True Single Domain and Configuration-Assisted Switching of Submicron Permalloy Dots Observed by Electron Holography

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The switching behavior of submicron circular Permalloy nanomagnets has been investigated. Electron holography provides a magnetic resolution of down to 10 nm. This allows us to observe in detail the switching and to measure the induction within single nanodots with diameters down to 150 nm at a thickness of 6 nm. Particles of these dimensions show a single domain state during the whole switching process which takes place at external fields of only a few 100 A/m. For larger or thicker particles the magnetization reversal runs via the formation of a C state or an intermediate vortex state.

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There has been extensive interest in the magnetic properties of small ferromagnetic elements, due to their possible applications in patterned magnetic recording media, nonvolatile magnetic random access memories [1], and highly sensitive magnetic sensors like reading heads or field-programmable logic devices [2]. The magnetic properties of flat, circular submicron cylinders are well described by a number of studies [3–6]. The magnetization reversal of the disks investigated there is usually dominated by the creation, propagation, and annihilation of magnetic vortices, as long as the diameter and thickness is not smaller than certain critical values described basically by their exchange length. Theoretical considerations [7] and numerical simulations [8–10] predict that for particles below certain dimensions the single domain state is energetically more favorable than the vortex state. Therefore, these particles are expected to form a state, where the switching process is believed to be achieved by a collective rotational motion of all individual spins rather than by the formation of either a domain wall or a magnetic vortex, followed by a subsequent annihilation thereof. In this Letter we present measurements of the micromagnetic configuration throughout a complete remagnetization cycle. We are, therefore, able to discriminate between particles which reverse their magnetization in an external field in an unaltered single domain state and particles which change their micromagnetic configuration during reversal. In this Letter the term “single domain” describes a state where the magnetization inside the particle shows in general in one direction. Slight deviations of the homogeneous magnetization cannot be excluded.

The switching of circular dots with a single domain magnetization scheme has already been observed with integrative methods [6]. However, doing magneto-optical Kerr effect [6] or alternating gradient magnetometry measurements [11] the magnetization information is averaged over some hundreds or thousands of particles. The switching behavior observed is therefore the ensemble average over the individual switching behaviors of each single particle. As these particles vary slightly in size and shape due to the production process the hysteresis loop of an array of particles has to be expected to differ substantially from that of single particles, especially in a regime, where the switching depends critically on minor differences in size, thickness, or geometrical shape.

In order to observe dots with single domain switching, we prepared flat cylinders with diameters between 150 and 700 nm and thicknesses between 6 and 8 nm. The magnetic elements are located on ~30 nm thick self-supporting electron transparent Si_3N_4 membranes. The Permalloy elements have been produced by a combination of electron beam lithography, thermal evaporation, and a lift-off process. The spacing between the dots was chosen large enough ($>1.5\ \mu$m) so that interdot coupling can be excluded; i.e., it was considerably larger than the range of possibly existing dipolar fields.

For the experiments, off-axis electron holograms were recorded at 150 and 300 kV using a FEI TECNAI F30 transmission electron microscope equipped with a field emission gun. The use of a Lorentz lens provides us with a field-free specimen location. However, in order to be able to do magnetization experiments the standard objective lens or objective prelens is slightly excited which gives us a magnetic field of 6.4 to 44 kA/m perpendicular to the specimen. Remagnetization cycles were done by tilting the specimen in the field created by the respective lens and so an in-plane component was achieved. The residual perpendicular component of the applied field has only negligible influence on the magnetic specimen [5,12].

Holographic imaging is capable of detecting the phase shifts of the electron wave passing through the specimen. There can be both magnetic phase shifts (caused by the Aharonov-Bohm effect) and electrostatic phase shifts (due to the inner electrostatic potential of the specimen). In one dimension the phase experienced by the electron wave is given by

$$\phi(x) = C \int V(x, z) dz - \frac{e}{\hbar} \iint B_{pp}(x, z) dx dz,$$

where z is the direction of the incident beam, x lies in the specimen plane, V is the mean inner potential, and B_{pp} is the component of the magnetic induction perpendicular to x and z. C is a constant that depends on the wavelength of the electron and its energy. The effect of the electrostatically induced phase shift can be separated and removed following the procedures given in [13,14]. The phase images now contain the magnetic phase shift only. From this quantitative information the magnetic induction can be deduced and an induction map of the image can eventually be drawn. This enables us to plot the hysteresis loop of a remagnetization cycle of a single particle [15]. In contrast to hysteresis loops only, we obtain both the hysteresis loop *and* the corresponding phase images and thus get a detailed view of all aspects of the switching process. In the reconstructed phase images lines of constant color correspond to lines of constant phase which represent lines of magnetic induction.

