Corrigendum: Generation and stability of dynamical skyrmions and droplet solitons (2018 Nanotechnology 29 325302)

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We have updated figure 3. The labels of the y axis corresponding to the initial angle of magnetization given in degrees should go from $0^\circ$ to $5^\circ$. The condition of $M$ being out of the film plane is given by an angle of $0^\circ$.

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Generation and stability of dynamical skyrmions and droplet solitons

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Abstract

A spin-polarized current in a nanocontact to a magnetic film can create collective magnetic oscillations by compensating the magnetic damping. In particular, in materials with uniaxial magnetic anisotropy, droplet solitons have been observed—a self-localized excitation consisting of partially reversed magnetization that precesses coherently in the nanocontact region. It is also possible to generate topological droplet solitons, known as dynamical skyrmions (DSs). Here, we show that spin-polarized current thresholds for DS creation depend not only on the material’s parameters but also on the initial magnetization state and the rise time of the spin-polarized current. We study the conditions that promote either droplet or DS formation and describe their stability in magnetic films without Dzyaloshinskii–Moriya interactions. The Oersted fields from the applied current, the initial magnetization state, and the rise time of the injected current can determine whether a droplet or a DS forms. DSs are found to be more stable than droplets. We also discuss electrical characteristics that can be used to distinguish these magnetic objects.

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(Some figures may appear in colour only in the online journal)
magnetic nano-oscillators and have a growing interest as key elements in neuromorphic computation [31, 32] and in communication devices [33]. Droplets are topologically trivial objects—they can be created continuously from a uniform ferromagnetic state where all spins are aligned in the same direction. A similar magnetic object having topologically non-trivial spin texture could be created in a similar experimental geometry: a dynamical skyrmion (DS). Zhou et al [34] have shown with micromagnetic simulations that DS can be nucleated and sustained with a large spin-polarized current in a nanocontact and are, indeed, fundamental solutions for the magnetization excitations in a film with PMA [35]. Liu et al [36] presented an experimental observation of a solitonic mode modulation that could indicate the existence of a DS. So far, the topology modification of droplets has been associated to the Dzyaloshinskii–Moriya interaction (DMI) present in some magnetic films [37].

A schematic plot of both solitonic modes, droplet and DS, is shown in figure 1 where the blue region represents magnetization pointing out-of-plane ($\theta = 0$) and the brown, in the opposite direction ($\theta = 180^\circ$). The magnetization of a droplet or a DS is precessing, with a small amplitude near its center and with a larger amplitude at the boundaries. The lower panels of figure 1 show the magnetization orientation in a transversal cut of both droplet and DS. The main difference is in the region separating the center of soliton from the rest of film’s magnetization; droplets have no topology (the magnetization shown in figure 1(a) can be transformed continuously into a ferromagnetic state with all spins aligned in any arbitrary direction) whereas the DSs have topology (such a transformation is not possible). The topology can be described by the skyrmion number ($S$), which is calculated mathematically as $S = -\frac{1}{4\pi} \int \mathbf{m} \cdot (\partial_x \mathbf{m} \times \partial_y \mathbf{m})$. A droplet has $S = 0$, and a DS has $S = 1$.

Here, we investigate the conditions that lead to either droplet or DS formation and we study their stability in nanocontacts to ferromagnetic thin films with PMA and without interfacial DMI. Our micromagnetic simulations show that the Oersted fields associated with the localized electrical current, the initial magnetization state, and the rise time of the injected current, play a key role on determining whether droplet or DS form. DS are more stable to perturbations and can be sustained with much lower currents than droplets. We also provide characteristic features of droplets and DS that could distinguish the two magnetic objects experimentally.

