Current Applied Physics xxx (2011) 1–3

Contents lists available at ScienceDirect

Current Applied Physics

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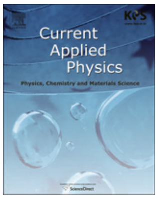

Hyperfine FePt patterned media for terabit data storage

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ARTICLE INFO

Article history:
Received 30 November 2010
Received in revised form
13 April 2011
Accepted 13 April 2011
Available online xxx

Keywords:
FePt patterned media
CrV seed layer
Deposition-last process
Perpendicular anisotropy
Magnetic storage

ABSTRACT

FePt patterned media were fabricated with varying pattern size, employing a deposition-last process and a CrV seed layer. The FePt patterns of sizes down to 30 nm showed a well-developed FCT structure characteristic of $L1_0$ phase. Due to the chemical and structural ordering, even 30 nm-sized FePt patterns exhibited a high ratio (3.4) of out-of-plane coercivity to in-plane coercivity and almost the same remanent magnetization as the saturation magnetization, indicating that a high perpendicular anisotropy is retained in the tiny patterns. The array of 30 nm patterns corresponds to a bit density of 1.8 Tbit/in^2, demonstrating that terabit-density magnetic storage can be fabricated using the deposition-last process.

1. Introduction

The need for high density data storage is continually growing, keeping pace with the revolutionary development of information technology. Magnetic recording has been a key technology for data storage in many areas, such as computers, audio, and video [1]. However, the increase of bit density in conventional longitudinal magnetic recording faces a serious challenge, primarily due to the limit in reducing the magnetic film thickness and the average grain size [2,3]. Moreover, the issue of magnetic moment instability becomes serious with reduced grains because both thermally activated magnetic disordering (called superparamagnetism) and the exchange interaction between neighboring grains increase as the grain size diminishes [1,4]. This issue is relevant even to perpendicular magnetic recording [5,6]. Patterned magnetic recording, in which each bit is stored in lithographically isolated dot patterns, is recognized as one of the best ways to achieve the ultra-high density data storage of more than 1 Tbit/in^2 [1,7–9]. Materials and patterning scheme are of critical importance for the success of patterned magnetic media since the high perpendicular anisotropy of a magnetic film should be retained after undergoing all of the steps for fabrication of the patterned media.

FePt is a good candidate for patterned magnetic media because of its high coercivity (H_c = 1–10 kOe) [10–12] and high magnetocrystalline anisotropy ($K_c = 7.0 \times 10^7$ erg/cm^3) [11–14]. Perpendicular magnetic anisotropy appears only when FePt is transformed into an ordered face-centered tetragonal (FCT, $L1_0$ phase) from a chemically disordered face-centered cubic (FCC, $A1$ phase) at a specific temperature [15,16]. The temperature of this transition and the magnitude of perpendicular anisotropy in FePt patterned media strongly depend on the buffer layer and fabrication process. In a previous work, we demonstrated that a CrV layer functions well as a seed layer, and a deposition-last process enables FePt patterned media to retain a high coercivity and high perpendicular anisotropy even at a low post-annealing temperature of 400 °C [17]. At that time, however, the pattern size was 100 nm, and correspondingly, the estimated bit density fell short of the desired level of 1 Tbit/in^2. In this work, we fabricated patterned magnetic recording media from a thin FePt film on a CrV seed layer, employing the deposition-last process. The pattern size was reduced to 30 nm, and it was observed that the perpendicular magnetic anisotropy was still sustained in the pattened media. To our best knowledge, this is the smallest FePt pattern size ever reported where the perpendicular anisotropy remains high, demonstrating that terabit data storage is possible by use of perpendicular magnetic recording.

