Control of Hall angle of Skyrmion driven by electric current*

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Skyrmions are very promising for applications in spintronics and magnetic memory. It is desired to manipulate and operate a single skyrmion. Here we report on the thermal effect on the motion of current-driven magnetic Skyrmions in magnetic metal. The results show that the magnon current induced by the thermal gradient acts on Skyrmions via magnonic spin-transfer torque, an effect of the transverse and longitudinal Skyrmions drift velocities, thus leading to the effective manipulation of the Hall angle through the ratio of thermal gradient to electric current density, which can be used as a Skyrmion valve.

Keywords: spin-transfer torque, Hall angle, magnon current, Skyrmion valve

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1. Introduction

A Skyrmion is a topologically stable spin texture which consists of opposite core spins and peripheral spins swirling up with a unique spin chirality determined by the underlying chiral crystal structure of the hosting material.[1,2] Since they were observed in 2009,[3] magnetic Skyrmion crystals (SkX) have been extensively investigated, and by now they have been discovered in various materials. There are three kinds of materials. (i) The cubic chiral B20-type helimagnets with lattices exhibiting broken or lacking parts. The materials configurations can be crucially stabilized by the strong Dzyaloshinskii–Moriya interaction (DMI) in these materials,[4] such as MnSi,[5–7] $Fe_{1-x}Co_xSi$,[8,9] FeGe,[10–12] β-Mn-type chiral magnet,[13] and Cu_2OSeO_3.[14,15] (ii) The non-spiral materials where the Skyrmions state can be induced by the competing of exchange interaction with other strong magnetostatic interactions[16–18] whether there is DMI or not, i.e. the four-spin interaction, typically the monolayer Fe/Ir (111) where the 3d–5d hybridization between the Fe monolayer and the Ir substrate plays a key role in determining the unusual magnetic properties.[16,17,19] (iii) The artificial material in which an artificial skyrmion is created by embedding a magnetic vortex into an out-of-plane aligned spin environment.[20–22] Skyrmions are very promising for applications in spintronics[23,24] due to their topological stabilities, ultimate small sizes and low dissipations, and varieties of methods have been proposed to control the creation, movement and removal of a Skyrmion.[20,25,26] Proposals of manipulations and operations of Skyrmions are highly desired.[27]

A Skyrmion can be manipulated with ultralow energy consumption due to its extremely small threshold current density ($\sim 10^6$ A·m^{-2}) compared with that of a domain wall in ferromagnet ($\sim 10^{11}$ A·m^{-2}), because the Skyrmion lattices in a chiral magnet are coupled very weakly to the atomic crystal structure and pinned very weakly to disorder, and electric currents couple very efficiently to Skyrmions in addition.[23] When an electric current flows through a ferromagnetic metal, the conduction electron spins are coupled ferromagnetically to, i.e., forced to be parallel to the localized spin at each atomic site by Hund's-rule coupling, eventually collecting a Berry phase, which arises from an emergent electromagnetic field or fictitious electromagnetic field in real space. At the same time the current becomes spin-polarized, and spin angular momentum is transferred to the magnetization through the mechanism known as spin-transfer torque (STT) due to spin conservation.[28] Consequently the electron current drives the flow of Skyrmions. The motion of the Skyrmions leads to a temporal change of the emergent magnetic field and hence to an emergent electric field due to electromagnetic induction. On the one hand, the induced emergent electric field acts on the electrons like the ordinary magnetic field, and, in particular, gives rise to a Lorentz-type force, which deflects electrons and results in the topological Hall effect.[29–32] On the other hand, the velocity of the Skyrmion has its transverse component, that is, the Skyrmion Hall effect arises, albeit with a small constant.[29,33,34] However, Skyrmions can also be manipulated by the magnon current induced by thermal gradient due to the coupling of magnetization to magnonic spin trans-

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fer torque even in the absence of charge flows, and move from the cold to the hot region.[35,36] Recently, Troncoso and Núñez have shown that thermal torques can increase the mobility of Skyrmions by several orders of magnitude.[37] The progress in the magnetic skyrmions in chiral magnetic materials has been reviewed in Refs. [38] and [39].

