Local electron states in chromium-cobalt alloys

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Cr-Co alloys containing up to 10 at.% Co have been investigated. Measurements of the resistivity ρ at temperatures in the range 4.2–420 °K and of the longitudinal magnetoresistivity $\Delta\rho/\rho_0(H)$ at 4.2 °K in magnetic fields up to 120 kOe are presented. It is shown that at low temperatures T the resistivity is a linear function of $T^{1/2}$ with a negative slope; this leads to a minimum on the $\rho(T)$ curves at low temperatures. The magnetoconductivity $\Delta\sigma = \sigma(H) - \sigma(0)$ is found to be proportional to H^2 in weak fields and to be a linear function of $H^{1/2}$ in strong fields. The results of the measurements are discussed from the point of view of the localized-state theory.

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It is of interest to investigate chromium-cobalt alloys for a number of reasons. First, chromium is one of the two metals with antiferromagnetic ordering in the entire 3-*d* series. The temperature dependence of the magnetic structure of chromium below the Néel point T_N is described by a longitudinal or transverse spin-wave density whose wave vector **Q** is incommensurable with the period of the reciprocal lattice. Second, when chromium is doped with transition metals that have more valence electrons than chromium, a new "commensurable" antiferromagnetic structure that is not observed in pure chromium appears at a definite impurity density. As a rule, such impurities raise the Néel temperature T_N, while impurities having fewer valence electrons per atom lower it. A few metals, and these include cobalt, are exceptions to this rule. Neutron diffraction studies[1] have shown that T_N depends nonmonotonically on the cobalt density C. It is of interest to investigate various physical properties of the system of Cr-Co alloys because of the variety of its magnetic structures and the unusual density dependence of its Néel point T_N; moreover, this system is of considerable practical importance because of its Invar-like properties.[2]

We have investigated the electrical resistivity ρ as a function of temperature T in the range $4.2 \leqslant T \leqslant 420$ °K and the longitudinal magnetoresistivity $\Delta\rho/\rho_0$ at $T = 4.2$ °K as a function of the magnetic field strength H at field strengths up to 130 kOe for chromium-cobalt alloys containing up to 10 at.% of cobalt (see Table I).

Figure 1 shows the $\rho(T)$ curves. It will be seen that at cobalt densities $C \geqslant 4$ at.% the curve has a minimum in the low-temperature region. An analogous minimum observed in alloys with cobalt densities up to 8 at.% was attributed by the authors of Refs. 3 and 4 to the Kondo effect. In that case the relation $\rho \sim -\ln T$ should hold, whereas it is evident from Fig. 2 that it does not. That a minimum not associated with the Kondo effect might appear on the $\rho(T)$ curves for disordered metals, semimetals, and highly doped semiconductors was pointed out in Ref. 5, where it was shown that a square-root singularity $\delta\nu(E,T) \sim T^{1/2}$ in the density of states $\delta\nu(E,T)$ near the Fermi surface E_F (E is the energy reckoned from the Fermi level), as well as a square-root singularity in the temperature dependence of the electric resistivity, could be explained by taking the inelastic electron-electron interaction and the elastic scattering of electrons by impurities into account. The presence of electron-electron correlations leads to a decrease of the resistivity with increasing temperature according to the law $\rho \sim -(T)^{1/2}$ when $T \ll 1/\tau$, where τ is the electron relaxation time. When the temperature is increased further the resistance begins to increase, and this leads to a minimum on the $\rho(T)$ curve. As Fig. 2 shows, the experimental $\rho(T)$ curves are well described by the relation $\rho \sim -(T)^{1/2}$ predicted in Ref. 5 at temperatures below that at which the minimum appears. The following relation, ob-

TABLE I.

Specimen	Composition, at.%;	T_N, °K;	T_{min}, °K
1	Cr – 0.4 Co	303	–
2	Cr – 0.8 Co	290	–
3	Cr – 2.0 Co	284	–
4	Cr – 4.1 Co	310	28
5	Cr – 6.2 Co	306	59
6	Cr – 7.9 Co	287	64
7	Cr – 10.0 Co	237	69

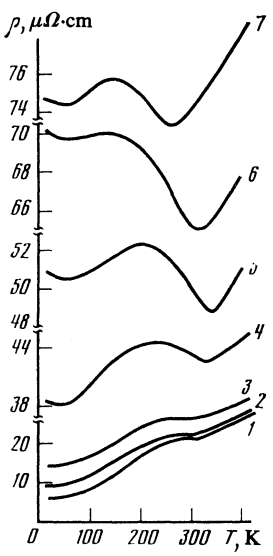

FIG. 1. Temperature dependence of the resistivity of Cr-Co alloys.

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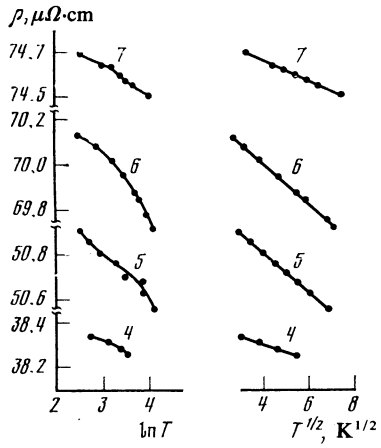

FIG. 2. Temperature dependence of the resistivity of Cr-Co alloys at temperatures T below T_{min}.

tained in Ref. 5, is also satisfied within the measurement errors:

$$\rho_0-\rho(T_{min})\sim T_{min}^{1/2}\rho_0^{5/3}.$$

The high resistivities of the Cr-Co alloys, which are an order of magnitude higher, for example, than those of Cr-Re alloys with corresponding impurity densities, speak in favor of the applicability of the theory proposed in Ref. 5 to the Cr-Co system. In addition, when the cobalt density in the alloys is increased to 6 at.%, the usual metallic trend of the $\rho(T)$ curves disappears throughout a wide range of temperatures.

