acta physica slovaca vol. 46 No. 2, 175 – 178 April 1996

MAGNETIC ANISOTROPY FROM DIPOLAR INTERACTIONS IN MAGNETIC NANOSTRUCTURES[1]

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Received 31 July 1995, accepted 8 February 1996

A simple formula is proposed to describe the shape anisotropy of ferromagnet with a nonuniform distribution of the magnetization. The shape anisotropy is expressed as a sum of the shape anisotropy of a ferromagnetic body regarded macroscopically and a term involving magnetization fluctuations due to microscopic structure. An example of application of our approach for an inhomogeneous magnetic Fe/Zr multilayer is presented.

1. Introduction

Magnetic nanostructures, i.e. granulated films or discontinuous multilayers, are novel magnetic materials with promising potential applications to their giant magnetoresistance [1]. Magnetic properties of these inherently heterogeneous structures involve interplay between magnetic anisotropy resulting from dipolar interactions and structural details on a microscopic scale [2]. Although the magnetic heterogeneous films are not completely new, rigorous calculations of the shape anisotropy have been given only for some specific cases [2, 3, 4]. Therefore, there is a need for simple and general approach to describe the effect of microscopic heterogeneity on the shape anisotropy. We confine ourselves to nanostructures shaped macroscopically as thin films. For simplicity, other sources of the uniaxial anisotropy will be neglected. The full analysis of our approach will be given elsewhere.

2. A model result

We consider an internally heterogeneous film characterized, in its principal directions, by the macroscopic demagnetizing tensor $N^{macro} = 4\pi[0,0,1]$. Let D_x,D_y, D_z be the demagnetizing factors of a single particle and $N^{micro} = 4\pi[D_x, D_y, D_z]$ (Fig. 1). If the film consists of an array of coherently distributed particles of the same shape with

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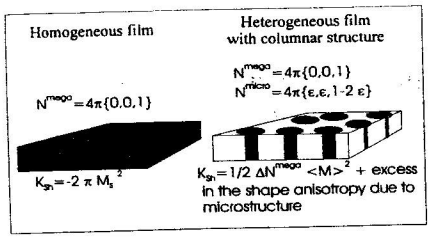

Fig. 1. A sketch showing the effect of anisotropic microstructure heterogeneity on the shape anisotropy in a thin film.

magnetization M_S, the shape anisotropy energy density $K_{sh} = U_{\|} - U_{\perp}$ ($U_{\|}$ ($U_{\perp}$) is the magnetic self-energy density for magnetization parallel (perpendicular) to the surface of the film) may be expressed as

$$K_{Sh} = \frac{1}{2}\Delta N^{mega} < M >^2 + \frac{1}{2}\Delta N^{micro}(< M^2 > - < M >^2), \qquad (1)$$

where $<\ >$ denotes the space average and $\Delta N = N_{\|} - N_{\perp}$. The first component in Eq. (1) describes the shape anisotropy of the film regarded macroscopically. The second term describes the excess in the magnetostatic energy (and thus, in the shape anisotropy) due to the microscopic structure. It derives from the average energy of particles embedded in the effective medium (like in Lorentz's model). Eq. (1) can be transformed into expressions, which have previously been proposed to approximate the shape anisotropy K_{sh} for some particular cases of microstructural heterogeneity, i.e., for multilayered films [4] and columnar films [3]. The dependencies of $K_{sh}/2\pi M_S$ *vs.* a/b, calculated according to Eq. (1) for a film consisting of cylindrical particles of diameter a and interparticle distance b, is shown in Fig.2. The demagnetizing tensor of a single particle, in its principal directions, is expressed as $N^{micro} = 4\pi[\epsilon, \epsilon, 1 - 2\epsilon]$ with an ellipticity factor $\epsilon = \epsilon(t/a)$ dependent on the ratio of the film thickness t to particle diameter a according to Bozorth's data [5]. For a cylindrical film consisting of an array of cylindrical particles, Eq. (1) takes the form

$$K_{Sh} = -2\pi M_S^2 f[1 - 3\epsilon(\frac{t}{a})(1 - f)]. \qquad (2)$$

In our calculations, we assume that the average magnetization $< M >= fM_S$, where $f = \pi/2\sqrt{3}(a/b)^2$ is a volumetric filling factor for cylindrical particles. It is seen in Fig. 2 that our approach leads to the same result as Masuda's approach [3] who used rather tedious calculations and the form of the final formula is not very useful for the experimenters. On the other hand, a substantial deviation from the frequently used Netzelmann's formula [6] is seen, especially in the range of low filling factors.

