Journal of Magnetics 2(3), 76-85 (1997)

Magnetic and Magnetostrictive Properties of Amorphous Tb-Fe and Tb-Fe-B Thin Films

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(Received 11 August 1997)

Magnetic and magnetostrictive properties of Tb-Fe and Tb-Fe-B thin films are systematically investigated over a wide composition range from 40.2 to 68.1 at.% Tb. The films were fabricated by rf magnetron sputtering using a composite target which consists of an Fe plate and Tb chips. The microstructure, examined by X-ray diffraction, mainly consists of an amorphous phase and, at high Tb contents, a pure Tb phase also exists. A progressive change in the direction of anisotropy from the perpendicular to in-plane occurs as the Tb content increases and the boundary at which the anisotropy change occurs shifts significantly towards to higher Tb contents with the addition of B. The saturation magnetization exhibits maxima at the Tb contents of 42 and 48 at.% for Tb-Fe and Tb-Fe-B thin films, respectively, and it is decreased by the addition of B. The coercive force, measured in the easy direction, decreases monotonically with the Tb content. Excellent magnetostrictive characteristics, particularly at low magnetic fields, are achieved in both Tb-Fe and Tb-Fe-B thin films; for example, a magnetostriction of 138 ppm is obtained in a Tb-Fe-B thin film at a magnetic field as low as 30 Oe. The excellent magnetostrictive properties of the present thin films are supported by the equally excellent magnetic softness, the coercivity below 10 Oe and a typical squared-loop shape with the saturation field as low as 1 kOe. Due to the excellent low field magnetostrictive characteristics, the present Tb-Fe based thin films are thought to be suitable for Si based microdevices.

I. Introduction

Giant magnetostriction at room temperature of the order of 2500 ppm (2.5×10^{-3}) was first reported about 25 years ago by Clark and Belson [1] and Koon et al [2] in the cubic Laves phase $TbFe_2$. Later, similar level of room-temperature magnetostriction was also observed in various rare earth-iron (R-Fe) intermetallic compounds as well as other Tb-Fe based compounds [3]. Due to their large magnetostriction, much work has been done to apply the compounds to electromagnetic devices. Initial applications include actuators, motors and acoustic wave generators [4] and, in these applications, materials of a bulk form were frequently utilized. In the early nineties, however, great interest arose to apply giant magnetostrictive materials to microdevices such as microactuators and micropumps [5-8]. Since then, many research results on thin films of R-Fe based alloys have been reported.

Since magnetocrystalline anisotropy as well as magnetostriction of R-Fe compounds is very large, a large magnetic field is required to achieve large magnetostriction, which may cause a serious problem in the practical applications of the compounds. One of the most important aspects in the research of R-Fe compounds, therefore, is to achieve large magnetostriction at a low magnetic field. This is particularly true in the case of thin-film type magnetostrictive materials, since the strength of applied magnetic field is considered to be limited up to hundreds Oe in micro magnetoelastic devices to which the thin films are to be applied.

Numerous methods have been used to fabricate R-Fe thin films with good magnetostrictive characteristics, viz., large strain at a low magnetic field. They include amorphization [9, 10], alloy design (the addition of Dy as a third element, for example) [11, 12] and the control of fabrication conditions during sputtering [9, 12]. For example, amorphization, which easily occurs at normal sputtering conditions, is considered to be effective in reducing magnetocrystalline anisotropy but not without the disadvantage of large reduction in intrinsic magnetostriction. Even with the many efforts, however, magnetostriction at low fields is not very satisfactory in most cases, when the results for thin films are compared with those obtained for bulk and ribbon type samples.

In this work, magnetic and magnetostrictive properties of amorphous Tb-Fe based thin films are systematically investigated, in an effort to increase low field magnetostriction through the improvment of the magnetic softness. The composition is varied widely, particularly, extended to large Tb concentrations where no data are available so far. The effects of fabrication condition and the B addition are also investigated. The effects of B on magnetostriction and other magnetic properties of Tb-Fe based alloys were previously investigated for melt-spun ribbons produced by rapid-quenching [13, 14] and amorphous bulks fabricated by high speed sputtering [15, 16] but no attempts were made so far for thin films, although B was found to be effective in improving magnetostrictive properties of the melt-spun and bulk amorphous alloys [13-16]. The improvement in the properties with the addition of B is considered to come mainly from the modification of microstructure; one example is the improvement in the glass forming ability by the presence of B. This role of B may also be important in thin film type samples with the consideration of a recent observation that an amorphous phase in Tb-Fe thin films is composed of magnetically hard ultrafine clusters with the size of 1 nm [17-19] which are not detected by x-ray experiments but are considered to affect magnetic properties.

Ⅱ. Experimental Details

Tb-Fe and Tb-Fe-B thin films with the thickness of about 1 μm were coated by rf magnetron sputtering on Si (100) substrates. A composite target consisting of an Fe disc (4 inches in diameter) and Tb chips was used. A pure Fe disc and an Fe (99.0 at.%)-B (1.0 at.%) disc were used to fabricate Tb-Fe and Tb-Fe-B thin films, respectively. Argon was used as the sputtering gas and the sputtering pressure was varied widely from 1 to 30 mTorr. The other sputtering conditions used in this work were; the base pressure of below 7 × 10^{-7} Torr, the target to substrate distance of 60 mm and the rf input power of 300 W. The film thickness was measured by using a stylus-type surface profiler. The film composition of Tb and Fe was determined by electron probe microanalysis. The amount of B was analyzed by spectro-photometry. With the difficulty of B analysis, only a couple of thin films were analyzed. The composition of B was obtained to be 0.51 at.% for the thin films with the Tb/Fe ratio close to $TbFe_2$. Since the Tb content of the thin films investigated in this work ranges from 40.2 to 68.1 at.% being higher than that corresponding to $TbFe_2$, the amount of B in the present films is expected to be lower than 0.51 at.%. The microstructure was observed by x-ray diffraction with Cu Kα radiation. Magnetostriction was measured by the optical cantilever method using an apparatus of Naruse Co. (Sendai, Japan, Model MS-F) with the application of rotating in-plane magnetic fields (H) up to 5 kOe. Magnetic properties were measured by using a vibrating sample magnetometer with a maximum magnetic field of 15 kOe.

