

Facilitating electrical and laser-induced skyrmion nucleation with a dipolar-field-enhanced effective Dzyaloshinskii-Moriya interaction

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We demonstrate experimentally how the nucleation of skyrmions in an Ir, Co, and Pt based magnetic multilayer is affected by introducing a layer dependent sign for the Dzyaloshinskii-Moriya interaction (DMI). In one stack, the bottom half of the stack is given a positive DMI and the top half a negative DMI, and as a result, the in-plane component of the dipolar field is aligned parallel to the effective field of the DMI in every layer, enhancing the effective DMI. We show that this enhanced DMI facilitates the nucleation and stability of skyrmions using both current-driven and laser-induced skyrmion nucleation. In the devices with an enhanced effective DMI, the density of nucleated skyrmions is greater by up to a factor ~ 20 and skyrmions can be observed in stronger magnetic fields—suggesting that their stability is also improved. These results show that skyrmion nucleation depends strongly on the magnitude of the effective DMI in a magnetic multilayer and that the dipolar field within such a multilayer presents an effective route towards controlling the effective DMI, and thereby, the nucleation of chiral magnetic textures.

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I. INTRODUCTION

A key interaction required for the stability of chiral magnetic textures such as skyrmions is the Dzyaloshinskii-Moriya interaction (DMI) [1–5]. In magnetic multilayers, the interfacial DMI stabilizes chiral Néel-type domain walls and skyrmions over their Bloch-type counterparts. This chirality is vital for devices that make use of skyrmions as information carriers, since it ensures that all skyrmions in the device experience the same forces when a current is sent through the system [4,6]—which enables shifting data through the device. Additionally, the DMI lowers the domain-wall energy density, which increases the stability of the skyrmion texture [7,8]. Therefore, control over the DMI strength—and in particular, increasing the DMI strength—is of great technological and academic interest.

In a magnetic multilayer, however, the DMI is not the only interaction that can influence the chirality of domain walls and skyrmions [9,10]. In systems where the thickness is larger than the exchange length and with a large magnetic moment, the dipolar interaction between the out-of-plane magnetization in the domains and the in-plane magnetization inside the domain walls can be significant

(compared to the DMI) [11,12], resulting in the formation of Néel caps [9,13,14]. In the top of the stack, a clockwise chirality is energetically favored and conversely, a counter-clockwise chirality is favored in the bottom half of the stack. Depending on the stack geometry, magnetic parameters, and the scheme that is used to inject a spin-current into the multilayer, the dipolar interaction can significantly affect the current-driven motion of chiral magnetic textures [15] and is, therefore, often seen as a negative effect. Avoiding this effect is however nontrivial, as the dipolar field generated by the domains—while detrimental to current-driven motion—is essential for the high stability and small size of skyrmions [7,16–18].

Here, we utilize this internal dipolar field in combination with opposite stacking orders of the layers in the top and bottom half of the stack, to either enhance or reduce the effective DMI of the system [19,20]. By choosing the appropriate sign of the interfacial DMI for repeats in the bottom and top half, a stack can be created where the DMI and the dipolar field stabilize the same (opposite) chirality in all layers, effectively enhancing (reducing) the DMI. Using this method we can study the effect of significant differences in the effective DMI of the stack on the nucleation of skyrmions in isolation, which has hitherto not been done in skyrmion nucleation experiments. This is because conventional methods of varying the magnetic parameters, such as changing the thickness of the magnetic layers (see, e.g., [7]), ion irradiation with either Ga⁺ or He⁺ ions (see, e.g., [12,21,22]), or changing the stack composition [7] almost always lead to changes in multiple magnetic parameters. In Ref. [20], we showed that this dipolar induced change in the effective DMI can be measured

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and we examined its effect on the skyrmion energy using micromagnetic simulations. Here, we experimentally examine the effect on skyrmion nucleation and show that skyrmion nucleation is facilitated in the samples with an enhanced effective DMI when compared to a reduced effective DMI. Using the stacking orders described above, we fabricated two samples with identical (average) saturation magnetization and uniaxial anisotropy strength, but an effective DMI that is different by almost a factor three, as shown in Sec. II. We then use both nanosecond-current-pulse-driven and femtosecond-laser-pulse-induced skyrmion nucleation to study the effect of changes in the effective DMI strength on the skyrmion nucleation in Sec. III. Irrespective of the nucleation method, we find that the change in the effective DMI has a significant effect on the density of nucleated skyrmions, while the threshold current and threshold fluence seem only weakly affected. Furthermore, we observe that skyrmions remain present in the enhanced stack at larger fields compared to the reduced stack, suggesting that the skyrmion stability is also improved by the increased effective DMI. Interestingly, the effect of the dipolar enhanced and reduced effective DMI on both the current-driven and laser-induced nucleation is qualitatively and quantitatively similar, even though the timescales on which the systems are excited are very different. These results not only show that the internal dipolar field can be exploited to facilitate the nucleation of chiral magnetic textures, but they also present a first insight into the dependence of laser-induced skyrmion nucleation on the internal dipolar interactions in a magnetic multilayer and a possible route towards measuring this dependence.

II. SAMPLES AND METHODS

The samples have the following double trilayer structure as building blocks: [Pt(1)|Co(1)|Ir(1)] and [Ir(1)|Co(1)|Pt(1)], with the numbers in brackets indicating the thickness in nm. The former (latter) trilayer has a positive (negative) intrinsic DMI and, therefore, stabilizes counter-clockwise (clockwise) Néel-type domain walls [13].

