Heat Assisted Magnetization Reversal on Perpendicular Magnetized Nano-Dot

Nur Aji Wibowo[1], Cari[2], and Budi Purnama[3]

Abstract—**Heat assisted magnetization reversal on perpendicular magnetized nano-dots has been studied by solved Landau Lifshift-Gilbert equation for magnetic recording application. The heat assisted magnetization reversal scheme has been proven to be effectively reduces threshold field down to 90 %. Otherwise, this field doesn't depend on heating time. To understand a read-write information process, cooling time dependence of threshold field has been evaluated. As a result, the threshold field depends on the cooling time and become constant after 300 ps. This result corresponds to data transfer of Hard Disc Drive about 30 Gb/s.**

Keywords—**magnetic recording, PMA, heat assisted, threshold field, heating time and cooling time**

Abstrak—Telah dilakukan evaluasi mode magnetisasi reversal berbantukan panas pada nanodot magnetik beranisotropi tegak lurus dengan menyelesaikan persamaan Landau Lifshift-Gilbert untuk aplikasi perekaman magnetik. Skema magnetisasi reversal berbantukan panas terbukti efektif menurunkan medan threshold hingga 90%. Namun demikian, medan threshold tidak bergantung pada lamanya pemanasan. Untuk lebih memahami proses baca-tulis informasi, telah dilakukan evaluasi pola hubungan medan threshold terhadap lamanya pendinginan. Dan didapatkan bahwa medan ini bergantung pada lamanya pendinginan dan menjadi konstan setelah 300 ps. Hasil ini terkait dengan kecepatan transfer data pada Hard Disc Drive dalam orde Gb/s.

Kata Kunci—***perekaman magnetik, PMA, berbantukan panas, medan threshold, lama pemanasan, lama pendinginan***

I. INTRODUCTION

To increase a magnetic disks density, magnetic size must be downsized to nanometer order. When the magnetic size is very small, the room temperature magnetization direction becomes unstable (the recorded magnetic domain relax due to thermal decay over time) [1, 2]. Large anisotropy magnetic material is required to overcome this thermal fluctuation [3]. Ferromagnetic with 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 magnetic recording technology. Since 1990, recording densities of magnetic disks have an excellent annual growth up to 100%. In 2005, the commercial magnetic disks density is about 130 Gbit/cm^2. Yet, writing magnetic field becomes insufficient if the media have large anisotropy [1]. A promising method that can be proposed to solve this problem is a Heat Assisted Magnetization Reversal (HAMR). This method was developed since 1999. The main idea of HAMR method is using a heating pulse on nano-dots recording media to reduce the writing magnetic field [4]. By the uses of HAMR method, the densities of magnetic recording exceeding Tbit/cm^2, can be achieved [1]. Therefore, comprehension about HAMR mechanism becomes important to be investigated.

In this HAMR scheme, double pulse i.e. writing field pulse and heating pulse, was adopted. The aim of this paper is to evaluate dependence of threshold field H_{th} with respect to heating pulse configuration. The threshold field, associated with the writing magnetic field, is a field which required to aligning magnetization parallel to this field direction.

Reorientation of the magnetization process under an effective field was described by Landau Lifshift Gilbert equation (LLG) [6]:

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

where M is a magnetization, α is a gilbert damping constant (= 0.3), γ is a gyromagnetic ratio (= 1.76.10^7 Oe^{-1}s^{-1}), H_{eff} is an effective field, M_s is a magnetic saturation and dt is an integration time step (= 0.12 ps). First term in the right hand side of eq.(1) describes the gyromagnetic precession and the second term is the damping term which describes the motion of the magnetic moment toward the H_{eff}. The effective field introduced in eq.(1) arises from the following four source [5, 6]: (a) exchange field H_{ex}, which appears from interaction between neighboring magnetic moments; (b) magneto-statics field H_d, that breaks large magnetic particles into smaller magnetic domains, (c) anisotropy field H_k, which appears from interaction of atomic moments with the crystal surrounding and causes the magnetic moments to be oriented along certain crystallographic direction, (d) at non zero temperatures a random stochastic field H_T may be included. This H_T will be discussed in numerical method. The H_{eff} is given as the functional derivative of the energy density w respect to M

