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Citation: Journal of Applied Physics **117**, 053913 (2015); doi: 10.1063/1.4907584
View online: http://dx.doi.org/10.1063/1.4907584
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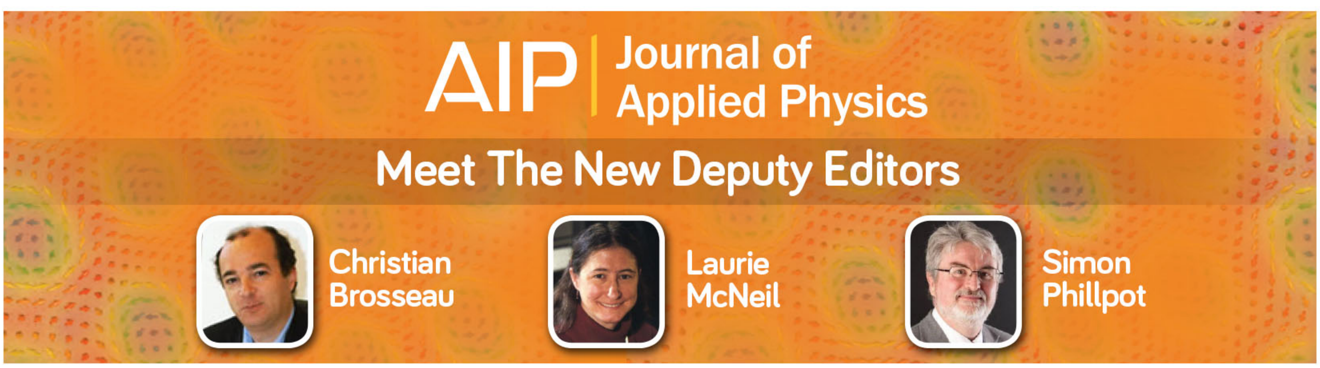

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JOURNAL OF APPLIED PHYSICS 117, 053913 (2015)

Coupled domain wall oscillations in magnetic cylindrical nanowires

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(Received 27 October 2014; accepted 25 January 2015; published online 5 February 2015)

We report on transverse domain wall (DW) dynamics in two closely spaced cylindrical nanowires. The magnetostatically coupled DWs are shown to undergo an intrinsic oscillatory motion along the nanowire length in addition to their default rotational motion. In the absence of external forces, the amplitude of the DW oscillation is governed by the change in the frequency of the DW rotation. It is possible to sustain the DW oscillations by applying spin-polarized current to the nanowires to balance the repulsive magnetostatic coupling. The current density required to sustain the DW oscillation is found to be in the order of 10^5 A/cm^2. Morover, our analysis of the oscillation reveals that the DWs in cylindrical nanowires possess a finite mass. © *2015 AIP Publishing LLC*.
[http://dx.doi.org/10.1063/1.4907584]

I. INTRODUCTION

The understanding of domain wall (DW) dynamics in ferromagnetic nanostructures is crucial for the realization of next generation non-volatile magnetic solid state memory and logic devices.[1–3] The DW dynamics behavior in planar ferromagnetic nanowires has been relatively well studied, either in in-plane or perpendicular magnetic anisotropy materials.[4–9] A prevailing obstacle that limits fast DW dynamics in the in-plane structures is the Walker breakdown phenomenon,[10,11] at which the speed of the DW drops drastically due to a complex DW transformation. Such a limitation, however, is not present for DWs in sub-50 nm magnetic cylindrical nanowires, where the DW speed can be ten times higher than that in the planar nanowires.[12,13] Due to the symmetry of the cylindrical nanowire, the movement of a transverse DW is always accompanied by a rotation around the longitudinal axis. In contrast to a DW in in-plane structures, the rotation of a DW in cylindrical nanowire does not transform the DW shape and it also does not reduce the speed.[12–20] Additionally, the critical current density that is required to initiate the DW movement and DW depinning in cylindrical nanowire is much lower as compared to that in planar structures.[12–15] The DW characteristics that are discussed above have been attributed to possibility of the DW in cylindrical nanowire to have zero mass.[12] However, the massless behavior is undetermined, as no studies have specifically pointed out the absence of DW mass in cylindrical nanowire.

