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Finite-Size Effect에 의한 강자성 Gd박막의 상전이온도 이동

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Phase Transition Temperature Shift of a Ferromagnetic Gadolinium Film due to the Finite-Size Effects

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초 록 Gd박막의 강자성－상자성 상전이 온도(Tc)이동을 조사했다. 강자성－상자성 상전이 온도에서 전기저항이 변화되는 변곡점을 관측하여 Tc를 결정하였는데, 두께가 6600Å인 Gd박막의 상전이 온도는 bulk상태의 Gd의 전이온도보다 4±0.3℃정도 아래로 이동됨을 알았다. 이것은 강자성 Gd박막의 Tc이동에 대한 최초의 측정이며, 실험과 finite-sime scaling이론을 비교 분석했다.

Abstract We report the result of measurement for the ferro-to paramagnetic phase transition temperature shift of a gadolinium film. The phase transition temperature has been determined by measuring the resistance changes of film as function of temperature. At the ferro-to paramagnetic transition temperature, we can observe the inflection point of resistance changes. The phase transition temperature of 6600 Å gadolinium film is found to be shifted by 4 ± 0.3℃ below the transition temperature of bulk gadolinium. This is the first measurement for the phase transition temperature shift of ferromagnetic gadolinium film. This and further results might give a milestone in resolving the differences between experiments and finite-size scaling theory.

Ⅰ. Introduction

Near the phase transition temperature, the physical quantities of finite system deviate from those of bulk system. The finite-size scaling theory[1] gives the formalism for those systematic deviations according to the smallest dimensions of finite system. The liquid helium gives much greater experimental signal for these finite-size effects since it shows macroscopic quantum effects near superfluid transition temperature. So far, several experimental efforts with liquid helium for testing finite-size scaling theory have been done. Those are the measurements of heat capacity[2], superfluid density[3], and thermal conductivity[4] of confined helium. However, those experimental data did not explain the finite-size scaling theory well.

In general, the phase transition materials show the heat capacity anomalies at transition temperature. Fisher and Langer[5] predicted that the resistivity anomalies would be observed in bulk ferromagnet at the ferro- to paramagnetic transition temperature, that is, Curie point. This idea comes from the fact that heat capacity is proportional to $d\rho/dT$, where ρ and T are resistivity and temperature, respectively. On the basis of these predictions, the resistivity anomalies for bulk nickel[6] were observed. Later, the experiment to test finite-size scaling theory by the measurements of resistivity anomalies of nickel fims has been performed[7]. Due to the abscence of theory for the resistivity anomalies in finite systems, these film data were analyzed by using Fisher-Langer's theory for bulk system on the assumption that this theory might be applicable for rather thick films.

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[1] the shift of phase transition temperature

$$\frac{Tc(\infty)-Tc(L)}{Tc(\infty)} \sim bL^{\lambda} \qquad (1)$$

is expressed by where $Tc(\infty)$ and $Tc(L)$ are the phase transition temperatures of bulk, and finite system of smallest dimension L, respectively. Also, the critical exponent λ has relation of $\lambda=1/\nu$, where ν is the critical exponent of correlation length, $\xi(T)=\xi_0 L^{\lambda}$. From the data of nickel films[7], λ is determined to be 1.01 ± 0.11 which clearly deviates from the expected value of $\lambda=1/\nu=1.49$.

To our best knowledge, the phase transition temperature shift of gadolinium film has not been reported yet. Only the dynamic specific heat measurements for bulk system were reported[8]. Therefore, this experiment is the first meaurement for the phase transition temperature shift of a gadolinium film due to the finite-size effects. We hope that this and further measurements give a milestone to resolve the differences between experiments and theory.

Ⅱ. Experimental Details and Results

In this experiment, we are going to measure the change of resistance of thin gadolinium film as the function of temperatures. By tracing the trends of this resistance changes, we can determine the phase transition temperature of ferromagnetic material to paramagnetic one. However, the resistance change is generally very small, less than 2~3% changes for the temperature span of 50℃. Therefore, we need the film of as higher resistance as possible to improve the experimental sensitivity. For this purpose, the thinner and longer film might be the best candidate. But, thinner film might have much larger tendency to have the nonuniformity of film thickness. So, we have chosen rather thick film of about 6000Å for our first test sample to measure phase transition temperature shift due to finite-size effects. In addition, the resistance of film could be increased with the use of zig-zag pattern. The zig-zag pattern mask is made by etching the desired region of copper with Ferric Chloride. The gadolinium ingot of 99.99% purity and room temperature resistivity of 1.4×10^{6} Ω-m is used for thermal evaporation. The thermal evaporation has been done in the ambient pressure of $\sim10^{-6}$ Torr at very slow rate of ~5Å/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℃ for about 4 hours. Then, SiO film of about 1000Å is e-beam evaporated for the protection of gadolinium film surface. The schematic figure for the sample film is shown in Fig. 1.

The sample film is then mounted on the heating plate. The schematic arrangement of heater system is shown in Fig. 2. In mounting the sample film, we use the silver paste of high thermal conductivity as adhesives for the better thermal contact between the substrate of film and the copper heating plate.

