Micro Magnetic Study of Thermally Assisted Magnetization Reversal Mechanism on Perpendicularly Magnetic Anisotropy $CO_XSI_YB_Z$

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Abstract: ***Micromagnetic simulation for perpendicular magnetic anisotropy $Co_xSi_yB_z$ substance which utilizes thermal activating for several parameter such as anisotropy constant and saturation magnetization parameter has been examined using Landau-Liftshitz Gilbert equation. Perpendicular Magnetic Anisotropy is used to realize storage medium with sizable capacity. However, it has a disadvantage in the need of a large writing field. Providing of heat can be used as a solution to lessen magnitude of writing field. At room temperature, combination value of anisotropy constant and saturation magnetization give impact to energy barrier, switching field and domain wall propagation rate in magnetization reversal. When nano-dot is heated at Curie temperature then cooled abruptly until room temperature, writing field is needed to reverse the magnetization has been successfully reduced up to ~ 90%.***

Keywords: anisotropy constant, saturation magnetization, probability, domain wall and reversal field**.**

1. Introduction

The rapid development of Personal Computer (PC) is mainly caused by the human needs of processing data and information using PC. One motivating aspect in the development of PC is the worldwide needs of the existence of a storing media with massive capacity and high speed in reading and writing abilities. In 2006, Perpendicular Magnetic Recording (PMR) was introduced as a new technology of a magnetic recording of hard drive which unitizes Perpendicular Magnetic Anisotropy (PMA) as storing media. This technology offers a bigger capacity, better ability and endurance. In PMR, the magnetic bits directions are perpendicular to its surface. Whereas in the conventional recording technology, Longitudinal Magnetic Recording (LMR) which developed, its magnetic bits was arranged parallel to the surface, so that, a larger area is needed in storing the information [1] [2]. However, in PMR technology, a greater energy is required in reversing the direction of magnetized composer bits. A promising alternative solution that can be used to reduce the energy is by giving an amount of heat during the reversing magnetization [3].

The magnetic material's properties are very influential in the reversal process of magnetization. There are several parameters that can be used in determining the characteristics of the material such as anisotropy constant and saturation magnetization. In this paper, the influence of those parameters in reordering the magnetization at room temperature altogether with thermal activation examined in a simulation of micromagnetic by using the Landau-Liftshitz Gilbert (LLG) Equation.

2. Methods

Influence of magnetic material properties to the reversal mechanism of magnetization was investigated by modeling ferromagnetic material with perpendicular magnetic

Anisotropy $Co_xSi_yB_z$ as a perpendicular magnetized nano-dot having $50 \times 50 \times 20$ nm^3 in dimension.

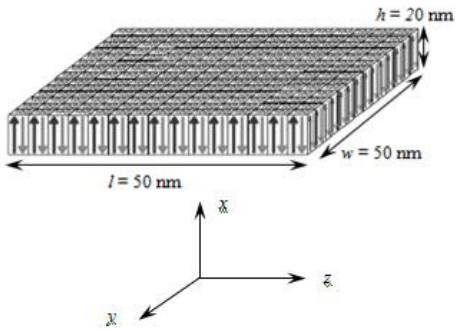

Figure 1: Nano-dot models which the volume is 50×50×20 nm^3 with appropriate coordinate.

Chosen magnetic material parameters for $Co_xSi_yB_z$ are $4\pi M_s$ = 4116, 6 G with $K_\perp = 2 \times 10^6$ erg/cm^3 [4]. Magnetization reversal simulation is done by accomplishing the Landau - Liftshitz Gilbert (LLG) Equation. It contains the time derivative of the magnetization on one of side only which is shown in Eq. (1). This equation describes the magnetic material response which is characterized by the magnetization direction if it is induced by a current field [5].

