

Multiple magnetic droplet solitons from exotic spin-orbit torques

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Robin Klause^{a)}  and Axel Hoffmann 

AFFILIATIONS

Department of Materials Science and Engineering and Materials Research Laboratory, University of Illinois Urbana-Champaign, Urbana, Illinois 61801, USA

^{a)} Author to whom correspondence should be addressed: klause2@illinois.edu

ABSTRACT

Materials with large spin-orbit interactions generate pure spin currents with spin polarizations parallel to the interfacial surfaces that give rise to conventional spin-orbit torques. These spin-orbit torques can only efficiently and deterministically switch magnets with in-plane magnetization. Additional symmetry breaking, such as in non-collinear antiferromagnets, can generate exotic, unconventional spin-orbit torques that are associated with spin polarizations perpendicular to the interfacial planes. Here, we use micromagnetic simulations to investigate whether such exotic spin-orbit torques can generate magnetic droplet solitons in out-of-plane magnetized geometries. We show that a short, high current pulse followed by a lower constant current can nucleate and stabilize magnetic droplets. Through specific current pulse lengths, it is possible to control the number of droplets in such a system, since torques are generated over a large area. Additionally, the nucleation current scales with the out-of-plane component of the spin polarization and is linear as a function of magnetic field strength.

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In today's digital world, we are faced with an ever increasing amount of computationally demanding tasks. As the miniaturization of traditional semiconductor components is coming to its end, new technology is needed to efficiently complete these tasks. Toward this end, neuromorphic computing is a promising approach. However, so far neuromorphic computing has mainly been implemented in software using traditional semiconductor based hardware. To further improve energy efficiency, new hardware implementations are needed.¹ One promising research area is spintronics based oscillators, which could be the next generation technology in our electronic devices for brain-inspired functionalities.^{2,3} Spintronic oscillators are stable and persistent, nonlinear in amplitude and frequency as a function of applied current and field, and can couple to each other through a variety of mechanisms.⁴⁻⁷ This makes them appealing for neuromorphic computing, where information may be encoded in oscillation frequencies, amplitudes, and phases. Oscillators based on magnetic tunnel junctions that use spin-transfer torques as their driving force have already demonstrated speech and pattern recognitions.^{8,9} At the same time, spin-orbit torques, e.g., originating from spin Hall effects, provide a much more energy efficient way of driving magnetic oscillators. Based on spin-orbit torques, spin-Hall nano-oscillators have been shown to synchronize in a one-dimensional line as well

as a two-dimensional array of oscillators; the latter of which has been used in proof-of-principle neuromorphic computing.¹⁰⁻¹²

In order to have directly coupled, complex networks of magnetic oscillators, it is advantageous to consider oscillators in magnetic films with perpendicular magnetic anisotropy, since they will have isotropic in-plane interactions. Magnon drops are conservative magnetodynamical solitons that can be sustained in thin films with uniaxial perpendicular magnetic anisotropy and zero damping through a balance between dispersion and nonlinearity.^{13,14} Magnon drops are characterized by a circular core whose magnetization is nearly opposite to that of the surrounding volume. The magnetic moments at the edge of the core have an in-plane component that processes homogeneously through a 360° rotation. A dissipative magnetic soliton, known as magnetic droplet, can also form in dissipative, perpendicular-magnetic-anisotropy materials and must balance dissipation with energy gain. Magnetic droplets were theoretically predicted in a nano-contact geometry where spin-transfer torques serve as the gain to drive the local damping to zero.¹⁵ Subsequently, they were experimentally realized in Co/Ni multilayers^{16,17} and have since been studied and observed in both experiments and simulations using the spin-transfer torque driving mechanism.¹⁸⁻²³ Magnetic droplets were also generated using spin-orbit torques for compensating the damping in a nano-constriction geometry.²⁴ In a previous work by Divinskiy *et al.*, an

external in-plane magnetic field was required to tilt the magnetization away from the perpendicular direction, since the conventional spin-orbit torque generates an in-plane spin polarization, which can only compensate the damping of in-plane magnetizations.