$$H_{eff} = -\frac{\delta w}{\delta M} \qquad (2)$$

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

$$E = \int w dv \qquad (3)$$

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

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

$$E_a = K_0 V_0 \left(1 - \frac{H}{H_0}\right)^2 \quad (4)$$

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

$$\tau = \tau_0 \exp\left(\frac{E_a}{k_B T}\right) \quad (5)$$

where E_a is the activation energy associated with the energy barrier ΔE, k_B is a boltzman constant, T is a temperature and value of $\tau_0 \approx 10^{-10}$s. equation (5) can also be expressed as:

$$E_a = k_B T \ln\left(\frac{\tau}{\tau_0}\right) \quad (6)$$

when we assumed loss data stored at Hard Disc Drive (HDD) for 10 years, $\tau \approx 10$ years (10^8s), so the corresponding ΔE for insured thermal stability at room temperature should be much larger than 40 k_bT [2, 6].

II. Method

In consideration a PMA magnetized nano-dots as a magnetic recording media, reversal mode of HAMR evaluated by solve the LLG equation. An approximation of thermal fluctuation effect occurring during magnetization is taken into account by involving randomly oriented effective fields with zero mean value,$\langle H'_{eff}(t)\rangle=0$. Whereas, strength of the random field due to the thermal fluctuation effect is calculated by using a fluctuation dissipation theorem [7]:

$$\sigma = \sqrt{\frac{2k_B T\alpha}{\gamma V M_s \Delta t}} \quad (7)$$

where σ is a fluctuation factor, V is a volume of cell memory (= 50 × 50 × 20 nm^3) and Δt is time increment. To evaluate heat effects with respect to threshold field and initial condition of magnetization, calculation of magnetization probability aligning to field direction was performed for 20 different series of random number. This probability reaches to 1 at threshold field H_{th}. Temperature dependence of exchange stiffness and anisotropy constant which are related with the thermally reduced magnetization was assumed as [5]:

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

where A is a exchange stiffness constant and $K_\perp$ is a perpendicular anisotropy constant. While the temperature dependence of magnetization defined by following equation [8].

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

Value of this physical parameters used in the simulation are exchange stiffness constant $A = 1.10^7$ erg/cm, anisotropy constant $K_\perp = 8.10^4$ erg/cc, $4\pi M_S = 2.1$ kG which corresponds to energy barrier ≈ 150 k_bT at room temperature and Currie temperature = 373 K.

Figure 1 illustrates the HAMR scheme in this paper. A bias field H_w, which pulse width is 4.75 ns, was applied. And a heating pulse T_w, which its pulse width is 2.5 ns, was applied after 1 ns.

III. Results and Discussion

A. Types Modes of Magnetization

In order to know deeply a heat fluctuation effect in Heat Assisted Magnetization Reversal mode, a change of energy barrier ΔE because of this heat fluctuation effect is evaluated for four different models. Physical properties which used in this simulation are $K_\perp = 3.10^5$ erg/cc and $4\pi M_S = 2.1$ kG. Model A is the magnetization process by excluding the heat fluctuation effect in a configuration of initial magnetization and the H_{eff}. Model B is the magnetization process by including the heat fluctuation effect in the configuration of initial magnetization. Model C is the magnetization process by including the heat fluctuation effect in the H_{eff}. Finally, model D is the magnetization process by including the heat fluctuation effect in the configuration of initial magnetization and the H_{eff}. Furthermore, the magnetization reversal mechanism is evaluated by observe a visualization of micrograph of magnetization. In this paper, ΔE is defined as a difference of a value between a minimum and maximum level energy as shown in Figure 1. This ΔE separates the two of difference minimum state. In the magnetic recording application, the two of difference minimum state associated with an opposite direction of magnetization (in the H_w direction and the oppositely). And a switching field H_{swt} is defined as a minimum H_w which is required to overcome the ΔE so that the magnetization reverse into H_w direction.

Figure 2 illustrates an energy barrier shape from four different models. From Figure 1(a-b) observed that a characteristic of ΔE is symmetric and smooth. Whereas a decreasing of the minimum level energy and the ΔE with an increasing of temperature T as shown at Figure 1(b-d). The different result was obtained if the fluctuation of H_{eff} include in the calculation. Figure 1(c-d) shows that under the fluctuation of H_{eff} effect, the characteristic of ΔE becomes asymmetric and ripple. And the ΔE vanish when T close to T_c so that the material lose its magnetism.

