FEATURES OF MAGNETO-OPTICAL RESPONSE OF NANOSTRUCTURES FORMED IN VARIOUS REGIMES OF ION SURFACE TREATMENT

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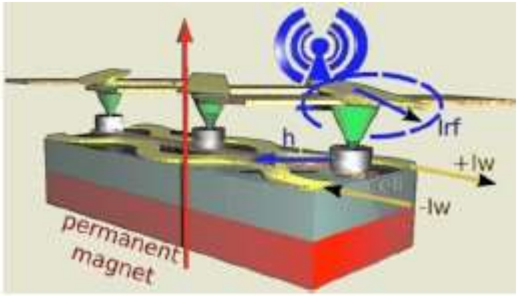
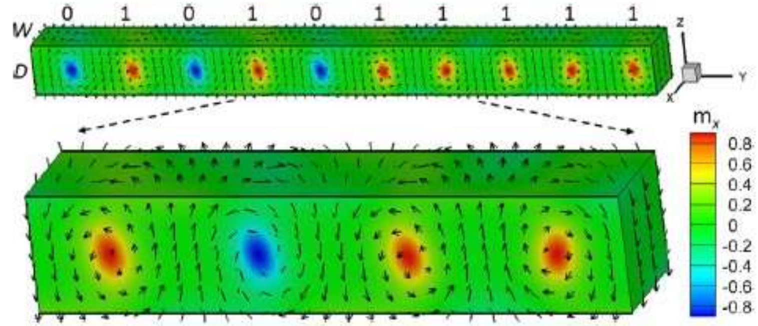
Введение





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A frequency-controlled magnetic vortex memory

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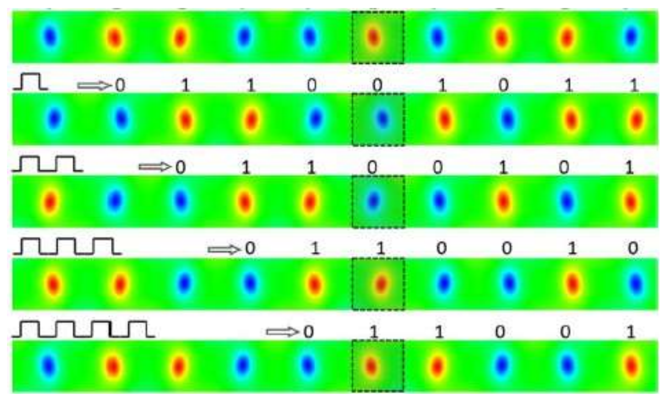

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Magnetic vortex racetrack memory

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Figure 1. **The scheme of functioning of race-track memory.**
It is ferromagnetic linear structure with the data that are coded as regions of magnetic domains or vortices along a nanowire.

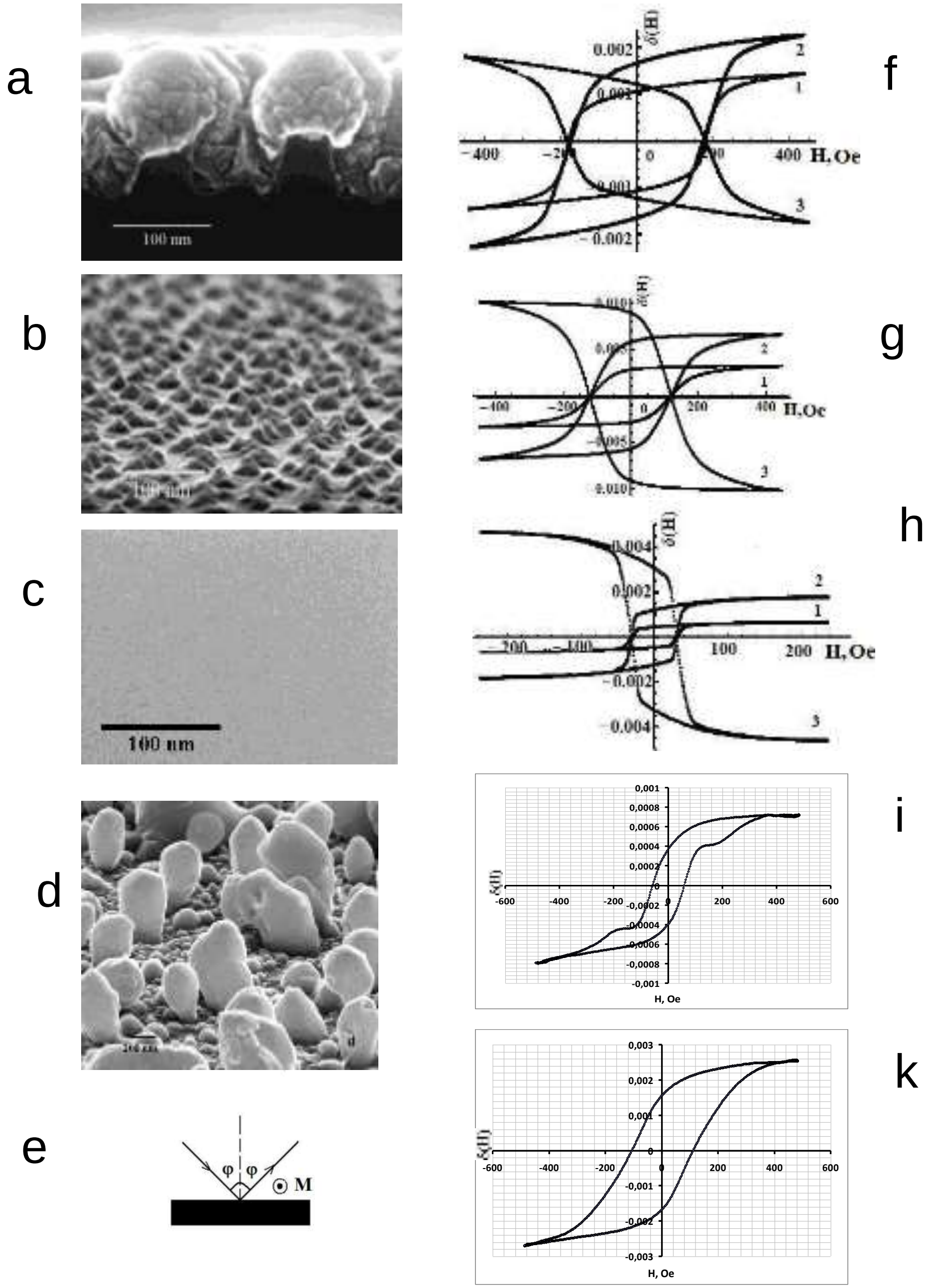
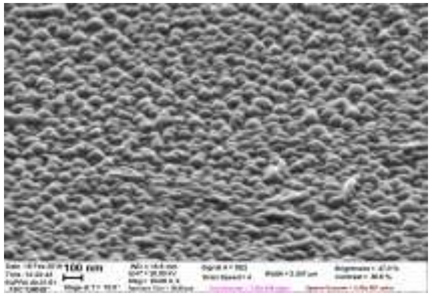


