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Magnetic skyrmions on a two-lane racetrack

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E-mail: jmueller@thp.uni-koeln.de**Keywords:** racetrack memory, interfacial Dzyaloshinskii–Moriya interaction, skyrmions, Thiele equation, Landau–Lifshitz–Gilbert equationSupplementary material for this article is available [online](#)

Abstract

Magnetic skyrmions are particle-like textures in magnetization, characterized by a topological winding number. Nanometer-scale skyrmions have been observed at room temperature in magnetic multilayer structures. The combination of their small size, topological quantization and their efficient electric manipulation makes them interesting candidates for information carriers in high-performance memory devices. A skyrmion racetrack memory has been suggested, in which information is encoded in the distance between skyrmions moving in a one-dimensional nanostrip. Here, I propose an alternative design where skyrmions move in two (or more) parallel lanes and the information is stored in the lane number of each skyrmion. Such a multilane track can be constructed by controlling the height profile of the nanostrip. Repulsive skyrmion–skyrmion interactions in narrow nanostrips guarantee that skyrmions on different lanes cannot pass each other. Current pulses can be used to induce a lane change, and combining these elements provides a robust, efficient design for skyrmion-based storage devices.

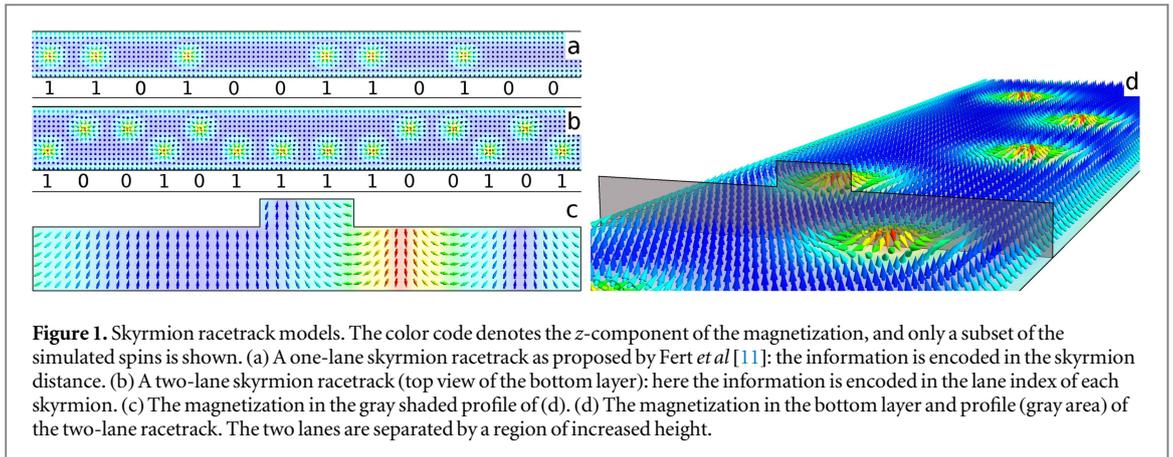
1. Introduction

Magnetic storage devices today predominantly use the orientation of magnetic domains to encode huge amounts of information [1]. The information density is limited by the size of the domains, which not only have to be thermally stable, but should also support features such as the easy and non-mechanically controlled reading and writing of information. Magnetic skyrmions are particle-like textures of nanometer size in magnetization [2–4], which can be controlled by ultra-low electronic [5–7] or magnonic [8, 9] current densities. Due to these properties, they are often treated as promising candidates for information carriers in high-density, non-volatile, solid-state storage devices [10, 11].

Since the experimental discovery of the skyrmion lattice in the chiral magnet MnSi at low temperatures [2], skyrmion lattices and also single skyrmions have been observed in many different systems. The energetic stability of skyrmions can be explained by Dzyaloshinskii–Moriya interaction (DMI), which is a spin–orbit coupling effect which arises either from broken inversion symmetry within the unit cell [12–14] (bulk DMI) or inversion broken by an interface [15] (interfacial DMI). In the latter case, the thermal stability of the skyrmions can be enhanced by the chiral stacking of thin films [16], meaning that skyrmions have recently been stabilized at room temperature in these multilayer systems [17].

