IOP Conf. Series: Materials Science and Engineering **176** (2017) 012050 doi:10.1088/1757-899X/176/1/012050

Micromagnetic simulation of vortex-antivortex magnetization in permalloy nano particle

B Purnama[1], **S Muhammady and Suharyana**
Department of Physics, Faculty of Mathematics and Natural Sciences,Universitas Sebelas Maret, Jl. Ir. Sutami 36A Kentingan Surakarta 57126, Indonesia

E-mail: bpurnama@mipa.uns.ac.id

Abstract. A process of vortex-antivortex magnetization reversal in a Permalloy nano particle with uniform polarity of magnetization has been investigated numerically. Micromagnetic simulation is performed using the Landau–Lifshitz–Gilbert equation. A short field pulse is applied in a film plane anti parallel to magnetization direction. Sequences of simulation of reversals mechanism are evaluated for thickness of nano particle. As the results in the case of thickness of 20 nm thin layer, magnetization reversal realizes through a creation-annihilation of Neel-Bloch wall pair. Contrarily, reversal mechanism via a creation-annihilation process of vortex-antivortex pair occurs for thickness of 60 nm thin layer. By analyzing barrier energy of the sample, we find that a maximum barrier energy reaches a threshold value (e.g., ~ 2.6×10^6 erg/cm^3 for Permalloy in this simulation).

1. Introduction

Nanometer-order size of magnetic devices is desired to be realized a high density hard disk drive (HDD), i.e. exceed to 10 Tbit/in^2 in the near future. For realizing, the most important effort up to now is how to maintain the magnetic property if a magnetic material scales down to nanometer-order without a significant thermal effect. As known well, the thermal effect causes the parts of magnetic property lost.

Generally, read-write mechanism of magnetic device employs magnetization reversal. Conventionally, magnetization reversal even occurs at infinite large medium such as continues films or bulk materials. There are two type of switching i.e. spontaneous magnetization via coherent rotation and magnetization reversal via domain nucleation following wall propagation to single domain configuration. Furthermore, configuration of domain wall should be Néel wall and Bloch wall. The magnetization reversals also may occur via vortex-antivortex formation [1-6]. In-depth information regarding the magnetization reversal mode will guide the design of nano devices with a minimum magnetic field require for reversal.

In this paper, a numerical investigation to study magnetization reversal on nanometer pattern Permalloy is carried-out using micromagnetic simulation by solved Landau-Lifshitz-Gilbert (LLG) equation. The discussion focus on the vortex-antivortex formation during magnetization reversal under magnetic field with nano second duration. In order to modify the vortex-antiovortex formation, thickness dependence of magnetic field required for switching is also investigated.

[1] To whom any correspondence should be addressed.

2. Experimental

Generally, magnetization under the influence of H_{eff} is given as Landau-Lifshitz-Gilbert (LLG) equation

$$\frac{dM^i}{dt} = -|\gamma| M^i \times H^i_{eff} + \frac{\alpha}{M_S} M^i \times \frac{dM^i}{dt} \quad (1)$$

where M_s is saturation magnetisation, $|\gamma|$ is gyromagnetic ratio ($|\gamma| = 1{,}76 \times 10^7$ $Oe^{-1}s^{-1}$ for free electron in metal) and α is Gilbert attentuation parameter. Magnetic energy consists of components, i.e. exchange energy, anisotropy energy, demagnetisation energy, and Zeeman energy. Without Zeeman energy, magnetic energy can be written as

$$E_{tot} = \int_V \left(A \sum_{i=x,y,z} (\nabla m_i)^2 + \varepsilon_a - \tfrac{1}{2} M \cdot H_d \right) dV \quad (2)$$

with $\boldsymbol{H}_d$ is demagnetisation vector, $\varepsilon_a = K[1 - m \cdot k]$, $m = M/M_S$ and k is unit vector directed to in-plane. In this simulation, 50 nm × 100 nm sized nanoparticel permalloy was subdivided into rectangular elements of 15 × 15. The nanosize permalloy is assumed here as uniaxial anisotropy structured in-plane nanoparticles with anisotropy constant K = 5000 erg/cm^3, exchange constant $A = 1{,}3 \times 10^{-6}$ erg/cm, saturation magnetisation $4\pi M_s = 1{,}0 \times 10^4$ gauss, $\alpha = 0{,}3$ and step time integraltion (dt) = $2{,}5 \times 10^{-13}$ s [4-5].

