JOURNAL OF NANO- AND ELECTRONIC PHYSICS
Vol. 7 No 1, 01010(3pp) (2015)

ЖУРНАЛ НАНО- ТА ЕЛЕКТРОННОЇ ФІЗИКИ
Том 7 № 1, 01010(3cc) (2015)

Two Approaches in Computer Simulation of the MFM-images

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(Received 03 December 2014; revised manuscript received 10 March 2015; published online 25 March 2015)

Two approaches to the interpretation of the data of magnetic force microscopy are considered. The first approach involves the reconstruction of the magnetization distribution in the researched samples on the base of an assumption about the magnetic state and the subsequent numerical magnetic force microscopy experiment. The second is related to an experimental data processing.

Keywords: Scanning tunneling microscopy, Magnetic force microscopy.

PACS numbers: 75.10.Nr, 75.50.Lk, 68.18.Jk, 11.15.Ha

1. INTRODUCTION

The single magnetic nanodots and it's ordered arrays are interesting both from a fundamental and from a practical points of view, as far as they could be applied in a high capacity recording medium. The magnetic nanoarrays potentially could be used for the production of a random access memory (MRAM) and high integrated magneto-electron devices [1-4]. The abrupt progress of informational technologies is obviously caused by the achievements also and in research of magnetic particles [5-7]. It is probably, that in the future the magnetic logic devices will be constructed with using of magnetic nanoarchitectures.

The construction of magnetic logic elements of nanoscale superstructures is impossible without a detailed understanding of it's magnetic states nature. One of the most important problems leaves the interpretation of experimental magnetic force microscopy (MFM) data. The authors of this work have used computer model of magnetic force microscopy experiment [7] and elaborated the original software package.

In recent years, there has been significant progress, both experimental and theoretical studies of nanostructures using magnetic force microscopy. However, many open questions need to be addressed in the application of this method. In particular, the influence of the magnetic tip on the magnetic state of the nanoobject [9], the scattering of the useful signal in the measurement process, atom rearrangements induced by short range interactions between tip and sample [10-12], etc.

For the interpretation of MFM-images and for determination of the magnetic state the numerical simulation of MFM-experiment was used. The dummy nanodot is divided on magnetic subareas (macrospins), which ones interact with the magnetic tip by magnetostatically, i.e. by means of dipole-dipole law. Such virtual experiment could give the understanding of the experimental MFM-images. The method can be used for interpretation of magnetic states of single nanoparticles, and in principal for understanding of magnetic phenomena in 1D arrays, 2D and quasi-2D arrays. The possibility of the nanodots magnetic states reconstruction by the space distribution of gradient dipole-dipole interaction force is theoretically justified.

2. EXPERIMENTAL TECHNIQUES

The 10 nm films of cobalt were deposed in ultrahigh vacuum 10^{-10} Torr on naturally oxidized monocrystals (100) Si at room temperature. Co-film was covered with 3 nm layer of Cu for the prevention of oxidation. A more detailed description of the preparation samples method interested reader can find in the work [8]. The method of magneto-force microscopy (MFM) was used to obtain the images of magnetic structure of the individual cobalt nanodots. The correctness of the interpretation of a magnetic state was corroborated by simulation of MFM-experiment in frame of the model magneto-hard tip by means of author program package. The model assumes the segmentation of a sample and MFM-tip on N_s and N_t magnetic dipole (magnetization vectors), correspondently. Each element of tip discretization interacts independently by magneto-statically with all discretization elements of a sample, and vice-versa.

2.1 MFM-Experiment and Simulation

Fig. 1a is shown MFM contrast obtained experimentally for cobalt nanodots. Fig. 1b is the assumption about the nanodot magnetic state and Fig. 1c simulated MFM contrast, respectively. The distribution of the magnetic vectors in nanodots built in a single layer.

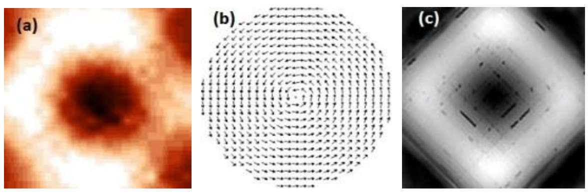

Fig. 1 – Interpretation of data for physical MFM-experiment (a), as vortex magnetic state of circle Co-nanodot by means of micro magnetic simulation (b) and numerical MFM-experiment (c)

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The calculation of the magnetic moments of the two layers leads to contradictory results, disagreement with the experimental data.

The distribution magnetization Fig. 1a corresponds to the magnetic moments of the magnetic vortex state. For all vectors of the magnetic moments z-components are altered. The value of z-component increases from the edges of nanodisk and achieves the maximum value at the center.

For more accurate and reasonable simulation of magnetic properties of nanodots, obviously, it need have the accurate information about the geometric shape not only.

