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Magnus Induced Diode Effect for Skyrmions in Channels with Periodic Potentials

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Abstract. Using a particle based model, we investigate the skyrmion dynamical behavior in a channel where the upper wall contains divots of one depth and the lower wall contains divots of a different depth. Under an applied driving force, skyrmions in the channels move with a finite skyrmion Hall angle that deflects them toward the upper wall for $-x$ direction driving and the lower wall for $+x$ direction driving. When the upper divots have zero height, the skyrmions are deflected against the flat upper wall for $-x$ direction driving and the skyrmion velocity depends linearly on the drive. For $+x$ direction driving, the skyrmions are pushed against the lower divots and become trapped, giving reduced velocities and a nonlinear velocity-force response. When there are shallow divots on the upper wall and deep divots on the lower wall, skyrmions get trapped for both driving directions; however, due to the divot depth difference, skyrmions move more easily under $-x$ direction driving, and become strongly trapped for $+x$ direction driving. The preferred $-x$ direction motion produces what we call a Magnus diode effect since it vanishes in the limit of zero Magnus force, unlike the diode effects observed for asymmetric sawtooth potentials. We show that the transport curves can exhibit a series of jumps or dips, negative differential conductivity, and reentrant pinning due to collective trapping events. We also discuss how our results relate to recent continuum modeling on a similar skyrmion diode system.

1. Introduction

Diodes are crucial devices in modern electronics that can be used to control the electron flux. Electrical diodes permit easy current flow with small or zero resistance in one direction, and hinder the flow with a high or infinite resistance in the other direction [1]. This unidirectional diode flow has inspired investigations in several other branches of physics, including photonics [2, 3, 4, 5], heat-transfer dynamics [6, 7], fluidics [8, 9], and magnetism [10, 11, 12, 13, 14, 15, 16, 17, 18].

The basic unidirectional flow property of diodes can be implemented in several different ways depending on the physical system. For example, in electrical diodes, electrons may flow in one direction and not the other depending on the density of positive or negative charge carriers present in a semiconducting material. Analogously, for thermal diodes the heat has preferential directions of flow. For magnetic diodes that affect the flow of superconducting vortices or magnetic textures, the diode mechanism can be controlled by an external magnetic field, a driving current, or by using Hall effects. In the case of superconducting vortices, a diode effect can be produced with a combination of asymmetric pinning potentials and oscillating drives that cause the vortices to undergo ratcheting motion [19, 20, 21]. It was also shown that dc drives can produce diode effects since multiple vortices under the influence of constriction arrays can flow easily in one direction and clog in the other [22, 23]. More recently, increasing effort has focused on developing ways to control the motion of magnetic textures such as magnetic skyrmions, since their high stability and reduced size makes them ideal for use in novel technological devices.

Skyrmions are a topologically stable particle-like object composed of spins pointing in all directions wrapping a sphere [24, 25, 26]. They can be set in motion by the application of a spin polarized current that is larger than depinning threshold, similar to superconducting vortices [27, 28, 29, 30]. The main difference between skyrmions and other overdamped particles is that skyrmions exhibit strong gyroscopic effects, so there is a Magnus term in their equation of motion that results in the appearance of a skyrmion Hall effect [31, 32, 26]. The Magnus term produces a force that is perpendicular to the skyrmion velocity, and it has been suggested that this is the main cause of the low depinning thresholds observed for skyrmions. When skyrmions flow in a pure sample without defects, they move at an intrinsic angle, known as the intrinsic skyrmion Hall angle θ_{sk}^{int} , to the applied drive direction [31, 26, 33]. The magnitude of this angle depends on the ratio of the Magnus term to the damping term. Experimentally, skyrmion Hall angles have been observed that span the range from a few degrees up to very large angles, depending on the system parameters and the size of the skyrmions [33, 34, 35].

The theoretical idea of a skyrmion diode was recently proposed by Jung *et al.* [14], who used continuum-based simulations to demonstrate a skyrmion diode device exhibiting unidirectional skyrmion transport. The device is designed as a nanostrip with asymmetric edges, where there is a pinning site in one of the edges. The skyrmions experience different pinning potentials depending on the direction of the applied transport force, resulting in a diode effect. In another theoretical proposal for a skyrmion diode device, Feng *et al.* [15] consider a rectangular channel connected to a smaller strip. For driving applied in one direction, the skyrmion is trapped by the intrinsic skyrmion Hall angle in the smaller region, where it annihilates. If the drive is applied in the other direction, the skyrmion flows in a straight line following the edge of the sample without being annihilated. This creates a clear diode effect where there is absolutely no flow in one direction and ordinary flow in the other direction. These papers only treated the case of single skyrmion dynamics. Additional work on similar geometries for systems with modified edges describes the creation of NAND and NOR gates [36]. There is also an interesting proposal to create a skyrmion diode using spin waves

in the presence of a transverse magnetic field [13].

In this work we investigate the collective behavior of skyrmions under the influence of asymmetric potentials and dc drives. We conduct simulations of two types of channel geometries. The first geometry, labeled S1, is similar to that used by Feng *et al.* [15], where the top wall of the channel is featureless and the bottom wall contains divots that can trap skyrmions. The second geometry, labeled S2, has divots on both the upper and lower walls, but the divots on the upper wall are shallower than those on the bottom. Our results show that due to the asymmetry in the potentials, the skyrmions exhibit a preferred direction of motion, leading to a diode effect. In the high asymmetry S1 sample, for drives applied along the $+x$ direction, the intrinsic Hall angle causes the skyrmions to become trapped in the lower divots. On the other hand, when the drive is applied along the $-x$ direction, the intrinsic Hall angle pushes the skyrmions against the featureless wall, where they can travel with high velocities. For the lower asymmetry S2 sample, when the drive is applied along the $+x$ direction, the skyrmions become trapped in the deeper lower divots, and their motion is hindered. In contrast, for drives applied along the $-x$ direction, the skyrmions are brought into contact with the upper shallower divots, which do not impede the motion as much. Our work not only complements the results of the continuum based simulations, but also allows us to consider large assemblies of skyrmions in order to study collective effects and velocity-force curves more clearly. For example, we find that the velocity-force curves show not only diode effects but also negative differential conductivity where the magnitude of the velocity drops with increasing drive, as well as reentrant pinning where the system is strongly pinned at high drives but flows easily at low drives.

