PECULIARITIES OF THE MAGNETIZATION BEHAVIOR IN THIN FILMS WITH UNIAXIAL ANISOTROPY

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PACS Ref: 75.70.Kw

Abstract

A study about qualitative physical behavior of the magnetization in thin one-domain films, with uniaxial anisotropy in the film plane is made. Being based on the Stoner–Wohlfarth model it determines peculiarities of the magnetization behavior by means of analytic techniques. A benefit of the method is avoiding the necessity to find the explicit solutions of the Stoner–Wohlfarth equations, which is rather cumbrous. Similar attempts might be of use for other convenient expressions, like Taylor expansions and determination of singularities in situations more complicated than one domain model.

1. INTRODUCTION

In soft magnetic materials (without coercitive reminiscence) magnetization is caused by interaction between crystalline potential and magnetostatic dipole momentum, which affects the initial distribution of the magnetic particles. The crystalline interaction is completely quantum effect, but in macroscopic terms it could be described as the variation of the energy of the crystal as a function of the variations of some crystal parameters. In ferromagnetic materials the existence of particles with dipole momentum is a quantum effect (but not a corollary from classic magnetic forces between electron spins). Thus the type of the elementary dipoles strongly depends on the chemical composition and on the way the crystal has been prepared.

2. THEORETICAL BACKGROUND

Supplement restrictions appear in case some dimensions of the sample are of the same order as the dimensions of the elementary magnetic particles. This situation will be considered about soft ferromagnetic films with uniaxial anisotropy. As the thickness of the film is commensurable to the size of the magnetic particles, the vector of magnetization lies in the plane of the sample, because having a perpendicular

component would be very unprofitable. The proportion between the surface of the films and its cross section is ~ 10^4. In this order is the proportion between the magnetic fluxes around the sample for cases **B** being perpendicular and **B** being in the film plane. The magnetostatic energy in some volume V is $W \sim \int_V B^2 \mathrm{d}^3 x$, will be bigger in the space (where **B** has remarkable values) and therefore the more energy is necessary to establish such direction of the magnetization.. Thus for $\mathbf{M}_s$, laying in the sample plain the energy distribution is much more favourable, and this is the situation really occur.

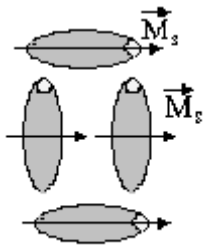

Figure 1. Both types of elementary particles propagating the magnetization

Processes in such samples are described by the Stoner-Wohlfarth model [1], according which the magnetization is determined by ellipsoid particles with fixed dipole momentum. Two types of particles take part in the magnetization – prolate ellipsoid with dipole momentum along long axis and oblate ellipsoid with momentum along short axis (Figure 1). In the materials with uniaxial anisotropy in the sample plain, there is a direction along which the vector of magnetization is placed in absence of external field (so called easy axis) [2,3]. This is realized usually by preparing the sample in homogeneous magnetic field.

According to the Stoner-Wohlfarth model the full energy E per unit volume is the sum of the anisotropy energy E_k, needed to divert the vector of magnetization $\mathbf{M}_s$ to some angle φ from the easy axis, and the energy of interaction E_H between the magnetization and the external field **H**.

$$E = E_k + E_H = K \sin^2 \varphi - \mathbf{M}_s \,.\, \mathbf{H}, \qquad (1)$$

where K is the constant of the magnetic anisotropy, H and θ are the magnitude and the angle with respect to the easy axis of the external field. The vector of magnetization is supposed to have fixed size, depending on the material structure and corresponding to

the anisotropy field $H_a = 2K/M_s$. Therefore the aim is to determine the angle φ between the magnetization vector and the easy axis. It could be found from the conditions for local minimum of the full energy, i.e. for stable stationary position of the magnetization:

$$\frac{\partial E}{\partial \varphi} = 0 \tag{2}$$

$$\frac{\partial^2 E}{\partial \varphi^2} > 0 \tag{3}$$

Physically this means that the angular momentums of anisotropy, which trends the domain towards the easy axis, and of dipole magnetic interaction, are compensated in stable stationary at some positions of φ. Further only fields applied at angles $\theta \in (0, \pi)$ will be considered because of the obvious symmetry with respect to easy axis. The goal is to explain qualitatively the behavior of the magnetization and especially to determine the maximal declination the magnetization could gain under certain field.

It is convenient to express **H** in non-dimensional parameters $\mathbf{h} = \mathbf{H}/H_a$. Than Eq. (1) turns to

$$E = K\sin^2\varphi - \frac{2K\,\mathbf{M_s}.\mathbf{H}}{M_s} = \left(\frac{K}{2}\right)\left(1 - \cos 2\varphi - 4h\cos(\theta - \varphi)\right) \tag{4}$$

As E is a potential energy, the constant term doesn't play role and might be omitted. Than the fool energy could be written in a modified form

$$E = -(K/2)\,(\cos 2\varphi + 4h\cos(\theta - \varphi)) \tag{5}$$

This expression often is more convenient for calculations.

