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Power Dissipation in Nanomagnetic Logic Devices

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Abstract — **We investigate power dissipation phenomena in individual and coupled nanoscale magnets using micromagnetic simulations. We will demonstrate that nanomagnet dots pumped with slowly varying external fields can dissipate as small as a few-ten milliectronvolts of energy per switching. This makes coupled nanomagnets promising candidates for realizing low-power computing devices.**

Index Terms — **Micromagnetics, Magnetic logic devices, Field-Coupled Computing, Power dissipation, Hysteresis behavior.**

I. INTRODUCTION

The energy dissipated during the magnetization reversal of larger size (bulk) magnets is well known to be equal to the area of the hysteresis curve. This 'hysteresis loss' originates from the irreversible change of a complex (practically random) domain pattern.

In submicron or nanoscale magnets one can design the domain pattern and the reversal behavior by designing the shape of the nanomagnet. The reversal behavior of such magnets strongly depends on the direction of applied magnetic field. Such magnets can be characterized by several hysteresis curves (as opposed to a single static hysieresys curve describing a bulk magnet). As one could expect, the energy that this magnets dissipate also depends on the direction and sequence of applied fields.

The power dissipation in such structures became an important question in the light of recent proposals [1][2] of magnetic logic devices. These devices transmit and process information in an entirely magnetic way, exploiting the dipolar interaction of single-domain magnets and/or propagating domain walls to perform (Boolean) logic operations. Though the experimental feasibility of these structures has already been demonstrated, it remains unclear whether nanomagnet logic devices could ever compete with state-of-the-art CMOS circuits in terms of speed and integration density. We will demonstrate that their beneficial characteristic is low dissipation, as nanomagnets can waste as small as a couple of room-temperature kT (Boltzmann's constant times temperature) energy during switching.

In the next section we introduce a simple method for calculating power dissipation from micromagnetic simulations. Section III will scrutinize the dissipative behavior of a single-domain nanomagnet in different external field pumping scenarios, and a more complex structure, a nanomagnet-wire will be investigated in Section IV. As a conclusion, we will discuss on the lowest possible value dissipation which is achievable in field-coupled structures.

II. MICROSCOPIC MODEL OF DISSIPATION IN MAGNETS

Micromagnetic simulators (such as the widely used OOMMF code [3], which we have also used) numerically solve the lime-dependent Landau-Lifshitz Equation:

$$\frac{\delta \mathbf{M}^{(i)}(\mathbf{r},t)}{\delta t} = -\gamma \mathbf{M}^{(i)}(\mathbf{r},t) \times \mathbf{H}^{(i)}_{\text{eff}}(\mathbf{r},t) - \frac{\alpha\gamma}{M_s}\left[\mathbf{M}^{(i)}(\mathbf{r},t) \times \left(\mathbf{M}^{(i)}(\mathbf{r},t) \times \mathbf{H}^{(i)}_{\text{eff}}(\mathbf{r},t)\right)\right], \quad (1)$$

where $\mathbf{M}(\mathbf{r},t)$ is the magnetization distribution, α is a damping constant, γ and M_s are the the gyromagnetic ratio and saturation magnetization, respectively.

The definition of effective magnetic field is [4]:

$$\mathbf{H}_{\text{eff}} = \frac{1}{\mu}\frac{\partial E}{\partial \mathbf{M}}. \quad (2)$$

So one can immediately calculate the density of dissipated power:

$$P_{diss}(\mathbf{r},t) = \mu H_{eff} \left.\frac{\partial M}{\partial t}\right|_{\text{diss}} = \mu H_{eff}\left(\frac{\alpha\gamma}{M_s}\left[\mathbf{M}^{(i)}(\mathbf{r},t) \times \left(\mathbf{M}^{(i)}(\mathbf{r},t) \times \mathbf{H}^{(i)}_{\text{eff}}(\mathbf{r},t)\right)\right]\right) \quad (3)$$

The OOMMF code can save the sequence of magnetization distribution and effective field distribution, so by post-processing these files one can calculate the density and distribution of dissipation from the simulation.

