Domain Wall Dynamics in Stepped Magnetic Nanowire with Perpendicular Magnetic Anisotropy

Suleiman Al Risi, Rachid Sbiaa,* and Mohammed Al Bahri

Micromagnetic simulation is carried out to investigate the current-driven domain wall (DW) in a nanowire with perpendicular magnetic anisotropy. A stepped nanowire is proposed to pin DW and achieve high information storage capacity based on multibit per cell scheme. The DW speed is found to increase for thicker and narrower nanowires. For depinning DW from the stepped region, the current density $J_{\text{dep}}$ is investigated with emphasis on device geometry and material intrinsic properties. The $J_{\text{dep}}$ can be analytically determined as a function of the nanoconstriction dimension and the thickness of the nanowire. Furthermore, $J_{\text{dep}}$ is found to exponential dependent on the anisotropy energy and saturation magnetization, offering thus more flexibility in adjusting the writing current for memory applications.

1. Introduction

Magnetic random access memory (MRAM) gained attention as a possible replacement to conventional memories such as static and dynamic RAMs and even flash memory. It has several advantages as reported in few articles.[1–6] For the MRAM device based on magnetic tunnel junctions (MTJs), the direction of magnetization defines the magnetic state, thus only one bit per cell could be stored. For increasing the storage capacity of the memory, there were attempts to use MTJs with two free layers to achieve four magnetic states.[7,8] For even more storage capacity, domain wall (DW)-based MRAM was intensively investigated.[9–23] The first generation of DW-based devices was based on materials with in-plane magnetic anisotropy (IMA). However, the continuous reduction of device size makes these materials less effective in keeping the magnetic state (information) stable. In contrast, materials with perpendicular magnetic anisotropy (PMA) have the advantage to provide better thermal stability due to the higher magnetic anisotropy. Different studies have been focused on DW movement in nanowires with in-plane anisotropy and an emphasis on the dependence of the velocity of DW on nanowire dimensions. It has been reported that DW motion can be controlled by adjusting the nanowire width and thickness.[24,25] For in-plane (IMA) material, DW velocity could be made larger by increasing nanowire width and decreasing its thickness.

To store the information in magnetic domains, the DW should be stable at a predefined position within the nanowire. Pinning DW at a precise position has been investigated with several schemes. One of them was based on creating triangular notches with different geometries for DW made of permalloy material.[26–28] Another way like using a magnetic field perpendicular to the direction of DW motion to reduce the speed of DW to zero at a required position was also proposed.[29] In such a method, the magnetic field needed to pin DW is higher than the Walker field and causes deformation for the DW structure.

In our previous work, we proposed nanowire with a stepped area to pin DW in materials with IMA.[25,31] In this article, we focus on material with perpendicular anisotropy, and we used micromagnetic formalism with the inclusion of spin-transfer torque effect with both adiabatic and nonadiabatic terms.

2. Theoretical Model

In this study, we investigate a magnetic nanowire of fixed length $L = 200$ nm and varied width $w$ and thickness $t$, as shown in Figure 1a. The device is divided into small meshes with the size of $(2.5 \times 2.5 \times t_w)$ nm$^3$. The size of the mesh is chosen to be smaller than the exchange length $l_{\text{ex}}$ of the materials considered in this study. In the last part, the saturation magnetization ($M_s$), the PMA ($K_u$) are varied, whereas the exchange length ($A$) was kept constant ($A = 2 \times 10^{11}$ J m$^{-1}$). These chosen values correspond to the actual magnetic properties of the Co/Ni multilayers as reported previously.[32] The calculation is carried out with the object-oriented micromagnetic framework (OOMMF) based on the Landau–Lifshitz–Gilbert (LLG) equation with spin-transfer torque (STT) term.[33]

$$\frac{d\vec{m}}{dt} = -\gamma (\vec{H}_{\text{eff}} \times \vec{m}) + \alpha \left( \vec{m} \times \frac{d\vec{m}}{dt} \right) + \vec{u} \times \left( \vec{m} \times \frac{d\vec{m}}{dt} \right) + \beta \frac{\vec{m} \times d\vec{m}}{dt}. \tag{1}$$
Figure 1. a) Conventional nanowire with length L and width w and b) Nanowire with a stepped area at its center with dimensions d and l to pin the DW.

