Dzyloshinskii – Moriya interaction, magnetism and magnetoelectricity of magnetic states in nanodots

Highlights

• DMI induced magnetic transformations are explored in restricted system (nanodot)

• Differences of transformations of Easy Axis and Easy Plane states are revealed

• Electric field induced bubble nucleation depends on the initial state (Easy Axis or Easy Plane)

Abstract

In this paper we explore transformations of the uniform magnetic states of the "easy axis" and "easy plane" types induced by the Dzyaloshinskii – Moriya – like interactions (DMI - like) considering the rectangular nanodot as an example of a system with restricted dimensions. We showed that DMI induces the series of phase transitions: uniform magnetic state – vortex – antiskyrmion/meron – multidomains – domain structure (K</>0) and construct phase diagrams in terms of "DMI constant – nanodot size". Our findings show that manifestation of DMI in the system of restricted geometry depends on initial magnetic configuration. In the case of perpendicular magnetic anisotropy stabilizing "easy axis" configuration DMI leads to formation of the single vortex – like state, and the change of the DMI sign inverts spin chirality while the vortex polarity remains conserved. On the contrary, in the case of "easy plane" state DMI leads to the formation of coupled vortices with opposite polarities, and the change of DMI sign turns over each of vortices polarities and chiralities. Since in multiferroics electric field acts on magnetic states via DMI, the magnetic response to electric field will be different for confined magnetic structures (e.g. bubbles) differing by their initial configurations ("easy axis" and "easy plane"). In the "easy axis" case change of voltage polarity isn't of principal importance while in the "easy plane" case the change of electric field direction can essentially influence the nucleation processes of bubble – like magnetic structures.

Introduction

Magnetic structures of non – trivial topology attract considerable attention due to the prospect of their implementations in spintronics, information processing and storage devices. The progress in this field is concerned with study of nanoscale magnetic states of different types (magnetic vortices, bubbles, skyrmions, merons) [1 -5] which can be realized in ferromagnets and multiferroics. Each type of the curling magnetic configuration has its own advantage, so it is of interest to have a system allowing realization of various structures differing by their topology.

Topological magnetic states are stabilized due to an interplay between exchange, magnetostatic, and relativistic anisotropic interactions. An important role belongs to Dzyaloshiskii – Moriya interaction (DMI) arising in the systems whose symmetry lacks of space inversion operation. DMI can arise in ultrathin magnetic films due to strong spin orbital interaction at the interfaces between magnetic films and non – magnetic metals [6 - 8], here the strength of DMI depends on the chemical composition of magnetic film / heavy metal interface [9]. DMI is actual in multiferroics, magnetoelectric effect as well as DMI arise in the system with broken space inversion symmetry [10 - 14]. In multiferroics DMI is closely related with ferroelectric properties of a material. Here, electric field control of magnetic states is carried out through the DM - like interactions [14 - 16]. To predict an expected magnetic response to electric agent it is necessary to understand the mechanism of DMI impact in a combination with another important factors related with the properties of a systems (magnetic anisotropy, exchange stiffness, system dimensions).

Recent researches demonstrate plethora of possibilities to manipulate nanoscale whirling magnetic states through electric current, magnetic field and voltage [1 - 18]. They reveal the strong correlation between the induced outcome and the topology of initial magnetic state [15 - 19].

In this paper we discuss the DMI influence on the magnetic structures in the samples of restricted geometry. We present typical examples of magnetic states with an in – plane magnetization (IPM) and out – of plane magnetization (OPM) and analyze the transformations induced by DMI, strain – induced magnetic anisotropy and applied electric field. As we will see, the effects arising due to DMI can be extensive, DM- like interactions can induce the magnetization reversal as well as the transitions from the single domain state into multidomain state with the developed domain structure. We show that magnetic response to DMI depends on the initial magnetic state and has essential differences for the IPM and OPM configurations. Finally, we consider the electric field induced magnetization manipulation in multiferroics.

