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Cite as: AIP Advances 8, 056501 (2018); https://doi.org/10.1063/1.5005039
Submitted: 16 September 2017 . Accepted: 18 October 2017 . Published Online: 11 December 2017

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Paper published as part of the special topic on 62nd Annual Conference on Magnetism and Magnetic Materials

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Improvement of perpendicular anisotropy of columnar FePt-ZrO$_2$-C films with FePt insert layer

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(Submitted 7 November 2017; received 16 September 2017; accepted 18 October 2017; published online 11 December 2017)

The effects of various thicknesses of FePt insert layer on the microstructure and magnetic properties of FePt-ZrO$_2$-C thin films have been investigated. It is found that with inserting 0.4 nm FePt films between the TiON intermediate layer and FePt-ZrO$_2$-C layer, the perpendicular anisotropy indicated by $H_{c\perp}/H_{c//}$ ratio would increase from 4 to 13.1, suggesting the perpendicular anisotropy could be improved a lot with using FePt insert layer. Simultaneously, the FePt grains of FePt-ZrO$_2$-C thin films maintained columnar structure and the grain isolation could also be improved in a certain degree. With further increase of the FePt insert layer thickness, although the perpendicular anisotropy was still larger than that without FePt insert layer, the grain size of the FePt-ZrO$_2$-C films would increase and the isolation would be deteriorated. © 2017 Author(s). All article content, except where otherwise noted, is licensed under a Creative Commons Attribution (CC BY) license (http://creativecommons.org/licenses/by/4.0/). https://doi.org/10.1063/1.5005039

I. INTRODUCTION

FePt based heat assisted magnetic recording (HAMR) medium has drawn a lot of attention because of its ability to extend the areal density to 5 Tb/in$^2$ in theory due to the high magnetocrystalline anisotropy of FePt. For the practical application of FePt thin film in future heat assisted magnetic recording, great progresses have been made in the fabrication of columnar FePt thin films with high magnetic anisotropy and small grain size by introducing selecting various materials into FePt films. Until now, only limited work has attempted to fabricate the (001) textured FePt films with isolated columnar grains by doping amorphous Ta$_2$O$_5$, TiO$_2$, and SiO$_2$. However, these FePt films exhibited poor perpendicular anisotropy. Recently, we have proposed a new method of doping crystalline ZrO$_2$ into FePt films for fabrication of columnar structural FePt thin films with high aspect ratio on TiON intermediate layer. Although, the perpendicular anisotropy of the columnar FePt films with ZrO$_2$ doping is better than that with amorphous oxide doping, it still needs further improvement for the practical application. For this purpose, a very thin FePt layer was inserted between the TiON intermediate layer and FePt-ZrO$_2$-C layer to create some nucleation sites. It is expected that the subsequent FePt grains would be grown on the pre-prepared FePt nucleation sites and not on the doping atoms (ZrO$_2$ or C) at the interface between FePt and TiON. Thus, it will decrease the formation of FePt (200) phase and enhance the (001) orientation and perpendicular anisotropy of FePt films. In this paper, the effects of various thicknesses of FePt insert...
layer on the microstructure and magnetic properties of FePt-ZrO\(_2\)-C thin films were systematically investigated.

II. EXPERIMENTS

FePt (8 nm)-ZrO\(_2\) 35 vol.\% C 10 Vol.\% FePt (0, 0.4, 0.6, 0.8 and 1 nm) on TiON 2 nm/TiN 3 nm/ CrRu (30 nm)/ glass were fabricated at substrate temperature of 500° C by a magnetron sputtering system with a base pressure better than 2 \times 10^{-8} \text{Torr}. All the FePt-ZrO\(_2\)-C layers were fabricated by co-sputtering of a Fe\(_{55}\)Pt\(_{45}\) alloy target, a C target and a ZrO\(_2\) target with Ar working pressure of 10 mTorr. The deposition temperature of TiN and TiON was 400° C, and the deposition temperature of CrRu was 280° C. At the end of sputtering, the samples were left to cool to room temperature in the main sputtering chamber and taken out for characterization thereafter. The crystallographic texture was examined with X-ray diffraction (XRD) using Cu K\(\alpha\) radiation. The microstructure of the films was characterized by a transmission electron microscope (TEM). The magnetic properties were measured using the superconducting quantum interference device (SQUID) at a maximum applied field of 50 kOe at room temperature.

