Microwave fields driven domain wall motions in antiferromagnetic nanowires

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Abstract

In this work, we study the microwave field driven domain wall (DW) motion in an antiferromagnetic nanowire, using the numerical calculations based on a classical Heisenberg spin model with the biaxial magnetic anisotropy. We show that a proper combination of a static magnetic field plus an oscillating field perpendicular to the nanowire axis is sufficient to drive the DW propagation along the nanowire. More importantly, the drift velocity at the resonance frequency is comparable to that induced by temperature gradients, suggesting that microwave field can be a very promising tool to control DW motions in antiferromagnetic nanostructures. The dependences of resonance frequency and drift velocity on the static and oscillating fields, the axial anisotropy, and the damping constant are discussed in details. Furthermore, the optimal orientations of the field are also numerically determined and explained. This work provides useful information for the spin dynamics in antiferromagnetic nanostructures for spintronics applications.

1. Introduction

Since the effective manipulation [1–4] and detection [5] of antiferromagnetic (AFM) states were realized, AFM materials have attracted extensive attentions due to their potential applications for AFM spintronics. In comparison with ferromagnets based storage devices [6, 7], antiferromagnets based devices are believed to hold several additional merits [8]. On the one hand, the AFM states are rather stable even under high magnetic fields, and information stored in AFM domains and/or domain walls (DWs) is also insensitive to applied magnetic fields. Furthermore, an AFM element would not magnetically disturb its neighbors due to its zero net magnetic moment, allowing the element arrangements in an ultrahigh density, noting that the demagnetization effect with AFM structure is essentially minimized. On the other hand, due to additional spin wave (SW) modes with higher frequencies in AFM structures, spin dynamics in antiferromagnets can be extremely fast. These advantages thus favor AFM materials for promising potentials in future devices.

However, one of the major challenges for AFM spintronic applications, at least on the current stage, is how to manipulate the AFM DWs and their motion via a spin dynamics scenario, noting that the static magnetic field and spin-polarized current may not work for an effective manipulation of AFM DW propagation due to the absence of net magnetic moment of the AFM domains. Based on the knowledge on the spin dynamics in ferromagnets [9–12], various efforts in searching for control scheme for the AFM DW motion have been reported [13–20]. For example, a high AFM DW velocity may be achieved if the so-called Néel spin–orbit torque (experimentally observed in CuMnAs) [21, 22] is utilized, as predicted theoretically [13]. This progress allows CuMnAs to be a good candidate for AFM spintronic applications. Moreover, it has been revealed that several SW modes can be used to drive the AFM DW motions, e.g. linear and circular SW can drive the DWs to move...
towards and away from the source, respectively [15]. Most recently, thermally driven AFM DW motion under a temperature gradient has been predicted by numerical calculations, where the competition between the entropic torque and the Brownian force is suggested to drive the AFM DW motion [16–18]. More interestingly, in these control schemes, the AFM DW remains non-tilted, indicating the higher wall mobility due to the missing of the walker breakdown [17].

While the temperature gradient driven AFM DW motion can be a scheme with more theoretical sense rather than realistic sense, electrically driven scheme is certainly more attractive. It has been evidenced that static magnetic field or electric current driving is an ineffective scheme for the AFM DW dynamics. Alternatively, the Néel spin–orbit torque driving as a possible scheme may be given sufficient attention. Along this line, a proper microwave field can be a favored choice, noting that the microwave driven DW motion in ferromagnets has been demonstrated [12]. In fact, earlier preliminary investigation suggested that polarized microwave fields [19] or asymmetric field pulses [20] do work for exciting the dynamics of an AFM DW. For example, as early as 1994, the collinear AFM DW motion driven by an oscillating magnetic field was predicted, based on the perturbation theory, and the dependence of the drift velocity on the frequency and polarization of the field was discussed [19].

However, only the case of oscillating field with small amplitude could be studied by the perturbation theory, and the drift velocity of the DW is estimated to be $\sim 1.0 \text{ cm s}^{-1}$ for a field amplitude of 10 Oe, which is too low to be used for spintronics devices [19]. Interestingly, it has been reported that the drift velocity of DW in ferromagnetic nanostructure is estimated to be $\sim 20 \text{ m s}^{-1}$, induced by microwave field with amplitude of 100 Oe at the critical frequency, demonstrating the prominent effect of field amplitude on the drift velocity [12]. Thus, it is expected that an oscillating magnetic field with a large amplitude probably leads to a very fast AFM DW motion, although its effects on the AFM dynamics are still not clear. Furthermore, the microwave driven DW motion has not been confirmed and explained directly by numerical calculations or experiments, as far as we know. Thus, considering the limitation of current technical ability in experiments which prohibits a complete realization of theoretical prediction, the AFM DW motion driven by microwave field urgently deserves for investigation numerically in order to uncover the physical mechanisms of AFM dynamics and promote the application process for AFM spintronics.

