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Dependence of Magnetostriction of Sputtered Tb–Fe Films on Preparation Conditions

Y. Hayashi, T. Honda*, K. I. Arai, K. Ishiyama and M. Yamaguchi
Research Institute of Electrical Communication, Tohoku University, Sendai 980, Japan
*Sendai Research Laboratory, TOKIN Corporation, Sendai 982, Japan

***Abstract*-Amorphous Tb–Fe thin films prepared by sputtering method in the compositional range Tb_xFe_{1-x} (x=0–0.5) have been investigated in view of their potential for use in electromagnetic thin film actuators. We examined the magnetostriction and the coercive force for the Tb–Fe films for different sputtering conditions to obtain both soft magnetic properties and large magnetostriction in this system. As a result, we obtained Tb–Fe thin films having large magnetostrictions (180×10^{-6} at 1kOe) and low coercive force (60–70 Oe). These films were prepared under the conditions of the composition of 45–50at%Tb, Ar gas pressure of 4mTorr, rf input power of 200W and using water cooled substrates. A trial actuator using magnetostrictive thin films is also reported.**

INTRODUCTION

The cubic Laves phase rare earth–Fe_2 alloys are known to possess large magnetostriction constants at room temperature[1]. In particular, $TbFe_2$ crystalline alloys have magnetostriction above 1500×10^{-6}. However they require very large magnetic fields to achieve their large magnetostriction because of large magnetocrystalline anisotropies. In order to reduce the magnetocrystalline anisotropy, Clark alloyed negative and positive magnetocrystalline anisotropic materials such as $(Tb-Dy)Fe_2$[2] in bulk form. Another method to eliminate the magnetocrystalline anisotropy is to prepare amorphous state at the expense of the decrease of magnetostriction due to the degeneration of total anisotropy energy.

In the $TbFe_2$ amorphous films[3–5], the magnetostriction of 400×10^{-6} at 25kOe with the coercive force of 120 Oe was successfully obtained[4]. These characteristics are acceptable for applications. However, there are no systematic study of the magnetostriction at low field for the Tb–Fe films, although it is an important design parameter for magnetic devices such as actuators and sensors.

In this paper, we investigated the possibility of obtaining the Tb–Fe thin films having large magnetostriction in small field. The sputtering conditions and the film compositions to realize both soft magnetic properties and large magnetostriction in this system were examined.

In addition, bending properties of a cantilever type actuator, which are made up of magnetostrictive thin films on polyimide substrate, were also reported.

EXPERIMENTAL

The $Fe_{100-x}Tb_x$(x=0–50at%) films were prepared by an rf-magnetron sputtering method. The targets used were composed of a iron (99.99%) target and Tb (99.9%) tips on it. The sputtering conditions were as follows;

rf input power: 100–400W
argon gas pressure: 4–40mTorr
film thickness: $1\mu m$
substrate temperature: water cooled or heated up to 300°C

The coercive force was measured by a VSM in the field of 18kOe parallel to the film plane. The magnetostriction was measured by using a three terminals capacitance method[6] at the maximum field within 16kOe. The field was rotated parallel to the film plane. Fig. 1 shows the structure of the capacitance cell used in this measurement. The movable electrode is the magnetic thin film on the substrate. Capacitor is composed between this movable electrode and fixed electrode. The three terminals are composed of these electrodes and shield case.

The magnetostriction λ[7] is calculated as follows;

$$\lambda = \frac{2}{3}\,\frac{\Delta D\,(1+\nu_f)E_s\,t^2}{3L^2E_f\,d\,(1-\nu_s)} \qquad (1)$$

In this equation E_f, E_s and ν_f, ν_s are Young's modulus and Poisson's ratios of the thin film and the substrate, respectively, and ΔD is the variation of distance between the electrodes, t and d are the thickness of the substrate and the film, and L is the film length.

Cantilever type actuators were made by sputtering Tb–Fe and Sm–Fe on both sides of polyimide substrates. The bending properties of these actuators were measured using the same capacitance cell used for magnetostriction measurements.

RESULTS and DISCUSSIONS

First we examined the dependence of the film composition on the rf input power and Ar gas pressure. The oxides of Tb_2O_3 and $\gamma-Fe_2O_3$ were observed by X-ray diffraction pattern about Tb–Fe films prepared in the conditions at 400W of rf input power or at 40mTorr of Ar pressure. When Ar pressure is high, the thin film can contain Ar atoms and it is easily oxidized. Therefore we prepared the Tb–Fe films at 200W of rf input power and 4mTorr of Ar pressure. This sputtering condition was used in all the following examinations.

