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Exchange coupled CoPt/FePtC media for heat assisted magnetic recording

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L1₀ FePtC granular media are being studied as potential future magnetic recording media and are set to be used in conjunction with heat assisted magnetic recording (HAMR) to enable recording at write fields within the range of current day recording heads. Media structures based on a FePtC storage layer and a capping layer can alleviate the switching field distribution (SFD) requirements of HAMR and reduce the noise originating from the writing process. However, the current designs suffer from SFD issues due to high temperature writing. To overcome this problem, we study a CoPt/FePtC exchange coupled composite structure, where FePtC serves as the storage layer and CoPt (with higher Curie temperature, T_c) as the capping layer. CoPt remains ferromagnetic at near T_c of FePtC. Consequently, the counter exchange energy from CoPt would reduce the noise resulting from the adjacent grain interactions during the writing process. CoPt/FePtC bilayer samples with different thicknesses of CoPt were investigated. Our studies found that CoPt forms a continuous layer at a thickness of 6 nm and leads to considerable reduction in the saturation field and its distribution. *Published by AIP Publishing.* <https://doi.org/10.1063/1.5012815>

Currently, hard disk drives (HDDs) provide the most cost-effective storage capacity to cater to the ever-increasing demand in data storage. So far, CoCrPt based perpendicular magnetic recording (PMR) media have been the workhorse for the HDD industry. However, any further development in PMR media is stalled by the so-called “magnetic trilemma,” referring to the three mutually conflicting requirements of high thermal stability, easy writability, and high signal-to-noise ratio (SNR).^{1,2} To push the areal density in HDDs beyond 1 Tb/in.², it would require well isolated magnetic grains with dimensions as small as 5–6 nm.³ Moreover, improving SNR would require more grains to be squeezed in a magnetic bit. Consequently, the grain sizes are being pushed to its superparamagnetic limits. Therefore, high anisotropy materials such as L1₀ FePt are considered for ultra-high density data storage due to their high magneto crystalline anisotropy constant K_u , ensuring greater thermal stability.^{4–6} However, high K_u comes at the cost of higher saturation fields H_s , much beyond the switching capability of present day write heads.

Energy assisted magnetic recording (EAMR) technologies such as heat assisted magnetic recording (HAMR) and microwave assisted magnetic recording (MAMR) have been proposed to overcome this challenge.^{5,7} In HAMR, laser-based localized heating of the recording media drives it near its Curie temperature (T_c), facilitating switching at a field much lower than H_s .^{8,9} L1₀ FePt is currently considered to be the most suitable candidate for HAMR media, which can ensure stable grains down to 3 nm, due to its very high

$K_u = 7 \times 10^7$ erg/cc.^{4,6} Segregants such as C, SiO₂, and TiO₂ have been used in FePt to reduce the exchange coupling between the grains.^{10–14} Single, dual, and multi-layer granular media with similar or different segregants have been used to optimize L1₀ FePt HAMR media.^{6,15–17} Although the non-magnetic segregant between the grain boundaries limits the intergranular exchange coupling between the grains, the magnetostatic interaction between the grains can lead to wider switching field distributions (SFDs) and consequently a reduced SNR. Media with capped layers can address this problem, as the exchange coupling added by layers (such as FePt, FeRh, or Fe, proposed by others) can compensate the magnetostatic interaction.^{16,18–26} However, these materials become ineffective in the case of HAMR, as materials such as FePt and Fe lose ferromagnetism at high temperature during recording. As a result, the high temperature SFD is still higher in HAMR media. Therefore, we study a bilayer structure having different Curie temperatures, where the storage layer at the bottom has a Curie temperature close to the write temperature (T_{wr}) and the capping layer on top has a significantly higher Curie temperature ($T_{c, cap} > T_{wr}$). A magnetic capping layer with higher T_c would be best suited for HAMR application, as the cap layer would remain ferromagnetic even at the write temperature (T_{wr}). As a result, this high T_c layer would still provide exchange coupling during the writing process and reduce high-temperature SFD. Using a lower T_c FePt at the bottom ensures that the laser write power is not compromised. Therefore, in this work, we investigate L1₀ FePtC granular media capped with the L1₀ CoPt continuous layer. L1₀ CoPt, owing to its higher Curie temperature ($T_{c, CoPt} \sim 840$ K), would retain ferromagnetism at T_{wr} near T_c of L1₀ FePtC ($T_{wr} \sim T_{c, FePtC}$).

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FIG. 1. Hysteresis loops for all samples with and without the CoPt capping layer: (a) out-of-plane and (b) in-plane.

