Investigation of Notch Dept Effect on Domain Wall Depinning in Ferromagnetic Nanowires by Micromagnetic Simulation

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Abstract. Utilization of topological nanostructure such as magnetic domain wall (DW) as a future generation of non-volatile memory as racetrack memory has been attracted more researchers due to potential to achieve higher speed of data read/writing and capacity. However, completed understanding of DW dynamics was still need to be improved by advanced analysis from the theoretical/simulation or experimental methods. In this study, the effect of geometrical notch dept on domain wall depinning in Permalloy (Py) nanowires by micromagnetic simulation method have been investigated. The varied double notch dept from 10 to 90 nm in 200 nm of wire width were used and the transverse type DW was triggered by nanosecond current pulse to observe the critical depinning current (\(J_d\)). It is observed that the depinning current was increased as the notch dept increases. However, the magnitude of \(J_d\) have a maximum values for all notch length variation. The increasing of notch length has shifted the maximum \(J_d\) to the larger notch dept values. This behavior indicated that the optimum notch design was needed to obtain higher speed and lower depinning energy in the development of domain wall based devices.

Keywords: Micromagnetic, domain wall, depinning, notch dept, nanowire.

1. Introduction
Due to the potential application as future non-volatile memories and logics, utilization of topological nanostructure such as magnetic domain wall (DW) has been an attractive research interest for the last decades [1-4]. The purpose of this research topic is to achieve higher speed of data read/writing and capacity. Another objective one was to continue the Moore’s law in storage media [5]. One of the interesting proposals about magnetic non-volatile memory that utilized DWs is the concept of racetrack memory by Parkin in 2008 [6, 7]. The racetrack memory concept uses the train of DWs that move simultaneously on the long magnetic media such as 2D or 3D nanowires by electrical current or magnetic field. Previous researches show that the accurate and faster DW creep motion could be achieved by spin polarized current better than by magnetic field [8-10]. However, completed
understanding of DW dynamics was still need to be improved by advanced analysis from the theoretical/simulation or experimental methods.

To optimally control the DW in the nanowire, there are some focuses on the utilization of geometrical notch as an artificial pinning potential. Most of the studies were intended to explain the dynamics of DW structure when passes or move out from the notch [11-14]. However, there is still a lack of discussion about the geometrical structure of notch in the nanowires. Piao et al. has studied the effect of asymmetrical notch in nanowire to obtain selective spin behavior using alternate magnetic field [15]. Gao et al. also studied the effect of asymmetrical notch effect to the DW random behavior during depinning out from the notch by experimental measurement and micromagnetic simulation [16]. Our previous studies explained the effect of notch length to the DW depinning behavior by electrical current and magnetic field pulse [17, 18].

This study has investigated the effect of geometrical notch dept on DW depinning driven by nano-second pulse current in Permalloy (Py) nanowires by micromagnetic simulation method. The critical current magnitude called depinning current ($J_d$) was observed for every notch dept parameter and the influenced depinning time ($t_d$) is discussed.

2. Micromagnetic simulation
A long and thin rectangular shape nanowire was modeled in this simulation. The length and thickness of the wire were 2000 nm and 5 nm, respectively. Double symmetrical triangular notch was placed at the center of the wire as shown in Figure 1. The varied double notch dept ($d$) from 10 to 90 nm and notch size ($s$) of 50, 100, and 200 nm in 200 nm of wire width were used in the simulation. Typical Permalloy material parameters are used as an input, such as magnetization saturation $M_s = 8 \times 10^5$ A/m, exchange constant $A = 13 \times 10^{-12}$ J/m, and zero magnetocrystalline anisotropy [19].

The initial transverse type domain wall (DW) was placed at the notch center with head-to-head domain structure. The DW was released in the ground state condition for 1 ns before the electrical current pulse injected for 1 ns on the $x+$ direction. The raising and lowering rate of current pulse was about 0.01 ns. The varied magnitude of the spin polarized current was performed to investigate the depinning current ($J_d$) that defined as the latest part of DW move out from the notch area. The electrical current pulse and the spin current direction are also illustrated in the Figure 1.

The simulation procedure was performed by micromagnetic simulation software package OOMMF based on the Landau-Lifshitz-Gilbert (LLG) Equation [20-22] with the spin transfer torque extension as provided by IBM [23]. The dynamic of current induced domain wall was described by the modified LLG equation as follows,

$$\frac{d\mathbf{m}}{dt} = -\gamma \mathbf{m} \times \mathbf{H}_{\text{eff}} + \alpha \mathbf{m} \times \frac{d\mathbf{m}}{dt} - (\mathbf{u} \cdot \nabla) \mathbf{m} + \beta \mathbf{m} \times [(\mathbf{u} \cdot \nabla) \mathbf{m}]$$

(1)

where $\alpha$ is the Gilbert damping constant, $\gamma$ is the gyromagnetic ratio, and $\beta$ is non-adiabatic constant. The spin drift velocity $\mathbf{u}$ is defined as $\mathbf{u} = P J_s \mu_B / e M_s$, where $J_s$ is the electrical current density, $P$ is the spin polarization, and $\mu_B$ is Bohr magneton. The ratio of $\beta/\alpha$ was set to be 4 with $\alpha$ damping constant of 0.01. The dimension of the finite difference cuboid unit cell was $5 \times 5 \times 5$ nm$^3$, with respect to the Permalloy exchange length value of 5.6 nm [5].
Figure 1. Geometry of the rectangular Permalloy nanowire with symmetrical triangular notch. The initial transverse type DW and head-to-head spin structure was defined. The current pulse was injected for 1 ns in the x+ direction and the amplitude represent the current magnitude. Color disks represent the spin direction in xy-axis.

