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Lorentz Microscopy of Permalloy Film Microdots

Vladimir S. Prokopenko*
Krasnoyarsk State Pedagogical University
Lebedevoy, 89, Krasnoyarsk, 660049,
Russia
Petr D. Kim†
Kirensky Institute of Physics, SB RAS,
Akademgorodok, 50/38, Krasnoyarsk, 660036,
Russia
Vitaly A. Orlov‡
Boris V. Vasiliev
Krasnoyarsk State Pedagogical University
Lebedevoy, 89, Krasnoyarsk, 660049,
Russia
Dmitry K. Vovk§
Sergey E. Zatsepilin¶
Kirensky Institute of Physics, SB RAS,
Akademgorodok, 50/38, Krasnoyarsk, 660036,
Russia
Roman Yu. Rudenko‖
Krasnoyarsk State Pedagogical University
Lebedevoy, 89, Krasnoyarsk, 660049,
Russia

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The results of an investigation into square permalloy film microdots with a quasivortical magnetic structure by the method of Lorentz electron microscopy are presented. The found before mechanism of the switching of microdot chirality in homogeneous plane magnetic field is discussed. The calculations are performed to evaluate the interaction of microdots under switching chirality.

Keywords: microdot, magnetic vortex, Bloch point, magnetic reversal.

Introduction

Micron and submicron magnetic objects such as ferromagnetic film micro- and nanodots are not only the subject of fundamental research but also they have practical applications. The interest to ferromagnetic nanodots is stimulated by their applications in various areas, for example,

*plufe@yandex.ru
†plufe@yandex.ru
‡orlhome@rambler.ru
§vovk.d@bk.ru
¶zacepilin@kspu.ru
‖rudenko-roma406@yandex.ru

in data storage and biomedical devices. The increase of density of data recording is possible by the use of a discrete magnetic medium which consists of the ordered set of isolated elements with almost closed magnetic flux in each element. When a film element has the form of a circle and has relatively small size the magnetic flux takes the form of a magnetic vortex. The structure of magnetization is circular in the film plane on the periphery of the element and magnetization is directed out of plane in the central region of the film element. The vortex core (Bloch point with magnetization directed perpendicular to the element plane) has the size about 10 nanometers. Depending on the magnetization direction in the vortex core ("up" or "down"), positive or negative vortex polarization is distinguished. Magnetic interaction of two or more vortices is much weaker than interaction of homogeneously magnetized bodies of the same form and volume. This feature allows the increase of density of information recording. The information storage ("0" or "1") by an element with vortical magnetic structure can be realized in two ways: by a sign of polarization ("up" or "down") or by direction of circular closure of the plane part of magnetic flux (the "right" and "left" chirality of an element).

One can exemplify two possible medical applications of ferromagnetic film micro- and nanodots. The first application is to use microdots as medication carriers in cancer treatment [1]. Water suspension which includes microdots covered with medication is inserted into a tumor. The external magnetic field results in movement of microdots and this increases the efficiency of the action of medication: in vitro experiments show that 80% of cancer cells die within 20-30 minutes in low-frequency magnetic field (several tens of hertz). The second application is to use microdots to clean blood of pathogenic microorganisms. Particles covered with antibodies to specific pathogenic microorganisms are inserted into patient blood. After that blood goes through a system with magnetic separation: magnetic particles with the attached microorganisms are extracted by magnetic field and the cleansed blood comes back to the patient.

1. Experimental data on magnetic reversal of microdots

The object of research in the real work were square film microspots in thickness of 30–60 nanometers. Samples turned out vacuum condensation steam an initial material (Permalloy 80Ni20Fe) on a transparent substrate for an electronic bunch (formvar) through a grid with square cells, and also photolithographic, from a continuous film. The magnetic structure of spots was visualized by a method of Lorentz microscopy [2] on electronic microscope UEMV-100A at accelerating tension of 100 kV.

For square spots the magnetic structure close to vortical (Fig. 1), but with a number of the features doing this form of a spot interesting in practical applications is characteristic.

