Reversal Mode of Thermally Assisted Magnetization Reversal on Perpendicularly Magnetized Nano-Dot

Nur Aji Wibowo, Budi Purnama

***Abstract* — In these micromagnetic simulations, a finite-grid approximation was adopted, where a parallelepiped dot with perpendicular anisotropy was discretized into a two-dimensional array of a rectangular numerical grid. The grid size was chosen to be larger than the exchange length. The demagnetization fields are calculated by integrating those from apparent surface magnetic charges on boundary of each grid element. Thermally assisted magnetization reversal, where the switching field is temporally reduced by heating the selected memory cell in the writing process, is considered in this simulation. Switching mode of thermally assisted magnetization reversal has been numerically investigated by solved Landau-Lifshift Gilbert equation for magnetic nano-dot with perpendicular anisotropy. This thermally scheme succeed to decrease reversal field down to hundreds Oe order. An oscilatory minimum field required for aligning magnetization along writing field direction was observed which can be attributed by an exchange length. This information gives the possibility to realize the high density of Magnetic Random Access Memories with small reversal field (up to hundreds Oersted order) in the reading and writing process.**

***Index Terms*— Perpendicular anisotropy constant, threshold field, exchange length.**

I. INTRODUCTION

In order to realize the high density of Magnetic Random Access Memories or MRAM (Gbit/cm^2), which has transfer rate in Gbit/s order, unit cell memories must be patterned in nanometer order. However, it will have a thermal stability problem [1]-[2]. To solve the problem, large anisotropy magnetic material is required. Ferromagnetic with a large perpendicular magnetic anisotropy (PMA), such as Co_x/Pd_y, Co_x/Pt_y, Fe_xPt_y , etc., are considered to be promising candidates for storage materials in MRAMs technology.

In the other hand, this material needs a large field to switch the magnetic moment. Thermally assisted magnetization reversal (TAMR) scheme to decrease the barrier energy is the one rational technique to be proposed [3]-[9]. TAMR scheme in this simulation is shown in Fig.1.

However, PMA used for memory applications needs more knowledge about reversal magnetization process. In this present study, we have investigated the field which is required in order to align magnetic moment parallel to writing field direction (H_{th}) of TAMR in magnetic nano-dots with perpendicular anisotropy to a realization of MRAM.

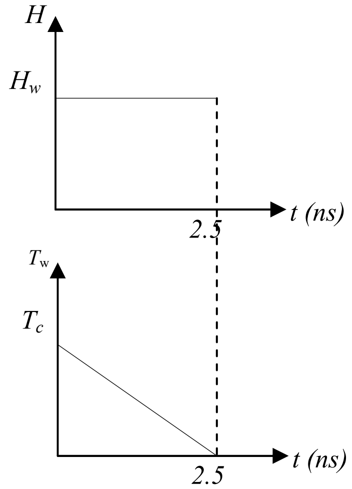

Fig.1. Thermally Assisted Magnetization Reversal (TAMR) scheme

II. NUMERICAL MODEL

In this study, a finite grid approximation was adopted, where a parallel piped dot with perpendicular anisotropy was discretized into a two dimensional array of rectangular numerical grid, which has Curie temperature T_c = 373 K. A field which is required in order to align magnetic moment parallel to the writing field of TAMR has been studied by solved Landau-Lifshift Gilbert equation [10]-[12]

$$\frac{d\mathbf{M}^i}{dt} = -|\gamma|\mathbf{M}^i \times \mathbf{H}^i_{eff} + \frac{\alpha}{M_s}\mathbf{M}^i \times \frac{d\mathbf{M}^i}{dt} \qquad (1)$$

An effective field is consist of anisotropy field (H_k), exchange interaction field (H_{ex}), demagnetization field (H_d) and thermal fluctuation field (H_T) [12]. An approximation of thermal fluctuation effect occurring during magnetization is taken into account by involving randomly oriented effective fields with zero mean value, $\langle \mathbf{H}_f^{'}(t)\rangle = 0$. Whereas, strength of the random field due to the thermal fluctuation effect is calculated by using a fluctuation dissipation theorem [13]-[14].

$$\sigma = \sqrt{\frac{2k_B T\alpha}{\gamma V M_s \Delta t}} \qquad (2)$$

where k_B is boltzman constant, T is temperature , α is gilbert damping constant (= 0,3), γ is gyromagnetic ratio (= 1,76×10^7

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$Oe^{-1}.s^{-1}$), V is volume of cell memory (= 50 nm × 50 nm × 20 nm), M_s is magnetic saturation and Δt is time increment. To evaluate the reversal probability, each calculation was performed 50 different series of random field. This probability reaches to 1 at threshold field (H_{th}).

