EPELBOIN, Y. (1975*a*). *Acta Cryst.* A**31**, 591–600.
EPELBOIN, Y. (1975*b*). International Summer School, X-ray Dynamical Theory and Topography, Limoges, France, A**15**,
ISHIDA, H., MIYAMOTO, N. & KOHRA, K. (1976). *J. Appl. Cryst.* **9**, 240–241.
KATO, N. (1961). *Acta Cryst.* **14**, 627–636.
KATO, N. (1976). *Acta Cryst.* A**32**, 453–457.
TAKAGI, S. (1962). *Acta Cryst.* **15**, 1131–1132.
TAKAGI, S. (1969). *J. Phys. Soc. Japan*, **26**, 1239–1253.
TAKAGI, S. (1975*a*). International Summer School, X-ray Dynamical Theory and Topography, Limoges, France, A**10**.
TAKAGI, S. (1975*b*). Private communication.
TAKAGI, S., ISHIDA, H., KOMAKI, K. & SAITO, K. (1974). *Int. Crystallogr. Conf.*, Melbourne, pp. 324–325.
TAUPIN, D. (1964). *Bull. Soc. Fr. Minér. Crist.* **87**, 469–511.
TAUPIN, D. (1967). *Acta Cryst.* **23**, 25–34.

Acta Cryst. (1977). A**33**, 767–770

The Transverse Magnetoresistance of Chromium in the Temperature Range 15–80 °C

BY C. I. SYMEONIDES AND C. N. KOUMELIS
Physics Laboratory, University of Athens, Athens 144, *Greece*

(*Received* 2 *February* 1977; *accepted* 11 *March* 1977)

Electrical measurements have been carried out on a 4*N*5 Cr single crystal in multi-**Q** and single-**Q** domains. It was found that the Néel temperature depends neither on the direction of current, nor on the existence of a magnetic field. In the multi-**Q** domains, the transverse magnetoresistance G changes according to $G=AH^n$. The magnetoresistance decreases with increasing temperature showing an anomaly at 40 °C. For the single-**Q** domain specimen, measurements with $\mathbf{H} \perp \mathbf{Q}$ showed in the antiferromagnetic state the existence of saturation in the curve $G=G(\mathbf{H})$. In the paramagnetic state, the transverse magnetoresistance is an increasing function of the magnetic field. Measurements with $\mathbf{H}\|\mathbf{Q}$ showed that G increases according to $G=AH^n$, and this is ascribed to the existence of open orbits along the direction of polarization.

Introduction

Chromium is an antiferromagnetic material at room temperature, becoming paramagnetic at a somewhat higher temperature. The transition is known as the Néel point and has been found in the region between 35 and 43·5 °C (Corliss, Hastings & Weiss, 1959; Marcinkowski & Lipsit, 1961; Koumelis, 1973).

Cr has kept the interest of many investigators because of the anomalous properties near the Néel temperature, *e.g.* the specific heat, elastic constants, Debye temperature. Of special interest are the anomalies of the electrical properties.

Marcinkowski & Lipsit (1961) measured the resistivity of polycrystalline Cr for various temperatures and found a minimum at 35 ± 2 °C. Arajs & Dunmyre (1965) found this minimum at 40 °C, while Sabine & Svenson (1968) found it at 37 °C. Muïr & Störm-Olsen (1971) measured the resistance of single-**Q** and multi-**Q** Cr *versus* temperature; all their curves showed a minimum at 39 °C, and a common linear part above it. Bastow & Street (1964) measured the temperature dependence of the magnetoresistance for an annealed specimen and found two linear parts that intersected at 38 °C.

Arco, Marcus & Reed (1968) found at 4·2 °K, that a single-$\mathbf{Q}\|[100]$ specimen with the current perpendicular to **Q**, showed a twofold symmetry of the magnetoresistance when the field was rotated around the direction of the current. For single-$\mathbf{Q}\|[001]$ and $i\|\mathbf{Q}$, the magnetoresistance showed a fourfold symmetry upon rotation of the field around the direction of current.

