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Remarkably enhanced current-driven 360° domain wall motion in nanostripe by tuning in-plane biaxial anisotropy

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By micromagnetic simulations, we study the current-driven 360° domain wall (360DW) motion in ferromagnetic nanostripe with an in-plane biaxial anisotropy. We observe the critical annihilation current of 360° domain wall can be enhanced through such a type of anisotropy, the reason of which is the suppression of out-of-plane magnetic moments generated simultaneously with domain-wall motion. In details, We have found that the domain-wall width is only related to $K_y - K_x$ with $K_{x(y)}$ the anisotropy constant in $x(y)$ direction. Taking domain-wall width into consideration, a prior choice is to keep $K_y \approx K_x$ with large enough K . The mode of domain-wall motion has been investigated as well. The traveling-wave-motion region increases with K , while the average DW velocity is almost unchanged. Another noteworthy feature is that a Walker-breakdown-like motion exists before annihilation. In this region, though domain wall moves with an oscillating behavior, the average velocity does not reduce dramatically, but even rise again for a large K .

Current-induced domain wall (DW) motion, which has potential application to the next generation data storage¹ and logic devices², has attracted much interest in recent years. The motion of transverse domain wall (TDW) due to a spin transfer torque of electrons has been extensively studied^{3–11}. For instance, it is well known that the velocity of TDW increases linearly with the applied current. However, for a driven current larger than a critical value, TDW motion would suffer from Walker breakdown^{12–14}. Recently, 360° domain wall (360DW), which is formed by the combination of two TDWs with opposite orientations, has attracted much attention^{15–33}. One of the advantages is that 360DW shows much weaker stray field as compared to TDW, allowing more stable packing density²⁷. The field- and current-driven behaviors of 360DW also differ qualitatively from those of TDW¹⁸. For example, 360DW may move along a magnetic stripe like TDW under a small driven current, but it will annihilate when the driven current is above a critical value u_c ^{18,26,33}. These characteristics may lead to interesting applications to DW devices^{16,18,20,24,25}, and may be also more suitable for building racetrack memory^{27,28,30,32}. Unfortunately, the annihilation current for 360DW is significantly small, even smaller than the Walker breakdown current of its constituent part, i.e., a TDW. Even though the annihilation may give rise to the application of spin-wave generators¹⁸, it may be unfavorable to other application (such as racetrack memory) where fast domain-wall motion is demanded. This poses a challenge to enhance the stability of 360DW under large current, i.e., to raise the critical current u_c for the annihilation.

Recently, there are intriguing experimental progresses on biaxial anisotropy materials^{34,35}. It is known such a magnetic anisotropy plays a crucial role in domain-wall formation as well as propagation. One may also expect this kind of anisotropy may be useful for 360DW case. On one side, 360DW is created from two transverse 180DWs, which have opposite topological charges. It is then stabilized through a balance between exchange and demagnetization energies, however, the stability of which may be broken by increasing of out-of-plane magnetic moment generated by fast domain-wall motion, where attractive demagnetization energies reduce accordingly^{26,33}. On the other side, supposing magnetic moments are constrained in xy plane, then the degree of spin freedom is reduced to 1. Thus 360DW corresponds to a nonsingular topological object, i.e., kink in the 1d xy model^{36,37}. However, this topological protection would be broken without such a constraint, since z -component

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Figure 1. Schematic illustration of the magnetic nanostripe. x , y and z directions are listed in the left corner. A 360DW is initially placed in the center of the stripe. For simplicity, only domain-wall part is presented.

of magnetic moments easily lowers the energy of a kink, or equivalently, there is no topological object in 1d classical Heisenberg model^{36,37}. Therefore, a suppression of out-of-plane magnetic moment by means of in-plane magnetic anisotropy may be feasible and necessary.

