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# Getting ferromagnetic metallic nanofilms for information recording on the magnetic moments of the electrons

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***Abstracts:***

*The ferromagnetic nanofilms are promising for recording information by means of electron spins. The preparation of such films is technologically very cheap. It is assumed in such matrices can be a huge recording density information. But the main difficulty was the fact that the magnetic structure of the films depends on technological parameters of the film. The magnetic structure of films, prepared at different deposition, differ from each other. We have theoretically calculated parameters of the films in which there is a given domain structure. This theory has been tested experimentally. The films were produced, in which the observed magnetic image in advance was calculated by us. The possibility of obtaining a magnetic structure has allowed us to explore the rotation of the magnetization vectors in the domains*

Keywords: *Domain, walls, magnetization, electron, spin, energy, anisotropy.*

## 1. Introduction

With the emergence of new trends in the field of microelectronics "spintronics" [1] dramatically increased the importance of studying the magnetization reversal of ferromagnetic nanofilms. Until now, the process of magnetization reversal is not fully understood. The ferromagnetic films may be suitable for the information recording via the magnetic moments of the electrons. Changing the domain structure and the distribution of the magnetic moments of the entire surface of the film takes place during the magnetization reversal of ferromagnetic metallic nanofilms. The distribution of the magnetic moments of the electrons can be seen in the distribution of the magnetization vectors on the surface of the film. The micro-magnetization process can be observed only at high magnification with a transmission electron microscope.

Part of the research program of search the minimum and maximum values of energy in thin films, they were held in Irkutsk State Pedagogical Institute in the laboratory of magnetic phenomena. Experimental results have been obtained with an electron microscope UEMV-100K (universal electronic microscope, an accelerating voltage of 100 kV, the increase is not less than $10^5$-fold) and additional devices for monitoring the magnetic structure in the electron microscope. All devices are made by the author. Analyses of the results were performed in the laboratory of nanophysics and electronics in the Kabardino-Balkaria University and the Laboratory of microphysics of particles in High Mountain Geophysical Institute, in Kabardino-Balkaria, Nalchik, Russia.

So, to study the rotation of the magnetization vectors in the films we needed to have on screen been has at least three domains. Conveniently for this purpose can be the films with double-walls found in [2] Domains must be very narrow. The distance between the domain walls should be about 0.5 – 1.0 micron. We have obtained a film with such a magnetic structure. Thus, the necessary conditions have been met: a sufficient increase in the microscope and of the required magnetic structure. This article describes a method of producing films with a given magnetic structure. Technological parameters of the films were calculated.

## 2. Calculation of energy interacting homogeneous walls in films

To obtain a film with a given magnetic structure we have chosen theoretical model of such a structure. In our view, the most of appropriate and simple model of double walls Bloch and Neel there is the model of Kaczer [3]. Evaluation energy of the walls is made depending on the distance between them in the films of nickel, cobalt and alloy $Ni_{0,90}$-$Fe_{0,10}$. In the calculation were used the parameters of films: film thickness t, the saturation magnetization I, constant of perpendicular anisotropy $K_{\perp}$, who have real films with dual of domain walls. To calculate the energy were used by the expression to a double-walls Bloch and Neel ($E_B$, $E_N$) [3].

$$E_B = 2\gamma_B t \pm 4\gamma_B t \cdot e^{-s/\delta} \mp \frac{2\pi^2 I_s^2 t^2 \delta^2}{s^2}, \quad (1)$$

$$E_N = 2\gamma_N t \pm 4\gamma_N t \cdot e^{-s/\delta} \mp \frac{4\pi^2 I_s^2 t^2 \delta^2}{s^2}, \quad (2)$$

Where $\gamma_B$ and $\gamma_N$ - the energy density without the interaction of individual walls Bloch and Neel; t - film thickness; s - distance between the walls; δ - the width of one wall; $I_s$ - the saturation magnetization. The upper signs in equations (1) and (2) correspond to the same rotation of the magnetization vectors in the two walls; bottom - opposite the direction of rotation of the magnetization vectors in the two walls.