In the present work, the resistance of multi-**Q** and single-**Q** Cr was measured *versus* temperature for a variety of directions of current and magnetic field.

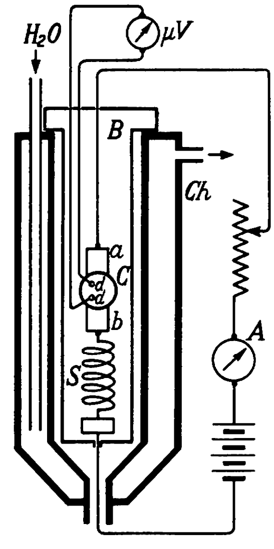

Fig. 1. The heating chamber with the crystal and the electric contacts.

Experimental details

A single crystal of Cr, 4*N*5 purity, in the form of a disc of 8mm diameter and 4mm height, was obtained from Metal Research Ltd, England. The crystal was held between two brass contacts (*a*, *b*) on an insulating slab *B* (Fig. 1). Spring *S* assured a good contact. The slab was inserted into the chamber *Ch* with double walls through which circulated water from a thermostat. The external diameter of the heating chamber was 28 mm. The DC electric current passing through the crystal was measured with the ammeter *A*. The voltage between the point contacts (*d*, *d*) was measured with a Keithley 150B microvoltometer. The temperature of the crystal was measured by a thermocouple. The heating chamber was inserted between the poles of a magnet giving $H_{max} = 19{\cdot}5$ kG.

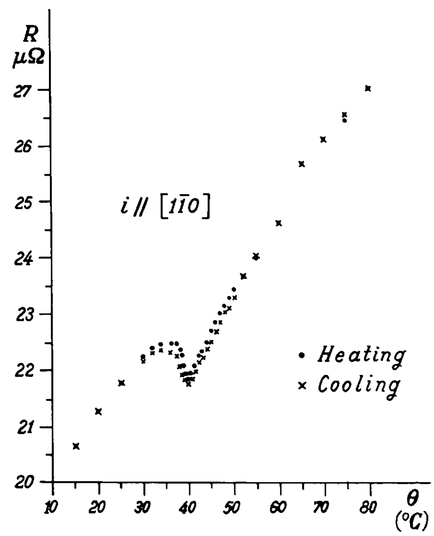

Fig. 2. The resistance *R versus* temperature *θ*.

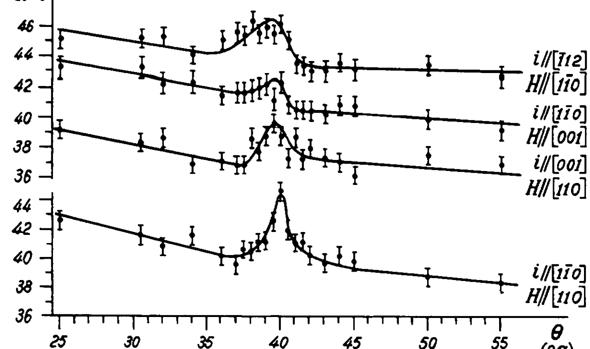

Fig. 3. The magnetoresistance *versus* temperature for various directions of current and in a magnetic field ($H = 15{\cdot}6$ kG).

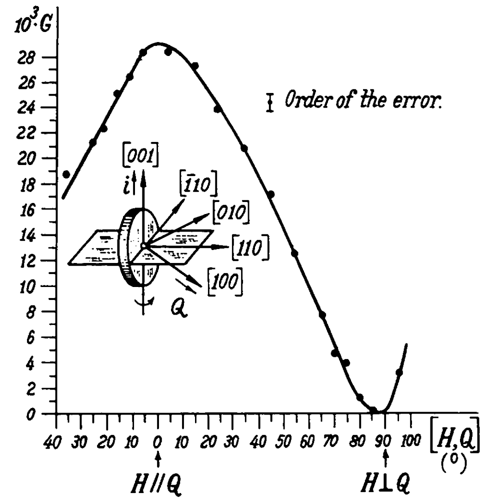

Fig. 4. The magnetoresistance *versus* angle [**H**, **Q**].

