

Tuning the angular dependence of the switching field of thin film nanomagnets

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Thin film nanomagnets show promise for a wide range of applications, such as in computing, data storage, sensors, and biomedical devices. Elongated single-domain nanomagnets are bistable, with the magnetization of its two stable states pointing in opposite directions along its long axis. We can switch the magnetization between the bistable states of the nanomagnet by applying an external field. Here, we investigate the switching characteristics of single-domain nanomagnets of different shapes, sizes, and aspect ratios, both in simulation and in experiment. We use a phenomenological approach to describe the angle dependence of the field required to switch the nanomagnets from one bistable state to the other. Our simulations and experimental results correspond well, and show that precise tuning of the angular switching characteristics is possible in a number of different ways. Such tuning of switching characteristics on a single-magnet level unlocks intriguing possibilities in nanomagnet device design, and could further pave the way for a variety of new nanomagnet-based technologies.

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I. INTRODUCTION

Nanomagnets are used as building blocks in a wide range of applications, ranging from data storage, biomedical applications, and magnetic sensors to emerging, low-power spintronic devices. The magnetic properties, and particularly the coercive field, of thin film nanomagnets are heavily dependent on their geometrical shape. Several studies have successfully tailored the geometrical shape and size of thin film nanomagnets to change their coercive fields [1–12], both in simulations and experimentally. Most of these are limited to investigating the switching fields of the nanomagnets at one or at most a few angles of the applied external field. However, Cimpoesu *et al.* [9] and Li *et al.* [11] both show in simulation that the switching field of the nanomagnet is also highly dependent on the angle at which the external field is applied. Although there are experimental studies of the angular switching characteristics of a wide variety of magnetic systems, such as magnetic tunnel junctions [13,14] and magnetic nanowires [15,16], nanotubes [17] and nanoparticles [18], experimental evidence of the effects of shape and size on the angular switching characteristics of thin film nanomagnets is scarce.

Nanomagnetic systems, such as artificial spin ice (ASI), typically contain multiple nanomagnet orientations. In such systems, the angular dependence of the switching field has been exploited to switch only a subset of the nanomagnets in the system using a single, global magnetic field [19,20].

Selective switching of nanomagnets has opened up for a wide range of applications, such as for controlling nanomagnetic micromachines [21,22], controlling spin-wave channels in reconfigurable magnonic crystals [23], the nanomagnetic shift register [24], and controlling domain states in pinwheel artificial spin ice [25,26]. Ultimately, precisely tailoring the switching characteristics of individual nanomagnets opens for further development of novel nanomagnetic devices.

The Stoner-Wohlfarth model [27] is an analytical model for the switching of a single-domain, ellipsoidal nanoparticle in an external magnetic field. The model assumes that the switching mechanism of the nanoparticle is coherent rotation. An important result of this model is the Stoner-Wohlfarth astroid, which shows the switching field of the nanoparticle for all angles of the external magnetic field with respect to the ellipsoids easy axis. Although the Stoner-Wohlfarth astroid is derived for an ellipsoidal nanoparticle, it is also valid in the case of a thin film elliptical nanomagnet, where the magnetization is constrained to the plane [28]. In the Stoner-Wohlfarth model, the astroid has a fourfold rotational symmetry, meaning that the field strength needed to switch the nanomagnets magnetization from one state along its easy axis to the other, is the same for fields applied directly along its easy and hard axis. However, the fourfold symmetry of the Stoner-Wohlfarth astroid does not hold for thin film nanomagnets of any shape [9,11,29]. Jensen *et al.* [29] introduce a generalized switching astroid, given by

$$\left(\frac{h_{\parallel}}{bh_k}\right)^{2/\gamma} + \left(\frac{h_{\perp}}{ch_k}\right)^{2/\beta} = 1 \quad (1)$$

which can capture asymmetric switching characteristics. $h_{\parallel}$ and $h_{\perp}$ are the parallel and perpendicular components of the external field with respect to the easy axis of the nanomagnet, while h_k is the anisotropy field of the nanomagnet, defined as the field at which the magnetization of the nanomagnet

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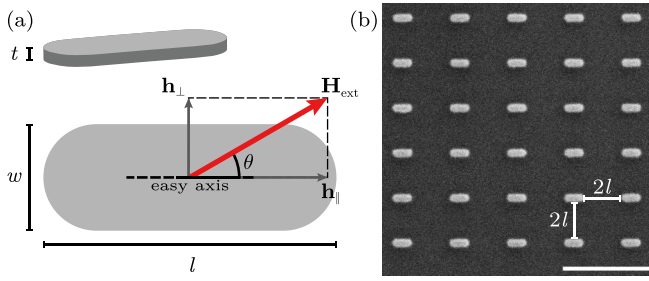


FIG. 1. (a) A stadium-shaped nanomagnet defined by its length (l), width (w), and thickness (t). In-plane, external magnetic fields $\mathbf{H}_{\text{ext}}$ are applied at angles θ to the easy axis of the nanomagnet. (b) Scanning electron microscope image of an array of $220 \text{ nm} \times 80 \text{ nm}$ stadium-shaped nanomagnets, with a $2l = 440 \text{ nm}$ spacing in both the horizontal and vertical directions. The scale bar is $1 \mu\text{m}$.

