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Remote Walker breakdown and coupling breaking in parallel nanowire systems

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In a multiple nanowire system, we show by micromagnetic simulations that a transverse domain wall in a current-free nanowire can undergo a remote Walker breakdown when it is coupled to a nearby current-driven domain wall. Moreover, for chirality combination with the highest coupling strength, the remote Walker breakdown preceded the current-induced Walker breakdown. The Walker breakdown limit of such coupled systems has also been shifted towards higher current densities, where beyond these, the coupling is shown to be broken. © *2014 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4891502]

The dynamic behavior of a magnetic domain wall (DW) under the influence of electrical current, which was first proposed in the mid-90s,[1] has been extensively studied in recent years for potential application in non-volatile magnetic solid state memory.[2] In the design of such memory devices, the magnetic data stored in the nanowires can be shifted to the position of the reading sensor by applying a spin polarized current. Such movement is initiated primarily by the spin-transfer torque phenomenon on the DW. Most studies, henceforth, have been focused on the effort to understand the dynamics of current-driven DW. For instance, it was found that the DW propagation velocity can be increased by using modulated nanowire structures[3,4] or by injecting high-frequency pulsed current.[5,6] Nevertheless, the design of high-density DW-based memory devices implies that the nanowires should eventually be placed as close as possible to each other. Therefore, it is important to investigate how the interaction between DWs in closely spaced nanowires affects the current-driven DW motions.[7,14] These DWs have been shown to carry intrinsic magnetic charges based on their chiralities and shapes,[8–11] and it is possible for them to interact with each other. We found that the interaction between two neighboring DWs that have the opposite magnetic charges is oscillatory in nature.[12,13] It is also possible to make use of the interaction to remotely drive a DW with a fixed chirality in the neighboring nanowire, without the direct application of current.[7] We showed that the remote drive technique can be extended by making use of the internal DW compression force to drive multiple DWs in the current-free nanowire.[7,24] However, the understanding of the effect of the chirality combinations of the two DWs on the remote-driving phenomenon is still illusive.

In this Letter, we show that it is possible to induce a remote-driving and also a remote-Walker breakdown phenomenon in a current-free nanowire by making use of the magnetostatic coupling between DWs in a system of closely spaced ($\sim$50 nm) nanowires. Such DWs are also found to be able to retain their fidelity at a higher current density limit. Depending on the chirality combinations of the coupled DWs, it is possible to induce a remote DW structural breakdown in the current-free nanowire.

The DW dynamics in the closely spaced nanowires are investigated by using the OOMMF[15] micromagnetic simulation program, with the addition of the spin-transfer torque term to the Landau-Lifshitz-Gilbert (LLG) equation. The chosen $Ni_{80}Fe_{20}$ material parameters were initially set to: saturation magnetization $(M_s) = 8.6 \times 10^5$ A/m, exchange stiffness constant $(A) = 1.3 \times 10^{-11}$ J/m, damping constant $(\alpha) = 0.01$, non-adiabatic spin-torque constant $(\beta) = 0.04$,[21,25] and zero magnetocrystalline anisotropy. Each nanowire has a length of 10 μm, width of 100 nm, and thickness of 6 nm. A mesh size of 5 nm $\times$ 5 nm $\times$ 3 nm was used throughout this work.

First, the interaction between two head-to-head (HH) transverse DWs in a two-nanowire structure was investigated. The DW is classified as a HH when the surrounding magnetic domains points towards it. Fig. 1(a) shows the schematic diagram of the simulation model of the two-nanowire structure (top view), in which a HH DW is nucleated at $x = 1\ \mu$m in the bottom nanowire, and at $x = 2\ \mu$m in the upper nanowire. The separation between the nanowires was maintained at 50 nm. Fig. 1(b) shows all possible four chirality combinations: Up-Down (UD), Up-Up (UU), Down-Down (DD) and Down-Up (DU), with the chirality of the DWs in the bottom and the upper nanowires indicated by the first and the second letters, respectively. Spin polarized current is then applied to the bottom nanowire to drive the bottom DW (current-driven DW). However, the simulations also show that the upper DW is driven in the same direction as the bottom DW, even though there is no current that is applied to the upper nanowire (remote-driven DW). The motion of the upper DW in the absence of direct current can be attributed to the stray magnetic field interactions between the upper and the bottom DWs.[16]