Ⅲ. Results and Discussion

It is well expected that the composition of thin films varies with the area fraction of Tb chips on the Fe disc. The composition also is found to change with the Ar gas pressure. In our experiments, the composition was varied by varying both the area fraction and the Ar gas pressure. More specifically, several experimental runs at various Ar gas pressures ranging from 1 to 30 mTorr were carried out at a fixed target configuration and thin films with varying compositions were then obtained. Similar experimental runs were again conducted at different target configurations, producing thin films with varying compositions and at various Ar gas pressures. In some cases, the films were produced by varying the area fraction of Tb chips at a fixed value of the Ar gas pressure. The Tb content in the thin films fabricated at a fixed target configuration is found to increase with the Ar pressure. Some results for Tb-Fe thin films, which are obtained from two separate experimental runs at two different target configurations, are shown in Fig. 1. A similar behavior is also observed in Tb-Fe-B thin films. It is seen from the figure that, as the Ar gas pressure increases, the Tb content initially increases rather rapidly up to 5 mTorr and then increases slowly thereafter. The change in the composition is large, even though the target configuration is fixed; for example, the Tb content is 43 at.% at the pressure of 1 mTorr but it is 64 at.% at 30 mTorr. These results may be explained by the

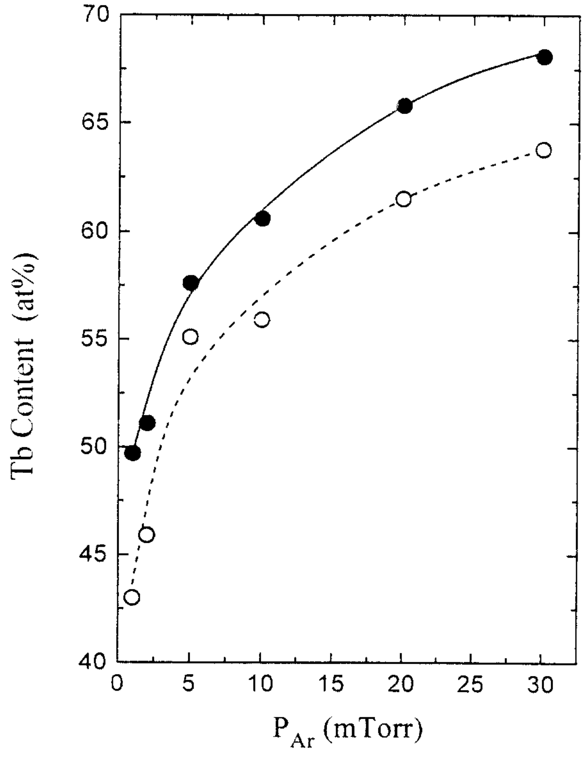


Fig. 1. The content of Tb (in at.%) in Tb-Fe thin films as a function of the Ar gas pressure during sputtering. Each series of thin films were fabricated at a fixed target configuration.

difference in the scattering of sputtered Fe and Tb particles. The scattering of the two elements will increase with the Ar gas pressure due to decreased mean free path of the particles. The relative magnitude of the scattering, however, will be smaller in the case of Tb, since Tb is heavier than Fe, enabling more Tb particles to reach the substrate.

All the fabricated films were checked by x-ray diffraction to examine the microstructure and some of the diffraction results are shown in Fig. 2 for a series of Tb-Fe-B films which were obtained at a fixed target configuration but at various Ar gas pressures. As can be seen from the figure, the microstructure mainly consists of an amorphous phase at low Tb contents but, at high Tb contents, it is composed of a mixture of an amorphous phase and an α Tb phase. The α Tb phase with diffraction peaks at 2θ = 31°, 51° and 65° is considered to have a rhombohedral structure rather than the commonly observed hexagonal one. This may indicate a distortion of α Tb precipitates during the film formation. The relative peak intensity of the Tb phase changes and even some peaks disappear with the change of composition, indicating that the precipitates exhibit some degree of texture. Note that the sharp peaks at 2θ = 33° and 70° are from the Si substrate. The peaks below 2θ = 30° which appear in some films may be related to oxides, possibly Tb oxides.