From Figure 2, the T/T_c dependence of the ΔE can be plotted. The decreasing of the ΔE to the increasing of the T/T_c observed from Figure 3. As shown from the figure that the H_{eff} fluctuation caused the fluctuating of ΔE. For models C and D, at $T/Tc \approx 99$ %, the ΔE can still be realized with the value larger than 100 k_BT. It means that the magnetization reversal possible to be realized at high temperature.

The magnetization reversal mechanism of each model can be observed from Figure 4. Figure 4(a) represents the reversal mechanism of state which excluding the heat fluctuation effect. Observed from the figure, at (i), $t = 0$ ns, the value of M_{easy}/M_{sat} is equal to zero. At this time, the magnetization saturated in the opposite direction of H_w. Then, throughout a present of H_w in a negative direction which the value rise linearly from 0 to 2 T, the value of M_{easy}/M_{sat} down towards negative value. At (ii), $t = 0.83$ ns, the value of M_{easy}/M_{sat} is equal to 0.1. And at (iii), $t = 0.85$ ns, the value of M_{easy}/M_{sat} is equal to -0.4. In this interval, the magnetization gradually turned towards H_w direction. After 0.85 ns, the magnetization is saturated in the direction of H_w which corresponds to the value of M_{easy}/M_{sat} equal to - 1.

Figure 4(c-d) describes that the fluctuation of H_{eff} caused the value of M_{easy}/M_{sat} drop and become ≈ 0 at T/T_c ≈100%. It means that at that time, randomly magnetized state be realized. In this paper, $t_{reversal}$ is defined as a time which is required to reverse the magnetization so that the magnetization saturate in the H_w direction. Reflected from the Figure 4(b-d) that the increasing of temperature shortening the $t_{reversal}$. From this figure, the T/T_c dependence of the $t_{reversal}$ can be plotted. The shortening of $t_{reversal}$ with respect to the increasing of the T/T_c observed from Figure 5. By comparing the $t_{reversal}$ at B, C and D, observed that the presence of the H_{eff} fluctuation shorten the $t_{reversal}$.

The magnetization reversal magnetization also can be reflected on micrograph of magnetization as shown in Figure 6. Which is the magnetization parallel to the H_w direction shown by black color, and white color shows the opposite direction, vice versa. This figure describes that for models A and B, the magnetization reversal mechanism begins with a smooth domain wall nucleation from a center. This domain wall expands until a single domain configuration in the H_w direction has been realized. In the other side, for models C and D, the magnetization reversal mechanism begins with the domain wall nucleation from an edge. This domain wall expands until a single domain configuration in the H_w direction has been realized.

B. Heat Assisted Magnetization Reversal

Figure 7 represents the HAMR mechanism under a bias field H_w. Observed from the figure that for t < 1 ns, the magnetization constant. Yet, when the heat is applied (t $\geq$ 1 ns), the magnetization change quickly and disordered when the heat approximate to Curie point. This randomly magnetized state shown with the value of M_{easy}/M_{sat} about 0. After 3 ns, the heat is lowered to room temperature. And the magnetization aligning to H_w direction at room temperature, which called reversal state. At this state, read and write information is going on and then the information saved at room temperature.

The heat assisted magnetization reversal mechanism also can be reflected on micro-magnetic-graph of magnetization as shown in Figure 8, which is the magnetization parallel to the H_w direction shown by white color, and black color shows the opposite direction, vice versa. Observed from micro-magnetic-graph, for t < 2 ns, the magnetization dominated by multi domain configuration. During heating process, 2 < t < 3 ns, the random magnetization realized. Whereas for cooling writing process, t > 3 ns, the magnetization re-versal mechanism starts with a domain wall nucleation and continued by domain wall annihilation so that single domain to the H_w direction realized.

