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

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Magnetic and magnetostrictive properties of amorphous Sm-Fe and Sm-Fe-B thin films are systematically investigated over a wide composition range from 14.1 to 71.7 at.% Sm. The films were fabricated by rf magnetron sputtering using a composite target composed of an Fe (or Fe-B) plate and Sm chips. The amount of B added ranges from 0.3 to 0.8 at.%. The microstructure, examined by X-ray diffraction, mainly consists of an amorphous phase in the intermediate Sm content range from 20 to 45 at.%. Together with an amorphous phase, crystalline phases of Fe and Sm also exist at low and high ends of the Sm content, respectively. Well-developed in-plane anisotropy is formed over the whole composition range, except for the low Sm content below 15 at.% and the high Sm content above 55 at.%. As the Sm content increases, the saturation magnetization decreases linearly and the coercive force tends to increase, with the exception of the low Sm content where very large magnitudes of the saturation magnetization and the coercive force are observed due to the existence of the crystalline α-Fe phase. The coercive force is affected rather substantially by the B addition, resulting in lower values of the coercive force in the practically important Sm content range of 30 to 40 at.%. Good magnetic softness indicated by well-developed in-plane anisotropy, a square-shaped hysteresis loop and a low magnitude of the coercive force results in good magnetostrictive characteristics in both Sm-Fe and Sm-Fe-B thin films. The magnetostrictive characteristics, particularly at low magnetic fields, are further improved by the addition of B; for example, at a magnetic field of 100 Oe, the magnitude of magnetostriction is −350 ppm in a Sm-Fe thin film and it is −470 ppm in a B containing Sm-Fe thin film.

1. Introduction

Giant magnetostrictive rare earth (R)-Fe based alloys were developed about a quarter century ago by Clark and Belson [1] and Koon *et al.* [2]. Although many R-Fe alloys are found to exhibit giant magnetostriction [3], work has mainly been directed to Tb-Fe and Sm-Fe based alloys due to their large room temperature magnetostriction. The compound $TbFe_2$ is known to exhibit the largest positive magnetostriction, while $SmFe_2$ the largest negative magnetostriction [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 the 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 (R being Tb or Sm) have been reported.

The well-known problem of giant magnetostrictive R-Fe compounds is that, due to very large magnetocrystalline anisotropy, a large magnetic field is usually required to achieve giant magnetostriction. 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. In an effort to solve this problem, amorphization has most frequently been used [9-11]. This method is particularly convenient in thin-film type materials, since an amorphous phase is easily formed at normal sputtering conditions.

Much more attention has so far been directed to Tb-Fe based alloys than Sm-Fe based ones. One reason may be due to the development of Terfenol-D alloys with nearly zero magnetocrystalline anisotropy, leading to excellent magnetostrictive characteristics [3]. Another reason is thought to be related to the sign of magnetostriction (positive magnetostriction). In device applications using materials of a bulk form, usually magnetostrictive materials are intentionally stressed and it is more convenient to apply compressive stress to the materials than tensile stress [4]. The compressive stress additionally plays an important role of aligning the spin direction via magneto-elastic interactions in a way to increase the strain [12]. It is noted that the opposite (the decrease of the strain) is true for a material with negative magnetostriction by the application of compressive stress. In thin film applications, however, no stress is intentionally applied to magnetostrictive materials and hence Sm-Fe based alloys with negative magnetostriction do not suffer from the problem related to applied stress. Rather, Sm-Fe based alloys have a price advantage over Tb-Fe based alloys, since the light rare earth Sm is more abundant and hence cheaper than the heavy rare earth Tb. These considerations lead to the importance of developing Sm-Fe based thin films with good magnetostrictive characteristics for microdevices applications.

In this work, magnetic and magnetostrictive properties of Sm-Fe based thin films are systematically investigated, in an effort to improve the magnetic softness and hence to achieve thin films with good magnetostrictive characteristics at low fields. Magnetic properties of amorphous Sm-Fe based alloys were previously investigated: for example, by Miyazaki *et al.* for thin films prepared by an evaporation method [13] and for melt-spun ribbons [14]; by Honda *et al.* for thin films fabricated by rf magnetron sputtering [9]; more recently, by Seqqat *et al.* for thin films of Sm-Fe and Sm-Fe-B alloys and also for melt-spun ribbons of Sm-Fe-B alloys [15]. Except for the results of Honda *et al.* [9], however, the previous investigations are more concerned about basic magnetic properties of rare earth-Fe alloys rather than the improvement of the magnetic softness pertinent to practical applications of giant magnetostrictive materials. The present work is performed in a way similar to that of Honda *et al.* [9], but the effects of B are additionally examined and a more systematic investigation is carried out. The effects of B on magnetic and magnetostrictive properties of Tb-Fe based thin films were recently investigated by the present authors [16, 17] and it was found that B affects magnetic properties substantially and also improves the magnetostrictive characteristics of the thin films. The effects of B on magnetostriction and other magnetic properties of Sm-Fe based alloys were previously investigated for melt-spun ribbons produced by rapid-quenching [18] and amorphous bulks fabricated by high speed sputtering [19, 20]. However, no attempts were made so far for Sm-Fe based thin films with magnetostrictive applications in mind. It is noted that Sm-Fe-B thin films were previously fabricated by Seqqat *et al.* [15], but the investigated films are not pertinent to magnetostrictive applications, since the composition is greatly deviated from the optimum one (the amount of B is very high (20 at.%) and the Sm content is very low). The improvement in the properties with the addition of B is considered to result 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 of magnetically hard ultrafine clusters with the size of 1 nm [21-23] in amorphous Tb-Fe thin films.

