

Supplementary information

Electric-Field-Driven Magnetic Domain Wall Dynamics: A Multiferroic Route Toward Scalable and Low-Power Spintronic Logic.

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Magnetization Evolution under Various Strain Directions

To validate the role of PMN-PT orientation in strain-mediated magnetization control, we performed micromagnetic simulations using OOMMF (Object Oriented MicroMagnetic Framework) with strain tensor fields derived from (001)- and (011)-oriented PMN-PT substrates. For (001)-oriented PMN-PT, vertical electric fields induced symmetric biaxial strain in the plane, leading to isotropic modulation of magnetic anisotropy. This resulted in disordered magnetization evolution with no preferential direction (Fig.S1 1a). In contrast, (011)-oriented PMN-PT generated anisotropic in-plane strain (compressive along $[100]$ and tensile along $[01\bar{1}]$ under upward electric fields), which introduced uniaxial magnetic anisotropy. This anisotropy drove directional domain formation and coherent magnetization rotation (SI Fig. 1b), consistent with the strain behavior described in the main text. These results confirm that (011) orientation is critical for achieving deterministic domain wall (DW) motion, supporting our device design choice.

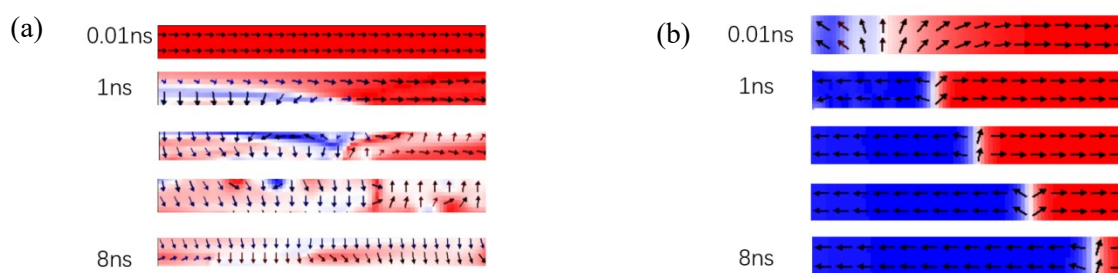


Fig. S1: (a) (001)-Oriented PMN-PT: Symmetric biaxial strain induced by vertical electric fields, Magnetization

evolves but lacks directionality. (b) (011)-Oriented PMN-PT: Anisotropic strain promotes uniaxial anisotropy and directional domain formation.

Domain Wall Propagation as a Function of Nanowire Size

We systematically investigated the effect of nanowire dimensions (length \times width) on DW propagation using COMSOL-derived strain profiles imported into OOMMF simulations. Key observations include:

1. 1000×100 nm nanowire: DW velocity was significantly reduced (~ 83 m/s) due to extended propagation distance and diluted strain gradients, leading to inefficient anisotropy modulation (SI Fig. 2a).
2. 400×50 nm nanowire: Optimized strain distribution resulted in peak velocity (~ 266 m/s), matching the performance reported in the main text. This size balanced strain gradient strength and geometric constraints, minimizing deformation energy barriers (SI Fig. 2b).
3. ≤ 30 nm width nanowire: DW propagation was hindered by severe stress concentration at the edges, creating energy barriers that prevented continuous motion (SI Fig. 2c).

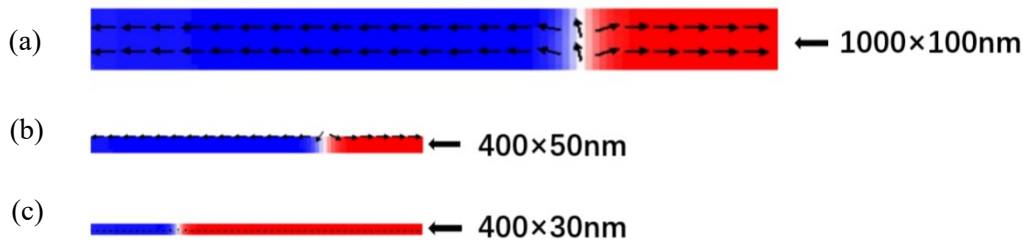


Figure S2: Nanowire DW dynamics at different lengths. (a) 1000×100 nm – Slower motion due to long wire; (b) 400×50 nm – Optimized motion (~ 266 m/s); (c) ≤ 30 nm length – Propagation hindered by stress barriers.

