Supporting Online Material for

Current-Controlled Magnetic Domain-Wall Nanowire Shift Register
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Current controlled magnetic domain-wall nanowire shift register

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A. Sample preparation and measurement setup

The permalloy nanowires are made from films with the structure 0.5 Fe/10 AlOₓ/10 Ni₈₁Fe₁₉/1 TaN/5 Ru (units in nm) deposited on highly resistive silicon substrates using magnetron sputtering in an ultra high vacuum deposition system. The films are patterned into the form of nanowires using electron beam lithography and Ar ion etching. Subsequently, 3 Ta/65 Rh (units in nm) films are deposited onto the substrate and patterned into contact lines using optical and electron beam lithography. The nanowire is 200 nm wide, with sharply tapered ends and with electrical contact lines (labeled A and B in Fig. 1A) spaced 6 μm apart. High frequency probes (40 GHz bandwidth) are used to make electrical contact to the samples at room temperature. During the experiments a small dc current (100 μA) is continuously passed along the nanowire to allow DC resistance measurements.

DWs are injected into the nanowire using the following procedure. The magnetic state of the nanowire is first initialized by applying a large external magnetic field (±300 Oe along the X direction in Fig. 1A). Subsequently, the field H is reduced to a value close to zero. Next a voltage pulse from one of the pulse generators (PG-1 or PG-2) is used to inject a current into line A. This serves two purposes: first this pulse generates a highly localized magnetic field in the nanowire beneath line A which, when sufficiently large, creates a DW in section A-B. Second, the pulse also injects current into the nanowire which drives the DW along the nanowire between A and B in a direction determined by the current flow direction; the DW moves from A to B when the electron flow in the nanowire is along the +X direction, i.e. when a negative voltage pulse is injected from line A. A HH (TT) DW is created in section A-B when a negative voltage pulse is injected from PG-2 (PG-1) (and when an external magnetic field of -300 Oe (300 Oe) is applied before the pulse application to set the magnetization direction in section A-B accordingly).

In Fig. 1 B and C note that when the pulse length is below the threshold value τ_p the probability of measuring a vortex wall in section A-B is not exactly 100% since a transverse wall is sometimes created. The probability of creating a vortex DW in section A-B of the nanowire depends on the polarity of the voltage pulse as well as its amplitude, and depends on the detailed mechanism of interaction of both the Oersted field (from the current along line A) and the spin polarized current that is injected into section A-B with the nanowire’s magnetization. We find that under the experimental conditions that were used the probability of creating a vortex wall is high only when a large negative voltage pulse is used (here we use a pulse amplitude of -3.2 V, corresponding to a current of ~2.0x10⁸ A/cm² flowing along the nanowire).
In Fig. 1 D and E, for very short or long (close to \( \sim \tau_p \)) injection pulse lengths, the position of the DW is less well defined. For example, the ejection time does not extrapolate to zero when negative probe pulses are used, indicating that there is an offset in the starting position of the DW from line A. During the application of the injection pulse, the localized field around line A may cause the DW to move an additional distance, resulting in the observed offset (see section F below for details). When the injection pulse length becomes close to \( \tau_p \), the ejection time appears to saturate, indicating that either the DW position does not change with the injection pulse length or that the DW is attracted to line B by the ejection pulse current. Although the origin of this effect is not clear, we attribute it to the local magnetic field generated around line B when the pulse is applied. To minimize the effect of the local field on the motion of DWs approaching line B, this line is terminated at both ends to achieve a symmetric current flow, as shown in Fig. 2 A.

