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Energy Method of Finding Distribution Constants of an Antiferromagnetic Vector for an Antidot System in a Two-sublattice Antiferromagnet

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The paper investigates the antiferromagnetic vector distribution in an antiferromagnetic film with a system of antidots. A static distribution of the antiferromagnetic vector is written and a method – based on the minimization of the antiferromagnet energy – that allows reducing the number of boundary conditions required for finding the constants of this distribution is proposed. Equations for the distribution constants are obtained for the both cases of minimizing the antiferromagnet energy by one and by two distribution constants that enter the expression for the antiferromagnet energy. The method is illustrated on a system of one isolated antidot. For such system, one additional condition – for the case when two boundary conditions on the surface of the antidot are given – and two additional conditions – for the case when one boundary condition on the surface of the antidot is given – on the distribution constants are written.

Keywords: Antiferromagnet, Magnetic thin film, Magnetic antidot, Magnetic energy, Antiferromagnetic vector.

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1. INTRODUCTION

Magnetic nanosystems of different configurations – magnetic quantum dots [1], thin magnetic films [2], magnetic nanospheres [3], nanowires [4], nanotubes [5] magnetophotonic crystals [6] and others – are a popular and actual topic of research in the last decades. These nanostructures are prospective, in particular, for a variety of technical applications – in information storage and transmission devices [7], in magnetic resonance tomography [8] and so on. In particular, systems of magnetic dots [1] and antidots [10] are prospective for a variety of practical applications.

While systems of magnetic dots, both ferromagnetic [11, 12] and antiferromagnetic [13, 14], are studied intensively during last years, systems of magnetic antidots – ferromagnetic [15, 16] and especially antiferromagnetic [17] – still remain poorly researched (and known papers on the subject are dedicated mostly to the problem of exchange bias of antiferromagnetic antidots). At the same time, systems of magnetic antidots are prospective for a variety of technical applications – for creating new information storage devices [18] and magnon waveguides [19], as two-dimensional magnonic crystals [20], as a basis for magnetic metamaterials [21] and so on. Therefore, investigation of magnetic properties of antidot systems, particularly in antiferromagnetic films, represents an actual topic of research.

In the study of the distribution of the antiferromagnetic vector in a system of antidots, the task of finding the constants of this distribution arises. In the previous papers [22, 23] the task was solved by imposing three (in accordance with the number of constants) boundary conditions for the antiferromagnetic vector. However, using an energy minimum condition for the antiferromagnet allows reducing the number of boundary conditions required for finding these distribution constants.

The presented paper continues the investigation of the antiferromagnetic vector distribution for a system for circular antidots in a film composed of a two-sublattice antiferromagnet started in the earlier papers of the authors [22, 23]. For such an antidot system, the antiferromagnetic vector distribution is written and an energy method (based on the condition of minimum of the antiferromagnet energy) of obtaining the constants of this distribution is proposed. The corresponding equations for the distribution constants are found. The method is illustrated on the case of a system consisting of one isolated antidot an in antiferromagnetic film; an expression for the antiferromagnetic vector distribution and equations for the distribution constants for this case are found.

2. SETTING OF THE PROBLEM

Let us consider a film (with a thickness d) composed of a two-sublattice antiferromagnet, and assume that for the magnetization density of the antiferromagnet sublattices ($\vec{M}_1$ and $\vec{M}_2$, respectively) the condition $\vec{M}_1 = -\vec{M}_2$, $|\vec{M}_1| = |\vec{M}_2| = M_0$ (M_0 = const) fulfils. Thus, the total magnetization vector $\vec{M} = 0$, and the antiferromagnetic vector is constant in magnitude: $|\vec{L}| = L_0 = const$. Let us denote the non-uniform exchange parameters of the antiferromagnet as α_1 and α_2 ($\alpha_1 > 0$) and the uniform exchange constant as A. Let us consider an uniaxial or uniform antiferromagnet, so the uniaxial anisotropy constants are equal to β_1 and β_2. An Oz axis of the Cartesian coordinate system is directed normally to the film.

Let us consider a system of antidots – with the radii R_i and planar radius-vectors of the centers $\{\vec{r}_{0i}\}$ – present in the film, see Fig. 1. A distribution of the antiferromagnetic vector for such system found in the previous articles of the authors [22, 23] requires finding the distribution constants as a separate task. In these articles

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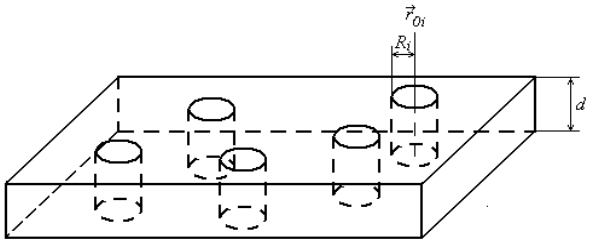

Fig. 1 – Antiferromagnetic film considered in the paper

the task was solved by imposing boundary conditions on the antiferromagnetic vector; in this approach, except for "natural" boundary conditions, additional ones (for example, on the outer border of the film) are necessary to obtain a complete set of the above-mentioned constants. In order to reduce the required number of boundary conditions, let us find condition on the distribution constants that imply from the condition of the magnetic energy minimum.

3. DISTRIBUTION OF THE ANTIFERROMAGNETIC VECTOR IN THE ANTIFERROMAGNETIC FILM IN THE PRESENCE OF THE ANTIDOT SYSTEM

First, let us consider an antiferromagnetic film (described in the previous section) without specifying the presence of the antidot system in it and find the distribution of the antiferromagnetic vector in such a film.

Let us use the spherical coordinate system (r, θ, φ), so the antiferromagnetic vector $\vec{L}$ can be written as follows:

$$\vec{L} = L_0\left(\vec{e}_x \sin\theta_L \cos\phi_L + \vec{e}_y \sin\theta_L \sin\phi_L + \vec{e}_z \cos\theta_L\right), \quad (1)$$

here $\vec{e}_x$, $\vec{e}_y$, $\vec{e}_z$ are unit vectors of the axes Ox, Oy and Oz of the Cartesian coordinate system, respectively (therefore, θ_L and φ_L are an azimuthal and polar angle of the antiferromagnetic vector, respectively). Let us use the system of equations for the static distribution of the antiferromagnetic vector that originates form the Landau-Lifshitz equation:

$$\begin{cases} c_1^2 \operatorname{div}\left(\sin^2\theta_L \nabla\phi_L\right) = 0 \\ c_1^2 \Delta\theta_L + \left((gH_0)^2 - c_1^2\Delta\phi_L - \omega_0^2\right)\sin\theta_L\cos\theta_L = 0 \end{cases}, \quad (2)$$

(see, e.g., [24,25]), here $\vec{H}_0$ is the external magnetic field, $c_1 = 4\mu_0 M_0 \sqrt{A\alpha_1}/\text{h}$, $\omega_0 = 4\mu_0 M_0 \sqrt{A\beta_1}/\text{h}$.