The optical contrast displaying distribution of magnetization in a spot, arises thanks to a magnetic deviation of electrons when passing through a spot in the conditions of a small defocusing of the image. The spot with the closed magnetic stream operates, as a first approximation, as «a magnetic lens», collecting or disseminating, depending on the direction of short circuit of a stream in relation to an electronic bunch. On Fig. 1 a spot chirality such is (conditionally right is reproduced) that "lens" is appears collecting, the electronic bunch deviates to the spot center. The thin periodic structure in the image of a spot testifies to existence of "ripples" of magnetization, characteristic for polycrystalline films. Dark radially going lines is the low-angular (it is less 90^o) Neel's domain borders, in which crossing is a Bloch's point (a vortex core). The lines in space between spots show existence in these parts a weak sign-variable magnetic field that speaks about interaction of spots. As it will be shown further, important feature of magnetic

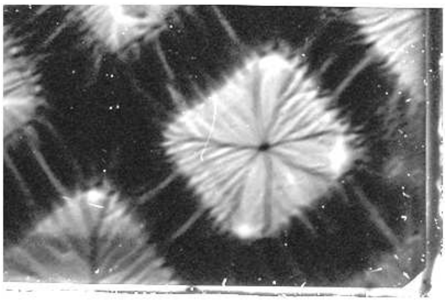


Fig. 1. Equilibrium domain structure of a square spot with the party of 20 microns (permalloy 80Ni20Fe, thickness of a film is $D = 60$ nanometers)

structure of a square microspot is existence in corners of a square of the light strips interpreted by us as borders of "nucleus" return (left in this case) chirality.

Prospective distribution of magnetization for a square microspot with quasivortical magnetic structure is given on Fig. 2.

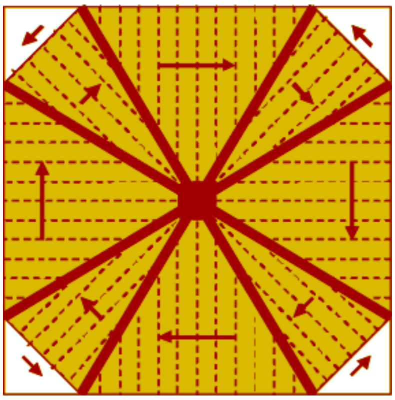


Fig. 2. Domain structure of magnetization of a microspot. Continuous fat lines in drawing is the low-angular (less than 90^o) domain borders. Shooters designated the average direction of magnetization on microspot sites

The dashed lines on Fig. 2 display the fact of existence of "ripples" of magnetization in domains. Thin lines in square corners is the borders separating germs of a return chirality from the main magnetic array of a spot. In drawing these borders are represented conditionally as 180-degree. In corners of magnetic the structure of nucleus more difficult and has thin structure with a vortex of the return chirality, shown on Fig. 3.

Influence of the sizes and a form of a film spot on its magnetic structure illustrates on Fig. 4. The technology of formation of these microspots didn't allow to carry out their annealing, the domain structure is partly deformed by mechanical stress.

One of unresolved problems of discrete magnetic "memory"-lack of almost realized way of a data recording by means of magnetic vortex. When coding information on a sign of polarization of a vortex, as well as in case of coding in the chirality direction, it is necessary to "switch" an element somehow. At a data recording switching of a chirality of a vortex an arising way – to influence a plane magnetic field with vortical structure. Such field can be created, passing

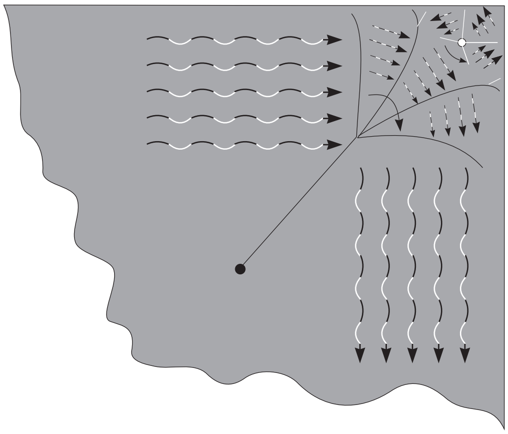
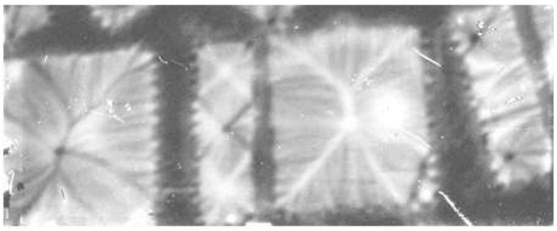


Fig. 3. The scheme of distribution of magnetization of a square microspot near a corner. Continuous lines represented domain wall, black and white lines – borders with a different chirality. Color alternation on the shooters specifying the direction of magnetization, show low-angular ripples of magnetization



5 mkm

Fig. 4. Domain structures of microspots of a different form and sizes

an electric current through a film spot perpendicular to a surface. Technical difficulties at realization of this way force to look for alternatives. In old experiments with square microspots the established fact was [3] us that at the single appendix and the subsequent its switching off of the plane homogeneous magnetic field directed along a diagonal of a square, occurs chirality changes on the opposite is the effect similar trigger [3]. The electronic-microscopic pictures illustrating this process, are given on Fig. 5.

