Journal of Magnetism and Magnetic Materials 452 (2018) 108–113

Contents lists available at ScienceDirect

Journal of Magnetism and Magnetic Materials

journal homepage: www.elsevier.com/locate/jmmm

Research articles

# Magnetic domains in Tb-Fe-Co thin films under anisotropy tilt

A. Talapatra [a], K. Umadevi [b,c], J. Arout Chelvane [b,*], J. Mohanty [a], V. Jayalakshmi [c]

[a] Nanomagnetism and Microscopy Laboratory, Department of Physics, Indian Institute of Technology Hyderabad, Kandi, Sangareddy 502285, Telangana, India
[b] Defence Metallurgical Research Laboratory, Hyderabad 500058, India
[c] Department of Physics, National Institute of Technology Warangal, India

ARTICLE INFO

*Article history:*
Received 12 October 2017
Received in revised form 1 December 2017
Accepted 17 December 2017
Available online 18 December 2017

*Keywords:*
Magnetic domains
Tilted anisotropy
Tb-Fe-Co thin film
Magnetic imaging
Micromagnetic simulation

ABSTRACT

Tailoring of magnetic domains of Tb-Fe-Co thin films with rapid thermal processing has been reported in this paper. While the as-deposited films show elongated, inter-connected domains with high out-of-plane magnetic phase contrast, the rapid thermal processed films at 550 °C with different time intervals display deterioration of magnetic contrast. A longitudinal extension of domains has been observed with the processing time of 5 min. With subsequent increase in processing time, the domain patterns exhibit considerable decrease in magnetic phase difference combined with strong intermixing between two oppositely magnetized areas. The out-of-plane magnetic contrast is seen to be very weak for the Tb-Fe-Co film processed for 30 min. The domain morphology and the contrast variation have been modeled with micromagnetic simulations, considering the in-plane (along *xz* plane) tilt of anisotropy axis. The ground state energy profile and the variation in magnetic properties indicate the threshold tilt angle to be around 30° wherein the in-plane and out-of-plane squareness ratio and coercivities are comparable and hence the system shows a spin re-orientation behavior at higher tilt angles.



## 1. Introduction

The ability to control the magnetism in magnetic nanostructures by tuning the properties such as anisotropy, exchange interaction and saturation magnetization has opened a new paradigm of research not only for understanding the fundamental aspects but also for the technological applications in the field of high density magnetic data storage [1], MRI contrast agent for bio-medical imaging [2] etc. Of these properties for device level application, saturation magnetization and exchange interaction must be of high strength to accomplish ordered and useful magnetic states and therefore potential to modify these properties are limited [3,4]. On the other hand, tailoring magnetic anisotropy can give rise to variety of magnetic function for wide range applications. Perpendicular magnetic anisotropy (PMA) with in-plane (IP) tilt has shown a considerable increase in writability by circumventing the high sensitivity of switching field distribution in conventional perpendicular memory devices [5]. Further, the tilted anisotropies are also employed for high frequency oscillations in magnetic layer for spin transfer torque effect based spin-torque oscillators [6,7]. Tuning of tilted magnetic anisotropy can be achieved by many ways. Growth of exchange spring materials have shown high potentiality to tilt the anisotropy when an IP magnetic layer was grown over a magnetic layer exhibiting out-of-plane (OOP) magnetic anisotropy [8–10]. In addition to this, use of external stimuli in the form of ion-beam irradiation [11–13], laser heating [14–16], rapid thermal processing (RTP) [17–19] are also very popular for engineering anisotropy in magnetic thin films. While techniques like ion-beam irradiation and laser heating can modify the magnetic properties locally, RTP has been found to be a promising route for achieving anisotropy modification globally.

