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Effects of thermal annealing on structural and magnetic properties of thin Pt/Cr/Co multilayers

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ABSTRACT

Thermal stability of thin Pt/Cr/Co multilayers and the subsequent changes in their structural, magnetic, and magneto-optical properties are reported. We observe CoCrPt ternary alloy phase formation due to annealing at temperatures about 773 K, which is accompanied by enhancement in the coercivity value. In addition, 360° domain wall superimposed on a monodomain like background has been observed in the pristine multilayer, which changes into a multidomain upon annealing at 873 K.

1. Introduction

Magnetic multilayers (MLs) have been studied extensively in recent years because of their unique magnetic properties [1–3]. They are the key elements in terms of their applications in several modern devices, e.g., high-density recording media, low-field magnetic sensors, etc. [4,5]. For instance, Co/Pt, Fe/Pt, and Co/Pd MLs have attracted much attention for their potential application as high-density reversible magneto-optical recording media due to their high perpendicular magnetic anisotropy and large coercivity [6–8]. For any such applications, one needs to have a fairly good information about the quality of the surface and interfaces since the latter plays a crucial role in controlling the structural and magnetic properties of such MLs.

Performance of devices based on layered structures depends, among other parameters, on the atomic mixing across interfaces. Thus, thermal stability of these interfaces needs to be studied very carefully. In addition, alloy based magnetic recording media materials prepared by thermal annealing of multilayers can process very different behavior. For instance, recently, it has been shown that starting with the Fe/Pt multilayer precursor, the ordering temperature for the formation of face-centered tetragonal (fct) FePt phase can be reduced to $<300\,^{\circ}$C by thermal annealing [9]. CoCrPt is another high-density perpendicular magnetic recording media material, which has certain favorable properties as compared with the above materials [10].

In this paper, we report on the effects of thermal annealing on structural, magnetic, and magneto-optical properties of thin Pt/Cr/Co multilayers. Complementary studies of X-ray reflectivity (XRR), grazing incidence X-ray diffraction (GIXRD), cross-sectional transmission electron microscopy (XTEM), magneto-optical Kerr effect (MOKE), atomic and magnetic force microscopy (AFM/MFM) were performed to correlate changes occurring in structural, magnetic, and magneto-optical properties across the thin Pt/Cr/Co ML interfaces.

2. Experimental

Electron beam evaporation technique was employed for sequential growth of Pt/Cr/Co multilayer samples on a native oxide covered Si(1 0 0) substrate at room temperature (RT). During deposition, the chamber vacuum was maintained in the range $2–5\times10^{-8}$ Torr and the films were deposited at a constant rate of 0.01 nm s^{-1}. Pt was chosen to be the top layer because of its inert nature and to avoid any possible oxidation of the underneath layers. Six trilayers of Pt, Cr, and Co, with the nominal period of 6.3 nm (2.5 nm Pt, 0.8 nm Cr, and 3.0 nm Co), were deposited. Total nominal thickness of the multilayer stack thus turns out to be 37.8 nm. Rutherford backscattering spectrometry measurements confirmed the absence of oxygen in the multilayer

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films. In order to study the thermal stability, the ML films were annealed for 1 h in the temperature range 573–873 K in vacuum (10^{-6} Torr). XRR measurements were employed to determine layer thickness, roughness, and a possible interface modification. Phase identification, before and after annealing, was studied by GIXRD with Cu-Kα radiation. Microstructures and crystallinity of the pristine and the annealed ML samples were studied by cross-sectional TEM (XTEM) and selected area diffraction (SAD) measurements. TEM samples were prepared by a standard preparation technique that included dimpling and subsequent 3 keV Ar^+ ion milling at low incident angles by Ar^+ ion milling using a GATAN precision ion polishing system. Subsequently, the samples were analyzed using a high-resolution FEI, TECNAI G^2 20, TWIN TEM machine operating at 200 kV and equipped with a GATAN CCD camera. Further, the magnetic properties of both the pristine and the annealed ML samples were measured by longitudinal magneto-optical Kerr effect (LMOKE) and magnetic force microscopy (MFM).

3. Results and discussion

Fig. 1 depicts low-angle XRR spectra of the pristine and the vacuum annealed Pt/Cr/Co ML samples. For the pristine sample, Bragg peaks up to the fourth order are present along with four (i.e., $n-2$, where n is the total number of stacks) subsidiary maxima between two successive Bragg peaks. This confirms a well-defined interface structures indicating a smooth growth of ML samples. In order to determine the changes that occurred in the micro-structural parameters due to vacuum annealing, the XRR spectra were fitted using Parratt's formalism [11]. Because of the small difference in the refractive indices of Cr and Co, the multilayer has been modeled by taking a single layer of Cr+Co with average electron density. Further, it should be noted that the XRR spectrum corresponding to annealing at the highest temperature (873 K) shows complete destruction of the multilayer structure, indicating complete mixing. Therefore, realizing the difficulty in practical interpretation, we have avoided the simulation of the same. It may be noted that the interface roughness, as obtained from XRR, consists of two components, viz. topological roughness and the interdiffusion $\sigma^2=\sigma_T^2+\sigma_{ID}^2$. The simulation of the pristine ML sample yields a multilayer period of 6.6 nm, which is close to the nominal thickness. Simulated thickness of the individual layers also matches closely with the one obtained from the RBS data. In addition, root mean square (rms) surface roughness of the pristine sample, obtained from the AFM measurements, matches closely with the simulated XRR roughness value.

