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Two types of magnetic vortex cores in elliptical permalloy dots

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Elliptical (track-shaped) permalloy ($Ni_{19}Fe_{81}$) dots, in which magnetic circular vortex and antivortex structures are stabilized, were prepared and the magnetic properties of perpendicular magnetization spots (turned-up magnetizations) at the cores of both types of vortices were studied. Using magnetic force microscopy, the direction of the turned-up magnetization was detected and the switching field was measured. It was found that the value of the switching field of the turned-up magnetization at the antivortex core is smaller by about 1000 Oe than that at the circular vortex core. It was confirmed that the switching of the turned-up magnetization in the antivortex is not influenced by the directions of the turned-up magnetizations in the neighboring circular vortices. Vanishing and regenerating processes of turned-up magnetizations were observed by increasing and decreasing the magnetic field applied to the in-plane direction.
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I. INTRODUCTION

Magnetic properties of nanoscale magnetic elements have been studied recently by a lot of groups because of not only industrial needs but also scientific interests. In particular, magnetization switching of small elements is a hot subject in technical and basic fields. For example, switching processes are relevant to the writing process in high density magnetic recording media and are also relating to the macroscopic quantum tunneling effect, which is theoretically predicted in magnetization reversal of small magnetic particles.[1] One of the small magnetic elements to which much attention has been paid is circular or elliptical dots with magnetic vortex structures,[2–6] which result from the competition between exchange and magnetostatic energy in dots made of magnetic material, with negligible anisotropy energy. At the vortex core, such competition forms a small perpendicular magnetization spot, which we call turned-up magnetization.[7] The size of the turned-up magnetization, which is in the order of several nanometers in radius, is so small that conventional magnetometer cannot detect the turned-up magnetization. That is why no experimental investigation had been reported until the turned-up magnetization in circular permalloy dots was detected with magnetic force microscopy (MFM).[8] Recently further experimental works on turned-up magnetizations have been carried out.[9–12] Whereas these studies were performed for turned-up magnetizations in the circular vortices appearing in circular disks or other patterns, there exists few studies on turned-up magnetizations in another type of magnetic vortex structure, i.e., antivortex. At the center of the antivortex, a perpendicular magnetization spot, which we call turned-up magnetization too, is realized with the same mechanism as at the circular vortex core. We have already reported that we can also detect turned-up magnetization at the antivortex core using MFM.[13] The antivortex is observed typically in a cross-tie magnetic domain wall. Along a cross-tie wall, circular vortices and antivortices appear alternately in line. In this article, we report on the magnetic properties of turned-up magnetizations at the cores of two types of vortices, which appear in a cross-tie wall formed along the long axis of elliptical dots.

II. EXPERIMENTAL PROCEDURE AND SIMULATIONS

The prepared samples are arrays of elliptical permalloy dots, of which the longitudinal and transverse size are 750 and 400 nm, respectively. The space between the dots is 400 nm in both longitudinal and transverse directions. The dots were fabricated by means of electron-beam lithography. The desired patterns were drawn in a spin-coated layer of resist (ZEP520) on thermally oxidized Si substrates, and after developing the resist pattern permalloy with 50 nm in thickness was deposited in an ultrahigh vacuum using an electron-beam gun. With the succeeding lift-off process the resist was removed and the dots as designed remained on the substrate surface. Because the deposition was performed onto the substrate at room temperature, the sample has a polycrystalline structure. The observation of the magnetic structure was carried out with MFM (Nanoscope IIIa under zero magnetic field and SPA300HV under magnetic fields). For the MFM observation, we used a low-moment ferromagnetic tip of CoPtCr in order not to disturb the magnetic structure of the samples by the stray fields from the tip, and operated the apparatus with an ac phase detection mode. We have per-

