Hysteresis loops observation of FePt and FePd square ferromagnets using micromagnetic simulation

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Abstract. In this study, we have investigated magnetic hysteresis loops of squared model FePt and FePd ferromagnets by a public micromagnetic simulation based on Landau-Lifshitz Gilbert (LLG) equation. The hysteresis loops of FePt and FePd ferromagnets are generated by in-plane and out-plane applied field with respect to the size and thickness variation. It is found that the coercivity field for both FePt and FePd squared ferromagnets exhibited different behavior for the size of ferromagnets around 50–100 nm and more than 100 nm. The results showed that the hysteresis loops produced a large coercivity when the in-plane field was applied and zero coercivity for external out-plane field. Interestingly, coercivity field was still observed for materials with size below 100 nm with ranging values between 20–40 mT. From this result, certain values of the coercivity field appeared for out-plane applied field at small thickness indicates a perpendicular magnetic anisotropy (PMA) behavior in FePt and FePd ferromagnets.

1. Introduction

Research on magnetic materials and understanding of magnetization process were such an interesting study in recent years, especially on the development of magnetic recording devices for high-speed data storage. The problem of this topic was raised in order to continue the rapid increasing of both capacity and speed of HDD storage and following the Moore’s law on data storage. Both experimental and micromagnetic approaches were utilized to understood the new phenomenon of magnetic based recording system. In addition to the increasing of magnetic recording capacity, the recording technology has also transformed. In the beginning, the longitudinal magnetic recording was applied for magnetic recording and then changed into perpendicular magnetic recording, which the magnetic bits are perpendicular to the film plane which was used on the materials with perpendicular magnetic anisotropy (PMA) [1].

FePt has 50 to 100 times greater magnetocrystalline anisotropy that allowing density area in T/inch^2 order [7]. FePt has anisotropy constants can reach as high as 10^7 J/m^3 [8–10]. The FePd is also one of the feasible Fe-Alloy candidates because of the strong responsiveness of PMA [11]. Based on a research road map of PMA properties on thin films for spintronic applications [12], FePt and FePd thin films exhibit a very large magnetocrystalline anisotropy but have large magnetic damping constants [13].
Table 1. Material parameters used in micromagnetic simulations [2,3]

| Materials | Exchange stiffness A (J/m) | Anisotropy constant K (J/m³) | Magnetization saturation Ms (A/m) |
|-----------|-----------------------------|-------------------------------|----------------------------------|
| FePt      | $10 \times 10^{-12}$        | $6.6 \times 10^{-6}$          | $1.14 \times 10^{6}$            |
| FePd      | $6.9 \times 10^{-12}$        | $2.6 \times 10^{-5}$          | $1.06 \times 10^{6}$            |

Figure 1. The dimension and geometry of FePt and FePd square ferromagnets. The length size $s$ was varied from 50 nm to 500 nm with external field applied in-plane and out-of-plane direction.

In this study, we investigated the characteristics of hysteresis loops from FePt and FePd square-shaped model with different sizes and thicknesses using micromagnetic simulation approach. The magnetic field on the in-plane direction and out-of-plane direction are used to analyze the magnetic properties of FePt and FePd thin layers which is connected with the appearance of PMA properties.

2. Simulation procedure

Hysteresis loops observation of FePt and FePd square ferromagnets was carried out using a public micromagnetic simulation software OOMMF (Object Oriented Micromagnetic Framework) [14]. The system works by solving the Landau-Lifshitz-Gilbert (LLG) equation, which is a function of differential equations [15]. The FePt and FePd square shaped were used in the simulation with the parameters given in Table 1. The length size, $s$ of the square shaped ($x = y$) was varied from 50 nm to 500 nm with two variations of thickness ($t$) of 5 and 10 nm. The cell size of discretization was fixed to be $2.5 \times 2.5 \times 2.5$ nm, and the damping constant $\alpha$ of 0.05. The magnetic field range from -1000 to 1000 mT with for in-plane ($H_x$) and out-plane ($H_z$) direction as illustrated in figure 1.

3. Results and discussion

The dependence of magnetization with the angle between the applied field $H$ and the easy magnetization direction caused possible different shapes of hysteresis loop. When the field $H$ is applied parallel to the easy magnetization direction in the material, a straight loops is obtained, whereas a slanted loop is observed if the field $H$ is applied perpendicular to the easy direction [8]. A significant change in the coercivity is observed with respect to different lengths $s$ and thicknesses $t$, as shown in figure 2. A large $H_c$ value of about 200 mT was obtained for FePt with $s = 50$ nm, which was measured parallel to the plane (in-plane field). It is observed that the coercivity decreases slowly with increasing size of the materials, but still keeps a large value of about 40 to 60 mT and 80 to 100 mT for FePd and FePt, respectively. In the mesoscopic scale, which the length size $s$ from 200 nm to 500 nm, coercivity decreases and tends to be constant for FePd with a value of 20 mT ($t = 10$ nm) and 40 mT ($t = 5$ nm). On the other hand, a drastic change of the magnetization loops is observed in the length size $s$ between 100 nm and 200 nm for FePt.
When the external field was applied in the out-of-plane direction, the hysteresis loops with different lengths and thicknesses showed nearly zero coercivity. It indicates that such typical of the hysteresis loops is given the external fields toward its hard axis direction. However, it is observed that the coercivity values ranging between 20 to 40 mT as shown in figure 2 (c and f). This small value of the coercivity indicates perpendicular magnetic anisotropy (PMA) behavior in FePt and FePd ferromagnets. According to previous research from Shima et al. [16], when magnetic field was employed in the perpendicular direction against the film plane, a huge coercivity of about 40 kOe was obtained for \( t = 10 \) nm at room temperature.

The domain structure of squared shaped model FePd and FePt with \( t = 5 \) nm at the coercive state can be seen in figure 3. In the in-plane direction, the multi domain state formation are observed from \( s = 50 \) nm to 500 nm. Meanwhile, in the out-of-plane direction, vortex structure are observed with reversal mechanism process that occurred was curling mode. This mode avoids creating stray field by passing through a vortex state where the magnetization lies everywhere parallel to the surface [17]. Curling mode requires less energy to make the magnetization minimum. So, generally on the vortex-wall materials, the coercivity field will decrease as the size of material increases. The color represents the magnetization value for the in-plane field direction is shown from the x component and the z component for out-of-plane field direction.

**Figure 2.** Hysteresis loops for (a, b) FePd and (d, e) FePt square-shaped with different lengths and thicknesses. The magnetic field was utilized in the in-plane direction and out-of-plane (perpendicular) direction. Coercivity \( H_c \) for (c) FePd and (f) FePt square-shaped as a function of lengths \( s \) and thicknesses \( t \).
Figure 3. The domain structure in (a, b) FePd and (c, d) FePt of square-shaped $t = 5$ nm with different length sizes. The magnetic field was employed in the in-plane direction and out-of-plane direction.
4. Conclusions
We have studied the hysteresis loops of FePt and FePd with square-shaped model at different lengths and thicknesses by micromagnetic simulation. The magnetic field was utilized in the in-plane and out-of-plane (perpendicular) directions. It was found that two different shapes of hysteresis loops are influenced by the direction of the applied field. The coercivity decreased as the size of materials increased but tends to be constant in mesoscopic scale. The results showed that the size of materials affected the magnetic properties of FePt and FePd thin layers. The highest coercivity of 200 mT was obtained for FePt, when the external field was applied in the in-plane direction. It was because the anisotropy constant of FePt is higher than FePd. Vortex state was found when the external field was applied in out-of-plane direction with curling reversal mode.

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