Magnetization switching dynamics in barium-ferrite nano-dot: dependence on magnetic damping constant

Ch Fendy Irawan1,2, Anis Pamilih2, Fasula Sekar Meta2, Nur Aji Wibowo1,3
1 Physics Department, Universitas Kristen Satya Wacana, Indonesia
2 Physics Education Department, Universitas Kristen Satya Wacana, Indonesia
3 Study Center for Multidisciplinary Applied Research and Technology, Universitas Kristen Satya Wacana, Indonesia
E-mail: nurajiwibowo@gmail.com

Abstract. The Landau-Lifshitz-Gilbert equation had been employed to study the effect of Gilbert damping on the dynamics of nano-Barium-Ferrite magnetization. This damping factor is necessary to investigate because of its impact on the dynamics of magnetization switching. In this study, Barium-Ferrite was chosen for study because it has large magnetic anisotropy, excellent chemical stability, and corrosion-free, potentially to be used as a magnetic storage medium with high-density. The nano-Barium-Ferrite magnetic parameters used were the anisotropy constants 3.0 × 10^6 erg/cm^3, 4800 G saturation magnetization, 6.3 × 10^-7 erg/cm exchange field, and Gilbert damping factor which varied from 0.4 to 0.9. By using the Micromagnetic Simulator software, Nano-Barium-Ferrite was simulated as a dot with surface-sized 50 × 50 nm^2 and 20 nm of the thickness. The simulation was conducted using Reduced Barrier Writing (RBW) scheme in which the sample was conditioned at room temperature of 298 K while induced by an external magnetic field. The magnetic field intensity linearly enlarged from 0 to 2 Tesla in 2.5 ns. As a result, the magnetization rate rises exponentially to the increase of Gilbert damping values at room temperature. Furthermore, the magnitude of Gilbert damping gives an impact on the propagation direction of the domain wall.

1. Introduction
Nowadays the magnitude of digital information encourages the creation of high-density magnetic data storage media [1,2]. Hard-disk Drive (HDD) is one of the magnetic-based data storage technologies; it has the potential to answer the need. High-density HDD media can be realized by reducing the size of cell units in nano-meter order [3]. However, minimizing the size of the cell unit cannot be excessive because it may interfere with the thermal stability of the material that affects the loss of data [4]. The minimum standard of thermal stability that must be possessed by the material which the material is capable of storing data for up to 10 years is 60 kBT [5,6]. Therefore, it takes a magnetic material that can be reduced to nano-meter size but still has a thermal stability of 60 kBT. This criterion is found in a perpendicular magnetic anisotropy (PMA) material with higher magnetic anisotropy [7]. The thermal stability of PMA material will persist even if it is formed in nano-meter sizes [8]. However, the magnitude of the magnetic anisotropy possessed by the PMA material causes the data writing process to require the consumption of large magnetic fields [9] since the direction of magnetization is challenging to control. The Gilbert factor plays a vital role in the dynamics of magnetization of PMA materials [10] which determines the precision motion of the material magnetization parallel to the magnetic field induction [11].
In this study, the effect of Gilbert damping will be examined towards the dynamics of magnetization of PMA material at room temperature. The chosen material for use in this research is Barium-Ferrite-based PMA (BaFe$_3$O$_5$). The material was selected because it has relatively large saturation magnetization [12], high chemical stability [12–14], high coercive force [12], and is not easily corrosive [12,15], which to ensure its durability over long periods of time. The effect of the Gilbert damping to the magnetic switching dynamics of the Barium-Ferrite will be investigated using Micro-magnetic Simulator software.

2. Method
The dynamics of Barium-Ferrite magnetization has been investigated by employing the Landau-Lifshitz-Gilbert (LLG) equation that shown in Equation (1) [16] via the improved micro-magnetic simulator created by Takamatsu, et al. from Kyushu University, Japan [6].

\[
\frac{dM}{dt} = -\gamma \frac{1}{1+\alpha^2} (M \times H_{\text{eff}}) - \gamma \frac{1}{1+\alpha^2} \frac{\alpha}{M_s} M \times (M \times H_{\text{eff}})
\]

(1)

The first part in Equation (1) denotes a gyromagnetic form of motion and the second part indicates the term of Gilbert damping which causes the magnetization of the material to tend to align itself with the inductor field, \(H_{\text{eff}}\). In Equation (1), \(M\) is the magnetization of the material, \(\gamma\) is the ratio of gyromagnetic (1.76×10$^7$ Oe$^{-1}$ s$^{-1}$), \(\alpha\) is the Gilbert damping factor varying from 0.4 - 0.9, with the \(dt\) integration step of 0.25 ps. \(H_{\text{eff}}\) is the effective field which is the resultant of the anisotropy field, \(H_{\text{a}}\); demagnetization field, \(H_{\text{d}}\); field of exchange, \(H_{\text{ex}}\); and external magnetic field, \(H_{\text{ext}}\) [10,17].

