Research Article

Design and Micromagnetic Simulation of Fe/ $L1_0$ -FePt/Fe Trilayer for Exchange Coupled Composite Bit Patterned Media at Ultrahigh Areal Density

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Exchange coupled composite bit patterned media (ECC-BPM) are one candidate to solve the trilemma issues, overcome superparamagnetic limitations, and obtain ultrahigh areal density. In this work, the ECC continuous media and ECC-BPM of Fe/ $L1_0$ -FePt/Fe trilayer schemes are proposed and investigated based on the Landau-Lifshitz-Gilbert equation. The switching field, H_{sw} , of the hard phase in the proposed continuous ECC trilayer media structure is reduced below the maximum write head field at interlayer exchange coupling between hard and soft phases, A_{ex} , higher than 20 pJ/m and its value is lower than that for continuous $L1_0$ -FePt single layer media and $L1_0$ -FePt/Fe bilayer. Furthermore, the H_{sw} of the proposed ECC-BPM is lower than the maximum write head field with exchange coupling coefficient between neighboring dots of 5 pJ/m and A_{ex} over 10 pJ/m. Therefore, the proposed ECC-BPM trilayer has the highest potential and is suitable for ultrahigh areal density magnetic recording technology at ultrahigh areal density. The results of this work may be gainful idea for nanopatterning in magnetic media nanotechnology.

1. Introduction

An ultrahigh areal density of magnetic recording media over 1 Tb/in² and overcoming the superparamagnetic limit of conventional perpendicular magnetic recording are required for the development of hard disk drive technology. Magnetic recording media must have smaller magnetic grains, higher magnetocrystalline anisotropy constant, K_u , and lower exchange coupling [1]. The high K_u is the cause of increasing coercivity, H_c , of the media; however, it may be over the maximum write field of about 24-25 kOe of heads because the saturation magnetization, M_s , of the write head material is limited [2]. These problems are called the magnetic recording trilemma [3]. There are three conditions of the trilemma that limits areal density growth of magnetic recording technology: (i) the write head field can record data on the media, (ii) the bits must be thermally stable, and

(iii) the number of grains per bit is sufficient to obtain the high signal to noise ratio.

From the above writing head field problem, several future magnetic recording technologies are proposed to reduce switching field, H_{sw} , to the maximum write head field or lower. Heat-assisted magnetic recording technology allows a reduced H_c of the media during the writing process [4]. The H_{sw} of the media under a microwave-assisted field in microwave-assisted magnetic recording technology is lower [5]. The magnetization reversal of the media is excited by the microwave field. The tilted media were proposed to reduce H_{sw} and areal density achieved was 62% higher than that of a perpendicular media with 45° easy-axis-tilted media under the same thermal stability and recording process [6]. In addition, the exchange coupled composite (ECC) media proposed by Victora and Shen and the exchange spring and exchange coupled graded media proposed by Suess provide

better thermal stability, writability, and improved signal to noise ratio [1, 7]. The H_{sw} of the media is reduced with the same thermal stability. Due to these media comprising soft and hard magnetic materials, the soft phase helps to reverse the magnetization of the hard phase. Therefore, the H_{sw} of the media can be reduced.

At ultrahigh density magnetic recording, the magnetic transition noise also becomes a significant problem. However, this problem is completely eliminated by bit patterned media (BPM) because of the separation of bits by nonmagnetic material [8]. Therefore, it is the candidate for magnetic recording technology to overcome the superparamagnetic limit at areal density of 1 Tb/in². Recently, the concepts of ECC-BPM of [Co/Pd]₅/Pd/[Co/Ni]₃/Co multilayer have been introduced, showing that H_{sw} can be reduced by inserting a Pd layer while maintaining thermal stability [9]. The ECC-BPM and graded BPM media for L₁₀-FePt material are investigated with K_u of 1–4 MJ/m³ [10]. After that the structure of high K_u of L₁₀-FePt and low K_u of a Co/Pd-Co/Ni multilayer with various the interlayer exchange couplings between hard and soft phases, A_{ex} , can reduce the H_c [11]. In addition, both the H_c and saturation field are reduced by 50% owing to exchange coupling between L₁₀-FePt and the Fe interface after the postannealing process [12].

