Domain wall creep motion dynamics in CoFeB nanowire strips of different thicknesses using micromagnetic simulation approach

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Abstract. Field-induced domain wall motion on thin magnetic films with perpendicular anisotropy has long been attributed with the universal creep theory, in which the domain wall (DW) is able to experience a slow-moving motion with driving fields below the depinning threshold. Despite the numerous research that has been conducted in regards to this phenomenon, creep motion thus far has yet to be observed on a typical single-layered magnetic film. The effects of the film's thickness towards the creep motion are also scarcely explored. In this study, we conduct micromagnetic simulations of CoFeB nanowire strips with perpendicular anisotropy and varying thicknesses to investigate the dynamics of the creep motion being exhibited. We then analyze the obtained DW velocities and its' agreement with the universal creep law equation. The velocities obtained with low driving fields is found to be in an agreement with the creep law equation. The varying thicknesses also seem to affect the overall DW velocity and DW width.

Keywords. Domain wall, micromagnetic simulation, CoFeb nanowire

1 Introduction

In the last couple of decades, the dynamics of magnetic domain wall (DW) motion has regained a considerable amount of attention. This is in large part due to its' recently discovered potential in future spintronic devices such as racetrack memories [1], magnetic tunnel junctions (MTJ) [2, 3], and magnetic random access memories (MRAM) [4, 5]. In its' infancy, many of the research was done using permalloy materials and ferromagnets with in-plane magnetization anisotropy (IMA) due to its' high DW velocities [6, 7]. In recent years however, research towards the dynamics of DW motion has expanded to include ferromagnets with perpendicular magnetization anisotropy (PMA) [8–10]. Despite exhibiting slower DW velocities than IMA ferromagnets, PMA ferromagnets have been found to exhibit smaller domain walls and lower depinning thresholds, allowing for more potential DW control [11, 12].

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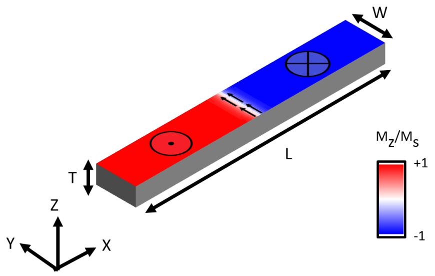


Fig. 1. A model of the simulated CoFeB nanowire strip

In a typical field-induced DW motion, the driving field that's applied needs to be above the depinning threshold in order to move the DW. However, multi-layered ferromagnet thin films have been found to exhibit the so-called creep motion, where applying driving fields below the depinning threshold is also capable of moving the DW, albeit with much slower speeds [13, 14]. Although numerous research has been conducted towards the investigation of creep motion, most, if not all, of those research was utlizing multi-layered thin films [13–15]. To our knowledge thus far, no comprehensive study has been conducted to investigate the dynamics of creep motion on single-layered ferromagnetic thin films.

In this study, we conduct micromagnetic simulations of CoFeB nanowire strips with PMA and varying thicknesses to investigate the dynamics of the creep motion being exhibited. The obtained magnetization data from the micromagnetic simulations are then used to calculate the DW velocities. The velocities obtained in the low driving field regime are then analyzed for its' agreement with the universal creep law equation. We also used the simulations to image the DW structure and numerically calculate the DW width to analyze its' characteristics.

2 Numerical methods

Figure 1 depicts the model of the nanowire strip that was used for the micromagnetic simulations. The length L and width W of the nanowire strip was kept constant at 600 nm and 50 nm respectively. The thickness T of the nanowire strip was varied with variations of 1, 2, 4, and 10 nm. The DW is initially placed at the center of the nanowire strip facing the y+ axis. The driving magnetic field was applied as a 1 ns pulse on the direction of the z+ axis, with a relaxation time of 1 ns, raising time of 0.1 ns, and lowering time of 0.1 ns. The material simulated was that of a CoFeB with PMA, with the saturation magnetization $M_s = 8.75 \times 10^5$, the exchange stiffness $A = 1 \times 10^{-11}$, and the anisotropic constant $K = 7 \times 10^5$ [16].

