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Micromagnetic Simulation of $L1_0$-FePt-Based Exchange-Coupled-Composite-Bit-Patterned Media with Microwave-Assisted Magnetic Recording at Ultrahigh Areal Density

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Abstract: In this work, we propose exchange-coupled-composite-bit-patterned media (ECC-BPM) with microwave-assisted magnetic recording (MAMR) to improve the writability of the magnetic media at a 4 Tb/in^2 recording density. The suitable values of the applied microwave field's frequency and the exchange coupling between magnetic dots, A_{dot}, of the proposed media were evaluated. It was found that the magnitude of the switching field, H_{sw}, of the bilayer ECC-BPM is significantly lower than that of a conventional BPM. Additionally, using the MAMR enables further reduction of H_{sw} of the ECC-BPM. The suitable frequency of the applied microwave field for the proposed media is 5 GHz. The dependence of A_{dot} on the H_{sw} was additionally examined, showing that the A_{dot} of 0.14 pJ/m is the most suitable value for the proposed bilayer ECC-BPM. The physical explanation of the H_{sw} of the media under a variation of MAMR and A_{dot} was given. Hysteresis loops and the magnetic domain of the media were characterized to provide further details on the results. The lowest H_{sw} found in our proposed media is 12.2 kOe, achieved by the bilayer ECC-BPM with an A_{dot} of 0.14 pJ/m using a 5 GHz MAMR.

Keywords: bit-patterned media; exchange-coupled-composite media; microwave-assisted magnetic recording; hysteresis loop

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1. Introduction

Recently, the capacity of hard disk drives has been heading towards a stalemate since the thermal stability of the conventional media has reached its limitation [1–6]. In order to increase recording densities, several techniques have been proposed to overcome the stability limitation, such as exchange-coupled-composite (ECC) media, heat-assisted magnetic recording (HAMR) bit-patterned media (BPM), and microwave-assisted magnetic recording (MAMR) [1,7–14]. The ECC media have been introduced to improve the magnetic properties of the media; the major goal is to reduce the magnitude of the switching field, H_{sw} [7,12,13]. The ECC media consist of magnetically isolated layers, which are the soft and the hard magnetic layers. The interface exchange coupling between two layers can provide a lower H_{sw} than the conventional one. It therefore enables the use of smaller media grain sizes with higher magnetic anisotropy, K_u, at high areal densities [7]. BPM technology has been extensively proposed to solve the magnetic transition noise and the interaction between magnetic bits of the conventional media since these factors could be the crucial issues at ultrahigh areal densities [1]. The principle of BPM is the magnetic separation of each magnetic bit, which eliminates the magnetic transition noise and yields a very low interaction between bits [1]. In previous research, the combination of ECC-BPM was reported, demonstrating that this combined technique can increasingly reduce the H_{sw} of the media beyond that using each technique individually [12]. Microwave-assisted magnetic recording (MAMR) is one promising technology for achieving higher areal densities [14–18]. The goal of this technique is to reduce the H_{sw} of the media by using an AC-magnetic field, H_{ac}, operated at a microwave range. During the writing process of MAMR, the H_{ac} is applied to the media simultaneously with the writing field, $H_{dc.}$ This strategy can increasingly reduce the energy barrier of the media by the ferromagnetic resonance (FMR) phenomenon. As a result, switching the magnetization of the media becomes easier. A significant reduction in the H_{sw} of the media under the use of MAMR can be seen in several recent publications [14–18].

As it is generally known that the maximum write head field is limited, it is challenging to continuously reduce the H_{sw} to enable the use of higher K_u materials as a media at higher recording densities [19]. Therefore, we proposed a novel technique to improve the writability of the media by the combination of three technologies, including the ECC media, BPM, and MAMR. The proposed media was targeted for use at an areal density of 4 Tb/in^2. The hybrid magnetic recording media based on the FePt alloy with the face-centered tetragonal $L1_0$ structure, $L1_0$-FePt, was focused. The object-oriented micro-magnetic framework (OOMMF) software [20] was used in the simulations implementing the Landau–Lifshitz–Gilbert (LLG) equation.

