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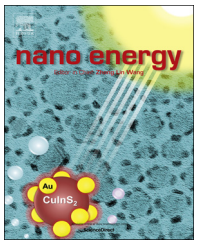

RAPID COMMUNICATION

Fundamental energy limits in the physics of nanomagnetic binary switches

M. Madami[a,*], D. Chiuchiù[a], G. Carlotti[a], L. Gammaitoni[a,b]

[a]*Dipartimento di Fisica e Geologia, Università di Perugia, via A. Pascoli, Perugia 06123, Italy*
[b]*Istituto Nazionale di Fisica Nucleare, Sezione di Perugia, Perugia I-06100, Italy*

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Abstract
Binary switches are the basic element of modern digital computers. In this paper we consider a magnetic binary switch consisting of a nanodot constituted by a single cylindrical ferromagnetic element with two stable energy minima and perform virtual experiments using numerical simulations based on the micromagnetic approach. The fundamental limits in minimum energy dissipation are discussed presenting two, popularly adopted, switching procedures. We show that the zero-power limit is only attainable with one of the two protocols, which does not involve any irreversible entropy increase. Moreover, the influence of the energy barrier height in the presence of fluctuations and the role of bit-flip errors is quantitatively analyzed.

Introduction

It is open the search for new nanoscale computing devices that can be operated with lesser and lesser amount of energy. Such a challenge has been motivated by the fact that the heat produced during computation in present microprocessors has become a serious limitation [1,2] to further increasing performances in future computers. In order to address such a goal, it is worth asking the following question: What is the minimum energy required to perform a computation?

In modern computers, computation is performed through assemblies of logic gates. Each logic gate is made by composing one or more binary switches. Moreover binary switches are also employed in the realization of memory devices, necessary to store the information processed by networked logic gates. Based on this architecture a computation operation, i.e. an information processing action, is realized by changing the status to a number of interconnected binary switches.

The energetic of computation is not a new field. The question associated with the minimum amount of energy has been addressed during the second half of last century by a number of scientists and has led to the contamination between thermodynamics and information theory. One of the main results in this field is known as *Shannon-Von-Newman-Landauer principle* [3–6], which sets the link

*Corresponding author. +39 34 9737 0240.
E-mail address: marco.madami@fisica.unipg.it (M. Madami).

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between the minimum heat produced by a computing device and the change in the information processed by the device itself [7]. This result has been recently put under experimental test [8-10] with the aim of exploring the limits in low power computation [11-13].

A single binary switch event, by itself, is an information preserving operation. Notwithstanding a general agreement that would set at zero the energy required by such an event, this statement is not yet supported by experimental evidences. As a matter of fact, no protocol with experimental relevance has ever been addressed or formulated to operate a generic binary switch according with the zero dissipation goal. In this paper we address this point, by proposing virtual experiments based on present technology. Using micromagnetic modeling and numerical simulations, we investigate the general features of a switch operation in an anisotropic nanomagnet, similar to those already exploited in current magnetic memories or in future bit-patterned storage media. In particular, we calculate the heat production during two different switching protocols. We show quantitatively that the first protocol requires a minimum heat production of $\log(2)\cdot k_B T$ while the second one allows to commute the state of one bit with null heat production. These results are discussed in terms of entropy variation along the two protocols. It is shown that the difference between the two disappears when they are performed with potential energy barrier heights comparable to the average thermal energy.

Model system and micromagnetic framework

The system here under study is constituted by a single cylindrical ferromagnetic nanoelement with a diameter of 50 nm and thickness of 5 nm. To make it bistable, we introduce an uniaxial anisotropy along the in-plane Z direction, as shown in Figure 1. In the absence of external magnetic fields, the presence of the uniaxial anisotropy makes energetically favorable for the magnetization to align along the Z direction, called the magnetization "easy" axis while the perpendicular in-plane X direction becomes the magnetization "hard" axis. The energy profile of the system is shown in Figure 1 where the circular dot has been represented using an "effective" elliptical shape, with its major axis parallel to the Z axis, which helps to graphically represent the presence of the uniaxial anisotropy. Labeling θ the in-plane angle between the Z axis and the average magnetization of the dot, we assume that it encodes a bit of information in the "0" and "1" states, for $-180^\circ<\theta<0^\circ$ or $0^\circ<\theta<180^\circ$, respectively. From Figure 1 it is clear that the two states are separated by an energy barrier that ensures states stability against small fluctuations. The barrier height can be easily modified varying the value of the uniaxial anisotropy constant (K_1). In fact, the system energy in the presence of an external field $\boldsymbol{H}=(H_X,0,H_Z)$ applied in the XZ plane can be expressed, in a Stoner-Wohlfarth or "macrospin" model, as:

