Available online at www.sciencedirect.com
SCIENCE DIRECT
Physica B 372 (2006) 286–289
PHYSICA B
www.elsevier.com/locate/physb

Thermal activation in Permalloy nanorectangles at room temperature

E. Martinez[a,*], L. Lopez-Diaz[a], L. Torres[a], C.J. Garcia-Cervera[b]

[a]*Departamento de Física Aplicada, Universidad de Salamanca, Plaza de la Merced s/n, E-37001, Salamanca, Spain*
[b]*Mathematics Department, University of California, Santa Barbara, CA 93106, USA*

Abstract

The effect of thermal activation in planar Permalloy nanorectangles of thickness $L_z = 2.5\,\text{nm}$, width $L_y = 20\,\text{nm}$ and different in plane aspect ratios ($r = L_x/L_y$) has been analyzed assuming uniform magnetization in the sample at room temperature. The relaxation times were computed by integrating the Langevin equation in presence of external fields that reduce the energy barrier separating the two energy minima. From these data we obtain the pre-exponential factor in the Arrhenius formula for each aspect ratio. That allows us to estimate the relaxation time in the absence of external field. A minimum aspect ratio of $r = 3.25$ is required for a lifetime larger than 100 years, which is a commonly accepted stability criterion.

PACS: 75.40.Mg; 75.75.+1; 75.20.−g

Keywords: Thermal activation; Langevin dynamics; Relaxation time

1. Introduction

A magnetic random access memory (MRAM) is an array of magnetic tunnel junctions (MTJs), each one comprising a soft magnetic element (free layer) and a hard element (pinned layer) separated by a thin insulating layer [1]. On each MTJ, the information is writen by passing electrical currents through two orthogonal metallized tracks (word and bit lines), which induce a magnetic field in the free layer to reverse its magnetization. In the reading processes, the state of the free layer can be determined by magnetorresistance measurements of the MTJ: if both free and pinned layers are magnetized in the same (opposite) direction, the MTJ has low resistance (high resistance).

The shape and dimensions of the free layer are chosen in order to achieve single domain bi-stable behavior. The two equilibrium states of opposite magnetization are separated by an energy barrier ΔE, which is due to shape and/or magnetocristaline anisotropy. This double-well structure of the energy is the archetype of the hysteretic behavior. In the deterministic case ($T = 0\,\text{K}$), the system can only jump from one state to the other if an external field is applied.

However, at finite temperature ($T \neq 0\,\text{K}$) the system can escape from one state to the other by thermal activation over the barrier ΔE even if the external field is null. Superparamagnetism concerns the loss of magnetic stability as a result of thermal fluctuations that occur when free layers are made too small [2]. In order to achieve higher density storage, the free layer dimensions must be reduced. However, superparamagnetism becomes increasingly important as magnetic particles become small, and it is thought to be the limiting factor for increasing storage densities in magnetic data systems.

It is a requirement for data storage that thermally activated hopping from one well to the other must be improbable over very long periods of time. According to the Arrhenius–Neel model, the relaxation time τ_R is given by

$$\frac{1}{\tau_R} = \frac{dp}{dt} = \frac{1}{\tau_0}\exp\left(-\frac{\Delta E}{K_B T}\right), \tag{1}$$

which describes the probability per unit time dp/dt, of hopping from one well to the other over an energy barrier ΔE. T is the temperature, K_B is the Boltzmann constant, and, τ_0 is a constant related to the gyromagnetic precession period of the magnetic system.

*Corresponding author. Fax: +34 923 294584.
E-mail address: a2577@usal.es (E. Martinez).

0921-4526/$ - see front matter
doi:10.1016/j.physb.2005.10.068

At low temperature and zero external field ($H_{\mathrm{ext}} = 0$), the energy barrier between the two states of opposite magnetization is too much high to observe an escape process by numeric simulations, where typical measures are limited to a few microseconds. However, the energy barrier can be reduced by applying a magnetic field ($H_{\mathrm{ext}} \neq 0$) in the opposite direction to that of the particle's magnetization. When the applied field is close enough to the switching field at zero temperature (H_{SW}), thermal fluctuations are sufficiently strong to allow the system to overcome the barrier, and therefore the magnetization is reversed.