The stack structures of $L1_0$ CoPt (t_{CoPt})/ $L1_0$ FePtC (10 nm)/MgO (3 nm)/CrRu (25 nm)/Glass were fabricated by sputter deposition. The CoPt layer thickness (t_{CoPt}) was varied from 2 to 6 nm. The granular ($L1_0$ FePtC) and continuous ($L1_0$ CoPt) layers were deposited at nominal temperatures of 600 °C and 640 °C, respectively. An uncapped sample (without any CoPt capping) was also prepared under similar conditions for reference. The FePtC layer was deposited using a composite sputter target with atomic concentration of Fe (37.5%), Pt (37.5%), and C (25%). The deposition conditions, the schematic stack structures, and the composite target composition details are provided in the [supplementary material](#).

Figures 1(a) and 1(b) show the out-of-plane and the in-plane hysteresis loops of both uncapped and CoPt capped granular $L1_0$ FePtC samples. The absence of any kink or step in the hysteresis loops suggests coherent reversal of the two magnetic layers due to strong exchange coupling between the two layers.²⁷ On introduction of the 2 nm $L1_0$ CoPt capping layer, the out-of-plane saturation fields (H_s) of the capped-granular ECC sample decreased. On increasing the thickness of the $L1_0$ CoPt layer, H_s decreased further. The squareness $S = M_r/M_s$ of out-of-plane loops increased gradually with an increase in the thickness of the capping $L1_0$ CoPt layer, where M_r and M_s are the remanent and saturation magnetizations, respectively. It was also observed that there was a small increase in the squareness of the in-plane loops as well. Probably, it is due to partial $L1_0$ ordering obtained in CoPt, as the deposition temperature of 640 °C was lower than that required for complete ordering.²⁸ It might also be due to partial in-plane alignment of the c-axis in the CoPt layer. M_s values of the samples with the CoPt capping layer were found to be slightly higher than that of the single layer granular $L1_0$ FePtC. Although CoPt has a lower M_s in

comparison to that of FePt, the increase in M_s with CoPt is because of the fact that FePt with the C dopant has a lower M_s , in comparison to CoPt.

The coercive field (H_c) and the anisotropy field (H_k) extracted from the out-of-plane loops are presented in Fig. 2(a). The CoPt thickness of $t_{CoPt} = 0$ nm corresponds to the single layer granular $L1_0$ FePtC sample. There was limited change in H_c on introduction of the $L1_0$ CoPt layer. H_k increased gradually on introduction of the $L1_0$ CoPt layers. For the 2 nm and 4 nm $L1_0$ CoPt layers, H_k increased marginally by 3% and 5.4%, respectively. Figure 2(b) shows the change in H_s and the percentage change in SFD compared to the uncapped FePtC sample ($\Delta SFD\%$), with the increase in the CoPt thickness. SFD was calculated as $SFD = (H_s - H_n)/H_c$, where H_n is the nucleation field and H_c is the coercive field, extracted from the out-of-plane loops. Both H_s and $\Delta SFD\%$ decreased steadily with an increase in the CoPt thickness. In fact, for the $t_{CoPt} = 6$ nm sample, H_s and $\Delta SFD\%$ decreased by 23.11% and 32.80%, respectively, as compared to that of the uncapped granular sample. Although the anisotropy fields (H_k) of undoped FePt and CoPt are comparable, H_k decreases with carbon doping in FePt. As a result, FePtC has a lower H_k in comparison to CoPt. Therefore, H_k of the bilayer stack would increase with the increase in the CoPt thickness.

Reduction in H_s is a confirmation of exchange coupling introduced by the CoPt capping layer. Reduced H_s can ensure ease of writing of the continuous-granular media, i.e., it can be written at a comparatively lower applied field, while a lower SFD can ensure improved SNR in such $L1_0$ CoPt/ $L1_0$ FePtC continuous-granular ECC media.

Structural characterization of the CoPt capped and uncapped FePtC granular media samples was carried out to study the crystallographic orientation of both the granular

FIG. 2. (a) The change in coercivity (H_c) and anisotropy (H_k) fields of all the samples with the increasing CoPt capping thickness. (b) The variation in the saturation field (H_s) and percentage reduction in switching field distribution ($\Delta SFD\%$) with the increasing CoPt thickness.