is saturated along a hard axis. b , c , β , and γ define the shape of the astroid. The b and c parameters determine the switching fields of the nanomagnet along the easy and hard axis, which are given by bh_k and ch_k , respectively. β and γ determine the curvature of the astroid along the easy and hard axis, where, for example, a large β would result in a sharp easy axis apex. The analytical Stoner-Wohlfarth astroid is refound for $b = c = 1$ and $\beta = \gamma = 3$. Cimpoesu *et al.* [9] also generalizes the Stoner-Wohlfarth astroid, but uses only two free parameters (using $b = 1$ and $\beta = \gamma$). In this work, we will use the generalization of Jensen *et al.* [29]. Following the model of coherent rotation, where the hard axis switching field ch_k is equal to the anisotropy field h_k , we set $c = 1$.

In this work, we investigate the angular switching characteristics of nanomagnets both in simulation and in experiment. We use a phenomenological framework, based on the generalized switching astroid, to quantify variations in the switching characteristics of the nanomagnets when varying their shape, thickness, size, and aspect ratio. This phenomenological framework can be used to predict changes in switching characteristics of nanomagnets, and can thus be used in the design of novel nanomagnetic devices.

II. EXPERIMENTAL SET UP AND SIMULATIONS

We investigate arrays of elliptical, rectangular and stadium-shaped [Fig. 1(a)] thin film nanomagnets of varying lengths (l), widths (w), and thicknesses (t). The nanomagnets are placed on a rectangular lattice, where the spacing between each magnet (end to end) is $2l$ in both the horizontal and vertical directions, as shown in Fig. 1(b). The $2l$ spacing (end to end) is chosen to avoid significant interactions between neighboring nanomagnets while maintaining satisfactory signal strength in magneto-optic Kerr effect (MOKE) microscopy imaging. All nanomagnets are oriented with their long axis along the horizontal direction. The arrays consist of varying numbers of magnets (from around 1600 to 7500, depending on the length l of the nanomagnets and the spacing $2l$ between them), designed so that they fill an area of $50 \mu\text{m} \times 50 \mu\text{m}$.

The arrays are fabricated using electron beam lithography and lift off. Three different thicknesses (5 nm, 10 nm, and 20 nm) of permalloy ($\text{Ni}_{81}\text{Fe}_{19}$) are deposited using e-beam

evaporation. To prevent oxidation of the magnetic material, we add a 2 nm Al capping layer on all samples.

The magnetic arrays are subjected to external magnetic fields, $\mathbf{H}_{\text{ext}}$, of increasing magnitude, applied in plane and at an angle θ with respect to the easy axis of the nanomagnets. When all nanomagnets have switched from one stable state to the other, we repeat this procedure for the reverse direction. We perform such measurements for $\theta = 0, \pm 15^\circ, \pm 30^\circ, \pm 45^\circ, \pm 60^\circ, \pm 75^\circ$, and $\pm 87^\circ$. After every 0.5 mT increase of the external field, the array is imaged using MOKE microscopy. All our fabricated nanomagnets are subject to fabrication defects, causing a spread in their switching fields. We therefore calculate the average switching field of all nanomagnets in the array from the intensity of the MOKE images. Images are acquired in oil immersion, with MOKE sensitivity along the easy axis of the nanomagnets.

We simulate the switching characteristics of nanomagnets of different shapes, aspect ratios, thicknesses and sizes using mumax³ [30]. In all simulations, we use material parameters commonly used for permalloy: saturation magnetization $M_{\text{sat}} = 860 \times 10^3 \text{ Am}^{-1}$, exchange stiffness $A_{\text{ex}} = 1.2 \times 10^{-11} \text{ Jm}^{-1}$, no magnetocrystalline anisotropy [11,30], and a damping constant $\alpha = 0.01$ [31]. We apply an in-plane magnetic field at an angle θ to the easy axis of the nanomagnet for at least 2.5 ns before increasing the magnitude of the magnetic field. The field increases in steps no larger than 0.3 mT, until the nanomagnet switches. Simulations are repeated for angles θ between 0 and 89° . To avoid numerical errors in our simulations, we consistently use an angle close to the easy axis (e.g., $\theta = 0.1$ or 0.5) instead of $\theta = 0$. In the simulated astroids in this work, the switching fields from simulations between 0 and 89° are transformed to the other quadrants to produce a full picture of the switching astroid.

The simulated anisotropy field h_k is determined by a linear regression from the switching fields for fields applied at $\theta = 87^\circ$ and 89° . We normalize the switching fields for all angles using h_k . c is restricted to 1, and the rest of the switching astroid parameters are determined by fitting Eq. (1) to the normalized switching fields. We determine the experimental h_k by fitting Eq. (1) with the simulated astroid parameters to the experimental switching fields. See the Supplemental Material [32] for details.

