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Letter to the Editor

Magnetic drops in a soft-magnetic cylinder

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Abstract

Magnetization reversal in a cylindrical ferromagnetic particle seems to be a simple textbook problem in magnetism. But at a closer look, the magnetization reversal dynamics in a cylinder is far from being trivial. The difficulty arises from the central axis, where the magnetization switches in a discontinuous fashion. Micromagnetic computer simulations allow for a detailed description of the evolution of the magnetic structure on the sub-nanosecond time scale. The switching process involves the injection of a magnetic point singularity (Bloch point) into the cylinder. Further point singularities may be generated and annihilated periodically during the reversal process. This results in the temporary formation of micromagnetic drops, i.e., isolated, non-reversed regions. This surprising feature in dynamic micromagnetism is due to different mobilities of domain wall and Bloch point.

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Ferromagnetic particles change their magnetization state under the influence of a magnetic field. The magnetization of a particle reverts towards an externally applied field if the field is strong enough to overcome a certain energetic barrier [1]. Because of their application in information storage media and spin-electronic devices [2], patterned magnetic elements of sub-micron size have become a major topic in magnetism in the last years. The typical time scale required to switch the magnetization direction in such patterned nanostructures is in the order of nanoseconds [3]. Except for special cases where the magnet is just a few nanometers in size [4], the magnetization reverts inhomogeneously [5]. Reversal processes would not be particularly interesting if the magnetic moments of the sample could rotate independently towards the field. But the exchange interaction enforces a local ordering of the magnetic structure. This makes magnetization reversal of ferromagnetic particles a complicated collective process in which the topology of the magnetization field plays a decisive role.

The theory of micromagnetism has been developed by Brown Jr. about 50 years ago [6]. It provides, in principle, the mathematical framework required to calculate the magnetization $\boldsymbol{M}(\boldsymbol{r}, t)$ as a function of space and time. In this theory, the magnetization of a ferromagnetic

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sample is represented by a directional field with constant magnitude $M_s = |\boldsymbol{M}(\boldsymbol{r}, t)|$. The magnetization dynamics is governed by the Landau–Lifshitz–Gilbert equation [7]

$$\frac{\mathrm{d}\boldsymbol{M}}{\mathrm{d}t} = -\gamma \boldsymbol{M} \times \boldsymbol{H}_{\mathrm{eff}} + \frac{\alpha}{M_{\mathrm{s}}} \boldsymbol{M} \times \frac{\mathrm{d}\boldsymbol{M}}{\mathrm{d}t}, \tag{1}$$

where γ is the gyromagnetic ratio and α is a phenomenological damping constant. The equation describes a combined precession and relaxation motion of the magnetization in an effective field $\boldsymbol{H}_{\mathrm{eff}}$. The effective field contains contributions from the significant micromagnetic energy terms, i.e., the exchange, the stray field, the anisotropy and the Zeeman energy in an external field [6].

Analytical solutions of micromagnetic problems can only be obtained for samples of simple shape and by making use of simplifying assumptions [8]. Because of their symmetry, samples with cylindrical geometry are particularly suited for such analytic calculations. Prominent examples are the basic reversal modes: curling, buckling and rotation in unison [9]. These modes have been derived analytically as instability modes in infinitely extended ferromagnetic cylinders. In 1979, Arrott et al. [10] suggested to drop the assumption of infinite extension and investigated the reversal process in an ideally soft-magnetic cylinder.[1]

Novel fabrication techniques allow to taylor the size and the shape of nano-scaled magnetic pillars that constitute extended and highly ordered arrays [11]. Such arrays might be used as high-density information storage devices [12]. In the course of this development, the question of magnetization reversal in soft magnetic cylinders has evolved from a purely acadamic one into one of practical importance since it addresses the time required to write a unit of information in such an array.

