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Current-induced coupled domain wall motions in a two-nanowire system

I. Purnama,[1] M. Chandra Sekhar,[1] S. Goolaup,[1,2] and W. S. Lew[1,a)]
[1]*School of Physical and Mathematical Sciences, Nanyang Technological University, 21 Nanyang Link, Singapore 637371, Singapore*
[2]*Department of Electrical and Electronic Engineering, University of Mauritius, Reduit, Mauritius*

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In two closely spaced nanowires system, where domain walls exist in both of the nanowires, applying spin-polarized current to any of the nanowire will induce domain wall motions in the adjacent nanowire. The zero-current domain wall motion is accommodated by magnetostatic interaction between the domain walls. As the current density is increased, chirality flipping is observed in the adjacent nanowire where no current is applied. When current is applied to both nanowires, the coupled domain wall undergoes oscillatory motion. Coupling breaking is observed at a critical current density which varies in a non-linear manner with respect to the interwire spacing. © *2011 American Institute of Physics*. [doi:10.1063/1.3650706]

There has been increasing interest to understand the motion of domain walls (DWs) driven by spin-polarized current, particularly for developing the next generation data storage[1] and logic devices.[2] For data storage, magnetic domains inside a nanowire are used as the data bits, with DWs separating each of them. Spin-polarized current is then used to move the DWs along the nanowire. Under applied current, DWs will move along the same direction irrespective to the DW type, contrary to the case where magnetic field was used;[3] the length of the magnetic domains is then expected to remain constant. The operating speed of the data storage depends on how fast the DWs can be moved within the nanowires, while the density is determined by how close the nanowires can be placed to each other. Many efforts have been spent to understand the motion of DWs inside a single nanowire. For instance, it was found that adjusting the rise time of the applied pulse current will amplify the motion of a DW.[4,5] It has also been shown that when the applied current density is higher than a critical value, a transverse DW undergoes a chirality flipping,[6,7] the phenomenon is known as Walker breakdown. High data density design implies that the nanowires will be placed very close to each other. Magnetostatic interaction between the DWs from adjacent nanowires then becomes important. It has been shown that the interaction can act as a pinning mechanism.[8,9] To overcome the pinning, external magnetic field has to be applied to the system. However, no report has been made on how the magnetostatic interaction will affect the motions of the DWs within the nanowires that are being driven by spin-polarized current. In this paper, by using micromagnetic simulation, we show how the magnetostatic interaction affects the motion of DWs in two nanowires system. The Walker breakdown limit of such system is found to be shifted to higher current density. Applying current to both of the nanowires with each in different direction results in an oscillatory motion of the two DWs. The interaction between the two DWs can then be modelled as two bodies with finite masses that are connected by a spring.

We consider $Ni_{80}Fe_{20}$ nanowires with width of 100 nm and thickness of 10 nm. At these dimensions, transverse DWs are the only stable configurations.[10] The distance between the two wires was set to 100 nm. The object oriented micromagnetic framework code (OOMMF) extended by incorporating the spin transfer torque term[11] to the Landau Lifshitz Gilbert (LLG) equation for the DW motion was used. The materials parameters are chosen for permalloy. The damping coefficient (α) is fixed to 0.005 and the non adiabatic constant β has been chosen as 0.04 in our simulations. The unit cell size for all simulations was set to be 5 nm × 5 nm × 5 nm.

We have studied the interaction between two types of transverse DWs: head-to-head (HH) and tail-to-tail (TT) in two adjacent nanowires. The system is relaxed at zero field and zero current. The two DWs are attracted to each other via their stray magnetic field, reaching an equilibrium position where the two DWs are aligned along each other as shown in the inset of Fig. 1(a). The interaction can be pictured as two magnetic charges with different polarities being attracted to each other.[12] In this stable configuration, the total energy of the system is minimized.