Domain Wall Propagation at Different Electrode Gaps

The distribution of strain fields varied with the size of the gap. For gaps of 200 nm, the strain fields from both electrodes significantly overlapped in the central region, facilitating complete domain wall (DW) propagation between the electrodes within the simulation timeframe. In contrast, at a gap size of 400 nm, this overlap diminished, resulting in a slower progression of the DW across the gap. For gaps measuring 600 nm, the strain fields from each electrode were largely decoupled; consequently, the DW was unable to traverse the entire gap and stalled in the central region where strain-induced driving forces were insufficient to overcome pinning effects (Fig. 3a-c).

These findings indicate that electrode gap size modulates DW propagation completeness: smaller gaps allow for full DW transfer while larger gaps lead to incomplete propagation or stalling. This behavior is consistent with a strain-mediated control mechanism and non-volatile strain retention observed in PMN-PT materials.

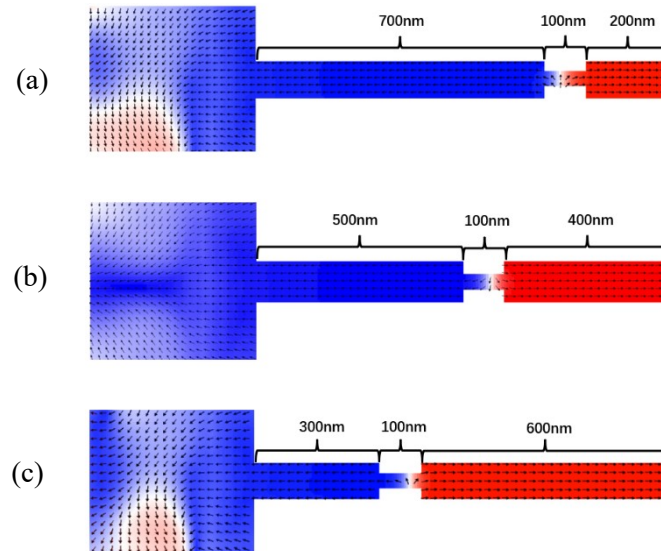


Figure S3: DW behavior with different electrode gaps. Gap distances: 50–700 nm. Stable motion occurs in the 100–200 nm range. Larger gaps weaken strain coupling and control.

Effect of Notch Shapes on Domain Wall Propagation

We investigated two sets of nanowire-electrode structures. One set features a nanowire width of $d = 100$ nm (left column), while the other has a width of $d = 50$ nm (right column). For the group with $d = 100$ nm, the parameters include an electrode width of $a = 400$ nm, an electrode height of $e = 400$ nm (for the topmost structure), an electrode-nanowire overlap of $b = 150$ nm, and varying nanowire segment lengths c (set at 1000 nm, 600 nm, and 400 nm). In contrast, for the group with $d = 50$ nm, we maintain a width of $a = 400$ nm and an overlap $b = 175$ nm; here too, c is varied as either 1000 nm, 600 nm, or 400 nm. A vertical electric field was applied to induce strain in the PMN-PT substrate. Micromagnetic simulations were conducted to track domain wall propagation through changes in magnetization orientation (indicated by blue/red colors representing opposite magnetization directions).

For the $d = 100$ nm nanowires (left column): As c (nanowire segment length) decreases from 1000 nm to 400 nm, the domain wall (DW) propagation path becomes shorter. When $c = 1000$ nm, $a = 400$ nm, $e = 400$ nm, and $b = 150$ nm, the DW moves across the long nanowire

segment, driven by strain from the larger electrode structure. At $c = 600$ nm and $c = 400$ nm, the DW continues to propagate along the nanowire; however, the shorter path length and altered strain distribution (resulting from the reduced c value) modify the magnetization transition region; For the $d = 50$ nm nanowires (right column): A smaller d reduces the nanowire volume, thereby affecting the strain-magnetization coupling. With $c = 1000$ nm, $a = 400$ nm, and $b = 175$ nm, the DW propagates along the nanowire, but the narrower width results in a more confined magnetization configuration. As c decreases, the DW response to strain evolves, and in the shorter $c = 400$ nm nanowire, the DW propagation process becomes more compressed due to the combined effects of reduced width and shortened length.

