ANISOTROPY OF THE HALL EFFECT AND THE ELECTRIC RESISTANCE OF A SCANDIUM SINGLE CRYSTAL

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The anisotropy of the Hall effect and of the electric resistance of a scandium single crystal is investigated at temperatures between 77 and 300°K. It is found that the effective Hall constant varies with the temperature like T^2 when the crystal is magnetized along the hexagonal axis and like $1/T$ for magnetization perpendicular to the axis. The difference in the temperature dependence of the Hall effect is ascribed to the influence of the anomalous part of the Hall field. The temperature dependence of the electric resistance is not linear and this fact is attributed to s-d electron scattering.

An investigation of the anisotropy of the Hall effect in paramagnetic transition metals, and particularly its temperature dependence, is of great interest in connection with the determination of the possible contribution made to the Hall field of these metals by the anomalous part of the Hall field, due to the spin-orbit interaction of the electrons—the carriers of the magnetic moment. The temperature dependence of the anomalous part of the Hall field in paramagnetic transition metals was considered theoretically[1] and was observed by us experimentally in polycrystalline samples of Zr and Re[2]. We present in this paper the results of an investigation of single-crystal and polycrystalline samples of scandium.

Single-crystal scandium was obtained in the Laboratory for Alloys of Refractory and Rare Metals of the Metallurgy Institute of the USSR Academy of Sciences, by the high-temperature recrystallization vacuum annealing method. The procedure for obtaining single-crystal scandium is described in[3]. The initial material for the single crystal was distilled scandium 99.6 wt.% pure (silicon ≤ 0.001, titanium ≤ 0.05, aluminum ≤ 0.01, calcium—0.002, iron—0.05, copper—0.1, nitrogen—0.03, oxygen—0.1, hydrogen—0.001, carbon—0.008 wt.%). At room temperature this metal has a hexagonal close-packed lattice of the magnesium A3 type, with parameters $a = 3.306 \pm 0.005$ Å, $c = 5.27 \pm 0.005$ Å, and $c/a = 1.594$.

The obtained single crystals have a resistance ratio $\rho(300°K)/\rho(4.2°K) = 8$. The samples for the measurements were cut from the single crystal in the form of plates ($6 \times 1.5 \times 0.2$ mm) in such a way, that the hexagonal axis C was parallel to the plane of the plate in one case, and perpendicular to it in the other case. The polycrystalline sample was prepared from the same single crystal.

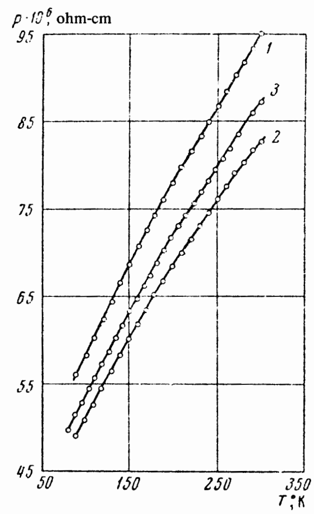

FIG. 1

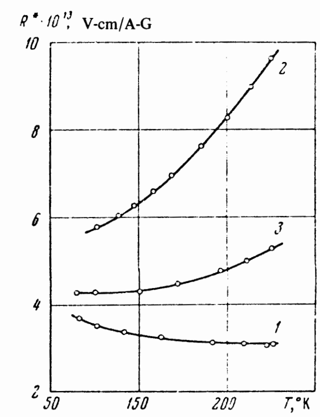

FIG. 2.

FIG. 1. Temperature dependence of the electric resistance of single-crystal scandium $\rho_{\parallel}$ (curve 1), $\rho_{\perp}$ (curve 2), and of a polycrystalline sample (curve 3).

FIG. 2. Temperature dependence of the effective Hall constant $R_{\parallel}^*$ (curve 1), $R_{\perp}^*$ (curve 2), and of the polycrystalline scandium sample (curve 3).

