Stable magnetic droplet solitons in spin-transfer nanocontacts

Ferran Macià¹,²*, Dirk Backes¹ and Andrew D. Kent¹

Magnetic thin films with perpendicular magnetic anisotropy have localized excitations that correspond to reversed, dynamically precessing magnetic moments, which are known as magnetic droplet solitons. Fundamentally, these excitations are associated with an attractive interaction between elementary spin-excitations and have been predicted to occur in perpendicular magnetized materials in the absence of damping. Although damping suppresses these excitations, it can be compensated by spin-transfer torques when an electrical current flows in nanocontacts to ferromagnetic thin films. Theory predicts the appearance of magnetic droplet solitons in nanocontacts at a threshold current and, recently, experimental signatures of droplet nucleation have been reported. However, to date, these solitons have been observed to be nearly reversible excitations, with only partially reversed magnetization. Here, we show that magnetic droplet solitons exhibit a strong hysteretic response in field and current, proving the existence of bistable states: droplet and non-droplet states. In the droplet soliton state we find that the magnetization in the contact is almost fully reversed. These observations, in addition to their fundamental interest, are important to understanding and controlling droplet motion, nucleation and annihilation.

Spin-transfer-torque nano-oscillators (STNOs) are nanometre-scale electrical contacts to ferromagnetic thin films that consist of a free magnetic layer (FL) and a fixed spin-polarizing magnetic layer. The spin-transfer torque in such contacts can compensate the damping torque and excite spin-waves in the free layer at a threshold d.c. current. When these spin-waves have a frequency that is less than the lowest propagating spin-wave modes in the ferromagnetic film—the ferromagnetic resonance (FMR) frequency—they are localized in the contact region. In free layers with perpendicular magnetic anisotropy (PMA) this has been predicted to lead to dissipative droplet solitons (hereafter referred to as droplet solitons), which are related to the conservative magron droplets that have been studied in uniaxial (easy axis type) ferromagnets with no damping. In the nanocontact, energy dissipated due to damping (essentially friction) is compensated by energy input associated with spin-transfer torques, resulting in steady-state spin-precession. Droplet solitons are expected to be strongly localized in the contact region, as well as to have spins precessing in phase in the film plane. In addition, with sufficient current the magnetization in the contact has been predicted to be almost completely reversed relative to the film magnetization outside the contact. Although precession frequencies below the FMR frequency have been observed to appear at a threshold current in recent experiments, there was no evidence for fully reversed spins in the contact.

To study droplet solitons we fabricated STNOs with a free layer with PMA, a 4-nm-thick CoNi multilayer and an in-plane magnetized polarizing layer (a 10-nm-thick Permalloy, N₈₀Fe₂₀, denoted Py), as shown schematically in Fig. 1a, and measured their d.c. and high-frequency electrical characteristics. We characterized the magnetic properties of these layers using FMR spectroscopy. Most important for these studies is that the CoNi has an effective perpendicular anisotropy field of µ₀Hₐ = 0.25 T, which is defined as the perpendicular anisotropy field minus the saturation magnetization, Hₐ = Hₛ – Mₛ, where µ₀ is the permeability of free space. We also studied samples with smaller µ₀Hₐ (~0.1 T). In this letter we focus on the results for STNOs with µ₀Hₐ = 0.25 T (the results for the other series of STNOs are presented in Supplementary Section I).