The selected PMA material in this study was Barium-Ferrite (BaFe$_3$O$_5$) which had anisotropic constants of 3.0×10$^6$ erg/cc [18]. Barium-Ferrite was modeled in a beam-sized 50 × 50 nm$^2$ in yz-axis direction with a thickness of 20 nm in the x-axis direction. It is referred to as a nano-Barium-Ferrite (as one-bit storage of information). Nano-Barium-Ferrite was composed of 15 × 15 cell units in which each surface cell unit of 3.3 × 3.3 nm$^2$ representing the direction of a single magnetic moment. The magnetic parameter used to describe the properties of nano-Barium-Ferrite was a saturation magnetization of 4800 G and an exchange field of 6.3×10$^7$ erg/cm [18].

The simulation using the Reduced Barrier Writing (RBW) scheme that runs with the sample was conditioned in a constant room temperature of 298 K. At first, the sample was in a saturated magnetization in the direction of \(x(+)\), and then a magnetic field, \(H\), was inducted in the direction of \(x(-)\)-axis. The intensity of this field was increased linearly (0 to 2 Tesla in 2.5 ns). The magnetization reversal criterion was defined when 85% of the actual magnetization of the material (\(M\)) is parallel to the induced magnetic field (\(H\)) [6,19]. In this simulation, nano-Barium-Ferrite was assumed to be in an ideal isolated system in which the field of exchange and demagnetization arise as a result of interactions between the unit cells.

In this study, the dynamics of the magnetization reversal of nano-Barium-Ferit will be studied using the basic parameters which are in this mechanism. Some of the things that will be studied are the nucleation fields, coercive fields, and reversal rates. The standard curve in the magnetization reversal mechanism at room temperature is presented in Fig. 1 (a) and (b). In the initial state (Fig. 1 (a)), the material is saturated in \(M_2\) and then give an external magnetic field (\(H\)) which increases linearly. The induced field required to initiate the magnetization movement is called the nucleation field (\(H_n\)), whereas the necessary field to invert 50% magnetization (\(M = 0\)) is referred to as the coercive field (\(H_c\)) [20]. When the nucleation field has been achieved, the magnetization of the material begins to move towards \(M_2\) and realigns itself with the inductor field (\(H\)). This movement takes place within a particular time (\(\Delta t\)) with a magnetization change of material amount as large as \(\Delta M\) (Fig. 1 (b)). The reversal rate is defined as a result of \(\Delta M / \Delta t\).
3. Results and discussion

Thermal stability of materials needs to be calculated (as a fundamental requirement of storage media) to examine the potency of nano-Barium-Ferrite for HDD media. The energy profile possessed by nano-Barium-Ferrite for two different Gilbert damping values on the magnetization reversal mechanism at room temperature is shown in Fig. 2 (a). In the original state, nano-Barium-Ferrite has a basic energy level indicating that the nano-Barium-Ferrite magnetic polarization is in the $x(+)$. Furthermore, nano-Barium-Ferrite energy significantly increases until it reaches the maximum energy level and this level describes the situation when the nano-Barium-Ferrite magnetic polarization will invert. The maximum nano-Barium-Ferrite energy level lasts briefly and then returns to the primary energy level with the nano-Barium-Ferrite magnetic polarization already in the $x(−)$ direction. The heights among the base and the maximum energy of nano-Barium-Ferrite is referred to as the embankment energy ($\Delta E$) which is related to the thermal stability of the material [7]. The calculation of embankment energy for various Gilbert damping values is shown in Fig. 2 (b). The results show that for all measured Gilbert damping values have $\geq 60 \, k_B T$ embankment energy to ensure that it can store stable data at room temperature up to 10 years. The pattern of linkage between Gilbert damping on the energy envelope of nano-Barium-Ferrite is related to the five-order polynomial.

The nano-Barium-Ferrite magnetization during induction with an external magnetic field that increases linearly from 0 to 2 T for 2.5 ns in room temperature is shown in Fig. 3 (a). In the initial state when the induced magnetic field is insufficient to change the direction of the nano-Barium-
Ferrite magnetic moment, $M/M_{\text{sat}}$ has a value of 1 indicating that all cell units have a magnetic polarization in the $x(+)$ direction. When the induced field is sufficient to change the direction of the nano-Barium-Ferrite magnetic moment, $M/M_{\text{sat}}$ begins to move and tends to realign itself against $H$. The movement will continue until $M/M_{\text{sat}}$ has a value $\geq 0.85$ and stable on that number. In the final state when the $M/M_{\text{sat}}$ value has been saturated, the $\geq 85\%$ magnetic moment of nano-Barium-Ferrite is at $x(-)$ or inline with $H$. The magnetization curves formed on the nano-Barium-Ferrite tend to form S where the dominant wall propagation dominates the magnetization reversal process. This result is in accordance with the result that was revealed by Belhi et al. (2010), i.e., that the magnetization reversal curve will be S-shaped when the magnetization reversal method is lead by the domain wall propagation [21,22]. The process of domain wall propagation will be explained in the discussion of Fig. 3 (b). As shown in Fig. 3 (a), the magnetization reversal curve shifts to the left as the damping value of Gilbert increases. It shows that the magnetization can be reversed with a lower induced field in a shorter time.