Spin-polarized current is then applied to move the nanowire with the TT DW. Our results show that as the TT DW moves, the HH DW in the adjacent nanowire also moves in the same direction. Similar phenomenon is observed when spin-polarized current is applied only to the wire with the HH DW. Both cases reveal that coupling between the two DWs is strong enough to induce DW motion within nanowires where spin-polarized current is not applied. The two DWs system can be considered as a coupled domain wall system (CDWS).

Shown in Fig. 1(a) is the displacement of the CDWS as a function of time for various current densities. For current densities $J \leq J_a$ where $J_a = 2.755 \times 10^{12}$ A/m^2, the CDWS moves with a constant speed along the nanowire. The magnitudes of the speed are 326.96 m/s for $J = 2.120 \times 10^{12}$ A/m^2 and 407.82 m/s for $J = 2.755 \times 10^{12}$ A/m^2. The speed of the CDWS is increasing linearly with respect to the current density value. The DWs also retain their shapes as they propagate along the nanowire. Here in Fig. 1(a), we show the displacement of the CDWS as a function of time for

a)Author to whom correspondence should be addressed. Electronic mail: wensiang@ntu.edu.sg.

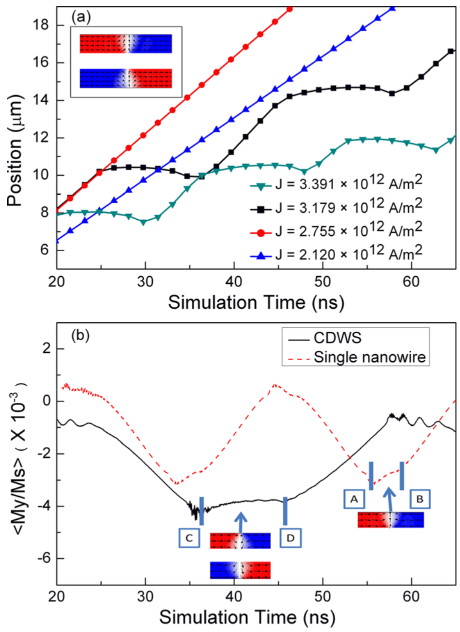

FIG. 1. (Color online) (a) The displacement of the CDWS as a function of time for various current density values. Inset is the remanent state of the CDWS. (b) The normalized transverse component of the magnetization as a function of time for a CDWS and a single nanowire. The applied current density is $J = 3.179 \times 10^{12}$ A/m^2.

$J = 3.179 \times 10^{12}$ A/m^2 and $J = 3.391 \times 10^{12}$ A/m^2. The average speeds are 163.21 m/s and 118.73 m/s, respectively. Increasing the current density beyond J_a results in a drastic drop of the average velocity. Thus, J_a is the Walker breakdown current density limit of the CDWS. It is higher than the Walker breakdown limit of a single nanowire which in our simulation was found to be $J_b = 1.696 \times 10^{12}$ A/m^2. Shown in Fig. 1(b) is the transverse component of the magnetization of a CDWS and a single DW as a function of time. The applied current density is $J = 3.179 \times 10^{12}$ A/m^2, which is well above Walker breakdown current density limit for both cases. The maximas and the minimas of the graph represent the times where transverse DWs are observed. The increase and decrease of the magnetization along the y-direction represent the chirality flipping of the DWs. Chirality flipping in CDWS is observed to occur in both of the nanowires, even though current is only applied to one of the nanowires. The timeframe where a DW retains its transverse shape in CDWS is found to be extended compared to the single nanowire case.

