EPJ Web of Conferences **75**, 02002 (2014)
DOI: 10.1051/epjconf/201475 02002

Gilbert damping constant of FePd alloy thin films estimated by broadband ferromagnetic resonance

T. Kawai[1], A. Itabashi[1], M. Ohtake[1], S. Takeda[2], and M. Futamoto[1]

[1]Faculty of Science and Engineering, Chuo University, 1-13-27 Kasuga, Bunkyo-ku, Tokyo 112-8551, Japan
[2]Magnontech Ltd., 787-16 Jurokken, Kumagaya, Saitama 360-0846, Japan

Abstract. Magnetic relaxation of FePd alloy epitaxial thin films with very flat surfaces prepared on MgO(001) substrate are measured by in-plane broadband ferromagnetic resonance (FMR). Magnetic relaxation is investigated as $\Delta\omega$ for FMR absorption peak by frequency sweep measurements. ΔH is calculated by using the measured $\Delta\omega$. Gilbert damping constant, α, is estimated by employing a straight line fitting of the resonant frequency dependence of ΔH. The α value for an FePd film deposited at 200 ˚C, which shows disordered $A1$ structure, is 0.010 and ΔH_0, which is frequency independent part of ΔH, is 10 Oe. The α value for a film annealed at 400 ˚C, which shows partially $L1_0$ ordered structure (S=0.32), is 0.013, which is slightly larger than that for the disorder $A1$ structure film. However, ΔH_0 for the annealed film is 85 Oe, which is much larger than that for the film with disordered structure. The results show that the magnetic relaxation of the 400 ˚C annealed film is mainly dominated by ΔH_0, which is related with magnetic in-homogeneity caused by the appearance of perpendicular anisotropy of partially ordered phase.

1 Introduction

Spin-transfer switching is an attractive technique to deduce the electronic current for switching the magnetization direction of a magnetic element in devices like perpendicularly magnetized magnetoresistance random access memory (PMRAM) [1, 2]. For PMRAM devices, perpendicularly magnetized magnetic thin films with small Gilbert damping constant, α, are required [1]. An $L1_0$ ordered FePd alloy epitaxial thin film is one of candidate materials. Ferromagnetic resonance (FMR) is a powerful method in studying Gilbert damping constant, α, of magnetic thin film . There are a few FMR studies of epitaxial FePd thin films with perpendicular magnetic anisotropy [3, 4]. It is reported that the line width of the uniform mode is found to be independent of frequency and hence departs from the linear frequency variation predicted by the Landau-Lifshitz-Gilbert (LLG) relaxation type [3]. However, it is well known that the magnetic relaxation in magnetic metal obeys mostly on the LLG type [5]. Therefore, it is interesting to investigate how the magnetic relaxation varies depending on the crystallographic ordering from disordered $A1$ to the ordered $L1_0$ state in FePd thin film.

In this study, Gilbert damping constant is estimated for $Fe_{50}Pd_{50}$ (at. %) alloy epitaxial thin films with very flat surfaces, which are obtained on MgO(001) single-crystal substrates by employing a two-step process; low-temperature deposition at 200 ºC followed by high-temperature annealing at 400 ºC [6]. Very flat surface is required in FMR measurements to evaluate intrinsic magnetic relaxation in order to avoid extrinsic effect by surface roughness [7]. Broadband FMR measurements using a VNA are carried out for 40nm thick films under static magnetic fields up to 1 kOe in the film plane to measure magnetic relaxation. A difference in the magnetic relaxation between FePd films with a disordered $A1$ structure and with a partially ordered $L1_0$ structure is discussed.

2 Experimental procedures

FePd alloy thin films were prepared on polished MgO(001) single-crystal substrates by using a radio-frequency (RF) magnetron sputtering system equipped with a reflection high-energy electron diffraction (RHEED) facility. The base pressures were lower than 4 × 10^{-7} Pa. The detail of sample preparation is reported in our previous paper [6]. FePd films of 40 nm thickness were deposited on MgO(001) substrates at 200 ºC. Then, the films were annealed at 300 and 400 ºC for 1 h. The structural properties were investigated by RHEED and Xray diffraction (XRD) with Cu-Kα radiation (λ= 0.15418 nm). Epitaxial growth of FePd film with $A1$(001) disordered structure was confirmed by RHEED for films deposited at 200 ºC. The epitaxial orientation

[a] Corresponding author: kawai@futamoto.elect.chuo-u.ac.jp

relationships were determined to be FePd(001)[100]$_{A1}$ || MgO(001)[100] and $L1_0$[100] || MgO[100] by RHEED and XRD. The surface morphology was observed by AFM. The magnetization curves were measured by using a vibrating sample magnetometer. A VNA was used to measure dynamic magnetic property covering up to 10 GHz, where RF magnetic field was applied orthogonally to the static magnetic field using a shorted micro-strip line [7, 8]. The resonant frequency was determined as a frequency when an experimental complex permeability, μ , showed a maximum value. Gilbert damping constant, α, was estimated by using measured half line width between 1/2-power points for frequency sweep, $\Delta\omega$, as explained in the next section.

