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Experimental and theoretical analysis of Landauer erasure in nanomagnetic switches of different sizes

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Bistable nanomagnetic switches are extensively used in storage media and magnetic memories, associating each logic state to a different equilibrium orientation of the magnetization. Here we consider the issue of the minimum energy required to change the information content of nanomagnetic switches, a crucial topic to face fundamental challenges of current technology, such as power dissipation and limits of scaling. The energy dissipated during a reset operation, also known as “Landauer erasure”, has been accurately measured at room temperature by vectorial magneto-optical measurements in arrays of elongated Permalloy nanodots. Both elliptical and rectangular dots were analysed, with lateral sizes ranging from several hundreds to a few tens of nanometers and thickness of either 10 nm or 5 nm. The experimental results show a nearly linear decrease of the dissipated energy with the dot volume, ranging from three to one orders of magnitude above the theoretical Landauer limit of $k_B T \times \ln(2)$. These experimental findings are corroborated by micromagnetic simulations showing that the significant deviations from the ideal macrospin behavior are caused by both inhomogeneous magnetization distribution and edge effects, leading to an average produced heat which is appreciably larger than that expected for ideal nanoswitches.

KEYWORDS: logic switches; nanodevice; fluctuations; zero-power ICT; nanomagnetism.

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1. Introduction

The progress towards better performance of computing devices has to face the tremendous problem of heat production during computation in current microprocessors, based on the well-established metal-oxide semiconductor (CMOS) technology [1,2,3]. They consist of logic gates containing binary switches, so that it is of outmost importance to test the limits of minimum dissipation for a single erasure or switching event. To this respect, the exploitation of magnetic switches in both memory cells and logic gates is attracting interest since they are intrinsically non-volatile and require very low operation power. However, the Landauer principle [4] and related works on the thermodynamical aspects of computation [5,6,7,8] define a fundamental limit of $k_B T \times \ln(2)$ to the minimum energy required for a single bit erasure (or reset) operation (where k_B is the Boltzmann constant and T is the temperature). This is known as the “Landauer limit” and is connected with the irreversible entropy variation of the system. For room temperature, such a limit corresponds to about 3×10^{-21} J, i.e. orders of magnitude below the switching energy required by current CMOS devices [3]. In principle, such a small energy consumption can be approached in resetting a nanomagnetic switch, as it was recently demonstrated by computational studies based on either the macrospin approximation or micromagnetic simulations [9,10,11]. These numerical simulations considered “ideal” nanomagnetic dots of Permalloy, subjected to thermal fluctuations. More recently, the first experimental tests of the Landauer’s principle have appeared in the literature, based on a micrometric bead confined within a double-well optical trap [12,13].

In this paper, we aim at testing the Landauer limit in the case of real nanomagnetic switches, i.e. a physical nano-system suitable for electronic application, where the encoded information is represented by the electron spin rather than the position of large particles or beads. In particular, we analyze bistable switches consisting of elongated ferromagnetic dots of different sizes and shapes, that are similar to those already exploited for data storage [14,15] and for nano-magnetic logic devices [16]. The energy dissipation during a Landauer erasure operation has been measured by vectorial magneto-optical Kerr effect (MOKE) experiments in sub-micrometric elliptical or

rectangular dots of Permalloy ($\text{Ni}_{80}\text{Fe}_{20}$). Their elongated shape introduces a uniaxial anisotropy of magnetostatic origin and defines the easy axis for the magnetization, so the logic states “0” and “1” are identified as the two possible orientations of the magnetization along this axis. The experimental data are complemented by micromagnetic simulations based on a customized version of the commercial software Micromagus [17]. It is shown that for magnetic dots with lateral dimension of several hundreds of nanometers edge effects and inhomogeneity in the magnetization distribution lead to significant deviations, up to three orders of magnitude, from the theoretical limit. However, on reducing the dot size down to sub-100 nm lateral dimensions, one finds values that approach, although without reaching it, the theoretical Landauer limit of $k_B T \times \ln(2)$ per erasure event.

Figure 1 Upper panel: Schematics of the magnetic nanodot, considered as a bistable switch and characterized by an easy (hard) magnetic direction along the z (x) axis. The corresponding double-well potential energy of the magnetic particle, characterized by two minima occurring for $\theta = \pm 90^\circ$ separated by a maximum at $\theta = 0^\circ$, is shown in the bottom panel.

Figure 2. (a-e) Evolution of the energy landscape during the reset (i.e. Landauer erasure) process. (f) Sequence of the applied external H_x and H_z field components as a function of time.

