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Remote driving of multiple magnetic domain walls due to topological interaction

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We present a method to drive multiple domain walls in the absence of direct current application in a coupled nanowire system. The domain walls were driven by a combination of remote coupling and exchange repulsion force from the domain wall compressions. The domain walls were compressed as they were unable to annihilate each other due to having similar topological charges. The compressions are present between the subsequent domain walls, which allow them to be driven as a group in the coupled nanowire system. © *2014 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4867468]

The basic operating mechanism of domain wall (DW)-based magnetic devices[1,2] lies on the controlled motion of the DWs within the ferromagnetic structure. To accomplish such feat, external magnetic field or spin-polarized current is used to move the DWs.[3–6] The disadvantage of applying external magnetic field is that we do not have control over the direction in which the DWs move. For instance, within a patterned permalloy nanowire, the Head-to-Head (HH) DWs are driven to move along the applied field direction, while the Tail-to-Tail (TT) DWs are driven in the opposite direction. Thus, the application of external field is not suitable when the nanowire possesses multiple DWs, as they would collide with each other with equal velocity. In the case where spin-polarized current is injected to the nanowire, all of the DWs are driven in the same direction, thus allowing for more control over the movements of the DWs. Most studies, henceforth, have been focused on the dynamics of a current-driven DW in a single nanowire system,[7–9,25] particularly on the aspect of enhancing its propagation speed. However, high data density design implies that multiple DWs within multiple nanowires have to be placed very close to each other. Hence, it is important to investigate how the dynamics of the DWs are affected by the inter-wire and the intra-wire interactions between the DWs. It has been shown that there exists an inter-wire coupling between two DWs due to their magnetostatic interaction when two nanowires are placed very close to each other.[10–12] The inter-wire coupling between the two DWs is spring-like in nature,[13,14] and when one of the DWs is driven by current, the other DW in the current-free nanowire will be remote-driven to move in the same direction.[15]

Here, we investigate the intra-wire interactions between multiple transverse DWs in a two-nanowire system by micromagnetic simulations. The intra-wire interaction is encountered when a remote-driven transverse DW collides with multiple DWs of similar topological structure within the current-free nanowire. The intra-wire interaction between the DWs is repulsive in nature, and it allows for multiple DWs in the current-free nanowire to move together with the remote-driven DW. By analyzing the structure of the DWs, the repulsive force is found to be related to the exchange energy contribution in the magnetization dynamics. We also show that the two-nanowire system allows for selective DW driving, which together with the multiple remote driving shall be taken into account into the design of any high-density magnetic device such as the racetrack memory.

With regard to the stray magnetic fields that they produce, HH DW can be considered as a positive magnetic charge, while TT DW can be considered as negative magnetic charge. When a HH DW and a TT DW are present in a single nanowire, the two DWs are attracted to each other by their opposite magnetic charge, where they eventually collide. If the two DWs have the opposite winding numbers, this attraction is unopposed which leads to DW annihilations, as shown in Fig. 1(a). However, when the two DWs have similar winding numbers, their topological nature prevents them to annihilate.[17–19] In this case, the DWs are compressed and the magnetostatic interaction is stabilized by the exchange repulsion force that arises from their topological defects interaction.

We consider a HH DW and a TT DW with opposite chirality in a single nanowire with thickness of 6 nm. The opposite chirality gives the two DWs similar placement of winding numbers. The two DWs are stabilized with the magnetostatic attraction balanced by the exchange repulsion force. Fig. 1(b) shows a diagram of the magnetization configurations of two DWs with similar winding numbers. The calculated half width, both the uncompressed (λ_{rem}, relaxed) and the compressed (δ_{rem}, compressed) in remanance are shown in the inset of Fig. 2(a).

