Electrical resistivity of Ni–Cr–Fe alloys: role of quantum interference effects and of the magnetic state

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An investigation was made of the temperature dependences of the electrical resistivity ρ of Ni–Cr–Fe alloys at 4.2–293 K and of the influence of an external magnetic field up to 30 kOe on these dependences. Minima of ρ were observed at low temperatures ($T \lesssim 20$ K) and these were hardly affected by the applied magnetic field. At higher temperatures the resistivity of the alloys obeyed a quadratic and then a linear temperature dependence. The magnetic and quantum interference contributions of conduction electrons to the dependence $\rho(T)$ were separated; they included the electron–electron, electron–magnon, and electron–phonon interactions.

1. INTRODUCTION

The development of a quantum interference theory has led to intensive investigations of the low-temperature quantum corrections to the conductivity of strongly disordered metals and alloys. However, the mutual influence of the various mechanisms of the scattering of conduction electrons and its role in the determination of the transport properties of such systems have not been investigated sufficiently thoroughly. In investigations of this kind we have to select an object in which we would expect different interference mechanisms of the scattering of conduction electrons: electron–electron, electron–phonon, and electron–magnon; it should also be possible to determine the transport properties in a fairly wide range of temperatures.

A suitable object is a system of high-resistivity Ni–Cr–Fe alloys rich in nickel and with a constant chromium concentration (18%), which have a wide spectrum of low-temperature magnetic states. For example, alloys with the iron concentration $c_{\rm Fe} \lesssim 0.02$ are Pauli paramagnets, a spin glass appears at low temperatures when $c_{\rm Fe} \approx 0.07$, and in the range $0.12 \leqslant c_{\rm Fe} \leqslant 0.37$ a paramagnetic–ferromagnetic–spin glass transition takes place as a result of cooling.[1-3] Such a complex magnetic behavior of Ni–Cr–Fe alloys is due to the presence of Fe, resulting in a negative spin polarization of the NiCr matrix, by analogy with Pd–Fe systems.[1] Moreover, Ni–Cr–Fe alloys are structurally disordered, so that they should exhibit quantum interference effects.

We investigated the electrical resistivity $\rho(c, T)$ of Ni–Cr–Fe alloys with $c_{\rm Cr} = 0.18$ and $c_{\rm Fe}$ ranging from 0.02 to 0.37 at temperatures 4.2–293 K in order to reveal the contributions of the various mechanisms of relaxation of conduction electrons, which can be done correctly only by a simultaneous analysis of the dependences $\rho(T)$ and other physical properties, such as the magnetoresistance $\Delta R/R$, the magnetic susceptibility χ, or the specific heat C.

2. MATERIALS AND MEASUREMENT METHODS

We investigated Ni–Cr–Fe alloys with the chromium concentration $c_{\rm Cr} = 0.18$ and iron concentrations $c_{\rm Fe} = 0.02$, 0.07, 0.12, 0.22, 0.32, and 0.37. Our samples were cylinders 30 mm long and 2 mm in diameter; before the measurements they were subjected to a heat treatment (heating to 1100 °C, maintaining this temperature for 1 h, and cooling in water) which ensured the maximum disorder in these alloys.

The electrical resistivity was determined in the temperature range 4.2–293 K by the four-point method to within 10^{-8} Ω·cm. The temperatures were measured with a Cu–(Cu + Fe) thermocouple, whereas the magnetoresistance measurements were carried out employing a superconducting solenoid capable of generating magnetic fields up to 30 kOe.

3. EXPERIMENTAL RESULTS AND DISCUSSION

The temperature dependences of the electrical resistivity $\rho(T)$ of Ni–Cr–Fe alloys with different Fe concentrations were quite complex (Fig. 1) and included the low-temperature minimum, followed by a power-law rise, and changing to a linear increase in ρ at sufficiently high temperatures. Such dependences $\rho(T)$ indicated that several different mechanisms of the scattering of conduction electrons were responsible for them.

