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Micromagnetic simulation of energy consumption and excited eigenmodes in elliptical nanomagnetic switches

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ABSTRACT

Sub-200 nm patterned magnetic dots are key elements for the design of magnetic switches, memory cells or elementary units of nanomagnetic logic circuits. In this paper, we analyse by micromagnetic simulations the magnetization reversal, the dissipated energy and the excited spin eigenmodes in bistable magnetic switches, consisting of elliptical nanodots with 100×60 nm lateral dimensions. Two different strategies for reversal are considered and the relative results compared: (i) the irreversible switching obtained by the application of an external field along the easy axis, in the direction opposite to the initial magnetization; (ii) the precessional switching accomplished by the application of a short magnetic field pulse, oriented perpendicular to the initial magnetization direction. The obtained results are discussed in terms of deviation from the macrospin behavior, energy dissipation and characteristics of the spectrum of spin eigenmodes excited during the magnetization reversal process.

1. Introduction

It is well known that bistable or multistable nanomagnetic switches can be used to store information, associating each logic state to a different equilibrium orientation of the magnetization. For instance, in current magnetic random access memories, as well as in prototypes of future discrete hard disks, the bits are encoded according to the orientation of the magnetic moment of submicrometric dots. After enormous advances in miniaturization and nanofabrication technology, it is now possible to pattern particles having size that are comparable to intrinsic exchange length, approaching the nanometric size. In this respect, sub-200 nm dots, where a nearly-single-domain behavior is expected, are candidates to realize nanomagnetic logic (NML) devices, known also as magnetic quantum cellular automata (MQCA) [1–4]. These systems have emerged as a novel paradigm to realize non-volatile, nanometer scale, ultra-low power dissipation digital logic. In this architecture, several nanodots are put close to each other in dense chains or clusters and the information is propagated and processed thanks to the dipolar coupling between neighbor dots. Although useful for rough estimate of the expected behavior of NML and MQCA, the macrospin approximation cannot be used to realistically simulate the behavior of such systems: it has been shown that deviation from the ideal shape, edge effects, metastable state and spin-waves excitation can introduce complex behavior leading to non-uniform magnetization reversal and faults. It appears that the design and realization of reliable nanomagnetic switches, to be used in either magnetic memories or NML devices, requires a detailed modeling and understanding of the switching mechanism and consequent dynamics. To this respect, relevant aspects are the analysis of the spin waves generated during the reversal, that are severe source of noise in real devices and represent a limit to the rate of data writing or processing [5], as well as the control of the dissipated power in view of low-energy consumption devices [6–8].

In this work, a computational study of the reversal mechanism of $100 \times 60 \times 5$ nm^3 elliptical permalloy dots is performed for (i) the conventional irreversible switching, obtained by the application of an external field along the easy axis, in the direction opposite to the initial magnetization (referred to as "conventional switching", CS) and (ii) the "precessional switching" (PS) obtained by the application of a short pulse of field, oriented perpendicular to the initial magnetization direction. Magnetization dynamics is calculated by the numerical solution of the Landau–Lifshitz–Gilbert (LLG) equations, within the standard micromagnetic approach. The characteristics of the reversal computed along the two above mentioned strategies are compared and discussed with emphasis given to the dissipated power and to the characteristics of the excited eigenmodes spectrum. Evidence is provided for appreciable deviations from the behavior expected from a macrospin approximation, in spite of the relatively small (nanometric) size of the dot under investigation.

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2. Details about micromagnetic modelling

Micromagnetic simulations have been carried on using a special version of the commercial software MICROMAGUS. Details about the code and its characteristics can be found elsewhere. [9].

The elliptical dot was discretized in cells with lateral size of $1 \times 1 \times 5$ nm, and the LLG equation solved, achieving a temporal evolution, at zero temperature, for the magnetization of the single cells. The magnetic parameters of polycrystalline Permalloy have been used, with $\gamma = 1.76 \times 10^7$ rad $\times$ (Oe $\times$ s)$^{-1}$ the gyromagnetic ratio, $\alpha = 0.02$ the phenomenological damping constant, $M_s = 860$ G the saturation magnetization, $A = 1.\ 3 \times 10^{-6}$ erg/cm the exchange stiffness, and a moderate uniaxial anisotropy ($K_1 = 1 \times 10^5$ erg/cm^3) directed along the major axis of the ellipse (x-axis). In addition to standard feature of the commercial version, we have used a special routine to calculate the temporal evolution of the dissipated power according to the well-known expression [8]

$$P_{diss} = \frac{\alpha}{\gamma M_s} \sum_{i,j} \left| \frac{dM_{ij}}{dt} \right|^2 \quad (1)$$

summed over the whole set of discrete cells (i and j are the indices of each cell in the two dimensional array).

