Metastable magnetic domain wall dynamics

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\textbf{Abstract.} The dynamics of metastable magnetic domain walls in straight ferromagnetic nanowires under spin waves, external magnetic fields and current-induced spin-transfer torque are studied by means of micromagnetic simulations. It is found that in contrast to a stable wall, it is possible to displace a metastable domain wall in the absence of external excitation. In addition, independent of the domain wall excitation method, the velocity of a metastable wall is much smaller than that of a stable wall and its displacement direction could be different from that of the stable wall depending on the structure of metastable walls. Under current-induced spin-transfer torque excitation, the direction of domain wall displacement is directly related to the intensity of non-adiabatic spin-transfer torque. In a rough nanowire, it is found that the displacement of a metastable wall could happen much below the critical excitation of a stable wall. Furthermore, we show that it is possible to have either a forward or a backward displacement of a metastable domain wall by changing the pulse width of the excitation.

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1. Introduction

The study of particle dynamics in a non-equilibrium system such as vortices in superconductors and domain walls in nanostructures has attracted much interest in recent years [1–7]. Recently, researchers investigated the out-of-equilibrium magnetic domain walls, metastable walls, not only because of the fundamental understanding of domain wall dynamics but also because of its technological applicability [8, 9]. The controlled displacement of magnetic domain walls by current-induced spin-transfer torque in a ferromagnetic nanowire is especially important because of its potential applications for next-generation solid-state memories [10, 11], logic [12–14] and microwave devices [15, 16]. In a ferromagnetic nanowire various types of domain walls with different energy states can exist. Typically, only one structure is in the global energy minimum state and forms a stable domain wall, while the other structures form metastable walls depending on the width and thickness of a ferromagnetic nanowire [17, 18]. However, it has been shown experimentally and by micromagnetic simulations that the phase diagram of domain walls could be changed when the domain wall is nucleated by the application of a transverse field [19, 20]. In addition, at an elevated temperature, a domain wall structure can transform into other structures [21, 22]. The thermal effect due to the high current density required for the domain wall displacement can also change the domain wall structure and nucleate a metastable domain wall [23–25].

The displacement of a magnetic domain wall under a magnetic field is expected to depend only on the direction of the magnetic field and on whether the domain wall is head to head or tail to tail, and be independent of domain wall structures. In addition, the domain wall motion induced by spin-transfer torque is anticipated to be related to the direction of the conduction electron flow. Although most experimental results have shown that the magnetic domain wall propagates in the direction of electron flow [23, 26–28], there have been some published works that have observed bi-directional domain wall motion in the presence of unipolar current pulses [29, 30].

In this paper, we have correlated the bi-directional motion with the dynamics of metastable domain walls. We have studied the dynamics of metastable domain walls under different types of excitations and compared it with that of a stable domain wall. It is found that under spin wave excitation, a stable wall always moves in the propagation direction of spin waves, whereas
a metastable wall could displace in the reverse direction until it transforms into a stable wall. In addition, the velocity of a metastable wall is much lower than that of a stable wall. In the case of current-induced domain wall motion, the direction of the metastable wall displacement is strongly related to the non-adiabaticity of spin-transfer torque. In a rough nanowire, it is found that the metastable wall could have a finite displacement in a magnetic field or current, much below the critical field or current density required to displace a stable wall. In addition, depending on the structure of the metastable wall and the excitation pulse width, the metastable wall could have a bi-directional displacement under a unipolar excitation.

