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Two-Step Temperature Deposited FePt Bilayer for Tunable Magnetic Properties

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Abstract

Tuning the magnetic properties of FePt media is of great interest in the bid to achieve high areal densities. In this work, we demonstrate that properties of FePt media can be tuned using a two-step temperature FePt bilayer. In this bilayer scheme, the first layer of FePt was deposited at a high nominal temperature ($600 \, ^\circ C$), whilst the second layer was deposited at a lower temperature over the first layer. This results in tunable magnetic and improved topographical properties, and is due to the interplay of a number of temperature-dependent factors such as epitaxial growth, new grain nucleation, surface mobility, and difference in the thermal expansion coefficients. The transmission electron microscopy imaging was used to understand the growth dynamics of the second FePt layer in the two-step temperature deposited structures.

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Introduction:

Hard disk drives have been using perpendicular magnetic recording for a decade now [1]. The areal density has grown from about 130 Gbpsi to 1 Tbpsi. However, the increase in further areal density of perpendicular magnetic recording is faced with the so-called “media trilemma”, which refers to the three conflicting requirements of high signal to noise ratios (SNR), thermal stability and writability[2,3]. It has become a challenge to push all the requirements upwards in order to achieve high areal density. As a result, alternative recording technologies such as heat-assisted magnetic recording (HAMR) are being investigated [4]. In HAMR technology, the recording medium is made of high anisotropy material such as L1_0 FePt and cannot be written by conventional recording heads. Therefore, it uses localized heating of the media to reduce the coercivity of FePt media to the level of field available from conventional magnetic recording heads.

L1_0 FePt has been extensively studied as a potential magnetic thin film material for future media because of its high magneto-crystalline anisotropy ($K_u \sim 7 \times 10^7 \text{ ergs/cc}$) [5,6]. Its high $K_u$ would allow for media with high out-of-plane coercivity, small bits with high thermal stability and also a considerably high SNR. In short, it would further push the limits of onset of superparamagnetism, paving the way for higher areal densities ($\sim 4 \text{ Tb/in}^2$). However, the high magneto-crystalline anisotropy of L1_0 FePt gives rise to a high switching field ($H_c \sim 30 \text{ kOe}$), much higher than the magnetization reversal capability of the present write head field. Therefore, such media are suitable only for HAMR. There have been many studies to tailor the properties of L1_0 FePt for practical application in hard disk drives (HDDs). These include control of grain size by addition of impurities, use of underlayers for epitaxial growth of L1_0 FePt (001) at reduced temperatures as well as tailoring out-of-plane coercivity [4,7-12]. However, there have been
limited studies to explore the application of bilayer structures to tailor various properties of L1₀ FePt media. Bilayer structures such as FePt/FeRh, Fe/FePt, FePt:C/Fe have been studied to tailor the switching field for exchange coupled composite (ECC) and graded anisotropy media [13-26]. \textit{Suzuki et al} have studied two-step deposition FePt bilayers for reducing domain size [27]. Furthermore, the correlation between high deposition temperatures and ordering in single-layer L1₀ FePt media has been extensively studied [7,10,28]. However, no studies to date have been carried out to examine the effect of the FePt (T_{dep})/FePt(600 °C) bilayer structure over a wide range of deposition temperatures (T_{dep}) in tailoring the properties of L1₀ FePt media. Therefore we propose a two-step temperature deposited FePt bilayer as a noble and facile approach for tuning properties of FePt media. It is expected that the first FePt layer, deposited at 600 °C, would result in ordered FePt with superior magnetic properties but undesirable topographical properties while the second FePt layer, deposited at lower temperatures, would compensate to improve the topographical properties. The homo-epitaxial relation between the two FePt layers would enable the desirable magnetic properties of the media to be retained while improving the topographical properties. It can also be used to induce ordering in the FePt media at low temperatures, hence avoiding the generally high temperature of deposition required otherwise.