2. Model system and micromagnetic framework

The energy landscape of the system is shown in Fig.1 where the Permalloy elliptical dot has been represented with its major axis parallel to the z axis. Labeling θ the in-plane angle between the x-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 Fig.1 it is clear that the two states are separated by an energy barrier that ensures states stability against small thermal fluctuations. The dynamic evolution of the whole system is analyzed through a micromagnetic

approach, using a customized version of the commercial software Micromagus [13]. The system is discretized into N unit cells of dimension $5 \times 5 \times 10 \text{ nm}^3$, i.e. comparable to the exchange length for Permalloy; each simulation cell contains a single spin interacting with all the others via both the long range dipolar and the short range exchange interactions. The dynamics of the magnetization in each simulation cell is described by the conventional Landau-Lifshitz-Gilbert (LLG) equation of motion [18] written in the form:

$$\frac{d\vec{M}_i}{dt} = -\gamma_0 \left[\vec{M}_i \times (\vec{H}_i^{\text{eff}} + \vec{H}_i^{\text{fl}}) \right] + \frac{\alpha}{M_s} \left(\vec{M}_i \times \frac{d\vec{M}_i}{dt} \right) \quad (1)$$

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 i -th cell, that includes contributions due to three terms: the external applied field, 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} , which 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 [19, 20, 21]. The dynamics of the system is obtained by numerically solving this system of N stochastic differential equations. The magnetic parameters assume conventional values for Permalloy such as the saturation magnetization $M_s = 800 \cdot 10^3 \text{ A/m}$, the exchange stiffness constant $A = 1.3 \cdot 10^{-11} \text{ J/m}$ and a damping coefficient $\alpha = 0.01$. As usual in Permalloy, a negligible intrinsic anisotropy is considered, so that the height of the potential barrier separating the two magnetization orientations is due to the shape of the dots.

We consider an erasure protocol similar to the one described in previous computational studies [10, 11, 11]. It starts with the magnetization at equilibrium and parallel to the easy axis. A sequence of external magnetic fields is applied along the two symmetry directions, as illustrated in Fig. 2, in order to bring the system from the initial state (either “0” or “1”) to the final state which

corresponds to the logic state “1”. The corresponding evolution of the energy landscape during the erasure process is shown in Fig. 2(a-e). One starts with the system in either the “0” or the “1” logic state (left or right well, Fig. 2(a)). During the Stage I an external field H_x is applied along the system hard axis (x direction), with the field intensity linearly increasing in time (Fig.2(f)) up to $\mu_0 H_x = 100$ mT. The effect of the applied external field is to lower the energy barrier between the two energy minima as shown in Fig. 2(b). When the height of the barrier is reduced down to a few $k_B T$, the probability of the system to “jump” over it becomes sizeable and it rapidly reaches the thermal equilibrium with the external environment (first half of stage I). This means that, for a finite temperature, M_z begins to oscillate around zero, so that the system goes through an “unknown” state which can be considered as a statistical mixture of “0” and “1”. As a consequence, the system entropy irreversibly increases. During the second half of Stage I the energy barrier between the two wells is totally suppressed and the system finds itself in a single-well potential (Fig.2(c)). This corresponds to a decrease of the system entropy that, according to the second law of thermodynamics, requires a work to be done on the system [11]. Through Stage II, a linearly increasing field is applied along the vertical (z) direction to break the symmetry and force the system towards the final logic state “1”, keeping the horizontal field H_x fixed at the value it reached at the end of Stage I. During Stage III H_x is removed and finally, in Stage IV, also the vertical H_z field is removed ending with the system in the logic state “1” (Fig.2(e)) and no applied field.

The heat produced during the above described process is equal to the net work done on the system by the external field during the whole magnetic field sequence. This can be easily calculated as the integral of the scalar product $dW = \mathbf{H} \cdot d\mathbf{M}$ where $\mathbf{H}$ is the external applied field and $\mathbf{M}$ is the magnetization of the system averaged over all the simulation cells.

In the simulations, the full switching procedure is then repeated several times (usually 100 repetitions) to extract statistically meaningful values. The time duration of the erasure process must be sufficiently long (above about 2-3 μs , as shown in Ref. 10) in order to make the influence from the viscous damping negligible.

Figure 3. Scanning electron microscopy images of samples E10, E11 and R2.