The electrical response of our samples is associated with the giant magnetoresistance (MR) effect. The device resistance depends on the relative magnetization alignment of the free and polarizing layers, MR = (R(H) – Rₚ)/Rₚ = Rₚ(1 – μₘₗ₂ₚₗₚ)/(μₘₗ₂ₚₗₚ), where H is the magnetic field, μₘₗ₂ₚₗₚ are unit vectors in the directions of the free magnetic layer and polarizer magnetization, respectively, and Rₚ = (R₂₃₄ – R₃₄)/R₃₄ is the fractional change in resistance between antiparallel (AP) and parallel (P) magnetization states of the device. A magnetic field applied perpendicular to the film plane tilts the Py magnetic moments out of the film plane, resulting in a perpendicular component of μₚ, given by μₚ = H/Mₛ for H < Mₛ with μ₀Mₛ ≈ 1.1 T, while the CoNi magnetic moments remain perpendicular to the film plane (that is, μₚ//μₗ₂ₚₗₚ). Thus, for µ₀H > µ₀Mₛ = 1.1 T, the layer magnetizations align, forming a P state. This results in the resistance of the STNO decreasing linearly with the applied field for H < Mₛ and saturating when H > Mₛ. On the other hand, precession of the in-plane component of the free magnetic layer magnetization leads to an oscillating resistance and thus a voltage response in the microwave range for fields less than the saturation field of the perpendicular layer (that is, when the polarizing layer has a component of magnetization in the film plane). However, this signal vanishes when the polarizer is saturated in the field direction.

Figure 1b shows measurements of the STNO high-frequency response versus d.c. current at two different applied perpendicular magnetic fields at room temperature. At 0.4 T (mₜₚ ≈ 0.36), the STNO signal output frequency decreases with increasing bias current (that is, there is a redshift of the signal). At 0.55 T (mₜₚ ≈ 0.5) there is initially a redshift of the oscillation frequency with increasing current, followed by an abrupt (~3 GHz) decrease of the signal frequency at a threshold current, which has been associated with the creation of a droplet soliton. The signal frequency after the jump is close to the Zeeman frequency, the prediction for a reversed droplet soliton, fᵥₑₑₑₗₚₚₗₚ = γμ₀H/(2π), where γ is the gyromagnetic ratio. We note here that a single spectral line is observed, with no self-modulation, as predicted for a sufficiently large free magnetic layer saturation magnetization or exchange constant. Figure 1c shows that at 0.8 T (mₜₚ ≈ 0.73) we only observe the lower-frequency (magnetic droplet) excitation and the...
frequency increases (blueshifts) with increasing current (Fig. 1c). Most interestingly, at 0.8 T the spectra are hysteretic—the spectra depend on the field sweep direction—as was first observed in a sample showing clear automodulation8.

We note also that with increasing field the magnetization of the Py saturates perpendicular to the film plane—in the same direction as the CoNi—and so the microwave signal vanishes. However, d.c. MR measurements still enable characterization of the droplet, because precession of the free magnetic layer changes its perpendicular component and this results in a variation in the d.c. resistance (even when \( \vec{B}_\text{app} = 0 \)).

Hence, to characterize magnetic droplet excitations—both their onset and annihilation—we measured the MR of our devices at low temperature (4.2 K) within a vector superconducting magnet. Figure 2a presents the MR for fields applied perpendicular to the film plane; an MR of zero corresponds to the plane perpendicular component and this results in a variation in the d.c. resistance (even when \( \vec{B}_\text{app} = 0 \)). The dashed red curve in Fig. 2a illustrates the expected MR for a reversed CoNi magnetization (that is, magnetization anti-aligned with the applied field). This curve is obtained by reflecting the measured MR about the horizontal line, MR(H = 0) = 4.2 K within a vector superconducting magnet. Figure 2b presents the MR for fields applied perpendicular to the film plane; an MR of zero corresponds to the fields at which the magnetizations of the Py and CoNi align parallel, and the overall MR of the STNOs (\( R_\text{c} = 0.9\% \)) corresponds to twice the value at zero field when the magnetizations of the Py and CoNi are orthogonal.

The resistance curves at constant applied fields (Fig. 2b,c) show the onset of droplet solitons when increasing the current, and the annihilation of the soliton states when decreasing the current. There is hysteresis, showing that there is an energy barrier separating STNO states and indicating that the droplet soliton is stable for a range of applied currents. In Fig. 2c we see that at low fields (\( \mu_0 H \approx 0.6 \) and 0.9 T) there is first a small step in resistance that corresponds to the onset of a (small angle precession) spin-wave excitation, then a larger step in resistance that corresponds to nucleation of the droplet soliton. We plotted the maximum change in the resistance step corresponding to the soliton excitation in Fig. 2d and compared it with the maximum expected change in resistance (that is, MR = \( R_\text{c} H/M_\text{S} \)). The overall change is almost the full MR, indicating that the CoNi magnetization is reversed nearly completely in the nanocontact area. The overall droplet MR increases with applied field because the relative alignment between Py and CoNi magnetization increases as the Py magnetization tilts with increasing applied field (see the schematic blue and pink arrows in the insets of Fig. 2d). The difference in resistance between that measured in the droplet state and full magnetization reversal of the free magnetic layer ranges from 20% at \( H = 0.6 \) T to just 5% at fields above 1 T; this difference may be due to precession in the droplet that decreases the overall perpendicular component of the magnetization or by a small displacement of the droplet from the contact centre.

