Production of $Fe_{3-x}Zn_xO_4$ Nanoparticles for Agents in Hyperthermia Treatment

H. Takeuchi, A. Kurokawa, T. Yanoh, S. Yano, K. Onuma, T. Kondo,
K. Miike, T. Miyasaka, M. Hachisu, K. Mori, Y. Ichiyanagi*

Graduate School of Engineering, Department of Physics, Yokohama National University,
Yokohama 240-8501, Japan

*yuko@ynu.ac.jp

***Abstract*- $Fe_{3-x}Zn_xO_4$ (x=0.2, 0.4, 0.6, 0.8, 1) nanoparticle with average diameters of 12 nm was produced by our novel wet chemical method. The crystal structure and magnetic property of the obtained particle were investigated by X-ray diffraction and superconducting quantum interference device (SQUID) magnetometer. Direct current (DC) magnetization measurement showed that the coercive force H_c and saturation magnetization M_s decreased as the composite parameter x increased. This phenomenon suggests that Zn^{2+} ions located on tetrahedral A sites weaken the superexchange interaction between tetrahedral A and octahedral B sites. From the alternative current (AC) magnetic susceptibility, a sample with composition of x=0.4 is expected for heating by external field. Temperature increase depending on the magnetic field strength and frequency supported that samples with composition of x=0.2, 0.4 were appropriate for use as an agent in hyperthermia treatment.**

Keywords*- *Ferrite; Nanoparticle; Hyperthermia; Magnetic Susceptibility

I. INTRODUCTION

Magnetic nanoparticles have attracted much attention in recent years because they have tremendous potential for use not only in magnetic recording media but also in biomedical applications.

One of the authors has proposed a novel method for the preparation of magnetic nanoparticles and has reported the magnetic properties of magnetic particles thus obtained [1–6]; further, possibilities of biomedical application have also been demonstrated [7, 8]. We have succeeded in modifying amino groups on the surface of the magnetic nanoparticles and introducing them into the cells. Cell-selective functionalized magnetic particles were also developed. Further, a magnetic material can be utilized in hyperthermia treatment for cancer patients because the material yields thermal energy upon application of an external field.

In this study, Zn doped Fe_3O_4 nanoparticles were prepared in order to carry out hyperthermia treatment, and the magnetic properties of these nanoparticles were investigated. Fe_3O_4 nanoparticle was focused on possibility of application for magnetic hyperthermia treatment [9, 10, 11]. On the other hand, magnetization value of some ferrites was improved by doping non-magnetic Zn^{2+} ions [4]. AC magnetic susceptibility of Fe_3O_4 would be also improved by doping Zn^{2+} ions.

Zn doped Fe_3O_4 has an inverse spinel structure, which is composed of tetrahedral A sites and octahedral B sites. A Zn doped Fe_3O_4 system, Zn^{2+} ions are expected to remain in the A sites and Fe^{2+} ions in the B sites.

It is known that imaginary part of AC magnetic susceptibility related temperature increase of magnetic materials by alternative field [12, 13]. In order to determine the optimum composition, the out of phase component of the AC magnetic susceptibilities χ'' of the nanoparticles and temperature rise were observed.

II. EXPERIMENT

Zn doped Fe_3O_4 ($Fe_{3-x}Zn_xO_4$) nanoparticles were produced by mixing aqueous solutions of $FeCl_2{\cdot}4H_2O$, $ZnCl_2$, $C_6H_8O_6$ and $Na_2SiO_3{\cdot}9H_2O$. The mole ratio of the prepared reagent was Fe: Zn: Si = 3–x : x : 3. The obtained precipitates were washed several times with distilled water and dried at approximately 350 K in a thermostat. The as-prepared samples were subjected to heat treatment in a furnace in an air or Ar environment at annealing temperatures of 1073 K to 1273 K. Each sample was examined by CuKα X-ray powder diffraction (λ = 0.154 nm). DC magnetization of the samples was measured by using a SQUID magnetometer (Quantum Design, MPMS) in a ±50-kOe magnetic field at temperatures from 5 to 300 K. The AC magnetic susceptibility of the samples was also measured under a 1-Oe, 100-Hz alternative magnetic field. Temperature rise of these particles was measured under a 220 Oe, 15 kHz alternative magnetic field by using a Bipolar DC Power Supply (nF).