We shall begin with the mechanism inducing a low-temperature resistivity minimum. Our analysis showed that below the temperature of the minimum of the resistivity ρ, i.e.,

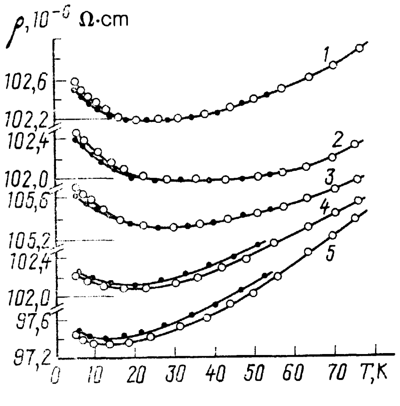

FIG. 1. Temperature dependences of the electrical resistivity of alloys with different iron concentrations $c_{\rm Fe} = 0.07$ (curve 1), 0.12 (curve 2), 0.22 (curve 3), 0.32 (curve 4), and 0.37 (curve 5), recorded in the absence of a magnetic field (○) and in a field $H = 20$ kOe (●).

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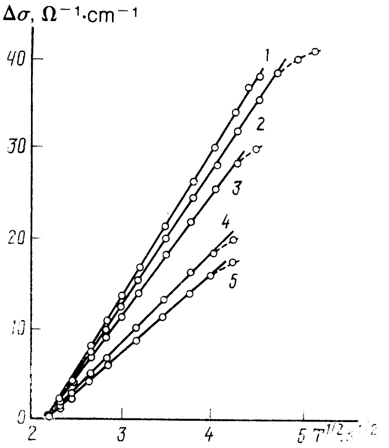

FIG. 2. Dependences of $\Delta\sigma$ on $T^{1/2}$ for alloys with $c_{Fe} = 0.07$ (curve 1), 0.12 (curve 2), 0.22 (curve 3), 0.32 (curve 4), and 0.37 (curve 5).

at $T < T_{\min}$, the temperature dependence was not logarithmic $\Delta\rho \propto \ln T$, which could be expected in the case of a minimum of ρ of magnetic origin,[4] but of the square-root type $\Delta\sigma \propto T^{1/2}$ $[\Delta\sigma = -(\rho_T - \rho_{4.2})/\rho_{4.2}^2]$ (Fig. 2). This circumstance, together with the smallness of the correction to the conductivity $\Delta\sigma/\sigma_0 \ll 1$ and the high value $\rho_{4.2} \approx 10^{-4}$ $\Omega\cdot$cm, was evidence of a strong disorder of the alloys, which enabled us to explain the resistivity minimum by quantum interference effects due to weak localization of electrons ($\Delta\sigma^{\text{loc}}$) and enhancement of the electron–electron interaction caused by the scattering on impurities ($\Delta\sigma^{e-e-\text{imp}}$).[5]

The quantum enhancement of the electron–electron interaction in the diffusion channel is described by the expression[1)]

$$\Delta\sigma^{e-e-imp}(T) = [0{,}61\lambda_\sigma^{(j=0)} + 0{,}69\lambda_\sigma^{(j=1)}]\frac{e^2}{2\pi^2\hbar}\left(\frac{kT}{\hbar D}\right)^{1/2}, \quad (1)$$

where D is the diffusion coefficient of conduction electrons; k and $\hbar$ are the Boltzmann and Planck constants; $\lambda_\sigma^{(j=0)}$ and $\lambda_\sigma^{(j=1)}$ are the constants of the interaction of particles with a total spin of 0 and 1, respectively. Here, $\lambda_\sigma^{(j=0)} = 1$, whereas $\lambda_\sigma^{(j=1)}$ can be expressed in terms of the statistical amplitude F of the scattering process:[5]

$$\lambda_\sigma^{(j=1)} = \frac{32}{3}\left[1 + \frac{3}{4}F - \left(1 + \frac{1}{2}F\right)^{3/2}\right]\frac{1}{F}. \quad (2)$$