Figure 1. Schematic representation of droplet (a) and dynamical skyrmion (DS) (b) magnetic configuration. Magnetization within droplet or DS is reversed with respect to the film’s magnetization and is precessing with a small amplitude at the center and with a larger amplitude at the boundaries. Lower panels show a transversal cut of the spin configuration for the droplet ($S = 0$) in (a) and DS ($S = 1$) in (b).
Results

Simulations details

We consider a circular nanocontact to a ferromagnetic thin film with PMA. The parameters for the material are taken from experiments using 4 nm thick Co and Ni multilayers [27, 38]. Magnetization saturation, $M_s = 5 \times 10^5$ A m$^{-1}$, damping constant, $\alpha = 0.03$, uniaxial anisotropy constant, $K_u = 2 \times 10^6$ J m$^{-3}$, exchange stiffness constant, $A = 10^{-12}$ J m$^{-3}$, and a nanocontact diameter of 150 nm for most of the presented results. We modeled the magnetization dynamics in the nanocontact by solving the Landau–Lifshitz equation adding the STT term [1] with a constant spin-polarization. We performed micromagnetic simulations using the open-source MuMax code [39] using a graphics card with 2048 processing cores. We considered the effects of Oersted fields but we did not include interfacial DMI. The applied magnetic field is perpendicular to the film plane. Temperature effects are not considered unless otherwise stated (full codes are available in the supplementary materials online at stacks.iop.org/NANO/29/325302/mmedia).

Creation process

To excite a droplet in a ferromagnetic layer with PMA using a spin-polarized current in a nanocontact, the STT must compensate the damping. There is a threshold current that depends on the NC size, the saturation magnetization, the film thickness, the spin-polarization of the current, and the external field [23, 28, 30, 40]. Such a threshold does not depend on the initial magnetization state or on whether the spin-polarized current is applied adiabatically or abruptly. For currents above the threshold, the magnetization in the NC forms a droplet state in a process that can take less than a nanosecond [41]. Once the droplet is created, the current in the nanocontact is still required to sustain the magnetic excitation—although smaller current values than the threshold current are needed [24, 27]. Droplet states can be inferred by measuring the dc resistance of the nanocontact—a reversal of the magnetization produces a change in the nanococontact resistance [24–30]. Further, the magnetization dynamics of droplets can be detected experimentally through the ac electrical resistance oscillations in the nanocontact [24–27, 29, 30] caused by the precessing magnetization in the droplet.

DS may also form in a NC to a ferromagnetic layer with PMA [34, 36] when a sufficiently large spin-polarized current is applied. The difference between droplet and DS is in the topology of spins at the boundary, which provides additional stability [34, 36]. For this reason, we are interested in determining the differences in stability between droplet and DS as well as the experimental conditions under which DS form.

In simulations we choose an initial magnetization state close to equilibrium—all spins nearly aligned with the applied field—and then we apply a spin-polarized current and record the evolution of magnetization in an area that is 5 times larger than the contact diameter. The initial magnetization state has to be non-collinear with the spin-polarized current in order to allow the STT to have an effect. We, thus, need to provide an initial condition for the magnetization. One option is to provide an arbitrary angle $\theta_i$ and $\phi_i$ for each spin followed by a magnetic relaxation for a given time—this goes asymptotically to a configuration close to equilibrium ($\theta = 0$ for all spins). Another option is to use an initial magnetization state close to the equilibrium given by a small $\theta_i$ and a constant value of $\phi_i$ for all spins. In our simulations we study the effect of initial magnetization states on the formation of droplet and DS and thus we use an initial magnetization state given by an angle $\theta_i$ as a parameter in simulations.