2.2 Inverse problem

The attempt to solve the inverse problem – the problem of reconstruction the distribution of magnetic moments on the basis of the known magnetic force contrast has led to an ambiguous result, Fig. 2a-c. It is known that experimental MSM contrast shown in Fig. 2a must corresponds to the single-domain state.

Co-nanodot is in an external magnetic field, the value of which was greater than the saturation magnetic field for a given material. Interesting that instead of a uniform state and single domain distribution of the magnetization vectors in the direction with a pronounced magnetic-force contrast, surprisingly, we received a strange evidence of the presence of two vortices, Fig. 2c.

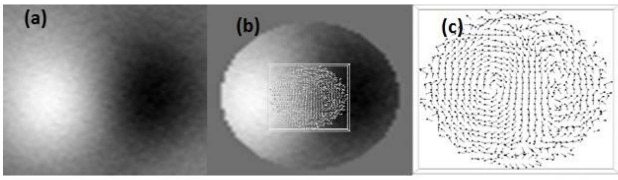

Fig. 2 – The possible solution of inverse problem (c) for experimental MFM image (a) of the cobalt nanodots $d = 600$ nm in array with period $3d$ in the saturation external magnetic field

This unexpected result may be due to the presence of assumptions and errors in the determination of the geometric border points, and oversized model nanodots. It will be showed below, that if the magnetic moments are distributed on the surface of the sample, there are no serious obstacles, however, it is possible the existence of technical troubles, for solving the inverse problem of magnetic force microscopy. Need to note, that the obtained results do not contradict the results of other researchers [13-14], as far as the simulation of the surface magnetic charges is used.

3. MATHEMATICAL MODEL AND INVERSE TASK

In the paper [7] it was described the algorithm of computer simulation of magnetic-microscopy images (MFM-images) on the Braun formalism. The phase shift

$$\vartriangle\varphi \sim \frac{\partial F_{z_j}}{\partial z_j}\,, \qquad (1)$$

which was measured in experiment. It was proportional to gradient of force of magnitostatical (dipole-dipole) interaction between nanodots and tip.

$$\vec{F} = -\vec{\nabla} E = -\sum_{j}^{N_t}\sum_{i}^{N_s} \vec{\nabla}\vec{M}(\vec{r}_{ij})\vec{H}(\vec{r}_{ij})\,. \qquad (2)$$

Energy of interaction for magnetic dipole system

$$E = \sum_{j=1}^{N_t}\sum_{i=1}^{N_s}\left(\frac{m_{xj}m_{xj} + m_{yi}m_{yj} + m_{zi}m_{zj}}{r^3_{ij}} - \right.$$
$$\left. - \frac{3(m_{xi}x + m_{yi}y + m_{zi}z)(m_{xj}x + m_{yj}y + m_{zj}z)}{r_{ij}^5}\right)_{i \neq j}.$$

In the case, when magnetic dipoles of tip have only nonzero z-component $m_{zj} = 1$, where $x = x_i - x_j$, $y = y_i - y_j$, $z = z_i - z_j$. The distribution of the gradient force interaction values in the space is defined by system of linear algebraic equations

$$\begin{cases} a_{11}m_{x1} + a_{12}m_{y1} + a_{13}m_{z1} + \ldots \\ + a_{1n}m_{xn} + a_{1n}m_{yn} + a_{1n}m_{zn} = grad_{zj}(F_1) \\ \ldots \\ a_{n1}m_{x1} + a_{n2}m_{y1} + a_{n3}m_{z1} + \ldots \\ + a_{nn}m_{xn} + a_{nn}m_{yn} + a_{nn}m_{zn} = grad_{zj}(F_n) \end{cases} \qquad (3)$$

Coefficients are controlled by the distance between given by magnetic moment (superspins) of tip $\{m_{zj}\}$ and magnetic moment of given discretization of sample $\{m_{xi}, m_{yi}, m_{zi}\}$.

If we know the values of the gradients, the system of linear algebraic equations is closed, i.e. the number of unknowns becomes equal to the number of equations. Thus, for sufficiently precise experimental measurements inverse problem may have a solution in case of surface distribution of magnetic charges.

4. SUMMARY AND CONCLUSIONS

The possible interpretation is done for magnetic states of single nanodots and quasi-2D nanoarchitectures in model of classical macrospins. Superposition of magnetic fields, which ones created by the system of the magnetic moments in given point of space, defines the linear dependence of dipole-dipole interaction force gradient of components magnetic vectors.

The consistency of linear system equations (3) is the evidence:

1) The uniqueness of the space distribution of force gradients values (MFM-contrast), for given configuration of magnetic moments;

2) The possibility of solution of inverse task – task of reconstruction of magnetic configuration over given experimental distribution of MFM-contrast for the planar magnetic structures.

AKNOWLEDGEMENTS

This work was supported by Program "Dal'niy Vostok", grant #15-I-4-038.

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