Figure 9 exhibits a decreasing of H_{th} as a function of a writing temperature to Curie temperature ratio (T_w/T_c). At T_w/T_c = 80 %, 2300 Oe of H_{th} is required to aligning the magnetization in the H_w direction. However, at T_w/T_c ≈ 99 %, only 250 Oe of H_{th} is needed. This HAMR scheme proven to be effectively to reduce the H_{th} down to 90 % (=(2300-250)x100%/2300). The decreased of H_{th} can be attributed to a reduction of ΔE during heating process. The reduced of the ΔE mechanism due to heat activation is illustrated at Figure 10.

Although a heating scheme has been proven to be effectively reduces the H_{th}, in the other hand, this field doesn't depend on heating time t_h as shown at Figure 11(a). This field is constant around 250 – 300 Oe in 800 ps. This t_h independence of H_{th} shows that the randomly magnetized state doesn't change with the vary of t_h. However, it is possible to shorten the t_h in femto seconds order.

In order to understand transfer data to or from HDD process, the cooling time t_w dependences of H_{th} has been evaluated. Observed from Figure 11(b), the H_{th} decreases with an increasing of t_w and becomes constant after 300 ps. The H_{th} reduced about 45% (=(550-300)x100%/550) from 550 Oe at t_w = 0.019 ps to 300 Oe at t_w = 300 ps. This field becomes stable around 250-300 Oe after 300 ps. It can be related to static and dynamic magnetization mechanism in the magnetization reversal process. This result corresponds to data transfer of HDD about Gb/s.

IV. CONCLUSION

The Heat assisted magnetization reversal on perpendicular magnetized nano-dots has been studied by solved Landau Lifshift-Gilbert equation for magnetic recording application. The heat assisted magnetization reversal scheme has been proven to be effectively reduces threshold field down to 90 %. Otherwise, this field doesn't depend on heating time. To understand a read-write information process, cooling time dependence of threshold field has been evaluated. As a result, the threshold field depends on the cooling time and become constant after 300 ps. This result corresponds to data transfer of hard disc drive about Gb/s.

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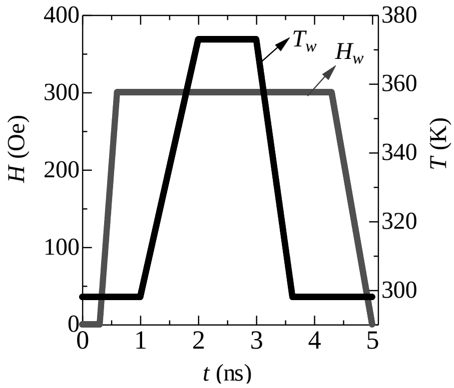


Figure 1. HAMR scheme which calculated for $K_{\perp}$= 3.10^5 erg/cc, 4πM_S = 2.1 kG

