Domain wall motion driven by an oscillating magnetic field

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Abstract

The coherent unidirectional motion of magnetic domain walls (DWs) is a key technology used in memory and logic device applications, as demonstrated in magnetic strips by electric current flow as well as in films by oscillation of a tilted magnetic field. Here we introduce a coherent unidirectional motion of DWs in the strip, utilizing an oscillating field, which is described within a previous 1D model. The essential criterion for DW motion in this approach is the oscillating-field-induced modulation of the DW width, which has not been previously considered. This DW motion driven by width modulation sheds light on high frequency domain manipulation in spin devices. A comprehensive inspection of field angle dependence reveals that unidirectional DW motion in this model requires chiral DWs, followed by asymmetric deformation of the domain shape.

Keywords: domain wall motion, oscillating magnetic field, chirality, domain wall width

(Some figures may appear in colour only in the online journal)

1. Introduction

The coherent unidirectional motion of domain walls (DWs) has been an important issue in magnetics due to its potential possibilities in future spin devices [1–4], such as the racetrack memory [1]. The racetrack memory utilizes the DW motion in a magnetic wire to move the information. Between two neighboring domains of opposite magnetizations, the magnetization gradually changes its direction across the DW. Thus, the motion of DWs should be coherent and unidirectional along the wire for an information process without information loss. Such motion has been achieved by electric current injection [1–6] into the wire. The current-induced DW motion requires high current density for observable motions, thus patterned wire structure is good for the motion. This means the current-based method is suitable for a local magnetization shift.

Recently, a complementary method for the DW motion has been suggested. This method uses a magnetic field. A static magnetic field expands or shrinks domains, and thus finally erases the information. On the other hand, an oscillating magnetic field could produce effective motion during forward and backward motions of the DW [7–11]. This oscillating-field-based method was proven by experiments using a low frequency field (<1 kHz) with large circular domains [9, 10] and by numerical simulations with a skyrmion of nanometre size [11]. Note that the field-based method is useful for motion of the global magnetization because the generation of the uniform field is relatively easy rather than the generation of the localized one. Thus, the field-based method is suitable for massively parallel racetrack memories, as Hoffman and Bader have pointed out [12].

All of the previous results on oscillating field methods show the shift of the magnetization state in films rather than wires. Therefore, we will report studies on DW motions driven by an oscillating magnetic field in wires using the frame of a one-dimensional (1D) model of DW dynamics. This 1D approach...
has been widely used for the description of DW dynamics for simplicity [13–20]. The term ‘1D’ in this context means that the magnetization directions vary with respect to only one space axis, thus 1D-DW is useful for studying DWs in narrow wires.

Figure 1(a) shows such a 1D-DW structure. There are up and down domains having \(+z\) and \(-z\) magnetization, respectively. Between two domains, the magnetization starts a gradual rotation from the \(+z\)-direction towards the \(-z\)-direction to link two opposite magnetization directions. To minimize the exchange and the anisotropy energy, this magnetization rotation occurs within a relatively short scale known as the DW width, \(\Delta\). Because of the magnetization rotation, the DW inevitably has a pure in-plane (\(x-y\) plane) magnetization at a DW position, \(q\). Such in-plane magnetization has a freedom for an azimuthal angle, \(\psi\). In the early days of the 1D-DW studies, these three parameters \((q, \Delta, \psi)\) have been used as time-dependent variables [14–16]. However, the effect of the variation in \(\Delta\) is known to be relatively small; thus, \(\Delta\) values have been generally treated as a constant until now [17–20]. In contrast, our results demonstrated the importance of \(\Delta\) oscillation in the DW motion. Once we treat \(\Delta\) as a time-dependent variable, we can expect an unprecedented mechanism for the DW motion. To show the core aspects of the motion, we employed two methods. One method uses micromagnetic simulations and the other uses analytic equations.