In Figs. 1(a) and 1(b), we show a sketch of the structure of a typical magnetic multilayer. The bottom and top half of the stack contain the same trilayer-building block and, therefore, have the same intrinsic DMI sign [(a) positive D, (b) negative D]. Consequently, the DMI in the top and bottom half of each stack stabilizes a uniform domain-wall chirality in the multilayer (thick arrows). However, in both stacks the dipolar field (white arrow labeled H_d) originating from the two domains (light and dark gray) is anti-parallel to the magnetization in the domain walls in either the top, or the bottom half of the stack. This reduces the effective DMI in this part of the multilayer and—when the number of layers is large or the intrinsic DMI is weak—can give rise to heterochiral domain walls [12–14]. In Fig. 1(c), we show that introducing an opposite intrinsic DMI sign for the two halves of the multilayer can result in a DMI effective field that is parallel to the dipolar field everywhere in the multilayer, thus enhancing the effective DMI of the entire stack with respect to the intrinsic DMI strength of the building blocks [20]. Additionally, as we show in Fig. 1(d), the same mechanism can be used to fabricate a multilayer where the dipolar field and DMI effective field

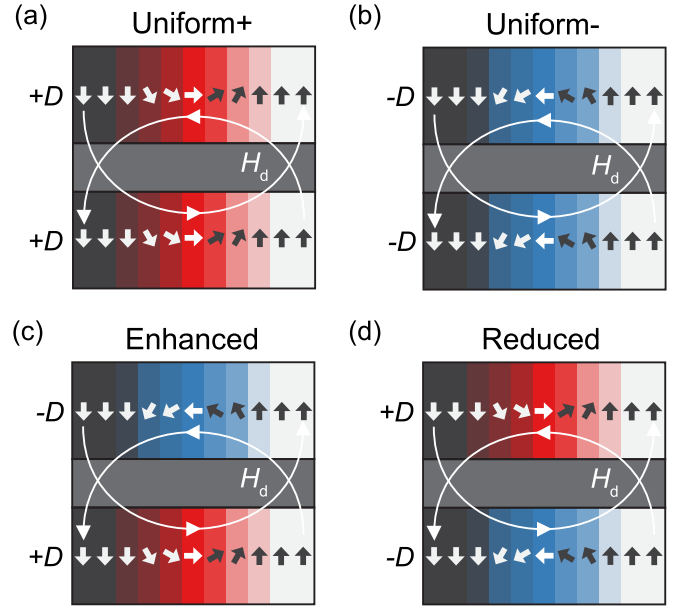


FIG. 1. Sketches of the different multilayer structures. Thick arrows represent magnetization and follow the DMI effective field, the long white arrows represent the dipolar field $\mu_0 H_d$. Note, that we only sketch the dipolar field contribution by the out-of-plane magnetization on one side of the magnetization pattern represented by the thick arrows. The top and bottom half of each schematic represent multiple repeats with the same layer order and intrinsic DMI (a) Uniform+ stack. All the layers in this stack have a positive DMI sign. (b) Uniform- stack. Same as (a), but with the opposite DMI sign. (c) Enhanced stack. Here the magnetic layers in the top half of the stack have a negative DMI and the layers in the bottom half a positive DMI, as a result the DMI effective field and the dipolar field are aligned in all layers. (d) Reduced stack. Opposite DMI signs compared to the Enhanced stack in (c), now the DMI effective field and the dipolar field are antiparallel in all layers.

are everywhere antiparallel, reducing the effective DMI. Thus, by changing the stacking order of the Pt, Co, and Ir-based building blocks, the effective DMI strength of a multilayer can be controlled [20]. These four configurations will be referred to as: (a) Uniform+, (b) Uniform-, (c) Enhanced stack, and (d) Reduced stack in the remainder of this article.

To this end, we fabricate four magnetic multilayer structures consisting of the following stacks:

$$\begin{aligned}
 \text{Uniform+} &: \overbrace{[\text{Pt}(1) | \text{Co}(1) | \text{Ir}(1)]}_{+D}^{\times 6} \\
 \text{Uniform-} &: \overbrace{[\text{Ir}(1) | \text{Co}(1) | \text{Pt}(1)]}_{-D}^{\times 6} \\
 \text{Enhanced} &: \overbrace{[\text{Pt}(1) | \text{Co}(1) | \text{Ir}(1)]}_{+D}^{\times 3} | \overbrace{[\text{Ir}(1) | \text{Co}(1) | \text{Pt}(1)]}_{-D}^{\times 3} \\
 \text{Reduced} &: \overbrace{[\text{Ir}(1) | \text{Co}(1) | \text{Pt}(1)]}_{-D}^{\times 3} | \overbrace{[\text{Pt}(1) | \text{Co}(1) | \text{Ir}(1)]}_{+D}^{\times 3}
 \end{aligned}$$

The substrate and seed layers for all stacks are Si | SiO₂(100) || Ta(4) | Pt(2) and the capping layer is either Ta(4) (characterization and laser-induced nucleation) or Pt(3) (current-driven nucleation). All samples are grown using DC

magnetron sputtering in an Ar atmosphere with a pressure of $p = 2 \times 10^{-3}$ mbar using a vacuum system with a base pressure better than $p = 5 \times 10^{-9}$ mbar. Using electron beam lithography and a standard lift-off procedure we pattern the samples into nucleation devices with large contact pads for wirebonding [$150 \times 100 \mu\text{m}^2$] and a narrow current line [$7 \times 1.6 \mu\text{m}^2$] (described in detail in Ref. [21]).