The calculated average velocities (v) of the coupled domain walls (CDWs) for all possible four chirality combinations are shown in Fig. 1(c). The average velocity is calculated by taking the average of the velocity of the remote-driven and current-driven DWs, using the formula

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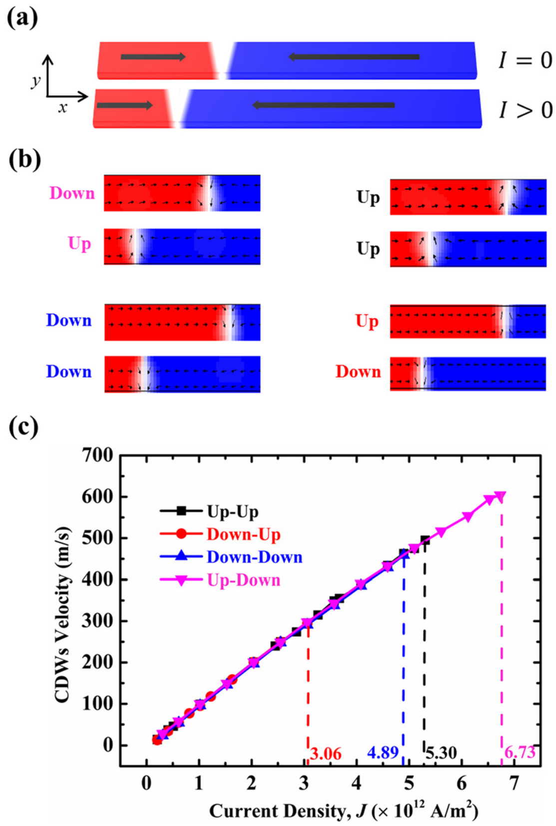

FIG. 1. (a) Schematic diagram (top view) of a two-nanowire system employed in our micromagnetic model. The current is applied to the bottom nanowire, while no current is applied to the upper nanowire. (b) Four possible domain wall chirality combinations: UD, UU, DD, and DU. (c) Plot of velocities of four possible domain wall chirality combinations as a function of applied current density. Dotted lines represent the threshold current densities for all four chirality combinations.

$v = \frac{L}{2}\frac{\Delta m_x}{\Delta t}$.[22] The velocity of CDWs is found to increase linearly with respect to the applied current density for all chirality combinations. For a fixed current density, the average velocity of the CDWs in the two-nanowire system is approximately half of the velocity of a single DW system.

The DWs can be depicted as two magnetic charges that are repelling each other but are confined along the length of the nanowires. For a HH transverse DW, the bulk of the magnetic charge is concentrated at the base of its triangular shape. Hence, the strength of the interaction between the two DWs is different depending on the chirality combination. The difference in the interaction strength does not affect the average velocity of the CDWs; however, it directly determines the maximum current density that can be applied to the system while still maintaining the coupling between the two DWs. As shown in Fig. 1(c), the coupling between the current-driven and remote-driven DWs are broken after a certain threshold current density (J_{th}), whose value depends on the chirality combination of the two DWs. The threshold current densities (J_{th}) for the UD, UU, DD, and DU chirality combinations are 6.73×10^{12}, 5.30×10^{12}, 4.89×10^{12}, and $3.06 \times 10^{12}\,\mathrm{A/m^2}$, respectively. The maximum velocities ($v_{\max}$) of the coupled DWs for UD, UU, DD, and DU chirality combinations are 604, 495, 459, and 294 m/s, respectively. UD has the strongest interaction as well as the highest J_{th} and v_{max} because the magnetic charges of the two DWs are located the closest as compared to the other chirality combinations. The coupling strength of UU and DD combinations are about equal because the distance between the magnetic charges in both combinations is the same. DU has the weakest interaction between the two DWs because the magnetic charges are located the furthest away from each other as shown in the Supplementary material.[23]

