Journal of Magnetism and Magnetic Materials 191 (1999) 339–344

Induced anisotropy, magnetic domain structure and magnetoimpedance effect in CoFeB amorphous thin films

D. García[a,*], J.L. Muñoz[a], G. Kurlyandskaya[a,1], M. Vázquez[a], M. Ali[b], M.R.J. Gibbs[b]

[a] *Instituto de Magnetismo Aplicado. UCM-RENFE and Instituto de Ciencia de Materiales, CSIC. P.O. Box 155, 28230 Las Rozas, Madrid, Spain*

[b] *Department of Physics, University of Sheffield, Sheffield, S3 7RH, UK*

Received 5 May 1998; received in revised form 24 June 1998

Abstract

CoFeB amorphous thin films have been prepared by radio frequency magnetron sputtering. The objective of the work has been to obtain very soft thin films, and to correlate their domain structure with the induced anisotropy and giant magneto-impedance (GMI) features. Tailored anisotropies were induced by either growth under stress, or by post-deposition annealing in the presence of a magnetic field. In certain cases these induced anisotropies give rise to significant GMI effect at a frequency, 5 MHz, relatively low for thin films. © 1999 Elsevier Science B.V. All rights reserved.

PACS: 75.30.Gw; 72.15.Gd; 75.60.Ch; 75.70. − i

Keywords: Magnetic anisotropy; Giant magnetoimpedance effect; Magnetic domains; RF sputtering; Thin films

1. Introduction

Magnetic anisotropy (MA) in thin films is well known to be important for both the control of magnetic properties and technological applications [1]. Magnetic anisotropy can be formed in thin films during preparation [2], and also using post-deposition heat treatments. In-plane MA has been found in FeBSi amorphous RF-sputtered thin films [3], but is weak. In this work we have aimed to produce controlled MA in CoFeB amorphous thin films, where the magnetostriction is low, but induced anisotropy may be high. This has involved controlled stress on the substrate during growth, or post-deposition heat treatment in the presence of a magnetic field. The GMI effect is a promising magneto-transport property for technological applications. This effect has been explained in terms of the skin depth changes suffered by the magnetic material when the permeability induced by a polarising AC electric current is varied through a bias magnetic field [4–6]. The magneto-impedance response of the magnetic material is highly dependent on its MA since magnetic anisotropy controls

* Corresponding author: Tel.: + + 34 1 630 1724; fax: + + 34 1 630 1625; e-mail: imass24@fresno.csic.es.

[1] Permanent address: Institute of Metal Physics UD RAS Kovalevskaya str. 18, GSP 70, 620219 Ekaterinburg, Russia.

PII: S0304-8853(98)00262-5

the films permeability. We have aimed to induce the most favourable MA for the GMI response of the thin films.

There are a number of publications connected with MA in Co-based amorphous ribbons. The underlying physics is understood in terms of inelastic response or pair ordering [7–9]. Currently there are no reported systematic investigations of the induced MA for amorphous CoFeB thin films. Our CoFeB samples have been sputtered on pre-stressed substrates to induce magnetoelastic anisotropy via the non-zero magnetostriction, or sputtered onto non-stress substrate and afterwards annealed in a DC or AC magnetic field post-production. The aim of this investigation has been to correlate their domain structure with features of the magnetisation process and of the GMI ratio behaviour, which can easily illustrate the anisotropy peculiarities.

2. Experimental techniques

The films were deposited using a planar magnetron radio frequency sputtering system. The base pressure was in the low 10^{-6} mbar range and argon pressure during deposition was 5×10^{-3} mbar. The deposition rate was 2.3 Å/s under these growing conditions. The composition of the target was $Co_{76}Fe_4B_{20}$ which, as an amorphous ribbon, has a magnetostriction constant $\cong -1\times10^{-7}$. The samples were grown on 40 mm × 20 mm glass substrates, and then cut transversely to 2 mm × 20 mm. The thickness of the films ranged from 1.5 to 4.3 μm. Uniaxial transverse magnetic anisotropy along the short dimension was induced using two different methods. The first method consisted of thermal treatments in the presence of either a DC or AC (50 Hz) 1.5 kA/m magnetic field oriented along the short in-plane sample direction. The treatments were carried out either at 300°C or 250°C in an Ar atmosphere for 1 h. The second method consisted in growing the films onto a 40 mm × 20 mm glass substrate bent along an axis parallel to the long dimension. The radius of curvature was 400 mm. A compressive stress was thus developed in the film upon removal of the substrate from the sputtering chamber. This compression produced an easy magnetisation direction parallel to the long dimension owing to the negative magnetostriction. The samples of this type chosen for measurements were transversely cut to 2 mm × 20 mm, and finally exhibit a transverse magnetic anisotropy.

