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X-ray magnetic circular dichroism and hard x-ray photoelectron spectroscopy of a perpendicularly magnetized $D0_{22}$-type $Mn_{72}Ge_{28}$ thin film

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Abstract

An epitaxially grown $Mn_{72}Ge_{28}$ film with tetragonal $D0_{22}$ crystal structure was fabricated and electronic structures were investigated by x-ray magnetic circular dichroism and hard x-ray photoelectron spectroscopy. It was clarified that the film has a perpendicular magnetization and a high perpendicular magnetic anisotropy energy of 17.6 Merg/cm^3. From XMCD measurements, it was clarified that the orbital moment monotonically decreased with the incident angle, revealing that the orbital moment governs the magnetocrystalline anisotropy of the $Mn_{72}Ge_{28}$ film.

1. Introduction

For spintronic applications such as spin transfer torque magnetoresistance random access memory (STT-MRAM), many materials have been researched and developed focusing on their magnetic properties. Recently, materials with high perpendicular magnetic anisotropy (PMA) energy are especially becoming popular for the spintronic devices, because these materials lead to reduce critical current density and to get a high thermal stability factor. Among these materials, Mn-based ordered alloys with tetragonal crystal structures are strongly attractive as proper materials to fulfill these requirements due to high uniaxial magnetocrystalline anisotropy. They also have lots of merits including low saturation magnetization, low Gilbert damping constant, and high spin polarization. There have been many studies on Mn-based tetragonal alloys including Mn-Ga, Mn-Co-Ga, Mn-Ge and Mn-Al. Especially, epitaxially grown Mn-Ge alloys with a tetragonal $D0_{22}$ crystal structure are suitable materials for the spintronic devices such as a magnetic tunnel junction in STT-MRAM devices. Several researches based on the $D0_{22}$-Mn_3Ge alloys have been reported. T. Ohoyama *et al.* first reported $Mn_{3.4}Ge$ alloy as a face-centered-tetragonal structure with ε_1 phase.[1],[2] The ε_1 phase of MnGe alloy was experimentally determined as $D0_{22}$ crystal structure by neutron scattering.[3] S. Mizukami *et al.* experimentally reported the epitaxially grown Mn_3Ge films with low M_s of 100 ~ 130 emu/cc and high K_u of 10 ~ 12 Merg/cc.[4],[5] However electronic structures of the $D0_{22}$ MnGe alloys have not been fully elucidated, and it is strongly needed to investigate the relation between magnetic properties and electronic structures for these alloys.

In this research, we focused on epitaxially grown $Mn_{72}Ge_{28}$ film with a tetragonal $D0_{22}$ crystal structure. To investigate crystal structures and magnetic properties of the film, we performed XRD and SQUID-VSM measurements. X-ray magnetic circular dichroism (XMCD) and hard x-ray photoelectron spectroscopy (HAXPES) measurements were also performed to investigate the electronic structures of the film. The relation between magnetic properties and electronic structures of the $Mn_{72}Ge_{28}$ film was investigated.

2. Experimental Procedures

$Mn_{72}Ge_{28}$ film was fabricated onto a single crystal MgO (001) substrate using ultra high vacuum magnetron sputtering with a pressure below 10^{-7} Pa. Co-sputtering method was performed with a Mn target and a Ge target for the deposition of $Mn_{72}Ge_{28}$ film. A stacking structure of the film was MgO (001) substrate / Cr (40 nm) / $Mn_{72}Ge_{28}$ (50 nm) / MgO (2 nm). For the deposition of $Mn_{72}Ge_{28}$ film, substrate temperature was set at 400˚C and any annealing process was not performed.

XMCD measurements were performed at the beamline of BL16A in KEK-PF, Japan. Magnetic field perpendicular to the film plane with ±50 kOe was applied during the measurement at room temperature. HAXPES measurements were performed at the beamline of BL15XU in SPring-8, Japan in an ultrahigh vacuum chamber at room temperature. Photon energy was set at 5.9 keV for measurements. Electronic structures of the $Mn_{72}Ge_{28}$ film were investigated from the measurements of Mn 2*p* core level, Ge 2*p* core level and valence band spectra.

