Hysteresis observation of CoFe and CoFeB model disk using micromagnetic simulation

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Abstract. In this work, hysteresis loop of CoFe and CoFeB disk ferromagnets are observed by using micromagnetic simulation OOMMF based on LLG equation. The diameter varied from 50–500 nm with the thickness 5 nm and 10 nm. For simulation process, the damping factor of 0.05 and the cell size 2.5 x 2.5 x 2.5 nm were fixed. We applied parallel and perpendicular external field to generate hysteresis loop of CoFe and CoFeB disk ferromagnets. Interestingly, we found two behaviours of coercivity, first less than diameter 100 nm and second, greater than 100 nm. For parallel-applied field of CoFe and CoFeB, the coercivity showed fluctuation around 20–160 mT. Greater than diameter 100 nm, the coercivity in a constant value around 40 mT for CoFe and around 20 mT for CoFeB. For perpendicular applied field of CoFe, we still observed the coercivity around 40 mT but greater than 100 nm, the coercivity dropped to zero. For CoFeB with perpendicular applied field, the coercivity decrease as the diameter increase until reach diameter 100 nm. Greater than the diameter 100 nm, the coercivity is constant at 20 mT. According to the results, we had observed the Perpendicular Magnetic Anisotropy (PMA) behaviour in both CoFe and CoFeB disk ferromagnets with certain value of the coercivity when the field applied in perpendicular direction.

1. Introduction

Recently, perpendicular magnetic anisotropy (PMA) has great potential applications as a high density of non-volatile memories [1]. The nonvolatile memory reduces power consumption than volatile that requiring 50 % power [2]. Perpendicular Magnetic Anisotropy (PMA) as a magnetic recording media has a moment magnet arrangement in perpendicular toward each other so it has high density capacity of more than longitudinal recording media [3]. PMA has a special characteristic with no thermal fluctuation which makes no superparamagnetic effect occurs. Superparamagnetic effect makes material to have no coercivity and information will be unstable and lost. To avoid it, anisotropy material increases the thermal stability and out of plane magnetization. Compared to longitudinal recording media, PMA recording media can save the data with 100 times higher density and smaller size than longitudinal recording media [4].

Currently, nanoparticle based magnetic material, which still in investigation are CoFe and CoFeB. CoFe has unique characteristics that can be used in many applications, which need high flux density such as data storage and electronic devices [5]. Unique characteristics are high Curie Temperature (Tc), low magnetocrystalline anisotropy, high permeability, and good hardness [6]. Not only CoFe, CoFeB is also interesting to be investigated because of low magnetocrystalline anisotropy,
high spin polarization (more than 65 %), and moderate saturation [7]. CoFeB can be used to decrease current density to change spin direction for spin transfer torque.

In this work, we have investigated CoFe and CoFeB model disk using micromagnetic simulation. The results from this simulation are hysteresis loop, coercivity field, and domain structure with variation of diameter and thickness. We get the influence of anisotropy material in perpendicular magnetic anisotropy (PMA) and in-plane magnetic anisotropy (IMA). Intrinsic magnetic properties materials were determined by anisotropy material and depend on size.

2. Simulation procedure
PMA phenomena are studied using the public micromagnetic simulation software OOMMF based on Landau Lifshitz Gilbert (LLG) equation [8]. The thicknesses (t) are 5 nm and 10 nm and the diameter of the disk (D) varied from 50 to 500 nm. Damping constant α is set to be 0.05. The cell size used in micromagnetic simulation is 2.5 x 2.5 x 2.5 nm³. External magnetic field is given in parallel and perpendicular directions (figure 1) with 1000 mT for CoFe and 2000 mT for CoFeB.

Material parameter plays an important role to the results of simulation. Thin film CoFe has magnetic saturation $M_s = 1.44 \times 10^6$ A/m, anisotropy constant $2.7 \times 10^5$ J/m³ and exchange constant $13 \times 10^{-12}$ J/m based on Piao et al. [9]. CoFe has cubic magnetocrystalline anisotropy with the direction (100) and (010). For CoFeB material parameter based on Chaves-O’Flynn et al. [7] has magnetic saturation $9.57 \times 10^5$ A/m, anisotropy constant $3.86 \times 10^5$ A/m, and exchange constant exchange $13 \times 10^{-12}$ J/m. CoFeB has uniaxial anisotropy in (001) direction [7].

3. Results and discussion
3.1. Hysteresis loop
To investigate the effects of directions external magnetic field and anisotropy material, we have performed a systematic study of hysteresis loop for diameter 50 nm and 5 nm thickness shown in figure 2. As shown in figure 2, CoFe and CoFeB given parallel and perpendicular external magnetic field represented by hysteresis loop. The hysteresis loop of CoFe has two characteristics when applied in parallel and perpendicular field. Different shape of hysteresis loop in two ways applied field is determined by anisotropy of materials. As given, parallel external field showed square loop hysteresis. Square loop hysteresis indicates that easy axis moment magnet orientation has the same direction with external magnetic field [10]. On the other side, when CoFe given perpendicular field hysteresis loops, it showed the same character as in hard axis. Interestingly, low coercivity field can be seen in hysteresis loop. When CoFe has low coercivity, it needs low external magnetic field to make all of moment magnet parallel with external magnetic field (saturation state). One of PMA material’s characteristics is low coercivity that exist when perpendicular is applied field. The same hysteresis loop of CoFe was revealed by Tekgul et al. [11].
Boron atom has diamagnetic characteristic, which influences magnetic properties to reduce oxidation and diffusion. Boron has smaller radius than Co and Fe thus stability of material will be increased [12]. With boron’s influence, the magnetic mechanism reversal of CoFe showed different shape as shown in figure 2b. CoFeB with parallel external magnetic field showed square loop hysteresis with low coercivity. Coercivity in hysteresis loop showed ability of material to save data in recording media. When applied perpendicular external field CoFeB showed high coercivity (~780 mT). It indicates that CoFeB has strong PMA behavior. Different shape of hysteresis loop when applied parallel and perpendicular indicates anisotropy effect in CoFe and CoFeB. Anisotropy of CoFeB in (001) in z-axis. So easy axis of CoFeB in perpendicular external field and proved with square hysteresis loop in perpendicular. Similar hysteresis loop was observed in the work of Meo et al. [2] although the investigated system has different shape as nanodot with thickness 1 nm.