2. Experimental Details

Sm-Fe and Sm-Fe-B thin films with a thickness of about 1 μm were coated by rf magnetron sputtering on Si (100) substrates with a thickness of 200 μm. A composite target consisting of an Fe disc (4 inches in diameter) and Sm chips was used. A pure Fe disc and an Fe (99 at.%)-B (1 at.%) disc were used to fabricate Sm-Fe and Sm-Fe-B thin films, respectively. Argon was used as the sputtering gas. The sputtering pressure was varied from 1 to 10 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 Sm 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 and the composition of B was obtained to be 0.64 at.% for the thin films with the atomic fraction of Sm close to 30 at.%. With the present composite target configuration, the amount of B in the films with the Sm content below (above) 30 at.% is expected to be larger (smaller) than 0.64 at.%. In the Sm content range of 14.1 to 71.7 at.% investigated in this work, it is estimated that the amount of B ranges from 0.3 to 0.8 at.%. The microstructure was observed by x-ray diffraction with Cu K_α radiation. Magnetostriction (λ) 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.

3. Results and Discussion

It is well expected from the present composite target configuration that the composition of thin films varies with the area fraction of Sm chips on the Fe disc. The composition is also found to vary with the Ar gas pressure. In our experiments, widely ranged compositions were obtained by varying both the area fraction of Sm chips and the Ar gas pressure. More specifically, several experimental runs at various Ar gas pressures 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. In the present Ar gas pressure range of 1 to 10 mTorr, magnetic and magnetostrictive properties are observed to be nearly independent of the Ar gas pressure, when thin films of a similar composition but fabricated at different Ar gas pressures are compared with one another. This is in agreement with the result of Honda *et al.* [9]. The Sm content in the thin films fabricated at a fixed target configuration is found to increase with the Ar pressure and some results are shown in Fig. 1. The present Ar gas dependence of the composition is similar to that observed for Tb-Fe based thin films [16] and may be explained by the difference in the scattering of sputtered Fe and Sm 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 Sm, since Sm is heavier than Fe, enabling more Sm 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 Figs. 2(a) and (b) for Sm-Fe and Sm-Fe-B systems, respectively, over a wide composition range. The peaks at 2θ=33° and 70° are from the Si substrate. Sharp crystalline peaks of α-Fe are clearly seen at low Sm content below ~20 at.%. The α-Fe peaks are slightly shifted toward lower diffraction angle indicating a lattice expansion of the α-Fe phase. The α-Fe crystalline peaks disappear and a broad peak characteristic of an amorphous phase emerges as the Sm content exceeds ~20 at.%. It is of interest to note that the position of the broad maximum (in 2θ) shifts toward lower diffraction angle as the Sm content increases. This is clearly seen for the films of $Sm_{24.0}Fe_{76.0}$ and $Sm_{34.1}Fe_{65.9}$ (Fig. 2(a)) where broad maxima occur at 2θ=41° and 35°, respectively. At the Sm content higher than 45 at.%, the microstructure consists of a mixture of an amorphous phase and the α-Sm phase. The relatively large peak below 2θ=30° observed in some samples is thought to be related to a Sm oxide, possibly Sm_2O_3.

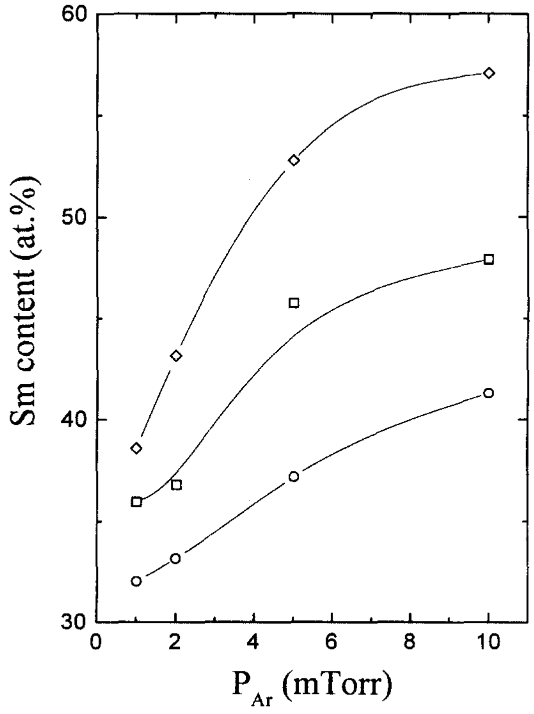

Fig. 1. The content of Sm (in at.%) in Sm-Fe based thin films as a function of the Ar gas pressure during sputtering. Each series of thin films were fabricated at a fixed target configuration.