In this work, we have investigated an oscillation mode that is intrinsic to DWs in cylindrical nanowires. In a coupled DW system, we found that the DWs exhibit an additional oscillatory motion along the nanowire length. We show that it is possible to achieve sustained DW oscillation and rotation under the application of an external current. We also show that the DW oscillation is accompanied by a cyclic change in the DW shape. The result reveals that the DW in the cylindrical nanowire possesses a mass of the order of 10^{-23} kg. Due to the small current density that is needed to sustain the oscillation and the rotation, it is possible to use the system as a DW-based oscillator for microwave generator applications.

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II. METHODOLOGY

DW dynamics behavior in $Ni_{80}Fe_{20}$ cylindrical nanowires is investigated by using object oriented micromagnetic framework code (OOMMF).[21,22] The material parameters were set corresponding to permalloy: saturation magnetization $(M_s) = 8.6 \times 10^5$ A/m and exchange constant $(A) = 1.3 \times 10^{-11}$ J/m. The damping coefficient (α) and non-adiabatic constant (β) were chosen as 0.005 and 0.04, respectively. A schematic of the coupled DW model is shown in Figure 1(a). The two nanowires have a diameter of 10 nm and length of 1 μm and are placed parallel to each other with 10 nm separation. The unit cell size for all simulations was set to be 5 nm $\times$ 1 nm $\times$ 1 nm in the x, y, and z axes, respectively. Two Tail-to-Tail (TT) DWs are relaxed in the two nanowires. To create the TT DW in the nanowire system, the magnetic moments on either side of the simulated DW were initially set to point away from each other. In practice, TT DWs can be injected in the two nanowires by applying a current to a stripe line to generate a local Oersted field.[23,24] By overlapping the stripe line with the edges of the two nanowires, two DWs can be generated adjacent to each other.

III. RESULTS AND DISCUSSION

We have investigated the behavior of the two DWs under the influence of magnetostatic coupling.[4,25–27] The translational motion of the DW along the nanowire is plotted as a function of simulation time in Figure 1(b). First, we see that, the two DWs are moving away from other, even without any application of external field or current. As the two DWs

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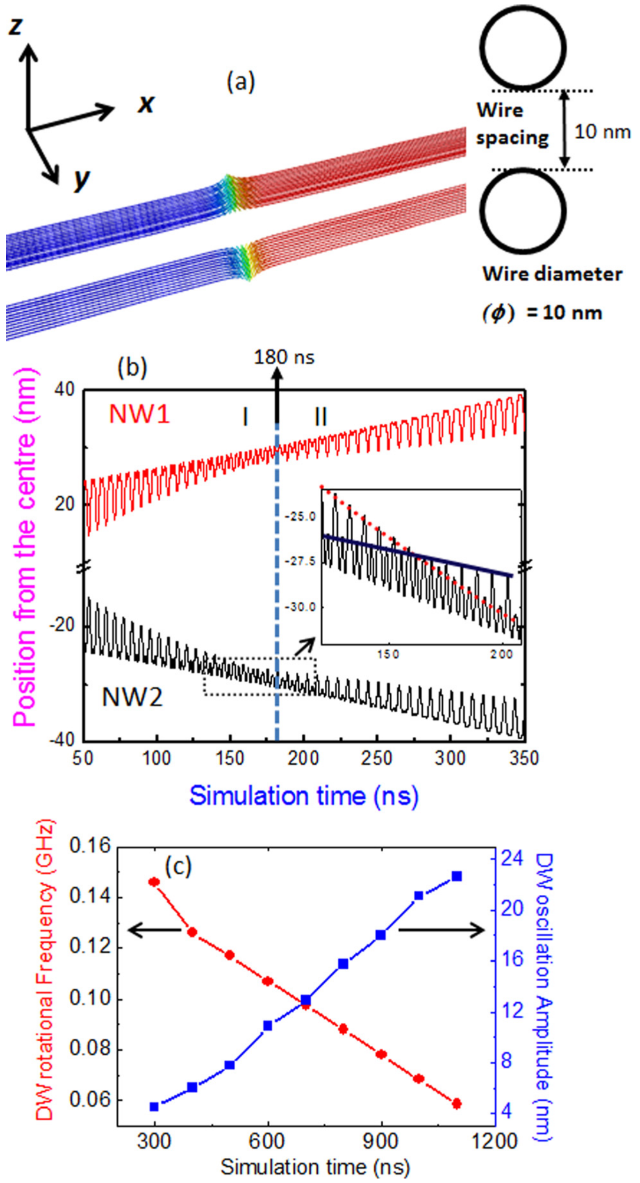