In an initial condition (Fig. 5-1) a magnetic stream of a spot will close, a chirality is left. With increase field (Figs. 5-2, 5-3) a Bloch's point it is displaced along a diagonal of a square, perpendicular to field, "carrying away" for myself system of a Neel's domain borders, the resultant magnetic moment of a spot increases. At some value of field H_P a spot visually it seems homogeneously magnetized (Fig. 5-4). After switching off of a field the spot structure with the closed magnetic stream is restored, but the chirality changes a sign!

The reason of change of a chirality on the opposite consists in existence of nucleus of an opposite chirality in corners of a square spot. The unique such nucleus (the right top corner in drawing 5-4), growing in the field $H < H_P$ "survives" at. At it expands on all spot, changing its chirality on right (Fig. 5-6). In corners of a spot the nucleus of a return chirality capable again to change its chirality on opposite after the new appendix and switching off of the field H_P are again visible. For a considered microspot the field H_P made about 30 Oe.

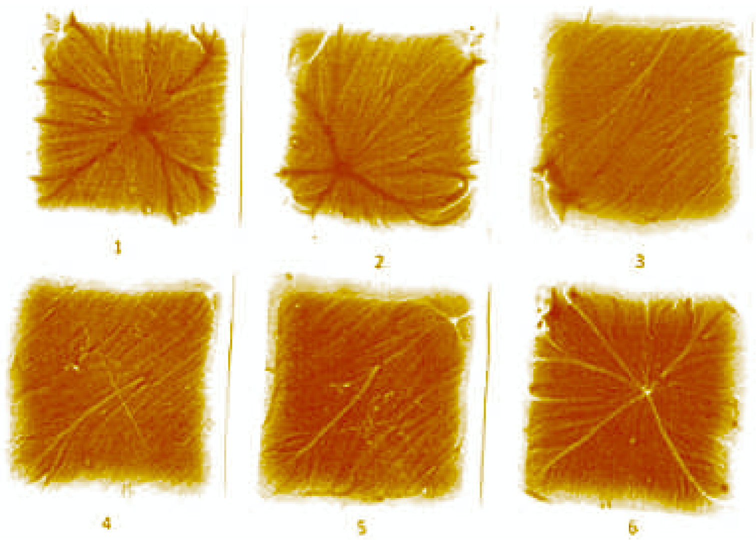


Fig. 5. Process of change of a sign of a chirality of a square spot (20×20 microns, permalloy 80Ni20Fe, $D = 40$ nanometers) in the magnetic field enclosed along a diagonal (connecting bottom right and top left square corners)

Existence of equilibrium quasivortical magnetic structure and the specific mechanism of switching of a chirality for square permalloy film spots is tracked to value of $D = 5$ microns.

2. Interaction between microdots

In the process of chirality switching the magnetic flux of a microdot ceases to be closed (Fig. 5) and microdots can interact with each other [4]. In what follows we evaluate the effect of magnetostatic interaction of switched microdot with the adjacent microdots. To define magnetostatic potential and magnetic field we use the method of magnetostatic charges which is used to describe magnets of certain symmetry.

Let us assume that microdot in the form of parallelepiped (Fig. 6) is magnetized to saturation along the edge. Then effective magnetic charges occur on the opposite sides of the parallelepiped. The density of magnetic charges are $\pm M_S$ (here M_S is magnetization of saturation). The dimensions of microdot are $a \times a \times h$ with $h \ll a$.

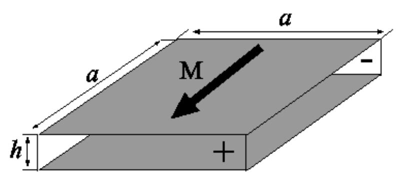


Fig. 6. Model of the magnetized to saturation parallelepiped. The arrow shows the magnetic moment of the microdot

Let us determine the magnetostatic potential induced by the "charged" sides at some point (x, y). For this purpose we represent the lateral surface as a set of small surface elements. Let us suppose that potential of the surface element is the potential of effective point charge. Fig. 7 explains the calculation procedure.