III. SHAPE DEPENDENCE

We first investigate rectangular, elliptical, and stadium-shaped nanomagnets, all with width $w = 80 \text{ nm}$, length $l = 220 \text{ nm}$, and thickness $t = 10 \text{ nm}$. The experimental and simulated angular switching characteristics, represented by switching astroids, are shown in Figs. 2(a) and 2(b). The switching astroids are normalized with respect to their calculated anisotropy fields, h_k , which are plotted in Fig. 2(c). For all three nanomagnet shapes, the shape of the simulated switching astroid closely resembles the corresponding experimental switching astroid. This suggests that effects such as interactions between nanomagnets and disorder in the switching fields of the nanomagnets are negligible.

The calculated anisotropy fields are larger in simulation than in experiment for all three shapes. This suggests that the demagnetization fields of the nanomagnets are smaller in

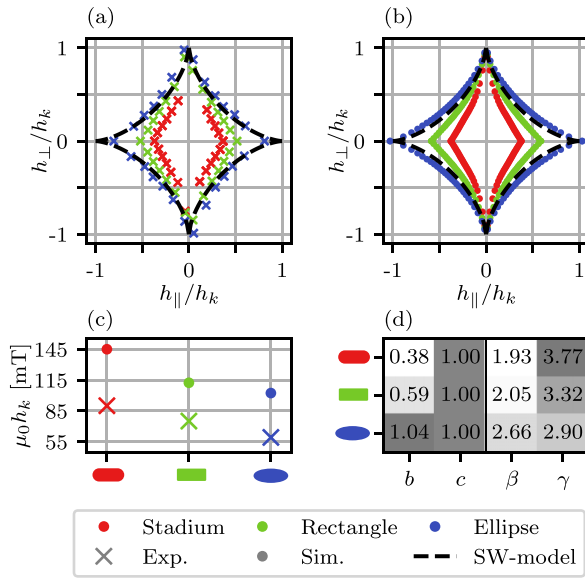


FIG. 2. (a) Experimental and (b) simulated switching astroids for stadium-shaped, rectangular, and elliptical thin film nanomagnets, all with $w = 80$ nm, $l = 220$ nm, and $t = 10$ nm. The analytical Stoner-Wohlfarth astroid is shown for reference. The components of the switching fields in (a) and (b) are normalized with respect to the anisotropy fields h_k , shown in (c). (d) The astroid parameters of the simulated switching astroids.

experiment than in simulation, possibly due to a lower saturation magnetization M_{sat} in our experimental samples than in the simulated nanomagnets. Effects such as oxidation could result in a lower effective M_{sat} and a lower demagnetization field of the experimental nanomagnets compared to the simulated nanomagnets. Surface roughness and other fabrication defects could also cause the demagnetization field of the experimental nanomagnets to be smaller than for the perfect, simulated nanomagnets.

The shape of both the experimental and simulated switching astroid of the elliptical nanomagnet (blue in Fig. 2) is similar, but not identical, to the analytical Stoner-Wohlfarth astroid (black dashed line). We capture the discrepancy between the simulated astroid and the Stoner-Wohlfarth astroid by finding the parameters of Eq. (1) which best fit the simulated astroid, shown in Fig. 2(d). In contrast to the Stoner-Wohlfarth parameters, we find that $\beta \neq \gamma$ and $\beta, \gamma < 3$. This corresponds well to the simulated switching astroid being less sharp around its apexes compared to the analytical switching astroid, as seen in Fig. 2(b). Surprisingly, the fit of the astroid parameters also results in $b = 1.04 > c$. We attribute this to a slight overestimation of the anisotropy field h_k , as the linear approximation (see the Supplemental Material [32]) can not capture the curvature close to the hard axis apex in this switching astroid.

The switching astroids of the rectangular and stadium-shaped nanomagnets are clearly different from both the analytical Stoner-Wohlfarth astroid and the simulated and experimental switching astroid of the ellipse. The rectangular and stadium-shaped nanomagnets are no longer close to having a fourfold rotational symmetry in their switching characteristics, as the switching field along their easy axis is much

lower than along the hard axis. This effect is captured by the b values (0.59 and 0.38) of the rectangular and stadium-shaped switching astroid being significantly smaller than $c = 1$. Asymmetric switching characteristics have been previously reported for simulated stadium-shaped nanomagnets [9,11,29] and experimentally for rectangular nanomagnets [13].

Surprisingly, the switching astroid of the stadium-shaped nanomagnet has the lowest b . Geometrically, the stadium shape has a mix of the smooth edges of the ellipse and the straight edges of the rectangle. Thus, only considering the shape of the nanomagnet, one might expect the switching astroid of the stadium-shaped magnet to lie in between those of the elliptical and rectangular nanomagnets.

Figure 3 shows simulated magnetization maps of the stadium-shaped, rectangular, and elliptical nanomagnets in the presence of a magnetic field applied at $\theta = 0.1^\circ$. Figures 3(a)–3(c) show simulated magnetization maps at low applied fields ($\mu_0 H_{\text{ext}} = 5.2$ mT $\ll b h_k$), with insets (i) and (ii) showing the x and y components of the magnetization, respectively. In the presence of small external fields, both the stadium-shaped and elliptical nanomagnets have relatively uniform magnetization, except for some canting along the edges. This is, however, not the case for the rectangular nanomagnet, where its sharp corners cause the magnetization to become nonuniform. Along the short edges of the rectangular nanomagnet, the magnetization cants away from the easy axis of the nanomagnet. This is clearly seen in inset (ii) of Fig. 3(b).

