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Hysteresis and switching dynamics of patterned magnetic elements

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Abstract

The hystersis properties and the switching time of Co-nanoelements were calculated using finite element micromagnetics. The calculated coercive field of 200x40x25 nm Co-nanoelements strongly depends on the model of the polycrystalline microstructure assumed in the simulations. For small, randomly oriented grains the magneto-crystalline anisotropy may be neglected, since the effective anisotropy vanishes due to averaging. Quasistatic simulations of magnetization reversal show that taking anisotropy into account favors the formation of vortices and therefore reduces the coercive field from 140 kA/m to 95 kA/m. Vortices immediately form after the application of an reversed field, assuming a polycrystalline microstructure. For an applied field close to the coercive field, vortices form only after after a certain waiting time.

Keywords

Numerical Micromagnetics, damping, magnetic nano-elements, magnetization reversal

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1. Introduction

Thin film, magnetic nano-elements may be used in future sensor and recording technology [1]. Both applications require a well defined switching characteristic. The switching time depends considerably on the Gilbert damping constant α. Kikuchi [2] derived the critical value of α which minimizes the reversal time. The critical damping occurs for $\alpha = 1$ and $\alpha = 0.01$ for uniform rotation of the magnetization in a sphere and an ultra-thin film, respectively. Leineweber and Kronmüller investigated the reversal dynamics of small hard magnetic particles using a dynamic finite element method [3]. They reported a waiting time after the application of an applied field, before the nucleation of reversed domains is initiated. Koch and co-workers [4] simulated the reversal dynamics of NiFe elements for MRAM applications.

In this work the hysteresis properties and the switching dynamics of NiFe and polycrystalline Co nano-elements were calculated using a hybrid finite element/boundary element technique. The influence of the polycrystalline microstructure on the coercive field and on the switching time of elongated Co-elements is investigated solving the Gilbert equation of motion. Section 2 of the paper gives the computational details. Section 3 presents the numerical results obtained for quasi-static calculations and dynamic simulations of switching processes under the influence of a constant applied field.

2. Computational details

The simulation of switching dynamics must include gyromagnetic precession and damping using the Gilbert equation of motion [5], which describes the motion of the magnetic

polarization vector $\boldsymbol{J}$ in an effective field $\boldsymbol{H}_{\text{eff}}$. The variational derivative of the magnetic Gibb's free energy gives the effective field, $\boldsymbol{H}_{\text{eff}} = -\delta E_t/\delta \boldsymbol{J}$. The Gilbert equation,

$$\frac{\partial \boldsymbol{J}}{\partial t} = -|\gamma| \boldsymbol{J} \times \boldsymbol{H}_{eff} + \frac{\alpha}{J_s} \boldsymbol{J} \times \frac{\partial \boldsymbol{J}}{\partial t} \tag{1}$$

describes the physical path the system follows towards equilibrium. Here γ denotes the gyromagnetic ratio of the free electron spin and α is the Gilbert damping constant. The time integration of (1), assuming a continuously decreasing external field, provides the demagnetization curve in dynamic micromagnetic calculations. Whereas static micromagnetics give equilibrium states before and after magnetization reversal, dynamic micromagnetics reveal the equilibrium configurations and the transient states during irreversible switching.

The thin film elements are divided into tetrahedral finite element. The average mesh size is in the order of the exchange length the material, leading to a total number of elements of 15 000. The semi-discretization of (1) leads to a system of ordinary differential equations which is integrated using either a Runge-Kutta method or a semi-implicit backward difference scheme depending on the current stiffness of the equations. A hybrid finite element / boundary element method [6] is applied to calculate the demagnetizing field.

Whereas a Runge-Kutta method suitable for mildly-stiff differential equations [7], proved to be effective for the simulation of acicular elements with zero magnetocrystalline anisotropy, taking into account the random anisotropy of the polycrystalline microstructure requires the use of a semi-implicit method for time integration.

Fig. 1 presents the flow-chart of the semi-implicit method for time integration. Since the stiffness arises mainly from the exchange term, the demagnetizing field can be treated explicitly and thus is updated after a time interval τ. During the time interval τ the Gilbert equation is integrated with a fixed demagnetizing field using a higher order backward difference method. This update time is taken to be inversely proportional to the maximum torque acting over the finite element mesh. Fig. 2 compares the CPU time as a function of the simulated time for the reversal of 200x40x25 nm Co element with polycrystalline microstructure for the different time integration schemes.