In this work, we study the microwave field driven AFM DW motion in an AFM nanowire, based on the classical Heisenberg spin model. We figure out that high velocity of the DW motion is achieved with a proper combination of a static magnetic field plus an oscillating field at the resonance frequency. Moreover, the dependences of resonance frequency and drift velocity on the static and oscillating fields, the axial anisotropy, and the damping constant are discussed in details. At last, optimal orientations of the microwave field are also numerically estimated.

2. Model and method

We numerically study the microwave field driven AFM DW motion based on the classical Heisenberg spin model with the isotropic nearest neighbors exchange interactions and biaxial anisotropy [17, 23]. The model Hamiltonian is given by

$$H = -J \sum_{\langle i,j \rangle} S_i \cdot S_j - d_x \sum_i (S_i^x)^2 - d_y \sum_i (S_i^y)^2 - \sum_i h \cdot S_i^z,$$  
(1)

where $J < 0$ is the AFM coupling constant, $d_x > d_y > 0$ are the anisotropic constants defining an easy axis in the $z$ direction and an intermediate axis in the $x$ direction, $S_i = \mu_i/\mu$, represents the normalized magnetic moment at site $i$ with the three components $S_i^x$, $S_i^y$ and $S_i^z$.

We consider an AFM nanowire with axis along the $z$ direction. It is noted that the AFM DW cannot be driven under the field along the $x/z$ axis, as will be explained in the end of the part III. Thus, unless stated elsewhere, the microwave field $h = h_{ac} \cdot \sin \omega t + h_{dc}$ is applied along the $y$ direction with a static field $h_{dc}$ and an oscillating field with frequency $\omega$ and amplitude $h_{ac}$. The AFM dynamics at zero temperature is studied by the Landau–Lifshitz–Gilbert (LLG) equation [24, 25],

$$\frac{\partial S_i}{\partial t} = -\frac{\gamma}{\mu_i(1+\alpha^2)} S_i \times [H_i + \alpha(S_i \times H_i)],$$  
(2)

where $\gamma$ is the gyromagnetic ratio, $H_i = -\partial H/\partial S_i$ is the effective field, and $\alpha$ is the Gilbert damping constant.

The nanowire is defined by a $2 \times 2 \times 181$ elongated three dimensional lattice (lattice parameter $a$), and the LLG simulations are performed by using the fourth–order Runge–Kutta method with time step $\Delta t = 8.0 \times 10^{-5} \mu_s/\gamma|J|$. Here, the periodic boundary conditions are applied in the $x, y$, and $z$ directions to reduce the finite–size effect. Unless stated otherwise, $d_x = 0.004|J|$, $d_y = 0.1|J|$, $\alpha = 0.01$, and $\gamma = 1$ are chosen in our simulations. Here, considering the current computing ability, $d_i$ is set to be one order larger than in real AFM materials to save the CPU time, which never affects our main conclusion. After sufficient relaxation of the Néel AFM DW
we apply microwave fields and study the DW motion. The staggered magnetization $m_2 = m_1 - m_2$ is calculated to describe the spin dynamics, where $m_1$ and $m_2$ are the magnetizations of the two sublattices occupied with the red and blue spins, respectively [17].

3. Simulation results and discussion

Figure 2(a) gives the position of an AFM DW under a static magnetic field $h_{dc} = 0.2$. Unlike the FM DW which propagates along a wire under nonzero $h_{dc}$ to save the total energy [10], the AFM DW could not be efficiently driven by the static field. Specifically, the DW quickly shifts to and stays at a new equilibrium position ($z = 84\alpha$) when $h_{dc}$ is applied, and then returns to its original position as soon as the field is turned off at $\tau = 300$. Similarly, the AFM DW could not either be driven by an oscillating magnetic field alone ($h_{dc} = 0$). The DW position as a function of $\tau$ for field amplitude $h_{ac} = 0.4$ at $\omega = 0.35$ and $h_{dc} = 0$, and (c) $h_{ac} = 0.4$ at $\omega = 0.35$ and $h_{dc} = 0.2$, and (d) and $h_{ac} = 0.4$ at $\omega = 1.0$ and $h_{dc} = 0.2$.

