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LETTER TO THE EDITOR

Perpendicular magnetic anisotropy of NdFe films

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Abstract. The perpendicular magnetic properties of NdFe alloy thin films have been studied on samples prepared by the facing targets sputtering method at a substrate temperature of 240–270 °C. All the films with Nd content over 35 at.% exhibit perpendicular magnetic anisotropy. The Curie and crystalline temperatures were about 400 K and 630 K, respectively. The x-ray diffraction patterns show that the uniaxial anisotropy of a NdFe film has a certain relation to the partial oxidation of Nd in the film. The direction of the magnetic easy axis is determined by the orientation of C–Nd_2O_3; (440)-oriented C–Nd_2O_3 contributes to the formation of a perpendicular magnetic film. It is proposed that the partial oxidation of Nd may induce some short range atomic order in NdFe films.

Research on light rare earth–transition metal (RE–TM) amorphous films, such as Nd(Pr)–Fe(Co), has become more and more attractive, because of their large magneto-optical (MO) rotation angle θ_k for MO recording applications and abundant storage in the earth (compared with heavy RE–TM) [1, 2].

Suzuki *et al* [3–5] have reported that a perpendicular magnetic anisotropy of 10^6–10^7 erg cm^{-3} could be induced in Nd(Pr)–Fe alloy films by RF sputtering at a substrate temperature of 200–250 °C. However, the details of the mechanism of perpendicular magnetic anisotropy of the films are still not clear. In order to understand further the origin of uniaxial anisotropy of NdFe films, a systematic investigation of x-ray reflective diffraction was made on Nd_xFe_{100-x} films.

Amorphous NdFe thin films were prepared by the facing targets sputtering system [6]. The distance between two parallel plane targets is 100 mm. For plasma confinement, a magnetic field from permanent magnets is applied perpendicular to each target plane. Pure Nd chips are put on Fe targets. The compositions of the films were controlled by altering the areas of Nd chips. The substrate is located in a plasma-free region and it is not necessary to consider the bombardment by high energy particles, such as electrons and negative ions, so the substrate is cool enough and amorphous NdFe films can be obtained without being cooled. The preparation conditions of Nd_xFe_{100-x} films are shown in table 1.

The composition of the films was determined by electron probe microanalysis (EPMA). The uniaxial anisotropy constant K_u was obtained by torque measurement. Saturation magnetisation, M_s, and magnetic hysteresis loops, M–H, were obtained with

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Table 1. Preparation conditions of Nd_xFe_{100-x} thin films.

Target type	Composite
Substrate	Glass
Residual gas pressure (Torr)	3×10^{-6}
Pressure of Ar gas (Torr)	5×10^{-3}
Applied voltage (V)	340–380
Discharge current (A)	0.3–0.4
Substrate temperature T_s (°C)	240–260
Deposition rate (nm min^{-1})	20
Film thickness (Å)	5000–6500

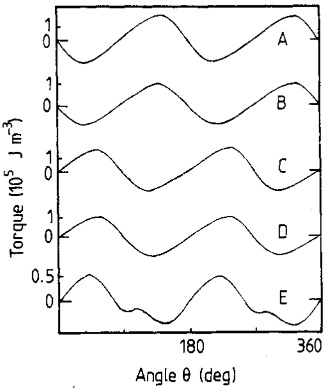

Figure 1. The torque curves of Nd_xFe_{100-x} thin films. A: $x = 23$; B: $x = 27$; C: $x = 35$; D: $x = 41$; E: $x = 45$.