Figures 3(d)–3(f) show simulated magnetization maps of the nanomagnets at $\theta = 0.1^\circ$ and $\mu_0 H_{\text{ext}} = 54.7$ mT. This is the largest field magnitude at which none of the three nanomagnets have switched. While the elliptical nanomagnet maintains a close to uniform magnetization, both the stadium-shaped and rectangular nanomagnets show significant canting of the magnetization close to the edges. In the rectangular nanomagnet, the magnetization cants to align with the straight short edge of the rectangle. Surprisingly, the canting occurs to an even larger extent in the stadium-shaped nanomagnet, where the magnetization seems to curl along the curved edge of the stadium. In certain areas along the curved edge, the x component of the magnetization even points in the opposite direction from the magnetization in the central area of the nanomagnet, as seen in inset (i) of Fig. 3(d).

Simulated magnetization maps for external fields $\mu_0 H_{\text{ext}} = 97.0$ mT applied at 89° , close to the hard axis of the nanomagnets, are shown in Figs. 3(g)–3(i). For fields applied at 89° , $\mu_0 H_{\text{ext}} = 97.0$ mT is the highest field magnitude at which none of the three nanomagnets have switched. At this field, the magnetization of all three shapes is more uniform compared to when the field is applied close to the easy axes of the nanomagnets. However, the magnetization of the ellipse shows some canting close to its ends, seen clearly in inset (i) of Fig. 3(i), as the magnetization follows the curved edges of the ellipse. The small canting observed in the ellipse in fields applied at 89° is larger, but reminiscent of the canting observed at 0.1° , as seen from the similarities of inset (ii) in Fig. 3(f) and inset (i) in Fig. 3(i). Surprisingly, at 89° , canting is more present in the rectangular nanomagnet than the stadium-shaped nanomagnet, even though the stadium-shaped nanomagnet also has curved ends. Contrary to the ellipse, it seems as though in the rectangular nanomagnet, the sharp