We next analysed the onset and annihilation of droplet solitons as a function of applied field at constant current. Droplet annihilation with increasing field has been demonstrated in ref. 9. Figure 3a shows the MR as a function of applied field for two fixed applied currents, \( I = 25.5 \) mA and \( I = 32.5 \) mA. The MR curves clearly show both the onset and annihilation of the droplet excitations as well as a remarkable hysteretic behaviour, especially at large fields. The MR curve for \( I = 32.5 \) mA (Fig. 3a, lower panel) shows the nucleation of a droplet soliton at a field of \( \sim 0.3 \) T. At this field the magnetization of the CoNi layer reverses and opposes the applied field. The resistance then increases with the applied field until it saturates when the Py magnetization saturates (that is, when the magnetization of CoNi and Py are antiparallel). At even larger fields (\( \sim 3 \) T) there is a step decrease in resistance, which we associate with droplet annihilation. When the applied field is reduced, the droplet nucleates at a much lower field (\( \sim 1.4 \) T). The large field hysteresis is consistent with the current-swept data at fixed field, as we discuss further in the following.

We note that within the field range where droplet solitons are present there are additional and highly reproducible small steps in the resistance curves (Fig. 3a). These may originate from pinning of the soliton at different sites within the contact. As the field increases, the droplet soliton state becomes less energetically favourable and the soliton might shift to different locations with slightly different effective fields caused by either current-induced Oersted fields or by small variations in the free layer’s magnetic anisotropy or magnetization. Such resistance states may also be due to changes in the droplet precession angle.
Figure 2 | Nucleation of droplet solitons with current. a, Magnetoresistance (MR) of a 150-nm-diameter STNO versus field with I = 5 mA (blue). The dashed red curve shows the expected MR for a reversed CoNi magnetization (magnetization anti-aligned with the applied field). b, MR as a function of applied current for fields ranging from $\mu_0 H = 0.5$ T to 1.4 T. Curves are shifted vertically for clarity. c, Expanded MR curves from b, for fields of $\mu_0 H = 0.6$ T and 0.9 T, with the onset of spin-wave excitations (left inset) and the droplet state (right inset) indicated. d, Resistance step $\Delta R$ (as a percentage) on droplet soliton nucleation as a function of applied field. The black curve is the expected maximum MR of the STNO as a function of the applied field, MR = $R_0 H/M_s$, where $R_0 = 0.9\%$ and $\mu_0 M_s = 1.1$ T. In the insets the light blue and pink arrows represent the magnetic moments of CoNi and Py. CoNi arrows that represent droplet soliton states are outlined in red throughout.

We next focus on the onset and annihilation of the soliton excitations when the Py layer is saturated ($\mu_0 H > 1.1$ T) so the spin polarization of the current is constant with increasing field. There is hysteresis both in current sweeps at fixed field and in field sweeps at fixed current. Figure 3b shows the onset and annihilation conditions of the droplet soliton found for both cases. The points marking the onset of the soliton fall on a straight line (both for decreasing field and for increasing current). Annihilation occurs at larger fields and also falls on a straight line, but with a larger slope. The large area between the two lines corresponds to the hysteretic region—the zone where both droplet and non-droplet states are stable but only one of the states is present depending on the field and current history. Similar measurements on a sample with smaller anisotropy ($\mu_0 H_D \approx 0.1$ T) also showed straight lines for both the onset and annihilation of the droplet soliton state, but with a hysteretic region with smaller area, and a width in the applied field of $\sim 0.3$ T (Supplementary Fig. 1).