3. Results and Discussion

Fig. 3 gives the microstructure of the polycrystalline sample, as well as the magnetization distribution of the minimum energy state at zero applied field, and of a transient state during irreversible switching. The remanent state was calculated solving the Gilbert equation for zero applied field. The initial state for this calculation was a C like domain pattern. However, after the calculation of the equilibrium state for zero applied field a nearly single domain state develops owing to the shape anisotropy of the needle-like particle. The competitive effects of shape and random crystalline anisotropy lead to a magnetization ripple structure at zero applied field. Sharp edge irregularities help to create vortices, which will move through the width of the element. This process starts at a reversed field of $\boldsymbol{H}_{\text{ext}}$ = - 95 kA/m and leads to the reversal of half of the particle. Following that, a second vortex forms and the entire Co-element becomes reversed.

The quasi-static simulation of the demagnetization curve was repeated for a particle with simular shape but with zero magnetocrystalline anisotropy and without any edge irregularities. The comparison of the demagnetization curves of fig. 4 shows that taking into account edge irregularities and random magnetocrystalline anisotropy drastically reduces the switching field in micromagnetic simulations. The decrease in the switching field has to be attributed to both edge irregularities and random anisotropy. Reference calculations using the irregular geometry and zero magnetocrystalline anisotropy reveal a switching field of H_s = - 110 kA/m as compared to H_s = - 140 kA/m for a regular geometry and zero anisotropy and H_s = - 96 kA/m for irregular geometry and random anisotropy. The ease of vortex formation also reduces the switching time. The magnetization reversal was calculated for a constant applied field of $\boldsymbol{H}_{ext}$ = - 140 kA/m, using the minimum energy state at zero applied field as initial state for the dynamic calculations. Fig. 5 compares the time evolution of the magnetization for the Co-element with random and zero magnetocrystalline anisotropy. The analysis of the transient states given in figures 6 and 7 shows that magnetization reversal occurs by the formation and motion of vortices in both samples. For zero magnetocrystalline anisotropy and an external field close to the coercive field a vortex breaks away from the edge, only after a waiting time of about 0.8 ns. Increasing the external field from H_{ext} = -140 kA/m to H_{ext} = -190 kA/m drastically reduces the waiting time. Fig. 8 gives the time evolution of the micromagnetic energy contributions during magnetization reversal. The formation of vortices leads to an increase of the exchange energy during the reversal process.

Fig. 9 shows the dependence of the reversal time on the Gilbert damping constant for a 200x40x25 nm Co element assuming zero magneto-crystalline anisotropy. T_1 and T_2 denote the times after which the magnetic polarization parallel to field direction reaches zero and -

0.99 J/J_s. The time T_2 at which the entire element is reversed shows a minimum at a Gilbert damping constant of $\alpha = 0.2$. For smaller values of the damping constant the magnetization switches rapidly. However, the precessional motion of the magnetization leads to large oscillations of the magnetization component parallel to the long axis as function of time.

4 Conclusion

Numerical micromagnetic finite element simulation show that the polycrystalline microstructure of Co-nanoelements significantly influence the magnetization reversal process. Edge irregularities and the random anisotropy reduces both coercive field and switching time as compared to reference calculations assuming zero magnetocrystalline anisotropy.

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Figure captions

Fig. 1. Flow-chart of the semi-implicit time integration scheme.

Fig. 2. CPU time (DEC alpha 533 Mhz) as a function of the simulated time required with the Runge-Kutta method (dashed line) and the semi-implicit scheme (solid line).

Fig. 3. Microstructure of the polycrystalline sample, and the magnetization distrubution for zero applied field, and at an applied field of 95 kA/m during irreversible switching.

Fig. 4. Numerically calculated demagnetization curve for a acicular Co-element with a polycrystalline grain structure and with zero magnetocrystalline anisotropy.

Fig. 5. Time evolution of the magnetic polarization during the reversal of Co elements for zero and random magnetocrystalline anisotropy under the influence of a reversed field, using a Gilbert damping constant $\alpha = 1$.

Fig. 6. Transient states during the reversal of Co-element under the influence of a constant reversed field (zero magnetocrystalline anisotropy).

Fig. 7. Transient states during the reversal of the polycrystalline Co-element with random magnetocrystalline anisotropy element under the influence of a constant reversed field.

Fig. 8. Time evolution of the micromagnetic energy contributions during the reversal of a 200x40x20 nm Co-element during irreversible switching.

Fig. 9. Switching times of Co nano-elements assuming zero magnetocrystalline anisotropy as a function of the damping constant.