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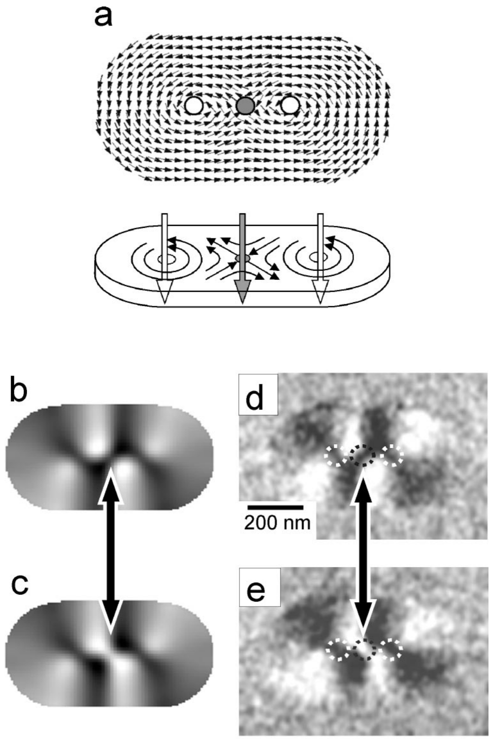

FIG. 1. (a) Equilibrium magnetization distribution obtained by micromagnetics simulation and schematic image. The gray circle and the white circles represent antivortex core and circular vortex cores, respectively. (b) MFM image simulated on the basis of the magnetic structure of Fig. 1(a). (c) Simulated MFM image of the magnetic structure with the opposite direction of the turned-up magnetization at the antivortex core. (d), (e) Experimentally obtained MFM images. The contrasts surrounded by dotted circular lines represent the directions of the turned-up magnetizations.

formed micromagnetics simulations and calculated MFM images on the basis of simulated magnetic structures. The simulation was based on the dynamic Landau–Lifshitz–Gilbert equation and was performed with the in-plane mesh size of 6.25×6.25 nm and the thickness of 50 nm, which is the same as the thickness of the prepared samples. In the simulations the magnetocrystalline anisotropy was neglected, and only the magnetostatic energy and the exchange energy were taken into account. Expected MFM images were obtained as maps of dH_z/dz at 40 nm above the sample surface, where the direction z is defined to be normal to the sample plane and H_z is the z component of the stray field from the sample.

III. RESULTS AND DISCUSSION

A. Equilibrium magnetization distribution

We calculated equilibrium magnetization distributions of an elliptical dot with the same size as the prepared sample. In Fig. 1(a), the result of micromagnetics simulation and the schematic image of the magnetic structure are shown. The obtained magnetic structure contains two circular vortices and one antivortex along the long axis, and can also be regarded as a cross-tie wall. We simulated MFM images based on the magnetic structures shown in Fig. 1(a) and the result is shown Fig. 1(b). Experimentally, we obtained the MFM images for elliptical dots as shown in Fig. 1(d), which is similar to the image in Fig. 1(b). Therefore, it was confirmed that a cross-tie wall containing two circular vortices and one antivortex is realized in the sample. Figure 1(e) is also an experimental MFM image for another dot. In this MFM image the contrast of the cores differs from that in Fig. 1(d). In the calculated MFM image shown in Fig. 1(c), which is based on the same magnetic distribution to Fig. 1(a) except the direction of the turned-up magnetization at the antivortex core, the contrast in the core of antivortex differs from that in Fig. 1(b). In this way, the direction of turned-up magnetization in a cross-tie wall is detectable with MFM observation.

