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

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Microwaves have much lower frequencies and weaker power density than laser light, yet they can heat electrically polarized liquid (water, alcohol) and powdered materials of metals and their oxides [1], and control chemical reactions [2]. Laboratory experiments showed that the efficiencies of these processes are much higher than those of the conventional methods that utilize heat furnace and 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.

In this study, we have elucidated on the basis of the Heisenberg model the mechanism of selective heating of magnetic metal oxides by the magnetic field component of microwaves [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 above the Verwey transition temperature (120 K) [6] since electrons are roughly localized [7]. 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

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

To obtain a thermally equilibrated state, we need to minimize the internal energy of the spin system Eq.(1) at a given temperature using the Monte Carlo method with the Metropolis criterion. We first calculate the equilibrated state without an applied magnetic field for the periodic crystal of magnetite with 3x3x3 unit cells. Below the Curie temperature, spins are ordered along the c-axis due to the exchange interactions and spontaneous magnetization appears, which vanishes above the Curie temperature.

Next, we apply a slowly varying magnetic field $\mathbf{B}_w$ to the equilibrium obtained above, and perform the Monte Carlo simulation. We have found that a weak microwave magnetic field generates a large change in the internal energy through the exchange interactions, and the heating of magnetite persists above the Curie temperature.

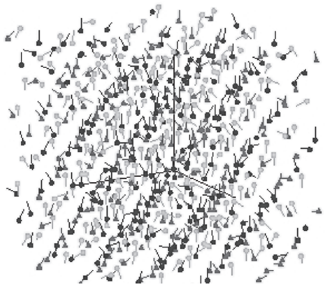
Fig.1 Electron spins

Figure 1 shows the three-dimensional view of the spins, in which spins are aligned along the c-axis (easy axis of magnetization) of magnetite. Figure 2 shows the calculated temperature dependence of the internal energy difference ΔU for magnetite when the microwave magnetic field is parallel either to the c-axis (filled circles) or to the a-axis (open circles), and also that of hematite by triangles.. Magnetite is best heated when the polarization of the microwave magnetic field is parallel to the c-axis, and the heating persists above the Curie temperature. However, hematite which has only weak spontaneous magnetization responds much less to the microwave magnetic field than magnetite. These results agree very well with those of laboratory experiments.

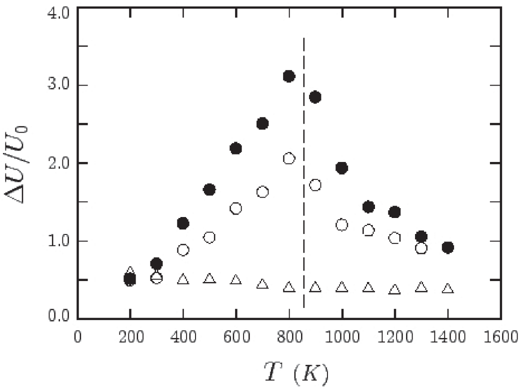

Fig.2

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