A MODEL OF EDGED DOMAINS IN THIN MAGNETIC FILMS WITH UNIAXIAL MAGNETIC ANISOTROPY

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Abstract

The paper describes the magnetization processes due to the incidence of the edged domains in thin magnetic films with uniaxial magnetic anisotropy in film plane. The advent and expansion of the edged domain in the applied magnetic field is connected with the energy changes of the domain structure. Two cases – of the open Kittel structure and of the closed Bloch structure in the initial state of domain configuration are discussed from energy point of view and the energy changes are described as a function of the magnetization of the sample.

1. INTRODUCTION

One of the basic mechanisms during the magnetization process in thin magnetic films (TMF) with an uniaxial anisotropy in the film plane is the appearance and volume growth of domains with a reverse magnetization. [1,2]. In polycrystal TMF, obtained by means of vacuum evaporation in the presence of a constant external magnetic field, are observed the structural inhomogeneities in TMF and, as many authors point out – they cause the heterogeneity of the magnetostatic field and they are considered to be the source of these domains. The influence of this field is especially manifested at the edges of the sample – the so-called “edge effect”. As a rule the magnetization of soft magnetic TMF starts from existing edge, growing at first in the direction of the film’s inside and increasing in a width.

This article represents an idealised scheme describing the edge domain appearance on magnetizing of a four–domain magnetic structure with initial magnetostatic energy equal to zero.

2. THEORETICAL BACKGROUND

Let's find the volume density of the free energy for two idealised structures represented (Fig.1 a,b) with relative magnetization $m_K = M_K/M_s$ and $m_B = M_W/M_s$ respectively [3]. In an external field $H = 0$ we suppose $m_K = 0$ and $m_B = 0$. For the structure in fig. 1 a (it is known as a Kittel structure):

$$\varepsilon_K = \frac{4\mu_0 M_s^2 w_K}{\pi^3 l}\zeta(3) + \frac{\sigma}{w_K} \tag{1}$$

where M_s is the saturation magnetization of the film, w_k and l are the width and the length of the structure respectively, σ is the density of the wall energy, $\zeta(3)$ is the Riemann function at an argument equal to 3, $\mu_o = 4\pi 10^7$ H/m. And for the structure in fig. 1 b (named Bloch structure):

$$\varepsilon_B = \frac{1}{2}K\frac{w_B}{l} + \sigma\left(\frac{1}{w_B} + \frac{\sqrt{2}-1}{l}\right) \tag{2}$$

where K is the constant of the uniaxial anisotropy, w_k and l are the width and the length of the structure respectively.

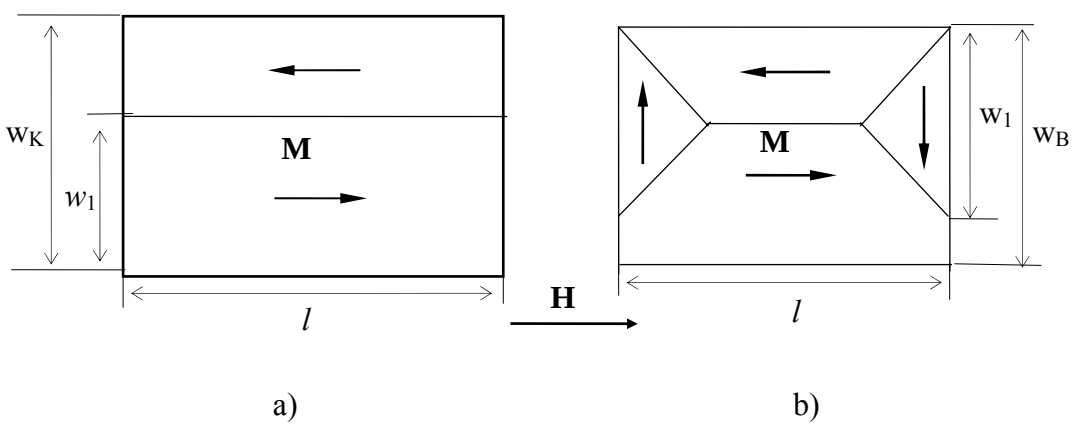

Figure 1. a)Kittel and b)Bloch domain structures in TMF.

