# Thermal magnetization noise in submicrometer spin valve sensors

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With decreasing device dimensions thermal fluctuations may ultimately limit the performance of spin valve sensors. Using finite element micromagnetic simulations, we investigate thermal magnetization noise in submicrometer soft magnetic sensor elements within the framework of Langevin simulations. Local random thermal fluctuations lead to a collective motion of the magnetization. The magnetization precesses in the end domains leading to an oscillation of the total magnetization parallel to the long axes with an amplitude in the order of 0.1 $M_s$ at 350 K. The noise power increases linearly with temperature. Irrespective of the bias field, the time averaged total magnetization parallel to the long axes decays approximately by 0.01 $M_s$ as the temperature is raised by 100 K. © *2003 American Institute of Physics.* [DOI: 10.1063/1.1557853]

## I. INTRODUCTION

With decreasing device dimensions thermal fluctuations may ultimately limit the performance of spin valve sensors.[1] Only recently thermal effects have been included in micromagnetic simulations. The computer models either solve the stochastic Landau–Lifshitz–Gilbert equations,[2] where a random fluctuating field mimics the thermal excitations, or apply the Monte Carlo method on an assembly of Heisenberg spins.[3]

Heinonen[4] calculated hysteresis loops and thermal fluctuations of patterned soft magnetic structures including finite-temperature effects by means of the Monte Carlo method. The simulations show a large increase in magnetic noise owing to fluctuations in both the reference and free layer of spin valve structures with reduced dimensions. Bertram and coworkers[5] analyzed magnetoresistive thermal magnetization fluctuations experimentally and theoretically as a function of the bias current. The results indicate that damping plays an important role and can be described in tensor form. The magnetization noise was found to be inversely proportional to the sensor volume and at low frequencies proportional to the dynamic damping. Smith and Arnett[1] showed that the measured magnetization noise in spin valve sensors is in good quantitative agreement with predictions based on the fluctuation dissipation theorem. Zhu[6] has found that in spin valve heads at deep submicrometer track widths the thermal magnetic noise is at a magnitude comparable to the head's Johnson's noise. Moreover, he found that the magnitude of noise and the noise spectra are strong functions of the sensor stripe height. Slavin*et al.*[7] studied the spatial and temporal distribution of linear and nonlinear spin-wave excitations in two-dimensional films. They performed their experiments using the space- and time-resolved Brillouin light scattering (BLS) technique. They report that in the nonlinear regime, stationary and nonstationary self-focusing effects were observed.

We solve the stochastic Landau–Lifshitz–Gilbert equation applying a robust semi-implicit time integration method.[8] Owing to exchange and magnetostatic interactions, local perturbations, as introduced by the fluctuating field, will lead to collective thermal excitations or spin waves. The origin of collective magnetization modes, which arise from random fluctuations, was originally investigated by Chantrell and co-workers.[9]

## II. THE 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:

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

The first term on the right-hand side of Eq. (1) accounts for the gyromagnetic precession of the magnetic polarization $\mathbf{J}$, the second term arises from viscous damping. After space discretization using the finite element method an equation similar to Eq. (1) has to be fulfilled at each node of the finite element mesh.[10]

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

$$\langle H_{\text{th},i}^{k}, H_{\text{th},j}^{l} \rangle = \varepsilon\, \delta_{ij} \delta_{kl} \delta(t-t'). \tag{2}$$

The average of the thermal field taken over different realizations vanishes in each direction $i$ in space. The thermal field is uncorrelated in time, uncorrelated at different node points $(k,l)$ of the finite element mesh, and uncorrelated in a different direction in space. The strength of the thermal fluctuations follows from the fluctuation-dissipation theorem:[11]

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

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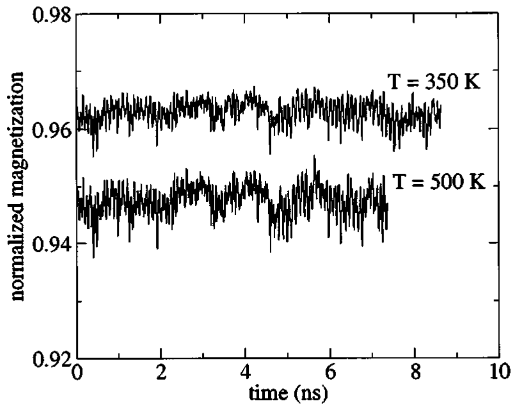


FIG. 1. Magnetization for two different temperatures ($T=350$ and 500 K). The bias field is 80 kA/m.

where $V_i$ is the volume surrounding the node $i$ of the finite element mesh, and $k_B$ is the Boltzmann constant. After discretization we can interpret the soft magnetic element as a collection of interaction magnetic moments, with the moments sitting on the nodes of the finite element mesh. The moments interact by magnetostatic and exchange interactions, and each moment feels its local effective field. In addition each magnetic moment feels a thermal fluctuation field which is determined by Eq. (3).