Experimentally, a wide range of techniques is now used to image single skyrmions, e.g. Lorentz transmission electron microscopy [3], magnetic force microscopy [18], spin-polarized scanning tunnelling microscopy [4] and also x-ray-based techniques, e.g. magnetic transmission soft x-ray microscopy [19]. For applications in memory devices it is important that single skyrmions can also be detected purely electronically, exploiting their non-coplanar magnetoresistance [20] or the topological Hall effect [21].

On the road towards applications, the controlled writing and deleting of single skyrmions has been shown to work in experiments using current injection [22]. The creation of chains of skyrmions at the edge of a sample has also been demonstrated experimentally [23]. Other processes for the creation of single skyrmions near the edge



have been proposed theoretically [24, 25]. Also, the driving of a chain of skyrmions by electric current in a nanowire was shown in experiments [19].

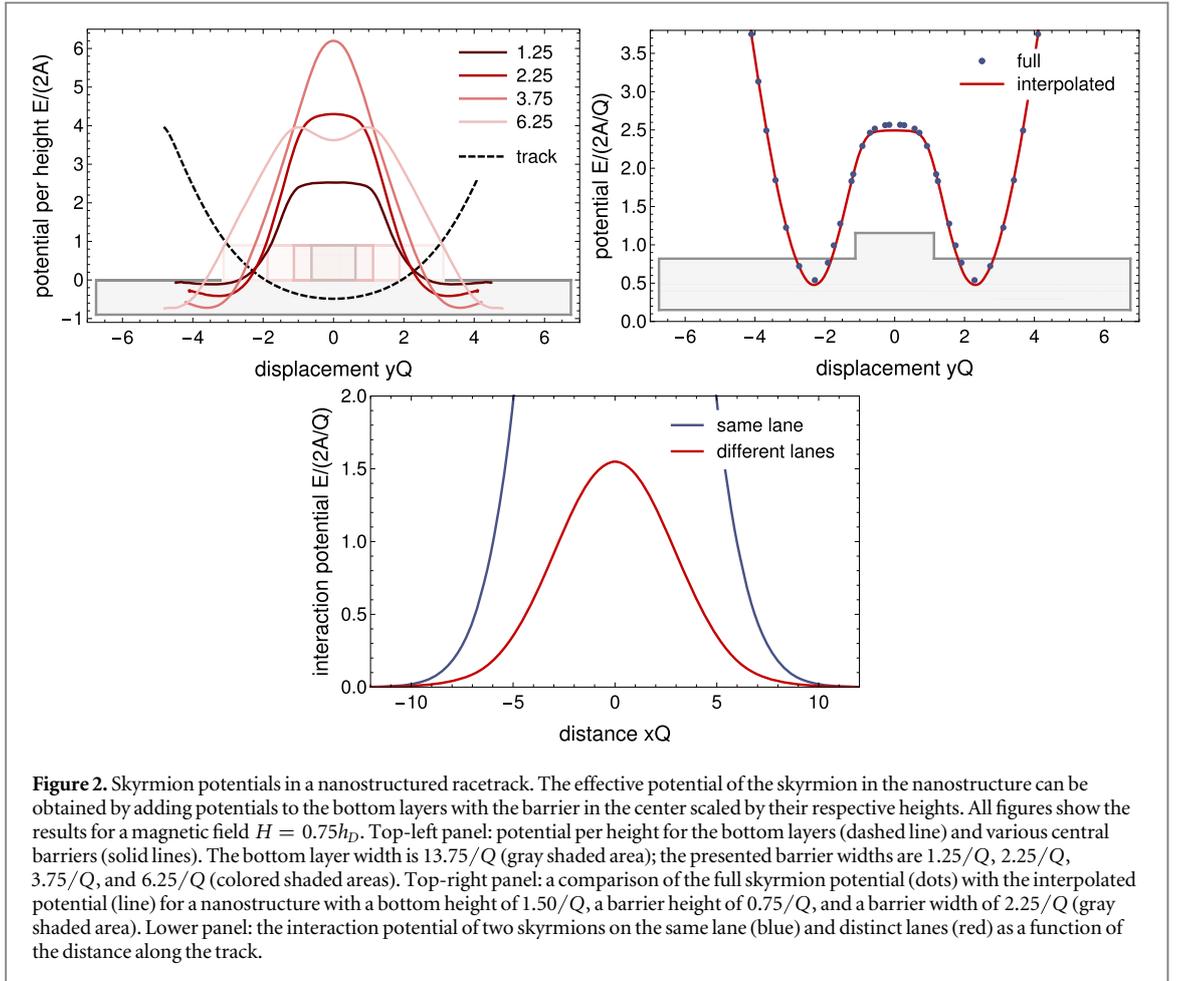
A prominent model for such a skyrmion-based storage device is the skyrmion racetrack [11], which is a nanostrip with a one-dimensional distribution of skyrmions, see figure 1(a). The information in this device is encoded over the distance between the individual skyrmions. By applying an electric current along the track, the train of skyrmions is pushed along the nanowire towards fixed read and write elements of the memory. Since the drift velocity of the skyrmions is increased by the Magnus force when they are pushed against the edges of the track, the translation can be designed more efficiently by using perpendicular driving forces, e.g. by the spin Hall effect [26]. This way, a non-volatile, non-mechanic, and high-density magnetic memory device is created [11].

