

Near-Field Interaction between Domain Walls in Adjacent Permalloy Nanowires

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The magnetostatic interaction between two oppositely charged transverse domain walls (TDWs) in adjacent Permalloy nanowires is experimentally demonstrated. The dependence of the pinning strength on wire separation is investigated for distances between 13 and 125 nm. The results can be described fully by considering the distribution of magnetic charge within rigid, isolated TDWs. Alternative DW internal structure cannot reproduce this observed dependence. Modeling suggests the TDW internal structure is not appreciably disturbed, and remains rigid although the pinning strength is significant.

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Quantifying the interaction between magnetic domain walls (DWs) in closely packed networks of ferromagnetic nanowires is of vital importance to recently proposed DW based logic and data storage schemes [1,2], as these interactions could potentially compromise coherent DW propagation and correct device function. In addition to these schemes, DWs in nanowires have also been suggested for use in a wide range of applications, such as atom trapping for quantum information processing [3]. Furthermore, the fundamental properties of DWs themselves are attracting great interest, and DWs can be considered not only as transition regions between oppositely magnetized domains, but as quasiparticles [4]. Their equilibrium [5], dynamic properties [6–9], and interactions with artificial defects [10] are being intensively studied. The ability to hold DWs at defined positions is required for a wide range of spin torque experiments, where current is used to depin the DWs; a continuously variable pinning strength which does not alter the current path is highly desirable in such cases [11].

The effect of the presence of a DW in a nearby structure on the magnetic state of a ferromagnetic ring has been reported [12,13], and quantified in terms of an additional local field due to the DW stray field, but no quantitative analysis of the full pinning potential created by a DW on another DW has been made. In this Letter, we experimentally study the interaction between two oppositely charged transverse DWs (TDWs) traveling in two parallel Permalloy (Py) nanowires. The interwire separations probed in this investigation are below the dimensions of the DW (~ 100 nm) itself and so are within the near-field limit. The simulated dependence of the interaction on DW internal structure is examined. By considering the rigid magnetostatic charge distribution of an isolated TDW we are able to reproduce fully the experimental result, suggesting that the internal structure of the DW is not appreciably perturbed by the interaction for the geometries studied. This work opens up the possibility of continuously tailorable, remote DW pinning, which does not affect the DW

internal structure. The possibility of a well-defined, tunable pinning potential where the DW acts as a truly rigid quasiparticle is appealing, for example, in current induced resonance experiments [14,15].

Thermally deposited Py nanowires (100 nm wide, 8 nm thick) were fabricated using electron-beam lithography and a lift-off method. Figure 1(a) shows a scanning electron microscope (SEM) image of a typical structure: two U-shaped nanowires with an edge to edge separation, d , between 125 and 13 nm, and vertical arm displacement, W , equal to 0.5, 1, or 1.5 μm . In the case shown, $d = 100$ nm and $W = 1.5 \mu\text{m}$. Magnetic field sequences were applied in the plane of the sample at a frequency of 1 Hz using a quadrupole electromagnet. Two experiments were performed. In the first experiment, two oppositely charged DWs were created in the nearest pair of corners (A_1 and A_2). In this case [see Fig. 1(b)], the DWs must pass within close proximity of one another before switching the remaining portion of each wire. The attractive interaction between the oppositely charged DWs will therefore directly influence the field required to separate them and switch the rest of the wire. In the second case, DWs are created in corners B_1 and B_2 and so switch the central portion of each wire before meeting. This second setup acts as a control experiment to observe switching without any DW-DW interaction.

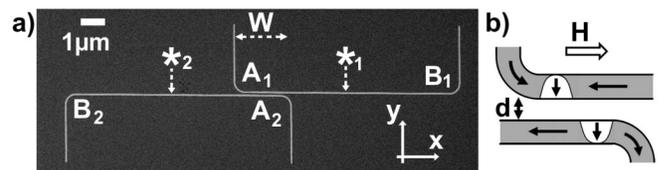


FIG. 1. (a) SEM image of a typical structure showing two $10 \mu\text{m}$ long U-shaped Py nanowires separated by an edge to edge distance $d = 100$ nm. The asterisks indicate the positions where the MOKE laser spot is focused. (b) Schematic of oppositely charged TDWs created in “A” corners moving, under field H , along wires separated by d .