In the present study, we investigate the dynamics of Skyrmions in a thin film of metallic chiral magnet in the presence of a thermal gradient and an electric current. Based on the stochastic Landau–Lifshitz–Gilbert–Slonczewski (LLGS) equation[40] the dynamic equation for Skyrmions is derived. The equation is in the form of a generalized Thiele's equation that describes the dynamics of a single Skyrmion at finite temperature. The results show that the Hall angle can be manipulated by the spin-transfer torque induced by a magnon current and an electric current. Based on the dependence of the Hall angle on the ratio of the thermal gradient to the electric current density, a Skyrmion valve is proposed.

2. Skyrmiom motion

We consider a thin film of a metallic chiral magnet well below the Curie temperature (Fig. 1), which is described by the magnetic free energy density $F(\boldsymbol{m}\partial_i\boldsymbol{m})$ (here $i=xy$; double indices are summed over)

$$F(\boldsymbol{m},\partial_i\boldsymbol{m}) = \sum_{i=x,y}\frac{J_{\rm ex}}{2}(\partial_i\boldsymbol{m})^2 - M_{\rm s}\boldsymbol{m}\cdot\boldsymbol{H}_{\rm ext} + D_{\rm d}\boldsymbol{m}\cdot(\boldsymbol{\nabla}\times\boldsymbol{m}), \quad (1)$$

where $\boldsymbol{m}=\boldsymbol{M}/M_{\rm s}$ is a unit vector denoting the magnetization direction, $\boldsymbol{M}$ the local magnetization and $M_{\rm s}=|\boldsymbol{M}|$ a fixed saturation magnetization modulus, $J_{\rm ex}$ the exchange stiffness, $\boldsymbol{H}_{\rm ext}$ the external field, which is perpendicular to the thin film, and $D_{\rm d}$ the strength of the DMI, which is the lowest-order chiral spin-orbit interaction originating from the relativistic effect that occurs due to the lack of inversion symmetry of the atomic structure. Generally, the strongest energy scale is ferromagnetic, which favors a uniform magnetization configuration. It is followed by the weaker DMI, which favors twisted magnetic structures typically by forming a spiral-like magnetization configuration that varies in size according to the competing DMI and ferromagnetic exchange interaction. The system favors a spiral configuration of magnetic moments (conical state) with a single wave vector due to the competition between the magnetic exchange and the DMI and then gradually becomes a stable Skyrmion lattice with triplet-vector in a range of applied magnetic fields from $0.2D_{\rm d}^2/J_{\rm ex}$ to $0.8D_{\rm d}^2/J_{\rm ex}$,[41–43] eventually is saturated to a ferromagnetic state at a higher field. Skyrmions are observed experimentally to keep stability much more easily in a thin film of helical magnet.[5,10,44] The mechanism to stabilize chiral Skyrmions is considered to originate from the chiral modulation across the thin film radically changing the Skyrmion energetics and providing a thermodynamical stability of a Skyrmion lattice in a wider range of applied magnetic fields.[45] Here we assume that the rigidity of Skyrmions has stability over a broad range of temperatures and magnetic fields in the thin film.

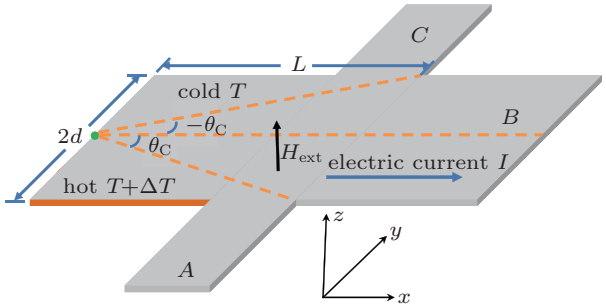


Fig. 1. (color online) Schematic of device, where the electric current flows from left to right and the applied magnetic field is perpendicular to the thin film.

