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<tr>
<td><strong>Citation</strong></td>
<td>Kumar, D., Gupta, S., Jin, T., Nongjai, R., Asokan, K., &amp; Piramanayagam, S. N. (2018). Tailoring the structural and magnetic properties of masked CoPt thin films using ion implantation. AIP Advances, 8(5), 056504-.</td>
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<td><strong>Date</strong></td>
<td>2018</td>
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<td><strong>URL</strong></td>
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Tailoring the structural and magnetic properties of masked CoPt thin films using ion implantation

Durgesh Kumar,1 Surbhi Gupta,1 Tianli Jin,1 R. Nongjai,2 K. Asokan,2 and S. N. Piramanayagam1,a
1Division of Physics and Applied Physics, School of Physical and Mathematical Sciences, Nanyang Technological University, 637371, Singapore
2Materials Science Division, Inter-University Accelerator Centre, New Delhi 110067, India

(Presented 7 November 2017; received 2 October 2017; accepted 28 October 2017; published online 14 December 2017)

The effects of ion implantations through a mask on the structural and magnetic properties of Co80Pt20 films were investigated. The mask was patterned using the self-assembly of diblock copolymers. For implantation, high (40 keV for 14N+ and 100 keV for 40Ar+) and low (7.5 keV for 14N+ and 4.5 keV for 40Ar+) energy 14N+ and 40Ar+ ions were used to modify the structural and magnetic properties of these films. X-ray diffraction and TRIM simulations were performed for understanding the structural changes due to ion implantations. These results revealed the intermixing of Co atoms in lower layers and lattice expansion in Co80Pt20 magnetic and Ru layers. A lateral straggling of Co caused an increase in the exchange coupling in the masked region. Depletion of Co atoms in Co80Pt20 layer caused a decrease in the anisotropy constant, which were further confirmed by the alternating gradient force magnetometer and magnetic force microscopy results. The magnetic force microscopy images showed an increase in domain width and domain wall width confirming the above-mentioned effects. © 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/10.1063/1.5007767

I. INTRODUCTION

Patterning of magnetic thin films is important for their potential applications in the hard disk drive industry, in particular, in heated-dot magnetic recording.1,2 One method to achieve patterning is to carry out ion-implantation in these magnetic materials through a mask.3 The main advantage of ion implantation based patterning is that it provides an additional degree of freedom to alter the magnetic properties according to needs4 without significantly changing the surface topography of the film,5 which is very important from magnetic media applications point of view. The ion implantation process creates the structural modifications via either changing the interface structure, the atomic short-range order, the crystalline phase, the degree of ordering or the composition of material.4 This, in turn, leads to changes in the magnetic properties of the material. For fabrication of mask, several lithography techniques may be used. The ability of block copolymers to self-assemble into nanometre sized regular and periodic arrays have attracted the attention of the researchers due to their ease of use.6 Moreover, the smallest feature size obtained using self-assembly of di-block copolymers is 3 nm,7,8 which is good enough for heated-dot magnetic recording at 10 Tbps.2,9,10 Therefore, we have been investigating the effect of low and high energetic 14N+ and 40Ar+ ion-implantations on Co80Pt20 films through masks fabricated by Polystyrene (PS) – Polydimethylsiloxane (PDMS) di-block copolymer based self-assembly. The reason for choosing Co80Pt20 is that the Co100-xPx system is an interesting system to study as the structural properties of these films largely depend on the Pt concentration, particularly at around 20-30 at%.11–13 For low energy implantation, we expect the

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aS.N. Piramanayagam is the corresponding author of this paper. Electronic mail: prem@ntu.edu.sg
species to be implanted in the magnetic layer. Whereas for high energy implantation, the ions are expected to pass through the magnetic film without residing in the magnetic layers. Our objective is to see and understand the differences caused by the two types of implantations on the magnetic layers.

II. EXPERIMENTAL DETAILS

The Co$_{80}$Pt$_{20}$ (hereafter CoPt) alloy with precise stack “Glass substrate/Ta (5 nm)/Ru (15 nm)/CoPt (14 nm)” was prepared using dc magnetron sputtering. A thin Ta layer provides adhesion between substrate and upper layers while Ru underlayer promotes perpendicular anisotropy in the magnetic layer.$^{14}$ A self-assembly of PS-PDMS di-block copolymers was performed for patterning the mask of PDMS/SiO$_2$ on these films. The schematic representation of the film stack with mask pattern is shown in FIG. 1(a). Details related to the self-assembly process is provided in the supplementary material. Subsequently, ion implantations of $^{14}$N$^+$ (40 and 7.5 keV) and $^{40}$Ar$^+$ (100 and 4.5 keV) on patterned films were performed at ion beam facilities at Inter-University Accelerator Centre, New Delhi. The Ion fluences such as $1\times10^{15}$, $5\times10^{15}$, $1\times10^{16}$, $2\times10^{16}$ ions/cm$^2$ for high energy and $1\times10^{15}$, $5\times10^{15}$, $1\times10^{16}$, $5\times10^{16}$ ions/cm$^2$ for low energy implantations were chosen to modify the structural and magnetic properties of the magnetic films.$^{15–18}$

