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Magnetization reversal dynamics in nickel nanowires

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Abstract

The analysis of ferromagnetic nanowires is a new and vivid field of research. Micromagnetic simulations based on the finite-element method are being used to gain an insight into the dynamics of the reversal process of such wires. Two different types of reversal modes occur, depending on the wire thickness. While in thin wires a simple domain wall nucleates and propagates along the wire axis, the reversal of thick wires is achieved via a localized curling mode. The latter mode involves the injection and propagation of a micromagnetic singularity (Bloch point). The transition between the different modes is observed in a cone-shaped wire with linearly varying thickness.

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1. Introduction

Highly ordered arrays of ferromagnetic nanowires have recently been produced and their magnetic properties have been investigated experimentally [1,2]. Such sets of nanowires are interesting for several reasons including their possible application in magnetic data storage devices [1]. Almost perfect Nickel nanowire arrays with a highly uniform degree of filling have been presented recently by Nielsch et al. [3]. From a micromagnetic point of view, two major questions arise concerning the magnetic properties of such arrays. First: How do the wires interact with each other? The magnetostatic coupling among the wires is expected to have a strong influence on their response to an external field. This question has already been addressed to a certain extent [4]. The other point refers to the reversal process of nanowires exposed to an external field. This is the topic of this paper. The time required for a particle to revert its magnetization is of growing importance since the operational speed of devices is now in the GHz range. In addition, and more fundamentally, the investigation of magnetization reversal modes in soft-magnetic cylinders deals with an old and yet unsolved problem in micromagnetism [5].

Because of their symmetry and simplicity, cylindrical geometries have always been particularly suited for analytic micromagnetic calculations. In fact, the well-known magnetization reversal modes including curling, buckling and rotation in unison, are analytically derived instability modes of infinitely extended cylinders [6]. The "ideally soft magnetic cylinder" has been proposed by Arrott, Heinrich and Aharoni in 1979

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as an idealized system to study inhomogeneous magnetization reversal processes [5]. It is by coincidence that the recently produced soft-magnetic nanowires represent an almost exact realization of this model. Owing to the drastic increase in computer power we now have the capability to accurately investigate the dynamics of magnetization reversal processes in ferromagnetic nanocylinders by means of micromagnetic simulations.

2. Micromagnetic modelling

The task of dynamic micromagnetic modelling consists in solving the Gilbert equation,

$$\frac{\mathrm{d}\boldsymbol{M}}{\mathrm{d}t} = -\gamma(\boldsymbol{M} \times \boldsymbol{H}_{\mathrm{eff}}) + \frac{\alpha}{M_{\mathrm{s}}}\left(\boldsymbol{M} \times \frac{\mathrm{d}\boldsymbol{M}}{\mathrm{d}t}\right), \qquad (1)$$

which describes the motion of the magnetization $\boldsymbol{M}$ in an effective field $\boldsymbol{H}_{\mathrm{eff}}$. The effective field is obtained from the local energy density e as a variational derivative with respect to the magnetization, $\boldsymbol{H}_{\mathrm{eff}} = -1/M_{\mathrm{s}} \cdot \partial e/\partial \boldsymbol{M}$. In Eq. (1), α is a phenomenological damping constant and γ is the gyromagnetic ratio. The relevant terms contributing to the energy density e are the stray field, the exchange, the anisotropy and the Zeeman energy in an external field [7].

To solve the micromagnetic problem numerically, we use the finite-element method which permits us to simulate particles with curved boundaries with high accuracy. The sample is discretized into tetrahedral elements of irregular size and shape. The magnetization is calculated at the corner points (nodes) of these elements. Inside each element, linear interpolation functions are used to approximate the vector field. Two major problems need to be tackled in dynamic micromagnetic simulations: first, the calculation of the long-range interaction connected with the stray field, and second, the stable and accurate time integration of the Gilbert equation. The first problem can be excellently solved by using a combination of the finite-element method and the boundary-element method (FEM/BEM). This FEM/BEM scheme allows us to quickly solve the Poisson equation $\Delta U = 4\pi\nabla M$ with correct boundary conditions, so that the stray field $\boldsymbol{H}_{\mathrm{s}}$ can be derived from the scalar potential U as a gradient field, $\boldsymbol{H}_{\mathrm{s}} = -\boldsymbol{\nabla} U$. For more details on the procedure see Ref. [4]. The Gilbert equation is integrated using the implicit Adams method [8], which allows the use of time steps of moderate size (in the sub-ps range). The time intervals for a single integration step are changed adaptively according to the torque acting on the magnetization.