From Arrhenius–Neel model (1), the relaxation time τ_R at a given temperature can be determined if the energy barrier ΔE and the pre-exponential factor τ_0 are known. In present work, we have measured the relaxation time τ_R when an external field is applied to reduce the energy barrier at room temperature by solving the Langevin dynamics. From these values, an estimation of the pre-exponential factor τ_0 can be obtained by fitting the numeric results to the Arrhenius–Neel formula (1). Once τ_0 is known for each sample, the relaxation time without external field can be inferred in order to compare it with the stability criterion of one hundred years.

2. Model and numerical details

Let us consider each free layer in a MRAM to be Permalloy (saturation magnetization $M_s = 8.6 \times 10^5$ A/m, $K_u = 0$, and damping parameter $\alpha = 0.02$) prisms $L_x \times 20\,\mathrm{nm} \times 2.5\,\mathrm{nm}$. We have analyzed samples with L_x between 40 nm ($r = L_x/L_y = 2$) and 120 nm ($r = 6$). Interlayer coupling from the pinned layer, and magnetocristalline anisotropy ($K = 0$) are ignored.

Deterministic ($T = 0$ K) hysteresis loops have been calculated assuming that the particle is uniformly magnetized by solving the Landau–Lifshitz–Gilbert equation for each external field value. We considered that the equilibrium state is reached if the torque between the magnetization $\boldsymbol{m}$ and the effective field $\boldsymbol{h}_{\mathrm{eff}}$ (external field and magnetostatic field) is $|\boldsymbol{m} \times \boldsymbol{h}_{\mathrm{eff}}| < 10^{-6}$. Several in-plane fields were evaluated forming different angles (φ_H) with $x > 0$ axis. The hysteresis loops along the external field directions are displayed in Fig. 1 for a sample with $r = 4$.

From the simulations we observe that the out-of-plane magnetization component (m_z) is always negligible ($m_z \approx 10^{-5}$), and therefore a 2D model is justified. Within this approximation the energy of the system can be written as [3]

$$\begin{aligned} E &= E_{\mathrm{dmg}} + E_{\mathrm{ext}} \\ &= K_{\mathrm{sh}} V \sin^2 \varphi_M - \mu_0 M_s V H_{\mathrm{ext}} \cos(\varphi_M - \varphi_H), \end{aligned} \quad (2)$$

where V is the volume of the particle, H_{ext} is the external field, and φ_M and φ_H are the angles of magnetization and external field measured from the easy axis of magnetization (x-axis). In this case, the shape anisotropy constant K_{sh} is given by

$$K_{\mathrm{sh}} = \frac{1}{2}\mu_0 M_s^2 (N_y - N_x), \quad (3)$$

where N_x y N_y are the demagnetizing factors [4]. The energy (2) has two minima separated by an energy barrier. The height of the barrier is related to the modulus of K_{sh} which increases with the in-plane aspect ratio $r = L_x/L_y$. According to the Stoner–Wohlfarth model, the angular dependence of the switching field H^0_{SW} (defined as the field at which the energy loses its biestable character, $\partial E/\partial\varphi_M = \partial^2 E/\partial\varphi_M^2 = 0$) is given by [3]

$$H^0_{\mathrm{SW}} = \frac{2K_{\mathrm{sh}}}{\mu_0 M_s} (\sin^{2/3}\varphi_H + \cos^{2/3}\varphi_H)^{-3/2}. \quad (4)$$

The switching fields obtained from the simulations (Fig. 1) agree with those obtained from Eqs. (4) and (3) with a relative

