Vol. 85 (1994) ACTA PHYSICA POLONICA A No. 2

Proceedings of the European Conference "Physics of Magnetism 93", Poznań 1993

ANGULAR DEPENDENCE OF SUSCEPTIBILITY IN THIN $Fe_{78}B_{19}Si_3$ FILMS

J. NOWAK

Solid State Physics Department, Polish Academy of Sciences
Wandy 3, 41-800 Zabrze, Poland

AND J. WENDA

Institute of Electronics, Academy of Mining and Metallurgy
Al. Mickiewicza 30, 30-059 Kraków, Poland

The differential transversal susceptibility as a function of an external magnetic field was measured for several directions of the magnetic field with respect to the anisotropy axis. Both the anisotropy field and coercive field were determined by analyzing the symmetry properties of the susceptibility field dependence. The Stoner–Wohlfarth model was modified by introducing an internal field and used to fit the experimental data. The hyperbolic parts of susceptibility curves corresponding to single domain states were well reproduced by fitting the appropriate constant value of the internal field.

PACS numbers: 75.70.-i, 75.60.Ej

1. Introduction

The simple modification [1] of the Stoner–Wohlfart (S–W) model [2] of coherent rotation gives very reasonable shapes of the hysteresis loop and corresponding susceptibility curves for thin ferromagnetic films exhibiting in-plane uniaxial anisotropy. In the previous paper [3], the microscopical magnetization processes in thin $Fe_{78}B_{19}Si_3$ films were described and the susceptibility field dependence for easy and hard directions was examined. The aim of this paper is to measure the susceptibility for the external field applied at an angle to the anisotropy axis and to interpret the data in terms of the modified S–W model.

Amorphous thin films of $Fe_{78}B_{19}Si_3$ were prepared by rf sputtering method and deposited onto typical glass substrates of 24 mm × 24 mm. The details of sputtering procedure are presented elsewhere [4]. The value of saturation magnetization $M_S = 44000$ A/m was found by a magnetic balance method. Measurements of differential transversal susceptibility were performed in the presence of quasistatically variable dc magnetic field with a maximal value of 4000 A/m. A small modulating ac magnetic field was applied perpendicularly to the dc field and the variations of the magnetic flux in a sample were picked up by a compensated collecting coil and measured by a selective nanovoltmeter. The 120 nm thick film was placed on a rotating holder and the transversal susceptibility was measured along several directions lying in the film plane.

2. Results

In Fig. 1 the susceptibility vs. the external magnetic field is shown for several configurations of the field direction and anisotropy axis. An individual curve in Fig. 1 can be denoted as $\chi_{\alpha}^{-}(H)$ (the external field is applied at an angle α with respect to the easy axis) and correspond to a descent branch of hysteresis loop. The susceptibility curves $\chi_{\alpha}^{+}(\mathrm{H})$ corresponding to the ascent branch of hysteresis loop are shifted relative to the H axis so that the symmetry relation $\chi_{\alpha}^{+}(H-L) = \chi_{\alpha}^{-}(H+L)$ is fulfilled [3]. We found that the longitudinal component of the internal field L is independent of the angle α and equal to $L = 200$ A/m. Thus, the coercive field magnitude ($H_c \equiv L$) and width of the corresponding hysteresis loop are independent of the angle α.

In Fig. 1 the consecutive susceptibility curves $\chi_{\alpha}^{-}(H)$ are additionally shifted

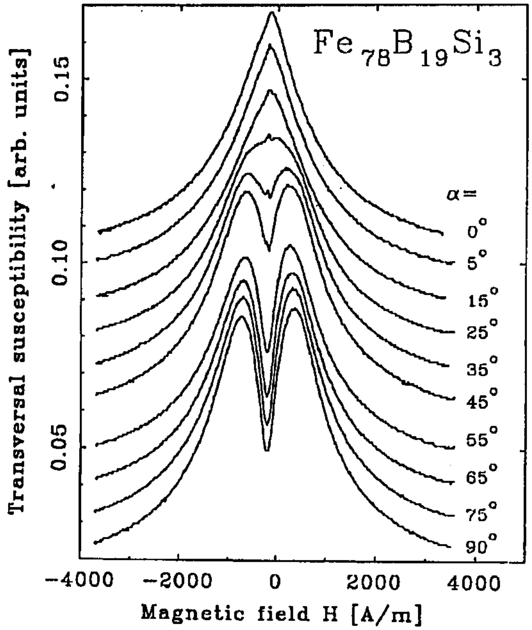

Fig. 1. Transversal differential susceptibility as a function of an external magnetic field applied at the angle α to uniaxial anisotropy axis. The individual curves are shifted vertically by 0.01.

vertically by 0.01 to visualize the change of the curve shape. When the field is applied along the easy axis ($\alpha = 0°$), the single peak characteristic for the easy direction, is obtained. This peak as a function of α gradually transforms to two peaks characteristic for the hard direction ($\alpha = 90°$). A single peak is obtained only within the angle range of ±25°. This means that the magnetization process near the easy axis direction proceeds by wall movement, while for greater α an incoherent rotation occurs. The susceptibility curves along the easy and hard axes are congruent [5] over a certain magnetic field range and the anisotropy field determined from the congruency relation $\chi_{90}^{-}(H - H_{\mathrm{k}}) = \chi_{0}^{-}(H + H_{\mathrm{k}})$ is equal to $H_{\mathrm{k}} = 280$ A/m.