Let us use the solution of (2) obtained in [24] and used in the previous papers of the authors [22, 23]:

$$\begin{cases} \operatorname{tg}(\theta_L/2) = H\left(P(X,Y,Z)\right) \\ \phi_L = Q(X,Y,Z) \end{cases}, \quad (3)$$

here $X = x/l_0$, $Y = y/l_0$, $Z = z/l_0$ and

$$l_0 = \begin{cases} \sqrt{\alpha_1/|\beta_1|}, & \beta_1 \neq 0 \\ 1, & \beta_1 = 0 \end{cases}. \quad (4)$$

The function H of this solution can be written in the following form:

$$P(X,Y,Z) = \int \frac{\pm dH}{\sqrt{H^2 + C_1\left(1+H^2\right)^2}}, \quad (5)$$

here C_1 is a constant. For the cases $-1/4 < C_1 < 0$ and $C_1 > 0$ this form of the function H can be expressed through Jacobi elliptic functions sn, dn. For $-1/4 < C_1 < 0$ we obtain

$$\begin{cases} \operatorname{tg}\left(\dfrac{\theta_L}{2}\right) = \dfrac{b}{\operatorname{dn}\left(c\sqrt{|C_1|}P(X,Y,Z),k_1\right)}, \\ \phi_L = Q(X,Y,Z) \end{cases} \quad (6)$$

here $c = \sqrt{\left(1+2C_1+\sqrt{1+4C_1}\right)/2|C_1|}$, $b = \sqrt{\left(1+2C_1-\sqrt{1+4C_1}\right)/2|C_1|}$ and $0 < k_1 \le 1$ is the elliptic function modulus:

$$k_1 = \sqrt{\frac{2\sqrt{1+4C_1}}{1+2C_1+\sqrt{1+4C_1}}}. \quad (7)$$

For $C_1 > 0$ we obtain

$$\begin{cases} \operatorname{tg}(\theta_L/2) = \sqrt{\dfrac{1-\operatorname{sn}\left(P(X,Y,Z),k_2\right)}{1+\operatorname{sn}\left(P(X,Y,Z),k_2\right)}}, \\ \phi_L = Q(X,Y,Z) \end{cases} \quad (8)$$

where $0 < k_2 \le 1$ is the elliptic function modulus: $k_2 = 1/\sqrt{1+4C_1}$. Functions P and Q of the solution satisfy the conditions

$$\begin{gathered} \left(\frac{\partial P}{\partial X}\right)^2 + \left(\frac{\partial P}{\partial Y}\right)^2 + \left(\frac{\partial P}{\partial Z}\right)^2 = \operatorname{sgn}(\beta_1) + \left(\frac{\partial Q}{\partial X}\right)^2 + \left(\frac{\partial Q}{\partial Y}\right)^2 + \left(\frac{\partial Q}{\partial Z}\right)^2, \\ \Delta P = 0, \quad \Delta Q = 0, \\ \frac{\partial P}{\partial X}\frac{\partial Q}{\partial X} + \frac{\partial P}{\partial Y}\frac{\partial Q}{\partial Y} + \frac{\partial P}{\partial Z}\frac{\partial Q}{\partial Z} = 0, \end{gathered} \quad (9)$$

and for an uniaxial or isotropic antiferromagnet can be written, for instance, as follows:

$$\begin{cases} P = \dfrac{\pm z}{l_0}\Theta(\beta_1) + \sum\limits_i n_i \ln\left(\dfrac{|\vec{r}-\vec{r}_{0i}|}{l_0}\right) + \dfrac{2}{\pi}k\cdot K(k)\sum\limits_i \tilde{n}_i\alpha_i + C_2 \\ Q = \dfrac{\pm z}{l_0}\Theta(-\beta_1) - \dfrac{2}{\pi}k\cdot K(k)\sum\limits_i \tilde{n}_i \ln\left(\dfrac{|\vec{r}-\vec{r}_{0i}|}{l_0}\right) + \sum\limits_i \alpha_i n_i + C_3 \end{cases}, \quad (10)$$

here $\vec{r} = \begin{pmatrix} x \\ y \end{pmatrix}$ is a planar radius vector of an observation point, $\vec{r}_{0i} = \begin{pmatrix} x_{0i} \\ y_{0i} \end{pmatrix}$ are planar radius vectors of a certain set of points, n_i and $\tilde{n}_i$ are certain (arbitrary) integer numbers, α_i is an azimuthal angle relative to the point $\vec{r}_{0i}$ (therefore, $\alpha_i = \operatorname{arctg}\left[(y-y_{0i})/(x-x_{0i})\right]$) and the functions

$$\Theta(\xi) = \begin{cases} 0, & \xi \le 0 \\ 1, & \xi > 0 \end{cases}, \tag{11}$$

$$K(k) = \int_0^{\frac{\pi}{2}} \frac{d\xi}{\sqrt{1 - k^2 \sin^2 \xi}} \tag{12}$$

(complete elliptic integral of the first kind), $k = k_{1,2}$.

Now, let us consider the presence of the antidot system described in previous section. In this case, the planar vectors $\{\vec{r}_{0i}\}$ in (10) correspond to the antidots' centers. After putting $\tilde{n}_i = 0$ for all i, let us rewrite the distribution (10) as follows:

$$\begin{cases} P = \dfrac{\pm z}{l_0} \Theta(\beta_1) + \sum_i n_i \ln\left(\dfrac{|\vec{r} - \vec{r}_{0i}|}{l_0}\right) + C_2 \\ Q = \dfrac{\pm z}{l_0} \Theta(-\beta_1) + \sum_i \alpha_i n_i + C_3 \end{cases}. \tag{13}$$

The system (13) together with the expressions (6) or (8) (depending on the value of the constant C_1) gives the required distribution of the antiferromagnetic vector for the above-described film with the antidot system.

4. ENERGY OF THE ANTIFERROMAGNETIC FILM WITH THE ANTIDOT SYSTEM

In the previous papers of the authors [22, 23] in order to find the distribution constants (13) C_1, C_2 and C_3, three boundary conditions were imposed on the antiferromagnetic vector. Therefore, the distribution of the antiferromagnetic vector was found depending on these boundary conditions. However, it is possible to reduce the number of required boundary conditions by imposing the condition of minimum of the antiferromagnet energy.