Owing to the tremendous increase in computer capacities it is now feasible to perform accurate numerical simulations of the dynamic magnetization reversal in sub-micron sized ferromagnetic particles. Here we reconsider the famous problem of reversal in an ideally soft-magnetic cylinder [10] by using a micromagnetic finite-element modelling method [13] to solve Eq. (1) numerically. The basic predictions of Arrott et al. [10] are confirmed by the simulations, but we find some astonishing additional features of the magnetization dynamics.

We investigate the magnetization reversal dynamics in a magnetic nanowire of cylindrical shape, with a diameter of 60 nm and 1 μm length. A Gilbert damping parameter $\alpha = 0.1$ is assumed. The material parameters are those of amorphous Nickel, i.e. saturation polarization $J_{\mathrm{s}} = \mu_0 M_{\mathrm{s}} = 0.52$ T, exchange constant $A = 1.05 \times 10^{-11}$ J/m, and zero anisotropy constant $K_{\mathrm{u}} = 0$ J/m^3. The shape, size and material corresponds to the specimen fabricated [11] by Nielsch et al. To simulate the reversal process, the wire is instantaneously exposed to a 200 mT field. The calculations are performed on different finite element meshes to make sure that the result is independent on the discretization scheme. The finest mesh used in the calculations contains 134469 tetrahedral elements of almost uniform size. The volume of the largest element is 0.024 V_δ, the smallest is 0.015 V_δ, where $V_\delta = \delta^3$ is the volume of a cube with an edge length of one exchange length $\delta = \sqrt{2\mu_0 A / J_{\mathrm{s}}^2}$ [14].

In the zero field (remanent) state, the magnetization of the thin elongated cylinder is mostly parallel to the symmetry axis. There is a slight fanning of the magnetization at the caps of the wire, a radial magnetization component which points towards the symmetry axis on one end of the wire and away from it on the opposite end. The fanning (cf. Fig. 1a) is caused by characteristic inhomogeneities of the stray field at the particle's ends and has become known as "Flower State" [15].

The switching of a nanowire of this thickness in a magnetic field applied antiparallel to the magnetization direction occurs via a localized curling mode [16,17]. Essentially, this reversal mode can be described by the following processes. First, a vortex structure develops at the ends of the wire. After that, magnetization reversal is accomplished by the propagation of the vortex along the wire axis. The reversal mode is localized in the

[1] Ideal magnetic softness means that there is no intrinsic preferential direction of the magnetization. This is in contrast to hard magnetic materials like FeNdB, which display a strong uniaxial anisotropy that forces the magnetization to align with an axis determined by the crystalline structure of the magnet.

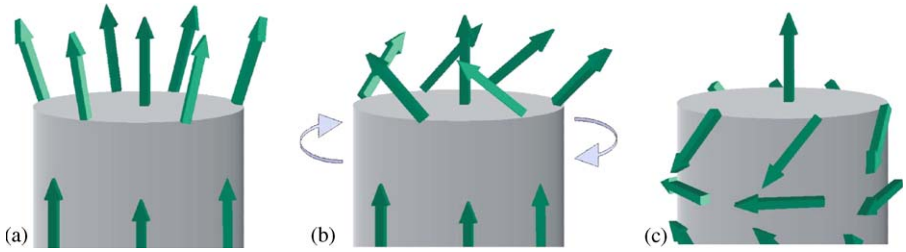

Fig. 1. Schematic representation of the initial stages of a vortex wall magnetization reversal mode. The remanent state (a) shows the Flower State fanning at the ends of the wire. Fast application of a reversed field leads to a vortex formation at the caps (b) due to the radial component of the magnetization. Magnetization reversal proceeds at the border of the wire by vortex propagation, while the magnetization in the axis remains antiparallel to the field (c).

vortex wall[2] that separates the reversed part from the non-reversed part.

