Micromagnetic simulation of magnetization reversal in rotational magnetic fields

J. Fidler*, T. Schrefl, W. Scholz, D. Suess, V.D. Tsiantos

Institute of Applied and Technical Physics, Vienna University of Technology, Wiedner Hauptstrasse 8–10, A-1040 Wien, Austria

Abstract

Transient magnetization states during switching are investigated numerically in thin Co nano-elements of square (100 \times 100 \text{nm}^2), rectangular (100 \times 300 \text{nm}^2) and circular (100 \text{nm} diameter) shapes with a thickness of 20 \text{nm}. Switching dynamics are calculated for external fields applied instantaneously and for rotational fields with field strengths in the order of the static critical field ($H = 0.20$–$0.32 \text{J}_s/\mu_0$). Reversal in the unidirectional field proceeds by the nucleation and propagation of end domains toward the center of the particle. It is found that the switching time strongly depends on the Gilbert damping parameter $\alpha$. Small values of $\alpha$ ($\leq 0.1$) lead to shorter switching times of $0.1$–$0.3 \text{ns}$. Reversal in rotational fields involves inhomogeneous rotation of the end domains toward the rotational field direction. Depending on the damping parameter, fast switching times ($\leq 0.1 \text{ns}$) are obtained by increasing the field strength to $H = 0.5J_s/\mu_0$. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Numerical micromagnetics; Precessional switching; Rotational fields; Co nano-elements

1. Introduction

In mesoscopic and nanostructured magnets the switching fields and times which are in the order of nano- to picoseconds are controlled by the choice of the geometric shape of the magnets, the intrinsic properties and the orientation and strength of the applied field. Understanding and controlling the magnetic switching dynamics of magnetic particles is the major challenge for technological applications [1]. We present solutions for the switching of uniaxial Co nano-elements under the presence of an unidirectional field and for comparison a rotational field with variable rotation speed. We use Landau–Lifshitz–Gilbert dynamics to characterize the reversal mechanism [2]. Thermal fluctuations, defects and other forms of disorder as well as eddy currents occurring during the fast switching process are not included in the simulations.

2. Micromagnetic concept

We have used a three-dimensional (3D) numerical micromagnetic model with tetrahedral finite elements with a constant edge length of 2.5 and 5 nm to study thin nanostructured Co elements with different shapes. The mesh was a 3D finite element grid with 3D spins interacting through the exchange interaction, magnetostatic, anisotropy and external fields [2]. Fig. 1 shows the square, rectangular and dot elements with dimensions...
used and assuming uniaxial magnetocrystalline anisotropy parallel to the y-axis. Our simulation model combines a hybrid finite element/boundary element method [3] for the magnetostatic field calculation with a BDF/GMRES method for the time integration of the Landau–Lifshitz–Gilbert equation of motion [4,5]. The effective field at the nodal points of the irregular finite element mesh is approximated by the box scheme [6]. A semi-implicit time integration scheme was applied to calculate the magnetization reversal dynamics. Backward difference schemes allow much larger time steps and thus the required CPU time remains considerably smaller than with the Runge–Kutta method. Since the stiffness arises mainly from the exchange term, the demagnetizing field can be treated explicitly and thus is updated after a certain time interval. The numerical results show that the Gilbert damping constant, $\alpha$, which was varied between 1.00, 0.10 and 0.02 drastically changes the reversal mode. In comparison to the application of an instantaneous static field a rotating magnetic field with a frequency of 1 and 10 GHz was applied in the $(x,y)$-plane, and the calculations were started after saturation parallel to the $y$-direction (easy direction).