The H_{eff} is given as the functional derivative of the energy density w respect to M

$$H_{eff} = -\frac{\delta w}{\delta M} \tag{3}$$

Interactions are expressed not as particle-particle interaction on the atomic scale, but are contained in macroscopic energy density. The form of the H_{eff} is understood as the total energy E which is given as the integral functional of the energy density w respect to volume element dv

$$E = \int w dv \tag{4}$$

This total energy E has a minimum value for the equilibrium configuration.

If the magnetic size sufficiently small, large energy barrier ΔE becomes crucial aspect to ensure thermal stability. Field dependence of ΔE is defined by following equation

$$\Delta E = K_0 V_0 \left(1 - \frac{H}{H_0}\right)^2 \tag{5}$$

where parameters K_0 is material anisotropy , V_0 is a volume and H_0 describe the magnet's real structure. Generally, thermal stability of small magnetic media demonstrated by Neel-Brown law

$$\tau = \tau_0 \exp\left(\frac{\Delta E}{k_B T}\right) \tag{6}$$

where a value of $\tau_0 \approx 10^{-10} s$. Eq. (6) can also be expressed as

$$\Delta E = k_B T \ln\left(\frac{\tau}{\tau_0}\right) \tag{7}$$

When we assumed loss data stored for 10 years, $\tau \approx 10\, years\ (10^8 s)$, so the corresponding ΔE for insured thermal stability at room temperature should be much larger than $40 k_b T$ [1],[12].

Other physical parameters used in the simulation are exchange stiffness constant $A = 1\times10^7$ erg/cm, integration time step dt = 0,12 ps and anisotropy constant $K_\perp = 8{,}0\times10^4$ erg/cm^3. Temperature dependence of exchange stiffness and anisotropy constant which are related with the thermally reduced magnetization was assumed as

$$A(T) = A^{(0)} \left(\frac{M_S(T)}{M_S(0)}\right)^2$$

$$K_\perp(T) = K_\perp^{(0)} \left(\frac{M_S(T)}{M_S(0)}\right)^2 \tag{8}$$

While the temperature dependence of magnetization defined by following equation [15]

$$M_S(T) = M_S^{(0)} \left(1 - T/T_C\right)^{0,5} \tag{9}$$

During the magnetization process, the magnetic moments coherently rotate with a certain area which called exchange length L_{ex}. These physical parameters defined as [16]

$$l_{ex} = \sqrt{\frac{A}{M_s^2}} \tag{10}$$

Evaluation of the TAMR process in this paper performed only to nano-dots that have physical dimensions bigger than the exchange length.

III. Result and Discussion

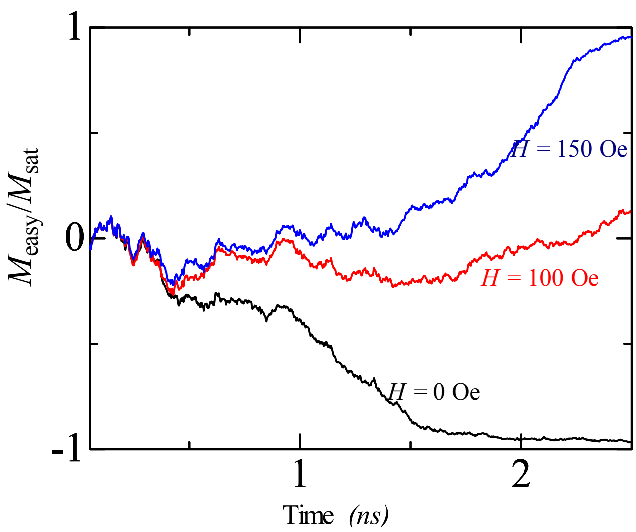
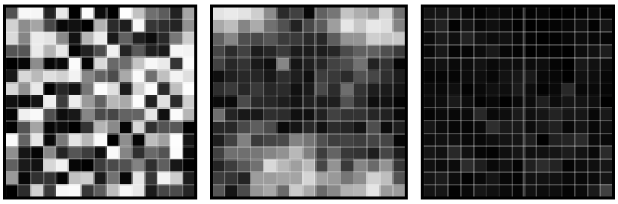
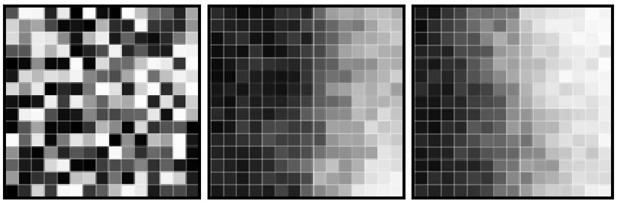


Fig. 2. The temporal evolution of magnetization in the cooling process calculated for $K_\perp = 8{,}0\times10^4$ erg/cm^3, $4\pi M_S$ =1500 G.