Figure 1 shows a hysteresis cycle of a 6 nm thick dot. The geometric shape of the dot is slightly elliptical [Fig. 1(a)] with a long and a short axis of 370 and 340 nm, respectively. The field was applied along its long elliptical axis, which is (in the absence of other anisotropies) an easy magnetic axis due to the shape anisotropy. After saturation the external field was reduced, and at a field of 0.22 kA/m a single domain state is still present. This can be clearly seen from the inset [Fig. 1(b)]. At zero field the particle is in a C state [Fig. 1(c)] and the net induction still has a positive value. With increasing field in the opposite direction the "C state" changes slightly [Fig. 1(d)] until at −0.33 kA/m the particle switches into a single domain state and is now magnetized in the opposite direction [Fig. 1(e)]. It should be noted that the chosen display mode does not allow one to distinguish the magnetization direction [Figs. 1(b) and 1(e) show the same contrast] but from the original dataset this information can also be retrieved. Coming from saturation in the $-x$ direction at −0.54 kA/m the single domain state is still present [Fig. 1(f)]. At −0.33 kA/m the magnetization again begins to bend [Fig. 1(g)]. With increasing field the magnetization bends to a sharp C state [Fig. 1(h)] which then begins to rotate [Fig. 1(i)], as can be seen in an increase of the measured induction in the hysteresis loop. Between 0.22 and 0.33 kA/m the magnetization switches completely and forms a single domain magnetization scheme [Fig. 1(j)]. The obvious asymmetry of the hysteresis loop in Fig. 1 is attributed to weak pinning of local magnetization configurations. From similar experiments we found that no precise sequence of configurational steps can be given for a complete remagnetization cycle. Instead, when the field is repeatedly inverted, slightly different configurations have been observed. Therefore, a reproducible remagnetization in a strict sense cannot be expected.

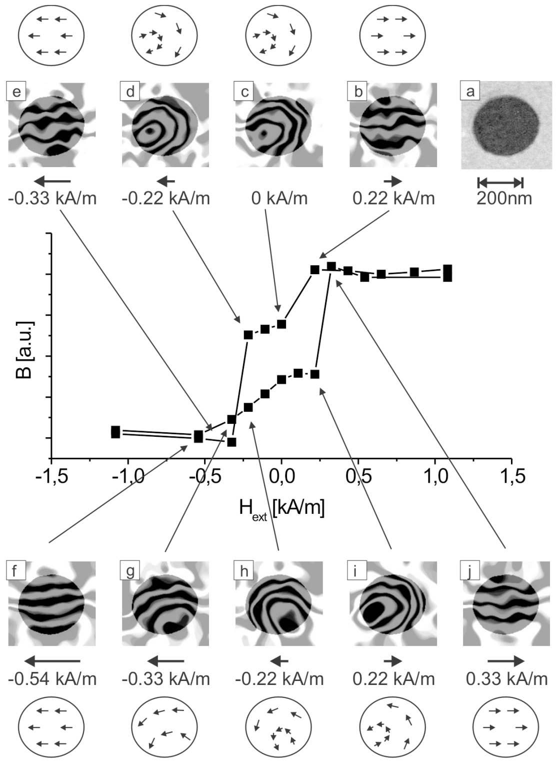

FIG. 1. Experimentally measured hysteresis loop with corresponding induction images. The particle has a size of 370 to 340 nm (a) at a Permalloy thickness of 6 nm.

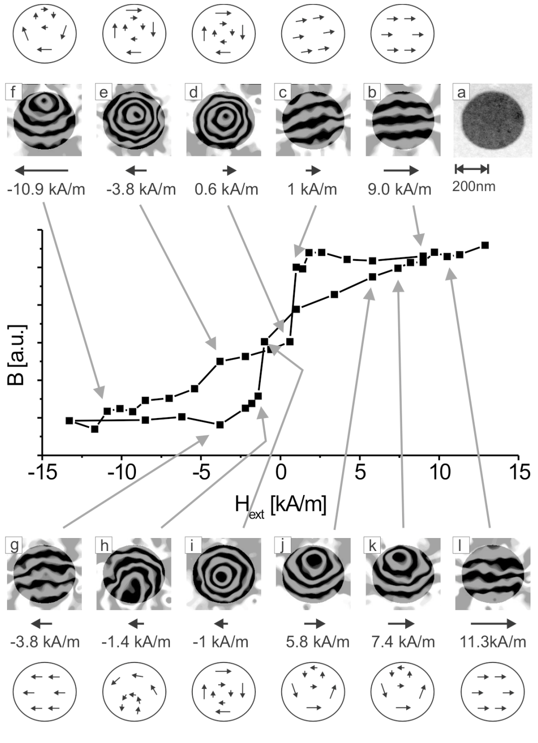

FIG. 2. Hysteresis loop and corresponding induction images of a switching via vortex nucleation, propagation, and annihilation. The dot has a size of 470 nm by 450 nm (a) at a thickness of 6 nm. The hysteresis loop starts at 9.0 kA/m (b).