We emphasize that the geometry we consider is distinct from the asymmetric potentials such as sawtooth shapes used to create ratchet effects. In those systems, the potential barrier is higher in one direction than the other, so that under an ac drive there is dc flow only in the easy direction. Ratchet effects for skyrmions in such asymmetric potentials have been studied previously [37, 38, 39]. In these systems, ratchet and diode effects occur even in the absence of Magnus forces, similar to what is found for vortex ratchets [19, 20, 21]. When a Magnus force is present, additional symmetry breaking arises due to the chirality of the Magnus term, making it possible to create ratchet effects even in a spatially symmetric potential [40]. For the geometries we consider, diode and ratchet effects do not occur in the overdamped limit. Beyond skyrmions, our results should be relevant for creating diode devices for any type of particle system with a Hall deflection, such as chiral active matter with odd viscosity [41] or charges in a magnetic field including Wigner crystals [42] and dusty plasmas [43].

2. Simulation

We simulate the dynamics of multiple interacting skyrmions in the presence of asymmetric channel potentials S1 and S2, illustrated in Fig. 1. The system is of size $L_x \times L_y$, with $L_x = L_y = 36\xi$, and there are periodic boundary conditions only in the x direction. Here ξ is the size of the skyrmion core. The samples contain prohibited areas for the skyrmions, shown in red in Fig. 1, where the energy potential is very high. As a result, skyrmions can only exist stably in the white regions where the sample is clean. The separation between the red and white regions is modeled with repulsive barrier walls that confine the skyrmions to the white region. In addition to interacting with the barrier walls, the skyrmions interact with each other and also with an applied dc current. We initially consider the simpler geometry labeled S1, shown in Fig. 1(a), where the upper channel wall is flat and the lower wall contains divots, giving a high asymmetry. We analyze the skyrmion

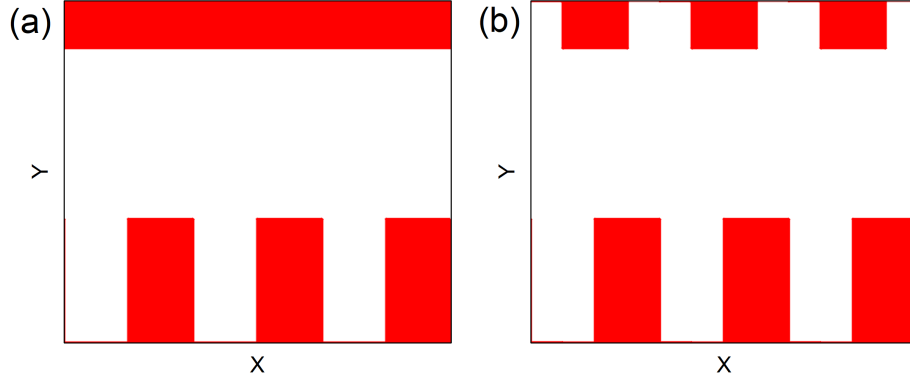


Figure 1. Images of the samples used in this work. Red areas are forbidden to the skyrmions. (a) The high asymmetry geometry S1. (b) The lower asymmetry geometry S2, where the lower divots have a depth of 13ξ and the upper divots have a depth of 5ξ .

dynamical behavior under dc transport forces applied along the positive and negative x direction. We next consider the lower asymmetry geometry S2, shown in Fig. 1(b), where both the upper and lower walls contain divots, but the divots on the upper wall are shallower than those on the lower wall. The skyrmion density is $n = N_{sk}/A_w$, where $A_w = L_x L_y - A_r$ is the area of the white region, A_r is the area of the prohibited red region, and N_{sk} is the number of skyrmions. The lower divots in both S1 and S2 have dimensions of $13\xi \times 6\xi$, and the upper divots in S2 are of size $5\xi \times 6\xi$. Unless otherwise noted, we consider samples with $N_{sk} = 26$ skyrmions, so that $n_{S1} = 0.0295/\xi^2$ and $n_{S2} = 0.0268/\xi^2$.

To simulate the skyrmion behavior we use a particle-based model for skyrmions [44], given by:

$$\alpha_d \mathbf{v}_i + \alpha_m \hat{z} \times \mathbf{v}_i = \mathbf{F}_i^{SS} + \mathbf{F}^W + \mathbf{F}^D. \quad (1)$$

Here, \mathbf{v}_i is the velocity of i th skyrmion. The first term on the left side with prefactor α_d is the damping term, which arises from spin precession and dissipation of electrons in the skyrmion core. The second term on the left with prefactor α_m is the Magnus force from gyroscopic effects. The Magnus force is oriented perpendicular to the skyrmion velocity. Throughout this work we use the normalization $\alpha_d^2 + \alpha_m^2 = 1$. The first term on the right side is the skyrmion-skyrmion repulsive interaction force, given by $\mathbf{F}_i^{SS} = \sum_j^{N_{sk}} K_1(r_{ij}/\xi) \hat{\mathbf{r}}_{ij}$, where K_1 is the modified Bessel function of the second kind, $r_{ij} = |\mathbf{r}_i - \mathbf{r}_j|$ is the distance between skyrmions i and j , and $\hat{\mathbf{r}}_{ij} = (\mathbf{r}_i - \mathbf{r}_j)/r_{ij}$. For $r_{ij} > 6.0$ the skyrmion-skyrmion interaction is cut off for computational efficiency. The second term on the right side is the interaction between skyrmions and the repulsive walls, given by $\mathbf{F}^W = 2r_{iw}U_0/a_0^2 \exp(-r_{iw}^2/a_0^2) \hat{\mathbf{r}}_{iw}$, where $U_0 = 30.0$ is the potential strength, $a_0 = 0.05\xi$ is the wall thickness, and r_{iw} is the distance between skyrmion i and wall w . The values of U_0 and a_0 were chosen large enough to prevent the skyrmions from crossing the barrier walls, so that the skyrmions remain trapped in the white regions shown in Fig. 1. The last term on the right in equation 1 is the force from the external drive, $\mathbf{F}^D = F^D \hat{\mathbf{d}}$, where $\hat{\mathbf{d}} = \pm \hat{\mathbf{x}}$ is the applied current direction. We increase F^D in small steps of $\delta F^D = 0.003$ and spend 5×10^5 simulation time steps at each drive increment. We normalize all distances by the screening length ξ and the average velocities are obtained with $\langle V_x \rangle = \langle \mathbf{v} \cdot \hat{\mathbf{x}} \rangle$ and $\langle V_y \rangle = \langle \mathbf{v} \cdot \hat{\mathbf{y}} \rangle$, where the averages are taken over the simulation time steps spent at each drive increment.