As the information in this device is encoded in the distance between skyrmions, the distance needs to be preserved in the operational time scales. Here the model has to deal with various problems, including thermal diffusion [27], and, more importantly, the fact that the noise created when operating the memory devices at high frequencies in a disordered environment will lead to the redistribution of the skyrmion distances. Furthermore, the interaction of skyrmions is repulsive [28]. These problems can, however, be solved, if the continuous translational invariance along the track is reduced to a discrete one. Devices based on the racetrack have been proposed, which, for example, use a regular arrangement of notches [29] or electric potentials [30, 31] to divide the track into a sequence of parking lots for the skyrmions. Such obstacles can, however, hinder the motion of the skyrmions towards read or write elements. Due to the complex pulsed motion of the skyrmions, disorder effects may also become more important [32, 33].

In this paper, I present a new ansatz for the application of skyrmions as information carriers in racetrack layout devices, which combines the digital encoding of information with the benefits of continuous driving. We prepare a racetrack with not one but two lanes on the same strip, see figure 1(b), which are separated by a high enough energy barrier such that the skyrmions do not change lanes through thermal activation. The barrier can have various origins, but in this paper we focus on an additional nanostrip on top of the racetrack. This creates a repulsive potential, figure 1(d), complementary to the idea in [34] where an attractive potential is created from scratch on the racetrack. In other skyrmion systems, however, the separation into lanes can even occur naturally [35, 36]. The two lanes are chosen to be sufficiently close that the skyrmions on different lanes repulsively interact and therefore cannot pass each other. The main difference with the original skyrmion racetrack concept is in the encryption of information: it is encoded in the index of the occupied lane and not in the distance between skyrmions [11]. The information in this model is therefore unaffected by the exact distance between the skyrmions. When applying an electric current to this densely packed sequence of skyrmions, they can still move along the track with all the speed-up benefits of the original skyrmion racetrack [26]. A writing element is installed in a fixed position, at the point where it induces a lane change, for example, by applying a strong electric current pulse. With the redefinition of the logic bit, thermal diffusion does not play a role anymore, as long as the potentials are large enough. Also, perturbations by disorder only become relevant if they are of the order of the artificial potentials between skyrmions and the nanostructure, or the other skyrmions, respectively.

2. Potentials and landscapes

The operation of a two-lane racetrack builds on (i) a potential which keeps the skyrmions on the lanes, (ii) the skyrmion–skyrmion repulsion both for skyrmions on the same and on different lanes, and (iii) a mechanism to let a skyrmion change lanes. We calculate the racetrack and interaction potentials based on a micromagnetic model which considers the exchange coupling A of the spins, the interfacial DM interactions D and an external



magnetic field H , see methods 5. I have checked that realistic anisotropy does not change the main results qualitatively, and thus neglect the anisotropies and also the dipolar interactions for simplicity. Within our setup, all the results depend only on a small number of dimensionless parameters, see methods 5. Most importantly, all the length scales are measured in units of $1/Q = 2A/D$, which ranges from 1–100 nm for the different types of skyrmion realizations [17, 19, 33]. The field $H = 0.75h_D$ is chosen such that it stabilizes single skyrmions and they do not decay into bimerons [37].