The direction of easy magnetization is known to be an important factor for the magnetic softness of R-Fe thin films [11, 16, 17] and hence the change in anisotropy is investigated as a function of the composition. The distribution of magnetic anisotropy is investigated by examining hysteresis loops measured in the in-plane and the direction perpendicular to the film plane. Some results for these hysteresis loops are shown in Fig. 3(a)-(d). Corrections with regard to demagnetizing fields are not made, so the loops shown in the figures are more squared than the "true" ones and, due to a larger demagnetizing field for a perpendicular loop, the degree of squareness of a perpendicular loop is expected to be larger. For the films with a similar Sm content, no noticeable difference in the direction of easy magnetization is observed with the addition of B, except for the films with low Sm content where the α-Fe phase exists. In this low Sm content range, both B-free and B containing films exhibit in-plane anisotropy but better in-plane anisotropy is observed for B added films. Also, at this low Sm content, the shape of hysteresis loops measured in the in-plane direction is inclined substantially. This is indicated by low magnitudes (below 0.1) of the remanence ratio, the results of which are shown in Fig. 4 as a function of the composition. In the composition range from 20 to 55 at.% Sm, well-developed in-plane anisotropy is formed and hysteresis loops are highly squared with the remanence ratio of most thin films being greater than 0.6 (Fig. 4). No substantial anisotropy is observed at the Sm content higher than 55 at.%, no substantial difference being noted in the shape of hysteresis loops measured in the in-plane and perpendicular directions. Intermediate magnitudes of the remanence ratio (0.29 to 0.40) are seen at this high Sm content. Anisotropy is little affected by the B addition and this behavior is in contrast with that observed in Tb-Fe based thin films where anisotropy is greatly influenced by the presence of B [16]. Ferromagnetic behavior is observed to exist in the present Sm content range (up to 71.7 at.%). This behavior is to be compared with that observed in Tb-Fe based thin films where superparamagnetic behavior appears as the rare earth content exceeds ~66 at.% [16].

The results for the saturation magnetization and the coercive force are shown respectively in Figs. 5 and 6 as a function of the composition. The magnetization at 15 kOe (M_{15}) is taken as the saturation magnetization and, since

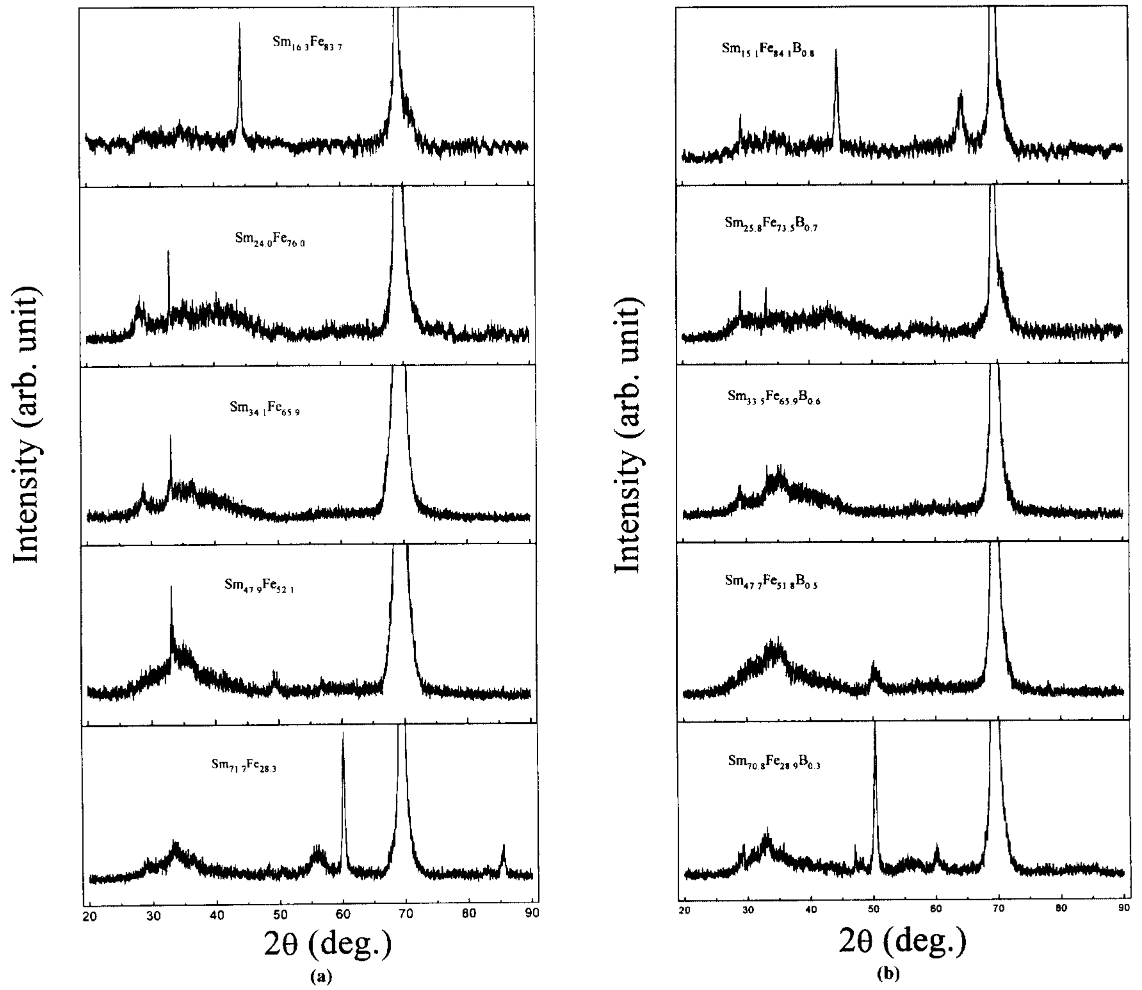

Fig. 2. The variation of the X-ray diffraction patterns with the Sm content for the systems of (a) Sm-Fe alloys and (b) Sm-Fe-B alloys.

most of the present thin films saturate at a magnetic field well below 15 kOe, M_{15} is practically identical to the saturation magnetization. The coercive force (H_c) is obtained by applying the maximum magnetic field of 15 kOe. The results are obtained from the hysteresis loops measured in the in-plane direction. In the case of the coercive force, the results of Honda *et al.* [9] obtained for Sm-Fe thin films are also shown in Fig. 6 for comparison.