![Figure 3](image)

(a) Normalization of nano-Barium-Ferrite magnetization, (b) Visualization of nano-Barium-Ferrite magnetization reversal for Gilbert damping 0.50 and 0.75.

![Figure 4](image)

(a) The nucleation field for various linearly attenuated Gilbert values, (b) Coercive field for different Gilbert damping values related exponentially, (c) The reversal rate for different Gilbert damping values.

Visualization of the nano-Barium-Ferrite magnetization reversal for two different Gilbert damping is presented in the micrograph of Fig. 3 (b). In the initial state, nano-Barium-Ferrite has a uniform magnetization in the $x(+)$ direction represented by the red region of the micrograph. When the induced field is sufficient to switch the direction of the magnetic moment of nano-Barium-Ferrite, the domain wall begins to form which is represented by the purple region. This region is an inter-domain region that has an opposite magnetic moment that separates the red area from the blue part. The blue region illustrates that the nano-Barium-Ferrite magnetic moment is in the direction of $x(-)$ or the direction of...
the inductor field \((H)\). The domain wall propagation continues unabated along with increasing induction field until a single domain is formed. From Figure 3 (b) it can be seen that the addition of Gilbert damping value causes a variation in the direction of propagation of the domain wall. The nucleation field information for various Gilbert damping values on the nano-Barium-Ferrite magnetization reversal mechanism is presented in Fig. 4 (a). This information is critical to know as it relates to the minimum field required to start the movement of material magnetization. The increasing of Gilbert damping value causes an increase in the nucleation field which corresponds linearly with a relatively small inclination. Meanwhile, the magnitude of the coercive field for the various damping values of the magnetization reversal mechanism is shown in Fig. 4 (b). This information is also essential to know as it relates to the required switching field. Previous investigations already confirmed that a low coercive field could be achieved by reducing the size of the cell units or by raising the temperature of the material \([23,24]\). In this study, it was found that lowering the coercive field also can be done by increasing of the Gilbert damping value approximately to 0.8. It appears that at room temperature, the coercive field changes quadratically against the Gilbert damping.

The rate of nano-Barium-Ferrite magnetization which is under induced magnetic field treatment for different Gilbert damping values is presented in Fig. 4 (c). The rate of magnetization switching is important to be investigated because of its correlation to the efficiency of the data recording mechanism. A high reversal rate will provide greater efficiency in terms of the duration of the reversal or the consumption of the inducing field. The reversal rate can be increased through the thickness reduction of the cell units \([25]\). Also found in this study, the damping level should be enlarged to increase the reversal rate. At room temperature, it is observed that the magnetization rate rises exponentially to the increase of Gilbert damping level.

4. Conclusion
The effect of Gilbert damping on the magnetization dynamics of Barium Ferrite-based PMA materials has been studied by solving the Landau-Lifshift Gilbert equations. It has been found that Barium-Ferrite has excellent thermal stability at all of the measured Gilbert damping values. Increasing the Gilbert damping value can shorten the magnetization reversal process and reduce the coercive field. However, this causes an increase in the nucleation field. The reversal rate increases exponentially as the damping value increases. In this study, it is also obtained that the value of Gilbert damping gives an effect on the propagation direction of the domain wall.

5. Acknowledgment
This research was supported by a grant from Kemenristekdikti through Student Creativity Program-Research (PKM-PE) 2018.

6. References

[1] Weller D, Moser A, Folks L, Best M E, Lee W, Toney M F, Schwickert M, Thiele J U and Doerner M F 2000 High Ku materials approach to 100 Gbits/in2 IEEE Transactions on Magnetics 36 10–5
[2] Mizukami S, Iihama S, Inami N, Hiratsuka T, Kim G, Naganuma H, Oogane M and Ando Y 2011 Fast magnetization precession observed in L10-FePt epitaxial thin film Appl. Phys. Lett. 98 052501
[3] Kim C, Loeding T, Jang S, Zeng H, Li Z, Sui Y and Sellmyer D J 2007 FePt nanodot arrays with perpendicular easy axis, large coercivity, and extremely high density Appl. Phys. Lett. 91 172508
[4] Wood R 2009 Future hard disk drive systems Journal of Magnetism and Magnetic Materials 321 555–61
[5] Krone P 2011 Magnetization Reversal Processes of Nanostructure Arrays
[6] Wibowo N A, Rondonuwu F S and Purnama B 2014 Low Writing Field on Perpendicular Nano-ferromagnetic Journal of Magnetics 19 237–40
[7] Azizah U M N, Jessajas M B, Handoyo C and Wibowo N A 2017 Characteristic of Nano-barium-ferrite as Recording Media Using HAMR Technology Chiang Mat J. Sci 44 1669–75
[8] Purnama B, Koga M, Nozaki Y and Matsuyama K 2009 Stochastic simulation of thermally assisted magnetization reversal in sub-100nm dots with perpendicular anisotropy Journal of Magnetism and Magnetic Materials 321 1325–30