Particles with the same thickness but larger lateral size (e.g., 680 or 580 nm diameter) can show the same type of switching. However, the C state is not necessarily the configuration with the lowest energy. Demagnetization in an ac field leads to vortex states in most of the investigated particles even if they switch with the help of an intermediate C state. This indicates that the C state is separated from the vortex state by a potential wall, i.e., the C state represents a local minimum of energy.

Figure 2 shows a particle of the same thickness (6 nm) and shape [Fig. 2(a)] but different size ($470\ \mathrm{nm} \times 450\ \mathrm{nm}$). The remagnetization of this particle runs via the well known formation and annihilation of a vortex and the hysteresis loop shows the typical shape as known from simulated data [8,9,16], integrative measurements [6], or from micro-Hall magnetometry measurements [17]. Coming from saturation [Fig. 2(b)] the magnetization begins to rotate slightly [Fig. 2(c)]. With further decreasing fields a centered vortex nucleates [Fig. 2(d)]. When the field is increased in the opposite direction, the vortex is forced out of the center of the dot [Figs. 2(e) and 2(f)] as areas with magnetization in the direction of the external field increase.

Between -10.9 and $-11.7\ \mathrm{kA/m}$ the vortex is pushed out of the nanodot and the particle is now in a single domain state [Fig. 2(g)]. In the reverse direction the magnetization begins to bend at about $-3.0\ \mathrm{kA/m}$. Up to $-1.4\ \mathrm{kA/m}$ [Fig. 2(h)] the C state gets sharper which also can be seen in the hysteresis loop. Between -1.4 and $-1.0\ \mathrm{kA/m}$ the vortex nucleates out of the C state and for the further increasing field the usual process of vortex propagation and annihilation can be observed [Figs. 2(i)–2(k)]. The crossover of the two branches in the hysteresis loop at -1.0 and $0.6\ \mathrm{kA/m}$ may occur for various reasons. Pinning at structural defects can influence the vortex movement. Another possibility is thermal switching between magnetization states with only a small energy barrier between.

Figure 3 shows the difference between the C state and the shifted vortex. Both particles have a similar shape and differ only in size ($370\ \mathrm{nm} \times 340\ \mathrm{nm}$ and $470\ \mathrm{nm} \times 450\ \mathrm{nm}$). The phase images look similar, and therefore it is difficult to distinguish between the C state and the shifted vortex. From simulations it is also known that from the phase images alone it is in general not always possible to discriminate clearly between the two configurations. The combination of a hysteresis loop and a series of phase images does, however, produce results beyond doubts. The result is illustrated in the magnetization schemes to make it clearer. In the case of a shifted vortex [Fig. 3(a)] the flux is closed inside the particle. In the C state the flux is not closed [Fig. 3(c)] and the magnetization bends like a C or an Ω. In this example, the external field to annihilate the vortex is about 35 times higher than the field that is necessary to switch between the C state and the single domain state.

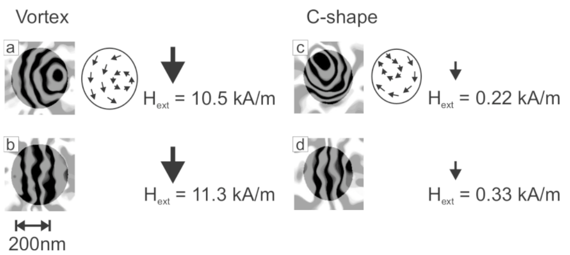

FIG. 3. Phase images of vortex annihilation (a),(b) and C state switching (c),(d). Both particles have the same thickness of magnetic material of 6 nm.

The subtle effects of edge roughness and individual particle shape are illustrated in Fig. 4. Both particles shown were prepared in the same identical preparation run; i.e., they can be considered to be prepared absolutely identical with regard to their history (especially magnetic). However, for particles of this lateral size the lithography process reaches its resolution limit. So, although nominal size and shape in the lithography process were the same, both particles do not show a perfect circular shape as can be seen clearly from the shadow images (topmost image at the right in Fig. 4).