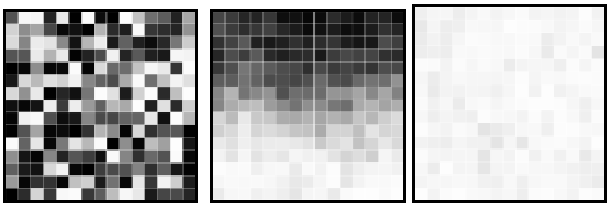
Fig. 2 shows the temporal evolution of magnetization versus time in cooling process from the Curie temperature T_c (373 K) to the room temperature (298 K) for different value of bias filed H_w (0 Oe, 100 Oe and 150 oe). At the beginning, the value of M_{easy}/M_{sat} = 0 shows that a randomly magnetized state realized. After t > 0 ns, for H_w = 0 Oe, the magnetic nano-dots relax into an opposite direction of H_w. However, from 0.5 ns to 1 ns, there are static circumstances which arising out of thermally effect. The value of M_{easy}/M_{sat} is equal to zero constantly, as a result of multidomain configuration when the value of H_w is 100 Oe. Whereas, for the value of H_w = 150 Oe, formation of domain wall realized at t = 1.6 ns. Then, domain wall expansion continuously occurs. After 2.25 ns, single domain configuration dominates the magnetization process. The temporal evolution of magnetization in the cooling process also can be reflected on micrograph of magnetization as shown in Fig. 3, which is the magnetization parallel to the H_w direction shown by white color, and black color shows the opposite direction, vice versa.



(a)



(b)



(c)

Fig. 3. Micromagneticgraph of the temporal evolution of magnetization in the cooling process calculated for $K_\perp = 8{,}0\times10^4$ erg/cm^3, $4\pi M_S$ =1500 G with (a) H_w = 0 Oe, (b) H_w = 100 Oe, and (c) H_w = 150 Oe. The magnetization parallel to the writing field direction shown by white color, and black color shows the opposite direction

Fig. 4 shows a probability as a function of bias field which calculated for $K_\perp = 8{,}0\times10^4$ erg/cc and $4\pi M_S$ = 1500 G and 2000 G. When the M_{easy}/M_{sat} exceeds 0.85, there is no magnetization in the opposite direction of H_w. Therefore, value of M_{easy}/M_{sat} as mentioned above used as the definition of switching point. With this definition, reversal probability into bias field direction countable for 50 different initial conditions.

Clearly observed from the Fig. 4 that the value of probability increase with the rise of H_w and reaches to 1 at a threshold field (H_{th}). The H_{th} is the minimum field which is required in order to align magnetic moment parallel to the writing field. At H_w= 0 Oe for $4\pi M_S$ = 1500 G, the probability equal to 0.5, needs H_{th} as big as 150 Oe. Whereas for $4\pi M_S$ = 2000 G, the probability value, i.e 0.2, at H_w= 0 Oe, require large enough H_{th}, that is 170 *Oe*.

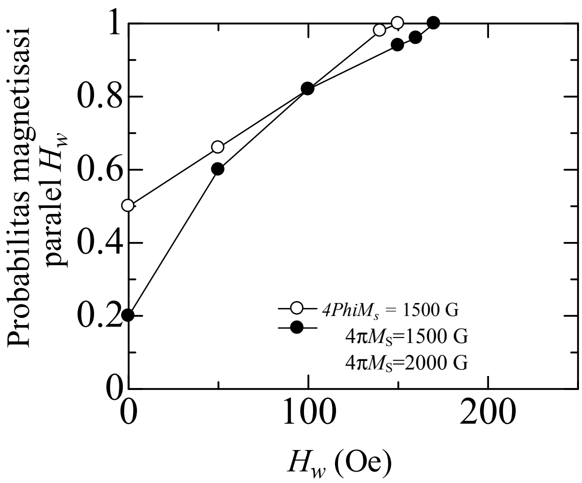


Fig. 4. Reversal probability along to field direction as a function of H_w calculated for $K_\perp = 8{,}0\times10^4$ erg/cm^3, $4\pi M_S$ = 1500 G dan 2000 G.

