Collective Motions Assisted by Magnetostatic Interactions in Coupled Domain Wall System

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We have investigated the coupling between a transverse head-to-head domain wall and a transverse tail-to-tail domain wall in closely spaced $Ni_{80}Fe_{20}$ nanowires. Micromagnetic simulation shows that the two domain walls are coupled to each other. When spin-polarized current is applied to any of the nanowires, the two domain walls move in the same direction. The Walker breakdown limit in such system is shifted to higher current density. We have also observed that the coupling is broken for some combinations of initial magnetizations of the two domain walls.

Index Terms—**Domain wall, spin-polarized current, Walker breakdown.**

I. Introduction

In a ferromagnetic material, a domain wall (DW) is an area that separates two regions that have different magnetizations. A head-to-head (HH) DW separates two regions with magnetization pointing to each other, and a tail-to-tail (TT) DW separates two regions with magnetization pointing away from each other. Understanding the motion of DWs within a nanowire under applied magnetic field or spin-polarized current have been gaining much interest in recent years, particularly for its possible applications as the next generation data storage and logic devices, where DWs are used as the working mechanism. For data storage, racetrack memory [1] is one of the potential candidates. In racetrack memory, data are represented by magnetic regions that are separated by DWs, and spin-polarized current is used to move the DWs. The performance of the device depends on how fast spin-polarized current can move the DWs and how precisely the DWs can be stopped, while the maximum density that the racetrack can achieve will depend on how close the nanowires can be placed close to each other. Presently, most of the works are focused on controlling the motion of a DW in a single nanowire [2]–[4], no reports have been made on the effect of inter-DW interactions on the motion of a DW under applied spin-polarized current. In this work, we show that two DWs that have different magnetic monopole moments will be coupled to each other. The two DWs can be moved along the nanowires when spin-polarized current is applied to any of the nanowires.

II. Simulation Methodology

We consider $Ni_{80}Fe_{20}$ nanowires with a width of 100 nm and a thickness of 10 nm. At these dimensions, transverse DWs are the only stable configurations [5]. The length of the nanowires is 20 μm. The stray field from the edges of the nanowires is compensated by applying a static magnetic field with equal magnitude as the stray field but directed opposite to it. The distance between the two wires was set to be 100 nm. The chosen material parameters were: saturation magnetization $(M_s) = 860 \times 10^3$ A/m, exchange stiffness constant $(A_{ex}) = 1.3 \times 10^{-11}$ J/m, and magnetocrystalline anisotropy $k = 0$. The object-oriented micromagnetic framework code OOMMF [6] extended by incorporating the spin transfer torque term [7] to the Landau Lifshitz Gilbert (LLG) equation was used to simulate the dynamics of the DW. The unit cell size for all simulations was set to be $5\text{ nm} \times 5\text{ nm} \times 5\text{ nm}$. The LLG equation including the spin torque terms can be written as follows:

$$\frac{\partial M(t)}{\partial t} = -\gamma_o M \times H_{\text{eff}} + \frac{\alpha}{M_3} M \times \frac{\partial M(t)}{\partial t} - (u \cdot \nabla) M + \frac{\beta}{M_3} M \times [(u \cdot \nabla) M]. \quad (1)$$

The first term on the right-hand side in the equation relates to the torque exerted on the magnetization vector $\boldsymbol{M}$ by the effective magnetic field $\boldsymbol{H}_{\text{eff}}$ and the second term describes (Gilbert) damping torque, parameterized by Gilbert damping constant (α) which is fixed to 0.005 in our simulations. The last two terms are the spin transfer torque terms which incorporate the two mechanisms---adiabatic and nonadiabatic torques, respectively. The nonadiabatic constant β has been chosen as 0.04 [8]. The effective drift velocity of the conduction electron spins (u) is defined as

$$u = \frac{Jg\mu_B P}{2eM_s} \quad (2)$$

where J is the current density, P is the spin polarization which is assumed to be 0.7 in our simulations, μ_B is the Bohr magnetron and e is the electron charge. In our simulation, the magnitude of the current density was varied by changing the drift velocity of the conduction electron.