Except for very low Sm content where the α-Fe phase exists, the saturation magnetization decreases nearly linearly from 8950 emu/g to 1580 emu/g as the Sm content increases from 14.1 to 71.7 at.%. Again, no substantial difference in the saturation magnetization is seen with the B addition and this is compared with relatively large reduction in Tb-Fe based thin films by the B addition [16]. As can be expected from the ferromagnetic coupling between Sm and Fe (note that Sm is a light rare earth element), no compensation composition is observed. The linear dependence of the magnetization may indicate that the total magnetization of the alloy is simply arithmetic sum of Fe and Sm elements, the magnetic moment of Fe being larger than that of Sm [15]. Of course, the relation of arithmetic sum will hold only in the composition range where no paramagnetic α-Sm precipitates exist. It is estimated from the extrapolation of the present data that the magnetization reaches zero at ~85 at.% Sm. The extraordinarily large magnitude of M_{15} at the low end of the Sm content is due to the formation of the α-Fe phase with a large magnetic moment.

The magnitude of H_c is large for the thin films with the α-Fe phase, but, with the disappearance of the crystalline phase, the value of H_c is reduced significantly to 10 Oe. This may be because intrinsic magnetocrystalline anisotropy is effectively reduced by the formation of an amorphous phase. The value of H_c tends to increase with increasing Sm content. This can be expected from larger anisotropy of Sm than that of Fe element. It may be noted however that, in the case of binary Sm-Fe thin films, a closer examination shows a tendency of a broad maximum in the H_c-Sm content plots at the Sm content of 40 at.% when the data of the thin films with well-developed in-plane anisotropy are taken into account. A similar result was previously reported by Miyazaki *et al.* for melt-spun Sm-Fe ribbons [14]. The coercive force of Sm-Fe thin films was also investigated by Honda *et al.* [9] but, with a paucity of data and a large data scattering at the Sm