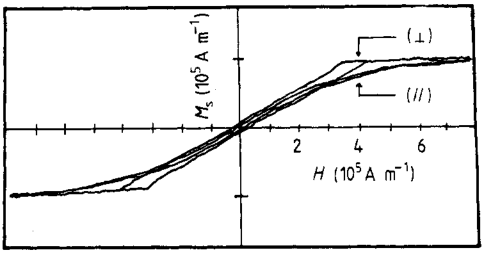

Figure 2. The M–H loops of $Nd_{35}Fe_{65}$ thin film. (⊥): magnetic field is perpendicular to the film plane. (‖): magnetic field is parallel to the film plane.

a vibrating sample magnetometer (VSM). The dependence of M_s on temperature was measured using a balance magnetometer above room temperature. The structure of the films was examined by x-ray diffraction.

The direction of the easy axis and uniaxial anisotropy constant K_u of NdFe films were primarily investigated by torque measurement under a magnetic field of 8×10^5 A m^{-1}; see figure 1. The initial directions of the external magnetic field were perpendicular to the film planes for all the torque curves. Samples A and B exhibit negative sine-type curves, and samples C, D and E show positive sine-type curves (the external magnetic field was not strong enough for sample F). It is indicated that the easy axis of the NdFe films was in-plane when the Nd content was less than 27 at.% and perpendicular to the film plane when the Nd content was over 35 at.%. This result can also be confirmed by M–H loops of the films. Figure 2 shows the typical M–H loops of the perpendicular magnetic NdFe films. It was investigated along normal (⊥) and in-plane (‖) directions.

Figure 3 shows the concentration dependence of the intrinsic uniaxial anisotropy constant K_u, perpendicular anisotropy energy $K_\perp(\equiv K_u - 2\pi M_s^2)$ and static magnetic energy $2\pi M_s^2$ for the NdFe films. $2\pi M_s^2$ declines monotonously with the increase of Nd content. K_u increases slowly in the beginning and $K_\perp = K_u - 2\pi M_s^2 < 0$; the film exhibits in-plane magnetisation. When the Nd content is over 27 at.%, K_u rises rapidly and declines afterwards, but $K_\perp = K_u - 2\pi M_s^2$ remains positive, so the films show perpendicular magnetisation.

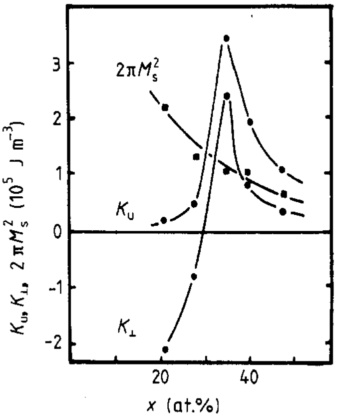

Figure 3. The concentration dependences of K_u, $K_\perp$ and $2\pi M_s^2$ for Nd_xFe_{100-x} thin films.

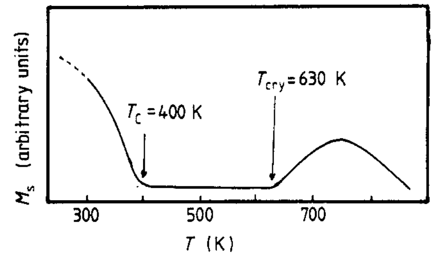

Figure 4. The dependence of saturation magnetisation M_s on temperature for $Nd_{45}Fe_{55}$ thin films.

Figure 4 shows the dependence of the saturation magnetisation M_s on temperature for $Nd_{45}Fe_{55}$ films. The Curie temperature T_C and the crystallisation temperature T_{cry} are 400 K and 630 K, respectively.

In order to obtain a better understanding of the origin of the intrinsic anisotropy of NdFe films, systematic investigations of x-ray reflective diffraction have been made on NdFe films from 6° to 60° under the same examination conditions, as shown in figure 5. Samples A, B, C, D and E were prepared at a substrate temperature of 240–260 °C, while sample F was prepared at room temperature. It was noted that all of the samples prepared at room temperature have no apparent diffraction peaks, but the samples prepared at 240–260 °C have one or two obvious peaks at angle 28.0° or (and) 46.5°. The sizes of the crystallites are in the microcrystalline range. It is very noticeable that the variation of the two peaks shows a regular pattern; in particular, the change of the peak at 46.5° very closely corresponds to the change of uniaxial anisotropy K_u in figure 3. These results indicate that there may be some relationship between uniaxial anisotropy and the structure corresponding to the peak at 46.5°.