Figure 1. The Néel domain wall in a AFM nanowire. Blue and red arrows represent spins in two sublattices.

Figure 2. The domain wall position as a function of time $\tau$ for (a) $h_{ac} = 0.2$ for $\tau < 300$ and $h_{ac} = 0$ for $\tau > 300$ at $h_{dc} = 0$, and (b) $h_{ac} = 0.4$ at $\omega = 0.35$ and $h_{dc} = 0$, and (c) $h_{ac} = 0.4$ at $\omega = 0.35$ and $h_{dc} = 0.2$, and (d) and $h_{ac} = 0.4$ at $\omega = 1.0$ and $h_{dc} = 0.2$. (depicted in figure 1), we apply microwave fields and study the DW motion. The staggered magnetization $2n = m_1 - m_2$ is calculated to describe the spin dynamics, where $m_1$ and $m_2$ are the magnetizations of the two sublattices occupied with the red and blue spins, respectively [17].

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More importantly, the drift velocity is significantly dependent of frequency $\omega$, and a high DW mobility could be achieved at particular frequencies. Figure 2 gives the results for $\omega = 1$, which clearly demonstrates the DW propagation with a high drift velocity [19]. The simulated results are summarized in figure 3(a) which presents the velocity as a function of frequency at $h_{ac} = 0.4$ and $h_{dc} = 0.2$. Three maxima are clearly shown at frequencies $\omega = 0.35$, 0.76, and 1.02, respectively.

The simulated results can be qualitatively understood from the competition between various torques acting on the DW [17]. Following equation (2), a magnetic field along the $y$ direction leads to two types of torques, i.e. the precession torque $\Gamma^p_h$ (gray arrow) and the damping torque $\Gamma^d_h$ (orange arrow), on the central plane of the AFM DW, as depicted in figure 3(b). In details, $\Gamma^p_h$ pointing in an opposite direction on the two sublattices and drives the DW, while $\Gamma^d_h$ pointing in the same direction slightly drives the spins out of the easy plane. When a static magnetic field is applied, additional exchange and anisotropic fields are induced by the deviation of the spins from the easy plane, resulting in additional precession torque $\Gamma^{ex}_p$ (brown arrow) and damping torque $\Gamma^{ex}_d$ (green arrow) which are opposite to those from the external field, respectively. As a result, the first torque, i.e. the precession torque, $\sim -S \times H$ (equals to $\Gamma^p_h + \Gamma^{ex}_p$) in equation (2) is quickly reduced to zero, and the DW stops at a new equilibrium position. Furthermore, the DW returns to its original equilibrium position driven by the precession torque when the static field is decreased to zero, as confirmed in our simulations.

When an oscillating magnetic field is considered, the change of the exchange and anisotropic fields induced by the spin deviation still fall behind that of the applied field. At $h_{dc} = 0$, the precession torque is antisymmetric and changes its direction during one oscillation period, resulting in the DW oscillation, as shown in figure 3(c) which gives the deviation of $S^z$ of a single spin in the DW. Thus, the DW could not be efficiently driven to propagate along the wire. Importantly, the symmetry of the precession torque (nonlinearly changes with the applied magnetic field) is broken by further considering a nonzero $h_{dc}$, and the local spins in domain cannot return to the original equilibrium directions especially near the resonance frequency ($\omega = 1.0$, for example), as clearly shown in figure 3(d). In other words, a rather large net torque is available and drives the motion of the DW. As a result, the DW could be efficiently driven by a proper combination of the static and
oscillating magnetic fields near the resonance frequency, as demonstrated in our simulations. However, for the frequencies significantly deviated from the resonance one, the coupling between the local spins and the applied field is very weak, and the DW cannot be driven efficiently. Moreover, the DW moves toward opposite direction when the net torque is reversed at $\omega = 1.03$, similar to the earlier prediction \cite{19}.

As a matter of fact, earlier work demonstrated the high DW mobility when an oscillating field matches the characteristic frequency of the magnetic domains \cite{22}. Furthermore, the resonance frequencies derive from the mode of spin precession which is manipulated by the internal and external fields \cite{26, 27}. When these fields cooperate with each other and generate strong torques acting on the local spins, the highest velocity $v_{\text{max}}$ is obtained at the high resonance frequency $\omega = 1.02$, which is comparable to that of the thermally driven AFM DW motion \cite{17}. Furthermore, low-frequency resonances corresponding to other modes of spin precession could also exist, and the consideration of the biaxial anisotropy may also lead to additional modes of spin precession and low resonance frequencies (for example, $\omega = 0.35$ and $\omega = 0.76$). Interestingly, the dependence of the direction of DW motion on the frequency allows one to control DW motion at ease, which is particularly meaningful for future applications \cite{19}. Thus, our work strongly suggests that microwave fields can be another control parameter for AFM DW motion in AFM nanostructures.