and the continuous layer. Figure 3 shows the X-ray diffraction (XRD) θ - 2θ scan results of the samples. The different FePt phases, viz., FePt (001), FePt (111), and combined peak of FePt (002) and FePt (200), along with MgO (200) and CrRu (200) peaks are indicated in the figure. The CoPt peaks of CoPt (001), CoPt (111), and CoPt (200) lie close to those of FePt, making them indistinguishable from the respective FePt peaks. The strong superlattice FePt (001) peak of the FePtC layer clearly indicates the presence of the superlattice tetragonal phase and ordering in the FePtC media. On increasing the CoPt layer thickness, the combined peak of FePt (001) and CoPt (001) grows stronger, indicating the presence of L1₀ ordering in the CoPt film. However, the combined fundamental peaks of FePt (002) + FePt (200) and CoPt (002) also strengthened with an increase in the CoPt thickness. The ordering parameter (*S*) was extracted from the relative intensities of the superlattice and the fundamental peaks as $S = 0.493 \sqrt{I_{001}/I_{002}}$.⁵ *S* decreased from 0.4988 to 0.4755 on introduction of the CoPt continuous layer when compared to the single FePtC layer, and it continued to gradually decrease with an increase in the CoPt thickness. Clearly, the ordering in the CoPt capping layer was partial as the temperature of 640 °C was lower than that required for complete ordering.²⁸ Nevertheless, the capping layer was effective in reducing *H_s* and SFD of the FePtC granular media, while ensuring higher thermal stability.

Top-view and cross-sectional transmission electron microscopy (TEM) was also carried out on the samples to check for the growth of the CoPt capping layer and to ascertain the effect of the capping layer on FePt grain sizes (see [supplementary material](#) for details). It was observed that the CoPt capping layer grew as a continuous layer beyond a thickness of 6 nm, and it had a limited effect on the grain size and the grain size distribution of the FePtC layer. Rocking curve measurements were also carried out at $2\theta = 23.7^\circ$ for the FePt (001) peak. $\Delta\theta_{50}$ was then measured from the rocking curves as an indirect measure of SFD arising from the distribution in crystallographic orientations (see [supplementary material](#) for details). It was found that the introduction of CoPt capping had limited effect on the

FIG. 3. θ - 2θ XRD data for both uncapped and CoPt capped FePtC granular samples. FCC peaks of FePt (111) and (200) along with ordered peaks of FePt (001) and FePt (002) are indicated. CoPt peaks of (111), (200), and (001) superimpose with those of FePt.

change in $\Delta\theta_{50}$, indicating that CoPt capping had no detrimental effects.

For the CoPt capping to be effective for L1₀ FePtC HAMR media, it is important that the capping layer remains ferromagnetic at temperature near T_c of L1₀ FePtC ($T_c < 700$ K). Therefore, out-of-plane hysteresis loops of the samples were measured at high temperatures of 250, 300, 350, and 400 °C. It was observed that 400 °C is well above $T_{c,FePtC}$ but lower than $T_{c,CoPt}$. Two additional samples were also prepared with 4 nm and 6 nm L1₀ FePt capping layers on the L1₀ FePtC granular layer (see [supplementary material](#) for details). Figure 4 shows the out-of-plane loops measured at high temperatures. It was observed that with increasing the temperature, the hysteresis loops of all the samples shrunk. H_c , H_s , and H_k at 250 °C were lower than those at room temperature and continued to decrease with a further increase in temperature. The magnetization at 250 °C was also lower as compared to that measured at room temperature. For 250 °C, the values of H_s and SFD were lower for L1₀ CoPt capped samples as compared to those of uncapped or L1₀ FePt capped samples. Although this is not the writing temperature, these results indicate that the heating requirements for complete reversal at the applied field (write head field) would be much stringent for L1₀ CoPt capped FePtC media. As the temperature increased beyond 300 °C, it becomes extremely difficult to ascertain the values of H_s and SFD for the different samples. However, as seen in Fig. 4(c), the loop for the single layer FePtC granular media turned paramagnetic, while all the capped samples remained ferromagnetic at 350 °C. On increasing the temperature beyond 350 °C, the sample with a 4 nm L1₀ FePt capped sample also turned paramagnetic. However, the CoPt capped media and the 6 nm FePt capped media remained ferromagnetic. Although the 6 nm FePt capped sample remains ferromagnetic at 400 °C, the magnetization was much lower compared to the CoPt capped samples. Clearly, the CoPt capping layer remains ferromagnetic at 350 °C and 400 °C although the uncapped FePtC granular media become paramagnetic at those temperatures. During the actual recording process using HAMR, the target grains are heated to T_c of the media, at which they become paramagnetic, with random magnetization alignment. During the cooling process, even before the write field is applied, the stray field from the adjacent grains can set the magnetization in the target grains, to minimize the magnetostatic energy. As a result, when the write field is applied, it would become difficult to desirably alter the magnetization of the target grains. However, the presence of the L1₀ CoPt capping layer (which remains ferromagnetic near T_c of L1₀ FePtC) will produce counter exchange energy to minimize the stray field from the adjacent grains. Consequently, the magnetization in the target grains would no longer be affected by the stray field during the recording process.