3. Results and discussion

The numerical simulations were performed for different geometries and damping parameters. The quasi-static simulation with field steps of $\mu_0\Delta H = 0.02$ T after saturation showed that switching occurred at the critical fields of 280, 310 and 450 kA/m for the square, rectangular and circular dot geometries, respectively. Fig. 2 compares the time evolution of the polarization for different damping constants. For $\alpha = 1$ switching occurs only after a waiting time of about 1.5, 1.0 and 0.5 ns for square, rectangular and dot shaped elements, respectively. For $\alpha = 0.02$ the waiting time reduces to about 0.3, 0.2 and 0.1 ns. These results are in agreement with previously reported switching times of ultra-thin magnetic films. Kikuchi [7] investigated the reversal time of a single domain sphere and a single domain thin film and found a minimum reversal time for $\alpha = 1$ and

Table 1
Number of surface/volume finite elements for different finite element edge lengths

<table>
<thead>
<tr>
<th>Nano-element shape</th>
<th>2.5 nm</th>
<th>5 nm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Square</td>
<td>8960/64000</td>
<td>2240/8000</td>
</tr>
<tr>
<td>Rectangular</td>
<td>21760/96000</td>
<td>6080/24000</td>
</tr>
<tr>
<td>Circular dot</td>
<td>8276/85797</td>
<td>1784/6373</td>
</tr>
</tbody>
</table>

100 $\times$ 100 $\times$ 20 nm$^3$, 100 $\times$ 300 $\times$ 20 nm$^3$, and 100 nm in diameter after discretization into finite elements. The total number of the elements varied from 8157 to 94,073 depending on the edge length and shape of the nano-element. Table 1 summarizes the number of surface and volume elements after discretization. Typical material parameters, such as $J_s = 1.76$ T, $K_1 = 0.45$ MJ/m$^3$, $K_2 = 0.15$ MJ/m$^3$ and $A = 13$ pJ/m have been
0.1 for the sphere and the thin film, respectively. The micromagnetic simulations revealed no difference between the calculations using the finite element edge length of 2.5 and 5 nm. Fig. 3a shows the nucleation and expansion of reversed domains during magnetization reversal at a constant reversed field of $H_{\text{ext}} = 280 \text{kA/m}$ parallel to the $-y$-direction. For $\alpha = 0.1$ the element switches by nonuniform rotation in 0.7 ns. Fig. 3b shows that the transient states during magnetization reversal in the high-frequency rotational field ($H_{\text{rot}} = 280 \text{kA/m/1 GHz}$) differ from the ones of Fig. 3a. Under the influence of the rotating field, the magnetization starts to rotate near the ends followed by the reversal of the center.

In the case of very fast switching ($H_{\text{rot}} = 280 \text{kA/m/10 GHz}$) the magnetization of only small regions inside the nano-element is able to follow the external field direction (Fig. 4a). Com-
plex magnetization distributions within the nanoelement occur (Fig. 4b). Inhomogeneous magnetization rotation occurs inside the square, if the field strength is increased to $H_{\text{rot}} = 700 \text{kA/m}$ at 10 GHz (Fig. 5b). This results in about 80% alignment of the polarization parallel to the rotating field and a slight delay after 10 cycles of field rotation (Fig. 5a). The angle between rotating field vector and total polarization vector increases for large damping constant $\alpha = 1$. The numerical simulations show that the switching behavior is also strongly influenced by the geometry of the nano-element. The magnetization reversal of the rectangular-shaped nano-element is found to proceed in a very similar way as in the square element. Under an instantaneously applied, unidirectional field the switching starts after nucleation at opposite corners (Fig. 6a). The application of a rotational field leads to an inhomogeneous rotation of the magnetization near the flat ends of
the element reducing the magnetostatic energy (Fig. 6b). Micromagnetic simulations of the magnetization reversal in the circular Co nano-magnet (Fig. 7) show that the inhomogeneous rotation in a rotational field also leads to partial flux-closure structures and therefore facilitates the switching by reduced switching times.

4. Conclusion

Micromagnetic modeling of the magnetization reversal process of Co nano-elements show that the dynamics of the switching behavior in an instantaneously applied, unidirectional field differs from the one in a rotating field, especially at high frequencies. The shape and the Gilbert damping parameter determine the critical switching field and time.

Acknowledgements

This work was supported by the Austrian Science Fund (P13260-TEC and Y-132 PHY).

References