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On the thickness dependence of electrical and magnetic characteristics near the critical point in gadolinium films

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강자성 가돌리늄박막의 큐리온도근방에서 두께에 따른 전기적 자기적 특성변화

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초 록 가돌리늄박막의 큐리온도를 비저항의 온도에 따른 변화를 측정함으로써 결정하였다. 이 비저항 실험치에서 구한 큐리온도의 값은 기존의 자화도에서 구한 큐리 온도값과 잘 일치함을 보여준다. 또한 박막의 큐리온도 실험값들은 얇은 박막일수록 큐리온도가 낮아지는 두께에 따른 변화를 잘 보여주고 있다. 유한 축척이론에 의한 분석에서 임계지수 λ는 0.82 ± 0.15가 나왔으며 이 값은 이론치인 1.48과 일치하지 않는다. 이 사실은 다른 많은 실험에서 확인한 바와 일치하고 있다.

Abstract The Curie point of gadolinium films has been determined by measuring the resistivity as a function of temperature. The values of Curie point in films obtained from these resistivity data are found to be well consistent with those determined from the magnetization data to within one degree. These data show the thickness dependence of Curie point in films, that is, the thinner the film is, the lower the Curie point is. By analyzing the data in light of finite-size scaling theory, we determine the exponent λ to be 0.82 ± 0.15. This deviates from the theoretical value of 1.48, which has also been seen in other experimental works.

1. Introduction

Ferromagnetic system, which undergoes the phase transition to the paramagnetic state at Curie point, shows the critical behaviors of second order phase transition, such as the anomaly of heat capacity, the disappearance of spontaneous magnetization at Curie point, and etc. If at least one dimension of a sample is greatly reduced to a value comparable to the correlation length near the Curie point, then the physical quantities of this finite system near the Curie point deviate greatly from those of a bulk sample, mainly due to a change of boundary conditions in the reduced geometry. These deviations are systematically dependent upon the smallest dimension of the finite system. A theoretical formalism for this is given by finite-size scaling theory.[1]

The simplest manifestation of finite-size effects is that the phase transition temperature of a finite system is shifted from that of the bulk system. The amount of this shift depends on the smallest dimension of the finite system, that is, the film thickness in a magnetic film. According to the finite-size scaling theory, the shift of the phase transition temperature can be expressed as

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

where $Tc(\infty)$ and $Tc(d)$ are the phase transition temperatures of the bulk system and a finite system of smallest dimension d, respectively. Also, the exponent λ is related to

$1/\nu$ where $\nu(=0.672)$ is the critical exponent of the correlation length, $\xi(T)=\xi_0(1-T/Tc(\infty))^{-\nu}$.

Several experimental works to test the above relation have been done by observing the thickness dependence of critical phenomena for the helium[2~4] and the magnetic[5,6] systems. However, these experimental results contradict that given by the finite-size scaling theory.

We have determined the Curie point in gadolinium films by measuring the resistance as a function of temperature. We find that these experimental data are consistent with those obtained from our magnetization data.[7] In this paper, we will discuss our result in light of finite-size scaling theory and show that the experimental result contradicts that given by the finite-size scaling theory.

II. Experimental

Gadolinium of 99.99% purity is evaporated on a Corning 7059 Na free glass substrate using a Leybold Univex 450 E-Beam Evaporator system in a clean room. The working pressure is kept at 10^{-7} Torr by a vacuum system consisting of two turbomolecular pumps and a rotary vane mechanical pump. The film is grown at a rate of 10 Å/sec with less than 10 % fluctuation in the e-beam power. The thickness of the film is monitored during evaporation with a quartz crystal thickness monitor to within an error of less than 5%. After evaporation, for better crystalline formation, the film sample is annealed in a vacuum of 10^{-5} Torr at 600℃ for 6 hours.