Figure 2(a) shows the magnetization precession frequency and amplitude within the NC as a function of the applied spin-polarized current under an applied field of 0.5 T. Each point corresponds to a different current value applied to an initial magnetization condition $\theta_i = 1.5^\circ$. For values of current below 10 mA the magnetization in the NC (the average value) has a small oscillation with a frequency close to the ferromagnetic resonance frequency. Above 10 mA there is an abrupt decrease of the frequency together with an increase of the precession amplitude, which corresponds to the creation of a droplet. If we continue applying current of larger amplitude (always starting from a same initial state), we reach a second threshold at 28 mA where a DS forms, having an almost identical magnetization precession frequency (blue dots) but a much smaller precession amplitude (red dots). The precession amplitude of spins is much larger at the boundary of the soliton than in the central part. Thus, the average nanocontact precession amplitude is mostly driven by the edge precession. In the DS the spins at the boundary precess at a similar amplitude than in droplets but the fact that they are not in phase causes a reduction in the amplitude of the contact’s overall magnetization oscillation—which is a feature that can be used to identify DS experimentally. The same argument applies to describe the smooth decrease in the precession amplitude of the NC magnetization in the droplet state as the current increases from 10 mA to 28 mA; the phase of droplet becomes less and less uniform along the overall droplet edge when increasing the applied polarized current [41].

We next study the time evolution of magnetization during the process of droplet and DS formation. Figure 2(b) shows the magnetization evolution in the NC region, $m_z$, as a response of an applied current for a droplet (yellow line) at 26 mA and for the DS (red line) at 36 mA; both time traces correspond to points in figure 2(a) having an initial magnetization state with $\theta_i = 1.5^\circ$. We see that the higher applied current values produce a faster magnetization reversal, which is something that occurs no matter whether the final state is a droplet or a DS and is caused by the larger STT effect—being proportional to the applied current [41]. We can also observe that the DS (red line) presents a larger oscillation of the magnetization indicating there is a breathing of the localized object at the precession frequency [34, 36]. We note here that the magnetization, $m_z$, averaged over the NC (plotted in figures 2(b) and (c)) is a relevant quantity for experiments as it can be directly associated to the NC resistance.
The initial state determines whether the response to an applied current is a droplet or a DS. In figure 2(c) we plot time traces for the magnetization, $m_z$, in the NC for a same applied current value, 30 mA, but different initial magnetization states, $\theta_i = 2.5^\circ$ (yellow line) and $\theta_i = 0.8^\circ$ (red line). We note that the initial state with $\theta_i = 2.5^\circ$ evolves to a droplet state whereas the initial state with $\theta_i = 0.8^\circ$ evolves to a DS state. The current threshold for DS formation thus has a dependence on the magnetization initial state. Additionally, we measured the precession frequency of droplet and DS for the case presented in figure 2(c). For the same current both the droplet and DC have nearly the same precession frequency: $f_d = 14.60$ GHz for droplet and $f = 14.58$ GHz for DC, which is not seen in the transition at 27 mA of figure 2(a) due to the small difference. We attribute such a small variation in frequency to the small changes in the size of the magnetic object and therefore in the value of internal magnetic fields—mainly dipolar fields. We note here that theory predicts a variation in frequency with current for droplet states [23]. However, our current densities and material’s parameters do not produce a considerable change in the size of the solitonic modes and, thus, we do not observe any variation of frequency with applied current, similar to experimental studies [24–30].

In order to understand how the threshold current for DS formation depends on the initial magnetization state, we repeat the process used in figure 2(a) with different initial magnetization states (different $\theta_i$) and we identify the current values that result in a droplet or a DS. Figure 3 shows the phase diagram of droplet and DS formation as a function of applied current and initial magnetization angle. We see that the threshold for droplet formation is always the same independent of the initial magnetization state; different initial states cause the process of droplet formation to become faster or slower (see traces for time evolution in the insets of figure 3) [41]. On the other hand, the threshold for DS formation has a strong dependence on the initial magnetization angle, $\theta_f$, increasing with larger angles. An additional map is provided in the supplementary materials showing the phase diagram of droplet and DS formation as a function the polarization of the applied current and the initial magnetization angle ($\theta_i$) for a fixed current of 30 mA. In that case the Oersted-field effects are fixed and only STT effects vary with spin-polarization. At a small polarization, there is a small STT effect and no excitations are present independent of the initial magnetization. As the current polarization increases we found first the onset of droplet states and with a further increase the onset of DS. Again the droplet threshold does not depend on the initial state whereas the DS threshold has a strong dependence requiring larger values of polarization at larger angles of the initial magnetization angle, $\theta_f$. 

