Observation of the domain wall propagation in CoFe and CoFeB nanowires driven by sub-nanosecond magnetic pulse using micromagnetic simulation

S Hawibowo, C Kurniawan and D Djuhana

- Department of Physics, Faculty of Mathematics and Natural Sciences (FMIPA), Universitas Indonesia, Kampus UI Depok, Depok 16424, Indonesia
- Research Center for Physics, Indonesian Institute of Sciences (LIPI), Gedung 440–442 Kawasan Puspiptek Serpong, Banten 15314, Indonesia

Corresponding author’s e-mail: dede.djuhana@sci.ui.ac.id

Abstract. In this study, we have observed the domain wall (DW) propagation in CoFe and CoFeB nanowires driven by sub-nanosecond magnetic pulse using micromagnetic simulation approach. The length of the nanowire is 2000 nm, the widths are varied of 50, 100, and 150 nm, and the thicknesses are 2.5 and 5.0 nm. The simulation was performed using a rectangular cell size of 5x5x1 nm with t is the thickness of the nanowire and the damping factor is 0.05. The sub-nanosecond magnetic pulse length of 0.5 ns was used to move DW through the nanowire. We found that the DW velocity increased as the magnitude of magnetic pulse increased then abruptly decreased which known as the Walker Breakdown (H_w). The transverse type DW structure is observed below the H_w field while vortex/anti-vortex wall structure was formed above H_w. We found that the H_w value of CoFe and CoFeB decreased as the width and thickness of the nanowire increased. The increasing of nanowire thickness also caused the velocity reduction of DW. The energy competition between exchange and demagnetization energy contributed to the DW structure during propagation. The exchange energy is higher than the demagnetization energy as the formation of vortex/anti-vortex wall.

1. Introduction
The domain wall-based memories are exciting topic issue that emerged from the proposal of racetrack memory which introduced by Parkin et al. [1] and Parkin [2]. High-speed racetrack memory could be achieved by propagating the domain wall (DW) through the nanowire using the magnetic field, spin-polarized current, or electrical field [3–7]. However, the DW density was relatively lower if we used a standard longitudinal or in-plane magnetization direction. The superparamagnetic effect was also raised in the in-plane magnetization type that can erase the data as the nanowire size decreased [8]. Depending on the external field, DW moves with or without changing its inner structure along on nanowire [3,9]. The perpendicular magnetization type materials were introduced to enhance its performance especially for achieving the smaller, faster, and efficient data storage system [8]. One of the high perpendicular magnetic anisotropic was CoFe-based materials which have been studied by some researchers both in experimental and simulation approaches [10–12]. Hirohata et al. [13] studied a multilayer CoFeB/MgO which has a high spin polarization and low damping effect so that potentially can be applied as high-density data storage.

In this study, DW propagation characteristics in CoFe and CoFeB nanowires driven by sub-nanosecond magnetic pulse was observed using micromagnetic simulation. The influence of parameter variation such as wire width and thickness to the DW dynamics was also investigated. The maximum DW propagation speed under a specific magnetic field called a Walker breakdown point (H_w) was examined to improve an understanding in the formation of DW structure and the energy included during propagation.
Figure 1. The geometry and dimension of CoFe and CoFeB nanowire with a transverse wall structure at the center of nanowire. A 500 ps time-length magnetic pulse is applied along the nanowire. The color bar is the magnetization direction.

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

2. Simulation procedure
The simulation model of nanowires was using a fixed length $L$ of 2000 nm and varied widths $W$ of 50, 100, and 150 nm, and thicknesses $t$ of 2.5 and 5 nm. The material parameters of CoFe using the magnetization saturation $M_s$, exchange constant $A$, and anisotropy constant $K$ of $1.4 \times 10^6$ A/m, $1.3 \times 10^{-11}$ J/m, and $2.7 \times 10^{-9}$ J/m, respectively [14]. While, the parameter of CoFeB the magnetization saturation $M_s$, exchange constant $A$, and anisotropy constant $K$ of $8.75 \times 10^5$ A/m, $1 \times 10^{-11}$, and $5.2 \times 10^{-9}$ J/m, respectively [15]. The cell size used in the simulation was $2.5 \times 2.5 \times t$ nm with $t$ is the wire thickness and the damping factor was $\alpha = 0.05$. The DW propagation simulation of CoFe and CoFeB nanowires was performed by public micromagnetic solver OOMMF based on the Landau-Lifshitz-Gilbert (LLG) equation [16,17]. In this simulation, the initial transverse wall (TW) was located at the center of the nanowire, as illustrated in figure 1. Then, a very short magnetic pulse of 500 ps length was applied on the nanowire in x-direction. For the purpose of this study, we have varied the magnitude of magnetic pulse to drive DW along the nanowire.
Table 1. The Walker breakdown field of CoFe and CoFeB nanowires with respect to the width and thickness variation

| Thickness (nm) | Width (nm) | 2.5 | 5 | 100 | 150 | 50 | 100 | 150 |
|---------------|-----------|-----|---|-----|-----|----|-----|-----|
| H_{wb} (Oe)   | CoFe      | 194 | 151| 144 | 162 | 138| 126 |
|               | CoFeB     | 219 | 197| 191 | 165 | 138| 129 |