Let us now discuss the dynamics of the reversal process in more detail. Generally, the decisive quantity for the temporal evolution of a magnetic structure is the torque $\boldsymbol{M} \times \boldsymbol{H}_{\mathrm{eff}}$ exerted by the effective field on the magnetic moments (see e.g. Ref. [18]). At the beginning of the reversal, the effective field is equal to the external field. In our case the starting point is the remanent magnetization state, where $\boldsymbol{M}$ is mostly aligned along the axis, except for the aforementioned small deviations of the Flower State. A reversed field hardly has an immediate effect on the homogeneously magnetized regions which are oriented antiparallel to the field. As a result of the Flower State fanning, the parts of the wire where the magnetization experiences the strongest torque are those near the perimeter at the top and bottom ends. The torque there leads to the formation of vortex structures on both ends. The sense of rotation is always clockwise on the upper end (Fig. 1b) and anti-clockwise on the lower end. The different sense of rotation is due to the opposite sign of the radial component of the Flower State on the respective ends of the wire, pointing inwards at the lower end and outwards at the upper. Once the vortices (with their core in the middle of the cap) are formed, an even stronger torque acts on $\boldsymbol{M}$ at the perimeter, where the magnetization is now perpendicular to the external field. This strong torque leads to a quick alignment towards the applied field at the border (Fig. 1c).

While the reversal begins at the caps, the rest of the wire remains magnetized antiparallel to the external field. Particularly, the magnetization in the core of the vortex is still antiparallel to the field, since no torque is exerted by the field and because the magnetization there cannot follow the motion of the surrounding magnetic moments for both topological and for symmetry reasons. Magnetization reversal proceeds quickly on the outer shell of the cylinder before the center of the wire switches. This leads to a very inhomogeneous magnetic structure. In the initial stages, the reversal is localized on a cone-shaped region along which the magnetization changes its direction by 180° (from up to down). The apex of this cone-shaped reversal front is the core in the middle of the cap. The cone separates the non-reversed region from the reversed part. The surface of this cone grows as the domain wall propagates on the boundary, thus expanding the reversal front in length (Fig. 2a). This results in a continuous increase of exchange energy at this stage of the reversal process. The structure is eventually resolved by the injection of a Bloch point into the wire on its surface, as shown in Fig. 2b.

A Bloch point or Feldtkeller singularity [19] is a singularity of the directional magnetization field.[3] It is a point to which no direction of the

[2] This kind of axial vortex wall should not be confused with the well-known transverse vortex wall frequently found in thin strips [24].

[3] For clarity, it is worth mentioning that the term "singularity" does not apply to the core of a vortex in soft magnetic thin film elements where the magnetization points perpendicular to the surface [25].

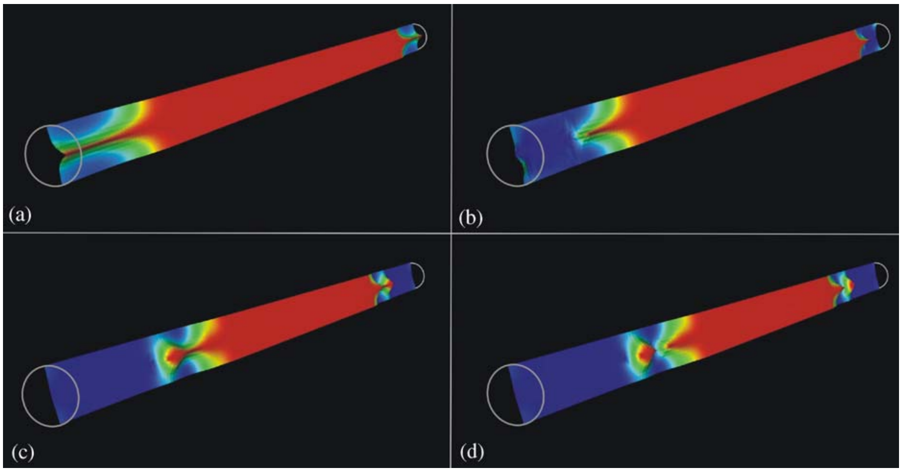

Fig. 2. Formation of magnetic drops during the vortex reversal mode in a Ni wire (60 nm diameter, 1 μm length) exposed to a reversed 200 mT field. Snapshots of the magnetization component along the field direction (blue: parallel, red: antiparallel) are taken on a cutplane through the wire at different times. The magnetic structure is cylindrically symmetric at any time. The time after application of the field is (a): 167 ps, (b): 185 ps, (c): 266 ps, and (d): 284 ps.