III. RESULTS AND DISCUSSION

A. X-ray Diffraction

The X-ray powder diffraction patterns of $Fe_{3-x}Zn_xO_4$ samples are shown in Figure 1 for various sample compositions: x =

0.2, 0.4, 0.6, 0.8 and 1. A broad peak corresponding to amorphous SiO_2 was observed around $2\theta = 23°$. Moreover, (220), (311), (511), and (440) peaks corresponding to the spinel structure can be clearly observed. The particle size of the spinel phase has been estimated from the broadening of the diffraction peaks by using crystal structure distribution analysis (CSDA). Particle size was controlled in 12 nm in order to observe effectiveness of doping amount of Zn^{2+} ions. Particle size of 12 nm was selected because imaginary part of magnetic susceptibility of this size would have a peak at 300 K according to a simulation of Néel relaxation Equation [12].

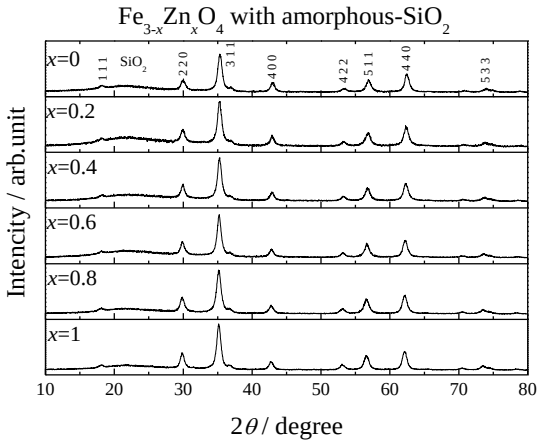

Fig. 1 Powder X-ray diffraction patterns of $Fe_{3-x}Zn_xO_4$ for various compositions and for particle sizes of 12 nm

B. DC Magnetization Measurements

Figure 2 shows the magnetization curves for $Fe_{3-x}Zn_xO_4$. The samples were measured at room temperature under a ±50 kOe field. For the conclusion, the coercivity H_c decreased as the composition parameter x increased. It is believed that non-magnetic Zn ions that are supposed to prefer the A sites in the spinel structure weaken the superexchange interaction among A-O-B. As a result, coercivity decreased according to the disordered magnetic spins increase. The saturation magnetization M_s of the sample for x=0.2 increased compared with pure Fe_3O_4, while the saturation magnetization M_s of the sample for x=0.4 decreased as the amount of Zn^{2+} ions increased. This phenomenon could be able to that Fe^{3+} ions with 5 μ_B replace non-magnetization Zn^{2+} ions in A sites, and the magnetic moment in A sites decreased. Total magnetic moment between A sites and B sites increased, and the saturation magnetization M_s of the sample for x=0.2 increased. The composition parameter x, particle sizes, coercivity, and saturation magnetizations are summarized in Table 1.

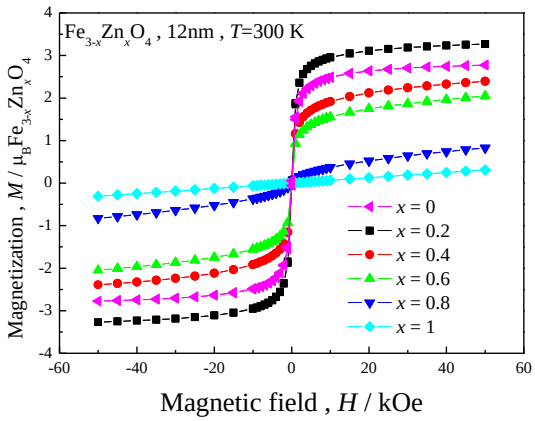

Fig. 2 Magnetization curves for $Fe_{3-x}Zn_xO_4$ for various compositions and for particle sizes of 12 nm