To achieve the reduction of H_{sw} below the maximum write head field at ultrahigh areal density, ECC media of Fe/L₁₀-FePt/Fe trilayer structure for BPM are proposed and investigated in this work. Exchange coupling coefficient between neighboring dots, A_{dot} , for the structure becomes a challenge due to magnetic bits being close to other bits [13]. Magnetic flux from individual bit will disturb neighboring bits. Therefore, the A_{ex} and A_{dot} on the H_{sw} of the hard layer, its hysteresis loop, magnetization reversal, and magnetic energy are investigated by the object oriented micromagnetic framework (OOMMF) program [14] based on the Landau-Lifshitz-Gilbert (LLG) equation [15].

2. Micromagnetic Simulation and Modeling

The LLG equation is used to describe the magnetization dynamics of magnetic particles, as shown in the following [15, 16]:

$$\begin{aligned} \frac{\partial \vec{M}(\vec{r}_i, t)}{\partial t} = & -|\gamma| \vec{M}(\vec{r}_i, t) \times \vec{H}_{eff}(\vec{r}_i, t) \\ & - \frac{|\gamma| \alpha}{M_s} \vec{M}(\vec{r}_i, t) \times [\vec{M}(\vec{r}_i, t) \times \vec{H}_{eff}(\vec{r}_i, t)], \end{aligned} \quad (1)$$

where γ is the gyromagnetic ratio, $\vec{M}(\vec{r}_i, t)$ is the magnetization vector of the magnetic particles, $\vec{H}_{eff}(\vec{r}_i, t)$ is the effective field vector, as illustrated in (2), and α is the Gilbert damping constant. For the first term, the magnetization is affected by the $\vec{H}_{eff}(\vec{r}_i, t)$, so the magnetization rotates around $\vec{H}_{eff}(\vec{r}_i, t)$ with the precession torque term. For the second term, the magnetization is damped to the $\vec{H}_{eff}(\vec{r}_i, t)$ called the damping torque term. The $\vec{H}_{eff}(\vec{r}_i, t)$ in the LLG equation includes anisotropy, demagnetization, exchange, and external

(Zeeman) fields that result from the derivative of the total magnetic energy density, E , with respect to $\vec{M}(\vec{r}_i, t)$. The E includes anisotropy, demagnetization, exchange, and Zeeman energy densities [15, 16]:

$$\vec{H}_{eff}(\vec{r}_i, t) = -\frac{1}{\mu_0} \frac{\partial E}{\partial \vec{M}_i(\vec{r}_i, t)}. \quad (2)$$

ECC media comprise soft and hard magnetic materials and L₁₀-FePt is used for the hard magnetic material of the recording layer because it has a high K_u . The ideal K_u value is about 7 MJ/m³ [17] and can be achieved with a minimum stable grain size of about 2.81 nm, but that value will be difficult to produce by the magnetron sputtering method. Therefore, we use K_u of 2.8 MJ/m³ [16, 18] for this work and the minimum stable grain size increases to 3.59 nm [16]. Fe material is used for the soft magnetic material because of epitaxial growth [19]. The M_s of soft and hard phases is 1200 and 500 kA/m, respectively [18, 20]. The K_u of the soft phase is 100 J/m³ [18, 21]. The exchange coupling constant of soft and hard phases is 28 and 12 pJ/m, respectively [18, 21]. The A_{ex} and A_{dot} are varied to investigate the effects of exchange coupling behavior on the reduction of H_{sw} . In the present work, H_{sw} is defined as the applied magnetic field that completely reverses the magnetization in the hard phase. The continuous media have width and length of 250 nm. The thickness of L₁₀-FePt hard phase, t_{FePt} , is 10 nm. The Fe soft phase thickness, t_{Fe} , of the ECC bilayer is 10 nm and the proposed ECC trilayer continuous media are 5 and 10 nm. For the proposed ECC-BPM, the dot dimension is 10 nm × 10 nm with the same t_{FePt} and t_{Fe} of the continuous media. The dot spacing is 2.5 nm to achieve an ultrahigh areal density, as shown in Figure 1. The mesh size of the finite difference time domain calculation is 2.5 nm × 2.5 nm × 2.5 nm by OOMMF program based on the LLG equation.