3. Results and Discussion

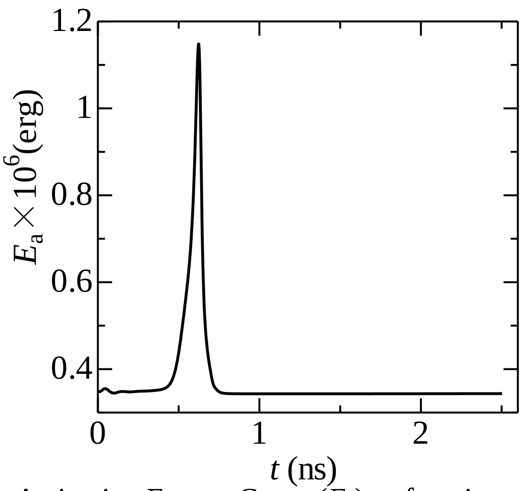

Figure 1. Activation Energy Curve (E_a) as function of time (t).

In this paper, energy which is needed to cause magnetisation reversal process is defined as activation energy (E_a) i.e. minimum energy that magnetic moment need to change from initial minimum condition into another minimum condition as shown at Figure 1. A left region of peak curve is initial condition and a right region of peak curve is other local minimum which obtains after the magnetization reversal. In this simulation, initial condition is set to be uniformly magnetization $M = 1$ when zero field is applied. Then, field with disagree orientation to initial magnetization is used to reverse the initial magnetization. So that magnetization gradually along to field direction. When the magnetization reduces to zero ($M = 0$) and starts to the reversed direction, the magnetization reversal occurs. The field is required for the magnetization reversal even define as switching field (H_{sw}).

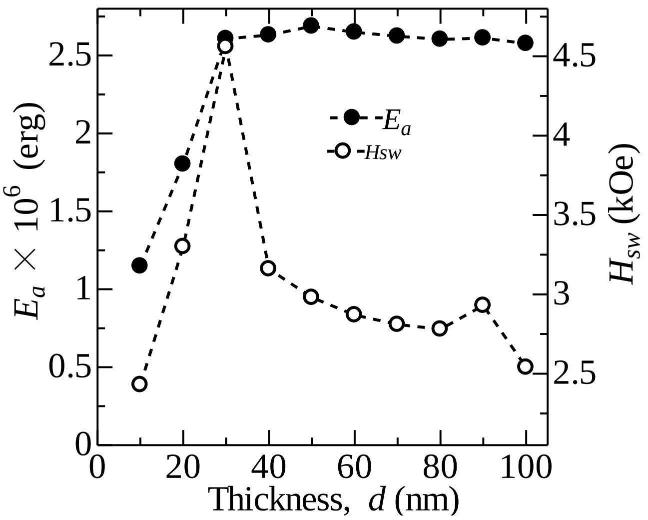

Figure 2. Thickness (d) dependence of the activation energy E_a and the switching field H_{sw}.

Figure 2 shows the thickness dependence of both the E_a and the H_{sw} under short pulse for 2.5 ns magnetic field of H_{eff} = 5 kOe. It is clear that the E_a goes up with the increase of the thickness, d and then becomes a constant at 2.6×10^6 erg after the critical thickness, d is obtained i.e. 30 nm. In this case, the maximum of the E_a is attained. Contrarily, the H_{sw} at the beginning linearly increases with the raise of the d, after d = 30 nm the remaining H_{sw} decreases with increasing the thickness. From the simulation results, it means that the addition mechanism for lowering the H_{sw} is necessary after the critical thickness is attained. When the d is equal 30 nm, the field required for switching H_{sw} is about 4.56 kOe. Moreover, the H_{sw} is only 2.54 kOe at d = 100 nm. Here, the lowering factor is about 44.3% (=((4.56-2.54)/4.56)×100%). The obtained result is well-suited to previous report by Zhang and Liu [7].