FIG. 1. (a) Schematic of the coupled DW system. A Tail-to-Tail DW is relaxed in each nanowire. (b) The position of the DWs along the long axis in both nanowires shows oscillatory translational motion. Regimes I and II represent the strongly coupled DW oscillation and weakly coupled (self-sustained) DW oscillation, respectively. (c) The DW rotational frequency and oscillation amplitude as a function of the simulation time for the DW motion in regime II.

have the same magnetic charge, the repulsive motion can be attributed to the magnetostatic interaction between the two DWs.[28]

Though the general trend is repulsive, both DWs also exhibit an oscillatory motion along the nanowire length. We attribute this oscillation to the DW "breathing"[29] mode, where the DW undergoes a process of expansion and contraction. By looking at the change in the amplitude of the oscillation over time, the oscillatory motion can be characterized by two distinct regimes: regime 1, which corresponds to $t < 180$ ns; and regime 2, which corresponds to $t > 180$ ns.

In regime I, the amplitude of the oscillation decreases as the two DWs move away from each other due to the decreasing effect of the magnetostatic coupling. The amplitude of the oscillation reaches a minimum at the end of regime 1, at around $t \approx 180$ ns, which corresponds to the two DWs being separated by 60 nm. At the crossover between the two regimes, a clear superposition of two distinct oscillations is present in the system, as seen in the inset of Figure 1(b). The dotted (red) line indicates the amplitude of the stray-field induced oscillation, while the solid (blue) line indicates the self-sustained oscillation.

In regime II, where the self-sustained oscillation is dominant, the oscillation amplitude increases as a function of time. As the DW is a closed system, the total energy of the DW should be a combination of both the energies from the oscillation to rotational motions. The DW rotational frequency and the oscillation amplitude are plotted as functions of time in Figure 1(c). As the two DWs move away from each other, the rotational frequency decreases linearly whereas the amplitude of the DW oscillation increases, i.e., the energy dissipated from the rotational motion becomes the energy source for the increase in the DW oscillation amplitude. To obtain the rotational energy, the DW can be modelled as a rotating disk, and thus the kinetic energy of the rotation can be written as $K_{DW} = \frac{1}{2}I(2\pi f)^2$, where I is the moment of inertia of the rotating DW, while f is the frequency of the rotation. I is related to the DW mass by $\sum_{i=1}^{n} m_i R_i$, where m_i is the mass that is attributed to each spin and R_i is the radial distance from the axis of rotation. Similarly, the oscillation energy can be obtained by attributing the oscillatory motion to a simple harmonic motion (SHM). The energy of such a system is given by $E_{os} = \frac{1}{2}kA^2$, where k is the spring constant and A is the amplitude of oscillation. From our assumption that the DW is a closed system, the loss in the rotational energy should give rise to an increase in translational oscillatory energy ($\Delta K_{DW} = \Delta E_{OS}$), which gives us $\Delta A = \sqrt{\frac{I}{K}}2\pi(\Delta f)$. This results in a linear relationship between the change in the rotational frequency and the change in the amplitude of oscillation, as can be clearly seen in Figure 1(c).