These features of the conductivity of Cr-Co alloys can be explained from the point of view of Anderson's[6] well-known localized-state theory. This theory, which was originally developed for nonmagnetic solvent metals, was extended in Ref. 7 to chromium, which is a collectivized antiferromagnet. Electron-hole pairing takes place when chromium and its alloys pass from the paramagnetic to the antiferromagnetic state, and this makes it possible to treat these alloys as exciton dielectrics.[8] The impurity level in Cr-Co alloys may fall within the antiferromagnetic gap, which manifests itself in the energy spectrum at temperatures below T_N.[9] When the splitting of spin-up and spin-down levels is large enough, the $E_{d\uparrow}$ level may turn out to lie considerably below the Fermi level E_F. The transition of electrons to this impurity level increases the resistivity over a wide range of temperatures below T_N. Since an excitonic dielectric is similar as regards conductivity to a semiconductor with an equivalent forbidden band Δ, one can calculate the energy gap Δ^ρ from the formula[10] $\rho\sim\exp(-\Delta/2kT)$; Δ^ρ turns out to be of the order of $\sim 10^{-14}$ erg, i.e., an order of magnitude smaller than the energy gap in pure chromium.

Calculations of the exchange splitting on the basis of low-temperature measurements of the magnetic susceptibility,[11] using the formula

$$\chi(0)=ng^2\mu_B^2/2\Delta^\chi,$$

proposed in Ref. 12, where n is the number of magnetic moments per unit mass, g is the Landé g factor, and $\chi(0)$ is the magnetic susceptibility at $T=0$ °K, yielded a value for the exchange splitting Δ^χ of the same order as Δ^ρ; moreover, Δ^χ changes most rapidly when the cobalt concentration C rises from 0.4 to 6 at.% and begins to taper off at $C\geqslant 8$ at.%. The nonmetallic trend of the $\rho(T)$ curves on approaching T_N is observed precisely at $C\geqslant 6$ at.%. At $C\geqslant 8$ at.%, Δ^ρ begins to diminish.

Since the exchange splitting characterizes the interaction of the impurity with the matrix, and is smaller the smaller the matrix element for mixing of the s and d states, the decrease in the growth rate of Δ^χ on increasing the cobalt concentration above 6 at.% may be associated with a decrease in the binding of the cobalt to the chromium matrix. A decrease in the binding to the matrix is accompanied by the formation of Co-Co pairs with a ferromagnetic interaction, and this leads to destruction of the antiferromagnetic structure and confirms the neutron-diffraction results of Ref. 1. At low impurity densities ($C<6$ at.%) the strong interaction of electrons on impurity levels with the matrix results in the magnetic susceptibility of the alloys becoming independent of temperature below T_N and in the absence of local magnetic moments on the cobalt ions.[11] On increasing the cobalt density above 6 at.%, Δ^χ increases and the binding of the impurity to the matrix becomes weaker. As a result, the magnetic susceptibility becomes temperature dependent in accordance with the Curie-Weiss law, and magnetic moments appear on the cobalt ions.

Localization of the electrons also affects the galvanomagnetic effect (Fig. 3). It has been shown[13,14] that local electron states give rise to negative magnetoresistivity, and in strong magnetic fields we have the relation $\Delta\sigma=0.918H^{1/2}$, where $\Delta\sigma=\sigma(H)-\sigma(0)$; here $\sigma(H)$ is the conductivity in an external magnetic field of strength H and $\sigma(0)$ is the conductivity in the absence of a magnetic field. $\Delta\sigma$ should be independent of the parameters of the system. Curves of $\Delta\sigma$ vs $H^{1/2}$ are shown in Fig. 4. It will be seen that in the region in which H is greater than ~ 80 kOe the curves become straight lines: $\Delta\sigma\sim AH^{1/2}$. The value of the coefficient A is 0.9 for specimen No. 5, and 1.0 for specimen No. 6; this is in quite good agreement with the theoretical value of A

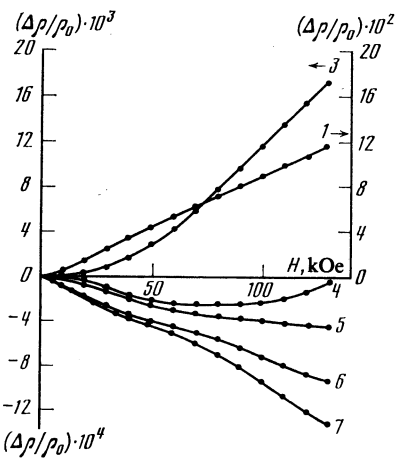

FIG. 3. Longitudinal magnetoresistivity of Cr-Co alloys vs magnetic field strength.

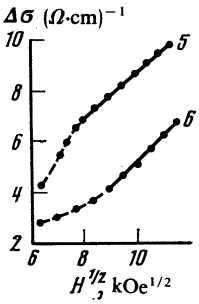

FIG. 4. Field-strength dependence of the magnetoconductivity in strong fields

(the greatest deviation from the theoretical value amounts to about 10%).

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