In general, for all chirality combinations, the coupling between the current-driven DW and the remote-driven DW is broken when the applied current density is increased beyond their respective J_{th}. However, the coupling breaking process is different depending on the chirality combination. Figs. 2(a) and 2(b) show the position of each DW in the system with respect to the simulation time for $J > J_{th}$, for UU and UD combinations, respectively. The shapes and relative positions of both the current-driven and remote-driven DWs at different stages of the simulation are also shown. For both UU and DD chirality combinations, the coupling breaking phenomenon is preceded by a change in the shape of the current-driven DW, which is also known as the Walker breakdown phenomenon.[17,18] For a single nanowire with a width of 100 nm and thickness of 6 nm, the Walker breakdown limit is $J_{WB} = 4.28 \times 10^{12}\,\mathrm{A/m^2}$. Hence, our results have shown that it is possible to suppress and shift the Walker breakdown limit of a current-driven DW by utilizing

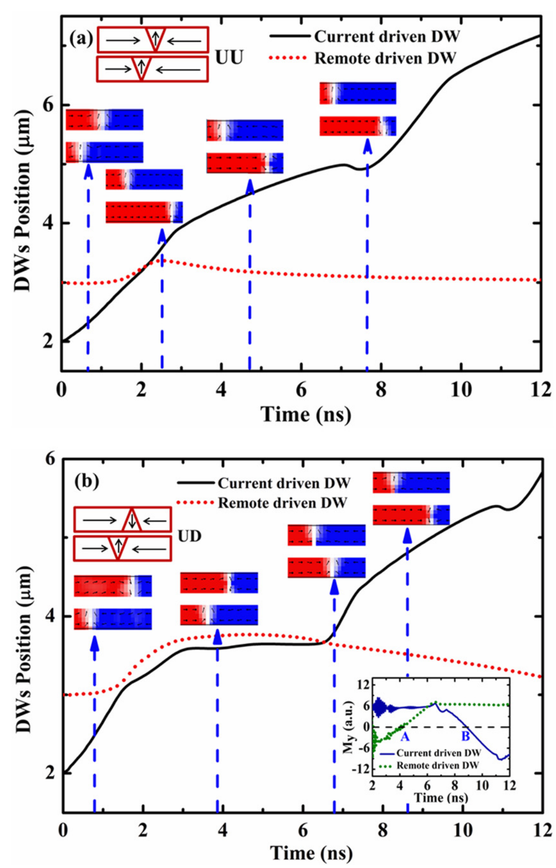

FIG. 2. (a) and (b) The position of the domain walls in two different systems as a function of simulation time for current densities higher than threshold. The domain wall chiralities and relative positions are also shown at different times of simulation. Dotted and solid lines represent the position of remote-driven domain wall and current-driven domain wall, respectively. (a) UU (b) UD, the inset represents the chirality change of DWs with time.

the two-nanowire system, as the J_{th} of the UU, DD, and UD chirality combinations are well above J_{WB} [Fig. 1(c)].