It follows from Eq. (2) that $\lambda_\sigma^{(j=1)} < 0$ and $\lambda_\sigma^{(j=1)} = -F$ if $F \ll 1$, so that in this case the first term predominates in Eq. (1). However, in the case of paramagnets with the Stoner enhancement the value of F is quite large and then $\Delta\sigma^{e-e-\text{imp}}$ can exhibit a change of the sign, but the state with $j = 1$ is not realized in the case of a strong spin–orbit interaction and $\Delta\sigma^{e-e-\text{imp}}$ is still governed by the first term in Eq. (1).

The localization correction to the conductivity $\Delta\sigma^{\text{loc}}$ is given by

$$\Delta\sigma^{loc}(T) = \frac{e^2}{2\pi^2\hbar}(D\tau_\varphi)^{-1/2}, \quad (3)$$

where τ_φ is the dephasing time of the electron wave function due to inelastic collisions. In contrast to the two-dimensional case, the localization correction can usually be ignored in the three-dimensional situation because of its smallness: $\Delta\sigma^{\text{loc}} \ll \Delta\sigma^{e-e-\text{imp}}$ (Ref. 5). The smallest correction is due to the fact that the electron–electron interactions characterized by a large transferred momentum predominate in the three-dimensional case, so that $\tau_\varphi^{-1} \propto T^{3/2}$, whereas in the two-dimensional situation we can expect interactions accompanied by a small transferred momentum and we then have $\tau_\varphi^{-1} \propto T$.

The above analysis thus allows us to conclude that the appearance of a low-temperature resistivity minimum is due to an enhanced electron–electron interaction and that at temperatures $T < T_{\min}$ the quantity $\Delta\sigma(T)$ can be described by Eq. (1). The dependences shown in Fig. 2 can then be used to find the diffusion coefficients D_d for alloys with different Fe concentrations (Fig. 3). It is found that D_d increases almost linearly on increase in the Fe concentration and the values of D_d are small compared with those found by calculation in the approximation of the model of free electrons:

$$D = \frac{(3\pi^2)^{2/3}\hbar^2}{3me^2\rho n^{1/3}} \approx 3 \text{ cm}^2/\text{s}.$$

This conflict can be eliminated if we assume that the low-temperature conduction processes involve not only "light" 4s electrons, but also "heavy" 3d electrons characterized by a low mobility and a low diffusion coefficient D_d. In fact, the condition

$$\hbar\tau_V^{-1} < kT, \quad (4)$$

where τ_V is the s–d umklapp time, allows us to rewrite Eq. (1) in the form

$$\Delta\sigma^{e-e-imp}(T) = 0{,}61\lambda_\sigma^{(j=0)}\frac{e^2}{2\pi^2\hbar}\left[\left(\frac{kT}{\hbar D_s}\right)^{1/2} + \left(\frac{kT}{\hbar D_d}\right)^{1/2}\right], \quad (5)$$

where D_s and D_d are the diffusion coefficients of the 4s and 3d electrons, respectively. It follows from Eq. (5) that the main contribution to the low-temperature conductivity correction $\Delta\sigma^{e-e-\text{imp}}$ comes from the 3d electrons with a low value of the diffusion coefficient D_d.

We can use Eq. (4) to estimate τ_V^{-1} which is such that at temperatures $T \ll 20$ the contribution of the s–d umklapp processes is small: $\tau_V^{-1} \ll kT/\hbar = 2.6\cdot 10^{-12}$ s^{-1}.