For the wire geometries in this investigation (100 nm wide, 8 nm thick) TDWs are stable [16,17]. Within a TDW, the chirality (sense of rotation of magnetization) is determined by the overall charge and magnetization direction of the core of the DW (up or down). To create TDWs at A (B) corners a 45° field pulse was applied in the $-x, -y$ ($+x, -y$) direction, giving a downwards head to head (HH) DW at corner A_1 (B_1) and a downward tail to tail (TT) DW at corner A_2 (B_2). The field was then decreased to zero at 45° , and a positive (negative) x field was applied to move the two DWs towards one another. The sequence was repeated with all fields reversed to create an upward TT DW at A_1 (B_1) and an upward HH DW at A_2 (B_2), moving them towards one another with a negative (positive) x field. Using the field sequences indicated above, the pair of TDWs are initially created with opposite chirality and opposite net charge.

High sensitivity, spatially resolved magneto-optical Kerr effect (MOKE) measurements were used to probe the magnetization of the central portion of each wire [marked with *, Fig. 1(a)]. The inset of Fig. 2 is an example of the observed hysteresis loop for the switching of a nanowire. The 70 Oe switching field is due to pinning from mutual interaction between the DWs. The switching fields of portions $*_{1,2}$ of the nanowires were measured as a function of d (measured using SEM images). The results for 90 structures are shown in Fig. 2. Switching of the nanowires in the control experiment (DWs created in corners B)

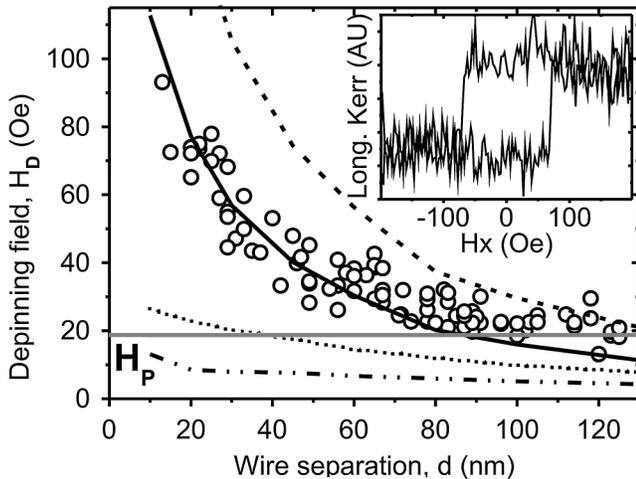


FIG. 2. Open circles: Experimental dependence of DW transmission field H_D on wire separation d . Gray line, average wire propagation field H_p . Modeled depinning fields considering charge distribution of the DWs with wide-wide (HHD, TTD; upper long dashed line), wide-narrow (HHU, TTD or HHD TTU; dotted line) or narrow-narrow (HHU, TTU; lower dashed and dotted line) sides closest. Solid black line, wide-wide interaction with a fitting scale factor of 0.54. Inset: Example MOKE observed hysteresis loop of a nanowire. Switching occurs at H_D , in this case 70 Oe, due to depinning from the DW-DW potential well.

occurs at an average propagation field $H_p = 19 \pm 4$ Oe (horizontal gray line). The mean difference between fields H_{D1} and H_{D2} at which $*_1$ and $*_2$ reverse is only 0.1 Oe (standard deviation of 2.1 Oe) for the case where the DWs interact (DWs created at corners A); therefore only the average value H_D for each structure has been plotted (open circles). We see a monotonic decrease of H_D as d increases from a maximum depinning field of 93 Oe measured in wires with $d = 13$ nm down to ~ 19 Oe ($\sim H_p$) for $d \sim 90$ nm. Above $d \sim 90$ nm, the dependence changes as H_D remains approximately constant at H_p . At these high d values the dominant pinning mechanism is due to the inherent roughness of the nanowires and so the interaction between the DWs is no longer measured. No observable dependence was found on W . Separate studies, not presented here, ruled out a localized change in wire geometry causing the observed DW pinning [18], suggesting H_D is solely due to the interaction between the two DWs. This is also supported by the fact H_{D1} and H_{D2} are almost identical for a pair of wires. Furthermore, the narrow distribution of H_p (as measured from control experiment) shows we are not measuring a statistical variation of H_p along these wires.