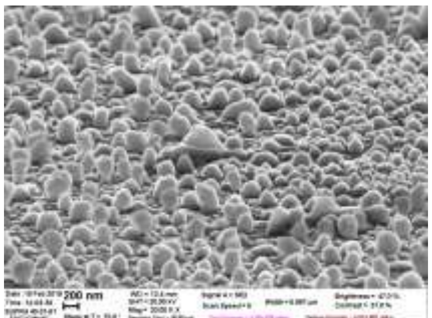
Figure 2. **Structures on the base of covered on top by cobalt silicon nanostructures after sputtering of Co (sample 1) – (a). Structure with cobalt nanofilm on the base of anodized aluminum on silicon substrate (sample 2) – (b). Structure with homogeneous Co layer on silicon (sample 3) – (c). Sample PbSe after treatment in Ar+ plasma during 4 minutes – (d). The scheme of experiment in configuration of transverse magnetic Kerr effect (TMOKE) – (e).Right (f, g, h) are corresponding TMOKE dependencies δ(H) for λ = 633 nm and** incident angles: **25° (1), 40° (2), 75° (3);** for PbSe sample: **52.5° – (i), 65° – (k).**

STRUCTURES ON THE BASE OF *PbSe* WITH DIFFERENT MORPHOLOGY

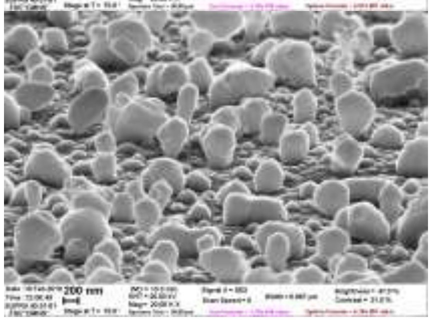
a



b



c



d

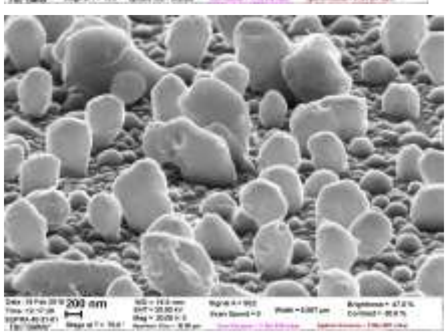


Figure 3. **Общий General view of structures which were formed by Ar+ plasma treatment and cobalt film sputtering with the thickness 30 nm,**

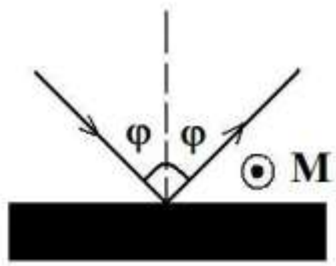
(a) – after 60 seconds etching in Ar+ plasma (region 1),

(b) – after 120 seconds etching in **Ar+ plasma (region 2),**

(c) – after 180 seconds etching in **Ar+ plasma (region 3),**

(d) – after 240 seconds etching in **Ar+ plasma (region 4).**

PROCEDURE OF MAGNETO-OPTICAL MEASUREMENTS



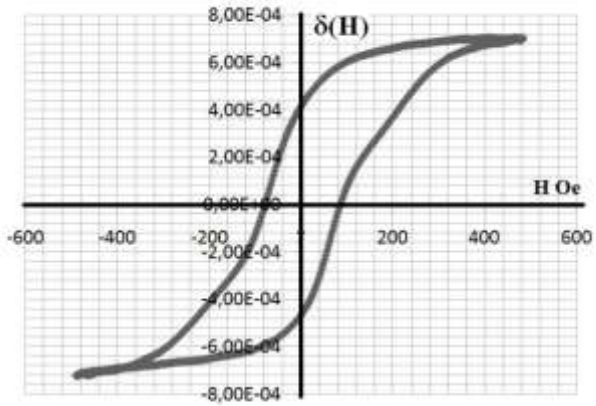
Wave length of incident radiation λ = 633 nm

$$\delta = \Delta I/I(0),$$

where $\Delta I = I(H) - I(0)$. Here $I(H)$ is an intensity of light which is reflected from magnetized surface, $I(0)$ is an intensity, which is reflected from non-magnetized surface, H is a magnetic field strength.
Значение ΔI value is proportional to the variable component of current of photo-detector. $I(0)$ is proportional to the constant component of current,
φ Is an angle of incident radiation.

CHARACTER OF MAGNETO-OPTICAL HYSTERESIS LOOPS FOR *PbSe* STRUCTURES

a



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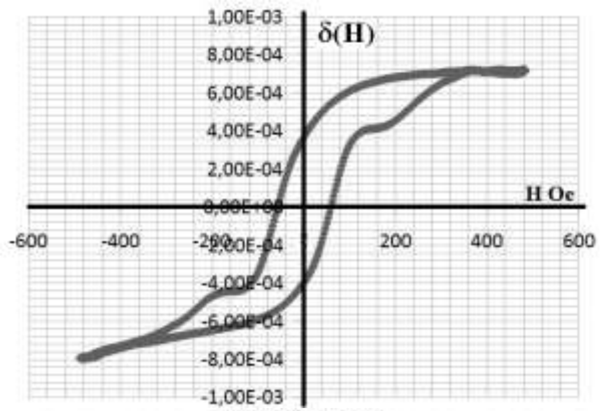

