Reversal Dynamics of Interacting Circular Nanomagnets

Dieter Suess, Thomas Schrefl, Josef Fidler, and Vasillios Tsiantos

***Abstract*—The Gilbert equation of motion is solved to investigate the reversal dynamics of interacting circular NiFe nanoelements. During magnetization reversal of isolated circular nanomagnets inhomogeneous transient states are formed. The exchange energy of the intermediates states, which is a measure for the uniformity of the magnetization, increases with decreasing Gilbert damping constant or increasing applied field. The magnetostatic interactions lead to a further enhancement of the nonuniformity during reversal of interacting nanomagnets.**

***Index Terms*—Magnetization reversal, magnets, micromagnetics, nanostructured.**

I. Introduction

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 of the nanomagnets. 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 platlets. They reported a decrease of the coercive field with decreasing diameter of the nanomagnet. The influence of magnetostatic interactions on the hysteresis of an array of circular nanomagnets was demonstrated in [1]. A reduction of the lattice spacing gives rise to shape anisotropy which increases the coercivity measured parallel to the long axis of the chain. Our work applies numerical micromagnetic modeling to investigate the switching process of isolated and interacting circular nanomagnets. The results provide details of the magnetization distribution during irreversible switching. In addition, the influence of the diameter of the nanomagnet and the effect of the Gilbert damping constant on the switching time are investigated.

II. Method and Model

The theoretical treatment of magnetization dynamics starts from the Gilbert equation [5],

$$\frac{d\mathbf{J}}{dt} = -\gamma_0 \mathbf{J} \times \mathbf{H}_{\text{eff}} + \frac{\alpha}{J_s}\mathbf{J} \times \frac{\partial \mathbf{J}}{\partial t}$$

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Fig. 1. Finite element model of a chain of circular nanodots. The surface mesh used for the boundary element method is given as a wireframe.

which describes the physical path of the magnetic polarization $\mathbf{J}$ toward equilibrium. The effective field $\mathbf{H}_{\text{eff}}$ is the negative functional derivative of the total magnetic Gibb's free energy, which can be expressed as the sum of the exchange energy, the magneto-crystalline anisotropy energy, the magnetostatic energy, and the Zeeman energy. γ_0 is the gyromagnetic ratio of the free electron spin. The damping constant α considers phenomenologically the relaxation toward equilibrium. All contributions to $\mathbf{H}_{\text{eff}}$, except the demagnetizing field, depend only locally on the magnetic polarization or its spatial derivatives. To avoid the calculation of the second derivatives which occurs in the analytical expression of the exchange field, it is approximated using the a box scheme

$$\mathbf{H}_{exch,\,i} = -\left(\frac{\delta E_{exch}}{\delta \mathbf{J}}\right)_i = \frac{1}{V_i}\frac{\partial E_{exch}}{\partial \mathbf{J}_i}, \quad \text{for } V_i \to 0,$$

where V_i is the surrounding volume of the node$_i$, such that

$$\sum_i V_i = V \quad \text{and} \quad V_i \cap V_j = 0 \text{ for } i \neq j.$$

The discretization of the LLG equation leads to three ordinary differential equations for each node for each component. In the case of a stiff problem it is advisable to use a backward differentiation formulae (BDF) for time integration, for the non stiff-case Adams [6] method was found to be appropriate. The BDF method, which is a implicit time integration scheme, leads to a system of nonlinear equations at every time step. After applying the Newton method one obtains a system of linear equations which is solved using the scaled preconditioned incomplete generalized minimum residual method (SPIGMR) [7], [8] based on (GMRES) [9].

Fig. 1 gives the finite element model of an array of interacting nanodots. The circular nanomagnets with a diameter of 110 nm are placed on a pitch of 135 nm. The thickness of the magnets is 10 nm. The circular platelets are divided into tetrahedral finite elements. The mesh size of 5 nm is equal to the exchange length of permalloy ($J_s = 1$ T, $A = 10^{-12}$ J/m). No mesh is required outside the ferromagnetic elements, since the magnetostatic interactions are taken into account with a boundary element method [10].