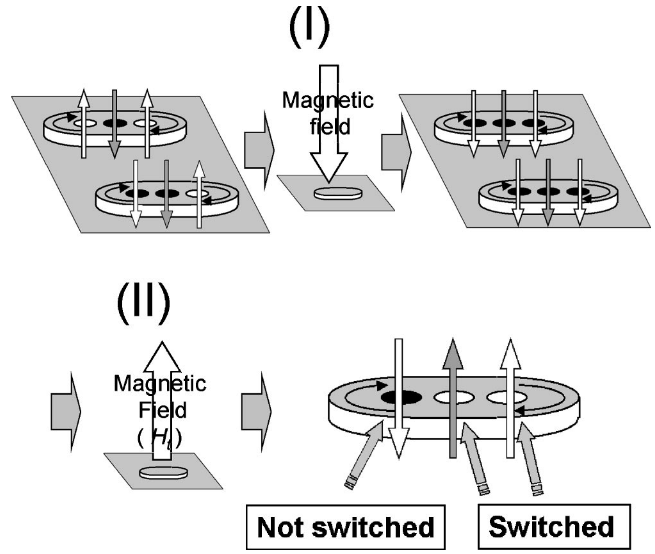

FIG. 2. Schematic images of the procedure for MFM observations for the measurement of the switching field of the turned-up magnetizations in elliptical dots. (I) A perpendicular magnetic field of about −8000 Oe was applied in order to align the turned-up magnetizations. (II) Magnetic field H_t was applied to the opposite direction. After the procedure (II), switching probability of turned-up magnetizations for H_t can be determined by taking MFM images and counting the number of switched turned-up magnetizations.

B. Switching under a perpendicular magnetic field

In order to measure the switching field H_{sw} for both types of turned-up magnetizations, we performed the following procedure. (The schematic illustration is shown in Fig. 2.) (I) A perpendicular magnetic field (−8000 Oe) strong enough to align the direction of all turned-up magnetizations in the same direction, down, was applied to the sample of dot arrays, so that the turned-up magnetization showed a dark contrast in the MFM images. (II) A magnetic field H_t was applied to the counter direction, up. Then MFM observation was performed at zero magnetic field and the number of turned-up magnetizations having switched was counted. For various H_t, this procedure was applied to 60 elliptical dots and 50 circular dots prepared on the same substrate, and the switching probabilities P were plotted against H_t for the turned-up magnetizations at the circular vortex in circular dots and those at the two kinds of the vortices in elliptical dots.

The results are shown in Fig. 3. The values of the mean

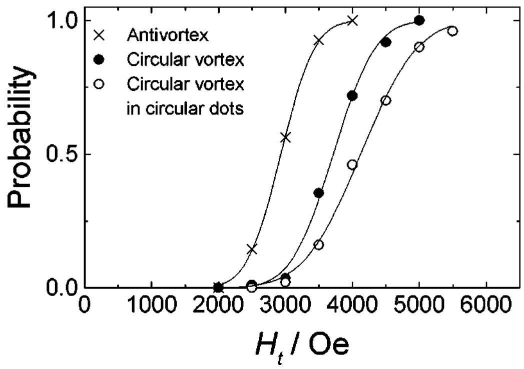

FIG. 3. Switching probabilities against H_t for the turned-up magnetizations in the antivortex and the circular vortex in elliptical dots and in the circular vortex in circular dots. The curves are fits with the error function in Eq. (1).

switching field, H_{sw}, and standard deviations of H_{sw}, σ, were determined by fitting the data with the error function $P(H_t)$ shown in the following:

$$P(H_t) = \mathrm{erf}\left(\frac{H_t - H_{sw}}{\sqrt{2}\sigma}\right), \tag{1}$$

$$\mathrm{erf}(x) = \frac{1}{\sqrt{\pi}}\int_{-\infty}^{x} e^{-u^2} du. \tag{2}$$