A figure of merit, $\xi = [H_{s,SL}/H_{s,BL}] [(T_{c,CL} - T_{c,SL})/T_{c,SL}]$, can be used to compare the effectiveness for such structures, where the suffixes SL, BL, and CL indicate single layer (without the capping layer), bilayer (with the capping layer), and the capping layer, respectively. The term $[H_{s,SL}/H_{s,BL}]$ accounts for the ease of switching, while the term $[(T_{c,CL} - T_{c,SL})/T_{c,SL}]$ accounts for the ability of the

FIG. 4. Out-of-plane hysteresis loops of uncapped, CoPt capped, and FePt capped samples at temperatures of (a) 250, (b) 300, (c) 350, and (d) 400 °C.

bilayer structure to retain ferromagnetism near T_c of the storage layer, thereby ensuring reduced noise during recording. If the Curie temperature of the cap layer $T_{c,CL}$ is not different from that of the single layer $T_{c,SL}$, the figure of merit (ξ) will be zero. For the figure of merit to have a higher value, it is necessary that $T_{c,CL} > T_{c,SL}$. ξ values for the FePtC/CoPt bilayers with CoPt capping $t_{CoPt} = 4$ nm and $t_{CoPt} = 6$ nm were 0.207 and 0.287, respectively, compared to $\xi = 0$ for FePtC single layer, while ξ values for FePt capped bilayers of $t_{FePt} = 4$ nm and $t_{FePt} = 6$ nm were merely 0.095 and 0.104, respectively.

Changes in remanence (M_r) and saturation magnetization (M_s) at elevated temperatures were also studied with changing temperature (T). Figure 5(a) shows the change in remanent magnetization at temperature T , $M_r(T)$, normalized to that at room temperature, $M_r(25^\circ\text{C})$. The reduction in $M_r(T)$ with an increase in T was steeper for granular L1₀ FePtC and L1₀ FePt capped media as compared to that for the media capped with L1₀ CoPt. For $T \geq 250^\circ\text{C}$, $M_r(T)/M_r(25^\circ\text{C})$ for L1₀ CoPt capped structures was higher than that for both uncapped and L1₀ FePt capped structures. The

magnetization of the different samples at an applied field of 22 kOe was measured with changing temperature (T) as $M_H(T)$. $M_H(T)$ normalized with the magnetization at 25 °C, $M_H(25^\circ\text{C})$, was plotted with changing temperature (T) as shown in Fig. 5(b). Similar to the change in $M_r(T)/M_r(25^\circ\text{C})$, the reduction in $M_H(T)/M_H(25^\circ\text{C})$ was steeper for granular L1₀ FePtC and L1₀ FePt capped media. Also, the value of $M_H(T)/M_H(25^\circ\text{C})$ at $T \geq 300^\circ\text{C}$ was almost zero for granular L1₀ FePtC and L1₀ FePt capped media, while $M_H(T)/M_H(25^\circ\text{C})$ for L1₀ CoPt capped samples was considerably higher than zero, confirming that L1₀ CoPt remains ferromagnetic at $T \geq 350^\circ\text{C}$. Thus, the L1₀ CoPt capping layer remains ferromagnetic at temperatures near T_c of L1₀ FePtC granular layer. Therefore, it can provide effective exchange coupling for capped L1₀ FePtC granular HAMR media.

In conclusion, we have demonstrated that L1₀ CoPt capping for L1₀ FePtC granular media can lead to lower saturation fields and improved switching field distribution while ensuring higher thermal stability. The presence of ferromagnetic exchange coupling from the L1₀ CoPt capping layer at

FIG. 5. (a) Normalized remanent magnetization $M_r(T)/M_r(25^\circ\text{C})$ plotted against the change in temperature (T). (b) Normalized magnetization $M_H(T)/M_H(25^\circ\text{C})$ plotted against the change in temperature (T) for an applied field of $H = 22$ kOe.

near Curie temperature of $L1_0$ FePtC makes $L1_0$ CoPt/ $L1_0$ FePtC media best suited for future HAMR technology. Therefore, it would not only improve the recording performance but also considerably ease the extreme challenges faced in HAMR technology.

See [supplementary material](#) for the details of the deposition conditions, the schematic stack structures, and the composite target composition details. TEM and $\Delta\theta_{50}$ information is also provided in the [supplementary material](#).

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