The simulations we present here refer to particles of ideally soft Nickel (saturation polarization $\mu_0 M_{\mathrm{s}} = 0.52\,\mathrm{T}$, exchange constant $A = 10.5\,\mathrm{pJ/m}$). A Gilbert damping constant $\alpha = 0.1$ is assumed.

3. Basic reversal modes

About two years ago, it had been reported independently by Forster et al. [9] and by Hertel [10] that soft magnetic nanowires can switch in two different modes depending on their thickness.[1] These modes have become known as the transverse wall mode and the vortex wall mode. The first refers to a thin ferromagnetic wire. If a wire is thin enough, the exchange interaction forces the magnetization to be homogeneous through any radial cross-section of the cylinder. The magnetic structure is then one-dimensional and depends only on the position z along the wire axis, and not on the radial coordinate. In such a thin wire the reversal starts by the nucleation of a head-to-head domain wall that subsequently propagates along the symmetry axis. The reason why the nucleation starts at the end is that there the demagnetizing field, which is essentially parallel to the external field, has its strongest value. While the wall proceeds along the wire, it performs a characteristic spiralling motion. This rotation occurs because the magnetic moments in the wall are oriented perpendicular to the external field so that a torque is exerted in the axial direction. This rotation of the wall along the wire axis is superimposed to the propagation. Since this motion is

[1] The results were first presented in 2001 at the International Workshop on Magnetic Wires in San Sebastian (Spain). The proceedings of that conference have been printed later than a follow-up paper [15].

typical for the reversal mode, we prefer to call it the "corkscrew" mode. Fig. 1 shows the initial stages of the corkscrew reversal mode in a Ni nanowire of 40 nm thickness. The rotation of the transverse wall results in characteristic oscillations of the magnetization components perpendicular to the wire, cf. Fig. 2. The progression of the transverse wall along the axis is solely due to damping. In the limiting case of zero damping, the wall processes with the Larmor frequency without propagating.

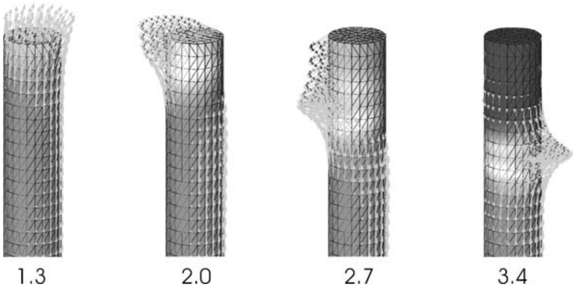

Fig. 1. Snapshots of the initial stages of the "corkscrew" reversal mode in a Ni wire with a diameter of 40 nm; the numbers indicate time in nanoseconds. The wire is exposed to a reversed field of 200 mT. A head-to-head domain wall is nucleated at the end of the wire. It propagates along the wire axis on a characteristic spiralling orbit.

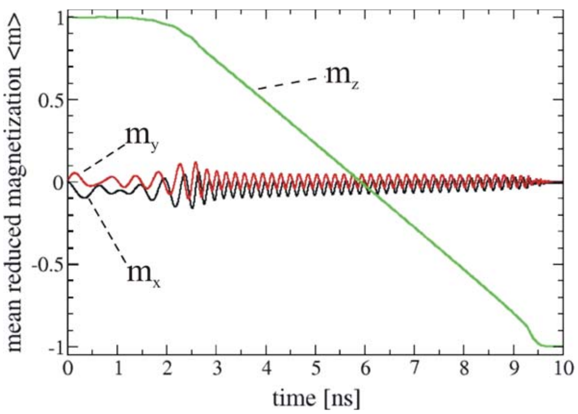

Fig. 2. Spatially averaged magnetization components as a function of time in the case of the corkscrew reversal mode in a Ni nanowire of 40 nm thickness and 1 μm length. The change in the axial magnetization component m_z indicates the propagation of the domain wall. The gyrating motion of the domain wall around the axis reflects in the oscillations of the perpendicular components m_x, m_y.