III. Simulation Results and Discussion

We have studied the interaction between two types of transverse DWs: head-to-head (HH) and tail-to-tail (TT). In the stable

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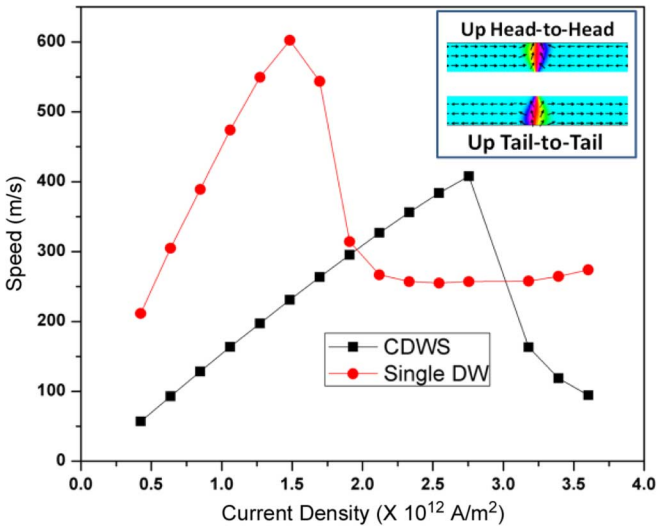

Fig. 1. Speed of a single DW and a CDWS as a function of current density. Inset shows equilibrium state of the CDWS.

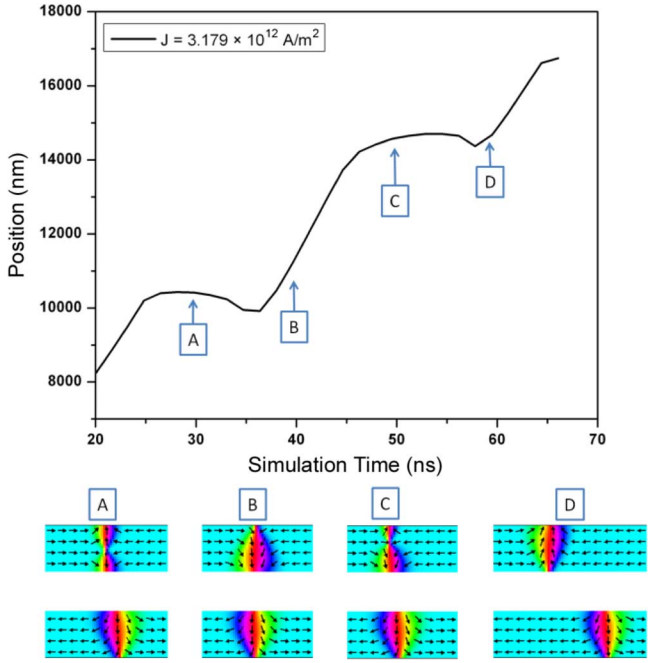

Fig. 2. Position of the CDWS as a function of time. Current is applied to the TT DW and the density is above its Walker breakdown current density limit. The type of CDWS studied here is up head-to-head against up tail-to-tail.

state, the magnetic spins within the transverse DW adopts a triangular shape. For the HH DW, the transverse component points to the base of the triangle, while the transverse component of the TT DW points to the apex of the triangle. The transverse components act as additional degree of freedom which is called the chirality of the DW. For nanowires directed along the x axis, the chirality of the DW is "Up" when the transverse component is directed along $+y$ direction and it is "Down" when the transverse component is directed along the $-y$ direction. The system is relaxed at zero fields and zero current density. The two DWs are attracted to each other via their stray magnetic fields, reaching an equilibrium position where the apexes of the two DWs are aligned along each other as shown in the inset of Fig. 1. The interaction can be pictured as two magnetic charges with different polarities being attracted to each other [9]. In this stable configuration, the total energy of the system is minimized. Spin-polarized current is then applied to move the TT DW within the nanowire. For the range of the current densities used in the simulations and with interwire spacing of 100 nm, the Oersted field from the electric current is found to be in the range of 50 Oe to 20 Oe, directed perpendicular to the two nanowires. 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. In this case, the TT DW moves in the same direction as the HH DW. The TT DW is coupled to the HH DW and vice versa. 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 are the speeds of a CDWS and a single TT DW as a function of current density. The speed of a single DW is a linear function of current density up until $\mathrm{J}_1 = 1.484 \times 10^{12}\ \mathrm{A/m}^2$, where beyond this, the speed is shown to drop appreciably. For the CDWS, the linear relation between the speed and the current density extends beyond J_1 up to $\mathrm{J}_2 = 2.755 \times 10^{12}\ \mathrm{A/m}^2$, where beyond this, the average speed of the CDWS drops appreciably similar to the single nanowire case. J_2 is then considered to be the Walker breakdown current density limit of the CDWS. In CDWS, the Walker breakdown current density limit is shifted to higher value compared to that of a single nanowire.