2. Modeling and Analytical Methodology

The model structures of the $L1_0$-FePt-based single-layer BPM and the $L1_0$-FePt/Fe bilayer ECC-BPM for an areal density of 4 Tb/in^2 are shown in Figure 1a,b, respectively. The media configuration has been determined on the basis of BPM and ECC-BPM requirements. To achieve an areal density of 4 Tb/in^2, the cube dot size of single-layer BPM of $10 \times 10 \times 10$ nm^3 and spacing between dots of 2.5 nm were assumed [12]. The bilayer ECC-BPM was introduced by magnetically adding a soft Fe layer with a 10 nm thickness under the FePt BPM. The Fe added layer was assumed to have the same dot pattern as the single-layer BPM. The magnetization of each layer was initially aligned along the +z direction for both media. The magnetic properties of the proposed media are detailed as follows: the $L1_0$-FePt hard layer had a saturation magnetization, M_s, of 1.175 MA/m, and a K_u of 2.8 MJ/m^3. The Fe soft layer had M_s of 1.71 MA/m and K_u of 100 J/m^3. For the bilayer media, the exchange coupling between soft and hard layers, A_{ex}, was assumed to be 25 pJ/m, whereas the exchange coupling between magnetic dots, A_{dot}, varied from 0.1 to 0.3 pJ/m. This variation of A_{dot} was based on the possible values of the filled material between the dot spacing, as can be seen in the literature [21,22]. In calculations, the time-varying magnetization was described by the LLG equation, given as Equation (1) [23]:

$$\frac{\partial \vec{M}}{\partial t} = -|\gamma|\mu_0(\vec{M} \times \vec{H}_{eff} + \frac{\propto}{M_s}\vec{M} \times (\vec{M} \times \vec{H}_{eff})) \quad (1)$$

where $\vec{M}$ is the magnetization, γ is the gyromagnetic ratio, and $\vec{H}_{eff}$ is the effective magnetic field given by Equation (2):

$$\vec{H}_{eff} = \vec{H}_{dc} + \vec{H}_{ex} + \vec{H}_{de} + \vec{H}_k + h_{ac}\sin(2\pi f_{ac} t)\vec{a}_x \quad (2)$$

where $\vec{H}_{dc}$, $\vec{H}_{ex}$, $\vec{H}_{de}$, $\vec{H}_k$, h_{ac}, f_{ac}, and $\vec{a}_x$ are the external static magnetic field, the exchange field between nearest-neighbor cells, the demagnetizing field, the field due to uniaxial anisotropy, the amplitude of microwave field, the microwave frequency, and the unit vector along the x-axis, respectively.

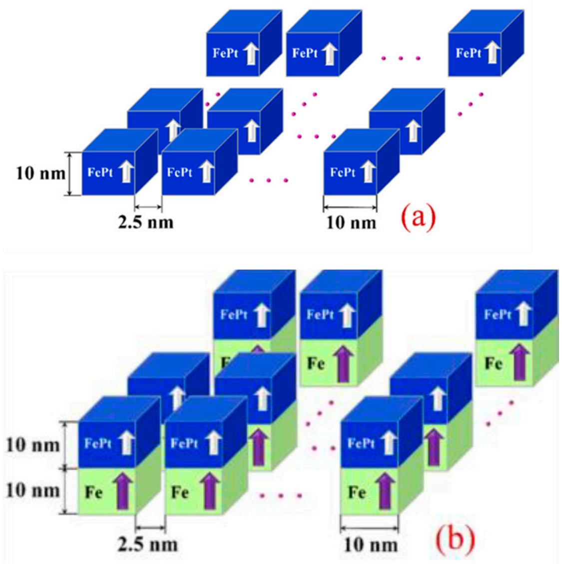

Figure 1. (**a**) Single layer BPM and (**b**) bilayer ECC-BPM.

To investigate the writability of the media, the external DC write field, H_{dc}, was applied to the media in the z-direction. The write head field region was defined as the region where the magnetization of the media can be written by the write head field. The H_{sw} of the media was collected in the condition that $M = -0.8M_s$. For the MAMR included, the H_{ac} was simultaneously applied to H_{dc} with a magnitude of 100 mT in the x-direction. The H_{sw} of the proposed ECC-BPM was examined at various frequencies of H_{ac}. Since A_{dot} typically has an influential impact on the H_{sw}, the dependence of A_{dot} on the H_{sw} was also taken into account. Then, the hysteresis loops and magnetic domain of a bilayer ECC-BPM were determined and compared with those of a single-layer BPM.