Spin-transfer torques, in comparison to spin-orbit torques, are less energy efficient for driving magnetization dynamics because each electron of the charge current can transfer angular momentum only once for spin-transfer torques, while it can do so multiple times for spin-orbit torques.²⁵ In conventional spin-orbit torque driven magnetization dynamics, a charge current along the in-plane x -direction generates a spin current along the out-of-plane z -direction with a spin polarization in the in-plane y -direction. The spin polarization is restricted to be in the y -direction by the symmetry of the spin-torque generating material. This spin current generates an anti-damping like torque of the form $\mathbf{m} \times (\mathbf{m} \times \hat{\mathbf{y}})$, where \mathbf{m} is the magnetization vector. This torque is only efficient at compensating damping for adjacent magnetic layers with an equilibrium direction of magnetic moments parallel to the injected spin polarization along the y -direction and not perpendicular to the spin polarization along the x - or z -direction.

Recently, it has been shown that by reducing the crystalline symmetry to only a single mirror plane, for example, in WTe₂, a charge current perpendicular to the symmetry axis can generate a spin current with a spin polarization that has an out-of-plane z -component.²⁶ Similarly, reducing the symmetry through magnetic structure, for example, in antiferromagnetic Mn₃GaN²⁷ and Mn₃Ir,^{28,29} also results in an out-of-plane z -component of the spin polarization. This allows for efficient excitation of magnetization dynamics in perpendicular-magnetic-anisotropy materials without the need of an in-plane magnetic field that tilts the magnetization away from the out-of-plane direction. Additionally, in spin-orbit-torque geometries, torques can be exerted over large areas without having to increase the current beyond an experimentally feasible level, as would be the case for exerting torques over large areas in spin-transfer-torque geometries.

To study the generation of magnetic droplet solitons with unconventional spin-orbit torques, we perform micromagnetic simulations using the software MuMax3.³⁰ Our simulation region consists of a $(1125 \times 250 \times 5)$ nm³ rectangular thin film slab divided into a mesh with $(576 \times 128 \times 1)$ cells, leading to a cell size of approximately $(1.95 \times 1.95 \times 5)$ nm³. The simulation parameters are similar to those of ferromagnetic Co/Ni multilayers and include an exchange stiffness $A = 10$ pJ/m, first order uniaxial anisotropy constant $K_u = 0.32$ MJ/m³ in the $(0, 0, 1)$ direction perpendicular to the film plane, and a saturation magnetization $\mu_0 M_s = 0.75$ T. The magnetization dynamics are governed by the Landau-Lifshitz-Gilbert equation with the addition of a spin-orbit-torque term,

$$\frac{d\mathbf{m}}{dt} = -\frac{\gamma}{1+\alpha^2} [\mathbf{m} \times \mathbf{H}_{\text{eff}} + \alpha \mathbf{m} \times (\mathbf{m} \times \mathbf{H}_{\text{eff}})] + \tau_{\text{SOT}}. \quad (1)$$

Here, γ is the gyromagnetic ratio, α is the Gilbert damping constant, \mathbf{m} is the magnetization vector, \mathbf{H}_{eff} is the effective magnetic field, and τ_{SOT} is the spin-orbit-torque term. Our simulations use a Gilbert damping of $\alpha = 0.02$, are done at zero temperature, include an external magnetic field (\mathbf{H}) along the z -direction, and use the default Neumann boundary conditions.

The spin-orbit torque acts on the ferromagnetic layer through the Slonczewski spin-transfer torque term. We do not specifically simulate the spin-torque generating layer, but we can think of it as being

below the ferromagnetic layer, as shown in Fig. 1. When a charge current (J_c) is applied along the x -direction, a spin current (J_s) is generated along the z -direction due to the spin-Hall effect. J_s has a spin polarization (σ) in the y - z plane at an angle φ from the y -axis, as dictated by the combination of conventional and unconventional spin accumulations (see Fig. 1). This situation can be implemented in the simulation using the Slonczewski spin-transfer torque term that is included in MuMax3, thereby turning it effectively into a spin-orbit torque term,