3 Estimation method of Gilbert damping constant, α, and perpendicular magnetic anisotropy

The magnetic relaxation of magnetic thin films are usually discussed by using ΔH, which is full line width between 1/2-power points for magnetic field sweep FMR measurements, and is expressed in the following formula [9].

$$\Delta H=\Delta H_0+\frac{4\pi\alpha f_r}{\gamma} , \tag{1}$$

where ΔH_0, which is magnetic relaxation caused by in-homogeneity, is frequency independent part of ΔH , α is Gilbert damping constant, f_r is resonant frequency, and γ is gyromagnetic constant.

However, our FMR measurements are carried out not by magnetic field sweep but by frequency sweep. Then the measured value is not ΔH but $\Delta\omega$. Therefore, we need to calculate ΔH by using the measured $\Delta\omega$ employing the following conversion formula [9].

$$\Delta H = \frac{2\Delta\omega}{\gamma}\cdot\frac{1}{\sqrt{1+\frac{1}{4}\cdot\left(\frac{\omega_m}{\omega_r}\right)^2}} , \tag{2}$$

where $\omega_r=2\pi f_r$, $\omega_m=\gamma M_s/\mu_0$, M_s is saturation magnetization, and μ_0 is permeability of vacuum. α is calculated from the straight line fitting of the formula (1) with the measured f_r dependence of ΔH. ΔH_0 is defined as the intercept from the straight fitting. On the other hand, damping constant, α, is also evaluated by fitting the calculated μ to each absorption peak of experimental μ with best fitting parameters [7]. The line width of each absorption peak includes magnetic relaxation resulting from various factors. Therefore, the damping constant evaluated by this method is denoted as α_{app}.

Perpendicular magnetic anisotropy field is determined using the following the Kittel resonant formula.

$$\left(\frac{2\pi f_r}{\gamma}\right)^2 = \left(H_{ex}-H_{in}\right)\cdot\left(H_{ex}+\frac{M_S}{\mu_0}-H_{out}\right), \tag{3}$$

where H_{ex} is applied static magnetic field, H_{in} is in-plane magnetic anisotropy field, and H_{out} is perpendicular magnetic anisotropy field. H_{out} is determined by fitting the formula (3) with the measured H_{ex} dependence of f_r.

4 Results and discussion

Very flat surfaces are realized for the FePd films prepared by employing the two-step process. The properties of the films employed in the present study are listed in Table 1 [6]. Thin film samples with very flat surface with R_a less than 0.3 nm are obtained. $L1_0$ order parameter, S, changes from 0 for an as-deposited film to 0.32 for a film annealed at 400 ºC. The magnetic easy axis is in-plane for all the films.

Table 1. Surface roughness, R_a, $L1_0$ order parameter, S, and magnetic anisotropy for FePd thin films prepared on MgO(001) substrate.

Sample	As-deposited	300ºC annealed	400ºC annealed
R_a (nm)	0.22	0.15	0.18
Structure	$A1$ (disorder)	$A1+L1_0$ (partial order)	$A1+L1_0$ (partial order)
S	0	0.21	0.32
Magnetic anisotropy	In-plane	In-plane	In-plane

In-plane magnetization curves are shown in Fig. 1. The easy magnetization axis is along <100> for all three films. The anisotropy fields of as-deposited and 300 ºC annealed films are almost similar at 30 Oe, whereas that of 400 ºC annealed film is 70 Oe which is larger than the other two films. In-plane magnetic anisotropy seems to have varied with increasing partial ordering of $L1_0$ structure. The coercivity is also changed from 10 Oe for the as-deposited film to 24 Oe for the 400 ºC annealed film which suggests that domain wall motions are suppressed in the 400 ºC annealed film. As shown in Table 1, small partial order (S=0.21) is developed even in the 300 ºC annealed film, but such small partial order shows no effect on static in-plane magnetic property.