<table>
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<tr>
<th>Sample</th>
<th>T_{dep} (°C)</th>
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<tr>
<td>Sample A</td>
<td>No top layer</td>
</tr>
<tr>
<td>Sample B</td>
<td>25</td>
</tr>
<tr>
<td>Sample C</td>
<td>75</td>
</tr>
<tr>
<td>Sample D</td>
<td>150</td>
</tr>
<tr>
<td>Sample E</td>
<td>250</td>
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<td>Sample F</td>
<td>350</td>
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\textbf{Figure 1: Schematic and description of samples A-F.}
**Experimental details:**

FePt bilayers that have a stack structure of FePt( T\text{dep} °C)/ FePt( 600 °C)/MgO/CrRu/Glass, were sputter deposited in an ultra-high vacuum (UHV) magnetron sputtering system at a base pressure of \(1.8 \times 10^{-9}\) Torr. The underlayers of MgO and CrRu were sputter deposited at 400 °C under a process pressure of 1.5 mTorr, while the FePt layers were deposited at a process pressure of 3.5 mTorr. The first FePt layer was deposited at a nominal temperature of 600 °C and the second FePt layer was grown at T\text{dep} = 25, 75, 150, 250, and 350 °C. The stack structures along with indicative thickness and nomenclature are shown in Fig. 1. These bilayer structures were compared against a reference sample which had a single FePt layer (atop MgO/CrRu) deposited at 600 °C (sample A). The magnetic properties of the samples were measured at 300 K using vibrating sample magnetometer utility function provided in the Quantum Design physical property measurement system (PPMS). The growth dynamics of the different layers were analyzed by transmission electron microscopy (TEM) using Phillips CM 300 FEG–TEM. The crystallographic data from the samples were obtained by using the Bruker D8 general area detector diffraction system (GADDS) equipped with a Cu-Kα source. An atomic force microscope (AFM) was also used to study the surface roughness of various media samples.

**Results and discussion:**

The hysteresis loops of samples A–F are plotted in Fig. 2(a) and the out-of-plane coercivities \((H_c)\) are shown in Fig. 2(b). All samples exhibit certain degree of kink at zero field. The reference sample A has a small kink at zero field which might be due to the presence of a magnetically soft FePt layer from incomplete ordering of FePt. The presence of soft layer is also evident from the XRD analysis of the sample in Fig 4 (a). The magnetically soft FePt is not completely exchange coupled with the hard layer causing a small kink at zero field. On the other hand, despite the presence of a soft FePt layer in
samples B to F, the kinks in the hysteresis loops are reduced most likely due to the strengthened exchange coupling between the hard and the soft FePt layers. The $H_c$ of the bilayer structures were less than that of the reference sample A ($\sim 20$ kOe). The $H_c$ values for the samples C–F remained nearly constant with a 45% reduction as compared to reference sample A. $H_c$ for the sample B was about 41% higher (15.5 kOe) as compared to the other bilayer structures ($\sim 11$ kOe). The saturation magnetization ($M_s$) of the the bilayers B to F remained nearly constant as shown in Fig 2 (c).

![Figure 2](image_url)

**Figure 2:** (a) Out-of-plane hysteresis loops of samples A-F. (b) Variation of $H_c$ from samples A-F. 
(c) Variation of $M_s$ from samples A to F.
Since FePt grows in the high-anisotropy L1_0 phase at higher temperatures and in a disordered lower anisotropy phase at room temperature, it was expected that sample B would have a lower coercivity than samples C–F, due to the exchange coupling between the soft and hard phases [14,15,20,29]. Hence, it was surprising that sample B had a higher coercivity than samples C–F.

We carried out in-plane hysteresis loops, XRD and TEM to further understand the origin of this result.

The in-plane coercivity ($H_c||$) of the samples gradually increased from samples A–F as the top layer deposition temperature ($T_{dep}$) increased. The $H_c||$ value for sample B was marginally higher than that of reference sample A, while it increased steeply for sample C as shown in Fig. 3(a).

