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Magnetic Structure of Nanowires and Magnetostatic Interaction

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Abstract. The ground state magnetization of nanowires built of ferromagnetic crystallites is considered taking into account the magnetostatic interaction. The criterion of formation of domains is found. The thickness of a domain wall is calculated analytically and the results are compared with the numerical simulations. We show that when the exchange coupling between crystallites is absent its role is played by magnetostatics that ensures the existence of stable domain structure. The direction of the induced anisotropy axis is shown to be determined by the shape of crystallites.

Introduction

The perspective application of arrays of nanowires in virtual data recording raises a special interest to the studies of magnetic properties of nanowires, since the sizes of individual carriers reach as small as tens nm[3]. The stable state of magnetization in such small elements is destroyed by the thermal motion. Nanowires, however, present an opportunity to overcome this obstacle. The diameter of nanowires deposited into a matrix may be a few nanometers which corresponds to the physical limit of the recording density. At the same time, nanowires have macroscopic sizes, thus considerably exceeding the size of superparamagnetic particles.

Nanowires attracted significant attention resulted in a number of theoretical papers where the studies were performed mostly numerically. In our previous work [1] we have considered the ground state of the magnetization of ultra-disperse quasi-one-dimensional magnet in the form of ferromagnetic layers coupled by the exchange interaction. The results were obtained neglecting the magnetostatic interaction. However, in nanowires the magnetostatic interaction plays an important role. In the present paper we take into account the magnetostatics when studying the magnetic structure of nanowires.

Magnetic structure of nanowires with stray fields

We use the model of cylindrical wire whose length is much larger than the radius. Moreover, the diameter is assumed to be much smaller than the domain wall width in the bulk. The anisotropy field in the wire is specified by the polar angle α and the azimuth angle ψ. The polycrystalline structure is modeled by the dependences $\alpha=\alpha(z)$ and $\psi=\psi(z)$ (see Fig. 1). The magnetization (unit vector **m**) is described by the polar and azimuth angles θ and φ. The size of crystallite along the direction of the z axis is $a<<\delta_0$, where $\delta_0 = \sqrt{A/K}$ is the width of domain wall in the bulk, A and K are the ferromagnetic exchange constant and the constant of crystallographic anisotropy, respectively.

Micromagnetic calculations are based on the phenomenological Landau—Lifshitz equations. In what follows, in order to simplify calculations we consider two limiting cases: a) the exchange coupling between crystallites is the same as within the crystallites, b) the exchange coupling between crystallites is absent. In the case a) the energy of nanowires consisting of N crystallites is written down without taking into account the magnetostatic interaction:

$$E = \int_V \left[A(\nabla m_x)^2 + A(\nabla m_x)^2 + A(\nabla m_x)^2 - M_S \mathbf{m}\mathbf{H}^{(eff)} \right] d^3\mathbf{r}, \quad (1)$$

where: $\mathbf{H}^{(eff)} = \frac{K}{M_S}(\mathbf{me})\mathbf{e} + \frac{1}{2}\mu_0 M_S \hat{\mathbf{N}}\mathbf{m} + \frac{\mu_0 M_S}{4\pi} V \sum_{n \neq m} \left(\frac{\mathbf{m}_m}{r^3} - 3\frac{\mathbf{r}(\mathbf{m}_m \mathbf{r}_{nm})}{r^5} \right) + \mathbf{H}.$

Here $\mathbf{e}$ is a unit vector along the direction of the local axis of anisotropy, $\hat{\mathbf{N}}$ is the tensor of demagnetizing factors, μ_0 is the magnetic constant, $\mathbf{r}_{nm}$ is the radius-vector connecting crystallites with numbers n and m (it is parallel to the z axis), $\mathbf{H}$ is the external magnetic field measured in units of magnetic induction, M_S is the saturation magnetization. Varying (1) with respect to angles θ and φ we obtain the equilibrium distribution of magnetization. These equations are convenient for the numerical simulations.

The analysis of numerical results shows that the resultant magnetostatic energy can be approximated by:

$$E_{st} \approx -KV \frac{1}{b^2}\left(b_N^2 + 0.6 b_m^2\right)\cos^2(\vartheta). \quad (2)$$

Here the dimensionless quantities responsible for the demagnetizing field of magnetic structure of nanowire are: $b = a/\delta_0$, $b_N^2 = \mu_0 M_S^2 b^2 (N_\perp - N_\parallel)/K$, $b_m^2 = \mu_0 M_S^2 b^2 S/(\pi K a)$, $N_\perp$ and $N_\parallel$ are the crystallite demagnetization factors along and normal to the z axis respectively, S is the crystallite cross-section. The demagnetizing field plays the same role as the field of anisotropy oriented along the axis of the wire. The coefficient $KV\left(b_N^2 + 0.6 b_m^2\right)/b^2$ in (2) is the constant of effective homogeneous anisotropy induced by the magnetostatic interaction.