The values of H_{sw} at the circular vortex in the circular dots, and at the circular vortex and the antivortex in the elliptical dots are fitted to be 4120, 3710, and 2930 Oe, respectively. The values of σ are 670, 400, and 500 Oe, respectively. Namely the value of H_{sw} in the antivortex is smaller than that in the circular vortex by about 1000 Oe. The values of H_{sw} even for circular vortices in two kinds of samples are also a bit different. It is supposed that the difference is caused by the magnetic charge around the vortex core, which does not appear in the circular dot. The reason why the switching field of the turned-up magnetization at the antivortex core is smaller than that at the circular vortex core would be that the magnetic charge exists in high density in the vicinity of the antivortex core while a magnetic moment very close to the circular vortex core would curl along ideal circles and there would be no magnetic charge. On the other hand, the distribution of the switching field of the turned-up magnetization at the antivortex core is as large as that at the circular vortex core. We have reported that the distribution of the switching field of turned-up magnetization depends strongly on the switching process.[11] Therefore, the result implies that the mechanism of magnetization switching process for the two types of the turned-up magnetizations is the same. Thiaville *et al.* propose a switching process of the turned-up magnetization, in which a Bloch point is generated at the surface of the element and propagates just like a domain wall in a magnetic wire.[14] Since the Bloch point is truly a nanoscale magnetic structure, it interacts with nanoscale defects, for example, grain boundaries. Therefore, it is supposed that the wide distribution of H_{sw} is caused by the interaction between the Bloch point and such defects. (In amorphous

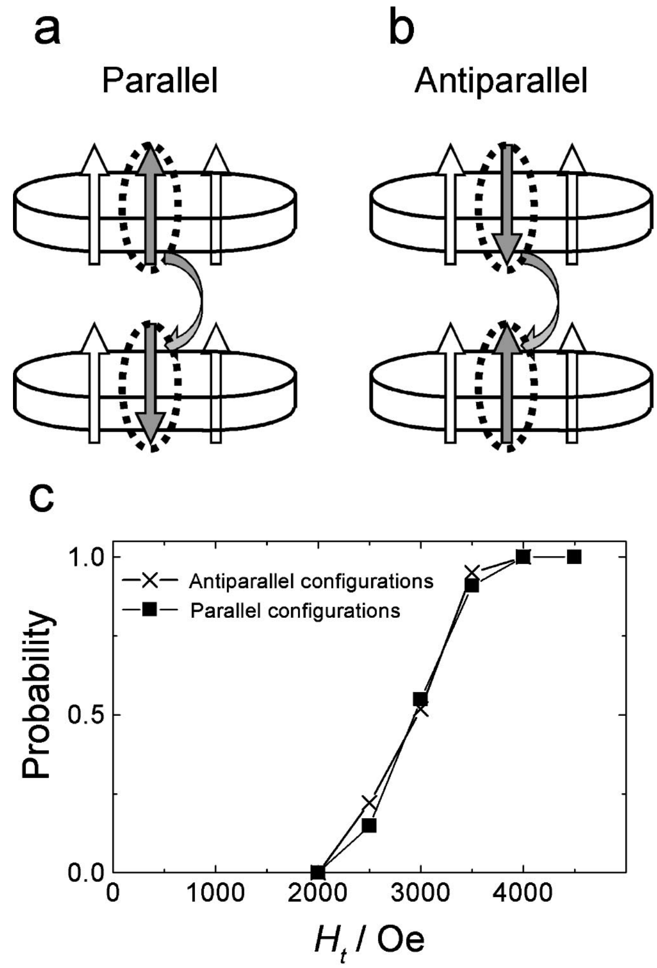

FIG. 4. Schematic images of the magnetic switching of antivortex cores from (a) the parallel and (b) the antiparallel configurations. (c) H_t dependence of switching probabilities of the turned-up magnetizations at the antivortex core for two configurations.

$Co_{83}Nb_{11.5}Zr_{5.5}$ samples, the distribution of H_{sw} is very recently found to be much smaller than that in the polycrystalline permalloy samples.)[15]

The interaction between the neighboring turned-up magnetizations was examined by comparing the switching fields of the antivortex core from two configurations, where the turned-up magnetizations in the antivortex is parallel [Fig. 4(a)] and antiparallel [Fig. 4(b)] to those in the neighboring circular vortices. The switching fields in two conditions are found to be the same [Fig. 4(c)], so that it is concluded that the turned-up magnetizations in the cross-tie wall switches independently without mutual interaction. This result guarantees that the difference in the switching fields of the turned-up magnetizations in the antivortex and the circular vortex is not caused by the interaction between neighboring turned-up magnetizations. There should be a perpendicular stray field generated by neighboring turned-up magnetizations. Assuming that a turned-up magnetization is a cylinder with 10 nm in diameter and the distance between the neighboring turned-up magnetizations is 100 nm [see Fig. 1(d)], the stray field which acts at the core of the neighboring antivortex should be several oersted, which is therefore negli-

