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Fast vortex core switching at high temperatures

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ABSTRACT

Fast ferromagnetic vortex core switching is investigated employing micromagnetic simulations. Short pulse (in the range of a few hundreds of picoseconds) of an in-plane oscillating magnetic field is applied to a thin disk (diameter 200 nm and thickness 20 nm) with material parameters resembling permalloy. Fundamental frequency of this excitation field is close to the resonance with the material spin waves. Thermal effects are introduced by replacing the Landau–Lifshitz–Gilbert equation by the Landau–Lifshitz–Bloch equation. Temperature from 300 K to 850 K is considered, just below the Curie temperature $T_C = 870$ K. Calculations are done within the OOMMF simulation framework.

We find that: (i) Period of the field necessary to switch the vortex increases approximately from 141 ps at 300 K to 572 ps for the high-temperature limit. (ii) Amplitude of the field necessary to switch the vortex core decreases roughly from 60 mT to 15 mT – even at high temperatures this amplitude is nonzero, contrary to the case of quasi-static switching. (iii) Time span between the excitation and switching (switching time) seems not to depend on the temperature. (iv) Duration of the switching itself (movement of the Bloch point in the sample) increases from a few picoseconds at low temperatures to tens of picoseconds at high temperatures.

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1. Introduction

A ferromagnetic vortex is an in-plane domain structure with a rotational character except for its very center – called core – where the magnetization points out of plane [1]. It can be found in many magnetic systems, examples being the planar Landau structure [2] or a periodic three-dimensional pattern in cobalt nanowires [3]. The magnetic vortex has attracted some interest recently related to possible application in magnetic memory devices [4] and GHz-frequency generators [5].

Although many magnetic phenomena at the nanoscale have been widely explored, both theoretically and experimentally, the role of temperature is still unknown to a large extent. This subject has recently intensely been studied because of intriguing experimental results. Firstly, laser-assistance allows dense magnetic recording, the so-called heat assisted magnetic recording, due to usage of very hard magnetic materials [6]. This is, of course, of great interest due to possible applications in the information storage industry. Secondly, it has been shown that the laser itself can switch the magnetization, without any external applied magnetic field [7] – this concept is called all-optical magnetic recording. Not every aspect of these findings has already been explained. One of the questions that might be raised is: what magnetic structure is most influenced by the temperature? One of the candidates is the vortex core, another is the Bloch point – a small structure that mediates the vortex core reversal, see below. Within our paper we shed a new light on this topic.

Vortex core is very small, usually a few nanometers in diameter [8]. Vortex core switching (VCS) can happen either in a quasi-static way, e.g., by applying an orthogonal (to the disk), slowly increasing magnetic field [9], or dynamically, i.e., by applying magnetic or electric pulses [10], or by applying oscillating magnetic or electric fields [4,5,11,12]. Many details of the VCS are already well known [13,10]; it is accompanied by short presence of a Bloch point (BP) [14], see Fig. 1. The BP is a mathematical singularity, thus proper description of the VCS is very difficult [9]. Only at elevated temperatures this problem can be avoided [9,14].

Here we present results of our latest study, where fast VCS is achieved by applying oscillating magnetic field pulses. This particular setup leads to a very fast switching [11].

2. Methods

We follow a temperature-aware micromagnetic approach based on the Landau–Lifshitz–Bloch equation of motion [15]. This equation is an extension of the well-known Landau–Lifshitz–Gilbert (LLG) equation for the case of non-zero temperature, $T \geq 0$. It can be written in the form [15]:

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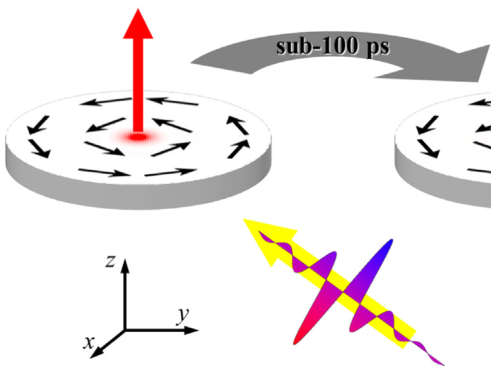