As an example of how to convert the simulation units to physical units for comparison with experiment, consider the case of an MnSi thin film with exchange energy $J \approx 3$ meV/ a , lattice constant $a \approx 0.5$ nm, and Dzyaloshinskii-Moriya energy $D \approx 0.3$ meV/ a^2 [44]. In this case the skyrmion size is $\xi \sim 2\pi J/D \approx 30$ nm. For the densities we consider in this paper, the average distance between skyrmions is $a_0 \approx 180$ nm. Typical skyrmion velocities observed in MnSi range from $v_s = 10^{-4}$ m/s [28] to 0.1 m/s [45]. This gives an average time scale t_s for a skyrmion to move by one skyrmion lattice constant ranging from $t_s = 1.8$ ms to 1.8 μ s. Finally, a typical energy scale can be obtained based on the elastic energy of the skyrmion lattice, given by $E_0 = Jd/a_0$ [46], where d is the film thickness. For a film with $d = 20$ nm, the elastic energy scale is $E_0 = 240$ meV/nm. The unit of force in the simulation is $F_0 \sim 10^{-5}$ N/m.

3. System S1 with higher asymmetry

We first analyze system S1 where there is a high asymmetry between the upper and lower part of the sample, as shown in Fig. 1(a). To measure the dynamic behavior of skyrmions inside this geometry, we add $N_{sk} = 26$ skyrmions to the sample and perform simulated annealing until a ground state is reached. We then apply an external driving force along the $-x$ (easy) and $+x$ (hard) directions. Since skyrmions exhibit finite Hall angles, it is expected that skyrmions might be pushed towards the smooth upper wall or toward the divots depending on the direction of the applied drive. Initially we explore the simpler case of a drive applied along the easy direction.

3.1. Easy direction ($-x$) driving

In Fig. 2 we plot $\langle V_x \rangle$ as a function of F^D for the system shown in Fig. 1(a) for selected values of α_m/α_d under a drive applied along $\hat{\mathbf{d}} = -\hat{\mathbf{x}}$. The magnitude of the velocity increases linearly with increasing drive since, in this configuration, skyrmions are pushed to the upper part of the sample and encounter the straight repulsive barrier wall. The skyrmions can not surpass this barrier, so they slide against the wall in the $-x$ direction. Note that the speed of the skyrmion motion changes as α_m/α_d varies. In the hypothetical case of a skyrmion with no Magnus force, $\alpha_m/\alpha_d = 0$, similar behavior appears but the magnitude of the velocity is diminished. The mechanism of the skyrmion sliding along repulsive walls due to the Magnus force was explained recently in Ref. [47]. In Fig. 3 we plot selected skyrmion trajectories for the system in Fig. 2 at $F^D = 0.3$. A sample with $\alpha_m/\alpha_d = 0.2$, where the intrinsic Hall angle $\theta_{sk}^{\text{int}} = 11.31^\circ$, appears in Fig. 3(a), while a system with $\alpha_m/\alpha_d = 1.0$ and $\theta_{sk}^{\text{int}} = 45^\circ$ is shown in Fig. 3(b). As expected, a portion of the skyrmions remain trapped in the lower divots, while the remaining skyrmions flow along the upper straight wall due to the skyrmion Hall effect.

3.2. Hard direction ($+x$) driving

We next consider applying the drive along the hard direction, $\hat{\mathbf{d}} = +\hat{\mathbf{x}}$. In this case, the skyrmion Hall angle pushes the skyrmions towards the divots. In Fig. 4(a,b) we plot $\langle V_x \rangle$ as a function of F^D for the system shown in Fig. 1(a) at several values of α_m/α_d . The results are separated into two plots for better visualization of the data. Figure 4(a) shows weak Magnus forces, $0 \leq \alpha_m/\alpha_d \leq 0.5$, while Fig. 4(b) shows intermediate Magnus forces, $1.0 \leq \alpha_m/\alpha_d \leq 3.0$. In Fig. 4(c) we construct a dynamic phase diagram as a function of F^D versus α_m/α_d .

For the low Magnus force regime in Fig. 4(a), we find when the Magnus force is completely absent, $\alpha_m/\alpha_d = 0$, the presence of divots has no influence on the dynamic behavior of the

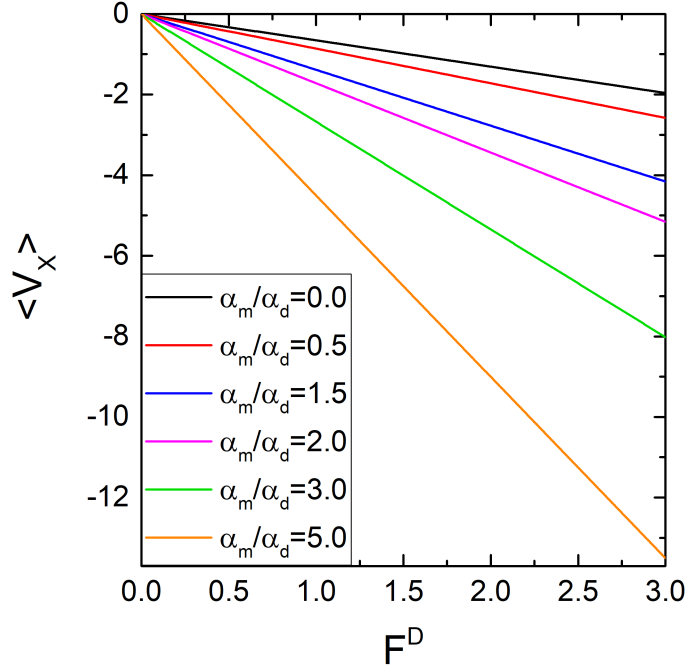


Figure 2. $\langle V_x \rangle$ vs F^D for selected values of α_m/α_d for the high asymmetry system S1 under an easy direction applied drive with $\hat{\mathbf{d}} = -\hat{\mathbf{x}}$. In all cases, the magnitude of the velocity increases linearly with the applied drive.