For a theoretical understanding of the effect of implantations, Transport of Ions in Matter (TRIM) program from Stopping and Range of Ions in Matter (SRIM)-2008.04 simulations$^{19}$ were employed. All experimental characterizations were performed using X-Ray Diffraction (XRD), Atomic/Magnetic Force Microscopy (AFM/MFM) and Alternating Gradient Magnetometer (AGFM).

III. RESULTS AND DISCUSSIONS

The self-assembly of PS-PDMS di-block copolymers resulted in a regular and periodic structure of the PDMS/SiO$_2$ spherical dots on the PS columns as shown in FIG. 1(b). The average pattern diameter as estimated from AFM images, is 27 nm (standard deviation = 4 nm) with center to center distance 45 nm as estimated from Fast Fourier Transform of these images.

FIG. 2 shows the XRD patterns of CoPt samples after the implantation of high and low energy $^{14}$N$^+$, $^{40}$Ar$^+$ ions. The pristine CoPt sample shows the presence of Ru (002) and Co (002) peaks at 20 values of $\sim42.20^0$ and $\sim42.84^0$ respectively, which confirms the texturing of the magnetic and underlayer in the perpendicular (002) direction, which is very important in hard disk media applications.$^{14}$ For high energy $^{14}$N$^+$ ion implantation, Ru (002) peak shifts towards higher 20 values and Co (002) peak shifts towards lower 20 values. As a result, both the peaks approach each other and merge in samples with ion fluence of $2\times10^{16}$ ions/cm$^2$. On contrary, implantation of low energy $^{14}$N$^+$ ions clearly induce the shift of both Ru (002) and Co (002) peaks towards the lower 20 values. But the shift in Co (002) peak is larger compared to that of Ru (002) peak. Consequently, Co peak shift chases the peak of Ru and the two merge in samples with higher ion fluences of $1\times10^{16}$ and $5\times10^{16}$ ions/cm$^2$.

FIG. 1. (a) Schematic of the film stack with PDMS/SiO$_2$ mask pattern; (b) AFM image of the mask pattern on the magnetic films.
FIG. 2. XRD patterns of CoPt samples upon implantation of (a) high, (b) low energy $^{14}$N$^+$ ions; (c) high, and (d) low energy $^{40}$Ar$^+$ ions.

In the case of high energy $^{40}$Ar$^+$ ion implantation, the shift of the Ru (002) peak towards lower 20 values is marginal while the shift of Co (002) peak is significant. Low energy ions did not cause significant changes in Ru peak. Only Co (002) peaks show a marginal shift towards lower 20 values. As shown in supplementary material, the TRIM simulations, which indicate that the low energy $^{40}$Ar$^+$ ions do not reach the Ru layer but stop at the Co layer, explain this observation.

The observations of high energy $^{14}$N$^+$ and $^{40}$Ar$^+$ ion implantations may arise from the following possibilities; (i) intermixing of Co and Pt atoms in the Ru layer and vice versa\cite{20} or (ii) occupation of interstitial positions by implanted ions\cite{21} or (iii) both. FIG. 3(a) shows the TRIM-simulated distribution profile of displaced host atoms taking part in collisions or scattering processes at different thicknesses. As ions (and host atoms) stop by losing all its energy via cascaded collisions, physically which means there is zero distribution signifying that there is no displacement of host atoms. High energy implantations clearly indicate an intermixing of involved atoms. However, the number of Co atoms moving from CoPt layer into Ru is much larger than that of any other atoms. As a result, the relative concentration of Co in the CoPt layer decreases. This results in the shift of Ru (002) peak towards higher 20 values and shift of Co (002) peak towards low 20 values.\cite{21,22} As high energy $^{14}$N$^+$ and $^{40}$Ar$^+$ ion implantations are showing the above-mentioned shift, intermixing is the main reason for the observed results. In the case of low energy $^{14}$N$^+$ ion implantation, the intermixing is not significant. Moreover, both the peaks shift towards lower 20 values, which could mean an increase in the interplanar spacing (d) in Ru as well as CoPt layer. The increase in d suggests the lattice expansion in both layers (mainly in magnetic layer) mainly arises due to the occupation of interstitial positions by implanted atoms.