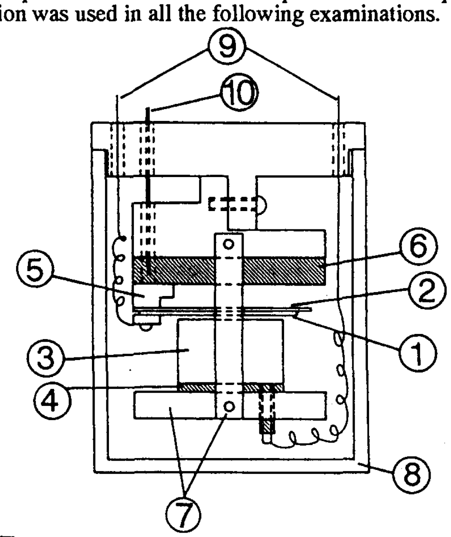

Fig. 1 The structure of the capacitance cell.
(1:moving electrode(magnetic thin film), 2:substrate, 3:fixed electrode, 4:isolator, 5:sample holder, 6:isolator, 7:fixed electrode holder, 8:shield case, 9:lead wire, 10:thermo-couple)

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We examined the dependence of the magnetic properties on the substrate temperature because it is one of the basic sputtering conditions. Fig. 2 shows the substrate temperature dependence of the coercive force. The coercive force kept a constant value up to 200°C and the value increased, reached a maximum value at 270°C and finally decreased at 300°C.

We measured the X-ray diffraction patterns to examine the causes of the behavior of magnetic properties under the substrate temperature. Fig. 3 shows the X-ray diffraction patterns for different substrate temperatures. The diffraction peaks were not observed up to 200°C, but at 270°C the peaks of the oxides of Tb_2O_3 and γ-Fe_2O_3 were observed. At the substrate temperature of 300°C single phase of α-Fe was also observed. For this reason the coercive force was low value at substrate temperature of 300°C. Therefore we prepared the Tb-Fe films on the water cooled substrates to avoid oxides in the Tb-Fe films.

Fig. 4 shows the magnetostriction at 16kOe of the films while varying Tb content. The magnetostriction was maximized at the 30-40at%Tb-Fe films. However it is important to possess large magnetostriction at lower field.

Fig. 5 shows the magnetic field dependence of the magnetostriction about the films with three kinds of Tb content. Though the magnetostriction of the Fe-36.1at%Tb is the largest at 16kOe, it is smaller than that of Fe-46.9at%Tb at low field such as 1-2kOe. The magnetostriction of Fe-46.9at%Tb rapidly increased with increasing the magnetic field. The value of 180×10^{-6} at 3kOe was larger than that of the other compositions at low field. The coercive force at this composition was 60-70 Oe, which is comparatively low value.

The tendency shown in Fig. 5 is thought to be related to the magnetic anisotropy. It is reported that easy-axis of Tb-Fe sputtered film is normal to the film plane[7] and the magnetic anisotropy changes with the Tb content[8]. We measured M-H loop of the films of the varied composition. Fig. 6 shows M-H loops of Tb-Fe films containing 36.1at% and 46.9at% Tb. Fig. 6 (a) shows that the film of Fe-36.1at%Tb has the magnetic easy-axis in normal direction to the film plane. In this study the films of 18-40at%Tb-Fe were found to have the perpendicular magnetic anisotropy. Fig. 6 (b) shows the M-H loop of Fe-46.9at%Tb. This film has large permeability in parallel to the film plane since the film has easy-axis parallel to the film plane. Therefore the film has large magnetostriction in a small field. These results say the Tb-Fe thin films have high potential for thin film actuators.

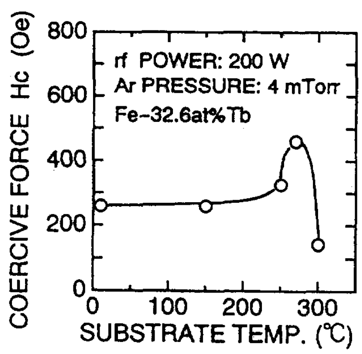

Fig. 2 Dependence of the coercive force of the Tb-Fe films on substrate temperature.

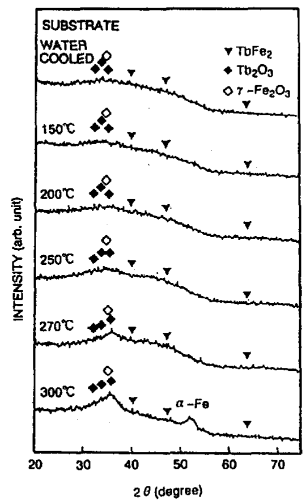

Fig. 3 The X-ray diffraction patterns while varying the substrate temperature.

