INVESTIGATION OF GALVANOMAGNETIC PHENOMENA IN CHROMIUM AT LOW TEMPERATURES

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The Hall effect and magnetoresistance have been studied in chromium in the temperature range 4.2 — 78° K for fields up to 27,000 oe. The electron concentrations and mobilities have been calculated from the data obtained. A preliminary investigation of the properties of zirconium has been carried out.

THERE have been few investigations of galvanomagnetic phenomena in transition metals at high effective fields (i.e., in the region of large magnetoresistance). Magnetoresistance has been studied in molybdenum and tungsten,[1,2] but simultaneous measurements of magnetoresistance and Hall effect at low temperatures have only been made on platinum.[3]

The aim of the present work was to widen the study of transition metals. It is mainly concerned with the properties of chromium, but zirconium has also been investigated in part.

1. SPECIMEN CHARACTERISTICS

The chromium specimen, obtained by vacuum distillation, was needle shaped, ~ 0.35 mm across and 8 mm long (between the potential leads). As the distillation took place onto a hot plate, the specimen was not annealed further. The zirconium specimen was produced by thermal decomposition of the iodide and further annealing was not carried out. Table I shows the temperature dependence of resistance (in zero field).

TABLE I

T, °K	$(r_{0T}/r_{0.273})\cdot 10^2$	
	Cr	Zr
78	8.04	—
20.4	1.35	3.89
4.2	1.28	3.55
2.4	1.28	—

2. EXPERIMENTAL RESULTS

The galvanomagnetic effects were observed with the magnetic field perpendicular to the direction of current flow in the specimen, which could be rotated about its axis parallel to the current direction.

Judged by the character of the light reflected from it,[4] the chromium specimen appeared to be a single crystal. The anisotropy of magnetoresistance for different parts of the specimen showed that there were apparently small inclusions, with orientations differing from the main one. It seemed that the length axis (the current direction) made a small angle with one of the twofold axes. The anisotropy of magnetoresistance was small, the largest deviation from the mean being less than 4%.

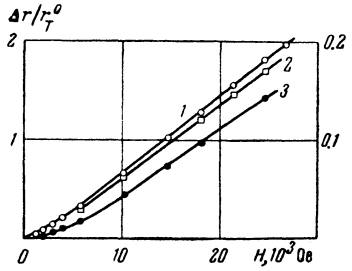

FIG. 1. Magnetoresistance in chromium 1 — at T = 4.2°K; 2 — at T = 20.4°K; 3 — at T = 78°K (the left hand ordinate scale applies to curves 1 and 2, the right hand to curve 3).

For the determinations of the dependence of the galvanomagnetic effects on field strength, the specimen was oriented in the direction corresponding roughly to the mean value of the magnetoresistance. Figure 1 shows the resistance change in a magnetic field. Above 10,000 oe at helium temperatures the resistance varies linearly with field. At 27,000 oe the resistance has increased threefold. The Hall constant is shown in Fig. 2.

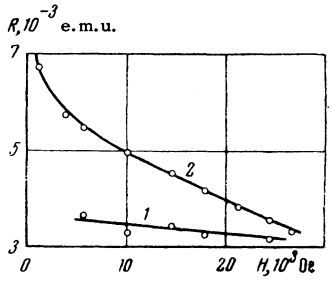

FIG. 2. Hall constant, R, for chromium 1 — T = 78°K; 2 — T = 4.2°K.

At nitrogen temperature it hardly depends on the field. The mean value $R = 3.4 \times 10^{-3}$ e.m.u. is close to the value of 3.6×10^{-3} e.m.u. found by Foner[5] at room temperature. At 4.2° K the Hall constant is very dependent on field.

As has been shown earlier,[6] it is more instructive to use the ratio of the Hall field, E_y, to the field in the current direction, E_x, rather than the Hall constant, in the region of large effective fields. This ratio, E_y/E_x, is plotted in Fig. 3.

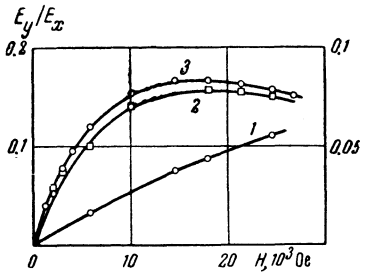

FIG. 3. Dependence of E_y/E_x on the magnetic field for chromium 1 – at T = 78°K; 2 – at T = 20.4°K; 3 – at T = 4.2°K (right hand ordinate scale for curve 1, left hand scale for curves 2 and 3).

