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Electrical Resistance of Single-Crystal Single-Domain Chromium from 77 to 325 °K*

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Detailed measurements of the electrical resistance of a pure chromium single crystal, $R_{300}/R_{4.2}=350$, have been made over the temperature range 77–325 °K for both the single-domain $\vec{J} \parallel \vec{Q}$ and multidomain cases. The resistance for $\vec{J} \parallel \vec{Q}$ was about 4% greater than for the multidomain case from 100 to 250 °K. No discontinuities in resistance or changes in the derivative of the resistance with respect to temperature were observed near the spin-flip temperature, nor were any discontinuities or precursor effects observed at the Néel temperature. The excess resistance due to the antiferromagnetic condensation below the Néel temperature obeys a power law in the reduced temperature difference, $(T_N - T)/T_N$, for more than two decades with an exponent of 0.57 ± 0.03 for $\vec{J} \parallel \vec{Q}$ and 0.58 ± 0.02 for the multidomain case.

INTRODUCTION

Chromium is an itinerant antiferromagnet[1,2] whose magnetism arises from some of the conduction electrons which condense through an exchange interaction to form a static spin-density wave (SDW) characterized by its wave vector $\vec{Q}$ and its spin polarization $\vec{S}$. Between the Néel temperature $T_N = 312$ °K and the spin-flip temperature $T_F = 122$ °K, the SDW has transverse polarization ($\vec{S} \perp \vec{Q}$). At T_F the spins rotate through 90° so that the SDW is longitudinally polarized ($\vec{S} \parallel \vec{Q}$). Both $\vec{Q}$ and $\vec{S}$ lie along ⟨100⟩ crystallographic directions. The transitions at T_N and T_F are first order and are accompanied by small changes in the lattice parameter.[3]

Recent measurements[4–7] have shown anomalies in the electrical resistivity of chromium around both T_F and T_N. The reported behavior around T_F ranged from a simple change[5] in $\partial\rho/\partial T$ to a change in the average value of $\partial\rho/\partial T$ with associated discontinuities in ρ.[4] All authors report the characteristic dip in ρ at T_N, although one group[6] reported a set of precursor oscillations both below and above T_N. The above results were obtained on polycrystalline samples. Single-crystal measurements indicate no change in $\partial\rho/\partial T$ at T_F in a very impure crystal,[5] and an anisotropy in ρ in a limited temperature range below T_N.[7] In this paper we present careful detailed measurements of the resistivity in a pure single crystal of chromium from 77 to 325 °K in both single- and multidomain states.

EXPERIMENTAL METHODS AND RESULTS

The chromium was obtained from Battelle Memorial Institute[8] in the form of a slab cut from a vapor transport grown polycrystalline ingot containing large crystallites. A single-crystal sample $1 \times 1 \times 7$ mm having a ⟨100⟩ direction along the sample length was cut by spark erosion from the slab. The sample was annealed at 1200 °C in an argon atmosphere for 250 h, then x rayed, and found to be strain free. Its resistance ratio ($R_{300}/R_{4.2}$) was 350. The sample was cooled from 70 to 0 °C in a magnetic field of 60 kOe oriented along a ⟨100⟩ direction. The single-domain nature of the resulting sample[9] was verified by suspending it in a magnetic field and observing its rotation through 90° as the temperature was lowered through the spin-flip temperature. This effect was observed both for $\vec{Q}$ parallel and perpendicular to the long axis of the sample, and in the parallel orientation resulted in rotation against the anisotropy in the demagnetization factor.

The resistance measurements were made in a double-chamber cryostat similar to one previously described,[10] except that the temperature control uses a differential thermocouple which senses the temperature difference between the sample plate and the outer chamber. The thermocouple voltage is read on a differential voltmeter[11] whose output programs a power supply which drives the sample-plate heater. The temperature could be stabilized to better than 0.01 °K. To reduce temperature gradients, 0.1 atm of helium exchange gas was present in the sample chamber. The sample was mounted on a copper plate and electrically insulated from it by a layer of cigarette paper varnished[12] to the plate, as shown in inset (a) of Fig. 2. A small drop of silver conductive paint was used between each of the spring-loaded phosphor-bronze current contacts and the ends of the sample to ensure a large-area low-resistance contact. The knife-edge phosphor-bronze potential contacts are spring loaded to press against the corner of the sample. The temperature was measured using a 10-Ω four-terminal copper resistance thermometer consisting of 10 ft of No. 40 copper wire noninductively wound and varnished onto the sample plate.