skyrmions. As illustrated in Fig. 5(a), the skyrmions travel in a straight line with $\theta_{sk}^{\text{int}} = 0^\circ$, and their velocity increases linearly with increasing applied drive. That is, without a Magnus force, this system exhibits no easy or hard direction of motion. On the other hand, when the Magnus force is present, the skyrmion Hall effect causes the skyrmions to move towards the divots, resulting in a significant reduction of the average skyrmion velocity $\langle V_x \rangle$ as shown in Fig. 4(a). Thus the possibility to control the skyrmion velocity using the type of geometry proposed in this work is only effective for particles where $\alpha_m/\alpha_d > 0$, such as ferromagnetic skyrmions. For intermediate values of Magnus forces, shown in Fig. 4(b), the skyrmion motion ceases above $F^D > 2.36$ for most values of α_m/α_d . Note that for $\alpha_m/\alpha_d = 0.5$ in Fig. 4(a), there is also a region where $\langle V_x \rangle = 0$ for $F^D > 2.75$. In Fig. 5(b) we show a snapshot of the skyrmion motion for the system with $\alpha_m/\alpha_d = 1.5$ or $\theta_{sk}^{\text{int}} = 56.31^\circ$ at $F^D = 1.0$, and in Fig. 5(c) we show the same system at $F^D = 2.5$. When $F^D = 1.0$, the skyrmions flow through the sample in an ordered fashion. Skyrmions accumulate on the left side of each divot and, due to a combination of skyrmion-skyrmion repulsion, applied drive, and Magnus forces, the skyrmions push each other toward the upper edge of the divot until the topmost skyrmion escapes from the divot and flows to the next one. This results in a chain-like motion. When $F^D = 2.5$, the motion ceases due to the increased drive and Magnus forces, so the skyrmions accumulate in the divots, producing a reentrant pinning phase. The location of this reentrant pinned state is shown in Fig. 4(c). Reentrant pinning only occurs for $\alpha_m/\alpha_d > 0.2$, while for $\alpha_m/\alpha_d < 0.2$, the Magnus force is not strong enough to trap the skyrmions inside the divots. We expect that for drives higher than those considered here, skyrmions can still become

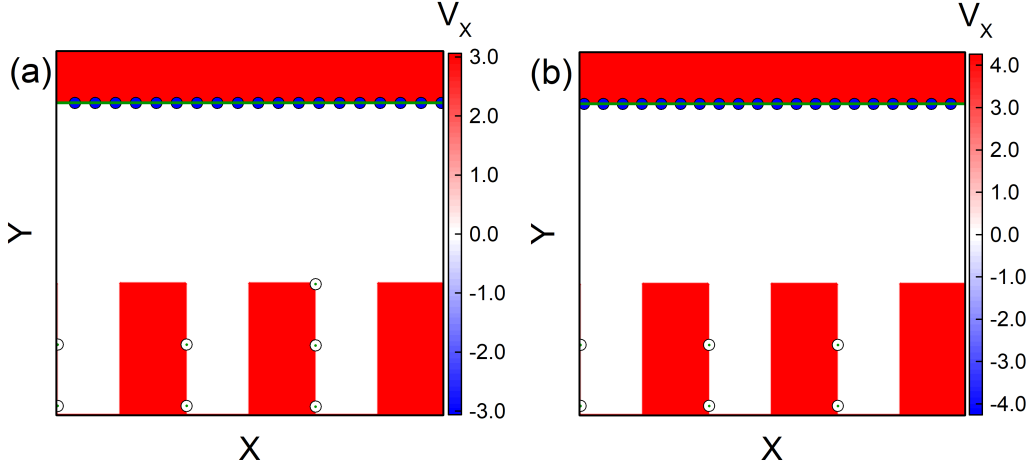


Figure 3. Skyrmion starting positions (circles) and trajectories (green lines) for $\hat{\mathbf{d}} = -\hat{\mathbf{x}}$ or easy direction driving in the high asymmetry system S1 with $F^D = 3.0$ at (a) $\alpha_m/\alpha_d = 0.2$ and (b) $\alpha_m/\alpha_d = 1.0$. Red areas are forbidden to the skyrmions. Each skyrmion instantaneous velocity, V_x , is represented by a color scale attached to the plot, where white are skyrmions with null velocity, blue negative and red positive velocities.

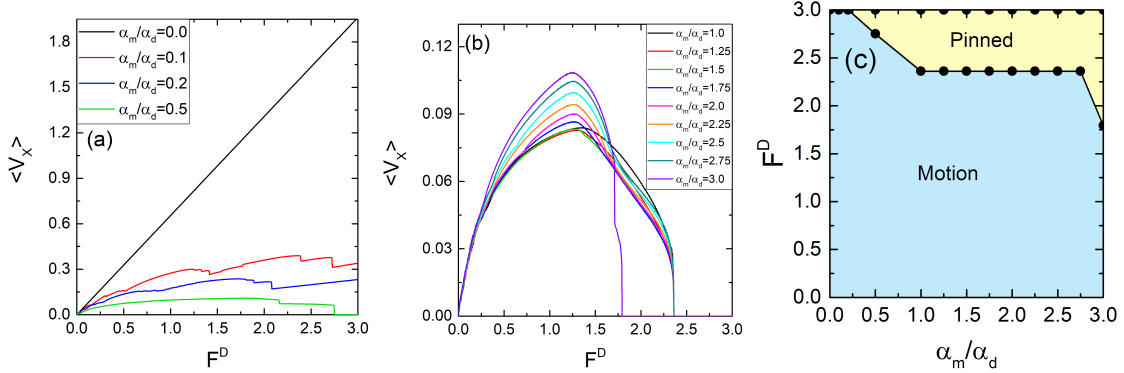


Figure 4. Results for hard direction driving along $\hat{\mathbf{d}} = +\hat{\mathbf{x}}$ for the high asymmetry system S1. (a) $\langle V_x \rangle$ vs F^D for several values of α_m/α_d in the weak Magnus force regime, $0 \leq \alpha_m/\alpha_d \leq 0.5$. (b) The same for the intermediate Magnus force regime, $1.0 \leq \alpha_m/\alpha_d \leq 3.0$. (c) Dynamical phase diagram as a function of F^D vs α_m/α_d showing the reentrant pinned phase (yellow) and the moving phase (blue).