**Figure 2.** Droplet and dynamical skyrmion creation process. (a) Resonance frequency (in blue dots) and amplitude (red dots) as a function of the applied current for the nanocontact overall magnetization. Both frequency and amplitude correspond to the average over the nanocontact of one of the in-plane components of the magnetization, $m_{y}$. The current values are always applied from a same initial magnetization angle in an applied field of 0.5 T and with a polarization of $p = 0.45$. At current values below the threshold (below 10 mA) the nanocontact magnetization precesses close to the ferromagnetic resonance frequency with a small amplitude. A first current threshold at 10 mA corresponds to a droplet formation and shows a much larger amplitude (red curve) and a frequency jump down to a lower value—that remains almost constant with increasing the applied current. A second current threshold at 28 mA corresponds to the DS formation and has a similar precession frequency and a smaller amplitude. The bottom panel show the skyrmion number, $S$, at each current step. (b) and (c) Time evolution of the normalized magnetization inside the NC for droplet (yellow line) and DS (red line) for the same external applied field of 0.5 T. In (b) both solitons are excited at an initial magnetization angle, $\theta_i = 1.5^\circ$ but using different applied currents. In (c) both solitons are exited at 30 mA with different initial magnetization angles.
and droplet currents below 10 mA neither droplet nor DS can be excited, orange region. When the current is higher than 10 mA a droplet is excited and droplet’s threshold current does not depend on $\theta_s$, yellow region. If the current is further increased, a DS is created, green region. The current threshold for DS (red line) is higher than the droplet and depends on the initial magnetization state, $\theta_s$. Insets correspond to time evolution curves of nanocontact magnetization at different conditions.

Next we study the influence of other factors such as the size of the nanocontact and the spin-polarization. An increase of polarization from $p = 0.45$ to $p = 0.6$ reduces the droplet threshold by 2 mA and reduces the DS threshold by 5 mA. The contact size determines the net current required to excited solitonic modes. We computed the thresholds for contact diameters of 50 and 100 nm and obtained values of 4 and 6 mA for the droplet threshold—which represents a decrease of 3 and 5 mA with respect to the diameter of 150 nm presented in figure 3. Here we note that the threshold does not scale exactly with the current density because there are always Oersted fields associated with the currents that depend also on the contact size. We observed a larger reduction of 5 and 9 mA for the DS formation. Both diagrams are presented in the supplementary materials.

The applied magnetic field increases, the required current for soliton formation [24–30]. We have studied the effect on the droplet and DS thresholds in a range of applied fields between 0 and 2 T and found that both current thresholds increase equally (and linearly) with the applied field (see supplementary materials).

The temperature modifies the initial magnetization state—a temperature of 300 K provides a fluctuation of spins larger than $\theta = 10^5$ for our studied configuration. However, the effect of temperature cannot be compared directly to the case studied in figure 3 because temperature also provides fluctuations of spins during the creation process. We have simulated a new phase diagram of the droplet and DS formation as a function of temperature in figure 4. We applied a spin-polarized current after an initial relaxation. We can see in figure 4 that droplet thresholds are the same we obtained with no temperature whereas DS thresholds increase with increasing temperature.

**Figure 3.** Phase diagram of the droplet and DS formation creation of both solitonic modes as a function of the applied current, $I$ (with polarization $p = 0.45$), and the initial magnetization angle, $\theta_s$. For currents below 10 mA neither droplet nor DS can be excited, orange region. When the current is higher than 10 mA a droplet is excited and droplet’s threshold current does not depend on $\theta_s$, yellow region. If the current is further increased, a DS is created, green region. The current threshold for DS (red line) is higher than the droplet and depends on the initial magnetization state, $\theta_s$. Insets correspond to time evolution curves of nanocontact magnetization at different conditions.