The effective magnetic anisotropy constant of samples A–F was calculated from the relation $K_{u, eff} = \frac{H_k M_s}{2}$, where $H_k$ and $M_s$ are the anisotropy fields and the saturation magnetization respectively [30]. As seen from Fig. 3(b), the $K_{u, eff}$ for the bilayers was considerably reduced as compared to reference sample A. The $K_{u, eff}$ decreased by 16.66 % for sample B as compared to reference sample A ($K_{u, eff} = 1.32 \times 10^7$ erg/cc). $K_{u, eff}$ decreased further with increasing $T_{dep}$ and reached its minimum of $0.92 \times 10^7$ erg/cc for sample D.

![Graph](image-url)
Figure 3: (a) Variation of $H_{c||}$ for samples A-F. (b) Variation in $K_{u,eff}$ for samples A-F.

Fig. 4(a) shows the XRD $\theta$–$2\theta$ scans carried out over a wide range of angles while Fig. 4(b) shows a zoomed-in image for $2\theta$ at about 41°. In all the samples, the CrRu (200) and the MgO (200) peaks can be seen, indicating that the deposition of the top FePt layer did not cause much changes to the texture of the underlying layers. The FePt (001) and FePt (002) peaks are also present in all the samples, indicating that the changes were mainly in the top layer.

Figure 4: (a) XRD pattern of samples A-F. (b) FePt (111) peak for samples A-F.
Figure 5: (a) Sample A – FePt (001) grain. (b) Sample B – FePt (111) over FePt (001) in columnar fashion. c) Sample C – encapsulation of FePt (001) grain. (d) Sample A – top view of FePt grains. (e) Sample E – nucleation of new FePt grains (top view).

Samples A–F were subjected to TEM to investigate the growth dynamics of the second FePt layer atop the first FePt layer. In sample B, the second FePt layer was found to grow on the existing FePt grains from the first FePt layer in a columnar fashion, without any further grain nucleation, as shown in Fig. 5(b). With an increase in $T_{\text{dep}}$, in samples C and D, the FePt grains of the underlayer were encapsulated by the new FePt layer, as shown in Fig. 5(c). Figs. 5(d) and 5(e) show that at higher $T_{\text{dep}}$ values in samples E and F, there was more and more physical nucleation of small FePt grains growing in FePt (002) as well as FePt (111) phases on the MgO underlayer. The grain size distribution was calculated from the top view of the samples. Two distinct peaks were visible in the grain size distribution for samples E and F, indicating new grain nucleation. The comparison of grain size distribution in sample E with the reference sample A is provided in Fig. 7. The grain heights of the samples were measured and the values
for samples C–F were found to be less than that of sample B, indicating columnar growth in sample B compared to encapsulating growth in the other bilayer samples. In addition, the grain size increased for samples C–F because of the encapsulating model of growth. The surface roughness of the FePt bilayers was also studied using AFM. The Root Mean Square roughness ($R_q$) for sample B remained fairly consistent at 2nm as compared to that of reference sample A ($R_q=2.01nm$). With increase in $T_{dep}$, $R_q$ decreased to 1.65 nm for sample D. The RMS roughness for bilayers C–F was lower than that of reference sample A.

![AFM images](image)