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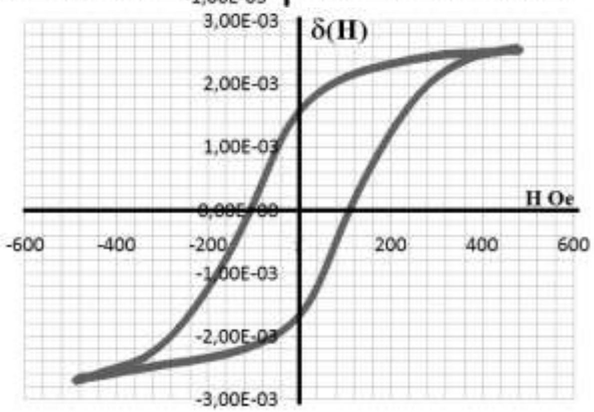
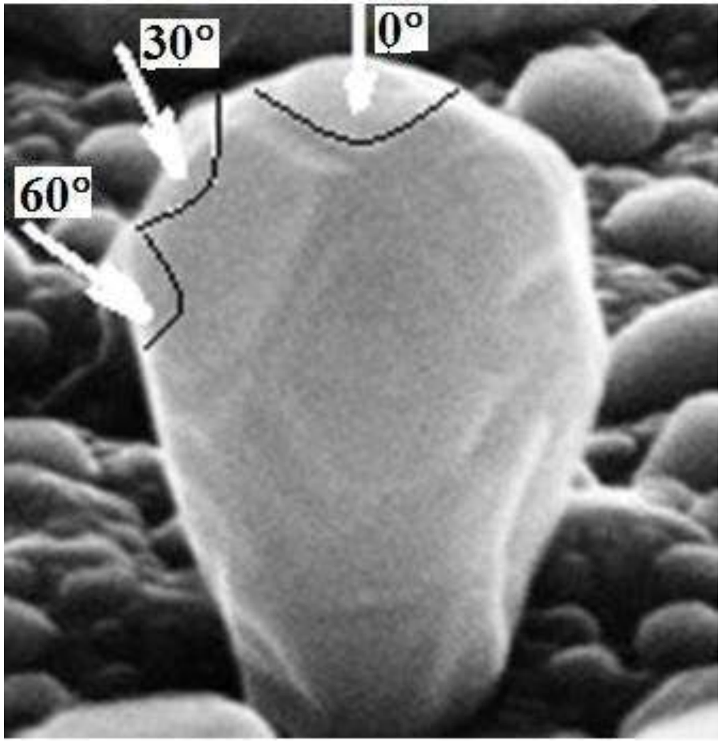




200 нм

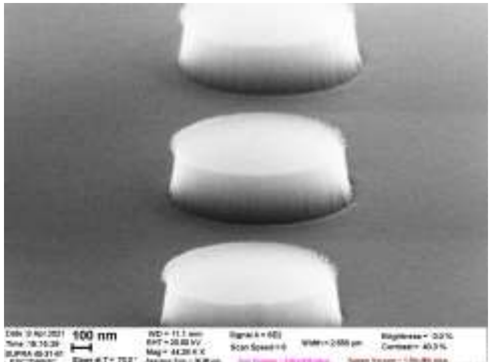
Figure 4. **Magneto-optical hysteresisl oops That were obtained for different angles of incidence for *PbSe:***

30° – (a), 52.5° – (b), 65° – (c)

The loop «*b*» corresponds to the presence of vortices In the system.

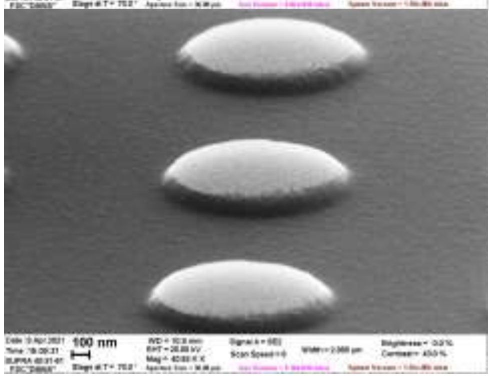
STRUCTURES ON THE BASE OF SiO2 WITH DEPOSITED *Co* NANOLAYER

a



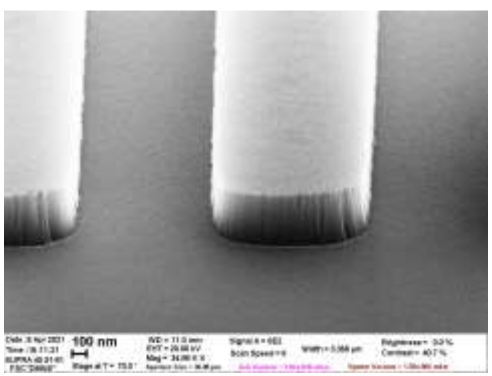
200 nm

b

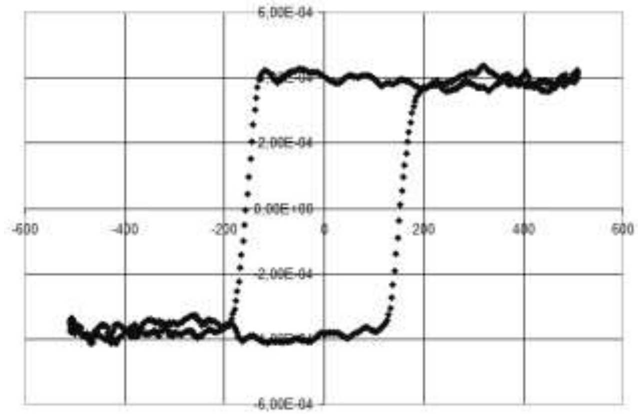


200 nm

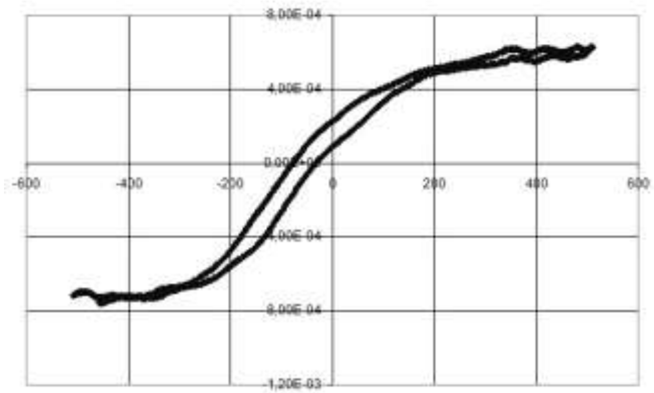
c



200 nm



d



e

Figure 5. **Magneto-optical hysteresis loops that were obtained on the structures of the stripe type (see Fig. *c*): magnetic field was applied along a stripes – (d), magnetic field was applied perpendicular to the stripes.**