To account for the DW-DW interaction dependence on d , we describe it in terms of the interaction between magnetic charges, where the magnetic charge density ρ_M is defined as $\rho_M = -\mu_0 \nabla \cdot \mathbf{M}$ and \mathbf{M} is the local magnetization. We expect a model which considers the full DW charge distribution within the wire to match experimentally determined data if the two DWs remain rigid throughout the interaction and we account for finite temperature. OOMMF simulations [19] ($3.5 \times 3.5 \times 4$ nm³ cell size, $M_s = 800$ kA/m, $A = 13$ pJ/m, and damping constant $\alpha = 0.5$) were used to calculate the micromagnetic configuration of the TDW, from which the charge distribution within the DW [20] was obtained. The charge is very inhomogeneously distributed, reflecting the triangular shape of TDWs [16]. In the case of a HH (TT) DW there is a positive (negative) surface charge along the wide edge of the DW, and a smaller negative (positive) charge along the narrow edge [20]. A more complete analysis of the distribution in our wire geometry shows 48% of the DW charge is located along the wide edge, and has a Gaussian shape. To obtain the strongest interaction achievable between DWs, the TDWs must pass with wide edges closest, which is the case in our setup [see Fig. 1(b)].

The interaction energy U between two extended charge distributions, D_1 and D_2 , is given by

$$U = \frac{1}{4\pi\mu_0} \sum_{i \in D_1} \sum_{j \in D_2} \frac{q_i q_j}{r_{ij}}, \quad (1)$$

where r_{ij} is the distance between the two charges q_i and q_j . In the case where the two distributions are associated with oppositely charged rigid DWs traveling in two adjacent wires separated by d , and x is their lateral separation [see

Fig. 1(b)], $U(x)$ is a potential well. The change in Zeeman energy δU_Z caused by separating the DWs by δx under a field H is $\delta U_Z = -2M_s HS \delta x$, where M_s is the saturation magnetization and S is the cross sectional area of the wire. $U(x)$ is sheared by a gradient equal to $-2M_s HS$, and the field required for DW depinning is therefore given by

$$H_D = \frac{1}{2M_s S} \left. \frac{\partial U}{\partial x} \right|_{\max}. \quad (2)$$

The dashed line in Fig. 2 displays H_D^{w-w} as a function of d when the wide sides of the DWs are closest [HH down (HHD), TT down (TTD)], i.e., the wide-wide interaction. This overestimates the experimental results, but does appear to show the correct trend. This modeling does not include the effect of temperature; however, DW depinning is a thermally assisted process. At room temperature, depinning fields have previously been found to be between 40% and 70% of the zero temperature simulated values [10,20]. Reference [21] experimentally shows reductions between measurements at 4.2 and 300 K between 40% and 60%. The solid black line in Fig. 2 shows a least mean squares fit of the wide-wide model to the experimental data using a scale factor of 0.54 to account for the reduction due to the experiment being conducted at room temperature, a reduction well within previously found values. Fitting is excellent up to $d \approx 90$ nm above which, as mentioned above, the inherent wire roughness becomes the dominant pinning mechanism.

During propagation, transformations can occur to DW structure via a process known as Walker breakdown [22]; a TDW, of a given charge, oscillates between the two chiralities [up (U) and down (D)] via an intermediate state where an antivortex (AVDW) is nucleated. If breakdown occurs in one or both of our DWs before they meet, the interaction will no longer be with widest sides nearest (w-w; HHD, TTD). Additionally, it has been observed that a TDW may transform into a vortex DW (VDW) (an alternative DW configuration stable in wider or thicker wires) during breakdown [23]. The distances chosen in the experiment over which a DW can propagate ($W < 1.5 \mu\text{m}$) before the interaction takes place are below the measured fidelity length to preserve initial chirality [24]. It is not expected, therefore, that breakdown will occur. For completeness, however, in Fig. 2 the modeled depinning fields for the alternative configurations interactions are plotted: wide-narrow (w-n; either HHD, TTU or HHU, TTD by symmetry), H_D^{w-n} , and narrow-narrow (n-n; HHU, TTU), H_D^{n-n} . These interactions have significantly lower depinning fields compared to the experimentally observed interaction, with values $\lesssim H_p$, and are clearly not observed for $d \lesssim 90$ nm. We therefore conclude that only the strongest w-w interaction occurs. Figure 3 shows the potential landscapes for the three possible TDW interactions in the case where $d = 10$ nm. The steep potential well for the w-w interaction accounts for the large observed

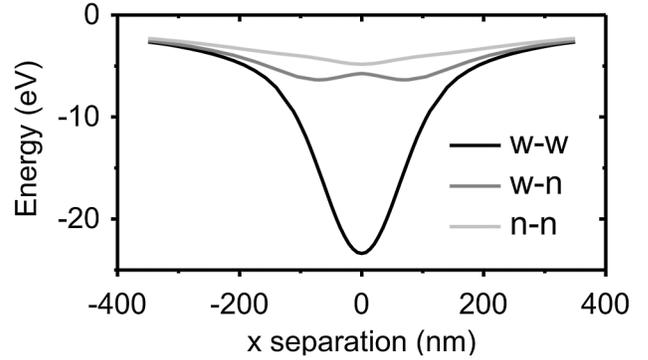


FIG. 3. Potential well obtained when laterally separating a pair of oppositely charged TDWs by x for the case $d = 10$ nm, from rigid charge model. The nearest sides of the TDWs are wide-wide (black line), wide-narrow (gray line), and narrow-narrow (light gray line).