First, let us analyze a physical sense of the constants C_2 and C_3. As it can be seen from (13), change of the constant C_3 by the value ΔC_3 corresponds to a rotation of the antiferromagnetic vector on the angle ΔC_3 in each point in the system. Change of the constant C_2 corresponds to scaling of the antidot system (of each antidot, to be exact):

$$\begin{aligned} P &= \frac{\pm z}{l_0} \Theta(\beta_1) + \sum_i n_i \ln\left(\frac{|\vec{r} - \vec{r}_{0i}|}{l_0}\right) + C_2 = \\ &= \frac{\pm z}{l_0} \Theta(\beta_1) + \sum_i n_i \ln\left(\frac{|\vec{r} - \vec{r}_{0i}|}{c_2 l_0}\right) \end{aligned}, \tag{14}$$

here $c_2 = \exp\left(-C_2 / \sum_i n_i\right)$.

Then, let us find the energy of the antiferromagnetic film with the antidot system described in the previous section, for which the distribution of the antiferromagnetic vector is described by the equations (13) and (6) or (8). Let us consider an isotropic antiferromagnet ($\beta_1 = 0$). Therefore, the functions P and Q can be written as follows:

$$\begin{cases} P = \sum_i n_i \ln\left(\dfrac{|\vec{r} - \vec{r}_{0i}|}{l_0}\right) + C_2 \\ Q = \sum_i \alpha_i n_i + C_3 \end{cases}. \tag{15}$$

The energy density of an antiferromagnet

$$w = \frac{1}{2} \alpha_1 \sum_i \left(\frac{\partial \vec{L}}{\partial x_i}\right)^2 \tag{16}$$

(see, e.g., [25]) in our case (the antiferromagnetic vector does not depend on the coordinate z and the antiferromagnet is isotropic) can be written as follows:

$$W = \frac{\alpha_1 d}{2} \int_S \left(\left(\frac{\partial \vec{L}}{\partial r}\right)^2 + \frac{1}{r^2}\left(\frac{\partial \vec{L}}{\partial \phi}\right)^2\right) dS, \tag{17}$$

here the integration is performed over the surface of the film. For the antiferromagnetic vector in the form (1) the integrand expression can be transformed as follows:

$$\begin{aligned} &\left(\frac{\partial \vec{L}}{\partial r}\right)^2 + \frac{1}{r^2}\left(\frac{\partial \vec{L}}{\partial \phi}\right)^2 = \\ &= L_0^2 \left(\left(\frac{\partial \theta_L}{\partial r}\right)^2 + \sin^2\theta_L \left(\frac{\partial \phi_L}{\partial r}\right)^2 + \frac{1}{r^2}\left(\left(\frac{\partial \theta_L}{\partial \phi}\right)^2 + \sin^2\theta_L \left(\frac{\partial \phi_L}{\partial \phi}\right)^2\right)\right) \end{aligned} \tag{18}$$

As partial derivatives of the function φ_L

$$\frac{\partial \phi_L}{\partial r} = \sum_i n_i \frac{\partial \alpha_i}{\partial r}, \quad \frac{\partial \phi_L}{\partial \phi} = \sum_i n_i \frac{\partial \alpha_i}{\partial \phi} \tag{19}$$

do not depend on constant C_3, the energy of the considered system also does not depend on this constant. Therefore, the energy (16) should be minimized only by the constants C_1 and C_2 that enter the function θ_L. The constant C_3 can be found if a value of the function φ_L is given in one point (for unknown n_i – in two or more points, depending on the specific values) of the film.

After substituting the solution (6), (8) and (15) into the expression (18) and integrating in accordance with (17) using properties of elliptic functions, after some transformations we obtain

$$\begin{aligned} W = 2L_0^2 h \alpha_1 b^2 \int_S \frac{dS}{\left(\mathrm{dn}^2\left(c\sqrt{|C_1|}u, k_1\right) + b^2\right)^2} &\left(c^2 |C_1| k_1^4 \left(\left(\sum_i \frac{n_i}{|\vec{r} - \vec{r}_{0i}|} \frac{\partial |\vec{r} - \vec{r}_{0i}|}{\partial r}\right)^2 + \frac{1}{r^2}\left(\sum_i \frac{n_i}{|\vec{r} - \vec{r}_{0i}|} \frac{\partial |\vec{r} - \vec{r}_{0i}|}{\partial \phi}\right)^2\right) \times \right. \\ &\left. \times \mathrm{sn}^2\left(c\sqrt{|C_1|}u, k_1\right) \mathrm{cn}^2\left(c\sqrt{|C_1|}u, k_1\right) + \mathrm{dn}^2\left(c\sqrt{|C_1|}u, k_1\right)\left(\left(\sum_i n_i \frac{\partial \alpha_i}{\partial r}\right)^2 + \frac{1}{r^2}\left(\sum_i n_i \frac{\partial \alpha_i}{\partial \phi}\right)^2\right)\right) \end{aligned} \tag{20}$$

for $-1/4 < C_1 < 0$,

$$W = \frac{L_0^2 h\alpha_1}{2}\int_S dS\left(1-\mathrm{sn}^2(u,k_2)\right)\left(\frac{\mathrm{cn}^2(u,k_2)dn^2(u,k_2)}{\left(1-sn^2(u,k_2)\right)^2}\left(\left(\sum_i \frac{n_i}{|\vec{r}-\vec{r}_{0i}|}\frac{\partial|\vec{r}-\vec{r}_{0i}|}{\partial r}\right)^2+\frac{1}{r^2}\left(\sum_i \frac{n_i}{|\vec{r}-\vec{r}_{0i}|}\frac{\partial|\vec{r}-\vec{r}_{0i}|}{\partial \phi}\right)^2\right)+\left(\left(\sum_i n_i\frac{\partial\alpha_i}{\partial r}\right)^2+\frac{1}{r^2}\left(\sum_i n_i\frac{\partial\alpha_i}{\partial\phi}\right)^2\right)\right) \quad (21)$$

for $C_1 > 0$, here

$$u(r,\phi) = \sum_i n_i \ln\left(\frac{|\vec{r}-\vec{r}_{0i}|}{l_0}\right)+C_2 . \quad (22)$$