pinned inside divots at smaller α_m/α_d . For $0.2 < \alpha_m/\alpha_d < 1.0$, the onset of the reentrant pinning phase shifts to lower applied drives with increasing α_m/α_d , and the threshold then stabilizes at $F^D = 2.36$ over the range $1.0 < \alpha_m/\alpha_d < 2.75$. The threshold drops again with increasing α_m/α_d above $\alpha_m/\alpha_d = 2.75$. We find that the Magnus force plays a major role in producing the reentrant pinning. The high asymmetry system S1 could serve as a topological sorter, since skyrmions with higher Magnus terms would be guided into the divots, while skyrmions with reduced Magnus terms can flow without entering the divots. This is in addition to other recent proposals for how to sort

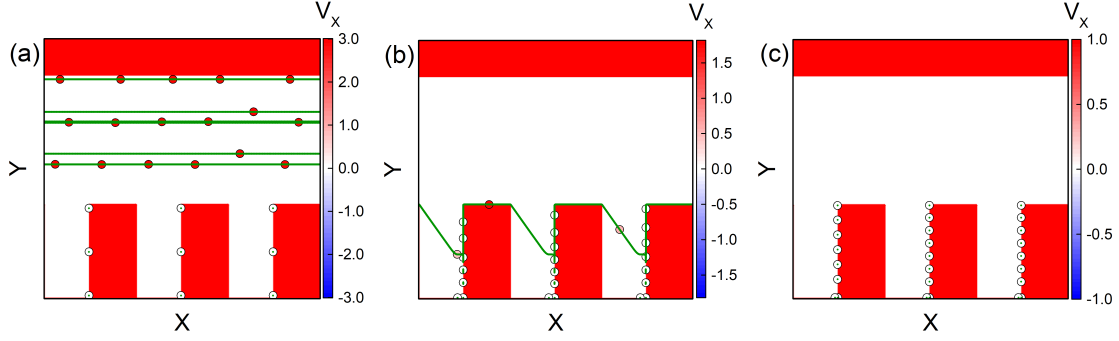


Figure 5. Skyrmion positions (black dots) and trajectories (green lines) for $\hat{\mathbf{d}} = +\hat{\mathbf{x}}$ or hard direction driving in the high asymmetry S1 system shown in Fig. 1(a). Red areas are forbidden to the skyrmions. Each skyrmion instantaneous velocity, V_x , is represented by a color scale attached to the plot, where white are skyrmions with null velocity, blue negative and red positive velocities. (a) $\alpha_m/\alpha_d = 0$ and $F^D = 3.0$, where skyrmions do not exhibit the skyrmion Hall effect due to the absence of a Magnus term, but instead flow along the direction of the applied drive. (b) $\alpha_m/\alpha_d = 1.5$ and $F^D = 1.0$, where a portion of the skyrmions in the lower part of the sample flow while the other skyrmions remain trapped. (c) $\alpha_m/\alpha_d = 1.5$ and $F^D = 2.5$, where there is a pinned phase.

skyrmions [48, 49, 50]. The ability to switch between skyrmion motion and reentrant pinning with an external drive can also be used to transfer data: for low drives, the skyrmions are able to flow and transport information, while for higher drives, they become pinned in the divots.

4. System S2 with lower asymmetry

We next consider system S2, illustrated in Fig. 1(b), where the asymmetry between the upper and lower part of the sample is reduced. Note that since the lower part of system S2 is exactly the same as that of system S1, the behavior under $\hat{\mathbf{d}} = +\hat{\mathbf{x}}$ or hard direction driving is identical for both systems and is as described in the previous section. Thus, in this section we only consider easy direction driving with $\hat{\mathbf{d}} = -\hat{\mathbf{x}}$. For $-x$ driving, the Magnus force pushes the skyrmions towards the upper part of the sample, where they interact with the shallow upper divots. An overview of $\langle V_x \rangle$ versus F^D in the lower asymmetry system S2 for different values of α_m/α_d appears in Fig. 6.

In the low Magnus force regime shown in Fig. 6(a), we again find that when $\alpha_m/\alpha_d = 0$, the skyrmion average velocity increases linearly with increasing F^D due to the absence of a Magnus force. When $\alpha_m/\alpha_d > 0$, however, the $\langle V_x \rangle$ curves become non-linear and the skyrmion velocity diminishes with increasing α_m/α_d . In addition, when α_m/α_d becomes large enough, a reentrant pinned phase emerges as shown in Fig. 6(b). Many of the features shown in Fig. 6(a,b) are similar to those described in previous section. This is due to the fact that, apart from a sign change in the driving direction, the dynamics of the skyrmions in Fig. 4(a,b) and in Fig. 6(a,b) differs only in the depth of the divots. The deeper divots can more easily pin the skyrmions, while the shallower divots permit the emergence of more complex dynamic regimes, in which transitions between pinned states and moving phases can occur under fine adjustments of the external drive. In Fig. 6(c) we plot a dynamic phase diagram for easy direction driving in the lower asymmetry system S2 as a function of F^D versus α_m/α_d . The extent of the reentrant pinned phase is reduced compared to what is shown in Fig. 4(c) due to the reduced depth of the divots. Here, skyrmions that have been trapped