The phase transition from the ferro-to the para-magnetic state can be recognized as the disappearance of spontaneous magnetization or as the change in the behavior of the resistivity versus temperature curve. The latter is based on the assumption that the first derivative of resistivity with respect to temperature is proportional to the heat capacity.[6] In this experiment, we determine the Curie point by measuring the resistance(resistivity) as a function of temperature. The Curie point is identified as the temperature where the trend in the increase of the resistance starts to change, which reflects the discontinuity of heat capacity at Curie point. We will compare the result in this experiment with that obtained from our magnetization measurement.[7]

The schematic block diagram of the experimental setup for this measurement is shown in Fig. 1. The sample is mounted on a cold head of a closed cycle helium refrigerator. The temperature on the cold head is controlled and measured by a temperature controller. The resistance of sample is measured by an ac bridge. Data collection is performed by a computer via IEEE interfaces mounted in the ac bridge and the temperature controller.

III. Data Analysis and Result

The resistance data for the bulk sample(a 0.025-㎜-thick Gadolinium foil) and the films with thicknesses of 1000 Å, 3000 Å, 5000 Å, 7000 Å and 9000 Å are shown in Fig. 2. In this figure, we can see that the trend in the increase of the resistance changes as a function of temperature, that is, the resistance increases with a slight curvature below a certain temperature and then increases nearly linearly above that temperature. From this behavior, we can recognize the approximate Curie point where the trend in the increase of the resistance starts to change. The straight lines in Fig. 2 are the least-squares fitting lines obtained using the data in the linearly increasing region. We can clearly see the thickness dependence of the Curie point shift, that is, the thinner the film is, the lower the Curie point is. A more accurate determination of the Curie point can be done by plotting the dR/dT versus T curve and identifying as the Curie point the temperature at which an abrupt change occurs in the slope. An example of this method, for the bulk sample, is shown in Fig. 3. From this figure, the Curie point for the bulk sample is determined to be 290K to within the error of 1K. Using these procedures, we determine the Curie points of the films with the thicknesses

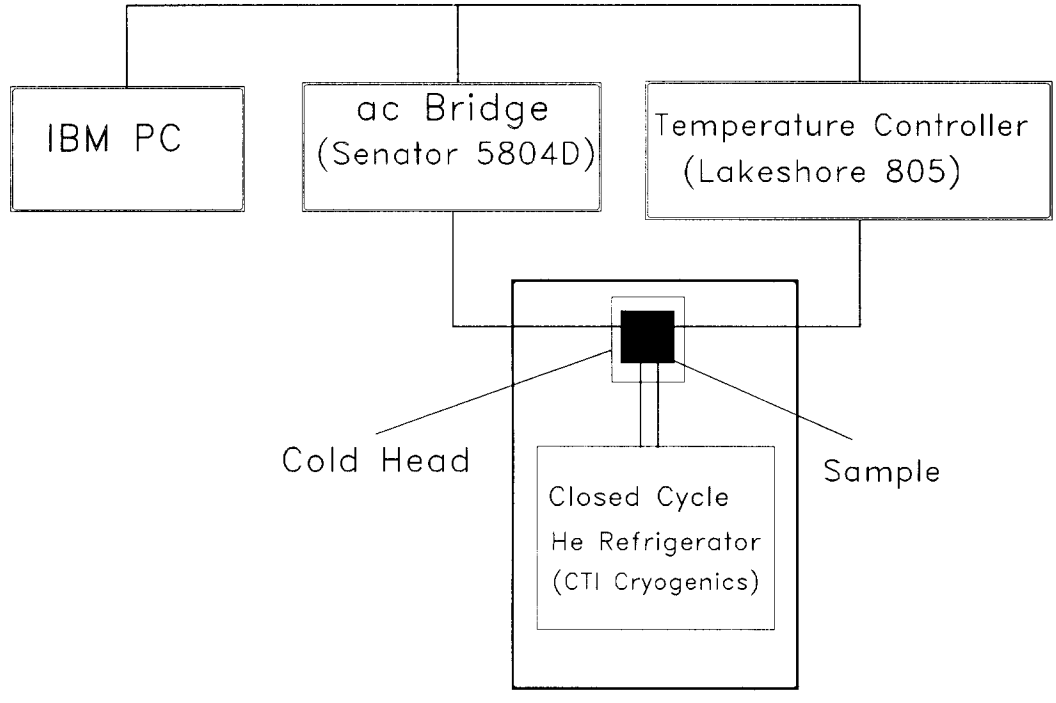

Fig. 1 The schematic block diagram of the experimental setup for the resistance measurement. Data collection is controlled by a computer via IEEE interfaces mounted in the ac bridge and the temperature controller.