2. Results

2.1. Micromagnetic simulation detail

To verify the mechanism, we performed micromagnetic simulations using the OOMMF code [21] with the Dzyaloshinskii–Moriya interaction (DMI) extension module [22–24]. Material parameters were used for perpendicular magnetization as follows. The saturation magnetization \(M_s\) was 580 kA m\(^{-1}\), the exchange stiffness \(A\) was 15 pJ m\(^{-1}\), the uniaxial magnetic anisotropy \(K_{1}\) was 0.8 MJ m\(^{-3}\) to the \(z\)-direction, and the DMI constant \(D\) was 0 for Bloch DW (figures 1 and 2) or \(-3.5\) mJ m\(^{-2}\) for DMI–Néel DW (figure 3). We used a relatively large damping constant \(\alpha\) of 0.3 to maintain the values of the Co/Pt films [25, 26]. All these parameters have been widely used in several studies [11, 27, 28].

The entire simulation structure was 2 \(\mu m\) in length in the \(x\)-direction, and the thickness \((d)\) in the \(z\)-direction was set to 0.4 nm. The length of the simulation structure in the \(y\)-direction was 1 nm. The unit cell was selected as 1 nm \(\times\) 1 nm \(\times\) 0.4 nm. We used a periodic boundary condition along the \(y\)-direction to remove the \(y\)-directional demagnetization field. Such boundary conditions resulted in a similar situation with the 1D-DW model that assumed that the DW had no shape or the DW was aligned with the \(y\)-direction. Note that real wires have a finite width of several hundred nanometers [5]. We think such a finite width makes no significant error in our study because the wire width is much larger than the length scale of the width of DW (\(\sim10\) nm) [26].

This large difference induces a negligible demagnetization field along the \(y\)-direction. Further discussion on the effect of wire width will follow later. The initial DW was placed and stabilized at the centre of the magnetic structure with a zero external field. Then, we applied a global oscillating magnetic field appearing in a spherical coordinate system using \(\dot{\theta}_H\) and \(\dot{\varphi}_H\) with the amplitude, \(H\) (figure 1(b)). \(\theta_H\) is a polar angle from the \(z\)-axis and \(\varphi_H\) is an azimuthal angle from the \(x\)-axis. We assumed a sinusoidal oscillation of the field with respect to time, \(t\). So, \(+H\) and \(-H\) are the maximum and the minimum values of the field. The term \(f (=\omega/2\pi)\) is the oscillation frequency. All results assumed zero temperature.

To obtain the three parameters of DW \((q, \Delta, \psi)\) shown for figure 1, we fitted the normalized perpendicular component of magnetization, \(m_y\), in \(-\tanh((x-q)/\Delta)\). The angle \(\psi\) was
determined by the in-plane angle of magnetization at $x = q$. Note that this fitting process was not perfect because it neglects domain oscillations as well as DW deformations. Nonetheless, this fitting is sufficient to show the existence of the oscillation behaviours of the three parameters of DW, $(q, \Delta, \psi)$.

2.2. Micromagnetic simulation for bloch DW motion

We define the DW state in figure 1(a) as \{up, +y, down\}, where ‘up’, ‘down’, and ‘+y’ denote the magnetization directions of the top-left, bottom-right domains, and the DW, respectively. Generally, $\psi$ energetically prefers $90^\circ$ or $270^\circ$ without DMI ($D = 0$), known as the Bloch DW states [18], and we chose $\psi = 90^\circ$ as the initial state. After turning on the oscillation field at $t = 0$, the magnetization exhibited an initial fluctuation and then finally reached a steady state. Such steady states of $\Delta$ and $\psi$ having oscillation amplitudes $I_\Delta$ and $I_\psi$, respectively, are shown in figure 1(c). Similarly, $q$ also shows oscillation behavior, but average $q$ values increase linearly with respect to $t$, where the slope represents the DW velocity, $V$.