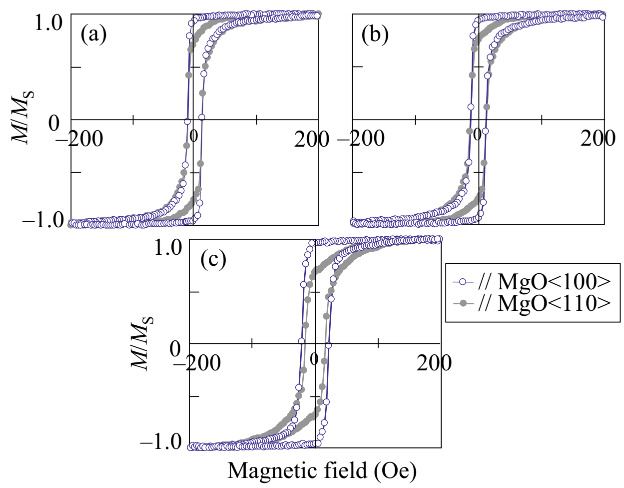

Fig. 1 In-plane magnetization curves measured for (a) FePd film deposited on MgO(001) at 200 ºC, and FePd films annealed at (b) 300 ºC and (c) 400 ºC after deposition.

The examples of measured complex permeability for three FePd films are shown in Fig. 2, where applied static magnetic filed is 174 Oe along <100>. Clear Lorenz type absorption peaks are observed for all samples. The permeability values for the 400 ºC annealed film are small compared with those of the other two films. This is possibly due to the enhanced in-plane anisotropy field (70 Oe) of the 400 ºC annealed film compared with the other films (30 Oe).

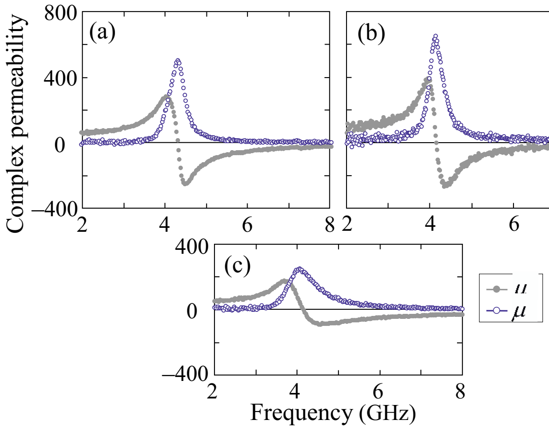

Fig.2 Examples of complex permeability measured for (a) FePd film deposited on MgO(001) at 200 ºC, and FePd films annealed at (b) 300 ºC and (c) 400 ºC after deposition.

Complex permeability measurements are carried out by changing the external static magnetic field from 0 to 1 kOe. Examples of absorption peaks are shown in Fig. 3. Resonant frequency is defined at the frequency where μ shows a maximum value. Solid lines show the calculated μ using best fitting parameters of M_s, K_1, and α [7], where g-factor is fixed at 2.07 [2]. There are very good agreements between the experiments and the calculations for the as-deposited film and the film annealed at 300 ºC for the applied static magnetic field range, whereas for the film annealed at 400 ºC, good agreements are recognized only for more than 300 Oe. As shown in Fig. 1, magnetic saturation is already reached at 200 Oe in the static magnetic field characteristic, but the FMR measurement indicates that more than 300 Oe magnetic field is required to excite the spin wave in the uniform mode in radio frequency region.

Figure 4 shows the static magnetic field dependence of resonant frequency, f_r, for three FePd thin films. Solid lines are the fitting curves by formula (3) using best fitting parameters of M_s, H_{in}, and H_{out}. There is no difference of magnetic field dependence of f_r between for the as-deposited film and for the 300 ºC annealed film, which suggests that any observable perpendicular anisotropy is not developed in the 300 ºC annealed film though a small partial $L1_0$ structural ordering is observed. The perpendicular anisotropy field is estimated to be 1.5 kOe by the fitting for the 400 °C annealed film.