Subsequently, we investigate the dependences of resonance frequency $\omega_0$ and highest drift velocity $v_{\text{max}}$ on various factors. Figure 4(a) gives the simulated $v(\omega)$ curves for various $h_{\text{ac}}$ at $h_{\text{dc}} = 0.2$, which shows that $\omega_0$ is less affected by $h_{\text{ac}}$ while $v_{\text{max}}$ increases with the increasing $h_{\text{ac}}$. Thus, it is indicated that $\omega_0$ is mainly related to the characteristic frequency of the magnetic domain which is hardly affected by $h_{\text{ac}}$. Furthermore, the net torque in one oscillation period is enlarged as $h_{\text{ac}}$ increases, speeding up the DW at $\omega_0$. Moreover, our work also reveals that both $v_{\text{max}}$ and $\omega_0$ can be modulated by $h_{\text{dc}}$, as shown in figure 4(b) which presents the $v(\omega)$ curves for various $h_{\text{dc}}$ at $h_{\text{ac}} = 0.4$. On the one hand, higher $h_{\text{dc}}$ increases the spin precession angular velocity, and in turn results in a higher resonance frequency. Thus, $\omega_0$ increases with the increase of $h_{\text{dc}}$, qualitatively consistent with the earlier theoretical prediction $\omega_0 \sim \frac{\gamma (2H_A H_k + H_k^2)^{1/2}}{2}$ where the damping effect is neglected, where $H_A$ and $H_k$ are, respectively, the anisotropy field and the exchange field \cite{26, 27}. On the other hand, the net driven torque in one period is also enlarged, leading to the increase of $v_{\text{max}}$ and the enlargement of the $\omega$ region in which the AFM DW can be efficiently driven.

In figure 5(a), we give the simulated $v(\omega)$ curves for various $d_z$ at $h_{\text{ac}} = 0.4$, $h_{\text{dc}} = 0.2$ and $d_z = 0.1$. It is demonstrated that both $v_{\text{max}}$ and $\omega_0$ are increased as $d_z$ increases. When only the biaxial anisotropy is
considered, the precession equations of a single spin $S$ are [27]

\[
\begin{align*}
S'_x &= -\gamma d_x S^y S^z \\
S'_y &= -\gamma (d_y - d_z) S^z S^y \\
S'_z &= \gamma d_z S^y S^z,
\end{align*}
\]

where $S'_k = \partial S^k / \partial \tau$ ($k = x, y, z$). Considering the fact that both $S^y$ and $S^z$ are very small due to the strong biaxial anisotropy, one can obtain the characteristic frequency of the spin precession $\omega \sim \gamma S^y (d_x d_z)^{1/2}$. As a result, the resonance frequency of the DW motion increases when the anisotropy is enhanced, as further confirmed in figure 5(b) which presents the calculated $\nu(\omega)$ curves for various $d_x$ at $d_z = 0.004$. However, converse to the case of $d_x$, larger $d_z$ results in a smaller $\nu_{\text{max}}$, which can be qualitatively understood from the energy landscape. Based on the continuum model, the total energy of the DW can be expressed as [28]

\[
E_{\text{DW}} = N_D \cdot 2 \sqrt{2(d_z - d_x)} |J|,
\]

where $N_D$ is the number of spins in the cross section along the z axis. It is well noted that $E_{\text{DW}}$ (its value depends on $d_z - d_x$) determines the mobility of the DW, specifically, higher $E_{\text{DW}}$ leads to a lower mobility of the DW. As a result, $\nu_{\text{max}}$ is increased with the increase/decrease of $d_x / d_z$, as demonstrated in our simulations.

Obviously, the damping term also affects the spin dynamics. Thus, we also investigate the effect of the damping constant $\alpha$ on $\nu_{\text{max}}$ and $\omega_{\text{D}}$ and give the simulated results in figure 5(c). It is clearly shown that both

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**Figure 5.** The calculated $\nu(\omega)$ curves (a) for various $d_x$ at $d_z = 0.1$, and (b) for various $d_x$ at $d_z = 0.004$, and (c) for various $\alpha$. 