Kaczer [3] has made calculations for massive materials. With reference for the films we used density of superficial energy of walls from [4]. In thin ferromagnetic films this energy develops not only of exchange energy and energy uniaxial anisotropy. Existing in films of the internal tensions and other factors (for example, of inclined deposition) result in occurrence perpendicular of anisotropy, characterized constant K⊥. Surface energy of the perpendicular anisotropy for walls Bloch in film is equal: $\gamma = 0,3 \cdot K_\perp$ [5]. In view of it, the density of superficial energy for walls Bloch and Neel will be written down, accordingly:

$$\gamma_B = A\left(\frac{\pi}{\delta}\right)^2 \cdot \delta + \frac{K_{II}\delta}{2} + \frac{\pi I_s{}^2 \cdot \delta^2}{t+\delta} + 0,3 K_\perp \cdot \delta \quad , \qquad (3)$$

$$\gamma_N = A\left(\frac{\pi}{\delta}\right)^2 \cdot \delta + \frac{K_{II}\delta}{2} + \frac{\pi I_s{}^2 \cdot \delta t}{t+\delta} + K_\perp \cdot \delta, \quad , \qquad (4)$$

Where A – is constant of the exchange energy; $K_{II}$ - is constant uniaxial anisotropy in a plane. Energy of double walls was defined by minimization of expressions (1) and (2) concerning width of wall δ and distance between walls s. At account the following value of parameters were used: $A = 0{,}9 \cdot 10^{-11}$ J/m; t=10-70 nm; $K_\perp$ = (2-10) $10^4$ J/m$^3$; $K_{II}$ = 2 $10^2$ J/m$^3$.

Type walls depend on the film thickness and the value of the perpendicular anisotropy. In this regard, various alloys were chosen in order to be able to obtain samples with different values of the constants perpendicular anisotropy. For example, films with negative magnetostriction can be using mechanical stresses set certain constant value perpendicular anisotropy. Furthermore, the magnitude of the linear density of the magnetostatic energy of domain walls (in the expressions 1 and 2) $(2\pi^2 \cdot I_s^2 \cdot t^2 \cdot \delta^2) / s^2$ depend on the value of the saturation magnetization. Thus, for the study were selected alloys with different values of the saturation magnetization and magnetostriction, Ni ($I_s$=0,48 A/m); $Ni_{0,90}$-$Fe_{0,10}$ ($I_s$=0,65 A/m); Co ($I_s$=1,40 A/m).

The following results were obtained from theoretical calculations of the energy for the Bloch walls in films.

The energy for double walls Bloch with an opposite direction of rotation is greater than the total energy of non-interacting isolated walls, the linear density is equal 2γt (Figure. 1a, b). The value energy of for Bloch double walls with the same direction of rotation of the magnetization vectors in the walls is less than the sum of energies of the isolated walls (Figure. 1c, d). Results are shown for films of a thickness of nickel 10 and 70 nm.

From results of account follows, that the double walls such as walls Bloch with an identical direction of rotation of vectors magnetization of saturation in them are energetically more favorable, than walls with unequal direction of rotation $I_s$. It is visible, that at distance s=$10^3$ nm linear density of energy of interaction of walls for nickel films aspires to zero.

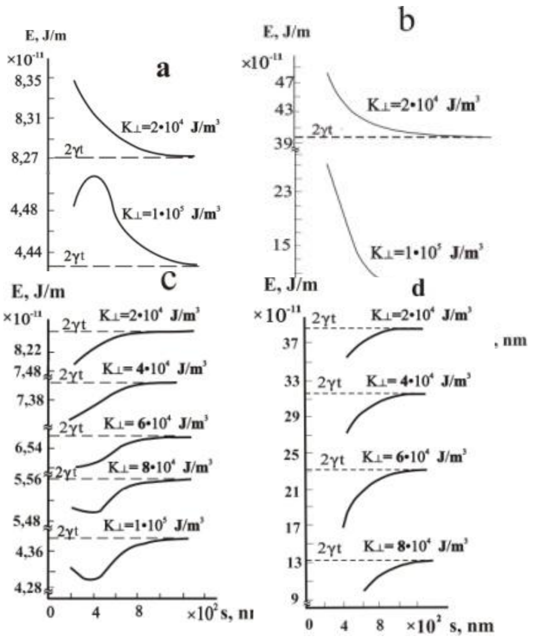

Figure 1. The linear energy density of two adjacent walls of the Bloch for films Ni depending on the distance between them and the values of the thickness of the film: a, b - t = 10 nm; c, d - t = 70 nm; a, b - the Unequal direction of rotation of the magnetization; c, d - the same direction of rotation. The dotted line in the chart shows the energy density of the two insulated walls with identical magnetization rotation.

Energy of walls is equal to the sum energy of the isolated walls, that is at distances s=$10^3$ nm the walls can be considered as isolated. The figure. 1c corresponds films nickel by thickness 70 nm and K⊥ > 8•$10^4$ J/m$^3$. On the diagram dependence of linear density of energy of walls with an identical direction of rotation of vectors magnetization of saturation in them from the distance between the next walls there is a minimum of value energy. It specifies an opportunity of existence in films with equilibrium magnetic structure of double walls, distance between which should be about 400 nm. For films of an alloy $Ni_{0,90}$-$Fe_{0,10}$ in an interval of thickness from 10 nm up to 80 nm was not found of minimum of energy for stable double walls Bloch in absence of an external magnetic field.

