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High switching efficiency in FePt exchange coupled composite media mediated by MgO exchange control layers

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Satisfying the mutually conflicting requirements of easy switchability and high thermal stability still remains a hindrance to achieving ultra-high areal densities in hard disk drives. Exchange coupled composite media used with proper exchange control layers (ECLs) presents a potential solution to circumvent this hindrance. In this work, we have studied the role of MgO and Ta ECLs of different thicknesses in reducing the switching field of FePt media. MgO ECL was found to be more effective than a Ta ECL. For a 2 nm MgO ECL, the switching field could be reduced by 41% and at the cost of only a limited loss in thermal stability. Furthermore, a very high switching efficiency of 1.9 was obtained using 2 nm MgO ECL. So, with a proper choice of ECL material and thickness, the switching field of FePt media can be substantially reduced while ensuring high thermal stability and a better signal-to-noise ratio, thus potentially paving the way for very high areal density media. *Published by AIP Publishing.* [<http://dx.doi.org/10.1063/1.4996366>]

The last decade has witnessed the highest ever increase in demand for data storage. Conventional magnetic storage in hard disk drives (HDDs) provides the most cost effective storage capacity to cater to this ever increasing demand in data storage. However, conventional perpendicular magnetic recording (PMR) suffers from the so called “magnetic trilemma,” which refers to the convergence of three mutually conflicting requirements of high signal-to-noise ratio (SNR), high thermal stability, and easy writability.^{1,2} High anisotropy materials such as L1₀ FePt are considered for ultra-high density data storage due to their high thermal stability.^{3–5} However, the high thermal stability comes at the cost of higher switching fields, much beyond the switching capability of present day write heads. Heat assisted magnetic recording (HAMR) and bit patterned magnetic recording have been proposed to overcome this challenge.^{5,6} In HAMR, laser-based localised heating of the PMR media drives it near its Curie temperature and therefore can be switched at a field much lower than its switching field.^{7,8} Bit patterned media (BPM) uses a different approach, wherein isolated magnetic islands are created which have higher thermal stability owing to their higher volume.⁶ These approaches have their own disadvantages in the form of stringent media or overcoat requirements for HAMR and ultra-high density patterning limitations for BPM.^{6,7,9–12} A plausible approach around this bottleneck of high switching fields for high thermal stability can be found in exchange coupled composite (ECC) media.^{13–15} This scheme has the exclusive advantage of requiring changes only in the media and no additional requirements for changes in reading/writing technology.

In ECC media, a soft magnetic layer is used in conjunction with a hard magnetic layer. The hard magnetic layer provides the high thermal stability due to its higher magnetocrystalline anisotropy (K_u), while the soft layer lowers the switching field of the composite structure by exchange coupling with the hard layer.^{13–15} ECC media has the potential of tailoring the thermal stability and the switching field of magnetic media concurrently to converge the mutually contradictory requirements of thermal stability and easy writability by choosing soft layers with appropriate magnetic properties and thickness. Furthermore, exchange control layers (ECLs), inserted between the hard and soft layers can be used for effective tuning of the switching fields and thermal stability for practical applications in HDDs.^{16–18} Wang *et al.* had previously explored the effect of soft layer thickness variation and ECL thickness in CoCrPt media.^{16–18} However, for future magnetic recording, it is imperative to tune the switching fields and thermal stability of L1₀ FePt media. It is therefore important to gain a proper understanding of the ferromagnetic exchange coupling and magnetisation reversal process in ECC structures with a change in ECL and a change in soft layer thickness for L1₀ FePt media.

A variety of ECC structures such as FePt/FeRh, Fe/FePt, and FePt/C/Fe have been studied to tailor the switching field for ECC media.^{19–23} However, it is challenging to fabricate the exact microstructure of the soft phase stacked over the hard phase in a single grain as was proposed by Vctora and Shen.¹³ We have previously proposed a two-step temperature deposited bilayer structure for ECC media with the face centred cubic (FCC) FePt grains stacked over L1₀ FePt grains in a columnar fashion.²⁴ The bottom FePt layer deposited at a high temperature of 600 °C ensured high thermal stability, while the top FePt layer deposited at room temperature

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reduced the coercive and switching fields by exchange coupling with the bottom FePt layer. In this work, MgO and Ta exchange control layers were used to tune the exchange coupling between the two FePt layers. It was found that using a proper thickness of ECL, the switching fields of these bilayer structures can be substantially reduced while ensuring limited reduction in the thermal stability. The switching efficiency (ξ), which represents a qualitative comparison of the change in thermal stability to the ease of switchability, could also be enhanced by 40% in the FePt bilayers.