Sample	<i>a</i> (nm)	<i>b</i> (nm)	<i>t</i> (nm)
E1	815	515	10
E2	405	280	10
E3	250	160	10
E4	180	115	10
E5	118	85	10
E6	100	70	10
E7	100	60	10
E8	83	63	10
E9	124	84	5
E10	105	90	5
E11	73	50	5
R1	100	60	10
R2	128	88	5

Table I List of the samples investigated. *a*, *b* and *t* represent the length, the width and the thickness of the Permalloy dots with either elliptical (E1 - E11) or rectangular (R1 - R2) shape, respectively.

3. Sample fabrication and experimental setup

Standard e-beam lithography, thermal evaporation, and lift-off procedure have been used to prepare several arrays of elliptical Permalloy ($\text{Ni}_{80}\text{Fe}_{20}$) dots on a single n-doped GaAs substrate. First, a positive resist (PMMA) with a height of around 100 nm was spin-coated on the substrate. The resist was exposed via electron beam lithography with exposure times between 25 to 50 ns and e-beam currents of around 1.4 nA. The explicit exposure time and e-beam current had to be optimized for every nanodot size and are typically not constant for the whole sample. After the lithographic process, the resists was developed for 30s in MIBK/Isopropanol (1/3) and then fixed for another 15s in Isopropanol. After the resist development, Permalloy films with a thickness of either 5 or 10 nm

were thermally evaporated at a low evaporation rate (0.01~0.02 nm/s) and with the substrate at room temperature, so the films are polycrystalline with nanometric grains. [22,23]. Atomic force microscopy (AFM) investigation of the GaAs substrate and of the Permalloy films was conducted to determine the surface roughness (calculated by the root-mean-square (rms) of the height fluctuation for areas with size $2\ \mu\text{m} \times 2\ \mu\text{m}$). The rms for the GaAs substrate and for a 10 nm thick film was 0.40 nm and 0.35 nm, respectively. The fabrication process was finalized by a lift-off process with Methylpyrrolidon. We prepared several samples with nominally elliptical or rectangular dots, of thickness 10 nm or 5 nm, consisting of squared arrays, each $200\ \mu\text{m} \times 200\ \mu\text{m}$ wide. The distinct arrays are $500\ \mu\text{m}$ apart from each other. In each array the nanodots are arranged in a hexagonal lattice, as seen in the scanning electron microscopy (SEM) images of Fig. 3, with a separation among adjacent dots larger than the length, i.e. chosen to insure negligible dipolar interaction, so that the dots behave as isolated elements. It is seen that the dot edges present some irregularities, on the scale of a few nanometers, due to the intrinsic limitation in the spatial resolution of e-beam lithography. In Table I, the dimensions of the major (a) and minor (b) axes of the dots, as measured by scanning electron microscopy (SEM), are listed together with the labels E1- E11 (R1-R2) relative to elliptical (rectangular) dots.

To measure the magnetization curves and the energy dissipation during a reset-to-one operation in the above samples, we have assembled a MOKE setup based on low-noise longitudinal magnetometry [24]. Fig. 4 shows a photograph of the setup: the light of an intensity-stabilized laser (wavelength 635 nm) is linearly polarized (perpendicular to the incidence plane) and focused on the surface of the sample. The diameter of the focused spot is about $200\ \mu\text{m}$, so that almost the entire patterned area is illuminated and the signal is obtained averaging over the whole array of each sample. The reflected beam crosses a photoelastic modulator (modulation frequency 50 kHz) and a polarization analyzer before reaching the photodetector (a biased Si photodiode, 1 MHz bandwidth). Using phase sensitive detection and a lock-in amplifier, the small ellipticity acquired by the light reflected by the magnetized sample due to the Kerr effect is measured. As H is swept, the measured

signal is proportional (first order approximation) to the component of the magnetization along the intersection between the sample surface and the light scattering plane (x-axis direction).

In order to reduce the noise during measurements, the apparatus is mounted on an anti-vibrating optical table and enclosed in a box (Faraday cage). The sample is mounted on a high-precision motorized rotation stage and inserted within the gap of a specially designed quadrupolar electromagnet. The maximum intensity of the two perpendicular magnetic fields, H_x and H_z , is about 180 mT. With this extremely low-noise apparatus, one can either measure the scalar hysteresis cycle of a sample along a specific direction or reconstruct the magnetization curves (M_x vs. H_x and M_z vs. H_z) while applying a sequence of fields in the sample plane to achieve a measurement of heat production during the reset-to-one protocol illustrated in Fig. 2. The typical time scale of such an experiment is a few tens of seconds.