3. Discussion

The density of total energy of thin ferromagnetic film with in-plane uniaxial anisotropy in the modified S–W model [1] is given by

$$E(\alpha, H_{\mathrm{k}}, L, T, H, \phi) = \frac{1}{2} M_{\mathrm{S}} H_{\mathrm{k}} \sin^2(\phi) - M_{\mathrm{S}}(H + L)\cos(\alpha - \phi)$$
$$- M_{\mathrm{S}} T \sin(\alpha - \phi), \tag{1}$$

where α — the angle between the external magnetic field and the anisotropy axis, ϕ — the angle between the magnetization direction and the anisotropy axis, H — the external magnetic field, M_{S} — the spontaneous magnetization, H_{k} — the uniaxial anisotropy field, L and T — the components of internal field longitudinal and transversal to the direction of the external field, respectively. The quantities H_{k}, L and T are expressed in the same units as external magnetic field.

An experimental susceptibility curve is fitted to the following formula

$$\chi_\alpha(H) = c \frac{M_{\mathrm{S}}^2 \cos^2(\alpha - \phi_0(H))}{\left[\frac{\mathrm{d}^2 E(\alpha, H_{\mathrm{k}}, L, T, H, \phi)}{\mathrm{d}\phi^2}\right]_{\phi = \phi_0(H)}} - b, \tag{2}$$

where $\phi_0(H)$ — the angle between magnetization direction and the anisotropy axis is determined from the equilibrium condition $\mathrm{d}E/\mathrm{d}\phi = 0$, c — the amplification constant and b — the background determined by the electronic device.

A fit of Eq. (2) to experimental data for three selected orientations $\alpha = 0°, 45°$ and $90°$ is shown in Fig. 2. Only one parameter, namely the transversal component of the internal field T is fitted, while other parameters are determined from independent measurements. As can be seen the modified S–W model describes well the hyperbolic parts of susceptibility curves corresponding to single domain states. This indicates that the rotation of ripple structure under the influence of the external field can be described in terms of constant internal field. Equation (1) describes the single domain states only and therefore the model curves evidently differ from experimental data if the domain structure is present.

The magnitude of transversal component T is the greatest for the easy axis magnetization process and the resultant internal field is inclined at an angle $\beta = \arctan(T/L)$ to the external field direction. In this case $\beta = 62°$, the rotation of mean magnetization is advanced up to the angle $\phi = \beta$ and then retarded. For the magnetization process along a hard direction, $\beta = 47°$ and in the angle

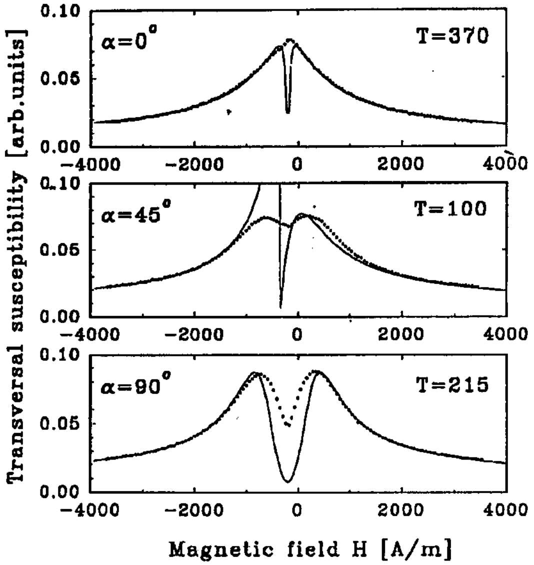

Fig. 2. Experimental data (circles) and model calculation (solid lines) of susceptibility for three selected configurations of the external field and anisotropy axis ($\alpha = 0°$, $45°$, $90°$). The magnitude of transversal component of the internal field obtained by a fitting procedure is also shown.

range ±47° the rotation process is advanced. For intermediate α, the angle β is much smaller and only at the beginning of magnetization process the rotation is advanced. Moreover, the magnitude of the resultant internal field is of order of the anisotropy field; thus, the examined films are similar to the type of film called "mottled" [6] and the magnetization direction reverses mainly by the incoherent rotation.

Acknowledgments

The authors thank Dr hab. J. Cisowski for critical reviewing the manuscript. This work was partially supported by the Committee for Scientific Research under grant No. PB 0902/P3/93/04.

References

[1] J. Nowak, *J. Appl. Phys.* **72**, 1490 (1992).

[2] E.C. Stoner, E.P. Wohlfarth, *Philos. Trans. R. Soc. A* **240**, 599 (1948).

[3] J. Nowak, J. Wenda, *J. Magn. Magn. Mater.*, in press.

[4] A. Milewski, J. Samuła, L.J. Maksymowicz, J. Wenda, H. Jankowski, A. Kułak, *J. Magn. Magn. Mater.* **75**, 165 (1988).

[5] E. Feldtkeller, *Z. Phys.* **176**, 510 (1963).

[6] M.S. Cohen, *J. Appl. Phys.* **33**, 2968 (1962).