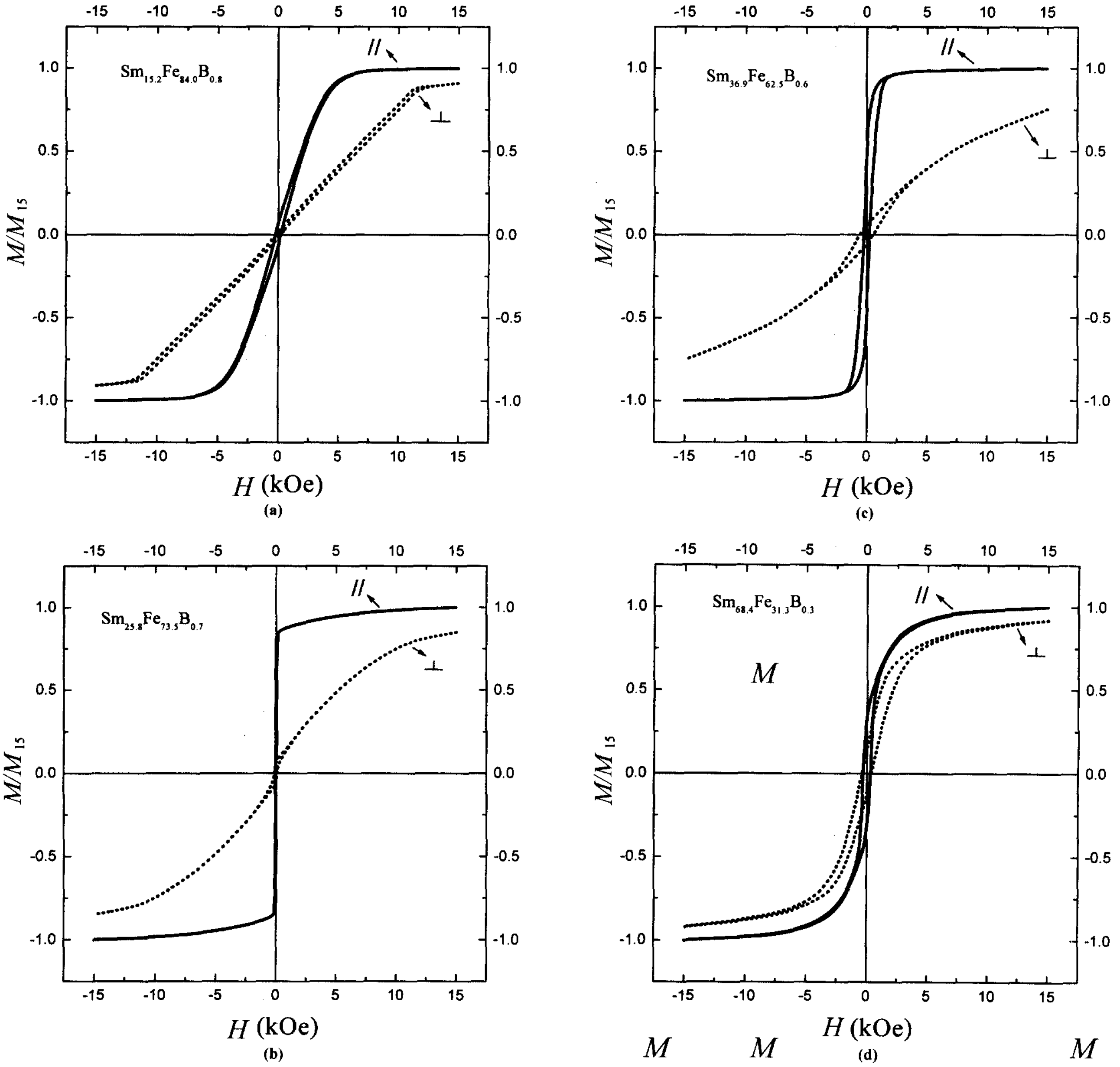

Fig. 3. The variation of the shape of *M-H* hysteresis with the Sm content for the alloys of (a) $Sm_{15.2}Fe_{84.0}B_{0.8}$, (b) $Sm_{25.8}Fe_{73.5}B_{0.7}$, (c) $Sm_{36.9}Fe_{62.5}B_{0.6}$, and (d) $Sm_{68.4}Fe_{31.3}B_{0.3}$. Two hysteresis loops are shown for each sample, one measured by applying magnetic fields in the in-plane direction and the other in the perpendicular direction.

content of 50 at.%, the tendency of the coercive force as a function of the composition cannot be drawn. Unlike the other magnetic properties, the coercive force is affected rather substantially by the addition of B; the H_c-Sm content plot is shifted toward higher Sm content with the B addition. This results in lower values of the coercive force of B containing thin films in the practically important Sm content range of 30 to 40 at.%. Since the coercive force is closely related to magnetostrictive characteristics at low magnetic fields, low field magnetostrictive characteristics are expected to be improved by the addition of B. As can be seen in Fig. 6, at the Sm content below 40 at.%, the present values of H_c of Sm-Fe thin films are in fair agreement with those reported by Honda *et al.* [9]. At the Sm content higher than 40 at.%, however, our values are lower than the reported ones.

Let us now consider magnetostrictive properties of the present thin films. The results for λ-H plots at some typical compositions are shown in Fig. 7 for Sm-Fe-B thin films. The value of λ in the figure (and also in the figures to be shown later) is so called saturation magnetostriction at a given field and is obtained by the relation $\lambda=2/3(\lambda_{\parallel}-\lambda_{\perp})$. 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 a rotating in-plane magnetic field is applied. It is seen from

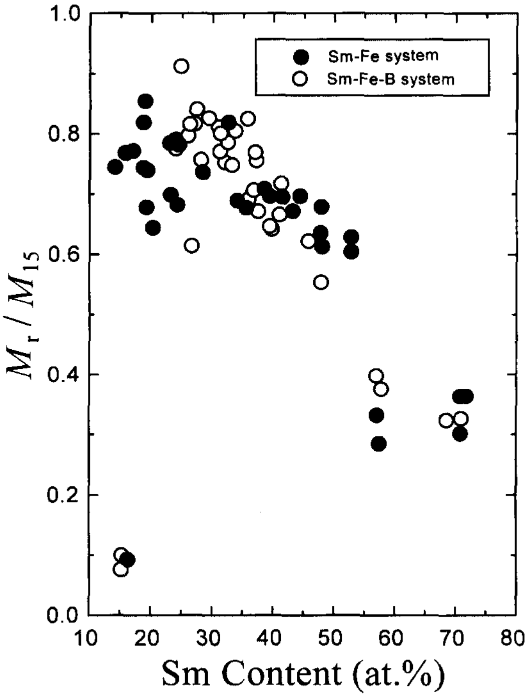

Fig. 4. The value of the remanence ratio (M_r/M_{15}) as a function of the Sm content for both Sm-Fe and Sm-Fe-B thin films. The results of Sm-Fe thin films are indicated by filled circles and those of Sm-Fe-B thin films by unfilled circles.

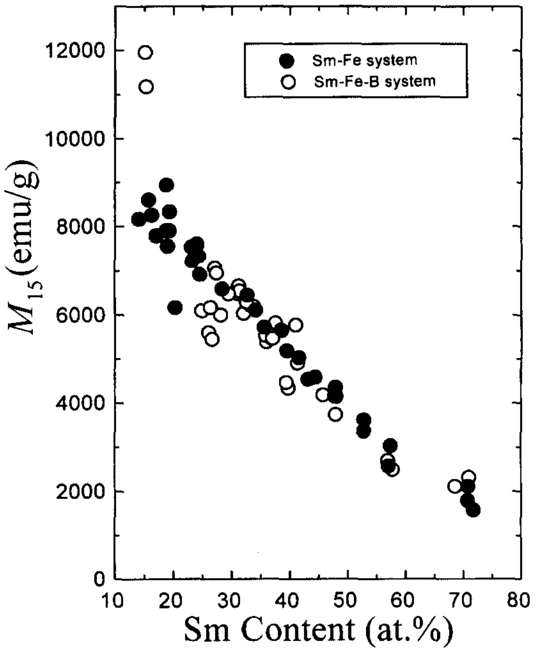

Fig. 5. The value of saturation magnetization (M_{15}) as a function of the Sm content for both Sm-Fe and Sm-Fe-B thin films. The symbols are as in Fig. 4.

