formation of $Ce_2Fe_{14}B$ phase, and excellent magnetic properties ($H_{ci} \approx 4.25$ kOe, $M_r/M_s \approx 0.81$) were observed for the Ce-Fe-B film with the thickness $d_m = 200$ nm. The results of the hysteresis loops for Ce-Fe-B film ($d_m = 200$ nm) at various measured temperatures show that a decoupling between the hard and the soft phases is observed at low temperatures, which is due to the regions with quite low anisotropy provided by the α-Fe. Moreover, it is clear that significantly various magnetization behaviors between the films with $d_m = 200$ and 300 nm were observed with a similar trend due to the existence of the α-Fe soft phase.

1. Introduction

The $Nd_2Fe_{14}B$-type permanent magnets have been utilized in a wide range of applications due to their outstanding magnetic properties.[1–4] In particular, these magnets have been applied in automotive components such as the motors for hybrid vehicles, the electric vehicles and in power steering.[5,6] Besides, the scarcity and cost of the rare-earth (RE) metals, especially for Nd, Pr, Dy and Tb that are proven essential to the high performance $Nd_2Fe_{14}B$-type permanent magnets production, become the important limitations for the corresponding applications.[7–14] Consequently, it was required for certain economically quite attractive materials to be discovered. The Ce was of interest in this regard, since it was the most abundant and low cost rare-earth element in the world.[7,15,16] Theoretically, the $Ce_2Fe_{14}B$ compound, bearing the anisotropy field of 26 kOe,[17] could be identified as a potential candidate for $Nd_2Fe_{14}B$ magnets.

Actually, the magnetic properties of the $Ce_2Fe_{14}B$ compound were quite inferior to that of the $Nd_2Fe_{14}B$ compound. Since the magnetic properties of permanent magnets are sensitive to both microstructure and phase constitution, the differences between the Ce-Fe-B and the Nd-Fe-B magnets possibly lead to a high variation in magnetic properties. In this paper, the Ce-Fe-B films were prepared by DC magnetron sputtering and the effects of magnetic layer thickness on the magnetic properties were systematically investigated combining with the microstructural analysis and magnetic interaction in the magnetic materials.

2. Experimental

The nanocomposites Si/Ta (50 nm)/Ce-Fe-B (d_m nm)/Ta (40 nm) ($d_m = 50$, 100, 200 and 300 nm) multilayer films were deposited by DC magnetron sputtering using $Ce_{15}Fe_{75}B_{10}$ as a target. A buffer layer of Ta (50 nm) was firstly deposited onto a Si substrate, followed by the magnetic layer and finally a capping layer of Ta (40 nm). The films were deposited at a substrate temperature of 883 K followed an *in-situ* rapid thermal annealing at 923 K for 30 min in a base pressure below 7.0×10^{-5} Pa. In this paper, the Ta buffer layer and the capping layer were sputtered at room temperature for the easy axis of the $Ce_2Fe_{14}B$ grains to be aligned perpendicular to the film plane and for the magnetic film oxidation to be prevented, respectively. The thickness of the films was measured by weighing the samples. The phase constituent of the films was identified by the X-ray diffraction with Cu Kα radiation. Dimension Icon atomic force microscope (AFM) was used in the tapping mode for surface morphology investigations. The magnetic

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properties of the films were measured with a physical property measurement system (PPMS) and a vibrating sample magnetometer (VSM). Moreover, all hysteresis loops were measured along the direction perpendicular to the thin films.

3. Results and discussion

Fig. 1 demonstrates the X-ray diffraction $2\theta/(°)$ patterns of the Ce-Fe-B thin films with the various magnetic layer thicknesses of $d_m = 50, 100, 200$ and 300 nm. As shown in Fig. 1, it can be seen that the films with the notable c-axis texture were obtained. The most intensive peak was the (105) peak for the $Ce_2Fe_{14}B$ phase in the films with $d_m = 50$, 100, 200, and 300 nm, whereas other distinct peaks for the $Ce_2Fe_{14}B$ phase were the (004), (006) and (214) except for the films with $d_m = 50$ nm and 100 nm. This suggests that the $Ce_2Fe_{14}B$ grains grew almost with the *c*-axis along the substrate normal, naturally, with a certain misorientation. However, it was quite difficult to be determined whether the α-Fe existed in the films or not for the overlap between the α-Fe phase (100) peak and the $Ce_2Fe_{14}B$ (006) peak. On the other hand, due to the similarity of the chemical properties and the atomic mass between Ce atom and Nd atom, it was impossible to be individually distinguished clearly for the $Ce_2Fe_{14}B$ and $Nd_2Fe_{14}B$ phases from the XRD patterns. The $Ce_2Fe_{14}B$ phase peaks of the film with $d_m = 50$ nm were quite weaker and significantly less pronounced than that of the film with $d_m = 200$ and 300 nm, indicating that the $Ce_2Fe_{14}B$ phase formation in the film with $d_m = 50$ nm was not easy. Moreover, it is clearly observed from Fig. 1 that a large amount of the $CeFe_2$ phase existed in the films except for $d_m = 50$ nm. Furthermore, it is observed that the $Ce_2Fe_{14}B$ phase formation became quite easier as the magnetic layer increased.