In this paper, we study the effects of a biaxial magnetic anisotropy on current-driven behavior of 360DW in a magnetic nanostripe by micromagnetic simulations. For simplicity, we consider a situation where two easy axes locate at x and y directions, respectively (see Fig. 1 for more details). We have found that the domain-wall width is only related to $K_y - K_x$. In principle, for a given K_x , u_c would always increase with K_y . However, for $K_y > K_x$, domain-wall width is broadening considerably. Thus, a prior solution is to keep $K_y \approx K_x$ with a possibly largest K . We also observe two types of domain-wall motion before annihilation. In the range of small current, the average velocity of 360DW increases linearly with the current (traveling-wave motion) and is almost independent of the in-plane biaxial anisotropy. On the other side, in the range of large current, the displacement, time-dependent velocity and the out-of-plane magnetic moment of 360DW oscillate synchronously, exhibiting a Walker-breakdown-like behavior, while the structure of 360DW keeps stable. The average velocity of 360DW does not reduce dramatically, or even re-rise for a large enough K .

Model

As shown in Fig. 1, the magnetic nanostripe (Permalloy stripe) used in this paper is 4096 nm long in the x direction, 48 nm wide in the y direction and 5 nm thick in the z direction. For a thin enough film, the magnetization in the z direction should be uniform. Thus we can treat such a system as a two-dimensional one. In the initial state, a 360DW is placed in the center of the nanostripe. In such a magnetic nanostripe, there are sizeable distortions occurring in left-end and right-end edges of the stripe, which may somewhat affect the dynamics of the DWs. In order to avoid the distortions, the local magnetization in the left-end and right-end edges of the stripe are pinned in plane. The Hamiltonian of the stripe with magnetic anisotropy can be written as

$$H = -J_{ex} \sum_{\langle i,j \rangle} \mathbf{M}_i \cdot \mathbf{M}_j - \sum_i K_\alpha (M_i^\alpha)^2 + \frac{\omega}{2} \sum_{i \neq j} \left[\frac{\mathbf{M}_i \cdot \mathbf{M}_j}{r_{ij}^3} - 3 \frac{(\mathbf{r}_{ij} \cdot \mathbf{M}_i)(\mathbf{r}_{ij} \cdot \mathbf{M}_j)}{r_{ij}^5} \right] \quad (1)$$

where $\mathbf{M}_i$ and $\mathbf{M}_j$ are the unit magnetization vector for cells i and j . J_{ex} is the exchange coupling constant for nearest neighbor cells. K_α (>0) is the anisotropic constant, and α can be x , y or z . The third term is the long-range dipole-dipole coupling, where $\mathbf{r}_{ij}$ denotes the lattice vector between cells i and j . ω is the dipole-dipole coupling parameter. The saturation magnetization and the exchange stiffness used in this paper are $M_s = 8.6 \times 10^5$ A/m and $A = 1.3 \times 10^{-11}$ J/m, respectively. Parameters J_{ex} and ω can be obtained by $J_{ex} = Aa$ and $\omega = \frac{\mu_0}{4\pi} M_s^2 V_{cell}$ ^{38,39}, where $V_{cell} = a^2b$.

Result

Biaxial anisotropy case with $K_x = K_y$. Based on a sequence of calculations, we find an effective way to enhance u_c by taking both easy x -axis and y -axis anisotropy into account. Figure 2 shows average velocity $\langle v \rangle$ (defined by a convergent value of displacement over time) of 360DW as a function of spin current velocity u with different values of biaxial anisotropy, where $K_x = K_y$ and $K_z = 0$ have been set. As a benchmark, we plot $u - \langle v \rangle$ curve of TDW with $K_x = K_y = K_z = 0$ in Fig. 2(a) as well (It should be noticed that, anisotropy can also enlarge the Walker breakdown current u_w of TDW^{40,41}). One could immediately see that, without any uniaxial anisotropy, the $\langle v \rangle$ of 360DW soon annihilates thoroughly after a short linear increasing region. We then define the annihilation point as the critical current u_c . Here, a vortex core emerges first and soon move out of the nanostripe. Thus the annihilation is irreversible. As a contrast, an antivortex appears in TDW case, which induces an oscillation in both the magnetic configuration and the velocity¹⁸. As u further increases, TDW would turn into a vortex wall, and one can observe the rapid increment of $\langle v \rangle$ for the vortex wall. Another distinction is u_c is significantly smaller than the benchmark u_w , which has also been reported before^{18,26,33}.