To obtain the repulsion force, we find the derivative of the exchange energy with respect to the DW compression, δ

$$F_{exc} = -\frac{\partial E_{exc\_left}}{\partial \lambda}\bigg|_{\lambda=\delta} = \frac{Awt}{\delta^2}. \quad (1)$$

For nanowire with width $w = 100$ nm and thickness $t = 6$ nm, and DW compression of $\delta_c = 15.1$ nm, the equation gives $F_{exc} = 3.42 \times 10^{-11}$ kg·m/s^2. The magnitude of the exchange

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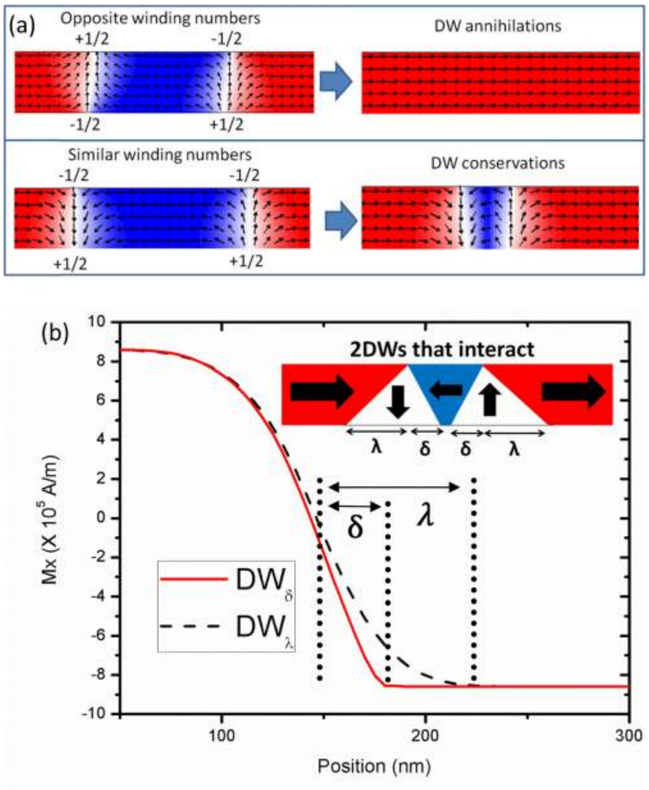

FIG. 1. Magnetic domain wall compression. (a) Schematic showing the winding numbers of transverse DWs. In the case where they have the same winding numbers, the two DWs are compressed upon collision. (b) The magnetization component in the x direction of an unperturbed DW (DW_λ) and a compressed DW (DW_δ). Inset is the illustration of the compressed DWs.

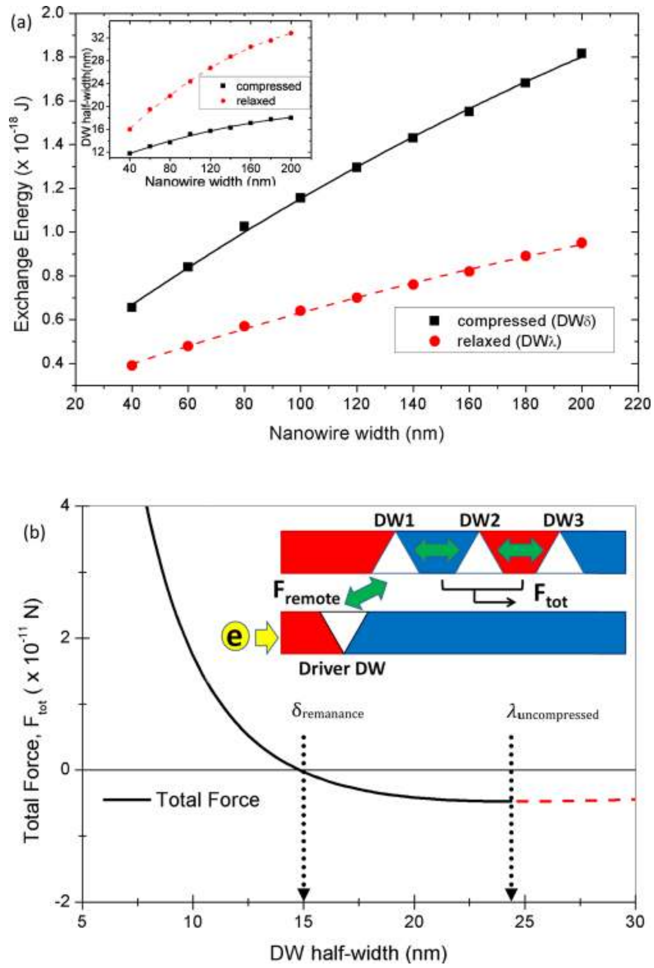

FIG. 2. (a) The exchange energy of unperturbed (E_λ) and compressed (E_δ) DWs as a function of wire width. Shown in the inset is the half-width of the unperturbed DW and the compressed DW. (b) The calculated total force (F_{tot}) as a function of DW compression length (δ) in a nanowire with width (w) of 100 nm and thickness (t) of 6 nm. Shown in the upper right inset is the schematic diagram of the simulation model. The two nanowires are separated 50 nm away. F_{remote} is the remote-driving force between the driver DW and DW1.