Magnetometry measurements of the saturation magnetization and the effective anisotropy, as well as demagnetization of the samples were performed at room temperature in a Quantum Design MPMS3. To nucleate skyrmions we employ two custom-built magnetic force microscopy (MFM) setups. The current-driven nucleation experiments and the characterization of the DMI are performed using a Bruker Dimension Edge atomic force microscope (AFM). A custom sample holder enables manipulation of the magnetic state of the multilayers using single 50 ns current pulses from an Agilent 33250A 80 MHz arbitrary waveform generator, as well as the simultaneous application of a magnetic field up to $\mu_0 H_z = 500$ mT during measurements. The pulse voltage is measured using an Agilent Infiniium DSO80604B oscilloscope connected in series and the current through the device is calculated by dividing the measured pulse voltage by the resistance of the oscilloscope (50Ω) [23]. Finally, the current density is estimated using the assumption that the current is uniformly distributed throughout all layers of the material stack.

The laser-induced nucleation experiments are performed using an NT-MDT NTEGRA AFM. The scanhead of this AFM can be removed to allow access to the sample for a single 70 fs laser pulse with a central wavelength of 800 nm, picked from the 1 kHz pulse train generated by a Spectra-Physics Spitfire Ace laser amplifier system using a Pockel's cell. After the application of such a pulse, the scanhead can be placed back over the sample, which results in only a small displacement of the tip position on the order of 1 μm . Hence, the same position can be measured before and after the application of a laser pulse with relative ease. The sharp edges of the devices are used to position the laser spot and to measure its full width at half maximum (FWHM). The laser-driven nucleation is then performed in the contact pads, away from the edges of the device. Since the laser spot is much larger than the area of the MFM scan, we assume that the fluence of the laser is equal to the peak fluence of the laser spot, everywhere in the MFM scan. The peak fluence is calculated by measuring the laser power, which is first converted into energy per pulse using the repetition rate of the laser and then into fluence using the measured FWHM of the spot, assuming a 2D-Gaussian beam profile. An out-of-plane magnetic field can be applied to the sample during skyrmion nucleation, using an electromagnet installed in the sample holder. When MFM images are taken with this setup, the magnetic field is switched off to improve the signal-to-noise ratio.

For these experiments we use two types of custom-coated MFM cantilevers fabricated from NANOSensors PPP-FMR AFM cantilevers. A magnetic coating is applied to these cantilevers using the same sputter deposition system used to grow the samples and consists of either $||\text{Ta}(4)|\text{Co}(5)|\text{Ta}(5)$ or $||\text{Ta}(4)|\text{Co}(7.5)|\text{Ta}(5)$. The two different coatings are

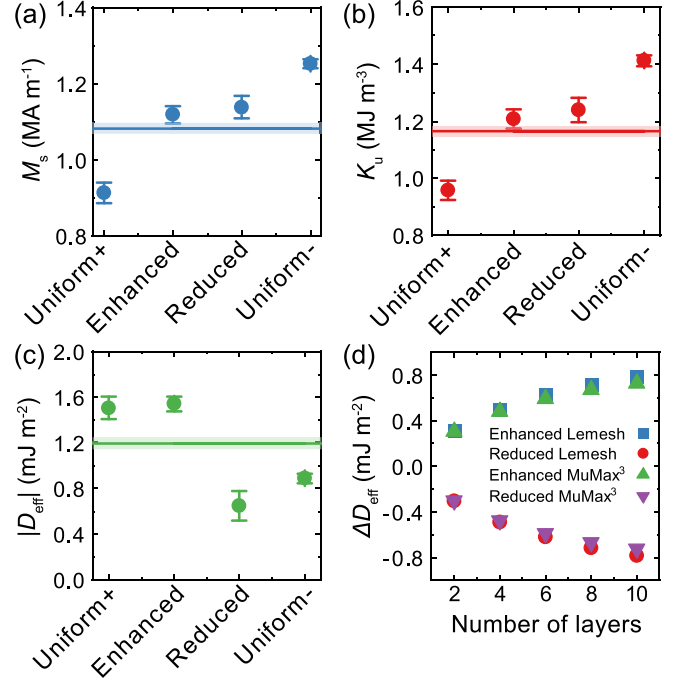


FIG. 2. Characterization of the different magnetic multilayers. (a) The saturation magnetization M_s and (b) uniaxial anisotropy K_u measured using SQUID-VSM. (c) The effective DMI strength $|D_{\text{eff}}|$ determined by first measuring the equilibrium domain width and then using a model for the expected equilibrium domain width by Lemesh *et al.* [25] to calculate $|D_{\text{eff}}|$. The horizontal lines in (a)–(c) show the average of the values measured for the two uniform stacks. (d) The expected contribution of the dipolar field to the effective DMI calculated using MuMax³ simulations (green and purple) and an analytical model by Lemesh *et al.* [12] (blue and red).

used since we always try to maximize the magnetic moment of the tip, but observed that domain walls in the reduced stack are influenced by the tip magnetization if a coating of Co(7.5) is used. In the case of the laser-induced nucleation experiments, the Co(5) coating was used for all stacks.