In Fig. 2(b), we take $K_x = K_y > 0$ into account, one can see both u_c and linear increasing region indeed increase with $K_{x(y)}$, and can easily go beyond u_w . In addition, one can notice there are two or three regions of domain-wall motion before it annihilates, depending on the strength of anisotropy. Taking the curve $K_x = K_y = 292$ KJ/m³ as an example, in the first region, i.e., $u < 81$ m/s, the average velocity of 360DW just increases linearly with the current. In fact, comparing to the other values of $K_{x(y)}$, the linear slope is almost unchanged. One then can deduce that biaxial anisotropy does not need any expense of DW velocity. When u is larger than 81 m/s, an oscillating region emerges, and $\langle v \rangle$ slightly drops. At last, only in the case of large anisotropy, as in this example, we observe an re-ascendance region just before annihilation.

Figure 2. Average velocity $\langle v \rangle$ of TDW and 360DW as a function of spin current velocity u with different in-plane biaxial anisotropy (solid symbols), where $K_x = K_y$ and $K_z = 0$ have been set. The dotted lines and dashed line denote the critical current u_c for the annihilation of 360DW and the Walker breakdown current u_w of TDW, respectively. m_z is the z -axis component of total magnetic moment of the 360DW, which is calculated within the area of 360DW (ranges about 120 nm in x and 48 nm in y). The average magnetization $\langle m_z \rangle$ for $K_x = K_y = 292 \text{ KJ/m}^3$ is plot with open orange squares.

It is known that domain-wall velocity depends on both u and m_z , where m_z denotes the z -axis component of total magnetic moment of 360DW, which is calculated within the area of 360DW (ranges about 120 in x and 48 nm in y). Since u simply increases here, we plot the corresponding average magnetization in z direction $\langle m_z \rangle$ (defined by an average value of m_z in the same time interval) to explore the possible reason behind this unique behavior. As displayed by the open orange square, one can see: 1) $\langle m_z \rangle$ simply increases in the first linearly increasing region; 2) in the slightly dropped region, the decline of $\langle m_z \rangle$ compete with the ascent of u ; 3) in the last region, $\langle m_z \rangle$ increases again and leads to the second rise of $\langle v \rangle$.

To explore the characteristic of domain-wall motion further, we present the details of these three types of domain-wall motion in Fig. 3, adopting $u = 53 \text{ m/s}$, 165 m/s and 245 m/s with $K_x = K_y = 292 \text{ KJ/m}^3$ as three typical examples. In Fig. 3(a), we show the displacement of 360DW. In the case of $u = 53 \text{ m/s}$, 360DW exhibits a stationary behavior and moves rigidly with a stationary velocity. Whereas for $u = 165 \text{ m/s}$ and 245 m/s , 360DW moves with a oscillation behavior. For a better sense of 360DW motion, we further present instant time-dependent velocity v and the z -axis component of the magnetic moment m_z of 360DW as a function of time in Fig. 3(b,c), respectively. One can notice, for $u = 53 \text{ m/s}$, both v and m_z soon become constant. As a contrast, for the cases of $u = 165 \text{ m/s}$ and 245 m/s , v and m_z show quasi-periodical oscillations, and the position of peaks and valleys match exactly to the displacement. The oscillation results in the poor linearity of $\langle v \rangle - u$ characteristic in the range of $u > 81 \text{ m/s}$ (shown in Fig. 2(b)), presenting a Walker-breakdown behavior. Interestingly, the average velocity of 360DW in large current does not reduce dramatically.

We also plot the domain-wall snapshots at the peaks and valleys. As shown in Fig. 3(d–g), one can see the 360DW expands and contracts quasi-periodically, however, keeps stable. When 360DW contracts, both m_z and velocity increase. On the other hand, the expansion would oppose motion. As a result, one could observe a Walker-breakdown-like behavior. This mechanism is different to the stalled anti-vortex nucleation⁴² or a complete suppression of the anti-vortex¹⁴ in the TDW case.