B. Magnitude of the current flowing through the contact lines and the nanowire

The current that flows through the contact lines and the permalloy nanowire can be calculated using a resistor network theory. The circuit elements are illustrated in Fig. S1 (a), where \( R_D \) and \( R_C \) represent the nanowire device and each of the contact line resistances. The output impedance of each of the pulse generators, \( Z_0 \), is 50 \( \Omega \).

\[
I_C = \frac{(R_D + (R_C + Z_0))2V_1}{(R_C + Z_0)(2R_D + 3(R_C + Z_0))}
\]

\[
I_D = \frac{2V_1}{2R_D + 3(R_C + Z_0)}
\]

\[
I_o = \frac{2V_3}{R_o + \frac{3}{2}(R_C + Z_0)}
\]
The equivalent circuit is shown in Fig. S1 (b) and (c) when a voltage is applied from pulse generator PG-1 (or PG-2), and PG-3, respectively. The currents that flow through the contact line ($I_C$) and the nanowire ($I_D$) are calculated in each case. For the nanowire used here, we measure $R_D \sim 584 \Omega$ and $R_C \sim 23 \Omega$, which results in $I_C \sim 42$ mA and $I_D \sim 4.6$ mA when a 3.2 V pulse is applied from PG-1 (see Fig. S1 (b)). Similarly, we obtain $I_D \sim 4.6$ mA when a 1.6 V pulse is applied from PG-3 (see Fig. S1 (c)).

C. Statistics of moving two DWs simultaneously

Fig. S2 (b) and (c) show the pulse sequence used to perform a single operation to move two DWs simultaneously. The resulting variation of the nanowire resistance is shown in Fig. S2 (a). An illustration of the expected motion and the corresponding number of DWs in section A-B is shown in Fig. S2 (d). The number of DWs changes from the initial state, zero, to successively, 1,2,1 and finally 0, indicating that the two DWs move together. Fig. S2 (e) shows the nanowire resistance variation when this pulse sequence is repeated many times. Whenever a transverse wall is created in section A-B, this process fails and the two walls are annihilated (see, for example, the 46th iteration). In addition, there are occasions where the 1,2,1,0 sequence is not achieved even when vortex walls are successfully injected, as can be seen in the 25th and the 43rd iterations in Fig. S2 (e). In the 25th iteration, the failure occurs when the attempt is made to inject the second wall. The resistance level indicates that the first wall has been ejected during the injection of the second wall. By contrast, in the 43rd iteration, the failure occurs after the...
injection of the second wall; the resistance change indicates that one of the two walls may have transformed into a transverse wall during or after the application of the third pulse (i.e. the 22 ns long pulse from PG-2). Note that this failure could also be attributed to the first wall traveling toward the right contact line (line B in Fig. 1A) but not being completely expelled from section A-B so that the nanowire exhibits resistance levels that correspond neither to one nor to two vortex walls.

To explore in more detail the statistics of these failure events, Fig. S2 (f) shows the conditional histograms of the resistance levels (ΔR is the resistance of the nanowire compared to the resistance level without any DW in section A-B) after each pulse application when a series of pulse sequences are applied. Each histogram is obtained by counting subsequent events only when the previous resistance level is at the expected value, as indicated by the shaded region in each panel. The pulse length is marked on each histogram and the pulse generator used is indicated by the corresponding color of this number (blue: PG-1, red: PG-2). The number included within the brackets shows the total number of times the resistance value lay within the shaded region.

The failed operations observed in Fig. S2 (e) are included in the histograms; for example, the failure occurring at the 25th iteration corresponds to the state located around ΔR ~0.25 Ω in the second panel from the top in Fig. S2 (f). The probability of injecting a transverse wall, which caused the failure shown in the 46th iteration, is relatively low when the pulse sequence shown in Fig. S2 (b) and (c) is used; see the number of states located around ΔR ~0.18 Ω in the top panel in Fig. S2 (f). In this case, the probability of successfully moving two DWs is very high; all the other failure mechanisms occur rarely. However, it turns out that this process is sensitive to details of the pulse sequence. For example, when the first pulse is too short, even though there is still a high probability of injecting a vortex wall, the probability of injecting two DWs drops significantly, as shown in Fig. S2 (g), second panel from the top. In this case, when an attempt is made to inject the second wall with the second current pulse, the two walls tend to annihilate one another (corresponding to states at ΔR ~0 Ω), likely indicating that the walls interact when their separation distance becomes too small.
**D. Moving three DWs**

