Magnetization reversal of nanodots with different magnetic anisotropy and magnetostatic energy

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Abstract. The arrays of circle and square nanodots were prepared by Ga⁺ ion-beam etching of thing cobalt films with induced uniaxial magnetic anisotropy. The size of researched nanodots was \( d = 600, 450 \) and \( 250 \) nm that equal or less than radius of ferromagnetic correlation for continuous Co film. The distances \( l = 2d \) and \( 3d \) between center of nanodots in the arrays were taken. The interpretation of experimental magnetic force microscopy data was done by means of micromagnetic simulation and MFM-experiment simulation. Each nanodot of arrays with \( d = 600 \) nm has multidomain structure at demagnetisation state for \( l = 3d \) and magnetic vortex for \( l = 2d \). For arrays with size of element \( d < 600 \) nm and \( l = 2d \) and \( 3d \) at same condition occurred only vortex state.

1. Introduction

Magnetic nanoarchitectures today are very perspective object of research from application point of view. It can be used at the development of new devices for information storage [1], sensors and other elements on the base of magnetic logic [2]. For implementation of these appliances it is necessary the well understanding of the reversal magnetization processes, the origins of specific magnetic state and the influence of magnetostatic interaction between elements in the nanosystem. Nanomagnets in arrays with sizes from some microns to hundreds nanometers can have deferent magnetic states such as multidomain, “S” and “C” states, states with nonuniform magnetization such as vortex and others [3]. The magnetic state of single nanodot in array can depend from external magnetic field, magnetostatic interaction between neighbors, geometry shape of the array and it’s elements, from different types of magnetic anisotropy, properties magnetic material, etc. Cowburn et. al. [4] observed the transition from single domain to vortex state of nanodots in array of the permalloy nanodots at the variation of diameter to thickness ratio of nanodisk. The change of elliptic shape to disk in permalloy can attended by transition from single domain state to two-domain structure and vortex state at variation of eccentricity value [5]. The magnetic structure Landau-Lifshits with four 90° and one 180° boundaries was observed in thin film rectangular permalloy elements with size of some tens micron. The magnetocrystalline anisotropy [6] and induced magnetic anisotropy [7] play important role in the reversal magnetization process of nanomagnets additionally to shape anisotropy. Jubert and Allenspach [8] with help of theoretical analysis and numerical simulation found that these two type of

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anisotropy in the absence of shape anisotropy and in dependence of the ratio of diameter to thickness can move line of transition between single domain state and vortex. In this work the processes of magnetization reversal and formation of magnetic structure for the arrays of circle and square Co nanodots with different period between there and sizes of elements and with induced uniaxial magnetic anisotropy were investigated.

2. Experimental technique
The Co films with thickness 10 nm were deposited in ultrahigh vacuum $P = 10^{-10}$ Torr on naturally oxidised monocrystals (100) Si from diffusion cells at room temperature. From above Co film was covered with 3 nm layer of Cu for the prevention of oxidation. Then the arrays of square and circle nanodots were prepared from Co films by focused beam of Ga$^+$. The estimated deep of etching was 50 nm. The raster images of circle and square holes onto scanning field was used by way of mask during etching. Ion current of gun at the etching varied from 2 pA to 20 pA, and diameter of ion beam was varied from 10 to 17 nm in depending of formed nanodot size. Minimal size of element on images was interval from 10 to 30 nm, that was more than size of ion beam. In this case was raster image with rectangle in centre which one closed nanodots array from ion beam. For controlling of formation process was used scanning electron microscope with increment from 7000 to 25000.

The structure of films and arrays was investigated by means of reflection high energy electron diffraction (RHEED), transmission electron microscopy (TEM), scanning electron microscopy (SEM) and atomic-force microscopy (AFM).

The magnetic hysteresis loops of nanodots array were measured by means of longitudinal magnetooptic Kerr effect (NanoMOKE-2). The method of magneto-force microscopy (MFM) was used to obtain the images of magnetic structure and hysteresis loops of individual nanodots. The micromagnetic simulation of magnetic moment distribution in nanodots was made by means of program package The Object Oriented MicroMagnetic Framework (OOMMF) [9], which one uses Landau-Lifshits-Hilbert formalism. The correctness of micromagnetic simulation was collaborated by simulation of MFM-experiment in frame of model magneto-hard tip by means of author program package.

3. Result and discussion
An RHEED patterns showed that Co films was polycrystalline. The mean size of grain is 6 nm from TEM measurements. The loops of magnetic hysteresis showed presence of pronounced uniaxial induced magnetic anisotropy, which one was formed by inclined incidence of molecular beam at deposition. The coercive force of Co films is $H_c=18$ Oe, the anisotropy field is $H_a=40$ Oe ($K_a=H_aM_s/2\approx3*10^4$ erg/cm$^3$, where $M_s=1400$ G – saturation magnetization, which one was measured by SQUID magnetometer at the precision 50 G).