$$\frac{d\mathbf{M}^i}{dt} = -\frac{\gamma_0}{1+\alpha^2}\cdot\left[\mathbf{M}^i \times \mathbf{H}^i_{eff}\right] - \frac{\gamma_0}{M_s}\cdot\frac{\alpha}{1+\alpha^2} \cdot\left[\mathbf{M}^i \times \left[\mathbf{M}^i \times \mathbf{H}^i_{eff}\right]\right] \quad (1)$$

Where **M** as the magnetization, M_s as the saturation magnetization, α as the Gilbert damping constant (0.3), γ_0 as the gyro-magnetic ratio (1.7×10^7/Oe^{-1}.s^{-1}) and $\mathbf{H}_{eff}$ as the effective field. The $\mathbf{H}_{eff}$ is composed by anisotropy field (H_k), magnetostatic field ($\mathbf{H}_M$), the exchange interaction field ($\mathbf{H}_{ex}$), the external field ($\mathbf{H}_{ext}$) and a random stochastic field ($\mathbf{H}_T$) if a thermal field activated as seen in Eq.(2) [6].

$$\mathbf{H}^i_{eff} = \mathbf{H}^i_k + \mathbf{H}^i_M + \mathbf{H}^i_{ex} + \mathbf{H}^i_{ext} + \mathbf{H}^i_T \quad (2)$$

$\mathbf{H}_{ex}$ as an exchange stiffness constant function which described in Eq.(3)[7].

$$\mathbf{H}_{ex} = \frac{A}{\mu_0 M_s^2}\Delta\mathbf{M} \quad (3)$$

Where A as exchange stiffness constant (1×10^7 erg/cm), μ_0 as permeability of vacuum and function of ΔM as shown in Eq.[8].

$$\Delta\mathbf{M} = \frac{\partial^2}{\partial x^2}\mathbf{M}_x + \frac{\partial^2}{\partial y^2}\mathbf{M}_y + \frac{\partial^2}{\partial z^2}\mathbf{M}_z \quad (4)$$

The exchange energy between the magnetization i and j in a system of N spin is defined as [9] :

$$E_{ex} = \sum_{i,j,k=1}^{N} A\left\{\left[\nabla\mathbf{M}_x(\mathbf{r})\right]^2 + \left[\nabla\mathbf{M}_y(\mathbf{r})\right]^2 + \left[\nabla\mathbf{M}_z(\mathbf{r})\right]^2\right\} \quad (5)$$

Where $\nabla\mathbf{M}_{x,y,z}$ is the spatial gradient of the magnetization normalized components corresponding to the x, y and z axis. The temperature dependence of exchange stiffness can be formulated in Eq. (6)[10].

$$A(T) = A^{(0)}\left(\frac{M_s(T)}{M_s(0)}\right)^2 \quad (6)$$

Where T as actual room temperature (298 K).

Relation between $\mathbf{H}_k$ with anisotropy constant is expressed as a function of the unitary vector $\mathbf{m}$ can be seen at Eq.(7) [9].

$$\mathbf{H}_k = \frac{2K_\perp}{\mu_0 M_s}(\mathbf{u}.\mathbf{m})\mathbf{u} \quad (7)$$

Where $\mathbf{u}$ is the unit vector, along the direction of the uniaxial easy axis $(1 \quad 0 \quad 0)$ and $\mathbf{m} = \frac{\mathbf{M}}{M_s}$.

The effect of temperature toward the anisotropy and saturation magnetization constant is shown in Eq.(8) and (9) [10].

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

$$M_s(T) = M_s^{(0)}\left(1 - T/T_c\right)^{0,5} \quad (9)$$

where $K_\perp$ = anisotropy constant, M_s = saturation magnetization and T_c = curie temperature with the assumed value 373 K. The thermal fluctuation field has zero mean and is assumed to be Gaussian distributed with a variance α given by the fluctuation-dissipation theorem as shown in Eq. (10), Eq.(11) and Eq.(12)[11].

$$\left\langle H_T^i(t)\right\rangle = 0 \quad (10)$$

$$\left\langle H_T^i(t) H_T^j(t')\right\rangle = \delta_{ij}\delta(t-t')\sigma^2 \quad (11)$$

$$\sigma = \sqrt{\frac{2k_B T\alpha}{\gamma V M_s \Delta t}} \quad (12)$$

with $\delta(t)$ is the delta dirac function, δ_{ij} is the Kronecker delta, the indices i and j label the unit cell or the vector component, k_B = boltzman constant, V = volume of nano-dot ($50\times50\times20$ nm^3) and Δt = time increment ($0,25\times10^{-12}$ s).