Model

To develop strategies for DMI control, it is helpful to appeal to mechanisms of the DMI interaction. DMI arises due to the double – exchange interaction between two magnetic ions (MIs) separated with non – magnetic ion (NMI), the DMI Hamiltonian is of a form

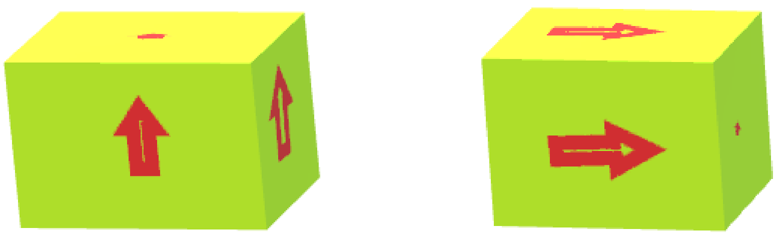
$$F_{DMI} = \frac{1}{2}\sum_{i<j} \boldsymbol{D}_{ij}\left[\boldsymbol{s}_i \times \boldsymbol{s}_j\right] \tag{1}$$

where $\boldsymbol{s}_i$, $\boldsymbol{s}_j$ are the spins of neighboring iron ions, the DM vector is determined by $\boldsymbol{D}_{ij} = V_0\left[\boldsymbol{R}_{O-i} \times \boldsymbol{R}_{O-j}\right] = V_0\left[\boldsymbol{d} \times \boldsymbol{r}_{ij}\right]$ where V_0 is the microscopic constant, $\boldsymbol{R}_{O-i}$, $\boldsymbol{R}_{O-j}$ are the vectors connecting the *i*-th magnetic ion (MI), in-between non - magnetic ion (NMI) and the *j* - the MI, $\boldsymbol{r}_{ij}$ is the radius – vector connecting the *i*-th and the *j* -th MIs; vector ***d*** determines the displacement of the intermediate NMI from the line connecting MIs. Accounting spin deviations along the axis connecting MIs with NMI $\boldsymbol{s}_{i,j} = \boldsymbol{S}_{i,j} + \delta\boldsymbol{S}_{i,j}(x)$ one can expand the DMI energy in the series of the $\delta\boldsymbol{S}_{i,j}(x)$ representing it via Lifshitz invariant.

The form of D_{ij} tensor and the DMI energy is determined by the crystallographic symmetry, in the crystals whose symmetry group has no inversion operation the DMI energy can be represented in the form [20] $F_{DMI} = \boldsymbol{\gamma} \cdot (\boldsymbol{S}_i \operatorname{div} \boldsymbol{S}_j - (\boldsymbol{S}_i \cdot \nabla)\boldsymbol{S}_j)$ where $\boldsymbol{\gamma}$ is the parameter sensitive to external effects such as electric field and strains $\boldsymbol{E}, \sigma_{ik}$. Generally it can be represented as a function of these parameters $\gamma_l(\boldsymbol{E}, \sigma_{ik}) = a_1 E_i + b_1\sigma_{ik} + a_2 E_i E_j + b_1 \sigma_{ik}\sigma_{kl} + cE_i\sigma_{ik} + \ldots$. We restrict ourselves with the action of electric field taken in the linear approximations $\gamma_i = a_1 E_i$ explored for example in Refs. [21]. Thus, the DMI strength can be manipulated by electric filed, also the direction of the ***D*** or $\boldsymbol{\gamma}$ vector can be controlled by electric filed direction of via changes of polarities of the applied voltage.

The DMI is the kind of interaction responsible for magnetization chiralilty, the direction of spins rotation is related with the sign of ***D*** – vector: ***D***>/<0 exerts anticlockwise/clockwise rotation of spins. DMI favours to stabilization of chiral magnetic structures such as magnetic vortices and skyrmions. However, to obtain the ground magnetic configuration it is necessary to account the balance between DMI, exchange, anisotropy and other relevant interaction for every particular system.

