Magnetization Dynamic Analysis of Square Model CoFe and CoFeB Ferromagnetic Materials Using Micromagnetic Simulation

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Abstract. In this study, dynamic magnetization of square model CoFe and CoFeB ferromagnetic materials were observed using micromagnetic simulation based on LLG equation. The geometrical side size was varied from 50 to 500 nm with the thickness of 5 nm and 10 nm. For simulation process, the used damping factor was 0.05 and the cell size of 2.5×2.5×2.5 nm\textsuperscript{3} was used with respect to exchange length of CoFe and CoFeB. The external magnetic fields were applied in in-plane and out-plane direction to generate magnetic hysteresis loop. It is found that the coercivity decreased as square size increased for both in-plane and out-plane magnetization direction. The coercivity were around 40 to 200 mT for in-plane field magnetization of CoFe. The coercivity tends to constant at 40 mT in diameter less than 100 nm and zero coercivity for diameter greater than 100 nm for out-plane field magnetization. Compared to CoFe, the coercivity in out-plane field is higher than in-plane field in CoFeB square. It is also observed that the switching time and nucleation field increased as the size increased in out-plane direction of both CoFe and CoFeB. The results showed that the different characteristics of magnetic anisotropy of both materials are important in the development of high density magnetic storage.

Keywords: CoFe, CoFeB, hysteresis, micromagnetic, magnetic anisotropy

1. Introduction
Previous publications showed that the Fe-based nanoelements were highly used because of the cheaper costs, easier to make, and easier modified [1]. Currently, many nanostructures based on CoFe and CoFeB ferromagnetic materials were developed because of some interesting properties. The CoFe based materials has unique properties that are widely used for applications requires high flux density such as data storage and electronic devices [2]. Soft magnetic CoFe thin film with high anisotropy $2.7 \times 10^3$ J/m\textsuperscript{3}, high Curie temperature, good permeability has been paid great attention [3]. To get material with large anisotropy more than $2.7 \times 10^3$ J/m\textsuperscript{3}, an additive material Boron was added to the CoFe structure to be CoFeB thin film [4]. By influence of Boron element, it was found that important characteristics of perpendicular magnetic anisotropy (PMA) was emerged [5]. Therefore the dynamic
magnetization process in CoFe and CoFeB become an interesting topic and can be studied by experiments and micromagnetic simulation [6]. The PMA materials raise great interest due to their potential in magnetic memory device as high-density non-volatile memory. The non-volatile memory reduces power consumption than volatile that requiring 50% power [7]. The arrangement of magnetic moment in PMA is perpendicular so that made PMA memory become small in size, high capacity, and no thermal fluctuation due to the superparamagnetic effect [8]. The superparamagnetic effect make material has zero coercivity and the information saved will be lost. Compared to longitudinal type memory, PMA can achieve more than 100 times capacity with smaller size memory [5].

When material size in the range of nanometer scale, different characteristics of magnetic, optic, electric, and mechanic will be obtained compared to bulk material [9]. These different characteristics caused by the higher surface to volume ratio of materials when in nanometer scale than bulk scale. Reactivity of material determined by the number of atom existed in the surface area. Quantum effect dominate the nanometer scale material to restrict electron movement in particle and give change to mechanical hardness, electric conductivity, and magnetization [10]. Therefore, the size dependence of nanometer size materials to its characteristics is high compared to the bulk material counterpart.

In this work, we have investigated the magnetic behavior of squared model CoFe and CoFeB thin film and explored the PMA behavior by micromagnetic simulation. Hysteresis loop provide magnetic characteristics so that intrinsic magnetic behavior can be explored from CoFe and CoFeB materials. The difference values of coercivity in in-plane and out-plane field was determined the PMA behavior. Therefore, comparable magnetic characteristics between CoFe and CoFeB will be obtained through the size optimization (thickness and diameter).

2. Simulation Method
The PMA behavior were studied by micromagnetic simulations using Object Oriented Micromagnetic Framework (OOMMF) based on Landau Lifshitz Gilbert (LLG) equation [11]. Micromagnetic simulation used the approximation to real material by discretization of cell size less than exchange length. In this work we use 2.5×2.5×2.5 nm³ of cell size for both CoFe and CoFeB. For best rapprochement of simulation and experiment, we use square shape thin film. The phenomenological damping term (α) that accounts for the dissipation and lead to parallel alignment of the magnetic moment were set to be α = 0.05. The external magnetic field was given in two directions along x-axis (in-plane) and z-axis (out-plane) with magnitude of 1000 mT for CoFe and 2000 mT for CoFeB to obtain the hysteresis curves.

![Figure 1. Geometry of thin film CoFe and CoFeB square given in-plane and out-plane field.](image)

The geometrical side size of thin film CoFe and CoFeB were considered in this work from 50 nm to 500 nm. The material was fixed as thin film with thickness varied of 5 nm and 10 nm. Material parameter used for CoFe are magnetic saturation $M_s = 1.44 \times 10^6$ A/m, anisotropy constant $K = 2.7 \times$
10^3 J/m^3, and exchange constant $A = 13 \times 10^{-12}$ J/m based on Piao, et al [3]. On the other hand, material parameter of CoFeB based on Chaves – O’Flynn, et al was set magnetic saturation $M_s = 9.57 \times 10^5$ A/m, anisotropy constant $K = 3.86 \times 10^5$ A/m, and exchange constant $A = 13 \times 10^{-12}$ J/m [12]. CoFeB has uniaxial anisotropy in (001) direction. The detail geometry of material was shown in Figure 1.

