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Unconventional drop in the electrical resistance of chromium metal thin films at low temperature

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ABSTRACT

We studied the electrical resistance of single-crystal and polycrystalline chromium films. The $\rho(T)$ curve of single-crystal films decrease with decreasing temperature and show humps at around 300 K consistent with the bulk chromium being an itinerant antiferromagnet. In the polycrystalline films, on the other hand, the $\rho(T)$ curves deviate from those of the bulk chromium. Moreover, we observed sudden decrease in the resistance around 1.5 K. Although previous studies suggested that chromium films become superconductive (Schmidt et al. (1972) [12]), it is difficult to conclude whether a superconducting transition occurs because the electrical resistivity is not zero in all films. No anomaly was detected by resistance measurements around room temperature, and the sudden decrease in the resistance at low temperature may be attributed to the suppression of antiferromagnetic interaction by thinning down the chromium element.

1. Introduction

Since magnetic ordering and superconductivity apparently compete in conventional superconductors, some magnetic materials do not exhibit superconductivity. For example, iron (Fe) is a typical magnetic metal element that shows ferromagnetism at room temperature and ambient pressure. However, superconductivity is observed in Fe under high pressure between 15 and 30 GPa at 2 K [1,2]. Such behavior is related to the structural phase transition under pressure from the ferromagnetic bcc (α-Fe) phase to the paramagnetic hcp (ϵ-Fe) phase [3]. This idea is partially supported by examples in heavy fermion systems that exhibit superconductivity after suppression of magnetism to some extent under pressure [4–8].

Chromium, an antiferromagnet below the Néel temperature $T_N = 311$ K [9] at ambient pressure, doesn't exhibit superconductivity even under pressure [1]. This may be attributed to the fact that T_N decreases with increasing pressure but tends to saturate. Such behavior can be explained by taking into account of a two-band model of itinerant antiferromagnetism [10,11].

On the other hand, Schmidt et al. reported that thin films of chromium metal suppress the antiferromagnetic ordering and become superconductive at $T_C \sim 1.5$ K, whereas there was no experimental data such as resistivity drop and the Meissner effect [12,13]. It will be remarkable if chromium thin film exhibit bulk superconductivity, because it has not been reported for strongly correlated 3*d* transition-metal compounds such as Cr-based superconducting compounds, except for CrAs [14,15]. In the present study, we perform precise electrical resistance measurements of chromium thin films to clarify the electronic state in a wide temperature range.

2. Experimental

Several polycrystalline chromium films were deposited on silicon substrate using ion beam sputtering with a base pressure of about 8×10^{-6} Pa. The working deposition gas was argon and a pressure was controlled between 1.15×10^{-2} and 1.17×10^{-2} Pa. Single-crystal chromium films were prepared using a conventional magnetron sputtering device in ultrahigh vacuum below 2×10^{-6} Pa [16]. The Ar pressure during deposition was 0.1 Pa. The substrate for growing chromium epitaxially (001) MgO. Since there are no capping layers in the same way of the previous reports, chromium oxide may exist on the surface. From the result of the X-ray reflectivity measurements, the thickness of the chromium oxide layer is obtained to be about 1 nm. The electrical resistance was measured by a four-point collinear four-probe dc method with the current direction on the film plane. Since the

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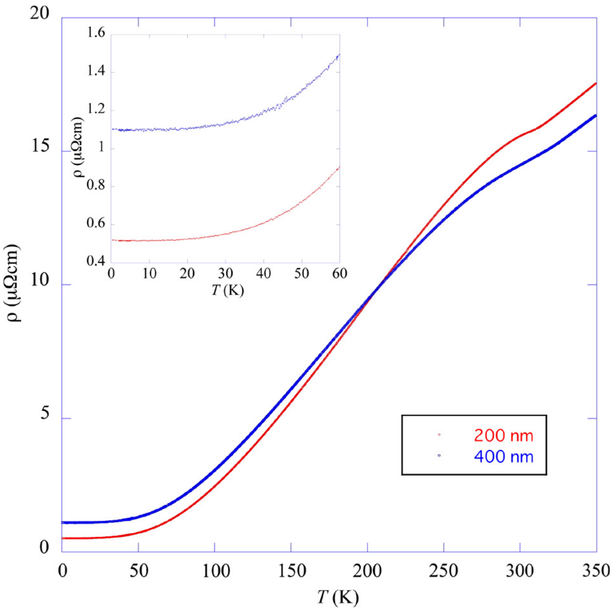

Fig. 1. Electrical resistivity ρ of single-crystals chromium films as a function of temperature. Inset shows the $\rho(T)$ curve at low temperature below 60 K.