2.3. 1D collective equation for DW motion

To support this simulation, we derived a 1D collective equation for the DW motion that includes the time-dependent $\Delta$ with the external magnetic field; $\mathbf{H} = (H_x, H_y, H_z) \sin \omega t = H \sin \omega t \left( \cos \varphi_H \sin \theta_H, \sin \varphi_H \sin \theta_H, \cos \theta_H \right)$. $H_i$ ($i = x, y, z$) is the field amplitude to the $i$-axis. The conventional 1D collective description for the DW using two spherical coordinate angles of local magnetizations ($\theta_H, \varphi_H$) is

$$\varphi_M(x, t) = \psi(t), \quad \cos \theta_M(x, t) = \tanh \left[ \frac{x - q(t)}{\Delta(t)} \right]. \quad (1)$$

By using the Lagrangian equation for micromagnetic dynamics [13–15] under $\mathbf{H}$ with equation (1), one arrives at

$$\dot{\psi} + \frac{\alpha \dot{q}}{\Delta} = \gamma H_z \sin \omega t, \quad (2a)$$

$$\frac{\dot{q}}{\Delta} - \alpha \psi = \gamma \left[ -\frac{K_u}{M_s} \sin 2\psi + \frac{\pi D}{2M_s \Delta} \sin \psi \right. \right.$$

$$\left. + \frac{\pi}{2} \sin \omega t (H_x \sin \psi - H_z \cos \psi) \right], \quad (2b)$$

$$\Delta = \frac{12 \gamma}{\pi^2 \alpha M_s} \left[ \frac{A}{\Delta} - \Delta (K_{eff} + K_u \cos^2 \psi) \right. \right.$$

$$\left. + \frac{\pi}{2} \Delta M_s \sin \omega t (H_x \cos \psi + H_z \sin \psi) \right]. \quad (2c)$$

Here, $K_u (\approx \mu_0 M^2 S d/(2\pi \Delta_0))$ is wall-type dependent anisotropy energy density with $\Delta_0 = \sqrt{A/K_{eff}}$. The effective perpendicular anisotropy, $K_{eff}$, is $K_{U} = \mu_0 M^2 S/2$ and $\mu_0$ is the permeability.
ϕ ≅ /uni + 2 αω ∝. (c) Velocities and their difference in comparison with ϕH = 0. (d) Gyration amplitudes of domain magnetization as a function of ϕH. The insets show schematics of the elliptic trajectories of the domain gyration (left) and the effective wall-width variation induced by domain tilting (right).

2.4. Analytic equation for Bloch DW motion

We assumed that the external field was sufficiently small and mainly generated harmonic oscillations of ψ and ∆ such that ψ(t) ≅ ψ0 + Iϕ sin(ωt − δϕ) and ∆(t) ≅ Δ0 + IΔ sin(ωt − δΔ). The insertion of these into equation (2a) and integration over one period of oscillation yields

\[ V \approx \frac{I_\Delta}{2\alpha} [\gamma H_\psi \cos \delta_\psi + \omega I_\psi \sin(\delta_\psi - \delta_\phi)]. \] (3)

Moreover, using these assumptions with equations (2b) and (2c) would give information about the oscillation. When we used D = 0 and ψ0 = 90° we obtained

\[ I_\Delta \approx \frac{6\gamma_\Delta \sin \delta_\Delta}{\pi \omega} H_s, \quad \tan \delta_\Delta \approx \frac{\pi^2 \omega^2}{12\gamma H_k}. \]

\[ I_\psi \approx \frac{\gamma \sin \delta_\psi}{(1 + \alpha^2) \omega} \left( H_s - \frac{\pi \alpha}{2} H_s \right), \quad \tan \delta_\psi \approx \frac{1 + \alpha^2 \omega^2}{\gamma \alpha H_s}. \] (4)

Here \( H_k = 2K_{eff} / (\mu_0 M_b) \), \( H_s = 2K_{eff}(\mu_0 M_b) \), \( \gamma \) is the gyromagnetic ratio, \( \delta_\Delta \) and \( \delta_\psi \) are the phases of \( \Delta \) and \( \psi \), respectively. Note that a nonzero \( V \) requires nonzero \( I_\Delta \), which directly points out the importance of time-dependent \( \Delta \) in DW dynamics in this model.