3. Results and Discussions

3.1. Fe/L₁₀-FePt/Fe Trilayer Structure for Continuous Media.

To demonstrate the advantage and performance of the proposed ECC trilayer structure, a comparison between the bilayer and the proposed ECC trilayer is investigated. The effective t_{Fe} for the trilayer structure is 5 and 10 nm to reduce H_{sw} below the maximum write head field. Figure 2 shows the dependence of normalized H_{sw} (divided by H_{sw} of single layer continuous media) on A_{ex} for bilayer and trilayer. The H_{sw} of the continuous single layer medium is independent of A_{ex} and constant at 1 while the normalized H_{sw} of the bilayer and trilayer continuously decreases. The normalized H_{sw} of the bilayer decreases faster than that of the proposed trilayer media with increasing A_{ex} from 0 to 9 pJ/m, but it is not in the writing head field region. For A_{ex} of 12.5–30 pJ/m, the H_{sw} of the trilayer media continuously decreases below the maximum write head field and its value is lower than the H_{sw} of the bilayer media. This result indicates that the proposed ECC trilayer media can reduce the H_{sw} lower than the bilayer media because of the double interface area [22].

Reduction of the H_{sw} corresponds to calculation of energy barrier height; both of them decrease with increasing

FIGURE 1: Structures of the proposed ECC-BPM trilayer: Fe/L1₀-FePt/Fe with 400 dots at areal density over 4 Tb/in².

FIGURE 2: Normalized H_{sw} and A_{ex} of single layer continuous media, ECC bilayer, and proposed ECC trilayer.

exchange energy per unit area [23] or A_{ex} . Energy barrier of the hard magnetic phase, E_{B-H} , in the proposed trilayer structure is calculated by the Stoner-Wohlfarth model as given in the following:

$$E_{B-H} = K_H t_H \left[1 - \frac{H + (2J/M_H t_H)}{H_{K-H}} \right]^2, \quad (3)$$

where K_H is K_u of hard magnetic materials, t_H is the thickness of hard phase, H is external magnetic field, J is exchange coupling constant, M_H is M_s of hard magnet, and H_{K-H} ($= 2K_H/M_H$) is the anisotropy field of hard phase. We have also found that a hard phase of the proposed ECC media trilayer

structure has a lower energy barrier than the bilayer structure with high thermal stability.

Moreover, the exchange energy density at full reversal (not shown here) of the ECC bilayer and trilayer rapidly increases at A_{ex} of 8–12.5 pJ/m for bilayer and trilayer ($t_{Fe} = 5$ nm) and 8–15 pJ/m for trilayer ($t_{Fe} = 10$ nm). Therefore, the H_{sw} in these ranges suddenly reduces. For A_{ex} over 15 pJ/m, the H_{sw} is almost constant according to the exchange energy. These results indicate that A_{ex} is important for ECC media in reducing the H_{sw} below the maximum write head field at ultrahigh recording density. Thus, the proposed ECC trilayer continuous media structure has more potential H_{sw} reduction than the ECC bilayer continuous media at the same t_{Fe} for ultrahigh density magnetic recording technology.

3.2. Fe/L1₀-FePt/Fe Trilayer Structure for BPM. The proposed ECC-BPM structure with t_{Fe} of 5 and 10 nm, as shown in Figure 1, is expected to achieve the goal of reducing H_{sw} below the maximum write head field at ultrahigh areal density. The H_{sw} of the bit patterned dots is normalized by the H_{sw} of the single layer without A_{dot} , as shown in Figure 3. It significantly decreases because of the A_{dot} and A_{ex} . The values of H_{sw} of ECC-BPM trilayer and bilayer tend to decrease unlike the BPM single layer. This indicates that the A_{ex} influence on the ECC structure is highly significant for BPM. Although there is no A_{dot} in the trilayer structure, the H_{sw} can be kept within the maximum head field region at very high A_{ex} . Under the influence of A_{ex} and A_{dot} , the H_{sw} of the ECC-BPM trilayer with t_{Fe} of 10 nm is the lowest. ECC-BPM bilayer ($t_{Fe} = 10$ nm) and trilayer ($t_{Fe} = 5$ nm) can reduce the H_{sw} close to the maximum write head field. However, the ECC-BPM trilayer with t_{Fe} of 10 nm is the most effective in reducing H_{sw} below the maximum write head field. This indicates that the A_{dot}

