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Ga^+ ion irradiation-induced changes in magnetic anisotropy of a Pt/Co/Pt thin film studied by X-ray magnetic circular dichroism

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Abstract. Ga^+ ion irradiation-induced changes in magnetic anisotropy of a Pt/Co/Pt ultrathin film are investigated by means of the X-ray magnetic circular dichroism (XMCD) technique. A large difference in the Co orbital moment is observed between out-of-plane and in-plane directions of the film at moderate Ga^+ fluences of ~1-2×10^{14} ions/cm^2, which corresponds to the perpendicular magnetic anisotropy (PMA), while further increased fluences reduce the orbital moment difference, resulting in in-plane magnetization. In contrast, at much higher Ga^+ fluences of ~5×10^{15} ions/cm^2, at which PMA is observed again, no significant difference is found in the orbital moment of Co between out-of-plane and in-plane directions. Different origins are thus suggested for the appearance of PMA induced by the irradiation between moderate and high Ga^+ fluences.

1 Introduction

A lot of effort was put already up to now to realize perpendicular magnetic anisotropy (PMA) in thin films and multilayers, in view of the application as high-density magnetic recording media. Among them, the control of magnetic anisotropy by ion irradiation has attracted much interest in this decade [1-9], due to a possibility of nanostructure patterning by using a focused ion beam [3,5]. In fact, a Ga^+-induced spin reorientation transition to perpendicular magnetization from an in-plane magnetized Pt/Co/Pt thin film has been reported at medium ion fluences in the 10^{14} ions/cm^2 region [1]. Although the film exhibits in-plane magnetization at higher doses, it has very recently revealed that PMA appears again at much higher ion fluences in the 10^{15} ions/cm^2 region [2]. Therefore, two perpendicular magnetization states are observed by changing Ga^+ fluences [2].

As possible changes induced by ion irradiation, Co-Pt intermixing and an $L1_0$-type ordered alloy formation have been suggested [2,4,5]. Moreover, a recent study using extended X-ray absorption fine structure (EXAFS) and X-ray magnetic circular dichroism (XMCD) reveals that enhancement of PMA in the moderate Ga^+ fluence region is directly related to an in-plane lattice expansion in the Co film and a larger orbital moment of Co in the out-of-plane direction compared with that in the in-plane direction [10]. However, the origin of the appearance of PMA at the high Ga^+ fluence region is still unclear. In the present study, we have performed XMCD experiments to investigate the Ga^+ irradiation-induced changes in magnetic anisotropy of a Pt/Co/Pt thin film in a wide range of the ion fluence.

2 Experimental details

An epitaxial Al_2O_3/Mo (20 nm)/Pt (20 nm)/Co (3.3 nm)/Pt (5nm) film was grown by a molecular beam epitaxy (MBE) method. A 20 nm thick Mo(110) buffer layer was first grown at 1000°C on the epi-ready sapphire Al_2O_3(11-20) substrate. It was followed by subsequent room temperature deposition of; (i) a 20 nm thick Pt(111) underlayer, (ii) a 3.3 nm thick Co(0001) magnetic layer and (iii) a 5 nm thick Pt(111) cover layer. The film was then irradiated with 30 keV Ga^+ ions as contiguous 1×2 mm^2 areas with different fluences up to 1×10^{16} ions/cm^2.

Co L-edge XMCD spectra were taken at room temperature in the total-electron-yield mode at the soft X-ray undulator beamline, BL-16A, of the Photon Factory in the Institute of Materials Structure Science, High Energy Accelerator Research Organization [11]. The XMCD measurements were performed at room temperature in an applied magnetic field of 1.2 T in the normal and grazing incidence configurations, in which the angle between the X-ray beam and sample normal is 0 and 55º, respectively.

3 Results and discussion

Figure 1 shows Co L-edge XMCD spectra for the Pt/Co/Pt film at different Ga^+ fluences. Although the XMCD intensity gradually decreases with increasing ion fluence, the normal and grazing incidence data at each ion fluence exhibit almost the same intensity. This indicates that the magnetic saturation is achieved in both the out-of-plane and the in-plane directions of the film at 1.2 T, which allows us to directly determine anisotropy of the orbital magnetic moment [12,13].