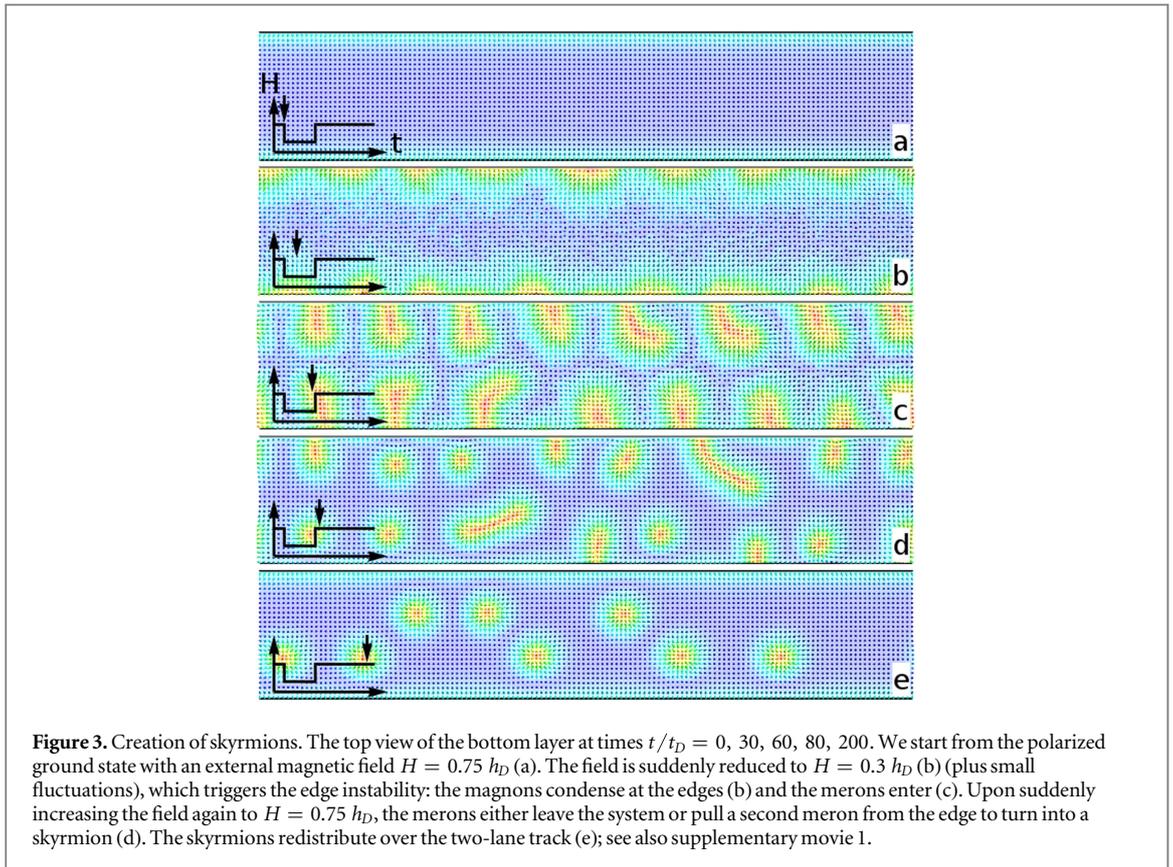
The effective skyrmion potential can be designed by changing the height and width of the track and the barrier. For fixed widths, we find that for a wide range of parameters, the dependence on the height of the track and the barrier can be obtained with high accuracy from a simple linear relation

$$V(y) = h_{\text{track}} v^{\text{track}}(y) + h_{\text{barrier}} v^{\text{barrier}}(y). \quad (1)$$

The simple additivity reflects that the deformations of the magnetic texture along the track normal are small, and it may be useful to design track potentials in experimental systems. Qualitatively, the shape of the potentials can be understood from the fact that the skyrmions are repelled by the edges [28]. Therefore, not only does the track potential rise towards the edge of the track, but the barrier itself is also repulsive, see figure 2(a). The magnetic texture is continued from the bottom layers into the nanostructured upper layers, where the skyrmion is effectively in close proximity to an edge. We find the largest potential barriers if the strip and the skyrmion are of comparable width, compare figure 2(a). If the strip is very broad, the skyrmion in the center of the track is again relatively far away from the edges in the barrier structure. The exact shape of the potential, however, strongly depends on the width of the strip.