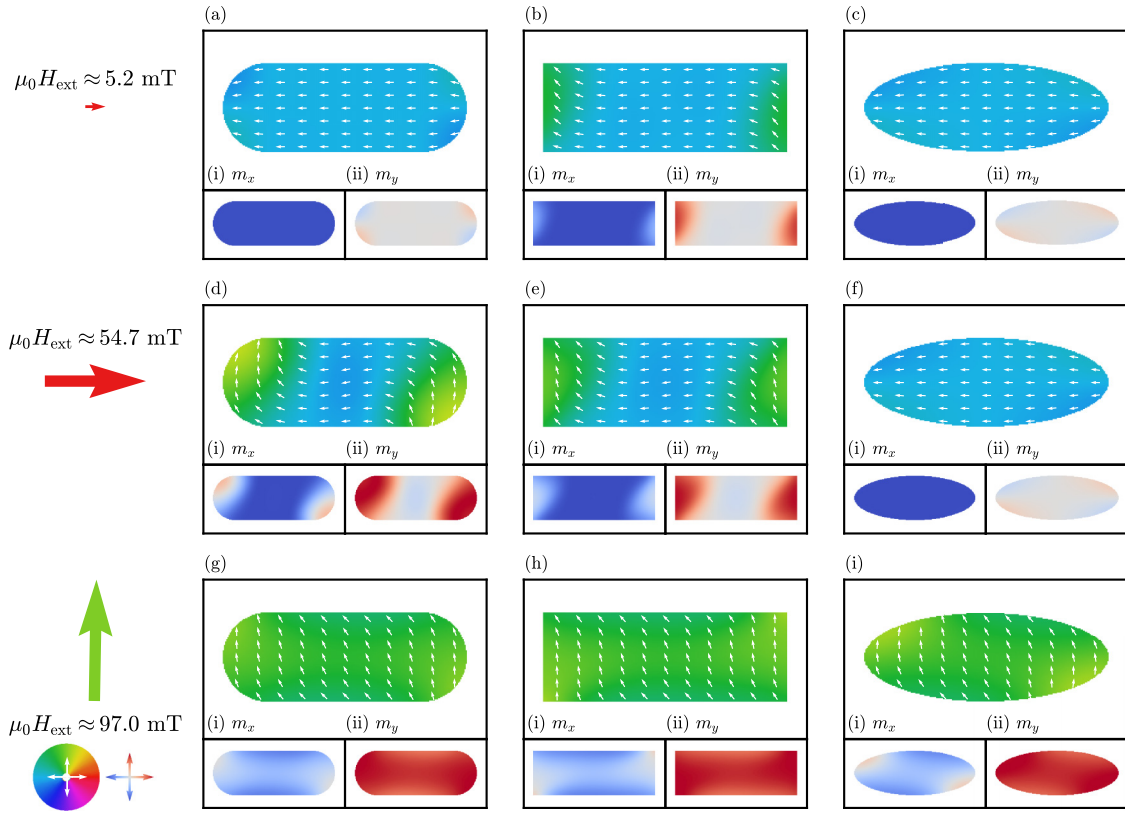


FIG. 3. Snapshots of simulated magnetization in an external field (a)–(c) $\mu_0 H_{\text{ext}} = 5.2$ mT, (d)–(f) $\mu_0 H_{\text{ext}} = 54.7$ mT applied at 0.1° . (g)–(i) show snapshots of the simulated magnetization in an external field $\mu_0 H_{\text{ext}} = 97.0$ mT applied at 89° . The insets (i) and (ii) for all states show the x and y components of the magnetic states, respectively.

corners result in nonuniformities in the magnetization close to the nanomagnet ends.

For the stadium-shaped and rectangular nanomagnets, we observe more canting of the magnetization at $\theta = 0.1^\circ$ than $\theta = 89^\circ$. These two shapes also have asymmetrical astroids, where $b < c$. This suggests that the nanomagnet switches at lower applied fields when substantial magnetization canting is present. This further explains the easy axis switching field of the rectangular nanomagnet being between that of the stadium-shaped and that of the elliptical nanomagnets, i.e., the magnetization of the stadium-shaped nanomagnet cants more than the magnetization of the rectangular nanomagnet at high fields, and thus switches at a lower external field.

We also find that the anisotropy fields h_k are largest for the stadium-shaped nanomagnet and smallest for the elliptical nanomagnet in both simulations and in experiment, as seen in Fig. 2(c). Once again, this can be explained by canting in the magnetization states for fields applied at 89° . For example, as most canting is observed in the elliptical nanomagnets, the switching field (at $\theta = 89^\circ$) is lowest for these nanomagnets, resulting in the lowest h_k .

The nonuniformity of the magnetization at large fields applied at $\theta = 0$ also shows that the switching mechanism in the stadium-shaped and rectangular nanomagnets is not coherent rotation for all θ . Although coherent rotation is the underlying assumption of the analytical Stoner-Wohlfarth model, using a phenomenological switching astroid to describe the angular

switching characteristics is still useful when more complex switching is dominant.

IV. THICKNESS AND SIZE DEPENDENCE

We next simulate and experimentally verify switching astroids for stadium-shaped nanomagnets of varying thickness, i.e., $t = 5$ nm, 10 nm, and 20 nm. The nanomagnets all have lengths $l = 220$ nm and widths $w = 80$ nm. The experimental and simulated switching astroids are shown in Figs. 4(a) and 4(b). Once again, the simulated switching astroids are similar to their experimental counterparts, for all three thicknesses. The anisotropy fields h_k for both experimental and simulated stadium nanomagnets of varying thickness are shown in Fig. 4(c), and the generalized Stoner-Wohlfarth astroid parameters found from the simulated astroids are given in Fig. 4(d).

Figure 4(c) shows a clear increase in h_k with thickness in both simulation and experiment. In nanomagnets which switch by coherent rotation, we do not expect h_k to change with thickness (or volume). The variation in h_k could suggest that the switching mechanism changes with the thickness of the nanomagnets, and that the thinner nanomagnets deviate more from coherent rotation. Compared to when varying the shape of the nanomagnets, the observed changes in h_k with thickness are significantly larger. As the switching astroids of the nanomagnets largely maintain their shape when the nanomagnet thickness is increased, the increase in h_k results in increased switching fields for all angles of the applied

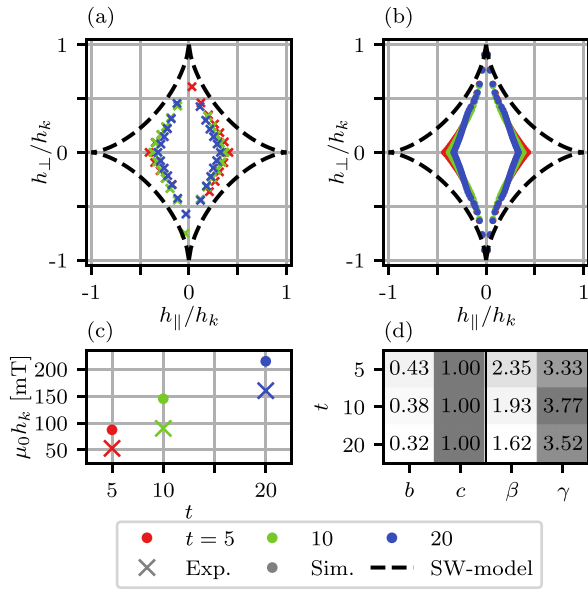


FIG. 4. (a) Experimental and (b) simulated switching astroids for stadium-shaped thin film nanomagnets of thicknesses $t = 5, 10$, and 20 nm. All nanomagnets have $l = 220$ nm and $w = 80$ nm. The analytical Stoner-Wohlfarth astroid is shown for reference. The components of the switching fields in (a) and (b) are normalized with respect to the anisotropy fields h_k , shown in (c). (d) The astroid parameters of the simulated switching astroids.

field, which is consistent with previous experimental [33] and simulated [11] results. Consequently, varying nanomagnet thickness is an effective way of modifying the switching fields of nanomagnets.