Amorphicity was checked before and after treatments using X-ray diffraction on a D-5000 Siemens Diffractometer using Cu K_α radiation.

Two hysteresis loops taken with a vibrating sample magnetometer (VSM) at room temperature were measured for each sample: one along the long in-plane sample direction, which is described as a longitudinal loop and another one along the short in-plane sample direction, described as a transverse loop.

The domain structure of the samples for different applied magnetic fields was observed using a magnetooptical Kerr effect (MOKE) imaging system.

The magneto-impedance has been measured using a set-up with a complete computer control, as described in Ref. [10]. The impedance changes of the samples were obtained by measuring the AC voltage drop across the film at a constant AC current amplitude. The contacts were carefully prepared using silver electric paint. The current was flowing along the longitudinal direction of the films. The GMI ratio was defined as

$$\frac{\Delta Z}{Z}(H) = 100\,\frac{Z(H) - Z(H_{\max})}{Z(H_{\max})}, \tag{1}$$

where $H_{\max}$ is the maximum bias longitudinal magnetic field, $H_{\max} = 10.5$ kA/m. This DC field was produced by a Helmholtz coils system. The AC current flowing through the film was kept at a constant amplitude of $I_{\mathrm{rms}} = 5$ mA. The frequency of the current was 5 MHz.

3. Results and discussion

Fig. 1 shows the domain structure in the remanent state for an as-grown film, a compressed film, and films thermally treated in the presence of a magnetic field. All of the images show 180° domain wall patterns, typical of magnetic materials with uniaxial anisotropy, where the easy axis is

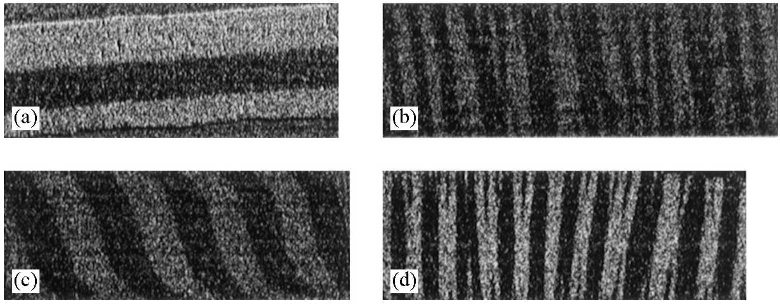

Fig. 1. Domain patterns of remanent magnetisation of different samples: (a) as-grown, (b) compressed, (c) 300°C AC field annealed and (d) 300°C DC field annealed samples.

determined by the particular treatment each sample has received. The as-grown sample (Fig. 1a) exhibits a longitudinal easy magnetisation direction, which may be determined by magnetron effect during preparation. The direction of the field while annealing and applied stress account for the transverse orientation of the magnetisation in the thermally treated and compressed samples.

The compressed (Fig. 1b) and the DC thermal treated (Fig. 1d) samples show stripe domains aligned with the transverse axis of the films together with small spike domains near the edges. The 300°C AC field annealed sample (Fig. 1c) presents a different domain structure consisting of wider curved stripes. The domain walls adopt a reversed 'S' shape. The running direction of the walls forms an angle of around 17° with the transverse direction in the central zone of the film and progressively increases up to an angle of about 65° near the edges. The 250°C AC field annealed sample has a similar domain structure but with an angle of 52° in the central region increasing up to 70° near the edges. It has to be inferred that the AC anneal induces a weaker anisotropy, and that shape effects compete in determining the net anisotropy direction. The mean effective field under AC excitation is certainly less than under DC excitation. But at the same time AC annealing could lead to destabilisation of the domain structure, which is very important for AC field demagnetisation. The sample was given a 250°C AC field annealing and it retained a large longitudinal component to its easy magnetization axis. The temperature may have been too low for sufficient thermal activation of the diffusion.