3. Results and Discussions

The H_{sw} of the proposed bilayer ECC-BPM at different A_{dot} values was investigated at f_{ac} between 0 and 25 GHz, as shown in Figure 2. It was discovered that changing A_{dot} or f_{ac} could change the H_{sw}. Without MAMR, the media with an A_{dot} of 0.14 pJ/m have the lowest H_{sw}, followed by those with an A_{dot} of 0.12, 0.25, and 0.30 pJ/m, respectively. A variation of A_{dot} under the MAMR indicates a similar trend of H_{sw} for all f_{ac}. When the MAMR was performed, it revealed that increasing the f_{ac} from 0 to 2 GHz slightly changes the H_{sw} of the media. Then, the H_{sw} was dramatically reduced to the range of f_{ac} about 5–7.5 GHz. Above f_{ac} of 10 GHz, the H_{sw} of all media tended to have a higher H_{sw} than that without MAMR and was insignificantly changed with varying f_{ac}. From the results, the media with A_{dot} = 0.25, 0.30 pJ/m indicate their lowest H_{sw} at a f_{ac} of 5 GHz, whereas the lowest H_{sw} of media with A_{dot} = 0.12, 0.14 pJ/m occurs at a f_{ac} of 7.5 GHz. The lowest H_{sw} found in this evaluation is 11.9 kOe, achieved by the media with an A_{dot} of 0.14 pJ/m with MAMR at a f_{ac} of 7.5 GHz. However, since the resonance frequency of our proposed system is 5 GHz, we therefore examined more details of A_{dot}'s influence on the H_{sw} at this frequency.

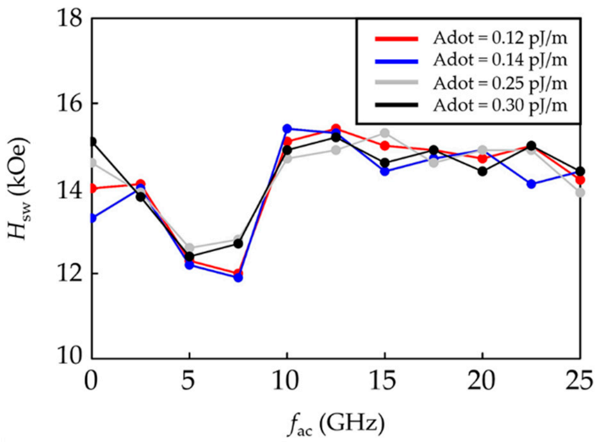

Figure 2. H_{sw} of the bilayer ECC-BPM versus f_{ac} at various A_{dot}.

Figure 3 displays the H_{sw} of the bilayer ECC-BPM as a function of A_{dot}, in the cases without and with the MAMR at f_{ac} = 5 GHz. Overall, it shows that using MAMR can significantly reduce the H_{sw} of the media for all A_{dot} values. Additionally, the media with MAMR indicate less variation of H_{sw} with a varying A_{dot} than that without MAMR. The lowest H_{sw} of ECC-BPM without and with MAMR is 13.1 kOe at A_{dot} = 0.16 pJ/m and 12.2 kOe at A_{dot} = 0.14 pJ/m, respectively. The H_{sw} alternation with varying A_{dot} at other f_{ac} is supposed to provide a higher H_{sw} than that at f_{ac} = 5 GHz due to its larger conventional value and therefore is not considered in this work.