The standard Landau–Lifshitz–Gilbert (LLG) equation is phenomenological and widely used to model magnetization dynamics, including the dynamics of the magnetization direction of the skyrmion lattice due to the very smooth magnetic structure in the skyrmion lattice phase and slight changes of its amplitude. Slonczewski has studied the effect of current-driven spin-transfer torque on magnetization.[40] However, when one studies the dynamics of skyrmions in metal magnets it is necessary to introduce another two novel damping terms relevant to non-collinear spin textures, $-\alpha'\{\boldsymbol{m}\cdot[\partial_i\boldsymbol{m}\times\partial_t\boldsymbol{m}]\}\partial_i\boldsymbol{m}$ originating from Ohmic damping of electrons coupled by Berry phases to the magnetic structure,[24,36] and $-\beta'\{\boldsymbol{m}\cdot[\partial_i\boldsymbol{m}\times(\boldsymbol{v}_{\rm s}\cdot\boldsymbol{\nabla})\boldsymbol{m}]\}\partial_i\boldsymbol{m}$ for the need of Galilean invariance, where $\boldsymbol{v}_{\rm s}$ is an effective spin velocity parallel to the spin current density. These terms might actually be the dominating ones in a good metal[46] except for non-adiabatic spin-transfer torque $\beta\boldsymbol{m}\times(\boldsymbol{v}_{\rm s}\cdot\boldsymbol{\nabla})m$.[47] So the extended LLGS equation[40] containing $\boldsymbol{h}_l$ the random fluctuating of $\boldsymbol{H}_{\rm eff}$ is expressed as

$$\begin{aligned}&(\partial_t+\boldsymbol{v}_{\rm s}\cdot\boldsymbol{\nabla})\boldsymbol{m}\\ &=-\gamma\boldsymbol{m}\times(\boldsymbol{H}_{\rm eff}+\boldsymbol{h}_l)+\alpha\boldsymbol{m}\times\left(\partial_t+\frac{\beta}{\alpha}\boldsymbol{v}_{\rm s}\cdot\boldsymbol{\nabla}\right)\boldsymbol{m}\\ &\quad-\alpha'\left\{\boldsymbol{m}\cdot\left[\partial_i\boldsymbol{m}\times\left(\partial_t+\frac{\beta'}{\alpha'}\boldsymbol{v}_{\rm s}\cdot\boldsymbol{\nabla}\right)\boldsymbol{m}\right]\right\}\partial_i\boldsymbol{m}. \quad (2)\end{aligned}$$

Here, $\gamma=M_{\rm s}/s$ is the gyromagnetic ratio, s the saturation spin density, $\boldsymbol{v}_{\rm s}=-(pa^3/2eM_{\rm s})\boldsymbol{j}$ is the spin velocity of the conduction electrons defined as the ratio of the spin current to the size of the local magnetization for smooth magnetic structures with constant amplitude of the magnetization,[46] with p being the spin polarization of the electric current density $\boldsymbol{j}$, which is over the threshold current density, e (>0) the elementary charge, and a the lattice constant, while α denotes

the Gilbert damping coefficient. The LLGS equation contains the adiabatic spin-transfer torque given by $(\boldsymbol{v}_s\cdot\boldsymbol{\nabla})\boldsymbol{m}$, and the non-adiabatic spin-transfer torque given by $\beta(\boldsymbol{m}\times v_s\cdot\boldsymbol{\nabla})\boldsymbol{m}$, where the strength of the non-adiabatic spin-transfer torque is characterized by the parameter β. The random Langevin field $\boldsymbol{h}_l$, which describes the fluctuating torques, is defined by the uncorrelated Gaussian white noises[48]

$$\begin{aligned}&\langle h_{l,i}(\boldsymbol{r},t)\,h_{l,j}(\boldsymbol{r}',t)\rangle\\ &=\frac{2\alpha}{\gamma M_s}k_BT(\boldsymbol{r})\,\delta_{ij}\delta(\boldsymbol{r}-\boldsymbol{r}')\,\delta(t-t'),\end{aligned}\tag{3}$$

which implies a Brownian motion of the Skyrmion. The Brownian motion vanishes on average along the direction perpendicular to the temperature gradient. While the Skyrmion is pushed by the Brownian motion from the hot side towards the cold side, and opposite by the magnon current along the direction parallel to the temperature gradient. However the velocity contributed by the Brownian motion is too small to mention it compared with the contribution of the magnon current.[35,36]

