The diameter effect on the magnetization switching time of sphere-shaped ferromagnets using micromagnetic approach

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Abstract. In this work, the magnetization switching time has been studied as the diameter variation of sphere-shaped ferromagnets by means of micromagnetic simulation. Some ferromagnetic elements such as cobalt, iron, nickel, and permalloy were numerically simulated with diameter size variation from 50 nm to 100 nm. The micromagnetic simulation was performed by public software Object Oriented Micromagnetic Framework (OOMMF) based on the Landau-Lifshitz-Gilbert (LLG) equation. The ferromagnetic nano-sphere was induced by the quasi-static magnetic field to observe its magnetization response. Generally, it is observed that the switching time increases as the diameter size increases on the ferromagnetic elements. However, the switching time are relatively insensitive as the diameter increases in the Cobalt element for the diameter range from 60 nm to 90 nm. This behavior is contributed to the distribution of magnetization easy axis on the ferromagnetic elements. The understanding of domain structures during magnetization switching process is important in the development of nano-patterned magnetic memory storage.

Keywords: Magnetization switching, sphere, ferromagnetics, micromagnetics

1. Introduction
The advancement of the magnetic recording technology in the last 20 years have made the dynamic of ferromagnetic nanomaterials are of the important research topics on the developing of Magnetoresistive Random-Access Memory (MRAM), microwave oscillators, and magnetic nanosensors as the potential applications [1-4]. One of the interesting issues in the development of granular magnetic recording media is the understanding of magnetization reversal in individual grain or element [5, 6]. It is known that the advantages of using individual magnetic grain for storing data is the reduction of bit transition jitter and increase the signal to noise ratio compared to the regular perpendicular magnetization media [7]. Another important attempt to improve the data density is by using the high magnetic anisotropy materials in the exchange-coupled system [8]. Therefore, the magnetic domain formation and evolution of individual grain with magnetic anisotropy variation are of the interesting approaches to improve our understanding in granular storage media application.

In magnetic materials, the magnetic properties are also contributed by the distribution of magnetic element size, shape, and the interelement interaction. There are many studies using different magnetic element shape, such as circle [9], square [10], nanoring [11] and Reuleaux’s triangle [12]. However, the
magnetization switching of sphere-shaped ferromagnetic element was rarely studied, although many of the nanoelement ferromagnetic material was a spherical shape.

In this work, the magnetization switching time has been studied as the diameter variation of sphere-shaped ferromagnets by means of micromagnetic simulation. Some kinds of basic ferromagnetic materials, such as cobalt, iron, nickel, and permalloy were numerically simulated under a quasi-static magnetic field induction to obtain the magnetic hysteresis curve. The switching phenomena are investigated by observing the domain structure evolution and time consumed during magnetization switching process, which called as the switching time.

2. Micromagnetic model

The micromagnetic simulation based on the Landau-Lifshitz-Gilbert equation was performed by public software OOMMF with damping constant ($\alpha$) of 0.1 and the cell size of 2.5 $\times$ 2.5 $\times$ 2.5 nm$^3$ by considering the exchange length ($l_{ex}$) of the materials [13, 14]. Some ferromagnetic elements used in the simulation, such as cobalt (Co), iron (Fe), nickel (Ni) and permalloy (Py) with the material parameters are depicted in table 1. The materials Co, Fe, Ni, and Py were chosen as they are the basic elements (and alloy for Py) of ferromagnetic materials. The sphere-shaped model was numerically simulated with diameter size varied from 50 nm to 100 nm as shown in figure 1. Such the size range was modeled as the representation of single-domain particle (smaller) and multi-domain particle (larger), as predicted by Kittel [15]. The ferromagnetic nano-sphere was induced by the quasi-static magnetic field to observe its magnetization response and produce a hysteresis curve. The domain structure was investigated using the time-resolve imaging technique during reversal process. The switching magnetization field and time were observed based on the produced hysteresis curve and compared to the time-resolved images.

Table 1. The material parameters used in the micromagnetic simulation.

| Materials       | $M_s$ [A/m] | $A$ [J/m] | $K$ [J/m$^3$] | $l_{ex}$ [nm] | Crystal structure | Ref.     |
|-----------------|-------------|-----------|---------------|---------------|------------------|---------|
| Cobalt (Co)     | $1,400 \times 10^3$ | $14 \times 10^{-12}$ | $53 \times 10^4$ | 4.7           | hcp              | [16]    |
| Iron (Fe)       | $1,700 \times 10^3$ | $21 \times 10^{-12}$ | $4.8 \times 10^4$ | 3.3           | bcc              | [12]    |
| Nickel (Ni)     | $490 \times 10^3$  | $9 \times 10^{-12}$  | $-0.57 \times 10^4$ | 7.6           | fcc              | [12]    |
| Permalloy (Py)  | $860 \times 10^3$  | $13 \times 10^{-12}$ | 0              | 5.1           | fcc              | [17]    |