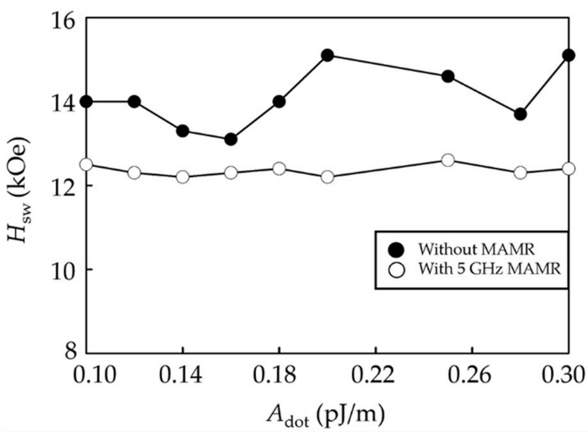

Figure 3. H_{sw} of the bilayer ECC-BPM with and without HAMR as a function of A_{dot}.

In a case without MAMR, the media with higher A_{dot} tend to have higher H_{sw}. A magnitude of A_{dot} normally represents an exchange interaction between magnetic dots of the media. This interaction indicates an interacting force between adjacent magnetizations. At higher A_{dot}, each magnetic dot is strongly related to each other due to a massive exchange interaction between them. When the write head field is applied to the media, the magnetization of the media with higher A_{dot} is more homogeneously processed, then it is more difficult to be switched.

The physical reason why a variation of f_{ac} can alter the H_{sw} of media with MAMR can be explained by the FMR phenomenon, as follows: when the magnetization precession of a ferromagnetic material is under the effect of an external magnetic field, the FMR frequency, f_0, can be obtained by $f_0 = \gamma(H - 4\pi M_{s,eff})$ [24] where H is the magnitude of media switching field with an absence of MAMR and $M_{s,eff}$ is the effective saturation magnetization of the bilayer ECC-BPM. The FMR itself can exert additional energy on the magnetization through the resonance phenomenon, which causes the additional magnetization precession. The magnitude of this added energy depends on the frequency of the external microwave field. The maximum added energy occurs when the f_{ac} is synchronized with the FMR frequency of the system, which typically provides a significant reduction in H_{sw}. In addition, the reason why the media with MAMR have a lower H_{sw} than the conventional media is that the magnetization precession of the media subjected to the microwave field receives the additional energy exerted by the microwave field. The magnetization of the hard layer, therefore, requires lower H_{sw} for switching than in a case without MAMR. In particular, this additional torque energy becomes massive when the frequency of MAMR corresponds with the precession frequency of its FMR.

A comparison of the hysteresis loops of the single-layer BPM and the bilayer ECC-BPM for cases without and with 5 GHz MAMR is indicated in Figure 4. The A_{dot} of 0.14 pJ/m was selected for this characterization for both media since this value previously demonstrates the lowest H_{sw} under MAMR. In this figure, the H_{sw} is determined at the point that $M = -0.8M_s$. From the results, the single-layer BPM has the H_{sw} of 27 kOe and 26 kOe for cases without and with MAMR, respectively. By adding the Fe soft layer to the single-layer BPM, the H_{sw} of the bilayer ECC-BPM for the cases without and with MAMR was reduced to 13.3 kOe and 12.2 kOe, respectively, which are significantly lower than that of the single-layer BPM. To provide more information about the magnetization orientation of the media, the magnetic domain of four media was characterized at the points where $H_{dc} = -18$ kOe since this particular H_{dc} can indicate the difference between them. Figure 5a,d show the magnetic domain from the cross-sectional side view of media at the points shown by circles (a–d) in Figure 4, respectively. It is seen that the magnetization of the single-layer BPM with MAMR contains more reversed magnetization than that without MAMR, demonstrating the effects of MAMR assisting the magnetization switching. Additionally, the magnetization of the bilayer ECC-BPMs is greatly reversed when compared to the single-layer BPM. The use of the MAMR in the bilayer ECC-BPM indicates a slightly better reversal of magnetization.

