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Perpendicularly Magnetized $L1_0$-FePt / MgO Epitaxially grown on GaAs for Electrical Spin Injection

Makoto Kohda[1, 2], Akihiko Ohtsu[1], Takeshi Seki[3], Asaya Fujita[1], Junsaku Nitta[1, 2], and Koki Takanashi[3]

[1]Department of Materials Science, Tohoku University, 6-6-02 Aramaki-Aza Aoba, Aoba-ku, Sendai 980-8579, Japan
[2]CREST, Japan Science and Technology Agency, 4-1-8 Honcho, Kawaguchi, Saitama 331-0012, Japan
[3]Institute for Materials Research, Tohoku University, 2-2-1, Katahira, Aoba-ku, Sendai 980-8577, Japan
Phone: +81-22-795-7317 E-mail: makoto@material.tohoku.ac.jp

1. Introduction

A ferromagnetic metal / semiconductor hybrid structure provides new functional devices based on spins operated at room temperature [1,2]. For utilizing spin degree of freedom in semiconductor, efficient electrical spin injection from ferromagnetic metal into semiconductor is indispensable. Zhu *et al.* demonstrated room temperature electrical spin injection from Fe into GaAs based light emitting diode (LED) structure for the first time, where the electroluminescence (EL) polarization was around 2 % [3]. Recently, Jiang *et al.* integrated FeCo / MgO tunnel injector on GaAs / AlGaAs LED and obtained 47 % EL polarization at 290 K in a 5 T [4]. However, most of the epitaxial magnetic thin films show in-plane magnetic anisotropy so that the large perpendicular external magnetic field is needed for injecting spin polarized electrons perpendicularly to the film plane. Since polarization control of the optoelectronic devices gives additional functionalities such as ultra-fast optical switching [5] and threshold current reduction in a vertical cavity surface emitting laser [6], electrical spin injection perpendicular to the quantum well without external magnetic field becomes a great challenge. A $L1_0$ ordered FePt thin film with perpendicular anisotropy has attracted much attention not only for the perpendicular magnetic recording media but also perpendicular spin injector without external magnetic field [7,8] and has been intensively studied in recent years [9,10]. In this point of view, we have investigated the epitaxial growth condition and the annealing effect on the perpendicular anisotropy of a $L1_0$-FePt on MgO / (001) *n*-GaAs substrate for electrical spin injection.

2. Epitaxial growth condition and structural characterization

FePt / MgO structures were prepared on a (001) *n*-GaAs substrate using a dc magnetron sputtering apparatus. Prior to the sputtering, a thin oxide layer on the *n*-GaAs surface is removed by chemical etching with hydrochloric acid and deionized water, and the etched sample is immediately transferred to the sputter chamber to prevent the surface oxidization. After annealing the sample at the substrate temperature, T_s = 350 ºC, reflection high-electron energy diffraction (RHEED) shows 1 × 2 streak pattern, which indicates that relatively flat surface is retained. A 5 nm MgO is deposited on the *n*-GaAs substrate at T_s = 300 ºC with Ar pressure of 10 mTorr. Fe and Pt were codeposited on the MgO layer in 5 mTorr Ar pressure with $Fe_{0.43}Pt_{0.57}$ composition at T_s = 300 ºC. We prepared two samples of different FePt thickness with 5 nm and 10 nm. As shown in Figs. 1 (a) and (b), streak RHEED patterns are obtained both for the MgO and the FePt layers, which shows that relatively flat surface and the epitaxial growth of the MgO and FePt layers are achieved on *n*-GaAs substrate. After the sputtering, the sample is annealed at T_s = 350 ºC for 60 min. It should be noted that the RHEED patterns remain streak in the end of the annealing. X-ray diffraction (XRD) was performed for structural characterization. Magnetic properties were measured by a polar magneto-optical Kerr effect (PMOKE) and a superconducting quantum interference device magnetometer (SQUID) at room temperature. Figure 2 shows XRD patterns of annealed FePt samples with 5 nm and 10 nm thicknesses. For the MgO layer, 002 diffraction peak indicates that MgO (001) is epitaxially grown parallel to GaAs (001). For the FePt layer, since 00*n* (*n* = 1 and 2) diffraction peaks are only observed, the FePt is strongly textured to (001) plane which indicates that the film was grown epitaxially on (001) MgO layer. In addition to the fundamental 002 peak, 001 superlattice peak associated

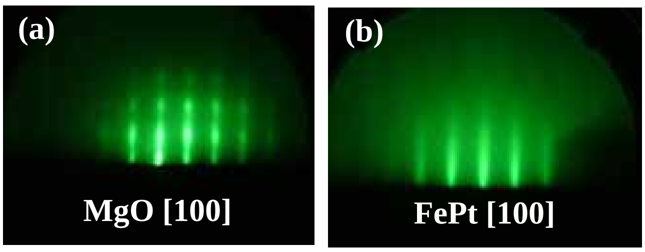

Figure 1. Reflection high-electron energy diffraction (RHEED) patterns of (a) MgO [100] sputtered on *n*-GaAs substrate and (b) as-deposited FePt [100] on MgO layer. Both layers are sputtered at T_s = 300 ºC.