3. Result and Discussion

3.1. Magnetization Reversal at Room Temperature

Nano-dot ferromagnetic with perpendicular anisotropy which analyzed numerically in this research magnetized upward, perpendicularly to its surface along $+x$ ($M\uparrow$). In the scheme of micromagnetic simulation of writing process through declining energy barrier mechanism, nano-dot is conditioned at the room temperature and then induced by a bias magnetic field (H_B) opposite to its initial magnetization with linearly increasing size from 0 to 20 kOe during 2,5 ns as shown in Figure 2.

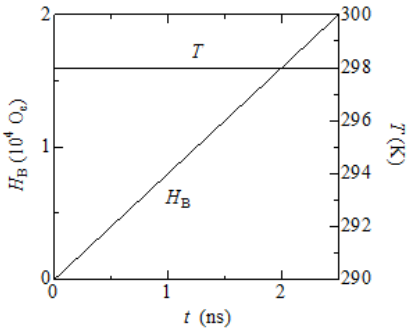

Figure 2: Scheme of micromagnetic simulation of the writing process through mechanism of declining energy barrier.

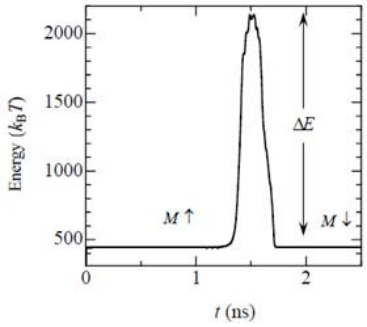

Figure 3: Energy barrier occurred in perpendicular magnetized nano-dot at room temperature (298K).

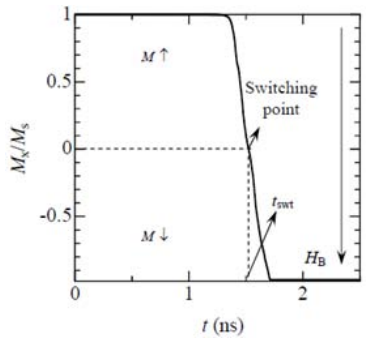

Figure 4: Magnetization reversal mechanism occurred in perpendicular magnetized nano-dot at room temperature (298K).

In order to reverse the nano-dot magnetization into $-x$ direction ($M\downarrow$), bias magnetic field in $-x$ orientation is needed to overcome an energy barrier inside. This energy barrier separates two minimum energy level, which representing the direction of upward and downward magnetization as seen in Figure 3.

Figure 4 shows that the reversal process is represented through the value of M_x/M_s. M_x and M_s are the actual magnetization in the x axis and initial magnetization respectively. For M_x/M_s = 1, magnetization of nano-dot saturated in $+x$ direction. While for M_x/M_s= 0, nano-dot magnetization is perpendicularly oriented to its initial magnetization and/or the number of upward and downward magnetic moment is equal so that they cancel each other. In other words, the nano-dot magnetization exactly will reverse and then this point is called as a switching point, whereas the current magnetic field and time related to this point is called as switching field (H_{swt}) and switching time (t_{swt}). Explicitly, H_{swt} and t_{swt} are the minimum bias field and time are needed to switch the magnetization. M_x/M_s= −1 shows that magnetization of the nano-dot is saturated toward the external magnetic field direction.