FIG. 3. (a) The number density of displaced Co, Pt and Ru host atoms due to implantation; Hysteresis loops of CoPt samples after implantation of (b) high and low energy $^{14}$N$^+$ and (c) high and low energy $^{40}$Ar$^+$ ions (hysteresis loops only for highest ion fluences are shown).
FIG. 3(b) and FIG. 3(c) show the hysteresis loops of the high and low energy $^{14}$N$^+$, $^{40}$Ar$^+$ ion implanted samples respectively. The coercivity of the pristine CoPt sample as estimated from the hysteresis loops is 106 Oe. This low coercivity is due to the fact that the grains are not well segregated and they have very large intergranular exchange coupling. In the case of fabrication of patterned media, the magnetic layers to be patterned are intentionally made with a high exchange coupling. In that case, nucleation and domain wall motion are dominant modes of reversal mechanism. As a result, a lower coercivity is observed.

After implantation, the hysteresis loops of samples with high energy $^{40}$Ar$^+$ (2 × 10$^{16}$ ions/cm$^2$) and low energy $^{14}$N$^+$ (5 × 10$^{16}$ ions/cm$^2$) ions show significant change in shape. The coercivity for these samples was estimated as 204 Oe and 322 Oe respectively, which is significant compared to the other samples (which showed an increase of 10 Oe after implantation). Such a larger change in the coercivity of these samples clearly suggests a decrease in the intergranular exchange coupling in the unmasked region. The marginal increase in the coercivity of other samples indicates a negligible decrease in the intergranular exchange coupling in them and these effects are not clearly visible from the hysteresis loops.

It is important to note that the masking causes more impact of implantation ions in the unmasked regions than in the masked regions. Though this effect is more significant for low energy N ion implantation, this cannot be neglected for the high energy Ar ion implantation. For low energy N ions, the lateral displacement of Co atoms and the presence of more nitrogen in the unmasked regions makes it less magnetic, leading to a reduced exchange coupling between the masked regions. While for high energy Ar ions, the displacement of Co atoms from this region to Ru layer makes it less magnetic. As a result, the intergranular exchange coupling is significantly reduced in both the cases, which is reflected in the hysteresis loops as an increase in coercivity.

FIG. 4(a) to 4(e) show the MFM images of pristine, $^{14}$N$^+$ and $^{40}$Ar$^+$ ion implanted CoPt samples respectively. FIG. 4(f) shows the variation of domain wall width as a function of ion fluences for these samples. These results indicate that the domain width ($\Delta$) as well as domain wall width ($\delta$) increases as a function of ion fluence for all the cases except for low energy $^{40}$Ar$^+$ ion implantation where the increase in $\Delta$ is marginal. Since $\Delta$ and $\delta$ are related to exchange coupling $A$ and the anisotropy constant $K_u$, the trend in the results of $\Delta$ and $\delta$ reflect the changes in $A$ and $K_u$ caused by ion-implantation, supporting the hysteresis loop observations.

IV. CONCLUSION

We have studied the effects of high and low energy $^{14}$N$^+$ and $^{40}$Ar$^+$ ion implantations on the masked CoPt films. High energy $^{14}$N$^+$ and $^{40}$Ar$^+$ ion implantation causes Ru (002) peak shift towards higher 2$\theta$ values, while low energy $^{14}$N$^+$ implantation causes Ru (002) peak to shift towards lower 2$\theta$ values. These results are explained to be arising from intermixing of Co, Pt and Ru atoms across the CoPt and Ru layer and occupation of implanted ions in the interstitial positions respectively.
Depletion of Co atoms in CoPt layer results in a shift of Co (002) peak towards lower 2θ values for all types of implantation. Hysteresis loops revealed a decrease of the intergranular exchange coupling in these films in the low energy $^{14}\text{N}^+$ and high energy $^{40}\text{Ar}^+$ ion implantations. MFM results showed an increase in $\delta$ with the increase in ion fluence in all the cases.

SUPPLEMENTARY MATERIAL

See supplementary material for the details of the self-assembly of PS-PDMS diblock copolymers for patterning the mask pattern on the magnetic films and implanted ion ranges for all the cases studied can be found in detail in supplementary material.

ACKNOWLEDGMENTS

The authors gratefully acknowledge MOE AcRF Tier1 grant RG163/15 and NRF-IIP grant (NRF2015-IIP003-001) for the partial financial support. We acknowledge FACTS lab (NTU) for the usage of XRD. We duly acknowledge the support of Mr. Raj Kumar for providing us low energy $^{40}\text{Ar}^+$ (4.5 keV) and high energy $^{14}\text{N}^+$ (7.5 keV) ions, and also LEBIF of IUAC for providing us high energy $^{40}\text{Ar}^+$ and $^{14}\text{N}^+$ ion implantations.