To overcome the repulsive magnetostatic interaction between the two DWs, spin-polarized current is applied to both nanowires but in opposite directions as shown in the schematic, Figure 2(a). At a critical current density of 2×10^5 A/cm^2, the magnetostatic interaction is found to be balanced by the spin transfer torque (STT) from the spin polarized current. As a consequence, the two DWs are held close to the centers of the nanowires, while still moving in an oscillatory manner, as shown in the inset of Figure 2(b). Fourier spectrum of the oscillatory motion in Figure 2(b) reveals that the DW oscillations occur at a constant frequency of 0.16 GHz. Shown in the inset of Figure 2(c) is the rotation of the transverse components ($m_y + m_z$) of one of the DW around the longitudinal axis of the corresponding nanowire. The corresponding Fourier spectrum in Figure 2(c) shows that the DW rotation occurs with periodic frequency modes with decreasing power. The maximum power is found to occur at 0.16 GHz, which is in synchronization with the DW oscillation.

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To understand the influence of the STT on the DW rotation, the calculations for different nanowire separations are analyzed. The critical current density to balance the magnetostatic coupling and the rotational frequency of the DWs are plotted as a function of the inter-wire spacing in Figure 3. Both the critical current density and the rotational frequency are shown to decrease as the separation between the nanowire is increased, which can be attributed to the weaker magnetostatic coupling between the two DWs. However, the result also shows that the rotational frequency does not decrease in the same manner as the critical current density, which implies that the applied current density does not affect the frequency of the DW rotation. As such, the applied current only works to balance the magnetostatic repulsion, thereby preventing the DWs from decoupling.

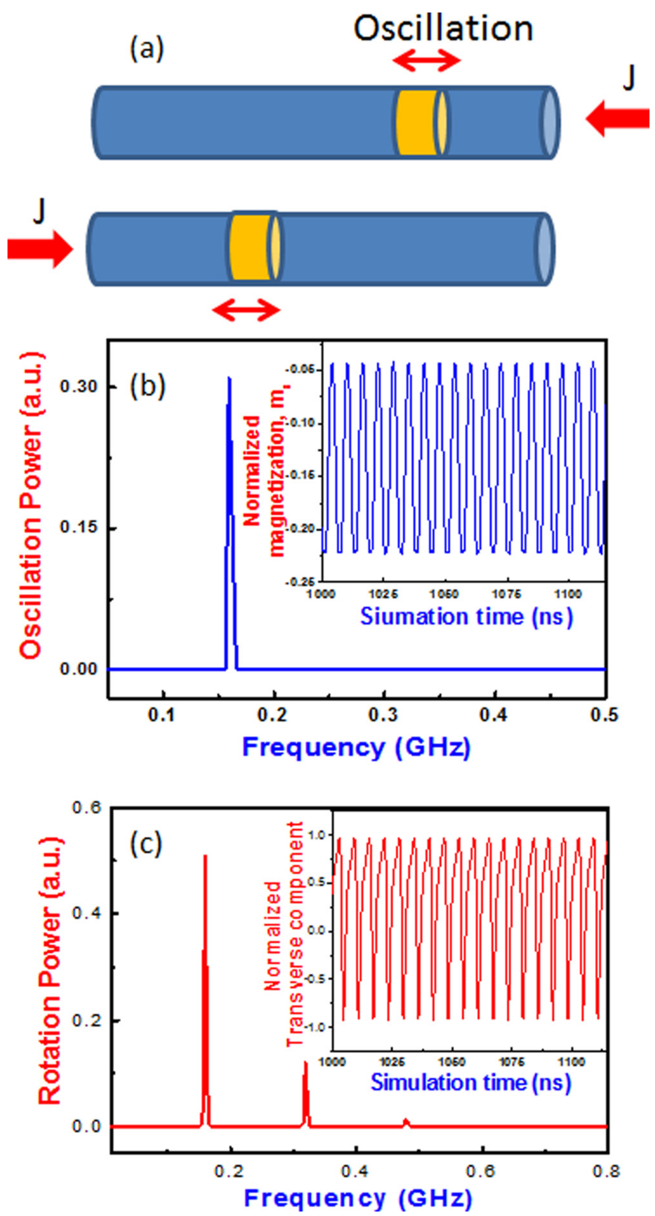

FIG. 2. (a) A schematic to illustrate the oscillatory motion of the two DWs and the direction of current in the two nanowires. (b) Fourier spectrum of the DW translational oscillation along the long axis shows that the frequency for maximum power occurs at 0.16 GHz when the coupling is balanced by the STT effect. Inset shows the DW oscillatory translational motion. (c) Fourier spectrum of the DW rotational motion shows periodical frequency modes occurs in the DW rotation. The fundamental mode with the highest power is around 0.16 GHz. Inset shows the rotation of the DW transverse component in one of the nanowires.