TWO-SOLITON APPROXIMATION OF SKYRMION SOLUTION

(*)

$$\theta(\rho,c,w)=\begin{cases}\sum\limits_{+,-}\left[\arcsin\left(th\left(\dfrac{-\rho\pm c}{w/2}\right)\right)\right]+\pi, & B_z>0\\ \sum\limits_{+,-}\left[\arcsin\left(th\left(\dfrac{-\rho\pm c}{w/2}\right)\right)\right], & B_z<0\end{cases}$$

$$\rho=\sqrt{x^2+y^2}$$

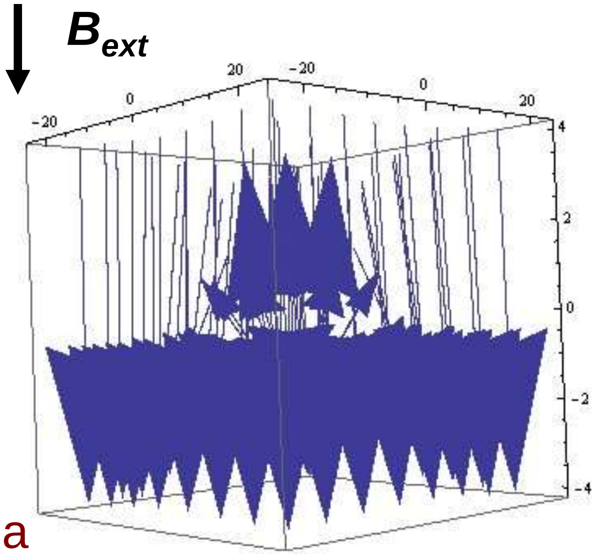
is radial distance from the center of skyrmion position, B_z is an induction of magnetic field along a OZ axis, *w* parameter which determines a size of skyrmion (2D skyrmion) is determined according to the expression:

$$w=2\cdot\sqrt{\frac{A_{ex}}{K_{eff}+M_sB/2}}$$

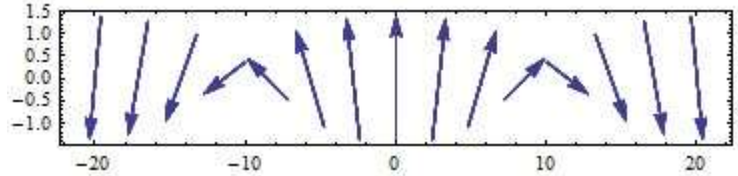
$$c=\frac{w}{2}\operatorname{arcsin h}\left(\sqrt{\frac{2K_{eff}}{M_sB}}\right)$$

where A_{ex} is a constant of exchange interaction, K_{eff} – is an effective anisotropy constant, *Ms* is saturation magnetization. For cobalt crystal these values have an order of : A_{ex} = 1.3 10^{-11} J/m, K_{eff} = 4.1 10^5 J/m^3

MAGNETIC MOMENTS DISTRIBUTION FOR TWO-SOLITON APPROXIMATION



a

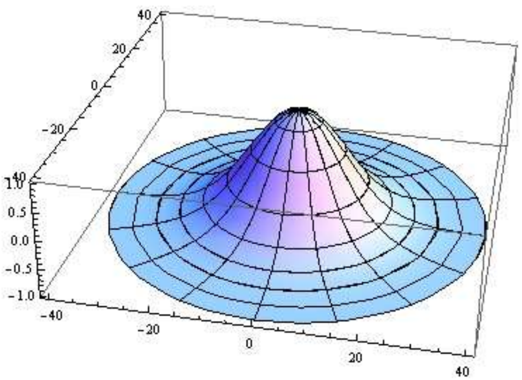


b

(**)

$$\vec{S}(x,y)=\begin{pmatrix} -\sin\left[\theta(\rho,c,w)\right]\cdot\left(x/\rho\right) \\ -\sin\left[\theta(\rho,c,w)\right]\cdot\left(y/\rho\right) \\ \cos\left[\theta(\rho,c,w)\right] \end{pmatrix}$$

- general formula for magnetic (spin) moments calculation



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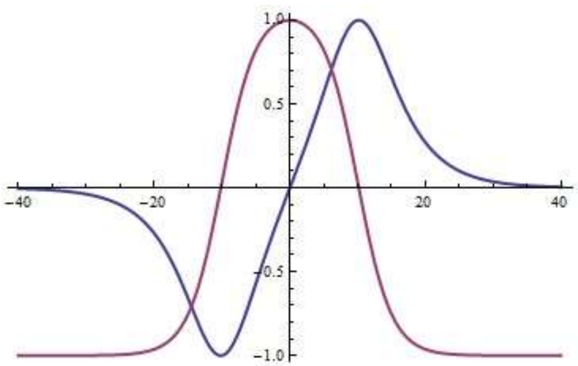


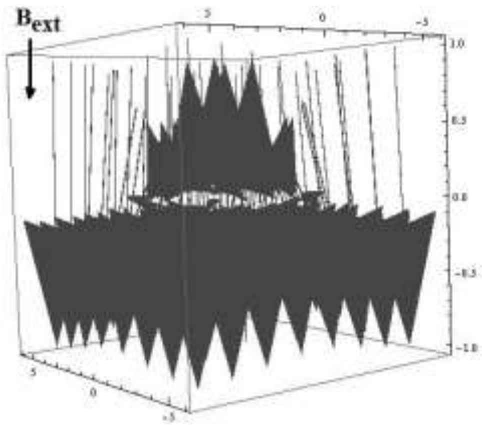
d

Figure 6. **General view of three dimensional image of 20×20 nm² region, which corresponds to the presence of magnetic vortex. The direction of magnetic field B_{ext} is shown. The calculations were carried out according to the formulae presented (*) and (**). a – general view of magnetic moments orientations, b – cross section of magnetic moments orientations, c – projection of magnetic moments on OZ axis, d – dependencies of magnetic moments projection on OZ (pink) and OX axis (blue).**

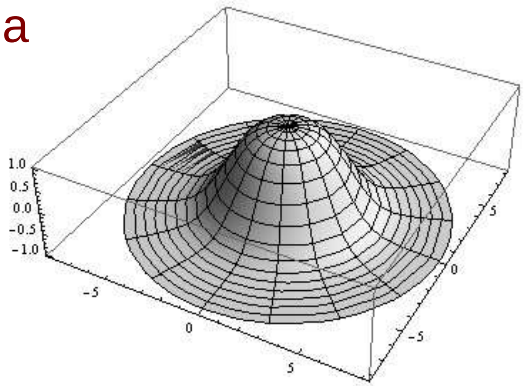
MAGNETIC MOMENTS DISTRIBUTION FOR TWO-SOLITON APPROXIMATION

Basic formula for chiral angle calculation in nuclear physics

(***) $$\theta = \pi - 2 \cdot \arctan\left[y\left(1 + b \cdot y^2\right)^{1/2} \right],$$