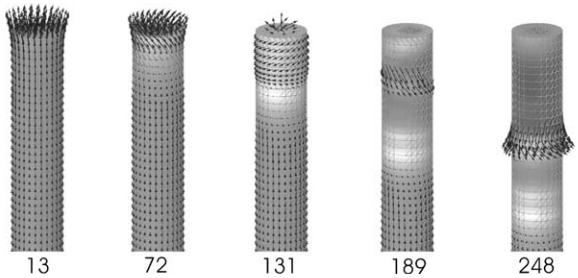

Fig. 3. Snapshots of the beginning of a localized curling mode reversal in a Ni wire of 60 nm thickness. The numbers are picoseconds after application of the reversed field. A vortex nucleates at the wire's end and propagates along the wire axis.

It is clear that with increasing diameter the one-dimensional structure eventually converts into a three-dimensional structure with radial inhomogeneity. Such a three-dimensional structure is observed in the reversal process of a Ni wire of 60 nm diameter, as shown in Fig. 3. At the end of the wire, a vortex is nucleated which propagates along the wire axis. Note that the vortex axis is parallel to the wire axis. This "vortex wall" should not be confused with the type of vortex wall structure described by McMichael et al. [11] in thin magnetic strips, where the vortex axis is perpendicular to the particle's symmetry axis. To avoid this misunderstanding, we call this type of reversal the "localized curling mode". This reversal mode is much faster than the corkscrew reversal mode.

4. Dynamic mode conversion

To investigate the thickness-dependent transition between the two basic reversal modes we consider a cone-shaped Ni wire with linearly varying thickness. The length is 1 μm, the diameter is 60 nm at one end and 30 nm at the other. When the particle is exposed to a reversed field of 200 mT, the reversal begins as a localized curling mode at the thick part. The vortex wall propagates until it reaches a region of the wire with a critical thickness, where the wire becomes too thin to sustain the vortex structure. In our case, this occurs at 42 nm. The localized curling mode then converts into the corkscrew mode, cf. Fig. 4. The transition can be clearly seen in Fig. 5 where the

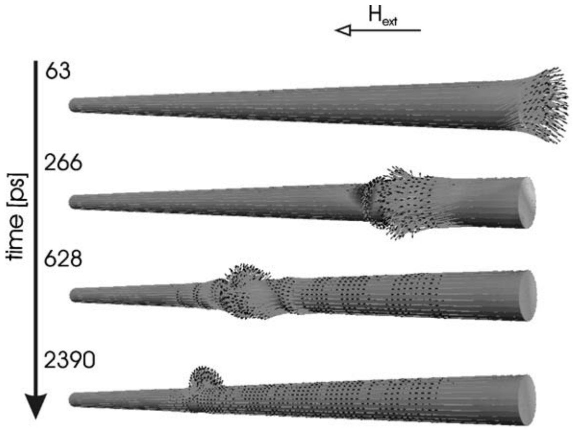

Fig. 4. Dynamic mode conversion in a cone-shaped wire of 1 μm length and linearly varying diameter between 30 and 60 nm. The reversal starts at the thicker end as a vortex mode. The reversal front propagates along the wire. When it passes through a range of critical thickness, the vortex mode converts into the corkscrew mode.

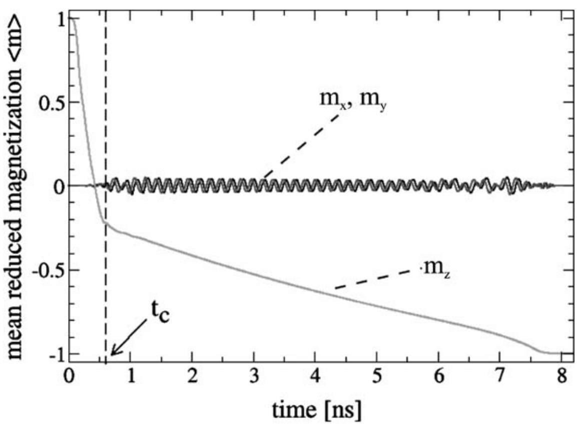

Fig. 5. Average magnetization components during the reversal of the cone-shaped particle. The mode conversion sets in at the time t_c. At that point, the slope of m_z changes drastically, indicating the conversion of the fast vortex reversal mode into the slow corkscrew mode. The conversion into the corkscrew mode also reflects in the onset of the characteristic oscillations in the m_x and m_y components.

onset of the typical oscillations in the perpendicular components and the change in the slope of the magnetization along the wire clearly indicates the conversion from the fast localized curling mode into the slow corkscrew mode.