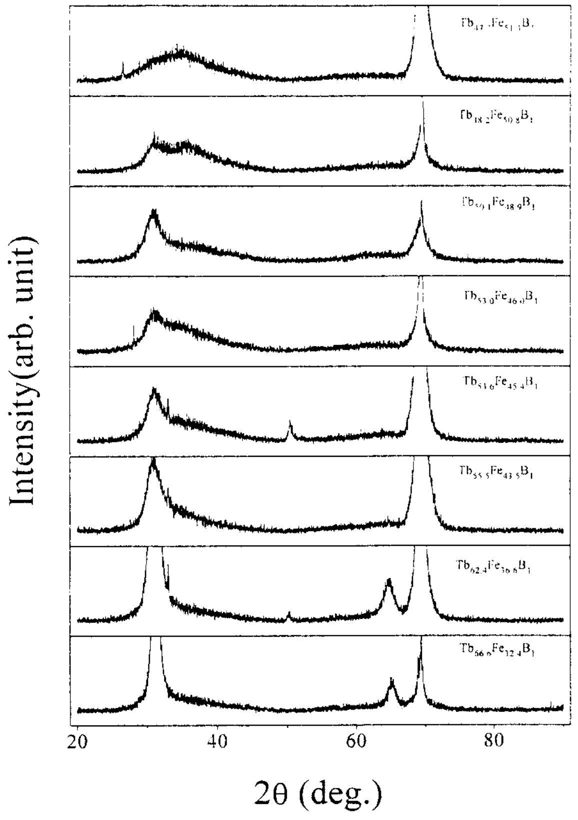
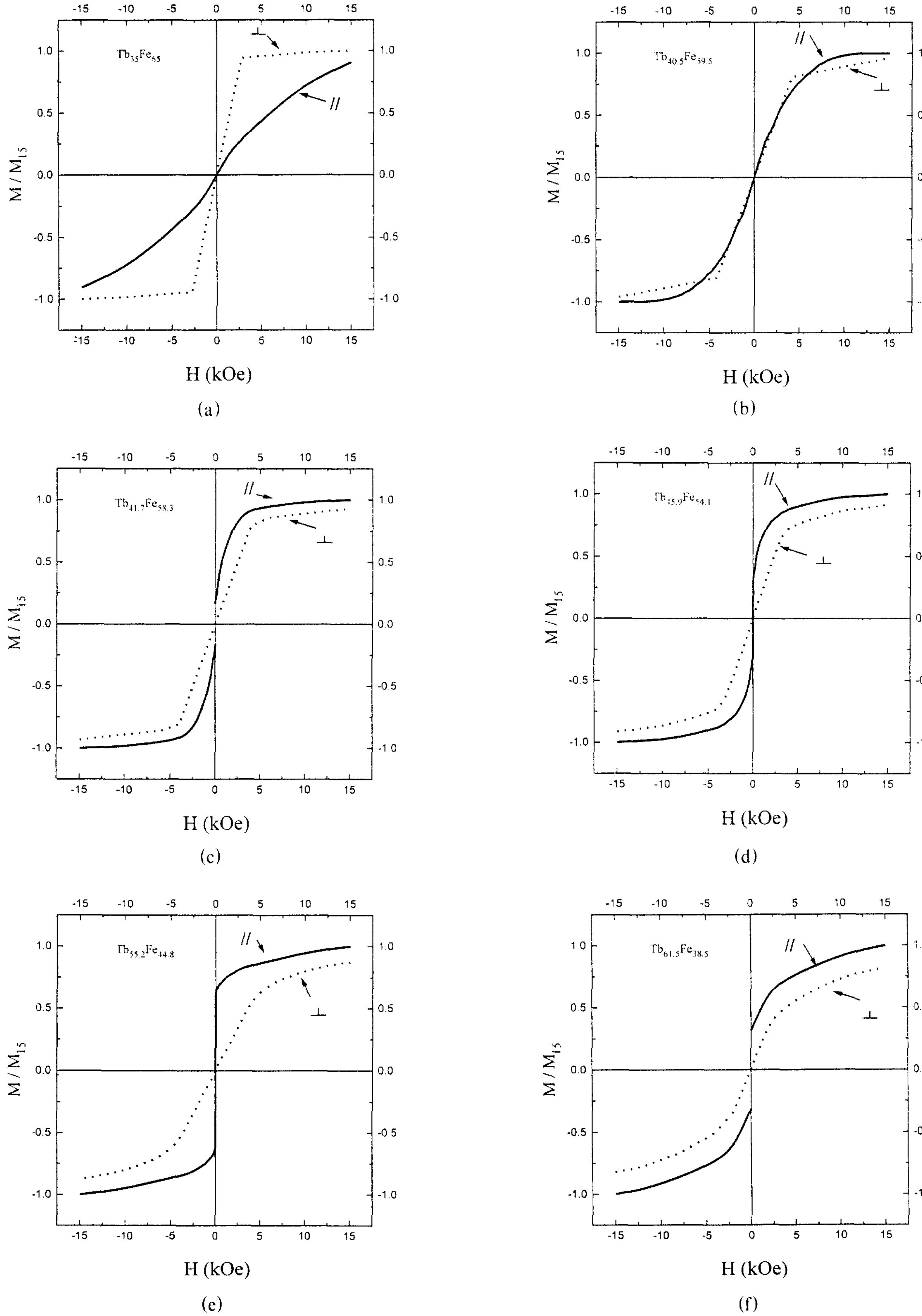


Fig. 2. The X-ray diffraction patterns for a series of Tb-Fe-B thin films which were fabricated by varying the Ar gas pressure for a given target configuration.