It can be seen from curve 3 (Fig. 3) that E_y/E_x has a maximum for a field around 17,000 oe. The maximum value of $E_y/E_x = 0.165$. E_y/E_x decreases in larger fields.

Magnetoresistance measurements on zirconium showed that although the residual resistance of the specimen was of the same order of magnitude as in chromium, the variation of resistance with field was appreciably less. At 4.2° K the resistance increase $\Delta r/r = 0.035$ for a field of 24,600 oe.

3. DISCUSSION

From the experimental data it is seen that, qualitatively, the properties of chromium do not differ appreciably from those of nontransition metals.[6]

The fields used were insufficient to decide definitely on the limiting magnetoresistance law for high fields. From the curves of E_y/E_x, chromium seems to belong to the group of metals for which the Hall field decreases in large fields, while the resistance increases indefinitely, i.e., metals which have equal numbers of holes and electrons.[6] Such a conclusion is not in conflict with the electronic structure of chromium — an element in the fourth group of the periodic table.

As for platinum,[3] a simple model with two or three groups of conduction levels cannot explain the experimental results. An isotropic model with four groups of levels fits the data satisfactorily — two electron groups with densities n_2 and n_4, and two hole groups with densities n_1 and n_3.

In the zero field the electrical conductivity of such a metal is given by the expression

$$\sigma_{0T} = \frac{n_1 e^2 \tau_1}{m_1} + \frac{n_2 e^2 \tau_2}{m_2} + \frac{n_3 e^2 \tau_3}{m_3} + \frac{n_4 e^2 \tau_4}{m_4}. \quad (1)$$

The effective magnetic field is determined by the dimensionless parameters

$$\varphi_i = eH\tau_i / m_i,$$

where τ_i and m_i are the mean time between collisions and the effective mass of the corresponding groups of conduction levels.

Equations for E_y/E_x and for the magnetoresistance on such a model are given in our paper on platinum[3] [Eqs. (7) and (8)].

Table II shows the values of the various parameters for this model which give the best fit with the experimental data. The carrier concentration per atom, n_i/n_a, the carrier mobility τ_i/m_i at 4.2° K and the effective field, $\varphi_i = eH\tau_i/m_i$ corresponding to H = 25,000 oe and T = 4.2° K, are given for each of the four groups.

TABLE II

Group	1	2	3	4
n_i/n_a	$0.59 \cdot 10^{-2}$	$0.346 \cdot 10^{-2}$	$0.246 \cdot 10^{-1}$	$0.271 \cdot 10^{-1}$
$(\tau_i/m_i)10^{-15}$	10.95	9.87	2.97	1.77
φ_i	4.38	3.95	0.91	0.71

A comparison between the curves calculated from the parameters given in Table II and the experimental data is shown in Fig. 4. The agreement is satisfactory for the field dependence of both the Hall field and the resistivity. Since the anisotropy of magnetoresistance is small, we can conclude that the isotropic model, discussed above, describes the properties of chromium sufficiently closely.

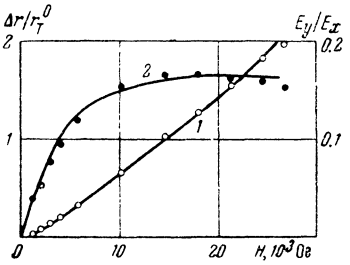

FIG. 4. Comparison between the experimental and calculated values of Hall field and magnetoresistance in chromium. The full curves are calculated values, 1 – for $\Delta r/r$; 2 – for E_y/E_x; the points represent the experimental data.

The small concentration of carriers — a total of only 0.06 per atom — is the most singular property of chromium. Such a small concentration is comparatively rare, and apart from group V elements (Bi, As, Sb) has only been found so far in gallium and beryllium.[6] The mobilities in the carrier groups 1 and 2 are appreciably greater than in groups 3 and 4. This large difference can be

explained if it is assumed that groups 3 and 4 are related to the carriers of the unfilled 3d states, characteristic of transition metals. The carriers of the first two groups, with high mobilities, are connected with the valence electrons. The presence of holes and electrons among the particles of high mobility (groups 1 and 2) can be attributed to overlapping of the 4s and 4p bands. To explain the presence of holes and electrons in the low mobility group one must assume that the d-state is split into separate overlapping bands.