[9] Alebrand S, Gottwald M, Hehn M, Steil D, Cinchetti M, Lacour D, Fullerton E E, Aeschlimann M and Mangin S 2012 Light-induced magnetization reversal of high-anisotropy TbCo alloy films Appl. Phys. Lett. 101 162408

[10] Herianto N A, Rondonuwu F S and Wibowo N A 2015 Damping Dependence of Reversal Magnetic Field on Co-based Nano-Ferromagnetic with Thermal Activation Smart Science 3 16–20

[11] Sadnawanto W and Purnama B 2014 Stochastic effect on thermally magnetization reversal in Pico second ordering process J. Phys.: Conf. Ser. 539 012024

[12] Meng Y Y, He M H, Zeng Q, Jiao D L, Shukla S, Ramanujan R V and Liu Z W 2014 Synthesis of barium ferrite ultrafine powders by a sol–gel combustion method using glycine gels Journal of Alloys and Compounds 583 220–5

[13] Yamauchi T, Tsukahara Y, Sakata T, Mori H, Chikata T, Katoh S and Wada Y 2009 Barium ferrite powders prepared by microwave-induced hydrothermal reaction and magnetic property Journal of Magnetism and Magnetic Materials 321 8–11

[14] Chen D, Liu Y, Li Y, Zhong W and Zhang H 2011 Microstructure and magnetic properties of low-temperature sintered CoTi-substituted barium ferrite for LTCC application Journal of Magnetism and Magnetic Materials 323 2837–40

[15] Shimizu O, Murata Y, Kurihashi Y, Harasawa T, Asai M, Sueki M and Noguchi H 2012 Long-Term Archival Stability of Barium Ferrite Magnetic Tape J. Magn. Soc. Jpn. 36 1–4

[16] Lisfi A and Lodder J C 2002 Relation between the microstructure and magnetic properties of BaFe12O19 thin films grown on various substrates Journal of Magnetism and Magnetic Materials 242–245 391–4

[17] Schrefl T, Fidler J, Suess D, Scholz W and Tsiantos V 2006 Micromagnetic Simulation of Dynamic and Thermal Effects Handbook of Advanced Magnetic Materials (Springer, Boston, MA) pp 128–46

[18] Boardman R P 2005 Computer simulation studies of magnetic nanostructures phd (University of Southampton)

[19] Purnama B, Nozaki Y and Matsuyama K 2007 Micromagnetic simulation of thermally assisted magnetization reversal in magnetic nanodots with perpendicular anisotropy Journal of Magnetism and Magnetic Materials 310 2683–5

[20] Richter H J and Harkness S D 2006 Media for Magnetic Recording Beyond 100 Gbit/in.2 MRS Bulletin 31 384–8

[21] Wibowo N, Handoyo C and Ricky Sasonkko L (in press) Thermally Activated Magnetic Switching Mode for Various Thicknesses of Perpendicular Ferromagnetic Nano-dot Nanoscience & Nanotechnology-Asia 08

[22] Belhi R, Adjano A A, Vogel J, Ayadi M and Abdelmoula K 2010 Magnetization reversal dynamics, nucleation, pinning, and domain wall propagation in perpendicularly magnetized ultrathin cobalt films: Influence of the Co deposition rate Journal of Applied Physics 108 093924

[23] Sepehri-Amin H, Ohkubo T, Gruber M, Schrefl T and Hono K 2014 Micromagnetic simulations on the grain size dependence of coercivity in anisotropic Nd–Fe–B sintered magnets Scripta Materialia 89 29–32

[24] Kilic U, Finocchio G, Hauet T, Florez S H, Aktas G and Ozatay O 2012 Magnetic switching driven by nanosecond scale heat and magnetic field pulses: An application of macrospin Landau-Lifshitz-Bloch model Appl. Phys. Lett. 101 252407

[25] Aji P P, Rondonuwu F S and Wibowo N A 2017 Thickness Dependence Of Magnetic Switching Dynamics Of Barium-Ferrite As A High-Density Perpendicular Magnetic Storage Media Jurnal Pendidikan Fisika Indonesia 13 112–8