TABLE I
SWITCHING TIMES (ns) FOR DIFFERENT PARTICLE SIZES, STRENGTHS OF THE APPLIED FIELD AND DAMPING CONSTANTS

Switching time (ns)	55nm		110nm		220nm	
	α = 0.1	α = 1	α = 0.1	α = 1	α = 0.1	α = 1
H=5.57kA/m	0.84	5.23	0.88	6.03	1.04	7.10
H=7.96kA/m	0.66	3.67	0.69	4.16	0.89	5.08

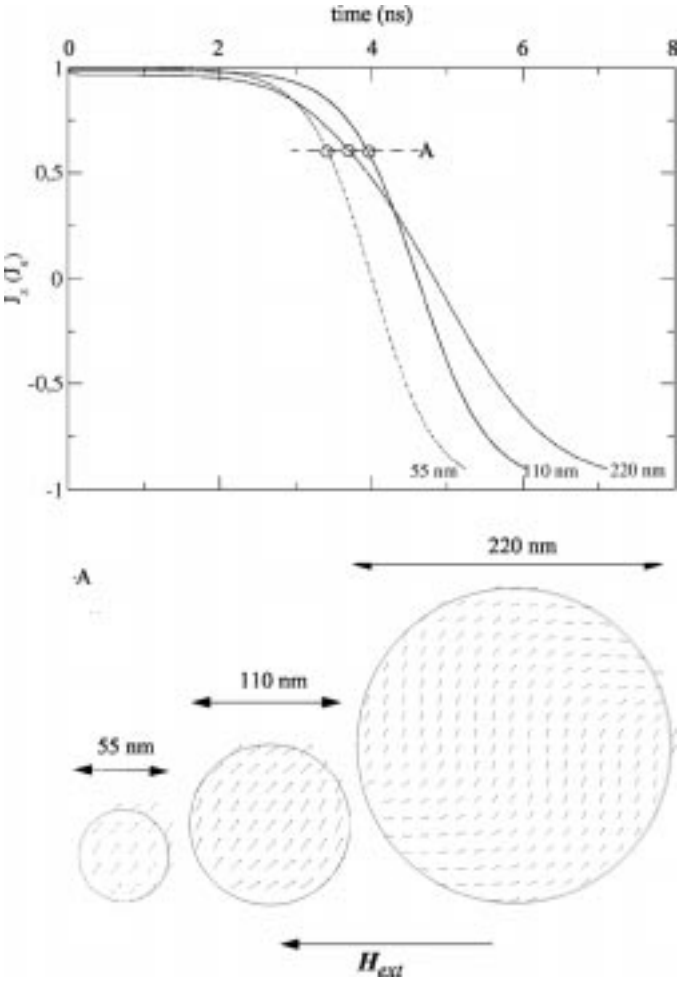

Fig. 2. Top: Magnetization component parallel to the field direction as a function of time for different diameters of the nanomagnet. Bottom: Transient magnetic states for $J_z/J_s = +0.6$.

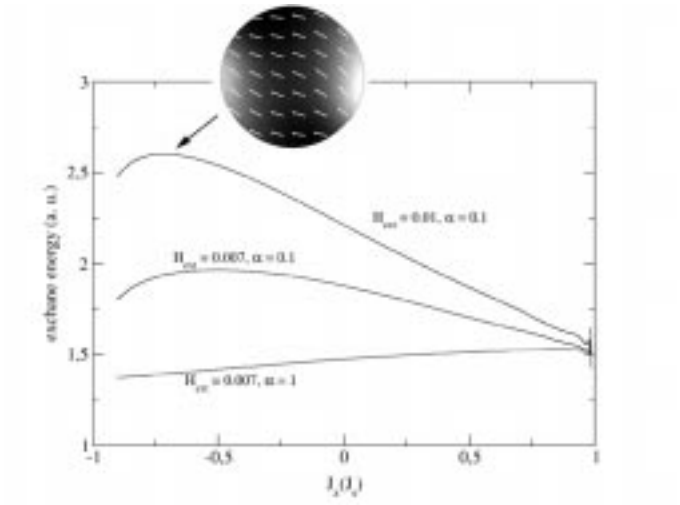

Fig. 3. Non-uniformity of the magnetic states during reversal: The plot gives the exchange energy as a function of J_z/J_s for different applied fields and damping constants. The external field is given in units of $2K_1/J_s$.