Fig. 2 shows the longitudinal hysteresis loops of the as-grown, 300°C DC and 300°C AC field annealed and compressed samples. The low values of the coercive fields, from 14 up to 30 A/m, and of the remanent magnetisation, below 5% of saturation magnetisation, are typical for soft magnetic materials with no structural and/or shape-related features which could give rise to high magnetic anisotropies. As-grown and 300°C AC field annealed samples displayed coercive fields of 14 and 16 A/m, respectively. These values are smaller than the coercive fields of the 300°C DC field annealed and compressed samples, which are 30 and 20 A/m, respectively. Remanent magnetisation values were

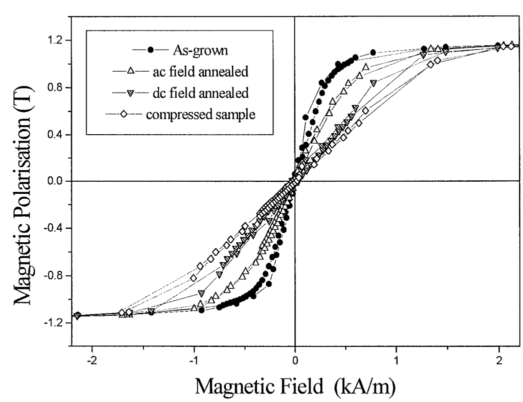

Fig. 2. Longitudinal hysteresis loops of samples. Note that transverse induced anisotropy can be deduced.

similar for all the samples and they correlate well with the remanent domain patterns shown in Fig. 1, where a large number of antiparallel domains are present, with approximately equal areas of the two magnetisation orientations.

The possible magnetic anisotropy sources in these films are reduced to directional ordering of atoms and stress induced effects which can be modified externally by appropriate treatments and the contribution of the geometry of the samples through the demagnetising fields created at their surfaces. The influence of the last source of anisotropy in the magnetisation process is considered to be similar in all the films since their demagnetising factors are the same. So, in the following we focus the discussion on the anisotropies induced by the various treatments.

As long as the longitudinal loops shown in Fig. 2 correspond to magnetisation processes in the direction near the hard magnetisation direction of the treated samples, a straight comparison of the effective anisotropies induced by each method can be made by taking into account the different values of the longitudinal fields needed to reach the saturation magnetisation (H_k^l) deduced from the loops.

The as-grown sample, whose easy magnetisation axis roughly lies in the longitudinal direction, has a H_k^l of 370 A/m and for 300°C AC field annealed sample it is 820 A/m. The AC annealing has turned the easy axis towards the transverse sample direction, although a longitudinal component of this axis still remains, as shown in Fig. 1c.

A further increase of H_k^l field is obtained for the 300°C DC field annealed sample, with $H_k^l = 1100$ A/m. This field is larger than the one for the AC annealed sample. This is explained in terms of the lower net field seen under AC field annealing which, for a given temperature, induce a lower anisotropy energy. The maximum H_k^l field is obtained for the strained sample, with a value of 1770 A/m. This is a typical value in comparison with the magnitudes of field and stress induced anisotropy parameters seen in ribbon samples [11].

Table 1 summarises the main parameters of the transverse hysteresis loops of the samples. The AC field annealed sample presents the lowest remanent magnetisation and the lowest coercive field. The absence of effective pinning centres due to wide domain walls produces such low figures for remanent magnetisation and coercive field. The highest coercive field corresponds to the DC field annealed film, where the domain structure stabilisation hardens the film due to non-uniform domain wall displacements.