The relative magnetizations of the structures are the nonevident function of the

parameters w'_K and w'_B which determine the domain wall position (Fig. 1). We will compare the energy densities in the case of $m_K = m_B = m \neq 0$ at different H_1 and H_2. In this case the energies are presented by the following expressions:

$$\varepsilon_K = \frac{(mM_s)^2}{2\mu_0} + \frac{4M_s^2}{\mu_0\pi^3}\frac{w_K}{l}\sum_{n=1}^{+\infty}\frac{1}{n^3}\sin^2\left[\frac{n\pi}{2}(1+m)\right]\left[1-\exp\left(-\frac{2n\pi l}{w_K}\right)\right] + \frac{\sigma}{w_K} + \varepsilon_{HK} \tag{3}$$

$$\varepsilon_B = \frac{M_s^2}{2\mu_0}\left\{m^2 + \frac{4}{\pi^3}\frac{w_B}{l}\sum_{n=1}^{+\infty}\frac{1}{n^3}\sin^2\left(m\frac{n\pi}{2}\right)\left[1-\exp\left(-\frac{2n\pi l}{w_B}\right)\right]\right\} + \frac{1}{2}K\frac{w_B(1-m)^2}{l}$$
$$+\sigma\left(\frac{1}{w_B} + \frac{(\sqrt{2}-1)(1-m)}{l}\right) + \varepsilon_{HB} \tag{4}$$

where $\varepsilon_{HK} = -mM_sH_1$, $\varepsilon_{HB} = -mM_sH_2$ are the volume densities of the energy for Kittel and Bloch structure respectively.

In the expressions (3) an (4) the terms denoting the own magnetostatic energy have been obtained by means periodizing the two structures along the y-axis and applying the method, detailed in [4]. Because of the presence of the magnetostatic term the energy density of the opened Kittel structure in its initial state is higher than of the closed Bloch one. If the closed magnetic structure complies with the suggested by us four-domain model [3] the increase of the external field will lead to the appearance of uncompensated "magnetic charges". The first term in (4) denotes their energy. Considering the expressions (3) and (4) as functions of one variable m (disregarding the effect of jumped change in the wall location, discussed in detail in [3]) the following conditions for their minimum were obtained:

$$\frac{d\varepsilon_K}{dm} = \frac{mM_s^2}{\mu_0} + \frac{4M_s^2}{\mu_0\pi^2}\frac{w_K}{l}\sum_{n=1}^{+\infty}\frac{1}{n^2}\sin[n\pi(1+m)]\left[1-\exp\left(-\frac{2n\pi l}{w_K}\right)\right] - M_sH_1 = 0 \tag{5}$$

$$\frac{d\varepsilon_B}{dm} = \frac{M_s^2}{\mu_0}\left\{m + \frac{2}{\pi^2}\frac{w_B}{l}\sum_{n=1}^{+\infty}\frac{1}{n^2}\sin(mn\pi)\left[1-\exp\left(-\frac{2n\pi l}{w_B}\right)\right]\right\} - K\frac{w_B(1-m)}{l}$$

$$-\sigma\left(\frac{\sqrt{2}-1}{l}\right)-M_s H_2 = 0 \qquad (6)$$

In the initial state ($H = 0$, $m = 0$) the energy is minimum, i.e. positive second-order derivatives are required. It can be verified that this condition is fulfilled for the equation (5). The same is for the equation (6) presumes the existence of internal field in (6), so that:

$$H_2 = H_1 - \frac{Kw_B + \sigma\left(\sqrt{2}-1\right)}{M_s l} \qquad (7)$$

The internal field, denoted in (7), is a direct consequence from the conclusions in [3], that points out the existence of a small domain wall deformation in the initial state due to a difference between the density of the energies for the magnetic phases of the closed structure. If the external field increases the energy densities of the two magnetic configurations will change in a different way preserving the same relative magnetization m.