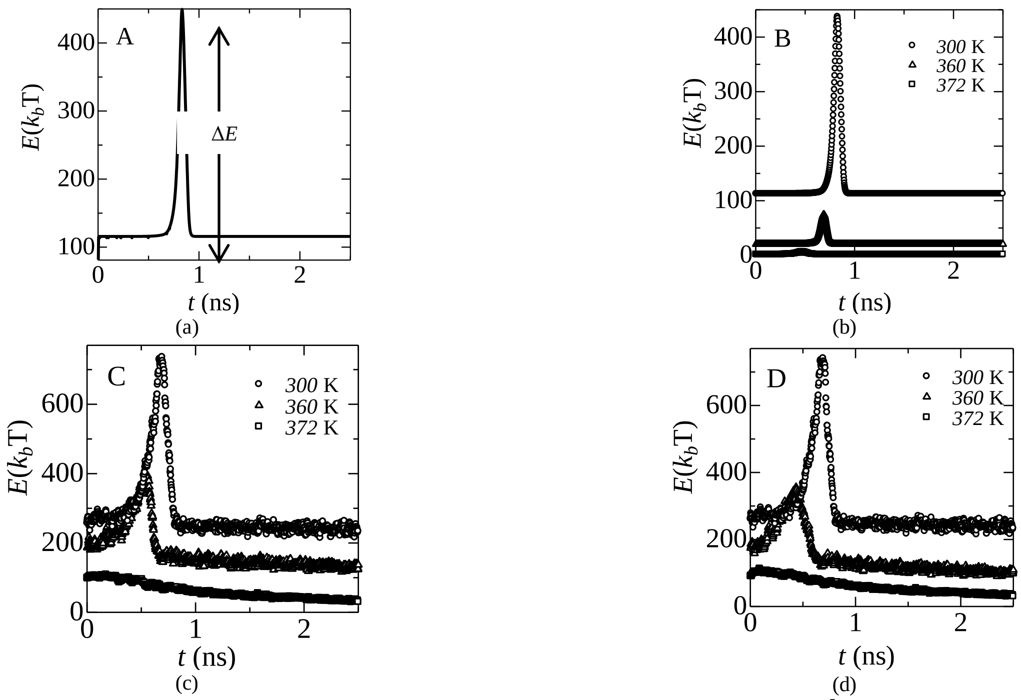


Figure 2. The energy barrier ΔE shape from four different models (a, b, c, and d) calculated for $K_{\perp}$= 3.10^5 erg/cc, 4πM_S = 2.1 kG. (a) the magnetization process by excluding the heat fluctuation effect in a configuration of initial magnetization and the H_{eff}, (b) the magnetization process by including the heat fluctuation effect in the configuration of initial magnetization, (c) the magnetization process by including the heat fluctuation effect in the H_{eff}, (d) the magnetization process by including the heat fluctuation effect in the configuration of initial magnetization and the H_{eff}

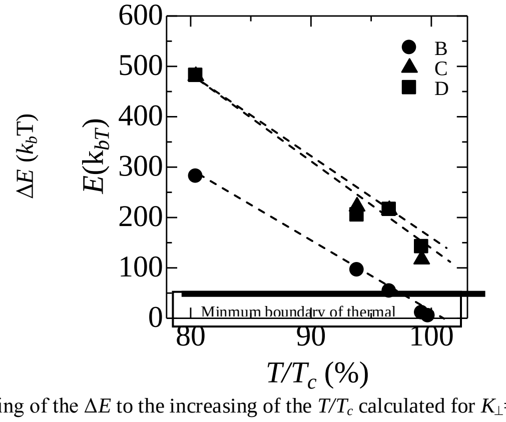


Figure 3. The decreasing of the ΔE to the increasing of the T/T_c calculated for $K_{\perp}$= 3.10^5 erg/cc, 4πM_S = 2.1 kG