When current with density smaller than J_2 is applied to drive the CDWS, the two DWs move with equal and constant speed. The two DWs also retain their triangular shape as they propagate along the nanowires. The magnitude of the speed of the propagation is observed to be reduced by approximately a factor of 3 compared to the single nanowire case. Njaka *et al.* [10] has shown that a change in the DW width changes the propagation speed of the DW. However, there is no change in the widths of the two DWs in CDWS; the reduction in the speed is not attributed to the change in the shape of the DWs. When current is applied to the TT DW, the magnetostatic attraction from the HH DW to the TT DW is acting against the direction of the motion that the spin-polarized current induces to the TT DW, resulting in the smaller speed of propagation.

For the case where the current density is higher than the Walker breakdown current density limit, the average speed of the CDWS drops appreciably due to the chirality flipping of the DWs. The chirality flipping process is mediated through the nucleation of antivortex. The propagation speed of the CDWS is reduced when an antivortex core is present in either of the two DWs, as shown in inset A and C of Fig. 2. The two DWs move along the two nanowires with highest speed when the two DWs are in their transverse shape, as shown in inset B and D of Fig. 2.

We investigated the coupling for all the possible combinations obtained by changing the chiralities of the DWs. In all

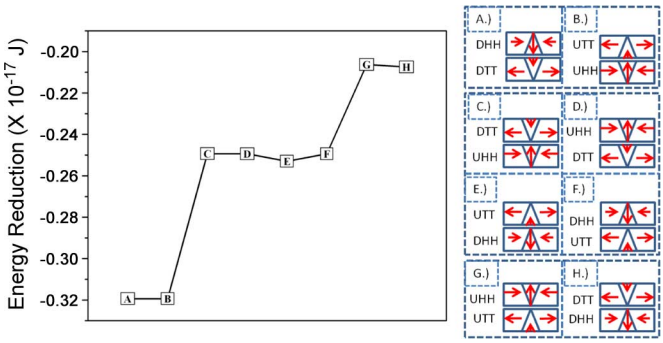

Fig. 3. Reduction in the total energy of the system for all eight possible combinations as compared to the no-interaction case. Here the separation between the two DWs is 100 nm.

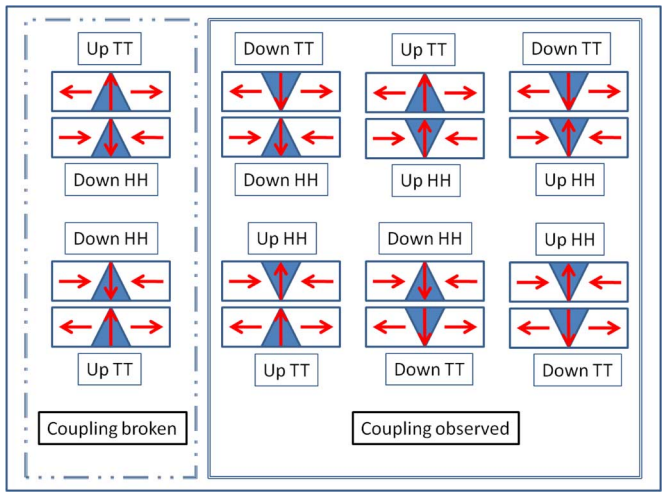

Fig. 4. Eight possible combinations of coupling between a head-to-head domain wall and a tail-to-tail domain wall. In each combinations, spin-polarized current is only applied to the bottom nanowire when viewed according to the diagram.

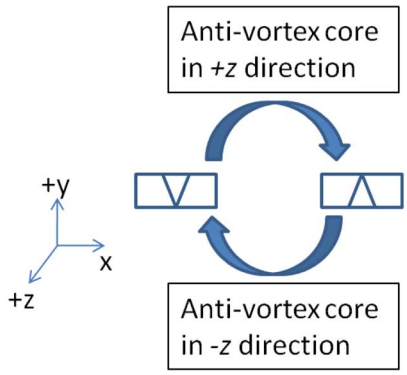

Fig. 5. Directions of the antivortex cores nucleated when a DW flips its chirality.

eight possible combinations, the total energy of the system is reduced compared to the case where no interaction is present, i.e., two nanowires placed infinitely far from each other. In the no-interaction case, the total energy of the system obtained from the simulation is 2.429×10^{-17} J.

As shown in Fig. 3, the eight combinations can be separated into three groups with respect to their energy value. In A and B where the two DWs have their bases of their triangular shapes facing each other, the energy of the system is the lowest. Changing the chirality of one of the two DWs gives four combinations $(\mathrm{C} \sim \mathrm{F})$ where the base of one DW is facing the apex of the other DW; these four combinations have the same energy which is higher than the energy in A and B. In G and H, the apexes of the DWs are facing each other; here the system has the highest total energy. The energy value of the system gives the information on the coupling strength of the combinations, lower energy value equals to stronger coupling. Thus, in A and B, the coupling between the DWs is the strongest while in G and H, the coupling is the weakest.