2. Experimental details

First, a 70 nm-thick CrV film was deposited on a glass substrate by sputtering at 400 °C. In this work, FePt patterned media was fabricated using the deposition-last process. Fig. 1 shows

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doi:10.1016/j.cap.2011.07.006

Please cite this article in press as: J.-S. Noh, et al., Hyperfine FePt patterned media for terabit data storage, Current Applied Physics (2011), doi:10.1016/j.cap.2011.07.006

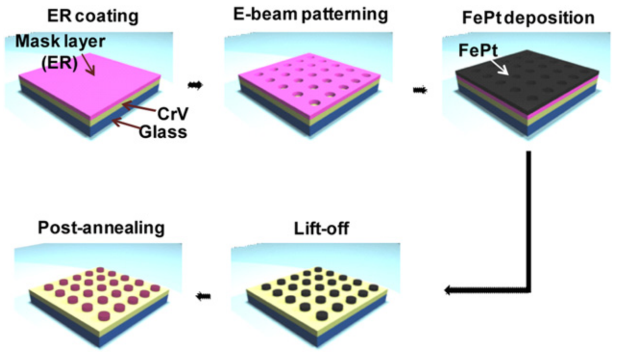

Fig. 1. Schematic pictures of FePt patterned media fabrication by the deposition-last process.

a schematic picture of this process. A type of positive E-beam resist (ER) was coated on the CrV film and it was baked at 110 °C for 60 s before E-beam irradiation. A regular array of circular holes with a fixed size was defined via E-beam exposure and development. The hole size was varied from 100 down to 30 nm. Then, a 7 nm-thick FePt film was sputter-deposited at room temperature under ultra-high vacuum (UHV, 3×10^{-8} Torr). The sample passed through a lift-off process using acetone in the next step, leaving behind a regular array of FePt nano-columns of a uniform size. Finally, The FePt patterns were post-annealed at 400 °C for 1 h to transform the phase of FePt from $A1$ to $L1_0$ (see the last picture of Fig. 1).

The magnetic properties of the patterned media were examined at room temperature using a superconducting quantum interference device (SQUID). Its sensitivity was 1×10^{-6} emu, which is enough to disclose a minute change of magnetic arrangement in the media. The magnetic field was swept in both in-plane and out-of-plane directons between ±1 Tesla. The crystal structures of the patterned media were analyzed by support of conventional $\theta - 2\theta$ X-ray diffraction (XRD). The quality, size, and size distribution of the patterned nano-columns were investigated using scanning electron microscopy (SEM).

3. Results and discussion

Fig. 2 shows SEM images of FePt patterns fabricated by the deposition-last process, which is a combination of E-beam lithography, global FePt deposition, and local FePt lift-off. The patterns are circular in shape and well arranged in regular square arrays. The diameters of individual patterns are 100 nm (Fig. 2(a)) and 30 nm (Fig. 2(b)). For both patterns, the spacing between adjacent patterns is exactly same as the pattern diameter, making the pitch a double of the pattern size (200 and 60 nm for the respective patterns). Surprisingly, the pattern quality is found to be good down to the size of 30 nm (see the magnified image of Fig. 2(b)), demonstrating the efficacy of our deposition-last process. To our best knowledge, the pattern size of 30 nm is the smallest size reported to date on lithographically fabricated FePt patterns. The possibility of reducing the pattern size further still needs to be investigated.

In our previous studies, the CrV seed layer was found to have well-defined columnar grains, thereby making the grains of a thin FePt film oriented perpendicularly, even at temperatures lower than conventional post-annealing temperatures [17]. We carried out XRD measurements on FePt patterned media to check if this is still effective in the tiny patterns shown in Fig. 2. The XRD diffraction patterns from the respective 100 and 30 nm-sized patterns are displayed in Fig. 3. For both patterns, characteristic FCT (001) and (002) peaks are observed without any significant FCC peaks. This reflects that FePt in the tiny patterns are indeed well-ordered in the $L1_0$ phase. The fine definition of $L1_0$ phase demonstrates that the deposition-last process is a good solution to the issue of chemical disordering and structural demolition observed during the conventional plasma etching process [18]. The noisy baseline and FePt peaks, which are broader than Cr peaks, most likely arise from the very small thickness (7 nm) and small areal fraction (20%) of the FePt patterns. Interestingly, comparison of the FCT major peak intensities of the FePt patterns with different sizes shows that the 30 nm-sized patterns have slightly stronger peaks than 100 nm-sized patterns. This probably suggests that FePt is more easily aligned perpendicular to the substrate during deposition into the smaller holes with a higher aspect ratio, which may be another advantage of our deposition-last process.

