FE-Simulation of fast switching behavior of magnetic nanoelements

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ABSTRACT

Numerical micromagnetics is an essential tool to optimize magnetic storage media, spin electronic devices, such as MRAM and microsensors. The application of these devices requires a profound knowledge of the reversal mechanism. In nanostructured magnets the switching fields and times which are in the order of pico- to nanoseconds are controlled by the geometric shape of the magnets, the intrinsic properties and the orientation and strength of the applied field. The differences of the magnetization reversal processes under various applied field profiles H(t), such as sweep field, constant unidirectional field, pulsed field and rotational field are studied using a 3D hybrid finite element/boundary element micromagnetic model. 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. The Gilbert equation of motion is solved to investigate the reversal dynamics of NiFe and Co nanoelements. The damping parameter $\alpha(H)$ drastically influences the critical switching field and time.

Keywords: Numerical micromagnetics, Precessional switching, Magnetization reversal, Nanomagnets.

1 INTRODUCTION

Magnetic switching of mesoscopic and nanostructured thin film elements, nanowires and particles becomes increasingly important in magnetic storage, microsensors and magneto electronic devices. Nanostructured magnetic elements may be used as storage elements [1], field sensors [2], or logic gates [3]. The functional behavior of these devices depends on the domain configuration and the reversal mechanism. Recently, the domain structure and the switching processes of circular nanomagnets were investigated using magnetic imaging and numerical micromagnetics. Cowburn and co-workers [4] measured the hysteresis loop of thin circular platelets. They reported a decrease of the coercive field with decreasing diameter of the nanomagnet. Detailed distribution of the magnetization inside the nano- and mesoscopic structured elements is obtained through numerical integration of the Landau-Lifshitz equation. Our work applies numerical micromagnetic modeling to investigate the switching process of isolated and interacting circular, square, dot shaped nanomagnets and nanowires. The results provide details of the magnetization distribution during irreversible switching depending on the shape and size of the elements. With decreasing size of the magnetic structures, thermally activated reversal process becomes significant. Thermally induced reversal may influence the writing process as well as the long-term stability of written bits in magnetic recording.

2 MICROMAGNETIC FINITE ELEMENT MODEL

We have used a 3D numerical micromagnetic model with tetrahedral finite elements to study thin (10-20 nm) square, rectangular and dot shaped structures with a length or diameter of about 100-300 nm comparing the influence of magnetocrystalline anisotropy on the switching behavior (Fig.1). The reversal process of single-crystalline elements is compared with granular elements with random orientation of the grains. The granular thin film element is modeled with columnar grains generated from Voronoi polyhedrons. The polyhedral grains are discretized into tetrahedral finite elements with a constant edge length between 2.5 nm and 5 nm. Previous micromagnetic studies [5] have shown that the results are independent of the mesh size, if the finite element size is smaller than the exchange length, which is determined, by the Neél or Bloch wall parameters.
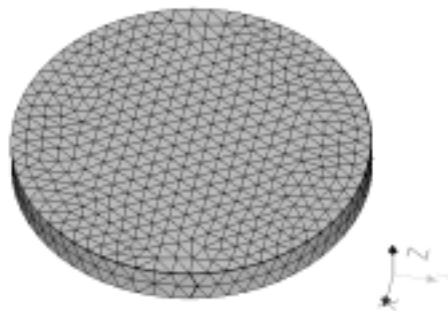

Figure 1: Finite element mesh of a circular dot shaped nanoelement with 100 nm in diameter and 20 nm thickness for an edge length of 5 nm. The surface mesh used for the boundary element method is given as a wireframe.

The basic geometry of the granular thin film element is shown in Fig.2. The thin, nanostructured square element with dimensions of $100 \times 100 \times 10$ nm^3 consists of 100 irregular shaped grains with an average diameter of about 10 nm. For the simulations we used two sets of materials

