ISSN 1028-3358, Doklady Physics, 2015, Vol. 60, No. 7, pp. 279–282. © Pleiades Publishing, Ltd., 2015.
Original Russian Text © P.D. Kim, V.S. Prokopenko, V.A. Orlov, R.Yu. Rudenko, T.V. Rudenko, B.V. Vasilyev, V.P. Zjivaev, T.A. Kim, 2015, published in Doklady Akademii Nauk, 2015, Vol. 463, No. 1, pp. 28–31.

PHYSICS

Magnetic Structures of Permalloy Film Microspots

P. D. Kim[a], V. S. Prokopenko[b], V. A. Orlov[b], R. Yu. Rudenko[c], T. V. Rudenko[c], B. V. Vasilyev[b], V. P. Zjivaev[b], and T. A. Kim[d]

Presented by Academician V.F. Shabanov August 26, 2014

Received September 17, 2014

DOI: 10.1134/S1028335815070046

The present-day interest in micron and submicron magnetic objects is stimulated, in particular, by their possible applications in computer engineering [1–4] and biomedicine [5, 6]. In the majority of publications, of concern is the problem of film disk-shaped spots. For reasonably small sizes of a disk, the magnetic vortex is formed with circular magnetization in the spot plane on the periphery and with the magnetization outcrop from the plane in the center (the vortex core). The magnetic interaction of two or more vortices is many times less intense than the interaction of uniformly magnetized magnetic cells of the same shape and volume, which makes it possible to decrease the sizes of spots with the vortex structure and, thus, considerably increase the information density in the medium. In dependence on the direction of core magnetization (conditionally upwards or downwards), one distinguishes the positive and negative vortex polarizations and the direction of the magnetic-flux closure of the vortex flat part determines its chirality (right or left). The store of information (0 or 1) in a cell with the vortex magnetic structure is possible in two ways: according to the sign of polarization and according to the type of chirality (right or left). The purpose of this investigation is to study the effect of sizes and shapes of a spot on its magnetic structure and to clarify the practical prospects of spots of different shape—square and triangular in addition to circular.

[a] *Krasnoyarsk Research Center, Siberian Branch, Russian Academy of Sciences, Krasnoyarsk, 660036 Russia*
[b] *Krasnoyarsk State Pedagogical University named after Astaf'ev, Krasnoyarsk, 660049 Russia*
[c] *Kirenskii Institute of Physics, Siberian Branch, Russian Academy of Sciences, Krasnoyarsk, 660036 Russia*
[d] *Siberian Federal University, Krasnoyarsk, 660041 Russia*
e-mail: plufe@yandex.ru

EXPERIMENTAL EQUIPMENT AND RESULTS

Permalloy film spots of 30–60 nm thick with transverse sizes from 20 to 1 μm were the object of investigation. The samples were made by photolithography from a continuous film obtained by the method of vacuum condensation of vapors of an initial material (permalloy $Ni_{80}Fe_{20}$) on a glass substrate. For the Lorentz microscopy, the metal vapors were deposited on a substrate (formvar) transparent to the electron beam through a grid with square cells. The magnetic structures were visualized with the help of a VEECO multimode III magnetic-force microscope, an UEMV-100A electron microscope, and an MBI-6 optical microscope (using a FER-01 diluted ferrofluid as the magnetic suspension).

In Fig. 1, we show the patterns of magnetic structures characteristic for permalloy spots of circular, square, and triangular shape. In the case of circular spots of 5 μm in diameter and smaller in the thickness range of 30–50 nm, a steady equilibrium structure of the classical magnetic vortex with a central core arises. For square spots, it is a structure with a closed magnetic flux (quasi-vortex) composed of four domains with the magnetization oriented along the adjoining side of the square that is equilibrium; the domains are separated with an approximately 90-degree Néel boundaries and with the Bloch point (quasi-core) in the structure center. It is characteristic for all investigated sizes of the spot and film thicknesses. In the case of triangular spots, the quasi-vortex with a quasi-core is also formed, but the spot-shape imperfections affect the structure appreciably.

One of the problems of discrete magnetic memory is the record of information on magnetic vortices. Observations using the method of powder figures enabled us to establish that there is a specific chirality-switching mechanism for square spots of all sizes investigated. Its details were clarified during electron-microscopy observations (Fig. 2). The optical contrast

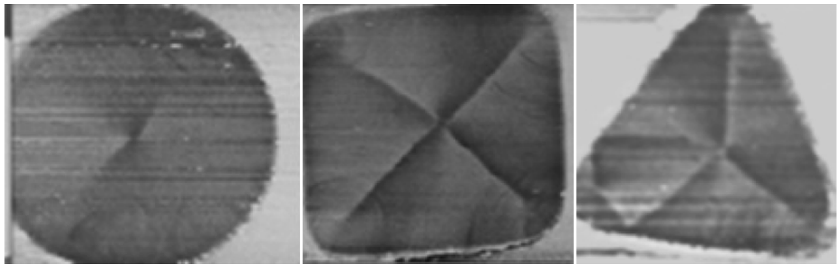

Fig. 1. Magnetic structure of 3-μm permalloy spots (permalloy, magnetic-force microscopy).

displaying the distribution of magnetization at a spot arises due to the magnetic deviation of electrons at the passage through the spot under conditions of a small defocusing of the image.