EXPERIMENTAL RESULTS AND THEIR DISCUSSION

Figure 1 shows the temperature dependence of the electric resistance ρ of single-crystal scandium (curves 1 and 2). The electric resistance of the scandium crystal is strongly anisotropic; the scandium has the maximum resistance in the direction of the hexagonal axis C and the smallest one perpendicular to this axis. Practically no anisotropy of ρ is observed in the basal plane. The presence of strong anisotropy of the electric resistance of crystalline scandium is a consequence of the anisotropy character of the quantity τ/m^* (τ—relaxation time, m^*—effective mass), as can be reasonably expected in the case of the highly anisotropic Fermi surface of scandium[4]. Figure 1 shows the calculated curve for polycrystalline scandium, obtained from the formula $\rho_{tot} = (1/3)\rho_{\parallel} + (2/3)\rho_{\perp}$, where $\rho_{\parallel}$ and $\rho_{\perp}$ are the resistance of the measured parallel and perpendicular to the C axis. The experimental values obtained by us from measurements with a polycrystal of the same degree of purity, marked by the points in Fig. 1 (curve 3), fit the calculated curve well in the entire investigated temperature region. The large value of the resistivity of scandium compared with other transition methods is due to the fact that the number of mobile holes in scandium is small, and the d-carriers that take part in the electric conductivity have a relatively low mobility, owing to the relatively large value of their effective mass. Furthermore, one cannot exclude the possibility that in the case of scandium a definite contribution ρ_{sd} to the resistance is made by the Mott mechanism of scattering of electrons connected with the transition from the s band to the d band. Attention is called to the unique form of the temperature dependence of $\rho(T)$. For both polycrystalline and single-crystal samples, the $\rho(T)$ dependence turns out to be nonlinear. To clarify the influence of impurities on the temperature dependence of the electric resistance, the measurements were performed also on a pure polycrystalline scandium sample with a ratio $\rho(300°K)/\rho(4.2°K) = 21$; in this case the character of the temperature dependence of the electric resistance likewise remained unchanged. A similar temperature dependence of ρ was observed earlier for polycrystalline scandium samples in[5] also at higher temperatures. Yet it was to be expected that the main mechanism of electron scattering at high temperatures is the phonon mechanism, which gives a proportional dependence of ρ on T. The measurement results show that the deviation from the linear $\rho(T)$ variation is due to additional resistance that depends on the temperature approximately like T^2. The presence of this additional resistance is possibly due to s-d scattering[6], which leads to a temperature dependence of the form

$$\rho_{s-d} = \rho(\varepsilon_F)\left\{1 - \frac{\pi^2}{6}\left[3\left(\frac{1}{n_d}\frac{dn_d}{d\varepsilon}\right)^2 - \frac{1}{n_d}\frac{d^2n_d}{d\varepsilon^2}\right](kT)^2\right\},$$

where $n_{d(\epsilon)}$ is the density of the state of the d-band, ϵ_F is the Fermi energy at 0°K. As is well known, the Fermi level of scandium lies near the maximum on the plot of the density $n(\epsilon)$ against the energy, so that $(dn_d/d\epsilon)_{\epsilon=\epsilon_F} = 0$ and $d^2n_d/d\epsilon^2 < 0$, and consequently ρ_{s-d} decreases in proportion to T^2 with increasing temperature.

It is possible that the decrease of the temperature coefficient of the electric resistance of scandium with decreasing temperature is connected to some degree with the fact that when the temperature changes there is a noticeable change in the parameters of the crystal lattice c and a and their ratio. The form of the temperature dependence c/a, as shown in[5,7] turns out to be essentially nonlinear.

An investigation of the Hall effect was carried out in the temperature interval 77–300°K in magnetic fields up to 15 000 Oe, by a potentiometer method, using an instrument with a voltage sensitivity 2×10^{-9} V/mm. The investigations have shown that in the entire temperature interval the Hall field changes in proportion to the magnetic field intensity. From the measurements, we determine the value of $E/H = R^*$, which we shall call the effective Hall constant. In the case when H is perpendicular to the C axis, the effective constants will be denoted by $R_\perp^*$, and when H is parallel to C, $R_\parallel^*$ will be used. In all the investigated cases, the effective Hall constant in the scandium crystal turns out to be negative ($R^* < 0$).