The micromagnetic simulations for this study were carried out using the open-source Object Oriented Micromagnetic Framework (OOMMF) software [17]. Using the finite difference method, the software first discretizes the simulated sample into multiple cubic cells of a finite size. It then carries out micromagnetic calculations on each cell based on the Landau-Lifshitz-Gilbert (LLG) equation to determine the magnetization equilibrium [18, 19]. From this equilibrium, the magnetization vector on each cubic cell of the sample can then be determined and presented as data from which further analysis can be performed. The LLG equation used in the simulations are written as follows:

$$\frac{d\mathbf{M}}{dt} = -|\gamma|\mathbf{M} \times \mathbf{H}_{eff} - \frac{|\gamma|\alpha}{M_s}\mathbf{M} \times (\mathbf{M} \times \mathbf{H}_{eff})$$

where γ is the gyromagnetic ratio constant given by 2.21×10^5 $m/A.s$ [17] and α is the Gilbert damping constant given by 0.1.

3 Results and discussion

To investigate the dynamics of the creep motion, this study will analyze the DW velocity and structure. The DW velocity can be determined by calculating the displacement of the DW while the external field pulse is applied. For the DW structure, the magnetization vectors obtained by the micromagnetic simulations can be directly used to image the simulated sample and the magnetization of the DW.

3.1 Domain wall velocities

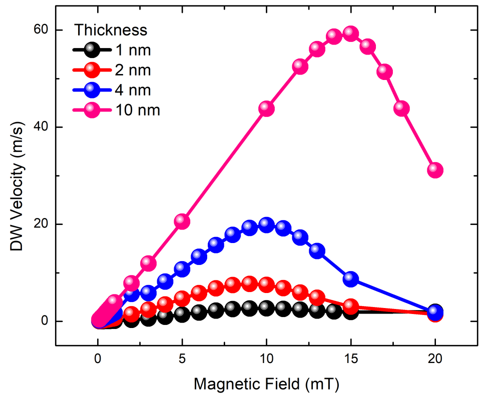
Figure 2a shows the profile of the calculated DW velocities with respect to the increasing applied magnetic field. The Walker breakdown field H_{WB}, the point where the DW velocity abruptly decreases [20], is observed to be higher as the nanowire strip becomes thicker. This is the exact opposite when compared to previously observed Walker field profiles on IMA nanowires [21, 22]. Even though the overall DW velocities are much slower than that of IMA nanowires, they also follow an opposite trend where thicker nanowires exhibit higher DW velocities. A possible explanation for this opposite trend may come from the different DW structures. Previously observed IMA nanowires have the Néel wall structure, while the PMA nanowires observed in this study have the Bloch wall structure. Due to their large dipolar energy, Bloch walls are usually energetically favored in thicker or bulk structures [19, 23]. This energy favoritism is one possible cause for the observed opposite trend.

To observe the dynamics of the exhibited creep motion, we plot the DW velocities of the low-field regime on Fig. 2b. We limit this low-field regime from 0.1 to 1 mT. Compared to previously observed creep motion velocities on a similar low-field regime [13, 14], the DW velocities observed in this study are much higher. This might simply be just a general characteristic of a single-layered system, since the overall DW velocity is also higher when compared to the multi-layered systems. As surmised from the higher velocities present on thicker nanowires, a higher velocity increase can also be observed for thicker nanowires.

