ELECTRON-MAGNON SCATTERING IN AN ERBIUM SINGLE CRYSTAL

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The electrical resistivity of an erbium single crystal was measured along the [0001] (c axis) and [1$\bar{2}$10] (a axis) directions in the temperature range 4.2-300° K. The magnetic component of the resistivity $\rho_m(T)$ was determined. The anisotropy of ρ_m in the paramagnetic region and the dependence $\rho_m(T)$ at low temperatures were discussed.

INVESTIGATIONS of the temperature dependence of the electrical resistivity $\rho(T)$, carried out on Tb and Dy single crystals,[1] demonstrated that the magnetic component of the resistivity $\rho_m(T)$ was strongly anisotropic. In view of this it seemed desirable to study the anisotropy of the magnetic component of the resistivity of other magnetically ordered rare-earth metals.

The present paper reports the results of measurements of $\rho(T)$ of an erbium single crystal grown by recrystallization annealing at T = 1400° C in an atmosphere of spectroscopically pure helium. Some of the properties of the erbium used in the investigation are listed in the table.

Orientation	$\rho_0 \cdot 10^6$, Ω·cm (4.2° K)	ρ(300° K)·10^6, Ω·cm	ρ(300° K)/ρ(4.2° K)
[0001]	3.5	47.1	13.4
[1$\bar{2}$10]	4.3	82.5	19.2

1. DETERMINATION OF THE MAGNETIC COMPONENT OF THE RESISTIVITY

We shall assume that the total resistivity can be written in the form

$$\rho(T) = \rho_0 + \rho_e(T) + \rho_m(T) + \rho_p(T),$$

where each term is responsible for a definite mechanism of the conduction-electron scattering: ρ_0 is the residual resistivity, $\rho_e(T)$ is the resistivity associated with electron-electron collisions, $\rho_m(T)$ and $\rho_p(T)$ are the components due to the scattering of electrons by magnons and phonons, respectively. It is known[2] that the electrical resistivity depends on the scattering processes via the relaxation time τ and on the electron structure characteristics via the conduction integral $\int v_i dS_j$, where v_i is the velocity of an electron in the i-th direction and dS_j is an element of the Fermi surface area.

The band structure of heavy rare-earth metals was calculated in [3] by the augmented plane-wave method with an allowance for the relativistic effects and it was found that the Fermi surfaces of Er and Lu are geometrically similar. This fact will be used in the identification of the contributions of the various electron scattering mechanisms. However, we shall ignore the change in the conduction integral of Er due to the transition from the paramagnetic to the antiferromagnetic or ferromagnetic ordering.

In an earlier paper[1] we pointed out that the relatively low purity of the investigated samples made it possible to ignore the influence of the internal magnetic field on the motion of electrons and to find ρ_0 by extrapolation of the total resistivity to 0°K. The data on the electron structure of Er and Lu—the similarity of the Fermi surfaces, the similar values of the electron density of states on the Fermi surface $N(E_F)$ and of the coefficients γ in the electronic specific heat—allowed us to assume that the contributions of the electron-electron collisions $\rho_e(T)$ in these two metals were of similar magnitude. The phonon component of the resistivity $\rho_p(T)$ was excluded by means of the Bloch-Gruneisen function and the characteristic temperature Θ_D = 193°K was deduced from the elastic constants of the lattice.[4] The phonon component of the resistivity at the temperature Θ_D, which was needed in the plotting

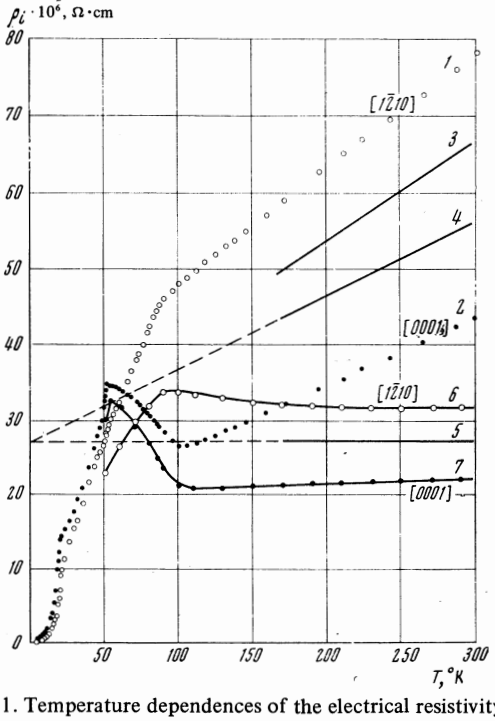

FIG. 1. Temperature dependences of the electrical resistivity of an erbium single crystal: 1), 2) ideal resistivity $\rho_i(T) = \rho(T) - \rho_0$ along the [1$\bar{2}$10] and [0001] directions; 3) ideal resistivity of a polycrystalline sample; 4) phonon and magnetic components of the resistivity of a polycrystalline sample ($\rho_p + \rho_m$); 5)magnetic resistivity of a polycrystalline sample $\rho_m(T)$; 6) $\rho_m(T)$ along the [1$\bar{2}$10] direction; 7) $\rho_m(T)$ along the [0001] direction.

of the function $\rho_p(T)$, was found from the corresponding component of the resistivity of Lu after correction for the atomic weight and the characteristic temperature of Er.