III. RESULTS

A. Sample characterization

1. Saturation magnetization and uniaxial anisotropy

We measured both the in-plane and out-of-plane hysteresis loops using SQUID-VSM, which are shown in Sec. SI of the Supplemental Material (SM) for all four stacks [24]. In Fig. 2(a), we plot the measured saturation magnetization M_s . The uniform+ and uniform− stacks are found to have the lowest and highest saturation magnetization, respectively, which is consistent with other reports on Pt | Co | Ir and Ir | Co | Pt multilayers [13].

Additionally, we extract the effective anisotropy K_{eff} from the SQUID-VSM hysteresis loops using the area method [26]. We convert this value into the uniaxial anisotropy K_u using

$$K_{\text{eff}} = K_u - \frac{1}{2} \mu_0 M_s^2, \quad (1)$$

and plot this value in Fig. 2(b). Since the measured effective anisotropy of the uniform+ and uniform− stacks are similar, the trend in K_u follows that of M_s^2 for these two stacks.

We will now consider the enhanced and reduced stack in the context of the two uniform stacks. Half of the layers in the enhanced and the reduced stack correspond to the stacking order of the uniform+ stack and the other half of those in the uniform− stack. In Ref. [20], we showed that the value of the saturation magnetization and the uniaxial anisotropy obtained from SQUID-VSM measurements for the enhanced and reduced stack can be understood as the average value of the two uniform stacks. Essentially, we assume that each layer in the multilayer contributes equally to the signal measured by the SQUID-VSM, and that each half of the enhanced and reduced stack has an M_s and K_u that is close to those found for the corresponding uniform stacks. Indeed, the measured values for M_s [Fig. 2(a)] and K_u [Fig. 2(b)] for the enhanced and reduced stacks are close to the average value for the two uniform stacks represented by the colored horizontal lines. The agreement between the values observed for the enhanced and reduced stacks with the average value of the two uniform stacks is not as good as that observed in Ref. [20]. We expect that this is because the number of layers in the multilayer was increased from four to six and that this slightly increased the cumulative effect of the bottom layers on the growth of the top layers.

2. The effective DMI

We determined the effective DMI $|D_{\text{eff}}|$ using a model by Lemesh *et al.* [25]. This model is used to predict the equilibrium domains size for a multilayer stack, if given the exchange stiffness A , the saturation magnetization M_s , the uniaxial anisotropy K_u , and the DMI strength D . By measuring the equilibrium domain size instead, it can also be used to determine D if the other parameters are known [25,27] [see Ref. [28] for a detailed description of our implementation of this method]. The results of this analysis are plotted in Fig. 2(c) for all four stacks. In Sec. SII of the SM [24], we show MFM scans of the demagnetized domain states that are used to determine the equilibrium domain width. Contrary to the results for the saturation magnetization and the uniaxial anisotropy, the measured effective DMI for the enhanced and the reduced stack does not correspond to the average value of the two uniform stacks [horizontal green line in Fig. 2(c)]. Instead, the DMI in the enhanced stack is found to be significantly larger than this average value (by $0.34(8) \text{ mJ m}^{-2}$) and the DMI in the reduced stack is found to be significantly lower (by $0.6(1) \text{ mJ m}^{-2}$), in accordance with our expectation based on Figs. 1(c) and 1(d).¹ The effective DMI in the enhanced stack is found to be a factor 2.5 greater than in the reduced stack. Despite this large difference in the effective DMI, the measured saturation magnetization and uniaxial anisotropy in both stacks are the same within our experimental uncertainty. This is important because this enables us to study the effect of the enhanced and reduced effective DMI on the nucleation of

skyrmions directly, without having to account for changes in the nucleation due to the other material parameters.

3. Modeling

We conclude this section with the results of MuMax³ [29] simulations and an analytical model [12], the details of both models can be found in Sec. SV of the SM [24]. In the MuMax³ model we calculate the domain-wall energy of two multilayer stacks consisting of N layers that are only coupled by the dipole interaction. The magnetic parameters for each layer in the simulation correspond to the average material parameters represented by the horizontal lines in Fig. 2, except the DMI which we vary between $|D| = 1 \text{ mJ m}^{-2}$ and $|D| = 3 \text{ mJ m}^{-2}$. The only difference between the two systems is the sign of the DMI in the top and bottom half, which is either: Enhanced ($D_{\text{Top}} < 0$; $D_{\text{Bottom}} > 0$) or Reduced ($D_{\text{Top}} > 0$; $D_{\text{Bottom}} < 0$). We then determine for which DMI strengths the two systems have the same domain-wall energy, the difference in DMI that is needed to obtain the same domain-wall energy is two times the gain/loss in effective DMI due to the dipolar field from the domains. In Fig. 2(d), we plot the obtained increase and decrease in the effective DMI for the enhanced and reduced stacks in green and purple, respectively. In addition, we also show the results from a model of the effective DMI due to the dipolar field by Lemesh *et al.* [12] in Fig. 2(d) in blue and red. These results are in excellent agreement with the simulations performed using MuMax³. The stack with $N = 6$ corresponds to the experiment and here we find a predicted change in the effective DMI of $|\Delta D| = 0.6 \text{ mJ m}^{-2}$. The simulated difference between the effective DMI of the enhanced and the reduced stack matches the measured difference ($|\Delta D_{\text{Meas}}| = 0.47(6) \text{ mJ m}^{-2}$) relatively well, which confirms the dipolar origin of the difference in the effective DMI between the enhanced and reduced stack.