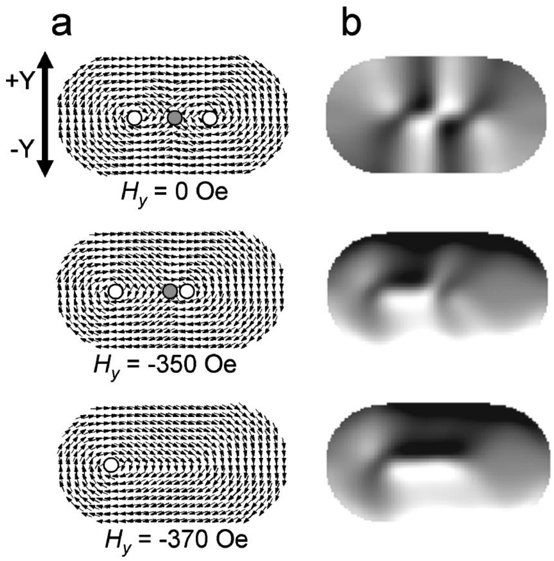

FIG. 5. (a) Magnetic structures obtained by micromagnetics simulation under magnetic fields along the y axis. In the initial structure the vortex has a clockwise rotation as a whole and the turned-up magnetizations at the circular vortices are down and that at the antivortex up. (b) Calculated MFM images based on the magnetic structure shown in (a).

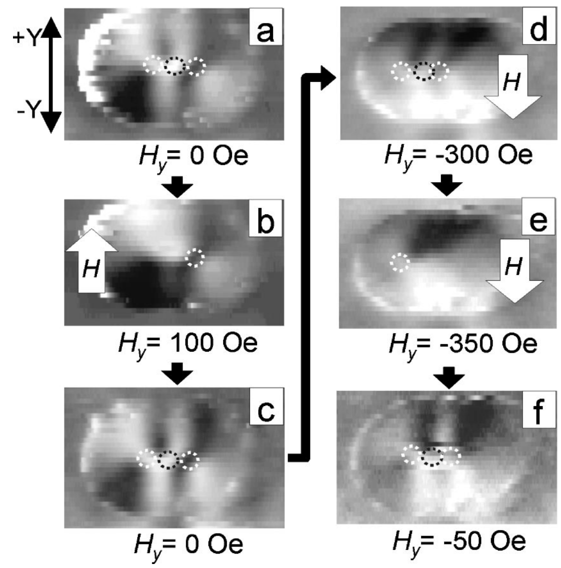

FIG. 6. MFM images obtained under magnetic fields of H_y. The dashed circles represent the area where the signals from the turned-up magnetizations appear.

gible in comparison with the distribution of the switching field.