As far as the dynamical calculations are concerned, here we have used a post-processing routine to calculate the power spectrum $P_{ij}(f)$ of the dynamical magnetization for every discretization cell. From these, one can then calculate the average power spectrum as the sum of the power spectra of the single cells. Moreover, it is possible to compute the two dimensional spatial distributions of each eigenmode present in the spectrum by calculating the Fourier coefficients of the corresponding eigenfrequency. These can be presented as bi-dimensional plots of both modulus and phase of the components of the dynamical magnetization. Concerning the labeling of the found eigenmodes, following the previous literature [10], we indicate as fundamental mode (F), the one without nodal lines, m-BA denotes the dipolar modes with m nodal lines perpendicular to the equilibrium direction of the magnetization (backward-like modes), and n-DE stands for modes with n nodal lines parallel to the direction of the magnetization (Damon–Eshbach-like modes). The 'mixed' modes are labeled m-BA $\times$ n-DE.

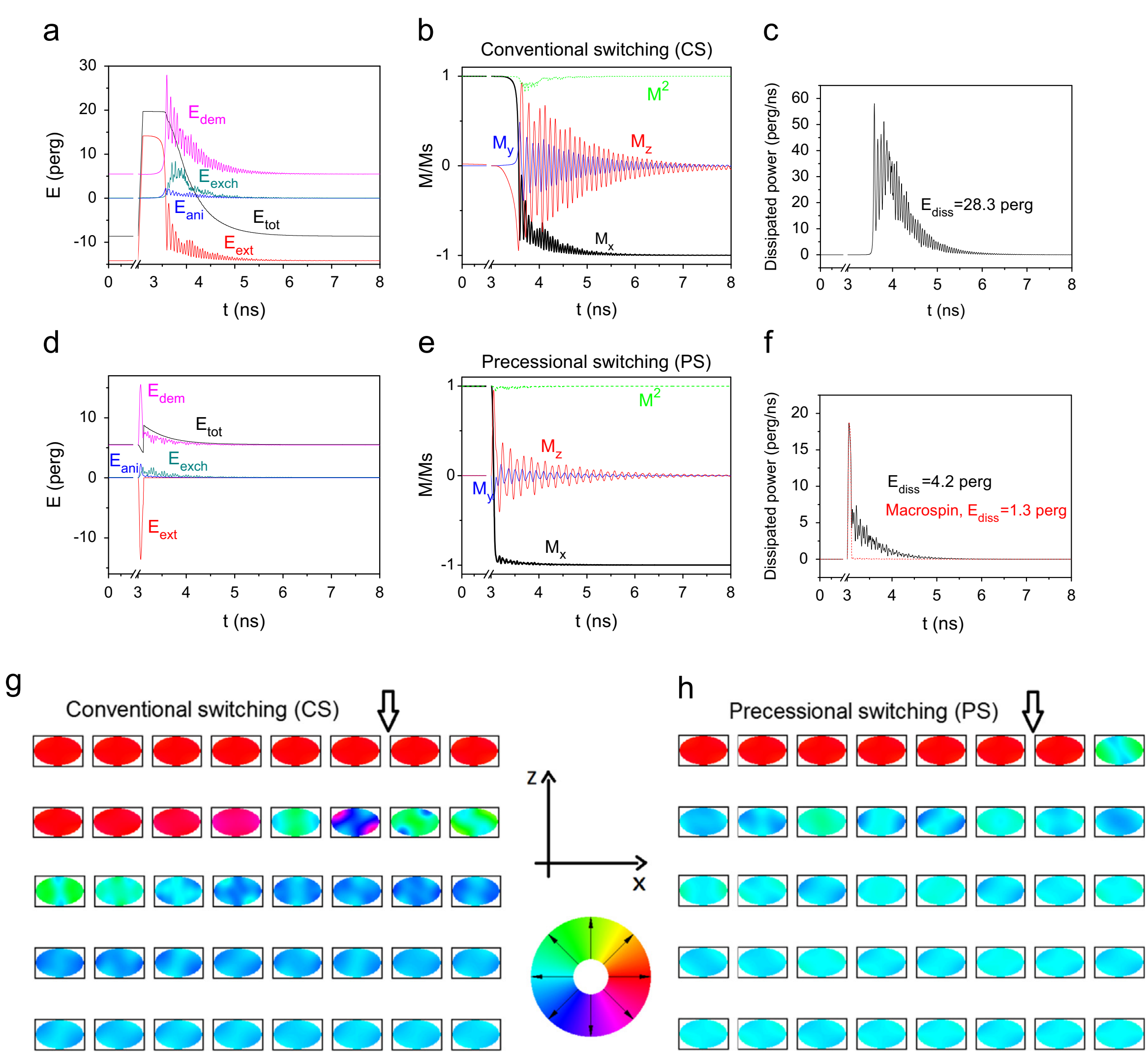

Fig. 1. Evolution of the different energy terms, of the averaged dot magnetization components and of the dissipated power during conventional switching (a)–(c) and during precessional switching (d)–(f). The former switching is obtained by inverting the external field H_x from +700 to −700 Oe at time $t=3$ ns (rise time 0.1 ns), while the latter is achieved thanks to the application of a trapezoidal field pulse, also at time $t=3$ ns, with pulse length 110 ps and height $H_z=750$ Oe (the red dashed curve in panel (f) refers to the dissipated power of a single macro-spin with the same magnetic parameters of the elliptical dot). Panels (g) and (h) show the snapshot of the dot magnetization, recorded every 100 ps, starting from $t=2.4$ ns; the black arrows indicate the time when the reversal field is applied, i.e. at $t=3$ ns. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)