In the following, we will focus on the particular example of a two-lane racetrack. We consider a track with a width of $13.75/Q$ and a height of $1.50/Q$. The additional nanostructure on top is $2.25/Q$ in width and $0.75/Q$ in height, see figure 1(c). From the scaling argument, equation (1), an estimation of the potential yields a double-well shape with two degenerate minima. As a check, we calculated the full potential of this geometry and found that the results were in very good agreement, see figure 2(b).

Finally, we also calculated the potential of two interacting skyrmions for which we have to distinguish the two cases where skyrmions move in the same or in different lanes, see methods 5. In both cases, the interactions are always repulsive, see figure 2(c), and scale linearly along the height of the structure. Note that for the chosen



parameters the repulsive interaction of skyrmions in different lanes is sizable and comparable to the height of the barrier between them.

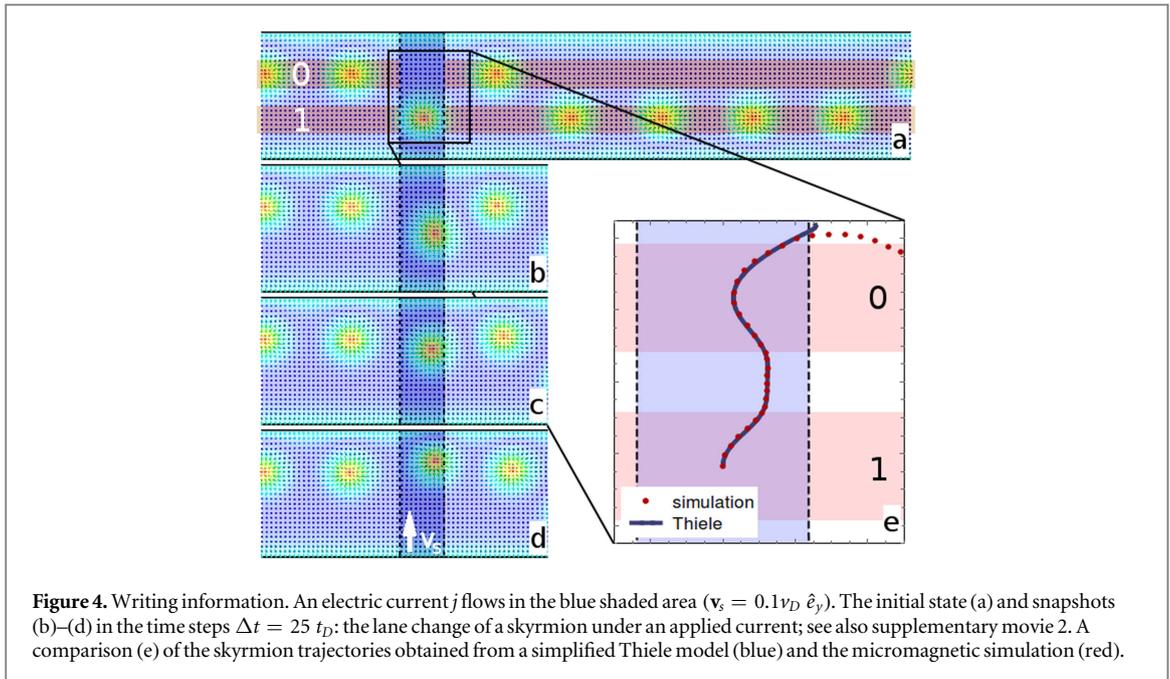
3. Operation of a two-lane racetrack

The above analysis of the separating potential provides a toolbox for engineering the barrier in a way that the order of the skyrmions is conserved with the help of repulsive potentials. For the operation of the two-lane racetrack as a memory device, a read and write protocol is needed.