B. Current-driven skyrmion nucleation

The experimental procedure followed during the nucleation experiments is as follows: First, we saturate the magnetization in the device in the negative z direction (out-of-plane, $\mu_0 H_z < -150 \text{ mT}$). Then, a small bias field is applied in the positive z direction and a single current (laser) pulse is sent to the device. Subsequently, an MFM scan is taken to record the magnetization state in the device. In the case of the current-driven nucleation, the bias field is applied while the MFM scan is taken, while in the case of the laser-induced nucleation it had to be turned off before scanning to get a good signal-to-noise ratio.

We will discuss the current-driven skyrmion nucleation experiments first. In Figs. 3(a)–3(c), we show three MFM scans obtained by scanning the enhanced stack. For all three scans, the bias field is set to $\mu_0 H_{\text{Bias}} = 10.3(5) \text{ mT}$, along the positive z direction. Before the scan shown in Fig. 3(a) is measured, no current pulses are applied through the device, while for Figs. 3(b) and 3(c) a current pulse with a current density of $J = 7.14 \times 10^{11} \text{ Am}^{-2}$ and $J = 7.77 \times 10^{11} \text{ Am}^{-2}$ is applied, respectively. When no current is applied [Fig. 3(a)], the magnetization in the device is in a demagnetized state, the domain that is parallel to the applied field (light gray) is slightly bigger than the antiparallel domain. In Fig. 3(c),

¹A hypothesis for the difference in magnitude is given in Sec. SV of the Supplemental Material [24].