TABLE 1 THE PARTICLE DIAMETERS, COERCIVITY, AND SATURATION MAGNETIZATIONS OF THE $FE_{3-X}ZN_XO_4$ NANOPARTICLES FOR DIFFERENT COMPOSITIONS

$Fe_{3-x}Zn_xO_4$	diameter /nm	coercivity /Oe	Saturation magnetization / μ_B
x=0	12 nm	38.1	2.776
x=0.2		35.4	3.273
x=0.4		17.3	2.397
x=0.6		9.0	2.034
x=0.8		5.4	0.817
x=1		0	0.303

C. AC Magnetic Susceptibility

Figure 3 shows the imaginary parts of the AC magnetic susceptibility χ'' of the samples; χ'' was measured when the samples were placed in a 1 Oe, 100 Hz AC magnetic field at room temperature. The temperature corresponding to the peak χ'' shifted toward lower temperatures as the parameter x increased except the sample of x=0.2. This phenomenon reflects the replacement of Fe^{3+} ions by Zn^{2+} ions, and due to the replacement, the anisotropy constant decreased as the parameter x increased. From this result, it is concluded that the sample of x = 0.4 has the highest magnetic susceptibility value (imaginary part) at room temperature for particle size of 12 nm and that this sample is the most appropriate sample for use as an agent in hyperthermia treatment.

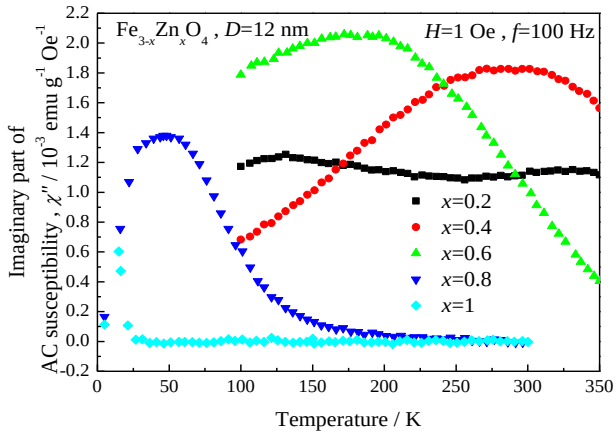

Fig. 3 The imaginary part of the AC magnetic susceptibility of the samples for various compositions and for particle sizes of 12 nm

D. Temperature Rising Measurement

Figure 4 shows that the temperature rise (Δ) of the samples was measured when the samples were placed in a 220 Oe, 15 kHz AC magnetic field at room temperature. From the experimental value of imaginary part of AC susceptibility, the sample of x = 0.4 would be expected to get highest temperature increase. However, in fact, the sample of x = 0.2 showed the highest value. We considered that this phenomenon attributed to different heating mechanism from other samples. This sample had the larger coercivity H_c than other samples, as a result, the heating mechanism for the sample of x = 0.2 changed to hysteresis loss from magnetic relaxation loss. The temperature of samples with a diameter of 12 nm and x = 0.2, 0.4 increased by about 20 K, so it is concluded that these samples are appropriate for use as an agent in hyperthermia treatment, because cancer cell would be destroyed by warming above 315.5 K for 5 minutes while body temperature is about 310 K.