3. Results and Discussions

From XRD measurements of the $Mn_{72}Ge_{28}$ film, (004) fundamental peak and (002) superlattice peak of $D0_{22}$-type tetragonal crystal structure were obtained. It was clarified that this sample has a $D0_{22}$-type Mn-Ge crystal structure. SQUID-VSM measurement was performed with the magnetic field up to ±70 kOe at room temperature. Figure 1 shows magnetization curve of the film. Magnetic field was applied perpendicular to the plane. As shown in the figure, the film has a clear hysteresis for perpendicular magnetic field. It was also clarified that the film has a perpendicular

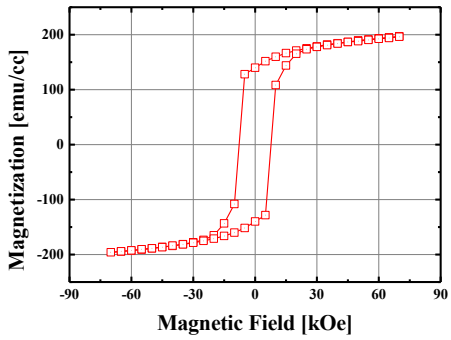

Figure 1. Magnetization curve of a $Mn_{72}Ge_{28}$ film. Magnetic field was applied perpendicular to the plane.

magnetization and a high perpendicular magnetic anisotropy energy of 17.6 Merg/cm^3 from hysteresis loops with magnetic fields parallel and perpendicular to the film plane.

Figure 2 shows x-ray absorption spectra and XMCD spectra of Mn 2*p* for the $Mn_{72}Ge_{28}$ film. Clear MCD spectrum was obtained as shown in the figure. From the XMCD measurements, the ratio of the spin moment to the orbital moment of the film was evaluated. To clearly investigate the origin of magnetocrystalline anisotropy for the film, we also performed an angle-resolved XMCD measurement by varying the incident angle (angle from normal) from 0 to 70˚. It was clarified that the orbital moment monotonically decreased with the incident angle. This means the orbital moment governs the magnetocrystalline anisotropy of the $Mn_{72}Ge_{28}$ film.

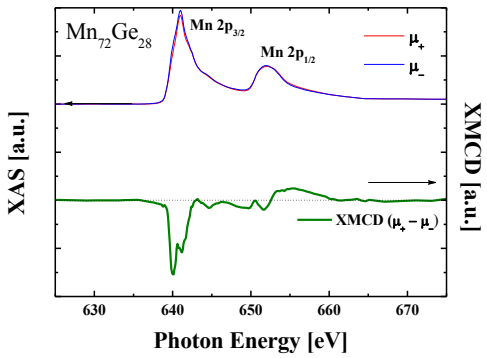

Figure 2. XAS and XMCD spectra of the $Mn_{72}Ge_{28}$ film.

From the HAXPES measurements, clear Mn 2*p* core level spectrum with $2p_{3/2}$ and $2p_{1/2}$ level peaks were obtained. Valence band spectrum was also measured to investigate the electronic structure of the film. The detailed relationship between the magnetic properties and the electronic structures will be discussed.

4. Conclusion

In summary, an epitaxially grown $Mn_{72}Ge_{28}$ film with tetragonal $D0_{22}$ crystal structure was fabricated and electronic structures were investigated by XMCD and HAXPES. It was clarified that the film has a perpendicular magnetization and a high perpendicular magnetic anisotropy energy of 17.6 Merg/cm^3. From XMCD measurements, it was clarified that the orbital moment monotonically decreased with the incident angle, revealing that the orbital moment governs the magnetocrystalline anisotropy of the $Mn_{72}Ge_{28}$ film. From the HAXPES measurements, clear Mn 2*p* core level spectrum with $2p_{3/2}$ and $2p_{1/2}$ level peaks were obtained.

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