Let us write down the vectors $\vec{r}_{0i}$ in the polar coordinates as $\begin{pmatrix} r_{0i} \\ \phi_{0i}\end{pmatrix}$. After writing down geometrical expressions for a_i and $|\vec{r}-\vec{r}_{0i}|$ we obtain

$$W = 2L_0^2 h\alpha_1 b^2\int_S \frac{dS}{\left(dn^2\left(c\sqrt{|C_1|}u,k_1\right)+b^2\right)^2}\left(\left(\left(\sum_i n_i\frac{r-r_{0i}\cos(\phi-\phi_{0i})}{r^2+r_{0i}^2-2rr_{0i}\cos(\phi-\phi_{0i})}\right)^2+\frac{1}{r^2}\left(\sum_i n_i\frac{rr_{0i}\sin(\phi-\phi_{0i})}{r^2+r_{0i}^2-2rr_{0i}\cos(\phi-\phi_{0i})}\right)^2\right.\right.$$
$$\left.\left.\times c^2|C_1|k_1^4 sn^2\left(c\sqrt{|C_1|}u,k_1\right)cn^2\left(c\sqrt{|C_1|}u,k_1\right)\right)+dn^2\left(c\sqrt{|C_1|}u,k_1\right)\left(\left(\sum_i(\pm n_i)\sqrt{1-\Phi_i^2}\frac{\partial\Phi_i}{\partial r}\right)^2+\frac{1}{r^2}\left(\sum_i(\pm n_i)\sqrt{1-\Phi_i^2}\frac{\partial\Phi_i}{\partial\phi}\right)^2\right)\right) \quad (23)$$

for $-1/4 < C_1 < 0$,

$$W = \frac{L_0^2 h\alpha_1}{2}\int_S dS\left(1-\mathrm{sn}^2(u,k_2)\right)\left(\frac{\mathrm{cn}^2(u,k_2)\mathrm{dn}^2(u,k_2)}{\left(1-\mathrm{sn}^2(u,k_2)\right)^2}\left(\left(\sum_i n_i\frac{r-r_{0i}\cos(\phi-\phi_{0i})}{r^2+r_{0i}^2-2rr_{0i}\cos(\phi-\phi_{0i})}\right)^2+\right.\right.$$
$$\left.\left.+\frac{1}{r^2}\left(\sum_i n_i\frac{rr_{0i}\sin(\phi-\phi_{0i})}{r^2+r_{0i}^2-2rr_{0i}\cos(\phi-\phi_{0i})}\right)^2\right)+\left(\left(\sum_i(\pm n_i)\sqrt{1-\Phi_i^2}\frac{\partial\Phi_i}{\partial r}\right)^2+\frac{1}{r^2}\left(\sum_i(\pm n_i)\sqrt{1-\Phi_i^2}\frac{\partial\Phi_i}{\partial\phi}\right)^2\right)\right) \quad (24)$$

for $C_1 > 0$, here

$$\Phi_i(r,\phi) = \frac{\sin(\phi-\phi_{0i})}{\sqrt{1+\frac{r_{0i}^2}{r^2}+\frac{2r_{0i}}{r}\cos(\phi-\phi_{0i})}} . \quad (25)$$

Thus, we found energy of the antiferromagnetic film described in the “Setting of the problem” section. Let us find an energy minimum condition for this energy.

5. OBTAINING DISTRIBUTION CONSTANTS FROM THE CONDITION OF THE ANTIFERROMAGNET ENERGY MINIMUM

Let us write down the condition of the antiferromagnet energy minimum. When two boundary conditions are given, minimizing the antiferromagnet energy by only one constant is sufficient. (As the expression for the function H depend on the constant C_1, it is more convenient to minimize by C_2).

Thus, after minimizing the antiferromagnet energy given by expressions (23) and (24) by the constant C_2, the following system of conditions can be obtained:

$$\begin{cases} \dfrac{\partial}{\partial C_2}\displaystyle\int_S \frac{c^2|C_1|k_1^4\,\mathrm{sn}^2\left(c\sqrt{|C_1|}u,k_1\right)\mathrm{cn}^2\left(c\sqrt{|C_1|}u,k_1\right)F_1(r,\phi)+\mathrm{dn}^2\left(c\sqrt{|C_1|}u,k_1\right)F_2(r,\phi)}{\left(\mathrm{dn}^2\left(c\sqrt{|C_1|}u,k_1\right)+b^2\right)^2}dS = 0 \\ \dfrac{\partial^2}{\partial C_2^2}\displaystyle\int_S \frac{c^2|C_1|k_1^4\,\mathrm{sn}^2\left(c\sqrt{|C_1|}u,k_1\right)\mathrm{cn}^2\left(c\sqrt{|C_1|}u,k_1\right)F_1(r,\phi)+\mathrm{dn}^2\left(c\sqrt{|C_1|}u,k_1\right)F_2(r,\phi)}{\left(\mathrm{dn}^2\left(c\sqrt{|C_1|}u,k_1\right)+b^2\right)^2}dS > 0 \end{cases} \quad (26)$$

for $-1/4 < C_1 < 0$, and

$$\begin{cases} \frac{\partial}{\partial C_2}\int\limits_S dS\left(1-sn^2\left(u,k_2\right)\right)\left(\frac{cn^2\left(u,k_2\right)dn^2\left(u,k_2\right)}{\left(1-sn^2\left(u,k_2\right)\right)^2}F_1\left(r,\phi\right)+F_2\left(r,\phi\right)\right)=0 \\ \frac{\partial^2}{\partial C_2^2}\int\limits_S dS\left(1-sn^2\left(u,k_2\right)\right)\left(\frac{cn^2\left(u,k_2\right)dn^2\left(u,k_2\right)}{\left(1-sn^2\left(u,k_2\right)\right)^2}F_1\left(r,\phi\right)+F_2\left(r,\phi\right)\right)>0 \end{cases} \quad (27)$$

for $C_1 > 0$. Here we have denoted

$$F_1\left(r,\phi\right)=\left(\sum_i n_i\frac{r-r_{0i}\cos\left(\phi-\phi_{0i}\right)}{r^2+r_{0i}^2-2rr_{0i}\cos\left(\phi-\phi_{0i}\right)}\right)^2+$$
$$+\frac{1}{r^2}\left(\sum_i n_i\frac{rr_{0i}\sin\left(\phi-\phi_{0i}\right)}{r^2+r_{0i}^2-2rr_{0i}\cos\left(\phi-\phi_{0i}\right)}\right)^2,$$
$$F_2\left(r,\phi\right)=\left(\sum_i\left(\pm n_i\right)\sqrt{1-\Phi_i^2}\frac{\partial\Phi_i}{\partial r}\right)^2+$$
$$+\frac{1}{r^2}\left(\sum_i\left(\pm n_i\right)\sqrt{1-\Phi_i^2}\frac{\partial\Phi_i}{\partial\phi}\right)^2 \quad . \quad (28)$$

If only one boundary condition for the antiferromagnetic vector is given, the antiferromagnet energy should be minimized by the both constants C_1 and C_2. Therefore, two additional conditions for finding the distribution constants are obtained.