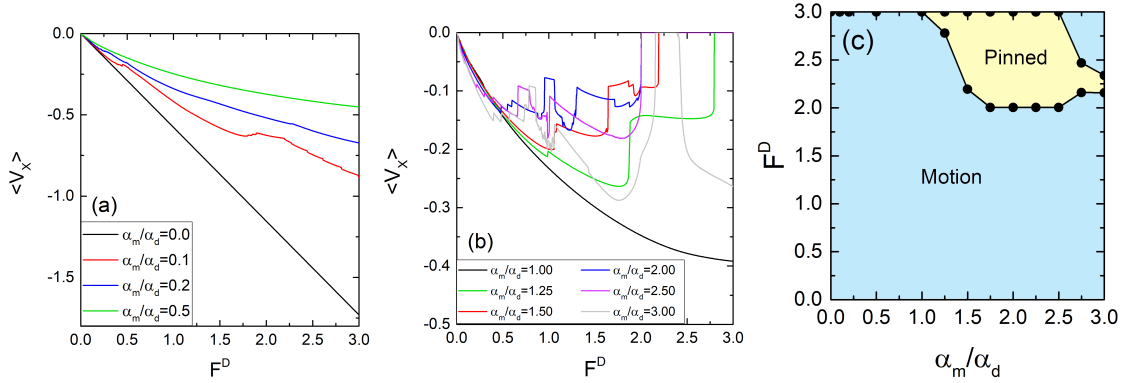


Figure 6. Results for easy direction driving along $\hat{\mathbf{d}} = -\hat{\mathbf{x}}$ for the lower asymmetry system S2. (a) $\langle V_x \rangle$ vs F^D for several values of α_m/α_d in the weak Magnus force regime, $0 \leq \alpha_m/\alpha_d \leq 0.5$. (b) The same for the intermediate Magnus force regime, $1.0 \leq \alpha_m/\alpha_d \leq 3.0$. (c) Dynamical phase diagram as a function of F^D vs α_m/α_d showing the reentrant pinned phase (yellow) and the moving phase (blue).

in the divots can begin to flow again when the drive increases, as shown for the samples with $\alpha_m/\alpha_d > 2.5$. Thus, the depth of the divots is another important parameter that can determine the response of a device constructed using a geometry of this type. In Fig. 7(a), the snapshot of the skyrmion trajectories at $\alpha_m/\alpha_d = 1.0$ shows that not all of the skyrmions in the upper part of the sample are flowing. Instead, some skyrmions remain trapped while the other skyrmions flow. When $\alpha_m/\alpha_d = 2.5$, Fig. 7(b) shows that at $F^D = 1.5$, all of the skyrmions in the upper part of the sample are moving; however, when the drive is increased to $F^D = 2.5$, the system enters the reentrant pinned phase, illustrated in Fig. 7(c).

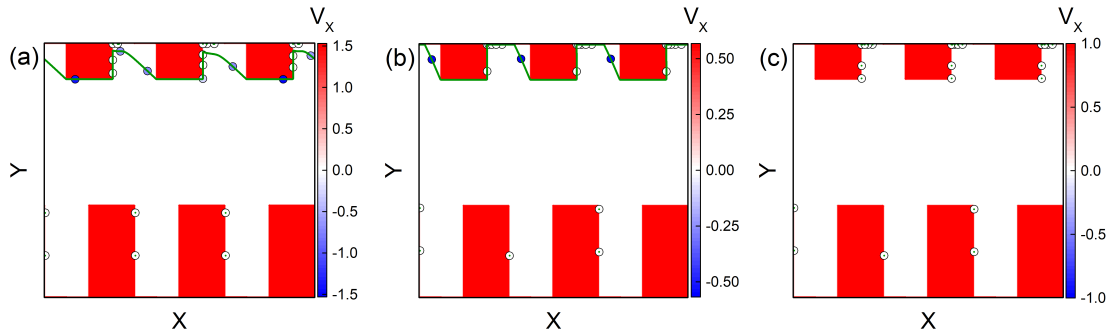


Figure 7. Skyrmion positions (black dots) and trajectories (green lines) for $\hat{\mathbf{d}} = -\hat{\mathbf{x}}$ driving in the lower asymmetry S2 system. Red areas are forbidden to the skyrmions. Each skyrmion instantaneous velocity, V_x , is represented by a color scale attached to the plot, where white are skyrmions with null velocity, blue negative and red positive velocities. (a) At $\alpha_m/\alpha_d = 1.0$ and $F^D = 1.0$, only a portion of the skyrmions in the upper portion of the sample are flowing, while the other skyrmions remain pinned. (b) At $\alpha_m/\alpha_d = 2.5$ and $F^D = 1.5$, all of the skyrmions in the upper part of the sample are moving. (c) At $\alpha_m/\alpha_d = 2.5$ and $F^D = 2.5$, the system is in the reentrant pinning phase.