$$E(\theta)=V\left(K_1\cos^2(\theta)-M_S(H_x\cos(\theta)+H_z\sin(\theta))\right) \quad (1)$$

where M_s is the saturation magnetization and V the particle volume. The dynamic evolution of the whole system is analyzed through a micromagnetic approach, using a customized version of the commercial software Micromagus [14]. The system is discretized into $N=100$ unit cells of dimension $5\times5\times5$ nm^3; each simulation cell contains a single magnetic moment which interacts with all other magnetic moments via both the dipolar and the exchange interactions. The advantage of using a micromagnetic approach over a so called "macrospin" one, which approximate the whole system as a single magnetic moment, is that it allows to simulate realistic magnetic systems, with their own shape, and to take into account edge effects which are responsible for sizeable contributions to the dissipated energy [13]. The dynamics of the magnetization in each simulation cell is described by the conventional Landau-Lifshitz-Gilbert (LLG) equation of motion written in the form

$$\frac{d\rightarrow M_i}{dt}=-\gamma_0\left[\rightarrow M_i\times\left(\rightarrow H_i^{eff}+\rightarrow H_i^{fl}\right)\right]+\frac{\alpha}{M_S}\left(\rightarrow M_i\times\frac{d\rightarrow M_i}{dt}\right) \quad (2)$$

where γ_0 is the absolute gyromagnetic ratio and α the dissipation constant. H_i^{eff} is the local deterministic effective field at the position of the ith cell, that includes contributions due to four terms: the external applied field, the anisotropy field due to the presence of the anisotropy constant K_1, the exchange field due to the exchange interaction with the neighboring spins and the dipolar field due to the dipolar interaction with all other spins. The fluctuating stochastic field H_i^{fl}, that accounts for the thermal noise, is assumed to be delta-correlated in both time and space. Moreover, the noise power is assumed to be proportional to the temperature and to the dissipation constant, according to the fluctuation-dissipation theorem. The dynamics of the system is obtained by numerically solving this system of N stochastic differential equations. The magnetic parameters are those of Permalloy ($Ni_{80}Fe_{20}$) which is the most commonly used material in nanomagnetic logic devices (saturation magnetization $M_S=800\times10^3$ A/m, exchange stiffness constant $A=1.3\times10^{-11}$ J/m and effective damping coefficient $\alpha=0.01$).

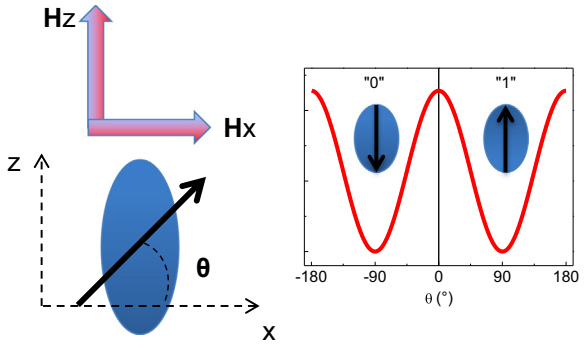

Figure. 1 The left panel presents a schematic picture of the magnetic switch considered in the simulation, characterized by an easy (hard) magnetic direction along the Z (X) axis. The right panel shows the corresponding double-well potential energy of the magnetic particle, characterized by two minima occurring for $\theta=\pm90^\circ$.

Results

Switching protocol A

The first switching protocol we consider, referred to as "protocol A", is similar to the one described in Berut et al.