Structural, Magnetic, and Magnetotransport Properties of FePt/MgO/CoPt Perpendicularly Magnetized Tunnel Junctions

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Abstract. Perpendicularly magnetized magnetic tunnel junctions (MTJs) were fabricated by depositing thin $L1_0$-ordered FePt films on MgO(001) substrates using a UHV sputtering system, and the dependence of structural, magnetic, magnetotransport properties of the junctions on the thickness of the FePt layers was investigated. A full epitaxial structure was observed when the thickness of the $L1_0$-ordered FePt film was 4 nm. The tunnel magnetoresistance (TMR) ratio was measured to be 6% at room temperature, and magnetization switching was clearly observed in the thin FePt layer.

1. Introduction
Current induced magnetization reversal has been attracting much attention since it was demonstrated by Berger, and Slonczewski. [1, 2] This phenomenon can be employed in the writing process of magnetoresistive random access memory (MRAM), [3, 4] which has the advantage of both better scalability and higher storage density than the conventional MRAM. [5] From the viewpoint of the reliability of MRAM, it is necessary to achieve both a small critical reversal current density ($< 0.5 \text{ MA/cm}^2$) and a high thermal stability ($K_u V/k_B T > 60$, where $K_u$ is the magnetic anisotropy energy, $V$ is the volume of the free layer of the ferromagnetic material, $k_B$ is the Boltzmann constant, and $T$ is the temperature). [6] Perpendicularly magnetized magnetic tunnel junctions (MTJs) fabricated using $L1_0$-ordered alloys [7, 8, 9] can satisfy these requirements, because they have higher magnetocrystalline energy, [10] lower effective magnetic field ($H_{eff}$), and greater magnetization uniformity in small device dimensions with a low aspect ratio as compared to those of junctions with in-plane anisotropy. In our previous study, we reported tunnel magnetoresistance effect in MTJs with perpendicularly magnetized $L1_0$-ordered CoPt alloy electrodes. [11] In this paper, since the magnetocrystalline energy of $L1_0$-ordered FePt is higher among $L1_0$-ordered alloys, [12] we fabricated full-epitaxial perpendicularly magnetized MTJs with a thin $L1_0$-ordered FePt layer and measured their magnetic as well as magnetotransport properties.

2. Experimental detail
All films were deposited using an ultrahigh vacuum ($P_{base} < 2 \times 10^{-7} \text{ Pa}$) magnetron sputtering system, without breaking vacuum. Before the deposition of the thin FePt films, the Ar gas
pressure was changed from 0.1 to 1.4 Pa during the deposition of the FePt film of the thickness of 20 nm, and the gas pressure was optimized at 0.6 Pa by evaluating the surface roughness as well as the degree of $L_1_0$-ordering of the films. For studying the dependence of structural and magnetic properties on the thickness of the FePt layers, Cr (40 nm)/Pt (10 nm)/FePt ($t = 1 \sim 4$ nm) films were deposited on a MgO(001) substrate (inset Fig. 1). The stacking structure of the perpendicularly magnetized MTJ was MgO(001)/Cr (40 nm)/Pt (10 nm)/FePt (4 nm)/MgO (2.5 nm)/CoPt (30 nm)/Ta (5 nm). During the deposition of the FePt and CoPt films, the substrate was heated at the temperature of 775 K and 675 K, respectively. Structural and magnetic properties were measured by an X-ray diffraction system (AXS: Bruker), a SQUID magnetometer (MPMS: Quantum Design), and a vibrating-sample magnetometer (VSM-5: Toei Industry). MTJs with various junction sizes were fabricated by photolithography. Magnetotransport properties were measured by a probe system with a perpendicularly applied magnetic field (TKS3V-PH10: Toei Scientific Industrial co.).