To reveal the principle differences of the DMI effect on the magnetic states we consider typical magnetic configurations: in – plane and out – of – plane magnetized states in a system of restricted geometry (Fig.1).



a *b*

Fig. 1. Schematic illustration of the nanodot geometry a) K>0, b) K<0

We stabilize initial magnetic configuration by external magnetic field applied in the "easy axis" direction and explore the transformations of magnetization due to the changes of DMI which can be related with various factors including an action of electric field. The free energy of the system is taken in the form

$$F = A\left(\partial_\mu m_\alpha\right)^2 + F_{DMI} - Km_z^2 - \frac{1}{2}M_s\mathbf{m}\cdot\mathbf{H}_m - M_s\mathbf{m}\cdot\mathbf{H}$$

where A is the isotropic exchange stiffness constant proportional to the Heisenberg exchange integral, K is the constant of magnetic anisotropy, α, $\mu = x, y, z$, $\mathbf{m} = \mathbf{M}/M_s$ is the unit magnetization vector, $\mathbf{H}_m$ is the magnetostatic field and $\mathbf{H}$ is the external magnetic field, F_{DMI} is the DMI energy. The micromagnetic simulation are performed by using the Object Oriented Micro Magnetic Framework (OOMMF) public code [22] with the additional module for DMI [23]. We consider nanocell 200x200 nm^3 with varying thickness 12nm<d< 120 nm with mesh size 5x5x3 nm^3. The material parameters are saturation magnetization $M_s = 10^3$A/m, exchange constant A = $2.9 \cdot 10^{-12}$ J/m, perpendicular magnetic anisotropy constant $K_u = 1 \cdot 10^3$ J/m^3, the chosen values correspond to iron garnets, DMI strength is varied in the range $-9\ 10^3$ J/m^3<D <$9\ 10^3$ J/m^3. Let us note that the peculiarities which will be discussed below are quite general, they will appear at the relevant relations between the mentioned material parameters.

Results and discussion

Magnetic anisotropy plays an important role in the stabilization of the ground magnetic configuration. Magnetic anisotropy allocates the direction of magnetization in an infinite uniformly magnetized media, in the case of uniaxial magnetic anisotropy dependent on its sign uniform magnetic states can be of the "easy axis" (EA) and "easy plane" type can be realized. Exchange interactions, stray magnetic fields which are essential in the systems of restricted geometry modify a uniform magnetic configuration which we consider below.

We start with consideration of OPM state supported by the perpendicular magnetic anisotropy (PMA) and external magnetic field applied in the z – direction. The initial magnetic configuration established at D=0 is shown in Fig. 1 a.

