Micromagnetic study of skyrmion racetrack and microwave oscillator

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Abstract—Skyrmions are topologically protected magnetic solitons which are attracting a lot of interest from either a fundamental or a technological point of view. Skyrmions can behave as static objects, being shifted in a racetrack memory or as dynamical solitons, giving rise to topological droplets.

This paper points out that a Néel skyrmion based racetrack memory driven by the spin-Hall effect could be a competitive memory architecture, and that, in nano-contact geometry, the spin-transfer torque, together with the Dzyaloshinskii–Moriya interaction, can excite stationary and non-stationary topological droplets.

Keywords—skyrmion; spin-transfer torque; Dzyaloshinskii–Moriya interaction; topological droplet.

I. INTRODUCTION

Several mathematical models have been used to analyze magnetic materials [1], [2], [3], [4], [5], [6], [7], [8], [9], [10], [11], [12], obtaining useful information about their behavior. However, micromagnetic simulations have been widely performed to study the static and dynamical properties of magnetic solitons [13], [14], such as domain walls [15] and skyrmions [16], [17], [18].

Skyrmions are static magnetic solitons [19] which can be achieved in out-of-plane devices and they can behave like particles, e.g. can be shifted in a track (racetrack memory) [20], via the spin-transfer torque (STT) [21] or the spin-Hall effect (SHE), [17], [18], or can rotate around a nanocontact in point contact geometries (oscillators) [22].

The key ingredient to stabilize a skyrmion is the Dzyaloshinskii–Moriya interaction (DMI) [23]. According to the type of DMI, two kinds of skyrmions can be obtained: the interfacial DMI, observed in bi-layer ferromagnet/heavy metal and linked to the inversion-symmetry breaking at the interface in the presence of strong spin-orbit coupling, stabilizes Néel skyrmions, having a radial configuration of the domain wall spins. The bulk DMI has its origins in the breaking of inversion symmetry within a non-centrosymmetric crystal with non-negligible spin-orbit interactions and leads to Bloch skyrmions, characterized by a vortex-like distribution of the domain wall spins [16], [18]. The main feature of skyrmions is the topological protection, due to a integer skyrmion number

\[
S = \frac{1}{4\pi} \int \mathbf{m} \cdot (\hat{\mathbf{r}} \times \mathbf{m}) dxdy = \pm 1.
\]

On the other hand, dynamical solitons, that are unstable in dissipative magnetic materials, can be sustained by the STT and used as source of microwave emissions (self-oscillations) in nanoscale oscillators [24], [25], [13], [14]. In the recent literature, much attention has been given to the investigation of dynamical properties of topologically protected particles in perpendicular materials, i.e. skyrmions, while only few works have been devoted to the identification and study of topological limit cycles.

In this work, we show that a promising skyrmion racetrack is the one where a Néel skyrmion is moved by the SHE, highlighting that the direction of the motion is perpendicular to the direction of the electrical current. Furthermore, we describe how, in point-contact devices, the transition from non-topological droplet (NTD) to topological droplet (TD) or dynamical skyrmion [26] occurs as a function of the DMI, giving rise also to incoherent spin wave emission.

II. RACETRACK MEMORY

We have micromagnetically analyzed four scenarios (A, B, C and D) for the design of a skyrmion racetrack memory, by combining skyrmion type (Bloch or Néel) and driving force (STT or SHE) [18]. The fundamental aspect is that we have considered "state of the art" material parameters in order to stabilize Bloch (bulk DMI) or Néel (interfacial DMI) skyrmion. In particular, for the scenario B, we have used: saturation magnetization of the CoFeB ferromagnet \( M_s = 1000 \) kA/m, exchange constant \( A = 20 \) pJ/m,
perpendicular anisotropy constant $k_{z}=0.8$ MJ/m$^{3}$, Gilbert damping $\alpha_{G}=0.015$, and DMI parameter $D=1.8$ mJ/m$^{2}$.

The comparison of velocity-current relations for the four scenarios (not shown) leads to the conclusion that the optimal strategy to design a skyrmion racetrack memory is when the Néel skyrmion is driven by the SHE, here called scenario B (see Fig. 1a). In particular, the SHE moves the Néel skyrmion along the direction perpendicular to the electrical current flow (y-axis if the current is along the x-axis). The physical origin of such motion can be heuristically understood by considering the SHE as source of anti-damping. These micromagnetic achievements are also confirmed by analytical calculations (see Fig. 1b) based on the Thiele’s equation [27]. In order to derive the analytical equations, we have considered that the “hedgehog” like topological magnetic texture of a Néel skyrmion can be parameterized as:

$$m(x, y) = \sin \theta(\rho) \cos \phi(\rho) + \sin \theta(\rho) \sin \phi(\rho) + \cos \theta(\rho) \hat{z}$$  \hspace{1cm} (1)

by setting $\phi_{h}=0$ (it defines the Néel skyrmion radial distribution of the magnetization, otherwise $\phi_{h} = \frac{\pi}{2}$ for the Bloch skyrmion). The translational motion is obtained by projecting the Landau-Lifshitz-Gilbert (LLG) equation, containing also the SHE, onto the relevant translational modes, yielding:

$$G \times \mathbf{v} - \alpha_{G} \dot{D} \cdot \mathbf{v} + 4\pi B \mathbf{K} \left( \phi_{h} = 0 \right) \mathbf{j}_{HM} = 0$$  \hspace{1cm} (2)