In nanocrystalline ferromagnetic films the effect of magnetization vector oscillation appears on the score of the random orientation of local crystallographic anisotropy in grains and magnetostatic interaction. This one leads to appearance of thin magnetic structure (magnetization ripple). For such films it is possible to enter the ferromagnetic correlation radius $R_i$ [10] which one can be determined from experiment as a period of short-wave magnetization ripple $\lambda_{ss}$ on images of thin magnetic structure. The short-wave component of magnetization ripple in researched films was measured from MFM images of a domain structure $R_i=\lambda_{ss}\approx600$ nm. Therefore the circle and square nanodots Co arrays with $d=600; 450$ and $250$ nm (i.e. $d\leq R_i$) were prepaid from polycrystalline films with pronounced uniaxial in-plane magnetic anisotropy. 10x10 nanodots were in each array. Magnetic properties of one nanomagnet in array have strong dependence from period $l$ (the distance between the centers of nanodots). As it was showed in [7] at $l=3d$ nanodisks practically have not interaction between each other, and the magnetostatic (dipole-dipole) interaction became essential at $l=2d$. In researched array period was $l=3d$ and $2d$. 

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At figure 1 (a, b and c) the MFM-images, configuration of magnetization from micromagnetic simulation and results of MFM experiment simulation for square nanodots of array with $d=R_f$ and period $3d$ in dependence from external magnetic field are shown. The external magnetic field was oriented along induced easy magnetization axis. In the micromagnetic simulation following parameter were used: a saturation magnetization $M_s=1400$ G, a constant of exchange interaction $A=2*10^{-6}$ erg/cm, a constant of induced uniaxial magnetic anisotropy $3*10^{-4}$ erg/cm$^3$, and the size of unit cell 6 nm, which one corresponds to the average film grain size. In a simulation of MFM experiment the ratio between nanodot and tip sizes was the same as in physical experiment.

From figure 1 it is visible that the decreasing of external magnetic field from the negative saturation value to the positive, the square nanodot has sequential transitions from single domain state ($H=-500$ Oe) to ‘S’-state ($H=-150$ Oe), ‘C’-type state ($H=-120$ Oe), which one transforms to four domain configuration ($H=30$ Oe). The simulation results obtained that sizes of domains unequal. The size is more for domains where vector of magnetization is collinear to the direction of induced easy magnetization axis, than for domains where magnetization is orthogonal to easy axis (figure 1b, $H=30$ Oe). There is light area with ‘cross’ type in the centre of square nanodot. Such distribution of the MFM-contrast can take place if there is small component of magnetization vector ($M_z/M_s\approx 0.01$), which one has orthogonal direction to sample plane. We supposed that presence of perpendicular component connect with cone like shape of nanodot, and it was confirmed by SEM and AFM.

On figure 2a is MFM-image of 4-domain structure of array part in field $H=30$ Oe. The magnetization of nanodots has different ‘chirality’ figure 2b and 2c (for example, the highest and the bottom-most MFM-images of array) on dependence from magnetization direction in C-state.
The magnetic loop square nanodots array, which one was obtained by micromagnetic simulation ‘figure 3b’, has qualitatively and quantitatively corresponds to hysteresis loop of longitudinal magneto-optical Kerr effect ‘figure 3a’. The jumps of magnetization on hysteresis curves correspond to the transitions ‘S’→‘C’→4-domain state and backwards. But the magnetic fields, in which ones the transition from one magnetic state to another takes place for single nanodot and for total array can be different. This one can be explained by asynchronous processes of array nanodots magnetic reversal ‘figure 2a’ and by presence of magnetic states with opposite chirality of magnetization.

![Figure 3](image.png)

**Figure 3.** The magnetic hysteresis loops for array of square nanodots $d=R_f$ and with period $l=3d$ which ones was obtained: (a) – MOKE, (b) – micromagnetic simulation, (c) – from MFM-images for single nanodot.

The recent research [7] of circle nanodots arrays with $d=R_f$ and period $l=3d$ showed that two-domain configuration generate at demagnetization state.

The MFM experimental data, micromagnetic simulation and MFM experiment simulation for circle and square nanodots arrays with $d=R_f$, $l=2d$ and $d<R_f$ showed that magnetization reversal carry out as with the formation of the vortex states with the vector of magnetization which one is orthogonal to the nanodot plane in core ‘figure 4.’

![Figure 4](image.png)

**Figure 4.** MFM image of vortex state of circle nanodot from array with $d=450$ nm at demagnetization state (a), micromagnetic simulation (b), MFM experiment simulation (c).