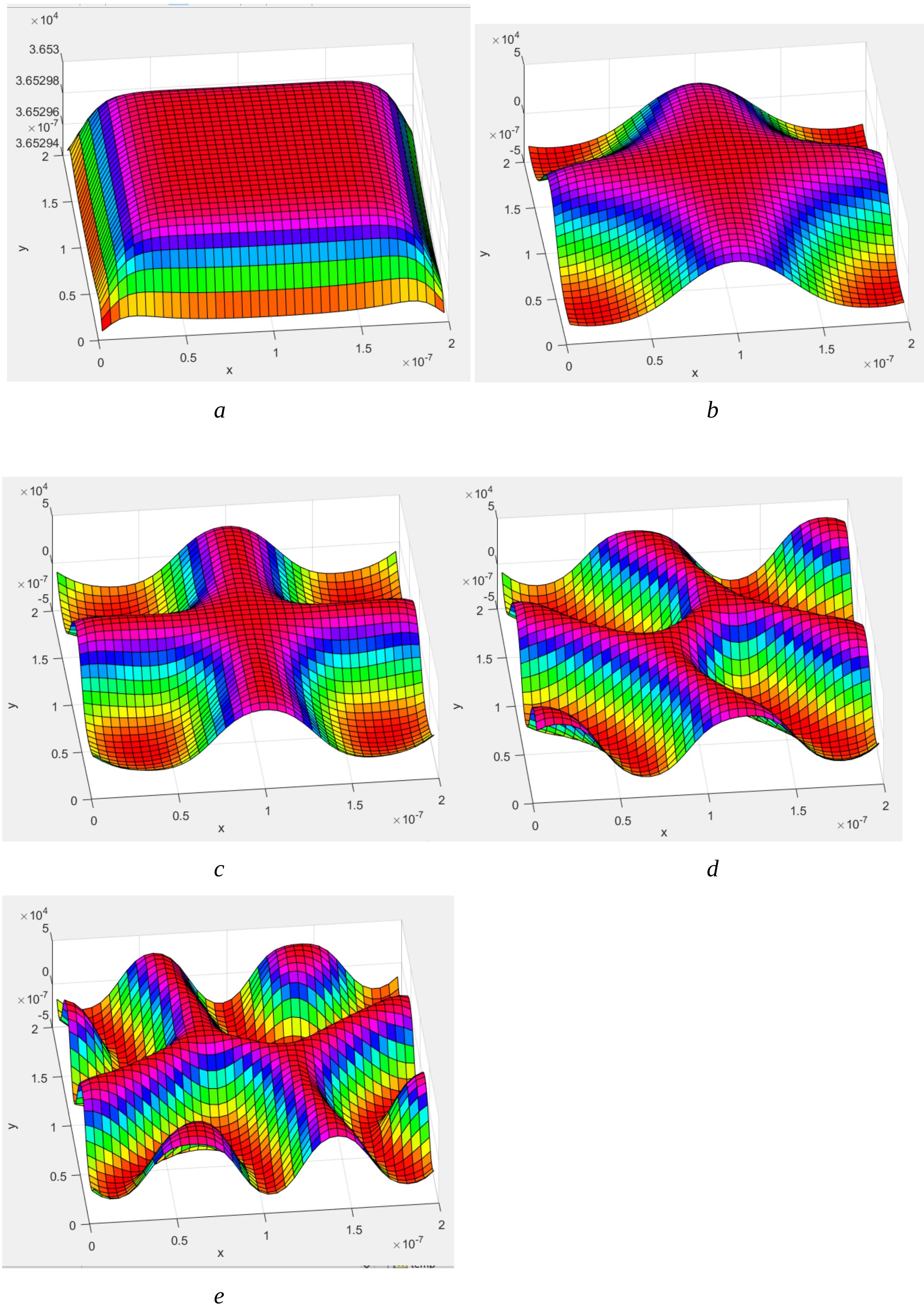
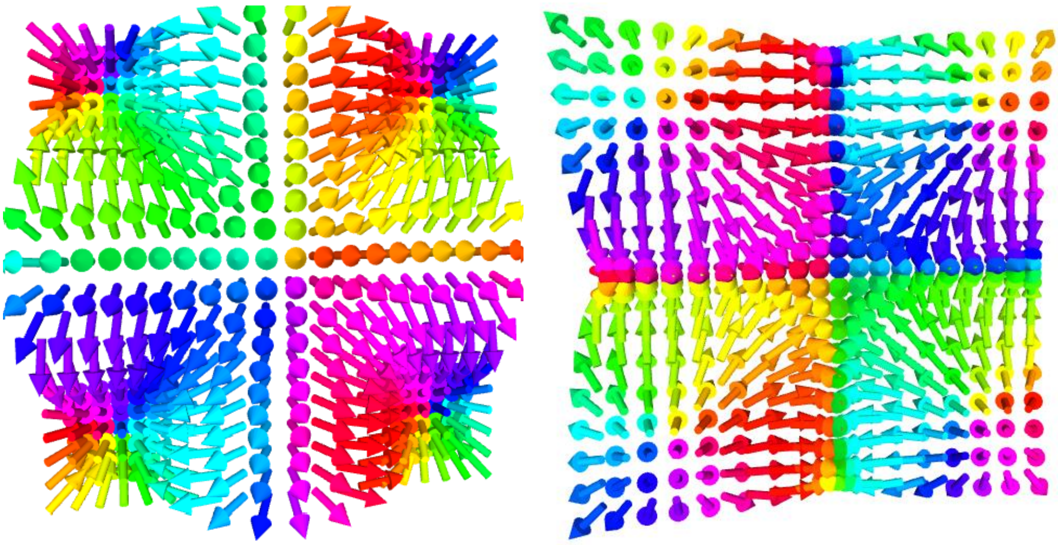