In this experiment, the precise measurements of temperatures at the sample film are very important. Therefore, we cement the K-type thermocouple on the bottom of substrate with silver paste. In addition to this thermocouple, AD590 thermometer[9] is mounted on the side of substrate as the reference thermometer and also for the calibrations of thermocouple. AD590 thermometer(microchip)is a precise current regulator which gives the current of μA exactly same as absolute temperature. The

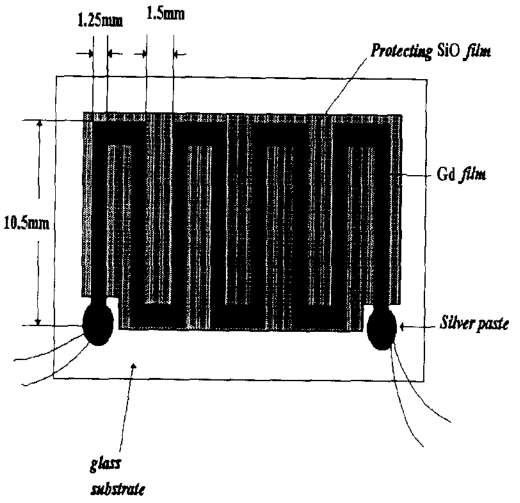

Fig. 1. The schematic figure of gadolinium film evaporated on the glass substrate. The SiO film is formed for protection of the surfaces of gadolinium film.

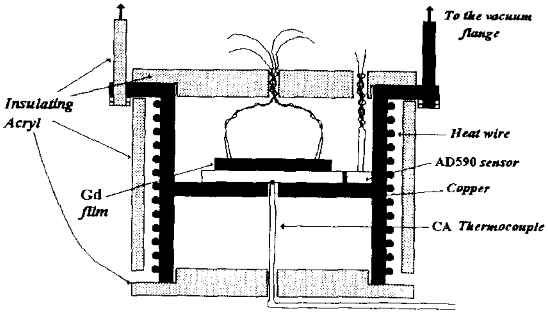

Fig. 2. The arrangement of heater system is shown in this figure. This whole system is inside the vacuum system of pressure of less than 10^{-5} Torr during the experiment.

fluctuations of temperature due to the thermal radiation are reduced by putting the whole heater system into the vacuum system which maintains the pressure of less than 10^{-5} Torr during the experiment. The thermal conductions from the vacuum system 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 Fig. 2 we can see the several other arrangements for reducing the fluctuations of temperatures due to the background.

The sample inside the vacuum system is cooled down by dry ice outside of the vacuum system. Then, the temperature is very slowly drifted, typically 1m℃/sec, by electrical resistance heating. The small changes of resistance of film are measured by a slightly unbalanced resistance bridge system. This bridge system is very powerful for the measurements of very small resistance changes, typically applicable up to 10% changes of resistance. The emf from the CA thermocouple and the unbalanced signal from the bridge system are recorded by a two-pen strip chart recorder. Later, the calibration of thermocouple with AD590 is done and the error of temperature is found to be less than 0.5%.

The data for these measurements are shown in Fig. 3. In this figure, we can see clearly the slow-down of rate of resistance changes around 15℃. The phase transition temperature can be determined by measuring the joint position of two linear square fitting lines above and below about 15℃ whithin the error of 0.3 ℃. Also, we attempted to determine the transition temperature by differentiating the data with respect to temperature, this gives $d\rho/dT$. Finally, this phase transition temperature is determined to be 15±0.3℃ which is about 4℃ below the bulk phase transition temperature of 19℃[5]. The values of $1/R(dR/dT)$ are found to be 2.9×10^{-4} and 1.0×10^{-3} for above and below transition temperature, respectively.

In conclusion, we observe that the phase transition temperature of ferromagnetic gadolinium film is shifted from that of bulk gadolinium due to the finiteness of sample. The shift of transition temperature for the film of 6600 Å thickness is determined to be 4±0.3℃. 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.

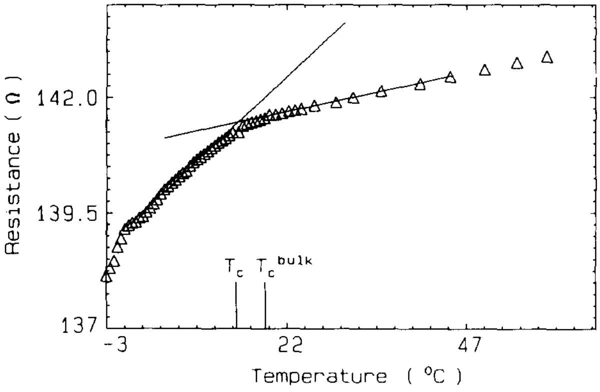

Fig. 3. The resistance data for the film of 6600Å thickness are shown in this figure. We can see the shift of transition temperature Tc for film, comparing Tc^{bulk} for bulk gadolinium.

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