Self-heating property under ac magnetic field and its evaluation by ac/dc hysteresis loops of $NiFe_2O_4$ nanoparticles

H. Kobayashi,[1,a)] A. Hirukawa,[1] A. Tomitaka,[1] T. Yamada,[1] M. Jeun,[2] S. Bae,[2] and Y. Takemura[1,a)]

[1]*Department of Electrical and Computer Engineering, Yokohama National University, Yokohama 240-8501, Japan*

[2]*Biomagnetics Laboratory, Department of Electrical and Computer Engineering, National University of Singapore, Singapore 117576, Singapore*

(Presented 22 January 2010; received 30 October 2009; accepted 16 November 2009; published online 12 May 2010)

The temperature rise of $NiFe_2O_4$ nanoparticles having diameters of 242 and 7.7 nm was measured. The results of the measurement were analyzed by comparing the areas of the hysteresis loops in order to clarify the mechanism of heat dissipation in the samples. The hysteresis loops were obtained by applying both ac and dc magnetic fields. It was found that the contribution of magnetic relaxation losses to the heat dissipation was negligible in the case of $NiFe_2O_4$ nanoparticle of diameter 242 nm. The contribution of the Néel relaxation to the heat dissipation in the case of $NiFe_2O_4$ nanoparticle of diameter 7.7 nm was observed as the difference between the areas of ac and dc hysteresis loops. From the dependences of temperature rise and hysteresis loops of the nanoparticles on the intensity and frequency of an applied magnetic field, the relaxation time for $NiFe_2O_4$ nanoparticle of diameter 7.7 nm was obtained as approximately 0.5–0.7 μs.
 [doi:10.1063/1.3355936]

I. INTRODUCTION

Hyperthermia is a cancer treatment in which cancer cells are killed by heating. It is known that cells are killed at temperatures above 42.5 °C, furthermore, tumor cells are more sensitive to an increase in temperature than normal tissues because they have a weak cooling function. Magnetic nanoparticles can be used as heating agents for hyperthermia.[1] It has been reported that the temperature of a tumor was increased by the self-heating of a magnetic nanoparticle injected into the tumor.

The self-heating property of magnetic nanoparticles is greatly dependent on their particle size. This property originates from hysteresis loss and magnetic relaxation loss. The heating mechanisms of magnetic nanoparticles have been elucidated by taking measurements of the magnetization curve and magnetic susceptibility under an ac magnetic field.[2,3] However, there are few reports of ac magnetization curves measured at the high frequencies used for hyperthermia.[4,5] In this study, the temperature rise and magnetization curves of $NiFe_2O_4$ nanoparticles were evaluated under both dc and ac fields. The magnetic relaxation time was derived from the field intensity and frequency dependences of the temperature rise and ac hysteresis.

II. HEAT DISSIPATION OF MAGNETIC NANOPARTICLES

Heat dissipation from magnetic particles is caused by hysteresis loss. It is principally related to pinning of magnetic domain walls at impurities and other factors.

Other than the heating due to conventional hysteresis loss, heating also occurs as a result of magnetic relaxation losses, which are caused by the delay in the relaxation of the magnetic moment rotation. When the effective relaxation time of particles is longer than the period of an applied ac magnetic field, the particles are heated as the rotation of magnetic moment lags behind the changing applied magnetic field. The heating power due to the magnetic relaxation loss is given by the following equation[6]:

$$P = \pi\mu_0\chi_0 H_0^2 f \frac{2\pi f\tau}{1+(2\pi f\tau)^2}, \qquad (1)$$

where P is the heat dissipation value; μ_0, the permeability of vacuum; χ_0 the initial magnetic susceptibility; and τ, the relaxation time. H and f are the intensity and frequency of an applied ac magnetic field, respectively.

III. EXPERIMENTS

$NiFe_2O_4$ nanoparticles of diameters 242 ± 73 and 7.7 ± 1.0 nm were used as samples. The nanoparticles of diameters 242 and 7.7 nm were synthesized by a modified sol-gel method[7] and by a high temperature thermal decom-

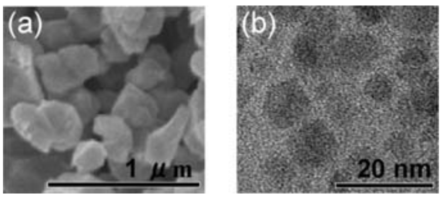

FIG. 1. Transmission electron microscopic images of $NiFe_2O_4$ nanoparticles of (a) diameter 242 nm and (b) diameter 7.7 nm.

a)Electronic addresses: d09gd135@ynu.ac.jp and takemura@ynu.ac.jp.

