Pressure-induced enhancement of the blocking temperature in FePt nanoparticles

Y Komorida1, M Mito1, H Deguchi1, S Takagi1, T Iwamoto2 and Y Kitamoto3

1Faculty of Engineering, Kyushu Institute of Technology, Kitakyushu 804-8550, Japan
2Department of Applied Chemistry, Faculty of Engineering, Tokyo University of Science, Yamaguchi, SanyoOnoda, Yamaguchi 756-0884, Japan
3Interdisciplinary Graduate School of Science and Engineering, Tokyo Institute of Technology, Yokohama 226-8502, Japan

E-mail: g586402y@tobata.isc.kyutech.ac.jp

Abstract. The magnetic properties of FePt magnetic nanoparticles with the particle size of 2.0 ± 0.6 nm were investigated through AC magnetic susceptibility measurements under hydrostatic pressure. At a frequency of 1 Hz, a blocking temperature increases linearly from 42.9 to 44.6 K by increasing pressure (P) up to 1.43 GPa. The X-ray diffraction experiments under hydrostatic pressure reveal that both the particle size and lattice parameter hardly change in the considered pressure region. These experimental results suggest that the effective magnetocrystalline anisotropy increases under hydrostatic pressure.

1. Introduction
Magnetic particle with size (D) below a certain value prefers a single-domain magnetic structure to multi-domain structure, and exhibits superparamagnetism. If the magnetic nanoparticle shows large coercive field (Hc), it is expected to realize the new application for magnetic recording media. For creating large Hc, the studies on magnetic anisotropy of the magnetic nanoparticle have been actively carried out on a variety of materials [1].

Of some candidate materials for magnetic recording media, FePt has been attracted much attention of material scientists for the last decade. It has been known that FePt with the structural form of either face-centered-cubic (fcc) or face-centered-tetragonal (fct) stabilizes in crystal structure. The fcc structure (A1 disordered phase) exhibits magnetically disorder phase. On the other hand, the fct structure (A1 disordered phase) exhibits magnetically disorder phase. The other hand, the fct structure (L10 ordered phase) with magnetic order displays a large magnetocrystalline anisotropy (6.6-10 × 106 J/m3) and a high coercivity (Hc = (7850/4π) × 103 A/m) [1]. Takahashi et al. reported experimentally and theoretically that the order parameter of the fct structure decreased below D of 2-4 nm [2]. The size dependence of stability for the fct structure of FePt nanoparticles is an important subject.

We have changed the magnetic properties of some magnetic nanoparticles such as maghemite (γ-Fe2O3) and ferrihydrite (FeOOH•nH2O) by utilizing of hydrostatic pressurization so far [3,4,5]. It has been experimentally confirmed that magnetic anisotropy can be tuned by pressure. Given these
backgrounds, we expect that pressurization in a FePt nanoparticle with $D$ near the critical size will trigger the prominent change of magnetic properties.

2. Experimental

The FePt nanoparticles with $D = 2.0 \pm 0.6$ nm were prepared according to the procedure mentioned elsewhere [6]. The value of $D$ was estimated by transmission electron microscopy (TEM) study. TEM image and size distribution are given in Fig. 1. The nanoparticles were coated by organic polymer PVP (poly(N-vinyl-2-pyrrolidone)) as a protective polymer. It is considered that there is no physical contact between FePt nanoparticles. The AC magnetic susceptibility measurements at AC field of $(4/4\pi) \times 10^3$ A/m were carried out using a superconducting quantum interference device (SQUID) magnetometer (Quantum Design, MPMS-5S) under hydrostatic pressure up to $P = 1.43$ GPa. Pressurization and sample preparation were performed in accordance to Ref. [7]. The values of pressure at liquid helium temperature were estimated based on the shift in the superconducting transition temperature of tin [8]. Synchrotron radiation powder XRD measurements under pressure at room temperature were performed at the Photon Factory (PF) of the Institute of Materials Structure Science, the High Energy Accelerator Research Organization (KEK). The wavelength of the incident X-ray was 0.68872(5) Å. The angle resolution was 0.015 degree. Pressure was attained using a diamond anvil cell (DAC). The culet size of the diamond anvil was 0.8 mm in diameter. The thickness of Cu-Be gasket and sample hole were 0.3 mm and 0.4 mm in diameter, respectively. The sample and a few ruby crystals were held with the aid of a pressure-transmitting medium fluorine oil (FC77). The pressure value was calibrated by the ruby fluorescence method [9].

3. Experimental Results

Figure 2 shows the XRD patterns of the FePt nanoparticles with $D = 2.0$ nm at room temperature. The patterns cannot explain the fct structure of the FePt nanoparticles. There is no prominent change of the XRD against pressure up to 2.16 GPa, and the diffraction peaks hardly shifted. The variation in the lattice parameters and the full-width at half-maximum (FWHM) of the diffraction peak are less than 1%.

Figure 3 shows temperature dependence of the out-of-phase component of the AC magnetic susceptibility, $\chi''(T)$ at $f = 1$ Hz. $\chi''$ increases as temperature increases, and reaches to the maximum. The nanoparticles’ magnetic moments freeze below the blocking temperature $T_B$ at which $\chi''$ has the maximum. Figure 4 shows pressure dependence of $T_B$ at $f = 1$ Hz. The value of $T_B$ at ambient pressure was determined to be 42.9 K. It increased to 44.6 K at $P = 1.43$ GPa. $T_B$ increases linearly with increasing pressure as $T_B [K] = 42.9 + 1.2 \times P [GPa]$.