The normalized simulated switching astroids, shown in Fig. 4(b), are quite similar for $\theta > 30^\circ$ for all simulated thicknesses. However, the switching field when the external field is applied closer to the easy axis, is relatively larger for thinner nanomagnets, resulting in an increasing b for decreasing t . This also results in a sharper easy axis apex of the switching astroid compared to the thicker nanomagnets, captured by the increase in β with decreasing t . We attribute the variation of the normalized switching fields around the easy axis to canting in the magnetization at fields close to switching. In particular, in external fields applied close to the easy axis, the 20 nm nanomagnet exhibits a larger degree of canting in its magnetization than the 5 nm nanomagnet at field magnitudes close to the switching fields of the respective nanomagnets. Thus, this could explain that the switching field for angles applied close to the easy axis is relatively smaller for thicker magnets, when compared to the switching fields for larger angles θ . We emphasize that this effect is prevalent in the normalized switching astroids, and that the 20 nm nanomagnet still has larger switching fields for fields applied at all angles. This effect does, however, make the difference in the switching fields close to the easy axis smaller, as the switching fields of the nanomagnet which is hardest to switch is lowered for fields applied at angles close to 0 .

The simulated switching fields of the 20 nm nanomagnet increase slightly at around 60° . In Fig. 4(b), this increase results in a small bump in the switching astroid. We are not

able to capture this bump with the generalized switching astroid [Eq. (1)]. To accurately represent switching astroids with features such as this bump, it is clear that a more complex phenomenological model is required.

Next we investigate the switching characteristics of nanomagnets of varying lateral dimensions. Figures 5(a) and 5(b) show experimental and simulated switching astroids for stadium-shaped nanomagnets of three different sizes; S, M, and L-sized magnets have lateral dimensions $l \times w$ of 220 nm $\times$ 80 nm, 330 nm $\times$ 120 nm, and 470 nm $\times$ 170 nm, respectively. All nanomagnets have thickness $t = 10$ nm. The calculated anisotropy fields, h_k , and astroid parameters for these stadium-shaped nanomagnets are given in Figs. 5(c) and 5(d). Figures 5(e)–5(h) show experimental and simulated astroids, anisotropy fields, and astroid parameters for elliptical nanomagnets of varying size. The simulated astroids for both the stadium-shaped and elliptical nanomagnets correspond well to their respective experimental astroids. Once again, all stadium-shaped nanomagnets have asymmetric switching astroids, with $b < c$, while the elliptical nanomagnets are closer to the analytical Stoner-Wohlfarth astroid. However, we see that the L-sized elliptical nanomagnets also deviate significantly from the Stoner-Wohlfarth astroid.

The calculated anisotropy fields, h_k , are again larger in simulation than in experiment for both the elliptical and stadium-shaped nanomagnets. However, the calculated anisotropy fields for the two different nanomagnet shapes respond very differently to variations in the lateral dimensions of the nanomagnets. Varying the lateral dimensions of the stadium-shaped nanomagnets results in only a slight increase in h_k with size, as seen in Fig. 5(d). The shape of the astroids also change significantly with the size of the stadium-shaped nanomagnets. In particular, close to the hard axis apex, the astroids are sharper and thinner for larger nanomagnets. Since we determine h_k from a linear extrapolation based on simulated points close to the hard axis apex, we expect a small error in h_k which is more prevalent when the hard axis apex is less sharp. Thus, this error contributes to the slight increase in h_k with size in the stadium-shaped nanomagnets. This is the same error which causes the parameters of the elliptical nanomagnet to have $b > 1$, but it is likely present in many of the astroids.

Varying the lateral dimensions of the elliptical nanomagnets results in a large decrease in h_k with size, as shown in Fig. 5(g). As the astroid of the elliptical nanomagnets largely maintains its shape for varying lateral dimensions, this large decrease with size also applies to the easy axis switching field, bh_k . This behavior is consistent with previous experimental results of elliptical nanomagnets of varying size [1].

The stadium-shaped nanomagnets also exhibit a decrease in their easy axis switching field, bh_k , with increasing nanomagnet size, similar to the trend observed in bh_k for elliptical nanomagnets. For larger magnets, the b parameter decreases, resulting in a large change in the shape of the switching astroid with size. The variation in the easy axis switching field, bh_k , is therefore also large, even though there is only a slight increase in h_k . Interestingly, these results are consistent with experimental astroids of micron-sized, rectangular thin films in MTJs [14].