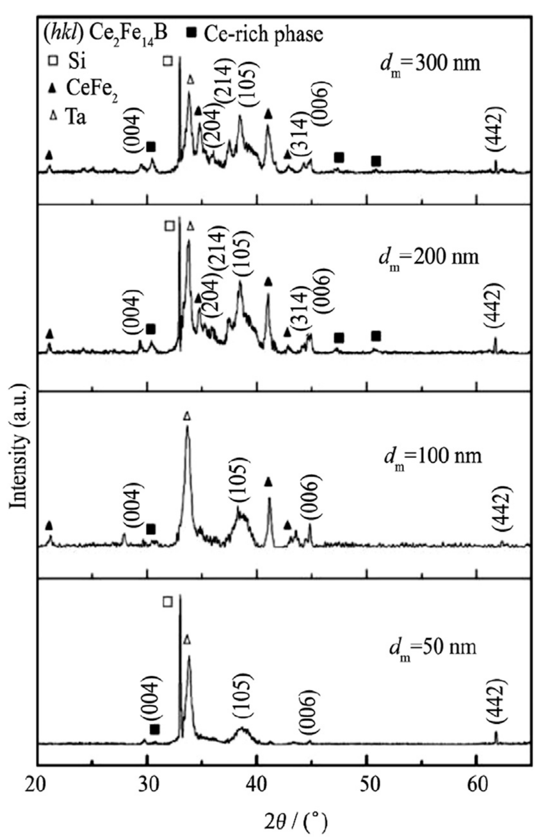

Fig. 1. XRD patterns for Si/Ta (50 nm)/Ce-Fe-B (d_m nm)/Ta (40 nm) multilayer thin films with various magnetic layer thicknesses.

The AFM images for the Si/Ta (50 nm)/Ce-Fe-B (d_m nm)/Ta (40 nm) ($d_m = 200$ and 300 nm) are shown in Fig. 2. The average grain sizes of the film samples with the thickness of 200 and 300 nm were calculated by software, respectively, at 124.15 and 152.90 nm. It is obvious from the figure that the grain size of the 200 nm thick film was smaller than that of the 300 nm thick film, but the grain size was more uniform, which had a great influence on the magnetic properties of the thin film. In addition, many grains in a 300 nm thick film were agglomerated together, which led to a decrease in magnetic properties.

The perpendicular hysteresis loops at room temperature for the Si/Ta (50 nm)/Ce-Fe-B (d_m nm)/Ta (40 nm) ($d_m = 50$, 100, 200 and 300 nm) multilayer films by annealing at 923 K for 30 min are presented in Fig. 3(a). No demagnetization correction was executed for all measurements. No hard magnetic behavior was observed in the films with $d_m = 50$ and 100 nm, because only a small amount of hard magnetic phases existed in these films. For the films with $d_m \geq$ 200 nm, the hysteresis loops possess good coercivity H_{ci} values higher than 3.8 kOe. The magnetic hysteresis loops of the film ($d_m = 200$ nm) with the external magnetic fields perpendicular (⊥)/parallel (//) to the film plane is demonstrated as an inset in Fig. 3(a). Regarding the film with $d_m = 200$ nm, both the remanent magnetization $M_{r\perp}$ and coercivity $H_{ci\perp}$ in the perpendicular

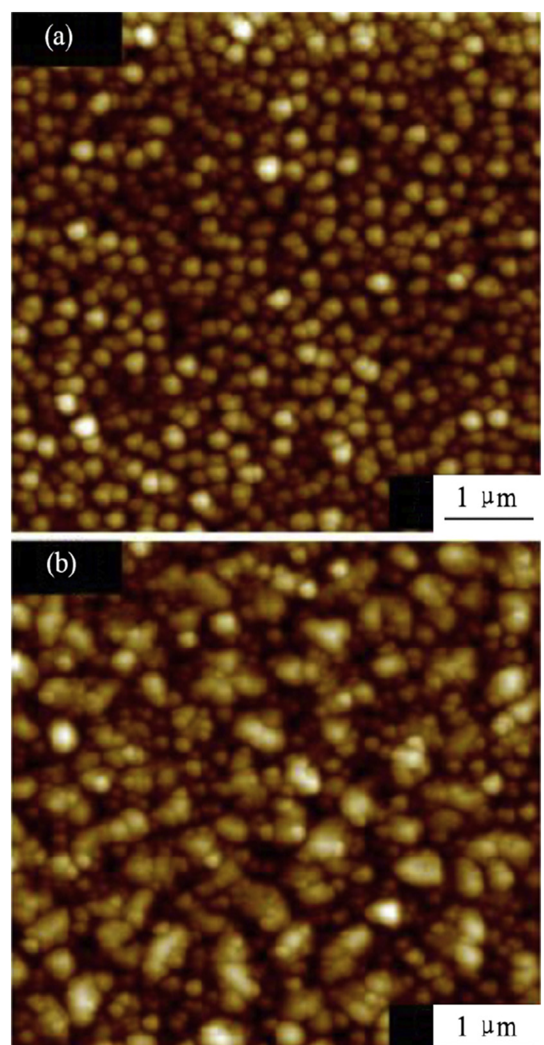

Fig. 2. AFM images for the Si/Ta (50 nm)/Ce-Fe-B (d_m nm)/Ta (40 nm) thin films with different thickness of 200 nm (a) and 300 nm (b).

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