The effective field is derived from the free energy density, Eq. (1), as follows:

$$\boldsymbol{H}_{\rm eff}=-\frac{\delta F}{\delta \boldsymbol{M}}=\sum_{i=x,y}\frac{J_{\rm ex}}{M_s}\partial_i^2\boldsymbol{m}+\boldsymbol{H}_{\rm ext}-\frac{2D_{\rm d}}{M_s}(\boldsymbol{\nabla}\times\boldsymbol{m}).\tag{4}$$

Induced by the magnon current, the normalized magnetization $\boldsymbol{m}$ can be decomposed into the slow component $\boldsymbol{m}_s$ corresponding to the equilibrium configuration of the Skyrmion, and the fast component $\boldsymbol{m}_f$ orthogonal to $\boldsymbol{m}_s$:[36]

$$\boldsymbol{m}=(1-\boldsymbol{m}_f^2)^{1/2}\boldsymbol{m}_s+\boldsymbol{m}_f\approx\boldsymbol{m}_s+\boldsymbol{m}_f.\tag{5}$$

Following the procedure in Refs. [49] and [50] and the coarse-graining over $\boldsymbol{m}_f$ where linear terms in $\boldsymbol{m}_f$ can be discarded by taking the average over time because $\boldsymbol{m}_f$ is a fast mode behaving as a function of the sine or cosine form in time,[36] equation (2) becomes

$$\begin{aligned}&(\partial_t+\boldsymbol{v}_s\cdot\boldsymbol{\nabla})\boldsymbol{m}_s\\ &=-\gamma\boldsymbol{m}_s\times\boldsymbol{H}_{\rm eff}-(1+\beta_s\boldsymbol{m}_s\times)(\mathbf{J}\cdot\boldsymbol{\nabla})\boldsymbol{m}_s\\ &\quad+\alpha\boldsymbol{m}_s\times\left(\partial_t+\frac{\beta}{\alpha}\boldsymbol{v}_s\cdot\boldsymbol{\nabla}\right)\boldsymbol{m}_s\\ &\quad-\alpha'\left\{\boldsymbol{m}_s\cdot\left[\partial_i\boldsymbol{m}_s\times\left(\partial_t+\frac{\beta'}{\alpha'}\boldsymbol{v}_s\cdot\boldsymbol{\nabla}\right)\boldsymbol{m}_s\right]\right\}\partial_i\boldsymbol{m}_s,\end{aligned}\tag{6}$$

where the tensor $\boldsymbol{J}=\gamma J_{\rm ex}\boldsymbol{m}_f\times\boldsymbol{\nabla}\boldsymbol{m}_f/M_s$ (Ref. [35]) is the spin current density with polarization along $\boldsymbol{m}_s$ carried by magnons[36,49] and the magnon spin transfer torque is given by $\partial_i\boldsymbol{J}=J_i\partial_i\boldsymbol{m}_s$,[49,50] β_s is the dissipative correction to the thermomagnonic torque, and J_i is the magnon current density.