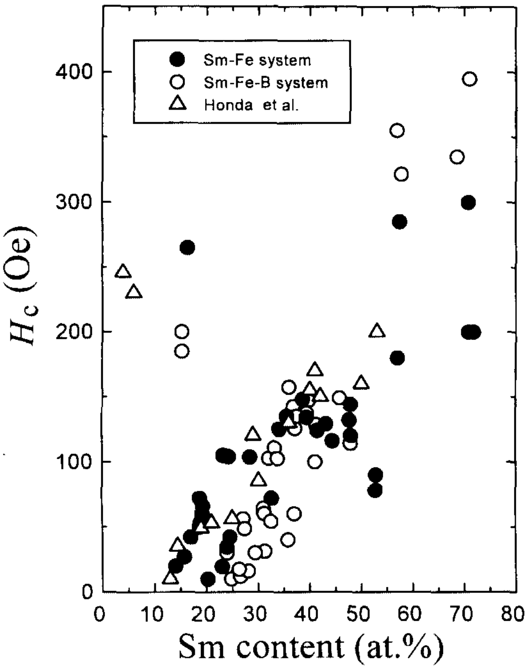

Fig. 6. The value of the coercive force (H_c) as a function of the Sm content for both Sm-Fe and Sm-Fe-B thin films. The symbols are as in Fig. 4. Also shown are the results of Honda *et al.* [9] for Sm-Fe thin films, which are indicated by triangles, for comparison.

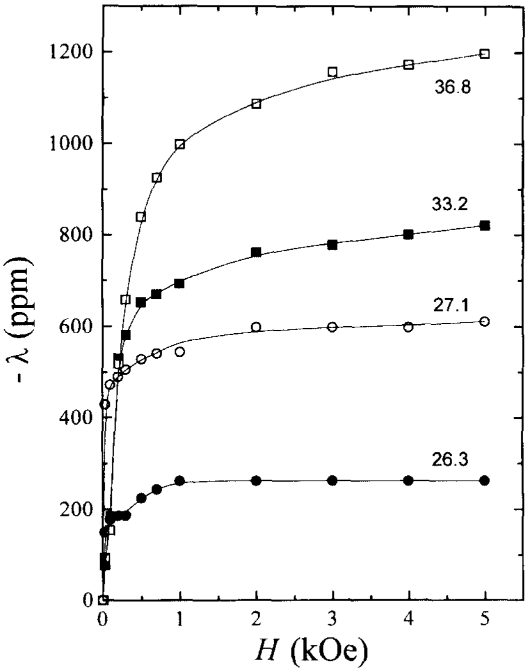

Fig. 7. The λ-H plots for some Sm-Fe-B thin films. The numbers at the curves indicate the Sm content in at.%. Since the sign of magnetostriction of Sm-Fe based thin films is negative, -λ is actually plotted in the figure so that the data shown are positive.

Fig. 7 that, at low magnetic fields, the magnitude of λ increases rapidly with magnetic field over the whole composition range, indicating very good low field sensitivity of λ with magnetic field. The low field sensitivity is particularly good at the Sm content of 27.1 at.%. The field sensitivity of the present Sm-Fe thin films is much better than that of Tb-Fe based thin films [17]. Also, saturation is reached at low magnetic fields; for example, in the films with the Sm content less than 30 at.%, nearly complete saturation is reached at a magnetic