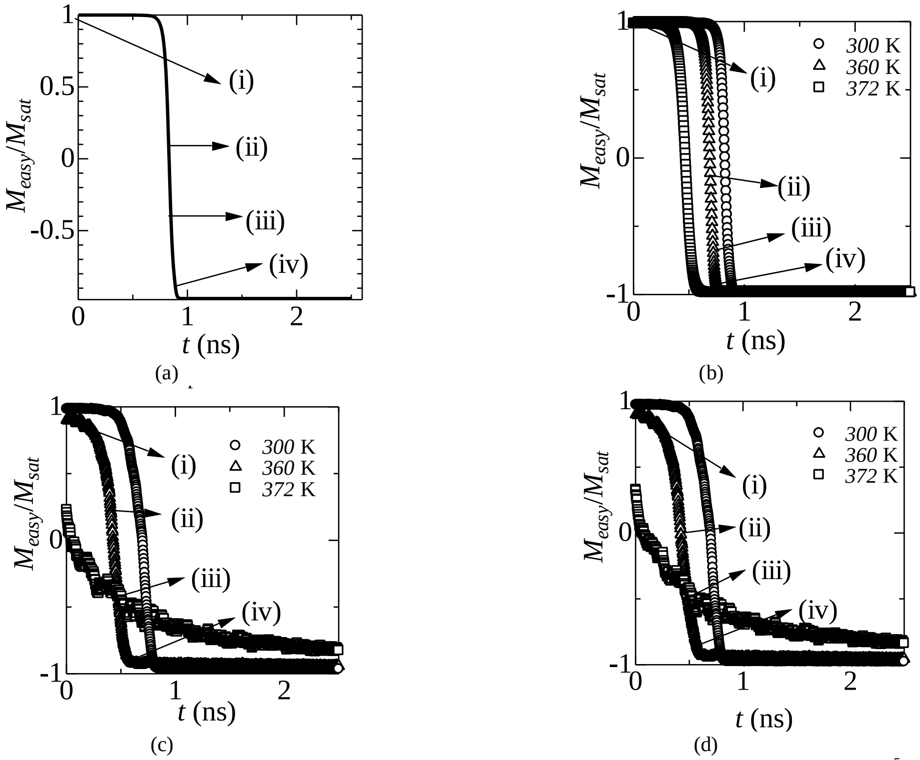


Figure 4. The magnetization reversal mechanism from four different models (a, b, c, and d) calculated for $K_{\perp}$= 3.10[5] erg/cc, $4\pi M_S$ = 2.1 kG

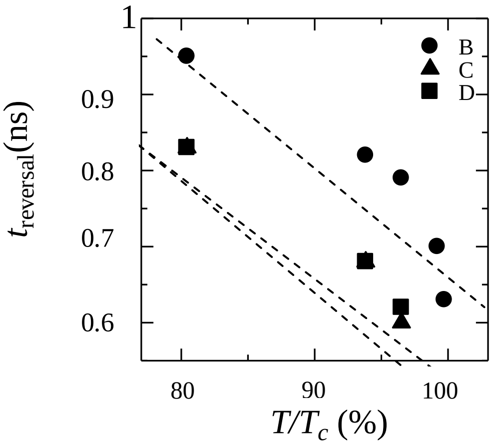


Figure 5. The T/T_c dependence of the $t_{reversal}$ calculated for $K_{\perp}$= 3.10[5] erg/cc, $4\pi M_S$ = 2.1 kG