FePt bilayers with a stack structure of FePt(25 °C)/ECL/FePt(600 °C)/MgO/CrRu/Glass was sputter deposited, with other deposition conditions similar to those described in our previous work on FePt bilayers.²⁴ Figure 1(a) shows a schematic of the reference sample with a single FePt layer, sputter deposited at 600 °C under 3.5 mTorr pressure. Figures 1(b) and 1(c) illustrate the schematic of the bilayer structures with no ECL and with ECL, respectively. Two soft layer thicknesses (t_s) of 2 nm and 5 nm were used for this work. FePt bilayers with MgO and Ta as ECL were fabricated with various ECL thicknesses of $t_{ECL} = 0.5$ nm – 4 nm. The indicated thicknesses were measured using a profilometer. Transmission electron microscopy (TEM) was also carried out to image the cross-section of selected FePt bilayer samples as shown in Figs. 1(d)–1(h). The thicknesses of the ECL layers were also verified from TEM, and it was found to be 5%–8% more than that measured by using the profilometer. The coercivity (H_c) and saturation magnetisation (M_s) of the reference FePt sample were 18 kOe and 810 emu/cc, respectively. The hard FePt layer had an out-of-plane easy axis. The magnetization of the 2 nm soft FePt layer was mostly out-of-plane, while that of the 5 nm soft FePt layer showed an increase in in-plane magnetization orientation.

Coercive and switching fields of the FePt bilayers could be substantially decreased by introduction of an exchange control layer. A proper choice of the ECL thickness enabled tuning of both the coercive and switching fields desirably to address present day write field limitations. Figure 2(a) shows the variation in H_c with a change in the ECL thickness. It was seen that by introducing an ECL between the two FePt layers, H_c could be changed as compared to that without any ECL ($t_{ECL} = 0$ nm). For ($t_s = 2$ nm), introduction of both Ta and MgO exchange control layers had the effect of decreasing H_c . While, for $t_s = 5$ nm, introduction of ECL increased H_c in the case of Ta ECL and decreased H_c for MgO ECL till $t_{ECL} = 1.5$ nm, beyond which H_c decreases for both Ta and MgO. It was also found that for the thinner soft layer ($t_s = 2$ nm), H_c can be reduced from 15.3 kOe to 12.3 kOe, comparable to that for the thicker soft layer ($t_s = 5$ nm) by proper choice of the exchange control layer. Switching fields (H_s) for all the samples are shown in Fig. 2(b). H_s for the reference sample was 39 kOe. For the FePt bilayers with $t_s = 2$ nm and $t_s = 5$ nm, the H_s reduced to 29.5 kOe and 23.2 kOe, respectively, without any ECL. However, on introduction of an ECL between the two FePt layers, H_s decreased significantly for $t_s = 2$ nm. This is significant as it would mean attaining reduced switching field while retaining higher values of effective anisotropy ($K_{eff} = ((K_{u,hard}t_{hard} + K_{u,soft}t_{soft})/(t_{hard} + t_{soft}))$). Thus, MgO ECL was found to be more effective in reducing H_c as well as H_s as compared to Ta.

In ECC PMR media, ensuring high thermal stability of the media is also an important and necessary condition in addition to having lower switching fields comparable to the write field available today. Thermal stability is expressed in terms of the ratio of the anisotropy energy ($E_k = H_k M_s / 2$)

FIG. 1. Schematic of the stack structure for (a) reference sample and (b) bilayer samples without ECL and (c) with ECL. Cross-sectional TEM images of (a) MgO_{ECL} (2 nm)/FePt_{soft} (2 nm), (b) MgO_{ECL} (2 nm)/FePt_{soft} (5 nm), (c) MgO_{ECL} (4 nm)/FePt_{soft} (2 nm), (d) Ta_{ECL} (2 nm)/FePt_{soft} (2 nm), and (e) Ta_{ECL} (4 nm)/FePt_{soft} (5 nm).