3. Application to the dynamics of the Skyrmion

Following the Thiele approach,[51] a modified version of Newton's equation describing the translational motion of a Skyrmion domain[52] is derived by multiplying both sides of Eq. (6) with $\boldsymbol{m}_s\times$ (cross product) and then with $\boldsymbol{m}_s\cdot$ (dot product), and integrating the resulting equation over the area around the Skyrmion or the Skyrmion domain finally[46] the following equation is obtained:

$$\begin{aligned}&\boldsymbol{G}\times\dot{R}+\tilde{\alpha}\boldsymbol{D}\cdot\dot{R}=\boldsymbol{F}_{\rm c}+\boldsymbol{F}_{\rm m}+\boldsymbol{F}_{\rm pin},\\ &G_i=\varepsilon_{ijk}\int{\rm d}^2r\frac{1}{2}\boldsymbol{m}_s\cdot(\partial_j\boldsymbol{m}_s\times\partial_k\boldsymbol{m}_s),\\ &D_{ij}=\int{\rm d}^2r\partial_i\boldsymbol{m}_s\cdot\partial_j\boldsymbol{m}_s,\\ &D'_{ij}=\int{\rm d}^2r\,[\boldsymbol{m}_s\cdot(\partial_l\boldsymbol{m}_s\times\partial_i\boldsymbol{m}_s)]\,[\boldsymbol{m}_s\cdot(\partial_l\boldsymbol{m}_s\times\partial_j\boldsymbol{m}_s)],\\ &\boldsymbol{F}_{\rm c}=\boldsymbol{G}\times\boldsymbol{v}_s+\tilde{\beta}\boldsymbol{D}\cdot\boldsymbol{v}_s,\quad\boldsymbol{F}_{\rm m}=-\boldsymbol{G}\times\mathbf{J}-\beta_s\boldsymbol{D}\cdot J,\\ &\tilde{\alpha}=\alpha+\frac{\alpha'D'}{D},\quad\tilde{\beta}=\beta+\frac{\beta'D'}{D}.\end{aligned}\tag{7}$$

Here the first term on the left-hand side of the above equation describes the Magnus force. The gyromagnetic coupling vector $\boldsymbol{G}=-4\pi\boldsymbol{e}_z$ with $\boldsymbol{e}_z$ being the unit vector along the z direction or the direction of the applied field. $\dot{R}=\partial_t\boldsymbol{R}$ is the drift velocity of the Skyrmion. The second term represents the friction of the Skyrmion. The components D_{ij} of the tensor $\boldsymbol{D}$ are $D_{xx}=D_{yy}=D$ and 0 otherwise. Similarly, the components D'_{ij} of the tensor $\boldsymbol{D}'$ are $D'_{xx}=D'_{yy}=D'$ and 0 otherwise. The first and second term on the right-hand side are the forces on Skyrmions arising from electric current ($\boldsymbol{F}_{\rm c}$) and magnonic current or temperature gradient ($\boldsymbol{F}_{\rm m}$). The third term $\boldsymbol{F}_{\rm pin}$ is the force acting on the spin texture from the boundaries, impurities, magnetic field, etc. Our attention focuses on the motion driven by the current transverse to the edge. The Skyrmions are affected by a repulsive potential from the boundary only within a range of about a size of a Skyrmion, and cannot reach the boundary because it cannot overcome the repulsive potential if the electric current density is not over 10^{11} A/cm^2.[53] So it is reasonable to neglect the effect of boundary when Skyrmions are far from the boundary. The $\boldsymbol{F}_{\rm pin}$ can be neglected also when $|G\boldsymbol{v}_s|\gg|\boldsymbol{F}_{\rm pin}|$ is satisfied.[54]

4. Control of the Hall angle

For the steady translation motion, the magnetization profile of a rigid Skyrmion domain is represented by $\boldsymbol{m}_s(\boldsymbol{r},t)=\boldsymbol{m}_s(\boldsymbol{r}-\boldsymbol{R}(t))$ where $\boldsymbol{R}(t)=\boldsymbol{v}_{\rm d}t$, $\boldsymbol{v}_{\rm d}$ is the drift velocity of the Skyrmion,[36,37,54] when the electric current is flowing in the x direction while the magnon current is flowing in the y direction as shown in Fig. 1. The present situation can be described by setting $v_{sy}=J_y=0$, $\boldsymbol{F}_{\rm pin}=0$, $v_{sx}=v_s$ and $J_x=J$ in Eq. (7). The resulting drift velocity components perpendicular and parallel to the flow direction of the electric current read