We can check the above hypothesis on the separate contributions of the 4s and 3d electrons to the quantum interference corrections by considering a situation in which the cor-

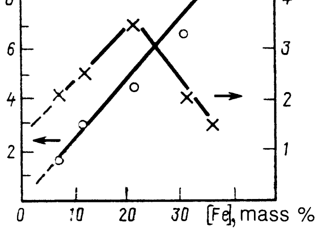

FIG. 3. Diffusion coefficients of the 4s and 3d electrons (D_s and D_d, respectively), plotted as functions of the Fe concentration in the alloys.

rection $\Delta\sigma$ is predominantly due to the 4s electrons. We shall therefore consider the electron localization effects. As pointed out already, in our case we have $\Delta\sigma^{\mathrm{loc}}(T) \ll \Delta\sigma^{e-e-\mathrm{imp}}(T)$ and the temperature dependences of the conductivity do not exhibit the localization correction. However, in the presence of an external magnetic field the contribution of the electron–electron interaction does not change $[\Delta\sigma^{e-e-\mathrm{imp}}(H) = 0]$, whereas the localization contribution changes in accordance with the expression[6]

$$\Delta\sigma^{loc}(H) = \frac{e^2}{2\pi^2\hbar}\left(\frac{eH}{\hbar c}\right)^{1/2} f_3\left(\frac{4DeH}{\hbar c}\tau_\varphi\right), \tag{6}$$

where $f_3(x)$ is a certain function with the asymptotes

$$f_3(x) = \begin{cases} 0{,}605, & x \gg 1, \\ x^{3/2}/48, & x \ll 1. \end{cases}$$

The contribution $\Delta\sigma^{\mathrm{loc}}(H)$ appears because the application of an external magnetic field disturbs the interference conditions and, in general, this contribution is negative.[6] It follows from Eq. (6) that when the condition (4) is satisfied, the main contribution to $\Delta\sigma(H)$ should come from the 4s electrons characterized by higher diffusion coefficients.

The experimental dependences of the magnetoresistance $\Delta R/R$ on the field H were determined at temperatures 4.2–20 K (Fig. 4). Clearly, the values of $\Delta R/R$ for the alloys with $c_{\mathrm{Fe}} = 0.07$–0.22 were negative, whereas in the case of the alloys with $c_{\mathrm{Fe}} = 0.32$ and 0.37 it was found that $\Delta R/R > 0$ and it differed from zero not only at $T < T_{\min}$, but also at $T > T_{\min}$ (it was found that $T_{\min} = 16$ and 12 K for the alloys with $c_{\mathrm{Fe}} = 0.32$ and $c_{\mathrm{Fe}} = 0.37$, respectively; see Fig. 1).

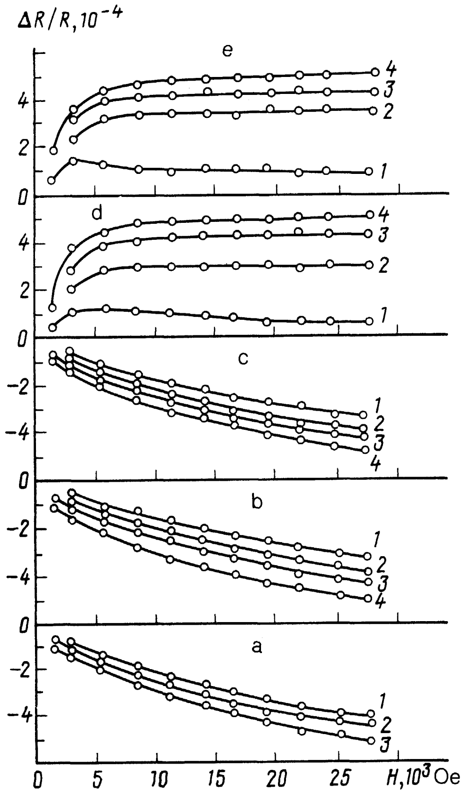

FIG. 4. Magnetoresistance of alloys with $c_{\mathrm{Fe}} = 0.07$ (a), 0.12 (b), 0.22 (c), 0.32 (d), and 0.37 (e) at temperatures 4.2 K (1), 10 K (2), 15 K (3), and 20 K (4).