FIG. 2. (a) Coercivities (H_c) and (b) switching field (H_s) of the FePt bilayer samples for different thicknesses of ECL.

and thermal energy ($E_T = K_B T$), where H_k , K_B , V , and T are the anisotropy field, the Boltzmann constant, the volume of a bit, and the temperature, respectively. A thermal stability factor of ($E_k/E_T \geq 60$) is desirable in PMR media for high stability and a low bit error rate (BER) up to 10 years. Therefore, a higher anisotropy field (H_k) would ensure a highly stable media. Figure 3(a) shows the anisotropy field (H_k) change with an increase in ECL thickness. H_k for the reference sample is also indicated in Fig. 3(a). On introduction of Ta or MgO ECL, H_k drops initially for both $t_s = 2$ nm and $t_s = 5$ nm. However, for MgO ECL of 2 nm, H_k increased substantially for both $t_s = 2$ nm and $t_s = 5$ nm. On the other hand, for Ta ECL, H_k remains almost similar for all thicknesses of ECL. It was observed that MgO ECL was also more effective in obtaining high thermal stability as compared to Ta ECL.

For ECC media, a trade-off between high thermal stability and easy switchability is essential. Switching efficiency ($\xi = (2\Delta E_k M_s / H_s M)$) is a figure of merit for ECC media which provides a qualitative measure of this trade-off between changes in thermal stability compared to the ease of switchability. Victora and Shen had predicted a switching efficiency as high as ($\xi = 2$) (double that of PMR media, $\xi = 1$) for ECC media by suitable selection of hard and soft layers.¹³ Figure 3(b) shows the plot of ξ with a change in ECL thickness. For $t_s = 2$ nm, a switching efficiency as high as 1.9 for 2 nm MgO ECL was obtained. Ta ECL was not found to be very effective in enhancing the switching efficiency. In fact, on introduction of Ta ECL, ξ remained fairly constant for a 2 nm soft FePt layer, while for a 5 nm soft FePt layer, ξ decreased by 25% from 1.6 to 1.2 (nearly the same as the reference sample) on introduction of Ta ECL.

Figures 4(a)–4(d) show the out-of-plane hysteresis loops of FePt bilayers for various soft layer thicknesses and ECL

thicknesses. All the hysteresis loops are plotted together with those of the reference sample and the FePt bilayer sample with no ECL. It was observed that the out-of-plane hysteresis loops for the thinner soft layer ($t_s = 2$ nm) had higher squareness as compared to those with ($t_s = 5$ nm). The introduction of ECL resulted in reduced squareness for most of the samples. However, FePt bilayers with MgO ECL were found to have better squareness as compared to those with Ta ECL. For $t_s = 2$ nm and MgO ECL, no kinks were noticed, indicating an optimum exchange coupling between the two FePt layers.

Although high switching efficiency with comparatively high squareness could be achieved using the MgO ECL and thinner soft FePt layer, it is also important to ensure that the switching field distribution (SFD) is not deteriorated due to the introduction of ECL. High SFD can lead to increased noise in FePt bilayer media, deteriorating SNR performance. First order reversal curves (FORC) were measured to extract the nucleation field (H_n). Thereafter, switching field distribution ($SFD = (H_n - H_s)/H_c$) for all the samples was calculated. Figure 4(e) shows the change in SFD with an increase in ECL thicknesses (both MgO and Ta). SFD for FePt bilayers remained nearly unchanged on introduction of both MgO and Ta ECLs. For the 2 nm FePt soft layer, the SFD was comparatively lower as compared to that with the 5 nm soft layer irrespective of ECL thickness. SFD was found to be strongly influenced by soft layer thickness and deteriorated for thicker soft layers. However, SFD seemed to be independent of ECL thickness. Therefore, FePt bilayer samples with the 2 nm soft layer and MgO ECL had the lowest SFD among all bilayer samples with ECL.

