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Effect of ion beam irradiation on magnetic and structural properties of Pt/Cr/Co multilayers

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Abstract

This paper discusses the effect of ion beam irradiation on the magnetic and structural properties of Pt/Cr/Co multilayers. We observe Co–Cr–Pt ternary alloy phase formation in 1 MeV N^+ ion irradiated $[Pt (2.5 nm)/Cr (0.8 nm)/Co (3.0 nm)]_{\times 6}/Si$ multilayers for a fluence of 1×10^{16} ions cm^{-2} and beyond. The observed phase formation is accompanied by an enhancement in the average grain size, surface roughness and coercivity. Monte Carlo simulation has been performed to study ion-induced defect evolution and atomic displacements to correlate the above observed effects.

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Keywords: Ion Irradiation; Pt/Cr/Co multilayer; Co–Cr–Pt ternary alloy; Coercivity

1. Introduction

Co–Cr–Pt ternary alloys thin films are the most promising candidates for high-density perpendicular magnetic recording media [1] and are used by the hard disk industry over the decades [2]. Co–Cr–Pt alloys show drastic variation in magnetic anisotropy and have higher coercivity and low media noise [1,3–5]. It is known that addition of Pt in Co–Cr-based alloys helps in achieving high coercivity due to increased magnetocrystalline anisotropy, but excessive addition of Pt also increases in media noise originating from magnetic exchange coupling between columnar grains [6,7]. Usually, Co–Cr–Pt ternary alloy thin films are grown by co-sputtering of elemental targets and/or physical vapor deposition of alloy targets prepared by solid state reaction route. In contrast, ion-beam mixing induced synthesis of novel phases offers lower processing temperature and a high degree of spatial selectivity. It is not governed by equilibrium thermodynamics and often leads to the formation of metastable phases which are otherwise not possible to grow by solid state reaction route. It can be mentioned that Co–Cr–Pt ternary alloy system shows the existence of many metastable phases and thus, ion beam induced interface mixing across Pt/Cr/Co multilayers would be helpful to look for the most suitable one which will offer superior magnetic properties.

In recent years, besides phase formation, ion irradiation of magnetic multilayers has been shown to modify several extrinsic magnetic properties like coercivity, magnetic anisotropy and magnetic exchange coupling in a highly localized region [8–14]. Depending on the ion energy, mass, fluence and sample configuration, magnetic properties can be tuned in a controlled manner [10]. The existing reports help to understand the nature of the structural changes

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responsible to the magnetic changes to a large extent. In particular, magnetic multilayers are more sensitive to light-ion irradiation. For instance, irradiation of Co/Pt multilayers by 2 MeV He^+ ions leads to higher degree of changes than those caused by 2 MeV Ar^+ ions or keV Ga^+ ions [15]. However, a very little has been done on Pt/Cr/Co multilayers particularly with ion beam irradiation technique and hence based on the above facts, in this paper, we focus mainly on 1 MeV N^+-ion induced Co–Cr–Pt ternary alloy phase formation across the Pt/Cr/Co multilayer thin films and changes occurring in their structural and magnetic properties. Complementary studies of high resolution Rutherford backscattering spectrometry (HRBS), atomic force microscopy (AFM), grazing incidence X-ray diffraction (GIXRD) and magneto-optical Kerr effect (MOKE) techniques have been used. In addition, Monte Carlo SRIM-2006 simulation [16] has been performed for evaluating ion induced atomic displacements and to correlate the above observed effects.

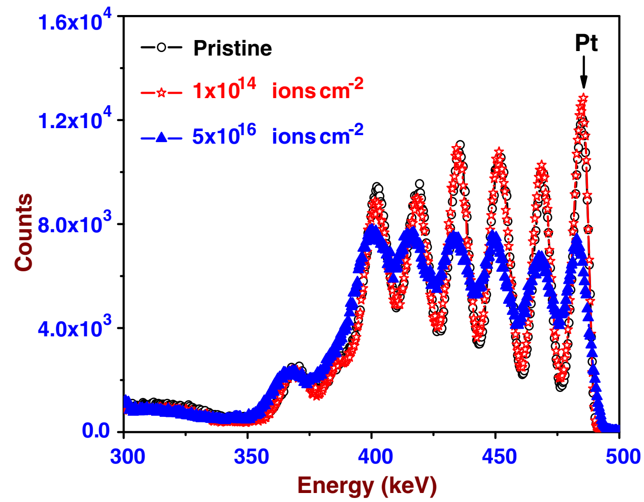

Fig. 1. 500 keV He^+-ion induced representative HRBS spectra obtained from pristine and 1 MeV N^+-ion irradiated Pt/Cr/Co multilayers to the fluences of 1×10^{14} and 5×10^{16} ions cm^{-2}.