The Landau–Lifshitz–Gilbert (LLG) equation including the spin-transfer torques can be written as

$$\frac{\partial M}{\partial t} = -\gamma_0 H_{\text{eff}} \times M + \frac{\alpha}{M_s} M \times \frac{\partial M}{\partial t} + T_a + T_{\text{na}}, \quad (1)$$

where $\gamma_0$ is the gyromagnetic constant. In this equation, $T_a$ and $T_{\text{na}}$ are adiabatic and non-adiabatic torque terms, respectively, and are defined as

$$T_a = -(u \cdot \nabla) M, \quad (2)$$

$$T_{\text{na}} = \frac{\beta}{M_s} M \times [(u \cdot \nabla) M]. \quad (3)$$

The dimensionless coefficient $\beta$ characterizes the non-adiabatic contribution and the $u$ parameter is the effective drift velocity of the conduction electron spins defined by $u = J P g \mu_B / (2e M_s)$, where $J$ is the current density, $P$ is the spin polarization, $\mu_B$ is the Bohr magneton and $e$ is the electron charge. If we assume that $P = 0.7$ and $u = 5 \text{ m s}^{-1}$, the current density is $J = 1.1 \times 10^7 \text{ A cm}^{-2}$.

The structure that we have used in the simulations is shown in figure 1(a). The wire has a width of 100 nm, a thickness of 10 nm and a length of 4 $\mu$m. The simulation cell size is $4 \times 4 \times 10 \text{ nm}^3$ and the nanowire is made of Permalloy (Py) with the saturation magnetization ($M_s$) of $860 \times 10^3 \text{ A m}^{-1}$, the exchange stiffness ($A_{\text{ex}}$) of $1.3 \times 10^{-11} \text{ J m}^{-1}$ and the Gilbert damping constant ($\alpha$) of 0.01. We have located different types of domain walls in the nanowire and measured the total energy of the system. It is found that a transverse wall has the minimum energy of $1.268 \times 10^{-17} \text{ J}$, while the total energy of the nanowire in the presence of a vortex and an antivortex wall is $1.374 \times 10^{-17}$ and $1.474 \times 10^{-17} \text{ J}$, respectively, as shown in figure 1(b). Although the total energy of the nanowire for the vortex and the antivortex is only 8.4 and 16.2%, respectively, larger than that of the transverse wall, we observe drastic changes in the domain wall dynamics in the presence of external excitations such as spin waves, external magnetic fields and current-induced spin-transfer torque. A higher-energy state of the nanowire in the presence of the metastable wall is associated with the energy stored inside the domain wall as anisotropy energy \[33\]. It is possible to release this stored anisotropy energy and transform a metastable wall into a stable wall by overcoming the energy barrier, which is $\Delta E_1$ between the antivortex and the transverse wall, and $\Delta E_2$ between the vortex and the transverse wall in figure 1(b). If the external excitation is strong enough to overcome this energy barrier, the stored energy in a domain wall can displace the domain wall in either the forward or backward direction even after removing the external excitation. It should be pointed out that the reverse of this process happens for the excitation above the Walker breakdown that could transform a stable wall into a metastable wall \[34, 35\]. We first present domain wall dynamics in a perfect nanowire and compare the results with the domain wall automotion equation. Then the domain
wall dynamics in a periodic-rough and a random-rough nanowire are shown and compared with the case of a perfect nanowire.

2. Metastable wall dynamics in perfect nanowires

2.1. Spin wave excitation

In order to generate spin waves, we applied an external magnetic field to the first $4 \times 100 \times 10 \text{nm}^3$ on the left side of the nanowire. The applied field varied sinusoidally in time with frequency ($f$) and amplitude $H_0$ as $H = H_0 \sin(2\pi ft) \hat{y}$ in the $y$-direction. We have used an absorbing boundary condition to prevent spin wave reflection from the edge of the nanowire [32, 36, 37]. Figure 2(a) shows the motion of an antivortex (metastable) wall under spin waves with $f = 16 \text{GHz}$ and $H_0 = 3 \text{kOe}$. In contrast to the previous papers [32, 38, 39], the domain wall moves in the reverse direction (toward spin wave source) for $1.7 \mu\text{m}$ until its core transits the width of the nanowire at $34 \text{ns}$. The antivortex wall is then converted into a transverse wall, which is the minimum energy state and moves in the forward direction (+$x$-direction). The domain wall displacement profile is shown for a transverse, a vortex and an antivortex wall in figure 2(b). The velocity of a vortex wall is much smaller than that of a transverse wall, although both walls move in the same direction.