In CDWS, the speed of the two DWs is a linear function of the applied current density until it reaches its Walker breakdown current density limit where the speed starts to drop significantly. The Walker breakdown current density limit, when the coupling between the two DWs is the weakest, is found to be equal to J_2. When the chiralities of the DWs are changed to the case where the coupling is the strongest, the Walker breakdown current density limit is shifted to $\mathrm{J}_3 = 2.967 \times 10^{12}$ A/m^2. The stronger coupling between the DWs increases the stability of the transverse shapes resulting in higher Walker breakdown current density limit.

Interestingly, above their respective Walker breakdown current density limit, the behavior of the eight combinations is not the same. We observe that in the CDWS, there are two combinations where coupling is only observed at the early stage of the simulations.

Current with density of 3.179×10^{12} A/m^2 is applied to the bottom nanowire, the density of the current is above the Walker breakdown current density limit of all eight combinations. The motion and the chirality flipping of the two DWs are observed. The simulations show that in A, B, C, and D combinations, chirality flipping is occurring only in the upper nanowire. In G and H combinations, the first chirality flipping occurs in the lower nanowire; however, as the two DWs propagate along the nanowires, chirality flipping is again only occurring in the upper nanowire. In E and F combinations, the lower DWs move faster than the upper DW, breaking the coupling between them. After the coupling has been broken, the upper DW stops while the lower DW undergoes continuous chirality flipping as it propagates along the nanowire. Above the Walker breakdown current density limit, chirality flipping in CDWS in general occurs in the nanowire where no current is applied, contrary to the single nanowire case. However, when the DW that is being driven by the spin polarized current has its apex of the triangular shape facing the other nanowire, the DW will flip first.

The initial chiralities of the two DWs in CDWS strongly determines the motion of the two DWs. DWs change their chiralities by nucleating an antivortex, the magnetization of the antivortex core is directed out-of plane of the nanowire. A DW that is being driven in $+\mathrm{x}$ direction will nucleate antivortex cores in $+y$ $(-y)$ direction when the DW is going to change the position of the apex from the lower (upper) side of the nanowire to the upper (lower) side of the nanowire.

In the E and F combinations, the two DWs are nucleating antivortex core at the same time, similar to the case of the G and H

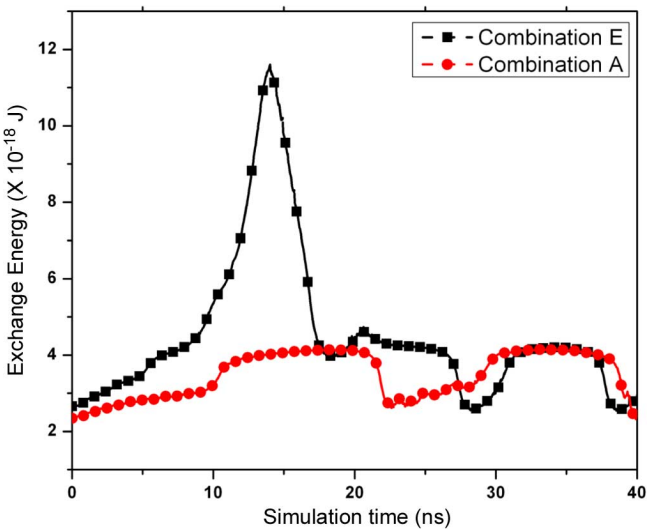

Fig. 6. Exchange energies of the A and E combinations as a function of time. The magnitude of the current density is $3.179 \times 10^{12}\ \mathrm{A/m^2}$.

combinations. However, in E and F both of the antivortex cores are directed to $-z$ direction; this increases the exchange energy and consequently increases the total energy of the system. Increase in the total energy of the system gives weaker coupling between the two DWs which results in the breaking of the coupling. Shown in Fig. 6 is the exchange energy of the A and E combinations as a function of simulation time. The sharp increase in the exchange energy of the E combination refers to the instance where the coupling is broken.

IV. Conclusion

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 DWs within the adjacent nanowires are induced to move in the same direction as the current-driven DW. The system is termed coupled DW system (CDWS). In the CDWS, the Walker breakdown is shifted to higher current density limit. When current with density above the Walker breakdown current density limit is applied to the system, the initial chiralities of the two DWs determine the motion of the two DWs. There are two combinations where the coupling is broken, in these combinations; antivortex cores that have the same orientations are nucleated simultaneously. Nucleation of two antivortex cores that have the same orientation increases the total energy of the system resulting in the weaker coupling.

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