Figure 1. Sphere-shaped ferromagnets with random initial magnetization modeled in the micromagnetic simulation.
3. Results and discussion

The hysteresis curves of the sphere-shaped ferromagnets produced from the simulation are displayed in figure 2. The quasi-static magnetic field was induced in the $x$-direction, which simulated the hard-axis orientation (HAO) of the sphere-shaped ferromagnets. There are some point marked with number 1–4 in the hysteresis curves, that are the saturation point, remanence point, coercivity point, and opposite saturation point. It can be seen that the hysteresis curves are relatively slanted for all ferromagnets as the diameter increases. However, the materials with smaller anisotropy, such as Nickel and Permalloy showed the square shaped hysteresis loop in the smaller size as depicted in figure 2a. It means that the slanted hysteresis curve was depended on the magnetocrystalline anisotropy of the materials. In the larger diameter, the slanted level of hysteresis curves is relatively higher. It means that the magnetic field needs to switch to uniform the saturation magnetization is also increased. At this point, the switching phenomena was expected to have a linear behavior with the slanted level of hysteresis curve.

To improve the understanding of switching phenomena, the evolution of domain structures during switching magnetization process was also investigated. As shown in figure 3, the domain structure of all sphere-shaped ferromagnets at saturation (and the opposites), remanence and coercivity condition are observed. Generally, the switching processes are followed by the vortex domain structure formation, which can be seen at remanence and coercivity condition (point 2 and 3). However, it is observed that the different domain structure can be formed at remanence condition. At smaller diameter size of Co and Ni, the vortex core is not observed at the remanence condition. For Co sphere, this effect is due to the higher anisotropy value, that might be not allowing the formation of vortex core at the smaller size close to single domain particle size. On the other hand, the absence of vortex core for Ni sphere might be contributed by the squareness effect of hysteresis curve. As compared with the figure 2a, the Ni sphere has a higher squareness of hysteresis curve. This behavior caused the domain wall nucleation did not happen in the remanence condition and made the Ni sphere has the higher magnetization remanence value at smaller size. We have expected that the domain nucleation is the important factor during the switching process.

![Figure 2](image)

**Figure 2.** Hysteresis curve of sphere-shaped ferromagnets at (a) $d = 50$ nm and (b) $d = 100$ nm. The bullet number pointing the domain structure observation during switching process.
Figure 3. Domain evolution of sphere-shaped ferromagnets during switching process for $d = 50$ nm and $d = 100$ nm. Point 1 and 4 show the opposite direction of saturation magnetization. Point 2 and point 3 show the remanence and coercive condition, respectively.
Figure 4. Switching time for sphere-shaped ferromagnets with the diameter variation.

As displayed in figure 4, the switching time of sphere-shaped ferromagnets are plotted as the diameter size increases. Generally, it is observed that the switching time increases as the diameter size increases on the ferromagnetic elements. This result agrees with the previous result of magnetization reversal in hexagonal-shaped BaFe12O19 materials [18]. However, the switching time are relatively insensitive as the diameter increases in the Cobalt element for diameter ranges from 60 nm to 90 nm. This behavior is contributed to the distribution of magnetization easy axis on the ferromagnetic elements. It also observed that the switching time for Co has one order value larger compared to the other sphere-shaped ferromagnets. This result agrees with the hysteresis curves produced in the simulation. It can be compared that the slanted hysteresis is linearly correlated with the switching time. Therefore, the larger magnetocrystalline anisotropy material produced a larger switching time value at hard-axis orientation. This study showed that the understanding of domain structures evolution during the magnetization switching process could be an important step in the development of nano-patterned magnetic memory storage.

4. Conclusion
In this paper, the magnetization switching time has been studied as the diameter variation of sphere-shaped ferromagnets, such as cobalt, iron, nickel, and permalloy by means of micromagnetic simulation using public software OOMMF based on the LLG equation. It was observed that the switching processes were followed by the vortex domain structure formation, which can be seen at remanence and coercivity condition. It was observed that the switching time increases as the diameter size increases on the ferromagnetic elements. However, the switching time are relatively insensitive as the diameter increases in the cobalt element for diameter ranges from 60 nm to 90 nm contributed to the distribution of magnetization easy axis on the ferromagnetic elements. It can be compared that the slanted hysteresis is linearly correlated with the switching time. Therefore, the larger magnetocrystalline anisotropy material produced a larger switching time value at hard-axis orientation. The understanding of domain structures evolution during the magnetization switching process is important in the development of nano-patterned magnetic memory storage.

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