We have used different excitation amplitudes and calculated the amount of reverse displacement and the required time for the transformation of an antivortex to a transverse wall in figure 2(c). By increasing the excitation amplitude from 3 to 9 kOe at a constant frequency of $16 \text{GHz}$, the reverse displacement decreases from 1.7 to $1 \mu\text{m}$ and the transformation time decreases from 34 to $15.6 \text{ns}$. The only mechanism for the nucleation of a stable wall in the perfect nanowire is the external excitation; therefore, by increasing the excitation amplitude of spin waves, the antivortex could transform to a stable wall in less time. We have also simulated a transverse and a vortex wall under spin waves with a frequency of $16 \text{GHz}$ and different excitation amplitudes, and measured the domain wall linear velocity as shown in figure 2(d). The domain wall linear velocity has been determined based on the time required for the displacement of domain wall between 5 and 200 nm. It is found that they always move in the +$x$-direction in contrast to the case of an antivortex and the velocity of the vortex wall is about 7 times smaller than that of the transverse wall in all the excitation amplitudes.
Figure 2. (a) The real-time position of an antivortex wall for spin waves of $f = 16$ GHz and $H_0 = 3$ kOe. (b) Displacement profile of a transverse, a vortex and an antivortex wall in the presence of spin waves with $f = 16$ GHz and $H_0 = 3$ kOe. (c) Antivortex automotion displacement and transformation time for spin waves of $f = 16$ GHz with different excitation amplitudes. (d) Linear velocity of a transverse and a vortex wall for spin waves of $f = 16$ GHz with different excitation amplitudes.

The dynamics of the magnetic domain wall can be explained based on the Hamiltonian conjugate variables: the domain wall center position ($q$) and the domain wall tilting angle toward the out of plane center of the domain wall magnetization ($\phi$) [40–42]. The dynamics of the metastable domain wall in a ferromagnetic nanowire could be understood from the domain wall automotion or domain wall streaming equation. For any type of domain wall in a perfect nanowire the following equation holds [30, 40]:

$$\frac{d\phi}{dt} + \frac{\alpha}{\Delta_t} \frac{dq}{dt} = F_{\text{ext}}$$

in which $\alpha$ is the Gilbert damping constant, $\Delta_t$ is the Thiele domain wall width and $F_{\text{ext}}$ represents any external excitation. As seen in equation (4), in the absence of external excitation, any change in the domain wall tilting angle would result in a change in the domain wall position. For a vortex or an antivortex wall, the tilting angle is essentially determined by the domain wall core and by time integration, one can obtain

$$[q] = \pm \frac{\Delta_t \pi}{\alpha w} p[y_c].$$

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Here $p$ is the vortex core polarity, $w$ is the width of the nanostrip and $y_c$ is the transverse displacement of a vortex or an antivortex core in the $y$-direction. The directions of displacement for the vortex and the antivortex are opposite [30, 43]. This is consistent with our findings for the spin wave excitation in a vortex and in an antivortex wall. The maximum amount of displacement in the nanowire due to the domain wall transformation based on equation (5) is expected to be about $1.9 \mu m$ for $\Delta t = 12 \text{ nm}$, which is very close to our results shown in figure 2(c) for the antivortex case driven by spin waves. A minimum external excitation is required to overcome the energy barrier $\Delta E_1$ or $\Delta E_2$ in figure 1(b) in order to observe the transformation of a vortex or an antivortex to a transverse wall. The value of $\Delta E_1$ or $\Delta E_2$ could be determined from the results of the magnetic field excitation.