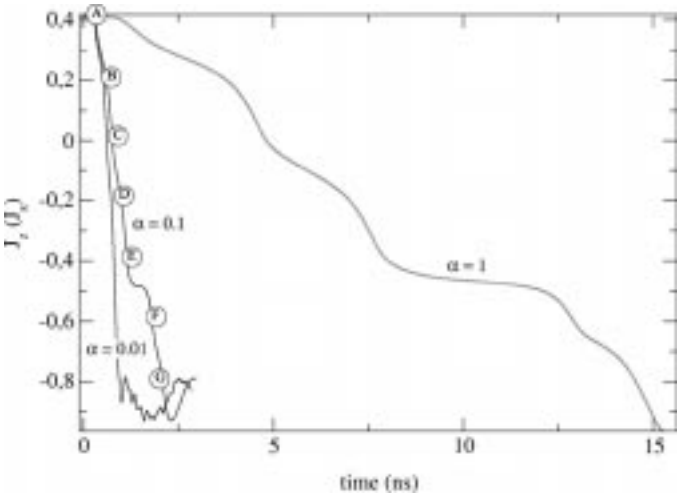

Fig. 4. Magnetization component parallel to the long axis of the array as a function of time for three different values of the Gilbert damping constant. The circles refer to the magnetization patterns of Fig. 5.

III. NUMERICAL RESULTS

A. Single Dot Reversal

The diameter of the dot is varried (55 nm, 110 nm and 220 nm) whereas the thickness remains constant 10 nm. First, a large field is applied to saturate the particle. 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. Table I compares switching times for different particle diameters, damping constants and strengths of the external field. The switching time measures the time from applying the external field until the magnetization parallel to the external field (J_z) becomes smaller than -0.9.

For the weaker damped dot ($\alpha = 0.1$) the switching time increases only about 10% as the particle diameter changes from 55 nm to 220 nm. The particle size has much more influence on the switching time for $\alpha = 1$. Fig. 2 shows nonequilibrium states during reversal for different particle diameters. Although the single domain state has the lowest energy in equilibrium the particle with $d = 220$ nm forms a inhomogeneous S-state during reversal.

The reversal process becomes more inhomogeneous when the damping constant is decreased or the strength of the external field is increased. Fig. 3 compares the exchange energy, which measures the homogeneity of the state, during reversal for different damping constants and field strength for a particle with a diameter of 110 nm. In the highly damped case ($\alpha = 1$) the exchange energy decreases monotonically during reversal. However in the weakly damped case ($\alpha = 0.1$) the reversal becomes more inhomogeneous if the external field is increased from 5.57 kA/m to 7.96 kA/m. The maximum inhomogeneity occurs shortly before equilibrium is reached $(J_z/J_s) < -0.6)$. For a dot with $d = 220$ nm the maximum of the exchange energy occurs shortly after applying the external field $(J_z/J_s) = 0.3)$.

