Micromagnetic analysis of current-driven domain wall motion of multi-bit in a nanowire with perpendicular magnetic anisotropy

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Abstract. The current-driven domain wall motion of a multi-bit in a magnetic nanowire with perpendicular magnetic anisotropy has been analyzed by performing a micromagnetic simulation. The multi-bit motion is determined by the applied current density and the non-adiabatic spin torque parameters, which is similar to the current-driven domain wall motion of the single wall. Consequently, it was found that there are two modes in the multi-bit motion: (a) the bit length remains constant and (b) the bit length varies or the bit vanishes in the nanowire. It was found that these modes of the multi-bit motion can be classified by the critical current density or Walker breakdown for the single wall motion in a magnetic nanowire with perpendicular magnetic anisotropy.

1. Introduction
Current-driven domain wall motion (DWM) in nanowires has attracted considerable attention[1]-[3] and new devices based on this principle have been proposed by some researchers[4]. In order to realize such devices, it is necessary to reduce the critical current density required to move a domain wall in a nanowire. Current-driven DWM in a nanowire with perpendicular magnetic anisotropy (PMA) is expected to have a lower critical current density than current-driven DWM in a nanowire with in-plane magnetic anisotropy[5]. Moreover, the DWM memory with PMA is anticipated to achieve ultrahigh areal recording densities. However, the DWM of a multi-bit in a nanowire has not been discussed. A micromagnetic simulation of current-driven DWM of a multi-bit in a nanowire with PMA was performed in this study.

2. Calculation method
The current-driven DWM of a multi-bit in a magnetic nanowire with PMA has been analyzed by utilizing the micromagnetic simulation in this study[6][7]. Figure 1 shows the calculation model for a multi-bit in a PMA nanowire. The nanowire was assumed to be 2000 nm long and the infinite boundary condition was imposed at the nanowire edges along the longitudinal direction. The magnetostatic field derived from the semi-infinite nanowire outside the calculation region is taken into account. The nanowire is 100 nm wide and 5 nm thick. The calculation region is divided into rectangular parallelepiped cells with dimensions $4 \times 4 \times 5$ nm$^3$. The nanowire with PMA was assumed to have six bits and seven walls and the bit length was assumed to be 200
The schematic illustration shown in Fig. 1 indicates that initially the seven Bloch walls are alternately magnetized up and down. The equilibrium magnetization distribution was obtained by solving the following Landau–Lifshitz–Gilbert equation:

\[
\dot{M} = -\gamma M \times H_{\text{eff}} + \frac{\alpha}{M_s} M \times \dot{M} - b_1 (J \cdot \nabla)M + c_1 M \times (J \cdot \nabla)M, \quad b_1 = \frac{\mu_B P}{e M_s}, \quad c_1 = \beta b_1, \quad (1)
\]

where \(M\) is the local magnetization, \(\gamma\) is the gyromagnetic ratio, \(H_{\text{eff}}\) is the micromagnetic effective field, \(\alpha\) is the Gilbert damping constant, and \(\beta\) is the non-adiabatic spin-torque parameter. The initial equilibrium magnetization state preserved the seven Bloch walls. Each domain wall was indexed to be \(W_1, W_2, \ldots, W_7\) as shown in Fig. 1.

In order to simulate multi-bit motion, the equation (1) of Landau–Lifshitz–Gilbert equation with a spin transfer torque term was utilized. The magnetic nanowire has a saturation magnetization of 600 emu/cm³, an exchange stiffness constant of \(1.0 \times 10^{-6}\) erg/cm, an anisotropy field of 14 kOe and a Gilbert damping constant \(\alpha\) of 0.02. For simplicity, the spin polarization is assumed to be unity. The motion of the multi-bit was investigated with varying the applied current density \(J\) and the non-adiabatic spin torque parameter \(\beta\).

**Figure 1.** Calculation model of a multi-bit with six bits and seven domain walls in a nanowire with perpendicular magnetic anisotropy.