2.2. Magnetic field excitation

Figure 3(a) shows the domain wall displacement profile for a transverse, a vortex and an antivortex wall under 10 Oe magnetic field excitation. Similar to the spin wave excitation, the antivortex starts to move in the $-x$-direction, while the transverse and vortex walls move in the $+x$-direction. From equation (5), the displacement direction of domain wall automation is independent of the excitation method, which is in line with our results. For the vortex wall, it moves 320 nm in the $+x$-direction for the first 8.4 ns and then moves back to 76 nm up to 9.5 ns till the vortex core transits the nanowire width and transforms to a transverse wall. For the antivortex wall, it moves 670 nm in the $-x$-direction for the first 6.6 ns and then moves in the $+x$-direction after transformation into a transverse wall. The average domain wall velocity for a transverse wall at different values of the magnetic field is shown in figure 3(b). The Walker field is about 17 Oe for the transverse wall above which the velocity of the domain wall drops from 402 m s$^{-1}$ to less than 183 m s$^{-1}$. From the field excitation, the energy barrier between the antivortex and the transverse wall ($\Delta E_1$) is determined to be about 3 Oe, and the energy barrier between the vortex and the transverse wall ($\Delta E_2$) is determined to be about 1.5 Oe. By increasing the excitation field from 5 to 20 Oe, we determine the automotion displacement and the transformation time from a vortex or an antivortex to a transverse wall. In the case of a vortex wall, it is found that the amount of automotion displacement decreases from 440 to 16 nm and the transformation time also declines from 22.6 to 4.5 ns when the field changes from 5 to 20 Oe as shown in figure 3(c). For an antivortex wall, the reverse displacement decreases from 1000 to 416 nm and the transformation time also decreases from 11.2 to 3.7 ns when the field increases from 5 to 20 Oe in figure 3(d).

We have also simulated the response of a vortex and an antivortex wall for the pulse magnetic field of 10 Oe with different pulse widths in figure 3(e) and (f), respectively. It is found that when the pulse width is less than the domain wall transformation time, the vortex or antivortex continues its displacement without any transformation until it reaches the end of the nanowire due to the finite momentum of the domain wall. When the pulse width is longer than the domain wall transformation time, which is 9.5 and 6.5 ns for the vortex and the antivortex, respectively, the vortex or antivortex wall experiences transformation and then the transverse wall moves in the $+x$-direction.

2.3. Electric current excitation

For a better understanding of the behavior of the metastable domain wall, we have used current-driven spin-transfer torque and simulated the response of different domain walls to spin-transfer
torque. Based on the one-dimensional model for a transverse wall, the domain wall dynamics can be described as [41]

\[\dot{\phi} + \alpha \frac{\dot{q}}{\Delta} = \gamma_0 H_a + \frac{\beta u}{\Delta}, \quad \dot{q} - \alpha \frac{\dot{\phi}}{\Delta} = \gamma_0 H_k \sin(\phi) \cos(\phi) + \frac{u}{\Delta},\]  

(6)

where \(H_a\) is the applied magnetic field, \(H_k\) is the hard-axis anisotropy and \(\Delta\) is the domain wall width.

Figure 4(a) displays the response of a vortex wall to an electric current with \(u = 50 \text{ m s}^{-1} \) \(\sim J = 1 \times 10^8 \text{ A cm}^{-2}\) and different non-adiabatic coefficients. For small non-adiabatic coefficients \(\beta/\alpha < 2\), a vortex wall cannot overcome the energy barrier of \(\Delta E_2\) and no transformation from a vortex into a transverse wall has been observed, whereas for larger value of \(\beta \ (\beta/\alpha \gtrsim 2)\) transformation of a vortex into a transverse wall could happen and the transformation time decreases as the non-adiabatic spin-transfer torque increases for the simulated time range. The displacement of an antivortex wall due to the spin-transfer torque excitation is also shown in figure 4(b). In contrast to the magnetic field excitation, it is found that an antivortex wall first moves in the +x-direction similar to a vortex wall, but moves in the
In order to understand this behavior, we should note the difference between the spin-transfer torque excitation and the magnetic field excitation. In principle, the magnetic field tilts the energy profile in figure 1(b) in such a way that a metastable domain wall could easily overcome the energy barrier and transform into a stable wall. The non-adiabatic spin-transfer torque is similar to an effective magnetic field of $H_{\text{eff}} = \frac{\beta u}{\Delta \gamma}$, as can be seen from equation (6). A minimum value of the non-adiabatic torque is required to overcome the energy barriers and a larger non-adiabatic value decreases the transformation time of a metastable wall. For example, the value of an effective field originating from non-adiabatic spin-transfer torque is about 11.8 Oe for $\beta = 0.05$, $u = 50$ m s$^{-1}$ and a domain wall width of $\Delta = 12$ nm.