The general form of the Langevin equation can be written as follows:[3]

$$d\mathbf{J}(\mathbf{r}_i,t)=\mathbf{B}[\mathbf{J}(\mathbf{r}_i,t)]\mathbf{H}_{\mathrm{det}}(\mathbf{r}_i,t)dt + \sqrt{\in}\mathbf{B}[\mathbf{J}(\mathbf{r}_i,t)]d\mathbf{W}(\mathbf{r}_i,t), \tag{4}$$

where $\mathbf{H}_{\mathrm{det}}$ is the deterministic part of the local field at $\mathbf{r}_i$, $dW$ are Gaussian random numbers with mean zero and standard deviation one, and $B[J(r_i,t)]$ is given by

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

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

$$\overline{J}=J(t+\Delta t/2)=[J(t)+J(t+\Delta t)]/2. \tag{6}$$

If $j$ counts the time step then

$$t_{j+1}=t_j+\Delta t. \tag{7}$$

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

$$\overline{J}_{n+1}=J(t_j)+(1/2)(B[\overline{J}_n]\Delta t+\sqrt{\varepsilon}B[\overline{J}_n]\Delta t). \tag{8}$$

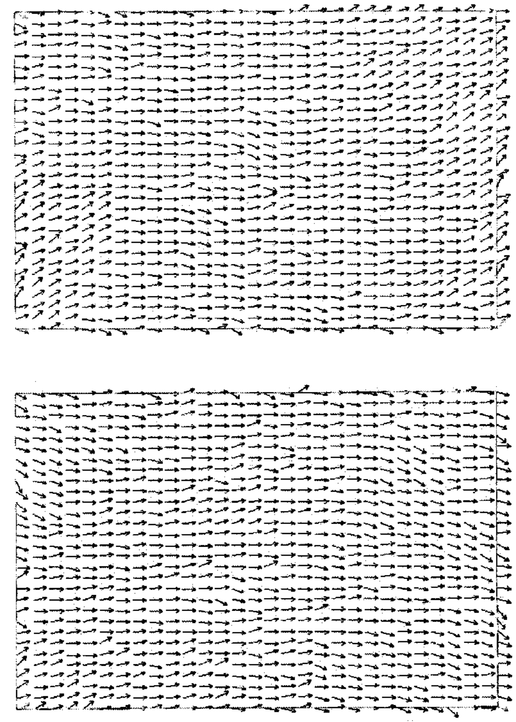

FIG. 2. Magnetization distribution of a $150\times100\times5\ \mathrm{nm}^3$ platelet at $T=500$ K. The time interval between the two images is 0.2 ns.

Here we evaluate $B$ at $\overline{J_n}$. We assume $\overline{J_0}=J(t_j)$. After a few iterations of Eq. (8) we evaluate $J(t_{j+1})$, the magnetic polarization at $t=t+\Delta t$, as

$$J(t_{j+1})=2\overline{J}-J(t_j). \tag{9}$$

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

## III. RESULTS

The stochastic Landau–Lifshitz–Gilbert equation is solved for a $150\times100\times5\ \mathrm{nm}^3$ Permalloy element. The exchange constant $A$ was set to $1.3\times10^{-11}$ J/m, the crystalline anisotropy $K$ was $5.0\times10^2$ J/m$^3$, and the saturation polarization $J_s$ was 1 T. The damping constant used in the simulations was $\alpha=0.02$. An induced anisotropy was assumed with its axis parallel to the long axis of the element. The long axis is parallel to the $x$ direction. It is also the direction of the easy axis bias field. In order to investigate the thermal magnetization noise we apply the following procedure. A small field is applied at an angle of 10° 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. Then we solve Eq. (1) for a given temperature and external field for a period of 1 ns. We continue the calculations for several nanoseconds and analyze the magnetization data, $M_x(t)$ for $t>1$ ns, to obtain the spin-wave frequencies and thermal noise.

Local random thermal fluctuations lead to a collective motion of the magnetization. The magnetization precesses in the end domains leading to an oscillation of the magnetization parallel to the long axes. Figure 1 shows the spatial

