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Tailoring magnetic domains in Gd-Fe thin films

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This paper presents the global modification of magnetic domains and magnetic properties in amorphous $Gd_{19}Fe_{81}$ thin films with rapid thermal processing at two distinct temperatures (250°C and 450°C), and with different time intervals *viz.*, 2, 5, 10 and 20 minutes. 100 nm thick as-prepared films display nano-scale meandering stripe domains with high magnetic phase contrast which is the signature of perpendicular magnetic anisotropy. The films processed at 250°C for various time intervals show successive reduction in magnetic phase contrast and domain size. The domain pattern completely disappeared, and topography dominated mixed magnetic phase has been obtained for the films processed at 450°C for time intervals greater than 2 minutes. The magnetization measurements indicate the reduction in perpendicular magnetic anisotropy with increase in saturation magnetization for all the rapid thermal processed films. The experimental outputs have been used to simulate the domain pattern. Reduction in uniaxial anisotropy along with the increase in saturation magnetization successfully explain the experimental trend of decrease in domain size and magnetic contrast. https://doi.org/10.1063/1.5006413

I. INTRODUCTION

Magnetic thin films with perpendicular magnetic anisotropy (PMA) have accelerated the progress of magnetic and magneto-optic (MO) recording technologies. Presently the industry is moving towards high density patterned media with heat-assisted magnetic recording which facilitates the demand for thermal stability as well as switching of the highly anisotropic magnetic bits within the limited field of the present write-heads. To meet the pace of the technological advancement, the role of external perturbations has been investigated to modify the magnetic properties. The use of ultrafast laser[1,2] and focused ion-beam[3,4] are very popular for the local modification of magnetic properties, where the spatial extent of the modification is limited by the diameter of the laser spot and ion-beam respectively. Here we are going to present a systematic modification of magnetic domains by rapid thermal processing (RTP), a facile route for the global tuning of magnetic properties. Gd-Fe thin film system, an important member of the rare-earth-transition-metal (RE-TM) alloy family which displays PMA in amorphous as-prepared condition, has been chosen for the study.[5] When the anisotropy is tuned towards in-plane (IP) from out-of-plane (OOP) direction of the film surface, these RE-TM films display large magnetostriction.[6] Gd-Fe thin film has been checked as MO media and proved to be a suitable candidate for bubble memories.[7,8] This system has also been used for the technical development of high-resolution domain imaging with X-ray.[9,10] However, a systematic approach for tailoring magnetic domains has not been reported so far which paved interest for the present study. The modification in domain pattern and overall magnetic properties has been studied here. The

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experimental observation of magnetic domains has been complemented with micromagnetic simulation using OOMMF software.[11]

II. EXPERIMENTAL DETAIL

Gd-Fe thin films were deposited on Si <100> wafers by electron beam evaporation at room temperature using an alloy target of composition $Gd_{50}Fe_{50}$. The background pressure was maintained at 2×10^{-6} torr. The rate of deposition was optimized to be 2Å/sec for the growth of films with thicknesses up to 100 nm. 3 nm thin layer of Cr was deposited as capping layer to protect the film from oxidation. The substrate was rotated at a speed of 10 rpm during the growth process to ensure uniformity in film thickness. RTP was performed at two different temperatures (250°C and 450°C), for different time intervals *viz.*, 2, 5, 10 and 20 min using an RTP furnace, operating at 1×10^{-7} torr and the ramp rate of heating was optimized at 250°C/min. The topographic feature and magnetic domains were imaged simultaneously with atomic force microscopy (AFM) and magnetic force microscopy (MFM) respectively using CoCr coated Antimony doped Si tip. Vibrating sample magnetometer (VSM) was used for the magnetization measurements.

III. RESULTS AND DISCUSSIONS

As-prepared Gd-Fe thin films are amorphous which is similar to the observations made in akin RE-TM thin film systems.[12,13] The film composition was estimated to be $Gd_{19}Fe_{81}$. The disparity in composition between the target and the film occurs due to the difference in vapor pressure at melting point for Fe and Gd. Fig. 1(a) and (b) display the AFM and MFM images respectively for 100 nm thick as-prepared Gd-Fe film. The surface roughness was found to be around 0.4 nm with no identifiable feature in the AFM micrograph. The MFM image at the same position of the AFM image depicts a topography free magnetic phase with meandering stripe domain pattern, having appreciable curling and branching. The two opposite contrasts in the MFM image designate the presence of domains with opposite magnetization. The MFM measurement offers maximum interaction between the magnetized tip and the OOP component of the stray field emanating from the film surface. Hence,