III. SWITCHING CHARACTERISTICS OF INDIVIDUAL NANOMAGNETS

Macro-scale magnets dissipate power when their domain structures quickly rearrange in the presence of a varying external field. The dissipated energy calculated from the above microscopic model is the same as the area of the hysteresis curve.

If a nanoscale magnet is sufficiently small, no internal domain wall can exist inside the structure [4]. Moreover, the switching of such near single-domains magnets can be accurately controlled by the applied external field sequence. One could expect that these magnets will dissipate much less, than their macro-scale counterparts.

We will scrutinize on a pillar-shaped nanomagnet, which is schematically illustrated in the inset of Figure 1.

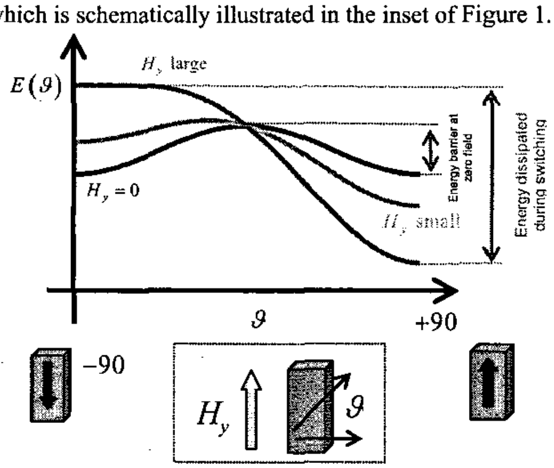

Figure 1. The energy of a nanomagnet as a function of the angle between magnetization direction and the easy axis. The three curves correspond to different easy-axis fields.

Nanomagnets with elongated-shape show bistable behavior, as their steady-state magnetization points parallel with their longest axis. The two states are separated by an energy barrier (the bump of the $H_y = 0$ curve of Figure 1). The most obvious way of switching this magnet is to apply a field which is antiparallel to its present magnetization state. This deforms the energy landscape of the magnet the way it is illustrated in Figure 1. When the field reaches a sufficiently large value, the barrier disappears and the magnet slides down its other magnetization state which is parallel to the external field. The energy dissipated in this process is approximately equal to the height of the energy barrier.

A different switching scenario (which we will refer to as 'adiabatic pumping') is illustrated in Figure 2. First a slowly increasing horizontal (hard axis) field is applied, which gradually sets the magnetization direction parallel to the pumping field. A small vertical field is than 'bends' the magnetization upwards, and after releasing the external pumping field the magnet is set to the upward-pointing steady state.

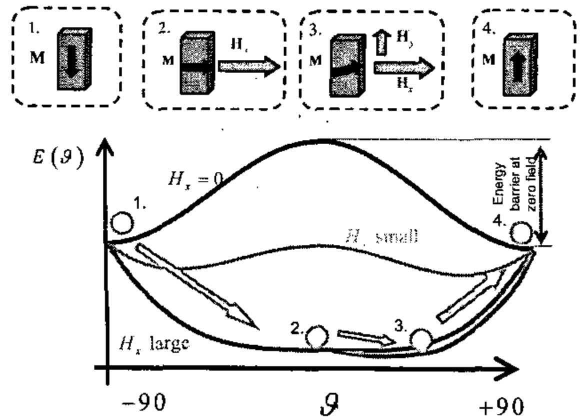

Figure 2. Adiabatic switching illustration. After a horizontal pumping field eliminates the potential barrier between the up and down magnetization states, a weak vertical field can switch the magnetization.

The path of the system on the energy surface is illustrated in Figure 2. If the pumping is performed sufficiently slowly, then the dot always stays in its actual ground state and the system never 'falls down' an energy barrier like it did in the case of Figure 1.

