Micromagnetic Study on the Influence of Nanowire Width and Dzyaloshinskii–Moriya Interaction on Domain Wall Propagation in CoFeB Nanowires under Nanosecond Current Pulses

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Abstract. The rapid growth of data storage demand drives the development of advanced spintronic devices beyond the limits of conventional hard disk drives and solid-state drives. Racetrack Memory is a promising technology due to its potential for ultrahigh density, non-volatility, and low energy consumption. This study investigates micromagnetic domain wall propagation in CoFeB nanowires driven by nanosecond current pulses, emphasizing the role of Dzyaloshinskii–Moriya Interaction (DMI). Simulations were performed using the Object Oriented Micromagnetic Framework with a spin-transfer torque model and an extended DMI module. Nanowire width, material parameters, and current pulse profiles were systematically varied to evaluate their effects on domain wall dynamics. Results show that reducing nanowire width increases domain wall velocity up to an optimum, beyond which instability occurs. DMI improves stability by suppressing distortions and enabling steady motion at high current densities. Nanosecond pulses allow controlled domain wall displacement without thermal degradation.

Keywords: Racetrack memory, domain wall propagation, CoFeB nanowire, Dzyaloshinskii–Moriya Interaction (DMI), micromagnetic simulation, spintronics.

1 Introduction

Spintronics has emerged as a promising technology that exploits the spin degree of freedom of electrons, enabling low-power and high-speed data processing and storage devices. The discovery of the Giant Magnetoresistance (GMR) effect in 1988 revolutionized data storage,

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paving the way for advanced non-volatile memories such as Magnetic Random Access Memory (MRAM) and Racetrack Memory (RM) [4]. RM operates based on the controlled motion of magnetic domain walls (DW) in a nanowire driven by current or magnetic fields, offering high density and low cost compared to conventional HDD and SSD.

However, DW motion efficiency is influenced by several factors, including current density, nanowire geometry, and spin–transfer interactions [5]. The Dzyaloshinskii–Moriya Interaction (DMI), arising from spin–transfer coupling and structural inversion asymmetry, plays a crucial role in stabilizing chiral magnetic structures and enhancing DW velocity. Understanding DMI's contribution to DW dynamics is essential for optimizing RM performance [3]. This study investigates the micromagnetic effect of DMI on DW propagation in CoFeB nanowires under sub-nanosecond current pulse injection, using numerical simulations via the Object Oriented Micromagnetic Framework (OOMMF). The objective is to analyse how DMI strength and nanowire width affect DW velocity and structure evolution, providing insights for developing next-generation spintronic memory devices [1]. Although previous studies have extensively examined DW dynamics under continuous or nanosecond-scale currents, the combined influence of sub-nanosecond current pulse injection and DMI strength on DW propagation in CoFeB nanowires remains insufficiently explored. This study addresses this gap by investigating the micromagnetic effects of DMI on DW propagation in CoFeB nanowires under sub-nanosecond current pulses using numerical simulations with the Object Oriented Micromagnetic Framework (OOMMF). Specifically, this work systematically analyses the interplay between DMI strength and nanowire width on DW velocity and domain wall structural evolution, highlighting regimes of enhanced stability and controlled motion. The findings provide new insights into ultrafast DW manipulation, offering design guidelines for high-speed and energy-efficient next-generation racetrack memory device [6].

2 Research Methodology

This research was conducted at the Research Centre for Materials and Energy, BRIN, from May to August 2025. The simulation was performed using OOMMF software, with supporting tools including Origin, ImageJ, Tcl/Tk, and Notepad++. The simulated system consists of a CoFeB nanowire with a fixed length of 10,000 nm, thickness of 1 nm, widths of 50, 100, and 150 nm and four variations of DMI values [10]. The DW was initialized in a head-to-head transverse configuration. A 1 ns current pulse was applied along the +x direction with a 0.01 ns rise time as shown in **Figure 1**.