From the vast reports available in the literature, it is clearly evident that studies on the global tuning of magnetic anisotropy are limited. Further, with reference to the measurement of such anisotropies, most of the studies carried out till now were on a macroscopic length scales, either by measuring the overall magnetization [17] or by employing ferromagnetic resonance [20,21]. However, microscopic investigations employing magnetic domain imaging towards understanding tuning of anisotropy is limited [9,18]. Visualization of magnetic domains directly offers the access to nano-scale magnetic properties and to understand the local change in magnetic properties when perturbed with external stimuli. Further, it also helps to apprehend magnetization reversal mechanism in magnetic thin films.

Tb-Fe-Co exhibiting strong PMA with high temperature stability [17] and giant Kerr rotation [22] has been studied for magneto-optical recording application [23,24]. When the anisotropy is tuned

* Corresponding author.
*E-mail address:* aroutchelvane@gmail.com (J. Arout Chelvane).

https://doi.org/10.1016/j.jmmm.2017.12.062
0304-8853/

to lie along the film plane, it shows a considerable magnetostriction [25]. Recently, exchange bias and bi-stable magnetoresistance states have been unfurled in amorphous Tb-Fe-Co film [26]. Mansuripur and colleagues have contributed immensely for understanding the magnetization reversal dynamics [27], computation of demagnetization field [28] and domain wall motion [29] in amorphous rare-earth transition-metal (RE-TM) alloy systems. However, a systematic investigation of magnetic domains with its variation in response to external perturbations for Tb-Fe-Co films is not well documented. In our earlier attempt, easy axis tuning from OOP to IP direction in amorphous Tb-Fe-Co films has been understood by employing RTP [17]. Detailed cross-sectional transmission electron microscopy studies coupled with bulk magnetization measurements showed the nucleation of Fe-Co phase, leading to the deterministic tilting effect with change in RTP time. In this paper, we present magnetic microscopy studies carried out on Tb-Fe-Co thin films under anisotropy tilt. 3D micromagnetic simulation has been carried out to complement the experimental findings. Efforts were made to understand different types of domain patterns, contrast variation and ground state magnetic energies as a function of anisotropy tilt.

## 2. Experimental detail

Electron beam evaporated Tb-Fe-Co films were deposited over Si $< 100 >$ substrates at room temperature with a background pressure of $1 \times 10^{-7}$ torr. A constant growth rate of 5Å/sec was maintained during the growth of the films with thickness of 200 nm, recorded by quartz crystal monitor, associated to the deposition unit. The substrate was allowed to rotate at a speed of 10 rpm for uniformity in thickness. A thin capping layer (3 nm) of Cr was used to protect the film from oxidation. The as-deposited films were processed by RTP at 550 °C for different time intervals *viz.,* 5, 10, 20 and 30 min (min) under vacuum, better than $5 \times 10^{-7}$ torr employing RTP furnace. Magnetic domain imaging was performed by magnetic force microscopy (MFM) using a CoCr coated n-type Si tip. The domain patterns were modeled by micromagnetic simulation using Object Oriented Micromagnetic Framewrok (OOMMF) software [30].

## 3. Results and discussions

The as-deposited films are amorphous in nature with elemental composition (atomic %) of $Tb_{21}Fe_{62}Co_{17}$. A detailed structural and magnetic studies for both the as-deposited and rapid thermal processed films can be found in reference [17], characterized for the same set of films. Fig. 1(a) and (b) display the room temperature atomic force microscopy (AFM) and MFM images respectively for the as-deposited film. The roughness value, estimated from the AFM studies was $\sim 1nm$. The MFM image displays unusual elongated domain pattern with very high magnetic phase difference, probably reported for the first time in this material system. The two different contrasts in the MFM image designate the presence of oppositely magnetized domains. The domains are interconnected, comprising the combination of wider and narrower elongated stripes. As MFM is sensitive to the OOP component of the stray field emanating from the sample, higher magnetic phase difference in the MFM image confirms the presence of strong PMA in the film, which is in concurrence with the magnetization measurements, reported earlier [17]. From the histogram analysis, the contribution from two different contrasts are found to be 62% and 38% respectively, which clearly indicates that the film is not demagnetized under as-deposited condition. The 2-D isotropic power spectral density (PSD), calculated from the fast Fourier transform (FFT) of the MFM image is shown in Fig. 1(c). Performing line scan over the FFT image (inset of Fig. 1(c)), it can be estimated that the overall domain network in Fig. 1(b) is oriented about 32° off with respect to the transverse direction. This could be probably due to the presence of domains with broader size distribution which is unlike the case, observed for Gd-Fe thin films having perfectly periodic domains with circular FFT pattern, signifying random orientation [18]. The average domain periodicity, determined from the PSD peak turned out to be $1(\pm 0.01)$ µm.