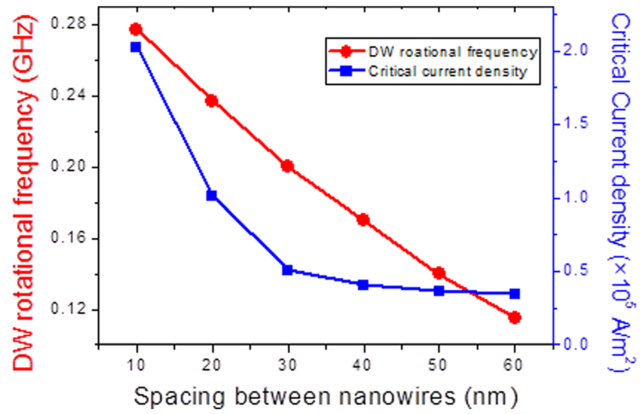

FIG. 3. Critical current density required to sustain the DW oscillation and the DW rotational frequency as a function of the spacing between the cylindrical nanowires.

When the magnetostatic repulsion is balanced by the applied current, the oscillations of the two DWs follow the simple harmonic motion, in contrast to the damped harmonic motion of DWs in planar nanostructures.[4,25] To understand the mechanism behind the sustained oscillation, the transverse component of the DW in the top nanowire and the exchange energy of the system are extracted as a function of simulation time as shown in Figures 4(a) and 4(b). The transverse component and the exchange energy are shown to change continuously in a cyclic manner, which suggests that the DW shape varies during the oscillation. During the sustained oscillation, the DW changes its shape continuously between two distinct configurations, i.e., a compressed state and a relaxed state. The variance of the shape can be attributed to a finite mass of transverse DW in the cylindrical nanowire.[12,30] The mass of the DW can be calculated by solving the equation of the simple harmonic motion of two masses connected by a spring. The demagnetization energy of the system shown in Figure 4(c) can be approximated as the potential energy of a spring system.[4,25] The spring constant (K) is extracted by solving the equation of simple harmonic motion at two extreme points of separation ["A" and "B" in Figure 4(d)] between the two DWs, and is found to be $K = 3.54 \times 10^{-5}$ J/m^2. The expression for the mass can be deduced from the equation of simple harmonic motion, which is $m = \frac{K}{4\pi^2 f^2}$, which gives us 2.95×10^{-23} kg. However, the mass of the coupled DW system represents the reduced mass of the two DWs. As the two DWs are of same type and equal size, the mass of a single DW is twice of the reduced mass, $m_{DW} = 5.9 \times 10^{-23}$ kg. This mass is in the same order as calculated for DWs in planar nanostructures.[5,25] We have also calculated the mass of the DWs in different cylindrical nanowires with various diameters as shown in Figure 4(f). The results show that the mass of the DW increases linearly with larger nanowire diameter, which