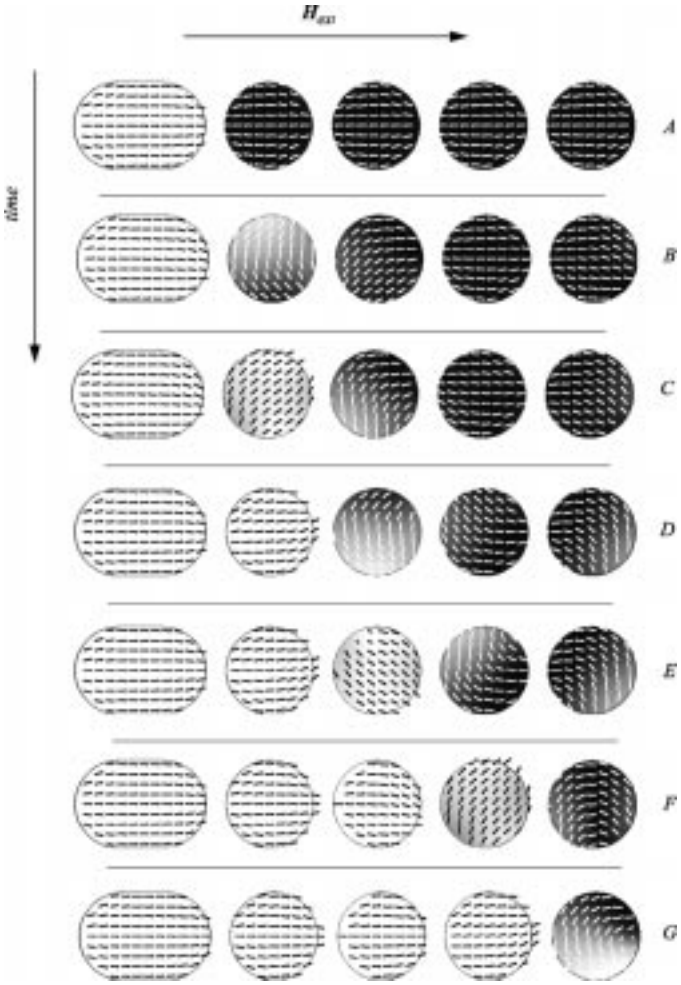

Fig. 5. Initial state and transient states during irreversible switching of the array of circular nanomagnets. The greyscale maps the magnetization component parallel to the long axis. The simulation time increases from the top to the bottom.

B. Interacting Circular Nanomagnets

The influence of the Gilbert damping constant on the switching dynamics of circular nanodots has been investigated. The system consists of an elongated nanoelement and 4 circular nanomagnets as shown in Fig. 1. The shape anisotropy of the array causes the magnetization to be aligned parallel to the long axis of the chain. First, the magnetization of the input dot was set antiparallel to the magnetization of the circular elements. Then the system was relaxed to equilibrium. This equilibrium state is used as initial state for the simulations of the switching process. Switching of the nanomagnets requires a field of at least 5.57 kA/m. Small fields cause a strongly inhomogeneous magnetic state in the circular nanomagnet placed next to the already reversed input dot. Fig. 4 compares the time evolution of the magnetization component parallel to the long axis obtained for different values of the Gilbert damping constant. A uniform reversed field of $H_{ext} = 5.57$ kA/m was applied instantaneously with an angle of 1 degree with respect to the long axis of the chain. With decreasing damping constant the switching time decreases drastically. The slope of the $J_z(t)$ curve changes considerably as the damping constant is increased from $\alpha = 0.1$ to $\alpha = 1$. Non-uniform magnetic states with low magnetostatic energy form in regimes where the change of J_z with time is small. Fig. 5, which gives the magnetization patterns for different times during irreversible switching for $\alpha = 0.1$, clearly shows the influence of magnetostatic interactions on the switching of individual nanodots. The magnetization of neighboring elements rotates in opposite directions, forming partial flux closure structures during the reversal process.

IV. Conclusions

Circular nanomagnets with a diameter smaller than 220 nm are single domain in equilibrium. Nevertheless, highly nonuniform magnetic states form during switching. The magnetization rotates in plane. Different velocities of the magnetization in different parts of the circular region cause transient domain structures which reduce the magnetostatic energy. A small Gilbert damping constant decreases the reversal time as compared to the reversal time obtained for $\alpha = 1$. The numerical results confirm Kickuchi's [11] prediction that the minimum reversal time for rotation in magnetic thin films occurs for $\alpha < 1$.

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