The calculations show that the two peaks do not belong to any Nd–Fe structure; they are BCC C–Nd_2O_3 (222) with $d = 3.20$ Å at 28.0° and (440) with $d = 1.96$ Å at 46.5°, respectively. This result is reasonable. The purity of Nd chips is not very high, and there may be an oxidic film on the surface of Nd chips. Moreover, O can be very easily combined with Nd to form C–Nd_2O_3 when the substrate is heated.

The results above show that the uniaxial anisotropy of NdFe film is related to the partial oxidation of Nd in the films. It could be explained that C–Nd_2O_3 may induce some short range order of Nd–Fe in NdFe films. The crystal lattice constant of C–Nd_2O_3 ($a = 11.08$ Å) is 1.5 times as long as that of cubic Fe_2Nd ($a = 7.45$ Å) [7]. The orientation of C–Nd_2O_3 fixed the orientation of the short range order of Nd–Fe and further determined the easy direction of the NdFe film. According to figures 3 and 5, the orientation of C–Nd_2O_3 varied from (222) to (440), while the directions of the easy axes of NdFe films changed from in-plane to normal. This shows that the orientation of (440) helps to support the easy axis perpendicular to the film plane.

Further calculations show that the lattice (440) is the most dense, so it is most easily formed. Any lattices (440) have other lattices (440) in a perpendicular direction. When

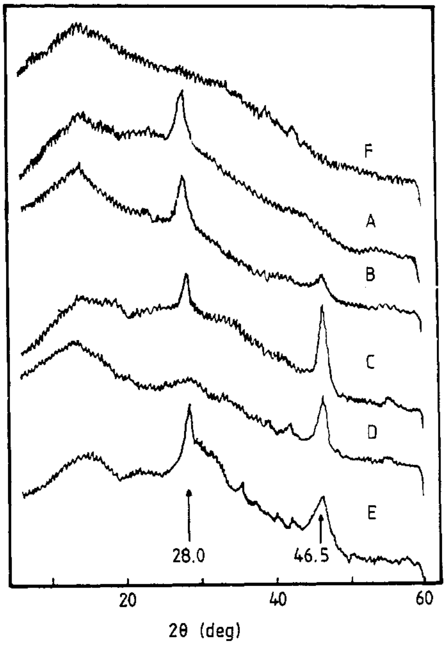

Figure 5. The x-ray reflective diffraction patterns of Nd_xFe_{100-x} thin films A: $x = 23$; B: $x = 27$; C: $x = 35$; D: $x = 41$; E: $x = 45$. Samples A, B, C, D, and E were prepared at $T_s = 240$–270 °C. Sample F was prepared at room temperature.

C–Nd_2O_3 is oriented according to (440), the lattice (440) in the perpendicular direction must be perpendicular to the film plane seen in the film surface. In other words, the stripey lattice C–Nd_2O_3 (440) with $d = 1.96$ Å should be seen in the surface of a perpendicular magnetic film. This deduction is exactly the same as the results found by Suzuki [5]. Through high resolution electron microscopic observation. Suzuki found some stripey short range atomic order with $d = 2.0$ Å in the amorphous matrix for perpendicular magnetic NdFe films [5].

According to the discussions above, we know that the uniaxial magnetic anisotropy of NdFe film is related to the partial oxidation of Nd in the film. It was proposed that partial oxidation of Nd may induce some short range atomic order in the films. The direction of the magnetic easy axis of the NdFe film is determined by the orientation of C–Nd_2O_3 in the film. (440)-orientation of C–Nd_2O_3 is useful for supporting the easy axis perpendicular to the film plane; however, details about the short range order of Nd–Fe are still not clear.

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