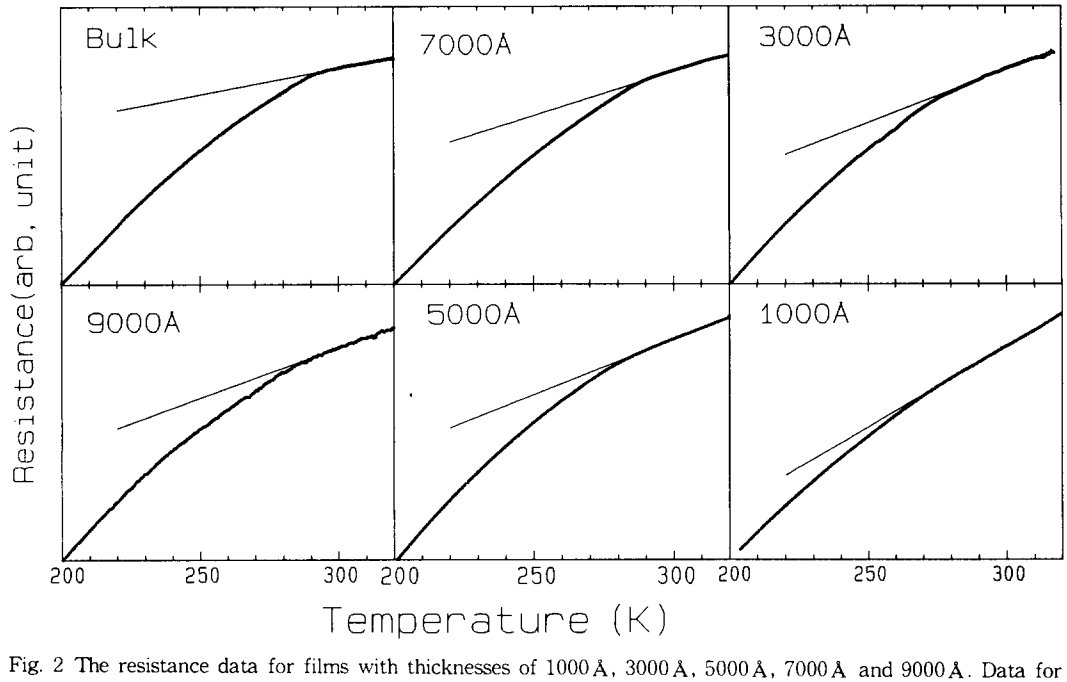

Fig. 2 The resistance data for films with thicknesses of 1000 Å, 3000 Å, 5000 Å, 7000 Å and 9000 Å. Data for the bulk sample are also shown in this figure. The straight lines in this figure are the least-squares fitting lines obtained using the data in the linearly increasing region.

of 1000 Å, 3000 Å, 5000 Å, 7000 Å and 9000 Å to be 270 ± 2K, 280 ± 2K, 283 ± 2K, 286 ± 1K