Overall, narrower nanowires ($d = 50$ nm) and shorter nanowire segments (c) influence domain wall (DW) propagation efficiency and magnetization patterns, as strain-induced effects are more localized in smaller geometries. These variations, which are governed by parameters a , b , c , and d , contribute to the optimization of strain-mediated DW devices for spintronic applications.

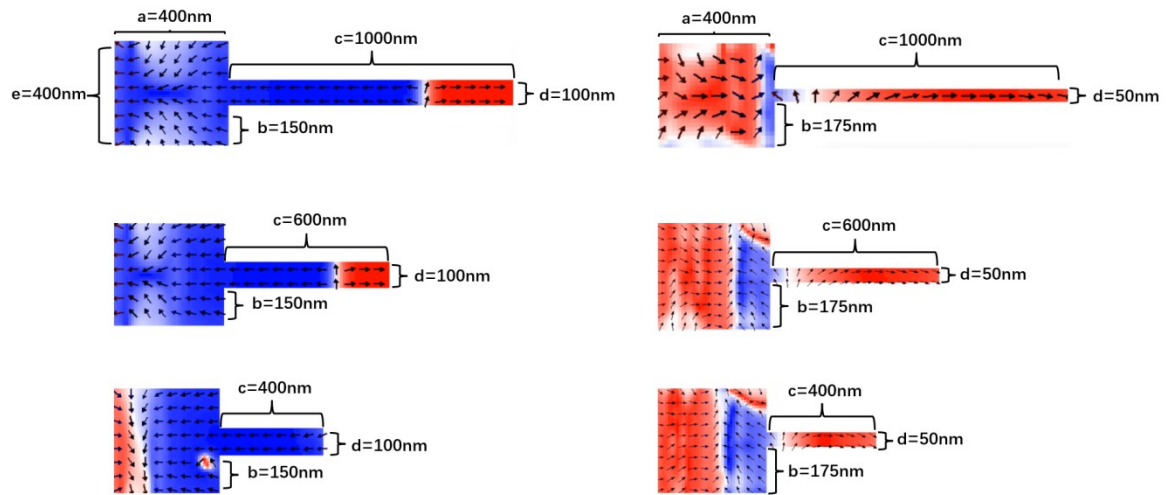


Figure S4: Effect of Notch Shapes on Domain Wall Propagation Voltage pulse: 0.05 ns at 400 V. DC case used same voltage with varied ground configurations. Geometries tested: $a = 400$ nm; $b = 150$ – 175 nm; $c = 400$ – 1000 nm; $d = 50$ – 100 nm; $e = 400$ nm. Notches enhance pinning and propagation control. Best performance observed at $b = 175$ nm.

Velocity Evaluation at Nanoscale

To quantify DW velocity in the optimized 400×50 nm nanowire, we tracked DW displacement over time using high-resolution OOMMF simulations. Under a 400 V pulse, the DW traveled 240 nm over 3.22 ns, yielding an average velocity of 74.4 nm/ns (266 m/s) (Fig. 5a–c). This matches the peak speed reported in the main text and confirms that strain-

mediated driving achieves velocities comparable to current-driven methods but with lower energy consumption.

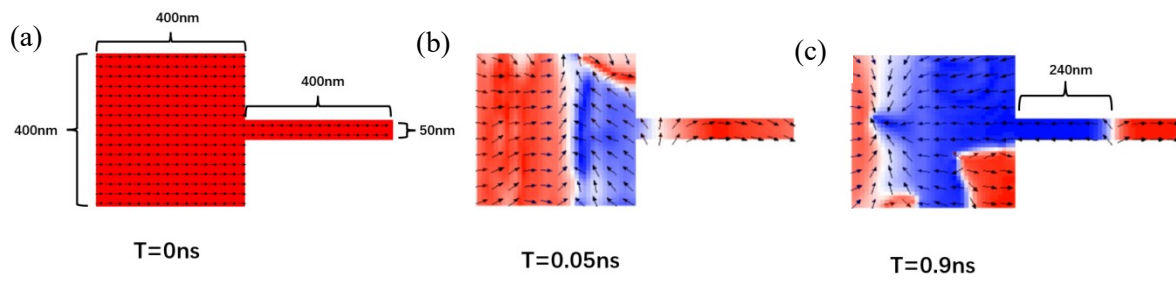


Figure S5: Velocity Evaluation at Nanoscale. For nanowire 400×50 nm with 400 nm length: velocity ≈ 74.4 nm/ns (~ 266 m/s).