where \( \vec{m} \) is the normalized magnetization vector, \( \gamma \) is the gyromagnetic ratio, \( \alpha \) is the Gilbert damping parameter, the vector \( \vec{u} = \left[ (P/\mu_B)/2eM_s \right] J \) is the adiabatic spin torque which has the dimension of velocity, \( J \) is the current density, \( g \) is the Lande factor, \( P \) is the spin polarization, \( e \) is the charge of electron, and \( \mu_B \) is the Bohr magneton. In the middle of the nanowire, a stepped junction is designed by shifting one part in the \( x \)-direction and the other in the \( y \)-direction, called \( l \) and \( d \), respectively, to pin DW (Figure 1b). Initially, the magnetic moments are saturated in \( z \)-direction then the DW was created at the left edge of the nanowire so the DW could move easily under a reasonably low current density. The DW could be pinned at the stepped region, then at a certain value of current density, the DW is released. This critical current density is called the depinning current density \( (J_{\text{dep}}) \). The calculations are carried out using LLG equation. Different values of the width and thickness of the nanowire were chosen to explore the dependence of DW velocity and the depinning current on device geometry. The dimensions of the stepped area are also varied. Figure 1a shows the conventional nanowire, whereas Figure 1b illustrates the proposed stepped type, which is efficient in pinning/stabilizing DW for memory applications.

3. Results and Discussion

In this study, all magnetic moments within the nanowire are initially considered to be aligned in the negative \( z \)-direction (perpendicular to the nanowire plane). The spin-polarized current was then applied from the left edge of the nanowire to the right edge along the \( x \)-direction perpendicular to the direction of magnetization. First, the simulations are carried out using a conventional nanowire without any stepped region to investigate the DW dynamics, as shown in Figure 1a. In this case, DW is created as an initial state at nanowire left edge and moves through the nanowire without observing any pinning within the device, as shown in Figure 2a. The motion of DW from the initial state \( (m_z = -1) \) to the final state \( (m_z = +1) \) happens with constant velocity as shown by the linear dependence of \( m_z \) with time \( (m_z = M_s / M_s) \) is the normalized \( z \)-component of the magnetization). The insets of Figure 2a are captured images showing a temporary displacement of DW along the nanowire.

Figure 2b shows the plots of DW velocity \( v \) as a function of \( J \) for different widths of the nanowire. It is found that \( v \) has a linear dependence with \( J \), similar to what was reported by several groups for nanowires with PMA.\(^{[13,14–17]} \) The velocity versus current density could be described by

\[
\nu = \frac{\epsilon \gamma \hbar P}{2eM_s \alpha^2} J
\]

where \( \hbar \) is the reduced Planck constant and \( \epsilon \) is the nonadiabatic parameter.\(^{[14,38]} \)

For a device with 10 nm width, the velocity rose from 110 m s\(^{-1} \) (at a current density of \( 6 \times 10^{11} \text{ A m}^{-2} \)) to 160 m s\(^{-1} \) (at a current density of \( 20 \times 10^{11} \text{ A m}^{-2} \)). We confirmed this result by investigating the influence of nanowire width on the dynamics of DW. From Figure 2c, it shows that the DW velocity increases as nanowire is made narrow following the relation

\[
J = i/w \Delta.
\]

The Equation (2) becomes

\[
\nu = \frac{\epsilon \gamma \hbar P i}{2eM_s \alpha w \Delta}
\]

where \( i \) is the current flow, \( w \) is the nanowire width, and \( \Delta \) is the DW width.\(^{[36]} \)

It has been argued that as the nanowire width becomes smaller, the hard axis anisotropy field decreases, and the Néel wall becomes more stable, therefore, the current density enhances the DW dynamics.\(^{[19]} \) The other key parameter which has a strong effect on DW dynamics is the nanowire thickness. Figure 2d shows a plot of the dependence of \( v \) on \( t_w \). Insets are the DW configuration for different nanowires thicknesses. It was found that the velocity has an almost linear dependence on the thickness for a certain range of values \( (t_w \text{ between 1 and 5 \text{ nm}}) \) and agrees with the relation

\[
\nu = \frac{0.01 \gamma a_i t_w}{\alpha}
\]

where \( a_i = \hbar P/2eM_s \).\(^{[39]} \) In this study, a current density of \( 2.3 \times 10^{11} \text{ A m}^{-2} \) was applied and \( t_w \) was varied from 1 to 12 nm, whereas the other parameter was kept constant \( \nu = 40 \text{ nm} \). It shows that DW velocity increases rapidly as thickness was varied from 1 to 5 nm to reach a velocity of about 110 m s\(^{-1} \) for a device with 5 nm thickness. Figure 2d also shows that the velocity did not change much for large thickness (more than 5 nm). As the thickness varies, the micromagnetic simulation shows the transformation from a Néel wall to Bloch wall (insets of Figure 2d). This could be the reason for the fast increase in the velocity with thickness.