Figure 1 shows the temperature dependences of the electrical resistivity $\rho_i(T) = \rho(T) - \rho_0$ (curves 1 and 2) which were obtained for the crystallographic directions $[1\bar{2}10]$ and [0001]. The residual resistivities are listed in Table I. Curve 3 represents the electrical resistivity of a polycrystalline sample found by averaging in accordance with the well-known formula $\rho_{polycryst} = \frac{1}{3}\rho^c + \frac{2}{3}\rho^a$. Elimination of $\rho_e(T)$ from the resistivity yielded curve 4 which represented the contributions of the scattering by phonons and magnons. Linear extrapolation of curve 4 to 0°K gave ρ_m in the paramagnetic region: $\rho_m = 27\ \mu\Omega \cdot$ cm. When the values of $\rho_p(T)$ were subtracted from curve 4, it was found that the magnetic component ρ_m of erbium was independent of temperature in the paramagnetic region and was equal to the value extrapolated to 0°K. These two observations confirmed the validity of the method used for determining the magnetic component of the resistivity.

The similarity of the Fermi surfaces of Er and Lu could be used, as in [1], to find the values of $(\rho_e + \rho_p) = f(T)$ along the c and a axes of an erbium crystal. Next, subtracting at each temperature the values of $(\rho_e + \rho_p)$ from $\rho_i(T)$ for each of these axes, we found the dependences $\rho_m^c(T)$ and $\rho_m^a(T)$ which were of interest to us. Curve 6 in Fig. 1 represents the magnetic component of the resistivity along the a axis and curve 7 shows the same component along the c axis.

2. ANISOTROPY OF ρ_m IN THE PARAMAGNETIC REGION

The magnetic component of the resistivity of Er was found to be strongly anisotropic throughout the investigated temperature range: we found that $\rho_m^c(T) > \rho_m^a(T)$ in the magnetically ordered state and $\rho_m^c < \rho_m^a$ in the paramagnetic range, as reported earlier for Tb and Dy.[1] The anisotropy of the scattering of the conduction electrons by the magnetic disorder in Er could be explained in the following way. If the relaxation times of electrons interacting with phonons and magnons (these relaxation times occur in the electrical conductivity formula) are isotropic, we find that in the paramagnetic region

$$\rho_m^a/\rho_m^c = \alpha_a/\alpha_c = \int v_c\, dS_c \Big/ \int v_a\, dS_a,$$

where α_a and α_c are the coefficients associated with the electron-phonon component of the resistivity. In the case of Er the ratios $\rho_m^a/\rho_m^c = 1.45$ and $\alpha_a/\alpha_c = 1.5$ are indeed similar. Moreover, a similar value is obtained if the results of calculations given in [3] are used to estimate the ratio of the areas of the projections of the Fermi surface onto planes perpendicular to the current in the two configurations.

Thus, in spite of the fact that the electron velocities depend on the actual nature of the dispersion law of electrons, the anisotropy of the resistivity of Er in the paramagnetic region can be attributed principally to the anisotropy of the Fermi surface.

We note that a similar determination of $\rho_m(T)$ carried out for a single crystal of Gd without allowance for the difference between the Fermi surfaces of Gd and Lu gave results quite different from those obtained for other rare-earth metals. This means that our method for finding $\rho_m(T)$ is, as expected, inapplicable to Gd because of the considerable differences between the electron structures of Gd and Lu.[3]

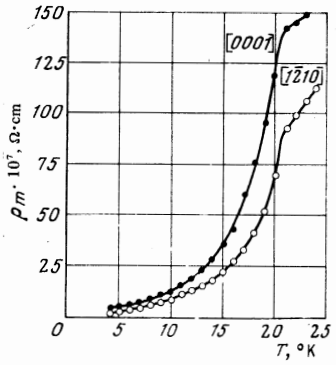

FIG. 2. Temperature dependences of the magnetic component of the resistivity of an erbium single crystal in the ferromagnetic.

3. DEPENDENCE $\rho_m(T)$ AT LOW TEMPERATURES

The results of our investigation of $\rho_m(T)$ of an erbium single crystal at low temperatures are presented in Fig. 2. In the ferromagnetic region ($T < 20$°K) we found that

$$\rho_m^a(T) \sim T^{3,7\pm0,3}, \quad \rho_m^c(T) \sim T^{4,0\pm0,2}.$$

One of the principal characteristics which determines the temperature dependence $\rho_m(T)$ in this region is the dispersion law of spin waves. In the case of a helicoidal magnetic structure, which is exhibited by Er in this range of temperatures, the dispersion law should be linear.[5] This leads to the following theoretical temperature dependences of the magnetic component of the resistivity, the spontaneous magnetization σ_s, and the magnetic component of the specific heat C_m: $\rho_m(T) \propto T^4$, $\sigma_s(T) \propto T^2$, $C_m(T) \propto T^3$.

Thus, measurements of the magnetic component of the electrical resistivity support the hypothesis that the dispersion law of spin waves in Er is linear. Measurements of the magnetization[6] yield $\sigma_s(T) \propto T^2$, which is in agreement with our data on $\rho_m(T)$.

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199