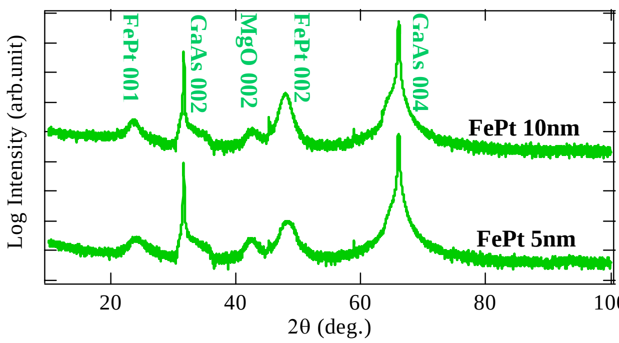

Figure 2. X-ray diffraction of 5 nm (bottom) and 10 nm (top) annealed FePt grown on MgO layer / *n*-GaAs substrate.

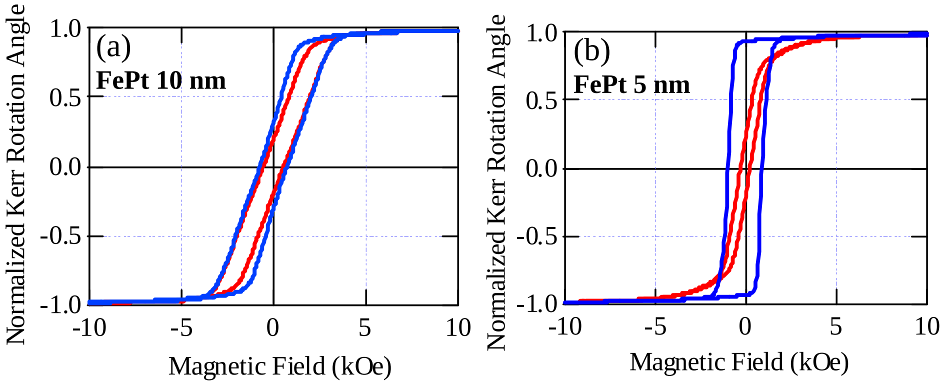

Figure 3. Magnetic field dependence of the normalized polar Kerr signal for (a) 10 nm FePt and (b) 5 nm FePt on MgO layer with *n*-GaAs substrate at room temperature. Black (blue) and gray (red) curves are annealed (T_s = 350 ºC for 60 min) and as-deposited samples, respectively.

with the formation of $L1_0$ ordered structure has been clearly observed. From all the diffraction peaks, the epitaxial relationship of the sputtered thin films is FePt (001) // MgO (001) // GaAs (001). From the integrated peak-area ratio of the fundamental 002 and the superlattice 001 peaks, the degree of long-range order, S, is deduced. 5 nm and 10 nm FePt layers show S = 0.75 and 0.52, respectively.

3. Magnetic properties and annealing effect

Figures 3 (a) and (b) show magnetic field dependence of normalized PMOKE signal in 5 nm and 10 nm FePt layers. As-deposited and annealed samples are indicated as gray (red) and black (blue) curves, respectively. The measured PMOKE exhibits hysteresis loops for both 5 nm and 10 nm FePt layers, which resulted from perpendicular magnetic anisotropy. In the case of 10 nm FePt, the remanent magnetization ratio, M_r / M_s, increases only from 0.19 to 0.3 by post annealing. However, in the case of 5 nm FePt, the magnetization curve shows good squareness after annealing. M_r / M_s becomes 0.93 for the annealed layer while that for the as-deposited one remains 0.22, which significantly increases remanent magnetization as well as coercive field in the annealed FePt film. It suggests that the post annealing strongly enhances the perpendicular anisotropy of $L1_0$-FePt on MgO / *n*-GaAs substrate. Since 2θ of the fundamental 002 and the superlattice 001 peaks for 5 nm FePt are shifted slightly higher angle than those for 10 nm in the XRD measurement, the *c*-axis becomes shorter in 5 nm FePt, which indicates that in-plane tensile strain is enhanced for 5 nm FePt due to the lattice mismatch between MgO and $Fe_{0.43}Pt_{0.57}$ leading to the higher perpendicular magnetic anisotropy [9]. To compare magnetic anisotropy constant K_u between FePt grown on the MgO layer with the *n*-GaAs substrate and FePt on a MgO substrate, we prepared 5 nm FePt film sputtered on (001) MgO substrate with the identical growth condition for FePt sputtered on MgO / *n*-GaAs substrate and measured in-plane and out-of-plane magnetic field dependences of the magnetization. Obtained K_u for FePt layer becomes $1.0 \pm 0.1 \times 10^7$ erg/cc on MgO layer with *n*-GaAs substrate and $1.4 \pm 0.03 \times 10^7$ erg/cc on MgO substrate, which exhibits the same order of magnetic anisotropy both on *n*-GaAs and MgO substrates. It is also noted that the degree of long-range order for 5 nm FePt on MgO substrate becomes 0.78, which is slightly higher compared to the FePt film on MgO / *n*-GaAs substrate. Consequently, highly ordered $L1_0$-FePt thin film is obtained by post annealing on MgO / *n*-GaAs substrate. It is expected the efficient perpendicular spin injection through MgO tunnel barrier into GaAs without perpendicular magnetic field.

4. Conclusion

We have investigated the epitaxial growth condition and the annealing effect on perpendicular anisotropy of a $L1_0$-FePt on MgO layer / (001) *n*-GaAs substrate. Remanent magnetization ratio of 5 nm FePt is enhanced up to 0.93 by 350 ºC post annealing for 60 min. The perpendicular magnetic anisotropy constant K_u and the degree of long-range order are $1.0 \pm 0.1 \times 10^7$ erg/cc and S = 0.75, respectively, which are comparable to those for the FePt sputtered on (001) MgO substrate.

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