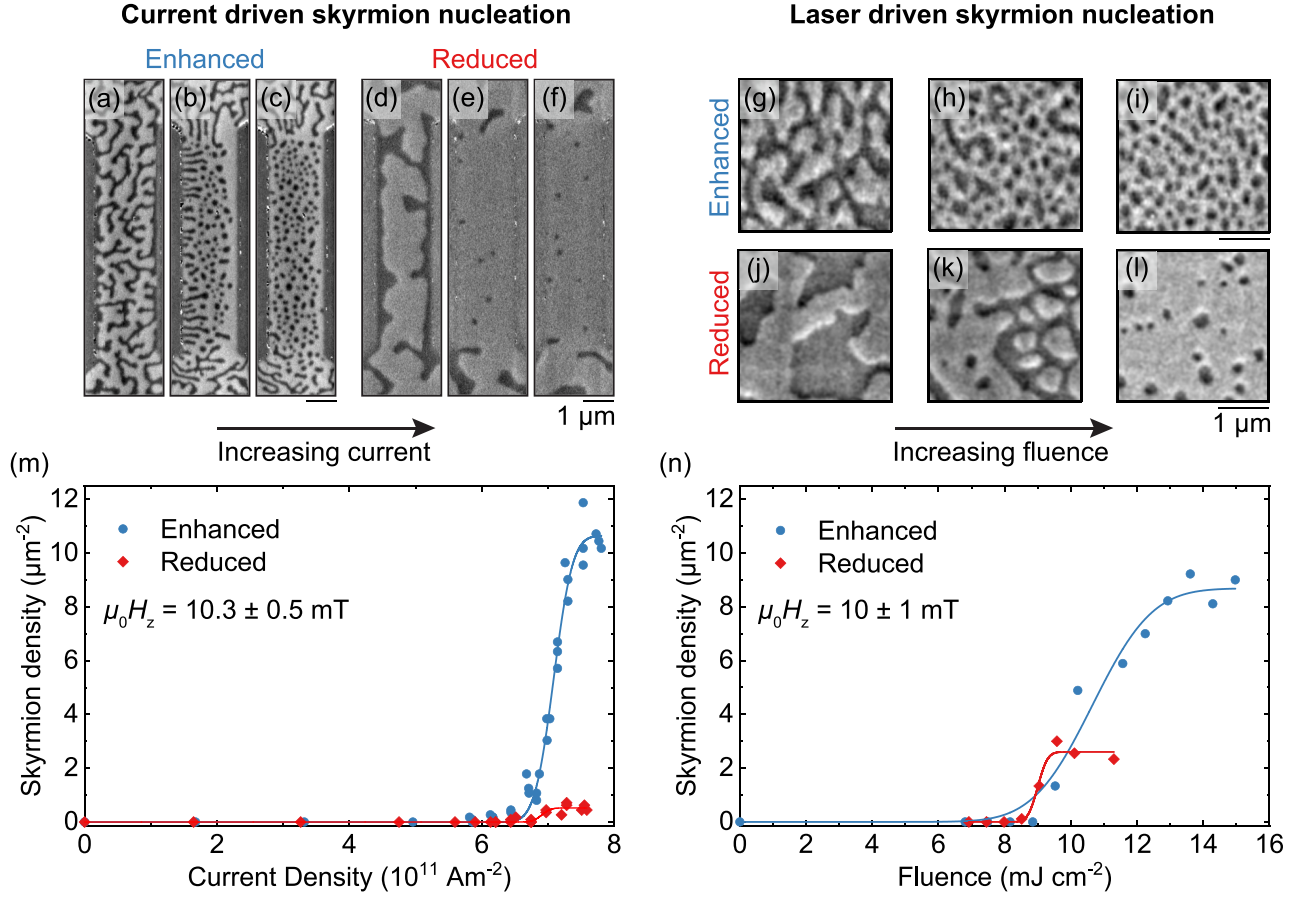


FIG. 3. Effect of the enhanced and reduced effective DMI on the current- and laser-induced nucleation of skyrmions. In (a)–(l), we show MFM scans of the magnetization in the devices fabricated from the enhanced and reduced multilayer stack after applying a single nucleation pulse. (a)–(c): Enhanced stack after current-induced nucleation, the current densities are: $J = 0 \text{ A m}^{-2}$, $J = 7.14 \times 10^{11} \text{ A m}^{-2}$, and $J = 7.77 \times 10^{11} \text{ A m}^{-2}$, respectively. (d)–(f): Reduced stack after current-driven nucleation, the current densities are: $J = 0 \text{ A m}^{-2}$, $J = 6.97 \times 10^{11} \text{ A m}^{-2}$, and $J = 7.55 \text{ A m}^{-2}$. In (a) through (f) the current flows from top to bottom. (g)–(i): Enhanced stack after laser-induced nucleation, the fluences are: $F = 8.9 \text{ mJ cm}^{-2}$, $F = 11.6 \text{ mJ cm}^{-2}$, and $F = 15.0 \text{ mJ cm}^{-2}$, respectively. (j)–(l): Reduced stack after laser-induced nucleation, the fluences are: $F = 6.9 \text{ mJ cm}^{-2}$, $F = 9.1 \text{ mJ cm}^{-2}$, and $F = 10.1 \text{ mJ cm}^{-2}$. In (m) and (n), we summarize the results from the current-driven and laser-induced skyrmion nucleation, respectively. For each current density we plot the average skyrmion density in the scanned area, for both the enhanced (blue dots) and reduced stack (red diamonds). The solids lines in (m) and (n) are fits to the data using Eq. (2).

we show the magnetization after the highest current density that can be reached by our pulse generator is sent through the device. Here, the magnetization inside the narrow strip is fully in the skyrmion state with 117 skyrmions in the strip. The average skyrmion diameter is found to be $d_{\text{sk}} = 135(3) \text{ nm}$, see Sec. SIII of the SM for details [24]. The scan that is shown in Fig. 3(b) depicts the magnetization state when an intermediate current density is applied. Here, skyrmions only appear on the right side of the strip and wormlike domains fill the left half of the strip.² Since the direction of the current flow is top-to-bottom (along negative y), the Oersted field generated by the current pulse is parallel to the bias field in the right half of the stack. This increase in field strength decreases the stability of the antiparallel dark

gray domains, resulting in skyrmion nucleation only on this side of the device. If the polarity of the current is reversed the skyrmions are observed to nucleate on the other side of the strip, because the Oersted field changes sign.

We also repeated the nucleation experiment for a device fabricated from the reduced stack, with the same bias field applied. In Figs. 3(g)–3(i), we show three MFM scans that were taken on a device fabricated from the reduced stack for zero current, an intermediate current ($J = 6.97 \times 10^{11} \text{ A m}^{-2}$) and a current above the nucleation threshold ($J = 7.55 \times 10^{11} \text{ A m}^{-2}$), respectively. The density of skyrmions in the device after the nucleation pulse is applied is much lower compared to the devices fabricated from the enhanced stack, with only a few isolated skyrmions present in the strip after nucleation. For the scans above the threshold current we can determine the average skyrmion diameter and find $d_{\text{sk}} = 184(7) \text{ nm}$, slightly larger than in the case of the enhanced stack. A lower effective DMI is expected to decrease the skyrmion size [8], because the domain-wall energy density

²The orientation of these wormlike domains is perpendicular to the current flow. This has been observed before and a phenomenological explanation can be found in Ref. [23].

increases, which is not observed. We hypothesize that, in the case of the enhanced stack, the high skyrmion density in combination with the narrow strip prevents the skyrmions from expanding to the radius expected for isolated skyrmions.

We used the same skyrmion counting procedure that was used in Ref. [21] to determine the number of skyrmions in the device for both the enhanced and reduced stacks. To facilitate the comparison with the laser-induced skyrmion nucleation later, we convert the number of skyrmions into the skyrmion density by dividing by the strip area: $7 \times 1.6 \mu\text{m}^2$. In Fig. 3(m), we plot the skyrmion density ρ_{Sk} as a function of the applied current density, the solid lines are fits to the data using the following, Eq. [21]:

$$\rho_{\text{Sk}} = \frac{1}{2} \rho_{\text{Sk,sat}} \left[1 + \text{erf} \left(\frac{J - J_c}{\sqrt{2} \sigma} \right) \right], \quad (2)$$

where J_c is the threshold current density and σ the width of the transition region. The maximum skyrmion density that is reached is $\rho_{\text{Sk,sat}}^{\text{Enh}} = 10.6(1) \mu^{-1} \text{m}^2$ and $\rho_{\text{Sk,sat}}^{\text{Red}} = 0.52(1) \mu^{-1} \text{m}^2$ for the enhanced and reduced stacks, respectively. Hence, the number of skyrmions after nucleation in the enhanced stack is greater by a factor of 20 compared to the reduced stack. Because the measured saturation magnetization and uniaxial anisotropy of both stacks are the same within our experimental uncertainty, and the difference in resistance is only 3%,³ we attribute this difference in skyrmion density to the dipolar enhancement and reduction of the effective DMI of our multilayer stacks.