The thermodynamic ground state of the two-lane racetrack is the polarized phase for the parameters discussed above. Due to their topology, metastable skyrmions are, however, very stable even at room temperature [19]. To initialize the track, i.e. fill it with skyrmions, I suggest simply lowering the magnetic field for a short period, see figure 3 and the supplementary movie 1. As discussed in [25], this triggers an edge instability in which the magnons with finite momentum condense at both edges. The polarized phase then becomes unstable and a chain of merons invades from the edges. Technically, one has to add a small noise term or an edge inhomogeneity to trigger the magnon condensation. In an experimental realization this is done by defects and thermal fluctuations. By increasing the field above the critical field to its original value afterwards, each meron either pulls a second meron from the edge to form a skyrmion, or is pushed back into the edge and vanishes, and the system thereby automatically generates a finite density of skyrmions. We find that the average distance between skyrmions, which here is approximately $8/Q$, is equal to the wavelength of the edge instability. The initialized configuration, however, is random. Lowering the external field on only one lane generates a homogeneous initialization, but is technically more difficult.

For a high operational speed and maximal durability, the read and write elements should be non-mechanic. I suggest installing them both in a combined operational unit, as a write operation requires the state to be read first. Reading information can be realized in various ways: one option is to use a tunnel contact on top or below each lane, which exploits the non-collinear magnetoresistance of a skyrmion [20]; alternatively, one could also use the topological Hall effect [21] to detect them.

Once a skyrmion is detected, one can decide if it has to switch lanes or whether it already represents the desired information. The lane change, in general, can be induced by a variety of forces. However, in insulating materials, the magnonic currents provide an extremely efficient method for controlling skyrmion motion in nanostructures [38], and we restrict our considerations to electric currents only. The write element considered



here consists of a pair of nanocontacts attached to both edges of the track, such that an applied electric current pulse flows predominantly through a narrow strip, as depicted in figure 4. The strip has to be narrow enough for only one skyrmion to be affected by the current pulse. For our calculations, we choose a strip with a width of $5/Q$. The minimal current density required to induce a lane change can be roughly estimated from the separating potential barrier $V(y)$ in a Thiele approach [39]. The simplified Thiele equation, the equation of motion for the skyrmion coordinate \mathbf{R} , see methods 5, reads:

$$-\frac{1}{h_{\text{track}}} \frac{dV}{d\mathbf{R}} = \mathbf{G} \times (\dot{\mathbf{R}} - \mathbf{v}_s) + \mathcal{D}(\alpha \dot{\mathbf{R}} - \beta \mathbf{v}_s). \quad (2)$$

A suitable current density for a lane change, v_s , requires the transversal shift of the skyrmion to be smaller than the width of the current-carrying region during the lane change. Solving the Thiele equation numerically for various v_s , which can easily be done, we find that these requirements are fulfilled for $v_s \geq 0.1 v_D$. Comparing the simplified Thiele estimate to the full micromagnetic simulation, we find that they are in very good agreement, see figure 4, and the current density is indeed suitable for a writing process. The excellent agreement indicates that all skyrmion dynamics are entirely governed within the Thiele approach and its effective potentials. In the simulation, we applied a current pulse that was significantly longer than necessary for a lane change, to explore the skyrmion motion beyond the limits of our simple Thiele approach. Instead of leaving the track, the skyrmion pushes its neighbor (which is artificially fixed in the Thiele ansatz) and all the following skyrmions in the train to the side, while the order is still being preserved. Consequently, for the writing process, a pulse time of $\Delta t = 50 - 75 t_D$ is sufficient, see figures 4(a)–(d), although the operation is very robust against disturbance during the process timing.

Since the read and write elements are fixed in position, the skyrmions have to be moved. The current-driven motion of the skyrmions in a nanostructure has been nicely discussed in [26] and [40]. As previously pointed out by the authors, one can obtain much higher velocities for skyrmions moving in racetracks compared to freely moving skyrmions. Alternatively, the skyrmions can be driven highly efficiently by a magnonic current [9, 38]. Using one of these methods, the bit sequence is driven along the two lanes, see also supplementary movie 2.

4. Summary

I propose a new approach for skyrmion-based storage devices. The two-lane skyrmion racetrack uses the displacement of the skyrmions in a racetrack relative to the center of the track to encode information. Therefore, in contrast to previous models, there is no need to ensure a constant distance between single skyrmions. I provide methods for calculating the potential barrier between the different lanes as well as the interaction between the skyrmions in the lanes. In this paper I show that these potentials can be used to efficiently design such a two-lane racetrack and to determine the current pulses to write information. With this information, I explain how to operate a particular example of a two-lane racetrack by electric current pulses, and confirm the results by micromagnetic simulations. Despite the fact that the model we used throughout this work does not

take into account uniaxial anisotropy or dipolar interactions, which may be of interest for realistic systems, the idea presented here is universal. The idea of a two-lane racetrack combines the powerful idea of a skyrmion racetrack with the promising properties of skyrmion lattices—i.e. low depinning current thresholds and the highest possible information carrier densities—while the information is protected against perturbations. I believe that designs based on the two-lane skyrmion racetrack are promising candidates for future skyrmion-based information technology.

