The Shift of Curie Point for a Gadolinium Film due to the Finite-Size Effects*

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We report the results of measurements for the ferro- to paramagnetic phase transition temperature shift of a gadolinium film from that of bulk system. The phase transition temperature of magnetic system, so called Curie point, can be determined by measuring the resistance of sample as function of temperatures. At Curie point, we can observe the resistivity anomaly which arises due to the heat capacity difference between below and above Curie point. In this paper, we present the results of these measurements for the bulk gadolinium and a gadolinium film of 6600Å thickness. From these data, we find that the Curie point of 6600Å gadolinium film is shifted by $4.3 \pm 0.3\ ^{0}$ C below that of bulk gadolinium.

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I. Introduction

In general, the materials show the heat capacity anomaly at phase transition temperature. This phenomenon is associated with the disappearance of long range order at phase transition temperature. Fisher and Langer(1) predicted that the resistivity anomaly would be observed in bulk ferromagnet at the ferro- to paramagnetic transition temperature, that is, Curie point. This idea comes from the fact that the heat capacity might be proportional to $d\rho/dT$, where ρ and T are resistivity and temperature, respectively. According to these predictions, the resistivity anomaly for bulk nickel were observed(2).

Near the phase transition temperature, the physical quantities of finite system deviate from those of bulk system. The finite-size scaling theory(3) gives the formalism for those systematic deviations according to the smallest dimensions of finite system.

The simplest manifestation of the finite-size effects is that the phase transition temperature is shifted from that of bulk system. The amount of this shift depends on the smallest dimension of finite system, for example, film thickness. According to finite-size scaling theory(3) the shift of phase transition temperature is expressed by

$$\frac{T_C(\infty) - T_C(L)}{T_C(\infty)} \sim b\, L^{-\lambda}$$

where $T_C(\infty)$ and $T_C(L)$ are respectively the phase transition temperatures of bulk, and finite system of smallest dimension L. Also, the critical exponent λ has relation of $\lambda = 1/\nu$, where ν is the critical exponent of correlation length, $\xi(T) = \xi_0 (T - T_C(\infty))^{-\nu}$.

To our best knowledge, the phase transition temperature shift of gadolinium film has not been reported yet. Only the specific heat and the coefficient of expansion measurements for bulk system have been reported(4)-(7). Therefore, this experiment is the first measurement for the phase transition temperature shift of gadolinium film due to the finite-size effects.

II. Experimental Details and Results

In this experiment, we measure the changes of resistance according to temperature changes for the bulk gadolinium sample and a gadolinium film of 6600Å thickness. For the bulk gadolinium sample, we use a well-polished gadolinium plate of 3cm × 2cm × 0.5mm dimensions and 99.99% purity. To achieve the larger electrical resistance, this plate is carefully cut in the form of zig-zag pattern (same pattern of film sample, refer to Fig. 1). Then, the rough edges are carefully mechanically polished. On the other hand, the sample of gadolinium film is formed on the carefully prepared glass plate by thermal evaporation method. Also, here, we put the copper mask of zig-zag pattern on the substrate during the thermal evaporation process to finally obtain the film of larger resistance. The thermal evaporation has been done in the ambient pressure of $\sim 10^{-6}$ Torr at very slow rate of $\sim$ 5 Å/sec. The thickness of film is measured by a quartz oscillator thickness monitor. After thermal evaporation of gadolinium is performed, the sample is annealed at mild temperature of 400^{0}C for about 4 hours. Then, SiO film of about 1000 Å is e-beam evaporated for the protection of gadolinium film surface. The schematic figure for the sample film is shown in Fig. 1.

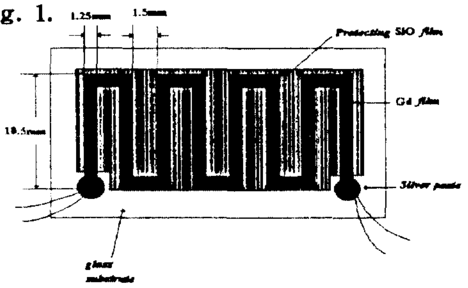

Fig 1. Schematic figure of film sample.

The sample film is then mounted on the heating plate. The schematic arrangements for heater system are shown in Fig. 2. The bulk sample is tightly mounted on the heating plate with thin layer of electrically neutral crystal bond. On the other hand, in mounting the film sample, we use the silver paste.