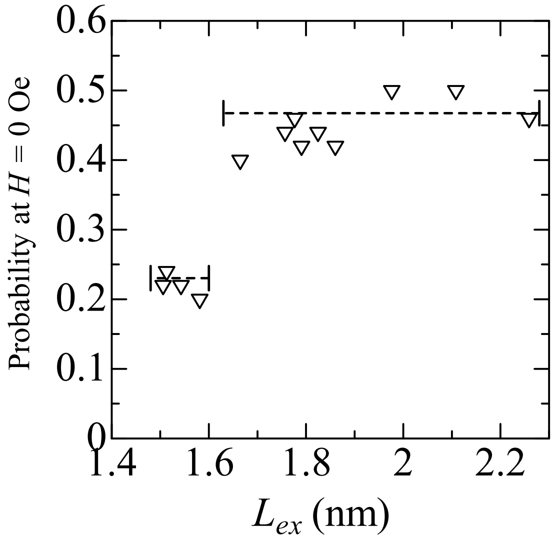
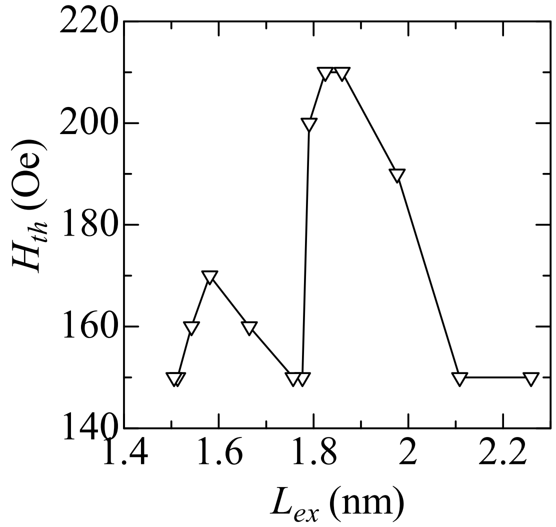


Fig. 5. Probability aligning to the field direction at H_w= 0 Oe as a function of exchange length (L_{ex}) calculated for $K_\perp = 8{,}0\times10^4$ erg/cm^3.

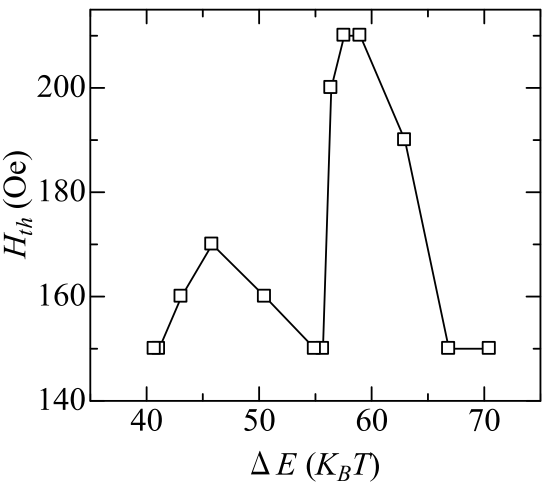
To confirm the reversal mode process, we evaluate the probability at H_w = 0 Oe as function as L_{ex}, which is calculated for 50 different random number, as shown in Fig. 5. For L_{ex} < 1.6 nm, the probability is obtained about 0,2 , in contrast, for L_{ex} > 1.6 nm, the probability is obtained about 0,45.

Consequent of L_{ex} dependence of probability at H_w = 0 Oe, it is expected that L_{ex} also affect the H_{th} as shown in Fig. 6. (a). An alteration of H_{th} as function as L_{ex} forms oscillating pattern have period about 0.3 nm. We assumed the same oscillating pattern will be formed for large L_{ex}, as result, material having a large ΔE with small H_{th} is obtained. This phenomenon can be related to oscillating H_{th} to energy barrier ΔE, as shown in Fig. 6 (b). A minimum H_{th} is obtained 150 Oe at ΔE = 70 K_BT. The interesting thing is, at the large ΔE, which ensure high level of thermal stability, the minimum H_{th} is achieved. The increasing of *ΔE elongate* the L_{ex}, with the result that coherent rotation take place on the reversal process.

This information gives the possibility to realize the high density of MRAM with small reversal field (up to hundreds Oersted order) in the reading and writing process.



(a)



(b)

Fig. 6. Alteration of H_{th} to ΔE, as well as L_{ex}, in TAMR scheme calculated for $K_{\perp}$ = 8,0×10^4 erg/cm^3 and $4\pi M_S$ at interval 1400 - 2100 G.

IV. Conclusion

Switching mode of thermally assisted magnetization reversal has been numerically investigated by solved Landau-Lifshift Gilbert equation for magnetic nano-dot with perpendicular anisotropy. This thermally scheme succeed to decrease reversal field down to hundreds Oe order. An oscilatory minimum field H_{th} required for aligning magnetization along writing field direction was observed which can be attributed by an exchange length L_{ex}. The alteration of H_{th} as function as L_{ex}, which corresponds to ΔE (40-70 k_bT) give the optimum configuration at $4\pi M_S$ as big as 1400 G, 1500 G, 1780 G, 1800 G, 2090 G and 2100 G, calculated for $K_{\perp}$ = 8,0×10^4 erg/cm^3. This information gives the possibility to realize the high density of MRAM with small reversal field (hundreds Oersted order) in the reading and writing process.

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