In the first approximation, the spot with a quasi-vortex operates as a magnetic converging or diverging lens in dependence on the quasi-vortex chirality sign. In the photograph (Fig. 2), the spot chirality is such that the "lens" proves to be converging and the electron beam deviates to the center of the spot (the image is negative).

A thin periodic structure on the spot image testifies to the presence of magnetization "ripples" characteristic for polycrystalline films. The dark radial lines are small-angle (less than 90°) Néel domain boundaries, in the intersection of which the Bloch point (the vortex quasi-core) is located. The lines in the space between spots show the presence of a weak sign-alternating magnetic field at those places that evidence spot interaction. As is shown, an important feature of the magnetic structure in the square microspot is the existence of bright strips in the angles of the square interpreted by us as the boundaries of the reverse-chirality germs.

At a single application and the subsequent switching-off of the plane homogeneous magnetic field directed along the square diagonal, the chirality changes to opposite. The electron-microscopic n illustrating this process are shown in Fig. 3.

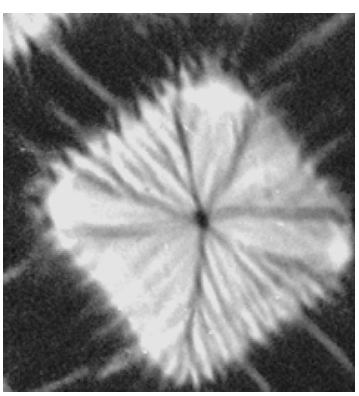

Fig. 2. Quasi-vortex magnetic structure of a square microspot (permalloy, square side of 20 μm).

In the initial state (Fig. 3a), the magnetic flux of the spot is closed, the chirality is left, and the spot operates as a diverging lens with respect to the electron beam (the electrons deviate from the spot center to the edges). With increasing the field (Figs. 3b, 3c), the central Bloch point (quasi-core) displaces along the square diagonal perpendicular to the field direction carrying the system of Néel domain boundaries; the resulting magnetic moment of the spot increases. At a certain field H_p, the spot visually appears uniformly magnetized (Fig. 3d). After switching off the field, the spot structure with the closed magnetic flux is restored, but the chirality changes to the opposite. The change in the contrast of domain boundaries and the quasi-core (they become bright, and the electrons deviate to the spot center) testifies to a change in the sign of chirality.

The reason for the change to the opposite chirality is a feature of the equilibrium magnetic structure of the spot consisting in the existence of germs of opposite chirality in the angles of the film square. In the field H_p, only one such germ "survives" (Fig. 3d, the right upper angle) growing (Fig. 3e) at $H < H_p$. At $H = 0$, it expands onto the entire spot changing its initial left chirality to the right one (Fig. 3f). At the spot angles, the germs of reverse chirality capable to change its chirality again to the opposite after the new application and switching-off of the field H_p are seen. For a spot, the switching process of which is shown in Fig. 3 ($a = 20$ μm), the field H_p amounts to about 3 mT. With decreasing the spot sizes, the field H_p increases (in particular, to 8 mT for 5-μm spots).

The presence of an equilibrium quasi-vortex magnetic structure and the specific mechanism of switching the chirality for the square permalloy-film spots is tracked to the spot-side size L= 1 μm.

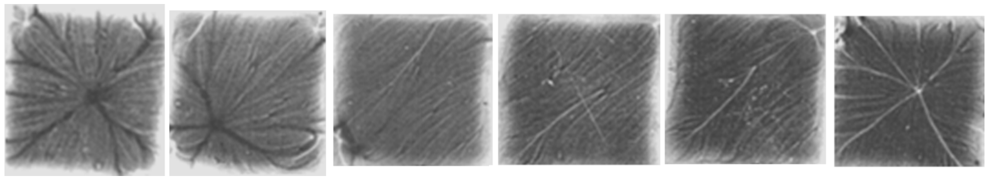

Fig. 3. Process of chirality switching for a square spot.