Let us write the energy minimum condition by two constants. For $-1/4 < C_1 < 0$ we obtain

$$\begin{cases} \frac{\partial}{\partial C_2}I_1\left(C_1,C_2\right)=0 \\ \frac{\partial}{\partial C_1}I_1\left(C_1,C_2\right)=0 \\ \frac{\partial^2}{\partial C_2^2}I_1\left(C_1,C_2\right)>0 \\ \frac{\partial^2}{\partial C_2^2}I_1\left(C_1,C_2\right)\frac{\partial^2}{\partial C_1^2}I_1\left(C_1,C_2\right)-\left(\frac{\partial^2}{\partial C_1\partial C_2}I_1\left(C_1,C_2\right)\right)^2>0 \end{cases} ,(29)$$

here

$$I_1\left(C_1,C_2\right)=\int\limits_S\frac{dS}{\left(\mathrm{dn}^2\left(c\sqrt{|C_1|}u,k_1\right)+b^2\right)^2}\times$$
$$\times\left(c^2\left|C_1\right|k_1^4\,\mathrm{sn}^2\left(c\sqrt{|C_1|}u,k_1\right)\mathrm{cn}^2\left(c\sqrt{|C_1|}u,k_1\right)F_1\left(r,\phi\right)+\right. ,(30)$$
$$\left.+\mathrm{dn}^2\left(c\sqrt{|C_1|}u,k_1\right)F_2\left(r,\phi\right)\right)$$

and for $C_1 > 0$

$$\begin{cases} \frac{\partial}{\partial C_2}I_2\left(C_1,C_2\right)=0 \\ \frac{\partial}{\partial C_1}I_2\left(C_1,C_2\right)=0 \\ \frac{\partial^2}{\partial C_2^2}I_2\left(C_1,C_2\right)>0 \\ \frac{\partial^2}{\partial C_2^2}I_2\left(C_1,C_2\right)\frac{\partial^2}{\partial C_1^2}I_2\left(C_1,C_2\right)-\left(\frac{\partial^2}{\partial C_1\partial C_2}I_2\left(C_1,C_2\right)\right)^2>0 \end{cases} ,(31)$$

here

$$I_2\left(C_1,C_2\right)=\int\limits_S dS\left(1-sn^2\left(u,k_2\right)\right)\times$$
$$\times\left(\frac{cn^2\left(u,k_2\right)dn^2\left(u,k_2\right)}{\left(1-sn^2\left(u,k_2\right)\right)^2}F_1\left(r,\phi\right)+F_2\left(r,\phi\right)\right). \quad (32)$$

Note that method is applicable (for a given set of n_i) only when the resulting value of C_1 lie in the corresponding range, $C_1 > 0$ for the conditions (31) or $-1/4 < C_1 < 0$ for the conditions (29). The existence of such solution for at least one case is shown in the chapter "Discussion".

Thus, we have written down a system of equations for the constants C_1, C_2 of the distribution (3)-(9), (13) that implies from the condition of the antiferromagnet energy minimum. During the study of a specific system one may use the system (29) or (31) together with one boundary condition on the function φ_L (or more, if the values of n_i are unknown) that allows to find the constant C_3, or use the system (26) or (27) together with two boundary conditions for the antiferromagnetic vector.

Let us illustrate the above-given method on the case of an isolated antidot.

6. DISTRIBUTION OF THE ANTIFERROMAGNETIC VECTOR IN AN ANTIFERROMAGNETIC FILM WITH AN ISOLATED ANTIDOT

Let us consider a system investigated in previous work of the authors [23] – an isolated antidot in a large antiferromagnetic film – and apply the above-described method of finding the distribution constants. In order to determine the limits of integration let us consider an antidot with the radius R in the center of antiferromagnetic disk with the radius R_e ($R_e >> R$). In [23], three boundary conditions were imposed to find the three constants C_1, C_2 and C_3. In addition to two boundary conditions for the antiferromagnetic vector on the antidot boundary (vortex distribution), a third – "artificial" – boundary condition was necessary to complete the system of equations for the sought constants (for example, boundary condition on the edge of the film: $R = R_e$). This approach allows obtaining a complete distribution; however, it narrows the limits of applicability of the results. Let us apply the method described in the previous section – first, let us replace the third boundary condition with the energy minimum condition (therefore, only two boundary conditions – vortex distribution of the antiferromagnetic vector on the antidot surface – are required) and find a complete system of equations for the distribution constants, and second, let us use only one boundary condition – vortex distribution of the antiferromagnetic vector projection on the xOy plane on the antidot surface – together with both conditions ((29) or (31)) that imply from the energy minimum condition by the constants C_1 and C_2.

The functions P and Q for an isolated antidot in an isotropic antiferronmagnet have the following form:

$$\begin{cases} P = n\ln(r/l_0)+C_2 \\ Q = \phi n + C_3 \end{cases}. \qquad (33)$$

Let us choose boundary conditions for the antiferromagnetic vector as follows:

$$\begin{cases} \theta_L\big|_{r=R} = \pi/2 \\ \phi_L\big|_{r=R} = \phi+\pi/2\pm\pi \end{cases}. \qquad (34)$$

The expression (34) defines a "positive vortex" distribution of the antiferromagnetic vector (in the plane xOy) on the antidot surface. From the second boundary condition in (34) we obtain $n = 1$, $C_3 = \pi/2\pm\pi$. After substituting (33) and (34) into the solutions (6) and (8), one can obtain the following distributions:

$$\begin{cases} tg\left(\dfrac{\theta_L}{2}\right) = \dfrac{b}{dn\left(c\sqrt{|C_1|}\ln(r/l_0)+C_2,k_1\right)} \\ \phi_L = \phi+\pi/2\pm\pi \end{cases} \qquad (35)$$

with the constants C_1 and C_2 related by the equation

$$c\sqrt{|C_1|}\ln\left(\frac{R}{l_0}\right)+C_2 = F\left(\arcsin\frac{\sqrt{1-b^2}}{k_1},k_1\right)+4K(k_1)N \qquad (36)$$

for $-1/4 < C_1 < 0$ (here N is an integer, $F(\xi,k)$ is an incomplete elliptic integral of the first kind

$$F(\xi,k) = \int_0^{\xi}\frac{d\rho}{\sqrt{1-k^2\sin^2\rho}}, \qquad (37)$$

and

$$\begin{cases} tg\left(\dfrac{\theta_L}{2}\right) = \sqrt{\dfrac{1-sn\left(\ln(r/l_0)+C_2,k_2\right)}{1+sn\left(\ln(r/l_0)+C_2,k_2\right)}}, \\ \phi_L = \phi+\pi/2\pm\pi \end{cases} \qquad (38)$$

with for the constants C_1 and C_2 related by the equation

$$C_2 = 4NK\left(\frac{1}{\sqrt{1+4C_1}}\right)-\ln\left(\frac{R}{l_0}\right) \qquad (39)$$

for $C_1 > 0$.