Since magnetic properties, including magnetostriction, of this kind of thin films are most sensitively affected by the distribution of magnetic anisotropy, the change in the anisotropy is systematically investigated as a function of composition and the Ar gas pressure. It is found that the direction of the anisotropy depends mainly on the film composition, but it is nearly independent of the Ar gas pressure. There have been some arguments on the effects of sputtering condition on the magnetic properties of R-Fe thin films. According to Arai et al [9, 20], magnetic properties are not affected by sputtering condition but the results of Quandt et al [8, 10] and Grundy et al [21] indicate that magnetic properties are sensitive to sputtering condition. The present result is in accord with those of Arai et al [9, 20]. The variation of the anisotropy with the composition, indicated by the shape of hysteresis loops measured in the in-plane direction and the direction perpendicular to the film plane, is displayed in Fig. 3 (a)~(f) for Tb-Fe thin films. Corrections with regard to demagnetizing fields are not made, so the loops shown in the figures are more squared than the "true" ones and the degree of squareness is larger for the loops measured in the perpendicular direction due to larger demagnetizing fields. It is seen from the figures that, as the Tb content increases from 35 to 61.5 at.%, the anisotropy direction changes progressively from the perpendicular to in-plane; strong perpendicular anisotropy is clearly seen at 35 at.% Tb, in-plane anisotropy appears at the Tb content of about 42 at.% and, at higher Tb contents, well-developed in-plane anisotropy is observed. The present anisotropy results are in good agreement with the results reported by Arai et al [9] and Grundy et al [21] but are only in qualitative agreement with the results of Mimura and Imamura [22] who reported in-plane anisotropy appears at 30 at.% Tb. A similar tendency is also observed for Tb-Fe-B thin films which are not shown here due to space limitation, but the composition at which the anisotropy changes from the perpendicular to the in-plane direction differs significantly. In the case of Tb-Fe-B thin films, the boundary at which the in-plane anisotropy begins to form is at the composition of about 50 at.% Tb, viz., the composition where the anisotropy changes from perpendicular to in-plane direction shifts toward higher Tb content with the B addition. The origin of the anisotropy in R-Fe thin films is still not explained clearly so far, although much work has been done, particularly on thin films for magneto-optic recording. Four different origins responsible for the anisotropy may be identified [23]; intrinsic, anelastic, pair ordering and magnetoelastic. Among these, pair ordering is considered to be a main factor behind the anisotropy change with the composition and some experimental results supporting this view were previously reported in binary amorphous Tb-Fe thin films [17-19]. In the framework of pair ordering, the present results may indicate that the presence of the small amount of B affects rather substantially the degree of pair ordering, viz., the number of Tb-Fe pairs residing in in-plane and out-of plane.



(a) (b) (c) (d) (e) (f)

Fig. 3. The M-H hysteresis loops of Tb-Fe thin films with varying compositions. Two hysteresis loops are shown for each sample, one measured by applying magnetic fields in the in-plane direction and the other in the perpendicular direction.

One more point to be noted with regard to the variation of the shape of hysteresis loops with the composition is the occurrence of a superparamagnetic phase at high Tb content. Some typical hysteresis loops exhibiting a superparamagnetic behavior are shown in Fig. 4 for both Tb-Fe and Tb-Fe-B thin films. From Fig. 4, it is seen that the films are far from saturated even at the maximum magnetic field of 15 kOe and they exhibit a very small value of the coercive force and small hysteresis, all being the signs of superparamagnetism. This superparamagnetic behavior at high Tb content is well expected, since, at these compositions, the amount of magnetic phase and hence the size of magnetic particles become small. The occurrence of superparamagnetism may be facilitated by a small value of anisotropy of an amorphous phase, since the particle size at which the transformation into superparamagnetism occurs is inversely proportional to the anisotropy [24]. The composition at which superparamagnetism begins to appear also shifts toward higher Tb content by the addition of B, in a way similar to the anisotropy change. This is clearly illustrated in Fig. 4 for Tb-Fe and Tb-Fe-B thin films with a similar composition. The B-free thin film with the Tb content of 65.9 at.% exhibits nearly complete superparamagnetic behavior, while the Tb-Fe-B thin film with a similar composition (even slightly higher Tb content) still shows a substantial amount of the ferrimagnetic contribution indicated by the initial steep increase in M and a large value of the coercive force.

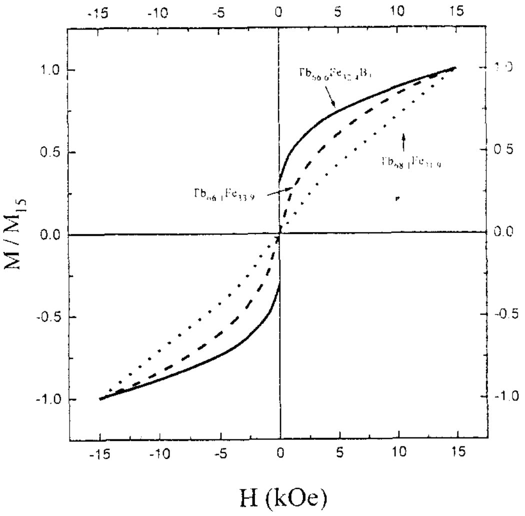
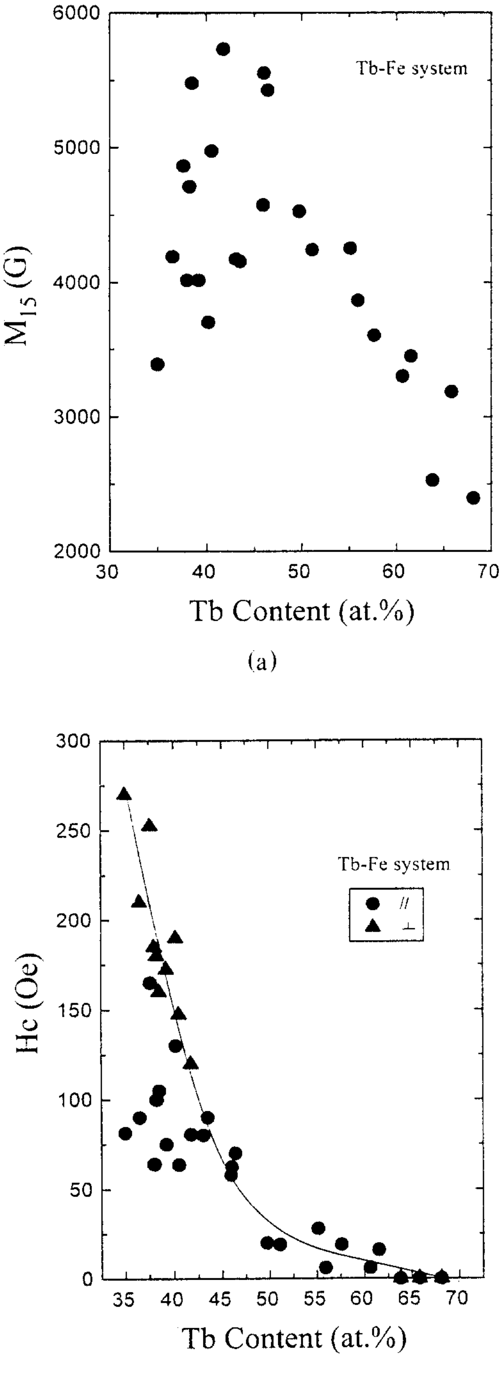