For the use of the stepped nanowire as a memory device, the effect of the stepped region dimension of the depinning current density is of great importance. There is a balance between the stability of the DW and the minimum \( J_{\text{dep}} \) needed to move it to the next step (i.e., state). First, the DW is created in the left edge of stepped nanowire and the current is applied to move the DW. Once the DW is stabilized/pinned in the stepped region, considered as the initial state, the current was varied continuously until the DW is depinned. The depinning current density was investigated for stepped nanowires with widths of values varied from 20 to 60 nm with a step of 10 nm, whereas the length
of the step (d) was fixed to \((w/2)\). Figure 3a shows that for \(w = 40\), 50, and 60 nm, \(J_{\text{dep}}\) decreases exponentially with \(\lambda\). For smaller values of \(w\), an almost linear behavior was observed. Figure 3b shows the dependence of \(J_{\text{dep}}\) on the thickness of the device for different values of \(d\). The most striking result to emerge from the data is that \(J_c\) increases with the thickness for different values of \(d\) (here \(\lambda\) was fixed to zero). Hence, with these results, we can achieve a higher depinning current and higher speed with larger thickness and narrow nanowire. The numerical data obtained from LLG equation can be described analytical using the expression \(J_{\text{dep}} = A + Be^{-\xi/\xi}\). Here, \(\lambda\) is the width of nanoconstriction in the \(x\)-direction, and \(\xi\) is a fitting parameter as well as \(A\) and \(B\). The values of \(\xi\) for different nanowire widths \(w\) are shown in Table 1. It is important to mention that for small values of \(w\), \(J_{\text{dep}}\) shows a linear behavior with \(\lambda\), as shown in

![Figure 2](image1)

**Figure 2.** a) Normalized magnetization of a conventional nanowire as a function of time for device with \(L = 200\) nm, \(w = 40\) nm, \(M_s = 802 \times 10^7\) A m\(^{-1}\), \(K_u = 5.3 \times 10^8\) J m\(^{-3}\), \(A = 2 \times 10^{11}\) J m\(^{-2}\), and \(J = 2.3 \times 10^{11}\) A m\(^{-2}\). b) Plot of the average of DW velocity as a function of current density for various nanowire widths. c) DW average velocity as a function of the thickness of conventional nanowire for various applied current density values. d) A plot of the average velocity and the conventional nanowire thickness for \(J = 2.3 \times 10^{11}\) A m\(^{-2}\) and wire width of 40 nm. Insets are snapshots of magnetic moments at the vicinity of DW showing the transformation from Néel wall to Bloch wall.

![Figure 3](image2)

**Figure 3.** a) Plots of \(J_{\text{dep}}\) versus the step width \(\lambda\) for various widths of nanowire \(w\). For the plots, \(d\) was fixed to \(w/2\). b) \(J_{\text{dep}}\) versus the nanowire thickness \(t_z\) for \(d = 25, 30,\) and 35 nm and \(\lambda = 0\).
Table 1. The dependence of the fitting parameters ξ and B on the width of the nanowire. The device dimensions and material properties, as shown in Figure 3a.

| d [nm] | ξ [nm] | B (×10^1 A m^-2) |
|-------|-------|------------------|
| 40    | 12.6 ± 1.0 | 8.2 ± 0.3 |
| 50    | 6.8 ± 0.5  | 8.1 ± 0.2 |
| 60    | 8.5 ± 0.7  | 10.0 ± 0.3 |

Table 2. The fitting parameters taken from exponential growth function and shown in Figure 3b for different values of d.

| d [nm] | ρ [nm^-1] | J_0 (×10^1 A m^-2) |
|-------|-----------|-------------------|
| 25    | 0.350 ± 0.006 | 14.5 ± 0.1 |
| 30    | 0.307 ± 0.005 | 18.9 ± 0.1 |
| 35    | 0.311 ± 0.004 | 20.6 ± 0.1 |

Figure 3a. By looking carefully at Figure 3b, it is shown that J_0 has an exponential growth with the nanowire thickness. In this case, the depinning current density can be expressed as

\[ J = J_0 (1 - e^{-\rho d}) \]  
(5)