Structural characterisation using XRD was carried out to investigate the role of MgO and Ta ECL in these bilayer structures. Figure 5(a) shows the XRD $\theta - 2\theta$ scan results

FIG. 3. (a) Anisotropy field (H_k) and (b) switching efficiency (ξ) of the FePt bilayer samples for different thicknesses of ECL.

FIG. 4. Out-of-plane hysteresis loops for Ta ECL with (a) $t_s = 5$ nm and (b) $t_s = 2$ nm and MgO ECL with (c) $t_s = 5$ nm and (d) $t_s = 2$ nm. (e) $(H_s - H_n)/H_c$ indicating switching field distribution (SFD) of the FePt bilayer samples for different thicknesses of ECL.

FIG. 5. (a) θ -2 θ XRD data for the bilayer samples. (b) Fitted disordered FCC FePt (111) and FePt (200) peaks and (c) fitted ordered FePt (001) and FePt (002) peaks for the FePt bilayer samples for different MgO and Ta ECL thicknesses.

for FePt bilayer samples with different exchange control layers. The different FePt phases, viz., FePt (001), FePt (111), combined peak of FePt (002) and FePt (200), along with MgO (200) and CrRu (200) peaks, are indicated in the figure. Figure 5(b) shows the fitted disordered FCC FePt (111) and FePt (200) peaks for the samples, while Fig. 5(c) shows the fitted $L1_0$ ordered fundamental and superlattice peaks of FePt (001) and FePt (002), respectively. It was found that for thin soft FePt layer ($t_s = 2$ nm) without any ECL, the FePt (200) peak was absent. The soft FePt layer grew primarily in FePt (002) due to the stress induced from the underlying hard FePt layer and also in the FePt (111) phase.²⁴ On introduction of a thin MgO ECL, the soft FePt layer continued to grow primarily in the FePt (002) due to the stress induced from the underlying MgO (200) ECL, which in turn was strained due to the hard FePt layer.²⁵ However, beyond a critical thickness ($t_{MgO} = 4$ nm), the epitaxial stress

underwent relaxation, and consequently, the soft FePt layer grew in the FePt (200) phase. On the other hand, an amorphous Ta ECL promoted the growth of the soft FePt layer primarily in the FePt (111) phase and the FePt (002) phase decreased gradually with an increase in Ta thickness.

For the thicker soft layer ($t_s = 5$ nm), the soft FePt layer grew partially in FePt (200) + FePt (002) and FePt (111) phases in the absence of any ECL. On introduction of MgO (200) ECL, FePt (200) and FePt (111) phases strengthened. This is in accordance with the observations of Kim and Lee, who had reported that the FCC phases of FePt (200) and FePt (111) reappear and strengthen beyond a certain critical thickness of FePt (~ 2.8 nm) when grown on a MgO (200) substrate.²⁵ In the case of FePt bilayers with Ta ECL, the soft FePt layer ($t_s = 5$ nm) predominately grew in the FePt (111) phase, because of the amorphous nature of Ta.²⁶

The FePt (111) phase has a tilted axis.^{26,27} Therefore, the FePt (111) phase reduced the effective demagnetisation field (in the out-of-plane direction) acting on the hard FePt layer as compared to that from FePt (002) or FePt (200) due to the tilted axis. Consequently, the coercivity (H_c) and switching field (H_s) are higher for Ta ECL and also for thicker soft layers ($t_s = 5$ nm) as in Figs. 2(a) and 2(b). The lower anisotropy for FePt (111) also resulted in a reduced anisotropy field (H_k) for all FePt bilayers with Ta ECL as seen in Fig. 3(a). Similarly, H_k also reduced for thick MgO ECL ($t_{MgO} = 4$ nm). Hence, MgO ECL of 2 nm with a soft layer thickness of $t_s = 2$ nm was found to be the most effective in reducing the switching field while ensuring high thermal stability.

In conclusion, we have demonstrated that MgO exchange control layers can tune the coercive and switching fields in FePt bilayer ECC media, while ensuring high thermal stability. A proper choice of MgO ECL and a thinner FePt soft layer can enable very high switching efficiency, resulting from higher thermal stability and easy switchability while also ensuring better SNR performance.

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