Thermal Fluctuations in Magnetic Sensor Elements

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Abstract

Langevin micromagnetics treats finite temperature effects by adding a thermal fluctuation field, H_{th}, to the effective field. If combined with the finite element method a large system of stochastic differential equations (SDEs) has to be solved. In this paper a new semi-implicit method is used to treat the system of SDEs on magnetic sensor elements. Fluctuations are of immense importance in recording industry because they lead to instabilities and also increase the noise. The results show that according to the model conclusions the fluctuations of the magnetization increase slightly with the temperature.

Keywords: numerical micromagnetics, Langevin equation, magnetic sensor elements.

Introduction

Magnetic sensors are very important for a large number of applications, such as magnetic recording industry, automotive applications, etc. Various techniques have been employed for sensing, such as linear variable differential transformer (LVDT) that is well-known for its applications in displacement measurement [1]. More specifically, giant magnetoresistance (GMR) sensors overcome the weaknesses of conventional magnetoresistors and Hall sensors, due to their advantage to be less sensitive to air gap deviations [2]. Micromagnetics has been used to model magnetic phenomena in small elements of sub-micron size. Moreover, it provides a powerful tool to model the magnetic behavior of read sensors in magnetic recording systems [3].

A magnetic material of permalloy type with size 150x100x5 nm has been used for the micromagnetic simulations. The exchange constant A was set to $1.3\text{x}10^{-11}$ J/m, the crystalline anisotropy K was $5.0\text{x}10^{2}$ J/m^3, and the saturation polarization J_s was 1T. The simulations ran for 3 ns. The uniaxial anisotropy axis was parallel to the long axis of the element.

The thermal simulations started from an s-state that has been obtained using a deterministic micromagnetic model. Then we applied an external field of 0.1T parallel to the magnetization (x direction) to imitate the presence of the permanent magnet [3].

Method

The theoretical treatment of thermally activated magnetization reversal for particles with an extension greater than the exchange length requires solving the Langevin equation numerically.

The Langevin equation follows from the Gilbert equation of motion by adding a random thermal fluctuation field to the effective magnetic field:

$$\frac{\partial \mathbf{J}}{\partial t} = -|\gamma| \mathbf{J} \times (\mathbf{H}_{eff} + \mathbf{H}_{th}) + \frac{\alpha}{J_s} \mathbf{J} \times \frac{\partial \mathbf{J}}{\partial t} \quad (1).$$

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. After space discretization using the finite element method an equation similar to (1) has to be fulfilled at each node of the finite element mesh.

The term γ is the gyromagnetic ratio, and α is the Gilbert damping constant. The thermal field is assumed to be a Gaussian random process with the following statistical properties:

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

The average of the thermal field taken over different realizations vanishes in each direction i in space. The thermal field is uncorrelated in time and uncorrelated at different node points (k,l) of the finite element mesh. The strength of the thermal fluctuations follows from the fluctuation-dissipation theorem:

$$\varepsilon = \frac{2\alpha k_B T}{\gamma J_s V_i} \tag{3}$$

where V_i is the volume surrounding the node i of the finite element mesh, and k_B is the Boltzman constant.

The general form of the Langevin equation can be written as follows [4]:

$$d\mathrm{J}(\mathrm{r_i}, t) = \mathrm{B}\left[\mathrm{J}(\mathrm{r_i}, t)\right] \mathrm{H}_{\det}(\mathrm{r_i}, t)\, \mathrm{d}t + \sqrt{\in}\, \mathrm{B}\left[\mathrm{J}(\mathrm{r_i}, t)\right] d\mathrm{W}(\mathrm{r_i}, t) \quad (4)$$

where, dW are Gaussian random numbers with mean zero and standard deviation one, and $B[J(r_i,t)]$ is given by,

$$B\left[J(r_i,t)\right]=\frac{1}{1+\alpha^2}\begin{pmatrix} \alpha(J_y^2+J_z^2) & -J_z-\alpha J_x J_y & J_y-\alpha J_x J_z \\ J_z-\alpha J_x J_y & \alpha(J_x^2+J_z^2) & -J_x-\alpha J_y J_z \\ -J_y-\alpha J_x J_z & J_x-\alpha J_y J_z & \alpha(J_x^2+J_y^2) \end{pmatrix} \quad (5)$$

We use a semi-implicit method to solve (4). The right hand side of (4) is evaluated in the middle of time interval. The magnetization in the middle of the time interval is

$$\bar{J} = J(t+\Delta t/2) = (J(t) + J(t+\Delta t))/2. \quad (6)$$

If j counts the timestep then,

$$t_{j+1} = t_j + \Delta t. \quad (7)$$

We introduce a new index n for the functional iteration to solve the nonlinear equation at each time step. The n+1 iteration is defined as,

$$\bar{J}_{n+1} = J(t_j) + B[\bar{J}_n]\,\Delta t + \sqrt{\varepsilon}\; B[\bar{J}_n]\,\Delta t. \quad (8)$$