Various combination of anisotropy. In order to further understand the effective enhancement of u_c caused by the biaxial anisotropy with $K_x = K_y$, we then investigate the effects of various combination of biaxial anisotropy on u_c for a comparison. We first start with the simplest case, i.e., uniaxial anisotropy.

In Fig. 4, we present the results with only x -direction anisotropy. One can see that in subpanel (a), u_c decreases with the increasing of K_x , and subpanels (b)–(d) show the local magnetization in x , y and z directions, respectively. From all plots of magnetization, one can see that domain-wall width shrinks (we define the domain-wall width as the region of $M_z \neq 0$ or $M_x \neq M_y$). However, the maximum of M_x and M_y almost not change, while the peak of M_z increases. It suggests that the width of 360DW as well as M_z plays an important role to u_c . In the case of increasing K_x , the width of 360DW should decrease. Then, the local magnetization vector near and at the area of 360DW should turn out of plane to reduce the exchange coupling energy. As a result, the M_z of the 360DW increases, which deduces the contribution of demagnetization energy, leading to the decreasing of u_c .

Figure 3. (a) Displacement, (b) time-dependent velocity v and (c) the z-axis component of the magnetic moment m_z of 360DW as a function of time under different currents. The biaxial anisotropy is set as $K_x = K_y = 292 \text{ KJ/m}^3$. (d,e) The domain-wall snapshots at the peaks for $u = 245 \text{ m/s}$ and $u = 165 \text{ m/s}$, respectively. (f,g) The domain-wall snapshots at the valleys for $u = 245 \text{ m/s}$ and $u = 165 \text{ m/s}$, respectively.

Figure 4. (a) Critical current u_c for the annihilation of 360DW as a function of K_x , where $K_z = 0$ and $K_y = 0$ have been set. (b) The x-axis component M_x , (c) The y-axis component M_y , and (d) The z-axis component M_z of the local magnetization on $y = 24 \text{ nm}$ as a function of x with different K_x , where small current $u = 37 \text{ m/s}$ is applied.

Figure 5. (a) Critical current u_c for the annihilation of 360DW as a function of K_y , where $K_x = 0$ and $K_z = 0$ have been set. (b) The x -axis component M_x , (c) The y -axis component M_y and (d) The z -axis component M_z of the local magnetization on $y = 24$ nm as a function of x with different K_y , where small current $u = 37$ m/s is applied.

Figure 6. (a) Critical current u_c for the annihilation of 360DW as a function of $K_x = K_y$, where $K_z = 0$ have been set. (b) The x -axis component M_x , (c) The y -axis component M_y and (d) The z -axis component M_z of the local magnetization on $y = 24$ nm as a function of x with different $K_x = K_y$, where small current $u = 37$ m/s is applied.

We now turn to the case with only K_y . As shown in Fig. 5. One can observe that both u_c and domain-wall width increases with the increasing of K_y in Fig. 5(a–d), respectively. As a contrast to the result under only $K_x \neq 0$, the width of 360DW now increases with K_y . Another characteristic is only the maximum of M_z shown in Fig. 5(d)

Figure 7. Contour plot of domain-wall width against K_x and K_y .

Figure 8. Contour plot of critical current u_c against K_x and K_y .

decreases with K_y , which supports the significance of M_z . As K_y increasing, the descend of M_z mainly comes from the in-plane anisotropic field. The increasing of u_c can be owed to the decreasing of the M_z of 360DW, preserving the demagnetization energy. Even though the u_c can be enhanced by tuning K_y , it is not a good choice because the width of 360DW is significantly enhanced, which is not suitable for practical use.

Based on the results shown in Figs 4 and 5, one can naturally realize that u_c may be effectively enhanced simultaneously with a fixed DW width by the combination of K_x and K_y . As shown in Fig. 6(a–d), u_c indeed increases with equal biaxial anisotropy, i.e., $K_x = K_y$, and the width of 360DW almost remains unchanged due to the different effects of K_x and K_y on DW width. The increasing of u_c is owed to the decreasing of the M_z of 360DW, which is demonstrated clearly in Fig. 6(d).

