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Magnetoresistance in $ErCo_2$ and $HoCo_2$ single crystals

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Abstract

The longitudinal magnetoresistance along the principal crystallographic directions in single crystals of $ErCo_2$ and $HoCo_2$ compounds has been measured in the range of field-induced first-order phase transition at temperatures above the spontaneous magnetic ordering temperature, T_C. The sharp decrease of electrical resistivity ($\Delta\rho/\rho$ up to -50%) is observed at critical fields, H_C. In $ErCo_2$, the critical fields have different values along the principal crystallographic directions and the $H_C(T)$ dependences are nonlinear. For $HoCo_2$ the absence of critical fields anisotropy and linear $H_C(T)$ dependences are observed. The behaviour of the electrical resistivity in an applied magnetic field at $T>T_C$ for both compounds is generally associated with suppression of the spin fluctuations at metamagnetic phase transitions.

1. Introduction

The magnetism of the Co 3*d* electron system in the cubic Laves phase compounds $ErCo_2$ and $HoCo_2$ as well as in other RCo_2 compounds is satisfactorily described in the band magnetism model taking into account the spin fluctuations [1, 2]. The magnetic moment on the cobalt atom μ_{Co} in RCo_2 depends on the type and on the concentration of the R-ions, which have an intrinsic magnetic moment. In the heavy rare earth compounds RCo_2 (R = Tm, Er, Ho, Dy) the ferrimagnetic–paramagnetic transition at $T=T_C$ is of first-order but of second-order in $GdCo_2$ and $TbCo_2$ [3–7]. The compounds with first-order spontaneous magnetic phase transitions in the temperature range just above T_C show the metamagnetic transition in an applied magnetic field. This behaviour is determined by the peculiarities of the electronic structure of the RCo_2 compounds. The Fermi level of RCo_2 lies on a sharply falling part of the curve of density of state (DOS), as a function of energy [8, 9]. This situation also causes unusual temperature dependences of the electrical resistivity ρ and thermopower for RCo_2 [10]. The $\rho(T)$ curves are characterised by discontinuities at first-order transition at T_C and by the tendency of saturation at high temperatures.

This paper reports the results of the investigation of the longitudinal magnetoresistance along the principal crystallographic directions of the $ErCo_2$ and $HoCo_2$ single crystals.

2. Experimental details

The $ErCo_2$ and $HoCo_2$ compounds were melted in an arc furnace with 6% excess of rare earth. Single crystals were obtained by remelting the ingots in a resistance furnace with high temperature gradient. The magnetoresistivity was measured by means of the four-points method in the temperature range from 4.2 up to 100 K in a magnetic field up to 7.5 T on prismatic specimens of about $1\times1\times6$ mm^3 in size.

3. Results and discussion

The isotherms of the field dependences of the longitudinal magnetoresistance $\Delta\rho/\rho$ measured along the [1 1 1] and [1 0 0] crystallographic directions of $ErCo_2$ single crystals are presented in Fig. 1. As can be seen, an application of the magnetic field at $T<T_C$ causes a small decrease in the electrical resistivity ($<6\%$). This change is determined by decreasing the volume of the domain boundaries [11] at the saturation of magnetization and by increasing the magnetic order in an applied field. Above T_C, the increasing field at first causes a small drop, but when the critical field H_C is reached, a sharp decrease in the electrical resistivity ($\Delta\rho/\rho$ up to -50%) accompanied the first-order transition from the paramagnetic to the ferrimagnetic state [12]. The temperature region, in which this transition is of first-order, along the [1 0 0] axis is significantly smaller than along the [1 1 1] axis (see Fig. 1).