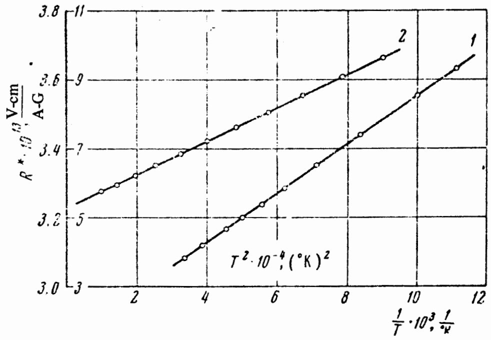

FIG. 3. Dependence of the effective Hall constant R* on the square of the temperature T^2 (curve 1, internal scales for both axes), and of R* on 1/T (curve 2, external scales).

The temperature dependence of the absolute magnitude of the effective Hall constant for single-crystal scandium ($R_\perp^*$ and $R_\parallel^*$) is shown in Fig. 2. As seen from the figure, the effective Hall constant in the scandium single crystal has a very strong anisotropy as a function of the orientation of the magnetic field intensity vector H. The Hall effect reaches the largest absolute value in the case when H is parallel to the hexagonal axis C. The anisotropy of the Hall field becomes less noticeable when the temperature is decreased. It is important that the anisotropy of the Hall effect in scandium becomes manifest not only in the difference of the value of the Hall field, but also in the form of the temperature dependence of this field. Indeed, in the case when H ∥ C, the effective Hall constant R^* increases (in absolute magnitude) quite sharply, in proportion to the square of the temperature, and a relation of the type $R^* = a + bT^2$ is satisfied in the entire investigated temperature interval (Fig. 3, curve 2), where a and b are constants independent of the temperature. As to the value of $R_\perp^*$, the latter changes with increasing temperature very weakly, like 1/T (Fig. 1).

Figure 2 (curve 3) gives also the temperature dependence of the effective Hall constant for a polycrystalline sample R_{poly}^*, calculated from the values of $R_\parallel^*$ and $R_\perp^*$ using the relation $R_{\text{poly}}^* = R_\parallel^*/3 + 2R_\perp^*/3$, which coincide with the experimental values obtained directly in the measurements (the points denote the experimental values).

The temperature dependence of the effective Hall constant of single-crystal scandium obtained in our experiments is quite complicated. According to present day notions, the temperature dependence of the effective constant R^* is due to the temperature dependence of the ordinary (classical) constant R_0 and the temperature dependence of the anomalous part of the Hall field, in terms of the temperature dependence of the electric resistance and of the magnetic susceptibility. Investigations[8] of the Hall effect in non-transition metals, however, show that in the region of increased temperatures the Hall constant R_0 is practically independent of the temperature or has a weak dependence on it.

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[1] E. I. Kondorskiĭ, Zh. Eksp. Teor. Fiz. **55**, 2367 (1968) [Sov. Phys.-JETP **28**, 1256 (1969)].

[2] D. I. Volkov, T. M. Kozlova, V. N. Prudnikov, and E. V. Kozis, ibid. **55**, 2103 (1968) [**28**, 1113 (1969)].

[3] E. M. Savitskiĭ, V. F. Terekhova, O. P. Naumkin, and I. V. Burov, Tsvetnye metally (Nonferrous Metals), 1963, No. 5, 51.

[4] S. L. Altmann and C. J. Bradly, Proc. Phys. Soc. **92**, 764 (1967).

[5] P. G. Mardon, J. L. Nichols, J. H. Pearce, and D. M. Poole, Nature **189**, 566 (1961).

[6] H. Jones, Handbuch der Physik **19**, 278 (1956).

[7] N. Schmitz-Pranghe and Ph. Dunner, Z. Metallkunde **59**, 377 (1968).

[8] J. E. A. Anderson, T. Farrell, and C. M. Hurd, Phys. Rev. **174**, 729 (1968).

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