Study of Domain Wall Propagation in FePt and FePd Nanowires Driven by Sub-nanosecond Pulse of Magnetic Field by Micromagnetic Simulation

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Abstract. In this study, we investigated the domain wall propagation behavior in FePt and FePd nanowires by micromagnetic simulation based on LLG equation. A rectangular shape nanowire model was generated with a fixed length of 2000 nm and varied thicknesses of 2.5 nm and 5 nm. The wire widths were varied of 50 nm, 100 nm, and 150 nm. The 500 ps length of magnetic-pulse was applied in-plane to a transverse type domain wall. We observed the Walker Breakdown field ($H_{WB}$), which means the maximum domain wall velocity before it was abruptly decreased. The transverse DW structure was maintained below $H_{WB}$ while vortex/antivortex wall structure was formed in the higher magnetic field. Interestingly, the $H_{WB}$ value of both FePt and FePd were decreased as the width and thickness of the nanowires increased. We have also analyzed the changing of the demagnetization and exchange energy for the domain wall structure transition from transverse wall to vortex/ anti-vortex wall.

Keywords: micromagnetic, nanowire, Walker Breakdown, domain wall, transverse wall, vortex wall.

1. Introduction

The new effective data storage devices such as Magnetic Random Access Memory (MRAM) have become one of the interesting development non-volatile memory technology that was trying to establish for electronics equipment with the utilization of electron spin [1]. The spin direction manipulation process provides a new paradigm for data storage processes in the development of spintronics-based technology [2,3]. Another important invention idea was the Racetrack Memory which was developed by Stuart Parkin from IBM [4,5]. In perpendicular magnetic recording, magnetic bits were built perpendicularly to the magnetic thin layer film. Depending on the external field, DW can move with or without changing its inner structure along on nanowire [6,7]. Materials that have the properties of perpendicular magnetic anisotropy (PMA) are expected to reduce the superparamagnetic effect and become a important improvement for the development of technology by utilizing the dynamics of domain-wall magnets, considering the needs for storage media that requires the development of devices that are smaller, faster, and more efficient [8].
Several studies of thin film layers on FePt and FePd alloys show very large uniaxial magnetocrystalline anisotropy and can be applied to an anisotropic axis perpendicularly to the film plane. These properties made it suitable for applications in particular high-density magnetic recording media [9,10]. To correlate the film microstructure with its magnetic properties, it should be considered with typical structural defects [11]. The crystallographic structure of FePd undergoes tetragonal distortion induces strong PMA (Perpendicular Magnetic Anisotropy) in a thin layer parallel to the film plane [12,13].

In this study, the materials used are alloy materials of FePt and FePd nanowires with rectangular geometries that are varied in thickness and width. Then, it will be observed the characteristics of the domain-wall propagations when triggered with a magnetic field that is varied when triggered with a magnetic field pulse for 0.5 ns. Domain wall will move with a certain speed until it reaches the field of Walker Breakdown ($H_{WB}$). This method can be carried out with a micromagnetic simulation so it can be further analyzed the influence of magnetic energy on the speed and structure of the domain wall.

2. Simulation Method
The simulation process of domain-wall propagation was performed by using public software Object Oriented Micromagnetic Framework (OOMMF) based on the LLG equation (Landau-Lifshitz Gilbert) [14,15]. This domain-wall propagation simulation used a thin rectangular geometry of nanowire. A magnetic pulse of 500 ps length was applied on the nanowire in the x-direction. We have varied the magnitude of a magnetic pulse to drive DW along the nanowire. The wire sizes used a fixed length ($L$) = 2000 nm, thickness ($t$) 2.5 nm and 5 nm, and width varied to 50 nm, 100 nm, and 150 nm. The cell size used was $5 \times 5 \times t$ nm$^3$ where the $t$ value indicates the thickness of the wire and the damping constant value was $\alpha = 0.05$. The material parameters of FePt using the magnetization saturation $M_s$, exchange constant $A$, and anisotropy constant $K$ of $1.14 \times 10^6$ A/m, $1.0 \times 10^{-11}$ J/m, and $6.6 \times 10^6$ J/m$^3$, respectively [16]. While, The parameter of FePd the magnetization saturation $M_s$, exchange constant $A$, and anisotropy constant $K$ of $1.03 \times 10^6$ A/m, $6.9 \times 10^{-12}$, and $2.6 \times 10^5$ J/m$^3$, respectively [17]. The geometry of the nanowire form used in this simulation is shown in Figure 1 as the initial transverse wall (TW) was located at the center of the nanowire.

![Figure 1](image)

**Figure 1.** The geometry and dimension of FePt and FePd nanowire with a transverse wall structure at the center of a nanowire. A 500 ps time-length magnetic pulse was applied along the nanowire. The color bar is the magnetization direction.