**Figure 6:** AFM images for samples A–F and RMS surface roughness ($R_q$) in nm.
We now provide a cohesive discussion based on the various experiments. Sample A exhibited the highest coercivity. This is understandable because the entire FePt layer was sputtered at a temperature suitable for L1\(_0\) growth. This was reflected in a low in-plane coercivity and the high anisotropy constants as shown in Fig. 3. Sample B showed a coercivity value that was 41% higher than the other bilayer structures. We believe that this result was obtained due to the epitaxial growth of the two FePt layers. When the FePt top layer was sputtered at room temperature (\(T_{dep} = 25 ^\circ C\)), it grew in the FePt (111) phase which is thermodynamically most favorable. It was observed from TEM that the second layer of FePt grew in a columnar fashion over the existing FePt grains. The high surface energy of the underlayer FePt grains and lack of surface mobility at low temperature promoted the growth of the new FePt layer atop the underlying FePt grains in a columnar fashion and prevented new grain nucleation. The FePt (111) peak for sample B in Fig. 4(b) was slightly shifted towards higher values of 2\(\theta\) (\(\sim 40.9^\circ\)) as compared to (fcc) FePt (111) (2\(\theta\) \(\sim 40.58^\circ\)), indicating the epitaxial growth between the two FePt
layers. This highly epitaxial growth of the FePt growing in (111) phases resulted in a relatively higher $H_c$ as compared to the other bilayer structures. The coercivity of exchange coupled media is dependent on the thickness of the soft layer. The thickness of the 2nd FePt layer ($t_s$) in the FePt bilayer stacks used in this study remains constant at 5nm. For constant $t_s$ the coercivity would vary according to the anisotropy difference $(K_{u,h} - K_{u,s})$ of the hard and the soft layers [15,25]. $K_{u,h}$ for the hard layer is constant for all the bilayers. Therefore, the difference in anisotropy of the two layers would then vary linearly with the effective anisotropy ($K_{u,eff}$) as from the relation

$$K_{u,eff}(t_h + t_s) = K_{u,h}t_h + K_{u,s}t_s.$$  

As from Fig. 3(b) $K_{u,eff}$ for the samples C to F remains nearly constant, the coercivity of bilayers C to F also remains nearly the same.

As $T_{dep}$ increased, there was an increase in the surface mobility of the newly sputtered FePt, resulting in the second layer of FePt growing in a fashion encapsulating the FePt grains in the first layer as seen in Fig. 5(c). TEM images indicate that the second FePt layer sputtered tended to grow around the existing FePt grains as the surface mobility was not enough to induce island growth, thus encapsulating the already existing grains. This second layer of FePt, however, grew in the (111) as well as (200) phases, as analyzed from the TEM and XRD data obtained. As $T_{dep}$ increased to 150 °C, the (111) peak disappeared and the combined FePt (002) and FePt (200) peaks strengthened further. As $T_{dep}$ increased further to 250 °C, the encapsulating FePt growth continued along with nucleation of new FePt grains.

We believe that at higher temperatures ($T_{dep}$), the greater thermal expansion coefficient of the underlying MgO layer makes it favorable for the FePt to have new grain nucleation on the MgO underlayer, thus forming small isolated grain islands. The new FePt grains grew in the (111) phase with L10 ordering induced from the high deposition temperature, as seen in Fig. 4. The
peak location of FePt (111) indicated the presence of partial ordering in these samples. The strengthening of the combined peaks of FePt (002) and FePt (200) in samples E and F indicated partial ordering. In this case the ordering was induced by the high temperature which was still not sufficient to induce out-of-plane anisotropy by the (001) phase. Zha et al have shown that the L1₀ ordering in FePt (111) can be induced at high temperatures [31]. The lack of columnar growth and increased grain nucleation were also corroborated by the surface roughness measurements. The decreased inter-granular spacing resulted in reduced surface roughness, hence the drop in $R_q$ values of samples C–F. Although the partially ordered L1₀ FePt (111) would have enhanced the out-of-plane coercivity, the combined effects of grain encapsulation and new grain nucleation effectively restrained the out-of-plane coercivity and the anisotropy values for samples E and F.

**Conclusion:**

In this work the effect of two-step temperature deposition of FePt on magnetic properties was investigated. The magnetic properties and the surface roughness of the FePt media varied with change in the deposition temperature of the second FePt layer. At room temperature, the second FePt layer grew over the existing grains from the first FePt layer in a columnar fashion with high epitaxy. While at higher temperatures FePt grains from the second layer grew by encapsulation of the FePt grains from the first layer or by nucleation of new grains. This change in growth model at different temperatures resulted in changes in the properties of FePt media. In conclusion, we have demonstrated that the magnetic and topographical properties of the L1₀ FePt can be tailored by a very simple two-step temperature deposition due to the interplay of factors such as induced epitaxial growth, new grain nucleation, surface mobility, and difference in thermal expansion coefficients of the underlayers.
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