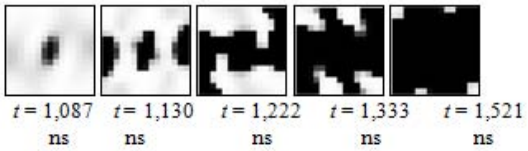

Figure 5: Visualization of magnetization reversal mechanism with corresponding properties for $Co_xSi_yB_z$ material are $4\pi M_s$ = 5316,6 G and $K_\perp = 2\times10^6$ erg/cm^3 at room temperature (298 K).

Figure 5 visualizes the nano-dot magnetization at room temperature for $4\pi M_s$ = 5316,6 G and $K_\perp = 2\times10^6$ erg/cm^3. Black color illustrate the magnetization which aligned in H_B direction, whereas white color shows the initial direction of magnetization. Magnetization reversal of nano-dot occurred through domain wall nucleation from its center, continuing on its edge-center. This domain walls propagate up to saturated parallel to H_B direction. The middle region of the nano-dot is easier to be reversed rather than its edge caused of domination of exchange field in the middle. Whereas at the edge, reversal mechanism are led by anisotropy field.

The changing of material characteristic with $K_\perp$ variation influences ΔE and H_{swt}, as seen in Figure 6. Increasing of $K_\perp$ causes ΔE and H_{swt} also accrue. The reason is that increasing of bonding of atomic moment with crystal lattice as a consequence of large $K_\perp$ needs a substantial energy to reverse the magnetization.

Except $K_\perp$ parameter that influences the ΔE and H_{swt} values, variances of ΔE and H_{swt} magnitudes also affected by saturation magnetization constant ($4\pi M_s$), as seen in Figure 7. A substance that has a substantial $4\pi M_s$ value, it has a tiny ΔE, thus it needs a bit of H_{swt} .

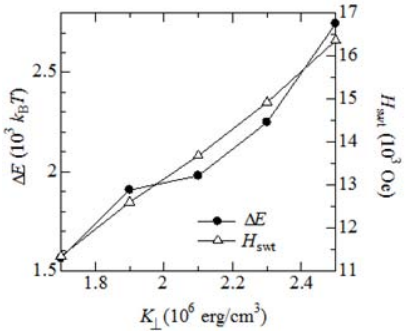

Figure 6: Rising of energy barrier (ΔE) and switching field (H_{swt}) towards $K_\perp$ value at room temperature (298 K) and for $4\pi M_s$ = 4116,6 G.

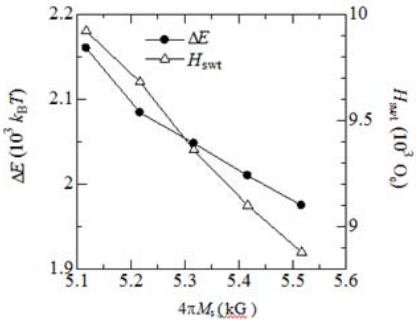

Figure 7: Decreasing of ΔE and H_{swt} values towards saturation magnetization on room temperature (298 K) and with $K_\perp = 2\times10^6$ erg/cm^3.

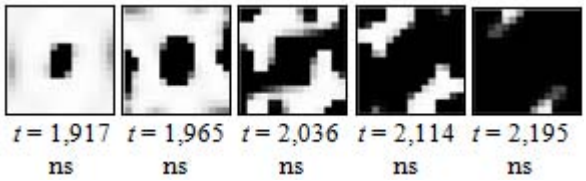

Figure 8: Visualization of reversal magnetization for $Co_xSi_yB_z$ material with $4\pi M_s$ = 4116,6 G with $K_\perp = 2{,}5\times10^6$ erg/cm^3 at room temperature (298 K).

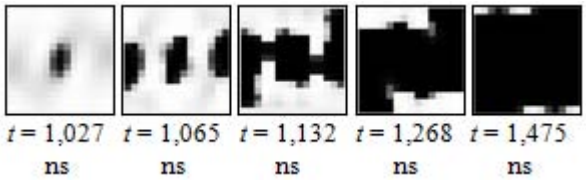

Figure 9: Visualization of reversal magnetization for $Co_xSi_yB_z$ material with $4\pi M_s$ = 5516,6 G with $K_\perp = 2\times10^6$ erg/cm^3 at room temperature (298 K).