An analysis of the negative magnetoresistance of the alloys with $c_{\mathrm{Fe}} = 0.07$–0.22 carried out using the localization theory showed that the dependences plotted in the form $\Delta\sigma(H)/H^{1/2} = f(\ln H)$ were in good agreement with the theoretical dependences

$$(e^2/2\pi^2\hbar)(eH/\hbar c)^{1/2}H^{-1/2}f_3(4DeH\tau_\varphi/\hbar c) = f[\ln(4DeH\tau_\varphi/\hbar c)].$$

When the scales of $\ln H$ and $\ln(4DeH\tau_\varphi/\hbar c) = \ln H + \ln D\tau_\varphi + \mathrm{const}$ were made to coincide along the abscissa, we were able to determine the value of $D\tau_\varphi$, whose temperature dependence should be described by the expression $(D\tau_\varphi)^{-1} = AT^3$ (Fig. 5). The power exponent found in this way was 3 and it demonstrated the dominant role of phonons in the processes of inelastic scattering of conduction electrons, because in the case of scattering on electrons it should amount to 3/2 (Refs. 5 and 7).

The coincidence of the experimental curves for the alloy with $c_{\mathrm{Fe}} = 0.07$ with the theoretical dependences was observed as a result of an additional shift along the ordinate, indicating the presence of a small ($\lesssim 7\%$) additive contribution to the magnetoconductance. This contribution reached saturation in a magnetic field ≈ 1 kOe and could be related to the ordering of the local magnetic moments in the low-temperature spin glass phase.[3]

The values of $D\tau_\varphi$ allowed us to determine the diffusion coefficients D_s of the conduction electrons by comparison of the experimentally determined (Fig. 5) values of $\tau_\varphi^{-1} = AD_sT^3$ with the expression for the electron–phonon relaxation time:[8]

$$\tau_{e-ph}^{-1} = \frac{7\pi}{2}\lambda_{e-ph}\zeta(3)\,\frac{kT^3}{\hbar\theta^2}. \tag{7}$$

Here, $\lambda_{e-\mathrm{ph}}$ is the electron–phonon interaction constant; $\zeta(x)$ is the Riemann zeta function; θ is the Debye temperature. Using $\theta = 390$–400 K (Ref. 9), $\lambda_{e-\mathrm{ph}} = 0.6$ (Ref. 10), and $\zeta(3) = 1.2$, we obtained $D_s \approx 1$–4 cm²/s, in good agreement with the calculated value $D_s \approx 3$ cm²/s, obtained using the theory of free electrons (Fig. 3).

The magnetoresistance of the alloys with $c_{\mathrm{Fe}} = 0.32$ and 0.37 was found to include not only the localization contribution, but also an additional term manifested by a positive value of $\Delta R/R$ at $T > T_{\min}$ (Fig. 4) and associated with ferromagnetism. Separation of this contribution yielded

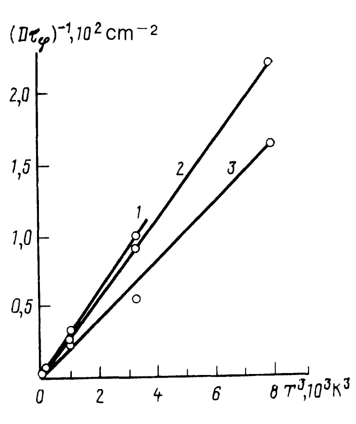

FIG. 5. Dependences $(D\tau_\varphi)^{-1} = f(T^3)$ obtained for alloys with $c_{\mathrm{Fe}} = 0.07$ (line 1), 0.12 (line 2), and 0.22 (line 3), obtained from Eq. (6) (continuous lines). The points are the experimental values.

negative values of $\Delta R/R$ at $T < T_{\min}$. An analysis using the localization theory also allowed us to obtain the value of D_s for these alloys (Fig. 3).