Figure 5 shows the Arrhénius plots of $1/T_B$ against the natural logarithm of the frequency, $\ln (2\pi f)$. The solid lines show the results of least-squares fits when using the Arrhénius equation as follows:

$$\frac{1}{T_B} = -\frac{k_B}{\Delta E} \left\{ \ln(2\pi f) + \ln(\tau_0) \right\}, \quad (1)$$

where $k_B$ is the Boltzmann constant, $\Delta E$ is the effective energy barrier and $\tau_0$ is a pre-exponential factor. $\Delta E/k_B$ is estimated from the inverse of slope of the Arrhénius plots. At ambient pressure, the values of $\Delta E/k_B$ and $\tau_0$ are estimated to be $2.64 \times 10^3$ K and $1.72 \times 10^{-15}$ sec. The obtained value of $\tau_0$ is too small compared to the commonly observed values for superparamagnetic systems ($10^{10}$-$10^{12}$ sec) [10]. Similar small value of $\tau_0$ was often found for metal oxide nanoparticles or coordination polymer nanoparticles, and they are normally interpreted as the signature of a magnetic moment correlation introduced by considerable interparticle interactions. Herein, we do not evaluate the obtained values of $\Delta E/k_B$ and $\tau_0$ as meaningful value.
4. Discussion

In the ferromagnetic nanoparticle FePt, $D$ and lattice parameters hardly change under pressure. The increase of $T_B$ indicates that the effective magnetocrystalline anisotropy increases due to the applied pressure.

In the case of ferrimagnetic maghemite nanoparticles [3,4], the nanoparticles consisted of a core with structural periodicity and a disordered shell without the periodicity, and the core exhibited superparamagnetism. $\Delta E/k_B$ decreased against the initial pressure ($P \leq 0.38$ GPa), recovering at $P \geq 0.38$ GPa. This result indicated that the ratio of the core and shell changed due to the applied pressure [3,4]. $\Delta E/k_B$ was proportional to the volume of the core for $P \geq 0.38$ GPa and magnetic anisotropy energy in both the core and the shell could be estimated on the basis of the pressure response [4].
Figure 5. Arrhénius plots of the inverse blocking temperature ($1/T_B$) as a function of frequency for FePt nanoparticles with $D = 2.0$ nm under hydrostatic pressure. The solid line expresses Eq. (1).

In the case of antiferromagnetic ferrihydrite (FeOOH•$n$H$_2$O) nanoparticles [5], the magnetization curve up to $(50000/4\pi) \times 10^3$ A/m exhibited the coexistence of saturation and linear contributions. The uncompensated magnetic moment decreased with increasing pressure for $P \leq 1.00$ GPa, while the linear contribution increases up to about twice of the initial. These effects of pressure were probably related to changes in the anisotropy energy [5].

In magnetic nanoparticles, the magnetic anisotropy is a physical quantity sensitive to pressure. The particle volume of the FePt nanoparticle hardly changes by pressure, whereas $T_B$ increases with increasing pressure. By contrast with the two previous experiments, the present data of FePt including both the structural and magnetic properties under pressure show better experiment on investigating the magnetic anisotropy.

5. Conclusion
We investigated the magnetic properties of FePt magnetic nanoparticles with $D = 2.0 \pm 0.6$ nm through AC magnetic susceptibility measurements under hydrostatic pressure. The crystal structure under pressure was also investigated by the XRD experiment. $T_B$ increased linearly with increasing pressure as $T_B [K] = 42.9 + 1.2 \times P$ [GPa]. The particle size and lattice parameters hardly changed in the considered pressure region. These experimental results suggested that the effective magnetocrystalline anisotropy increased due to the applied pressure.

References
[1] See, for example, Weller D, Moser A, Folks L, Best M E, Wen Lee, Toney M F, Schwickert M, Thiele J -U and Doerner M F 2000 IEEE Trans. Magn. 36 10
[2] Takahashi Y K, Koyama T, Ohnuma M, Ohkubo T and Hono K 2004 J. Appl. Phys. 95 2690
[3] Komorida Y, Mito M, Deguchi H, Takagi S, Millan A and Palacio F 2007 J. Mag. Mag. Mater. 310 e800
[4] Komorida Y, Mito M, Deguchi H, Takagi S, Millan A, Silva N J O and Palacio F 2009 Appl. Phys. Lett. 94 202503
[5] Komorida Y, Silva N J O, Mito M, Deguchi H, Takagi S, Palacio F and Amaral V S 2009 J. Phys.: Conf. Ser. 150 042098
[6] Iwamoto T, Kitamoto Y and Toshima N 2009 Physica B 404 2080
[7] Mito M 2007 J. Phys. Soc. Jpn. Suppl. A 76 182
[8] Jennings L D and Swenson C A 1958 Phys. Rev. 112 31
[9] Piermarini G J, Block S, Barnett J D and Forman R A 1975 J. Appl. Phys. 46 2774
[10] Dormann J L, Bessa L and Fiorani D 1988 J. Phys. Chem. C 21 2015