To model the magnetic domain in Tb-Fe-Co films, micromagnetic simulation was carried out using the following input parameters, reported in the literature [29]. The considered values are, exchange constant $(A) = 1 \times 10^{-12}$ J/m, uniaxial anisotropy constant $(K_u) = 1 \times 10^5$ J/m$^3$ and saturation magnetization $(M_s) = 4 \times 10^5$ A/m. The value of $M_s$ was tuned to satisfy the experimental inferences with reference to the domain configuration. Fixing these parameters, the system has been relaxed to find the minimized energy configuration (ground state) starting from a random state with uniform vertical magnetization (+ Z direction). The volume of each cell considered for simulation was $(4\ \text{nm})^3$, which is less than the exchange length of the material. Moreover this cell volume provides enough resolution to visualize the domain wall, dimension ($\delta$) of which can be determined theoretically using the relation, $\delta = \pi \cdot \sqrt{A/K_u}$. The finite temperature effect and the pinning effect in the real film due to the presence of defect were not considered in the simulation. All the simulations were performed over the area of $(3\ \mu\text{m})^2$ to incorporate the effect of continuity with respect to the characteristic dimension of the simulated domains and hence periodic boundary conditions were not applied. In this paper, emphasis has been given towards the understanding of domain pattern, contrast formation and their variation under anisotropy tilt along with the trend of the variation of domain size instead of comparing their absolute values.

Fig. 2(a) and (b) display the simulated domain and domain wall configuration respectively for the 200 nm thick Tb-Fe-Co film. The two opposite contrasts (red and blue) in Fig. 2(a) represent the two

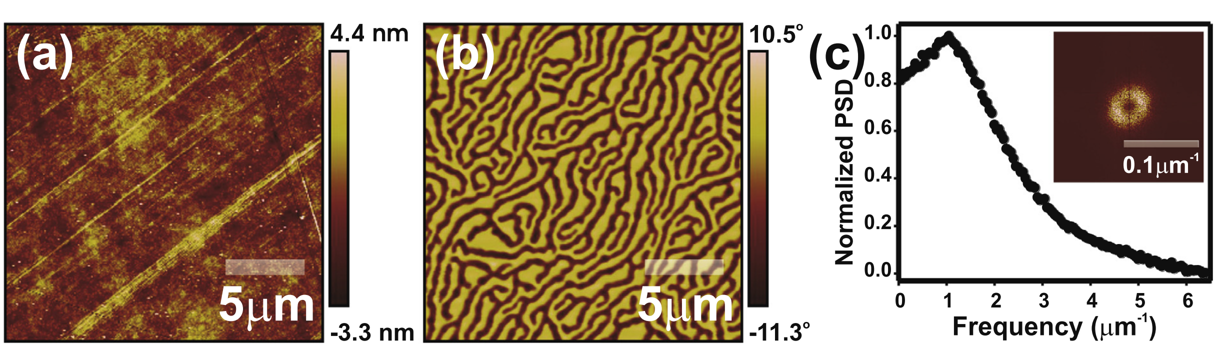


**Fig. 1.** (a) AFM, (b) MFM and (c) PSD curve, derived from the FFT pattern of the MFM image (shown as inset) for 200 nm thick as-deposited Tb-Fe-Co film.