Our investigation of the low-temperature conductivity of Ni–Cr–Fe alloys at $T = 4.2$–20 K thus revealed the existence of separate contributions of the $3d$ and $4s$ electrons to the electron–electron interaction and to the weak localization of electrons, resulting in an increase in ρ as a result of lowering of T and the appearance of a magnetoresistance, respectively. The magnetic contribution to the temperature dependence $\rho(T)$ was negligible and in the field dependences of the magnetoresistance it was important for the alloys with $c_{\rm Fe} = 0.32$ and 0.37.

We shall now consider the power-law rise of ρ with temperature in the range $T \approx 30$–100 K (Fig. 1). According to Ref. 11, in the systems in which the effects of the weak localization of electrons and of the electron–electron interaction predominate at low temperatures, an increase in temperature should reveal interference between the electron–phonon and electron–impurity interactions, whereas in the case of magnetically ordered systems there should be additional electron–magnon–impurity interference processes. It therefore follows that the total correction to the conductivity is governed by the sum of the corrections representing the electron–phonon $\Delta\sigma^{e-\rm ph}$ and the electron–magnon $\Delta\sigma^{e-m}$ mechanisms, by the interference corrections to the electron–electron $\Delta\sigma^{e-e-\rm imp}$, electron–phonon $\Delta\sigma^{e-\rm ph-imp}$, and electron–magnon $\Delta\sigma^{e-m-\rm imp}$ interactions under the impurity scattering conditions, as well as by the correction $\Delta\sigma^{U}$ associated with the umklapp (U) processes:

$$\frac{\Delta\sigma}{\sigma_0}(T)=\frac{\Delta\sigma^{e-ph}}{\sigma_0}+\frac{\Delta\sigma^{e-m}}{\sigma_0}+\frac{\Delta\sigma^{e-e-imp}}{\sigma_0}+\frac{\Delta\sigma^{e-ph-imp}}{\sigma_0}+\frac{\Delta\sigma^{e-m-imp}}{\sigma_0}+\frac{\Delta\sigma^{U}}{\sigma_0}, \tag{8}$$

where σ_0 is the conductivity at 0 K.

The expressions for the corresponding contributions have different signs and different temperature dependences. We shall consider them separately. The electron–phonon contribution is

$$\frac{\Delta\sigma^{e-ph}}{\sigma_0}=-\frac{60\pi\zeta(5)\beta_l}{(p_F u_l)^2}T^5=-A_1T^5, \tag{9}$$

where $\beta_l = (\frac{2}{3}\varepsilon_F)^2\nu(\varepsilon_F)/2MNu_l^2$; ε_F is the Fermi energy; $\nu(\varepsilon_F)$ is the density of the electron states; M is the atom mass; N is the number of unit cells; u_l is the longitudinal velocity of sound; p_F is the Fermi momentum. The contribution of Eq. (9), representing the Grüneisen formula, is shown in Ref. 11 to be negligible compared with the other terms of Eq. (8).

The contribution of the electron–magnon interaction is described by

$$\frac{\Delta\sigma^{e-m}}{\sigma_0}=-\frac{\pi^3 S\tau Z}{4aT_C}T^2=-A_2T^2, \tag{10}$$

where S is the spin; Z is the valence; τ is the total relaxation time of electrons; T_C is the Curie temperature; a is a constant close to unity. The presence of magnons in the investigated alloys is due to the magnetic ordering in that range of temperatures where the alloys become Stoner paramagnets with an enhanced exchange interaction. At low temperatures this state changes to the glass phase. The actual temperature of these transitions in our alloys can be found in Ref. 3. We shall simply note here an agreement between the temperature of the resistivity minimum $T_{\min}$ and the temperature of the transition to the spin glass state T_f.