5. Methods

5.1. Model and units

The starting point of our analysis is a non-linear sigma model in which the magnetization is described by the normalized vector field $\hat{n}^T = (\hat{n}_x, \hat{n}_y, \hat{n}_z)$ with $\|\hat{n}\| = 1$. The free energy functional, $F = \int d^3r \mathcal{F}$, with the minimal set of interactions that we choose in this work, contains only the ferromagnetic exchange interaction A , the interfacial Dzyaloshinskii–Moriya interaction D , and an external magnetic field H :

$$\mathcal{F} = A(\partial_\alpha \hat{n}_\beta)^2 + D(\hat{n}_\gamma \partial_\gamma \hat{n}_z - \hat{n}_z \partial_\gamma \hat{n}_\gamma) - \mu_0 H M \hat{n}_z, \quad (3)$$

with $\alpha, \beta = x, y, z, \gamma = x, y$ and M as the saturation magnetization. The scales for momentum, total energy, and magnetic field are chosen in accordance with previous works

$$Q = \frac{D}{2A}, \quad E_D = \frac{2A}{Q}, \quad h_D = \frac{2AQ^2}{\mu_0 M} \quad (4)$$

and are used throughout the work. From the LLG equation

$$[\partial_t + (\mathbf{v}_s \cdot \nabla)] \hat{n} = -\gamma \hat{n} \times \mathbf{B}_{\text{eff}} + \alpha \hat{n} \times \left[\partial_t \hat{n} + \frac{\beta}{\alpha} (\mathbf{v}_s \cdot \nabla) \hat{n} \right], \quad (5)$$

with the effective magnetic field $\mathbf{B}_{\text{eff}} = -\frac{1}{M} \delta F / \delta \hat{n}$ we deduce the dependence of the drift velocity of the spin currents \mathbf{v}_s and the time t on the spin density $s = \frac{M}{\gamma}$:

$$t_D = \frac{s}{2AQ^2}, \quad v_D = \frac{2AQ}{s}. \quad (6)$$

Note that s is the spin per unit cell of the atomic lattice, i.e. independent of Q .

With realistic values [16] for the exchange coupling $A = 10 \text{ pJ m}^{-1}$, the interfacial DMI $D = 1.9 \text{ mJ m}^{-2}$ and a saturation magnetization of $M = 956 \text{ kA m}^{-1}$, the corresponding magnetic field that we apply in our simulations is $\mu_0 H = 0.75 \frac{2AQ^2}{M} = 0.14 \text{ T}$. Note that systems with uniaxial anisotropy skyrmions of a similar size can be realized with a considerably smaller (or even vanishing) external magnetic field. Here, the unit of length corresponds to approximately $1/Q = 10.5 \text{ nm}$; hence, our simulated racetrack has a width of $13.75/Q = 145 \text{ nm}$ and a height of $1.5/Q = 16 \text{ nm}$, while the strip has a width of $2.25/Q = 24 \text{ nm}$ and a height of $0.75/Q = 8 \text{ nm}$. With the unit of energy $E_D = 2A/Q = 2.1 \times 10^{-19} \text{ J}$ we obtain an activation energy for the barrier between the lanes of about $2E_D/k_B = 30 \text{ 000 K}$, implying thermal stability at room temperature. Finally, with the unit of time $t_D = \frac{s}{2AQ^2} = 0.03 \text{ ns}$ (assuming $g = 2$), the writing process with a minimal current (of the order of 10^{10} A m^{-2}), as described in the main text, takes only 1.5–2.2 ns.

