Effects of pressure and magnetic field on transport properties of \(Y_{1-x}R_x\)Co\(_2\) alloys (R=Gd, Tb, Dy, Ho and Er)

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Abstract. Electrical resistivity \(\rho\) and thermopower \(S\) of \(Y_{1-x}R_x\)Co\(_2\) (R=Gd, Tb, Dy, Ho and Er) Laves phase alloy systems were measured at temperatures from 1.5 K to 300 K in magnetic fields up to 15 T and under hydrostatic pressure up to 2 GPa. We show that there is a universal linear relation between the pressure and magnetic field derivatives of the resistivity, \(d\rho/dP\) and \(d\rho/dB\), with gradient, determined by pressure derivative of the critical metamagnetic field of the cobalt 3d electron system. A similar scaling behavior was found for the thermopower dependencies on pressure and alloy composition.

1. Introduction

The cubic Laves phase compounds RCo\(_2\) (R stands for rare-earth elements and Y) have been extensively studied because of their outstanding magnetic and transport properties. In these compounds, YCo\(_2\) is known as a strongly enhanced Pauli paramagnet whose itinerant 3d-electron subsystem undergoes a metamagnetic transition into the ferromagnetic ground state in the external magnetic field \(B_c \approx 70\) T [1]. In RCo\(_2\) compounds with a nonzero rare-earth 4f magnetic moment, the 4f system has magnetically-ordered ground state. The 4f-3d exchange field of ordered 4f moments exceeds \(B_c\) and it drives the Co subsystem into ferromagnetic ground state too[2]. Due to antiferromagnetic 3d-4f spin-spin coupling [3], the compounds with light R elements are ferromagnetic, whereas those with heavy R are ferrimagnetic.

When a magnetic R-element is substituted by non-magnetic Y, the Curie temperature \(T_c\) decreases and vanishes at a critical composition \(x_c\). Many properties of \(Y_{1-x}R_x\)Co\(_2\) alloys have revealed unusual features. Recently, a strong enhancement of the residual resistivity was found in \(Y_{1-x}\)Gd\(_x\)Co\(_2\) alloys near the phase boundary between the paramagnetic and the ferromagnetic phases [4]. Moreover, in the ferromagnetic part of the phase diagram a large positive magnetoresistance was observed. The latter feature means that, contrary to common expectation, the external magnetic field enhances static magnetic disorder in the ferromagnetic system in its ground state. This unusual characteristic behavior was observed also in other \(Y_{1-x}R_x\)Co\(_2\) (R=Tb, Dy, Ho and Er) alloys [5, 6]. The anomalous behavior of
the low temperature conduction in $Y_{1-x}R_xCo_2$ was explained by the interplay of metamagnetic instability of Co 3d itinerant electrons and structural disorder in the R sublattice, which induces a spatially random distribution of high and low Co 3d magnetization, leading to a partially ordered state of the 3d itinerant electron system [4, 6].

This new state reveals an enhanced susceptibility to external fields, with many of its properties still unexplored. In this paper, we present experimental results on electrical resistivity and thermopower of $Y_{1-x}R_xCo_2$ (R=Gd, Tb, Dy, Ho and Er) alloys measured under pressures ($P$) up to 2 GPa and in magnetic fields ($B$) up to 15 T.

2. Experimental
Polycrystalline samples of $Y_{1-x}R_xCo_2$ were prepared by arc-melting mixtures of rare-earth metals (99.9%) and cobalt (99.9%) with R/Co ratio of 1/1.93 in order to avoid the formation of the magnetic RCo$_3$ phase. The ingots were annealed in vacuum for one week. The cubic Laves phase structure was verified by X-ray diffraction measurement. The measurements of $\rho$ and $S$ were carried out by using standard four-probe dc method and the differential method with a seesaw heating procedure [9], respectively. $\rho$ and $S$ were measured simultaneously at temperatures from 1.5 K to 300 K. A clamp-type piston cylinder pressure cell was utilized for the measurements of $\rho$ and $S$ under pressures up to 2 GPa. The measurements of $\rho$ in magnetic fields up to 15 T were performed at ambient pressure. The direction of the external magnetic field was parallel to the current to reduce additional galvanomagnetic effects.

3. Results and Discussion
Magnetic phase transition temperature of $Y_{1-x}R_xCo_2$ alloys decreases with decreasing content of magnetic R element $x$ and vanishes at a critical concentration $x_c$ - the phase boundary between magnetically ordered ground state and paramagnetic state of 4f localized moments. The magnetoconductivity MR and pressure resistivity PR, defined as $MR = \{\rho(B, T) - \rho(0, T)\} / \rho(0, T)$, and $PR = \{\rho(P, T) - \rho(0, T)\} / \rho(0, T)$, are positive for alloys with $x \geq x_c$ and negative for $x < x_c$. Residual resistivity of the alloys $\rho_0$ rapidly increases with increasing $x$ and attains a maximum value near $x_c$, where MR and PR change their sign. At the maximum $\rho_0$ constitutes about 70% of the room-temperature value of total resistivity of the alloy [4, 5, 6].