Replacing (5) in (2) gives

$$2h\sin(\theta - \varphi) - \sin 2\varphi = 0. \tag{6}$$

Finding the explicit solution φ(θ) for Eq.(6), as is shown in [4], is a cumbersome mathematical problem. Here we will consider an analytical approach to this problem in order to determine points of qualitative changes of the magnetization behavior. Regarding the left side of Eq.(6) as function in two variables θ and φ its total differential gets:

$$2h\cos(\theta - \varphi)\,(d\theta - d\varphi) - 2\cos 2\varphi\, d\varphi = 0, \text{ or} \tag{7}$$

$$((1/h)\cos(2\varphi) + \cos(\theta - \varphi))\, d\varphi = (\cos(\theta - \varphi))\, d\theta \tag{8}$$

thus

$$\frac{d\varphi}{d\theta} = \frac{\cos(\theta - \varphi)}{\cos(\theta - \varphi) + (1/h)\cos(2\varphi)}. \tag{9}$$

For the maximal angle φ_{max}

$$\frac{d\varphi}{d\theta} = 0 \Big|_{\varphi = \varphi_{max}} \tag{10}$$

i.e.

$$\cos(\theta - \varphi_{max}) = 0. \tag{11}$$

$$\theta - \varphi_{max} = \pi/2 \tag{12}$$

3. CONCLUSIONS

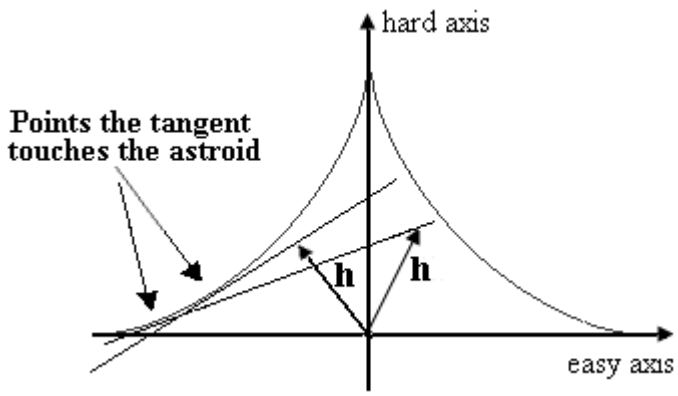

Figure 2. As the field rotates, the tangent slides along the astroid. Thus it is nor geometrically evident whether the max. attained inclination would be perpendicular to the field

The relation (12) shows that if under certain field the magnetization possesses the maximal available inclination against the easy axis, than it is perpendicular to the field. The common picturesque expression for the course of the magnetization with an astroid is unfit to determine this fact by elementary trigonometric relations.

It is well known, that for $1 > h > 0.5$ there are intervals in θ where the solution for φ is doublet and for $h < 0.5$ this doubling occurs for every θ [2,4]. Which of the both directions is realized depends on the history of the magnetization process. The result, obtained above, holds for all those cases, because no supplement information fixing a concrete process was used in the proof. (here a precision should be made – saying inclination we mean the sharp angle between magnetization and easy axis, because in case of doubled one of the values of φ is obtuse angle (Figure. 3).

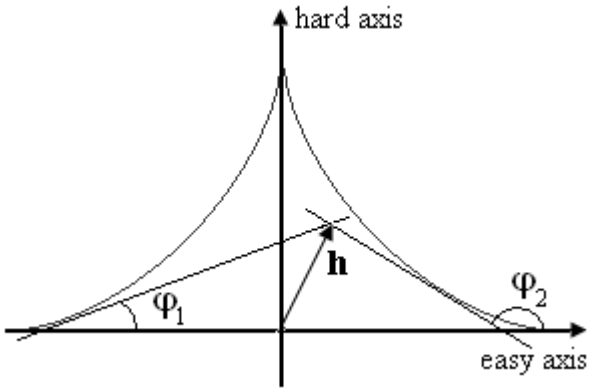

Figure 3. Sharp and obtuse angles of the magnetization direction under the same field

As the angular momentum on dipole in homogeneous field is maximal if the dipole is perpendicular to the field, qualitatively this means that the magnetostatic momentum decreases faster than the momentum of the crystalline tension beyond the perpendicular disposition of **H** and $\mathbf{M_s}$**.** Let the position of both vectors **H** and $\mathbf{M_s}$ is in interval (0 , π) and the fields starts to rotate from some initial state in the same interval. The relation (12) gives out, that following the field, the inclination the magnetization reaches only one maximum.

Also this shows that the magnetization reaches max. inclination for a field placed in the opposite quadrant to it, no matter what the magnitude it has. It could seem surprising, because for small enough fields one could expect that the anisotropy action well in advance would bring the magnetization to the easy axis.

The proposed analytic method doesn't depend on the concrete form of the implicit Eq.(6). It could be applied for more complicated models to quest a singularities in the magnetization behavior. It also could be expanded in order to obtain relations between higher order differentials in θ and φ, which take part in various series extensions.

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