In the Fig. 7, we plot the contour plot of domain-wall width against K_x and K_y . It can be clearly seen from the plot that the domain-wall width only depends on the value of $K_y - K_x$. As for $K_x > K_y$, i.e., the lower right part of Fig. 7, domain-wall width increases slowly with the value of $K_y - K_x$. One can see that from $K_x - K_y = 125 \text{ kJ/m}^3$ to $K_x = K_y$, the width only changes from 72 to 155. However, as for $K_y > K_x$, i.e., the upper left part of Fig. 7, the width increases rapidly from 155 nm to 280 nm, corresponding $K_y = K_x$ to $K_y - K_x = 40 \text{ kJ/m}^3$. Besides these regions, 360DW becomes unstable in our simulations, which corresponds to the white area in the contour plot.

We finally plot the contour plot of u_c against K_x and K_y in the Fig. 8. From the contour plot, one can learn that in principle, u_c would always increase with K_y for a fixed K_x . However, for $K_y > K_x$, domain-wall width is broadening considerably. Thus, a prior solution is to keep $K_y \approx K_x$ with a possibly largest K_x .

Discussion

Though previous work mainly focuses on the theoretical simulation, we notice that materials with a biaxial anisotropy have already been realized experimentally, examples ranges from CoFe_2O_4 films on (100) MgO substrates³⁴ to Fe films on BaTiO_3 substrates³⁵. 360DW on those materials as well as related applications may need further study.

Conclusions

We have found the motion of 360DW can be well promoted by introducing an biaxial anisotropy. In general, the critical annihilation current of 360DW would always increase with K_y . However, taking domain-wall width into consideration, we found the case of $K_x \approx K_y$ would be a better choice. In this case, the width of 360DW almost remains unchanged due to the different effects of K_x and K_y on DW width, meanwhile, out-of-plane magnetic moments are suppressed. We also observe two types of DW motion. For the range of small current, both the linearity and slope of velocity-current characteristics remains unchanged, i.e., independent to the anisotropy. On the other side, for large current, though a Walker-breakdown-like behavior appears, the average velocity of 360DW does not reduce dramatically. We hope our findings could shed lights on the potential applications of 360DW.

Method

In simulations, the unit cell size ($a \times a \times b$) is $4 \text{ nm} \times 4 \text{ nm} \times 5 \text{ nm}$. In order to minimize the edge effect of demagnetization energy in the moving direction, a scheme that keeps the 360DW centered in the stripe has been used. We use the Landau-lifshitz-Gilbert (LLG) equation with additional adiabatic and nonadiabatic spin-transfer torque^{43,44} to describe the magnetization dynamics. When the current is applied along $+x$ direction, the LLG equation is

$$\frac{\partial \mathbf{M}}{\partial t} = -\gamma \mathbf{M} \times \mathbf{H}_{\text{eff}} + \alpha \mathbf{M} \times \frac{\partial \mathbf{M}}{\partial t} + u \mathbf{M} \times \left(\mathbf{M} \times \frac{\partial \mathbf{M}}{\partial x} \right) + \beta u \mathbf{M} \times \frac{\partial \mathbf{M}}{\partial x}, \quad (2)$$

where $\mathbf{H}_{\text{eff}} = -\frac{\partial H}{\partial \mathbf{M}}$ is the effective field acting on the unit magnetization vector $\mathbf{M}$, γ is the gyromagnetic ratio, α is the Gilbert damping constant, β denotes the non-adiabatic spin torque coefficient, u is the spin current velocity defined as $u = jPg\mu_B/2eM_s$ with P the spin polarization, j the current density, μ_B the Bohr magneton and e the electron charge, respectively. In this paper, we set $\alpha = 0.01$ and $\beta = 0.05$ according to previous works^{18,44}.

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Author Contributions

Y.C.S. and J.G.H. conceived the idea. Y.C.S., L.H.W. and W.J.D. performed simulations. Y.C.S., W.J.D., L.H.W. and B.X. plot figures. Y.C.S., B.X., X. R. and J.G.H. wrote the manuscript. All authors contributed to the analysis, reviewed and commented on the manuscript.

Additional Information

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