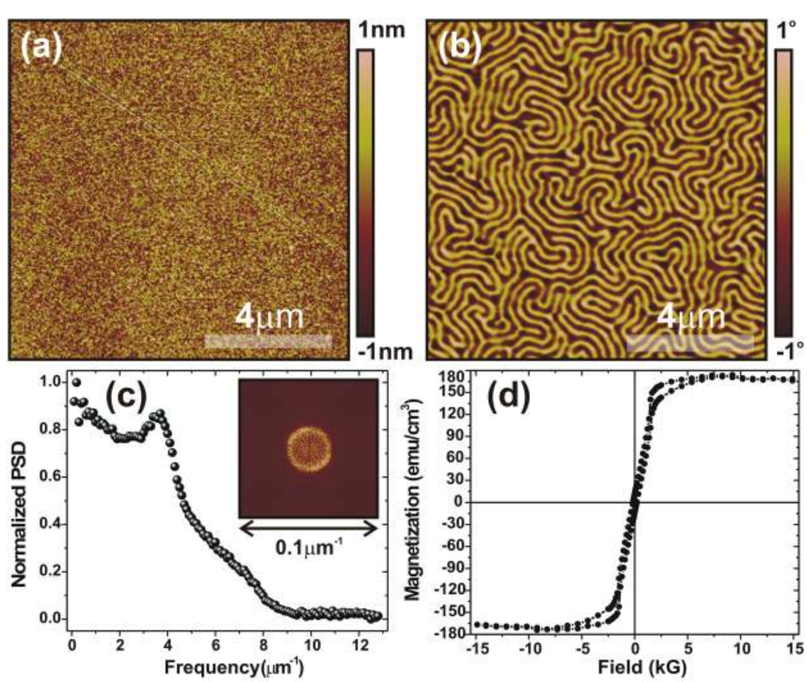

FIG. 1. (a) AFM, (b) MFM, (c) PSD profile extracted from the FFT pattern of the MFM image (shown as inset) and (d) OOP hysteresis loop for the as-prepared Gd-Fe thin film.

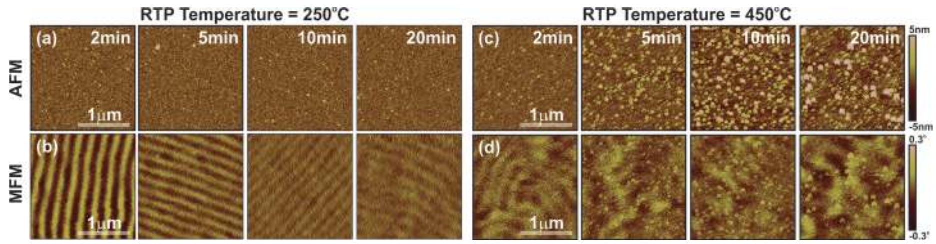

FIG. 2. (a) and (c) represent the AFM images, (b) and (d) represent the MFM images for the films after RTP at 250°C and 450°C respectively with different time interval, mentioned in the respective images (same for the vertical images). The scale bar is same for all the normalized AFM and MFM images.

the presence of strong magnetic contrast suggests the development of PMA in the film. Fig. 1(c) shows the two-dimensional (2D) isotropic power spectral density (PSD) profile, obtained from the 2D fast Fourier transform (FFT) of the MFM image (shown as an inset in Fig. 1(c)). The domain size and associated error have been found to be 141 (±1) nm, calculated from the peak of the PSD curve and its full-width half maxima respectively.[14,15] Fig. 1(d) shows a slanted OOP hysteresis loop with a low remanence around 12.4 emu/cm^3. This type of loop can be observed due to the minimization of the magnetic energy when the system breaks into multiple domains. A similar observation has also been found for Co/Pt multilayer with PMA.[2]