Fig. 1. We consider following process (schema) – flat, ferromagnetic, round island is initially magnetized in a "vortex state", where the central part (core) is pointing upwards (red arrow). After exposing the sample to a short pulse of an in-plane oscillating magnetic field, the core reverses leading to a vortex with the same chirality but opposite polarity (blue arrow).

$$\dot{\vec{M}} = -\bar{\gamma}\,\vec{M}\times\vec{H}_{\mathrm{eff}} + \bar{\gamma}\,\alpha_{\parallel}\frac{M_{\mathrm{s}}}{M^2}(\vec{M}\cdot\vec{H}_{\mathrm{eff}})\vec{M} + \bar{\gamma}\alpha_{\perp}\frac{M_{\mathrm{s}}}{M^2}(\vec{M}\times\vec{H}_{\mathrm{eff}})\times\vec{M},$$
$$\alpha_{\parallel} = \alpha 2T/3T_{\mathrm{C}},$$
$$\alpha_{\perp} = \alpha(1 - T/3T_{\mathrm{C}}). \tag{1}$$

Here, $\bar{\gamma}$ is the gyromagnetic ratio, $\vec{M}$ is the magnetization, $\vec{H}_{\mathrm{eff}}$ is the effective field, M_{s} is the saturation magnetization at $T=0$, $M = |\vec{M}|$, α is the Gilbert damping constant at the atomic level, T_{C} is the Curie temperature, and only the case $T \le T_{\mathrm{C}}$ is considered. This approach is already well established and frequently used when thermal effects play an important role, e.g. laser-induced phenomena are successfully described in that way [16]. Other applications can also be found in the literature, like the spin Seebeck effect and its influence on the domain wall motion [17], or description of the ferromagnetic resonance as a function of temperature [18]. Effective field entering Eq. (1) is computed in a similar way to the case of the LLG equation. In the Landau–Lifshitz–Bloch approach it has the dependence [15]

$$\vec{H}_{\mathrm{eff}} = \vec{H}_{\mathrm{d}} + \vec{H}_{\mathrm{ext}} + \frac{2A\nabla^2\vec{M}}{\mu_0 M_{\mathrm{e}}^2} - \left(\frac{M^2}{M_{\mathrm{e}}^2} - 1\right)\frac{\vec{M}}{2\chi_{\parallel}},$$

where $\vec{H}_{\mathrm{d}}$ and $\vec{H}_{\mathrm{ext}}$ are the demagnetization and the external field, respectively, A is the exchange constant, μ_0 is the vacuum permeability, M_{e} describes equilibrium magnetization, and $\chi_{\parallel}$ is the longitudinal susceptibility. There is no anisotropy term as we focus our attention on a soft material. The LLB approach was implemented as an extension to the OOMMF simulation package [19].

Three material parameters with values representative for permalloy have an important temperature dependence. Magnetization equilibrium, $M_{\mathrm{e}}(T)$, reflects the well-known M–T dependence [20], where the magnetization continuously decreases from 860 kA/m at zero temperature to zero at the Curie temperature of 870 K. In the Landau–Lifshitz–Bloch approach the exchange "constant" A is not really a constant, it decreases with temperature – from 13 pJ/m to zero at T_{C}. What brings a *new behavior* is the parallel susceptibility $\chi_{\parallel}$. This parameter describes the possibility to drive the magnetization magnitude away from its equilibrium value M_{e}, usually to lower values. The nonzero value of $\chi_{\parallel}$ leads to the magnetization squeezing effect (M-squeezing effect), a situation when locally $|\vec{M}| < M_{\mathrm{e}}$. This happens inside a domain wall [21], inside a vortex core [22], and to the highest extent in the vicinity of the BP [9,14]. Parallel susceptibility increases continuously being zero at $T=0$ and diverging at T_{C}. To give the reader some feeling about its role, we list some values: $\chi_{\parallel}(300\ \mathrm{K}) = 0.00057$, $\chi_{\parallel}(600\ \mathrm{K}) = 0.0023$, $\chi_{\parallel}(800\ \mathrm{K}) = 0.010$, and $\chi_{\parallel}(850\ \mathrm{K}) = 0.035$. Graphical dependence of these parameters can be found in Ref. [23].