Fig. 4. M-H hysteresis loops exhibiting superparamagnetic behavior. Only the loops measured by applying magnetic fields in the in-plane direction are shown.

Previously, magnetic properties of Tb-Fe thin films were mainly investigated in the composition range below the Tb content of 50 at.%. One of the possible reasons for this may be that, for amorphous binary Tb-Fe thin films, the materials are reported to be paramagnetic when the Tb content exceeds 50 at.% [25]. However, the present results are not in agreement with the reported ones in that the values of the magnetization are substantially large for all the samples investigated in the present work. It is reminded that thin films with the compositions up to 68.1 at.% Tb are studied for the B-free system and up to 66.6 at.% for the Tb-Fe-B system.

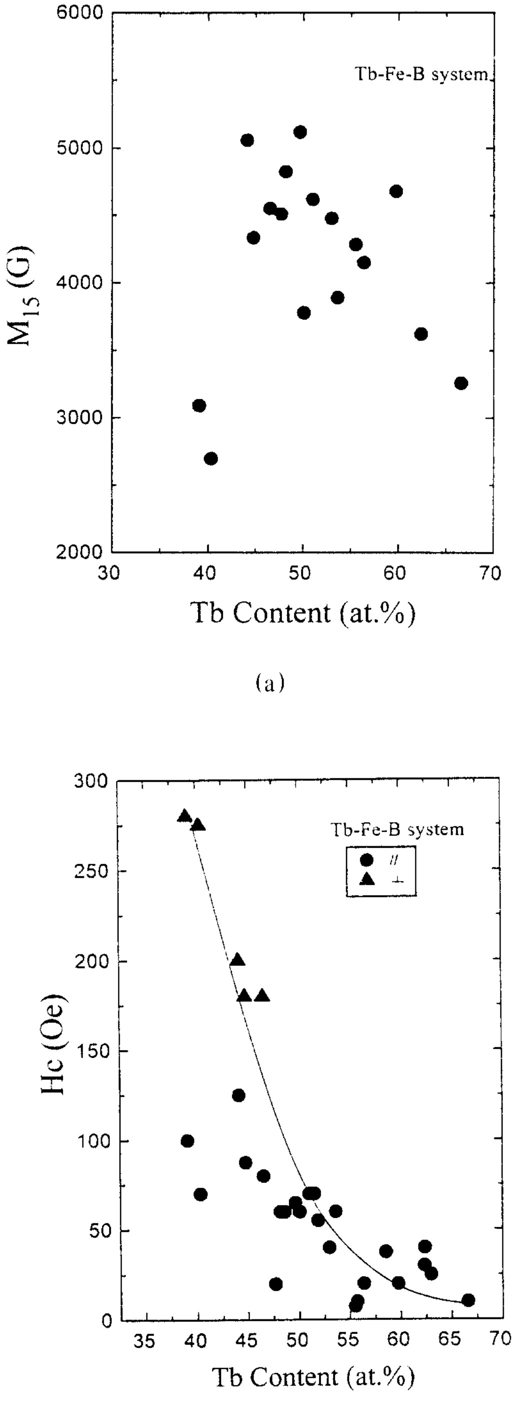
Other magnetic properties of the saturation magnetization and the coercive force, which are obtained from the hysteresis loops discussed so far, are shown in Figs. 5 and 6 for Tb-Fe and Tb-Fe-B thin films, respectively. The magnetic properties are given as a function of the composition, since the shape of hysteresis loops mainly depends on the composition. The magnetization at 15 kOe (M_{15}) is taken as the saturation magnetization and the coercive force (H_c) is obtained by applying the maximum magnetic field of 15 kOe. For each property, two sets of data are available depending on the direction of applied magnetic field. The values of M_{15} shown in Figs. 5 (a) and 6 (a) are the higher ones among the two sets of data, which are in most cases those measured in the in-plane direction, except for the films with very strong perpendicular anisotropy. The values of the coercive force given in Figs. 5 (b) and 6 (b), on the other hand, are those measured in the easy direction, viz., at Tb contents below 42 at.% (in the case of Tb-Fe thin films) or 50 at.% (in the case of Tb-Fe-B thin films) the values are measured in the perpendicular direction and, at the higher Tb contents, they are measured in the in-plane direction. In-plane results for the coercive force are also shown at the lower compositions where the perpendicular anisotropy is dominant, since in-plane magnetic fields are usually applied during practical applications of the thin films and hence the coercive force in this direction is of practical importance. As can be seen from Figs. 5 and 6, the compositional dependences of the magnetization and the coercive force are qualitatively similar to each other in both Tb-Fe and Tb-Fe-B thin films. As the Tb content increases, the magnetization increases with the Tb content, reaches a maximum and then decreases with the further increase of the Tb content. The coercive force, however, tends to decrease monotonically with the Tb content. The maximum value of M_{15} is about 5800 G and it is obtained at 42 at.% Tb in the case of B-free thin films. This result is in good agreement with that reported by Mimura and Imamura [22], with regard to both the value of magnetization and its dependence of the composition. In the case of Tb-Fe-B thin films, the maximum value is 5100 G which is lower than the value obtained in Tb-Fe thin films by 700 G. The Tb content at which the maximum in M_{15} occurs is 48 at.% and it is shifted toward to higher Tb content by the presence of B. This is considered to be related to the fact that the anisotropy change from the perpendicular to in-plane direction occurs at higher Tb content by the addition of B. A rather large scattering in the measured values of M_{15} is seen at the composition of the boundary between in-plane and perpendicular anisotropy. This is because the saturation is not attained either in the in-plane or the perpendicular direction. It is reminded that, for each sample, high magnetization values from the two sets of data measured in the in-plane and the perpendicular directions are shown only in the figures.