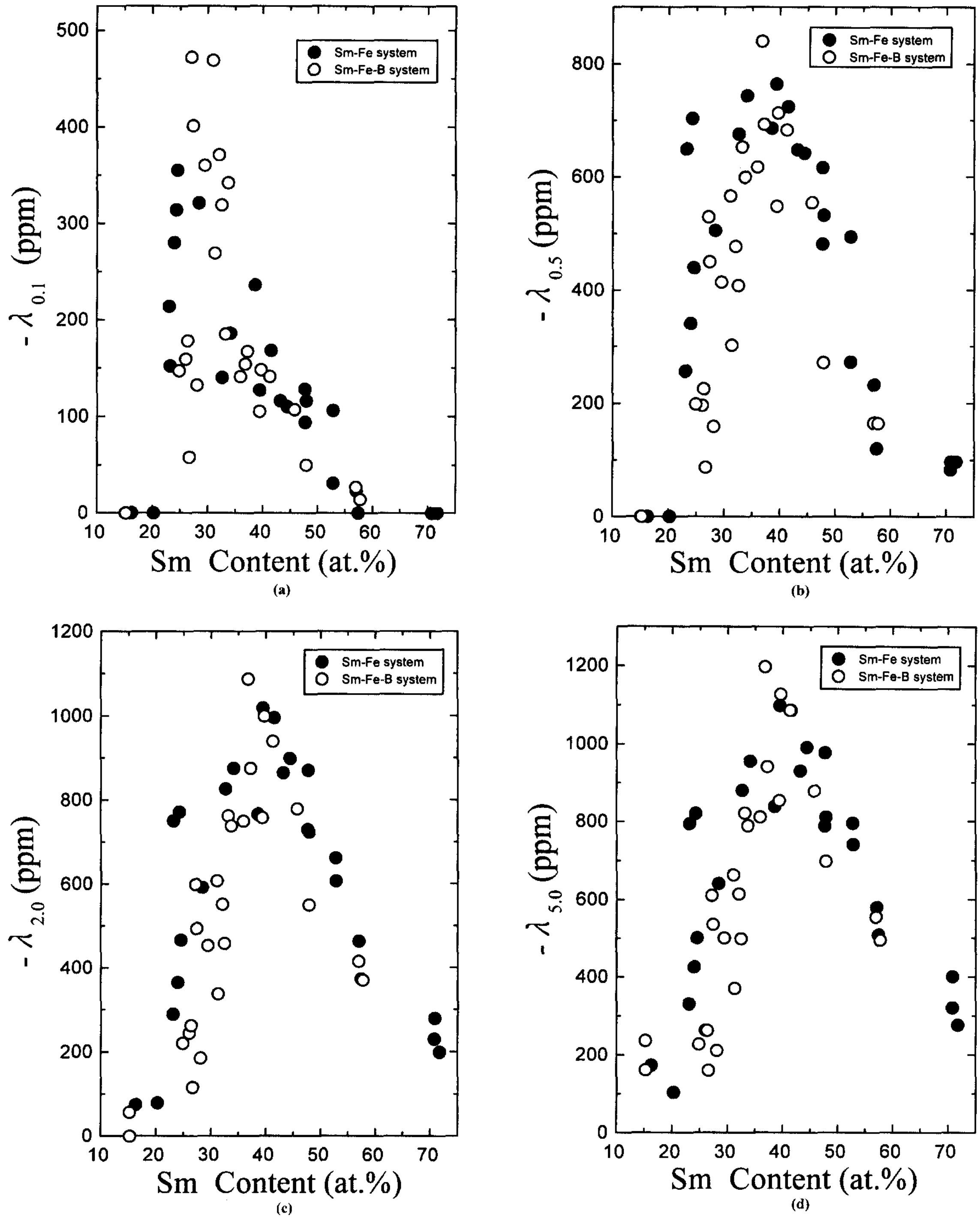

Fig. 8. The value of λ as a function of the Sm content at fixed magnetic fields of (a) 0.1 kOe, (b) 0.5 kOe, (c) 2 kOe and (d) 5 kOe. The results of Sm-Fe thin films are indicated by filled circles while those of Sm-Fe-B thin films are denoted by unfilled circles. As in Fig. 7, -λ is actually plotted in the figures so that the data are positive.

field of 1 kOe. The good sensitivity and the attainment of saturation at low magnetic fields are considered to be due to, among others, very well-developed in-plane anisotropy. Intrinsic saturation magnetostriction, however, is low at low Sm content.

In order to present the results more compactly and clearly, magnetostriction at a fixed value of magnetic field is presented as a function of the Sm content. The results at some typical magnetic fields of 0.1, 0.5, 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 λ at practically important low magnetic fields as well as the compositional dependence of λ. In Figs. 8(a)-(d), the results of Sm-Fe thin films are indicated by filled circles while those of Sm-Fe-B thin films by unfilled circles.

At H=0.1 kOe (Fig. 8(a)), a sharp maximum occurs in the λ-Sm content plots, indicating that the value of λ varies sensitively with the composition and the optimum composition is narrow at this low field. The composition at which the maximum occurs is 25 at.% Sm for the Sm-Fe system and 27~31 at.% Sm for the Sm-Fe-B system. As magnetic field increases, changes occur in the shape of the λ-Sm content plots, together with the increase of the absolute magnitude of λ. Two points can be noted with regard to the changes in the shape of the λ-Sm content plots. Firstly, maximum in the λ-Sm content plots becomes broad with increasing magnetic field, resulting in broad optimum composition. This is more true for the Sm-Fe system where the optimum composition ranges from 23 to 45 at.% at intermediate applied magnetic fields. This wide optimum composition is advantageous in the practical applications in the sense that high magnitudes of λ can be reliably obtained without necessitating to adjust the film composition accurately. Secondly, the optimum composition varies with magnetic field. The optimum Sm content of the Sm-Fe system is ~25 at.% at $H \leq 0.1$ kOe, 23~45 at.% at H=0.2~0.5 kOe and 40 at.% at $H \geq 1$ kOe. On the other hand, the optimum Sm content of the Sm-Fe-B system is 27~31 at.% at $H \leq 1$ kOe, 33 at.% at H=0.2 kOe and 37 at.% at $H \geq 0.3$ kOe. In both systems, the optimum Sm content tends to increase with increasing applied magnetic field, this tendency being more obvious in the Sm-Fe-B system. The optimum composition observed in this work can be compared with that of 30~40 at.% Sm (more specifically 39 at.% irrespective of applied magnetic fields) reported by Honda *et al.* for Sm-Fe thin films [9].