On depending linear energy density of domain walls of Neel from distance between them (figure 2) there is a minimum value of energy. In double of walls with identical direction of rotation of the magnetization $I_s$ in them, has occurs minimum, when distance between them s ~ 200 nm (figure 2a), for walls with varying rotation of the magnetization - about ~ 400 nm (figure 2b).

That is, in the films Ni, Co, Fe Ni of thickness 10 nm with a small value constant perpendicular anisotropy, may exist equilibrium magnetic structures type Neel with distance between them ~ 200-400 nm.

The formation at the curve of the minimum energy linear density the from distance between walls and for the Bloch walls and for the Neel walls due to the fact that the energy density of the linear expression (1, 2) includes components of this energy (the second and third terms) with opposite signs, having unequal dependence on the distance between the walls.

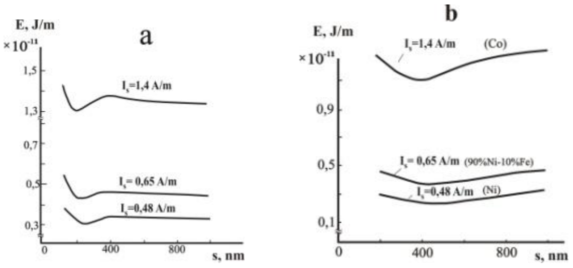

Figure 2. Dependence of energy of walls Neel from distances between them: a - identical rotation **I**$_s$; b - unequal rotation **I**$_s$. At account was the value $K_\perp = 2\cdot10^4 J/m^3$, $K_{II}=2\cdot10^2 J/m^3$

Thus, for films of cobalt 10 nm in thickness in table 1 shows the values of the energies $4\gamma_N t e^{-s/\delta}$ and $2\pi^2 I_s^2 t^2 \delta^2/s^2$ depending on the distance between them for the same rotation in the walls $I_s$ Neel. It is seen that these energies are approximately equal to each other (in absolute value) at distances s ~ 200 nm. In this interval, and was found the minimum energy (figure 3).

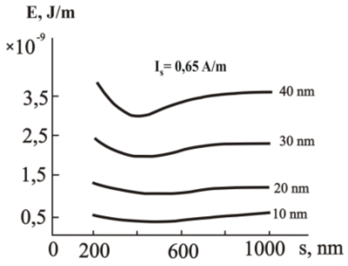

Figure 3. Dependence of energy of double walls Neel walls from distance between them for different thickness films. Structure films: $Ni_{0,90} - Fe_{0,10}$, $I_s = 0,65$ A/m; $K_{II} = 2\cdot10^2 \cdot J/m^3$; $K_\perp = 2\cdot10^4 J/m^3$.

| The distance between the walls of s, nm | $4\gamma_N t e^{-s/\delta}$ G /m | $\dfrac{2\pi^2 I_s t^2\delta^2}{s^2}$ G /m |
|---|---|---|
| 100 | $+11,7\cdot10^{-14}$ | $-11,7\cdot10^{-16}$ |
| 200 | $+5,2\cdot10^{-17}$ | $-8,7\cdot10^{-17}$ |
| 400 | $+12,0\cdot10^{-29}$ | $-3,8\cdot10^{-17}$ |
| 600 | $+23,6\cdot10^{-38}$ | $-2,7\cdot10^{-17}$ |
| 800 | $+5,36\cdot10^{-46}$ | $-3,8\cdot10^{-17}$ |
| 1000 | $+1,0\cdot10^{-54}$ | $-3,8\cdot10^{-17}$ |

Table 1.Dependent functions $4\gamma_N t e^{-s/\delta}$ and $2\pi^2 I_s^2 t^2 \delta^2/s^2$ the distance between the walls of s ,

Linear dependence of the energy density of interacting Neel walls of the distance between them for different film thicknesses (composition $Ni_{0,90}$-$Fe_{0,10}$, $I_s = 0,65$ A / m) is shown in figure 3. It is seen that with increasing film thickness energy Neel walls in the case of unequal direction of rotation of the magnetization vectors in adjacent walls increases. The same conclusion was reached for the wall with the same rotation $I_s$.