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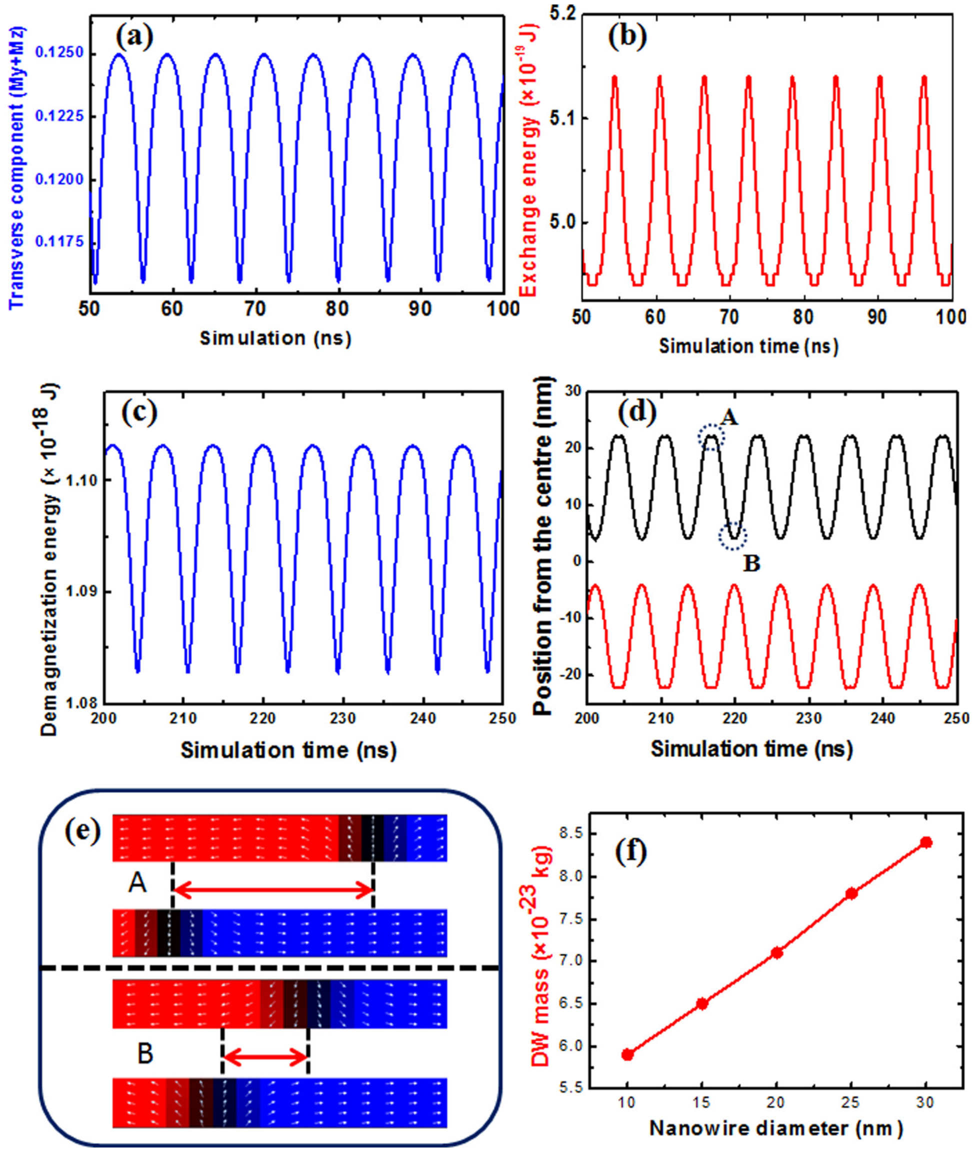

FIG. 4. (a) Transverse component of the DW as a function of simulation time when the DW oscillation is sustained by spin-polarized current. (b) The exchange energy of the system as a function of the simulation time. (c) The demagnetization energy as a function of the simulation time (d). The position of the two DWs during the sustained oscillation as a function of the simulation time. The system resembles two masses connected by a spring undergoing a simple harmonic motion. (e) The magnetization configurations of the nanowires at the two extreme positions ("A" and "B") of the DW oscillation. (f) The DW mass as a function of the nanowire diameter.

further confirms the finite mass characteristic of the DW in cylindrical nanowire.

IV. CONCLUSION

To summarize, we show that in a coupled DW system, the DWs possess an intrinsic oscillatory behavior. By balancing the repulsive magnetostatic interaction between the DWs with spin-polarized current, the sustained DW oscillation and rotation can be achieved. Modeling the oscillation as a simple harmonic motion, the mass of a DW is calculated to be of the order of 10^{-23} kg. The critical current density for sustained DW oscillation is in the order of $10^5\,\text{A/cm}^2$. The implication of this work is that coupled DW in cylindrical nanowires may be used as magnetic microwave generator, which can operate at low current density.

ACKNOWLEDGMENTS

This work was supported by the Singapore National Research Foundation CRP Grant (Non-volatile logic and memory integrated circuit devices, NRF-CRP9-2011-01). The authors thank Christian Engel for useful discussions.

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