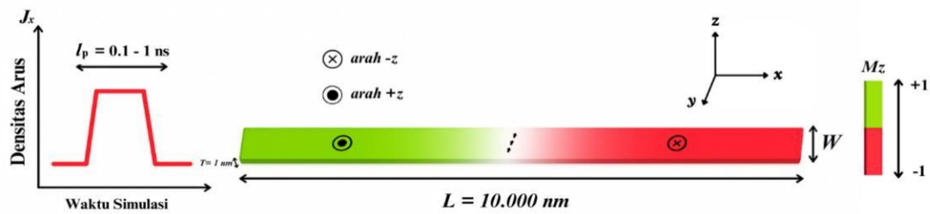


Fig. 1. Geometry of the simulated CoFeB nanowire showing current direction, coordinate axes, and initial domain wall configuration.

The magnetic parameters used in the simulations were adapted from previous experimental and theoretical studies. The saturation magnetization (Ms) was set 8.75×10^5 A/m, while the exchange stiffness constant (A) was 1×10^{-11} J/m. The uniaxial anisotropy constant (K) was defined as 7×10^5 J/m^3 with the easy axis aligned along the (001) crystallographic direction. The Gilbert damping constant (α) was taken as 0.01, and the non-adiabatic spin-transfer torque coefficient (β) was assumed to be zero to focus on the intrinsic effects of Dzyaloshinskii–Moriya Interaction (DMI) [11].To ensure numerical accuracy, the computational cell size was defined as $2\times2\times1$ nm^3, which is smaller than the calculated exchange length (l_{ex}=4.56 nm), thereby maintaining proper spatial resolution of the magnetization dynamics [19]. The simulation process began with defining the geometric structure and magnetic properties of the CoFeB nanowire through a micromagnetic input file (.mif). The initial magnetization state, including the domain wall configuration, was specified in this file, along with the boundary conditions and current pulse parameters [14]. The magnetization dynamics were governed by the Landau– Lifshitz–Gilbert (LLG) equation extended with spin-transfer torque terms, which was solved numerically by OOMMF. The time evolution of the magnetization was computed during and after the current pulse application to observe the displacement, deformation, and velocity of the domain wall. The results were analysed using Origin for velocity and temporal graphs, and ImageJ for spin configuration visualization [2].

3 Result and Discussion

3.1 Groundstate

This state represents the initial magnetic structure before any external excitation, such as current or magnetic field, is applied. Analysing the ground state is crucial because it determines the stability and equilibrium state. The analysis shows that the strength of DMI and the width of the nanowire play crucial roles in defining the stability and chirality of the magnetic ground state. However, the effectiveness of DMI decreases with increasing nanowire width due to stronger demagnetization fields and non-uniform spin interactions. The 50 nm nanowire exhibits the most coherent and stable chiral ground state, providing the ideal condition for fast and stable DW motion. In contrast, wider wires (100–150 nm) experience increasing internal distortions that may result in reduced DW velocity and stability. These findings confirm that narrow CoFeB nanowires with strong interfacial DMI are optimal for achieving stable chiral configurations and efficient domain wall propagation in racetrack memory applications [6].

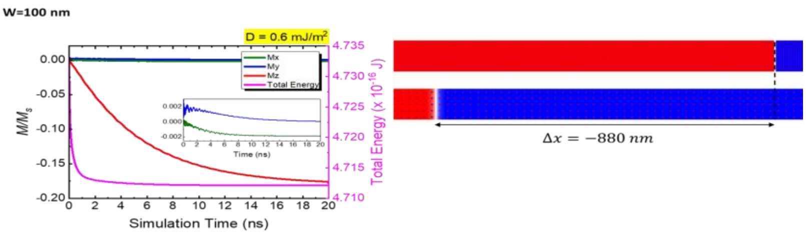


Fig. 2. Equilibrium (ground state) configuration of the CoFeB nanowire showing the lowest energy magnetization state and stabilized domain wall position.

Figure 2 shows the equilibrium or ground state represents the magnetic configuration of the nanowire when the system has reached its lowest total energy and all internal torques are balanced. In this condition, the magnetization no longer changes with time, indicating that the system is fully relaxed and dynamically stable. The domain wall (DW) has settled at its equilibrium position, where the competing energies such as exchange, anisotropy, Dzyaloshinskii–Moriya Interaction (DMI), and demagnetization are perfectly balanced. This state serves as the initial condition for dynamic simulations, ensuring that any subsequent DW motion results purely from external excitation (such as current or magnetic field), not from internal instability. The slight shift of the DW position during relaxation reflects the system's natural tendency to minimize total energy and reach a stable configuration.