(a)

(b)

Fig. 5. The values of (a) M_{15} and (b) the coercive force of Tb-Fe thin films as a function of the Tb content. In the case of the coercive force, the results measured in the easy direction are shown for all the samples and the line is drawn through these results. At the low Tb contents where the perpendicular anisotropy is dominant, in-plane results which are of more practical importance are also shown in the figure.



(a)

(b)

Fig. 6. The value of (a) M_{15} and (b) the coercive force of Tb-Fe-B thin films as a function of the Tb content. In the case of the coercive force, the symbols are as in Fig. 5 (b).

The values of H_c of the present thin films with in-plane anisotropy, which are practically more important since these in-plane films exhibit large magnetostriction at low magnetic fields, range from 7.5 to 100 Oe in both Tb-Fe and Tb-Fe-B thin films. Here the superparamagnetic Tb-Fe thin films which exhibit the coercivity value of zero both in the in-plane and perpendicular directions are not taken into account. For the films with the perpendicular anisotropy, the coercive force measured in the in-plane direction tends to decrease with decreasing Tb content. This result can be understood from the Stoner-Wohlfarth calculation on the magnetization by spin rotation for a material with uniaxial anisotropy [26] where the coercivity decreases as the angle between the anisotropy and the applied magnetic field increases from 0 to 90°.

It is known that amorphous Tb-Fe alloys are ferrimagnetic, the same with the crystalline Tb-Fe ones, and the compensation composition at room temperature where the magnetization is zero resides at the Tb content of 22 at.% [22]. This indicates that the magnetization increases with decreasing Tb content below the compensation composition and, above the composition, it also increases with increasing Tb content. The increase in M_{15} with the Tb content observed in the present work may be understood from the compensation phenomenon for both Tb-Fe and Tb-Fe-B thin films. In addition to the intrinsic origin, the initial increase in M_{15} also results from the improvement in in-plane anisotropy enabling to saturate at lower magnetic fields. The rather steep increase is therefore due to the combined effects of these. One of the reasons for the decrease in M_{15} with the composition after exhibiting a maximum results from the presence of the paramagnetic Tb phase, the amount of which increases with the Tb content. In addition, the decrease in M_{15} at high Tb content is also related to the occurrence of superparamagnetic fine particles which makes the sample hard to saturate. Again these two effects combine to result in the steep decrease observed in this work. The steeper decrease observed in Tb-Fe thin films than in Tb-Fe-B thin films may support the view, since the superparamagnetic phase is formed more easily in B-free Tb-Fe thin films (Fig. 4). The preceding discussion indicates that the slope in the "true" saturation magnetization vs. composition curve is less steep than that in M_{15} vs composition curve shown in Figs. 5 (a) and 6 (a). The results for H_c can also be explained by the phenomenon related to the compensation where the coercivity exhibits a maximum (a behavior similar to singularity) [22] and it decreases with decreasing Tb content below the compensation composition and, above the composition, decreases with increasing Tb content. In addition to this intrinsic origin, the decrease in H_c is also related to the improvement in in-plane anisotropy with increasing Tb content as shown in Figs. 3 (a)~(f). The relation between H_c and the anisotropy is obviously supported by the fact that a very good coincidence is obtained between the two sets of results of Tb-Fe and Tb-Fe-B thin films, when the values of H_c of Tb-Fe thin films are shifted to the right by the difference in composition of the anisotropy change (8 at.%).

The magnetic softness achieved in the present thin films is found to be excellent, as can be illustrated by a very low coercive force (below 10 Oe), together with squared hysteresis loops. A very small coercive force of the order of 10 Oe was previously observed in a binary Tb-Fe thin film, but, in spite of this low coercive force, the saturation was not possible even at the magnetic field of 6 kOe [8, 10, 27]. On the other hand, the present films with the low coercive force saturate at a field as low as 1 kOe. This clearly indicates that the magnetic softness of the present thin films is much better than that reported previously and the level of the softness, to our knowledge, is considered to be highest in this kind of alloys.