Fig.1. Magnetization distribution at K_u>0 in nanodot d=30 nm. a) D=0, b) D= ± 2 kJ/m^2, c) D= ± 3 kJ/m^2, d) D= ± 4 kJ/m^2, e) D= ± 5 kJ/m^2

DMI modifies the uniform magnetic state leading to appearance of the skyrmion – like state at small values of D<<1, the single domain configuration is kept up to D= $\pm$ 3 kJ/m^2, after which it transforms into the multidomain state as Fig.1c,d show. An increase of the DMI strength results in the appearance of skyrmionic-like configurations inside the domains (Fig.1e) and formation of extended domain structures with the further *D* enhancement. The principal stages of DMI induced transformations of OPM state are shown in Fig.1.

The DMI brings chiral effects into magnetism, in the PMA case they are manifested in the change of the direction of magnetization rotation: clock – wise at *D*<0 and anticlockwise at *D*>0 (Fig. 2a, b).



a *b*

Fig.2. Distribution of magnetization in nanodot *K*>0, effects of chirality, a) D= -3 kJ/m^2, b) D= +3 kJ/m^2

It is of importance that in this case the sign of the DMI vector influences only magnetization rotation chirality, it doesn't affect the polarities of skyrmionic-like states and the transformations of magnetic order described above.

In the case of the developed in – plane magnetic anisotropy (*K*<0) the ground magnetic state is of "easy plane" (EP) type. We turn to consideration of the IPM state in nanodot supported also by magnetic field applied in the *x* – direction when DMI is absent. As in previously considered case the change of the DMI strength leads to transformations of magnetic structure shown in Fig. 3.

