Research Article

Design and Micromagnetic Simulation of Fe/L1₀-FePt/Fe Trilayer for Exchange Coupled Composite Bit Patterned Media at Ultrahigh Areal Density

Warunee Tipcharoen, Arkom Kaewrawang, and Apirat Siritaratiwat

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 1TB/in\(^2\). Recently, the concepts of ECC-BPM of \([\text{Co/Pd}]_3/\text{Pd}/(\text{Co/Ni})_3/\text{Co} \) 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 \(L_0\)-FePt material are investigated with \(K_u\) of 1–4 MJ/m\(^3\) \([10]\). After that the structure of high \(K_u\) of \(L_0\)-FePt and low \(K_u\) of a \(\text{Co/Pd}/\text{Co/Ni}\) multilayer with various the interlayer exchange couplings between hard and soft phases, \(A_{ex}\), can reduce the \(H_{sw}\) \([11]\). In addition, both the \(H_s\) and saturation field are reduced by 50% owing to exchange coupling between \(L_0\)-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/\(L_0\)-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 \([15, 16]\):

\[
\frac{\partial \vec{M}(\vec{r}, t)}{\partial t} = -\gamma \frac{\vec{M}(\vec{r}, t) \times \vec{H}_{eff}(\vec{r}, t)}{\mu_0 M_s} - \frac{\gamma \alpha}{M_s} \frac{\partial \vec{M}(\vec{r}, t)}{\partial t} \times \left[ \vec{M}(\vec{r}, t) \times \vec{H}_{eff}(\vec{r}, t) \right],
\]

where \(\gamma\) is the gyromagnetic ratio, \(\vec{M}(\vec{r}, t)\) is the magnetization vector of the magnetic particles, \(\vec{H}_{eff}(\vec{r}, t)\) is the effective field vector, as illustrated in (2), and \(\alpha\) is the Gilbert damping constant. For the first term, the magnetization is affected by the \(\vec{H}_{eff}(\vec{r}, t)\), so the magnetization rotates around \(\vec{H}_{eff}(\vec{r}, t)\) with the precession torque term. For the second term, the magnetization is damped to the \(\vec{H}_{eff}(\vec{r}, t)\) called the damping torque term. The \(\vec{H}_{eff}(\vec{r}, t)\) 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 \(\vec{M}(\vec{r}, t)\). The \(E\) includes anisotropy, demagnetization, exchange, and Zeeman energy densities \([15, 16]\):

\[
\vec{H}_{eff}(\vec{r}, t) = -\frac{1}{\mu_0} \frac{\partial E}{\partial \vec{M}(\vec{r}, t)}. \tag{2}
\]

ECC media comprise soft and hard magnetic materials and \(L_0\)-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/m\(^3\) \([17]\) 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/m\(^3\) \([16, 18]\) 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/m\(^3\) \([18, 21]\). 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 \(L_0\)-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/\(L_0\)-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
exchange energy per unit area \[ E_{\text{B-HT}} \] or \( A_{\text{ex}} \). Energy barrier of the hard magnetic phase, \( E_{\text{B-HT}} \), in the proposed trilayer structure is calculated by the Stoner-Wohlfarth model as given in the following:

\[
E_{\text{B-HT}} = K_H t_{\text{H}} \left( 1 - \frac{H}{H_{\text{K-H}}} \right)^2. \tag{3}
\]

where \( K_H \) is the thickness of hard magnetic materials, \( t_{\text{H}} \) 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 \( H_{\text{K-H}} = 2K_H/M_H \) 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 \( A_{\text{ex}} \) of 8–12.5 pJ/m for bilayer and trilayer (\( t_{\text{Fe}} = 5 \) nm) and 8–15 pJ/m for trilayer (\( t_{\text{Fe}} = 10 \) nm). Therefore, the \( H_{\text{sw}} \) in these ranges suddenly reduces. For \( A_{\text{ex}} \) over 15 pJ/m, the \( H_{\text{sw}} \) is almost constant according to the exchange energy. These results indicate that \( A_{\text{ex}} \) is important for ECC media in reducing the \( H_{\text{sw}} \) below the maximum write head field at ultrahigh recording density. Thus, the proposed ECC trilayer continuous media structure has more potential \( H_{\text{sw}} \) reduction than the ECC bilayer continuous media at the same \( t_{\text{Fe}} \) for ultrahigh density magnetic recording technology.

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

4. Conclusions

The proposed Fe$/L_1$, 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 $A_{ex}$ of 5 pJ/m. The magnetization of the $L_1$-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.

**Acknowledgments**

This work is financially supported by Khon Kaen University, Thailand, under Incubation Researcher Project. This work is also financially supported by Thailand Research Fund (TRF) and Khon Kaen University, Grant no. TRG5780125. TRF and Khon Kaen University are not always necessarily in agreement with the authors’ discussions in this paper. The authors deeply thank Assistant Professor Dr. Anupap Meesonboon, Dr. Sataporn Pornpromlikit, and Dr. Ian Thomas for suggestions.

**References**