Surprisingly, considering the results presented in Ref. [21], there is almost no difference in the threshold current that we observe for the two stacks. We find $J_c = (7.09 \pm 0.01) \times 10^{11} \text{ A m}^{-2}$ and $J_c = (6.90 \pm 0.02) \times 10^{11} \text{ A m}^{-2}$ for the enhanced and reduced stacks, respectively. Hence, the skyrmion density appears to be much more sensitive to the increase and decrease in effective DMI than the threshold current. Before we discuss these results further, we will present the results from the laser-induced skyrmion nucleation in the same two material stacks.

C. Laser-induced skyrmion nucleation

MFM images obtained after laser-induced nucleation as a function of fluence for both samples are shown in Figs. 3(g) through 3(l). Additionally, we plot the skyrmion density as a function of fluence in Fig. 3(n). The nucleation of a skyrmion with a laser pulse shows a threshold behavior as a function of fluence, qualitatively similar to the current-driven nucleation experiment. Far below the threshold, the sample continues to have the labyrinth domain state after the laser pulse has hit the sample. The threshold fluences for both samples are found to be $F_c = 9.0(2) \text{ mJ cm}^{-2}$ and $F_c = 10.7(2) \text{ mJ cm}^{-2}$. Note, that the first skyrmions appear at approximately the same fluence in both samples—similar to the current-driven nucleation—and that the higher threshold fluence in the enhanced stack is

the result of an increase in the relative width of the transition region between the labyrinth and skyrmion states.⁴ Around the threshold fluence an intermediate region exists for both samples [see Figs. 3(h) and 3(k)]. Here, the state can be characterized by the growth of the skyrmion density in the fluence range from approximately 9 to 12 mJ cm^{-2} [see Fig. 3(n)]. The appearance of different magnetic textures happens in the intermediate region: bubbles with a light core (parallel to the bias field), worm domains, skyrmionium-like structures, and skyrmions with a black core (antiparallel to the bias field).

After the intermediate region, the skyrmion phase appears, characterized by a saturation of the skyrmion density [Fig. 3(n)]. Only one type of magnetic texture is present in the samples in this region: skyrmions with a dark core in a light background, i.e., the magnetization in the core is antiparallel to the bias field. By comparing the magnetization state in Figs. 3(i) and 3(l) and the two datasets in Fig. 3(n), it is clear that the enhancement of the DMI leads to an increase in skyrmion density in the whole fluence range. The skyrmion density in the saturation region in the enhanced sample is four times higher than in the reduced sample, which correlates with the difference in the effective DMI for both samples.

D. Bias field dependence

Finally, we examined the dependence of the number of skyrmions after nucleation on the bias field that is applied during nucleation, for both nucleation methods and stack types. In Fig. 4, we plot this data for the current-driven and laser-induced skyrmion nucleation experiments. For the current density we used the maximum current density that could be reached with our pulse generator, the laser fluence in Fig. 4(b) however, is slightly lower than the maximum fluence used in Fig. 3.

At low bias fields the magnetization in all stacks consists mostly of wormlike domains with an occasional skyrmion. As the field increases, the proportion of skyrmions increases until a maximum is reached. For even greater fields, the device contains only skyrmions after nucleation but the number of skyrmions decreases as the field goes up since the skyrmions become less stable at higher fields [8]. The bias field at which the maximum number of skyrmions is found is greater for the enhanced stack than the reduced stack, for both nucleation methods.⁵ Additionally, we find that the skyrmion density is greater in the enhanced stack than in the reduced stack for all bias fields. Taken together, these observations show that

³Using a 2-wire geometry, the resistance of the devices fabricated from the enhanced and reduced stacks are measured to be $R_{\text{Enh}} = 168.2 \Omega$ and $R_{\text{Red}} = 173.3 \Omega$, respectively.

⁴To achieve a good signal-to-noise ratio the bias field had to be switched off during the MFM scans, i.e., after nucleation. This could have affected the relative width of the transition region for the laser-induced nucleation experiment if some of the nucleated skyrmions expand back into wormlike domains at zero field.

⁵We note that the optimal bias fields are higher in the case of the laser-driven nucleation, even though the ratio between the optimal bias field for the enhanced and reduced stack is the same for both nucleation methods. We suspect that this is most likely the result of the fluence being closer to the threshold fluence for nucleation, but cannot rule out a small calibration error in one, or both, of the experiments.