The electronic structure of chromium, like platinum,[3] is thus more complicated than is usually assumed for transition metals.

Since the absolute values of mobility, given in Table II, are determined by the purity of the given specimen, direct comparison with other metals is not possible. For such a comparison, the mobility must be determined in a temperature region where the residual resistance is unimportant. For this purpose the Debye temperature is suitable, and the mobility at this temperature can be calculated from the experimental resistivity-temperature curve from the relation

$$(\tau_i / m_i)_\Theta = (\tau_i / m_i)_T \, r_{0T} / r_{0\Theta},$$

where $(\tau_i/m_i)_\theta$ is the mobility at the Debye temperature, $r_{0\theta}$ is the resistivity in zero field at the Debye temperature, $(\tau_i/m_i)_T$ and r_{0T} are the same quantities at the temperature of measurement. Such a calculation assumes the same temperature dependence of mobility for all the groups. Table III gives the results of this calculation for chromium (using the data of the present work), platinum,[3] and zinc.[6]

The maximum and minimum values of mobility are given in the table. Comparison of the data in the last column shows that the maximum mobility in chromium is even a little greater than the maximum in the non-transition metal zinc, and four times greater than the maximum in platinum. The mobilities in chromium are, therefore, closer to those of a normal metal. Presumably this is connected with the small carrier concentration. It was noted earlier[6] that the mobility increases in metals with small carrier concentrations.

Because of the small magnetoresistance, only the order of magnitude of the largest mobility in zirconium can be derived from the preliminary results. This turns out to be the same as in platinum.

It is possible to compare the data on carrier concentration with electronic specific heat data on chromium, and obtain values for the effective masses. This comparison can be made in the manner described previously.[6] Strictly speaking, one should consider the contribution of all four carrier groups to the specific heat. However, as the concentration of particles in the first two groups is nearly an order of magnitude smaller and the mobility is several time greater, the contribution of these groups can be neglected.

From the data of Estermann, Friedberg and Goldman[7] the electronic contribution to the heat capacity, $c_V = 3.62 \times 10^{-5} RT$ cal/mole-deg. Using the concentrations shown in Fig. 2, the ratio of the effective mass, m*, to the free electron mass, m_0, is found to be $m^*/m_0 = 5.3$. This value of m* is slightly less than the value in platinum[3] and considerably greater than that deduced by Estermann et al.[7] from the concentration derived from the valence ($m^*/m_0 = 2.93$).

CONCLUSIONS

As for platinum,[3] no direct effect of magnetization shows up in chromium. There is some evidence that chromium becomes ordered antiferromagnetically below 475°K.[9] If so, the magnetization at low temperatures must be small and the direct influence of it must be small. One might expect a low-field anomaly connected with the antiferromagnetic domain structure. However, the experimental data give no evidence of such an anomaly.

The characteristic property of chromium revealed in these experiments is the small concentration and high mobility of the conduction elec-

TABLE III

Metal	Θ	$T = 4.22°$ K		$T = \Theta$	
		$r_{0T} / r_{0.273}$	τ_i / m_i	$r_{0\Theta} / r_{0.273}$	τ_i / m_i
Cr	485	$1.28 \cdot 10^{-2}$	$11 \cdot 10^{15}$ $1.8 \cdot 10^{15}$	1.95	$7.2 \cdot 10^{13}$ $1.16 \cdot 10^{13}$
Pt	225	$6.78 \cdot 10^{-4}$	$20 \cdot 10^{15}$ $1.3 \cdot 10^{15}$	0.81	$1.7 \cdot 10^{13}$ $1.1 \cdot 10^{12}$
Zn	213	$4.7 \cdot 10^{-4}$	$65 \cdot 10^{15}$ $56 \cdot 10^{15}$	0.74	$4.1 \cdot 10^{13}$ $3.5 \cdot 10^{13}$

trons. These properties made possible the attainment of high effective fields, although our specimen had a large residual resistivity. Preliminary measurements on zirconium show that it does not have such anomalous properties.

In conclusion, we would like to express our thanks to B. G. Lazarev for his interest in this work.

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