It is practically important to verify whether the FePt pattermed media with tiny patterns down to 30 nm in size have magnetic properties suitable for magnetic storage. Therefore, we performed magnetic field sweepings on the FePt patterned media of various pattern sizes with more emphasis on 30 nm patterns. The curves of magnetization (M) versus magnetic field (H) were obtained using an SQUID. Fig. 4 shows the M vs. H loops measured at room temperature for FePt patterned media with sizes of 30 nm (both in-plane and out-of-plane) and 100 nm (out-of-plane). The coercivity ($H_{c,30}$) and saturation magnetization ($M_{s,30}$) of the 30 nm-sized patterns are ~4.6 kOe and ~1090 emu/cm^3, respectively, for the out-of-plane field sweep. The $H_{c,30}$ is 35% higher than the coercivity value ($H_{c,film}$~3.4 kOe) previously reported for an $L1_0$ FePt film, while $M_{s,30}$ is close to the value ($M_{s,film} = 900–100$ emu/cm^3) of its

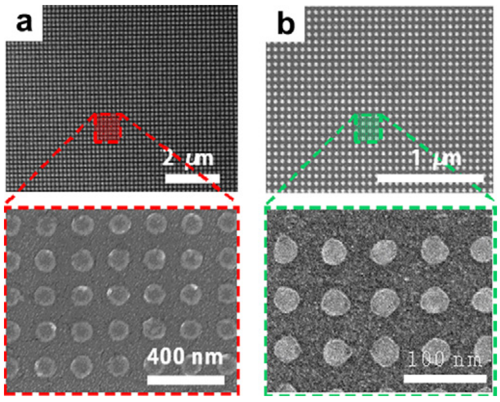

Fig. 2. Scanning electron microscopy (SEM) images of FePt patterned media with (a) 100 nm patterns and (b) 30 nm patterns. The images in dotted boxes show magnified views on selected areas, respectively.

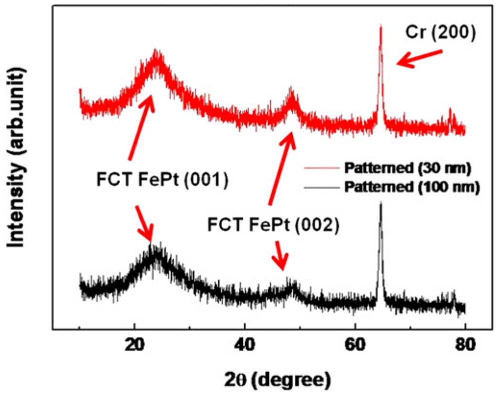

Fig. 3. XRD diffraction patterns of FePt patterned media with 100 nm (black line) and 30 nm (red line) patterns, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

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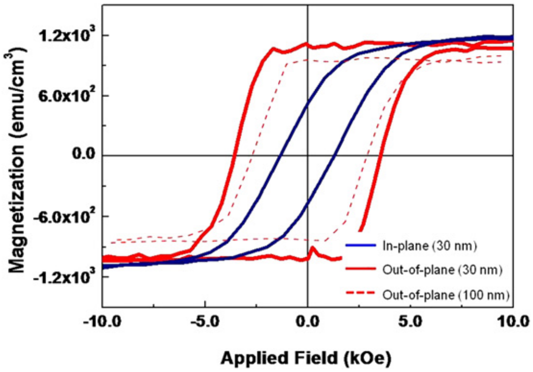