5. The influence of skyrmion density

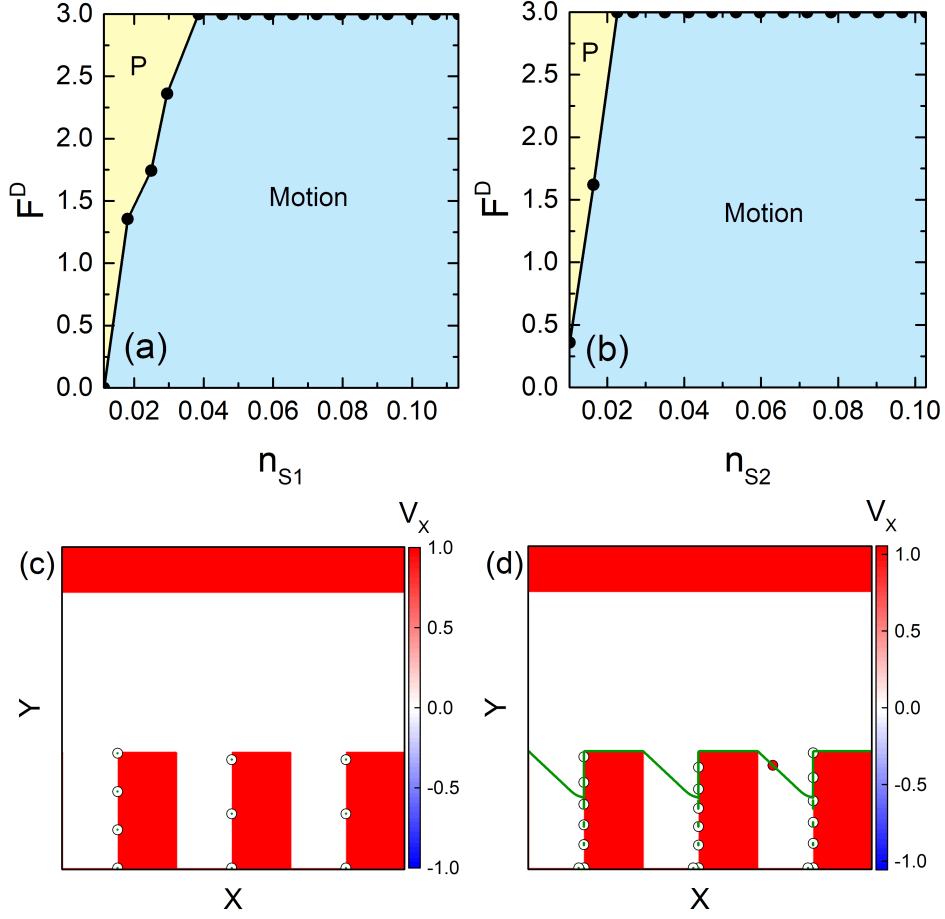


Figure 8. (a,b) Dynamical phase diagrams as a function of F^D vs skyrmion density (a) n_{S1} in high asymmetry system S1 for hard direction driving with $\hat{\mathbf{d}} = -\hat{\mathbf{x}}$ and (b) n_{S2} in lower asymmetry system S2 for easy direction driving with $\hat{\mathbf{d}} = +\hat{\mathbf{x}}$ for samples with $\alpha_m/\alpha_d = 1.0$. Moving regions are shown in blue and pinned (P) regions are shown in yellow. (c,d) Skyrmion positions (black dots) and trajectories (green lines) for the high asymmetry system S1 under hard direction driving with $\hat{\mathbf{d}} = -\hat{\mathbf{x}}$. Red areas are forbidden to the skyrmions. Each skyrmion velocity is represented by a color scale attached to the plot, where white are skyrmions with null velocity, blue negative and red positive velocities. (c) A pinned state at low n_{S1} . (d) A chain of moving skyrmions for higher n_{S1} .

Next we explore how the dynamics change as a function of skyrmion density. We vary the number of skyrmions inside the sample between $N_{sk} = 10$ and $N_{sk} = 100$ while holding the Magnus intensity fixed at $\alpha_m/\alpha_d = 1.0$. In Fig. 8(a) we plot a dynamic phase diagram as a function of F^D versus skyrmion density for the high asymmetry system S1 under hard direction driving with $\hat{\mathbf{d}} = -\hat{\mathbf{x}}$, and in Fig. 8(b) we show the dynamic phases for the lower asymmetry system S2 under

easy direction driving with $\hat{\mathbf{d}} = +\hat{\mathbf{x}}$. As a function of increasing skyrmion density or decreasing drive, there is a transition in both cases from the pinned to the moving state. The pinned phase is only present for low skyrmion densities, indicating that diode behavior would be most prominent at densities where the skyrmions are widely spaced and their motion is dominated by the skyrmion Hall angle. In this situation, the skyrmions are driven against the divots where they become trapped, as illustrated in Fig. 8(c). When the skyrmion density increases, the skyrmions approach each other more closely, and a competition between the skyrmion-skyrmion interactions and the skyrmion Hall effect emerges. This leads to a chain motion of a portion of the skyrmions that never become stuck in the divots, as shown in Fig. 8(d). Furthermore, in sample S1 with driving along $\hat{\mathbf{d}} = +\hat{\mathbf{x}}$, shown in Fig. 8(a), the skyrmions experience the influence of the deeper divots, resulting in the presence of pinned phases for $n_{S1} \leq 0.0385$. On the other hand, in sample S2 for driving along $\hat{\mathbf{d}} = -\hat{\mathbf{x}}$, shown in Fig. 8(b), the skyrmions interact with the shallower upper divots, resulting in a pinned phase only over the reduced range $n_{S2} \leq 0.0226$. These results indicate that introducing deeper divots could produce stronger pinning effects for the skyrmions. In order to make a diode device that can support a high skyrmion density, a good option would be to use the high asymmetry geometry S1 with deeper divots. This would result in an easy flow for driving in one direction and a pinned state or hindered motion for driving in the other direction. The depth of the divots is an important parameter for controlling the skyrmion motion.

6. Diode Effect

In the previous sections we showed that skyrmion transport in both samples S1 and S2 exhibits a very significant dependence on the direction of the applied drive. In the high asymmetry sample S1, when the drive is applied along the easy direction, the velocity of the skyrmions increases linearly with increasing drive. On the other hand, when the drive is applied along the hard direction, the skyrmions may get stuck, and their velocity is strongly reduced. We also showed that in the lower asymmetry sample S2, the direction of the drive is very important in determining the nature of the skyrmion motion. Although in this case the asymmetry is reduced, it is also possible to see clear differences in the skyrmion motion depending on the direction of the drive.

In Fig. 9 we show a comparison of $\langle V_x \rangle$ versus F^D for driving in the easy and hard directions for samples S1 and S2 at $\alpha_m/\alpha_d = 1.5$. In the high asymmetry sample S1, illustrated in Fig. 1(a), changing the driving direction produces very different behaviors. Skyrmions driven along the $\hat{\mathbf{d}} = -\hat{\mathbf{x}}$ easy direction have a velocity that increases in magnitude with increasing drive. For driving along the $\hat{\mathbf{d}} = +\hat{\mathbf{x}}$ hard direction, the magnitude of the skyrmion velocity is greatly reduced. Additionally, $\langle V_x \rangle$ drops to zero when $F^D > 2.36$, so for drives in this window, a device could be created that gives insulating transport behavior of the skyrmions for motion in one direction and conducting transport behavior for motion in the other direction, similar to what was proposed in Refs. [14] and [15]. The Magnus term pushes the skyrmions toward the divots when the drive is in the hard direction, and the skyrmions must overcome the potential barrier of the divots via the chain motion described in previous sections.