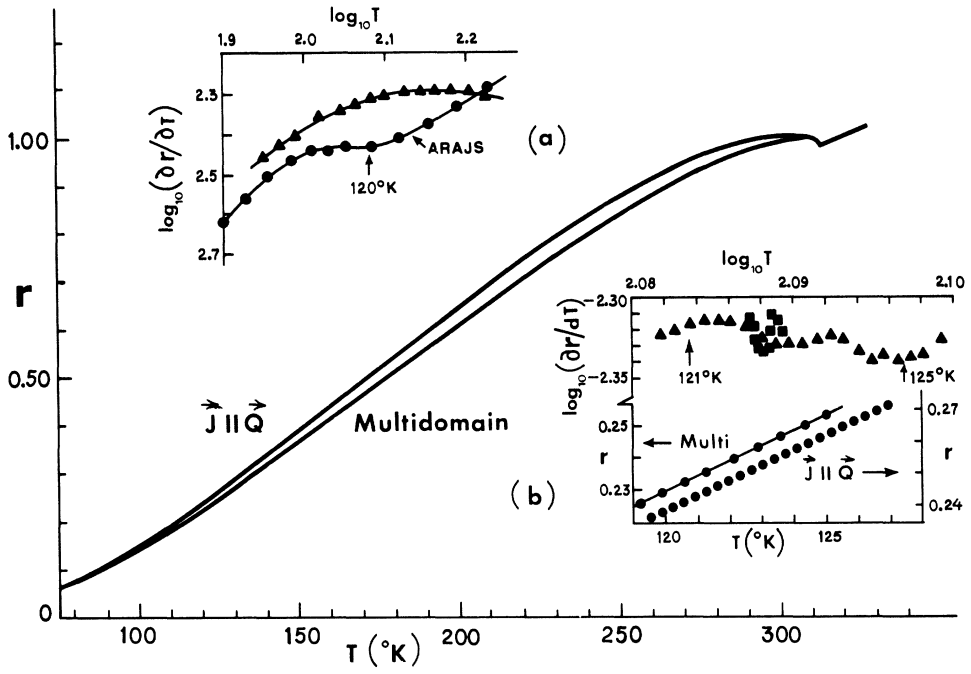

FIG. 1. Resistance ratio $r(T) = R(T)/R(320)$ as a function of temperature. Inset (a) shows $\log_{10}(\partial r/\partial T)$ as a function of $\log_{10} T$ for the present experiments with $\vec{J} \parallel \vec{Q}$ and for Arajs's (Ref. 5) data. Inset (b) shows the details of the resistance around T_F. For clarity only a quarter of the points are plotted for $\vec{J} \parallel \vec{Q}$.

This resulted in a temperature accuracy of[13] 0.1 °K while the measuring circuit allowed a sensitivity of better than 0.01 °K.

The potential measurements on the chromium were made using a nanovoltmeter whose output was read on an integrating digital voltmeter.[14] At a given temperature, ten potential measurements were made in current-reversed pairs. The reported resistance is derived from the average value of the five pairs of potential measurements and the measured current. Any set of measurements having a standard deviation greater than 0.1% was discarded and usually the standard deviation was less than five parts in 10^4. The potential across the copper resistance thermometer was measured directly by the digital voltmeter and averaged for both directions of current. Temperature measurements were made at the beginning and the end of each set of resistance measurements. Current in both the sample and thermometer circuit was measured and remained stable to better than a few parts in 10^5 during a set of resistance measurements.

RESULTS AND DISCUSSION

Figure 1 shows the resistance ratio $r(T) = R(T)/R(320)$ as a function of temperature from 77 to 325 °K for the current $\vec{J} \parallel \vec{Q}$ and for the multidomain case. The resistance in the multidomain case is seen to be about 4% less than that for $\vec{J} \parallel \vec{Q}$.