C. Behavior under an in-plane magnetic field

By applying a magnetic field to an in-plane direction instead of the perpendicular direction, magnetic vortex cores can be displaced because the magnetic field enlarges the area with the magnetization parallel to the magnetic field and makes the area with antiparallel magnetization small.[2,11,16] When an in-plane magnetic field is applied perpendicularly to the cross-tie wall in the elliptical dot, one of the circular vortex cores is expected to approach the antivortex core. With micromagnetics simulation we estimated the displacement of the vortex cores under magnetic fields in the sample plane along the direction perpendicular to the cross-tie wall (y axis). The results are shown in Fig. 5(a). In this calculation, the initial magnetization rotation is set to be clockwise as a whole. The simulation shows that the right circular vortex and the antivortex approach to each other with increasing magnetic field to the $-y$ direction and that they finally collide and vanish together when the magnetic field is strong enough, i.e., -370 Oe in this case. Which circular vortex vanishes together with the antivortex core depends on the rotational sense of the whole magnetic structure in the elliptical dot and on the direction of the applied magnetic field. To confirm it experimentally, we took a series of MFM images for the elliptical dot under magnetic fields along the y axis. The images are shown in Fig. 6 and compared with the simulated images in Fig. 5(b). The MFM image taken under zero magnetic field [Fig. 6(a)] shows that the rotational sense of the magnetization in the dot is clockwise as a whole. In Fig. 6(b) one of the circular vortex cores and the antivortex core have vanished in the field of 100 Oe. The vanished circular vortex is the left one, which is confirmed experimentally by checking the directions of the turned-up magnetizations at the two circular vortex cores in Fig. 6(a) with that of the remaining turned-up magnetization in Fig. 6(b) (see the areas surrounded by the white dashed circles). In addition, while the positive field of 100 Oe is able to make the antivortex core and the left circular vortex core (the left pair of the turned-up magnetizations) vanish [Fig. 6(b)], the negative magnetic field of -300 Oe is not enough to make the right pair of the turned-up magnetizations vanish [Fig. 6(d)]. The directions of vanishing left pair of the turned-up magnetizations were parallel and those of the right pair were antiparallel. In order to confirm whether this directional alignment causes the difference of the vanishing fields we performed further MFM observations for parallel and antiparallel pairs of turned-up magnetizations using other dots. It was found that the vanishing fields of the antiparallel pairs and the parallel pairs are different. In micromagnetics simulation, the vanishing fields of an antiparallel pair and a parallel pair are also found to be different, and are 350–370 and 250–270 Oe, respectively. Therefore, the difference of the vanishing fields in the parallel and the antiparallel arrangement is intrinsic. It is because the origin of the energy barrier in the vanishing processes is different in the parallel and the antiparallel pair. The magnetic structure between turned-up magnetizations of a parallel and an antiparallel pair is illustrated in Fig. 7. In the vanishing process it is expected that, for the parallel pair, magnetization in the area between the turned-up magnetizations must turn up once against the magnetostatic energy and that, for the antiparallel pair, the winding magnetic moments connecting the turned-up magnetizations must be destroyed against the exchange energy. These vanishing processes of a parallel pair and an antiparallel pair are similar to those of an unwinding and a winding pair of Bloch lines in yttrium iron garnet (YIG) films.[17]

With decreasing the field to zero in Fig. 6(c) or -50 Oe in Fig. 6(f), the vanished pair of turned-up magnetizations is regenerated. We performed MFM observations for vanishing

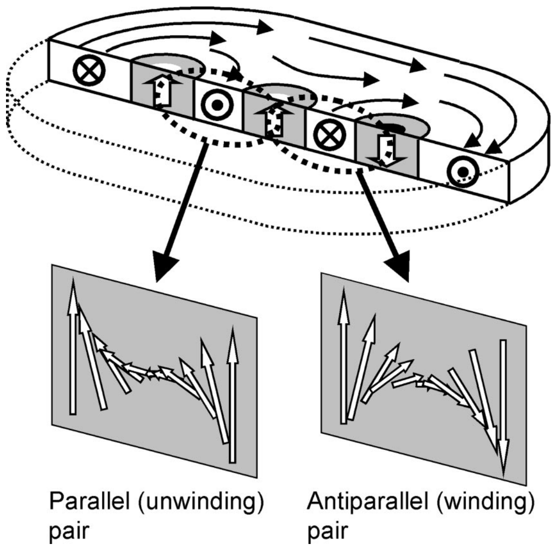

FIG. 7. Schematic illustration of cross section of magnetization distribution of an elliptical dot and enlarged images of the magnetic structure between turned-up magnetizations in a parallel and an antiparallel pair.

pairs and regenerated ones and found that regenerated pairs of turned-up magnetizations are always parallel whether the vanishing pairs are parallel or antiparallel and that the direction of the regenerated pairs is not correlated with the remaining turned-up magnetization. The directions of turned-up magnetizations were changed through vanishing and regenerated processes but not controlled by in-plane magnetic field.