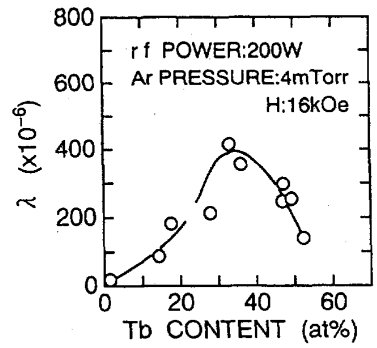

Fig. 4 Dependence of the magnetostriction of the Tb-Fe films on Tb content.

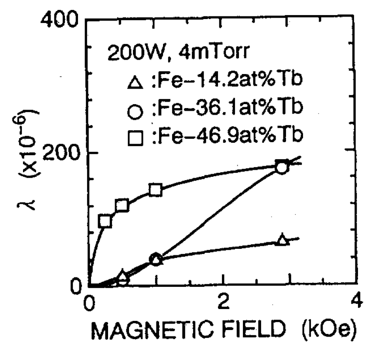

Fig. 5 Dependence of the magnetostriction of the Tb-Fe films with three kinds of Tb content on the applied field.

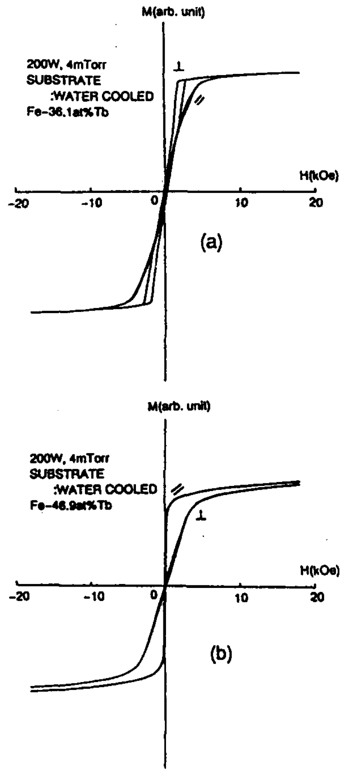

Fig. 6 M-H loops of Tb-Fe films.

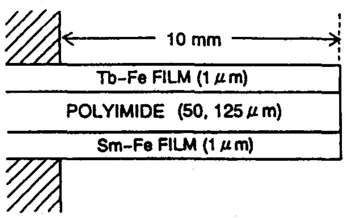

Fig. 7 General view of micro actuator.

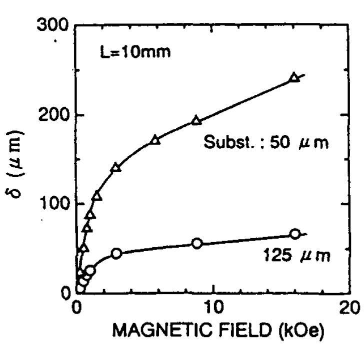

Fig. 8 Applied field dependence of displacement of the cantilever type actuator.

Using the magnetostrictive thin film, we tried to obtain a thin film actuator. A general view is shown in Fig. 7. The composition of the sputtered magnetostrictive films on both sides of a polyimide substrate were measured as Fe-51.4at%Tb and Fe-39.5at%Sm. Sm-Fe alloy has negative magnetostriction while Tb-Fe has positive one. Therefore the specimen having Tb-Fe and Sm-Fe film on both sides expected to bend remarkably in magnetic field.

The results are shown in Fig. 8. The displacement δ was measured at the free end of the cantilever. The length of the cantilever was 10mm. The thicknesses of the polyimide substrate are 50μm and 125μm. The displacement increased with the increase of the magnetic field. With the substrate thickness of 50μm, the displacement was 250μm at 16kOe and 90μm at 1kOe. These values are almost same or larger than that of other cantilever type actuators such as piezoelectrical[9] or thermal expansive[10] ones.

Conclusion

We investigated the magnetostriction of amorphous Tb-Fe films at low field for different compositions and sputtering conditions. As a result, Tb-Fe films having easy-axis parallel to the film plane were obtained under the conditions of rf input power of 200W, Ar pressure of 4mTorr, and the composition of 45-50at%Tb. Those films had large magnetostriction as 180×10^{-6} at low field of 3kOe, and low coercive force as 60-70 Oe. Using the magnetostrictive amorphous film of Tb-Fe and Sm-Fe, the cantilever type micro actuator having large displacement was obtained.

Acknowledgment

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