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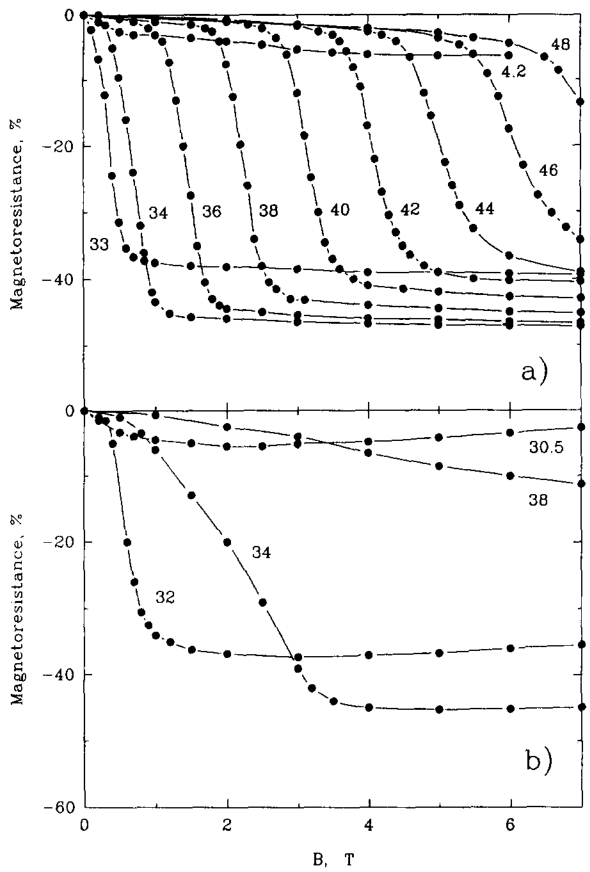

Fig. 1. Field dependences of the longitudinal magnetoresistance $\Delta\rho/\rho$ at various temperatures along [1 1 1] (a) and [1 0 0] (b) axis of $ErCo_2$.

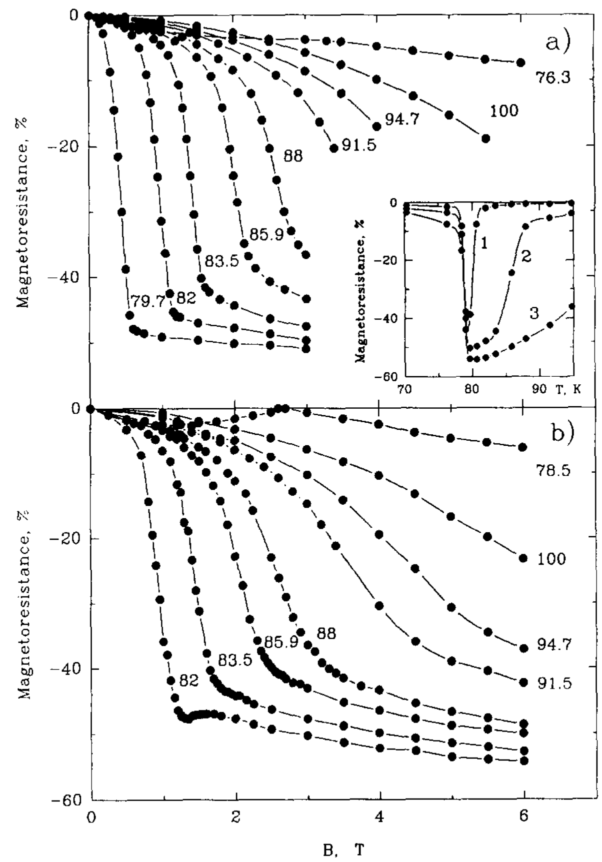

Fig. 2. Magnetoresistance $\Delta\rho/\rho$ *vs.* field for single crystals $HoCo_2$ at various temperatures along [1 1 0] (a) and [1 0 0] (b) axis. Insert shows the temperature dependences of the longitudinal magnetoresistance at different fields: 1 − 0.5; 2 − 2.0; 2 − 6 T.

As can be seen in Fig. 2, a similar behaviour of magnetoresistance at $T > T_C$ is also observed for $HoCo_2$ single crystals. As the RCo_2 compounds have two magnetic subsystems each with a different nature of magnetism (RKKY exchange interaction of localised $4f$ electrons of the rare earth atoms and an itinerant magnetism of the d electrons of Co), both these subsystems can play a role in the transport phenomenon. The electrical resistivity of RCo_2 can be given by an expression:

$$\rho(T, H) = \rho_0(H) + \rho_{ph}(T) + \rho_m(T, H) \quad (1)$$

where $\rho_0(H)$ is the residual resistivity, which includes the spin fluctuations contribution; $\rho_{ph}(T)$ is the phonon scattering contribution; and third term $\rho_m(T, H)$ is due to the scattering on the localised f-electrons, s–d interband scattering and spin fluctuations. As it follows from investigations of the electrical resistivity of RCo_2, the maximal value of ρ_m does not practically depend on the type of R-ion [13] and ρ_m has almost the same value in YCo_2 and in $HoCo_2$, for example. This fact indicates that the contributions from the scattering on localized f-electrons due to the s–f exchange interaction and from s–d scattering are significantly smaller than the contribution from spin fluctuations. The change in the spin fluctuation contribution with temperature causes, in particular, a tendency for saturation of the electrical resistivity in all RCo_2 compounds with increasing temperature.

The calculations of the electronic structure of YCo_2 show that the DOS has the different values in paramagnetic and in high-field induced ferrimagnetic states [9]. The spin fluctuations in RCo_2 can be suppressed by splitting the d-band in an applied magnetic field. This situation has been observed for $Er_{0.55}Y_{0.45}Co_2$ by specific heat and resistivity measurements [14] and for $Y(Co, Al)_2$ by analysis of the magnetization measurements [15]. The sharp decrease in the electrical resistivity at the critical fields in $ErCo_2$ and $HoCo_2$ above T_C can be explained by three phenomena: (a) the quenching of spin fluctuations, (b) the change of s–d interband scattering with splitting of the d-band and (c) decreasing s–f scattering contribution. It follows from the above that the spin fluctuations play a predominant role in the behaviour of magnetoresistance above T_C.

Figure 3 shows the temperature dependences of the critical fields of the metamagnetic transition $H_C(T)$

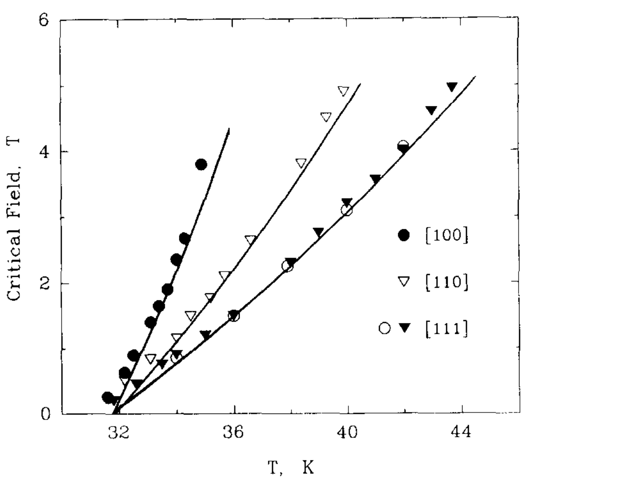

Fig. 3. Temperature dependences of the critical fields measured along the principal crystallographic directions of single crystal $ErCo_2$ (●, ▽, ○ – from magnetization results [12], ▼ – from magnetoresistance results). The solid curves are given by expression: $H_C = \alpha[(T/T_C)^2 - 1]$.

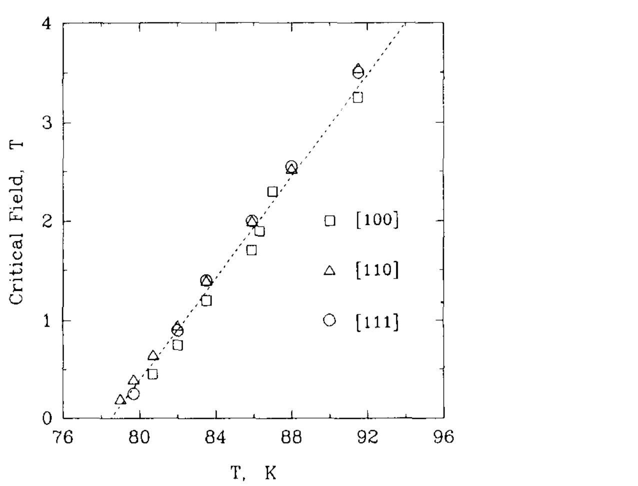

Fig. 4. Temperature dependences of the critical fields measured along the principal crystallographic directions of $HoCo_2$.