magnetization can be assigned. In other words, *any* direction of the magnetization is present in the close vicinity of a Bloch point. As shown schematically in Fig. 3, the localized vortex reversal mode contains such a point in the center of the vortex wall. Strictly speaking, the continuum theory of micromagnetism is not suitable to describe the magnetic structure in the close vicinity of a Bloch point because of the strong inhomogeneities of the magnetization occurring there on an atomic length scale. The details of the magnetic structure on this length scale might be treated using ab initio electron theory. Nevertheless, the difficulties refer only to a small region of the size of a few lattice constants around this point, whereas the structure around that region can be treated safely with micromagnetic theory. Simulating micromagnetically such structures is less problematic than it might seem [20,21].

The formation of the Bloch point is a direct consequence of the vortex structure developing at the wire's ends. Once the point singularity is injected, the magnetization near the wire's ends can align towards the external field and the reversal continues by means of the propagation of the vortex wall. As mentioned before, in the surroundings of the Bloch point any magnetization direction can be found. Due to this magnetic "hedgehog" structure around the Bloch point, the average magnetic moment of a small volume containing the singularity is practically zero. Therefore, also the torque $\boldsymbol{M} \times \boldsymbol{H}$ acting on the magnetization in such a volume is small. Consequently, the arrangement of the magnetization around the singularity near the wire axis has a lower mobility than the domain wall close to the perimeter of the wire, where $\boldsymbol{M}$ is perpendicular to the external field. The Bloch point lags behind the reversal front on the outer shell that proceeds much faster. Unlike the sketch of Fig. 3, the Bloch point is not exactly in the middle of the vortex wall during the reversal. As can be seen on a cutplane through the middle of the wire (Fig. 2b), the different reversal speeds of the outer region and the core lead again to a cone-shaped reversal front, with the Bloch point at the apex of the cone. It is remarkable that a qualitatively similar profile of the reversal front has been predicted by Sixtus and Tonks already in 1931 (cf. Fig. 13 in Ref. [22]). Interestingly, the growing deformation of the reversal front reaches a dynamic equilibrium through repeated disruptions: magnetic "drops" are formed, i.e. isolated, non-reversed regions which are emitted periodically. In topological terms, these drops result from a sequence of pair creation [23] and annihilation of singularities in

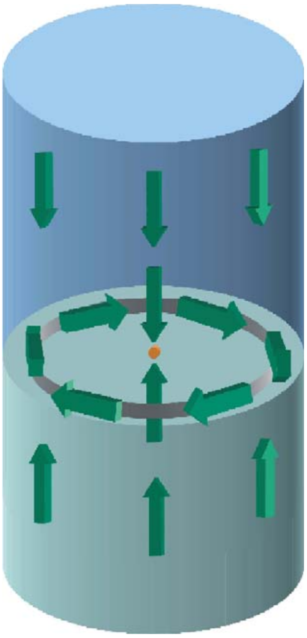

Fig. 3. Sketch of a Bloch point structure. In the vortex reversal mode in a cylindrical ferromagnet two regions of opposite magnetization are separated by a vortex structure. For topological reasons, this arrangement inevitably contains a micromagnetic singularity (Bloch point), where the direction of the magnetization is not defined.

