

Fast Vortex Core Switching at Moderate Temperatures

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Ferromagnetic vortex core switching is investigated using micromagnetic simulations. For that the OOMMF program is used together with a temperature extension we have developed recently. This is a continuum micromagnetic approach, where the well-known Landau–Lifshitz–Gilbert equation (valid for zero temperature) is replaced by the Landau–Lifshitz–Bloch equation. In our research we simulate switching of a ferromagnetic vortex core in a flat disk (diameter 200 nm, thickness 20 nm) with material parameters that resemble permalloy. Temperatures in the range 400 K to 700 K are considered. Switching itself is caused by application of a very short oscillating magnetic pulse. Parameters used resemble conditions met in the experiment: oscillation period 141 ps (equal to the peak width) and amplitude 60 mT. Surprisingly, no large temperature- or discretization dependence is found. Reasons for that are discussed.

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1. Introduction

A ferromagnetic vortex is an in-plane domain structure with a rotational character except of its very center — called core — where the magnetization points out-of-plane [1]. This magnetic texture has attracted quite a lot of interest recently, possible applications in magnetic memory devices [2] or GHz-frequency generators [3] have been proposed. Vortex core is very thin, usually with a few nm in diameter. Vortex core switching (VCS) can happen either in a quasi-static way — e.g. by applying an orthogonal, slowly increasing magnetic field [4, 5], or dynamically — e.g. by applying magnetic or electric pulses [6, 7], or by applying oscillating magnetic or electric fields [2, 3, 8–10]. In every case the VCS is accompanied by a short presence of a very unstable object — the Bloch point (BP) [6], see Fig. 1. The BP is

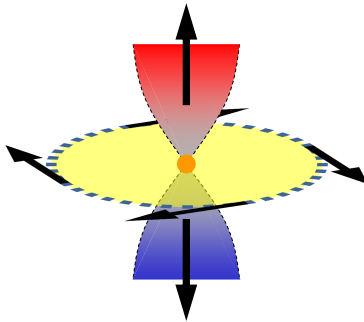


Fig. 1. Schema of a Bloch point — a very unstable object mediating the vortex core reversal. Arrows indicate the magnetization direction close to the Bloch point, placed in the center (orange-marked). Colors are used to stress (i) the vertical tendency close to the vertical axis (red-blue) (ii) the rotational tendency close to the horizontal plane containing the Bloch point (dark yellow).

a mathematical singularity, thus proper description of the VCS is very difficult [4, 5]. Only at an elevated temperature this problem can be avoided [5, 11]. Thus, we present here results of our latest study, where fast VCS in a wide temperature range is simulated.

2. Methods

We follow a temperature-dependent micromagnetic approach, based on the Landau–Lifshitz–Bloch equation of motion [12]. This equation is an extension of the well-known Landau–Lifshitz–Gilbert (LLG) equation of motion for the case of non-zero temperature, $T \geq 0$. It can be written in the form [12]:

$$\dot{\mathbf{M}} = -\bar{\gamma}\mathbf{M} \times \mathbf{H}_{\text{eff}} + \bar{\gamma}\alpha_{\parallel} \frac{M_s}{M^2} (\mathbf{M} \cdot \mathbf{H}_{\text{eff}})\mathbf{M}$$

$$+ \bar{\gamma}\alpha_{\perp} \frac{M_s}{M^2} (\mathbf{M} \times \mathbf{H}_{\text{eff}}) \times \mathbf{M},$$

$$\alpha_{\parallel} = \alpha 2T/3T_C, \quad \alpha_{\perp} = \alpha(1 - T/3T_C).$$

Here, $\bar{\gamma}$ is the gyromagnetic ratio, \mathbf{M} is the magnetization, \mathbf{H}_{eff} is the effective field, M_s is the saturation magnetization at $T = 0$, $M = |\mathbf{M}|$, α is the Gilbert damping constant at the atomic level, T_C is the Curie temperature, and only the case $T \leq T_C$ is considered. The effective field is similar to the case of the LLG equation,

$$\mathbf{H}_{\text{eff}} = \mathbf{H}_d + \mathbf{H}_{\text{ext}} + \frac{2A\nabla^2\mathbf{M}}{\mu_0 M_e^2} - \left(\frac{M^2}{M_e^2} - 1 \right) \frac{\mathbf{M}}{2\chi_{\parallel}},$$

where \mathbf{H}_d and \mathbf{H}_{ext} are, respectively, the demagnetization- and the external field, A is the exchange constant, μ_0 is the vacuum permeability, M_e describes (temperature dependent) equilibrium magnetization length, and χ_{\parallel} is the longitudinal susceptibility [12].

In our research we have simulated a flat disk with material parameters resembling permalloy [5, 11, 13]. Its diameter was 200 nm, its thickness was 20 nm. Fast VCS was achieved by applying a very short (pulse-shaped [14]), rotating in-plane magnetic field, see Fig. 2a.