In order to obtain a complete set of constants – and,therefore, a complete distribution – one more relation between the constants C_1 and C_2 should be found. In [23] authors used a boundary condition on the outer surface of the disc-shaped film, thus narrowing essentially the range of the applicability of the results. Instead, let us use the energy minimum condition in a form obtained in the previous section.

The equation (35) for the considered system can be rewritten as follows:

$$W = \frac{h\alpha_1}{2}\int_0^{2\pi}d\phi\int_r\left(\left(\frac{\partial \vec{L}}{\partial r}\right)^2+\frac{1}{r^2}\left(\frac{\partial \vec{L}}{\partial \phi}\right)^2\right)rdr. \qquad (40)$$

After substitution of the solutions (6) and (8) and the expression for the function Q into (40) and consideration of the system symmetry, with account for the properties of the elliptic functions, one can obtain

$$W = 4\pi\alpha_1 hL_0^2b^2\int_{\ln\left(\frac{R}{l_0}\right)+C_2}^{\ln\left(\frac{R_e}{l_0}\right)+C_2}\frac{du}{\left(dn^2\left(c\sqrt{|C_1|}u,k_1\right)+b^2\right)^2}\times$$
$$\times\left(k_1^4c^2|C_1|sn^2\left(c\sqrt{|C_1|}u,k_1\right)cn^2\left(c\sqrt{|C_1|}u,k_1\right)+dn^2\left(c\sqrt{|C_1|}u,k_1\right)\right) \qquad (41)$$

for $-1/4 < C_1 < 0$, and

$$W = \pi\alpha_1 hL_0^2\int_{\ln\left(\frac{R}{l_0}\right)+C_2}^{\ln\left(\frac{R_e}{l_0}\right)+C_2}\frac{cn^2(u,k_2)dn^2(u,k_2)+\left(1-sn^2(u,k_2)\right)^2}{1-sn^2(u,k_2)}du \qquad (42)$$

for $C_1 > 0$. Thus, the condition (26) for the constant C_2 in this case can be written

$$\begin{cases} \dfrac{\partial}{\partial C_2}\displaystyle\int_{\ln\left(\frac{R}{l_0}\right)+C_2}^{\ln\left(\frac{R_e}{l_0}\right)+C_2}\left(k_1^4c^2|C_1|cn^2\left(c\sqrt{|C_1|}u,k_1\right)sn^2\left(c\sqrt{|C_1|}u,k_1\right)+dn^2\left(c\sqrt{|C_1|}u,k_1\right)\right)/\left(b^2+dn^2\left(c\sqrt{|C_1|}u,k_1\right)\right)^2du = 0 \\ \dfrac{\partial^2}{\partial C_2^2}\displaystyle\int_{\ln\left(\frac{R}{l_0}\right)+C_2}^{\ln\left(\frac{R_e}{l_0}\right)+C_2}\left(k_1^4c^2|C_1|cn^2\left(c\sqrt{|C_1|}u,k_1\right)sn^2\left(c\sqrt{|C_1|}u,k_1\right)+dn^2\left(c\sqrt{|C_1|}u,k_1\right)\right)/\left(b^2+dn^2\left(c\sqrt{|C_1|}u,k_1\right)\right)^2du > 0 \end{cases} \qquad (43)$$

for $-1/4 < C_1 < 0$ and

$$\begin{cases} \dfrac{\partial}{\partial C_2} \displaystyle\int_{\ln\left(\frac{R}{l_0}\right)+C_2}^{\ln\left(\frac{R_e}{l_0}\right)+C_2} \frac{\mathrm{cn}^2(u,k_2)\,\mathrm{dn}^2(u,k_2)+\left(1-\mathrm{sn}^2(u,k_2)\right)^2}{1-\mathrm{sn}^2(u,k_2)}du = 0 \\ \dfrac{\partial^2}{\partial C_2^2} \displaystyle\int_{\ln\left(\frac{R}{l_0}\right)+C_2}^{\ln\left(\frac{R_e}{l_0}\right)+C_2} \frac{\mathrm{cn}^2(u,k_2)\,\mathrm{dn}^2(u,k_2)+\left(1-\mathrm{sn}^2(u,k_2)\right)^2}{1-\mathrm{sn}^2(u,k_2)}du > 0 \end{cases} \quad (44)$$

for $C_1 > 0$.

In order to simplify the system (43), let us analyze the dependence of the energy given by (41) on the constant C_2. Integrand expression in (41) is a periodic function of u, with a period $2K(k_1)\big/\left(c\sqrt{|C_1|}\right)$. This means, in particular, that the energy W does not depend on the constants C_2 in the case when the interval $[R, R_e]$ contain an integer number of periods, so that $c\sqrt{|C_1|}\ln(R_e/R) = 2qK(k_1)$ (here q is an arbitrary integer). The system (43) does not become an identity when $c\sqrt{|C_1|}\ln(R_e/R) \neq 2qK(k_1)$; in this case after differentiating the expressions that enter the system of equations (43) one can obtain

$$\begin{cases} f\left(\ln\left(\dfrac{R_e}{l_0}\right)+C_2,C_1\right)-f\left(\ln\left(\dfrac{R}{l_0}\right)+C_2,C_1\right)=0 \\ \left.\dfrac{\partial f}{\partial u}\right|_{u=\ln(R_e/l_0)+C_2}-\left.\dfrac{\partial f}{\partial u}\right|_{u=\ln(R/l_0)+C_2}>0 \end{cases}, \quad (45)$$

here

$$f(u,C_1)=\frac{1}{\left(b^2+dn^2\left(c\sqrt{|C_1|}u,k_1(C_1)\right)\right)^2}\left(dn^2\left(c\sqrt{|C_1|}u,k_1(C_1)\right)+\right.$$
$$\left.+k_1^4c^2|C_1|\,cn^2\left(c\sqrt{|C_1|}u,k_1(C_1)\right)sn^2\left(c\sqrt{|C_1|}u,k_1(C_1)\right)\right) \quad (46)$$