2.5. Field angle dependence of Bloch DW motion

One can rewrite \( V \) as functions of \( H_s \), as well as \( \theta_H \) and \( \varphi_H \). The replacement of \( I_\Delta, I_\psi, \Delta_0, \) and \( \delta_\psi \) with \( H_s \) and material parameters in equation (3) yields

\[ V(H_s, H_s, H_s) \approx C_1 H_s [C_2 H_s + C_3 H_s]. \] (5)

Here, \( C_1, C_2, \) and, \( C_3 \) are constants determined by the material parameters and \( f \). Equation (5) clearly exhibits the dependence of \( V(\varphi_H) \) on both \( \sin \varphi_H \) and \( \sin 2 \varphi_H \), because \( H_s H_s \sin(2 \varphi_H) \) and \( H_s H_s \sin 2 \varphi_H \) for a fixed \( \theta_H \). In figure 2(a), the red curve is the velocity derived from equation (5), which shows good agreement with the simulation results (black circles). Similar results were also obtained for the \{up, −y, down\} DW states shown in figure 2(b). Note that \( V(\varphi_H) \) of the \{up, +y, down\} and \{up, −y, down\} states are interchangeable by a 180° shift in \( \varphi_H \).

Figures 2(a) and (b) also show the \( V(\varphi_H) \) of the \{down, −y, up\} DW state (dotted green curves). These curves provide information on an essential condition for the coherent unidirectional motion of multiple DWs in a strip; the crossing point of velocities of different DW states maintains a finite value. We can combine \{up, +y, down\} and \{down, −y, up\} states into a \{up, +y, down, −y, up\} state with two DWs while maintaining the chirality. Then two DWs have the same and nonzero \( V \) at \( \varphi_H = 90° \) and 270°. This denotes the coherent unidirectional motion of multiple DWs (figure 2(c)). In contrast, when two DWs have the same magnetization direction, such as the \{up, −y, down, −y, up\} state, the crossing point of two Vs in figure 2(b) is located at zero value. Thus, the unidirectional motion is impossible.

Another notable effect of \( V(\varphi_H) \) is a deformation of domain shape, as shown in figure 2(d). When we assume that the large circular domain has aligned DW magnetization to the DW
length direction with fixed chirality (inset of figure 2(d)), every DW at every position can be treated as independent 1D-DWs. Based on this assumption, one could expect asymmetric deformation of the initial circular domain (white dashed line) by the uniform field oscillation. Under the process of this deformation, the coherent unidirectional motions were confined only in the black boxed area at the beginning. Note that this asymmetric deformation is analogous to the recent experimental observation of non-collinear DW motion induced by spin Hall torque [29]. Such non-collinear motion is described by an angle difference between the current direction and the distorted magnetization direction of DW by the spin Hall torque [29, 30].

2.6. DMI–Néel DW motion

We checked the influence of the driving frequency on DWs having fixed chirality. It is well known that DWs can have fixed chirality due to DMI [5, 22–24]. The effect of DMI is similar to inserting an additional in-plane field (DMI field, \( H_{\text{DMI}} \)) [7, 8, 19], which tends to prefer a Néel type DW to a Bloch type DW [7, 18]. If we assumed \( |\psi| \) having fixed chirality. It is well known that DWs can have similar to inserting an additional in-plane field (DMI field, \( H_{\text{DMI}} \)) [7, 8, 19], which tends to prefer a Néel type DW to a Bloch type DW [7, 18]. If we assumed \( |\psi| \) having fixed chirality. It is well known that DWs can have

\[
H_{\Delta} \approx -\frac{6\pi\Delta_0 \sin \delta_{H}}{\pi \omega} H_{\perp}, \quad \tan \delta_{\Delta} \approx \frac{\pi^2 \alpha \omega}{12 \gamma (H_K + H_L)}, \\
I_{\psi} \approx \frac{\gamma \sin \delta_{\psi}}{1 + \alpha^2} \omega \left( H_L + \frac{\pi \alpha \epsilon}{2} H_L \right), \quad \tan \delta_{\psi} \approx \frac{1 + \alpha^2 \omega}{\gamma \alpha (H_D - H_L)}.
\]

(6)

Here, \( H_{\Delta} (=\pi D/2 \mu_0 M_0 \Delta_0) \) is an effective in-plane field known as the DMI field. In equation (6), \( \Delta_0 \) was changed to \( \sqrt{\lambda (K_{\text{eff}} + K_L)} \). Combining equations (3) and (6) gives

\[
V(H_D, H_L, H_{\perp}) \approx C_{1}^{\text{DM}} H_{L} + C_{2}^{\text{DM}} H_{L} + C_{3}^{\text{DM}} H_{L}.
\]