For UD chirality combination, the coupling breaking is preceded by two shape-change phenomena, as shown by Fig. 2(b). Inset shows how the chiralities of both the current-driven and remote-driven DWs change with respect to the simulation time. The first shape-change occurs at the remote-driven DW (point A in the inset), as the transverse component (M_y) of the remote-driven DW changes from negative to positive. The second shape-change occurs at the current-driven DW (point B in the inset). The shape-change phenomenon at the remote-driven DW is unexpected as there is no current being applied to the corresponding nanowire. To substantiate the result, separate simulations on a single nanowire were performed. We found that for a single nanowire with a width of 100 nm and thickness of 6 nm, Walker breakdown can be achieved by driving the DW up to $v_{WB} \approx 620$ m/s with the application of an external field (H_{WB}) of 18 Gauss. In a two-nanowire system, the stray magnetic field from the current-driven DW is responsible for the remote driving of the DW in the current-free nanowire. It is possible for the stray field from the current-driven DW to exceed H_{WB}[19] and drive the remote DWs with the speed of >620 m/s, which results in the remote Walker breakdown in the current-free nanowire. The detailed explanation of remote Walker breakdown is described in supplementary material.[23]

The distance between the current-driven lower DW and the remote-driven upper DW along the x- axis for various applied current densities for UD chirality combination is shown in Fig. 3(a). The interwire separation here is 50 nm, and the applied current density is below the Walker breakdown limit. The distance between the two DWs is shown to decrease as the applied current density is increased, which shows that the coupling between the two DWs is Columbic in nature. Fig. 3(b) shows the change in the distance between the two DWs for various interwire separations. The results show that the distance between the two DWs decreases as the interwire separation is increased. However, two different trends are observed depending on the proximity between the nanowires. When the two nanowires are placed very close to each other ($d < 30$ nm), the distance between the two DWs decreases abruptly with applied current density. The different trends can be attributed to the charge distribution within the DWs. Petit *et al.*[20] have shown that the magnetic charge distribution of a DW has a Gaussian shape: For the HH DW, a strong positive charge is spread out along the base of the triangular shape of the DW, while a weak negative charge is spread out along the apex of the triangular shape. The weak negative charge at the apex of the DW affects the coupling in the two-nanowire system when the interwire spacing is small ($d < 30$ nm). Each of the DW then forms a dipole, and the interaction between the two DWs becomes dipole-to-dipole. However, when the interwire spacing between the two nanowires is large ($d > 30$ nm), the presence of the weak negative charge is suppressed, and thus, the interaction between the two DWs becomes charge-to-charge. The charge-to-charge interaction is depicted by the gradual change in the DW distance in Fig. 3(b) for interwire separation (d) > 30 nm. The threshold current density is also found