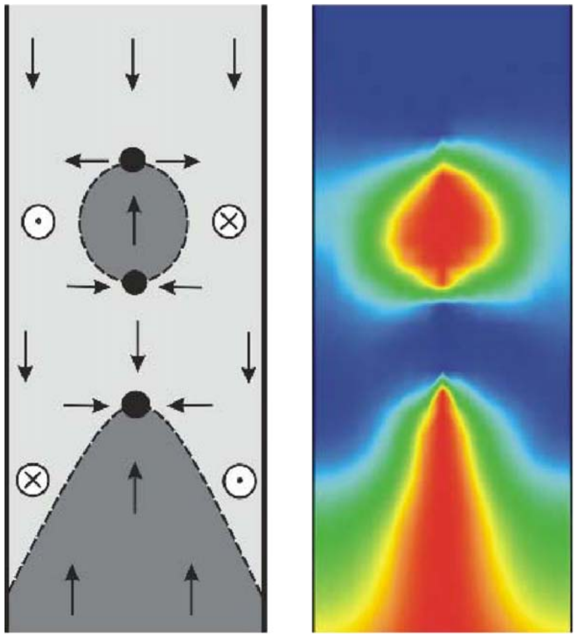

Fig. 4. Fine structure of a magnetic drop. The right part of the image is the result of the micromagnetic simulation, the left part is a schematic representation to elucidate the details of the drop structure. This is a magnified view on a part of a cutplane along the wire axis. The color coding refers to the z-component of the magnetization, where z is the wire axis (red: up, blue: down). The structure is axially symmetric. There are three Bloch points in this arrangement, all of which are placed on the middle axis. The drop is enclosed on the top and on the bottom by point singularities, and there is a further point singularity at the apex of the cone-shaped reversal front. The snapshot shows the magnetic structure as it has evolved 289 ps after the reversed field has been applied, right after a pair creation process.

the vector field. The dynamic formation of such drops is shown in Figs. 2c and d. The magnetic fine structure of a drop is described in Fig. 4. The drop consists of two Bloch points, one on the upper and one on the lower point. The singularities are above and below the center of a vortex with the core magnetized antiparallel to the field. The structure preserves the cylindrical symmetry of the sample. The drop is resolved after some picoseconds when the Bloch point pair annihilates.

It should be beared in mind that the reversal mode described in this paper is a genuinely dynamic magnetization process. This hold particularly, and most importantly, for the vortex formation according to Fig. 1b. This vortex formation is due to the precession of magnetic moments in an external field. For the occurrence of such a precessional effect it is essential that the system is not in an equilibrium. In other words, the field-driven vortex formation is a result of the sudden application of the external field. It does not occur in the quasi-static case, where the external field is slowly increased and the system remains equilibrated. In fact, the quasi-static switching process is quite different from the aforementioned dynamic processes. Since the vortex-formation does not occur in this case, an external breaking of symmetry is required to switch the magnetization. The quasi-static switching field is ill-defined in this case when the field is applied exactly parallel to the axis. If the field is tilted by 1° off the axis, and if it is increased quasi-statically, the simulations yield that the reversal occurs at 110 mT, however via a different switching mode. The absence of vortices, in combination with the axial symmetry breaking, leads to a switching mode with propagating transverse walls [16,17]. The vortex reversal mode occurs in the quasi-static case only in wires of larger diameter, when the remanent state is not a pure Flower-State but contains also a more or less pronounced vortex component which develops in order to reduce magnetic surface charges (similar to, e.g., the Twisted Flower State described in Ref. [20]). According to the two different senses of rotation of the static vortex components on opposite sides of the wires, four different remanent magnetic configurations are possible. The investigation of the differences concerning the quasi-static reversal process and the reversal fields for these four different structures goes beyond the scope of this paper.