Figure 8 and 9 describe visualization of reversal magnetization of ferromagnetic nano-dot at room temperature for two different characteristic materials, i.e. small $4\pi M_s$ - large $K_\perp$ and small $K_\perp$ - large $4\pi M_s$ respectively. Nucleation and propagation profile of domain wall that occurs for both materials are identical, however, rate of domain wall propagation is faster for materials with large $4\pi M_s$ - small $K_\perp$ (5116,6 G and 2×10^6 erg/cm^3) i.e. 1,110 ns. Mean while, for small $4\pi M_s$ - large $K_\perp$ (4116,6 G and $2{,}5\times10^6$ erg/cm^3), it require longer time, i.e. 2,045 ns to reverse.

3.2 Magnetization Reversal with Activating Thermal

In second part of this paper concerning to investigation of reversal magnetization with support of heat. Meantime, the performed scheme is as follows, nano-dot is heated at Curie temperature, then cooled abruptly in 2,5 ns until reaching the room temperature 298 K under influence of constant H_B at $+x$ direction, just as seen in Figure 10. Heating causes both, field and initial magnetization turns to be random, therefore, the calculation should be performed using 50 different random numbers. Probability of magnetization with direction parallel to H_B after cooling process for 50 random numbers called is as reversal probability P. As seen in Figure 11, switching probability is a function of bias field. The minimum H_B that

required to reach the probability equal to 1 called as Threshold Field (H_T).

A swift cooling, in fact, has not been able to magnetize nano-dot spontaneously at +x direction. As shows in the value of $P(H_B) = 0$ while $H_B = 0$. Furthermore, H_B that less than 250 Oe, does not sufficient to magnetize nano-dot in line with its direction. Value of probability become larger when H_B is more than 250 Oe, and increases rapidly for interval 550 Oe to 700 Oe. H_T is achieved, when H_B as much as 870 Oe, 980 Oe, 910 Oe, 960 Oe, and 970 Oe for each $4\pi M_s$ consecutively from 5116,6 G to 5516,6 G.

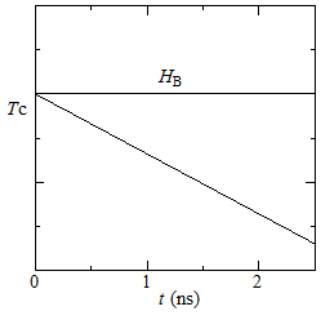

Figure 10: Simulation scheme on reversal magnetization with support of heat.

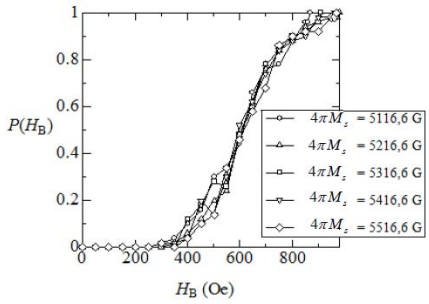

Figure 11. Dependence of P with respect to H_B on reversal magnetization scheme with heat activation for five different value of $4\pi M_s$.

The size of H_T towards value of $4\pi M_s$ tends to fluctuate as seen in Figure 12. Effect of thermally assisted plays a pivotal role in magnetization process during the cooling process, and as a result, the influence of initial nano-dot magnetization is eliminated. Supplying of heat has successfully decreases the reversal field up to ~90% for $4\pi M_s$ value about 5116,6 G to 5516,6 G.