a



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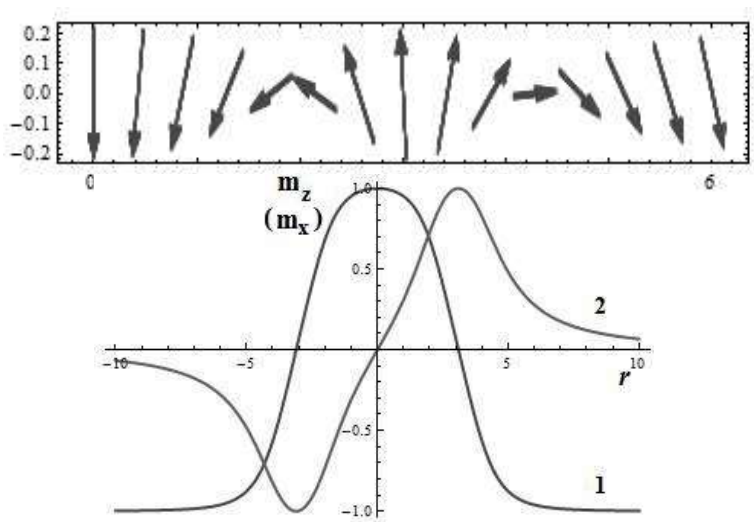


b

d

Figure 6. **General view of three dimensional image of 20×20 nm² region, which corresponds to the presence of magnetic vortex. The direction of magnetic field B_{ext} is shown. The calculations were carried out according to the formulae presented (**) and (***). a – general view of magnetic moments orientations, b – cross section of magnetic moments orientations, c – projection of magnetic moments on OZ axis, d – dependencies of magnetic moments projection on OZ (1) and OX axis (2).**

LANDAU-LIFSHITZ EQUATIONS FOR MAGNETIC (SPIN) MOMENTS

Simulations on the base of Landau-Lifshitz equations

$$\frac{d\vec{M}}{dt} = -\gamma \vec{M} \times \vec{H}_{eff} - \frac{\gamma\alpha}{M_s} \vec{M} \times \left(\vec{M} \times \vec{H}_{eff} \right)$$

$$\vec{H}_{eff} = -\mu_0^{-1} \, \partial E \big/ \partial \vec{M}$$

**** $$E = -J \sum_{\langle i,j \rangle} \vec{M}_i \cdot \vec{M}_j + \sum_{\langle i,j \rangle} D_{ij} \left(\vec{M}_{\boldsymbol{i}} \times \vec{M}_{\boldsymbol{j}} \right) - \mu_0 \vec{H} \sum_{\boldsymbol{i}} \vec{M}_{\boldsymbol{i}} - \frac{1}{2} \mu_0 \sum_i \vec{M}_{\boldsymbol{i}} \cdot \vec{H}_{\boldsymbol{d}}$$

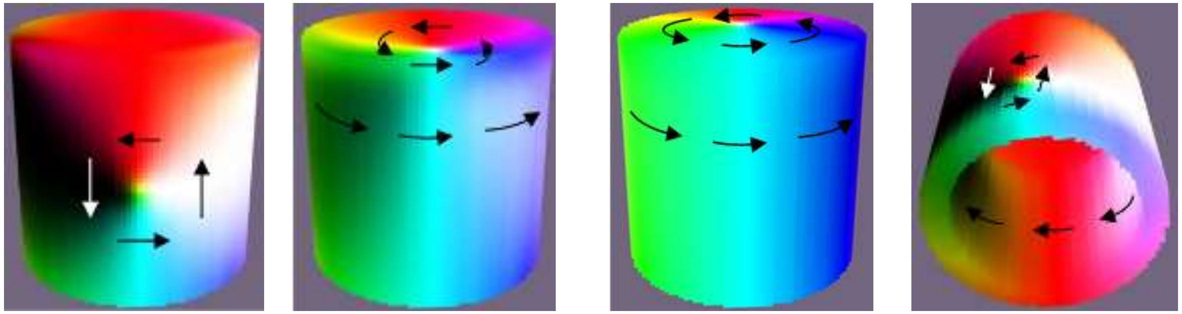
where *J* is exchange constant, D_{ij} is parameter of Dzyaloshinskii-Moriya interaction,

***M* is a magnetization of i-*th* element of a mesh (i-*th* cell)**

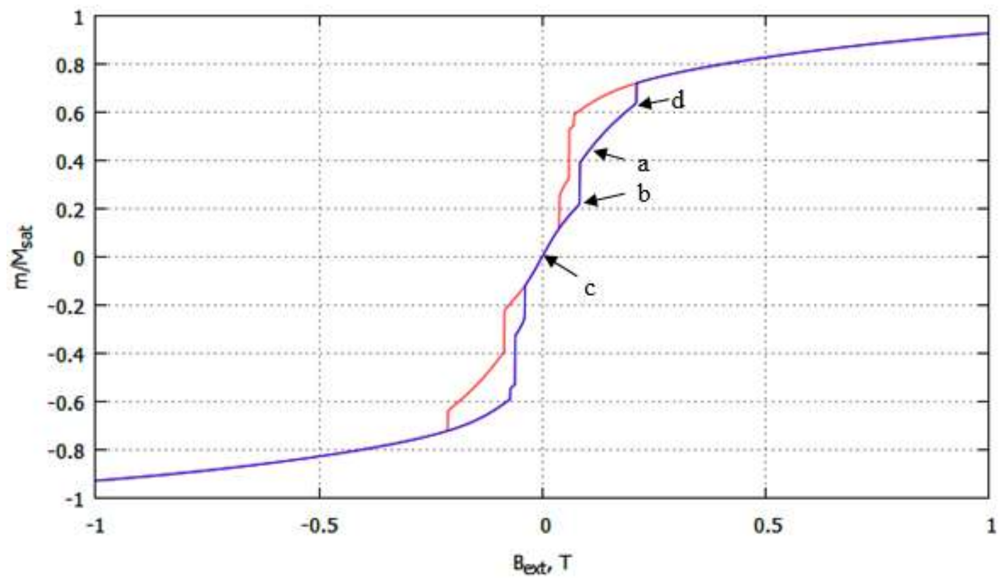
***H* is a vector of magnetic field strength,**

H_d – is a vector of demagnetization.
Another kind of energy can be added into expression (****),
for example, anisotropy crystal energy.