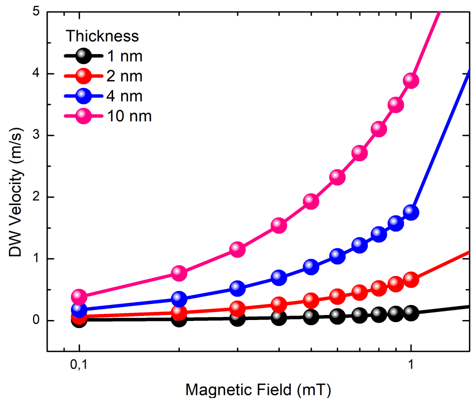
The DW creep motion is often described by the universal creep law equation which is written as [13, 24]:

$$v = v_0 \exp\left[-\left(\frac{T_{dep}}{T}\right)\left(\frac{H_{dep}}{H}\right)^{1/4}\right] \tag{1}$$

To verify whether creep motion can explain the obtained low-field velocities, we fitted said velocities to equation (1) by plotting $\ln(v)$ with $H^{-1/4}$. This plot can be seen in Fig. 3. The linear behavior of $\ln(v)$ can be seen as the low-field velocities corresponding to the creep law equation. In a previous study, the creep law equation is found to be able to describe the DW velocities well up to higher applied fields [13]. In this study however, the creep law equation begins to fall apart even at an applied field of 2 mT. The creep law equation is usually only valid in the low-field driving regime ($H << H_{dep}$) [24]. With the creep equation falling apart at an applied field of 2 mT, it might be safe to assume that the depinning field for this study is located between 1 and 2 mT. However, there's a possibility that the depinning field is in fact located at a point much lower than 0.1 mT, and the linearity of $\ln(v)$ at the 0.1-1 mT range is simply a coincidence that resembles the creep law equation. That being said, the observed correspondence cannot be simply ignored.



(a)



(b)

Fig. 2. (a) Profile of the DW velocity with respect to the applied driving field for varied nanowire strip thicknesses. (b) Profile of the DW velocity on the low-field driving regime (0.1-1 mT).

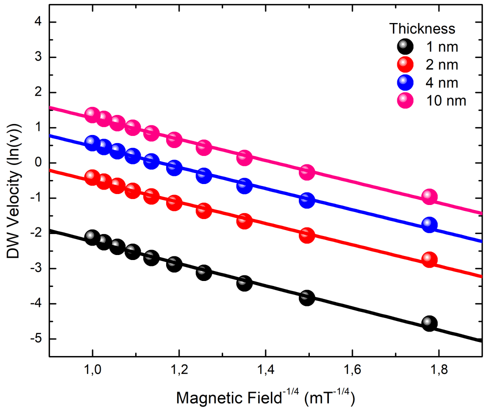
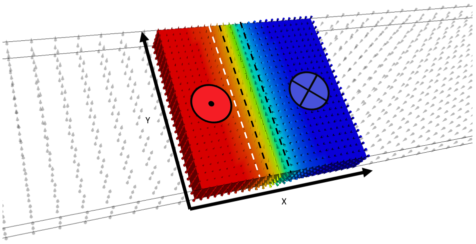


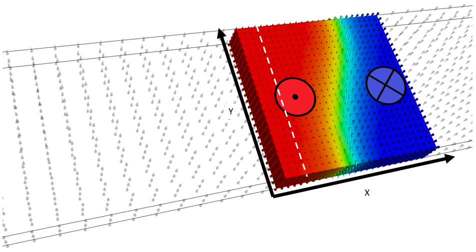
Fig. 3. Plot of the natural logarithm of the low-field regime DW velocity versus the scaled applied external field fitted to the creep law equation given by Equation (1).

3.2 Domain wall structure

Next, we investigate the characteristics of the DW structure at the low-field pulse regime as it exhibits creep motion. Figure 4a shows the DW imaging of the 10 nm thick nanowire at



(a)



(b)

Fig. 4. Domain wall structure imaging of the 10 nm thick nanowire strip at (a) 1 mT and (b) 18 mT. The black dashed lines on (a) represent the width of the DW and the white dashed lines represent the original position of the DW relative to Fig. 1.