FIGURE 3: Dependence of normalized H_{sw} on A_{dot} with various A_{ex} .

also affects the reduction of H_{sw} . Therefore, this structure has benefit for magnetic recording technology to solve the magnetic recording trilemma issues at ultrahigh areal density.

Figure 4 shows the hysteresis loops and magnetic domain of the ECC-BPM bilayer and the proposed trilayer. The bilayer and the first trilayer structure denoted by trilayer 1 have A_{ex} and A_{dot} of 10 pJ/m and the second trilayer structure denoted by trilayer 2 has A_{ex} of 10 pJ/m and without A_{dot} . There are different steps in the hysteresis loop shapes. Principally, the reasons are that (i) magnetization reversal of soft and hard phases is separate and the soft phase reverses early because the magnetic properties of the soft magnetic material allow the magnetization to reverse easily and after that the hard phase will reverse and (ii) exchange coupling between interface of soft and hard phases is not enough [1, 24, 25]. Therefore, magnetization reversal of soft and hard phases is separate. The proposed trilayer 1 has a sharp loop and no step because of its structure and the existence of A_{ex} and A_{dot} .

Magnetization reversal processes in Figures 4(a)–4(c) and 4(d)–4(f) are shown without and with an applied external magnetic field, H_{ex} , of -18 kOe, respectively. Without H_{ex} , the magnetization of soft phases in trilayer 2 and bilayer structures begins to reverse but the hard phase magnetization still remains in the $+z$ direction (pointing up). When H_{ex} increases in the $-z$ direction (pointing down), the magnetic domain wall moves to the interface between soft and hard phases. All magnetization of soft phases will be reversed but hard phase magnetization is still in the same direction, as shown in Figures 4(d) and 4(f). Magnetization of the ECC-BPM trilayer 1 is fully reversed, as shown in Figure 4(e). The magnetic domain shows that an added Fe soft layer to the

FIGURE 4: Hysteresis loops of ECC-BPM bilayer with A_{ex} and A_{dot} of 10 pJ/m (solid line), trilayer 1 with A_{ex} and A_{dot} of 10 pJ/m (dotted line), and trilayer 2 with A_{ex} of 10 pJ/m and without A_{dot} (dashed line). Magnetization reversal process of single dot in bilayer: (a) and (d), trilayer 1: (b) and (e), and trilayer 2: (c) and (f). Magnetization reversal of (a)–(c) without H_{ex} and (d)–(f) at H_{ex} of -18 kOe.

proposed trilayer structure can reduce the H_{sw} below the maximum write head field.

4. Conclusions

The proposed Fe/ $L1_0$ -FePt/Fe ECC trilayer structure for continuous media and BPM was investigated by a micromagnetic model. The proposed trilayer continuous media has lower H_{sw} than that of bilayer and the maximum write head field at A_{ex} over 20 pJ/m. For the proposed ECC-BPM structure, the A_{ex} and A_{dot} have more influence on the reduction of H_{sw} .

The H_{sw} of the ECC-BPM is lower than the maximum write field at A_{ex} of 10 pJ/m and A_{dot} of 5 pJ/m. The magnetization of the $L1_0$ -FePt hard phase of the proposed ECC-BPM trilayer easily reverses compared to the bilayer. To the best of the authors' knowledge, the proposed ECC-BPM trilayer is the most effective in reducing the H_{sw} compared to the other structure schemes in literature. The results of this work will lead to the nanomaterials development of the magnetic recording technology at ultrahigh areal density, potentially solving the writability issue of the trilemma.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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