$$v_{{\rm d}x}=\frac{\eta(\beta_s-\tilde{\alpha})J+(1+\eta^2\tilde{\alpha}\tilde{\beta})v_s}{1+\eta^2\tilde{\alpha}^2},\tag{8}$$

$$v_{{\rm d}y}=\frac{-(1+\eta^2\tilde{\alpha}\beta_s)J+\eta(\tilde{\beta}-\tilde{\alpha})v_s}{1+\eta^2\tilde{\alpha}^2},\tag{9}$$

where $\eta = D/4\pi$ is dimensionless, which encodes the information about the strength $D_{\rm d}$ of the DMI and the applied field $\boldsymbol{H}_{\rm ext}$ is called the form factor (or shape factor) of a Skyrmion.[29] Generally the form factor is close to unity.[36,55]

Inserting the outcome of the previous section into the definition of the Hall angle $\theta_{\rm H}$, we have

$$\tan\theta_{\rm H} = \frac{v_{{\rm d}y}}{v_{{\rm d}x}} = \frac{-\left(1+\eta^2\tilde{\alpha}\beta_{\rm s}\right)\frac{J}{v_{\rm s}} + \eta\left(\tilde{\beta}-\tilde{\alpha}\right)}{\eta\left(\beta_{\rm s}-\tilde{\alpha}\right)\frac{J}{v_{\rm s}} + \left(1+\eta^2\tilde{\alpha}\tilde{\beta}\right)}. \quad (10)$$

From Eq. (10), it is evident that $\tan\theta_{\rm H} \to \infty$ or $\theta_{\rm H} \approx \pi/2$ as $J/v_{\rm s} \to -1/\eta\left(\beta_{\rm s}-\tilde{\alpha}\right)$, and $\tan\theta_{\rm H} \to -1/\eta\left(\beta_{\rm s}-\tilde{\alpha}\right)$ or $\theta_{\rm H} \approx -\pi/2$ as $J/v_{\rm s} \to \infty$. In Fig. 2, we show the dependence of the Hall angle on the ratio of magnon current density induced by the thermal gradient to electric current density for typical parameters. So the maximal (minimal) Hall angle approaches $\pi/2$ $(-\pi/2)$. Thus the Hall angle can be controlled in a wide range, which is useful in spintronics.

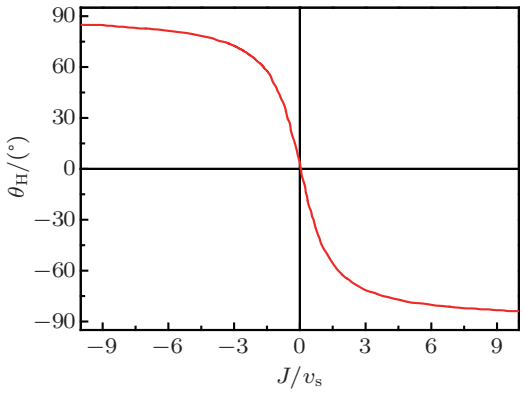


Fig. 2. (color online) Dependence of the Hall angle on $J/v_{\rm s}$. For estimates we have taken $\tilde{\alpha}$= 0.021, $\tilde{\beta}$= 0.045, $\beta_{\rm s}$= 0.032, and $\eta = 1.4$.

5. Skyrmion valve

Finally, we propose a Skyrmion valve in confined geometries based on the control of the Hall angle. The setup of the Skyrmion valve is shown in Fig. 1. The Skyrmion can indeed be drained by an additional terminal, like the setup reported by Jiang *et al.*[56] Then the Skyrmion will be driven by the Magnus force and the dissipative force, and may arrive at any of the edges of the thin film. Subsequently, the repulsive potential of the boundary induces a motion transverse to the boundary because of the Magnus force,[53,54,57] and eventually the Skyrmions would move along the edges from left to right due to the edge effect.