RESULTS OF COMPUTER SIMULATIONS ON THE BASE OF LANDAU-LIFSHITZ EQUATION



a b c d



e

Figure 8. **Vortex magnetic structure on cylindrical surface with flat top without anisotropy (a-d) against applied magnetic field (simulation in MuMax3).Magnetization reversal that corresponds to the structures on (a-d) – (e).**

RESULTS OF COMPUTER SIMULATIONS ON THE BASE OF LANDAU-LIFSHITZ EQUATION

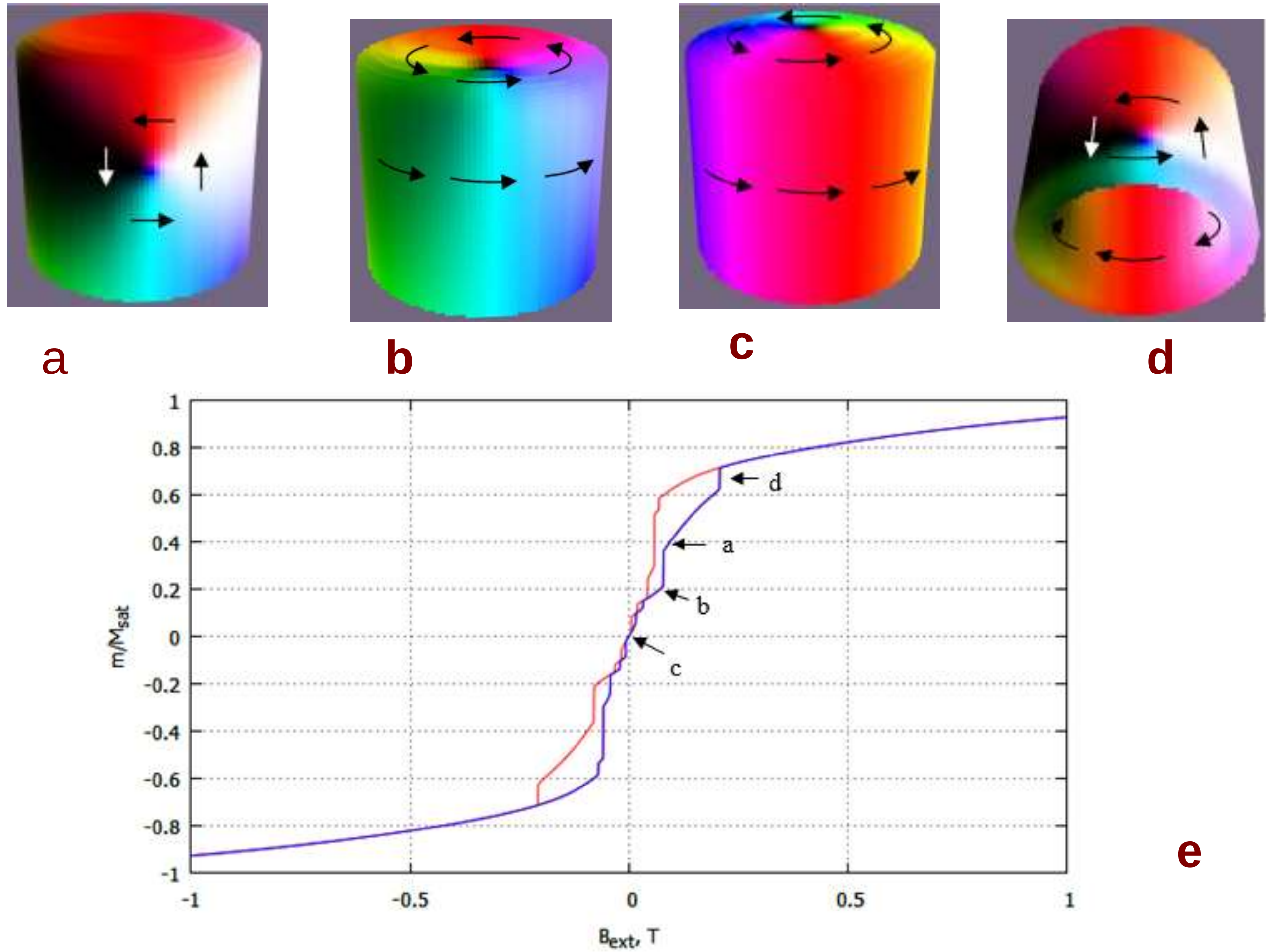


Figure 9. **Vortex magnetic structure on cylindrical surface with convex top without anisotropy (a-d) against applied magnetic field (simulation in MuMax3).Magnetization reversal that corresponds to the structures on (a-d) – (e).**