Figure 4. Photographs relative to the experimental MOKE apparatus that has been designed and built for the specific experiments of this work. The left panel shows the sample within the poles of the quadrupolar electromagnet.

4. Experimental procedure and results

In Fig. 5 one can see typical hysteresis cycles measured along either the hard (a) or the easy (b) direction of the E7 sample. It appears that the signal-to-noise ratio is very good[25], as a result of multiple efforts to avoid mechanical and thermal drifts, as well as electronic noise. In order to measure the magnetization curves M_x vs. H_x and M_z vs. H_z (shown in panels (c) and (d)), the sample is first carefully aligned with an accuracy better than one tenth of a degree, looking at the transverse component of the magnetization during a hard-axis hysteresis cycle (i.e. the component M_z measured while sweeping H_x). Then, the sequence of fields reported in Fig. 2 is applied while acquiring the component of the magnetization along the z axis (i.e. M_z) that coincides with the axis of sensitivity of the MOKE apparatus. Subsequently, the sample is rotated by 90° and the measurement is repeated, acquiring the M_x component. To further reduce the noise in the acquired signal, each measurement is repeated five times (ten times for the 5 nm thick dots) and then averaged.

Given the high sensitivity of this measurement, we have verified that second-order effects, usually negligible in standard MOKE measurement gave a small, but measurable, contribution to our measurement. In order to remove the above mentioned slight second-order contributions in M (i.e. proportional to $M_x \cdot M_z$) from the MOKE signal as well as to average out the effects arising from the unavoidable asymmetries in the shape of real dots, each measurement sequence was applied to the four quadrants of the H_x - H_z space ($+H_x, +H_z$; $+H_x, -H_z$; $-H_x, +H_z$; $-H_x, -H_z$). The final magnetization curves, an example of which is shown in Fig. 5 (c) and (d), are those mediated on the four quadrants. From addition of the areas enclosed within the two above-mentioned averaged magnetization curves, we extracted the value of the heat production during the Landauer erasure process. The results relative to 10 nm (5 nm) thick elliptical nanodots are reported as black (grey) open circles in Fig. 6 as a function of the volume of the investigated switches. The overall uncertainty of each experimental point, indicated by the error bars, is of about 25%, resulting from

proper addition of the uncertainties in the dot dimensions, magnetic field calibration, and saturation magnetization. The latter quantity was extracted by Brillouin light scattering measurements [26] performed on a reference Permalloy film and turned out to be $M_s = (795 \pm 85) \times 10^3 \text{ A/m}$. It can be seen that the measured values decrease almost linearly with the dot volume and that the minimum value, achieved for sample E11, is still an order of magnitude larger than the theoretical limit of $k_B T \times \ln(2)$. This deviation is even slightly larger for rectangular, rather than elliptical, dots (magenta squares in Fig. 6).

Figure 5 Typical scalar hysteresis cycles measured on Sample E7 along the easy (a) and hard (b) direction. Typical magnetization curves M_x vs. H_x (c) and M_z vs. H_z (d) measured on the same sample during the reset-to-one protocol.

Figure 6. Experimental values of the dissipated energy during Landauer erasure: open black and grey crossed circles are for 10 nm and 5 nm elliptical dots, respectively. The open and crossed magenta squares are for 10 nm and 5 nm thick rectangular dots, respectively. The results of simulations relative to elliptical and rectangular dots, 10 nm thick, are shown as half-filled blue circles and squares, respectively. The dashed lines are guides to the eye.

In order to complement and shed light on the above experimental results, we have exploited the micromagnetic approach described in Section 2 to investigate the heat production during the reset operation on elliptical (rectangular) dots with the same volumes of those measured by MOKE; the output of the simulations are reported in Fig. 6 as blue half-filled circles (squares). It can be seen that also the simulations account for a heat production that grows with the dot volume, although the simulated values are always below the measured ones. Remarkably, the values obtained from