The α_{app} values obtained by the fitting for each absorption peak are shown in Fig. 5 as a function of resonant frequency reciprocal, $1/f_r$. The α_{app} values tend to become small as the frequency reciprocal, $1/f_r$, becomes small. The α_{app} values are almost similar for the as-deposited and for the 300 ºC annealed films, whereas α_{app} is large for the 400 ºC annealed film compared with other films. Gilbert damping constant, α, defined in the LLG equation should be frequency independent. Therefore, we tried to separate the measured magnetic

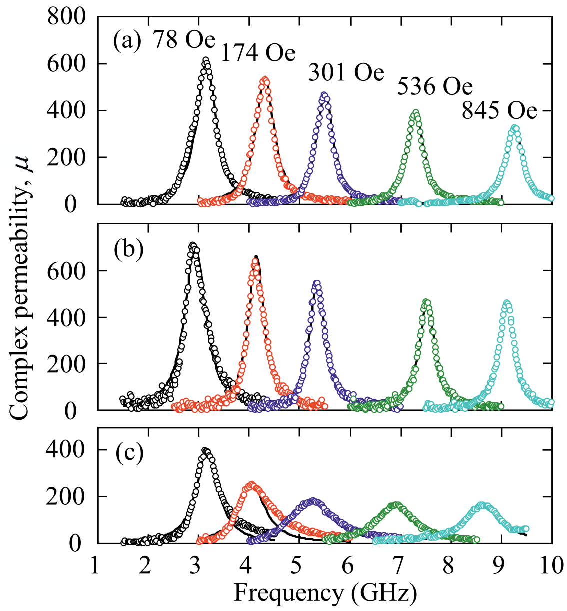

Fig. 3 Complex permeability measured under various static magnetic fields for (a) the FePd film deposited on MgO(001) at 200 ºC, and FePd films annealed at (b) 300 ºC and (c) 400 ºC after deposition. Solid lines are fitting curves.

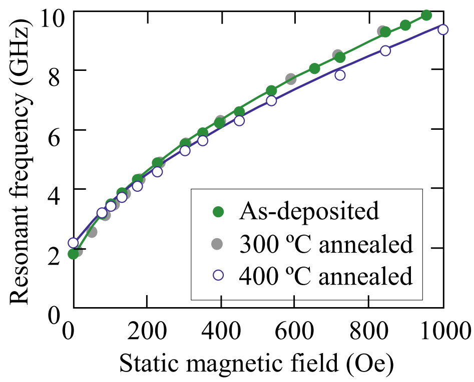

Fig. 4 Static magnetic field dependence of resonant frequency for (a) the FePd film deposited on MgO(001) at 200 ºC, and FePd films annealed at (b) 300 ºC and (c) 400 ºC after deposition. Circles are experiments and solid lines are calculations.

relaxation into the frequency independent part and the frequency dependent part as denoted in formula (1) using the measured $\Delta\omega$. $\Delta\omega$ is defined by a parabolic fitting using the reciprocal of μ near the resonance peak. ΔH is calculated by formula (2) using the measured $\Delta\omega$. Frequency dependences of ΔH are shown in Fig.6. Gilbert damping constant, α, is calculated by using the slope of the straight line and ΔH_0, which means ΔH caused by inhomogeneous effect, is defined as an intercept at y-axis. These Gilbert damping constants, α, and ΔH_0 values are shown in the insets of the figure. ΔH values for the as-deposited and for the 300 ºC annealed films are almost similar. However, ΔH values for the 400 ºC annealed film are much larger than those of other films.

The α value for the as-deposited film is 0.010 and ΔH_0 is 10 Oe. The α value for the 400 ˚C annealed film is 0.013, which is slightly larger than that for the as-deposited film. However, ΔH_0 for the annealed film is

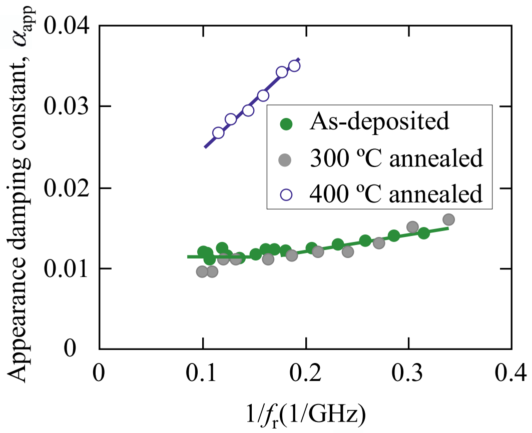

Fig. 5 Appearance damping constant, α_{app}, as a function of $1/f_r$ for (a) the FePd film deposited on MgO(001) at 200 ºC, and FePd films annealed at (b) 300 ºC and (c) 400 ºC after deposition.