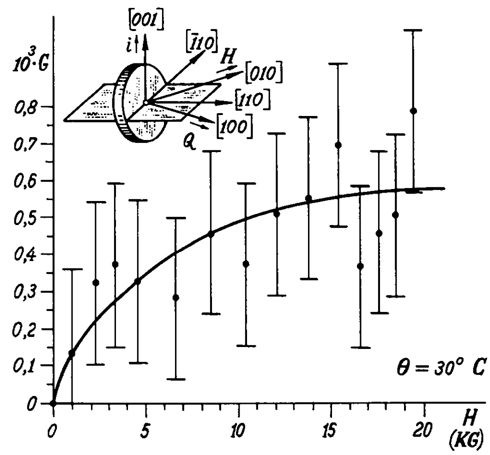

Fig. 5. The magnetoresistance *versus* magnetic field for **H**⊥**Q** in the antiferromagnetic state.

Measurements and results

*A. Multi-**Q** domains*

1. *Measurement of the resistance versus temperature θ*

For a current along [1$\bar{1}$0], the resistance of the crystal was measured from 15 to 80°C. The two families of points (Fig. 2) correspond to heating and cooling. The two curves show a common minimum at $T_N = 40$°C. This minimum does not agree with the value, $43{\cdot}5 \pm 0{\cdot}5$°C, found for the same crystal by X-ray Debye-temperature measurements (Koumelis, 1973; Florias & Koumelis, 1974), suggesting that the elastic constants do not have their anomaly at exactly the same temperature as the conductivity. As the dotted and crossed points show, an antiferromagnetic memory seems to exist, which vanishes above 60°C.

The measurements were repeated for various directions of current. It was concluded that the Néel temperature does not depend on the direction of the current.

2. *Measurements in a magnetic field*

The resistance of the crystal was measured *versus* temperature in a 15·6 kG magnetic field for various combinations of current and field directions. All the curves showed a minimum at 40 °C. Fig. 3 shows the magnetoresistance *versus* temperature for $H = 15{\cdot}6$ kG. The number of combinations of current and field directions was limited by the apparatus. All the curves at temperatures far from T_N become straight lines with different slopes for the antiferromagnetic and paramagnetic states.

*B. Single-***Q** *domain*

1. *Creation of the single-***Q** *domain*

If we apply a strong magnetic field to a heated crystal along one of the spontaneous ⟨100⟩ spin directions, and then cool the crystal in the field, the crystal will consist of only one **Q** domain (Akiba & Mitsui, 1972).

The measurements of the magnetoresistance were taken for **Q**∥[100] and **Q**⊥[001]. The crystal was heated to 75 °C in a field of $H = 27{\cdot}5$ kG, and then cooled to 25 °C in two hours.

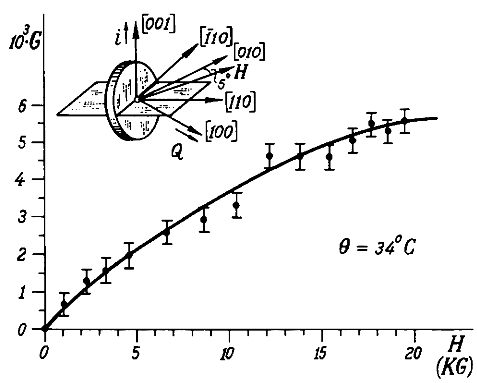

Fig. 6. The magnetoresistance for $\theta = 34$ °C for a field slightly deviating from normal to **Q**.

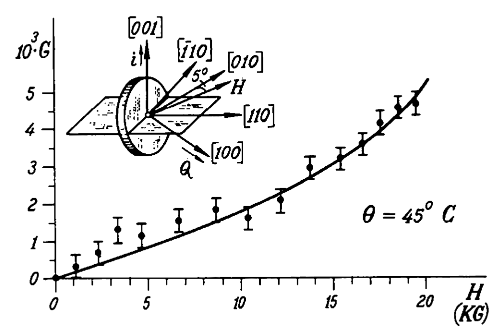

Fig. 7. The magnetoresistance for $\theta = 45$ °C for a field slightly deviating from normal to **Q**.