The present results for λ can be explained by the compositional variation of the coercive force and intrinsic magnetostriction. In the practically important composition range of 20 to 50 at.% Sm, the coercive force increases with increasing Sm content. This may cause the optimum composition at a low magnetic field to reside at a low Sm content. However, as magnetic field increases, intrinsic magnetostriction may become more important. This can be expected, since the coercive force of most thin films is low being below 150 Oe. It is estimated from the present results that intrinsic magnetostriction is maximum at about 37~40 at.% Sm, which is higher than the composition corresponding to $SmFe_2$.

One of the most striking features of the present thin films is the attainment of very high magnitudes of λ in both Sm-Fe and Sm-Fe-B thin films, even at low magnetic fields. For example, at H=0.1 kOe, the maximum absolute strain is ~470 ppm and, at H=5 kOe, it is ~1200 ppm. This level of λ is two or three times larger than that observed in Tb-Fe based thin films. Also the values of λ are much higher than those reported in the literature by Honda et al. for Sm-Fe thin films; the maximum absolute strains are 150 ppm at 0.25 kOe, 300 ppm at 1 kOe, and 390 ppm at 16 kOe [9]. The excellent magnetostrictive characteristics of the present thin films are well matched with well-developed in-plane anisotropy and low magnitudes of the coercive force, particularly in Sm-Fe-B thin films.

Another important feature of the present work is the improvement of magnetostrictive properties by the addition of B, although the excellent characteristics are achieved in both Sm-Fe and Sm-Fe-B thin films. The addition of B is particularly effective at low magnetic fields; for example, at H=0.1 kOe, the maximum absolute strain is ~350 ppm and ~470 ppm for Sm-Fe and Sm-Fe-B thin films, respectively. These results can be expected by the attainment of low coercive force of B containing thin films in the practically important Sm content range.

The present maximum strain of 1200 ppm is comparable to the strain of 1560 ppm (at 25 kOe) for polycrystalline $SmFe_2$ [3]. The very high magnitudes of λ of the present amorphous thin films are in contrast with the previous observation that λ is usually much reduced by amorphization [24]. It is not clear at the moment whether the large absolute values of λ obtained in the present amorphous Sm-Fe based thin films represent "true" magnetostriction. With regard to this, it is worth noting that the magnitude of λ is affected by the value of Young's modulus of a magnetostrictive thin film in the estimation of λ from the cantilever method used in this work [25]. With the absence of Young's moduli for amorphous R-Fe thin films, it has been a common practice to use Young's moduli of crystalline phases, usually crystalline RFe_2. In the present work also, Young's modulus of 39 GPa obtained for crystalline $SmFe_2$ [3] was used for all the samples in the calculations. Since the absolute magnitude of λ is inversely proportional to Young's modulus of a magnetostrictive thin film [25], the "true" value of λ will be reduced if Young's modulus of the present thin films is "actually" greater than 39 GPa. In the case of amorphous Tb-Fe alloys, Young's modulus is reported to be reduced by amorphization [3]. If this is the case for Sm-Fe based alloys, the absolute magnitude of λ will further be increased. It is also worth noting that, in order to accurately estimate the value of λ from the cantilever method, it will be necessary to know Young's modulus of (amorphous) thin films as a function of composition and also as a function of magnetic field. The latter one, viz., the magnetic field dependence of Young's modulus, can be an important factor, since the ΔE effect of this kind of alloys is very large [3]. It is of interest to note that Huang *et al.* [26] recently reported very large magnitudes of λ (~1000 ppm) for amorphous Tb-Fe thin films, which are very similar to the values observed for polycrystalline Tb-Fe compounds. In the case of Sm-Fe alloys, the largest absolute magnetostriction reported so far is 450 ppm, which was obtained "directly" from the strain gauge method for an amorphous bulk with the composition $(SmFe_2)_{0.992}B_{0.008}$ [19, 20].

4. Conclusions

Thin films of Sm-Fe and Sm-Fe-B alloys with widely ranged compositions from 14.1 to 71.7 at.% Sm are fabricated by rf magnetron sputtering and their magnetic and magnetostrictive properties are investigated. An amorphous phase is formed at intermediate Sm contents from 20 to 45 at.% and, at low and high ends of the Sm content, crystalline phases of Fe and Sm, respectively, are also formed. Well-developed in-plane anisotropy, which is essential to good low field magnetostrictive characteristics, is formed in the wide composition range of 20 to 55 at.% Sm. The saturation magnetization decreases linearly and the coercive force tends to increase with increasing Sm content and these results for the saturation and the coercive force can be explained, respectively, by smaller magnetic moment and larger anisotropy of Sm than those of Fe.

The addition of B to Sm-Fe thin films affects the coercive force rather substantially, in a way to reduce the coercive force of B containing thin films in the practically important Sm content range of 30 to 40 at.%. The magnetostrictive characteristics, particularly at low magnetic fields, are found to be good in both Sm-Fe and Sm-Fe-B thin films and they are further improved by the addition of B. An example is the attainment of a magnetostriction of −470 ppm in a B containing thin film at an applied magnetic field of 100 Oe. This has been made possible by good magnetic softness of the present thin films, mainly indicated by well-developed in-plane anisotropy, a square-shaped hysteresis loop and a low magnitude of the coercive force. A very high magnetostriction reaching −1200 ppm, which is comparable to that of a crystalline $SmFe_2$ compound, is observed at high magnetic fields, in contrast with the fact that absolute magnitude of magnetostriction is significantly reduced by the formation of an amorphous phase.

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