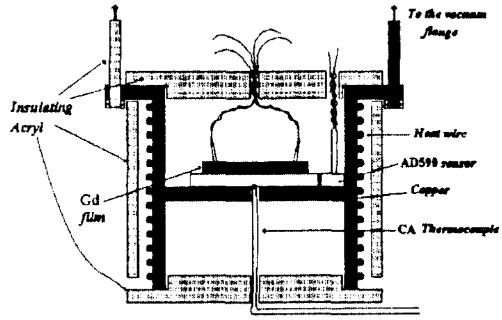

Fig.2 The arrangements of heater system

In this experiment, the precise measurements of temperatures at sample position are very important. Therefore, following arrangements are carefully done. Firstly, we cement the CA thermocouple on the position of sample itself to minimize the temperature difference between at sample and at the position of thermocouple. Secondly, the fluctuations of temperatures due to the thermal radiations are reduced by putting the whole heater system into the vacuum can which maintains the pressure of less than 10^{-5} Torr during the experiment. Thirdly, the thermal conductions from the vacuum can flange to the heater system through the supports are also greatly reduced by using the supports of poor thermal conductivity material such as the acryl. In addition to these, as shown in Fig. 2, we can see the several other arrangements for reducing the fluctuations of temperatures due to the backgrounds.

The sample inside the vacuum can is cooled down by ice water outside of the vacuum can. Then, the temperature is very slowly drifted, typically 1 m^{0}C/sec, by electrical resistance heating. The small changes of resistance of sample according to the changes of temperatures are measured by a slightly unbalanced resistance bridge system. Later, the validity of this technique was confirmed by dc resistivity measurements with measuring currents(10mA) provided by HP 6320 power supply of stability of 5 parts in 10^5. The emf from the CA thermocouple and the unbalanced signal from the bridge system are recorded by a two-pen strip chart recorder, model of μR180, which is equiped with the function of amplication for the thermocouple signal.

The data for bulk gadolinium sample are shown in Fig. 3. In this figure, we can see clearly the deflection of rate of resistance changes around 19°C. Here, also, the first derivatives of resistance data, which are proportional to the heat capacity, are shown in the inset. From these data, the Curie point of bulk gadolinium is found to be 19 ± 0.3 °C. Here, the error indicates the ambiguity in determining the peak position in the inset.

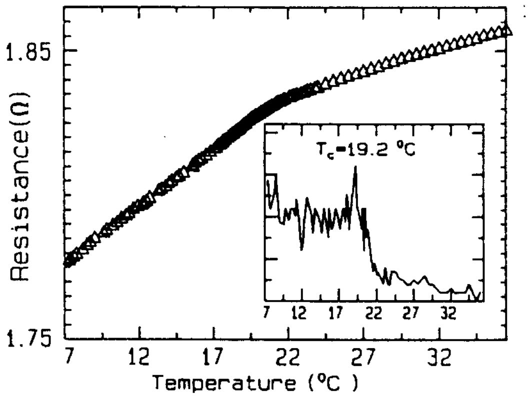

Fig. 3 Data of bulk sample.

The data for film sample are shown in Fig. 4. In this figure, we can also see clearly the deflection of rate of resistance changes around 15°C. Since the data has some fluctuations around the assumed Curie point, the first derivatives of these data are hard to be used to determine the Curie point. Therefore, we determine the Curie point of film sample by finding the cross point of two linear slopes of data below and above the assumed Curie point, ~15°C. This method is somewhat reseanable sincee the deflection region is very clear and the first derivatives of data do not severely deviate from linearity in the small region of deflection. Finally, this phase transition temperature is determined to be 15±0.3°C which is about 4°C below the bulk phase transition temperature. Here, the error indicates the ambiguity in determining the slopes below and above around ~15 °C.

In conclusion, we observe that the phase transition temperature of a gadolinium film is shifted from that of bulk gadolinium due to the finiteness of sample. The shift of transition temperature for a film of 6600 Å thickness is determined to be 4.3 ± 0.3 °C. The further measurements for the films of several different thicknesses might give a milestone to resolve the differences between experiments and finite-size scaling theory.

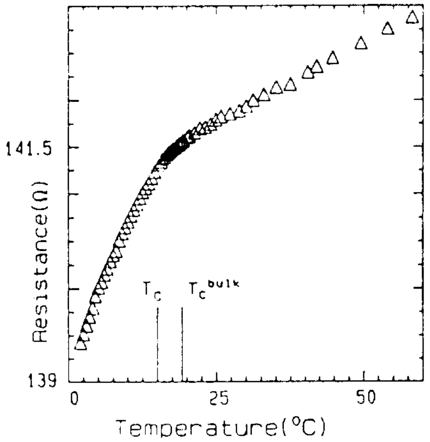

Fig. 4 Data of film sample.

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