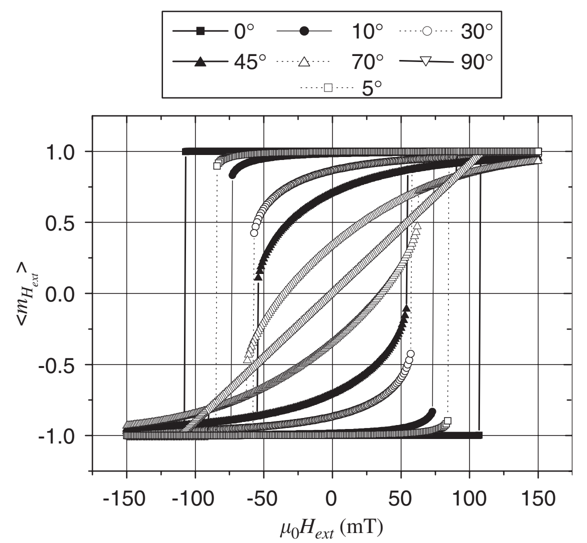

Fig. 1. Hysteresis loops for a prism of 80 nm × 20 nm × 2.5 nm ($r = 4$). $\langle m_H \rangle = \cos(\varphi_M - \varphi_H)$ represents the magnetization along the external field.

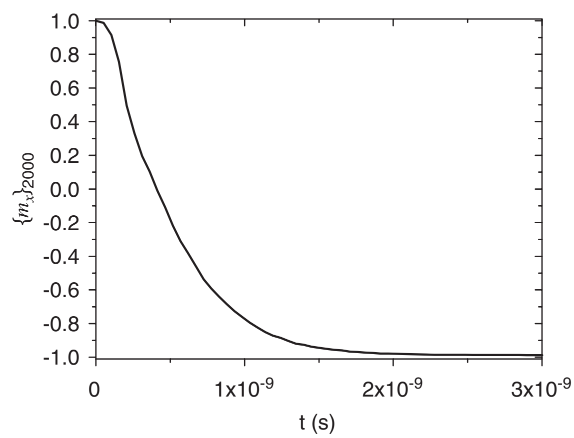

Fig. 2. Averaged trajectory over 2000 stochastic realization of the magnetization parallel to the easy axis. The specific sample (40 nm × 20 nm × 2.5 nm, $r = 2$) is initially magnetized along $x > 0$, and the external field is 50 mT at 185° (around 4.5 mT smaller than the corresponding coercive field).

error smaller than 10^{-2}. This reinforces the assumption that our samples behave like 2D Stoner–Wohlfarth particles.

3. Langevin dynamics: thermal effects

Thermal fluctuations are included in the numerical calculations by adding a random thermal field $\boldsymbol{H}_{\mathrm{th}}$ to the deterministic effective field $\boldsymbol{H}_{\mathrm{eff}}$ in the Landau–Lifshitz–Gilbert equation of motion applied to a single domain particle [5],

$$(1+\alpha^2)\frac{\mathrm{d}\boldsymbol{m}}{\mathrm{d}t} = -\gamma_0 \boldsymbol{m} \times (\boldsymbol{H}_{\mathrm{eff}} + \boldsymbol{H}_{\mathrm{th}}) - \alpha\gamma_0 \boldsymbol{m} \times [\boldsymbol{m} \times (\boldsymbol{H}_{\mathrm{eff}} + \boldsymbol{H}_{\mathrm{th}})], \tag{5}$$

where $\boldsymbol{m}$ is the unitary vector describing the magnetization orientation, γ_0 the gyromagnetic ratio, and α the damping parameter. The thermal field $\boldsymbol{H}_{\mathrm{th}}$ is assumed to be a Gaussian distributed random vector with the following statistical properties:

$$\langle H_{\mathrm{th},k}(t)\rangle = 0, \tag{6}$$

$$\langle H_{\mathrm{th},k}(t) H_{\mathrm{th},l}(t')\rangle = 2D\delta_{kl}\delta(t-t'), \tag{7}$$

where k and l refer to the Cartesian indexes (x,y,z), and D is a constant determining the strength of the thermal field. From fluctuation–dissipation theorem, or by checking that the Maxwell–Boltzmann distribution is recovered when thermodynamic equilibrium is reached, one obtains

$$D = \frac{\alpha K_{\mathrm{B}} T}{\mu_0 V \gamma_0 M_{\mathrm{s}}}, \tag{8}$$

where V is the volume of the sample.