Equally excellent magnetostrictive properties are therefore expected from the excellent magnetic softness of the present films. In Fig. 7 are shown the results for some λ-H plots for binary Tb-Fe thin films. The value of λ in the figure (and also in the figures to be shown later) is so called the saturation magnetostriction at a given field and is obtained by the relation $\lambda = \frac{2}{3}(\lambda_{\parallel} - \lambda_{\perp})$. Here $\lambda_{\parallel}$ and $\lambda_{\perp}$ are respectively the values of magnetostriction measured in the parallel and the transverse directions in the film plane and the difference $(\lambda_{\parallel} - \lambda_{\perp})$ corresponds to the peak to peak value when rotating in-plane magnetic fields are applied. It is seen from Fig. 7 that the behavior of the field dependence of magnetostriction varies substantially with the composition of Tb. The sensitivity of λ with H at low magnetic fields is very poor for the film with the lowest Tb content of 43 at.% but it increases with increasing B content, exhibiting a maximum at the Tb content of 55.1 at.%. The sensitivity, however, decreases again with the further increase of the Tb content. The main factor for the observed magnetostrictive behavior is thought to be related to the variation of the magnetic anisotropy with the Tb content. The poor sensitivity at low fields for the films with low Tb content is due to the fact that, at this Tb content, well-developed in-plane anisotropy is not formed. On the other hand, the poor low field sensitivity at high Tb content, where well-developed in-plane ani-

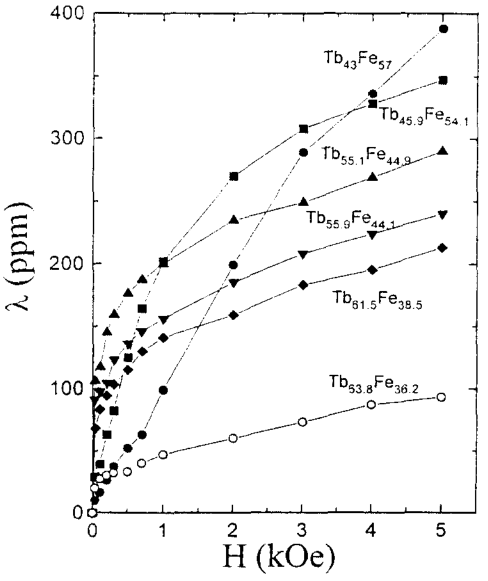
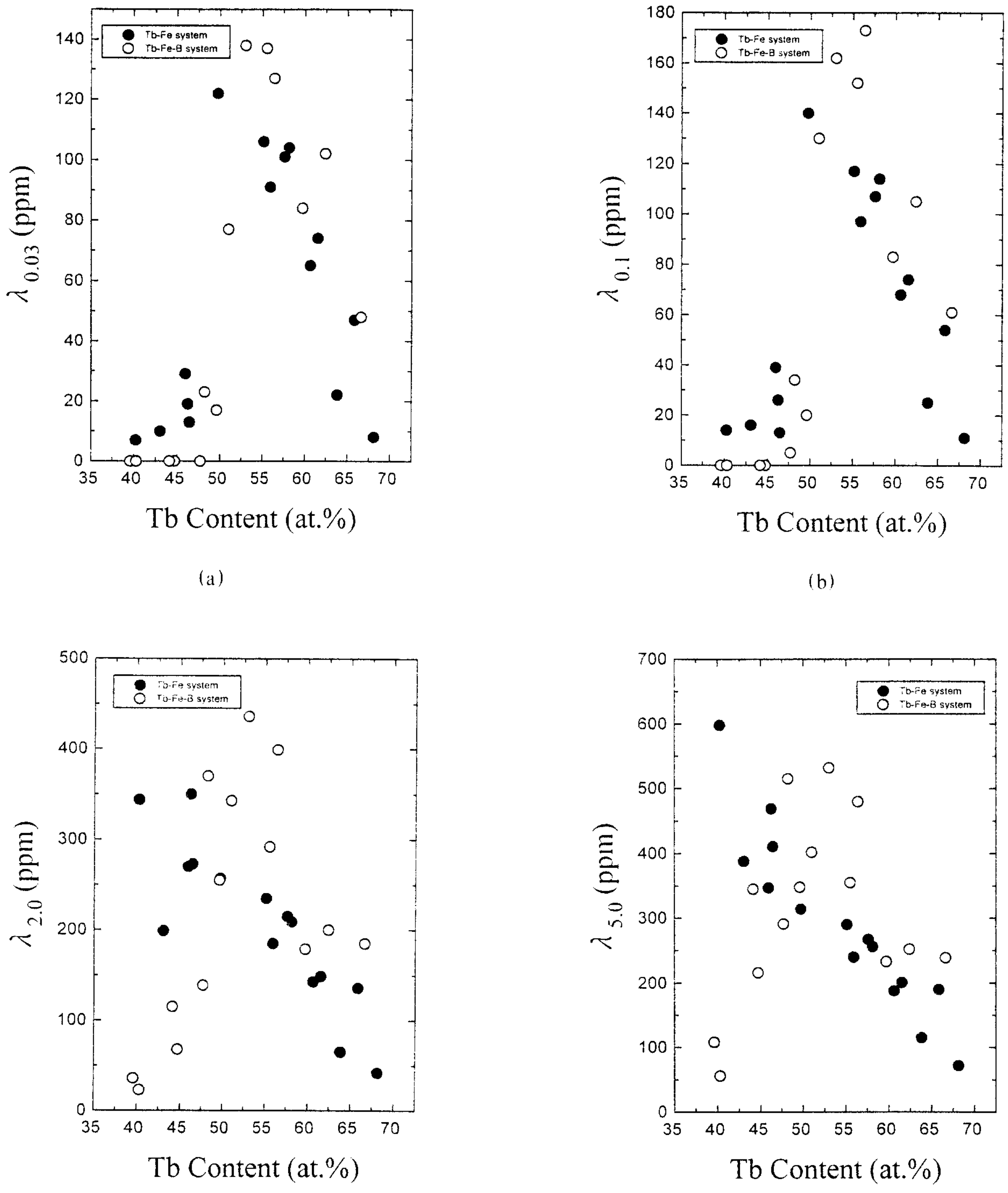


Fig. 7. The λ-H plots for a binary Tb-Fe system obtained at a fixed target configuration but at different Ar gas pressures.