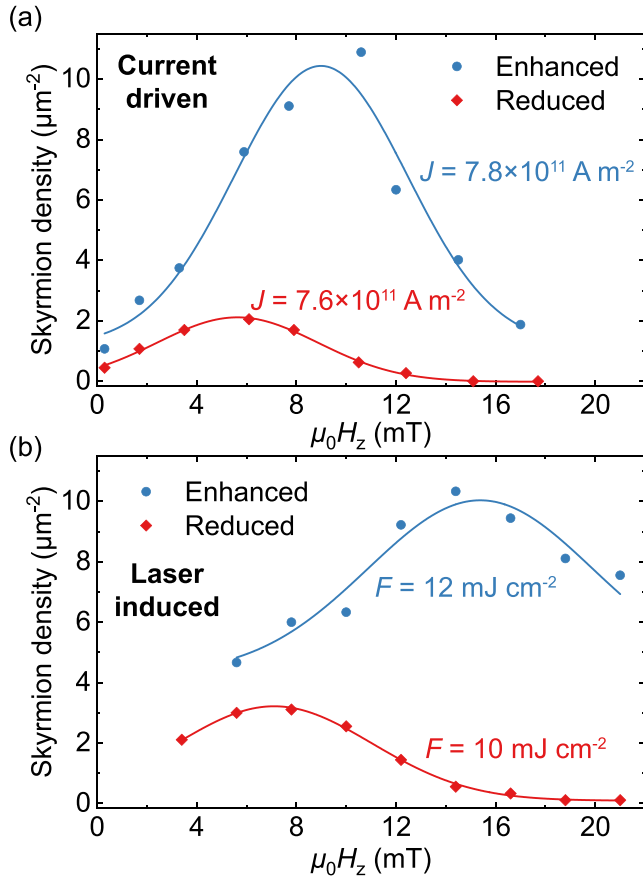


FIG. 4. Dependence of the number of skyrmions after nucleation on the strength of the bias field applied during nucleation. (a) Current-induced nucleation (b) laser-induced nucleation. The lines are a guide to the eye.

skyrmions are more stable in the enhanced stack compared to the reduced stack. We attribute this increase in stability to the increase in the effective DMI due to the dipolar field.

Finally, in Supplemental Material SIV [24], we show some preliminary measurements that indicate that the spin-orbit torque (SOT) can still drive domain walls and skyrmions in the enhanced stack, even though the stacking order is inverted in half of the stack. This is expected, since the Pt layer—which is likely the primary contributor to the SOT [30]—is moved from the bottom to the top of the Co layer by this inversion, both the SOT and the chirality of the domain walls change sign. Hence, the direction of motion of any chiral magnetic texture in the Co should remain the same. Nevertheless, it would be interesting to study how the SOT-driven motion of domain walls and skyrmions is affected by the inversion of the stacking order in half the stack, but this falls outside the scope of this work.

IV. DISCUSSION AND CONCLUSION

We discuss our results in the context of thermally activated skyrmion nucleation models that have been applied to both current-driven and laser-driven excitation [22,23,31,32]. In

these approaches, atomistic spin-dynamics simulations [33] describe a single magnetic layer with short-range exchange and DMI and an out-of-plane anisotropy. Upon heating above $\sim 0.5 T/T_c$ in an out-of-plane field, the system enters a topological fluctuating regime in which topological charges appear and annihilate on pico- to nanosecond timescales [23,31]. During subsequent cooling, a fraction of these excitations becomes trapped, yielding skyrmions whose final density depends on field [32], magnetic parameters (e.g., anisotropy [22] and DMI), and likely the cooling rate.

Two ingredients central to our multilayers are typically absent from such simulations because of computational cost: the multilayer nature and long-range dipolar interactions. Without interlayer dipolar coupling, the dipolar enhancement or reduction of the effective DMI does not occur.

We conjecture that in the high-temperature fluctuating regime, the two stacks should behave similarly because the layer composition is identical and the reduction of M_s at elevated temperature [31] is expected to weaken interlayer coupling. During cooling, however, dipolar coupling is reinstated and the effective DMI in the enhanced and reduced stacks diverges, primarily affecting skyrmion stability and survival rather than the onset of nucleation. This is consistent with our observation of comparable nucleation thresholds but different post-excitation skyrmion densities, and it naturally explains why current-driven and laser-driven nucleation show the same qualitative contrast between stacks: although the excitation durations differ strongly (50 ns vs 70 fs), the relevant cooling dynamics may be much less different. However, static imaging alone, as employed in this work, cannot resolve such time-dependent dynamics and follow-up work might look into time-resolved methods (e.g., as in this recent work [34]).

To conclude, we engineered Ir/Co/Pt multilayers with a layer-dependent DMI sign by reversing the trilayer stacking order in one half of the stack. This design aligns (or anti-aligns) the interfacial-DMI effective field with the in-plane component of the dipolar field, producing an effective DMI in the enhanced stack that is 2.5 times larger than in the reduced stack while keeping M_s and uniaxial anisotropy comparable. In skyrmion nucleation devices, both nanosecond current pulses and femtosecond laser pulses yield systematically higher post-excitation skyrmion densities in the enhanced stack, whereas the threshold current density and threshold fluence are found to be similar.

Taken together, these results indicate that a dipolar-field-modified effective DMI, created by choosing the right stacking order for the heavy metal and magnetic layers, is an effective tool to facilitate both current-driven and laser-induced skyrmion nucleation in magnetic multilayers.

A possible next step is to probe the proposed sequence directly with time-resolved measurements [34], ideally for laser-driven nucleation to avoid additional spin-orbit-torque contributions from the spin Hall effect in Pt and Ir [35]. Pump-probe magneto-optical Kerr experiments and reciprocal-space probes such as small-angle x-ray scattering [31,34] could potentially establish when the dipolar-field-induced modification of the effective DMI becomes operative. On the theory side, extending atomistic spin-dynamics descriptions to multilayers with long-range dipolar interactions and layer-resolved DMI

would provide a quantitative framework for interpreting such data.

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DATA AVAILABILITY

The data that support the findings of this article are available upon reasonable request.

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