4. Estimation of the relaxation time

Starting from an initial state magnetized along the $x>0$ axis, the fields H_{ext} are applied in the xy plane at 185° from the $x>0$-axis. The values of H_{ext} are always smaller than the coercive field H_{C} but large enough to observe relaxation in a numerically accessible time scale. The Langevin Eq. (6) is integrated by means of a second-order Heun scheme using a dimensionless time step of $\Delta t = 0.52\,\mathrm{ps}$. For each sample and field, 2000 stochastic

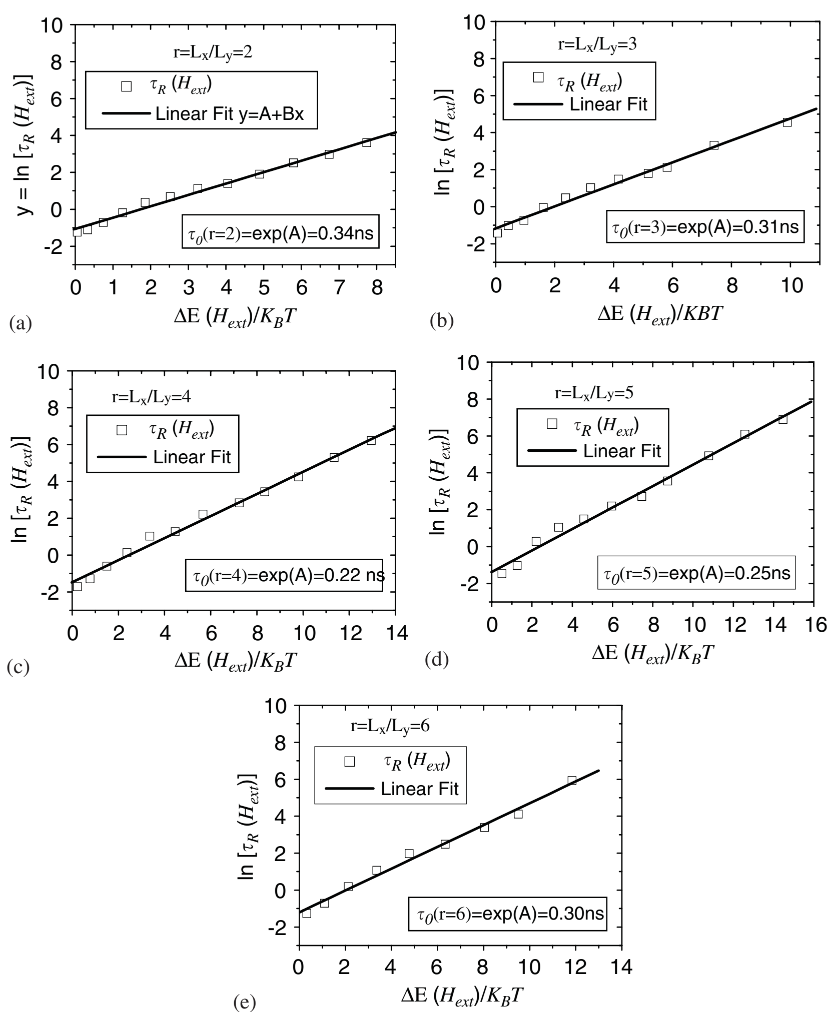

Fig. 3. Computed relaxation times as a function of $\Delta E/K_{\mathrm{B}}T$ at room temperature. (a) $r=2$, (b) $r=3$, (c) $r=4$, (d) $r=5$, and (e) $r=6$. White symbols correspond to results obtained after averaging over 2000 stochastic trajectories ($\{m_x\}_{2000}$), and τ_{R} is defined as the time elapsed until $\{m_x\}(\tau_{\mathrm{R}})=0$. In each case, the energy barrier was computed from Thiaville's expression (9). Black lines correspond to linear fits.

realizations were computed, from which an averaged trajectory of the magnetization along the easy axis $\{m_x(t)\}$ was obtained. The range of evaluated fields is $1\,\mathrm{mT} \leqslant \mu_0(H_C H_{ext}) \leqslant 25\,\mathrm{mT}$ for all r between 2 and 6. Fig. 2 shows a typical relaxation curve for the particular case of $r = 2$ when an external field of 50 mT ($\mu_0(H_C - H_{ext}) \approx 4.5\,\mathrm{mT}$) is applied at 185° from $x > 0$.