Considering expression (2) according to [2], we derive the following expression for the domain wall width $\delta_W \approx \delta_0 \sqrt{b^2/\left(b_N^2 + 0.6 b_m^2\right)}$.

Making Euler's equations dimensionless (using the domain wall width δ_W as the unit of length) we obtain the following equation for equilibrium magnetization: $\tan(\vartheta(z)/2) = \exp(z)$, $\varphi(z) = const$. Formally this solution coincides with that found in [2], except for a special geometry of domains - magnetization of adjacent domains is directed toward each other, and inside the wall $\nabla \mathbf{m} \neq 0$.

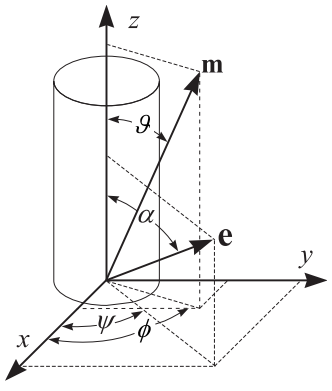

Fig. 1. Crystallite and coordinate system.

The numerical simulation has shown that there are critical values of the parameters: b, b_N and b_m, distinguishing the situations when the domains are present and when they are absent. Domain walls manifest themselves in the characteristic distribution of the polar angle while the azimuth angle is not sensitive to the presence of domain walls. When an external magnetic field is applied along the z axis domain walls move. Up to some threshold value of the external field the change of magnetization is not accompanied by the motion of domain walls. The threshold value is the start field. In Fig. 2 the solid line shows the angular distribution of magnetization within a domain wall found by simulation of a nanowire with parameters: $b = 0.1$, b_m=0.025 and b_N=0.05.

The demagnetizing field affects the variation of magnetization directions in a similar fashion as an external field. If the magnetization direction is close to the axis of nanowire, the variation of the transversal component of magnetization decreases with increasing demagnetizing field (increasing M_S) as is seen in Fig. 3. The dependence of the variation on b_m is close to the exponential.

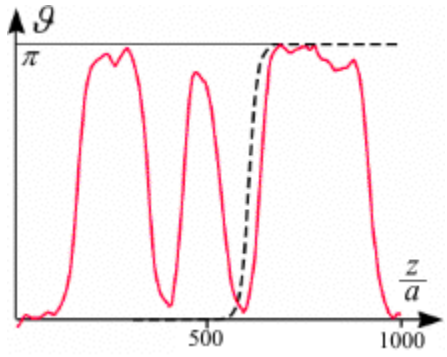

Fig.2. Profile of a domain wall (numerical simulation, solid line) compared with the analytical expression of Landau-Lifshitz magnetization.

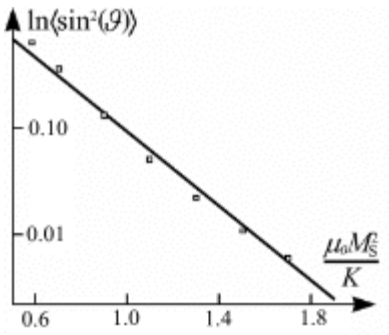

Fig. 3. Dependence of the variance of transversal magnetization on the saturation magnetization.

If initially the wire is magnetized along the z axis up to saturation and the external magnetic field is applied in the opposite direction, the domain structure of special form may appear with co-directed magnetization in adjacent domains separated by 360-degree walls. The profile of such walls is similar to a profile of 180-degree wall. The nuclei of domains are the fluctuations of magnetization caused by the inhomogeneities of crystallographic anisotropy. Figure 4 depicts the domain structure arisen from such state of quasi-homogeneous magnetization under the action of an external magnetic field applied along the z axis. The solid line shows the nuclei of domains in oppositely oriented magnetic field with a value $h = -0.001$. The dashed line corresponds to the distribution of the polar angle for the field $h = -0.005$.

After switching the magnetic field off the domain walls do not disappear. They do not move under the action of the external field. Increasing the magnitude of the magnetic field creating such structure only changes the thickness of domain walls.

