Langevin Micromagnetics of Recording Media Using Subgrain Discretization

Thomas Schrefl, Werner Scholz, Dieter Süss, and Josef Fidler, *Member, IEEE*

***Abstract*—Finite element based micromagnetics is applied to study thermally assisted switching of thin film media in the high speed regime. The space discretization leads to a system of stochastic differential equations with multiplicative noise which is interpreted in the sense of Stratonovich and solved using the method of Heun. For a CoCrPt alloy system, an external field of −255 kA/m was found to be sufficient to switch the magnetization in less than 1 ns in about 80% of the realizations of the stochastic process. However, reversal times up to 1 ns and higher are observed for about 20% of the calculations. Then the system switches from the high remanent state to a metastable state where it remains trapped for several nanoseconds.**

***Index Terms*—Finite element method, high speed switching, magnetic recording, thermal activation.**

I. INTRODUCTION

WITH increasing recording density and decreasing bit size, thermally activated magnetization reversal becomes an important issue in magnetic recording [1]. The Gilbert equation of motion is believed to give the physical path of the system toward equilibrium, taking into account gyromagnetic precession and damping. However, in real systems thermal activation changes the deterministic motion of the magnetization into a random walk. A theoretical description must treat magnetization reversal as a stochastic process. The magnetic properties like coercivity and remanence follow from averages over many numerical realizations of the reversal process. In high speed switching, highly nonlinear effects are important. Chantrell [2] and Safanov [3] showed that nonuniform magnetic states and spin waves influence the damping mechanism and the relaxation process.

This paper uses the finite element method to study the magnetization reversal of thin film media. The finite element method effectively treats the granular structure of thin film recording media. Variations in the size and shape of the grains and the Cr segregation near grain boundaries are taken into account [4]. The magnetization within each grain may become nonuniform, as each grain is further subdivided into tetrahedral finite elements. The comparison of the numerical results obtained from energy minimization, time integration of the Gilbert equation, and Langevin dynamics provides detailed insight into magnetization reversal in the high speed regime.

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The authors are with the Institute of Applied and Technical Physics, Vienna University of Technology, A-1040 Vienna, Austria (e-mail: {thomas.schrefl; scholz; suess}@atp330.tuwien.ac.at; fidler@email.tuwien.ac.at).

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Section II of the paper reviews the micromagnetic background and numerical background. Section III presents finite element micromagnetic simulations of thermally activated magnetization reversal in thin film recording media.

II. LANGEVIN MICROMAGNETICS

In order to treat thermally activated processes a stochastic, thermal field, H_{th}, is added to the effective field, H_{eff}. It accounts for the interaction of the magnetic polarization with the microscopic degrees of freedom which causes the fluctuation of the magnetization distribution. The Langevin equation [5]

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

is believed to give the random motion of the magnetization at finite temperatures. The effective field, $\boldsymbol{H}_{\mathrm{eff}} = \delta E_t / \delta \boldsymbol{J}$, is the variational derivative of the magnetic Gibb's free energy. γ is the gyromagnetic ratio of the free electron spin. A Gilbert damping constant $\alpha = 0.02$ was used as measured by Inaba and co-workers [6] in FMR experiments for CoCrPt recording media. Zhang and co-workers [7] proposed a Galerkin method and an Euler scheme for the space and time integration of (1). In this work applies the box method for space discretization and the method of Heun for the integration of the stochastic differential equations. The effective field at the node k of an irregular finite element mesh may be approximated

$$\boldsymbol{H}_{\mathrm{eff}}^{(k)} = -\frac{1}{V_k} \frac{\partial E_t}{\partial \boldsymbol{J}}, \tag{2}$$

where V_k is the volume associated with the node k. The following conditions hold for the box volumes

$$\sum_k V_k = \int dV, \qquad V_k \cap V_l \quad \text{for } k \neq l. \tag{3}$$

The thermal field is assumed to be a Gaussian random process with the following statistical properties:

$$\left\langle \boldsymbol{H}_{th,\,i}^{(k)} \right\rangle = 0, \tag{4}$$

$$\left\langle \boldsymbol{H}_{th,\,i}^{(k)} \boldsymbol{H}_{th,\,j}^{(l)} \right\rangle = 2D \delta_{ij} \delta_{kl} \delta(t - t') \tag{5}$$

The average of the thermal field vanishes taken over different realizations vanishes in each direction i in space. The thermal field is uncorrelated in time and space. The strength of the thermal fluctuations follow from the fluctuation-dissipation theorem:

$$D^{(k)} = \frac{\alpha k_B T}{\gamma J_s V_k}, \tag{6}$$

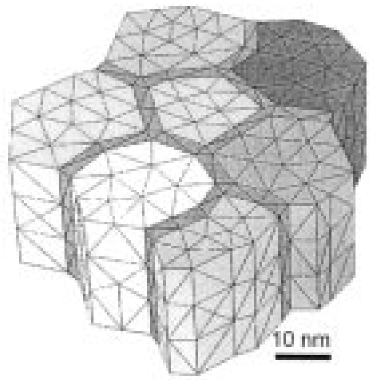

Fig. 1. Finite element model of the grain structure and the surface of the finite elements.