Figure 1 depicts the magnetic filed ($\rho(B)$) and pressure ($\rho(P)$) dependencies of resistivity of
Y_{0.82}Gd_{0.18}Co_{2} alloy ($x_{c} = 0.12$ for $Y_{1-x}R_{x}Co_{2}$ system). Both, $\rho(B)$ and $\rho(P)$, measured at $T=2$ K, show almost linear variations with magnetic field or pressure, respectively. From the model developed in our previous papers [4, 6], we can obtain the following relations:

\[ \frac{d\rho}{dP} = \frac{dB_{c}}{dB} \frac{d\rho}{dB}, \quad (1) \]

\[ \frac{d\rho}{dP} = -\frac{1}{B_{\text{exc}}} \left( \frac{dB_{c}}{dP} \right) \frac{d\rho}{dx}, \quad (2) \]

Here $B_{\text{exc}}$ and $B_{c}$ are the exchange molecular field and the critical field of the metamagnetic transition for the 3d band in RCo_{2} compounds, respectively. Equation (1) implies that if the parameter $dB_{c}/dP$ is the same for $Y_{1-x}R_{x}Co_{2}$ alloys (in other words, if the electronic structure of the Co 3d band has the same general features in all $Y_{1-x}R_{x}Co_{2}$ alloys) then there exists a universal linear relation between $\rho/\rho$ and $\rho/B$ for these alloys.

The pressure derivative of resistivity $d\rho/dP$ against magnetic field derivative $d\rho/dB$ for the $Y_{1-x}R_{x}Co_{2}$ alloys is shown in Fig. 2. The plot presents the results for two alloys of each $Y_{1-x}R_{x}Co_{2}$ system (R=Gd, Tb, Dy, Ho and Er): an alloy with $x < x_{c}$ (empty symbols) and another alloy with $x > x_{c}$ (filled symbols). The pressure and magnetic field derivatives were obtained as the mean gradient of the pressure or field dependence of $\rho$ over pressure range from 0 to 2 GPa or magnetic field range of 1 to 15 T. Figure 2 indeed shows a good linear relation between $d\rho/dP$ and $d\rho/dB$, with gradient of about 27 T/GPa, which is in a good agreement with the theoretical estimate for $dB_{c}/dP$ [7] and with the independent experimental determination of $dB_{c}/dP$ for $Y_{1-x}Er_{x}Co_{2}$ and Tm$_{1-x}Er_{x}Co_{2}$ alloys [8].

It has been shown that the electron scattering due to the random distribution of high and low 3d magnetization of partially ordered 3d itinerant electron system has the dominant role for the low temperature thermopower in $Y_{1-x}R_{x}Co_{2}$ alloy systems [10]. This implies that scaling relations similar to those held for resistivity are valid also for the thermopower. From eq. (2), we can obtain the scaling relation between variation of pressure $\Delta P$ and alloy composition $\Delta x$:

\[ \Delta x = -\frac{1}{B_{\text{exc}}} \frac{dB_{c}}{dP} \Delta P. \quad (3) \]

Now we apply this relation to compare in Fig. 3 the composition and pressure dependencies of the low-temperature $a = dS/dT$ for $Y_{1-x}Gd_{x}Co_{2}$ alloys. In this figure, the crosses with broken line as the guide for the eye, show the composition dependence of the thermopower temperature gradient $a$, measured at $T = 2$ K. The results of the thermopower measurements
under pressure for alloys with $x = 0.1 (\triangle), 0.18 (\bigcirc)$ and $0.3 (\bigtriangledown)$ are presented in this figure with pressure transformed into the change of Gd content according to the scaling relation (3). As one can see, the pressure-induced changes and the composition dependence of the thermopower coincide with the scaling relation (3). This indicates the validity of the basic assumptions used to derive the relations (1) to (3) and the dominant role of conduction electron scattering on static magnetic disorder of partially ordered 3d cobalt electron system in the low-temperature electronic transport.

In summary, we have measured the electrical resistivity and thermopower of the five $\text{Y}_{1-x}\text{R}_x\text{Co}_2$ alloy systems ($\text{R} = \text{Gd, Tb, Dy, Ho and Er}$) in magnetic fields up to 15 T and under pressures up to 2 GPa. We obtained a linear relation between the pressure and magnetic field derivatives, $\frac{d\rho}{dP}$ and $\frac{d\rho}{dB}$, for the $\text{Y}_{1-x}\text{R}_x\text{Co}_2$ alloys, with gradient equal to $\frac{dB_c}{dP} \approx 27 \text{ T/GPa}$. A similar scaling relation exists between the pressure-induced changes and the composition dependence of thermopower of the alloys. These results give a further support to the theoretical model of the electronic transport in $\text{Y}_{1-x}\text{R}_x\text{Co}_2$ alloys, developed in our previous publications and indicate that the electronic structure of the Co 3d electron system has common general features in all $\text{Y}_{1-x}\text{R}_x\text{Co}_2$ alloys.

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