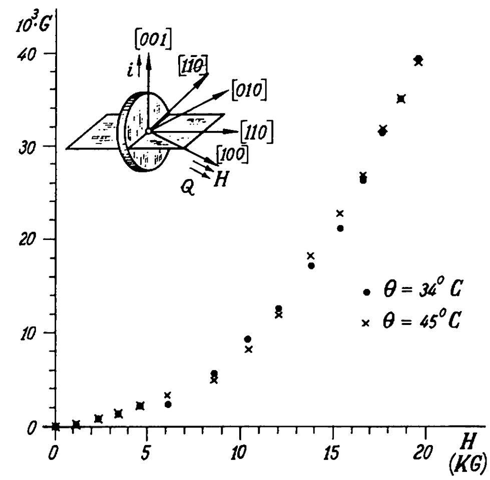

Fig. 8. The curve $G = G(H)$ for **H**∥**Q**∥[100] in the antiferromagnetic state. The statistical error is too small to be shown.

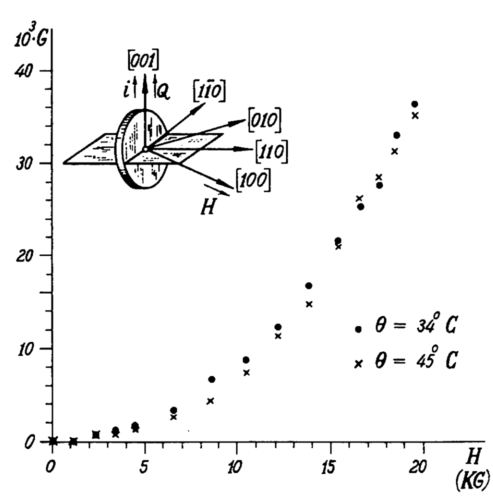

Fig. 9. The curve $G = G(H)$ for **i**∥**Q**∥[001] and **H**∥[100]. The statistical error is too small to be shown.

2. *Measurements for* **i**⊥**Q**∥[100]

(*i*) *Rotation diagram of the magnetoresistance*

Fig. 4 shows the magnetoresistance *versus* angle [**H**, **Q**]. The magnetoresistance becomes a maximum for **H**∥**Q** and exceedingly small for **H**⊥**Q**. This is the criterion for the existence of a single-**Q** domain (Arco, Marcus & Reed, 1968).

(*ii*) *Measurements of the magnetoresistance*

(*a*) *Measurements for* **H**⊥**Q**∥[100]

The transverse magnetoresistance *versus* H for 30 °C is seen in Fig. 5. The error is large because the magnetoresistance for **H**⊥**Q** is only about 0·7 ‰. This curve shows a saturation which has been explained theoretically (Jones & March, 1974); it is well known from other experiments and is ascribed to the existence of open orbits.

(*b*) *Measurements for* **H** *almost perpendicular to* **Q**‖[100]

Because of the large errors when **H**⊥**Q**, the measurements were repeated for [**H**, **Q**] = 85°, at various temperatures, both in the antiferromagnetic and paramagnetic states. Figs. 6 and 7 give the magnetoresistance for $\theta = 34$ and 45 °C respectively. The saturation is clearly visible in the antiferromagnetic state.

(*c*) *Measurements for* **H**‖**Q**‖[100]

The curves of Fig. 8 show the magnetoresistance for a magnetic field parallel to **Q**, both above and below the Néel point. It has been shown (Arco, Marcus & Reed, 1968; Falicov & Zuckerman, 1967) that in this case no saturation should occur in the antiferromagnetic state.

3. *Measurements for* **i**‖**Q**‖[001]

A change in the choice of the single-**Q** orientation allows measurements with **i**‖**Q**, as is shown in an insert to Fig. 9, which shows *G versus H* when **H**⊥**Q** for the two states. For this situation no saturation appears in the antiferromagnetic state.