parameters: The $Ni_{80}Fe_{20}$ nanoelement has the following material properties: $J_s=1$ T, $K_1=K_2=0$, A=13 pJ/m. The polycrystalline Co square element consists whether of 3D randomly oriented grains with uniaxial magnetocrystalline anisotropy or of 2D textured grains with random orientation of the easy axes within the film plane. For the simulations the intrinsic bulk properties of hcp-Co were used ($J_s=1.76$ T, $K_1=0.45$ MJ/m^3, $K_2=0.15$ MJ/m^3, A=13 pJ/m).
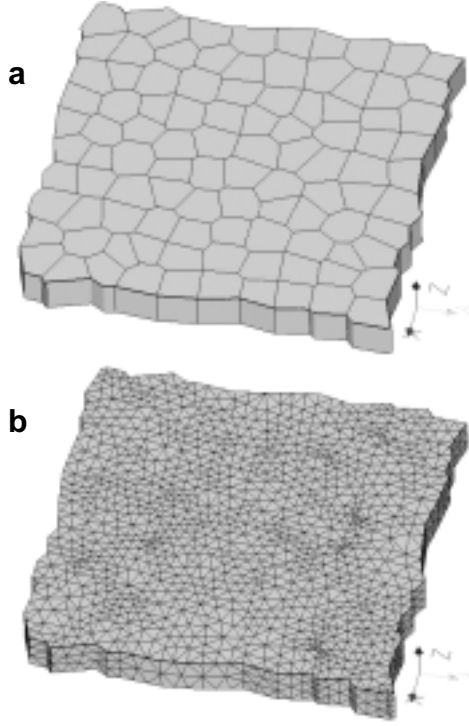

Figure 2: (a) Schematic granular structure of a square thin film element of 100x100x10 nm^3 consisting of 100 grains with a grain size of about 10 nm. (b) Discretization into tetrahedral finite elements used for the numerical simulation of the switching behavior of randomly oriented Co grains.

Three different external field profiles were used for the simulations. In the first case a monotone, increasing "sweep" field with constant sweep rate (2.0 J_s/μ_0 per ns) was uniformly applied along the –y direction until complete magnetization reversal took place. Second, a homogeneous field was applied after rising the field from zero to h=0.1 and h=0.2 J_s/μ_0 (80 and 160 kA/m for NiFe and 140 and 280kA/m for Co) after 0.05 and 0.10 ns, respectively. Third, in comparison a half cycle (0.05 ns) of a rotating magnetic field with a frequency of 10 GHz was uniformly applied in the (x,y)-plane.

The time evolution of the magnetization at each nodal point of the finite element mesh was calculated using the Gilbert equation of motion [6], which describes the physical path of the magnetic polarization **J** towards equilibrium [7].

$$\frac{d\mathbf{J}}{dt} = -\left|\gamma_0\right|\mathbf{J}\times\mathbf{H}_{eff} + \frac{\alpha}{J_s}\mathbf{J}\times\frac{\partial\mathbf{J}}{\partial t} \qquad (1)$$
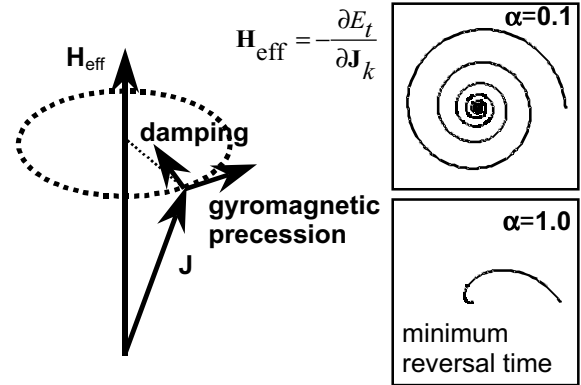

Figure 3: Damped gyromagnetic precession motion of a single magnetic polarization vector **J** towards the effective magnetic field $\mathbf{H}_{eff}$ according to the Gilbert equation of motion.

At each time step, which is in the order of fs, the effective field term H_{eff} include the applied field, the exchange field, the magneto-crystalline anisotropy field and the demagnetizing field. The effective field $\mathbf{H}_{eff}$ is the negative functional derivative of the total magnetic Gibb's free energy E_t of the system. The term γ_0 is the gyromagnetic ratio of the free electron spin and α is the damping constant. The first term on the right hand side of equation (1) accounts for the gyromagnetic precession of the magnetic polarization **J**, the second term arises from viscous damping (Fig.3). At high damping the magnetization rotates more or less directly towards the field direction, as the second term is dominant. If the precession term becomes dominant, the polarization precesses several times around the field direction before it reaches equilibrium. In order to apply various profiles for the external field or study the effect a rotating external field, the strength and direction of the external field is treated as a continuous function of time. To solve the Gilbert equation numerically the magnetic particle is divided in finite elements. Our simulation model combines a hybrid finite element/boundary element method for the magnetostatic field calculation [8]. The scalar potential on every node point of the finite element mesh is calculated. The demagnetizing field, which contributes to the effective field, is the negative derivative of the scalar potential. The effective field $\mathbf{H}_{eff,k}$ at the node point i of an irregular finite element mesh can be approximated using the box scheme for $V_k\rightarrow0$ (Fig. 4)

$$\mathbf{H}_{eff,k} = -\left(\frac{\delta E_t}{\delta\mathbf{J}}\right)_k = -\frac{1}{V_k}\frac{\partial E_t}{\partial\mathbf{J}_k} \qquad (2)$$

where V_k is the volume of the surrounding node k.