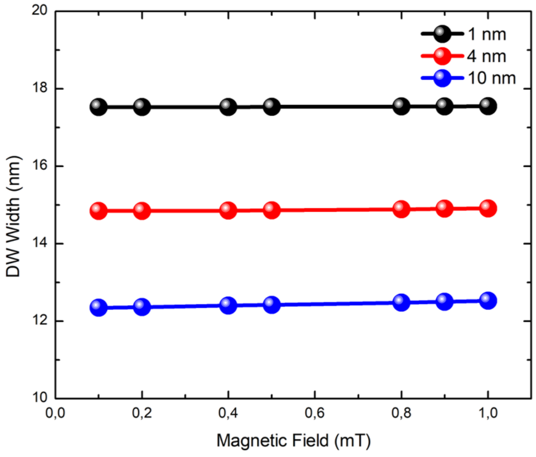


Fig. 5. Plot of the calculated DW width versus the applied field pulse at the low-field regime for various thickness variations.

a field pulse of 1 mT and just before the pulse begins to lower. From the imaging, it can be seen that the DW does not experience any visible structural changes. This is to be expected, as changes to the DW structure are usually observed at higher fields near or above the Walker breakdown field [25, 26]. The lack of changes to the DW structure can also be observed at lower fields and other nanowire thickness variations.

To further investigate the characteristics of the DW structure, we turn our attention to the opposite end of the spectrum, that is the high-field regime beyond the Walker breakdown field. Figure 4b shows the DW imaging of the 10 nm thick nanowire at a field pulse of 18 mT and just before the pulse begins to lower. Unlike the previous DW imaging at the low-field regime, a visible change to the DW is observed in the form of a bend. Observed alongside with this bend is the complete re-orientation of the DW magnetization, with some parts of the DW facing the -y axis and other parts to be in a tilting angle between the -x and -y axis. Since the imaging of Fig. 4b is taken at a field pulse higher than the Walker breakdown field, a change to the DW structure is to be expected as previous research had observed [25, 26]. Interestingly, the DW structure change observed here is very different to what was observed on IMA nanowires. Despite the bending of the DW and the re-orientation of its' magnetization, the structure itself is observed to be intact and does not change into that of a vortex or anti-vortex wall. For the nanowire strips with lower thickness variation, the bending of the DW is less pronounced. However, the magnetization of the DW can be seen tilting from its' original orientation.

In addition to the structure of the DW, we also investigated the DW width at the low-field pulse regime. We determined the width of the DW by numerically calculating the full width-half maximum (FWHM) of the DW magnetization data. Figure 5 shows the plot of the calculated DW width versus the applied low-field pulse for the 1, 4, and 10 nm thick nanowires. At the low-field pulse regime, it can be seen from Fig. 5 that the DW width is not affected by the increasing applied field pulse. On the other hand, the thickness of the nanowire strip seems to have an effect, with thicker nanowires having smaller DW widths. As previously stated, the structure of the DW in this study is that of a Bloch wall. A possible cause as to why thicker nanowires have smaller DW widths may again come from the fact that Bloch walls energetically favor thicker or bulk structures [19, 23], leading to lower DW energies and smaller DW widths overall.

4 Conclusion

We have successfully conducted micromagnetic simulations of CoFeB nanowire strips with perpendicular anisotropy and varying thicknesses to investigate the dynamics of the DW and the creep motion that's exhibited. The DW velocity overall is observed to be much lower when compared to nanowire strips with in-plane anisotropy. The velocity and Walker breakdown field is also observed to have an opposite trend than the in-plane nanowires. At the low-field pulse regime of 0.1-1 mT, it's observed that the DW is moving with a very slow velocity that corresponds to the creep motion. When the low-field velocities are fitted to the creep law equation, it shows a linear behavior which can be understood as an agreement with the creep motion.

The structure of the DW is observed to be unaffected on the low-field regime. On the other hand, a visible change to the DW structure can be observed on the high-field regime beyond the Walker breakdown field. However, unlike the generally observed DW structure change into a vortex or anti-vortex wall, the structure change observed here is in the form of a bend and re-orientation of the DW magnetization. The DW width is also observed to be unaffected by the increasing applied field pulse at the low-field regime. It is however, affected by the thickness of the nanowire, with thicker nanowires having smaller DW widths.

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