2. Experimental

Ultra high vacuum e-beam evaporation technique was employed for sequential growth of [Pt (2.5 nm)/Cr (0.8 nm/Co (3.0 nm)]$_{\times 6}$/Si multilayer samples on a native oxide covered Si (1 0 0) at room temperature (RT) under a base vacuum of 5.0×10^{-8} Torr and a deposition rate of 0.01 nm s^{-1}. The multilayers were uniformly irradiated at RT by 1 MeV N^+ ions in the fluence range of 1×10^{14}–5×10^{16} ions cm^{-2} at RT using a 3 MV Pelletron accelerator.

The projected ranges of the nitrogen ions in Pt, Cr and Co layers are 482 nm, 661 nm and 673 nm, respectively. Therefore, in our case, nitrogen ions will pass through the [Pt (2.5 nm)/Cr (0.8 nm)/Co (3.0 nm)]$_{\times 6}$/Si multilayer stack and get buried in the substrate Si (up to depth of 1.4 μm).

Interface mixing was studied by HRBS measurements using 500 keV He^+ ions at an incident angle of 60° and the scattering angle of 65°. The detection system consists of a 90° double focusing sector magnet and a 1D-MCP focal plane detector and offers a sub 1 keV energy resolution [17]. The surface morphology of the samples was studied by AFM. GIXRD studies were performed for phase identification. The MOKE measurements were performed in longitudinal mode to study the change in the magnetic properties of the Pt/Cr/Co ML samples before and after N ion irradiation.

3. Results and discussion

Fig. 1 shows the overlapped HRBS spectra of the pristine and the representative irradiated ML samples. At higher fluences, there is a reduction in the peak height followed by a significant increase of scattering yields in the valleys between Pt peaks. This is accompanied by a significant peak broadening at the highest fluence. Thus, it is clear that with increasing ion fluence, interface mixing becomes more prominent. These features could arise due to ion induced surface roughening [8] and formation of bigger surface nanostructures.

The surface morphology of the pristine and the irradiated samples were studied by AFM. The morphology of the pristine sample (image not shown) shows nano-granular features with wide distribution of grain sizes (average grain size ~40 nm). It is observed that the average size of these features increases with increasing ion fluence and reaches a maximum size of 120 nm at the highest fluence of 5×10^{16} ions cm^{-2}. In addition, irradiation results in an increase in the *rms* surface roughness of the film from a meager 0.5 nm to 3.3 nm. These observations corroborate well with our HRBS results described above.

GIXRD measurements were performed for phase identification of the samples before and after nitrogen irradiation. GIXRD spectra shown in Fig. 2 were recorded at a grazing incidence of 0.5°. The XRD pattern of the pristine multilayer film [Fig. 2(a)] exhibits the presence of *fcc* Pt(1 1 1) and the *hcp* Co(10.0) peaks. The presence of the Pt satellite peak indicates a strong structural coherence among the multilayers. It is significant to note that the satellite peak disappears even at a fluence of 5×10^{15} ions cm^{-2} [Fig. 2(b)]. Such a signature of disappearing Pt satellite peak indicates an intermixing among the constituent layers. At a higher fluence of 1×10^{16} ions cm^{-2}, many new peaks evolve. The new peaks arising due to irradiation [Fig. 2(c)], corresponding to the 2θ values of 42.1° and 43.5°, match closely to the Co–Cr–Pt (10.0) and (00.2) reflections, respectively [18]. Thus, nitrogen ion irradiation of Pt/Cr/Co multilayers leads to the formation of Co–Cr–Pt ternary alloy phase at RT. However, it is clear that the complete mixing is yet to be achieved.