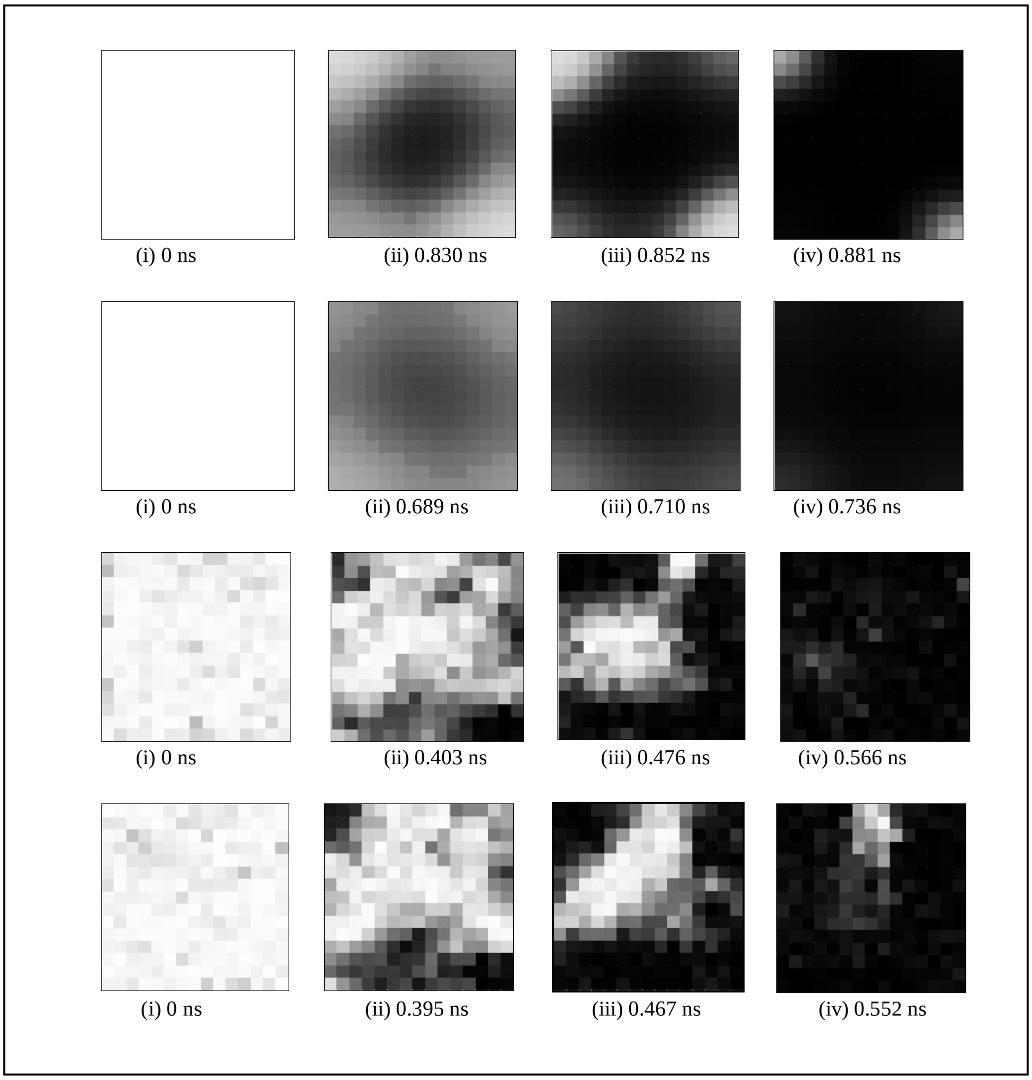


Figure 6. The micromagneticgraph of the magnetization reversal mechanism from four different models (A, B, C and D) calculated for $K_{\perp}$= 3.10^5 erg/cc, 4πM_S = 2.1 kG. Which is the magnetization parallel to the H_w direction shown by black color, and white color shows the opposite direction, vice versa

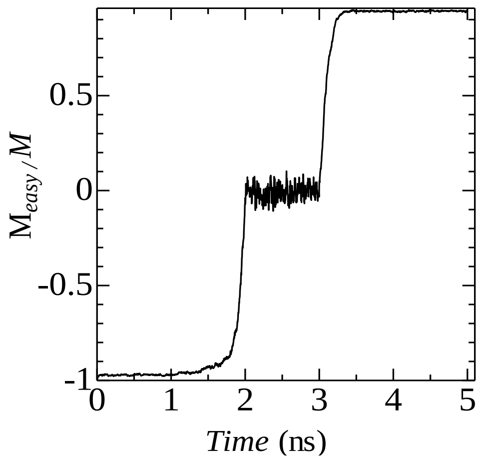


Figure 7. Magnetization reversal process which calculated for $K_{\perp}$ = 3.10^5 erg/cc, 4πM_S = 2.1 kG and a heating pulse T_w = 372.3 K

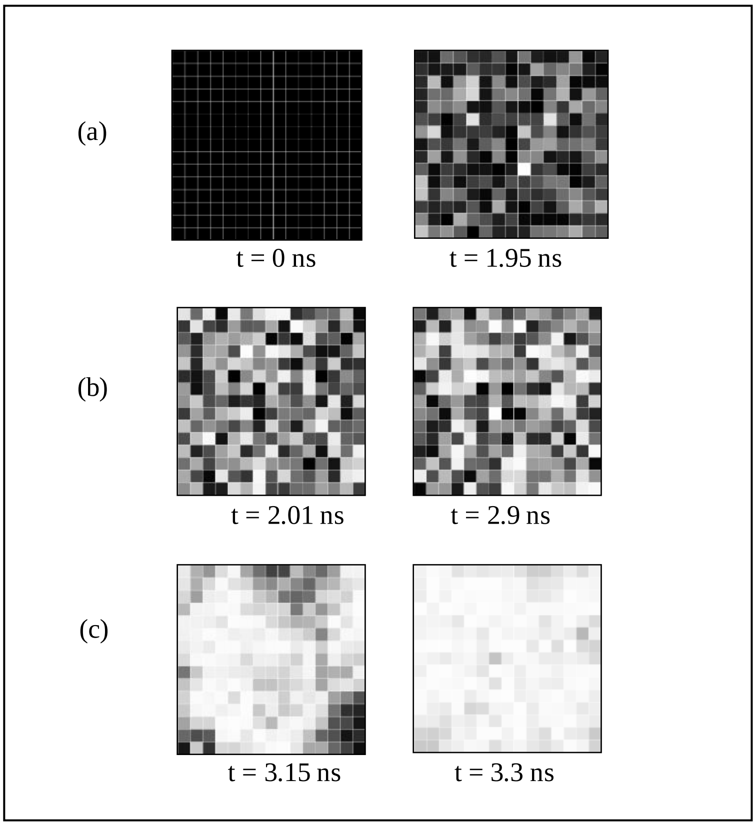


Figure 8. Micromagneticgraph of HAMR which calculated for $K_{\perp}$ = 8.10^4 erg/cc, 4πM_S =1.5 kG and a heating pulse T_w = 372.3 K. (a) before heating applied, t < 2 ns, (b) during heating process, 2 < t < 3 ns and (c) cooling writing/after heating process, t > 3 ns. Which is the magnetization parallel to the H_w direction shown by white color, and black color shows the opposite direction, vice versa