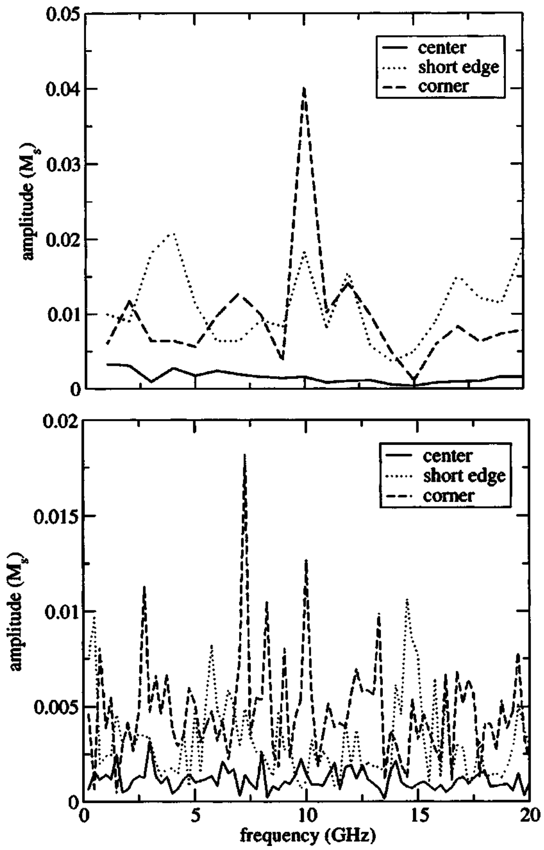


FIG. 3. Fourier spectrum of the magnetization component parallel to the long axis for different points inside a $150\times100\times5\ \mathrm{nm}^3$ NiFe platelet at 350 K. Top: $H_{\mathrm{bias}}=16$ kA/m, bottom: $H_{\mathrm{bias}}=80$ kA/m.

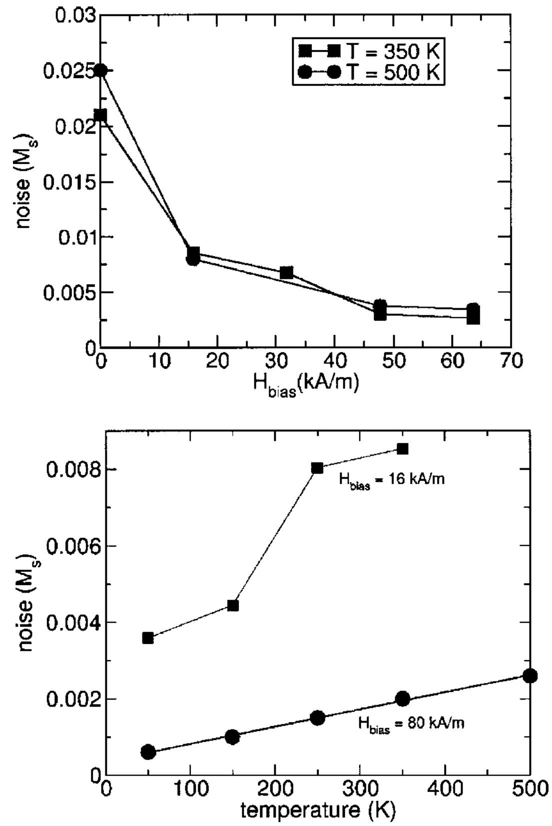


FIG. 4. Magnetization noise as a function of the easy axis bias field and as a function of the temperature.

average of the magnetization parallel to the long axis, which is given by

$$M_x=\frac{1}{VJ_s}\int \mathbf{J}\cdot\hat{\mathbf{x}}dV. \tag{10}$$

Figure 2 gives snapshots of the magnetization distribution at different times. The time interval is 0.2 ns. Figure 3 shows the Fourier spectra of the magnetization parallel to the $x$ axis at three different points within the soft magnetic platelet: a point in the center of the element, a point on the $x$ axis at a distance of 5 nm from the short edge, and a point near the corner at a distance of 5 nm near the short edge and 5 nm near the long edge. At a bias field of 16 kA/m a distinct dominating frequency is found for the point in the corner. At higher bias field (80 kA/m) more spin-wave modes are excited. Generally, the Fourier spectra show that the fluctuations are located near the corners.

The time averaged total magnetization parallel to the long axes, $\langle M_x\rangle$, decreases almost linearly with increasing temperature. The slope of $\langle M_x\rangle(T)$ shows only a weak dependence on the bias field. $\langle M_x\rangle(T)$ decays approximately by 0.01 $M_s$ as the temperature is raised by 100 K.

In order to quantify the thermal fluctuations as a function of temperature we calculate

$$\delta M_x=\sqrt{\langle M_x^2\rangle-\langle M_x\rangle^2}, \tag{11}$$

where $\langle\ \rangle$ denotes the time average. Following Heinonen,[4] the value of $\delta M_x$ can be assumed to be proportional to the magnetization noise of a sensor element. The giant magnetoresistance (GMR) signal is proportional to the scalar product of the magnetization in the reference layer and the free layer. If magnetization of the reference layer is assumed to be fixed and parallel to the $x$ direction, $\delta M_x$ as defined in Eq. (11) is related to the GMR noise. Figure 4 shows the noise as a function of the easy axis bias field and the temperature. The noise decreases rapidly with the easy axis bias field. For $H_{\mathrm{bias}}=16$ kA/m the noise increase considerably as the temperature is raised from 150 to 250 K. For $H_{\mathrm{bias}}=80$ kA/m, the noise increases linearly with temperature.

## ACKNOWLEDGMENT

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