Figure 3. DW structure of CoFe and CoFeB nanowires for thickness t = 5 nm, width W = 100 nm. The structure shows a transverse wall below $H_{wb}$ (100 Oe) and anti-vortex wall after $H_{wb}$ (250 Oe)

3. Results and discussion

With varying the magnitude of magnetic pulse, the magnetic pulse driving the DW along the nanowire is observed. DW velocity for CoFe and CoFeB nanowires to the magnitude of magnetic pulse with the width and thickness variation were presented in figure 2. DW velocity was determined from the change of DW position and time during the magnetic pulse was switched on [18]. In this figure, it is found that DW velocity increased to a certain value and decreased as the magnitude of the magnetic pulse increased. The decrease of the DW velocity was known as Walker breakdown ($H_{wb}$) [4,19]. It is found that the DW velocity decreased as the thickness increased and relatively constant as the width of nanowire increased. Then, it is observed that the $H_{wb}$ decreased as the thickness and width of nanowire increased. The results exhibited a similar trend to other reported results [3,5,7]. Interestingly, the DW velocity of CoFe and CoFeB nanowire did not abruptly decreased as it was found in Py [3] but slowly decreased as the magnitude of magnetic pulse increased. The DW velocity in CoFe showed higher than CoFeB nanowire. In a sense, the anisotropy properties of material have affected the DW velocity. Table 1 shows $H_{wb}$ values for the width and thickness variation for CoFe and CoFeB nanowires. The table shows that the DW velocity was sensitive to the thickness rather than the width of nanowire.
Figure 4. Magnetic energy properties of (a) CoFe and (b) CoFeB nanowires for thickness \( t = 5 \) nm and width \( W = 100 \) nm. The energy curve shows increasing exchange energy and decreasing demagnetization energy for magnetic field above \( H_{WB} \).

Furthermore, the DW structure dynamics around \( H_{WB} \) was also observed. For example, it is presented the DW structure of CoFe and CoFeB for the case of thickness \( t = 5 \) nm and width \( W = 100 \) nm. For sample case below and above \( H_{WB} \) the magnetic field was 100 Oe and 250 Oe, respectively, as shown in figure 3. The DW structure exhibited a transverse structure below \( H_{WB} \), while anti-vortex structure is formed above the \( H_{WB} \). This nucleated anti-vortex is seen to move cross the width of the nanowire and producing a turbulent motion of DW leading to lower the average domain wall velocity [20].

The changing of DW structure from transverse to vortex/anti-vortex structure can be explained by the energy density contributed to the system. We have plotted a sample case of the energy density changing from the CoFe and CoFeB nanowire system around \( H_{WB} \) value with wire width of 100 nm and thickness of 5 nm as shown in figure 4. We can see that the demagnetization and exchange energy are dominant in the process of DW formation. Generally, the exchange energies are lower below \( H_{WB} \) and increases as the magnetic field increases at above \( H_{WB} \) value. On the other hand, the demagnetization energies are higher for magnetic field below \( H_{WB} \) and decreases at above \( H_{WB} \). Compared to the magnetization evolution image in figure 3, we can see that it is related to the DW structure in the nanowire system both CoFe and CoFeB materials. The increasing of energy exchange around \( H_{WB} \) is related to the vortex/anti-vortex DW formation during propagation. Meanwhile, the decreasing of demagnetization energy around \( H_{WB} \) is related to the spin interaction of the neighboring magnetization so that the anti-parallel magnetization from vortex type wall produces less demagnetization energy. The geometry of the nanowires were also influenced the energy density. The larger width and thickness in the nanowire geometries produced higher energy density.

4. Conclusions

In this study, we have observed DW propagation characteristics in CoFe and CoFeB nanowires driven by sub-nanosecond magnetic pulse using micromagnetic simulation. The influence of parameter variation such as wire width and thickness to the DW dynamics was also investigated. We found the DW velocity decreased as the thickness increased and relatively constant as the width of nanowire increased. We also observed the \( H_{WB} \) decreased as the thickness and width of nanowire increased. Interestingly, the DW velocity of CoFe and CoFeB nanowire did not abruptly decrease, but slowly decreased as the magnitude of magnetic pulse increased. The DW velocity in CoFe showed higher than CoFeB nanowire. In a sense, the anisotropy properties of the material have affected the DW velocity. The exchange energies were lower below \( H_{WB} \) and increased as the magnetic field increases at above \( H_{WB} \) value. On the other hand, the demagnetization energies were higher at the magnetic field below \( H_{WB} \) and decreased at above \( H_{WB} \). The increasing of energy exchange around \( H_{WB} \) was related to the vortex/anti-vortex DW formation during propagation.
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