In more detailed, the gradually magnetization reversal on the micro-magnetic graph is analyzed as depicted at Figure 3. Three sequence of magnetization reversal for thickness d of 20 nm (after that call **X**), 30 nm (**Y**) and 60 nm (**Z**) is compared their type of nucleation mode. For X case, formation mode is most simple than for both Y and Z cases. Here, a very fast creation and domain wall propagation is appeared. And then the domain wall is quickly disappeared. There are 3 domains separated by Néel walls with typical S-state during in about 0.09 ns (90 ps). Contrast for the Y and the Z cases. A pairing vortex-antivortex is observed during the magnetization reversal. For the Y case, the first vortex-antivortex appears at t = 1.11 ns then makes an interaction with the other and finally disappeares as a single domain configuration at t = 1.21 ns. Duration time of the pairing vortex-antivortex is available about 0.1 ns (100 ps). For the Z case, very fast creation type of the vortex-antivortex is turned up at t = 0.68 ns and it makes interaction for t = 0.13 ns (130 ps) with other configuration to be a single domain formation via annihilation of domain wall. This means clearly that time for the first nucleation type of vortex-antivortex much effectively influences the assisted magnetization reversal. For the Y case, the time required for the first nucleation is much longer than the Z case because magnetic energy compensation of Bloch wall creation decreases with the increase of the thickness. From this fact, the field required for switching (H_{sw}) decreases with enlargement of the thickness (d) although the energy activation (E_a) is not so much different (see also the Fig. 2). From the above discussion, although the magnetic field require for switching H_{sw} is still ~ kOe orde, the critical thickness for a constant of the E_a is one point interesting for practical application. The high enough of the E_a will ensure thermal stability when sample down scale to nano meter orde without loss their magnetization at room temperature.

IOP Conf. Series: Materials Science and Engineering **176** (2017) 012050 doi:10.1088/1757-899X/176/1/012050