simulation of rectangular dots agree very well with the experimental values of the dissipated energy in the four larger samples. This effect can be explained if one considers that the presence of sharp edges and corners favors the inhomogeneity of the magnetization, resulting in a larger heat production via dynamically irreversible and discontinuous “jumps” during the erasure procedure. According to the simulations, such an additional energy dissipation caused by the above-mentioned mechanisms is more marked for the rectangular shape and decreases with the volume of the dots, approaching the Landauer limit for volumes below about 8×10^4 and $4 \times 10^4 \text{ nm}^3$ for elliptical and rectangular shape, respectively. Although our simulations clearly show that the presence of sharp corners (rectangular shape) enhances the energy dissipation, it should be also considered that our model system did not take into account the polycrystalline nature of the dots and the unavoidable irregular surface morphology and rough edges of the real samples (as discussed in Sect. 3 and seen in the SEM images of Fig. 3) that can further induce inhomogeneity and pinning of the magnetization. This can further explain the observed misfit between the experimental results and those of the simulations for relatively small volumes. To verify that the main contribution to heat production can be ascribed to friction mechanisms connected with the microstructure and the unavoidable roughness of the real sample, rather than to the entropic origin responsible for the Landauer limit, we also performed a series of measurements where the protocol of Fig. 2 was modified such that the z-component of the field was not decreased down to zero, but to a finite value of about 10 mT. In such a way, the energy barrier between the “0” and “1” states was not completely removed at any stage of the protocol, so that the “erasure” (thermalization, end of Stage I in Fig. 2) was avoided and no irreversible entropy increase was caused. Therefore, strictly speaking, this latter procedure did not imply any entropic cost. The results of this “modified” experiment, yielded values of the dissipated energy that were, within the experimental uncertainty, as those measured during the Landauer erasure. This indicates that the main mechanism responsible of heat production is also present when the entropy of the system is not irreversibly increased, confirming its dependence on dynamically irreversible mechanisms. From extrapolation

of the almost linear dependence of the energy dissipation shown in Fig. 6, one could hypothesize that if the dimensions of the dots would be further reduced, one could observe a reduction of the measured heat production, approaching the expected theoretical limit. This will require, however, to push the lithographic technique to its ultimate limits, with the additional inconvenience that dots with lateral size as small as a few nanometers are not useful for data storage, because they become superparamagnetic at room temperature.

As a final step of this study, we have also analyzed two more samples where the elliptical dots, of the same size as in sample E8, were placed side-by-side in pairs, with a separation of either 25 nm or 35 nm, to put in evidence the role of dipolar coupling. As shown in Fig. 7, the measured dissipated energy (black points) increases as the separation is reduced and this trend is found also in the micromagnetic simulations. To qualitatively understand this behavior we have to keep in mind that, in this configuration, the effect of reducing the separation distance is to make the anti-parallel state energetically favorable over the parallel one. So, when the system thermalizes during the Stage I of the erasure process (Fig. 2), the dipolar interaction tends to favor the anti-parallel state of the two dots which is the real energy minimum of the system. But since the final state of the erasure process is, by definition, the parallel state, the external field will perform a net positive work on the system to reach this final state. This work is proportional to the energy difference between the parallel and anti-parallel states which becomes larger as the separation distance is reduced. From a quantitative point of view, however, also in this case the agreement between experiments and simulation is only semi-quantitative, because the dipolar coupling in the real sample is probably less effective than in the simulations, because of edge-imperfection and distribution of interdot-separation in the real sample.

Figure 7. Experimental (black circles) and simulated (blue half-filled circles) values of the dissipated energy during a Landauer erasure process for couples of elliptical dots (of lateral dimension $83 \times 63 \times 10 \text{ nm}^3$) placed side-by-side, as a function of the interdot separation S .

5. Conclusions

In conclusion, we have presented the results of a joint experimental and micromagnetic investigation of the energy consumption during the reset operation of magnetic binary switches consisting of either elliptical or rectangular ferromagnetic dots of different lateral sizes, down to a few tens of nanometers. From a careful magneto-optical measurement of the magnetization curves along two orthogonal directions, it turned out that the produced heat is appreciably larger than the expected Landauer limit for ideal nanodots. Based on the output of micromagnetic simulations, such a deviation from the ideal behavior has been attributed to dynamically irreversible processes

caused by the inhomogeneity of the magnetization distribution, as well as by structural and morphological imperfections of the real nanodots. Similar important deviations from the ideal case have been also found if the magnetic switches are not isolated, but are dipolarly coupled with adjacent switches. In any case, the measured values of energy dissipation in both isolated and coupled dots are orders of magnitude below those occurring in current CMOS-based switches [3], so we are confident that these results will stimulate further progress in the field of low-power computing and data storage using nanomagnetic switches.

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Accepted manuscript

Highlights

- We test the Landauer limit for nanomagnetic switches
- Results of magneto-optical experiments and micromagnetic simulations are compared
- Edge-effects and structural imperfections cause dissipation in excess of the Landauer limit