In our ~6 μm long nanowire, we were able to store and move up to three DWs, as shown in Fig. S3. The pulse sequences used are shown in Fig. S3 (b) and (c). As clearly shown in Fig. S3 (a), the resulting sequence of resistance levels corresponds to successive nanowire magnetic configurations with zero, 1,2,3,2,1 and 0 DWs. This proves that a sequence of properly timed current pulses can move 3 DWs simultaneously. However, this process was even more sensitive to details of the pulse sequence than that for 2 DWs. For example, the probability of successfully injecting a sequence of 3 DWs after 2 DW injections was only ~40%, as shown in the conditional histograms of Fig. S3 (d). This is not so surprising given the minimum separation distance between DWs compared to the nanowire’s length. To make the process of injecting a sequence of DWs more robust local pinning centers could be fabricated along the nanowire to provide stable positions for the DWs. This would likely allow DWs to be spaced even closer and would make the DWs more resilient to perturbations.

![Fig. S3](image)

**E. Measurement of the minimum separation distance between two neighboring DWs**

To estimate the minimum separation distance that is needed between adjacent DWs to avoid their annihilation in the nanowire used, we measured the probability of injecting two DWs into section A-B by using two voltage pulses: a first voltage pulse whose length was varied and a second voltage pulse whose length was fixed between 1-6 ns. The second pulse length was made as short as possible so that its role was primarily to inject a second DW (HH) without causing any significant motion of the first DW (TT). The minimum length of the first pulse which allowed for the subsequent injection of a second domain wall, without annihilation of the DWs, can be used to determine the minimum separation distance of the two walls. The position of each DW in the nanowire is determined by the product of the corresponding pulse length and its velocity. The minimum separation distance, i.e. the difference in the position between the two DWs, is
plotted as a function of the global magnetic field in Fig. 3E. The error bars show the variation in the position of the second wall caused by the variations in the second pulse length (1-6 ns).

**F. Estimation of the minimum separation distance via magneto-static interaction**

The minimum separation distance of two injected DWs can be estimated by comparing the propagation field with the sum of the magneto-static field at either DW from its neighboring DW and the Oersted field associated with the voltage pulse. The propagation field is the minimum field needed to move a DW along the nanowire without any assistance from the current via the spin transfer torque. The propagation field may vary along the nanowire due to local variations in the nanowire’s structure and consequent DW pinning potential. In this model, we use the measured average propagation field of ~5 Oe. Thus when a DW experiences a magnetic field of more than ~5 Oe, it will move along the nanowire.

First, both DWs feel the Oersted field associated with the voltage pulse that is passed through line A (black solid line in Fig. S4 (a), thin dotted lines in Fig. S4 (b,c)). In addition, the first injected DW (TT, white bar in the SEM images in Fig. S4 (b,c)) experiences the stray field from the second injected DW (HH, black bar in the SEM images) and vice versa. The stray fields from the vortex DWs are calculated using micromagnetic simulations and are shown as blue and red lines for the TT and HH walls, respectively, in Fig. S4 (a). Note that the local Oersted field from the voltage pulse, as well as the stray fields from the DWs, always favor annihilation of the two injected DWs. Thus, when the total magnetic field each DW is subjected to, i.e. the sum of the Oersted field and the stray field, exceeds the propagation field, shown by the thick dashed lines in Fig. S4 (b,c), the two DW will spontaneously annihilate. The total field that the TT and HH walls experience are shown by the red and blue lines in Fig. S4 (b,c), respectively. (Note that in Fig. S4 (a), the red and blue lines represent the stray fields emanating from the TT and HH walls, whereas in Fig. S4 (b,c), the red and blue lines represent the total field the HH and TT walls experience, respectively.)