$$\tau_{\text{SOT}} = -\beta \frac{\theta_{\text{SH}}}{2(1+\alpha^2)} (\mathbf{m} \times (\mathbf{m} \times \boldsymbol{\sigma}) - \alpha (\mathbf{m} \times \boldsymbol{\sigma})), \quad (2)$$

where $\beta = \frac{J_c d}{M_s e d}$, J_c is the charge current density in the spin-orbit torque layer, e is the elementary charge, and d is the ferromagnetic layer thickness. θ_{SH} is the spin-Hall angle that we set to $\theta_{\text{SH}} = 0.08$, which is similar to that of Mn₃Ir.²⁸ The spin-orbit-torque term allows us to set the spin polarization to any arbitrary angle enabling us to study the droplet behavior as a function of differing unconventional spin accumulation amplitudes.

The initial magnetization is uniform throughout the ferromagnetic layer with moments in the positive z -direction. The system is then relaxed to its ground state while applying the external magnetic field used throughout each simulation. We then start by applying a constant current of $J_c = 4.0 \times 10^8$ A/cm² with spin polarization angle $\varphi = 50^\circ$ and magnetic field $\mu_0 H = 0.9$ T. The spin polarization angle was chosen based on spin polarization components reported in Ref. 27.

Figure 2 shows a top-down view of the magnetization landscape at different times after the start of the simulation. The black region shows moments pointing into the page, the gray region shows out of the page, and the colors represent in-plane components as shown in the inset on the top right of (a). At 5 ns, we see a droplet forming at the center of the simulation region [Fig. 2(a)], whereby the magnetization gradually reverses over the 5 ns time period, as shown in Fig. 2(i). The circular center has almost opposite magnetization to the rest of the ferromagnet. The moments between the two regions all point in the same direction while precessing homogeneously, confirming a droplet. We find the precession frequency of the droplet to be lower than the ferromagnetic resonance, further confirming droplet formation.¹⁶ At 7.6 ns, the droplet has grown in size, and a second set of droplets forms with one droplet on either side of the first one [Fig. 2(b)]. The two new droplets precess in phase with each other, but not in phase with the first one. We also observe spin waves emitted from the droplets as indicated by the periodic out-of-plane component of the moments. The spin wave frequency is almost a factor of two larger than the droplet frequency. At 10.1 ns, the first two sets of

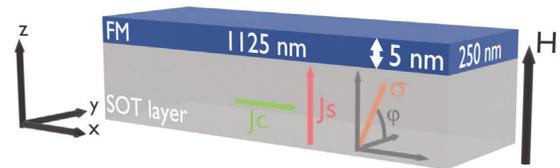


FIG. 1. Ferromagnetic layer on top of spin current generating the spin-orbit-torque (SOT) layer and the external magnetic field (H) in the z -direction. A charge current (J_c) in the x -direction generates a spin current (J_s) in the z -direction with spin polarization (σ) in the y - z plane at an angle φ from the y -axis.