RESULTS OF COMPUTER SIMULATIONS ON THE BASE OF LANDAU-LIFSHITZ EQUATION

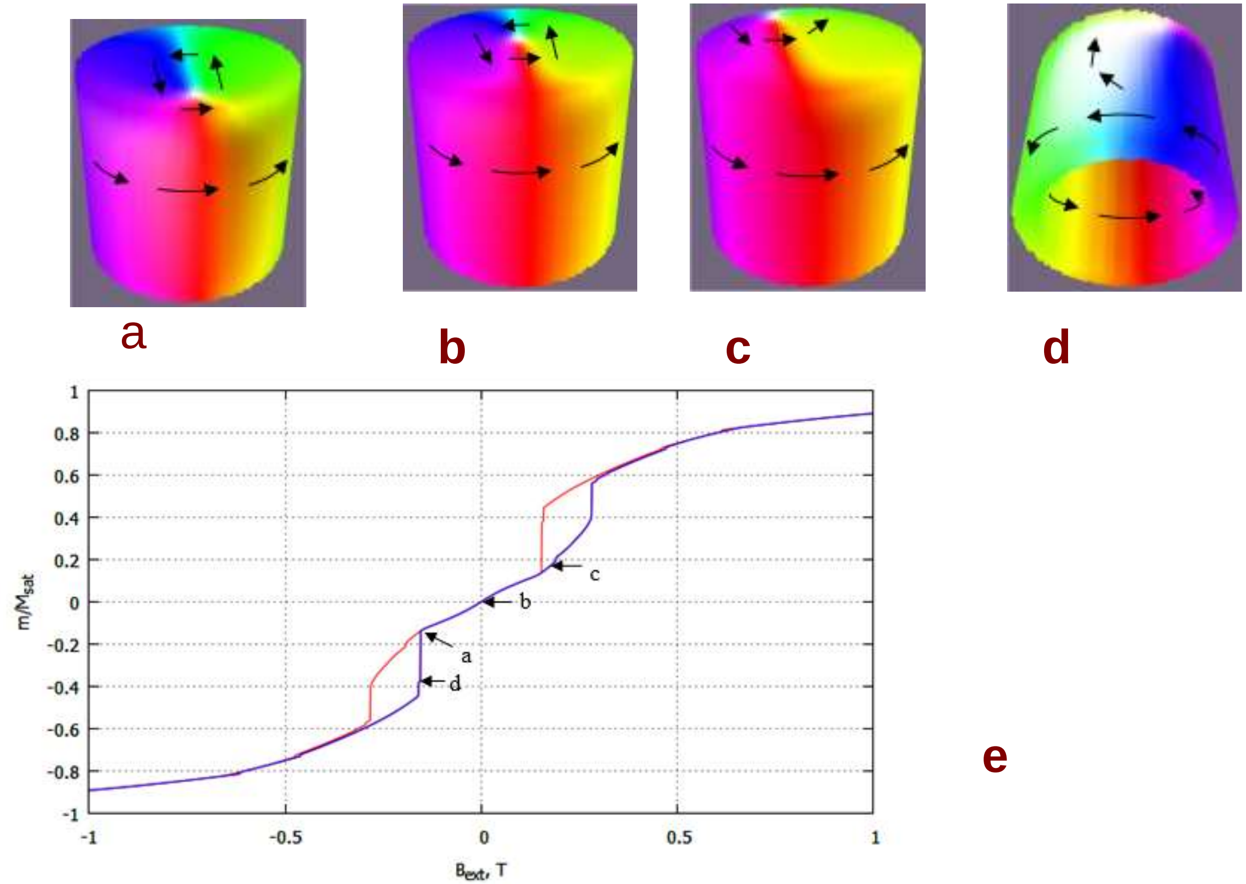
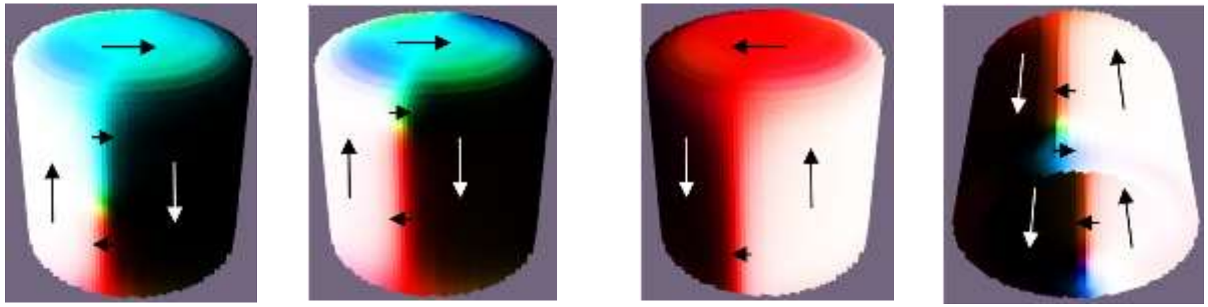
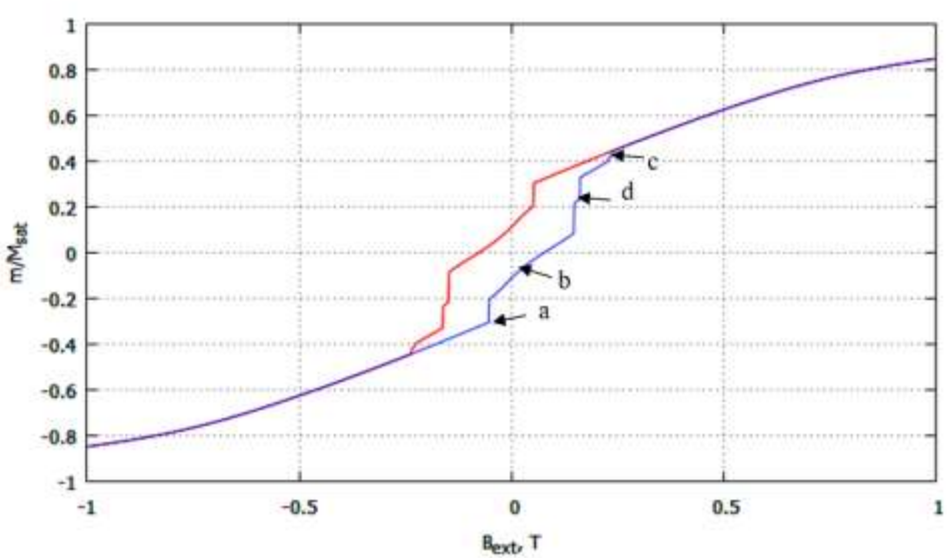


Figure 10. **Vortex magnetic structure on cylindrical surface with flat top with anisotropy (0,1,0), K = 4.4·10^{5} J/m^{3} – (a-d) against applied magnetic field (simulation in MuMax3). Magnetization reversal that corresponds to the structures on (a-d) – (e).**

RESULTS OF COMPUTER SIMULATIONS ON THE BASE OF LANDAU-LIFSHITZ EQUATION



a b c d



e

Figure 10. **Vortex magnetic structure on cylindrical surface with convex top with anisotropy (0,0,1), К = $4.4 \cdot 10^5$ J/m^3 – (a-d) against applied magnetic field (simulation in MuMax3). Magnetization reversal that corresponds to the structures on (a-d) – (e).**

EVALUATIONS OF ENERGY LOSSES ON MAGNETIZATION REVERSAL

$$E_{vor} - E_0 = \pi n^2 J \ln(R/a)$$

where E_0 is an energy of ground state in a ferromagnetics,
$E_0 = 2JN$, n = 0, 1, 2, …,
J is an exchange integral, R is a characteristic size of a system,
a – is a distance between atoms.

$\varepsilon = \oint \vec{H} d\vec{B}$ **are specific energy losses on magnetization reversal.**

For pure cobalt film with the thickness of 10 nm evaluations give the value $\varepsilon_{Co} \approx 23 \cdot 10^3$ J/m^3

Evaluation of specific energy losses for magnetization reversal in the presence of magnetic vortices has an order of $\varepsilon_V \approx 41 \cdot 10^3$ J/m^3.