The Bloch structure with closed domains (Fig. 1 b) has lower energy and this is the reason for its being in initial state thermodynamically more probable for realisation. The difference between (3) and (4) come to be a function of the relative magnetization. For zero values of this function at defined m the energy of the Bloch structure will come to be equal to that of the Kittel structure. A subsequent increase of m leads to thermodynamically unfavourable state of the Bloch structure. The rate of the function $\Delta\varepsilon(m) = \varepsilon_K - \varepsilon_B$.

$$\Delta\varepsilon(m) = \sigma\left[\frac{1}{w_K} - \frac{1}{w_B} - \frac{\left(\sqrt{2}-1\right)}{l}(1-m)\right] - \frac{4w_B}{\pi^3 l}K_u(1-m)^2$$
$$+\frac{4M_s^2}{\mu_0\pi^3 l}\sum_{n=1}^{+\infty}\frac{1}{n^3}\left\{w_K \sin^2\left(\frac{\pi n}{2}(m+1)\right)C_1 - w_B \sin^2\left(\frac{\pi n}{2}m\right)C_2\right\} \qquad (8)$$

where $C_1 = 1-\exp\left(-\frac{2\pi nl}{w_K}\right)$ and $C_2 = 1-\exp\left(-\frac{2\pi nl}{w_B}\right)$, respectively, is represented in fig.2.

The numerical calculations have been made using the following values: $K = K_u = 100$ J/m^3, $M_s = 1$T, $l = 10^{-3}$ m, $\sigma = 4.6\times10^{-3}$J/m^2 (Bloch–wall for a 100 nm thin permalloy film) where w_K , w_B have their values from (1) and (2) respectively after minimization of the structure width. If the relative magnetization arises the energy densities become equal at some value of m and after that the Kittel's structure possesses lower energy. During the evolution of a similar closed structure on observe the appearance of the edged domains with a reverse to the main magnetic phase magnetization [5].

The newly–formed structure's energy can be presented as a sum of the energies of a closed magnetic structure with volume V_1 and an opened magnetic structure with volume V_2. The relative magnetization must be the same or higher (if this configuration transition leads to Barkhausen's effect). The problem in this case is the ex-

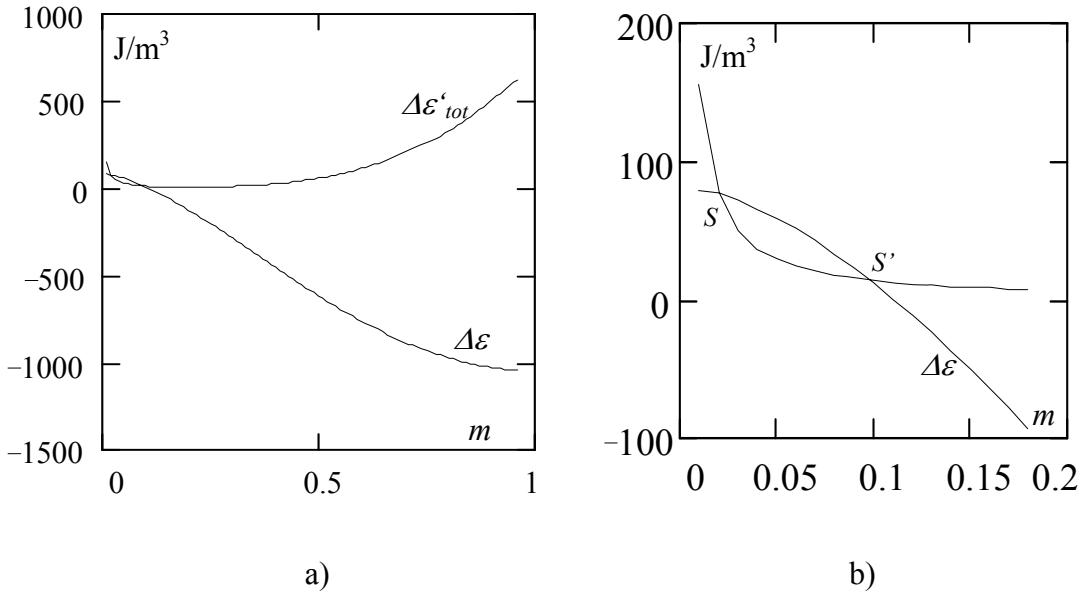

Figure 2. Energy density as a function of relative magnetization of the film.