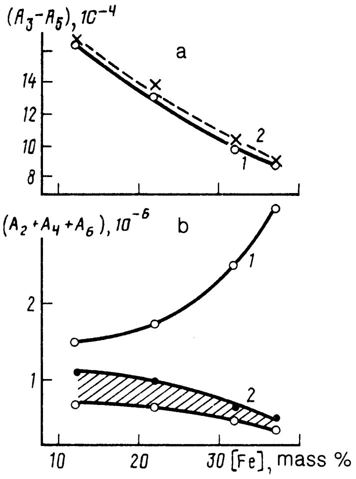

FIG. 6. a) Composition dependence of the coefficients (A_3-A_5) (curve 1) and A_3 (curve 2). b) Composition dependences of the coefficients $(A_2+A_4+A_6)$ (curve 1) and A_2 (curve 2) for $v_F = 1.5\times 10^8$ cm/s (●) and 1.8×10^8 cm/s (○).

The quantities in Eq. (10) are, in principle, known so that we can calculate the coefficient A_2. Its composition dependence is plotted in Fig. 6. The multivalued nature of the curve is due to a certain interval of the possible values of $v_F = (1.5$–$1.8)\times 10^8$ cm/s, which govern the relaxation time

$$\tau=\frac{3\sigma_0}{e^2\nu(\varepsilon_F)v_F{}^2}$$

[the values of $\nu(\varepsilon_F)$ for these alloys are taken from Ref. 9]. An important feature is the rise of the value of A_2 on reduction in the Fe content in the alloys.

The quantum correction to the conductivity associated with the electron–electron interaction is governed (as shown already) by the $3d$ electrons and can be represented in the form

$$\frac{\Delta\sigma^{e-e-imp}}{\sigma_0}=0{,}61\lambda_\sigma^{(j=0)}\frac{e^2}{2\pi^2\hbar}\left(\frac{k}{\hbar D_d}\right)^{1/2}\sigma_0{}^{-1}T^{1/2}=A_3T^{1/2}. \tag{11}$$

The quantum corrections due to the electron–phonon and electron–magnon interactions under the impurity scattering conditions are described respectively by the following expressions:

$$\frac{\Delta\sigma^{e-ph-imp}}{\sigma_0}=\left[\frac{4}{3\pi^2}-\frac{1}{12}-\frac{8}{3\pi^2}\left(\frac{u_l}{u_t}\right)^3\right]\frac{\pi^4\beta_l}{2\varepsilon_F p_F u_l}T^2=-A_4T^2, \tag{12}$$

$$\frac{\Delta\sigma^{e-m-imp}}{\sigma_0}=-2{,}5\frac{3\pi^2}{32}SZ\left(\frac{J}{\varepsilon_F}\right)^2T_C{}^{-1/2}T^{1/2}=-A_5T^{1/2}, \tag{13}$$

where u_t is the transverse velocity of sound; S is the spin; Z is a valence; J is the exchange integral. Equation (13) is valid if the phonon wave vector satisfies the condition $q_T \gg q_0 = 2JS/v_F$ (Ref. 11), which for these alloys corresponds to $T > T_f$. If $q_T \ll q_0$, then the functional nature of the correction changes so that we have $\Delta\sigma^{e-m-\mathrm{imp}}/\sigma_0 \propto T^{3/2}$. However, as pointed out already if $T < T_f$, the investigated alloys become magnetically disordered.

Finally, the contribution due to the umklapp processes is of the form

$$\frac{\Delta\sigma^U}{\sigma_0} = -\frac{e^2 m^3 r_s^4 \tau k^2 \Delta_U}{8\pi\hbar^7} T^2 = -A_6 T^2, \tag{14}$$

where r_s is the screening radius; τ is the electron elastic-relaxation time; $\Delta_U \lesssim 1$ is a factor associated with the umklapp (U) processes. Estimates indicate that the contribution of Eq. (14) is negligible in the case of the 4s electrons. However, if we allow for the umklapp processes in the 3d-electron bands, we find that the magnitude of this contribution can become comparable with the contributions of Eqs. (10)–(12).