4. *Calculation of the coefficients A, n*

All magnetoresistance curves not showing saturation follow the general expression:

$$G = AH^n$$

or

$$\log G = \log A + n \log H\,.$$

From this equation, the coefficients A, n have been calculated by the least-squares method. The results are shown in Table 1. The coefficient n is the same in the antiferromagnetic and paramagnetic states. The coefficient A seems to decrease with increasing temperature at least for the combination **i**‖**Q**‖[001] and **H**‖[100]. The values of n in the present work are larger than $n = 1{\cdot}47$, 1·58 (Bastow & Street, 1964), and $n = 1{\cdot}9$ (Arco, Marcus & Reed, 1968), for low temperatures.

Table 1. *Values of A and n calculated by the least-squares method*

	i‖[001]			
	Q‖[001]⊥**H**‖[100]		**Q**‖[100]‖**H**	
θ (°C)	A $[10^5\cdot(\text{kG})^{-n}]$	n	A $[10^5\cdot(\text{kG})^{-n}]$	n
34·0	6·7 ± 0·6	2·11 ± 0·04	5·5 ± 1·6	2·19 ± 0·12
38·5	5·9 ± 0·6	2·16 ± 0·04	8·8 ± 1·3	2·03 ± 0·06
41·0	5·1 ± 1·1	2·20 ± 0·09	6·3 ± 0·6	2·15 ± 0·04
45·0	3·7 ± 0·7	2·31 ± 0·07	6·5 ± 1·4	2·13 ± 0·09

Summary and conclusions

1. *Multi-***Q** *domains*

The electrical measurements show that the Néel temperature has the value 40 ± 0·2 °C for various current and field directions. This differs from the value, 43·3 ± 0·5 °C, found on the same Cr single crystal by X-ray lattice-constant determination and Debye-temperature measurements. The specimen shows antiferromagnetic memory. Measurements of the magnetoresistance *versus* temperature in a magnetic field showed an anomaly in the region of the Néel temperature. In all cases the magnetoresistance was positive.

2. *Single-***Q** *domain*

Because of the narrow temperature range, the lattice constant was practically unchanged, and therefore the observed changes in the magnetoresistance must be due to the Fermi-surface changes. In no case was negative magnetoresistance observed.

For **i**⊥**Q**, a twofold symmetry of the magnetoresistance was observed. This orthorhombic symmetry is due to the presence of spin density waves. In this case, and for **H**⊥**Q**, the observed saturation of the magnetoresistance *versus H* in the antiferromagnetic state is explained by the existence of open orbits along the direction of **Q**. The unlimited increase of the magnetoresistance in the antiferromagnetic state for **i**⊥**Q** and **H**‖**Q** can be ascribed to the open orbits along the direction of **Q**. The absence of saturation when **i**‖**Q** is due to the open orbits along the current direction. For the curves not showing saturation, the analytical expression is explained by the existence of compensation.

References

Akiba, C. & Mitsui, T. (1972). *J. Phys. Soc. Japan*, **32**, 644–652.

Arajs, S. & Dunmyre, G. R. (1965). *J. Appl. Phys.* **36**, 3555–3559.

Arco, A. J., Marcus, J. A. & Reed, W. A. (1968). *Phys. Rev.* **176**, 671–683.

Bastow, T. J. & Street, R. (1964). *Phil. Mag.* **10**, 269–276.

Corliss, L. M., Hastings, J. M. & Weiss, R. J. (1959). *Phys. Rev. Lett.* **3**, 211–212.

Falicov, L. M. & Zuckermann, M. J. (1967). *Phys. Rev.* **160**, 372–382.

Florias, P. J. & Koumelis, C. N. (1974). *Acta Cryst.* A**30**, 506–509.

Jones, W. & March, N. (1973). *Theoretical Solid State Physics*, pp. 723–730. New York: John Wiley.

Koumelis, C. N. (1973). *Phys. Stat. Sol.* (*a*), **19**, 65–69.

Marcinkowski, M. J. & Lipsit, H. A. (1961). *J. Appl. Phys.* **32**, 1238–1240.

Muïr, W. B. & Störm-Olsen, J. (1971). *Phys. Rev.* B**4**, 988–991.

Sabine, T. M. & Svenson, A. C. (1968). *Phys. Lett.* **28**A, 443–443.