To study the magnetic properties of the multilayer samples, MOKE measurements were carried out. Fig. 3 depicts

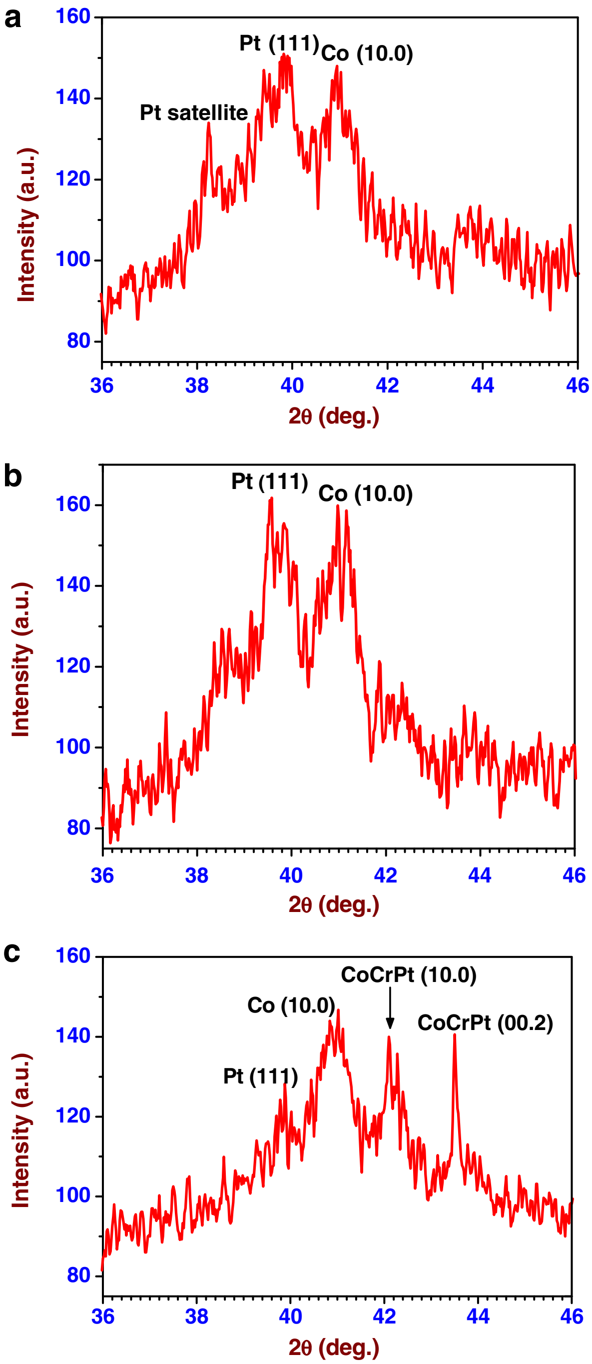

Fig. 2. Representative GIXRD patterns obtained from Pt/Cr/Co multilayers: (a) before and after 1 MeV N^+-ion irradiation at RT; (b) to the fluence of 5×10^{15} ions cm^{-2}; (c) to the fluence of 1×10^{16} ions cm^{-2}.

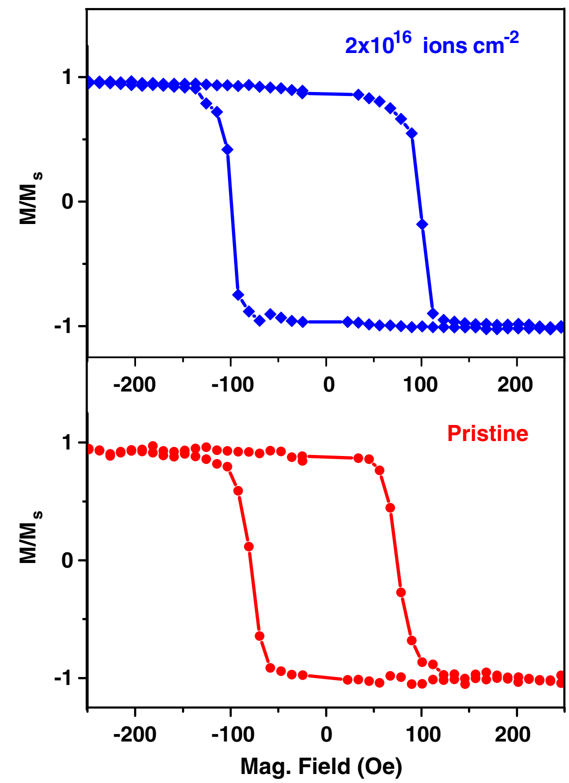

Fig. 3. Representative longitudinal MOKE plots of pristine and 1 MeV N^+-ion irradiated Pt/Cr/Co multilayers to the fluence of 2×10^{16} ions cm^{-2}.