To understand the characteristics of the coupling in the CDWS, spin polarized current is applied to the TT DW along $+x$ direction and to the HH DW along $-x$ direction. The applied current causes the two DWs to move in the opposite direction, while the magnetostatic coupling tries to bring the two DWs together. The resultant motion of the DWs is due to the competition between the two forces. Shown in Fig. 2(a) is the separation between the two DWs along the horizontal direction as a function of simulation time. The distance between the two DWs increases and decreases until it reaches a certain equilibrium position. At any time, the velocities of the two DWs are equal in magnitude but opposite in direction. The final separation (x_f) between the two DWs increases linearly with respect to the current density as shown in

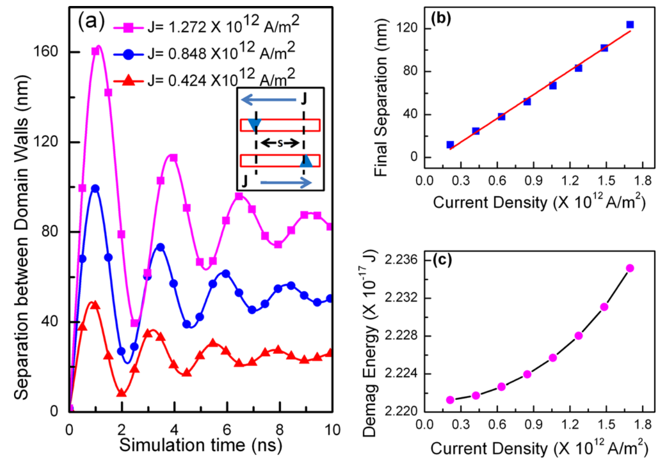

FIG. 2. (Color online) (a) Separation between the two DWs as a function of simulation time. Inset shows the directions of the applied current on both nanowires. The magnitude of the applied current is equal at anytime. (b) The final separation between the two DWs as a function of current density. (c) The demagnetization energy of the system as a function of the final separation between the DWs in the equilibrium states.

Fig. 2(b). According to the one-dimensional model, the force exerted by spin-polarized current (F_s) on a DW is a linear function of current density;[13] x_f increases linearly as F_s is increased linearly. In equilibrium, the force from the spin-current is equal to the force from the coupling, thus both forces are linear functions of x_f. The behaviour of the coupling force is similar to the behaviour of a spring. The CDWS can be modelled as two masses connected by a spring.

The spring constant of the CDWS gives the information of the coupling strength and also can be used in determining the motion of the two DWs under various applied current density. To obtain the spring constant, we look at how the energy of the system evolves. The total energy of the system is a sum of its demagnetization energy and exchange energy. The demagnetization energy represents how the stray magnetic field affects the magnetization while the exchange energy represents the shape of the DWs. In this case where current is applied to both of the nanowires, the two DWs retain their transverse shapes as the magnitude of the applied current density is below the Walker breakdown current

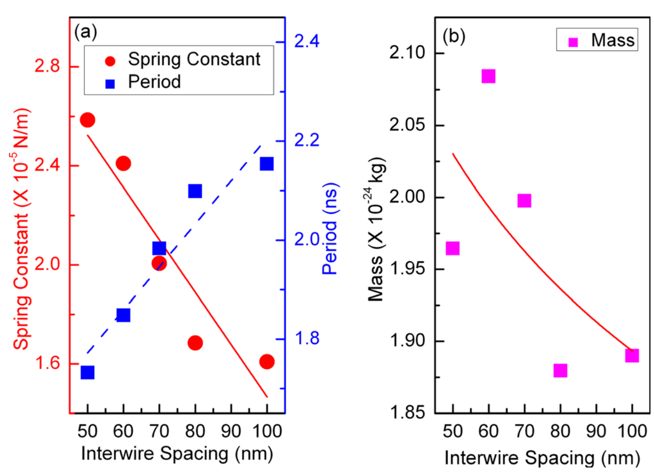

FIG. 3. (Color online) (a) The period of the oscillation and the spring constant of the CDWS as a function of interwire spacing. (b) The mass of the DWs in CDWS as a function of interwire spacing.