In Fig. 9(b), the $\langle V_x \rangle$ versus F^D curves for easy and hard direction driving in the lower asymmetry system S2 indicate that the reduction of asymmetry produces significant changes in the behavior. The magnitude of the skyrmion velocity remains higher for easy direction than for hard direction driving due to the reduced depths of the divots traversed by the skyrmions during easy direction driving. Thus, the depth of the divots is a very important parameter that can control the skyrmion velocity. Additionally, for both directions of drive, the system enters a reentrant pinning

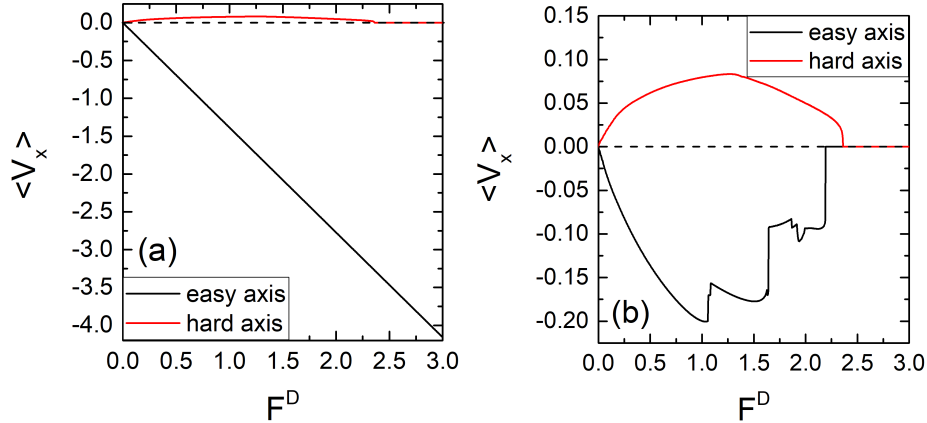


Figure 9. $\langle V_x \rangle$ vs F^D for samples with $\alpha_m/\alpha_d = 1.5$ under easy $\hat{\mathbf{d}} = +\hat{\mathbf{x}}$ (black) and hard $\hat{\mathbf{d}} = +\hat{\mathbf{x}}$ (red) direction driving. (a) High asymmetry sample S1. (b) Lower asymmetry sample S2. The dashed line indicates in both figures where $\langle V_x \rangle = 0$.

phase, although the threshold drive above which this phase appears is lower for easy direction than for hard direction driving. These features make it possible to construct different types of diodes using the high asymmetry sample S1 and the low asymmetry sample S2.

7. Discussion

The asymmetric potentials proposed in this work generate a diode motion of skyrmions when the external driving force is applied in one direction or the other. The diode effect emerges from the combination of the asymmetric potentials and the skyrmion Hall effect. The presence of the Hall effect is crucial, and we demonstrated that skyrmions with no Magnus term, such as antiferromagnetic skyrmions [51, 52] or liquid crystal skyrmions [53], do not exhibit a diode effect. Moreover, we showed that both strong and weak diodes can be constructed. Since we consider asymmetric potentials, if ac rather than dc driving were applied, we expect that clear ratchet effects would emerge in which there would be a net motion of skyrmions along the easy direction. There have been a number of proposals for how to construct ratchet geometries for skyrmions, such as by using asymmetric potentials [37, 38, 39], interfaces [54, 55], or even purely periodic obstacle lattices [40]. We note that for asymmetric substrates such as sawtooth potentials, a ratchet or diode effect will still occur even in the absence of a Magnus force.

In the model considered in this work, the skyrmions are rigid bodies that can not deform, merge, or be created or annihilated. It would be interesting to investigate multiple skyrmions in asymmetric potentials of the types we consider using continuum-based simulations, where the impact of skyrmion deformations could be explored. Our results should be valid in the limit of low skyrmion densities and low currents, where internal modes of the skyrmions are not excited.

With regard to thermal effects, it is known that temperature can change the location of transition points or even induce skyrmion creep [56, 48]. We expect that inclusion of a finite temperatures would modify the reentrant pinned phases; however, for low temperatures we expect our results to be accurate. One possible way to mitigate thermal effects on the diode behavior is

to increase the depth of the divots, making the trapping of skyrmions more efficient.

We also note that our proposed geometries could be used for sorting mixtures of skyrmions with different skyrmion Hall angles, where the skyrmions with higher skyrmion Hall angles would be trapped or move more slowly. Finally, we note that our geometries can be applied more generally to particle-like systems that have a Hall angle, including active spinners or chiral active matter [41], charges in a magnetic field such as Wigner crystals [42], and dusty plasmas in magnetic fields [43].

8. Summary

We have investigated a Magnus-induced diode effect using a particle based model for skyrmions in two different channel geometries containing periodic array of divots on one side of the channel and either a smooth wall or shallower divots on the other side of the channel. Under an applied drive, a diode effect emerges since the skyrmions are deflected to opposite sides of the channel depending on the driving direction. When the skyrmions are deflected toward the deeper divots, they either become completely trapped or exhibit a chain-like flow of low velocity compared to the motion for driving in the opposite direction. We highlight the difference in transport properties for the two channel geometries and show how the results change as the Magnus term increases in importance. The diode effect we observe only occurs when the Magnus force is finite. Our geometry is distinct from previously considered periodic asymmetric sawtooth potentials, which produce diode effects even in the absence of a Magnus force. When multiple interacting skyrmions are present in the channel, there can be a variety of dips or jumps in the transport curves due to collective trapping or, in some cases, escape over the barriers. This leads to regimes of negative differential conductivity or reentrant pinning in which the skyrmions can flow at low drives but become strongly pinned at higher drives. Our results should be general for other particle-based systems that have a Hall effect, such as chiral active matter, Wigner crystals in a magnetic field, and magnetized dusty plasma systems.

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