As shown the MOKE measurements the magnetic loops had the hysteresis. The hysteresis in such arrays was caused by existence of induced magnetic anisotropy and probably by the presence of uniform rotation of magnetization vector in nanodots at changing of external magnetic field. For arrays with $l=2d$ critical field of reversal magnetization and saturation field more than for arrays with $l=3d$, that explained by gaining of magnetostatic interaction at the decreasing of $l$. The pronounced core of vortex on MFM-images of circle and square elements of arrays with $d<R_f$ probably, caused by with cone-like shape of nanodot, which one depend on the fabrication method. SEM and AFM images testify to it: the shape of nanodots is truncated cone-like. For small size of nanodot this geometry stands more pronounced that one evidence by research of MFM-images, where the vortex core was more stable and it can be observed in more wide range of external magnetic field. By the indirect evidence of this can be the fact that decreasing of nanodots sizes leads to increasing of switching magnetic field value. It need to say that the analysis of MFM images let us to find only two from four possible types of vortex.

The Hamiltonian for polycrystalline nanodots is $E = E_{\text{ex}} + E_{\text{an}} + E_{\text{ms}} + E_z$, where $E_{\text{ex}}$ – the exchange energy, $E_{\text{an}}$ – energy of uniaxial induced magnetic anisotropy, $E_{\text{ms}}$ – magnetostatic energy, $E_z$ – energy of nanodots in the external magnetic field. The calculation of magnetostatic energy is very complicated task, but for case of uniform magnetization of disk...
The dependence of saturation field $H_s$ of square (empty squares and dotted curve) and circle (black circle and dashed straight line) nanodots and demagnetization field $H_N$ of ideal nanodisk (solid curve) from size of nanodots.

$$ E_{mc} = \frac{1}{2} NM_s^2, $$ (1)

where $N$ – demagnetization factor in-plane of disk. If ratio between thickness and diameter of disk more less then unity

$$ N = \frac{t}{\pi d} \left[ \ln \left( \frac{d}{t} \right) - 0.5 \right], $$ (2)

where $t$ – thickness of disk [9].

On the ‘figure 5’ are dependence of saturation field $H_s$ and demagnetization field $H_N$ in dependence from their sizes. It is visible that the behavior of both $H_s$ and $H_N$ is identical and independent from nanodots shape. The deviation of behavior of experimental curve from theoretical, especially for square shape nanodots, is caused rather by real shape of nanodots, which one of course is differ from ideal disk. Under the ideal nanodisk we understand the disk for which the ratio of a thickness to diameter is much less than unit and defects of form are not considered.

The saturation field (the external magnetic field in which the sample is magnetized completely) develops of an internal field direct influencing orientation of the magnetic moments and demagnetization field. On ‘figure 5’ the dependence of a saturation field (it is received experimentally) for circle and square nanodot arrays and a demagnetization field for an ideal nanodisk (is received from the analytical formula) is resulted.

At the $d<R_f$ demagnetization energy of nanodot in array increases and stands more than energy of induced magnetic anisotropy, therefore at zero external magnetic field in given nanodots magnetic vortex was generated. The similar situation is in case of nanodots with $d=R_f$ at decreasing of array period from $l=3d$ to $l=2d$, as far as energy of dipole-dipole interaction between nanodots in array increases.

4. Conclusions

The arrays of circle and square ferromagnetic ultrathin nanodots were investigated. Source Co films have pronounced magnetic induced anisotropy to which one added the shape anisotropy (truncated cone) at ion beam etching. Vortex state of all nanodots in array is possible at $E_c=0$, if energy of induced iniaxial magnetic anisotropy less than energy of dipole-dipole interaction and magnetostatic energy single nanodot in arrays. The competition between energy of induced magnetic anisotropy and energy of shape anisotropy at decreasing of nanodot size can be used as control factor for generation definite magnetic state.

It is known from the literature, that in circle and square nanodots with diameter of less micron are observed either a vortex or single-domain state, and there is no accurate criterion of transition from these states in the multidomain state. Also there is a number of theoretical works where influence of magnetic anisotropy on transition from one magnetic state in another is calculated at change of geometrical parameters of nanodot. Our paper shows that even in the presence of the induced magnetic anisotropy the transition from a multidomain state in the vortex occurs at diameter of a nanodot (and round and square) equal to radius of ferromagnetic correlation of a continuous Co film, that is caused by increase magnetostatic energy (the reduction of the nanodot size or distances between them in the array). The nanodots which size is equal to radius ferromagnetic correlation reverse magnetization with formation of a multidomain state (for circle nanodot - a two-domain state, for square - four-
domain). Both circle, and square nanodots which size is less than radius of ferromagnetic correlation, reverse magnetization through formation, displacement and annihilation of a magnetic vortex.

Also we have found that the used by us conditions of a preparation (FIB) of the truncated form of nanodot are causes the domination only two types of a magnetic vortex with different chirality of magnetization.

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