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\(v_{\text{max}}\) and \(\omega_0\) are decreased with the increase of \(\alpha_1\), demonstrating the fact that an enhanced damping term lowers the mobility of the DW. On the one hand, the damping term always impedes the spin precession and diminishes the characteristic frequency of the magnetic domain, resulting in the decreases of \(\omega_0\) and the effectively driven region of \(\omega\). On the other hand, the second torque \(\sim -S \times (S \times H)\) is significantly enhanced with the increasing \(\alpha_1\), and arranges the spins along the effective field \(H\) direction more quickly. As a result, the precession torque during an oscillating period is reduced, which speeds down the DW.

As a matter of fact, the field direction probably has a prominent impact on the dynamics of DWs, as revealed in the earlier work which studied the case of the 90° AFM DWs [20]. Without loss of generality, we study the velocities of the DW under \(h_{dc} = 0.34\) and \(h_{ac} = 0.2\) applied along various directions \((\cos \Phi \sin \Theta, \sin \Phi \sin \Theta, \cos \Theta)\) defined by the polarization angle \(\Theta\) and the azimuth angle \(\Phi\) to figure out the optimal field orientation. The simulated results at \(\omega = 1.00\) are summarized in figure 6(a). It is clearly shown that the AFM DW can be efficiently driven in four \((\Theta, \Phi)\) regions (blue and red areas). One may understand the result using symmetry operations. For example, the spin configuration is not changed, while the field orients from \((\Theta, \Phi)\) to \((\pi - \Theta, 2\pi - \Phi)\) by rotating the system by 180° around the \(x\) axis, resulting in a reverse motion of the DW, as clearly shown in our simulations. Furthermore, as a polar vector, the velocity (along the \(z\) axis) is invariant by the mirror image operation with respect to the \(x-z\) plane, and so is the spin configuration \((\mathbf{m}_1\text{ turns into }\mathbf{m}_2, \text{ and } \mathbf{m}_3\text{ turns into }\mathbf{m}_4)\). Moreover, the field (an axial vector) is turned from \((\Theta, \Phi)\) to \((\pi - \Theta, \pi - \Phi)\) by this operation, as further confirmed in figure 6(b) which gives the calculated results at \(\omega = 1.06\). Similar optimal orientations of the microwave field are clearly shown, suggesting the stability of these optimal orientations, which is very useful in AFM based device design.

Most recently, it has been confirmed both experimentally and theoretically that AFM domain in an antiferromagnet with biaxial anisotropy such as NiO film deposited on SrTiO\(_3\) substrate could be reversed by applied electric current [29, 30], which is very meaningful for the development of AFM spintronics. Taking NiO as an example to estimate the real physical values, we set the exchange stiffness \(A \approx 5 \times 10^{-13}\) J m\(^{-1}\), \(a \approx 4.2\) Å, \(\mu_\parallel \approx 1.7\mu_\circ\). For \(h = 0.1\) T and \(d_z = 10^{-2}\), the resonance frequency and velocity are estimated to be \(\omega/2\pi \approx 100\) GHz and \(v \approx 200\) m s\(^{-1}\), respectively. The frequency is in the microwave region and the velocity is one order larger than that in ferromagnet \((\approx 20\) m s\(^{-1}\)), further demonstrating the fast spin dynamics in antiferromagnet. Moreover, the microwave could be generated by means of optical methods such as the photo-injection, optical phase-locked loop, and two-mode laser method.

At last, it is worth noting that microwave field also can be used to drive multiple DWs in a system since the direction of DW motion is independent of magnetic charge [19, 20], which is different from the effect of Néel spin–orbit torque and essential for racetrack memory. Moreover, similar effects of microwave fields on AFM Bloch walls are expected, and a high mobility of DW is probably available when the microwave field is applied perpendicular to the DW plane. This phenomenon has also been confirmed in our simulations, although the corresponding results are not shown here for brevity.

![Figure 6](image_url)
4. Conclusion

In general, we have studied the AFM DW motion driven by microwave fields using the LLG simulations of the classical Heisenberg spin model. It is revealed that a proper combination of a static field and an oscillating field can drive the DW motion in AFM nanostructures, and a large drift velocity comparable to that induced by temperature gradients can be obtained at the resonance frequency. Furthermore, the dependences of the resonance frequency and velocity on several parameters are investigated and explained in details. Thus, our work provides useful information for the spin dynamics in AFM nanostructures for spintronics applications.

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