Here we evaluate B at $\bar{J}_n$. We assume $\bar{J}_0 = J(t_j)$. After a few iterations of eq. 8 we evaluate $J(t_{j+1})$, the magnetic polarization at t= t+Δt, as

$$J(t_{j+1}) = 2\,\bar{J} - J(t_j). \quad (9)$$

The last equation follows from equation (6). Finally, we solve the non linear equation by functional iteration.

Results

A small field is applied at an angle of 10^0 to the long axis of the element. This field is gradually reduced and the equilibrium state is calculated for each field at T = 0 K. This procedure gives the s-state, which has been used as initial state for the thermal simulations. Fig. 1 shows the magnetization configuration of the s-state at T = 0 K.

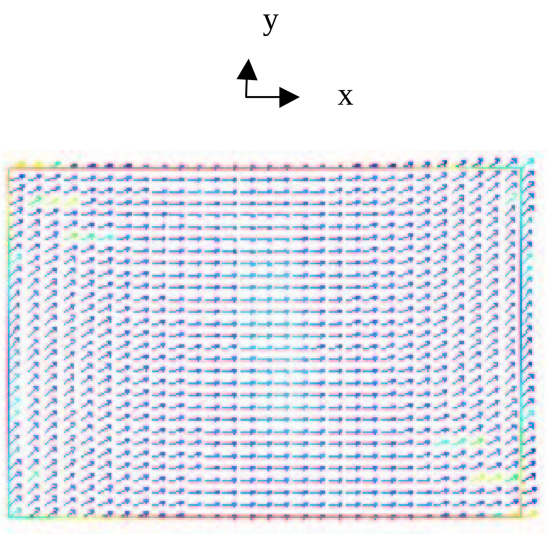

Figure 1: The initial magnetisation distribution used for the stochastic calculations (s-state, T=0), and the co-ordinate system.

In order to mimic the thermal fluctuations in the free layer of a GMR sensor we assume an external field of μ_0 H_{ext} = 0.1T parallel to the long axis of the element. In realistic applications this field will result from permanent magnets that are used to stabilize the magnetization of the sensor elements. At time t=0 we increase the temperature to T=350K and T=500K.

Temperature	**Fluctuations**
350	0.0790
500	0.0912

Table 1: The fluctuations of the magnetization for the two temperatures.

Table 1 gives δM_x for 350K and 500K. The thermal noise increases slightly with increasing temperature.

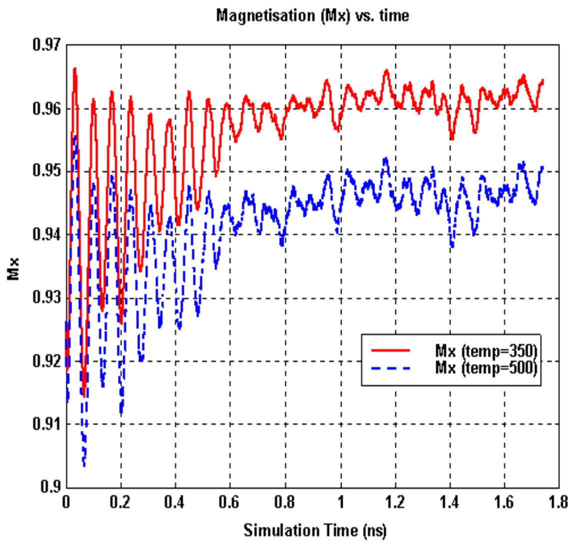

Figure 2: The x-component of the magnetization (T=350 K / 500 K).

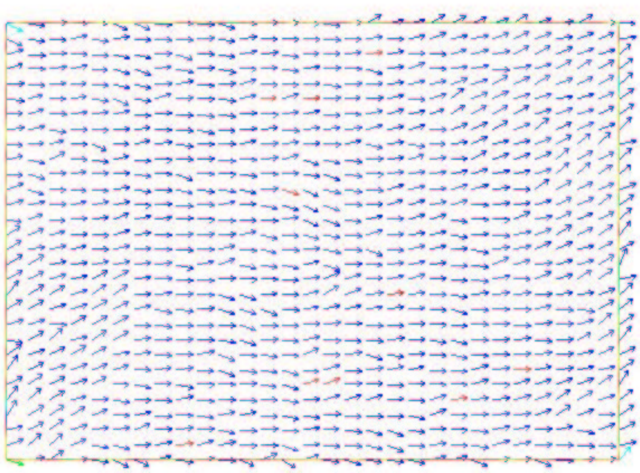

Figure 3: The magnetisation distribution after 0.4ns (T=500 K).