repulsion force is comparable to the driving force that is exerted by the spin-polarized and the intrawire magnetostatic force.[20–22] The total force as a function of δ is plotted in Fig. 2(b). The graph shows that the total force that acts to the compressed DW is an attractive force, until the half-widths of the two DWs reach the remanance value, whereby further compression will change the total force into a repulsive force.

To explore the role of the exchange repulsion force in DW dynamics, we consider the case of one-directional collision between two DWs. In the one-directional collision, a single DW is driven by a local driving force and is allowed to collide with another DW. To create a local driving force for the first DW, the remote driving technique is employed.[13–16] In the remote driving technique, another nanowire is placed next to our nanowire of interest. The first nanowire, or the nanowire of interest, is called as the active nanowire, while the second nanowire is called as the driver nanowire. A single DW, which shall be called as the driver DW, is generated in the driver nanowire to be used as a stray magnetic field generator. The driver DW and the first DW (DW1) in the active nanowire are coupled, and their dynamics are related to each other.[13–15,23] Shown in upper-right inset of Fig. 2(b) is the diagram of the simulations. The driver DW and DW1 are oriented such that the triangle bases face each other to assure the strongest magnetostatic attraction between them.[24] To ensure that the topological repulsion is present, the next DWs in the active nanowire need to have similar winding numbers placement, this is achieved by aligning all of the DWs in the active nanowire such that the bases of their triangular shapes face the driver nanowire. The method to generate DWs in the active nanowire with the desired chirality is described in detail in the supplementary material.[21]

Spin polarized current is then applied to the driver nanowire. As the driver DW moves, it interacts with DW1 in the active nanowire due to their stray magnetic field interaction. Due to the magnetostatic interaction, DW1 is remote-driven in the same direction as the driver DW. Eventually, DW1 collides with the next DW (DW2) in the active nanowire. While the remote driving technique serves as the driving force for DW1 in the active nanowire, it is the exchange repulsion that continuously drives DW2 ahead. Here, DW2 and DW1 are compressed further beyond the half-width remanance ($\delta_{remanance}$); the interaction between DW1 and DW2 then becomes repulsive, which then serves to reduce the speed of DW1 and at the same time becomes the driving source for DW2. Shown in Fig. 3(a) are the snapshots of the simulation to show the motion of the DWs. The width (w) and the