the longitudinal MOKE measurement data corresponding to the pristine and the irradiated multilayer samples. In our case, the applied magnetic field was parallel to the multilayer film plane. It is observed that the MOKE hysteresis loop area increases with increasing ion fluence. In addition, the coercivity increases from 74.2 Oe (pristine) to 206.4 Oe for the sample irradiated to the highest fluence of 5×10^{16} ions cm^{-2}. The increase in the coercivity may be attributed to the formation of Co–Cr–Pt alloy phase by ion beam mixing at RT. This is in good agreement with our HRBS and GIXRD results that show the strong signature of ion beam mixing. Such enhancement in the coercivity values due to irradiation of Co/Pt multilayers has been reported earlier [8]. In addition, since it is known that coercivity increases with increasing roughness of magnetic alloy thin films [19], our MOKE results are well supported by the AFM data described earlier.

In order to correlate the change in the physical properties of Pt/Cr/Co multilayers due to defect evolution under N-ion bombardment, we performed Monte Carlo SRIM-2006 simulation for 20,000 incident N ions on the above multilayer samples. Fig. 4 shows the vacancy distribution profile in a Pt/Cr/Co multilayer used in this study. It is clear that a reasonably good number of Pt, Cr and Co vacancies are created. In addition, there exists a gradient in Pt, Cr and Co vacancy concentrations across the interfaces and they are even seen to be driven into the neighbouring layers. Thus, the interfaces can be considered to be a good defect clustering sites. It is observed that an average of 0.9 ion^{-1} nm^{-1}, 0.6 ion^{-1} nm^{-1} and 1.2 ion^{-1} nm^{-1} vacancies are created in Pt, Cr and Co layers, respectively. This would mean that corresponding to a fluence of 1×10^{16} ions cm^{-2}, the vacancy concentration in Pt, Cr and Co layers will be 6.3×10^{22} ions cm^{-3}, 1.3×10^{23} ions cm^{-3} and 7.2×10^{22} ions cm^{-3}, respectively. However, all the vacancies will not survive because of the recombination/trapping process. In addition, many of them will form

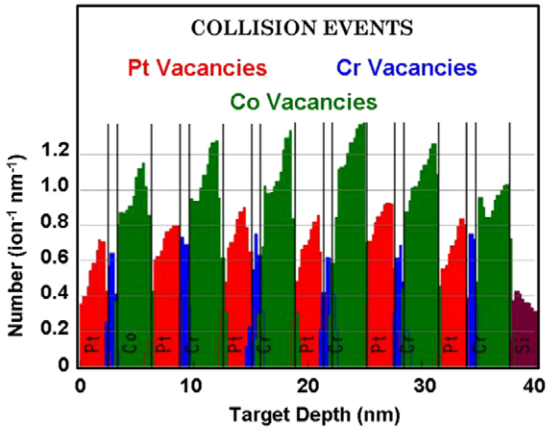

Fig. 4. SRIM-2006 simulated vacancy profiles corresponding to 1 MeV N^+-ion irradiation of Pt/Cr/Co multilayer deposited on Si. Pt, Cr and Co layer boundaries are marked with vertical lines.

clusters under continuous ion bombardment. These defect clusters may act as domain wall pinning sites giving rise to higher coercivity as discussed above [8].

Let us now try to find out the possible mechanism leading to the ion beam mixing across the [Pt (2.5 nm)/Cr (0.8 nm/Co (3.0 nm)]$_{\times 6}$/Si multilayer interfaces. From Fig. 5(a)–(c), it is observed that more Co atoms (1.3 $ion^{-1}\,nm^{-1}$) are displaced than those of Pt (0.8 $ion^{-1}\,nm^{-1}$) and Cr atoms (0.55 $ion^{-1}\,nm^{-1}$). Further, it is observed that, Pt atoms not only get displaced from their regular sites within the Pt layers but also a fraction is pushed into the Cr and Co layers. From a detailed analysis of SRIM simulation data, it is observed that for a fluence of 1×10^{16} ions cm^{-2}, on an average, 22 Pt at.% are pushed into Cr layers and 18 Pt at.% get pushed into Co layers due to nitrogen ion bombardment on the Pt/Cr/Co multilayers. Similarly, number of recoiling Cr atoms within Pt and Co layers is 18 and 3 Cr at.%, respectively. On the other hand, recoiling Co atoms in neighboring Pt and Cr layers are found to be 29 and 15 at.%, respectively. These recoiled atoms lead to the intermixing and subsequent Co–Cr–Pt ternary alloy phase formation in the Pt/Cr/Co multilayer samples.