(a) (b) (c) (d)

Fig. 8. The value of λ as a function of the composition of Tb at fixed magnetic fields of (a) 0.03 kOe, (b) 0.1 kOe, (c) 2 kOe and (d) 5 kOe. The results of Tb-Fe thin films are indicated by filled circles while those of Tb-Fe-B thin films are denoted by unfilled circles.

sotropy is observed to exist, is related to low saturation magnetostriction. This is clearly seen in Fig. 7 and can be expected from the fact that the paramagnetic α Tb phase increases with increasing Tb content when the ratio of Tb to Fe exceeds about 48 at.% [7].

In order to present the results more compactly and clearly, the magnetostriction at a given value of magnetic field is presented as a function of the composition of Tb and the results at some typical fixed magnetic fields of 0.03, 0.1, 2 and 5 kOe are shown in Figs. 8 (a)~(d), respectively. In the figures, λ_N (N is a number) denotes the value of λ at a magnetic field of N kOe. This way of presenting the results has the particular advantage of clearly showing the magnitude of magnetostriction at a practically important low magnetic field as well as the compositional dependence of magnetostriction. In Figs. 8 (a)~(d), the results of Tb-Fe thin films are indicated by filled circles while those of Tb-Fe-B thin films by unfilled circles. At the magnetic field of 2 kOe and below, the Tb content dependence of λ_N is similar in both Tb-Fe and Tb-Fe-B thin films, exhibiting a maximum at an intermediate Tb content. In this magnetic field range, maxima in the plots occur at the Tb contents of about 50 and 53 at.% for Tb-Fe and Tb-Fe-B films, respectively. This indicates that good magnetostrictive characteristics are achieved for the films with very well-developed in-plane anisotropy and with the microstructure consisting of a mixture of an amorphous phase and the α Tb phase. The shift in the optimum Tb content by about 3 at.% with the addition of B seems to be related to the fact that in-plane anisotropy begins to form at higher Tb content for Tb-Fe-B thin films. The optimum Tb content obtained in the present work is higher than that reported in the literature; in binary Tb-Fe thin films, the optimum composition of Tb was reported to be 46.9 at.% [8] and 42 at.% [9].

One of the most striking features of the present magnetostrictive results is that, in both Tb-Fe and Tb-Fe-B thin films, a very high magnitude of magnetostriction is achieved at a practically important low magnetic field and magnetostriction is increased further by the addition of B. For example, the value $\lambda_{0.03}$ is as high as 138 ppm for a B containing thin film, while it is reduced to 122 ppm for a B-free thin film. To our knowledge, this level of magnetostriction in the low magnetic field range has not been achieved so far for thin film type materials. These excellent magnetostrictive properties are supported by the excellent magnetic softness of the present thin films which exhibit the coercivity below 10 Oe and a typical squared-loop shape with the saturation field as low as 1 kOe, as discussed in the earlier sections. With these excellent magnetostrictive characteristics, the present thin films are now thought to be suitable for Si-based microdevices. At high magnetic fields ($\geq$ 3 kOe), the shape of the plots of λ_N-Tb content is qualitatively unchanged for Tb-Fe-B thin films. This is not the case, however, for Tb-Fe thin films; the magnitude of magnetostriction at the magnetic field of 3 kOe and higher tends to decrease monotonously with increasing Tb content. This result is in agreement with the microstructural results. Saturation magnetostriction of Tb-Fe-B thin films is also expected to decrease with the Tb content, but the results of λ_N at magnetic fields up to 5 kOe do not show this tendency. This is because Tb-Fe-B thin films with low Tb content exhibit very strong anisotropy with the direction perpendicular to the film plane and hence they are far from saturated at (in-plane) magnetic fields up to 5 kOe. It is noted that Tb-Fe thin films with low Tb content are not completely saturated either, as can be seen from Fig. 7. Taking this fact in consideration, a steeper decrease in "true" saturation magnetostriction is expected with increasing Tb content than that shown in Fig. 8.

Ⅳ. Conclusions

In this work, a systematic investigation has been carried out on magnetic and magnetostrictive properties of giant magnetostrictive Tb-Fe and Tb-Fe-B thin films over a wide composition range. The films are fabricated by rf magnetron sputtering using a composite target which consists of an Fe plate and Tb chips. The anisotropy mainly depends on the composition and its direction changes progressively from the perpendicular to in-plane with increasing Tb content. The boundary at which the anisotropy direction changes is shifted toward to higher Tb content by the addition of B. The saturation magnetization exhibits a maximum at the Tb contents of 42 and 48 at.% and the values are about 5800 and 5100 G for Tb-Fe and Tb-Fe-B thin films, respectively. The coercive force, measured in the easy direction, decreases continuously with the Tb content and ranges from 7.5 to 100 Oe when the films with in-plane anisotropy are taken into account. The present results for the magnetization and the coercive force, which are in general accord with those reported in the literature, are explained by the microstructure, the anisotropy change and the compensation phenomenon. The excellent magnetic softness is achieved in the present thin films with the coercive force of below 10 Oe and the saturation magnetic field of 1 kOe. Equally excellent magnetostrictive characteristics, particularly at low magnetic fields, are achieved in both Tb-Fe and Tb-Fe-B thin films, B containing thin films exhibiting even better magnetostrictive properties. For example, a magnetostriction of 138 ppm is obtained in a Tb-Fe-B thin film at a magnetic field as low as 30 Oe. It is considered that, due to the excellent low field magnetostrictive characteristics, the present Tb-Fe based magnetostrictive thin films are suitable for Si based microdevices.

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