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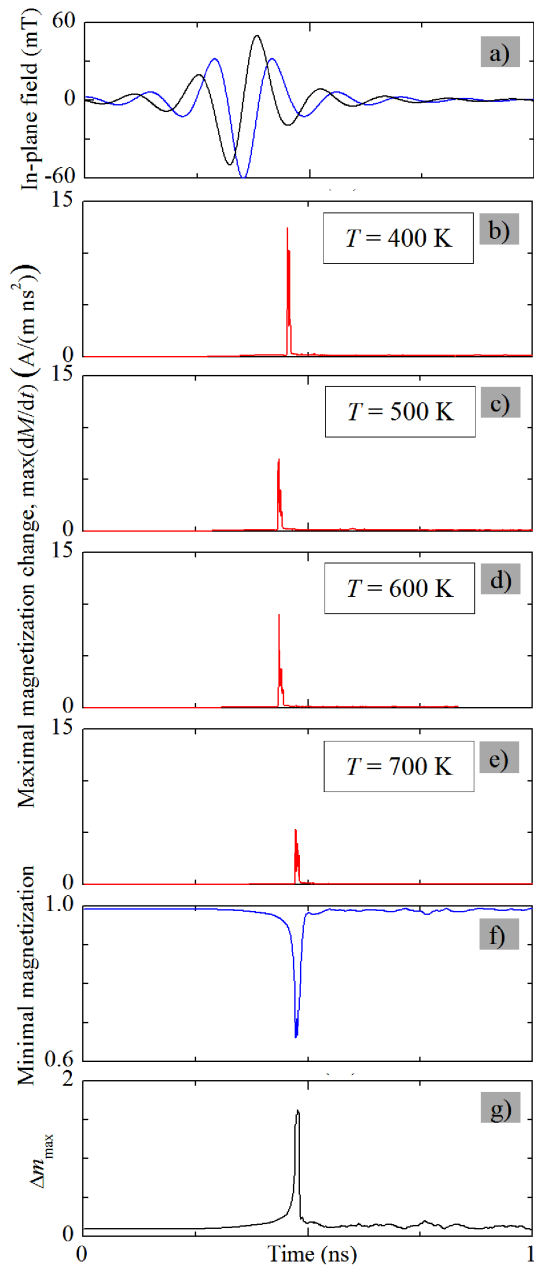


Fig. 2. Applied in-plane magnetic field, pulse-shaped (a). We show here both in-plane field components. Maximum of the magnetization change, $\max(dM/dt)$, for the indicated temperatures (b)–(e). Alternative parameters associated with the switching: minimum magnetization length in the sample (f) and maximal magnetization change between neighboring cells (g) — both normalized; in both cases $T = 700$ K. In all cases discretization grid no. 4 was used.

Thus, sub-100 ps switching was achieved, in accordance with earlier studies [9, 10]. The pulse shape was carefully chosen to mimic the experimentally available conditions, cf. Fig. 2b in Ref. [10]. Such a switching is caused by an excitation of spin waves. Following notation introduced in Ref. [9] we have excited the azimuthal spin wave with

radial mode number $n = 1$ and CW sense of rotation, $m = -1$; initial vortex state had CCW chirality and a positive polarity, $p = 1$. According to the experiment, it is easier to switch the vortex with a CW excitation, in such a case the excitation field is smaller [9]. This was also our case — we used a CW excitation with a period 141 ps. We point out that the peak amplitude we had to use (60 mT) is larger compared to Ref. [10] because of a smaller sample size considered here. According to the literature using appropriate discretization cell size is a crucial point when simulating BP-related phenomena [4, 5, 11, 15]. This is because of the complex nature of this object: when approaching it from opposite directions, the magnetization sign changes, see Fig. 1. Thus, “any direction of the magnetization is present in the close vicinity of a Bloch point” [16]. One has also to account for the small radius of magnetization-squeezing around this point [5, 11]. All this makes the Bloch point calculations very sensitive on the chosen cell size. Thus, we have performed a series of simulations for different grids listed in Table.

TABLE

List of used mesh grids. Every cell was a rectangular prism with dimensions $c_x \times c_y \times c_z$. The simulated disk was orthogonal to the z -axis.

Grid number	c_x [nm]	c_y [nm]	c_z [nm]
1	0.097656	0.097656	2.5
2	0.195312	0.195312	0.625
3	0.392157	0.392157	0.392157
4	0.645161	0.645161	0.645161
5	0.8	0.8	0.8
6	1	1	1

3. Results

Results presented in Fig. 2 are representative for all used grids. Temperature dependence of the switching time can be observed in Fig. 2b–e. Here, the maximum magnetization change across all the cells are plotted, $\max(dM/dt)$ — a handy parameter allowing to define the exact moment of the switching [4, 9, 10]. No special temperature dependence can be seen in Fig. 2. Figure 2f, g shows other possible parameters related to the VCS [5], respectively: minimal magnetization length, normalized, and simulation quality/validity parameter Δm_{\max} [11]. The last one is the maximal difference in magnetization for nearby cells (neighbors), normalized. In Ref. [11], where we have introduced this parameter, we also suggested its maximal value, a signature of appropriate micromagnetic simulations: 0.5. High Δm_{\max} values found in our present study exceed remarkably this threshold. This is true for all temperatures and for all grids and it means that our results might not be reliable, despite using a much finer grid as compared to other reports. This is in our opinion the reason why the results in Fig. 2

have no clear temperature dependence. BP-related simulations seem to be more complex than hitherto expected. One possibility would be to perform simulations at even higher temperatures, where the Δm_{\max} -problem ought to be smaller [11]. An even better approach was suggested recently by Andreas et al. [15]: to combine and perform in-parallel micromagnetic (continuum) simulations with atomistic (discrete) calculations.

4. Summary

We have numerically evaluated fast vortex core switching caused by a short oscillating magnetic field pulse. No remarkable temperature-dependence was found in the investigated region, from 400 K to 700 K. Also, no special grid-dependence was found, despite going down with the discretization cells up to sub-nanometer values. These strange results need further investigations. One cannot, however, exclude that the nature of the Bloch point is more complex than so far expected. Maybe, the continuum micromagnetic approach should be supported/replaced by a discrete atomistic study. Results shown here present challenges that need to be solved and questions that need to be answered while researching the phenomenon of the vortex core switching. Raised questions are important for further vortex studies.

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