Figure 13 displays the influence of H_B on $P(H_B)$ for several different $K_\perp$. When H_B is less than 150 Oe for all $K_\perp$, value of $P(H_B) = 0$. The field that has 150 Oe value considered as a beginning value at which sufficient to magnetize nano-dot at +x direction. The probability increases rapidly at interval H_B from 450 until 700 Oe. Nano-dot is completely magnetized at H_B direction for 50 random numbers when H_B reaching 810 Oe, 850 Oe, 980 Oe, 1050 Oe and 1140 Oe for respectively of $K_\perp$ from $1{,}7\times10^6$ erg/cm^3 to $2{,}5\times10^6$ erg/cm^3.

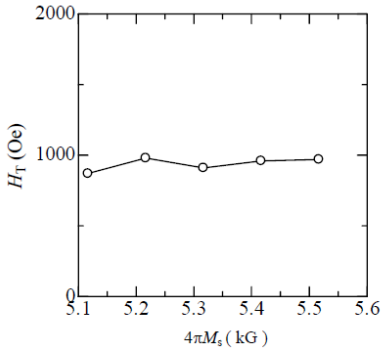

Figure 12: Increasing of H_T towards $4\pi M_s$ value by thermal assisting with constant $K_\perp = 2\times10^6$ erg/cm^3.

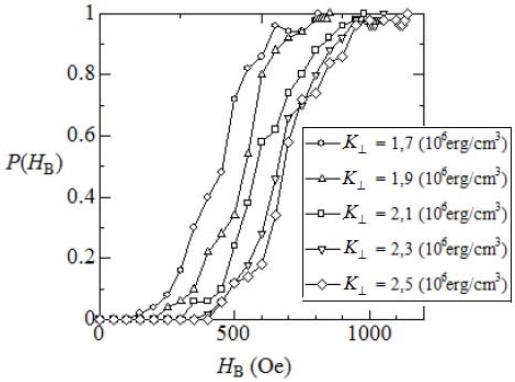

Figure 13: The dependence of P with respect to H_B on reversal magnetization scheme by thermal assisting for $K_\perp$ variation.

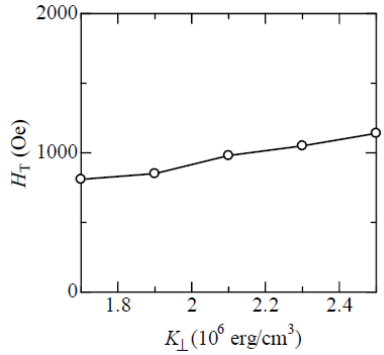

Figure 14: Increasing of H_T towards $K_\perp$ value by thermal assisting with constant $4\pi M_s$ = 4116,6 G.

During cooling process, the interaction of magnetization towards crystal lattice has a massive contribution in its magnetization reversal. It indicates that the increasing of $K_\perp$ needs larger H_T. Dependency of $K_\perp$ towards H_T seen in Figure 14. From Figure 6, it can be seen that for $K_\perp = 1{,}7\times10^6$ erg/cm^3, the field required to reverse the magnetization direction as much as 11.340 Oe. By thermal assisting, this field can be reduced up to ~ 90 %, and it applied for another $K_\perp$.

4. Conclusion

Previously, there has been a studied about the influence of material characteristic, as indicated at combination value of $4\pi M_s$ and $K_\perp$, and thermally assisted scheme towards the reversal process of magnetization reversal through miromagnetic simulation by solving Landau-Liftshitz Gilbert equation. Both parameters have an important role on reversal

magnetization process for a perpendicular anisotropy ferromagnetic nano-dot. Larger $K_{\perp}$ will increase ΔE, and with increasing of ΔE, then larger H_{swt} will be needed. On the other hand, the greater $4\pi M_s$ will decrease ΔE, and followed by declining of H_{swt}. In addition, they also influence domain wall propagation rate. Nano-dot with large $4\pi M_s$ - small $K_{\perp}$ combination gives a faster domain wall propagation rate comparing to nano-dot with small $4\pi M_s$ - large $K_{\perp}$. The interesting part of this research is that the thermally assisted scheme make a good decreasing of reversal field magnitude up to ~ 90% during the ongoing reversal mechanism.

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