The nanowire without the exchange coupling between crystallites

There are nanowires with such interlayers between the crystallites that isolate the exchange interaction [3]. In this case the characteristics of magnetic structure are only determined by the magnetostatic interaction and stochastic crystallographic anisotropy.

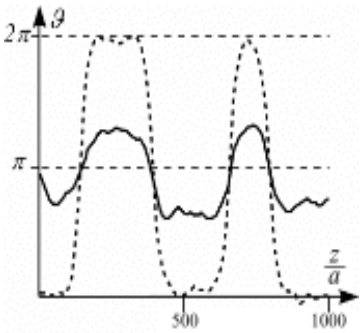

Fig. 4. Distribution of magnetization polar angle in 360° domain wall for different values of an external magnetic field.

The third term in field $\mathbf{H}^{(eff)}$ reaches the minimal value when the difference φ between the neighboring crystallites is equal to π. Assuming that antiferromagnetic ordering is realized through azimuth angle alternation and that the polar angle ϑ varies smoothly with coordinate z, we can write down the energy of the dipole-dipole interaction of the n-th crystallite as a function of only the polar angle

$$E_n^{DD} = \frac{1}{4}\frac{\mu_0 M_S^2}{4\pi a} V^2 \sum_{n\neq m}\left[\frac{2-(-1)^{|n-m|}}{2|n-m|^3}\left(\frac{d\vartheta_n}{dz}\right)^2 - 2\frac{2+(-1)^{|n-m|}}{a^2|n-m|^3}\cos^2(\vartheta_n)\right]. \quad (3)$$

Simulations have shown that only 5-6 crystallites fall inside a domain wall, therefore after performing summation in (3) we have for an effective exchange constant: $A_{eff} = 2.25\mu_0 M_S^2 V/(4\pi a)$

and for a constant of the directed anisotropy: $K_{eff} = 2.28\mu_0 M_S^2 V/(4\pi a)$. This yields $\delta_W \approx 2a$ for the width of the domain wall.

Depending on elongation of crystallites along the z axis two types of domain structure may appear (see Figs. 5 and 6).

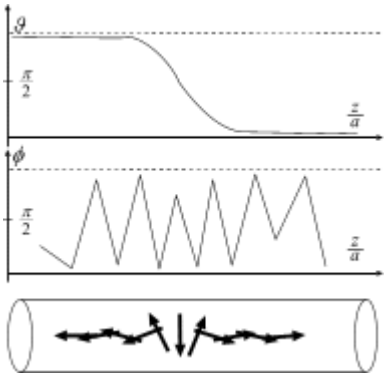

Fig. 5. The characteristic dependence of polar and azimuth angles of magnetization and its distribution within a domain wall for b_N=0.1.

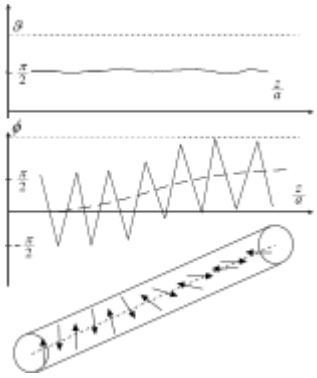

Fig. 6. The characteristic distribution of polar and azimuth angles of magnetization and its direction for b_N=0.002.

Depending on the value of b_N dominating homogeneous effective anisotropy may be of different types, “easy plane" or “easy axis”. There is a spin-reorientation transition of the type “easy axis - easy plane". After the transition a specific domain structure arises when the smooth dependence is exhibited not by the distribution of polar angle but by the azimuth angle.

Summary

We have carried out numerical and analytical examinations of the effect of magnetostatic interaction on the magnetic structure of nanowire represented as a chain of crystallites with random crystallographic anisotropy. Numerical experiments and analytical estimates have yielded the following results:

In the presence of the exchange and dipole-dipole interactions between the nanocrystallites a domain structure with 180-degree walls may form depending on the saturation magnetization, shape of the crystallites and the prehistory.

Within a two-angular description we have calculated analytically the effective constant of induced homogeneous anisotropy, the width of domain wall and its profile as functions of the saturation magnetization of crystallites and their shape.

The two-fold role of the dipole-dipole interaction in the formation of magnetic structure of nanowire is revealed. The qualitative explanation is given to the origin of domain structure in nanowire without the exchange coupling between nanocrystallites.

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