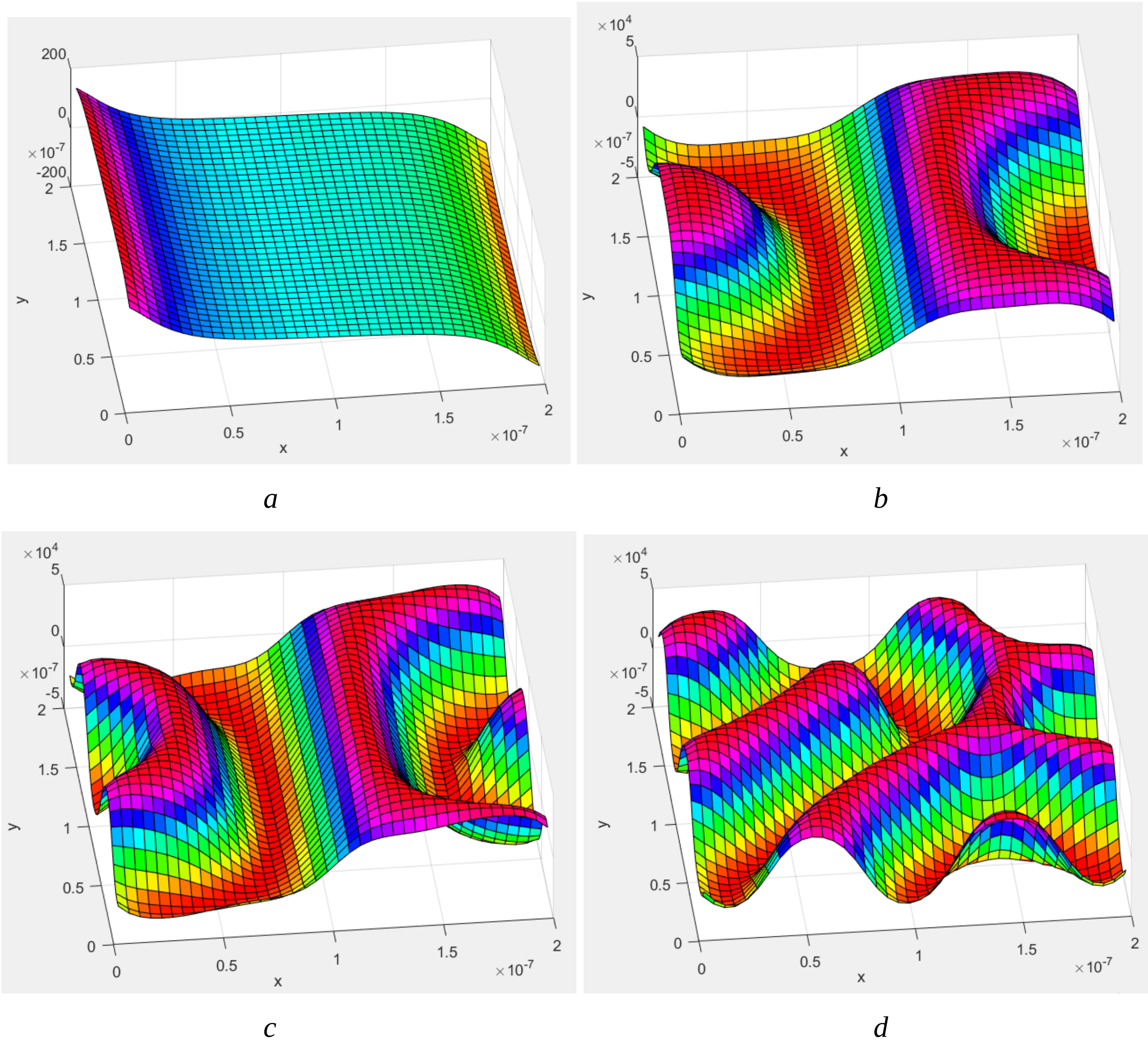


Fig.3. Magnetization distribution at K_u<0 in nanodot d=30 nm, the magnitudes of DMI constant a) D=0, b) D=3, c) D= 4 kJ/m^2, d) D= 5 kJ/m^2

However, here we see the distinguishing features of the EP state transformations comparing with the DMI induced transformations of the EA magnetic state (Fig.3b). In the case of in-plane magnetization DMI induces pair of coupled vortex – like states with the opposite polarities (Fig 3b), an increase of DMI strength at first changes the vortices topology (Fig. 3c), and afterwards leads to the multidomains represented here by the kind of labyrinth structure.

In the case of in – plane magnetic anisotropy DMI influences both chirality and polarity of the coupled vortices as shown in Fig.4.

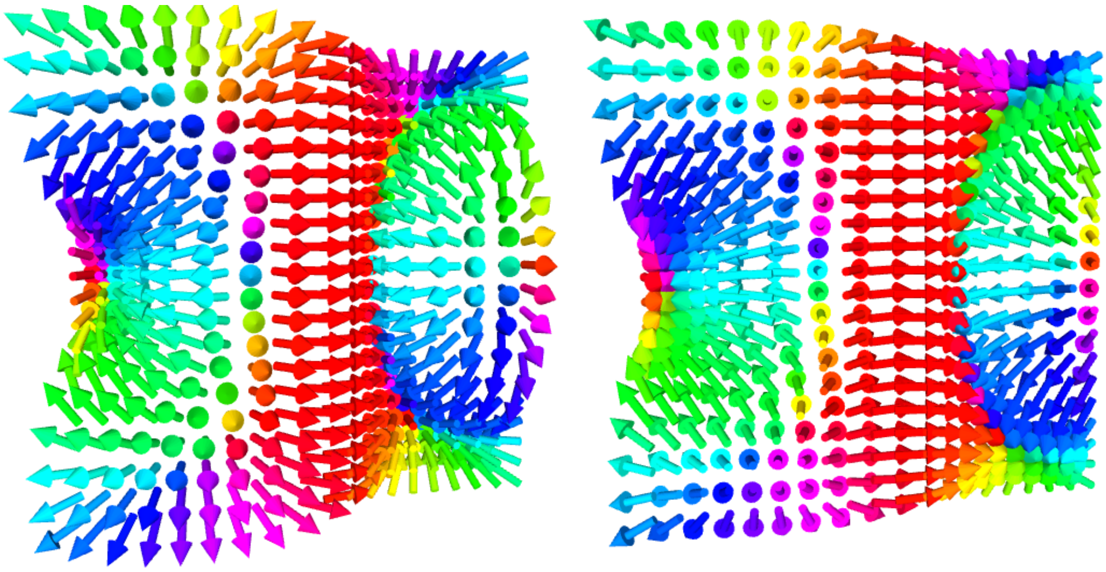


Fig.4. Distribution of magnetization in nanodot K<0, a) D= -3 kJ/m^2, b) D= +3 kJ/m^2