### 3. Results and discussion

Figure 2 shows the multi-bit motion modes up to 50 ns after applying the current for various values of \(J\) and \(\beta\). In Fig. 2, the crosses represent the multi-bit motion stop due to Gilbert damping, the closed circles represent the results obtained when the bit length was kept constant during the multi-bit motion and the triangles are the results obtained when the bit length was varied or the bits disappeared during the motion. The results reveal that there are two modes of multi-bit motion.

When \(\beta = 0\), the multi-bit motions resemble the DWM of a single wall reported by Fukami et al.[5]. When \(J < 6 \times 10^7\) A/cm², the single wall moves slightly and then stops due to the internal torque. When \(J > 6 \times 10^7\) A/cm², two domain walls in the multi-bit disappear when the applied current density exceeds the critical current density of a single wall when \(\beta = 0\). Moreover, the bit length varied remarkably when the applied current density exceeds the critical current density. Thus, the current dependence of DWM in the multi-bit can be classified in terms of that of a single wall.

When \(\beta = 0.03\), Walker breakdown (WB) occurs when the current density exceeds about \(8.0 \times 10^7\) A/cm² in the single wall motion[5][8]. And when \(\beta = 0.04\), WB also occurs when the current density exceeds about \(3.0 \times 10^7\) A/cm². When the applied current density is lower than the Walker threshold, \(J_{\text{WB}}, \ i.e.,\ the \ current \ density \ at \ which \ WB \ occurs, \ the \ bit \ length \ in \ the \ multi-bit \ did \ not \ vary. \ Several \ bits \ in \ the \ multi-bit \ disappear \ when \ the \ applied \ current\)
is almost the same as $J_{WB}$ and the bit length in the multi-bit changes remarkably when the applied current is larger than $J_{WB}$. Thus, the wall motion can be also classified by $J_{WB}$ in the relation between the current velocity $u$ and the wall velocity $v$.

Figure 2. Wall motion of a multi-bit for various current densities and non-adiabatic spin torque parameters.

Figure 3. Wall displacement as a function of time after application of a current density of $6.0 \times 10^7$ A/cm$^2$ when $\beta = 0.04$.

Figure 4. Magnetization distribution during multi-bit motion when the current density $J$ is $2.0 \times 10^7$ A/cm$^2$ and $\beta = 0.04$

On the other hand, several bits disappeared when the current density larger than $J_{WB}$. Figure 5 also shows the $x$-component of magnetization when the current density $J$ is $6.0 \times 10^7$ A/cm$^2$ and $\beta = 0.04$. Figure 5(a) shows the magnetization distribution at 65 ns, which is the magnetization state before the walls of $W_6$ and $W_7$ disappear. Figure 5(b) shows the magnetization distribution at 66 ns, which is the magnetization state just before the walls disappear. Figure 5(c) also shows the magnetization distribution at 69.5 ns, which is the magnetization state after the
walls disappear. Each illustration on the right-hand side of Fig. 5 shows the magnetization distribution near the walls of $W_6$ and $W_7$. Since each wall has a different velocity from the case shown in Fig. 3, each Néel wall rotates at a different rotational speed during the motion. The bit between the walls shrinks and then disappears because Néel walls that are magnetized in the same direction mutually attract each other. Thus, the distance between walls during the multi-bit motion is closely related to the bit disappearance.

Figure 5. Magnetization distributions (a) 65 ns, (b) 66 ns, and (c) 69.5 ns after the application of a current when the current density $J$ is $6.0 \times 10^7$ A/cm$^2$ and $\beta = 0.04$.

4. Summary
The current-driven motion of a multi-bit in a magnetic nanowire with PMA has been analyzed by performing a micromagnetic simulation. The motion of the multi-bit is determined by the applied current density and the non-adiabatic spin torque parameter $\beta$. The results reveal that there are two modes in the multi-bit motion: (a) the bits move with constant length, and (b) the bit length varies or the bit disappears in the nanowire because of the interaction between Néel walls. It is clarified that these modes can be classified by the critical current density or Walker breakdown for the single wall motion in a nanowire with PMA.

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