The curve of Figure 3 illustrates the result of a series of simulations, which were performed in the adiabatic pumping scenario, with different field rise times. A very rapid adiabatic pumping cycle dissipates about the same energy as the switching along the hard axis. However, if the rise time of the field becomes slower than a few nanoseconds (which is the characteristic time of damping as follows from Eq. (1)), than the dissipation rapidly decreases, and can reach about $20\,kT$ for this particular dot.

The fact that the dissipated energy does not become zero even at very slow pumping rates arises from the fact that this magnet is not perfectly single domain, and the rapid switching of end-domains yields to dissipation.

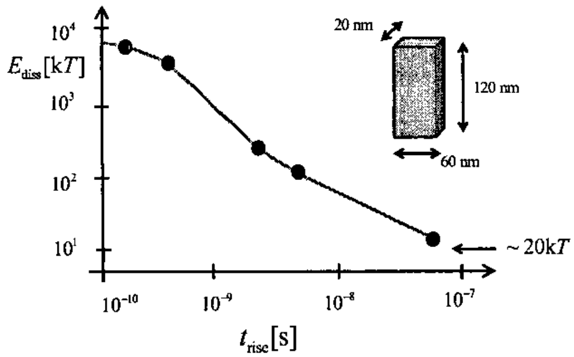

Figure 3. Dissipation//speed curve. Note that the field rise times at the left end of the curve are not experimentally feasible; so real nanomagnets pumped with the adiabatic field-sequence will always dissipate very low amounts of power. The line is a guide for eye.

IV Switching of Coupled Nanomagnets

Adiabatic switching of field-coupled nanomagnets was originally proposed for controlling their switching dynamics (see [2] for details). As an additional benefit, adiabatic pumping also minimizes dissipation. If a line of coupled nanomagnets is driven to ground state by a hard-axis field (see Figure 4.), then the magnets dissipate significantly less energy than the height of the potential barrier separating their steady states.

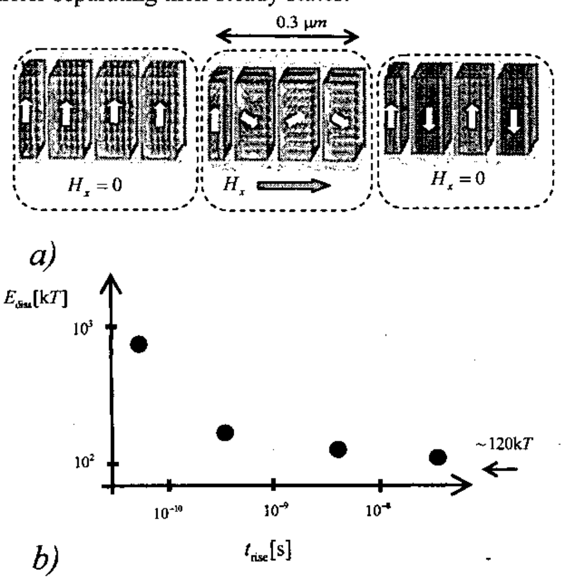

Figure 4. Adiabatic switching of the nanomagnet line. Part *a)* illustrates the switching process and part *b)* is the switching speed – dissipation curve for the entire structure.

However, there is a significant trade-off between minimizing power consumption and achieving robust operation. If there is a strong magnetic interaction field between the dots, the magnets switch abruptly (due to their neighbor's field) and the requirement for slow, adiabatic pumping can no longer be fulfilled. The dissipation could further be reduced only by decreasing the coupling fields (putting the dots farther, etc.) but it would make the device more vulnerable to temperature fluctuations and fabrication defects.

V. Conclusions

We developed a simple numerical procedure to investigate the dissipative behavior of magnets and analyzed the switching of individual and coupled nanomagnets by this method. Our results indicate that field-coupled nanomagnet devices (with reasonably fast operation) can dissipate only a few room-temperature kT energy per switching. This value is close to the theoretical lowest limit of any computation [5]. Field-coupled nanomagnets appear to be promising realization for low-power nanoelectronic devices.

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