3.2 Domain wall position analysis

Before analysing the dynamic behaviour of domain wall (DW) velocity, it is essential to first examine how the DW position changes under different DMI strengths and nanowire widths. The displacement of the DW over time provides insight into how effectively the spin–transfer torque and DMI contribute to its propagation. By comparing the DW position across various geometries (W = 50, 100, and 150 nm), the influence of geometric confinement and interfacial DMI on the overall stability and efficiency of DW motion can be better understood [12].

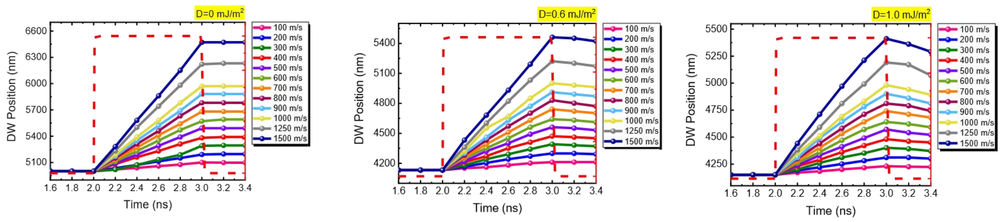
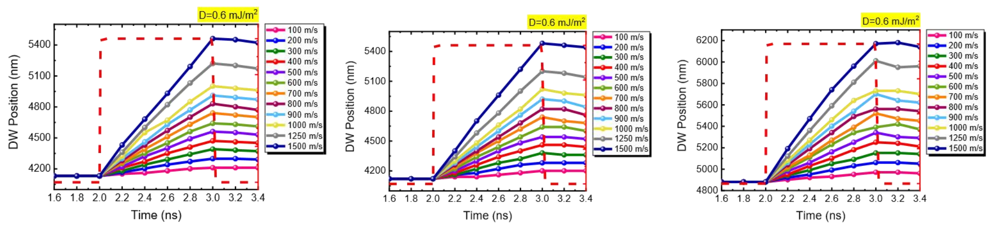


Fig. 3. Domain wall position of CoFeB nanowires at different DMI constants (D = 0, 0.6, 1) for various widths (W = 50 nm)

Figure 3 shows how the domain wall (DW) position changes over time for different DMI strengths value. As the DMI constant increases, the DW shifts farther from its initial position, indicating that stronger DMI enhances domain wall stability and improves its response to spin-transfer torque, resulting in larger displacement and the displacement is largest in the narrowest wire (W = 50 nm).

DMI is an antisymmetric exchange that favours chiral (handed) spin textures; it promotes an in-plane rotation sense across the wall and stabilizes Néel-type walls in perpendicularly magnetized films/strips. Changing D primarily affects (1) the ground-state wall type (Bloch ↔ Néel), (2) wall energy and width, (3) coupling of the wall to spin torques (STT), and (4) susceptibility to processional/Walker dynamics and internal modes. The practical consequences appear in the ground state profile, displacement per pulse, velocity profile, and stability (fluctuations, oscillations, pinning susceptibility) [18]. When D = 0, there is no Dzyaloshinskii– Moriya Interaction (DMI), so the domain wall (DW) in the CoFeB nanowire forms a Bloch-type configuration with no preferred chirality. The magnetic moments rotate out of the plane, and the system has no energetic preference for left- or right-handed rotation. Because of this, the DW is less stable and does not couple efficiently with the spin torque from the applied current. As a result, its movement is limited, and the position curve shows irregular motion with small oscillations. The wall may also experience internal deformation or precession (Walker breakdown), which reduces the average velocity and stability of its motion. At D = 0.6, the effect of DMI becomes noticeable. The interaction breaks the symmetry of the magnetic structure, partially converting the Bloch wall into a Néel-type wall. In this state, the magnetization within the DW tilts more in-plane, giving the wall a chiral character that increases its stability. The DW energy decreases, and its width becomes slightly narrower. When current is applied, the wall moves more smoothly and over a longer distance compared to D = 0. However, because the DMI is moderate, the wall can still be affected by demagnetizing fields, especially in wider wires, causing small fluctuations and distortions. Overall, moderate DMI improves the efficiency of DW motion but does not completely eliminate instability. At D = 1, the DMI is strong enough to fully stabilize a Néel-type domain wall with a fixed chirality. This creates a very stable and low-energy ground state. The wall becomes narrower and more uniform, making it highly responsive to current-induced torque. The position curve shows a steady and linear increase, meaning the wall moves quickly and smoothly without oscillations. The strong DMI also suppresses Walker breakdown, keeping the DW in a steady-flow regime. As a result, the DW velocity is the highest and most stable among all variations, and the motion becomes predictable and repeatable.