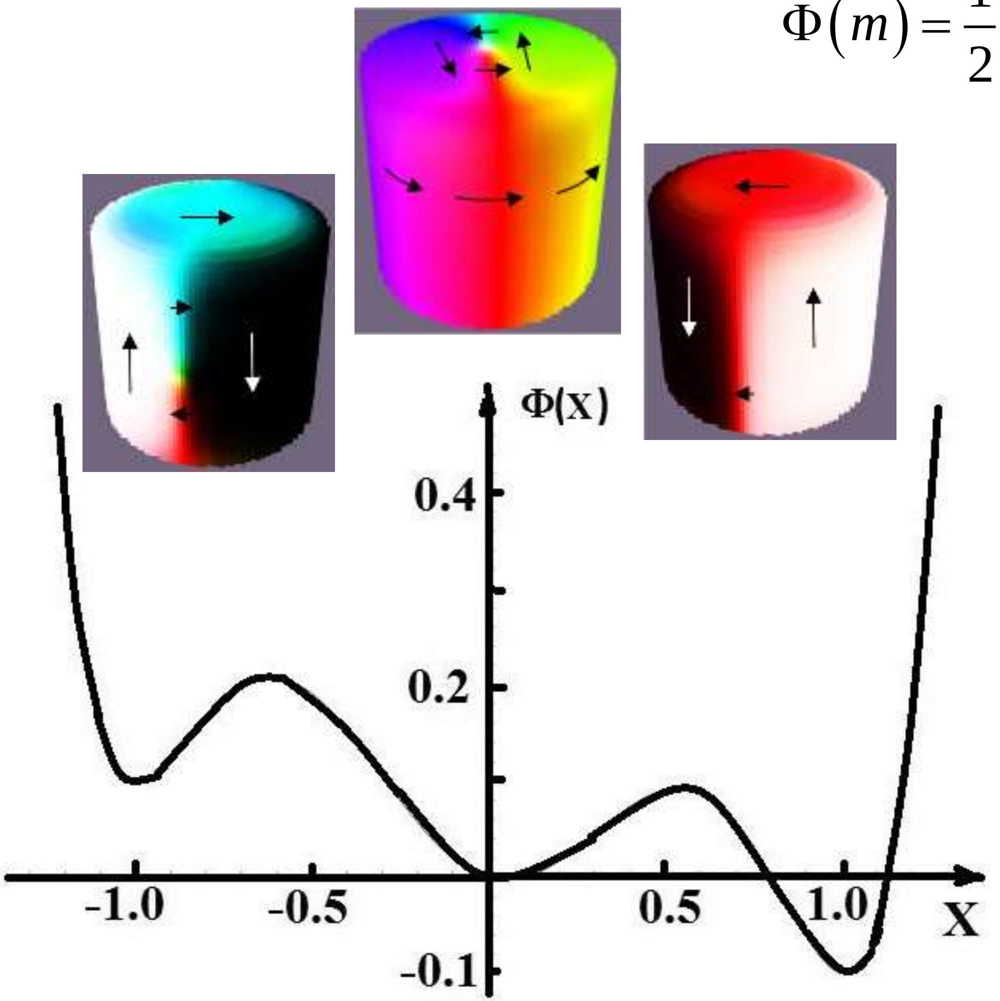
Evaluation of specific energy losses for magnetization reversal without the magnetic vortices has an order of $\varepsilon \approx 61 \cdot 10^3$ J/m^3.

ТЕРМОДИНАМИЧЕСКИЙ ПОТЕНЦИАЛ И СООТВЕТСТВУЮЩИЕ МАГНИТНЫЕ СТРУКТУРЫ

$$\Phi(m) = \frac{1}{2}a(T)m^2 + \left(\frac{1}{4}b - \frac{\lambda^2}{2K}\right)m^4 + \frac{1}{6}cm^6$$

$$\left(\frac{1}{4}b - \frac{\lambda^2}{2K}\right) > 0$$

$$\left(\frac{1}{4}b - \frac{\lambda^2}{2K}\right) < 0$$



K is an elastic modulus,
λ is a connection coefficient,
b is a coefficient

Yang S., Ren X., Song X. Phys. Rev. B. 2008. V.78. P. 174427.

Figure 12. **Small magnetic fields**

THERMODYNAMIC POTENTIAL AND CORRESPONDING MAGNETIC STRUCTURES

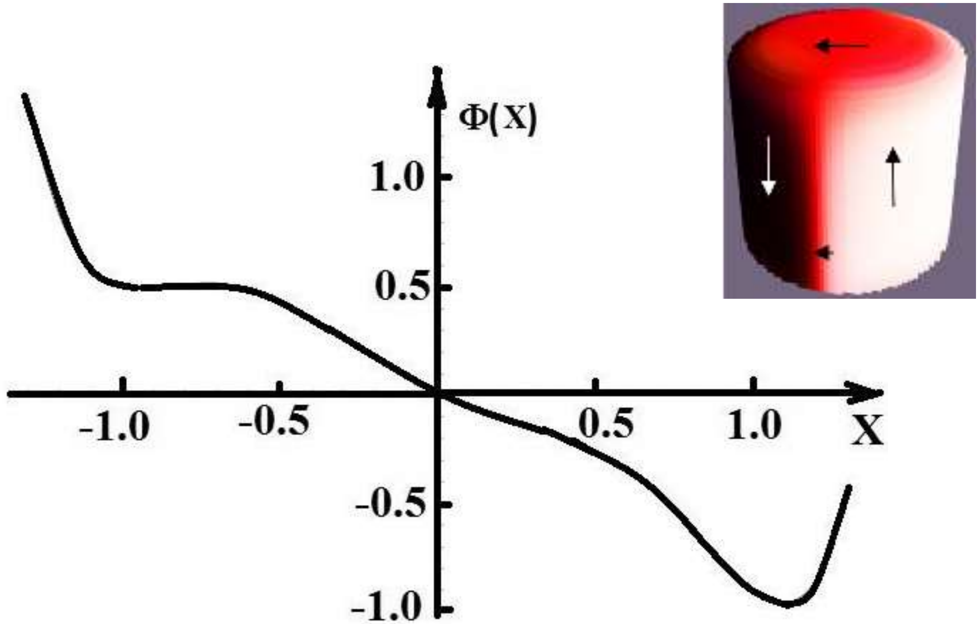


Figure 13. **Large external magnetic fields**

CONCLUSIONS

1. Normalized magneto-optical hysteresis loops, that were obtained at different Incident angles, for the structures with sizes less than 100 nm, are congruent.

2. For nanostructures on the base of PbSe at determined parameter values magneto-optical loops were obtained that are typical to the presence of magnetic vortices in the system.

3. For the sub-micron structures the displacement of hysteresis loops was observed which can be connected with the influence of interaction of the system elements with surroundings.

4. Two-soliton solutions approximations for skyrmion solution were obtained.

5. The position of magnetic vortex on a cylindrical surface depends on external magnetic field value.

6. Magnetization reversal at the presence of magnetic vortices occurs with less losses of energy then without magnetic vortices appearance.

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