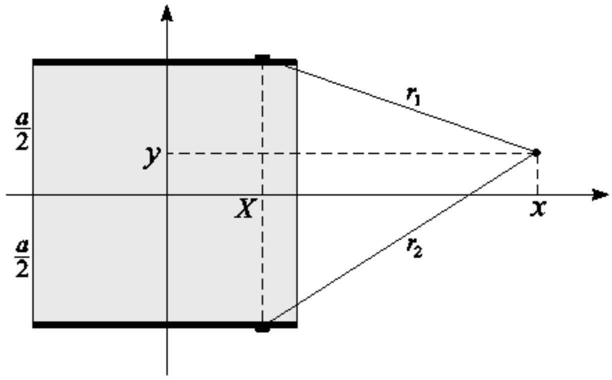


Fig. 7. Schematic related to the calculation of magnetostatic potential at a point (x, y). Top view

Magnetostatic potential of a small surface element at a point (x, y) can be written as

$$d\phi = \frac{\mu_0 M_S h dX}{\sqrt{(x-X)^2 + (y \pm \frac{a}{2})^2}}. \tag{1}$$

Potential of the square microdot is represented as

$$\phi(x,y) = \frac{\mu_0 M_S h}{4\pi} \int_{-\frac{1}{2}}^{\frac{1}{2}} \left[\frac{1}{\sqrt{(x-X)^2 + (y-\frac{a}{2})^2}} - \frac{1}{\sqrt{(x-X)^2 + (y+\frac{a}{2})^2}} \right] dX. \tag{2}$$

In this expression, x, X and y are dimensionless coordinates scaled by a. Upon taking the previous integral, we obtain

$$\phi(x,y) = \frac{\mu_0 M_S h}{4\pi} \ln \left[\frac{\left(\frac{1}{2} - x + \sqrt{x(x-1) + (y-\frac{1}{2})^2}\right)\left(-\frac{1}{2} - x + \sqrt{x(x-1) + (y+\frac{1}{2})^2}\right)}{\left(-\frac{1}{2} - x + \sqrt{x(x-1) + (y-\frac{1}{2})^2}\right)\left(\frac{1}{2} - x + \sqrt{x(x-1) + (y+\frac{1}{2})^2}\right)} \right] dX. \tag{3}$$

The components of the magnetic field generated by microdot are defined as follows

$$\begin{cases} H_x = -\dfrac{\partial \phi(x,y)}{\partial x}, \\ H_y = -\dfrac{\partial \phi(x,y)}{\partial y}. \end{cases} \tag{4}$$

Taking into account (3), one can determine the magnetic field components (4), but the resulting expressions are very cumbersome. One can find some approximate functions that give the best fit to the exact functions. The approximate functions are

$$\begin{cases} H_x = \dfrac{\mu_0 M_S h}{4\pi} \dfrac{2xy}{(x^2+y^2)^{5/2}}, \\ H_y = \dfrac{\mu_0 M_S h}{4\pi} \dfrac{2y^2 - x^2}{(x^2+y^2)^{5/2}}. \end{cases} \tag{5}$$

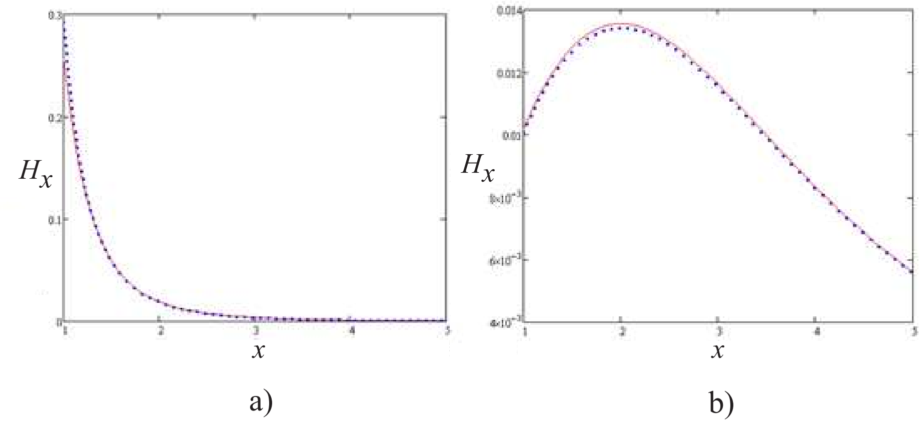


Fig. 8. The x-dependence of the dimensionless part of H_x at $y = 0.1$ (a) and at $y = 4.0$ (b). Solid lines are the exact functions (4) and points denote the approximate functions