3. Results and Discussion

Figure 1 shows XRD patterns of various FePt layers with different thicknesses. Two peaks with a high intensity were detected, which were derived from the buffer layers of Cr and Pt; the intensity of the peak was independent of the thickness of the FePt layer. The XRD pattern of the 4-nm-thick FePt film showed a peak at around $2\theta = 24^\circ$ with weak although clear intensity; it was derived from the $L_1_0$-ordered FePt(001) layer. This peak indicated that the FePt layer was epitaxially grown on the Cr/Pt buffer layer with a c-axis orientation. The peaks tended to disappear with a decrease in the thickness of the FePt layer, because the intensity of the peaks became weak as compared to those derived from the Cr and Pt layers. Figure 2 shows magnetization ($M$-$H$) curves of FePt layers with different thicknesses. In Fig. 2, the curves $\perp$ and // are perpendicular and parallel magnetization to the substrate plane, respectively. Perpendicular magnetoanisotropy was observed for films with a thickness above 3 nm. From the XRD and magnetization measurement results, we set the thickness of the FePt layer to 4 nm for the fabrication of FePt/MgO/CoPt MTJs.

Figure 3 shows the XRD pattern of FePt/MgO/CoPt multilayer films deposited on a MgO(001) substrate with Cr/Pt buffer layers (inset). A peak derived from the top $L_1_0$-ordered CoPt layer was observed, which indicated that the MgO(001)/Cr/Pt/FePt/MgO/CoPt multilayer was a fully epitaxial structure with a c-axis orientation. However, it was difficult
to separate the peaks derived from the FePt and CoPt layers because the peak positions were close to each other. Figure 4 shows the $M$-$H$ curve of the multilayer. The shape of the curve indicated that both the layers were perpendicularly oriented and the coercive forces of the FePt and CoPt layers were different.

The magnetotransport property of the FePt/MgO/CoPt MTJ was measured in a magnetic field perpendicular to the substrate plane, as shown in Fig. 5. The junction size of the MTJ was $10 \times 10 \mu$m$^2$. Parallel and antiparallel states could be clearly distinguished, and the antiparallel states were observed around $H = -2$ and 2 kOe. This result consistently corresponded to the difference in the coercive forces between the FePt and CoPt layers that was observed in the perpendicular $M$-$H$ curve shown in Fig. 4. Despite the thin FePt film that the thickness was 4 nm, the tunnel magnetoresistance (TMR) ratio was approximately 6% at room temperature. This result is expected to generate further interest in the research field of current-induced magnetization reversal observed in perpendicularly magnetized MTJs fabricated using $L1_0$-ordered materials.
4. Summary
We have fabricated perpendicularly magnetized MTJs consisting of $L_1_0$-ordered FePt/MgO/CoPt films and have measured magnetic and magnetotransport properties. A FePt/MgO/CoPt multi-layer with a 4-nm-thick FePt layer showed a full epitaxial structure and exhibited clear perpendicular magnetooanisotropy with different coercive fields of FePt and CoPt. The TMR ratio was 6% at room temperature under the perpendicular magnetic field, and the MTJs showed sharp magnetization switching corresponding to the difference in the coercive forces between the FePt and CoPt layers.

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[1] Berger L 1996 Phys. Rev. B 54 9353
[2] Slonczewski J C 1996 J. Magn. Magn. Mater. 159 L1
[3] Katine J A, Albert F J, Buhrman R A, Myers E B and Ralph D C 2000 Phys. Rev. Lett. 84 3149
[4] Huai Y, Albert F, Nguyen P, Pakala M and Valet T 2004 Appl. Phys. Lett. 84 3118
[5] Åkerman J 2005 Science 308 508
[6] Katine J A and Fullerton E E 2008 J. Magn. Magn. Mater. 320 1217
[7] de Person P, Warin P, Jamet M, Beigne C and Samson Y 2007 Phys. Rev. B 76 184402
[8] Hagiuda M, Mitani S, Seki T, Yakushi K, Shima T and Takanashi K 2007 J. Magn. Magn. Mater. 310 1905
[9] Yoshikawa M, Kitagawa E, Nagase T, Daibou T, Nagamine M, Nishiyama K, Kishi T and Yoda H 2008 IEEE Trans. Magn. 44 2573
[10] Seki T, Shima T, Takanashi K, Takahashi Y, Matsubara E and Hono K 2003 Appl. Phys. Lett. 82 2461
[11] Kim G, Sakuraba Y, Oogane M, Ando Y and Miyazaki T 2008 Appl. Phys. Lett. 92 172502
[12] Sakuma A 1994 J. Phys. Soc. Jpn. 63 3053