For $C_1 > 0$ we obtain a similar periodicity condition $\ln(R_e/R) \neq 2qK(k_2)$ and the same system of equations; however, in this case

$$f(u,C_1)=\frac{cn^2\left(u,k_2(C_1)\right)dn^2\left(u,k_2(C_1)\right)+\left(1-sn^2\left(u,k_2(C_1)\right)\right)^2}{1-sn^2\left(u,k_2(C_1)\right)} \quad (47)$$

Note that for $C_1 > 0$ we can use the explicit expression (39) for the constant C_2 and, therefore, rewrite (45) into a system of equations for one variable:

$$\begin{cases} f\left(\ln\left(\dfrac{R_e}{l_0}\right)+4NK\left(\dfrac{1}{\sqrt{1+4C_1}}\right)-\ln\left(\dfrac{R}{l_0}\right),C_1\right)- \\ -f\left(\ln\left(\dfrac{R}{l_0}\right)+4NK\left(\dfrac{1}{\sqrt{1+4C_1}}\right)-\ln\left(\dfrac{R}{l_0}\right),C_1\right)=0 \\ \left.\dfrac{\partial f}{\partial u}\right|_{u=4NK\left(1/\sqrt{1+4C_1}\right)+\ln(R_e/R)}-\left.\dfrac{\partial f}{\partial u}\right|_{u=4NK\left(1/\sqrt{1+4C_1}\right)}>0 \end{cases}. \quad (48)$$

Solutions (35) and (38) together with the conditions (36), (45), (46) or (39), (45), (47), correspondingly, describe the sought distribution in this case.

Now, let us use the condition of energy minimization by both constants C_1 and C_2 ((29) and (31)) together with one boundary condition on the antiferromagnetic vector (the second boundary condition of the pair (34), as it allows to find the constant C_3 that cannot be obtained from the energy minimum condition). Thus, the boundary condition

$$\left.\phi_L\right|_{r=R}=\phi+\frac{\pi}{2}\pm\pi\,, \quad (49)$$

from which we obtain $n = 1$, $C_3 = \pi/2 \pm \pi$, must be supplemented by the following system of relations:

$$\begin{cases} f\left(\ln\left(\dfrac{R_e}{l_0}\right)+C_2,C_1\right)-f\left(\ln\left(\dfrac{R}{l_0}\right)+C_2,C_1\right)=0 \\ \displaystyle\int_{\ln\left(\frac{R}{l_0}\right)+C_2}^{\ln\left(\frac{R_e}{l_0}\right)+C_2}\left(\frac{\partial b^2}{\partial C_1}f(u,C_1)+\frac{\partial f}{\partial C_1}b^2\right)du=0 \\ \left.\dfrac{\partial f}{\partial u}\right|_{u=\ln(R_e/l_0)+C_2}-\left.\dfrac{\partial f}{\partial u}\right|_{u=\ln(R/l_0)+C_2}>0 \\ \ldots \end{cases}, \quad (50)$$

$$\begin{cases} \ldots \\ \left(\left.\dfrac{\partial f}{\partial u}\right|_{u=\ln(R_e/l_0)+C_2}-\left.\dfrac{\partial f}{\partial u}\right|_{u=\ln(R/l_0)+C_2}\right)\times \\ \times\displaystyle\int_{\ln\left(\frac{R}{l_0}\right)+C_2}^{\ln\left(\frac{R_e}{l_0}\right)+C_2}\frac{\partial}{\partial C_1}\left(\frac{\partial b^2}{\partial C_1}f(u,C_1)+\frac{\partial f}{\partial C_1}b^2\right)du- \\ -\dfrac{1}{b^2}\left(\dfrac{\partial}{\partial C_1}b^2\left(\left.\dfrac{\partial f}{\partial u}\right|_{u=\ln(R_e/l_0)+C_2}-\left.\dfrac{\partial f}{\partial u}\right|_{u=\ln(R/l_0)+C_2}\right)\right)^2>0 \end{cases} \quad (50)$$

for $-1/4 < C_1 < 0$ and

$$\begin{cases} f\left(\ln(R_e/l_0)+C_2,C_1\right)-f\left(\ln(R_e/l_0)+C_2,C_1\right)=0 \\ \displaystyle\int_{\ln(R_e/l_0)+C_2}^{\ln(R_e/l_0)+C_2}\frac{\partial f}{\partial C_1}du=0 \\ \left.\dfrac{\partial f}{\partial u}\right|_{u=\ln(R_e/l_0)+C_2}-\left.\dfrac{\partial f}{\partial u}\right|_{u=\ln(R/l_0)+C_2}>0 \\ \left(\left.\dfrac{\partial f}{\partial u}\right|_{u=\ln(R_e/l_0)+C_2}-\left.\dfrac{\partial f}{\partial u}\right|_{u=\ln(R/l_0)+C_2}\right)\displaystyle\int_{\ln(R_e/l_0)+C_2}^{\ln(R_e/l_0)+C_2}\frac{\partial^2 f}{\partial C_1^2}du- \\ -\left(\dfrac{\partial}{\partial C_1}\left(\left.\dfrac{\partial f}{\partial u}\right|_{u=\ln(R_e/l_0)+C_2}-\left.\dfrac{\partial f}{\partial u}\right|_{u=\ln(R/l_0)+C_2}\right)\right)^2>0 \end{cases} \quad (51)$$

for $C_1 > 0$. Note that for the applicability of the presented method the solution of (50) or (51) should exist and the constant C_1 of this solution should lie in the appropriate range. If these conditions does not fulfill, another boundary condition for the function θ_L should be imposed and, therefore, the equations (35), (45), (46) or (39), (45), (47) should be used.

The systems (50) and (51) together with the boundary condition $\varphi_L = \varphi + \pi / 2 \pm \pi$ (vortex distribution of the antiferromagnetic vector projection on the plane xOy on the antidot surface), from which the equalities $n = 1$, $C_3 = \pi / 2 \pm \pi$ follow, provide nececcary values of the constants C_1, C_2 and C_3 and, therefore, defines the sought distribution completely.

7. DISCUSSION

Let us show the existence of a solution of the above-described type – and, therefore, applicability of the method – for the case of an isolated antidot. For such case, let us find a value of the constant C_2 that corresponds to the energy minimum for a given value of the constant C_1.