In the same manner as in Figure 3a, the parameters J_0 and ρ, which are shown in Table 2, could be obtained for different values of d (the nanoconstriction size along y-direction). Table 2 shows that the fitting parameter ρ is not much dependent on d in the investigated range. The parameter J_0, which is considered as the current density for relatively thick nanowire, is continuously increasing with d as expected. In fact, J_0 is higher for large values of d for any nanowire thickness value (Figure 3b). After investigating the effect of device geometry on the dynamics of DW and the depinning current density, the study focused on the effect of the key material properties such as M_s and K_u on J_0. First, M_s was fixed, whereas K_u was varied between 5.0 × 10^5 and 10.0 × 10^5 J m^-3. In this calculation, DW was first brought to the stepped region then a current was applied to depin DW from its initial position. Figure 4a shows a plot of J_0 as a function of K_u for different values of d (λ was fixed to 0 nm). Here, the saturation magnetization was fixed to 800 kA m^-1. It was found that the values of J_0 obtained from numerical calculation using LLG equation could be fitted to an exponential growth function exp(K_u/t_1). The parameter t_1 is a fitting parameter that has the dimension of energy. From the best fit, t_1 was found to be almost constant for d = 30 and 35 nm with values of 6.9 × 10^5 and 7.0 × 10^5 J m^-3, respectively. A slightly larger drop of t_1 to 4.5 × 10^5 J m^-3 was obtained for d = 25 nm. Similarly, the effect of M_s on J_0 was investigated. Figure 4b shows that under the same device geometry, J_0 shows, in contrast, and exponential decay (first order) with M_s for a constant K_u. The plots in Figure 4b are for K_u = 5.3 × 10^5 J m^-3. The J_0 can be described by the function exp(-M_s/t_2), where t_2 is a fitting parameter with values of 345, 656, and 1166 kA m^-1 for d = 25, 30, and 35 nm, respectively. Optimizing J_0 is essential for memory applications. It should be reasonably low to move the DW from one step to the other with a low applied current, i.e., changing the magnetic state by displacing DW within the nanowire. One can design the nanoconstriction dimensions for different values of K_u and M_s, as described analytically earlier by the growth and the decay functions, respectively. For the evaluation of the influence of K_u on DW stability and its magnetic configuration in the vicinity of the stepped area, we carried out the calculation of time dependence of the magnetization for three values of K_u.

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Figure 5a,b shows the snapshot images of the nanowire with K_u = 5 × 10^5 J m^-3 and 10 × 10^5 J m^-3 (M_s was fixed to 800 kA m^-1). These are typical values for Co/Pt, Co/Ni, Co/Ni/Co/Pt multilayers, and CoFeB commonly used for magnetic materials with perpendicular anisotropy. The device dimensions including the nanoconstriction size are L = 200 nm, w = 40 nm, d = 35 nm, and λ = 10 nm. The calculation was carried out with a current density of 4.1 × 10^11 A m^-2. Although DW could be stabilized in the stepped area, it will not remain for a long time. Figure 5c shows that DW takes less than 5 ns before vanishing; i.e., moving to the right edge of the device. To overcome this issue, an increase in K_u is necessary, which has been demonstrated for K_u = 10 × 10^5 J m^-3. It is important to mention that it is also possible to stabilize DW at the stepped region for relatively low K_u by enlarging d or shrinking λ. We noticed that magnetic moments configuration near the stepped area changes with K_u (Figure 5).

![Figure 4](image_url)  
**Figure 4.** DW depinning current density versus a) K_u and b) M_s for different values of d. The lines are fit to exponential growth function for case (a) and exponential decay for case (b), the nanowire length and width are fixed to 200 and 40 nm, respectively.
The dynamics of DW at the stepped area based on the influence of $M_u$ was also investigated. In the same manner, DW could be stabilized at the nanoconstriction for small values of $M_u$.

The stepped type nanowire offers an easy and accurate way of pinning DW within the device. In addition to the nanoconstriction dimension, the material magnetic properties, such as $M_u$ and $K_u$, provide a further degree of freedom to lower the depinning current density and stabilizing the DW for high-capacity memory applications.

4. Conclusions

DW dynamics was investigated in magnetic nanowires with perpendicular anisotropy. In conventional nanowire, the velocity showed a linear increase with the current density and dropped exponentially with the device width. In the stepped nanowire case, it was found that for particular dimensions of the nanoconstriction region, DW could be stabilized and pinned. The dependence of depinning current density $J_{dep}$ on the thickness of the nanowire and dimensions of the stepped region could be described analytically. Furthermore, the dependence of $J_{dep}$ on the material properties was studied. The $J_{dep}$ could also be fitted analytically by either exponential growth or exponential decay functions with $K_u$ and $M_u$, respectively. Tuning and predicting analytically the device geometry and material properties for an optimal $J_{dep}$ is important for designing DW-based memory devices.

Conflict of Interest

The authors declare no conflict of interest.

Keywords

domain wall motion, magnetic nanowires, perpendicular magnetic anisotropy, spin transfer torque