TABLE I
INTRINSIC MAGNETIC PROPERTIES

	K_u	J_s	A	
CoCrPt	0.265	0.44	10	[10]
Cr-rich boundary phase	0	0.34	6	

K_u (MJ/m^3), the anisotropy constants; J_s(T), the spontaneous magnetic polarization and the exchange constant A (pJ/m).

where k_B is the Boltzmann constant. The space discretization of (1) leads to a system of Langevin type equations with multiplicative noise. Garcia-Palacios and Lazaro [8] showed that the equation has to be interpreted in the sense of Stratonovic, in order to obtain the correct thermal equilibrium properties. The numerical integration is performed using the method of Heun. For the pure deterministic case the Heun method reduces to the standard second order Runge–Kutta method [9]. Numerical studies for simple spin systems confirmed that the Heun scheme is numerically more stable and allows larger time steps than the Euler or the Milshtein scheme. The size of the finite elements was about 6 nm, the time step was fixed to 0.1 fs.

III. Results and Discussion

A. Media Model

The numerical treatment of thermally activated magnetization reversal requires the computations of several realizations of the stochastic process. In order to obtain reasonable computation time, we limit the number of grains in the media model.

Fig. 1 gives the finite element model consisting of seven grains. The film thickness δ is 20 nm. The width of the Cr-enriched region near the grain boundaries is about 2 nm. The magnetocrystalline anisotropy axes are randomly in plane, giving a remanence to saturation ratio of $J_r/J_s = 2/\pi$ without any interactions between the grains. The intrinsic magnetic properties were taken from [10]. The exchange constants were adjusted, in order to obtain a coercive field of about 250 kA/m at 300K. Table I summarizes the intrinsic material parameters used for the calculations

B. Static and Dynamic Properties

Fig. 2 gives the demagnetization curve of the grain configuration depicted in Fig. 1. Intergrain exchange interactions lead

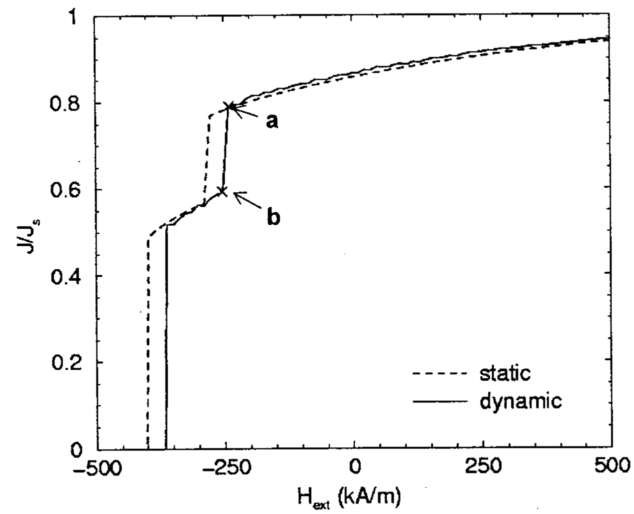

Fig. 2. Comparison of the numerically calculated demagnetization curves obtained from energy minimization (dashed line) and the time integration of the Gilbert equation (solid line).

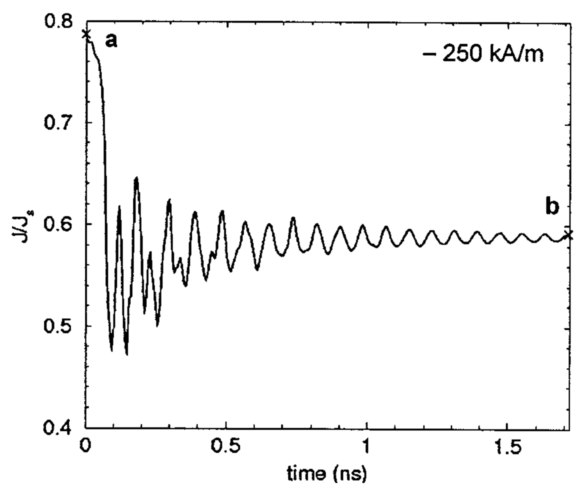

Fig. 3. Time evolution of the magnetic polarization between the points ***a*** and ***b*** of the demagnetization curve. The external field is -250 kA/m. The oscillations result from the precessional motion.