**Figure 4.** Phase diagram of the droplet and DS formation. The initial condition is here obtained after magnetic relaxation at a given temperature in the presence of an applied field of 0.5 T. Top panels show the evolution of magnetization ($m_x$ in colorscale and $m_y$ and $m_z$ with vector arrows) for a $T = 300$ K and a current of $I = 27.5$ mA. A dynamical skyrmion formed. For currents below 10 mA neither droplet nor DS can be excited at any temperature, orange squares. When the current is higher than 10 mA a droplet is excited and the droplet’s threshold current does not depend on temperature, blue circles. If the current is further increased, DS are created, red circles, at a different currents for each temperature.

**Stability**

Both droplet and DS exhibit magnetic bistability over considerable ranges of applied current and magnetic field [24–30, 34, 36]. We investigate here the conditions that produce the annihilation of the solitonic modes when a lower degree of spin-transfer torque—a lower current—is applied. In figure 5(a) we show two curves corresponding to the average magnetization within the NC, $m_x$, as the applied current decreases from an initial value of $I = 30$ mA. A droplet and a DS are created at 30 mA (using $\theta = 3^\circ$ and $\theta = 1^\circ$ respectively). The droplet collapses at about 9 mA whereas the DS requires a much lower current value of 4 mA to vanish revealing that the DS remains stable over a larger range of applied currents or in other words, the DS requires smaller current values to be sustained.

Next, we investigate the effect of a magnetic field gradient in the NC. A small constant in-plane field, a small change in anisotropy, or a variation in the film’s thickness combined with the Oersted fields from the charge current could result in a gradient of effective magnetic field in the NC that dephases the precession of magnetization in different locations of the NC and eventually may annihilate the magnetic excitation. Experiments revealed that the low frequency noise in droplets [28, 30, 40] is associated with a periodic process of shifting, annihilation, and creation. Simulations showed that an asymmetry of the effective field causes a drift instability resulting in an oscillatory signal of hundreds of MHz—a drift resonance. We excite droplet and DS states at 30 mA using different initial states (same as in figure 5(a)) and after a stabilization period we reduce the applied current until 10 mA, black squares in figure 5(a). We then apply a small in-plane field of 50 mT in order to destabilize the solitonic modes. The combination of a fixed in-plane field with the Oersted fields creates an in-plane field gradient in the nanocontact. Figure 5(b) shows the time evolution of the magnetization for a droplet (red line) and a DS (blue line). The small in-plane applied field causes a shift
value of the presence of an in-plane magnetic polarized current, say the magnetization is precisely aligned in the direction of the applied field. Both droplet and DS states are created at 30 mA using different initial states (same as in (a)) and after stabilization the applied current is reduced to 10 mA, black squares in (a), and a small in-plane field of 50 mT is applied. The magnetization of droplet and DS behaves completely differently; the droplet’s magnetization oscillates caused by a drift resonance (∼40 MHz) while the DS’s magnetization, although it initially oscillates, it stabilizes after ∼80 ns and remains with its initial (S = 1) topology.

Discussion

Two main effects are involved in the magnetization dynamics when a spin-polarized current flows through a nanocontact to a magnetic film. On the one hand, a spin-polarized current of the appropriate polarity interacts with the magnetization via the STT effect trying to align the magnetization in the opposite direction of the applied field. The STT effect is proportional to the non-collinear component of the magnetization with respect to the polarization of the current (i.e., if the magnetization is precisely aligned in the direction of the polarized current, say z for the studied case, there is no effect). On the other hand, the electrical current flowing through the nanocontact causes Oersted fields that curl the magnetization.