3. Results and discussion

3.1 Hysteresis Loop

In this section, the hysteresis loop of CoFe and CoFeB materials by micromagnetic simulation are showed in Fig. 2. The different shapes of hysteresis loop obtained in in-plane and out-plane direction. In Fig. 2(a), the CoFe with out-plane field shows a lean hysteresis curve and low coercive field. On the other hand, the square loop hysteresis and higher coercivity was showed in out-plane field direction. This suggested that the magnetization of CoFe is preferred to align in (100) plane. As revealed experimentally by Tekgul et al., magnetic easy axis direction of CoFe is parallel to the film plane [13]. By adding Boron in CoFe thin film structure to be CoFeB, the coercivity in out-plane direction is higher than the in-plane one as seen in Fig. 2(b). It is seen clearly from inset in Fig. 2 that the coercivity value has also changed by Boron influence. In CoFeB materials, the coercivity is reduced in in-plane compared to out-plane field direction. Therefore, the CoFeB is preferred to align in (001) plane. According to these results, the Boron addition has been influenced the PMA behavior of CoFe [14].

![Hysteresis Loop](image)

Figure 2. Hysteresis loop of (a) CoFe and (b) CoFeB square model given by the in-plane and out-plane magnetic field with diameter 50 nm and $t = 5$ nm.

3.2 Coercivity Field

Hysteresis loop provided information of magnetic properties such as the coercivity field as shown in Fig. 3. The coercivity values of CoFe and CoFeB has been achieved for in-plane and out-plane direction with diameter and thickness variation. Firstly, the CoFe thin film shows high coercivity value ($H_c = 200$ mT, $D = 50$ nm) then decreased ($H_c = 40$ mT, $D = 500$ nm) as diameter increased in in-plane direction as shown in Fig. 3(a). The reduced of coercivity field value follows the trend of coercivity after passing through the critical diameter [7]. On the other hand, the coercivity is also declining from 40 mT to 0 mT as diameter increased when out-plane field was applied. It is observed that the film thickness not significantly influenced the magnetic behavior. As expected from the hysteresis loop, it is proven that the easy axis of CoFe square was in parallel orientation to the plane. The coercivity field of CoFeB shows high coercivity ($H_c = 480$ mT with $D = 50$ nm) then decreased to 40 mT with $D = 500$
nm at the out-plane field direction as shown in Fig. 3(b). The $H_c$ values fluctuate in in-plane direction on nanometer scale and tend to constant at mesoscopic scale in 40 mT. The constant coercivity values in mesoscopic scale indicate a multidomain state formation which also influenced by the anisotropy [15]. The high coercivity values in out-plane field indicated that the CoFeB has a perpendicularly easy axis and determined as PMA material. Therefore, Boron provide important role to form a PMA materials, which has high spin polarization and high stability with no heat treatment step in experiment [5].

3.3 Switching Time and Nucleation Field

The magnetization switching time is displayed in Fig. 4, which was extracted from the hysteresis loop. The switching time of CoFe and CoFeB in out-plane direction tends to increase as diameter increases. These results show that with increasing film size, there are more magnetic moments in the film and the time to switch to the opposite direction from the saturation magnetization state will be longer. It is observed that the switching time of CoFe film is longer than CoFeB in the size below 200 nm. Due to the Boron addition, the CoFeB hysteresis loop has good squareness and magnetic moment will change the orientation easily. This result agree with the results from Liu et al., which showed that CoFeB has good squareness of hysteresis loop [16].

Figure 5 shows the nucleation field of CoFe and CoFeB in hard axis direction. It is observed that the nucleation field of CoFe is higher than CoFeB up to 1080 mT. The nucleation fields to change magnetic moment direction are slightly increase as the side size in CoFe film increased, while in CoFeB film the nucleation fields are not significantly changed. In CoFeB square film with PMA behavior obtained low coercivity in high squareness hysteresis loop. It means that the nucleation field will be lower and magnetic moment orientation can be switched easily. However, the similar trend is obtained for CoFe and CoFeB film as shown in Fig. 5. The nucleation field values have a constant tendency at the mesoscopic scale (above 200 nm) as the side size increases. As explained by Quach et al., the correlation of switching time and nucleation field are proportional, which the nucleation field increased as the sweep rate increased [17].

![Figure 3](image-url)  
**Figure 3.** Coercivity field of (a) CoFe and (b) CoFeB square model by given in in-plane and out-plane direction.
4. Conclusion
In this work, thin film CoFe and CoFeB square were simulated in in-plane and out-plane magnetic field direction with varied diameter and thickness using OOMMF. The CoFe found to be in-plane magnetic anisotropy with lowest coercivity value of 40 mT. It is found that the coercivity decreased as square size increased for both in-plane and out-plane magnetization direction. The coercivity values were around 40 to 200 mT for in-plane field magnetization of CoFe. The coercivity tends to constant at 40 mT in diameter less than 100 nm and zero coercivity for diameter greater than 100 nm for out-plane field magnetization. Compared to CoFe, the coercivity in out-plane field is higher than in-plane field in CoFeB square. It is also observed that the switching time and nucleation field increased as the size increased in out-plane direction of both CoFe and CoFeB. The results showed that the different characteristics of magnetic anisotropy of both materials are important in the development of high density magnetic storage.

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