The discretization of the Gilbert equation leads to an ordinary differential equation for every node for each component. For the time integration of the Landau-Lifshitz-Gilbert equation of motion a combination of a backward differentiation formula method with the scaled preconditioned incomplete generalized minimum residual method was used [9,10].
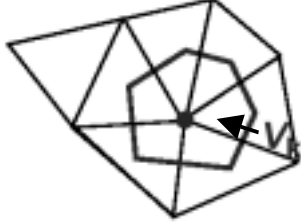

Figure 4: Schematic representation of the volume V_k used in the box scheme.

Previous micromagnetic simulations have shown that the damping parameter α strongly influences the switching time [11]. Shorter switching times are obtained at low external field strength values ($h < 0.5$ J_s/μ_0). In the present study the Gilbert damping parameter was kept constant to $\alpha=0.1$. Due to the small size, eddy currents are considered to be small and therefore are neglected.

3   NUMERICAL RESULTS AND DISCUSSION

The numerical simulations were performed for different geometries and damping parameters. The magnetization patterns of Fig.5 show the transient magnetization states during switching of circular dot shaped $Ni_{80}Fe_{20}$ elements with different diameters and thickness for a damping parameter of $\alpha=1.00$. First, a large field is applied to saturate the nanolement. After reducing the field to zero the dot relaxes toward equilibrium. To reduce the strayfield energy the magnetization tends to be aligned parallel to the surface. The external switching field is applied instantaneously to the saturated state. The particle size has strong influence on the switching time and switching behavior. Although the single domain state has the lowest energy in equilibrium the particle with a diameters larger than 100 nm forms an inhomogeneous state during reversal. The numerical simulations show that for small switching fields inhomogeneous magnetization rotation processes are dominant, whereas for a large field strength complex, inhomogeneous reversal processes (small damping parameter α) and nucleation and expansion of reversed domains (large α) are responsible for the different switching behavior.

The influence of the uniaxial magneto-crystalline anisotropy parallel to the external field direction leads to reduced switching times. The switching time of a circular Co dot is reduced to values less than 0.2 ns.
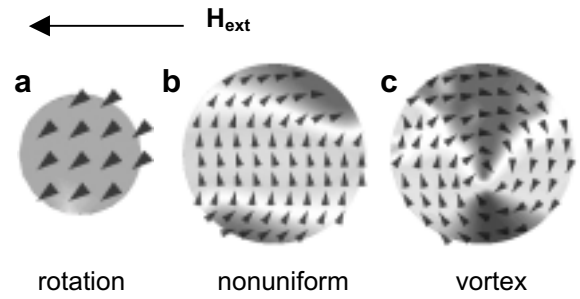

Figure 5: Transient magnetization states during switching of $Ni_{20}Fe_{80}$ circular dots for $\alpha=1.00$ with various diameter and thickness (a) 55 nm diameter, 10 nm thickness, (b) 110 nm diameter, 10 nm thickness (c) 110 nm, 15 nm thickness. The field strength was 8 kA/m.

Micromagnetic modeling of the magnetization reversal process shows that the dynamics of the switching behavior in a constant reversed field differs from the one in a rotating field, especially at high frequencies. Reversal in the unidirectional field proceeds by the nucleation and propagation of end domains towards the center of the element. The switching time strongly depends on the Gilbert damping parameter α. Small values of α (≤ 0.1) lead to shorter switching times at small field strength. Materials with uniaxial anisotropy (Co), require larger field, but exhibit shorter switching times.
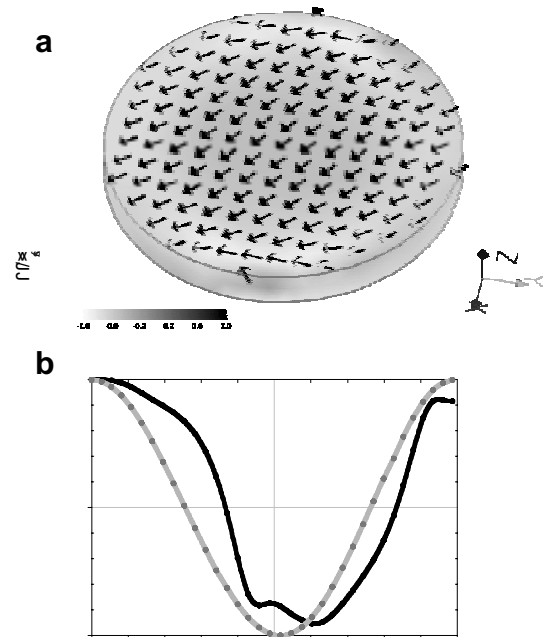