obtained from $\Delta\rho/\rho$ data as well as from $M(H)$ measurements [12]. It follows from Fig. 2 that H_C grows nonlinearly with increasing temperature and $(\partial H_C^{[100]}/\partial T) > (\partial H_C^{[110]}/\partial T) > (\partial H_C^{[111]}/\partial T)$. Thus, as noted in [12], in an external magnetic field the magnetic ordering temperature T_C becomes dependent on the direction of measurements. However, as follows from Fig. 4, an anisotropy of the critical fields H_C is absent for $HoCo_2$. This fact can be explained by the difference in the crystal field effects on the Er^{3+} and Ho^{3+} ions. The anisotropy of H_C in $ErCo_2$ at $T > T_C$ is in agreement with the magnetization anisotropy at $T < T_C$ [12]. In $HoCo_2$, as shown by Gignoux *et al.* [16], the free energy differences between the [1 1 0] and [1 0 0] axes and between the [1 1 1] and [1 0 0] axes decrease significantly with an increase in temperature above 40 K. A decreasing free energy difference can cause the small anisotropy of H_C in $HoCo_2$ at $T > 78$ K. The values of the magnetic ordering temperature obtained from the $H_C(T)$ dependences (Figs. 3, 4) for $ErCo_2$ ($T = 31.6$ K) and $HoCo_2$ ($T = 78.5$ K) are in good agreement with the results of other authors [3–7].

The temperature dependences of the critical fields for $ErCo_2$ can be described by the expression

$$H_C = \alpha[(T/T_C)^2 - 1] \tag{2}$$

where α is a coefficient which depends on the field direction. As already shown, in particular, McKinnon *et al.* [17] and Ponomarev [18], a quadratic dependence $H_C(T)$ is typical for first-order magnetic phase transitions of electronic origin, that is, of transitions for which the entropy jump

$$\Delta S = -\Delta \frac{\partial \Phi}{\partial T} = \frac{\partial \Phi_{FI}}{\partial T} - \frac{\partial \Phi_P}{\partial T} \tag{3}$$

is associated at first with a change in the linear term (γT) of the low temperature specific heat (Φ_{FI} and Φ_P are the thermodynamical potentials of the crystal for the ferrimagnetic and paramagnetic states). The thermodynamical potential in this case can be given by

$$\Phi = \Phi_0 - (1/2)\gamma T^2 + F_{em} + F_{me} + F_a - MH \tag{4}$$

where $\Phi_0 = \Phi_0(P)$, $(1/2)\gamma T^2$ is an electronic contribution to the free energy independent of magnetization; F_{em} is a magnetic part of the electronic contribution [19]; F_{me} is a magnetoelastic part of the free energy; F_a is a contribution due to the magnetocrystalline anisotropy; and M is magnetisation. At low temperatures the change in electronic free energy can give the main contribution to the entropy jump. Because Φ_{FI} and Φ_P at H_C are equal, we can write

$$H_C \Delta M = \Delta \Phi_0 - (1/2)\Delta\gamma T^2 \tag{5}$$

where ΔM, $\Delta\Phi$ and $\Delta\gamma$ are differences in M, Φ and γ in the ferrimagnetic and paramagnetic states. The last expression shows the quadratic dependence of $H_C(T)$.

The same situation can take place in $ErCo_2$. As follows from the paramagnon model, the coefficient γ includes not only an electronic contribution, but also the spin fluctuation contribution [20]. The change in the γ value in $ErCo_2$ due to a change in the DOS at the Fermi level and suppression of spin fluctuations at splitting the d-band in an applied magnetic field above T_C, can be significant and therefore can cause the entropy jump and quadratic $H_C(C)$ dependences. In particular, at the metamagnetic transition in $Er_{0.55}Y_{0.45}Co_2$ a decrease in γ by 44% is observed [14]. An increase in the temperature leads to an increase in the other contributions to the entropy jump, foremost of the magnetoelastic contribution. This can cause a change in the temperature dependences of the critical fields and can explain the difference in $H_C(T)$ for $ErCo_2$ and $HoCo_2$ at $T>T_C$, because the value of Curie temperature for $HoCo_2$ is higher than for $ErCo_2$.

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