istence of a great diversity of lower energy structures which makes theoretically impossible to define the new configuration without additional assumptions for its energetically topology [6]. That is why an idealised evolution scheme presented in fig.3, has been assumed. The results of the energy density's $\Delta\varepsilon'$ calculations as a function of

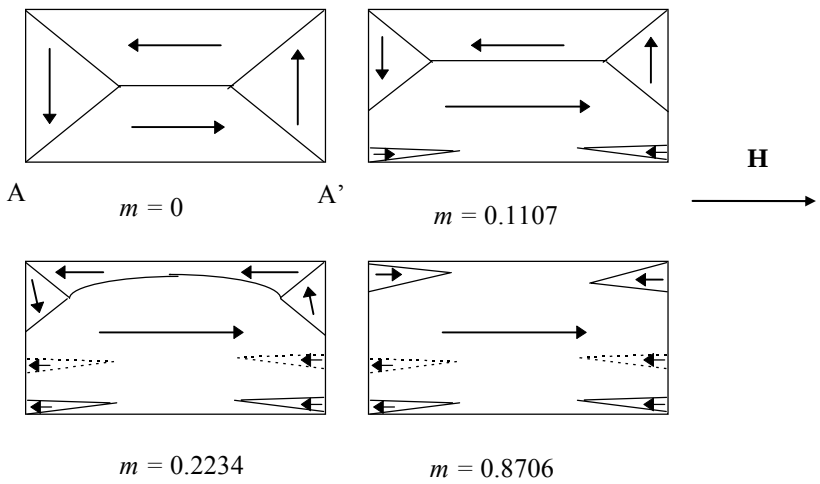

Figure 3. Evolution scheme of the edged domains at different magnetization values.

the changes of the relative magnetization are obtained (Fig. 2 a, b) for an evolution structure with a zero magnetostatic energy in its initial state (d'Blois–type). The new energy density's difference $\Delta\varepsilon'$ due to the appearance of the edged domain's are obtained by a modification of the function (7):

$$\Delta\varepsilon©(m) = \sigma\left[\frac{1}{w_B m} - \frac{1}{w_B(1-m)} - \frac{\sqrt{2}-1}{l}(1-m)\right] - w_B K\frac{(1-m)^2}{2l} + \frac{1}{2\mu_0}\frac{M_s^2 w_B^2 m^4}{l^2}\left\{\ln\left(\frac{2l}{w_B m}\right) - \frac{2}{\pi}\ln 2\right\}, \tag{9}$$

where the Kittel's width is denoted by w_B – d'Blois section width and m – relative magnetization ($w_K = m\, w_B$). The infinity sum revealing the magnetostatic field's contribution in (8) according to the evolution scheme, has been substituted with the effective demagnetization factor for a Kittel's structure's single element obtained in [4]. Fig.2 demonstrates that the appearance of edged domains keeps the positive value of the energy density's difference, i.e. this evolving scheme will procure an energy minimum (at the same relative magnetization m) as a scheme suggested in [3]. On the other hand the initial section (fig.2 b) shows that at low m values this structure scheme is energetically unfavourable related to a structure that encloses the magnetic flux.

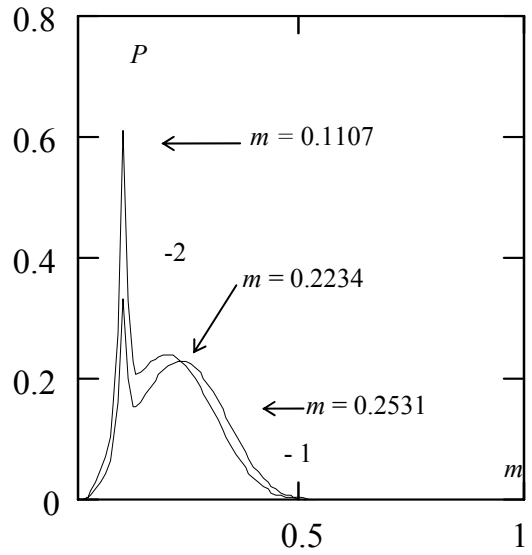

Figure 4. Probability of the appearance of the edged domain at different *m*-values.