Here, the vector $G$ can be identified as the “gyrocoupling vector”, $\mathbf{v} = [v_x, v_y]$ is the velocity of the skyrmion, where $v_x$ and $v_y$ are the skyrmion velocity components in the x- and y-direction respectively. The matrix:

$$\dot{D} = \begin{pmatrix} \dot{D} & 0 \\ 0 & \dot{D} \end{pmatrix}$$  \hspace{1cm} (3)

is the dissipative tensor describing the effect of the dissipative forces on the moving magnetic skyrmion, $\mathbf{K}$ is the in-plane rotation matrix, defined as:

$$R_{xx} \left( \phi_{h} \right), \quad R_{xy} \left( \phi_{h} \right), \quad R_{yx} \left( \phi_{h} \right), \quad R_{yy} \left( \phi_{h} \right)$$  \hspace{1cm} (4)

with $R_{xx} \left( \phi_{h} \right) = \cos \phi_{h}$, $R_{xy} \left( \phi_{h} \right) = \sin \phi_{h}$, $R_{yx} \left( \phi_{h} \right) = -\sin \phi_{h}$, $R_{yy} \left( \phi_{h} \right) = \cos \phi_{h}$. The coefficient $\alpha_{G}$ is the Gilbert damping and the coefficient $B = b'L_{s}I$ is linked to the SHE. In particular, $b' = \gamma_{0} \frac{\hbar \theta_{SH}}{2eM_{s}t}$, being $\gamma_{0}$ the gyromagnetic ratio, $\hbar$ the Plank constant, $\theta_{SH}$ the spin-Hall angle, $e$ the electron charge, $M_{s}$ the saturation magnetization of the ferromagnet, $t$ the thickness of the ferromagnet.

$$I = \frac{1}{4} \int_{0}^{\infty} d\rho \left( \sin \theta \cos \theta + \rho \frac{d\theta}{d\rho} \right)^{2}$$  \hspace{1cm} (5)

is a dimensionless integral in the dimensional radial variable $\rho$ and $L_{s}$ is a typical scaling length. From equation (2), it is possible to obtain the following expression for the two components of the skyrmion velocity:

$$\begin{pmatrix} v_{x} \\ v_{y} \end{pmatrix} = -B \begin{pmatrix} -\frac{\alpha_{G} \dot{D}}{1 + \alpha_{G}^{2} \dot{D}^{2}} & \frac{1}{1 + \alpha_{G}^{2} \dot{D}^{2}} \\ -\frac{\alpha_{G} \dot{D}}{1 + \alpha_{G}^{2} \dot{D}^{2}} & 1 \end{pmatrix} \begin{pmatrix} j_{HM} \\ 0 \end{pmatrix}. \hspace{1cm} (6)$$

by considering that the electric current flows along the x-direction through the heavy metal $\mathbf{j}_{HM} = (j_{HM}, 0)$. Eventually, a simple expression of the skyrmion velocities can be derived:

$$\begin{pmatrix} v_{x} \\ v_{y} \end{pmatrix} = \frac{\alpha_{G} \dot{D} B}{1 + \alpha_{G}^{2} \dot{D}^{2}} \begin{pmatrix} j_{HM} \\ 0 \end{pmatrix} \hspace{1cm} (6)$$

Both velocity components are proportional to $j_{HM}$. However, being $v_x$ also proportional to the $\alpha_{G} << 1$, it follows that $v_x << v_y$. The agreement between micromagnetic and analytical results is excellent (see Fig. 1b). The two velocity components depend on several parameters: the material of the ferromagnet (in terms of saturation magnetization, perpendicular anisotropy, Gilbert damping and thickness), the material of the heavy metal underlayer (in terms of intensity of the spin-orbit coupling, which influences the spin-Hall angle and the DMI parameter, as well as, the perpendicular anisotropy) and the skyrmion size (the larger is the skyrmion, the higher is the velocity). Since, so far, there is not yet any experimental evidence of the scenario B here described, it is not possible to indicate typical velocities.
The scenario B shows a physical limit which fixes the maximal applicable current. In detail, when the current is applied, a transient breathing mode (expansion-shrinkage) of the skyrmion is excited. The maximal expansion increases with the current, reaching the boundary of the strip at $j_{thr} \approx 65 \text{ MA/cm}^2$; as consequence, the skyrmion state disappears giving rise to a complex magnetic pattern. In other words, at high currents, the information stored in the skyrmion can be lost.