III. RESULTS AND DISCUSSION

Figure 1(a) shows the XRD 2\(\theta\) spectra of FePt (8 nm)-ZrO\(_2\) 35 vol.\% C 10 vol.\% films with various thicknesses of FePt insert layer. It can be seen that the L1\(_0\) and fcc FePt (111) peaks were not visible, and only FePt (001) and (002) peaks appeared in the FePt thin films. This indicates that these films exhibited dominant L1\(_0\) FePt (001) texture and chemical ordering. Furthermore, ZrO\(_2\) (200) peaks at the position of 34.71° appeared, suggesting ZrO\(_2\) crystallized at the sputtering temperature of 500° C. More importantly, the FePt (002) peak shifted to higher angle with increasing FePt insert layer thicknesses, which can be attributed to the decrease of both lattice constant c and fcc FePt (200) phase. These phenomenon predict that the (001) texture of FePt-ZrO\(_2\)-C films was improved by introducing FePt insert layer. The lattice constant c calculated from the FePt (001) peak as the function of the FePt thickness is shown in Fig. 1 (b). The lattice constant c decreased linearly to from 0.3755 nm to 0.3695 nm with increasing the FePt thicknesses from 0 nm to 1 nm, suggesting that the chemical ordering increased with increasing FePt insert layer thicknesses. The chemical ordering characterized by the ratio of the integrated peak intensity of FePt (001) to (002) - \(I_{001}/I_{002}\) is summarized in Fig. 1(b). \(I_{001}/I_{002}\) increased with the increase of FePt thicknesses which was consistent with the results of lattice constant c. The changes in the FePt-fct (001) preferred orientation and the degree of ordering can be interpreted by the elimination of FePt (200) phase grown on some doping atoms (ZrO\(_2\) or C) at the interface between FePt and TiON.

Figure 2 exhibits the low magnifications cross sectional TEM images and planar view TEM images of FePt (8 nm)-ZrO\(_2\) 35 vol.\% C 10 vol.\% films with various thicknesses of FePt insert layer.

![FIG. 1. (a) XRD 2\(\theta\) spectra and (b) lattice constant c and the summaries of the value of \(I_{001}/I_{002}\) of FePt (8 nm)-ZrO\(_2\) 35 vol.\% C 10 vol.\% films with various thickness of FePt insert layer.](image-url)
When FePt insert layer were 0 nm and 0.6 nm, very good columnar structural FePt films with a single layer structure were obtained on a TiON intermediate layer (Fig. 2a and b). Although the isolation of FePt-ZrO$_2$-C films with 0.6 nm FePt insert layer (Fig. 2d) improved a little as compared with that of FePt-ZrO$_2$-C films with 0 nm FePt insert layer (Fig. 2e), the maze-like particles consisting of several grains were predominant (Fig. 2d and e). The isolation of the obtained films needs further improvement for getting better signal noise ratio preference in HAMR application. Further increase of FePt insert layer to 1 nm caused the deterioration of both columnar structure and grain isolations (Fig. 2c and f).

In order to further elucidate the epitaxial growth of FePt-ZrO$_2$-C films on FePt insert layer, high resolution cross sectional TEM of FePt-ZrO$_2$-C films grown on 0.6 nm FePt insert layer were measured, and the results are shown in Fig. 3(b). It can be seen that columnar FePt grains with (001) orientation were epitaxially grown on the (200) textured TiON intermediate layer (Fig. 3a and b). Moreover, crystallized ZrO$_2$ were observed in the red elliptical regions (Fig. 3b) drawn for illustration. Combining with the XRD results above, it indicates that tetragonal (002) textured ZrO$_2$ were formed on the (200) textured TiON intermediate layer. Simultaneously, the crystalline ZrO$_2$ did not react with FePt during the high temperature processing of the thin films and the crystallized FePt and ZrO$_2$ were completely immiscible to each other. The columnar growth of FePt grains with large aspect ratio was caused by the ZrO$_2$ crystal phases.