In the creation process of solitonic modes there is a competition between the two mentioned effects. The STT effect increases rapidly as the magnetization tilts from the state perpendicular to the film plane, \( \theta_I = 0^\circ \), and thus if the initial magnetization state is sufficiently far from such a state, the solitonic mode forms without topology resulting in a droplet state. On the other hand if the initial state is closer to \( \theta_I = 0^\circ \) the effect of STT produces a much slower variation of the magnetization and there is a time lapse where the effect of the Oersted fields provides topology to the magnetization in the NC, which eventually results in the formation of a DS.

In summary, the farther from equilibrium the initial magnetization state is, the larger the current density required to create a DS is.

Preparing experimentally an initial state close to \( \theta_I = 0^\circ \) requires low temperatures. These states are usually avoided in other situations such as in a magnetic tunnel junction devices because they reduce the switching probability at a given time [42]. It is possible, on the other hand, to prepare initial states with \( \theta_I = 0^\circ \) by increasing the temperature, by applying a short in-plane field pulse or by using a polarized current not collinear with the magnetization state (e.g., using canted polarizers). We provide simulations in supplementary materials showing that the formation of a DS is avoided with a short in-plane magnetic field pulse or by using a canted polarizer.

There is another ingredient that plays a role in defining whether a droplet or a DS forms: the speed of ramping the polarized current from zero, or from a small value, to a high value that nucleates solitonic modes. Simulations in the diagram shown in figure 3 are done with a sharp step of current. However, we have seen that using ramping currents with a rise time (10\%-90\%) larger than 700 ps suppresses the formation of DS in favor of droplets. We include in supplementary materials a simulation comparing current rise times of 100 ps and 1 ns with identical initial conditions showing the formation of DS and droplet states respectively.

We, thus, speculate about the possibility of observing DS experimentally. Typically, an experimental setup used for the study of droplets contains a free layer with PMA where the solitonic modes may form, which corresponds to our simulated CoNi layer, and a fixed layer that is used as a spin polarizer for the current, [24–30, 43]. To create a DS instead of a droplet we need to either depart from an initial magnetization state close to all perpendicular or produce torques associated with the Oersted fields larger than those associated with the polarized currents. In the first case we can try to
apply large out-of-plane fields in order to set and appropriate initial magnetization state or lower the temperature to reduce the thermal noise that might produce fluctuations of the magnetization. It could be that experiments performed at low temperatures and large fields [27, 40] have already created DS. The second case consists in providing a current that is not polarized, producing large Oersted fields but no STT effect. With the same configuration, the current polarization has to increase so that the STT becomes predominant and promotes the creation of a solitonic mode. If the magnetization was already curled due to the Oersted fields it could result in the creation of a solitonic mode with topological protection: a DS.

This realization is feasible by using a perpendicular polarizer [43] with appropriate coercivity so that it switches at a field that can create the DS. One could then apply a constant current to the nanoncontact while the magnetic field sweeps, the perpendicular polarizer would then switch and create an abrupt change in the spin-polarization of the applied current while maintaining the Oe fields. We added in the supplementary materials simulations where the polarization is switched on in presence of an applied current (with no spin-polarization) and found that DS can be create at certain values of the polarization with no need of an artificial canted initial magnetization state—the Oe fields associated to the electrical current with no spin-polarization provide an initial magnetization state with $\theta_0 = 0$.

It is necessary however to distinguish experimentally the two solitonic modes once they are created. The differences in precession frequency are too small to serve as a signature of droplet or DS. Instead, studying the stability of the solitonic modes is the best option. One could study the hysteretic response or the response to small in-plane fields and the appearance of low frequency noise as seen in figure 5.

In conclusion we have shown that both droplet and DS can be created with a same configuration of applied field and spin-polarized current by controlling the initial magnetization state, the degree of spin-polarized current, or the speed at which the current—or the polarization—is changed. We also studied the difference in stability between droplet states and DS and found that DS is not only more stable against effective field variations but DS also requires much lower currents to be sustained. Our results provide a pathway for experimental studies of DS and their stability.

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