Furthermore, we compare the scenario proposed in [17], here called scenario B*, with the scenario B. We highlight that the threshold current to move the skyrmion is smaller in scenario B*, and that therefore the geometry and setup of B* can be used for ultra-low power storage devices. However, the skyrmion motion in scenario B is much more robust to thermal fluctuations and is much less sensitive to defects and edge roughness that are present in real devices. Skyrmion motion in scenario B can also be achieved for a wider current range and it is stable at larger currents implying larger skyrmion velocities. The scenario B* has been lately analyzed experimentally [28], showing velocities lower than the ones predicted by micromagnetic simulations, because of the presence of defects in real devices.

III. MICROWAVE OSCILLATOR

First of all, we wish to specify that the adjectives “nontopological” and “topological” are used to identify a limit cycle with a skyrmion number zero ($S = 0$) and one ($S = 1$), respectively. Fig. 2a shows a sketch of the studied device. The ultrathin Co layer acts as free layer (FL) (square cross section of $400 \times 400 \text{ nm}^2$), while the CoPt acts as fixed layer or polarizer and it is shaped as a circular point contact (diameter $d_c = 70 \text{ nm}$) in order to locally inject the current into the FL. Both FL and polarizer have an out-of-plane magnetic state at zero bias field. Fig. 2b summarizes the phase diagram of the magnetization as a function of the current density (swept back and forth) and the interfacial $i$-DMI parameter $D$. For the sake of simplicity, in the following the current density $j < 0$ is given in modulus. Five different states can be identified, two static states; uniform state along the $z$-direction (FM) and static skyrmion (SS), and three dynamical states, NTD, TD and a non-stationary NTD-TD.

The dotted line for $D = 3.7 \text{ mJ/m}^2$ marks the $i$-DMI value over which the skyrmion, once nucleated, is stable without current. In some current regions, the FM state is overlapped with the three dynamical states, since all the modes deal with a sub-critical Hopf bifurcation [29] (finite power at the threshold, current density hysteresis, the mode is switched off at a current density smaller than the excitation value, and the oscillation axis is different from the equilibrium configuration in the FM state). Starting from the FM state, the modes are excited at $J = 70 \text{ MA/cm}^2$ ($D < 3.0 \text{ mJ/m}^2$) independently of the $i$-DMI, while the switch-off current density depends on the $i$-DMI. The SS state is achieved for $1.6 < D < 3.0 \text{ mJ/m}^2$ from the TD state with a reversible transition, while a static skyrmion, once excited, is stable with no current for $D > 3.7 \text{ mJ/m}^2$.

The NTD dynamics concerns a $360^\circ$ in-plane rotation of domain wall spins [24]. Differently from previous studies, where the NTD is characterized by two or four regions of opposite topological density [24], [25], here the NTD exhibits a more complex behavior as can be also observed from a snapshot of the topological density in Fig. 3a. The TD exhibits a core breathing dynamics that is synchronized with a $360^\circ$ in phase rotation (space and time) of the domain wall spins, which can be seen as a continual change from Néel to Bloch skyrmion magnetic texture ($S = -1$, see a snapshot of the topological density in Fig. 3a).
In the i-DMI region $0.5 < D \leq 1.6$ mJ/m$^2$, time domain changes in the topology (skyrmion number) of the limit cycle are observed, in particular configuration linkable to NTD or to TD can be observed. The continual changes in the droplet topology generate incoherent emission of spin waves, being the topological transition non periodic. To highlight the main characteristics of the dynamical states of the phase diagram, the Fourier spectra for different values of i-DMI ($D = 0.25$, $0.75$, $1.00$, and $2.50$ mJ/m$^2$) are shown in Fig. 3b. The NTD and the TD are characterized by a single mode (see Fourier spectra for $D = 0.25$ and $D = 2.5$ mJ/m$^2$). In the NTD-TD region, the time-domain non-stationary topological transitions give rise to the excitations of incoherent spin waves, leading to noisy Fourier spectra (see the spectra for $D=0.75$ and $D=1.00$ mJ/m$^2$). From an experimental point of view, it is possible to detect the NTD-TD region by performing microwave emission measurements.

IV. CONCLUSIONS

In summary, we have analyzed the possible technological scenarios for controlling the shifting Néel or Bloch skyrmions driven by SHE or STT. Our results indicate that scenario B (Néel skyrmion motion driven by the SHE) is one of the most promising from a technological view, it is possible to detect the NTD-TD region by performing microwave emission measurements.

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