3.2. Coercivity field

Magnetic behaviour can be represented by coercivity field from hysteresis loop. Coercivity is a magnetic external field needed by material to make magnetization normalization comes to zero. Coercivity of CoFe and CoFeB given parallel and perpendicular external field with variation of thickness is shown in figure 3. Coercivity of CoFe with parallel external magnetic field tends to increase under diameter 100 nm until reach maximum diameter of nanoscale 100 nm. At the value greater than 100 nm coercivity fields tends to be constant at 40 mT. Constant coercivity in mesoscopic scale is caused by the effect of size dependent material. Ratio between surfaces to volume ratio in nanoscale is one of special characteristics for nanoscale material. Surface ratio to volume ratio gives an effect to increase magnetic properties of CoFe [13]. In perpendicular magnetic external field thin film CoFe has low coercivity ~40 mT. The coercivity drops to zero until diameter of thin film reach almost 100 nm. Above 100 nm diameters, thin film CoFe has no coercivity field, which indicate that the size of diameter affects magnetic properties. PMA behaviour in CoFe only exists in small diameter less than 100 nm.

From hysteresis loop we can find magnetic behaviour with coercivity. Thin film CoFeB given parallel and perpendicular external magnetic field. Interestingly, with boron’s influence in CoFe, the coercivity field decreases as the diameter increase. With thickness varied in 5 nm and 10 nm in perpendicular magnetic external field showed coercivity field decrease as the thickness increase. It follows the relation of reduce anisotropy energy by increasing thickness contribution in thin film [12]. In figure 3b, it shows that as the diameter increase, the coercivity field decreases until upper limit of nanoscale in 100 nm. In greater diameter than 100 nm, the coercivity field tends to be constant at 20 mT and 40 mT. Proportional with theoretic diameter vs coercivity field curve after through critical diameter, the coercivity will decrease and then constant [14]. In perpendicular external field treatment, showed existence of coercivity and proved that CoFeB has Perpendicular Magnetic Anisotropy (PMA) behaviour.

**Figure 2.** Hysteresis loop of (a) thin film CoFe disk (b) thin film CoFeB disk given external field parallel and perpendicular at \( D = 50 \) nm and \( t = 5 \) nm
Figure 3. Coercivity of (a) thin film CoFe disk (b) thin film CoFeB given external field parallel and perpendicular to the disk for two variation in thickness of 5 nm and 10 nm.

Figure 4. Domain structure of (a) CoFe disk and (b) CoFeB disk in critical diameter.

3.3. Domain structure

One of special from micromagnetic is efficient to show the domain structure transition in every state of hysteresis. Domain structure of coercive state CoFe and CoFeB in critical diameter is shown in figure 4. Thin film CoFe applied parallel external field has multidomain vortex structure in diameter 80 nm and in diameter 70 nm start to change the structure from single to multidomain as coherent rotation. In small size diameter (less than 80 nm) domain structure try to make multidomain state even in small area to minimize demagnetization energy, which tends to make single domain state [14]. CoFe showed different structure as a vortex state in diameter 80 nm. Vortex state exists from diameter 80 nm to mesoscopic scale diameters, which indicate that critical diameter (Dc) in 70 nm. From Kittle equation of critical diameter, it is found Dc of thin film CoFe is in 70 nm. It is proved with domain structure of CoFe made multidomain structure after crossed Dc.

CoFeB thin film in figure 4b showed transition between single to multidomain state with parallel external magnetic field. Diameter 100 nm showed single domain coherent rotation as impact of high demagnetization energy. In diameter 200 nm coercive state of CoFeB showed multidomain structure with vortex rotation. It caused by high exchange energy, which tends to make moment magnet.
antiparallel [10]. In diameter 100 nm domain structure of CoFeB has coherent rotation and in diameter 200 nm multidomain vortex structure of CoFeB is exist. It can be inferred from domain structure that critical diameter (Dc) of CoFeB is in 100 nm.

4. Conclusions
CoFe and CoFeB thin film have been studied by micromagnetic simulation. CoFe thin film performs PMA behaviour with low coercivity in small diameter less than 100 nm. On the other hand, boron’s influence increased the coercivity field in CoFe. CoFeB showed PMA behaviour when applied perpendicular magnetic field. It revealed by hysteresis loop of CoFeB. Anisotropy effect made different shape of hysteresis loop in CoFe and CoFeB. From micromagnetic, the domain structure of CoFe and CoFeB can be seen in detail at transition state in critical diameter. CoFe has multidomain structure in 50 nm diameter and CoFeB change to multidomain state at 200 nm diameters. In conclusion, by Boron addition in CoFe as CoFeB disk, PMA behaviour will exist at size fewer than 100 nm diameters.

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