Generally, $\beta_{\rm s} \sim \tilde{\alpha} \sim \tilde{\beta} \sim 10^{-1} - 10^{-3} \ll 1$, so $\tilde{\alpha}\tilde{\beta} \sim \tilde{\alpha}\beta_{\rm s} \sim 0$. Under these conditions the Hall angle can be reduced into

$$\theta_{\rm H} \approx \tan^{-1}\left(\frac{-\frac{J}{v_{\rm s}} + \eta\left(\tilde{\beta}-\tilde{\alpha}\right)}{\eta\left(\beta_{\rm s}-\tilde{\alpha}\right)\frac{J}{v_{\rm s}} + 1}\right). \quad (11)$$

The Skyrmion would move along the A channel when $\theta_{\rm C} < \theta_{\rm H}$, that is,

$$-\frac{1}{\eta(\beta_{\rm s}-\tilde{\alpha})} < \frac{J}{v_{\rm s}} < \frac{\eta\left(\tilde{\beta}-\tilde{\alpha}\right) - \tan\theta_{\rm C}}{1+\eta\left(\beta_{\rm s}-\tilde{\alpha}\right)\tan\theta_{\rm C}}, \quad (12)$$

where the critical angle $\theta_{\rm C} = \tan^{-1}(d/L)$, and $\eta(\tilde{\beta}-\tilde{\alpha})$ is neglected since $\tan\theta_{\rm C} \gg \eta(\tilde{\beta}-\tilde{\alpha})$ is satisfied usually.

Obviously, there is an equilibrium between the transverse force induced by electric current and the longitudinal forces induced by magnon current when

$$\frac{J}{v_{\rm s}} = -\frac{1}{\eta(\beta_{\rm s}-\tilde{\alpha})}. \quad (13)$$

When the equilibrium is reached, the value of $\beta_{\rm s}$ becomes

$$\beta_{\rm s} = \tilde{\alpha} - \frac{1}{\eta}\frac{v_{\rm s}}{J}. \quad (14)$$

This provides a method to measure $\beta_{\rm s}$ with the Skyrmion valve if the parameters $\tilde{\alpha}$ and η are known. Obviously, there are no Skyrmions flowing from left to right when $J/v_{\rm s} \leq -1/\eta(\beta_{\rm s}-\tilde{\alpha})$.

Similarly, the Skyrmion would move along the C channel when $\theta_{\rm H} < -\theta_{\rm C}$, that is,

$$\frac{\eta\left(\tilde{\beta}-\tilde{\alpha}\right) + \tan\theta_{\rm C}}{1-\eta\left(\beta_{\rm s}-\tilde{\alpha}\right)\tan\theta_{\rm C}} < \frac{J}{v_{\rm s}}. \quad (15)$$

The Skyrmion would move along the B channel when $-\theta_{\rm C} < \theta_{\rm H} < \theta_{\rm C}$, that is,

$$\frac{\eta\left(\tilde{\beta}-\tilde{\alpha}\right) - \tan\theta_{\rm C}}{1+\eta\left(\beta_{\rm s}-\tilde{\alpha}\right)\tan\theta_{\rm C}} < \frac{J}{v_{\rm s}} < \frac{\eta\left(\tilde{\beta}-\tilde{\alpha}\right) + \tan\theta_{\rm C}}{1-\eta\left(\beta_{\rm s}-\tilde{\alpha}\right)\tan\theta_{\rm C}}. \quad (16)$$

6. Conclusions

In this work, the Skyrmion dynamics under an electric current and a thermal gradient in a metallic chiral magnet is studied. Based on the LLGS equation the dynamic equation for Skyrmions is derived. The results show that the Hall angle can be controlled when magnonic current is perpendicular to electric current. Using this property, the proposed design of the Skyrmion valve in confined geometries can be used to move Skyrmions along a desired channel. Besides, a new method of measuring dissipative correction of thermo-magnonic torque is provided.

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