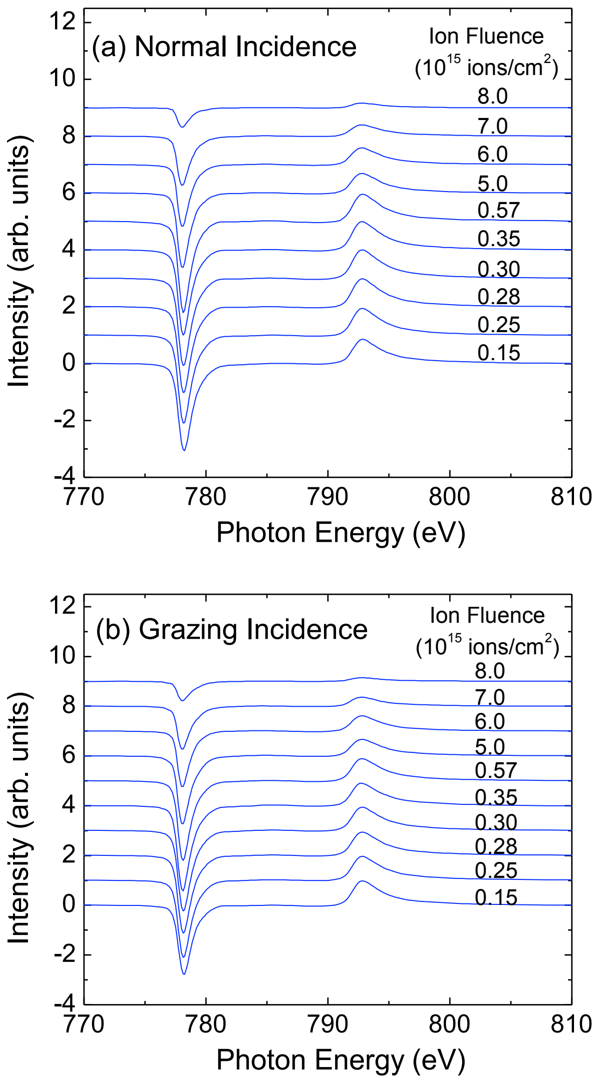

Fig. 1. Co L-edge XMCD spectra for a Pt/Co/Pt film irradiated with different ion influences taken at normal (a) and grazing (b) incidence configurations.

The spin and orbital magnetic moments are estimated by applying the XMCD sum rules [14,15] to each data, as summarized in figure 2. A larger orbital magnetic moment of Co in the out-of-plane direction compared to that in the in-plane direction is observed at the first PMA region with moderate ion fluences, which suggests a positive magnetic anisotropy energy in Co [16,17]. This is consistent with the recent study, in which the appearance of PMA is accompanied with larger out-of-plane orbital moment and a large lattice distortion as revealed by the EXAFS experiment [10]. On the other hand, no significant difference in the orbital moments is found in the second PMA region at higher ion fluences, suggesting a different origin for the appearance of PMA.

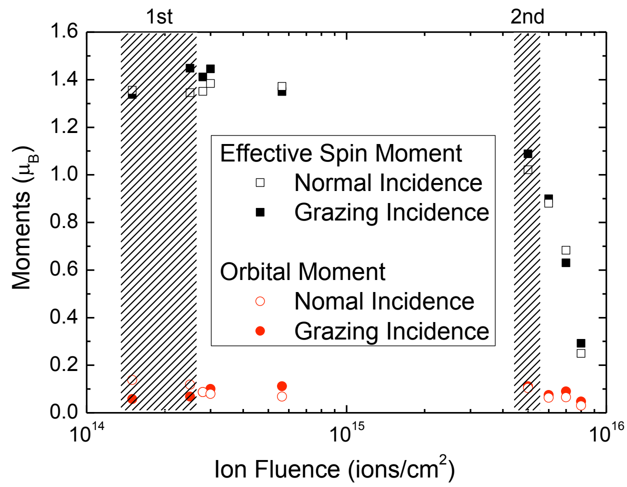

Fig. 2. Effective spin and orbital moments estimated by applying the XMCD sum rules. Hatched areas correspond to the PMA regions.

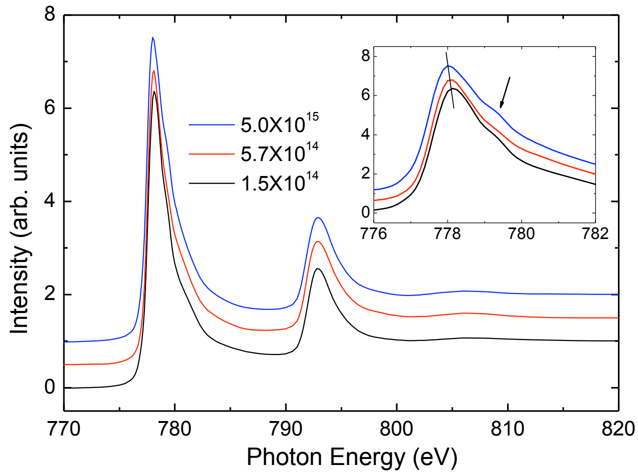

Fig. 3. Polarization-averaged Co L-edge X-ray absorption spectra for a Ga^+-irradiated Pt/Co/Pt film at different ion fluences taken at the normal incidence configuration. A satellite feature is indicated by an arrow in the inset.

Finally, let us discuss the possibility of a Co-Pt alloy formation, which might be an origin for the appearance of PMA. Figure 3 shows Co L-edge X-ray absorption spectra at different ion fluences. One can recognize the appearance of a satellite structure at ~779 eV, as well as a peak shift towards the lower energies, with increasing Ga^+ fluences. Similar peak broadening has been found in Pt/Co multilayers [18], in which the satellite feature increases by decreasing Co thickness from 15 to 3 ML. Since the component of the Co-Pt bond must be significant in the case of 3 ML Co, the ion irradiation-induced peak broadening could be attributed to the formation of a Co-Pt bond. However, more direct experiments such as EXAFS are necessary to reveal the formation of the Co-Pt alloy.

4 Summary

We have revealed, by means of Co L-edge XMCD, that a larger out-of-plane orbital moment compared to the in-plane one is induced in a Pt-sandwiched Co film by moderate Ga^{+} irradiations of ~1-2×10^{14} ions/cm^2, which corresponds to the appearance of PMA. In contrast, no significant difference is found in the Co orbital moment between out-of-plane and in-plane magnetization directions at much higher Ga^{+} fluences of ~5×10^{15} ions/cm^2, at which PMA is observed again. This suggests different origins for the appearance of PMA between the moderate and high Ga^{+} fluence regions. An EXAFS experiment is being planned in order to clarify the lattice distortion and the degree of Co-Pt mixing, in order to understand the origin of PMA.

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