The analysis of the DMI impact in a combination with dimensional effects showed that threshold values of DMI required for the described transitions is regulated by nanodot lateral dimensions. So, to obtain the single domain state instead of multidomains one should diminish nanodot area and increase the strength of DMI (Fig.5). Variations of nanodot thickness in a case of thin films (10 nm<d<120 nm) do not essentially influence magnetization transformations.

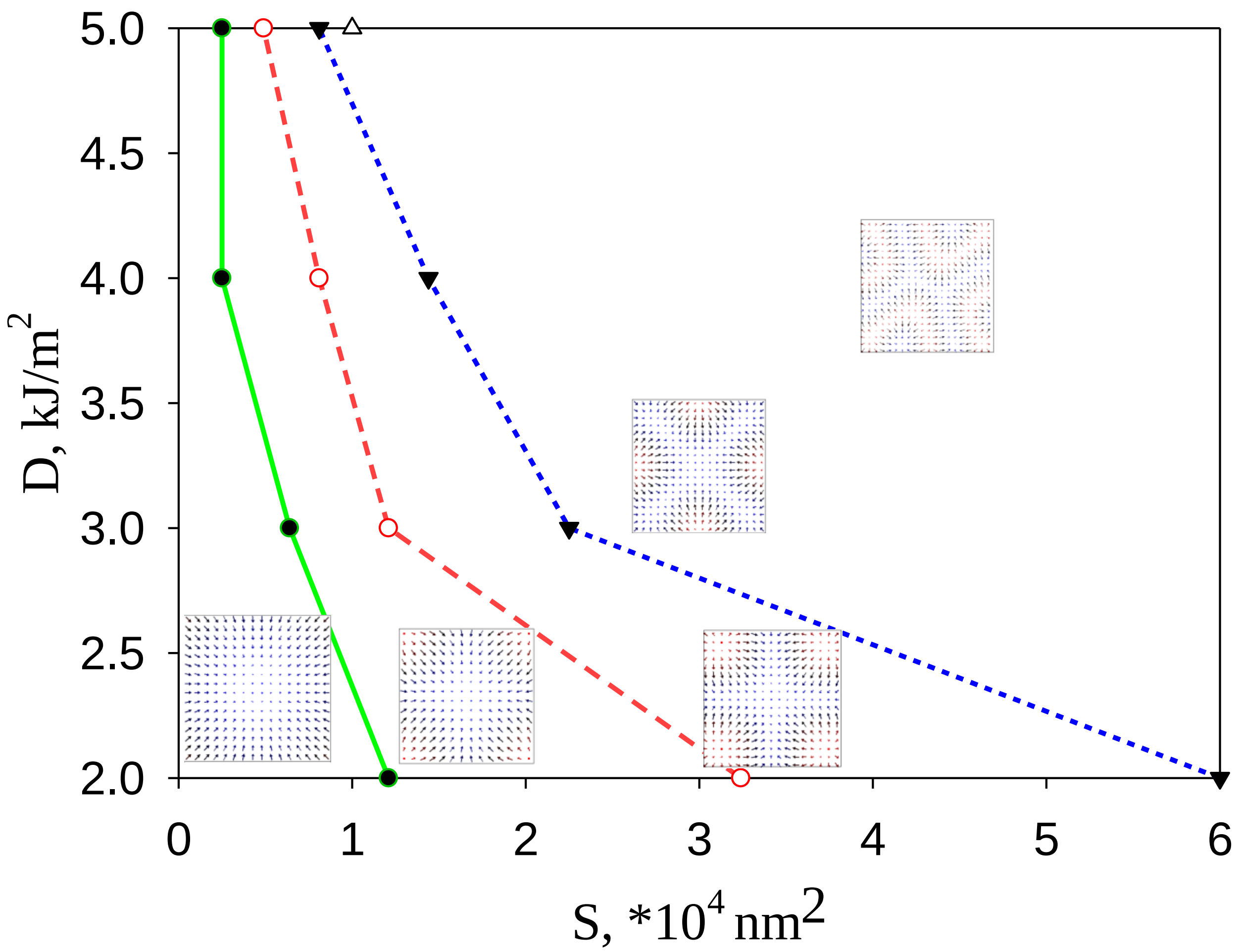


Fig.5. Phase diagram of the phase transitions in square nanodot K>0.