MUTUAL EFFECT OF SPOTS AND RELATION BETWEEN CORE POLARIZATION AND VORTEX CHIRALITY

While switching the chirality, the microspot magnetic flux ceases to be closed (Fig. 3d) and the spots can affect each other. The method of magnetostatic charges was used in the calculation of the interaction between the switched and neighboring spots. The spot was considered as a regular parallelepiped, the square-spot sizes were $a \times a \times h$, and $h \ll a$. At the spot saturation magnetization $\mathbf{M}_s$ along one of the edges a, magnetostatic charges with the density $\mathbf{M}_s$ arise on two opposite sides. The calculations show that, at the distance between the spot centers *2a*, the field arising in the center of the next spot is

$$H_y = \frac{\mu_0 M_s a^2 h}{4\pi b^3}.$$

At $h = 500$ Å, $a = 5$ μm, $b = 2a$, $M_s = 2.1$ T, and $H_m = 0.75$ mT, i.e., $H_m < H_p$.

In the case of a single circular spot, it follows from reasons of symmetry that there is no correlation between chirality and vortex polarization. However, for the square spots, the sign of quasi-core polarization also changes simultaneously in its center when switching the chirality. It is related to the existence of four more similar formations in the square angles (in the centers of germs of reverse chirality) in addition to the central quasi-core. It is possible to show that it is energetically more favorable, when the quasi-cores in the angles have polarization opposite to that in the central quasi-core. This circumstance explains the experimentally observable fact of the change in the polarization of the central quasi-core at the change in the square-spot chirality: the germ of an alternative chirality surviing in the square angle (Figs. 3d, 3e) initially contains the "anti-quasi-core" occupying the place in the center of the spot after termination of the switching process (Fig. 3f).

PROSPECT OF PRACTICAL USE OF SQUARE SPOTS

The features of a square-spot magnetic structure make it possible to consider the square ferromagnetic film microspots and nanospots as potentially promising cells when synthesizing discrete media for magnetic memory. A practically implementable way of recording information on the spot is described above. When coding the information on the core polarization, the same as in the case of circular spots, its magnetoresistive reading is possible. As far as we know, a way of reading the information from the magnetic film spot has not been proposed until now from the coding according to the chirality sign. The electron-microscopic observations suggest a possible variant: the photometry of a strongly defocused electron-beam image of the spot (Fig. 4).

For biomedical applications, the square spots may be promising as a nanosurgery tool. According to the procedure, the suspension of magnetic spots free from the substrate, which are covered with aptamer allied to a tumoral cell, is introduced into the tissue. The spot searches for tumor cells and "sticks" to them. The external magnetic field causes the motion of spots, which results in traumatizing the tumor cells. In the case of circular spots, the motion (turn) is caused by the interaction between the core magnetic moment and the external field. In the case of a square spot, the plane biaxial anisotropy (with an effective anisotropy field of about 5 mT for a spot with a side of 3 μm), which provides the conditions for additional motion (flat rotation) of the spot in an external variable magnetic field. In this case, as the estimation shows, the moment of force causing the rotation proves to be much higher than that in the case of a circular spot.

Fig. 4. Strongly defocused electron-microscopic image of spots with the left and right chiralities: the bright point at the center of the image is present for the right chirality of the spot and is absent for the left one.

ACKNOWLEDGMENTS

This work was fulfilled within the framework of interdisciplinary integration project no. 26 of the Siberian Branch, Russian Academy of Sciences, (2012–2014) and was supported by an interuniversity grant of Astaf'ev Krasnoyarsk State Pedagogical University.

REFERENCES

1. J. Raabe, R. Pulwey, R. Sattler, T. Schweinbock, J. Zweckand, and D. Weiss, Appl. Phys. **88** (71), 4437 (2000).
2. S. N. Vdovichev, B. A. Gribkov, S. A. Gusev, V. P. Mironov, D. S. Nikitushkin, A. A. Fraerman, and V. B. Shevtsov, Phys. Solid State **48** (10), 1102 (2006).
3. R. Hertel, S. Gliga, M. Fahnle, and C. M. Schneider, Phys. Rev. Lett. **98**, 117201-01 (2007).
4. Li Sun, Xao Zou, Wen Zhang, Guodong Li, Ya Zhai, Yongbing Xu, and Hongru Zhai, Phys. Status Solid **9** (1), 66 (2012).
5. E. A. Rozhkova, V. Novosad, D. H. Kim, J. Pirson, R. Divan, T. Rajh, and S. D. Bader, Appl. Phys. **105** (7), 07B306 (2009).
6. V. O. Shipunova, M. P. Nikitin, A. A. Lizunova, M. A. Ermakova, S. M. Deev, and R. V. Petrov, Dokl. Akad. Nauk **452** (3), 333 (2013).

Translated by V. Bukhanov