From Fig. 1, we observe that with thermal annealing there is a progressive shift in position of the Bragg peaks towards lower angle side. For instance, the first Bragg peak position moves from 1.16 nm^{-1} (pristine) to 1.14 nm^{-1} (573 K) to 1.13 nm^{-1} (673 K), while the second Bragg peak position moves from 1.99 nm^{-1} (pristine) to 1.95 nm^{-1} (573 K) to 1.94 nm^{-1} (673 K). This corresponds to a decrease in the modulation period and hence an increase in the density of the ML with increasing temperature. In addition, intensity of the Bragg peaks also decreases progressively upon increasing the annealing temperature, providing an evidence of intermixing at the interfaces.

Fig. 2 presents GIXRD spectra of the pristine and the thermally annealed ML samples. The spectra were recorded at the grazing incidence angle of 0.5°. The GIXRD pattern of the pristine sample shows signatures of fcc Pt(1 1 1) and hcp Co(10.0) at $2\theta=39.8°$ and 40.9°, respectively. In addition, a weak peak at $2\theta=38.3°$ is also observed. The origin of this peak can be described as follows. It is known that even in polycrystalline multilayers of Pt/Fe(Co), some degree of structural coherency is maintained among successive layers of Pt and Fe(Co) [9]. This gives rise to satellite peaks around the main peak at positions given by [12] $\sin(\theta_n)=\sin(\theta_0)\pm(n\lambda/2d)$, where θ_n is the nth order sattelite peak, θ_0 the position of the Pt(1 1 1) peak, d the modulation period of the multilayer, and λ the wavelength of the X-rays. Using the d value, obtained from the XRR simulation, calculated position of the first order satellite peak turns out to be 38.4°, which closely matches the experimentally observed peak position. We do not see any diffraction peak corresponding to the Cr layers. This may be due to the small quantity of Cr in the Pt/Cr/Co stacking combined with its high abnormal diffusion coefficient for Cu-Kα radiation. The Pt satellite peak disappears even after annealing at the lowest temperature of 573 K, which indicates intermixing across the constituent layers. However,

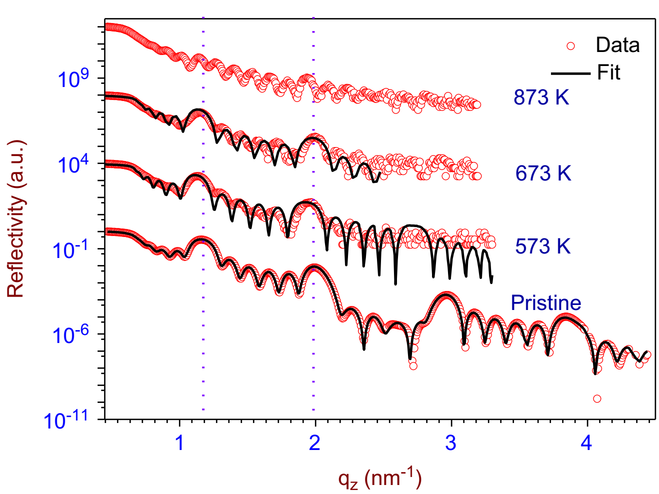

Fig. 1. XRR spectra of the Pt/Cr/Co multilayers—Pristine and thermally annealed in a temperature range 573–873 K. Fitting shows a multilayer periodicity of 6.6 nm (pristine), 6.9 nm (573 K), and 6.7 nm (673 K) whereas roughness values are 0.15 and 0.6 nm on surface and Pt on "Cr+Co" interface, respectively (pristine), 0.6 and 2.0 nm on surface and Pt on "Cr+Co" interface, respectively (573 K), and 0.7 and 3.0 nm on surface and Pt on "Cr+Co" interface, respectively (673 K). Data for the thermally annealed multilayer samples are vertically shifted for the sake of clarity.

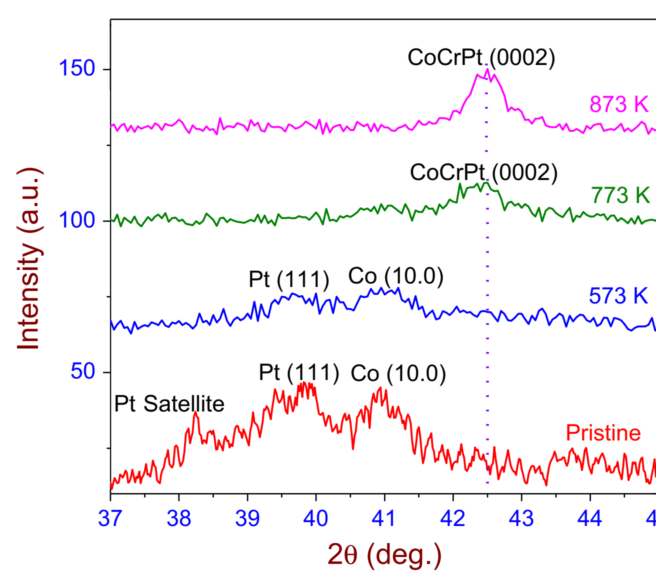

Fig. 2. GIXRD patterns of the Pt/Cr/Co multilayers—Pristine and thermally annealed in a temperature range 573–873 K. Data for the thermally annealed multilayer samples are vertically shifted for the sake of clarity.