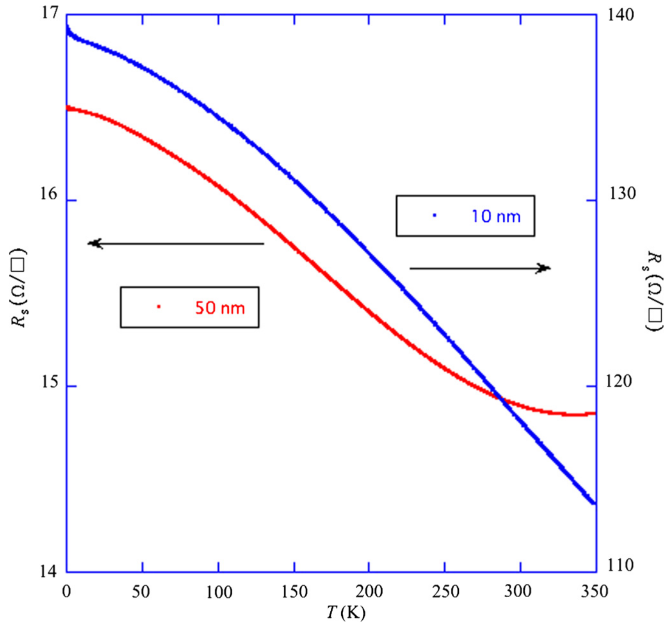

Fig. 2. Sheet resistance R_s of chromium polycrystalline films of 10 and 50 nm thick as a function of temperature.

chromium oxide layer is uncongenial to the gold wires, aluminum wires were bonded on the film plane by wire bonding. The temperature dependence of the electrical resistivity was measured using the Quantum-Design PPMS between 0.5 and 350 K in the low-temperature laboratory, Kanazawa University. The direction of the applied field was perpendicular to the film plane and the electrical current.

3. Results and discussion

Fig. 1 shows the electrical resistivity $\rho(T)$ of single-crystal chromium thin film as a function of temperature between 0.5 and 350 K. At 300 K, ρ is 15.6 and 14.5 μΩcm for 200 nm and 400 nm thick samples, and both compare well with previous studies for bulk single-crystal chromium [17]. Both $\rho(T)$ curves decrease with decreasing temperature and show humps at around 300 K. This differs from the previous study of the chromium film [12], but is consistent with the fact that bulk chromium is an itinerant antiferromagnet with T_N [9–11] below which the incommensurate spin density wave is stabilized. Below T_N, no anomaly is observed in the $\rho(T)$ curve. The inset of Fig. 1 shows the $\rho(T)$ curve at low temperature below 60 K. While $\rho(T)$ of bulk single-crystal chromium shows a T^3 power low below 100 K [17], such behavior is not observed in those of single-crystal thin films. The slope of $\rho(T)$ curve of 200 nm thick sample is almost same as that of 400 nm thick one in a wide temperature range below 60 K, and $\rho(T)$ becomes almost constant below 15 K within the experimental error. These results indicate that superconducting transition does not occur down to 0.5 K in single-crystal chromium films. It is strange that the residual resistivity ratio (RRR) of the 200 nm thick sample is larger than that of the 400 nm thick sample. From the results of the X-ray diffraction measurements, the lattice constant of the 200 nm thick sample is obtained to be 2.976 Å, which is almost same as 2.974 Å in that of the 400 nm thick sample. Such difference of RRR may come from the presence of impurities, defects, and strains in each thick films.

In polycrystalline films, on the other hand, the $\rho(T)$ value is much larger than that of single-crystal films. Because two-dimensional conductivity may be critical to the electrical resistance of polycrystalline films, we calculate the sheet resistance $R_s = RW/L$, where R is the electrical resistance of the film, and W and L are the width and length, respectively. The $R_s(T)$ curves in all polycrystalline chromium films differ from those of single-crystal films in Fig. 1 and bulk samples in previous studies [9–11]. First, no hump is observed around 300 K in the $R_s(T)$ curve, which is consistent with previous studies where a superconducting transition is observed [12,13]. Second, semiconducting behavior is observed at low temperature in all films.

Fig. 2 shows the R_s of 10 and 50 nm thick polycrystalline chromium films as a function of temperature between 0.5 and 350 K. In this figure, $R_s(T)$ increases monotonically with decreasing temperature. In Fig. 3, we show the sheet conductivity $\sigma(T) = R_s(T)^{-1}$ as a function of $\ln T$. We found that σ is proportional to $\ln T$ below 10 K. The coefficient of the $\ln T$ term is 1.0×10^{-5} and 3.0×10^{-5} $\Omega^{-1}/\square$ in 10 nm and 50 nm thick films, respectively. These values are close to $e^2/2\pi^2\hbar = 1.24 \times 10^{-5}$ $\Omega^{-1}/\square$ that is observed in two-dimensional disordered metals, which indicates that the localization and interaction effects of electrons in weakly disordered systems are important [18–22]. On the other hand, a metallic behavior is observed in the $R_s(T)$ curve of 50 nm thick film above 330 K. Similar behavior is often observed in doped semiconductors for impurity concentration varying from insulating to metallic range [23–26]. For example, the electrical resistivity of carbon-doped GaAs shows a minimum above 100 K [25]. It means that scattering from phonons can be dominant at high temperature range even in semiconductors. Taking account that both absolute value of the R_s and the slope of $R_s(T)$ curve of the 50 nm thick film are much smaller than those of 10 nm one, it is reasonable to assume that scattering from phonons is more important in the $R_s(T)$ at high temperature than the localization and interaction effects of electrons.

For films thicker than 200 nm the $\sigma(T)$ curves deviate from the $\ln T$ dependence, and tend to saturate at low temperature. This indicates that three-dimensional conductivity of chromium metal may be critical to the electrical resistance. Fig. 4 shows the electrical resistivity ρ as a function of the temperature for polycrystalline chromium films with thickness of higher than 200 nm. The $\rho(T)$ curve shows a minimum at $T_{\min} = 165$ K for the 200 nm thick, at 143 K for the 400 nm thick, and at 52 K for the 800 nm thick film, respectively. It is reasonable to assume that the minimum of the $\rho(T)$ curve is caused by the competition between