5. Magnetic drops

The localized curling mode has an interesting topological peculiarity. If we define the z-axis to be the wire axis, the vortex wall has a circular magnetic structure on a cross-section of the wire in the xy-plane. This vortex wall separates two regions of opposite magnetization along the z axis, $m_z = \pm 1$. Under these circumstances the magnetization field, that is assumed to be a directional field with constant magnitude, inevitably contains a point singularity (Bloch point). A Bloch point is a singularity in the sense that no direction of the magnetization can be assigned there for topological reasons. In other words, a Bloch point is a point in the directional field where one can find *any* direction in its close vicinity, i.e. on every sphere that contains the singularity.

A three-dimensional micromagnetic simulation of a magnetic structure containing a Bloch point has been reported by Hertel and Kronmüller [12]. By using different meshes and extrapolating the total energy of the arrangement to the limiting case of infinite discretization density, the authors demonstrated that the magnetic structure is one of the possible metastable states in a ferromagnetic cube. Very recently, an extended study on Bloch points in thin disk has been reported by Thiaville et al. [13].

It has been predicted by Arrott, Heinrich and Aharoni [5], that the curling reversal in a soft magnetic cylinder involves the injection and propagation of such a point singularity. Our micromagnetic simulations confirm and extend this prediction. Fig. 6 shows a series of snapshots of the axial magnetization component on a cross-section through the wire at different stages of the reversal process. The cutplane is located through the middle of the wire along its axis. As can be seen in Fig. 6 the reversal starts close to the perimeter while the core of the vortex remains magnetized antiparallel to the external field. As the reversal proceeds on the boundary, the non-reversed core region becomes narrower. After some time, in this case after 180 ps, a Bloch point is injected into the sample. Since the Bloch point has a much lower mobility than the vortex wall, it lags behind the reversal front. A dynamic equilibrium is

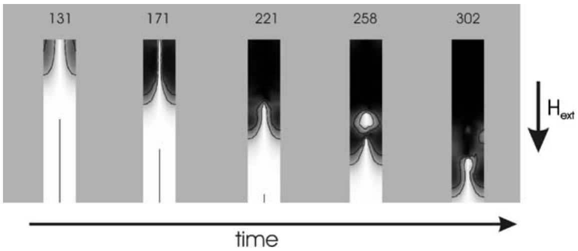

Fig. 6. Formation of magnetic "drops" during the localized curling reversal mode. The images represent the magnetization component parallel to the wire axis (white: up; black: down) on a cutplane through the middle of the wire. The numbers indicate the time elapsed (in ps) after application of the reversed field. Different mobilities of the vortex core and the domain wall on the shell lead to a dynamic equilibrium with periodic disruptions in the reversal front.

established by means of repeated pair creation and annihilation of Bloch points. This results in disruptions of the reversal front which lead to structures that are similar to ordinary "drops". These magnetic drops are isolated, non-reversed regions which are periodically emitted from the reversal front. They contain two Bloch points which annihilate after some characteristic time, thus resolving the "drop". A more detailed study on this surprising feature is given elsewhere [14].

6. Conclusions

Micromagnetic simulations allow for detailed predictions of the reversal dynamics in soft magnetic wires. The reversal occurs by means of one of the previously reported localized reversal modes, either the vortex wall or transverse wall, depending on the wire thickness. In a cone-shaped wire we find a spontaneous reversal mode conversion when the reversal front passes through a region of critical thickness. The reversal of a thick wire involves the injection of a Bloch point. Due to different mobilities of the inner and outer part of the vortex wall, the reversal front disrupts periodically. This leads to magnetic "drops", a surprising new feature of dynamic micromagnetism.

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