Fig. 2 shows the time evolution of

$$M_x = \frac{1}{V J_S} \int \boldsymbol{J} \cdot \hat{\boldsymbol{x}} \, dV \,, \tag{11}$$

which is the spatial average of the x-component of the magnetic polarization. M_x oscillates in time with a frequency of about 15GHz. In order to quantify the thermal fluctuations as a function of temperature we calculate

$$\delta M_x = \sqrt{<M_x^2> - <M_x>^2}\,, \tag{12}$$

where < > denotes the time average. Since the nature of the oscillations of M_x changes at time t=0.8 we build the time average only for time t > 0.8. The value of δM_x can be assumed to be proportional to the GMR response of a sensor element.

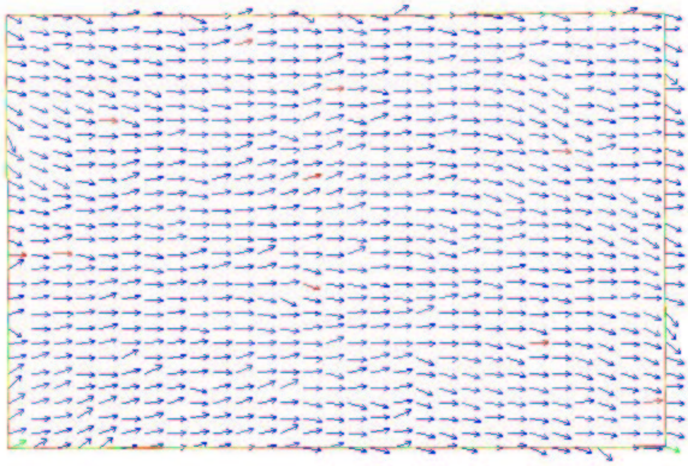

Figure 4: The magnetisation distribution after 0.6ns (T=500 K).

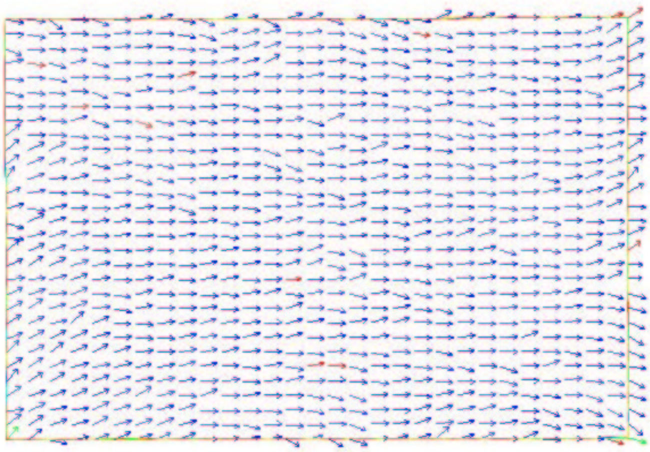

Figure 5: The magnetisation distribution after 1ns (T=500 K).

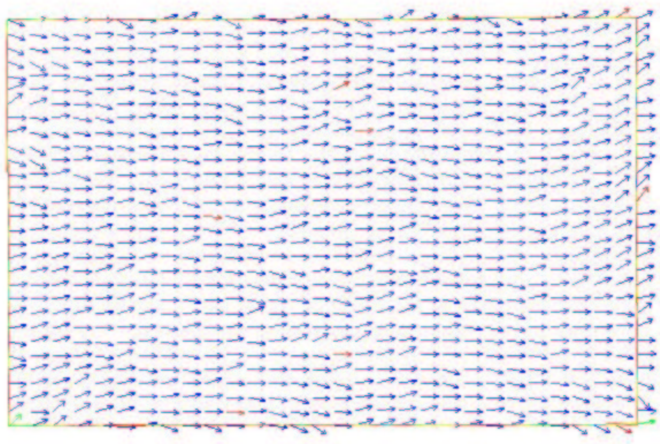

Figure 6: The magnetisation distribution after 1.7ns (T=500 K).

Fig. 3 to Fig. 6 show snapshots of the magnetization distributions for T=500K for increasing simulation time.

Conclusions

We proposed a new method to treat thermal noise in thin film elements. The semi-implicit time integration scheme is very robust and allows time steps up to Δt=60ps. The thermal effects changes lead to fluctuations of the average magnetization of the element of about 1%.

Acknowledgements

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