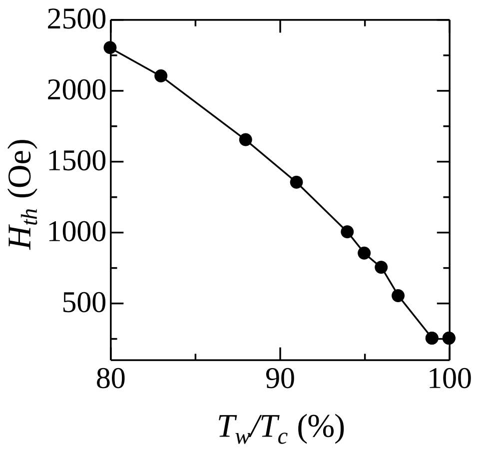


Figure 9. Reduces of threshold field H_{th} with respect to rising of T/T_c which calculated for $K_{\perp}$ = 3.10^5 erg/cc and 4πM_S = 2.1 kG

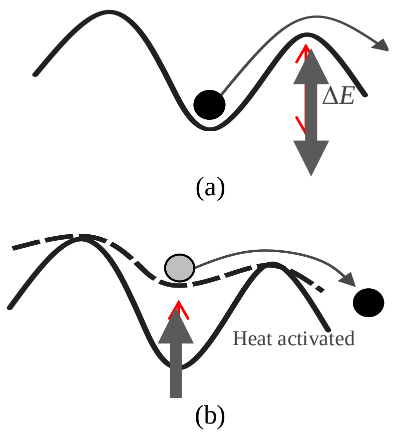
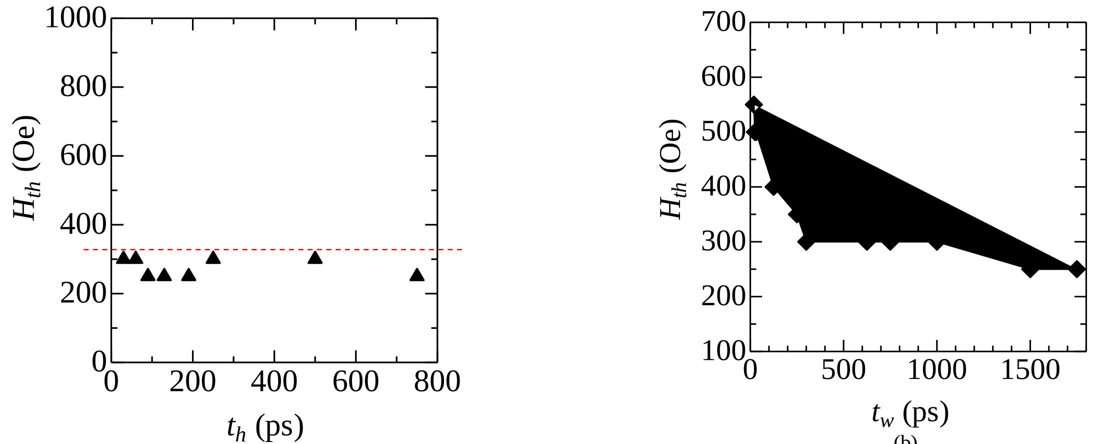


Figure 10. The reduced of the barrier ΔE mechanism caused by heating effect scheme: (a) Initial energy barrier, (b) energy barrier during heating process



(a) (b)

Figure 11. (a) Independences and (b) dependence of H_{th} with respect to heating time t_h which calculated for $K_{\perp} = 3.10^5$ erg/cc, $4\pi M_S = 2.1$ kG and $T_w = 372.3$K