Figure 6: (a) Incoherent magnetization rotation at t=0.07 ns inside the Co square element at $H_{ext}= 450$ kA/m (h=0.32 Js/μ_0). (b) Time evolution of the polarization during the application of a rotating field at 10 GHz starting from the +y-direction. $\alpha = 0.10$.

Under the influence of a constant, rotating field the magnetization tries to follow the external field direction and starts to rotate near the flat ends of the square reducing the magnetostatic energy, followed by the reversal of the center. In the case of very fast switching and small field strength the magnetization of only small regions inside the nanoelement is able to follow the external field direction. Incoherent magnetization rotation occurs inside the square, if the field strength is increased to 0.32 J_s/μ_0 at 10 GHz (Fig.6a). This results for the Co dot with 100 nm diameter in about 95% alignment of the polarization parallel to the rotating field and a slight phase shift between the external field and the total polarization vector (Fig.6b). The angle between the rotating field vector and the total polarization vector increases for large damping constant α=1.00. Micromagnetic simulations of the magnetization reversal 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.
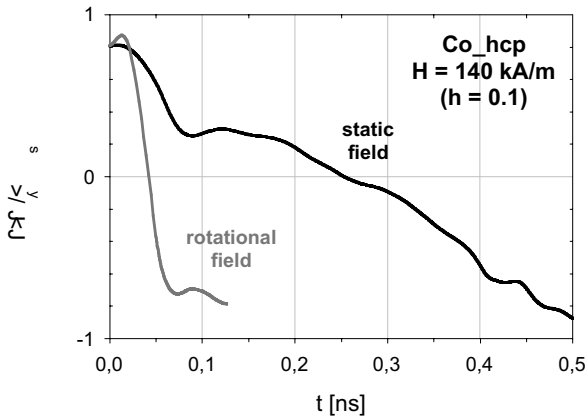

Figure 7: Comparison of the time evolution of the polarization inside the polycrystalline Co square during the application of a unidirectional field and a rotating field at 10 GHz for H_{ext}= 140 kA/m (h=0.1 J_s/μ_0) for α = 0.1.
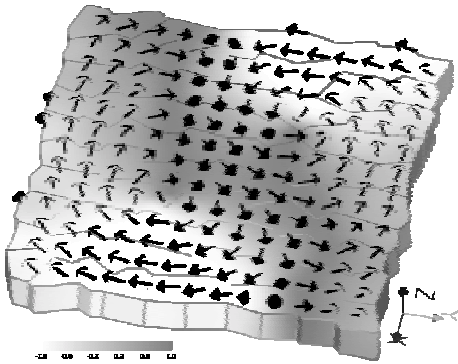

Figure 8: Magnetization distribution within the granular Co square during the switching process (<J_y>=0) in an uniformly applied field for H_{ext}=140 kA/m (h=0.1 J_s/μ_0) occurring at t=0.27 ns.

Figure 7 shows that faster switching occurs in a granular Co element of 100 x 100 nm^2 containing 100 randomly oriented grains, if a rotational field of 10 GHz and H_{ext}=0.10 J_s/μ_0 is applied in the (x,y) plane. A damping parameter of α=0.1 was used in the numerical simulations.

4 CONCLUSIONS

In mesoscopic and nanostructured magnets the switching fields and times that are in the order of pico- to nanoseconds 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. Micromagnetic modeling of the magnetization reversal process of meso- and nanoscopic 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. Comparing the transient magnetization states during reversal and the switching time of permalloy and Co elements, faster switching is obtained in materials with uniaxial anisotropy neglecting eddy current effects. The shape and the Gilbert damping parameter determine the critical switching field and time.

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