The schematic illustration of FePt insert layer and FePt-ZrO$_2$-C/FePt films grown on TiON/TiN/CrRu/Glass are drawn for better understanding the evolution of microstructures of FePt-ZrO$_2$-C films (Fig. 3c and d). When FePt insert layer was 0.4 nm, FePt films were grown on the TiON intermediate layer to form very small nucleation sites (Fig. 3e), the subsequent FePt grains in FePt-ZrO$_2$-C layer would grow on these small nucleation sites and FePt grains with (200) phase grown on some doping atoms (ZrO$_2$ or C) at the interface between FePt and TiON were eliminated, and thus the (001) preferred orientation and the degree of ordering were improved (Fig. 3c and d). With further increase of the FePt insert layer thickness, the density of FePt nuclei was saturated and FePt islands were formed by the coalescence of the neighboring nuclei (Fig. 3e). Thus, the FePt grain size of the subsequent FePt-ZrO$_2$-C films would increase and the isolation would be deteriorated. This was consistent with the TEM results in Fig. 2 (c) and (f).
FIG. 3. (a) Low magnifications cross sectional TEM image, (b) High resolution cross sectional TEM image of FePt (8 nm)-ZrO$_2$ 35 vol.%-C 10 vol.% films with 0.6 nm FePt insert layer. (c) and (d) the schematic illustration of FePt insert layer and FePt-ZrO$_2$-C/FePt films grown on TiON/TiN/CrRu/Glass. (e) the schematic illustration of the microstructure evolution of the FePt nucleation layer.

The typical out-of-plane and in-plane hysteresis loops of FePt (8 nm)-ZrO$_2$ 35 vol.%-C 10 vol.% films with various thicknesses of FePt insert layer measured by SQUID are shown in Fig. 4 (a)–(c). It can be seen that all the FePt films exhibit good perpendicular anisotropy. When the thicknesses of

FIG. 4. (a-c) M-H loops and (d) the summaries of out-of-plane coercivity and in-plane coercivity, as well as the $H_{c,\perp}/H_{c,\parallel}$ ratio of FePt (8 nm)-ZrO$_2$ 35 vol.%-C 10 vol.% films with various thickness of FePt insert layer. (a) for 0 nm FePt, (b) for 0.6 nm FePt and (c) for 1 nm FePt.
FePt insert layer increased from 0 to 0.4 nm, the out-of-plane coercivity increased from 12.4 kOe to 17 kOe, and the in-plane coercivity decreased from 3.1 kOe to 1.3 kOe (Fig. 4d). Moreover, the perpendicular anisotropy indicated by $H_{c\perp}/H_{c//}$ ratio increased from 4 to 13.1 (Fig. 4d), suggesting the perpendicular anisotropy was improved a lot with using FePt insert layer. Further increase of FePt insert layer thicknesses would cause the decrease of both out-of-plane coercivity and the $H_{c\perp}/H_{c//}$ ratio, but these values were still larger than that without FePt insert layer. The increases of the out-of-plane coercivity and the perpendicular anisotropy with increasing the FePt insert layer from 0 to 0.4 nm were attributed to the increase of the chemical ordering of FePt films. On the other hand, the decrease of the perpendicular anisotropy with further increase of FePt insert layer from 0.6 nm to 1 nm was due to the deterioration of the isolation of FePt films.

IV. CONCLUSION

The columnar structural FePt-ZrO$_2$-C thin films with large perpendicular anisotropy were obtained by inserting thin FePt layer between the TiON intermediate layer and FePt-ZrO$_2$-C layer. It is found that when FePt insert layer was 0.4 nm, FePt films were grown on the TiON intermediate layer to form very small nucleation sites, the subsequent FePt films in FePt-ZrO$_2$-C layer would grow on these small nucleation sites and FePt grains with (200) phase grown on some doping atoms (ZrO$_2$ or C) in the interface between FePt and TiON were eliminated, and thus the (001) preferred orientation and the degree of ordering were improved. With further increase of the FePt insert layer thickness, the grain size of the subsequent FePt-ZrO$_2$-C films would increase and the isolation would be deteriorated.

ACKNOWLEDGMENTS

This work is partially supported by the National Natural Science Foundation of China (Grant No. 51501168 and 41574175), the Key Science and Technology Support Program of Hubei Province (Grant No. 2015BCE054) and the Fundamental Research Funds for the Central Universities, China University of Geosciences(Wuhan) (No.CUG150632 and CUG160414).