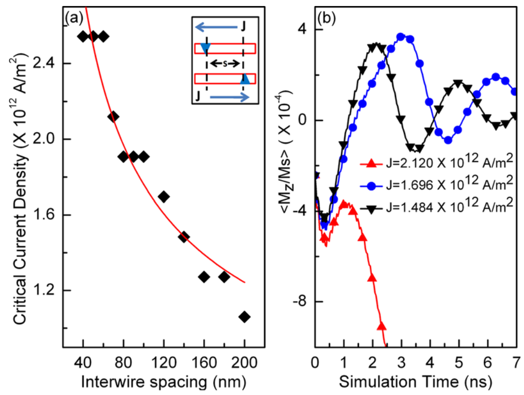

FIG. 4. (Color online) (a) The critical current density as a function of interwire spacing in CDWS. Inset is the direction of the applied current in both of the nanowires. (b) The normalized values of the magnetization of the system pointing along the z axis as a function of simulation time for various applied current density. The interwire spacing here is 100 nm with critical current $J = 1.908 \times 10^{12}$ A/m^2.

density limit. The exchange energy of the system thus remains constant; the evolution of the total energy of the system comes mainly from the evolution of the demagnetization energy. Fitting the demagnetization energy as a function of the equilibrium positions to a quadratic function will give us the spring constant of the system as shown in Fig. 2(c). Shown in Fig. 3(a) are the calculated spring constant and the oscillation period of the CDWS as a function of the interwire spacing. The spring constant is found to be decreasing as the distance between the nanowires is increased. This shows that the coupling between the two DWs is weaker for higher interwire spacing. The oscillation period increases as the distance is increased. The mass of the coupled domain wall can be found by using $m = \frac{kT^2}{4\pi^2}$. The mass shown in Fig. 3(b) is of the order 10^{-24} kg which is in a good agreement with the values reported before.[14,15]

Coupling between the two DWs is not observed when the current density is increased beyond a certain critical value. The coupling is broken and the two DWs move irrespective of each other. Shown in Fig. 4(a) is the critical current density as a function of interwire spacing. The critical current density decreases in a non linear manner with respect to the distance between the wires, which shows that the coupling is weaker for larger interwire spacing.

To understand the coupling breaking process, we consider the change in the internal structure of the DWs. When a transverse DW is driven into motion, the internal structure of the DW changes; part of the magnetization of the DW will start to point to the z axis. The direction that the magnetization faces, whether it is in the +z or the –z direction, is determined by the chirality of the DW and the direction of the motion. Fig. 4(b) shows the normalized values of the magnetization of the two DWs along the z axis. Here, we can see that for current below the critical value, the magnetostatic interaction induces a periodic change in the out-of-plane magnetization component of the DW. Beyond $t \approx 1.5$ ns, where the two DWs start to move closer to each other again, the out-of-plane component of the magnetization now points to the +z direction. However, for current above the critical value, the magnetization of the system after $t \approx 1.5$ ns keeps on building up to the –z direction. The different behavior of the system below and above the critical current density can, therefore, be explained as the two DWs being unable to reverse the direction of their out-of-plane magnetization component when current above the critical value is applied. The non-linear change of the magnetization in the early stage of the simulation ($t < 1.5$ ns) is due to the non-linearity of the stray magnetic field.

In conclusion, we have shown how current-driven DW motion is affected when the DW is coupled to adjacent DWs of opposite polarity. The coupled DW within the adjacent nanowire is induced to move in the same direction as the current-driven DW. In the CDWS, the Walker breakdown is shifted to higher current density limit. It is interesting to see that the chirality flipping is observed on both nanowires, even though spin-polarized current is only applied to one of the nanowires. Coupling two DWs or more can also be an alternative method to move DWs with only applying spin-polarized current to specific wires. When current is applied to both nanowires in opposite direction, the two DWs undergo a damped oscillation motion, revealing the spring-like nature of the magnetostatic coupling. Increasing the current density in this manner results in the breaking of the magnetostatic coupling, the critical current density varies with the interwire spacing in a non-linear manner.

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