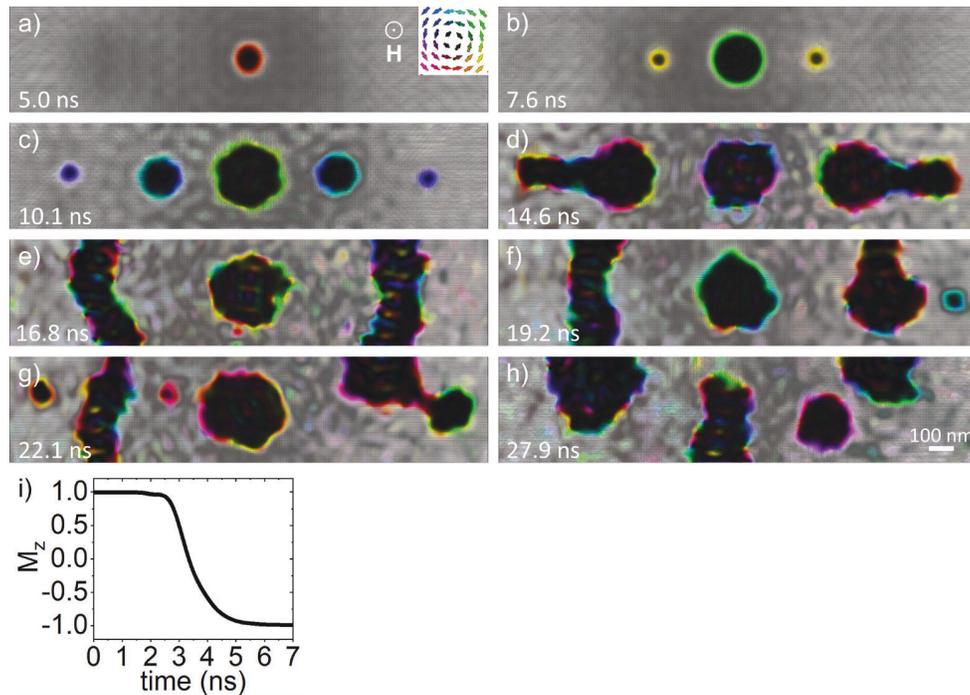


FIG. 2. Magnetization landscape (a) 5, (b) 7.6, (c) 10.1, (d) 14.6, (e) 16.8, (f) 19.2, (g) 22.1, and (h) 27.9 ns after the current is applied. $\mu_0 H = 0.9$ T, $\varphi = 50^\circ$, and $J_c = 4 \times 10^8$ A/cm². (i) z-Component of the magnetization over time at the center of the film. The inset of (a) shows the colors corresponding to the in-plane component of the magnetization.

droplets have a less circular shape, and the moments precess less homogeneously, which is a consequence of droplet perimeter eigenmodes³¹ [Fig. 2(c)]. Additionally, one-third set of droplets forms with one droplet on either side of the first two sets and precessing in phase with each other but not in phase with the first two sets. The droplets form in this sequence and these positions due to demagnetizing fields in the film, which result in the lowest effective field at the center of the film, creating a more favorable nucleation location.³² At finite temperature, the nucleation position is less predictable due to thermal effects that can create a more favorable nucleation environment away from the center. At 14.6 ns [Fig. 2(d)], the two outside droplets combine and spread toward the edges after 16.8 ns [Fig. 2(e)]. More droplets form and combine with previous ones over time, and the magnetization landscape becomes chaotic [Figs. 2(f)–2(h)].

From the results in Fig. 2, it is clear that the current required to nucleate a droplet is larger than the one necessary to sustain it. Therefore, we use short, high amplitude current pulses for nucleating droplets, after which we reduce the current. By choosing a specific current pulse length, we can control the number of droplets that form. For example, if we use pulses of 5, 7.6, and 10.1 ns corresponding to the magnetization snapshots in Figs. 2(a)–2(c), we can nucleate 1, 3, and 5 droplets, respectively. After nucleation, the current is reduced from $J_c = 4.0 \times 10^8$ to $J_c = 3.04 \times 10^8$ A/cm² to keep more droplets from forming and combining.

The non-local exertion of torque in our simulations is different from the nano-contact geometry, where torque is exerted only at the contact location. Thus, the spin-orbit torque geometry

allows us to use current pulses to change the number of droplets in our system. Using a magnetic field of $\mu_0 H = 0.3$ T and spin polarization direction of $\varphi = 50^\circ$, we nucleate three droplets using a 10 ns $J_c = 3.6 \times 10^8$ A/cm² current pulse and reduce the current to $J_c = 2.74 \times 10^8$ A/cm² to stabilize the droplets. We then use a 10 ns $J_c = 2.52 \times 10^8$ A/cm² pulse to annihilate the two droplets to either side of the center one after which we go back to the stable current. We can then go back to three droplets using a 10 ns $J_c = 3.67 \times 10^8$ A/cm² current pulse. Figure 3(a) shows this sequence of current pulses and the corresponding magnetization landscapes.