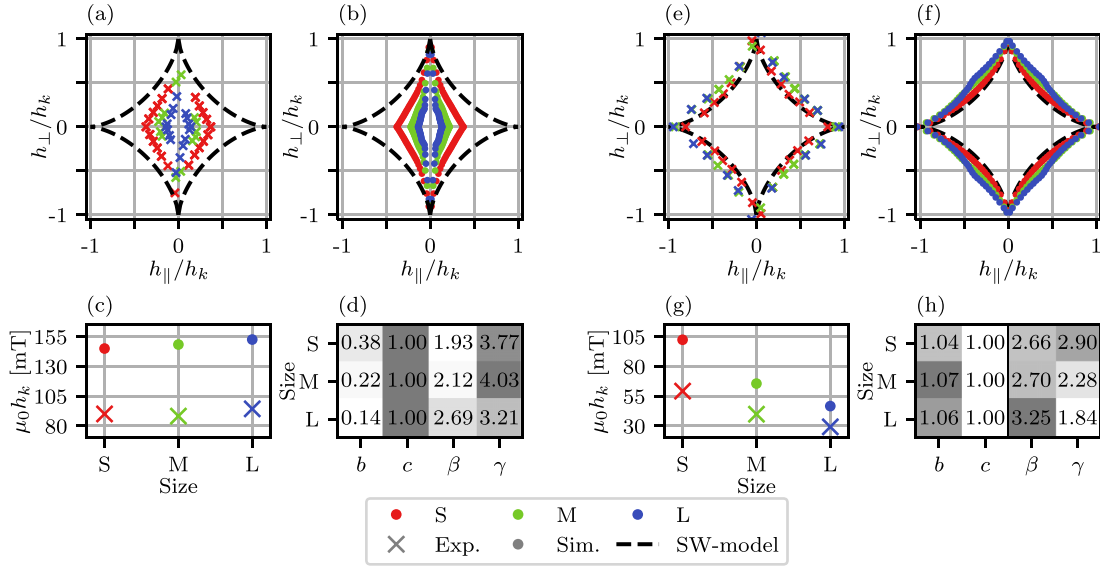


FIG. 5. (a) Experimental and (b) simulated switching astroids for stadium-shaped thin film nanomagnets of size S ($l = 220$ nm, $w = 80$ nm), M ($l = 330$ nm, $w = 120$ nm), and L ($l = 470$ nm, $w = 170$ nm). All nanomagnets have $t = 10$ nm. The analytical Stoner-Wohlfarth astroid is shown for reference. The components of the switching fields in (a) and (b) are normalized with respect to their corresponding anisotropy fields h_k , shown in (c). (d) The astroid parameters of the simulated switching astroids for the stadium-shaped/elliptical nanomagnets. (e)–(h) Experimental and simulated switching astroids, anisotropy fields, and astroid parameters for elliptical nanomagnets of size S, M, and L.

Similarly to the $t = 20$ nm stadium-shaped nanomagnet, the L-sized stadium-shaped nanomagnet also exhibits a bump in its switching astroid at around 60° . This time, the bump is accompanied by a dent at around 70° . Neither of these features can be captured by the generalized astroid [Eq. (1)], resulting once again in a too low γ parameter. From the simulated astroids in Fig. 5(b), we see that the L-sized nanomagnet clearly has a sharper hard axis apex than the two smaller nanomagnets, something which is not captured by its calculated γ parameter.

The bump at $\approx 60^\circ$ is also present in the L-sized elliptical nanomagnet and somewhat in the M-sized elliptical nanomagnet. In the case of the elliptical nanomagnets, the bump also seems to be present, although broader, in the corresponding experimental switching astroids. Generally, the bumps and dents seem to appear in the nanomagnets which exhibit clear nonuniformities in their magnetization before switching. This could suggest that features such as these indicate a switching mechanism which deviates considerably from coherent rotation. Although Eq. (1) cannot capture these features, a more complex phenomenological model could be able to describe more complex switching, in a way which could still be useful for nanomagnetic device design.

V. ASPECT RATIO DEPENDENCE

We also investigate arrays of stadium-shaped nanomagnets of different aspect ratios. Keeping the nanomagnet length and thickness fixed at $l = 220$ nm and $t = 10$ nm, we fabricate arrays of nanomagnets with widths $w = 70$ nm, 80 nm, 90 nm, and 100 nm. The resulting aspect ratios, l/w , are 3.14, 2.75, 2.44, and 2.20. We also simulate the angular switching characteristics of such nanomagnets. The experimental and simulated switching astroids are shown in Figs. 6(a) and 6(b).

The anisotropy fields are shown in Fig. 6(c). Once again, the shape of the experimental and simulated astroids are similar, and h_k is larger in simulation than in experiment.

The anisotropy field, h_k , increases with aspect ratio both in simulation and in experiment. Changing the aspect ratio by