In this work, the relaxation time $\tau_R(H_{ext}, \varphi_H, T)$ is defined as the time elapsed until $\{m_x\}(t) = 0$. The obtained values for the relaxation time $\tau_R(H_{ext}, \varphi_H, T)$ are showed in Fig. 3 for all fields and samples analyzed. The results are presented as a function of $\Delta E/K_B T$ for $T = 300\,K$, using Thiaville's expression [6] for energy barrier,

$$\Delta E = 4K_{sh}V\left(\frac{2}{3}\right)^{3/2}\frac{|\cos\varphi_H|^{1/3}}{1+|\cos\varphi_H|^{2/3}}\left(1-\frac{H_{ext}}{H^0_{SW}}\right)^{3/2}. \qquad (9)$$

From Fig. 3 is clear that, except for the small values of $\Delta E/K_B T$, the results ($\ln(\tau_R)$) gather round a straight line approximately for all samples. Therefore, the Arrhenius–Neel (1) can be used to provide the pre-exponential times τ_0 by linear fitting for each $r = L_x/L_y$. The observed discrepancies for smaller values $\Delta E/K_B T$ are not surprising, since the Arrhenius–Neel model (3) is only valid in the high-energy barrier regime ($\Delta E \gg K_B T$).

Computed values of τ_0 vary from 0.34 ns for $r = 2$, to 0.30 ns for $r = 6$. From them, the relaxation time for $H_{ext} = 0$ can be obtained using again the Arrhenius–Neel model (1). Fig. 4 shows the variation of the relaxation time in absence of external field depending on $r = L_x/L_y$ ($L_y = 20\,\mathrm{nm} = \mathrm{cte}$, $L_z = 2.5\,\mathrm{nm} = \mathrm{cte}$) at room temperature.

From results of Fig. 4, the relaxation time $\tau_R(H_{ext} = 0)$ increases with r from $\tau_R(H_{ext} = 0) = 1.34\,\mathrm{ns}$ for $r = 2$, to $\tau_R(H_{ext} = 0) = 5.66 \times 10^{28}$ years for $r = 6$. A minimum $L_x \approx 65\,\mathrm{nm}$ (for $L_y = 20\,\mathrm{nm} = \mathrm{cte}$, $L_z = 2.5\,\mathrm{nm} = \mathrm{cte}$) is required in order to avoid superparamagnetism behavior according with the $\tau_R(H_{ext} = 0) > 100$ years criterion. In this case, an information storage density around 130 Gb/in^2 could be achieved if the separation from one memory cell to its neighbors equals its size.

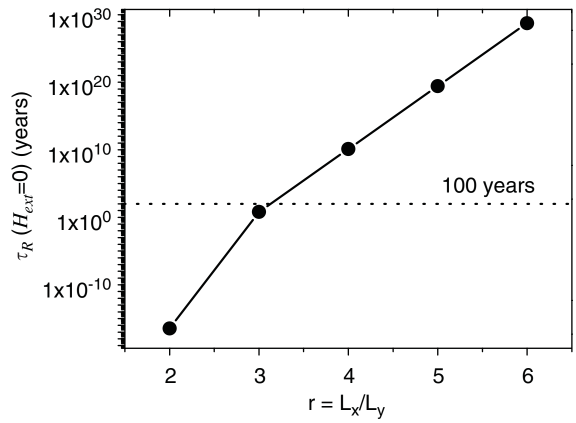

Fig. 4. Relaxation time in absence of external field depending on the $r = L_x/L_y$ ($L_y = 20\,\mathrm{nm} = \mathrm{cte}$, $L_z = 2.5\,\mathrm{nm} = \mathrm{cte}$) at room temperature.

Acknowledgements

This work was partially supported by projects MAT2002-03094 from Spanish Government and SA056/02 from Junta de Castilla y León.

References

[1] R.P. Cowburn, J. Appl. Phys. 93 (2003) 9310.
[2] L. Lopez-Diaz, et al., Phys. Rev. B 65 (2002) 224406.
[3] G. Bertotti, Hysteresis in Magnetism, 1998.
[4] A. Aharoni, J. Appl. Phys. 83 (1998) 3432.
[5] W.F. Brown, J. Appl. Phys. 34 (1963) 1319.
[6] A. Thiaville, et al., Phys. Rev. B 61 (2000) 12221.