3. Results and discussion
The domain-wall propagation is a change of the domain-wall position along the nanowire. When a magnetic field pulse was given, the position of the domain-wall would change, which means that the amplitude variation by an active pulse was expressed of the magnitude of the external magnetic field. Each of materials was given an external magnetic field ranging from $B = 20$ Oe to $B = 300$ Oe. The
domain-wall velocity profile will increase linearly with increasing low external magnetic field as shown in Fig. 2. This velocity will continue to increase until it reached the maximum value or critical field known as the Walker Breakdown [18,19]. Meanwhile, after a larger $H_{WB}$, the domain-wall velocity will be decreased. It is observed that the domain wall velocity decrease as the thickness and width of the geometry of the nanowire increased. This results exhibited a similar trend to other reported results. On the other hand for FePt material, when the thickness is 5 nm, the Walker Breakdown phenomenon is observed by giving a larger external magnetic field or more than 250 Oe. But interestingly, the change of the domain-wall structure occurred when the external magnetic field was giving around 9 Oe. It might be caused by the different anisotropy properties of those materials. Table 1 showed $H_{WB}$ value for the width and thickness variation for FePt and FePd nanowires. The table showed that the DW velocity was sensitive to the thickness rather than the width of the nanowire.

![Figure 2](image_url)

**Figure 2.** DW velocity as the magnitude of the magnetic pulse with the width and thickness variation for (a) FePt and (b) FePd nanowires. The critical magnetic field is known as the Walker breakdown field ($H_{WB}$) denoted by dotted-line.

**Table 1.** The Walker breakdown field of FePt and FePd nanowires concerning the width and thickness variation.

| Material | Thickness | Width | $H_{WB}$ | Material | Thickness | Width | $H_{WB}$ |
|----------|-----------|-------|----------|----------|-----------|-------|----------|
| FePt     | 2.5 nm    | 50 nm | 174 Oe   | FePt     | 2.5 nm    | 100 nm| 133 Oe   |
|          | 150 nm    |       | 123 Oe   |          | 150 nm    |       | 154 Oe   |
|          | 5 nm      | 50 nm | 148 Oe   | FePd     | 5 nm      | 100 nm| 101 Oe   |
|          | 150 nm    |       | 112 Oe   |          | 150 nm    |       | 93 Oe    |
Then, we also observed the change of the inner structure based on the simulation results as shown in Fig. 3. It shows the magnetization images of the domain-wall propagation in the given thickness of \( t = 5 \) nm and width of \( W = 100 \) nm. The results showed that when the external magnetic field is below the Walker Breakdown field \( (B = 100 \text{ Oe}) \), the domain-wall structure still maintains the transverse wall structure, whereas the external magnetic field is greater than the Walker Breakdown field \( (B = 250 \text{ Oe}) \), the domain-wall structure changed from transverse to the vortex / antivortex-wall structures as shown by Figure 3. For FePt material, when the thickness of nanowire is 5 nm the domain-wall structure was changed from the transverse wall into the antivortex-wall because the DW core nucleation appeared and by the difference in time of several seconds will be followed by the appearance of nucleated vortex-wall when \( t = 1.3 \text{ ns} \). This nucleated DW core was starting from the top and bottom edge of the nanowire. When the time took a longer than 1.6 ns it will be followed by the disappearance of the nucleated anti-vortex wall, which means the magnetic field pulse returns to zero.

![Figure 3](image.png)

**Figure 3.** The DW structure of FePt and FePd nanowires for the case thickness \( t = 5 \) nm and width \( W = 100 \) nm. The structure shows a transverse wall below \( H_{WB} (H = 100 \text{ Oe}) \) and antivortex wall after \( H_{WB} (H = 250 \text{ Oe}) \).

Furthermore, to find out the contribution of energy density involved in the nanowire, it can be represented by the changing of demagnetization energy (red color) and exchange energy (blue color) as shown in Figure 4. The demagnetization energy density for both materials was dominant than the exchange energy. The larger width and thickness in the nanowire geometries produced higher energy.
density. When the external magnetic field was given, the demagnetization energy will increase followed by increasing nanowire volume. However, for external magnetic fields around the Waker Breakdown field, the demagnetization energy density begins to decrease, which means that the interaction between magnetic moments is not uniform anymore or anti-parallel so that the domain-wall structure will change from transverse-wall to the vortex/antivortex wall. On the other hand, the energy exchange will gradually increase, which means there is a change in the domain-wall structure to the vortex/antivortex-wall where the direction of spin interaction of the neighboring magnetization is become anti-parallel or get into maximum energy. Compared to the DW velocity of FePt and FePd in Fig 2, the energy density also did not abruptly decreased as it was found in Permalloy [20] but slowly decreased as the magnitude of magnetic pulse increased.

![Energy Density vs Magnetic Field](image)

**Figure 4.** Magnetic energy properties of (a) FePt and (b) FePd nanowires for the case thickness $t = 5$ nm and width $W = 100$ nm. The energy curve shows an increasing exchange energy and a decreasing demagnetization energy for magnetic field above $H_{WB}$.

4. **Conclusion**

In this study, we have observed the characteristics of the domain wall propagation in the FePt and FePd nanowires by micromagnetic simulation. When the external magnetic field increased, the velocity of the domain-wall will remain increased until the critical field ($H_{WB}$). This critical field also relies on nanowire geometries. The thicker and wider the nanowire is, the $H_{WB}$ field will be decreased. Below the critical field, the domain transverse-wall structure was observed. When the external magnetic field has exceeded the WB field, the domain-wall structure was changed from transverse to vortex/antivortex-wall. During propagation, the demagnetization energy increased followed by the increasing of the external magnetic field before reaching the $H_{WB}$ field so it would be maintained as the transverse-wall structure. Meanwhile, after the $H_{WB}$ field, the vortex/antivortex structure has appeared from the edges of nanowire as followed as increasing the energy exchange.

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