A confirmation of these arguments is the probability of a edged domain appearance (fig. 4), leading to a decrease in the structure's magnetostatic energy. The latter has been calculated for an evolving scheme conducting to the changes in $\Delta\varepsilon'$ for the structures in fig.1. It is based on the thermodynamically expression representing the structure's configuration transition [9]. The edged domains, marked by dotted lines, present a probable appearance of such structures, because our consideration does not make a prediction for a precise location of the edged domain.

The probability of a edged domain appearance at $m > 0.5$ is very small as it can be concluded from the diagram (curve 1) represented in fig. 4. Actually at this stage of the process the decrease in the volume density of the energy is realised by a rotation of the magnetization in the enclosing 90^0 domains and because of the "swelling" effect on the domain wall. This configuration transition cannot be described by (8) anymore.

The rotation of the magnetization in these structures decreases the term of the anisotropy energy in $\Delta\varepsilon'$s expression and leads to the appearance of new "magnetic" charges. On the other hand the border between the reversal magnetized sections is not 180^0-wall because its deformation as a result from the "magnetic pressure" exercised by the applied effective field $\mathbf{H}_{\text{eff}}$. Such a structural state is very unstable [7,8] and a small change in $\mathbf{H}_{\text{eff}}$ or in $\mathbf{H}$ will lead both to the disappearance of the 90^0 domains and the wall between the reversal magnetized regions To find the difference $\Delta\varepsilon''' =$

$\Delta\varepsilon$ (from eq.8) between the energy densities in this stage of the magnetization process we modify the eq.9:

$$\Delta\varepsilon©©(m) = \sigma\left[\frac{1}{w_B m} - \frac{1}{w_B(1-m)} - \frac{\sqrt{2}-1}{l}(1-m)\right] - 4w_B K\frac{(1-m)^3}{\pi^3 l}$$
$$+\frac{1}{2\mu_0}\frac{M_s^2 w_B^2 m^4}{l^2}\left\{\ln\left(\frac{2l}{w_B m}\right) - \frac{2}{\pi}\ln 2\right\} - \frac{M_s^2\chi^2 m}{\mu^*}\left\{\frac{3}{2}\ln\left(\frac{1}{\chi^2}\right) - 1\right\} - \frac{4Km}{\pi}\chi, \quad (10)$$

where the energy density of the sector with the deformed domain wall is considered. The appearance of an additional magnetostatic field as a result of the wall's deformation heightens the probability of a edged domain appearance (fig. 4, curve 2). To compute this probability we used $\chi = 0.0145$ as the value of the domain wall's deformation parameter [8] which is typical for permalloy films with a thickness $t \approx 100$ nm

3. RESULTS AND CONCLUSIONS

In conclusion the result from (9) and (10) equations' calculation and especially, the initial sector of the Δε (m), Δε'(m) functions diagram (shown in fig.2 b) will be more closely discussed. Let suggest that the point of configuration transition is reached as a result of the applied external field and then the field begins to decrease towards zero. At these conditions the function *Δε (m)* will draw a closed curve from a state of a zero magnetization $m = 0 \rightarrow$ p.***S*** →(section Δε) → p.*S'* →(section Δε') → p.*S*). As it is shown in fig. 4, the probability of a reverse configuration transition at this point can be ignored, i.e. $m \neq 0$ even in a zero external field. The latter means that the domain appearance at this stage of the process marks the end of initial sectors of the magnetization curve and the above described closed cycle turns to be a private hysteresis loop of this scheme. Such a discussion could also be conducted for the subsequent stages of the evolution scheme if the values of *m* corresponding to the edged domains appearance will be fixed. The suggested scheme is quite general for a detailed research and presents a probable description of the possible domain appearance decreasing their own magnetostatic field. Of course, its concrete description is possible and could become a subject of another research.

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