Table 1
Transverse hysteresis loops data

Sample	Remanence (in units of M_s)	Coercive field (A/m)	Magnetisation work (kJ/m^3)
As-grown	0.010	19	1.65
AC field annealed	0.006	12	1.39
DC field annealed	0.010	22	1.53
Compressed	0.015	17	0.85

The magnetisation work (energy required to saturate the sample) considered in Table 1 is calculated taking a saturation magnetic polarisation of 1.18 T [12]. The as-grown sample needs more energy than the rest of the films due to its longitudinal component of easy magnetisation axis. The DC field annealed sample requires more energy to be saturated than the AC field annealed sample, although transverse anisotropy generated by DC field annealing is higher than by AC field annealing. The reason for that is attributed again to the stronger pinning of the domain walls at the edges of the DC field annealed sample. The lowest magnetisation work corresponds to the strained sample, which confirms that the stress method is the most effective to induce the transverse anisotropy in these films.

The scientific society undertakes special attempts to find thin films with low frequency (in the interval 5–15 MHz) magnetoimpedance response. The analysis of the GMI features together with anisotropy parameters and domain structure seems promising to predict the states with this response. Fig. 3 shows the variations of the GMI ratios with the bias longitudinal magnetic field for the 300°C AC field annealed (Fig. 3a) and compressed (Fig. 3b) samples. No appreciable magnetoimpedance effects were found on the other samples. Although the

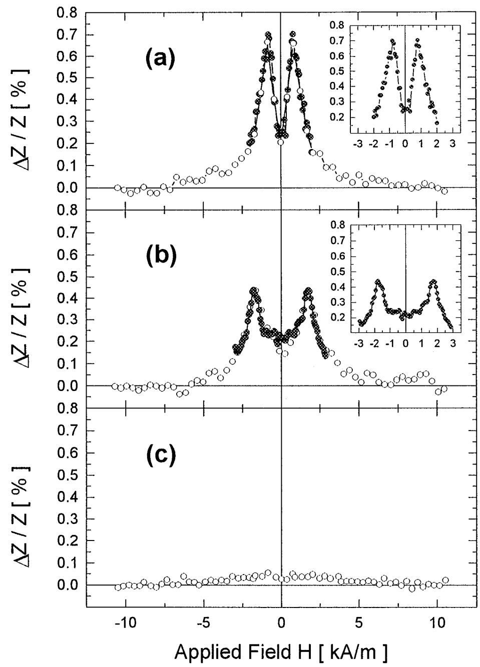

Fig. 3. GMI curves of the 300°C AC field annealed (a), compressed (b) and 300°C DC field annealed (c) samples. The insets show the magnetoimpedance response at low bias fields for (a) and (b) samples. Solid symbols refer to low bias fields GMI response and open symbols refer to high bias field's GMI response.

overall changes of the $\Delta Z/Z$ ratios were below 1% in both samples, the peaks associated with maxima in the permeability induced by the AC polarising current are clearly distinguished. These maxima in the GMI ratios are obtained for bias fields which correspond to the longitudinal H_k^1 fields of the two films. The presence of appreciable GMI effect suggests that the treatments carried out on these two samples favour the rotation of their magnetisations. In the same time 300°C DC annealed sample (Fig. 3c), which shows a higher transversal anisotropy than the AC field annealed film, presents no appreciable magnetoimpedance probably due to the processes of domain structure stabilisation. Also, no hysteretic GMI behaviour was observed for the films with nonzero $\Delta Z/Z$ ratios, but authors consider that no conclusion can be done on this subject, because the absolute values of the magnetoimpedance ratios were rather small.

4. Conclusions

Magnetic anisotropy induced in soft amorphous CoFeB thin films by different techniques is comparatively analysed. Low temperature heat treatments in the presence of an external magnetic field produce a complete change of the domain structure of the films and leads to changes of the position of easy magnetisation axis. The domain wall statics and dynamics can be directly correlated with the strength of induced anisotropy. Permanent stresses applied to the magnetic films through their substrates profit by the negative nature of magnetostriction of CoFeB films to easily induce magnetoelastic anisotropy. Under certain treatments to produce transversal anisotropy together with destabilised domain structures the CoFeB thin films show a magnetoimpedance response at a low 5 MHz frequency of AC polarising current.

Acknowledgements

G. Kurlyandskaya acknowledges the Spanish Ministerio de Educación y Ciencia for supporting the project SAB 95-0421. M. Ali acknowledges the provision of a studentship by the UK Engineering and Physical Sciences Research Council. The authors acknowledge Dr. A.V. Korolyov for helpful discussion.

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