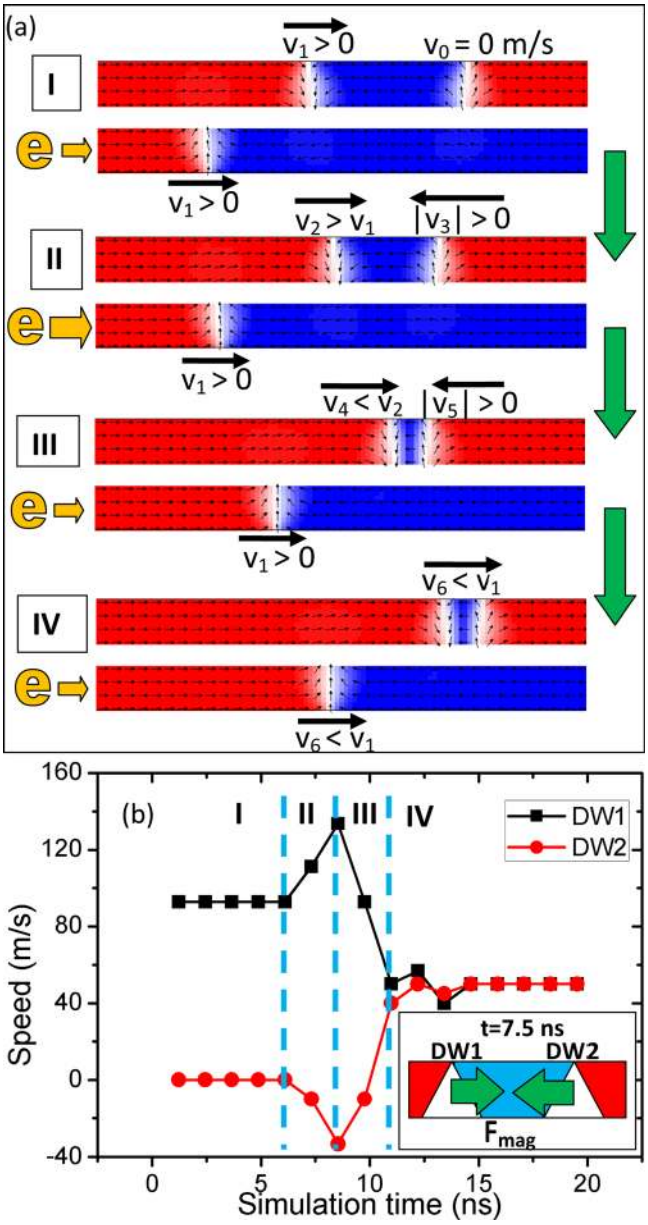

FIG. 3. Multiple remote DW driving (a) Snapshot of the simulations showing the collision between DW1 and DW2 in the active nanowire. (b) The velocity of the DWs as a function of simulation time. In [I], DW1 is being remote-driven and moves with the same velocity as the driver DW. In [II], DW2 moves back to approach DW1 due to the magnetostatic interaction. The magnetostatic interaction also increases the forward velocity of DW1. Shown in the inset is an illustration of the magnetostatic attraction between DWs of opposite magnetic charge. At [III], the two DWs collide and are being compressed. At [IV], the topological force drives DW2 to move in front of DW1. A time span of approximately $t \approx 6$ ns is needed for the two DWs to reach equilibrium starting from the moment of impact. The width (w) of the nanowire is 100 nm and the thickness (t) is 6 nm. The current density applied to the driver DW is $J = 1.06 \times 10^{12}$ A/m^2.

thickness (t) of the nanowire are 100 nm and 6 nm, respectively. The current density applied to the driver DW is $J = 1.06 \times 10^{12}$ A/m^2. Initially (I), the driver DW and DW1 move together with an equal velocity of $v_1 \approx 90$ m/s. For a short period of time (II) between $t \approx 6$ ns and $t \approx 8$ ns, the magnetostatic attraction between DW1 and DW2 propels DW1 to move forward, increasing its velocity to $v_2 \approx 130$ m/s. The attraction also pulls DW2 to move backward with a velocity of $v_3 \approx -40$ m/s. Shown in the inset is an

FIG. 4. The multiple DWs in the active nanowire is remote-driven by the driver DW in the driver nanowire. The magnetization of the nanowires is pointing to the $+x$ direction (red color) and $-x$ direction (blue color) (Multimedia view) [URL: http://dx.doi.org/10.1063/1.4867468.1].

illustration of the magnetostatic attraction between DWs of opposite magnetic charge. At $t \approx 8$ ns, the collision occurs and the topological repulsion starts to become prominent. The two DWs start to get compressed (III). As a result, DW2 is pushed by DW1 to move in the same direction (IV) with a velocity of $v_6 \approx 50$ m/s. Shown in Fig. 3(b) is the velocities of DW1 and DW2 as a function of time. From $t \approx 8$ ns to $t \approx 14$ ns, the two DWs are pushing each other by gradually changing their shapes until they arrive at an equal velocity.[15] Because the original velocity of the driver DW (v_1) is higher than the velocity of the two DWs in the active nanowire, the driver DW is able to move closer to DW1. However, this results in the increase in the magnetostatic interaction. The driver DW is decelerated, and in equilibrium, it moves with the same velocity as the DWs in the active nanowire (v_6).