Fig. 4. *M* vs. *H* curves in both out-of-plane (red solid line) and in-plane (blue solid line) directions for an FePt patterned medium with 30 nm patterns. An out-of-plane *M* vs. *H* curve for 100 nm patterns (red dotted line) is also shown for comparison. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

counterpart [17]. This strongly indicates that the 30 nm-sized FePt patterns are in well-developed $L1_0$ phase. The high ratio of remanent magnetization ($M_{r,30}$) to saturation magnetization, $M_{r,30}/M_{s,30} \approx 1$, may also indicate that the deposition-last-processed FePt patterns of 30 nm were magnetically ordered into $L1_0$ phase during post-annealing at 400 °C. Due to this complete transformation into the $L1_0$ phase, the ratio of coercivities in out-of-plane ($H_{c,out}$ ~ 4.6 kOe) and in-plane ($H_{c,in}$ ~ 1.3 kOe) directions, which is a good measure of the perpendicular magnetic anisotropy, reaches more than 3. The high ratio ($H_{c,out}/H_{c,in}$ ~ 3.4) of coercivities in two orthogonal directions reflects that magnetic moments of Fe atoms in the $L1_0$ phase are aligned perpendicular to the substrate.

Similar behaviors were observed in FePt patterns with a larger diameter. For instance, FePt patterns of 100 nm exhibit a high coercivity ($H_{c,100}$–3.0 kOe), moderate saturation magnetization ($M_{s,100}$–870 emu/cm^3), and high $M_{r,100}/M_{s,100}$ (~ 1) as can be seen in Fig. 4. Ignoring the surface anisotropy effect [19], the $H_{c,30}$ higher than $H_{c,100}$ or $H_{c,film}$ is attributed to reduction of the demagnetization field by the shape anisotropy effect. The high coercivity and perpendicular anisotropy of the FePt patterns irrespective of pattern size result from the complete formation of $L1_0$ phase at an annealing temperature that is lower than widely-used post-annealing temperatures (500 °C–800 °C) [15,20–22]. We believe that this is caused by morphology transfer from the CrV seed layer to an FePt film duing growth and Cr-initiated straining on the FePt lattice during post-annealing. Finally, we estimated the data storage density based on our smallest pattern array (30 nm-sized patterns) and found that it corresponds to approximately 1.8 Tbit/in^2, providing an opportunity to enter the terabit storage world.

4. Conclusions

We fabricated FePt-based magnetic patterned media using a deposition-last process, which is a combination of E-beam lithography, film deposition, lift-off, and post-annealing. A CrV film was used as a seed layer to induce perpendicular grain structure and facilitate FCC to FCT phase transformation in FePt patterns. Arrays of FePt patterns of controllable sizes down to 30 nm were successfully fabricated. The FePt patterns were found to be ordered well into the $L1_0$ phase via post-annealing at a relatively low temperature of 400 °C. Due to the well-developed $L1_0$ phase, the FePt patterns exhibited high coercivities, saturation magnetization, and squareness in their *M*–*H* loops. In particular, 30 nm-sized FePt patterns displayed a high ratio of out-ot-plane coercivity to in-plane coercivity and perfect squareness. This indicates that a high perpendicular anisotropy is maintained in these minute patterns, corresponding to a bit density of 1.8 Tbit/in^2. To our best knowledge, the 30 nm patterns are the smallest working FePt patterns reported to date that are lithographically fabricated. Our results provide a promising opportunity to achieve terabit-range magnetic data storage.

Acknowledgments

This research was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MEST) (No.2010-50193), a grant from the Fundamental R&D Program for Core Technology of Materials funded by the Ministry of Knowledge Economy, and the Pioneer Research Center Program (2010-0019313) through the National Research Foundation of Korea.

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