(7)

Here, \( C_{i}^{\text{DM}} (i = 1, 2, 3) \) is a constant. Figure 3(a) shows \( V(\varphi_H) \) obtained from equation (7). When \( f = 5 \text{ GHz}, V(\varphi_H) \) exhibited simple \( \cos \varphi_H \) behavior. This implies that a large circular bubble domain driven by a 5 GHz (low-frequency) field will move toward a field tilting direction, conserving a circular shape. A similar phenomenon was demonstrated by the so-called bubblecade experiment [9]. On the other hand, the circular shape starts to deform at a higher driving \( f \), where \( \cos 2\varphi_H \) dependence in \( V(\varphi_H) \) becomes sizable.

2.7. Difference between simulation and analytic result

The simulation results in figure 3(b) show good agreement with the analytical ones, in particular at low (5 GHz) and high (100 GHz) frequencies. However, at an intermediate value of the driving frequency (60 GHz), the calculated velocity was much smaller than that of the simulation results, although overall the velocity shapes were similar to each other.

Figure 3(c) presents the velocity obtained from both the simulation and equation (7), as well as their difference in comparison with \( \varphi_H = 0 \). This difference reveals the limit of the analytic equation, where the oscillation of the domain is neglected. To verify this, we obtained the oscillation of a uniform domain by the simulations. The oscillations can be simplified by an elliptic gyration. The normalized magnetization gyration has a major \( (a) \) and a minor \( (b) \) radius and the multiple of two radii \( (a \times b) \) denotes the gyration strength (figure 3(d)). As we expected, the result had an almost similar trend to the velocity difference.

3. Discussions

Note that two domains, at each side of the DW, had opposite magnetizations that induced opposite gyration directions. These opposite gyrotations should effectively induce additional DW oscillations. The inset of figure 3(d) depicts this situation. Typically, a DW has a 180° rotation of magnetization in itself to connect two opposite domain magnetizations. However, when the domain has tilted because of domain gyrotations, this tilting requires an additional rotation of magnetization in the DW. These additional angles oscillate because of domain gyrotations that should give rise to an effective \( \Delta \) oscillation for the DW motion.

Deriving the analytical form of the velocity requires intricate calculations, including domain oscillations. Instead, we suggest a simple way to estimate \( V \) using \( ab \). When the applied field frequency is far from the ferromagnetic resonance frequency \( (\approx \gamma K_{\text{eff}}/2 \mu_0 M_0), 62 \text{ GHz for this study}, \), then \( ab \) has negligible values, so we should use the simple velocity obtained in equations (3) and (7). However, when the field frequency is close to the ferromagnetic resonance frequency, the DW velocity has an additional multiplication factor, \((1 + \eta ab)\) that magnifies the velocity of the 1D equation, where \( \eta \) is a constant, and for this study \( \eta = 9.2 \times 10^4 \) is a suitable value.

In this study, we employed the periodic boundary condition along the \( y \)-direction for simplicity. However, realistic wire has finite width. Thus, we performed additional simulations with wire 100 nm wide. In figures 2(a) and 3(c), open square symbols represent the speed of DW in the 100 nm width wire structure. As expected, the finite width makes no significant difference due to the negligible demagnetization field along the \( y \)-direction.

4. Conclusions

To summarize, we report an alternative mechanism for DW motions induced by external magnetic field oscillations based on a 1D approach. The conventional 1D equation for the DW motion does not allow consideration of the domain gyration, so that the velocity cannot be described in the ferromagnetic resonance regime, but our model is sufficient for describing the DW motion under an oscillating magnetic field. Through this 1D-DW model, we found that the DW width oscillation is indispensable for its motion. The 1D model shows the angular dependence of DW motions with respect to the oscillating field angle, from which we obtained the importance of the chiral structure of DWs for coherent unidirectional motions, and we could expect shape deformation of large circular bubble domains. All these methods considered for the DW motion will pave the way to massive spin devices operated, in
particular, at high frequency, because the external field could be used to shift the entire magnetization of the device [9, 12].

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