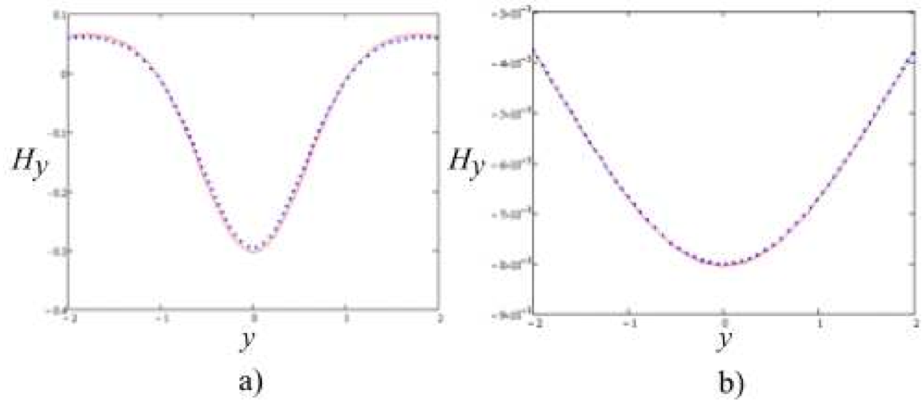


Fig. 9. The y-dependence of the dimensionless part of H_y at $x = 1.5$ (a) and at $x = 5.0$ (b). Solid lines are the exact functions (4) and points denote the approximate functions

Figs. 8 and 9 shows the approximate functions (5) in comparison with the exact functions (4).

As one can see the approximate and exact functions are in close agreement. In what follows, functions (5) are used to calculate the field intensity. The resulting field at the center of the adjacent microdot (point with coordinates $(b, 0)$) is

$$H_m = \frac{\mu_0 M_S a^2 h}{4\pi b^3}. \tag{6}$$

In this expression, all variables are dimensional. After substituting into previous expression the following typical values

$$\begin{cases} h = 50 \text{ nm}, \\ a = 5 \text{ mkm}, \\ b = 1.5a, \\ \mu_0 M_S = 2.1 \text{ Tl}, \end{cases} \tag{7}$$

we find that the maximum field H_m at the center of microdot due to adjacent microdot magnetized to saturation is about 0.001 Tl (10 Oe).

Conclusion

In this work we consider the mechanism of magnetic reversal of square microdots with the change of magnetization chirality. Evaluation of interaction between microdots shows that if we change magnetization chirality of one microdot the information stored earlier in the adjacent microdots is not changed. Indeed, the field variation at the microdot center due to magnetic reversal of the adjacent microdot is about 10 Oe. This value is less then critical value $H_P \approx 30$ Oe.

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References

[1] E.A.Rozhkova, V.Novosad, D.H.Kim and all, Ferromagnetic microdisks as carriers for biomedical applications, *J. Appl. Phys.*, **105**(2009), 07B 306.

[2] P.B.Hirsch, A.Howie, R.B.Nicolson, D.W.Pashley, M.J.Whelan, Electron Microscopy of Thin Crystals, Londres, Butterworths, 1965.

[3] V.S.Prokopenko, G.G.Vasiliev, V.P.Ivanov, Domain structures of film microspots. In the collection "Magnetic films (works VI of the international colloquium on thin magnetic films)", Minsk, Vyshaya shkola, 1974, 212-216 (in Russian).

[4] Li Sun, Xiao Zou, Wen Zhang, Guodong Li, Ya Zhai, Jing Wu, Yongbing Xu, Hongru Zhai, Local magnetic switching in patterned permalloy elements by focussed — MOKE measurements, *Phys. Status Solidi*, **C9**(2012), 66-69.

Лоренцева микроскопия пермаллоевых пленочных микропятен

В.С. Прокопенко
П.Д. Ким
В.А. Орлов
Б.В. Васильев
Д.К. Вовк
С.Е. Зацепилин
Р.Ю. Руденко

Приводятся результаты изучения методом лоренцевой электронной микроскопии квадратных пермаллоевых плёночных микропятен с квазивихревой магнитной структурой. Обсуждается механизм обнаруженного ранее эффекта переключения киральности пятна в однородном плоскостном магнитном поле. Выполнен расчёт по оценке взаимного влияния микропятен при переключении киральности.

Ключевые слова: наноточка, магнитный вихрь, точка Блоха, перемагничивание.