D. Switching with magnetic field at a tilted angle

In circular dots, we have demonstrated the switching of the direction of a turned-up magnetization using a tilted magnetic field, where the switching process occurs through the annihilation of the vortex out of the dot and nucleation of a vortex into the dot.[11] Here, for the elliptical dots we utilized the vanishing and regenerating process occurring inside the dot with applying a magnetic field at an angle to the sample plane in order to switch the direction of only two neighboring turned-up magnetizations selectively. One of the circular vortex cores and the antivortex core should collide and vanish due to the in-plane component of the tilted magnetic field. The vanishing pair in each dot depends on the rotational sense of the whole magnetization of the dot. When the field is reduced, vortices are regenerated, and the direction should be determined by the direction of perpendicular component of the tilted field. For this demonstration, at first we applied a perpendicular magnetic field of −8000 Oe in order to turn all the turned-up magnetizations down, and then a magnetic field of 600 Oe at an upward angle of 45° from the sample plane as shown in Fig. 8(a). Figure 8(b) is the MFM image obtained under zero magnetic field after this procedure. It is observed that two neighboring turned-up magnetizations are up (bright signal) and the other is down (dark signal) in all the elliptical dots (see the areas surrounded by the dashed circles). In this way we have succeeded in switching two neighboring turned-up magnetizations in elliptical dots selectively. For the use of the elliptical dot as a three-bit

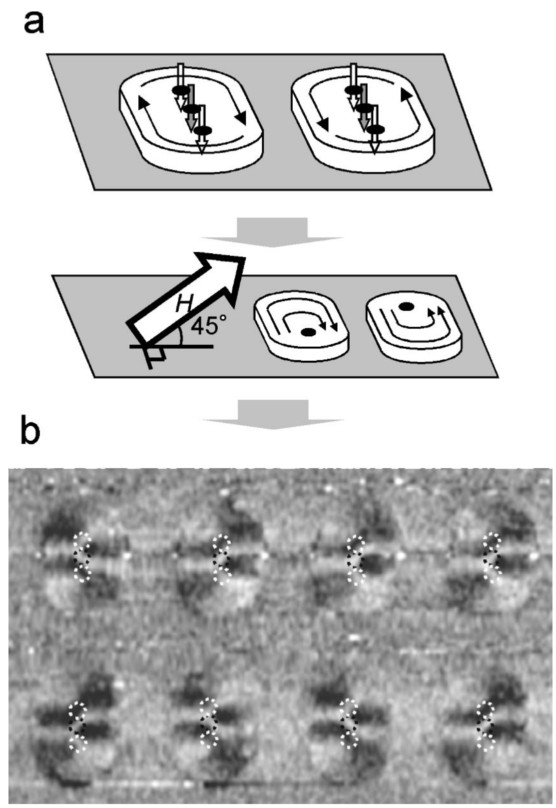

FIG. 8. (a) Schematic illustration of the procedure and the process to switch a turned-up magnetization selectively by a tilted magnetic field. (b) MFM image taken under zero magnetic field after applying a magnetic field 600 Oe at an angle of 45° to the sample plane perpendicular to the long axis of the elliptical dots.

memory, this switching process may be useful since necessary magnetic field for switching the bit is smaller than the switching process with a perpendicular field and the bit is switched selectively.

IV. SUMMARY

We have revealed experimentally that the turned-up magnetization at the antivortex core can be switched in smaller perpendicular magnetic fields than that at the circular vortex core. When a magnetic field is applied normal to the sample plane each turned-up magnetization switches independently without mutual interaction. In addition, we observed the vanishing and regenerating process with increasing and decreasing magnetic fields applied parallel to the in-plane direction. It was found that the value of magnetic field at which a pair of turned-up magnetizations vanishes depends on the directional arrangement of the vanishing turned-up magnetizations. We have demonstrated the selective switching of the turned-up magnetizations in the elliptical dots using a tilted magnetic field.

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