Thus, we considered the effect of the DMI on the EA and EP magnetic states localized in magnetic nanodots as an example. In the frame of the concept of magnetoelctric effect [14] inhomogeneous magnetic distribution leads to appearance of concomitant electric polarization. To illustrate this effect we constructed polarization plots for the typical cases (Fig. 6). As was discussed in the beginning, the DMI in magnetoelectric materials manifests itself as inhomogeneous magnetoelectric interaction where the $\boldsymbol{D}$ vector is directly related with applied electric field $\boldsymbol{D}=\gamma\boldsymbol{E}$, as in the case of iron garnets where γ ~[14]. So, we can apply the gained results to this definite material. We will interest in the electric filed induced transformations of a single domain configuration that can be achieved on small nanodots (we take them as analogous of magnetic bubbles) at strong electric filed corresponding to high values of the DMI constant. Our results show that electric filed nucleates magnetic vortex – like states, however an expected effect of electric field on the nanodots with EA and EP magnetic configurations will be quite different. The direction of electric field is not essential in the case of EA magnetic state, since the polarity of magnetic configurations aren't affected by the sign of electric field related with the sign of $\boldsymbol{D}$ – vector. On the contrary, the direction of electric field or the voltage polarity is significant in the EP case. The polarities of magnetic configurations (the nucleated by electric field vortices) depend on the sign of electric field ($\boldsymbol{D}$ – vector sign) as we showed above. As a consequence, the change of the voltage polarity will affect magnetic configuration.

Conclusion

To conclude, we considered the effect of the DMI and the factors related with DMI such as electric field on the uniform magnetic configuration of ferromagnet and multiferroics restricted in a space. We analyzed the DMI – induced modifications of typical uniform magnetic states of the "easy axis (EA)" and the "easy plane (EP)" types. In both cases an introduction of the DMI favors nucleation of vortex – like structures. An increase of the DMI strength modify the vortices topology, the topological number $N = M_s L \int d^2\boldsymbol{\rho}\mathbf{m} \cdot \left[\partial_x \mathbf{m} \times \partial_y \mathbf{m}\right]$ changes from 0 to 1 when DMI strength changes from from 0 to the critical value D_c, at $D>D_c$ the vortex structure breaks into multidomains which can evolve with the further DMI enhancement. These features are common ones for transformations of EA and EP initial configurations.

However, our findings show that the DMI manifests itself in the different ways for the out – of –plane (EA) and in – plane (EP) magnetic configurations. While DMI transforms the EA state into the single vortex of a definite polarity, the EP state becomes broken into coupled vortices with opposite polarities. In the case of EA state the change of the DMI constant sign affects only the vortex chirality, namely the direction of spin rotation in the vortex change with the change of the DMI constant sign, but the polarity of vortex state is conserved, it doesn't depend on the DMI sign. On the contrary, in the case of EP state DMI affects both polarities and chiralities of the coupled magnetic vortices, when the DMI constant changes its sign both of these quantities vary.

It will be more convenient to present the results in terms of electric field which can act on magnetization via the DMI in the case of multiferroic materials. As follows from our consideration the voltage polarity is not essential when one applies electric filed to the confined EA magnetic state that can be realized for example in magnetic bubbles with out – of – plane magnetization. In this case the polarity of is conserved when electric field changes its direction. However, in the case of EP magnetic state realized in magnetic bubbles with in – plane magnetization the selection of the direction of applied electric field can become significant, since the polarity and chirality of magnetic states depend on the sign of DMI constant. We beleive that our findings are of importance and can be helpful for interpretation of DMI related effects found in ferromagnets and multiferroics.

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