Figures 3(b) and 3(c) show the current density required to nucleate a droplet with a 10 ns long pulse as a function of external magnetic field and out-of-plane spin polarization angle, respectively. As the magnetic field increases, a larger torque is required to pull magnetic moments away from their equilibrium position, so a larger current is required to nucleate a droplet. The droplet diameter is also affected by the magnetic field. At large fields, the droplet is larger. As the spin polarization angle increases, the unconventional out-of-plane torque has a larger contribution to the overall torque. Thus, there is a larger torque that is efficient at compensating the damping in perpendicular-magnetic-anisotropy materials, so less current is required to form a droplet. On the contrary, at small angles, the unconventional torque component is small, so more current is required to generate a droplet. We also observe that the shape of the droplet is less circular, and the precession is less homogeneous at small angles. This is due to the large

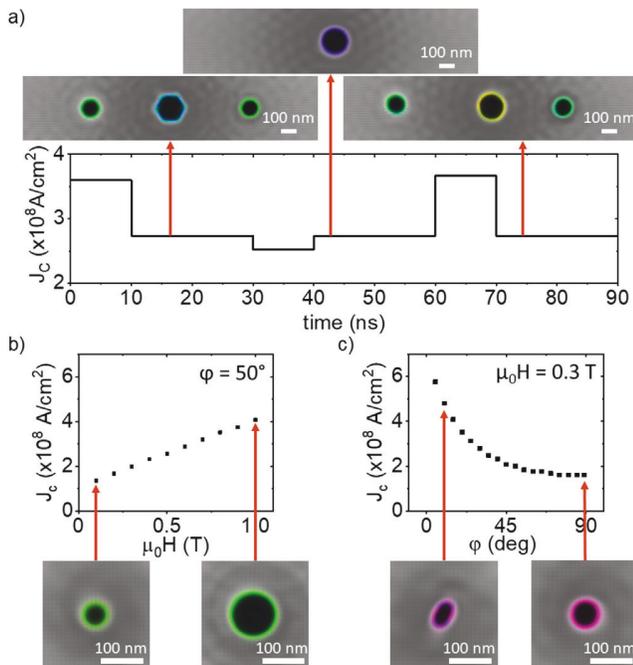


FIG. 3. (a) Magnetization landscape after specific 10 ns current pulses with $\mu_0 H = 0.3$ T and $\varphi = 50^\circ$. (b) Droplet nucleation current as a function of external magnetic field amplitude, with $\varphi = 50^\circ$. (c) Droplet nucleation current as a function of out-of-plane spin polarization angle with $\mu_0 H = 0.3$ T. Magnetization landscape after droplet nucleation is shown for 0.2 T and 0.9 T below (b) and $\varphi = 10^\circ$ and $\varphi = 89^\circ$ below (c).

in-plane spin polarization component that perturbs the droplet shape. We observe that this elliptical droplet spins similar to the cigar shaped soliton described by Song *et al.*³³

In summary, we show by using micromagnetic simulations that magnetic droplet solitons can be generated with exotic, unconventional out-of-plane spin-orbit torques in ferromagnetic materials with perpendicular magnetic anisotropy. The current required to nucleate a droplet is higher than the current necessary to sustain it. Therefore, a reduction in current is required after a higher nucleation current pulse in order to avoid a continuous nucleation of additional droplets. The number of droplets generated can be controlled by the length of the initial nucleation current pulse. Due to the non-local injection of spins, we can change the number of droplets in our system using current pulses of varying amplitude. We observe that the nucleation currents are linear as a function of magnetic field strength and scale with the out-of-plane spin polarization angle. These simulations provide a promising perspective for using electrically driven magnetization dynamics for next-generation computational approaches.

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AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

Author Contributions

Robin Klause: Data curation (lead); formal analysis (lead); investigation (lead); methodology (lead); visualization (lead); writing – original draft (lead); writing – review and editing (equal). **Axel Hoffmann:** Conceptualization (lead); funding acquisition (lead); resources (lead); supervision (lead); writing – review and editing (equal).

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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