Here, the main mechanism for annihilation of the injected TT and HH DWs is the motion of the HH wall towards the TT wall. In Fig. S4 (b), the initial TT wall position is ~3 μm away from line A. When the HH wall is injected, it will travel down the nanowire from the right edge of line A a distance of ~0.65 μm to a position where the total field (blue line) becomes less than 5 Oe, the propagation field. The field the TT wall experiences (red line) is less than 5 Oe, so the TT wall will remain at its initial position. The two DWs do not annihilate each other in this case. However, when the initial position of the TT wall is ~2.3 μm from line A, as shown in Fig. S4 (c), the total field the HH wall is subjected to is above ~5 Oe everywhere along the nanowire. Therefore, it will move toward the TT wall and the two walls will annihilate each other. The calculated threshold separation distance estimated in this manner is shown in Fig. 3E (solid line) as a function of magnetic field. Note that in this calculation, we only determine the position of the first DW for which the second DW is annihilated during injection. Thus we overestimate
the separation distance which will consequently be smaller than this value by the distance which the second DW is moved. The position of the second wall is influenced by the fields and the spin torque which it is subjected to during the injection process. We estimate that the DW travels ~0.65 μm from the right edge of line A due solely to the local field associated with the pulse.

Fig. S4
G. Demonstration of a serial-in serial-out 3 bit domain-wall shift register memory

Fig. S5 illustrates the basic operation of our domain-wall shift register memory device. As shown in Fig. S5 (a), data is encoded by the magnetization direction of the domains although shift registers which use the domain walls themselves for coding the data are also possible. The data is written into the leftmost domain in section A-B, whereas the readout is performed on the rightmost domain. The data bit, 0 or 1, is input into the shift register by passing current along line A in one direction or the other. Since our measurement technique is limited to probing the number of the DWs stored in section A-B, the readout process is indirect. We infer the state of the output bit from the magnetization configuration based on the number of DWs and the procedure used. In a more sophisticated device the output would be read directly and with much higher signal by, for example, using a magnetoresistive sensing element adjacent to the output bit.

Here, the shift register is a 3-bit unidirectional serial-in serial-out memory. Fig. S5 (d) and (e) show the magnetic configuration when a sequence of writing and shifting operations are performed. To explicitly illustrate the operation of the 3-bit register, arrows are used to represent the direction of magnetization of the 3 domains along the nanowire which comprise the shift register. The writing operation comprises a short pulse (3-4 ns) which is applied from PG-1 or PG-2. A longer pulse (20-25 ns) is used to shift the DWs to the right. In all cases, the pulse amplitude from PG-1 and PG-2 is fixed at -3.2 V so that a current density of $\sim 2.0 \times 10^8$ A/cm$^2$ flows along the nanowire.

To illustrate the operation of the shift register, we consider two possible input data sequences of (b, d) 010111 and (c, e) 010011. The pulse sequences used to write and shift these binary bits are schematically shown in Fig. S5 (b,c), bottom panels. The numbers indicate the pulse length in units of nanoseconds. In Fig. S5 (d), for example, the input, i.e. the magnetization direction of the leftmost domain (and the corresponding write current through line A (red or blue arrow)) evolves as 010111 in the operations a-f. Fig. S5 (b) shows the resulting sequence of measured resistance levels of the nanowire. The shaded regions in the Figure correspond to the shift operations whereas the white regions correspond to the write operations.

The state of each bit, inferred from the resistance levels, are shown in the tables in the middle panels of Fig. S5 (b,c). The tables have three rows which correspond to the evolution of each bit (B1, B2 and B3) during the sequence of operations a-f. A particular data bit that was input into the register is subsequently read out (i.e. from the magnetization direction of the rightmost domain) after the completion of two write/shift operations in this 3-bit shift register.

In this example, the cycle time to write and shift one bit is $\sim 30$ nanoseconds. This is determined by the write time (here $\sim 3-4$ nanoseconds) and the time to shift the series of domain walls by one domain length. This time is determined by domain length and the velocity of the domain walls which here, as shown in Fig. 3D, is fast and is $\sim 150$ m/sec.
Fig. S5