85 Oe, which is much larger than that for the as-deposited film. The results suggest that the magnetic relaxation of partially $L1_0$ ordered FePd film with perpendicular anisotropy is mainly dominated by ΔH_0 which is caused by magnetic in-homogeneity in the film. As shown in figures 1, 4 and 5, there is little difference in the magnetic relaxation between the as-deposited film (S=0) and the 300 ˚C annealed film with partial $L1_0$ ordering (S=0.21). The result indicates that the small structural in-homogeneity without perpendicular anisotropy shows almost no effect on magnetic relaxation but the magnetic in-homogeneity caused by the appearance of perpendicular anisotropy shows significant effect. Such magnetic in-homogeneity may cause frequency independent relaxation like two magnon process [10].

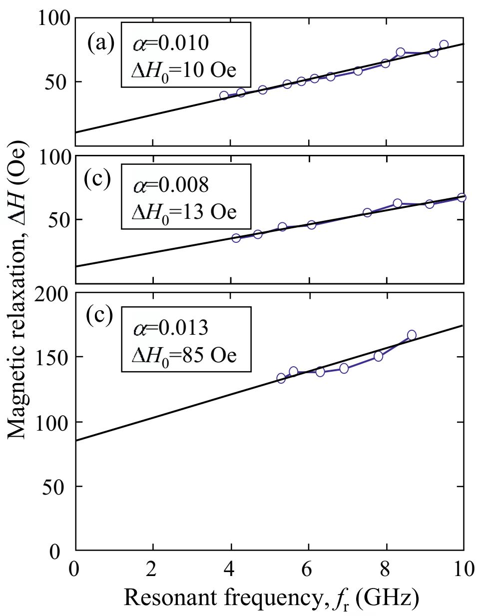

Fig. 6 Resonant frequency dependence of ΔH for (a) FePd film deposited on MgO(001) at 200 ºC, and FePd films annealed at (b) 300 ºC and (c) 400 ºC after deposition. Solid lines are straight line fittings.

4 Conclusions

Magnetic relaxation of FePd epitaxial thin films with very flat surfaces is measured by broadband FMR. Measured magnetic relaxation is evaluated by separating into a frequency independent part, ΔH_0, and a frequency dependent part. Gilbert damping constant, α, is calculated by using the slope of frequency dependent part. The α value for the FePd film deposited at 200 ˚C, which shows disorder $A1$ structure, is 0.010 and ΔH_0, is 10 Oe. Meanwhile, the α value for the 400 ˚C annealed film, which shows partially $L1_0$ ordered structure (S=0.32), is 0.013, which is slightly larger than that of the disorder $A1$ structure film. However, ΔH_0 for the 400 ˚C annealed film is 85 Oe, which is much larger than that for the disorder $A1$ structure film. The results show that the magnetic relaxation of partially $L1_0$ ordered FePd film is mainly dominated by ΔH_0, which is related with magnetic in-homogeneity developed by perpendicular anisotropy in the film during ordering process.

Acknowledgements

We wish to thank Hitachi Metals Ltd. for supporting this work. We also thank Dr. H. Suzuki of KEYCOM Corp. for his kind advice in the broadband FMR measurements.

References

1. J. C. Slonczewski, *J. Magn. Magn. Matter.* **159**, L1 (1996).
2. L. Berger, *Phys. Rev.* B **54**, 9353 (1996).
3. J. BenYoussef, H. Le Gall, N. Vukadinovic, V. Gehanno, A. Marty, Y. Samson, and B. Gilles, *J. Magn. Magn. Matter.* **202**, 277 (1999).
4. N. Vukadinovic, H. Le Gall, J. Ben Youssef, V. Gehanno, A. Marty, Y. Samson, and B. Gilles, *Eur. Phys. J.* B **13**, 445 (2000).
5. B. Heinrich, J.F. Cochran, and R. Hasegawa, *J. Appl. Phys.* 57, 3690 (1985).
6. A. Itabashi, M. Ohtake, S. Ouchi, F. Kirino, and M. Futamoto, *IEEE, Trans. Magn.*, **48**, 3203 (2012).
7. T. Kawai, Y. Asai, M. Ohtake, S. Takeda, and M. Futamoto, *EPJ Web of Conferences* **40**, 13001 (2013).
8. S. Takeda and H. Suzuki, *J. Magn. Soc. Jpn.*, **33**, 171 (2009).
9. S. S. Kalarickal, P. Krivosik, M. Wu, and C. E. Patton, *J. Appl. Phys.* **99**, 093909 (2006).
10. M. Sparks, *Ferromagnetic relaxation*, McGraw Hill p.163, (1964).