It is possible to drive multiple DWs in the active nanowire by utilizing multiple collision processes. For instance, when a third DW (DW3) is present in the active nanowire, it will collide with DW2. The collision will compress both of the DWs, and as a result, DW3 will move together with DW1 and DW2. We have extended the method to drive up to 4 DWs in the active nanowire at the same time, the DW group moves with a velocity of $v \approx 30$ m/s under applied current density of $J = 1.06 \times 10^{12}$ A/m^2. In the equilibrium, all of the DWs move with equal velocity as shown in the video of Fig. 4, with the driving force being balanced by the damping force from the energy dissipation.

As described before, the motions of DW2 and the subsequent DWs are the results of collisions with the remote-driven DW. However, as can be seen from Fig. 3(b), the process is not instantaneous; approximately $t \approx 6$ ns is needed for the DWs that are involved in the collisions to reach an equilibrium velocity. Therefore, it is possible for a driver DW that is moving with a high velocity to "bypass" a group of DWs in the active nanowire when there is not enough time for the DW group to reach equilibrium, as shown in a video of Fig. 5. Shown in Fig. 6 is the snapshots of the simulation with current density of 4.24×10^{12} A/m^2 applied to the driver nanowire. We expect no structural breakdown to occur within the DWs as the Walker breakdown limit of the two-nanowire system is higher than that of the single nanowire system.[15] DW1 and DW2 are initially placed very close to each other and far away from the driver DW. Due to the high propagation velocity of the driver DW, the interaction time between the driver DW and DW1 is very

FIG. 5. The selective remote driving phenomenon. The driver DW is shown to bypass a group of DWs in the active nanowire. The magnetization of the nanowires is pointing to the $+x$ direction (red color) and $-x$ direction (blue color) (Multimedia view) [URL: http://dx.doi.org/10.1063/1.4867468.2].

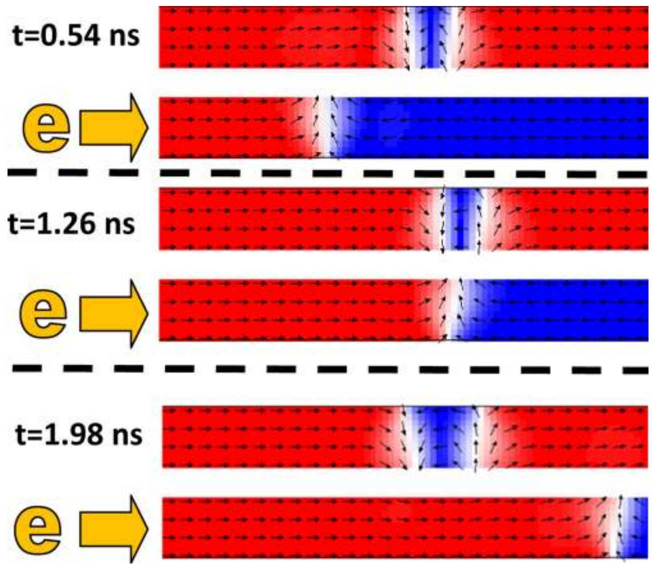

FIG. 6. Selective remote driving. Snapshots of the simulated DWs when a very high current density is applied to the driver nanowire. Due to the high velocity motion of the driver DW, it is able to move pass the DW group in the active nanowire. The applied current density is 4.24×10^{12} A/m^2.

short. Consequently, there is not enough time to decelerate the driver DW and accelerate DW2 to reach equal velocity. As a result, the driver DW is able to move pass DW1 and DW2 and continues its motion without any coupling to the DWs in the active nanowire. In other words, by adjusting the applied current density to the driver nanowire, we will be able to control the coupling between the DWs in the active and the driver nanowire.

In conclusion, the dynamics of multiple transverse DWs in a two-nanowire system that interact with each other through the exchange repulsion force have been investigated. The exchange repulsion force is shown to originate from the DW compression. The exchange repulsion force and the DW compression are encountered only when transverse DWs with equal winding numbers collide. The exchange repulsion force can be employed together with the remote driving technique to drive multiple DWs at the same time without direct application of current. The magnetostatic interaction and the exchange repulsion force are very likely to be encountered in a high-density device with a high number of DWs; therefore, the results that are presented here shall provide valuable insights into the behavior of the DWs in those devices.

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