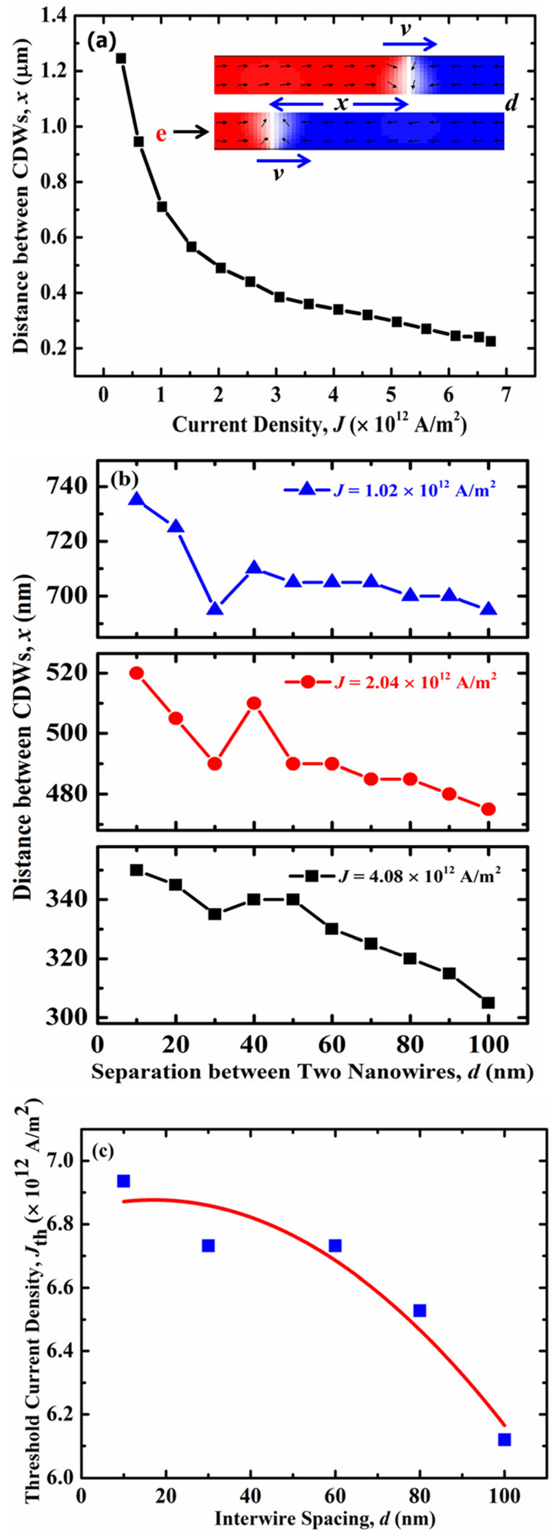

FIG. 3. (a) Distance between adjacent DWs as a function of applied current density showing Columbic force nature of magnetostatic forces. (b) Distance between adjacent DWs against separation between nanowires for different current densities. (c) Threshold current densities as a function of separation between nanowires.

to decrease with increasing nanowire spacing (d), as shown in Fig. 3(c).

Fig. 4 shows the comparison between the two- and three-nanowire systems of the strongest coupling strength (UD and UDD, respectively) with a single nanowire system

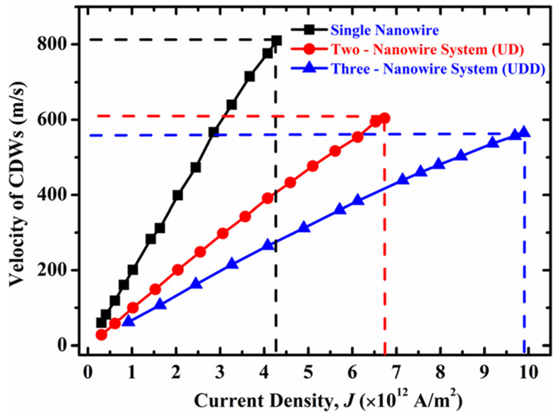

FIG. 4. Plot showing the velocity variation of the CDWs in different nanowire systems as a function of applied current densities.

in terms of the average velocity as a function of the applied current density. For interwire spacing = 50 nm, the average velocity of the CDWs is found to decrease with the increase of the total number of DWs in the system. For a particular current density, the velocity of the CDWs in the three- and two-nanowire systems is reduced to about 1/3 and 1/2 of the single nanowire system, respectively. The linear reduction in the velocity with the increase in the DWs in the system is due to an increase in the inertia of the system.[13] However, the maximum threshold current density for the CDWs is found to be increased with the number of the DWs in the system. The threshold current density of the three-nanowire system is twice as compared to the single nanowire system. The interaction between DWs in three-nanowire system and the comparison of it with single- and two-nanowire system are detailed in the supplementary material.[23]

In conclusion, we have shown that it is possible to induce a remote Walker breakdown in the current-free DW by exploiting the magnetostatic interaction between DWs in a closely spaced nanowire system. The remote Walker breakdown phenomenon strongly depends on the chirality combination of both current-driven and remote-driven DWs. The Walker breakdown limit of such coupled systems has also been shifted towards higher current density values. Increasing the current density beyond the Walker breakdown limit causes the breaking of the magnetostatic coupling. This is important in the design of high-density memory devices, where the nanowires shall be placed very close to each other. The results also show that it is possible to shift the Walker Breakdown limit even further for smaller nanowires spacing, which allows the DW in the current-free nanowire to be driven with higher speed. Hence, the results that are presented here shall give valuable insights to the DW dynamics in these devices.

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