After understanding how different DMI strengths influence the magnetic configuration and domain wall (DW) dynamics, it is also important to examine how the nanowire width affects these behaviours. The geometric dimension plays a crucial role in determining the balance between exchange, anisotropy, demagnetization, and DMI energies. As shown in **Figure 4**, varying the wire width from 50 nm to 150 nm produces clear differences in DW displacement and velocity profiles. Narrower wires tend to enhance chiral stability and efficient motion, while wider wires introduce greater magnetic inhomogeneity and demagnetizing effects. This analysis highlights how geometric confinement, in combination with DMI strength, determines the overall efficiency, stability, and uniformity of DW propagation in CoFeB nanowires.



a) W = 50 nm

b) W = 100 nm

c) W = 150 nm

Fig. 4. Domain wall position of CoFeB nanowires at different width (W = 50, 100, 150 nm) for various DMI constants (D = 0.6 mJ/m^2)

Figure 4 shows the domain wall position of CoFeB nanowires with different widths (50, 100, and 150 nm) at a DMI value of 0.6 mJ/m². The DW moves forward as the current pulse is applied and stops after the pulse ends. The narrowest wire (50 nm) shows the largest and most stable displacement, while wider wires move shorter distances and show less uniform motion. This indicates that narrower nanowires provide better control and faster DW motion due to stronger confinement and lower demagnetizing effects.

The variation in nanowire width has a strong influence on the domain wall (DW) position and its propagation behaviour. As shown in **Figure 4**, at a fixed DMI value of 0.6 mJ/m^2, the displacement of the DW changes noticeably as the width increases from 50 nm to 150 nm. In the narrowest nanowire (50 nm), the DW moves the farthest distance and shows a clear, linear increase in position with time. This occurs because the narrow geometry enhances magnetic confinement and strengthens the influence of DMI, leading to a more stable and efficient DW motion. The limited space also reduces demagnetizing effects and suppresses spin irregularities along the edges, allowing the wall to move coherently during the current pulse. When the width increases to 100 nm, the DW displacement becomes smaller and slightly less uniform. The weaker confinement allows more variation in the magnetic spins across the wire, creating small distortions that slow down the motion. Although the DMI still stabilizes the wall structure, part of the driving torque is lost due to these internal variations. In the widest nanowire (150 nm), the displacement is the smallest and the DW motion begins to show earlier saturation. This is mainly due to stronger demagnetizing fields and spin inhomogeneity that resist the wall's movement, causing it to lose coherence as it propagates. Overall, the results indicate that narrower nanowires provide faster, smoother, and more stable DW motion, while increasing the width leads to reduced displacement and stability. The geometric confinement in thin nanowires plays an important role in supporting efficient domain wall propagation, making smaller wire widths more suitable for high-speed and energy-efficient spintronic applications.

From the previous analysis, it can be seen that as the wire width increases, the domain wall (DW) motion becomes less stable and starts to show small irregularities in the displacement curve. These fluctuations, as shown in **Figure 5**, indicate the occurrence of a nucleation phenomenon during DW propagation. Nucleation refers to the spontaneous formation of new magnetic domains or reversed spin regions when the system becomes energetically unstable. This typically happens when the applied current or local magnetic torque exceeds the stability limit of the existing domain wall structure.