In the region of the spin-flip temperature 119–126 °K measurements were made at temperature intervals of about 0.05 °K. As shown in inset (b) of Fig. 1, no fine structure of the type reported by Meaden and Sze[4] was observed for either $\vec{J} \parallel \vec{Q}$ or for the multidomain case. Inset (a) shows $\log_{10}(\partial r/\partial T)$ as a function of $\log_{10} T$ for $\vec{J} \parallel \vec{Q}$. The differentiation was made directly from the experimental data by averaging the slopes of the lines joining five pairs of points equally spaced about the desired temperature. Also included are the data of Arajs[5] for his polycrystalline sample. In contrast to Arajs's results, the present data show no abrupt change in slope above 120 °K and thus no change in power law at T_F. Details of the logarithmic graph in the immediate neighborhood of T_F are shown in inset (b). This suggests that the anomalies at T_F may be induced by strains in the polycrystalline samples connected with the known change in lattice parameters[3] at T_F.

Figure 2 shows the details of $r(T)$ in the neighborhood of the Néel temperature. Agreement between the data and the much less detailed data of Koehler *et al.*[7] is remarkably good (± 0.2%). The fine structure reported by Meaden and Sze[6] in a polycrystalline specimen was not observed. However, the measured anisotropy below T_N is about ten times the size of the reported fine structure. This anisotropy along with the strains which will be induced in a polycrystalline sample due to lattice parameter changes at[3] T_N may well be sufficient to explain the observed fine structure. The resistance in the rather limited temperature range T_N to 325 °K was linear and no precursor curvature, such as that reported by McWhan and Rice,[15] could be detected. The details of the increased

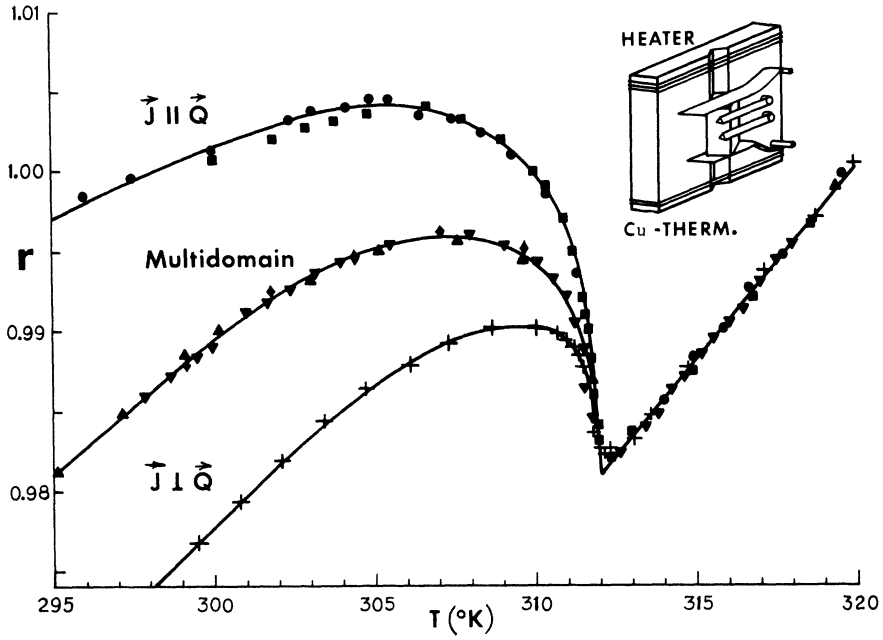

FIG. 2. Resistance ratio $r(T)=R(T)/R(320)$ as a function of T near T_N. $\vec{J} \parallel \vec{Q}$: ● is first run, ▼ is multidomain after first run; ■ is second run, ▲ is multidomain after second run. $\vec{J} \perp \vec{Q}$: +, ◆ is multidomain. The inset shows the details of the sample mounting.

resistance below T_N are shown in Fig. 3. On the assumption that complete condensation of the d-like electrons has taken place below 200 °K, the linear behavior of the resistance down to 125 °K is taken to arise from the phonon scattering of the noncondensed (s-like) electrons. As shown in the inset of Fig. 3, this term has been subtracted from the measured resistance to give the excess resistance Δr due to condensation effects. Figure 3 shows $\log_{10}\Delta r$ as a function of

$$\log_{10}\epsilon = \log_{10}[(T_N - T)/T_N]$$

for $\vec{Q} \parallel \vec{J}$ and for the multidomain case. In both cases Δr obeys a power law of the form

$$\Delta r = a\epsilon^{\gamma}$$

over a wide range of ϵ of more than two decades from 10^{-1} to 10^{-3}. The exponent γ is found to be identical within the standard deviation in both cases, being 0.57 ± 0.03 for the multidomain case and 0.58 ± 0.02 for $\vec{J} \parallel \vec{Q}$.