We also observed that droplet solitons can be annihilated (and thus rendered unstable) with magnetic fields applied in the film plane. We nucleated droplet solitons at a large perpendicular magnetic field and then applied an in-plane field until we annihilated the droplet soliton. Figure 3c shows the MR as a function of the in-plane field at different perpendicular applied fields. We see that all the high-resistance states show an abrupt step down to the low-resistance state with increasing in-plane field. Once we removed the in-plane field, we only nucleated droplet solitons in cases for which the perpendicular field made the soliton state stable and the non-soliton state unstable (that is, perpendicular fields and currents that are not in the hysteretic zone in Fig. 3b). Interestingly, the in-plane field values needed for droplet annihilation depend on the pinning state the soliton was in before applying the in-plane field. Again, we observed the same effect in samples with smaller anisotropy.

We now consider the basic physics of the soliton nucleation and annihilation. Droplet solitons form in PMA thin films because spin-torques can favour a layer magnetization anti-aligned with the magnetization of the polarizing layer (an AP state). As the applied perpendicular field is increased, the current required to sustain the droplet also increases and eventually the droplet annihilates. Hysteresis can result because the spin torque required to maintain the droplet state is less than that required to nucleate it.

A quantitative understanding of droplet soliton hysteresis is possible through analysis of the Landau–Lifshitz–Gilbert–Slonczewski equation describing the magnetization dynamics of the free magnetic layer. The simplest analysis considers a macrospin and thus does not include the exchange field or allow for spatial variations in the magnetization. The stability thresholds are given in terms of the applied field and current by

$$h_0 = \sigma_0 \eta(m_z)/\alpha \pm h_p$$  \hspace{1cm} (1)\

where the plus sign is for droplet annihilation ($m_z = -1 \rightarrow +1$) with increasing field and the minus sign is for droplet nucleation ($m_z = +1 \rightarrow -1$) with decreasing applied field. Here, $h_0$ is the applied field and $h_p$ is the effective anisotropy field (fields are normalized to the saturation magnetization, $M_s$). $m_z$ is the $z$-component of $\mathbf{m}$, $\alpha$ is the damping constant, and $\sigma_0 \eta(m_z)$ includes the torque asymmetry, $\eta(m_z)$. $\sigma_0 = I/\alpha$ is proportional to the current intensity $I$, with $I_0 = 2\mu_0 M_s^2 r_e^2 \delta/\hbar$; $r_e$ being the radius of the point contact, $\delta$ the film thickness and $\epsilon$ the spin-torque efficiency. (Further details on the analysis are provided in Supplementary Section II.) In the case with no spin-torque asymmetry, $\eta = 1$, the state diagram of
Figure 3 | Hysteresis in the MR data. a, MR curves as a function of the perpendicular applied field for currents of \( I = 25.5 \) mA (top) and \( I = 32.5 \) mA (bottom). Insets: Light blue and pink arrows represent the orientations of the magnetization in CoNi and Py. CoNi arrows that represent droplet soliton states are outlined in red. b, Stability map of droplet solitons: red circles show annihilation with increasing \( H_x \); orange squares show annihilation with decreasing \( I \), blue circles show onset with decreasing \( H_x \) and cyan squares show onset with increasing \( I \). Dashed lines correspond to fits to a macrospin model with a spin-torque asymmetry of \( \frac{1}{2} = 1.8 \) (see main text). c, MR curves as a function of the in-plane field \( H_x \) for a current of \( I = 26 \) mA. The three curves correspond to perpendicular applied fields of 2.0 T (blue), 2.1 T (green) and 2.2 T (red). The STNOs have a diameter of 150 nm.

applied field versus current (\( h_0 \) versus \( \sigma_0 \)) is two straight lines separating droplet and non-droplet states. The width of the hysteresis in the applied field is twice the effective anisotropy field, \( 2h_0 \). With an asymmetric spin torque \( \eta = 2\lambda^3/(\lambda^2 + 1) + (\lambda^2 - 1)\mu_i \), the stability condition for the non-droplet state is not changed. However, the slope of the line representing the threshold for droplet annihilation increases. Thus, an asymmetric spin torque gives a field hysteresis that increases with the applied current, \( 2h_0 + \sigma_0(\lambda^2 - 1)/\eta \). The data in Fig. 3b is fitted with the macrospin model and plotted as dashed lines (see Supplementary Section II for details on the fittings).