In general, it has been observed that the multilayers are much more sensitive to irradiation than expected on the basis of a nearest-neighbor coupling model and simple ballistic ion beam mixing. In particular, for lighter ions, the effect is more prominent [15,20], which could be due to inadequacies in the SRIM simulations for an ion species having small probability of displacement collisions near the sample surface. In addition, we have also obtained the simulated ionization events to find out that 1 MeV N^+ ions deposit ~200 times more energy into ionization events as they do into recoils. Thus, it is also possible that in such cases an additional mechanism based on electronic excitations may also contribute due to much higher energy deposition due to ionization events. This ionization energy may get coupled to the lattice phonons and contribute to

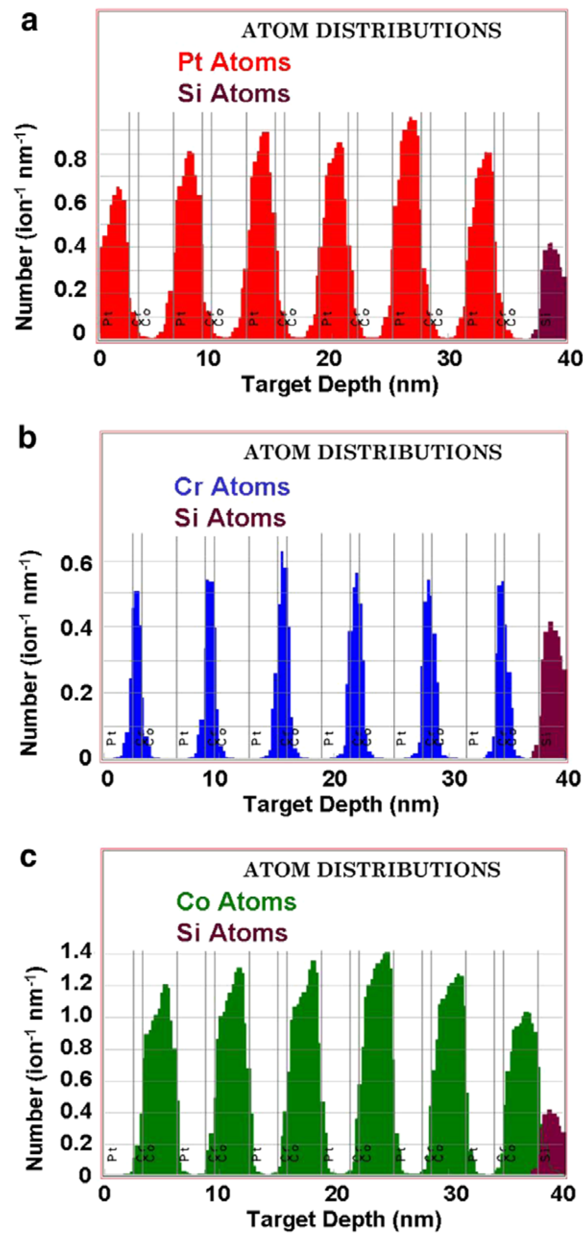

Fig. 5. SRIM-2006 simulated distribution of displaced (a) Pt, (b) Cr and (c) Co atoms due to 1 MeV N-ion irradiation of Pt/Cr/Co multilayer deposited on Si, Pt, Cr and Co layer boundaries are marked with vertical lines.

atomic rearrangements leading to interface mixing and subsequent phase formation.

4. Conclusions

In conclusion, we have shown that 1 MeV N^+-ion irradiation of Pt/Cr/Co multilayers at room temperature leads to change in their structural and magnetic properties through ion beam mixing and subsequent Co–Cr–Pt ternary alloy phase formation across the interfaces. Co–Cr–Pt ternary alloy phase is one of the most suitable candidates for perpendicular magnetic recording media. This is followed by enhancements in the surface roughness and average grain size of the irradiated samples. In addition, there is a significant increase in the coercivity, which may be attributed to the formation of the alloy phase due to interface mixing across the Pt/Cr/Co interfaces. Changes in structural and magnetic properties have been well correlated by HRBS, AFM, GIXRD and MOKE measurements. In order to explore the possibility of tuning the magnetic properties of the Pt/Cr/Co multilayer system in a more controlled manner, further experiments using heavier ions and different layer thicknesses are underway.

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