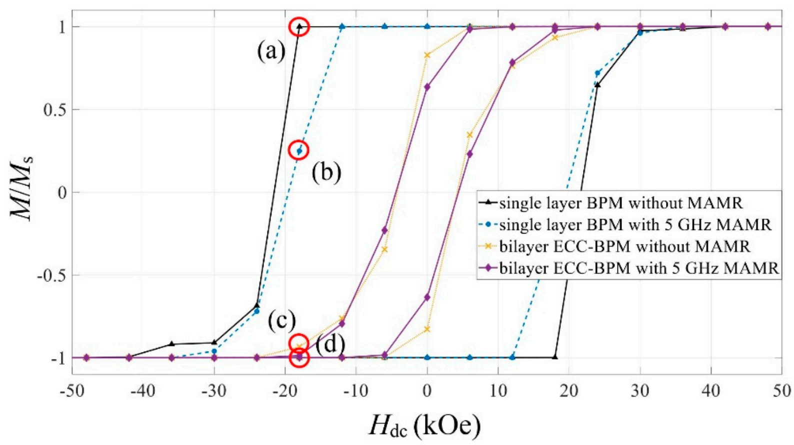

Figure 4. The hysteresis loops of the single-layer BPM and the bilayer ECC-BPM with and without MAMR (A_{dot} = 0.14 pJ/m for both media).

From overall evaluations, the lowest H_{sw} found in this work is 12.2 kOe, achieved by the proposed bilayer ECC-BPM with an A_{dot} of 0.14 pJ/m using a 5 GHz MAMR, which is below the maximum write head field existed in the literature. Therefore, this proposed bilayer ECC-BPM could be another choice as the magnetic media for an areal density of 4 Tb/in^2 of data storage technology. It should be noted that the suitable value of A_{dot} and f_{ac} for other media and areal densities recording systems needs to be carefully optimized. The theoretical findings can be the guidelines for its experimental verification as well as further development of magnetic media in the future.

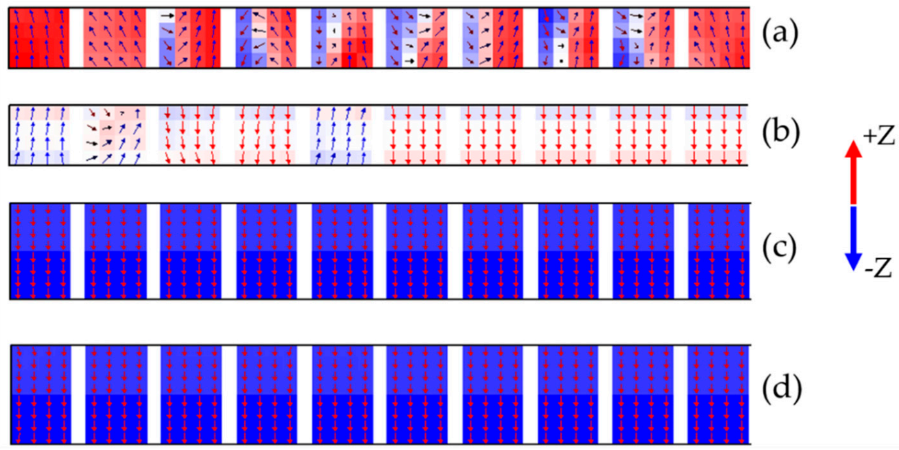

Figure 5. Magnetic domain from cross-sectional side view of (**a**) Single-layer BPM; (**b**) Single-layer BPM with MAMR; (**c**) Bilayer ECC-BPM; (**d**) Bilayer ECC-BPM with MAMR at H_{dc} = −18 kOe.

4. Conclusions

In this work, the $L1_0$-FePt single-layer BPM and $L1_0$-FePt/Fe bilayer ECC-BPM with MAMR technology were proposed to improve the writability of the magnetic media at a 4 Tb/in^2 recording density. It was found that the H_{sw} bilayer ECC-BPM was significantly lower than that of the single-layer BPM. The H_{sw} of those media could be increasingly reduced by using MAMR. The suitable frequency of the applied microwave field was 5 GHz, which was consistent with the FMR of the system. The suitable value of A_{dot} for the proposed bilayer ECC-BPM under MAMR was 0.14 pJ/m. The physical explanation of the H_{sw} of the medium regarding a variation of MAMR and A_{dot} was given. The hysteresis loops and magnetic domain of the medium have been considered to provide further details on the simulation results. The lowest H_{sw} found in this proposed medium is 12.2 kOe, achieved by the bilayer ECC-BPM with an A_{dot} of 0.14 pJ/m using a 5 GHz MAMR. Findings can be used for the future development of ultra-high areal densities magnetic recording technology.

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