Anisotropy energy and the magnetostatic energy may vary with the distance between the domain walls, which follows from the expressions for the linear energy density of domain walls (2). The numerical accounts given in the table 1, show, that magnetostatic energy at the certain distances brings in the contribution much greater, than energy anisotropy. For example, for walls Bloch with identical rotation $I_s$ the reduction magnetostatic of energy is caused by partial short circuit of a stream of magnetization when approaching walls. Walls called homogeneous that do not have cross-tie walls.

The picture (in figure 4) ripples magnetization (the dispersion of the magnetic anisotropy) abruptly appears and can say with confidence that this is the Neel's wall. It shows there is the interacting not only between the double walls, but also between the pairs of domain walls. Experimental measurements of the distance between the double walls are consistent with our calculations. Between pairs of double domain walls having domains with magnetization vectors in them, directed at an angle of 45° to the axis of easy magnetization. In our opinion, this phenomenon is associated with a decrease in magnetostatic energy.

At a film thickness of 20 nm and a low value $K_\perp$ the magnetization vector is not profitable to leave the plane of the sample, due to the demagnetization factor. This is analogous to the way in films of thickness of about 45-65 nm, decreasing the magnetostatic energy of the sample as a whole is due to the emergence of cross-links.

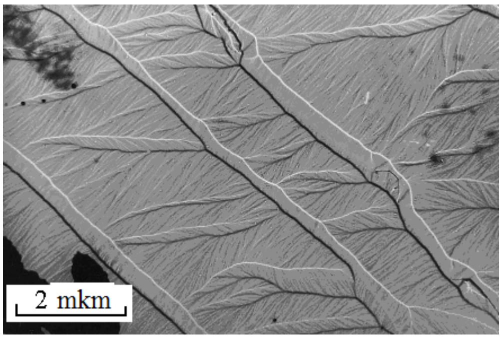

Figure 4. Domain wall Neel in films Fe-Ni, the film thickness t = 20 nm

Figure 5 shows the magnetic structure of the nickel film obtained on a cold substrate (300 K). In the image you can see that there is no magnetization ripple. The image of magnetic structure is not clear, there are many defects. But in this case we have a large constant perpendicular anisotropy ($K_\perp = 8 \cdot 10^4 J / m^3$). Comparison of experimental and calculated data for films of nickel thickness of 70 nm and $K_\perp = (8\text{-}10) \cdot 10^4$

J / m$^3$ gives grounds to assume that in these films take place Bloch wall (walls a large component of the distribution of the magnetization vectors of the film thickness) with the same direction of rotation $I_s$. The dispersion of the magnetic anisotropy of the film surface is missing (ripple magnetization is not observed).

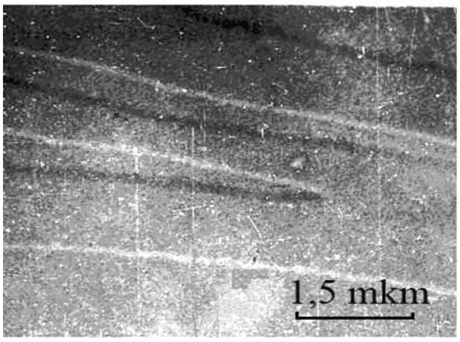

Figure5. Domain walls in films of nickel, previously were demagnetized in variable magnetic field with decreasing field to zero: film thickness t=70 nm; constant of perpendicular anisotropy $K_{\perp} = 8 \cdot 10^4$ J/m$^3$.

### 3. Results

1. Developed and tested technique for obtaining ferromagnetic films with a given magnetic structure. A similar procedure for the preparation of films is offered for the first time in the world literature. On the curve of the linear energy density, depending on the distance between of domain walls was detected a minimum of energy. Minimum energy means that at the given parameters of the film there are stable double walls. Films with double walls were received and investigated by us in [6]. The results were obtained from this work, by determination the rotation of the magnetization vectors in the domain walls.

From the analysis of the above calculation results, the following conclusions:

2. In films (thickness ~70nm), with constant $K_{\perp}$ (~ $8 \cdot 10^4$ J / m$^3$) are energetically more favorable double walls Bloch with the same direction of rotation of the magnetization $I_s$.

3. In nickel films (thickness ~10nm) may occur Neel double walls as with the same direction the rotation of the magnetization $I_s$ (distance s ~ 200nm) and unequal direction of rotation of the magnetization (s ~ 400nm)

4. The experimental results have confirmed our theoretical calculations. Figures 4-5 show the experimental double walls.

5. This method can be recommended for the production of films with the required parameters, both for scientific purposes and for industrial production.

6. Thus, summing up the above results can to make the main conclusion of this work: on the basis of theoretical and experimental research, we developed a methodology for producing ferromagnetic films with a given magnetic structure.

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