3. Results and discussion
The effect of notch dept to DW depinning current ($J_d$) is showed in Figure 2. It is observed that the depinning current increased as the notch dept increases. However, the magnitude of $J_d$ have maximum values for all notch length variation. The increasing of notch length ($s$) has shifted the maximum $J_d$ point to the larger notch dept values. For notch length of 50 nm, the maximum value of $J_d$ is obtained at notch dept ($d$) of 40 nm with the current value of $1.43 \times 10^{12}$ A/m$^2$. For notch length of 100 and 200, local maxium $J_d$ value are obtained at notch dept of 50 nm and 70 nm, respectively. This behavior shows that generally the notch dept value is proportional to pinning strength at nanowire. The pinning potential is needed for controlling the DW motion through the wire so that the read and write process for the non-volatile memory application can be done precisely. Therefore, the accurate process of notch shaping process is crucial in the design of nanowire based DW devices [24].

Figure 2. The effect of notch dept ($d$) to depinning current density ($J_d$) with respect to notch size ($s$) of 50 nm, 100 nm, and 200 nm represent with red-rectangle, blue-circle, and magenta-triangle, respectively. All simulations were performed in non-adiabatic regime with $\beta/\alpha$ ratio of 4.
Figure 3. The dynamic of domain structure during depinning process at local maximum value of $J_d$ at different notch size ($s$), the antivortex DW structure is formed during depining at (a) $s = 50$ nm, $d = 40$ nm, but kept transverse at (b) $s = 100$ nm, $d = 50$ nm, and (c) $s = 200$ nm, $d = 70$ nm.

The Figure 3 displayed the dynamic of domain structure during depinning process at local maximum value of $J_d$ at different notch size ($s$). It is showed that the DW depinning motion was accompanied by changing DW structure to anti-vortex for smaller notch size but kept the transverse structure for larger notch size, which are agreed with our previous results [18]. At first nanosecond after the DW release without external current, the DW structures are shown to be asymmetric compared to notch center. This affected by the asymmetrical energy landscape at certain notch geometry [3]. Then the nanosecond current pulse was applied to the DW and depicted that the DW was shifted to the $x+$ direction smoothly until depinned out from the notch before the applied current current was removed. These phenomena are correlated to the DW depinning speed which represent by depinning time ($t_d$) measured from the first time electrical current was applied until DW edge move out from the notch completely.

Figure 4. The effect of notch dept ($d$) to DW depinning time ($t_d$) with respect to notch size ($s$) of 50 nm, 100 nm, and 200 nm represent with red-rectangle, blue-circle, and magenta-triangle, respectively.
The depinning time \( (t_d) \) as the effect of notch dept is displayed in Figure 4. It is showed that in the \( s \) value of 50 nm, the \( t_d \) values are fluctuated as the increasing of notch dept. The depinning time are swinging from the value of 0.8 ns to 1.8 ns for \( d = 20 \) nm and 50 nm, respectively. However at larger \( s \), the \( t_d \) values are slightly decreased at medium size of \( d \) (around 30 or 40 nm) and increased at larger notch dept. The \( t_d \) values are sharply increased for \( s = 100 \) nm at notch dept larger than 40 nm. But for \( s = 200 \), the changing of \( t_d \) values at \( d \) larger than 30 nm are relatively slightly increases and still around the range of 1 ns. The simulation results above showed that the predictive DW dynamics at specific notch size are important to produce high reliability DW devices. This behavior also indicated that the optimum notch design was needed to obtain higher speed and lower depinning energy in the development of domain wall based devices.

4. Conclusion
In this study, the effect of geometrical notch dept on domain wall depinning in Permalloy (Py) nanowires by micromagnetic simulation method have been investigated. The varied double notch dept were used and the transverse type DW was triggered by nanosecond current pulse to observe the critical depinning current \( (J_d) \). It is observed that the depinning current was increased as the notch dept increases. However, the magnitude of \( J_d \) have local maximum values for all notch length variation. The increasing of notch length has shifted the maximum \( J_d \) to the larger notch dept values. This behavior shows that generally the notch dept value is proportional to pinning strength at nanowire. It is also showed that the DW depinning motion was accompanied by changing DW structure to anti-vortex for smaller notch size but kept the transverse structure for larger notch size. However, the fluctuated values of depinning time as the notch dept increased made the DW dynamic become complicated. This behavior indicated that the optimum notch design was needed to obtain higher speed and lower depinning energy in the development of domain wall based devices.

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