While the breaking of symmetry is decisive for quasi-static magnetization reversal, the formation of magnetic drops is not due to the absence of any symmetry breaking in the calculation. In fact, such magnetic drops result also if the external field is tilted by 1° or even 3° off the symmetry axis. The strength of the applied field, however, may have an influence on the occurrence of the drops. In the example with the drops discussed above, the external field strength was 200 mT. But a localized vortex mode with a Bloch point in the middle of the reversal front occurs also in a 140 mT field. At 130 mT, however, the wire does not switch if the field is applied instantaneously, parallel to the wire axis. There is an energetic barrier between the configurations according to Figs. 1b and c, and a sufficiently strong field is required to overcome this barrier. If the field is too weak, the structure changes temporarily from Fig. 1a to b, but relaxes back to Fig. 1a. In the case of the 140 mT field, magnetic drops are not formed. Instead, a cone-shaped reversal front similar to the one shown in Fig. 2b propagates through the sample, without disrupting. It is suspected that the formation of drops, i.e. the pair creation and annihilation process, increases energy dissipation if the field is strong and the intrinsic damping is low. A lower damping parameter is expected to facilitate the formation of drops. Surprisingly, the mesh size does not seem to have a decisive effect on the drop formation and dynamics. In micromagnetic simulations on the same sample, but with different mesh cell sizes, we always find drops that are of approximately the same size and that are formed at the same time. The mesh fricition or mesh pinning effect reported by Thiaville et al. [21] does not seem to play a role here. A likely explaination for the apparent absence of mesh friction effects is that the situation in Ref. [21] is quite different from the one discussed here. In our case, a dynamic switching with a relatively strong external field is studied, whereas in Ref. [21] the reversal was studied at a field strength corresponding to the static switching field. In the latter case, friction plays a more important role because the vortex motion is "viscous" in the sense that the driving force due to the external field is just as high as it is required to overcome the mesh friction. If the applied field is significantly stronger than what is required to dispace the vortex, the small inhomogeneities of the friction due to artificial mesh roughness are unimportant. They do not have an influence on the formation of drops in our case, provided that the mesh is reasonably fine to allow for accurate calculations.

To study whether the peculiarities involved with the dynamics of the Bloch point have a significant effect on the reversal process, particularly on its speed, we studied the magnetization reversal in a hollow magnetic wire. The finite-element meshes used for the simulations are shown in the inset of Fig. 5. Except for a cylindrical cavity with a diameter of 20 nm, the wire has the same properties as in the previous case (Nickel, diameter: 60 nm, 1 μm length). Evidently, the time required for reversal is almost identical for both wires. This demonstrates that the turbulences, the pair creations and annihilations occurring along the central axis of a solid wire are not hampering or slowing down the reversal process.

We have shown that micromagnetic simulations can give precise insight into the dynamics of magnetization reversal in a soft magnetic cylinder, which is an old and fundamental problem in micromagnetism. Several peculiarities of this reversal process have been found. The simulation of the dynamics of the Bloch point structure in a strong external field reveals the occurrence of pair creation and annihilation processes during the motion of the singularity. This is due to the low mobility of the Bloch point compared with the

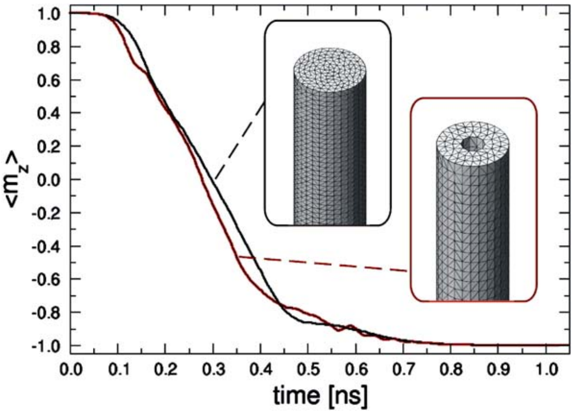

Fig. 5. Average magnetization parallel to the wire axis as a function of time after application of an external magnetic field. The two curves refer to the case of a solid and a hollow wire, respectively. The switching speed is almost the same in both cases.

domain wall, which eventually leads to the formation of magnetic drops. We are pleasantly surprised by the agreement of our computer simulations with early predictions on the vortex reversal mode by Arrott, Heinrich and Aharoni [10]. After about 25 years it has now become possible to confirm their statement according to which "the point singularities (…) are essential to understanding the process of magnetization. Complete reversal of magnetization is made possible by propagating point singularities down the axis of the cylinder."

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