5.2. Micromagnetic simulations

For simulations of the continuous model, we discretize the magnetization \hat{n} to the Heisenberg spins on a cubic lattice. We approximate the derivatives in equations (3) and (5) by finite differences. The lattice constant is $a = 0.25/Q$ throughout the paper in all three spatial directions. It is small enough that the results are independent of the discretization length. We have written a code which integrates the discretized LLG equation over time with a fourth order Runge–Kutta method. The boundary conditions are such that the wire is periodic in the extended direction and open in the other directions. The initial states in section 2 are polarized along the direction of the magnetic field. For the energies as a function of the skyrmion position, we manually inserted a single skyrmion, and for the skyrmion interaction two skyrmions, respectively. The initial state in section 3 is polarized, and the skyrmions are created automatically as a result of the system dynamics. In the creation process, we added a small random fluctuating field to \mathbf{B}_{eff} , see equation (5).

5.3. Calculation of the potentials

We calculated the skyrmion potential $V(y)$ numerically as the energy difference between a skyrmion at a given displacement from the center of the track y and the polarized state without skyrmions:

$$V(y) = E_{\text{skyrmion}}(y) - E_{\text{polarized}}. \quad (7)$$

The position of a skyrmion is here defined as the coordinate in the bottom layer, where the magnetization points are antiparallel to the external field H . Previous works fixed this center of the skyrmion to evaluate the potential at various positions [32, 41]. In this setup, however, the forces from the nanostructures are large compared to the artificial pinning forces. Therefore, we cannot fix the skyrmion coordinate. We resolve this problem using a dynamical evaluation of the potential, i.e. we record the energy while running a simulation of the Landau–Lifshitz–Gilbert equation, in which the skyrmion moves adiabatically, i.e. slowly enough that no internal modes are excited. In order to guide the skyrmion to different positions, we apply a sufficiently large current density, here $v_s = 0.032v_D$ and $\alpha = \beta = 0.1$, for the potential of the track. For these potentials of the skyrmion–skyrmion interaction, we define an inhomogeneous current density ($v_s = 0.128v_D$), which either drives the skyrmions into a collision if they start on the same lane or drives them in different directions if they start on different lanes, such that they pass each other. Note that when running on different lanes, the magnus force breaks the mirror symmetry of the motion, i.e. it makes a difference if the skyrmions run on the right or the left lane. For skyrmions on the same lane, the magnus force can induce a lane change if the damping is low ($\alpha \lesssim 1$). As we are interested in the low-energy limit, we suppress these effects by a relatively large damping of $\alpha = \beta = 2$.

5.4. Thiele analysis

In the Thiele analysis, one assumes that the dynamics of the magnetic texture reduce to an effective particle coordinate $\mathbf{R}(t)$ in the two-dimensional plane, $\hat{n}(\mathbf{r} - \mathbf{R}(t))$. This assumption is clearly violated in the system, but as the skyrmion centers are, to a good approximation, local and rigid objects, it still holds to a large extent. Along the track normal, we further assume that the magnetic texture is mainly constant, hence $\mathbf{R}(t)$ is equal in all the layers of the total height, h_{track} ; thus, the system is effectively two-dimensional. The Thiele equation is then recovered by first multiplying the LLG equation from the left with $\hat{n} \times$ and then projecting it down onto the translational mode by multiplying the equation with $\frac{d\hat{n}}{d\mathbf{R}}$ and integrating over space $\int d^3r$. Finally, this results in the equation of motion for the skyrmion coordinate $\mathbf{R}(t)$ in the two-dimensional track plane (x, y) :

$$-\frac{1}{h_{\text{track}}} \frac{dV}{d\mathbf{R}} = \mathbf{G} \times (\dot{\mathbf{R}} - \mathbf{v}_s) + \mathcal{D}(\alpha \dot{\mathbf{R}} - \beta \mathbf{v}_s) \quad (8)$$

where only the potential $V(\mathbf{R})$ is obtained from a full three-dimensional calculation. We approximated the values for \mathbf{G} and \mathcal{D} with the values for a single skyrmion in an infinitely extended polarized background in two dimensions. For the analysis of a lane change, we assume a constant current density in the whole system. However, we note that the Thiele ansatz then only holds as long as the skyrmion is at a sufficient distance ($\gtrsim 1/Q$) from the edges of the area where the current density is actually applied.

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Author contributions

JM performed the numerical calculations, analyzed the data and wrote the manuscript.

Competing financial interests

JM has a German patent application related to this work, number 10 2016 200 161.2, ‘Logischer Speicher mit einer Vielzahl von magnetischen Skyrmionen’.

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