We have also modeled the current pulse response of a vortex wall for different pulse widths of current excitations with a non-adiabatic coefficient of $\beta = 0.05$ (figure 4(c)). Similar to the magnetic pulse response, if the excitation pulse is less than the required time for the vortex transformation, the vortex wall preserves its structure and moves up to the end of the nanowire, whereas for a longer current pulse, the vortex wall transforms into a transverse wall. The same behavior is observed for the antivortex response to a current pulse in figure 4(d). For a short pulse ($< 5$ ns), the antivortex wall displaces 90 nm toward the $+x$-direction due to adiabatic spin-transfer torque. However, after removing the current pulse it moves in the $−x$-direction due to domain wall automotion according to equation (5). If the excitation pulse is long enough ($\geq 15$ ns) so that the antivortex wall could transform into a transverse wall, the domain wall eventually moves toward the $+x$-direction due to the finite momentum of a transverse wall.

Figure 4. Displacement profile of a vortex (a) and an antivortex (b) wall under currents of $u = 50$ m s$^{-1}$ and different non-adiabatic coefficients. Displacement profile of a vortex (c) and an antivortex (d) wall under currents of $u = 50$ m s$^{-1}$ and $\beta = 0.05$ for different current pulse widths.
3. Metastable wall dynamics in a rough nanowire

3.1. Periodic roughness

It is well known that the presence of roughness in a ferromagnetic nanowire could help in the nucleation of a domain wall [35, 44, 45]. In addition, a fabricated ferromagnetic nanowire always has a finite edge roughness and it would be interesting to see the roughness effect on the metastable domain wall dynamics. We have introduced a periodic roughness with a periodicity of $T = 25$ nm and a depth of $D = 4$ nm into the nanowire as shown in the inset of figure 5(b). The periodicity of roughness is chosen to be comparable with the width of the domain wall, and the chosen depth of roughness gives a depinning field of $\sim 20$ Oe for a transverse domain wall, which is close to the values in the experimental reports [46, 47].

We have tried to simulate the dynamics of different domain walls in a rough nanowire in the presence of the spin wave. However, it is found that none of the domain walls has any sizeable displacement under spin wave excitation because of the relatively strong pinning sites compared to the excitation level of spin waves.
3.1.1. Magnetic field excitation. Figure 5(a) shows the displacement of a stable transverse wall for different external magnetic fields. As can be seen, the transverse wall displacement is almost zero below 22 Oe. We have also calculated the average velocity of a transverse wall at different excitation fields in figure 5(b). The average velocity of the transverse wall is very small (1.5 m s\(^{-1}\)) up to 20 Oe and the velocity suddenly jumps to 360 m s\(^{-1}\) at 22 Oe. In addition, the Walker field has been shifted from 17 to 36 Oe as expected [35].

The response of a vortex wall to different values of the magnetic field in a rough nanowire is shown in figure 5(c). In contrast to the transverse wall, we observe a finite displacement of the vortex wall below the depinning field of a stable (transverse) wall. Due to the domain wall automotion, the stored energy inside the domain wall could assist in the displacement of the domain wall; however, after the vortex wall transforms into a stable wall (a transverse wall), it stops due to roughness pinning, unlike the case of a perfect nanowire in which it reaches the end of the nanowire. By increasing the magnetic field, the forward displacement of the vortex wall increases but the increase is not monotonic. This behavior could be explained based on the fact that in a rough nanowire there is a trade-off between the metastable automotion and the depinning of the domain wall. By increasing the field, the depinning process of the metastable wall would be assisted, while the automotion of the metastable wall would be limited. Therefore, at a certain value of the magnetic field, one can expect to observe maximum displacement of the domain wall, which is 10 Oe in our nanowire.