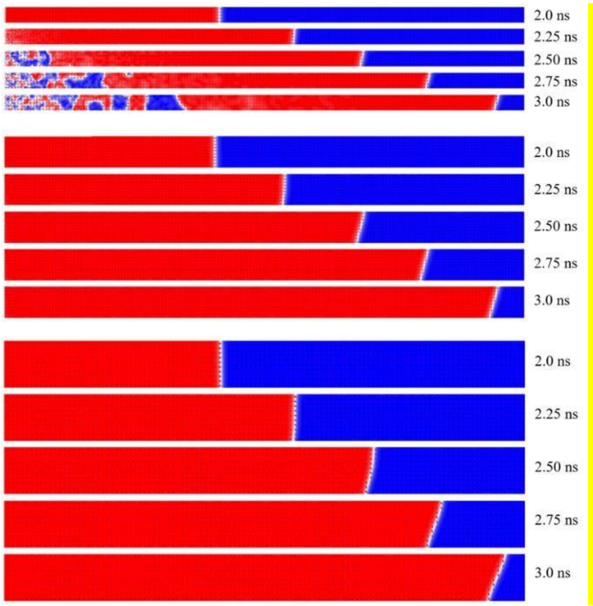


Fig. 5. Evolution of domain wall (DW) structure during nucleation in CoFeB nanowires at different widths (W = 50, 100, 150 nm), time steps (2.0–3.0 ns) and DMI value (D = 0)

Figure 5 illustrates the time evolution of the magnetization configuration during current-driven domain wall (DW) motion in CoFeB nanowires of different widths. The snapshots show how the DW propagates from 2.0 ns to 3.0 ns and how its stability changes with wire width. In the narrowest nanowire (W = 50 nm), the DW moves smoothly and maintains a coherent Néel-type structure, indicating a stable and uniform propagation. However, as the wire width increases to 100 nm and especially 150 nm, irregular spin regions start to appear near the DW front. These irregularities mark the onset of the nucleation phenomenon, where new reversed magnetic domains are spontaneously formed due to the breakdown of DW stability. This nucleation occurs when the applied current torque and internal magnetic interactions disturb the energy balance between exchange, anisotropy, demagnetizing, and DMI energies. In wider nanowires, the demagnetizing field and spin inhomogeneity become stronger, weakening the stabilizing effect of DMI and causing local regions to flip their magnetization direction. As the driving current continues, these reversed regions expand and merge with the main DW, disrupting its coherent motion. Consequently, the DW no longer moves as a single entity but splits into multiple local domains, which is consistent with the instability and velocity fluctuations observed in the previous figures.

Overall, **Figure 5** demonstrates that nucleation is a direct consequence of excessive driving torque and weak confinement, conditions that prevent the DW from maintaining a stable chiral configuration. The comparison between different widths clearly shows that narrow nanowires provide stronger confinement and suppress nucleation, while wider nanowires are more prone to instability. This highlights the importance of optimizing both DMI strength and wire geometry to achieve stable, nucleation-free DW motion for reliable spintronic device operation.

3.3 Domain wall velocity analysis

Furthermore, after examining the displacement behavior of the domain wall (DW), it is essential to analyze its velocity characteristics to better understand the overall dynamics of DW motion.

As shown in **Figure 6**, the change in DW position over time indicates that the wall's propagation is strongly influenced by the Dzyaloshinskii–Moriya Interaction (DMI) strength and nanowire width. To complement this observation, the velocity analysis provides a clearer view of how efficiently and stably the DW moves under the influence of spin–transfer torque during current pulse injection. Therefore, by comparing the DW velocity across different DMI constants and geometries, the combined effects of DMI and geometric confinement on the efficiency of DW propagation can be comprehensively evaluated [7] [9] [18].