H_D . Note that for the w-n interaction, when the two DWs are closest the interaction is dominated by the repulsion between the two closest line charges, which are of the same sign, giving a local potential barrier. Beyond lateral x separations of ~ 350 nm the far-field limit is reached, and all models give the same potential profile as DW internal structure is no longer crucial. To examine the case where the DWs meet during breakdown we consider when a perfect HH and TT AVDW interact. For the AVDW the only degree of freedom is the core direction. When $d < 125$ nm, micromagnetic simulation shows that the core of the DWs are expelled as the two DWs meet, restoring the original w-w TDW configuration, and is independent of the core directions of the AVDWs.

In addition, micromagnetic simulations were performed, calculating the interaction between oppositely charged TDWs and oppositely charged VDWs. The resulting depinning field dependence on d for TDWs is not shown, but is in good agreement with the near-field charge modeling, providing further evidence that little distortion occurs to the TDW shape. Within a VDW, the internal magnetization rotates around a core, where the magnetization points vertically. This configuration has two internal degrees of freedom, the sense of rotation of the magnetization and core direction. From micromagnetic simulations of all possible HH-TT pairings and $d > 80$ nm, it is found that the cores are displaced towards one another and all H_D are $\lesssim 16$ Oe. For $d \lesssim 80$ nm, i.e., our region of experimental interest, the core is expelled by the interaction, leaving the w-w TDW interaction. No significant dependence is found on core direction. The displacement of the core causes clear deformation of the DW and departure of the simulated H_D from that obtained using a rigid charge model. This analysis shows we are indeed experimentally measuring the w-w interaction between TDWs, as any other combination would either have a low H_D or transform into w-w TDWs. The resulting dependence on d is in

very good agreement with a rigid charge model of TDWs, where the internal structure and chirality of the DW must be considered.

The agreement between modeling and simulation is highly surprising as we only consider magnetostatic charge. This suggests the particular interaction between TDWs of opposite charge leaves the DW structure relatively unperturbed from its free, isolated configuration and that the TDWs can be considered as rigid, isolated quasi-particles. On the contrary, however, VDWs do not appear to act as rigid bodies when they interact. Should a TDW transform into a VDW during propagation, for our region of interest ($d < 80$ nm), the interaction will cause the DW cores to be expelled and the w-w TDW interaction to result.

Using one DW to pin another is a specific example of pinning by stray fields with little distortion to TDW shape. Reference [25] shows an example of using localized stray fields from multiple magnetic wire ends to create an asymmetric pinning potential, which will act as a DW diode or ratchet similar to the geometrical protrusions in Refs. [26,27]. Using a pinning potential that does not alter wire or TDW shape in spin torque experiments (for example, current induced resonances [15]) may allow clearer interpretation of current based effects. In addition, the interaction between DWs in neighboring nanowires is of great technological importance for DW based logic and data storage devices. Full charge modeling of DWs in nanowires of more technologically relevant dimensions (45 nm wide, 8 nm thick, 45 nm spacing) shows DW depinning at 71 Oe at 0 K. This large interaction could result in cross talk errors between adjacent data channels.

In conclusion, we have experimentally studied the interaction between two TDWs of opposite charge moving in parallel magnetic nanowires. The attractive interaction is found to result in depinning fields as high as 93 Oe, measured in wires separated by 13 nm. Modeling using the rigid magnetic charge distributions of isolated DWs reproduces the experimental results extremely well. Comparing results with modeling of DWs in different structural or chiral configurations does not reproduce the experimental results, showing that consideration of the inhomogeneity of the charge is essential to understand near-field DW interactions. Comparing micromagnetic simulations and charge modeling suggests TDWs remain unperturbed by the interaction whereas the VDW core is displaced or ejected, causing departure from a rigid model. Pinning fields at 0 K of 71 Oe are expected in the technologically relevant dimensions of DW based data storage and logic devices. This study experimentally demonstrates remote pinning using magnetostatic interaction with minimum perturbation to the DWs, opening up the possibility of continuous

tailoring of pinning strength with no alteration to the nanowire.

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