We have also studied the displacement profile of an antivortex wall for different values of magnetic field (figure 5(d)). By increasing the magnetic field, the domain wall transient time decreases as the field assists the domain wall depinning process. Furthermore, for small values of the field the mechanism of depinning is accompanied by resonant depinning of the antivortex [48, 49]. The roughness can create a local harmonic potential profile for an antivortex wall, and can help in the conversion between the kinetic and the potential energy of an antivortex wall. The antivortex wall oscillates between the pinning sites till its energy is large enough to overcome the energy barrier.

In figure 5(e), the response of a vortex wall to a pulse magnetic field is plotted for different pulse widths with a field amplitude of 10 Oe. By increasing the pulse width, the vortex wall displacement increases as the external field helps the vortex wall to overcome the pinning sites. The pulse field response of an antivortex wall at a field amplitude of 10 Oe is shown in figure 5(f). Due to resonance depinning of the antivortex wall, it is possible to have a displacement in either the forward or backward direction depending on the phase difference between the pulse magnetic field and the resultant transient response of a domain wall (below 25 ns with 10 Oe). The displacement is almost independent of the pulse width, which is about ±1.2–1.5 µm, slightly smaller than the automotion displacement (1.9 µm) in a perfect nanowire. It is interesting to compare the dc field excitation of an antivortex wall at 10 Oe in figure 5(d) and its short pulse excitation in figure 5(f). In the dc field excitation, the antivortex has a finite displacement of ~70 nm in the \(-x\)-direction, while it can have a much longer displacement in either the \(+x\) or \(-x\)-direction with a short pulse of magnetic field. If the pulse width of the field is longer than ~25 ns (the transformation time of the antivortex with 10 Oe), bi-directional displacement is suppressed.

3.1.2. Electric current excitation. We have also simulated the current effect on the wall dynamics in a rough nanowire. In figure 6(a), the displacement of a transverse wall at different values of \(u\) is shown for a non-adiabatic coefficient of \(\beta = 0.05\). For \(u\) values below 150 m s\(^{-1}\),
the transverse wall displacement is negligible, whereas for values of \( u \) above 160 m s\(^{-1}\) the domain wall transits to the end of the nanowire. In figure 6(b), we have measured the critical current density for depinning of the transverse wall at different values of the non-adiabatic coefficient. By decreasing the non-adiabaticity of the current, the critical current density increases, which is in line with previous studies [20, 50].

We have also studied the vortex wall behavior under the current-induced spin-transfer torque. Even with zero non-adiabatic coefficients, we have observed the finite displacement of a vortex wall before its transformation into a transverse wall in figure 6(c) below the critical current of a transverse wall (\( u = 600 \) m s\(^{-1}\) for \( \beta = 0 \)). By increasing the non-adiabatic coefficient to 0.05, the forward displacement increases due to the presence of a non-adiabatic effective field in figure 6(d). The current pulse response of a vortex wall is similar to that of the field response such that by increasing the length of the current pulse, the forward displacement of a vortex wall increases as seen in figure 6(e). Figure 6(f) shows the displacement profile of

**Figure 6.** (a) Displacement profile of a transverse wall at different current densities for \( \beta = 0.05 \). (b) Critical current density required for the depinning of a transverse wall at different non-adiabatic coefficients. Displacement profile of a vortex wall at different current densities for \( \beta = 0 \) (c) and \( \beta = 0.05 \) (d). (e) Displacement profile of a vortex wall for a current pulse of \( u = 50 \) m s\(^{-1}\) and \( \beta = 0.05 \) with different current pulse widths. (f) Displacement profile of an antivortex wall at different current densities for \( \beta = 0.05 \). Displacement profile of an antivortex wall for a current pulse of \( u = 50 \) m s\(^{-1}\) with \( \beta = 0.05 \) (g) and \( \beta = 0 \) (h) at different current pulse widths.
an antivortex wall due to the electric currents for different current densities with \( \beta = 0.05 \). Similar to the magnetic field excitation, a finite displacement of the domain wall has been observed much below the critical current density of a transverse wall. In addition, by increasing the current density, the backward displacement of an antivortex wall decreases since the spin-transfer torque enhances the transformation of the metastable wall into a stable wall.