Despite the existence of a power law, it is difficult to see how the behavior of r can be explained by critical-fluctuation effects for a number of reasons: First, the transition at T_N is known to be first order[3]; second, the effects of critical fluctuations in an antiferromagnetic transition are known to be very small[16] and are usually only observable in $\partial\rho/\partial T$; and third, the resistivity shows a dip at T_N rather than a peak as would be expected for increased scattering due to cirtical fluctuations. It seems more likely that the increase in resistance below the Néel point is associated with the onset of electron-hole pairing as the antiferromag-

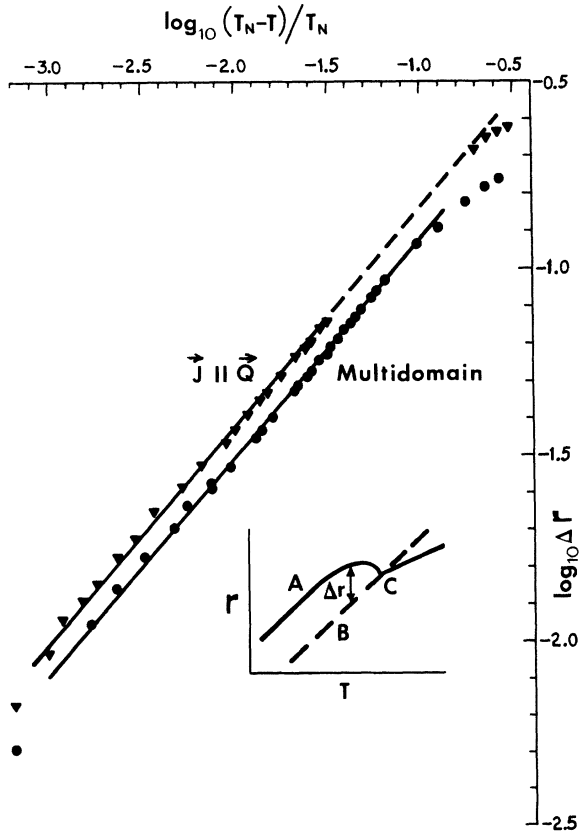

FIG. 3. $\log_{10}$ of the excess resistance Δr as a function of $\log_{10}$ of the reduced temperature difference $(T_N - T)/T_N$. Δr is defined in the inset where the line B is drawn parallel to line A through C, the minimum in the resistance at T_N.

netic condensation takes place.[15] This condensation induces a temperature-dependent BCS-like gap at the Fermi surface of the condensed electrons and also superlattice gaps in the electron distribution of the s-like electrons. In this context it may be worth noting that in superconductivity the gap varies as $\epsilon^{1/2}$ near the critical point.

CONCLUSIONS

Careful and detailed measurements on pure single-crystal chromium have been made in both the single-domain $\vec{J} \parallel \vec{Q}$ case and the multidomain case over the temperature range 77–325 °K. Less detailed measurements around T_N were made for the single-domain $\vec{J} \perp \vec{Q}$ case. The measured anisotropy between the multidomain and $\vec{J} \parallel \vec{Q}$ case remains roughly constant at about 4% from 100 °K to near T_N. No discontinuities in resistance or changes in $\partial r/\partial T$ were observed at T_F, nor were any oscillatory or precursor effects observed at T_N. The excess resistance due to the antiferromagnetic condensation below T_N obeys a power law in $\epsilon = (T_N - T)/T_N$ for more than two decades with an exponent of 0.57 ± 0.03 for $\vec{J} \parallel \vec{Q}$ and 0.58 ± 0.02 for the multidomain case.

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