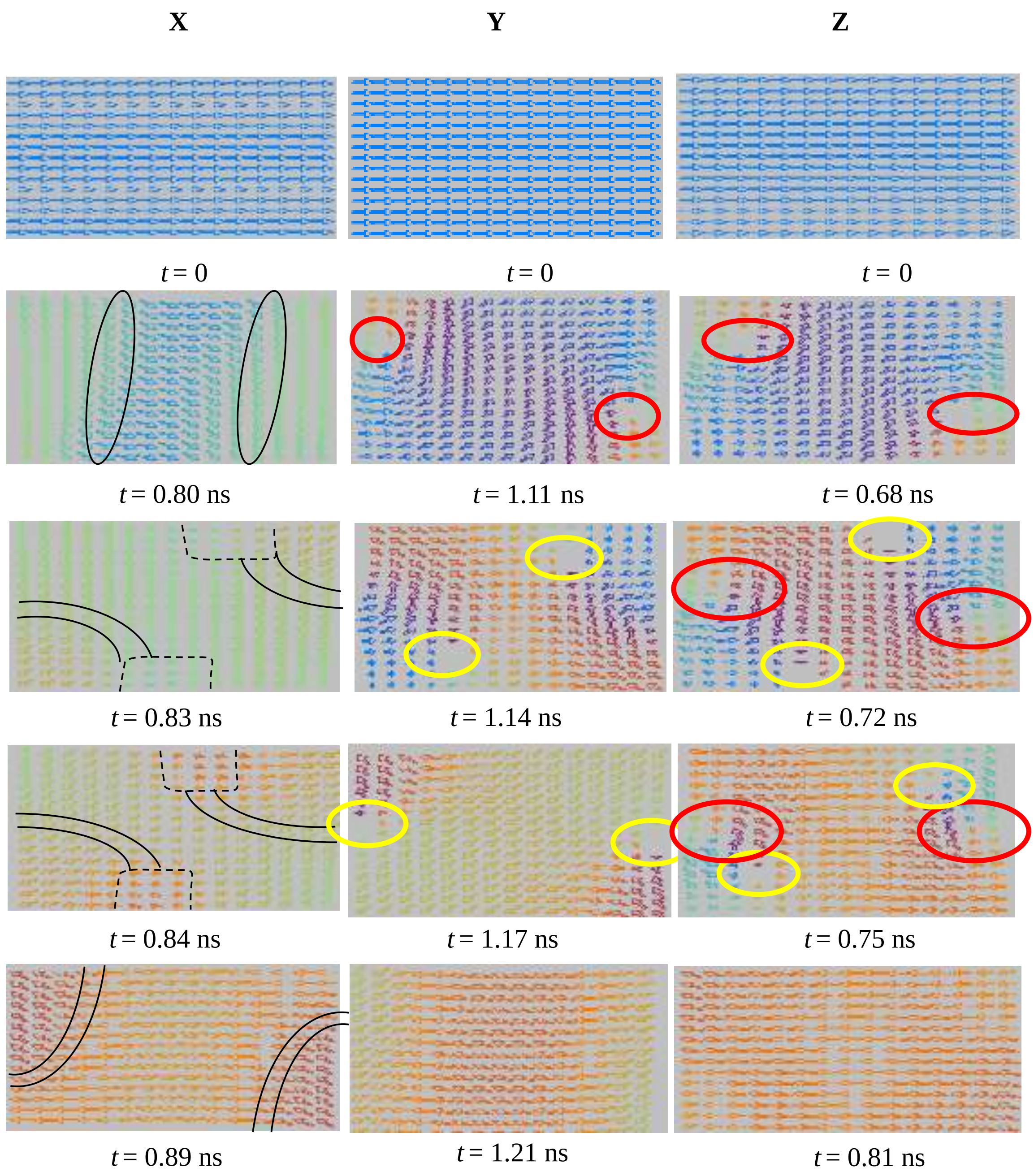

Figure 3. Micro-magnetic grapgh of magnetization reversal process in X (t = 20 nm), Y (t=30 nm) and Z (t = 60 nm). Yellow and red circles indicate vortex and anti-vortex.

4. Conclusion

We have studied a process of vortex-antivortex magnetization reversal in a Permalloy nano particle with uniform polarity of magnetization by Micromagnetic simulation. A short field pulse is applied in a film plane anti parallel to initial magnetization direction. Sequence of simulation of reversals mechanism is evaluated for thickness of nanometer order particle. In the case of thickness of 20 nm thin layer, magnetization reversal realized through a creation-annihilation of Neel-Bloch wall pair. Contrarily for the thickness of 60 nm thin layer, reversal mechanism via a creation-annihilation

IOP Conf. Series: Materials Science and Engineering **176** (2017) 012050 doi:10.1088/1757-899X/176/1/012050

process of vortex-antivortex pair. By analyzing barrier energy of the sample we find that a maximum barrier energy reaches a threshold value (e.g., ~ 2.6×106 erg/cm^3 for Permalloy in this simulation).

References

[1] Yaying Z. 2003 *Magnetic Simulation on Advanced Recording Media*. Thesis. Department of Electrical and Computer Engineering, National University of Singapore.

[2] Schrefl T, Hrkac G, Goncharov A, Dean J, Bance S, Bashir MA. 2008 Finite Element/Boundary Element Simulation of Future Hard Disk Recording. *Applied Computing Conference*, Istanbul, Turkey, May 27-30.

[3] Jian-Gang, Z. 2003. New Weights for Hard Disk Drives. Materials Today July/August. Department of Electrical and Computer Engineering and Data Storage Systems Center, Carnegie Mellon University, Pittsburgh, PA

[4] Gupta R, Gupta M, and Gutberlet T. 2008 J. Phys., **71**, 1123-1127

[5] Ross CA. 2001 *Annu. Rev. Mater. Res*., **31**, 203-235 (2001).

[6] Bolte MBW, Möller DPF, Meier GD, Thieme A. 2004 *Simulation of Micromagnetic Phenomena*. Proceedings 18th European Simulation Multiconference Graham Horton (c) SCS Europe.

[7] Zhang H and Liu Y. 2012 *J. of Nanosci. and nanotech.* Vol. **12**. 1063-1066