We also considered a two-dimensional model with exchange interactions and performed micromagnetic simulations. It was found that droplet solitons are created at a critical current\(^5\) and annihilated in a perpendicular applied field as in small in-plane magnetic fields. Our results show that the field hysteresis is the same as that of the macrospin model (Supplementary Section II). In-plane fields cause the droplet soliton to delocalize and eventually lose stability\(^19\). This occurs when the localized oscillations in the magnetization couple with the film’s propagating spin-wave modes.

An advantageous feature in structures with perpendicularly magnetized layers is the possibility to excite high-frequency spin dynamics at low fields (compared with the saturation magnetization)\(^16\). Our experiments and modelling show that droplet solitons should also be stable at small—or even zero—perpendicular fields, provided that the polarizing layer has a perpendicular component of magnetization at these small fields. This could be achieved with a polarizing layer that has PMA.

In summary, we have demonstrated bistable states—droplet and non-droplet—in nanocontacts to ferromagnetic thin films. Our experimental results reveal a nearly complete reversal of the magnetization in the nanocontact for the droplet state and a large region—both in field and current—where the two states are stable. This provides a new means for droplet solitons to carry and store information, in addition to their phase and amplitude\(^6\). Our modelling and micromagnetic simulations capture the main features of our experimental results and also predict that droplet solitons can exist at zero applied field. We have also observed small and reproducible variations in the nanocontact resistance when varying the field, suggesting that the droplet solitons can be trapped at pinning sites or may have discrete precessional states. These observations open up new applications for magnetic droplet solitons as multi-state high-frequency current- and field-tunable oscillators.

Methods

The layer stacks consisted of a Co and Ni multilayer, \( 6 \times (0.2\text{Co}|0.6\text{Ni}) \) capped with \( 0.2\text{Co}|5\text{Pt} \), separated by 10 Cu from a 10 Py layer (thicknesses in nanometres), deposited by thermal and electron-beam evaporation in an ultrahigh-vacuum chamber. The Cu spacer layer was chosen to magnetically decouple the in-plane magnetized Py layer from the out-of-plane magnetized Co|Ni multilayer, and the Pt capping layer was used to further enhance the interface-induced perpendicular magnetic anisotropy of the Co|Ni multilayer. Layer stacks were deposited on oxidized silicon wafers. The point contacts were defined by etching holes in a 50-nm-thick silicon dioxide layer deposited on top of the films. Electron-beam lithography was used to define the point contacts with diameters ranging from 70 to 200 nm. Devices were patterned with a bottom electrode and a top electrode into structures suitable for both d.c. and high-frequency (up to \( \sim 40 \) GHz) electrical measurements using optical lithography and etching techniques. Most of the nanofabrication processes were carried out at the Center for Functional Nanomaterials at Brookhaven National Laboratory. The contacts were characterized by atomic force microscopy and scanning electron microscopy.

Our layer stacks have been characterized previously and after patterning with FMR spectroscopy to determine the magnetic anisotropy of both Py and CoNi. We used frequencies ranging from 1 to 40 GHz as a function of the applied field at room temperature and a coplanar waveguide to create the microwave fields, together with a network analyser to record the absorption signal. For the high-frequency measurements the samples were contacted with picoprobes to a current source and to a spectrum analyser that recorded the signals in the presence of applied magnetic fields. A broadband low-noise 20 dB amplifier was used. The d.c. transport measurements were carried out by contacting devices with wire bonds. Low-temperature transport measurements were conducted at 4.2 K in a three-dimensional vector superconducting magnet capable of producing bipolar fields up to 8 T.

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**Author contributions**

All three authors conceived the experiment, discussed the results and wrote the manuscript. F.M. and D.B. fabricated the samples and performed the measurements.

**Additional information**

Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to F.M.

**Competing financial interests**

The authors declare no competing financial interests.