Aiming at domain modification, RTP has been performed in the as-deposited films. Fig. 2(a) and (b) show the AFM and MFM images respectively for the films, processed at 250°C for different time intervals. The AFM images clearly indicate the growth of fine island-like topographic feature. The average diameter (D_{avg}) of the islands increases with the increase in RTP time which culminates in an overall increase in the surface roughness (R_q) of the films. The MFM images displayed in Fig. 2(b) confirm the successive deterioration in magnetic contrast with increase in RTP time. Moreover, the branching and the meandering features no longer appear even with large MFM scan range. The estimated domain sizes were found to be 139 (±1), 116 (±5) and 113 (±2) nm for the films processed with various time intervals *viz.*, 2, 5 and 10 min respectively. Upon 20 min of RTP, the stripe pattern was found to be comparatively weaker. In order to further probe the change in magnetic microstructure, RTP was performed at 450°C with same time intervals as done for 250°C. The AFM and MFM images have been depicted in Fig. 2(c) and (d) respectively. AFM images are qualitatively similar to those presented in Fig. 2(a). Here the maximum R_q increases to around three times when compared with 250° C rapid thermal processed films (Fig. 3(e)). Accordingly, D_{avg} was also found to be higher with increase in RTP time and temperature. However, the errors associated with the measurements are high due to the irregular growth and broader size distribution of the granular islands (Fig. 3(f)). The

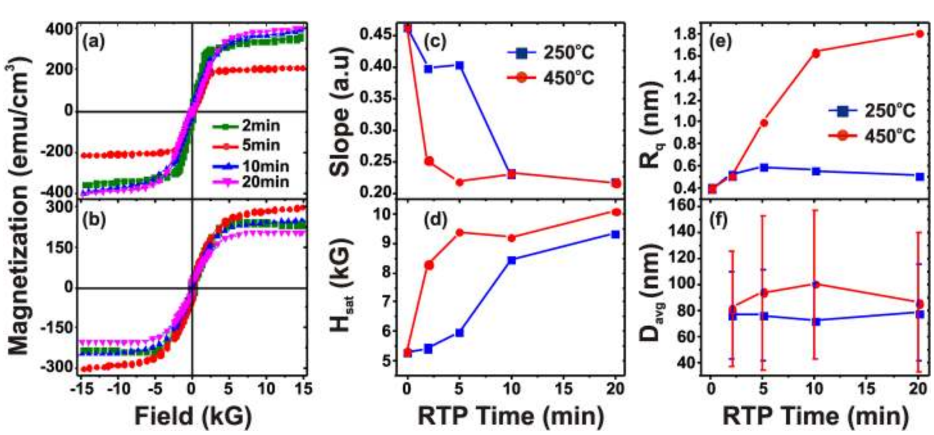

FIG. 3. OOP hysteresis loop for the films after RTP at (a) 250°C and (b) 450°C, variation of (c) slope of the remanence curve, (d) saturation field, (e) roughness and (f) average particle diameter with RTP time.

MFM images in Fig. 2(d) show the presence of two opposite magnetic contrast in the form of irregular patches, indicating that PMA of the films gets weakened and the formation of periodic stripe domains is no longer energetically favorable. Further, with the increase in RTP time, the magnetic anisotropy gets reduced and the most probable threshold height of the topographic features increases. Thus, topography dominated mixed phase has been observed in the MFM images displayed in Fig. 2(d) due to the dominance of short ranged Van der Waals force in comparison with the magnetic force. Hence, it limits the observation of topography free magnetic phase image with the increase in RTP temperature and time.

The OOP hysteresis loops have been depicted in Fig. 3(a) and (b) for the films processed at 250^{o}C and 450^{o}C respectively for different time intervals. It can be noticed that the saturation magnetization (M_s) for all the processed films is higher when compared with the as-prepared film. The slope of the linear region of the loop near remanence and the saturation field (H_{sat}), estimated from the normalized loops are shown in Fig. 3(c) and (d) respectively. The monotonic decrease in the slope and increase in H_{sat} with the increasing RTP time prove the gradual reduction of PMA,[16] which is in concurrence with the observations made from MFM studies. These results indicate that small RTP time interval of 2 min is also sufficient to modify the magnetic properties by destroying the inter-connected long ranged stripe domain pattern. A systematic variation of domain contrast and its size has been obtained with the precise control of RTP time and temperature. We have previously reported a detailed depth-resolved structural characterization which indicated the crystallization of Fe in the amorphous Gd-Fe matrix with the increase in RTP time, but the overall composition remains unaltered.[17] The Fe nucleation predominantly occurs in the top surface which increases the surface roughness of the films and the higher RTP temperature leads to the diffusion of Si into the film. Moreover, the magnetic moment of free iron is more than that of Gd-Fe,[18] and hence higher M_s is observed for the processed films.

