§20. Theory of Selective Heating of Magnetic Metal Oxides by Microwave Magnetic Field

Tanaka, M.,
Kono, H. (Tohoku Univ.),
Maruyama, K. (RIKEN)

Microwaves can heat electrically polarized liquid (water, alcohol) and powdered materials of metals and their oxides [1] although they have much lower frequencies and weaker power density than laser light. They can also control chemical reactions [2]. Laboratory experiments showed that the efficiencies of these processes are much higher than those of the conventional methods that utilize conventional heat furnace due to thermal conduction. Indeed, various metallic oxides including magnetite and titanium oxide with oxygen defects TiO_{2-x} ($x > 0$) were sintered quickly at the magnetic field maximum (i.e. the electric field node) of microwaves in the waveguide cavity experiments that spatially separated the electric and magnetic fields [1,3,4]. However, the mechanism of this efficient heating of magnetic metal oxides has never been addressed before.

We have elucidated the mechanism of selective heating of magnetic metal oxides by the magnetic field component of microwaves on the basis of the Heisenberg model [5]. We have shown that the heating can be caused by the response of electron spins in the 3d shell to the wave magnetic field.

The magnetization of magnetite and hematite is well described by the Heisenberg model since electrons are roughly localized on each atom. The internal energy U of the magnetic system is represented by the three-dimensional spin vector $\mathbf{s}_i$ of the electron at the i-th site, the exchange interaction coefficient J_{ij} between the i-th and j-th sites, and the external magnetic field $\mathbf{B}_w$ of microwaves, which reads

$$U(\mathbf{B}_w) = -\sum_{i,j} J_{ij}\mathbf{s}_i \bullet \mathbf{s}_j + \sum_i g\mu_B \mathbf{s}_i \bullet \mathbf{B}_w \qquad (1)$$

We minimize the above internal energy Eq.(1) by randomly flipping spins to obtain an equilibrium at a given temperature using the Monte Carlo method with the Metropolis criterion. Also, we solve the spin dynamics equation with a dissipation term,

$$\frac{d\mathbf{s}_i}{dt} = \sum_{i,j} \frac{2J_{ij}}{\hbar}\mathbf{s}_i \times \mathbf{s}_j - \sum_i \frac{g\mu_B}{\hbar}\mathbf{s}_i \times \mathbf{B}_w - \frac{\mathbf{s}_i - \mathbf{s}_i^{eq}}{\tau_D} \qquad (2)$$

in order to argue quantitatively the time dependence of energy transfer from microwaves to magnetic materials [5].

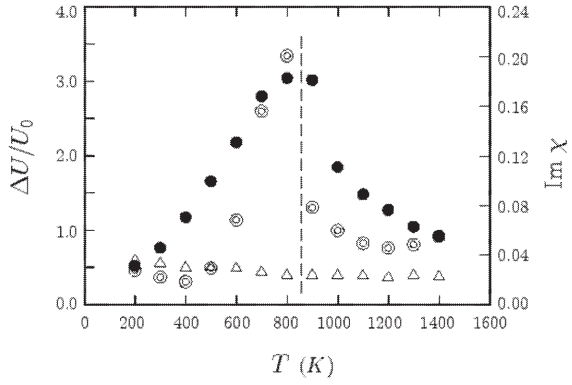

Fig.1 Temperature dependence of releasable energy (●, left axis) and the imaginary part of magnetic susceptibility χ (◎, right axis), both for magnetite. Releasable energy for hematite is shown with △.

Both methods conclude that the heating of magnetic material by microwave magnetic field is maximized around the Curie temperature T_c, unlike the spontaneous magnetization which decreases toward T_c.

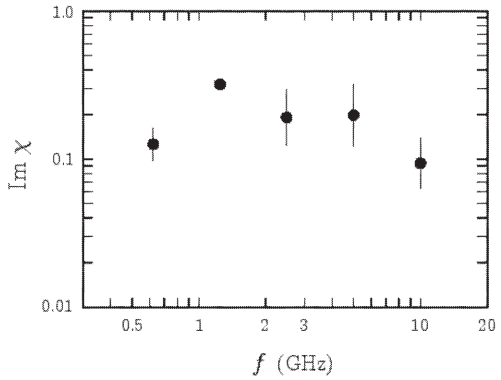

Fig.2 Frequency dependence of the heating rate of magnetite.

This work is performed under Grant-in-Aid for Prime Area Scientific Research No.18070005 from Japan Ministry of Education, Science and Culture. This study was awarded with the 1st Rustum Roy Innovator Award in August 2008 from the Global Congress of Microwave Energy Association.

1. R. Roy, D. Agrawal, J. Cheng and S. Gedevanishvili: Nature 399, 668 (1999).
2. A. Loupy (editor), "Microwaves in Organic Synthesis" (Wiley-VCH, Weinheim, 2006)
3. M. Sato et. al., 10th Intnat'l Conference on Microwaves and High Frequency Heating (Italy, 2005).
4. R. Peelamedu, M. Fleming, D. Agrawal and R. Roy, J.Amer.Chem.Soc., 85, 117.
5. M.Tanaka, H.Kono, and K.Maruyama, Phys.Rev. B, 79, 104420 (2009)..