The measurements shown were observed in the same remagnetization cycle. Both dots have a Permalloy thickness of 8 nm and a diameter of about 180 nm. Numerical calculations [18] predict that particles in these dimensions are in a C state at remanence. The experiment shows that both particles switch via the C state, as indicated by a gray shaded area in both hysteresis loops in Fig. 4. During the remagnetization process, however, they exhibit the C state at completely different field values and the switching takes

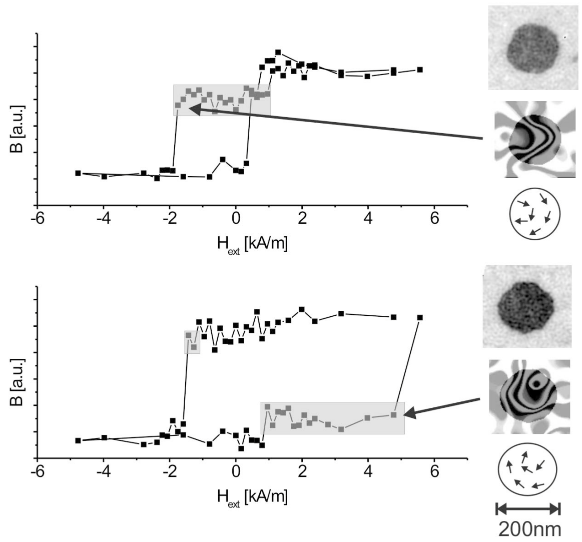

FIG. 4. Effect of individual shape on the hysteresis loop of two identically prepared particles with slightly different geometrical shapes. Both have a diameter of about 180 nm and a Permalloy thickness of 8 nm.

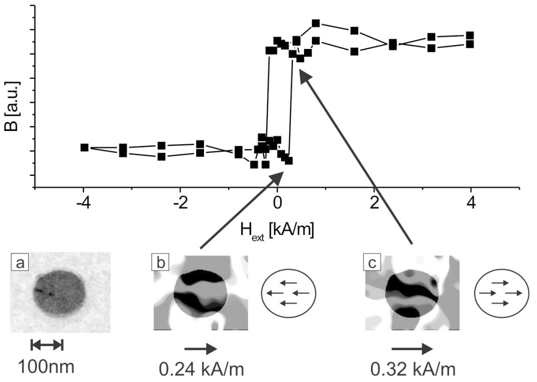

FIG. 5. Single domain switching of a 170 nm by 155 nm ellipse.

place at clearly separated values. While the upper particle switches at a field of only 0.4 kA/m the second dot switches between 4.8 and 5.6 kA/m. For the reversed field direction both dots switch at a field of about −1.6 kA/m.

In comparison to the larger but thinner dot before (shown in Fig. 1), the switching of the 8 nm particles takes place at much higher fields. While the perimeter of the 6 nm thick particles comes close to a perfect circle or ellipse, the particles with 8 nm thickness deviate stronger from these simple geometries, showing protrusions and comparably flat areas. Thus it can be assumed that the stronger edge roughness of the 8 nm thick dots hinders the rotation of the C state's magnetic configuration and also prevents the relaxation into the single domain state. This is also responsible for the strong asymmetric shape of the hysteresis loops. The combination of a slight unavoidable bias field (some 100 A/m) with the imperfect (i.e., non-smooth) particle shape causes the difference between the two remagnetization directions.

Obviously, the ability to investigate individual particles is a great benefit. An integrative measurement of an array of some hundreds or thousands of individual particles would result in an averaged signal that gives no information on the switching of one individual particle.

Finally, in Fig. 5 the hysteresis loop of a 170 nm by 155 nm ellipse with a thickness of 6 nm Permalloy is plotted. Obviously, for all field values throughout the hysteresis loop the magnetization is in a single domain state. Switching from one direction to the other takes place at fields of only 0.24 to 0.32 kA/m. For particles of this size the spatial resolution is at present not good enough to display all details of the magnetization state. Especially, it cannot be distinguished between an (unrealistic) perfectly homogeneous real single domain state or the onion state [8,18]. But the presence of a C state or *S* state can be excluded. Since in the hysteresis loop the induction is averaged over the whole particle, a rather smooth curve with the typical rectangular shape results.

Particles with less ellipticity are expected to switch at even lower fields. However, for the given dimensions, already approaching the superparamagnetic limit for Permalloy, the process of thermally activated switching has already been taken into account [19] which would then lead to a basically spontaneous switching between the two stable single domain states.

To summarize, it has been shown that with electron holography it is possible to investigate particles in the deep submicron regime and to measure the induction inside and outside of the particle. Therefore, we are able to plot hysteresis loops of individual particles and to illustrate the loop with the corresponding induction images. We showed that for particles with 6 or 8 nm thickness at diameters from about 200 nm to several hundred nm a switching via the C state can occur. The switching fields are much lower than via a vortex nucleation and annihilation process. For smaller particles we can see a single domain switching at very low external fields with a rectangular hysteresis loop. So for the first time a true and stable "single domain switching" of an individual particle has been demonstrated throughout a full remagnetization cycle.

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