Experimentally we have confirmed the decrease in magnetic anisotropy and increase in M_s for the processed films. But the topographic interference hindered the observation of the magnetic phase from MFM images which has been complemented with micromagnetic simulation with the visualization of domain and domain wall (DW). The input parameters are taken from Ref. 9 and include, anisotropy constant (K_u) = 18 kJ/m^3, M_s = 221 kA/m and exchange stiffness constant A = 2.6 pJ/m. The volume of each cell is taken to be (4 nm)^3, and the simulation has been started from a random state with uniform vertical (+ Z direction) magnetization. The top and bottom images of Fig. 4(a) depict the ground state configuration of the OOP (M_z component) and IP ($\sqrt{M_x^2 + M_y^2}$ component) magnetization respectively for 100 nm thick Gd-Fe film. The blue and red contrasts in the domain images designate the oppositely magnetized domains, having curling and branching, as seen for the as-prepared film in Fig. 1(b). The simulated domain size has been estimated to be around 107 (±12) nm, by performing line scan over different domains. The DW is the IP component between the OOP magnetized domains and the width of DW is found to be 35 (±3) nm. The finite temperature

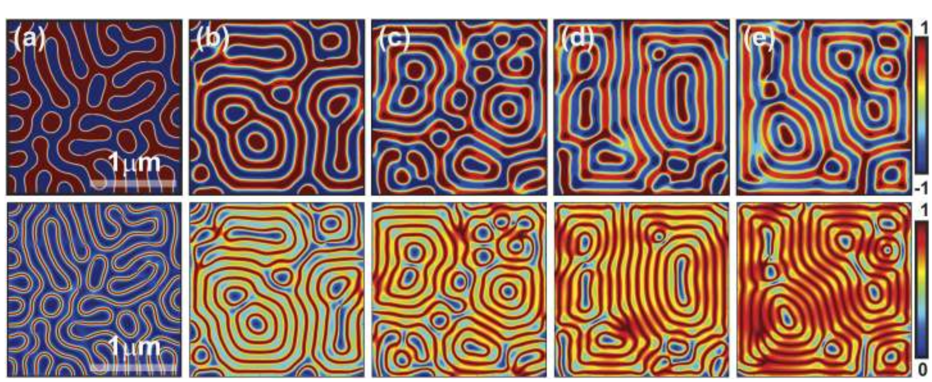

FIG. 4. Simulated domain (top) and domain wall (bottom) pattern with (a) original K_u and M_s, (b) 50% reduced K_u and original M_s, (c), (d) and (e) are having 50% reduced K_u with increase in M_s as 10%, 20% and 30% respectively. The scale bar is same for all the images.

effect and pinning sites of the real samples are not considered in the simulation. Thus, effort has been made to understand the trend of variation of OOP and IP magnetic contrasts, domain size and DW width instead of comparing their exact numerical values. Fig. 4(b) represents the domain (top) and DW (bottom) images with 50% reduced K_u, where the domain size reduces to 63 nm and the OOP contrast also decreases. Further, the M_s value has been increased by 10, 20 and 30% with 50% reduced K_u and the resulted patterns are shown in Fig. 4(c), (d) and (e) respectively. The further decrease in OOP contrast associated with the enhancement of the IP contrast can be understood by following the color bar. The elongated stripe domains try to shrink into a nearly circular pattern to minimize the magnetostatic energy and hence the domain size decreases to 47 nm. The width of DW also extends nearly up to 50 nm. The modification of K_u and M_s clearly indicates the change in preferential direction of magnetization along the plane of the film surface. A detailed micromagnetic study on the domain pattern and associated magnetic properties can be found in our previous publication.[19]

IV. CONCLUSION

Tailoring of magnetic domains has been presented in Gd-Fe thin film, showing meandering stripe domains in as-prepared condition. RTP at 250°C makes the OOP magnetic contrast weak and domain size decreases with subsequent increase in RTP time. The stripe domains are no longer observed upon RTP at 450°C and the weaker magnetic phase is dominated by topographic features. Magnetization measurements confirm the decrease in PMA and increase in M_s with RTP. Micromagnetic simulations with reduced K_u along with the increase in M_s successfully complement the experimental results on domain observation.

ACKNOWLEDGMENTS

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