We have simulated a flat disk placed in the *xy*-plane. Its diameter was 200 nm, its thickness 20 nm. Fast VCS was achieved by applying a very short, in-plane rotating magnetic oscillation. We wanted to design conditions met in the experiment. For that we analyzed the setup described in Ref. [11]. We evaluated the shape of the excitation field (Ref. [11, Fig. 2]) and compared it with the Lorentz- and Gauss-envelope function. In this way we ended up with a Lorentz pulse multiplied by a sinusoid. The full width at half maximum of the pulse was equal to the period of the sinusoid. Excitation with such a short pulse of magnetic field leads to sub–100 ps switching if strong enough field is applied [11].

The switching is caused by an excitation of azimuthal rotating spin waves. They can be distinguished by their rotation sense: counterclockwise (CCW) or clockwise (CW) [24]. They have different frequencies because the symmetry is broken by the chirality of the vortex. We have chosen the following initial vortex state: CCW chirality and a positive direction of the core (polarity) – see left side of Fig. 1. According to the experiment, it is easier to switch such vortex with a CW excitation, in such case the excitation field is smaller [11]. This was also our case. On the other hand, a short pulse contains a wide spectrum of different frequencies. To excite (mainly) a CW wave, the excitation should have a larger period to avoid a CCW excitation [11]. We have studied the periods of the CW and CCW spin waves separately for each considered temperature. Then, we performed a series of simulations for the room temperature and found a period of the pulse-formed wave that has lowest switching amplitude – 141 ps. Resonant CCW and CW spin waves at the room temperature have periods of 96 ps and 117 ps, respectively. We have used this ratio of periods for other temperatures and set up the excitation period p_{exc} according to the equation

$$p_{\mathrm{exc}}(T) = 130.5\frac{p_{\mathrm{CCW}} + p_{\mathrm{CW}}}{96 + 117} + \frac{p_{\mathrm{CW}} - p_{\mathrm{CCW}}}{2}, \tag{2}$$

where p_{CCW} and p_{CW} are (temperature dependent) periods of CCW and CW spin waves, respectively. Values of p_{exc}, p_{CCW}, and p_{CW} are shown in Fig. 3a.

According to the literature using appropriate discretization cell size is crucial for simulating BP-related phenomena [9,14] due to a complex nature of this object: when approaching it from opposite directions, the magnetization sign changes. Thus, "any direction of the magnetization is present in the close vicinity of a Bloch point" [25]. At higher temperatures one has to consider how abrupt the change is in the magnetization close to the BP, i.e., what volume is affected by the M-squeezing effect. All this makes calculations involving a BP very sensitive to the chosen cell size. To check the cell size-dependence of our results, we have performed simulations for different grids listed in Table 1.

3. Results

3.1. Time dependence

The typical results of our simulation are shown in Fig. 2. An applied field pulse is shown in Fig. 2a. We pointed out that the peak amplitude we had to use (40 mT for $T = 500$ K) is larger compared to the experiment [11] because of a smaller sample size considered here. Some time after the pulse the vortex core switches; in Fig. 2b this shift is roughly 500 ps and we call it a switching time t_{sw}. An exact moment of the switching can be precisely defined by observing the maximal rate of change of the magnetization across all simulation cells, $|\vec{M}'|_{\max} = \max(|\mathrm{d}\vec{M}/\mathrm{d}t|)$, see, e.g., Ref. [11]. Figs. 2c–h present in details the vicinity of the

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