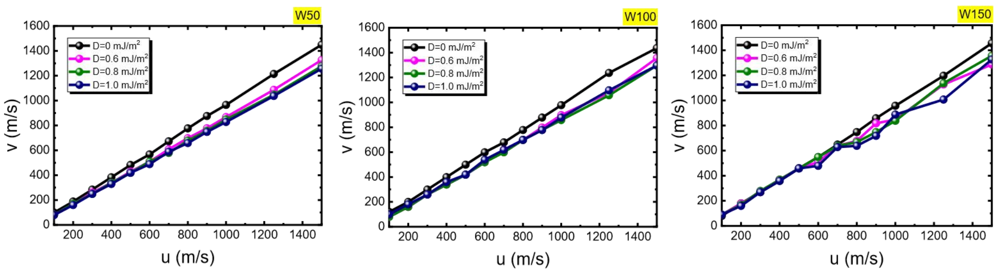


Fig. 6 Domain wall velocity (V) as a function of electron drift velocity (u) for CoFeB nanowires with different widths (W = 50, 100, and 150 nm) under various DMI strengths (D = 0, 0.6, and 1.0 mJ/m²).

Figure 6 illustrates the relationship between the domain wall velocity (V) and the electron drift velocity (u) for CoFeB nanowires with different widths (W = 50, 100, and 150 nm) under various DMI strengths. In general, the DW velocity increases almost linearly with the drift velocity, showing that the DW responds proportionally to the applied current. This linear trend indicates that, in the steady-flow regime, the spin–transfer torque efficiently drives the DW without significant distortion. Among all samples, the narrowest nanowire (W = 50 nm) exhibits the highest and most stable velocity, reflecting the strong geometric confinement that enhances DMI effects and reduces demagnetizing influences. In contrast, wider nanowires (W = 100 nm and W = 150 nm) show slightly lower velocities and small irregularities in the curve, caused by internal magnetic nonuniformities and reduced confinement. At higher drift velocities, especially in the wider wires, the DW motion begins to deviate from the linear trend. These deviations correspond to regions where the motion becomes unstable, leading to the nucleation phenomenon previously observed in **Figure 5**. When the driving torque exceeds the wall's stability limit, the magnetic configuration inside the wire can no longer maintain a single coherent DW. As a result, new reversed magnetic domains are nucleated near the original wall, disrupting smooth propagation and reducing the average velocity. This process momentarily slows down or fluctuates the DW speed, which appears as small drops or irregularities in the velocity curve. Therefore, the velocity analysis confirms that nucleation acts as the main limiting factor for high-speed DW motion, especially in wider wires where demagnetizing effects and spin distortion are stronger. Overall, **Figure 6** demonstrates that narrower nanowires and moderate DMI strengths provide the most stable and efficient DW propagation, while excessive current or wide geometries increase the risk of nucleation, leading to instability in the DW velocity and reduced control over its motion.

4 Conclusion

This study investigated the influence of Dzyaloshinskii–Moriya Interaction (DMI) strength and nanowire width on the magnetic ground state, domain wall (DW) position, and velocity in CoFeB nanowires using micromagnetic simulations. The results showed that increasing the DMI strength from 0 to 1.0 mJ/m² significantly stabilizes the domain wall by promoting a chiral Néel-type configuration, which enhances DW mobility and suppresses precession instabilities. Meanwhile, variations in nanowire width strongly affected the overall motion behavior. Narrower wires ($W = 50$ nm) produced smoother, faster, and more stable DW propagation due to stronger magnetic confinement and reduced demagnetizing effects, while wider wires exhibited decreased displacement and irregular motion [7]. At higher driving velocities, wider nanowires also displayed nucleation phenomena, where new magnetic domains were formed due to the breakdown of DW stability. This effect occurred when the balance between DMI, exchange, and demagnetizing energies was disrupted by excessive torque, leading to irregular domain structures and a sudden drop in DW velocity. To minimize nucleation and ensure stable propagation, an optimized combination of DMI strength and nanowire width is required. The results suggest that maintaining a moderate to strong DMI value (around 0.6–1.0 mJ/m²) combined with a narrow geometry ($W \leq 50$ nm) provides the best trade-off between stability and speed, effectively preventing nucleation while maximizing DW mobility. In summary, the interplay between geometric confinement and DMI strength plays a crucial role in determining DW dynamics. Optimizing these parameters allows the design of high-performance, nucleation-free spintronic devices, where domain walls can move rapidly and reliably under current induced torques, an essential step toward efficient racetrack memory and next-generation magnetic logic applications.

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