to a remanence squareness of $J_r/J_s = 0.85$. The demagnetization curves were calculated quasistatically. Starting from an external field $H_{ext} = 1200$ kA/m, H_{ext} was decreased in steps of 12 kA/m, when equilibrium was reached. Magnetization reversal occurs in a two step process. First two grains on the bottom left of the grain structure change the direction of the magnetization at a field of $H_{ext} = -250$ kA/m. The comparison of the demagnetization curves obtained from energy minimization and the time integration of the Gilbert equation clearly shows that the gyromagnetic precession reduces the switching fields by about 30 kA/m. Fig. 3 gives the time evolution of the magnetization between the points $\mathbf{a}$ $(J/J_s = 0.78)$ and $\mathbf{b}$ $(J/J_s = 0.59)$ of the demagnetization curve. The magnetization precesses around the internal effective field. Its magnitude $|\boldsymbol{H}_{\rm eff}| = 300$ kA/m can be estimated from the frequency of the oscillations. After about 1.8 ns the magnetization relaxes in a metastable equilibrium state. A field of $H_{ext} = -360$ kA/m is required to overcome the energy barrier and reverse the magnetization of the entire sample.

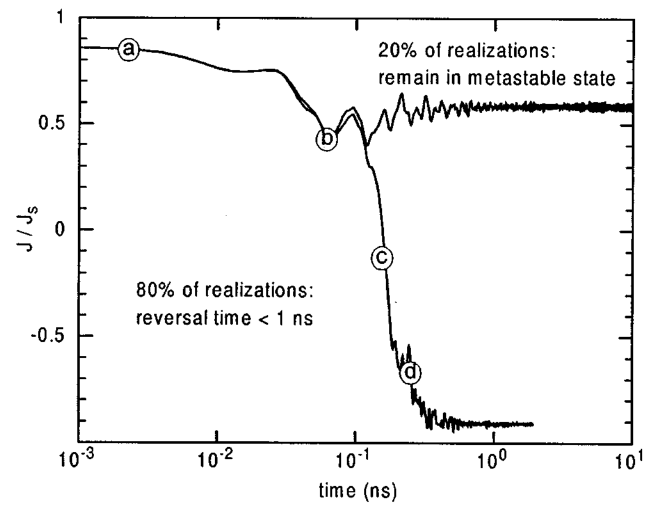

Fig. 4. Time evolution of the magnetization parallel to the saturation direction for Hext $= -255$ kA/m.

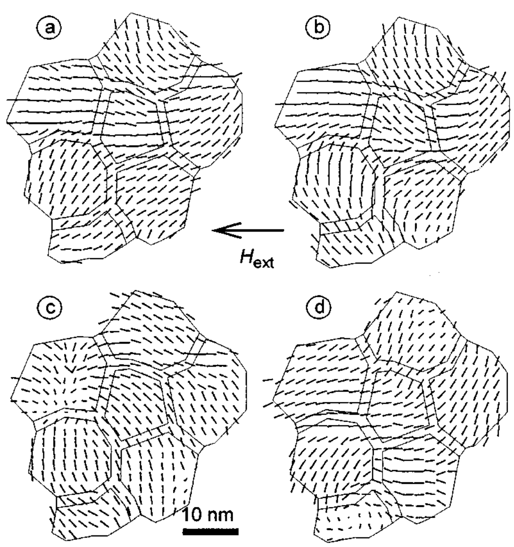

Fig. 5. Magnetization patterns at different times after the application of a reversed, external field of $H_{ext} = -255$ kA/m. The numbers refer to Fig. 4.

C. Thermally Activated Reversal

The numerical studies shows that an external field of $|\boldsymbol{H}_{ext}| < 260$ kA/m at $T = 300$K is sufficient to reverse the sample within a few nanoseconds. First, equation (1) was solved for about 20 ns for zero applied field, in order to obtain a thermal equilibrium state. Then, an external field was applied instantaneously.

Fig. 4 shows the time evolution of the magnetization for an external field of $H_{ext} = -255$ kA/m for two different realizations of the stochastic process. The system switches from the high remanent state to the metastable state $\mathbf{b}$, where it may remain trapped for several nanoseconds. The circles refer the magnetization distributions given in Fig. 5. The simulations where repeated 200 times to calculate the probability of not switching, given in Fig. 6. The magnetization switches in less than 0.3 ns in about 80% of the calculations. However, reversal times up to 1 ns and higher are observed for about 20% of the realizations. For an external field of $H_{ext} = -260$ kA/m, relaxation times greater than 1 ns are only found for about 2% of the realizations. The results clearly show that metastable energy minima and nonuniform magnetic states within the grains are important factors in the reversal dynamics at finite temperature.

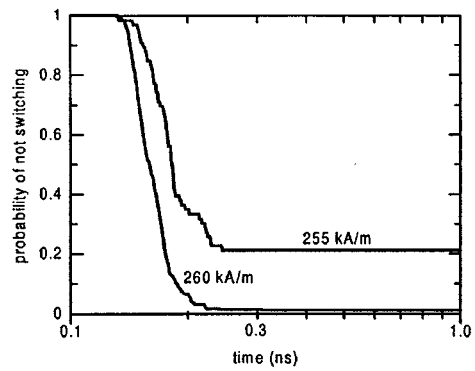

Fig. 6. Probability of not switching for different applied fields.

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