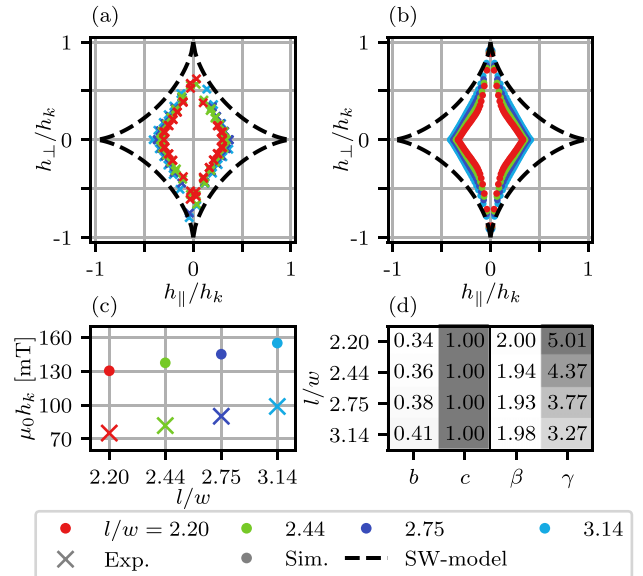


FIG. 6. (a) Experimental and (b) simulated switching astroids for stadium-shaped thin film nanomagnets of aspect ratios $l/w = 3.14, 2.75, 2.44$, and 2.20 . All nanomagnets have $l = 220$ nm and $t = 10$ nm. The analytical Stoner-Wohlfarth astroid is shown for reference. The components of the switching fields in (a) and (b) are normalized with respect to the anisotropy fields h_k , shown in (c). (d) The astroid parameters of the simulated switching astroids.

varying the width of the nanomagnet and keeping the length constant, as we have done here, also results in changes to the size of the nanomagnet. Specifically, increasing aspect ratio corresponds to decreasing the nanomagnet size. The observed trend in h_k is weaker, but reminiscent of the trend observed when changing the lateral dimensions of elliptical nanomagnets. The increase in h_k with aspect ratio can be explained by the increase in shape anisotropy in the nanomagnets with increased aspect ratio, which constrains the magnetization of the nanomagnets more tightly to their easy axis. Canting of the magnetization should thus be more prominent in the nanomagnets with lower aspect ratio, resulting in a decrease in their switching field. Interestingly, the nanomagnets with low aspect ratio show more prominent canting for applied fields at all simulated angles and thus have lower switching fields for all angles of applied field. This is in contrast to the trends observed when varying the size of the stadium-shaped nanomagnet (while keeping aspect ratio constant), where the hard axis switching field is greater for the largest nanomagnets.

Although more canting is observed in nanomagnets with lower aspect ratio for all angles of the external field, the amount of canting is dependent on the angle of the applied field. In other words, the aspect ratio of the nanomagnet clearly affects the angular dependence of the switching field of the nanomagnets. We note that the effect of aspect ratio on the angle dependence of the switching field does not come from the change in nanomagnet size, as it is also seen in nanomagnets with varying aspect ratio, but similar volumes. See the Supplemental Material [32] for details. We find that the largest difference in the switching fields of the nanomagnets with varying aspect ratios is at applied fields with θ between 45° and 75° . In Fig. 6(b), we see this clearly in the concave shape of the astroid of the nanomagnet with $l/w = 2.20$. This curve in the astroid further results in a sharp hard axis apex of the astroid and in an increased γ , which increases with decreasing aspect ratio.

For all aspect ratios, the magnetization is less uniform when the external field is applied close to the easy axis as compared to the hard axis. However, this difference in uniformity is larger for the low aspect ratio nanomagnets. As a result, the b value increases with increasing aspect ratio. The variation in b , in combination with the variation in h_k , results in a significant difference in the switching field of the nanomagnets when the field is applied along their easy axis (given by bh_k), in agreement with several previous simulation studies [11,18,34]. Adjusting the aspect ratio is thus an effective way to tune the easy axis switching field of nanomagnets and is widely used in the development of novel nanomagnetic applications [21,22].

We are able to capture the changes in the switching astroids of the nanomagnets of varying aspect ratio well using the

generalized switching astroid [Eq. (1)], even though we observe nonuniformities in the magnetization of the nanomagnets. Our results show clear trends in the parameters of the fitted astroids, and form the basis of a phenomenological model which could be used to predict the switching characteristics of stadium-shaped nanomagnets of other aspect ratios.

VI. CONCLUSION

We have investigated the switching characteristics of single-domain nanomagnets in the presence of an external magnetic field. In particular, we have explored how the field required to switch a bistable nanomagnet depends on the angle of the applied field. We use a phenomenological approach to quantify the angular dependence, and calculate switching astroids for a range of nanomagnets of varying shape, size, and aspect ratio. Our experimental results are verified using micromagnetic simulations. Despite the fact that the micromagnetic simulations generally overestimate the magnitude of the switching fields, we achieve a very good correspondence in the shape of the experimental and simulated switching astroids, for all investigated nanomagnets.

We find that by varying the shape, size, and aspect ratio, we can controllably change the angular dependence of the switching field. Although we here use external magnetic fields to switch the nanomagnet magnetization, similar angular switching characteristics have been reported for nanomagnet switching using spin-transfer torque [35], and field-switching of out-of-plane nanomagnets [36,37]. Thus, it may be possible to tune the switching characteristics of a variety of magnetic systems in a similar manner. Our results show that the effect on the switching astroid can be large by, for example, varying nanomagnet shape, or subtle, by varying nanomagnet thickness. We believe that our findings will be enabling in the design of novel nanomagnetic devices.

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DATA AVAILABILITY

The data that support the findings of this article are openly available [39].

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