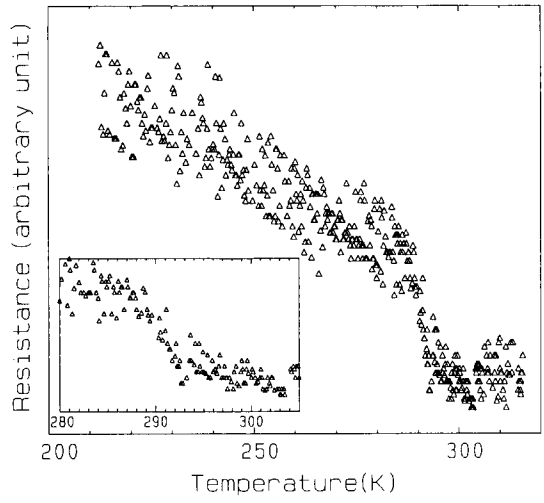

Fig. 3 The dR/dT versus T curve to determine the Curie point more accurately for the bulk sample. The Curie point is chosen as the temperature at which an abrupt change of slope occurs, which is identical to the starting temperature of the inflection in the resistace data(see Fig. 2.). The region of phase transition is enlarged in the inset.

and 287 ± 2K, respectively. The values of Curie points for the films with thicknesses of 1000 Å, 3000 Å, and 7000 Å are well consistent with those obtained from the magentization data to within less than one degree. Magnetization data for these samples are shown in Fig. 4. See Ref. 7 for the details of these measurements. To test finite-size scaling theory, Eq. (1) is cast into

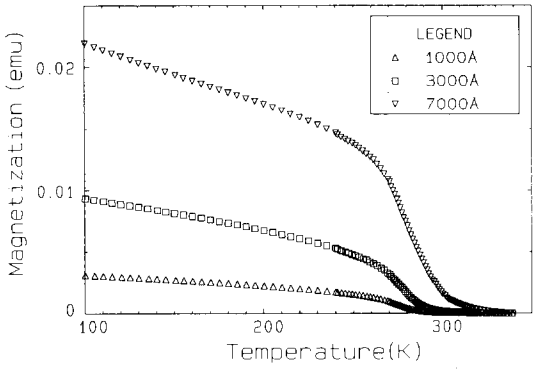

Fig. 4 The magnetization data near the Curie point for the films with thicknesses of 1000 Å, 3000 Å and 7000 Å. See Ref. 7 for details. The Curie points for these films obtained from these data are well confirmed from the data in Fig. 3.

$$\ln(T_c(\infty)-T_c(d))\sim-\lambda\ln d+\text{const.} \quad (2)$$

by taking the logarithms of both sides of Eq. (1). Then, if we plot $\ln(T_c(\infty)-T_c(d))$ versus $\ln d$, the slope of this line will be equal to $-\lambda$. These are shown in Fig. 5. From this figure, we find the exponent λ to be 0.82 ± 0.15. This deviates from the theoretical value of 1.48, which has also been seen in the previous works of others. The discrepancy between theory and experiment might come from the assumption that for a finite system, the same divergent correlation length as for the bulk is used, i.e. no new critical length scale (might be system dependent) is manifest due to the finiteness of the system, which is the central assumption of finite-size scaling theory (for more discussion, refer to Ref. 3). Since there are many experimental data not supporting the finite-size scaling theory, this theory might need some modifications or otherwise might not be correct. However, more data are needed in order to clearly resolve this problem. We believe that our experimental result is a first step.

Ⅳ. Acknowledgements

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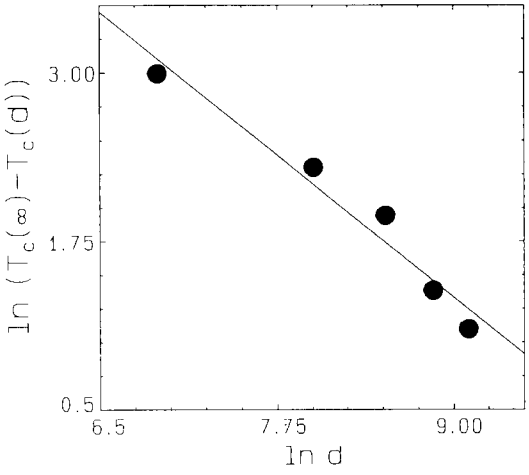

Fig. 5 The $\ln(T_c(\infty)-T(d))$ versus $\ln d$ curve to test the finite-size scaling theory. The slope of the solid line, the exponent λ, is determined to be 0.82 ± 0.15.

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