Let us consider an isolated antidot described in the previous section. Considering the fact that for a typical synthesized antiferromagnetic nanosystems the exchange constant $\alpha_1 \sim 10^{-12}$ cm^{-1}, for a typical antidot diameter (several nanometers), we can put $R/l_0 = 1$. Let us choose the value $C_1 = 1$ and use the boundary condition (49), so for the distribution (33) we obtain $n = 1$, $C_3 = \pi / 2 \pm \pi$ (planar distribution of the antiferromagnetic vector). For such values of C_1, C_3 and n the distribution form is given

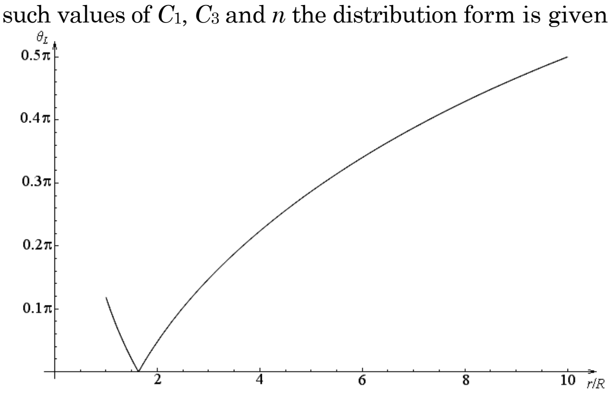

Fig. 2 – Distribution of the azimuthal angle of the antiferromagnetic vector for $R/l_0 = 1$, $C_1 = 1$, $C_2 \approx 1.32$

by (38). For example, for $R_e/R = 100$ the expressions $f\left(\ln\left(R_e/l_0\right)+C_2,C_1\right)-f\left(\ln\left(R/l_0\right)+C_2,C_1\right)$ and $\left(\partial f / \partial u\right)\big|_{u=\ln\left(R_e/l_0\right)+C_2}-\left(\partial f / \partial u\right)\big|_{u=\ln\left(R/l_0\right)+C_2}$ that enter the condition (45) (with the function f that in this case is given by (47)) depend on C_2 in a periodic way. In this case energy minimum condition given by (45) fulfils for values of C_2 approximately -2.30, 1.32, 4.94 and so on (for these values of C_2 $f\left(\ln\left(R_e/l_0\right)+C_2,C_1\right)-$, $-f\left(\ln\left(R_e/l_0\right)+C_2,C_1\right)=0$, $\left(\partial f / \partial u\right)\big|_{u=\ln\left(R_e/l_0\right)+C_2}-$ $-\left(\partial f / \partial u\right)\big|_{u=\ln\left(R/l_0\right)+C_2}\approx 0.02>0$.

Let us illustrate graphically the obtained results. The distribution of the azimuthal angle θ_L of the antiferromagnetic vector for the second of the above-mentioned values of C_2 ($C_2 \approx 1.32$) is presented on the Fig. 2. As we can see, the antiferromagnetic vector has a planar distribution ($\theta_L = 0$) for $r/R \approx 1.65$ and then, with increasing the distance r from the antidot center, tends to orthogonal ($\theta_L = \pi / 2$). Further investigation shows that the distribution becomes orthogonal for $r/R \approx 10$ and with further increase of the distance r tends to planar which is reached for $r/R \approx 61.2$.

8. CONCLUSIONS

Thus, we have investigated the distribution of the antiferromagnetic vector in the film composed of a two-sublattice antiferromagnet with a set of circular antidots. We have complemented a distribution obtained in the previous papers of the authors with a method of finding the constants of this distribution that allows reducing the number of required boundary conditions imposed on the antiferromagnetic vector. The method allows obtaining the necessary relations on the distribution constants from the condition of minimum of the antiferromagnet energy.

From the above-mentioned condition of antiferromagnet energy minimum, equations for the distribution constants have been written. The method proposed in the paper allows obtaining two out of three necessary relations between the three constants of the distribution (13) of the antiferromagnetic vector; therefore, one boundary condition for this vector is sufficient for obtaining a complete distribution. (In the previous papers on the subject the authors had to impose three boundary conditions in order to obtain all three constants.)

The method is illustrated via application on the system comprised of one isolated antidot in an antiferromagnetic film. For this case, a distribution of the antiferromagnetic vector and a system of equations for the constants of this distribution are found. Graphical representation of the obtained result for specific antidot parameters is given.

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Енергетичний метод пошуку констант розподілу вектора антиферомагнетизму для системи антиточок у двопідгратковому антиферомагнетику

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У роботі досліджено розподіл вектора антиферомагнетизму в антиферомагнітній плівці з системою антиточок. Записано статичний розподіл вектора антиферомагнетизму, запропоновано метод (що базується на мінімізації енергії антиферомагнетику), який дозволяє знизити число граничних умов, необхідних для знаходження констант цього розподілу. Рівняння для констант розподілу отримані як для випадку мінімізації енергії антиферомагнетику по одній з констант розподілу, що входять у вираз для енергії антиферомагнетика, так і для випадку мінімізації по двох константах. Метод проілюстровано на прикладі системи з однієї ізольованої антиточки. Для такої системи отримано одну додаткову умову на константи розподілу – для випадку, коли на поверхні антиточки задано дві граничні умови – та дві додаткові умови – для випадку, коли на поверхні антиточки задано одну граничну умову.

Ключові слова: Антиферомагнетик, Тонка магнітна плівка, Магнітна антиточка, Магнітна енергія, Вектор антиферомагнетизму.

Энергетический метод поиска констант распределения вектора антиферромагнетизма для системы антиточек в двухподрешеточном антиферромагнетике

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В работе исследуется распределение вектора антиферромагнетизма в антиферромагнитной пленке с системой антиточек. Записано статическое распределение вектора антиферромагнетизма, предложен метод (основанный на минимизации энергии антиферромагнетика), который позволяет снизить число граничных условий, необходимых для нахождения констант этого распределения. Уравнения для констант распределения получены как для случая минимизации энергии антиферромагнетика по одной из констант распределения, входящих в выражение для энергии антиферромагнетика, так и для случая минимизации по двум константам. Метод проиллюстрирован на примере системы из одной изолированной антиточки. Для такой системы получено одно дополнительное условие на константы распределения – для случая, когда на поверхности антиточки задано два граничных условия – и два дополнительных условия – для случая, когда на поверхности антиточки задано одно граничное условие.

Ключевые слова: Антиферромагнетик, Тонкая магнитная пленка, Магнитная антиточка, Магнитная энергия, Вектор антиферромагнетизма.

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