3. Comparison with the experiments

A lot of experimental results for heterogeneous magnetic thin films can be understood as originating from the effect of anisotropic heterogeneity on the shape anisotropy. As

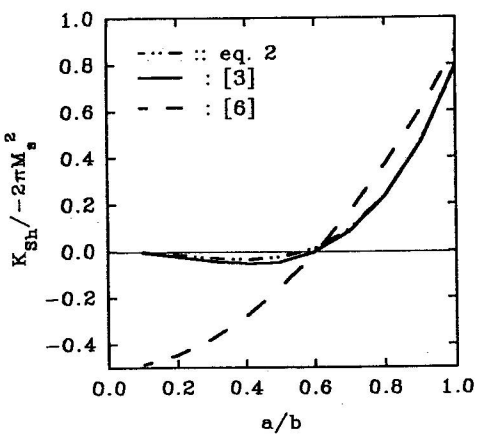

Fig. 2. Calculated shape anisotropy K_{Sh} *vs.* a/b (a-diameter of the particles, b-their separation) for a columnar film. Dash-dotted curve represents K_{Sh} calculated according to eq. (2) and follows a continuous curve [3]. Dashed curve represents Netzelmann approach [6].

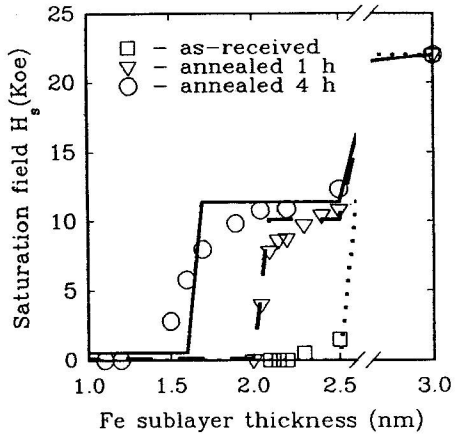

Fig. 3. Evolution of the saturation field H_s in Fe/Zr multilayer along a wedge at various stages of annealing of the wedge shaped Fe/Zr multilayer at 593 K. Lines represent fits according to eq. (3).

an example, we will only discuss here our recent investigations of a metastable magnetic behaviour of ultrathin Fe in Fe/Zr multilayers [7].

Analysis of hysteresis loops shapes obtained with a polar Kerr magnetometer yields information on a complex magnetic structure of ultrathin Fe sublayers, which may be conceived as a mixture of a ferromagnetic, superparamagnetic and paramagnetic states with volume fractions of each component strongly dependent on d_{Fe} and time of annealing. In the as-received Fe/Zr multilayers with $d_{Fe} < 2.5$ nm paramagnetic state of Fe prevails at room temperature due to spontaneous growth of amorphous Fe [9]. The simplest method leading to some structural changes in multilayers is annealing at elevated temperatures [8]. Annealing of our Fe/Zr wedge shaped multilayers at 573 K [9] causes crystallization of ultrathin Fe sublayers on the microscopic scale: paramagnetic Fe easily transformes to a partially ferromagnetic state due to growth and subsequent coarsening of bcc Fe grains. These structural changes involve significant modifications of the saturation field H_s determined from the polar Kerr loops. Symbols in Fig. 3 show the experimental values of H_s plotted *vs.* d_{Fe} for various stages of annealing of our Fe/Zr wedge-shaped multilayer. The data can be satisfactorily fit by taking into account

$$H_s = 4\pi M_{eff} = 4\pi M_S[1 - 3\epsilon\left(\frac{t}{a}\right)(1 - f)] \qquad (3)$$

and assuming a step-like dependence of volumetric filling factor along the wedge from $f = 0.1$ to $f = 0.35$ at $d_{Fe} > 2.1$ nm for 1 h of annealing, and from $f = 0.2$ to $f = 0.55$ at $d_{Fe} > 1.7$ nm for 4 h of annealing. Moreover, the best fits are achieved if separation

between bcc Fe grains decreases twice on annealing from 1 to 2 hours. Therefore, it seems reasonable to suppose that the evolution of H_s *vs.* d_{Fe} on annealing of our Fe/Zr wedge multilayer is due to coarsening of small bcc Fe grains approximated in our approach by an array of cylindrical particles. It is interesting that the decrease in H_s is sharp and, on the course of annealing, continously shifts towards smaller and smaller thicknesses of Fe sublayers.

In summary, our simple approach to the magnetic shape anisotropy of heterogeneous magnetic structures may describe some effects related to modifications of the magnetic properties of thin films due to changes in their morphology.

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