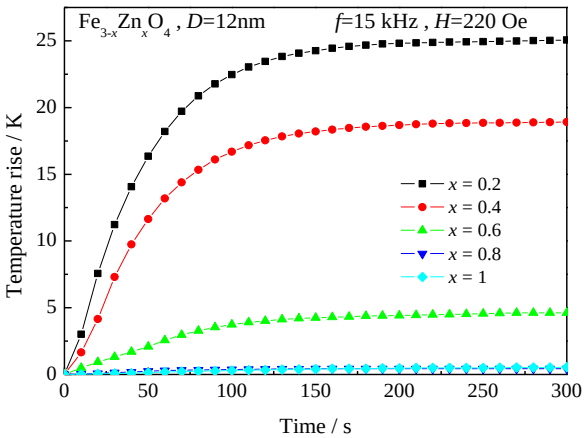

Fig. 4 The temperature rise of the samples in the AC magnetic field for various compositions and for particle sizes of 12 nm

IV. CONCLUSION

Zn doped Fe_3O_4 ($Fe_{3-x}Zn_xO_4$, $0.2 \le x \le 1$) nanoparticles were produced by using our novel wet chemical method. DC magnetization measurements showed that the coercive force H_c decreased and saturation magnetization M_s of x=0.2 sample increased more than Fe_3O_4 and then saturation magnetization M_s decreased as the composite parameter x increased. This phenomenon could be explained by the fact that Fe^{3+} ions with 5 μ_B replaced non-magnetic Zn^{2+} ions in tetrahedral A sites, and as a result, the magnetic moment in A sites decreased. Then, total magnetic moment between A sites and B sites increased, and the saturation magnetization M_s of the sample for x=0.2 increased. And Zn^{2+} ions replaced Fe^{3+} ions of A sites weakened

the superexchange interaction between A and B sites, as a result, coercivity decreased according to the disordered magnetic spins increase. From the imaginary part of the susceptibility χ'', the sample of x = 0.4 has the largest susceptibility at room temperature. This sample was expected to be much temperature rise upon an application of AC magnetic field. In fact, the sample with a diameter of 12 nm and x = 0.2 has the largest temperature rise. It could be considered that the heat dissipation mechanism of this sample would have changed to hysteresis loss from magnetic relaxation loss. As a result, samples with a diameter of 12 nm and x = 0.2, 0.4 showed temperature rise of about 20 K. In conclusion, these samples are appropriate for use as an agent in hyperthermia treatment, because cancer cell would be destroyed by warming above 315.5 K for 5 minutes while body temperature is about 310 K.

REFERENCES

[1] Ichiyanagi Y and Kimishima Y 1998 *J. Magn. Magn. Mater.* 177–81 964.
[2] Ichiyanagi Y and Tachibana Y 2001 *Trans. Mater. Res. Soc. J.* 26 1097.
[3] Ichiyanagi Y, Kondoh H and Ohta T 2003 *Chem. Phys. Lett.* 379 345.
[4] Ichiyanagi Y and Uehashi T 2004 *phys. stat. sol.(c)1* 12 3485.
[5] Ichiyanagi Y, Uehashi T, Yamada S, Kanazawa Y and Yamada T 2005 *J. Therm. Anal. Cal.* 81 541.
[6] Kubota M, Kanazawa Y, Nasu K, Moritake S, Kawaji H, Atake T and Ichiyanagi Y 2008 *J. Therm. Anal. Cal.* 92 461.
[7] Ichiyanagi Y, Moritake S, Taira S and Setou M 2007 *J. Magn. Magn. Mater.* 310 2877.
[8] Moritake S, Taira S, Morone N, Song S Y, Hatanaka T, Yuasa S and Setou M 2007 *J. Nanosci. Nanotech.* 7 937.
[9] Laurent S, Dutz S, Hafeli U, Mahmoudi M 2011 *A. Col. Inter. Sci.* 166 8.
[10] Suto M, Hirota Y, Mamiya H, Fujita A, Kasuya R, Tohji K and Jeyadevan B 2009 *J. Magn. Magn. Mater.* 321 1493.
[11] Atumi T, Jeyadevan B, Sato Y and Tohji K 2006 *J. Magn. Soc.* 30 555.
[12] Rosensweig R E 2002 *J. Magn. Magn. Mater.* 252 370.
[13] Ichiyanagi Y, Shigeoka D, Hiroki T, Mashino T, Kimura S, Tomitaka A, Ueda K and Takemura Y, 2012 *Thermochimica Acta* 532 123.