The current pulse response of an antivortex wall is shown in figure 6(g). Depending on the pulse width, it is possible for an antivortex wall to displace in either the forward or backward direction till it transforms into a transverse wall. As mentioned earlier, the pinning sites act as local harmonic potentials that help the conversion between kinetic and potential energy. Therefore, it is expected that in a rough nanowire, even with \( \beta = 0 \), one should observe the backward motion of an antivortex wall. As shown in figure 6(h), similar to the case with a finite non-adiabatic coefficient in figure 6(g), it is possible for an antivortex wall to have either backward or forward motion depending on the current pulse width even though \( \beta = 0 \).

In order to better understand the response of the vortex or antivortex wall to a current pulse, we have calculated the real time \( x \)- and \( y \)-positions of the domain wall as well as its tilting angle as shown in figure 7. For the vortex wall, we have injected a current pulse of 20 ns with \( u = 50 \text{ m s}^{-1} \) and \( \beta = 0.05 \). As the vortex moves along the nanowire in figures 7(a) and (b), its core displaces in the transverse direction. When the vortex core reaches the edge of the nanowire at 30.6 ns, the vortex wall transforms into a transverse wall. As shown in figure 7(c)
there is a sudden drop in the tilting angle of the domain wall at 30.6 ns, which is a sign of the transformation from a vortex into a transverse wall.

We have also studied the real-time behavior of an antivortex wall to a current pulse width of 0.1 ns with \( u = 50 \text{ m s}^{-1} \) and \( \beta = 0 \). The \( x \)- and \( y \)-positions of the antivortex wall show oscillatory behavior as shown in figures 7(d) and (e) due to the presence of local harmonic potentials from the edge roughness. The antivortex wall is highly unstable due to the excess wall energy in comparison with a stable wall. The roughness can also create a local harmonic potential profile for an antivortex wall and can help the conversion between kinetic and potential energy of an antivortex wall. The antivortex wall oscillates until the core reaches the edge of the nanowire, which corresponds to a displacement of the core of ±50 nm in the \( y \)-direction. In this large displacement regime, the dynamics of an antivortex wall is highly nonlinear and the displacement of the core in the \( x \)-axis is mainly determined by the transverse motion of the core (\( y \)-direction). When the core transits the width of the nanowire, the antivortex wall transforms into a stable wall (transverse wall). For the antivortex wall the transformation happens at 54.5 ns, at which time the antivortex core annihilates and a transverse wall nucleates in the nanowire. The tilting angle of an antivortex wall also presents a sudden drop from 90° to almost 0° at 54.5 ns as shown in figure 7(f).

### 3.2. Random roughness

We have simulated the nanowire with a random roughness of \( D = 4 \text{ nm} \) as shown in the inset of figure 8. The displacement profile of an antivortex wall due to the current pulse excitation is demonstrated for a current of \( u = 50 \text{ m s}^{-1} \) and \( \beta = 0.05 \). Since the antivortex depinning mechanism is similar to the nanowire with a periodic roughness in figure 6(g), the displacement profile depends strongly on the phase difference between the pulse width and the antivortex oscillation, which enables bi-directional displacements.

### 4. Conclusion

We have studied the dynamics of metastable domain walls in ferromagnetic nanowires. It is found that the average velocity of a metastable wall is smaller than that of a stable wall. In
addition, depending on the structure of the metastable wall, it can displace in either the forward or backward direction for the same type of excitation. In a rough nanowire, in particular, the metastable wall could have a finite displacement at an excitation much below the critical field or current required for displacing a stable wall. Our results demonstrate that the creation of a metastable wall could result in a displacement of the domain wall below the critical field or current of a stable wall, and explains some of the previous experimental observations in which a bi-directional displacement as well as a very slow velocity of domain walls was reported.

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