It therefore follows that the general expression (8) for $\Delta\sigma/\sigma_0$ is derived subject to the above considerations and can be represented in the form

$$\frac{\Delta\sigma}{\sigma_0}(T) = (A_3 - A_5) T^{1/2} - (A_2 + A_4 + A_6) T^2. \tag{15}$$

The results of an approximation of the experimental dependences with Eq. (15) are plotted in Fig. 7. It is clear from this figure that in a fairly wide range of temperatures (20–80 K) the dependence is linear when plotted in the form $\Delta\rho/\rho_0 T^{1/2} = f(T^{3/2})$. The intercept on the ordinate allows us to determine the coefficient $(A_3 - A_5)$. Since the values of A_3 were obtained earlier independently from an analysis of the low-temperature electrical resistivity minimum, we were able to find the coefficient A_5 and thus separate the contribution $\Delta\sigma^{e-m-\mathrm{imp}}$. The results are plotted in Fig. 6. We can see that the values of the coefficients $(A_3 - A_5)$ and A_3 were similar, i.e., we found that $A_3 \gg A_5$, so that the low-temperature resistivity minimum was indeed due to the interference electron–electron interaction.

The slopes of the straight lines in Fig. 7 allowed us to find the combined coefficient $(A_2 + A_4 + A_6)$, which increased on increase in the c_{Fe} concentration (curve 1 in Fig. 6). This composition dependence could not be due to the contribution of $\Delta\sigma^{e-m}/\sigma_0$ (curve 2 in Fig. 6) or the contribution of $\Delta\sigma^U/\sigma_0$, governed primarily by the corresponding dependence of the density of the electron states (curve 3 in Fig. 8). We therefore concluded that the dominant role was played by the contribution of $\Delta\sigma^{e-\mathrm{ph}-\mathrm{imp}}/\sigma_0$, whose composition dependence could be attributed mainly to ε_F.

Nevertheless, the role of the magnetic contribution was considerable in this range of temperatures, as deduced from an analysis of the experimentally observed correlation between the temperatures $T_{\min}$ and T_f for the investigated alloys and from an increase in these temperatures on increase in c_{Fe}. This could be explained bearing in mind that the transition to the spin glass state at T_f was accompanied by magnetic disordering and, consequently, by disappearance of the "magnetic" terms of Eqs. (10) and (13) in the overall dependence (15). Assuming that at $T = T_f$ the term $\Delta\sigma^{e-m}/\sigma_0$ (exactly as $\Delta\sigma^{e-m-\mathrm{imp}}/\sigma_0$) changed abruptly, we found that at $T < T_f$ of Eq. (15) became

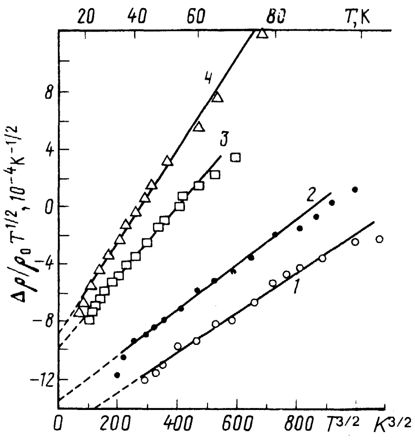

FIG. 7. Temperature dependences of $\Delta\rho$ plotted in the form $\Delta\rho/\rho_0 T^{1/2} = f(T^{3/2})$ on the basis of calculations carried out using Eq. (15) for alloys with $c_{\mathrm{Fe}} = 0.12$ (1), 0.22 (2), 0.32 (3), and 0.37 (4).

$$\frac{\Delta\sigma}{\sigma_0}(T) = A_3 T^{1/2} - (A_4 + A_6) T^2. \tag{16}$$

The two equations (15) and (16) represented curves with minima, so that $(T_{\min})_1$ was the temperature of the minimum when the magnetic contribution was allowed and $(T_{\min})_2$ when it was not allowed.

We thus found that the temperature of the minimum of the resistivity ρ on disappearance of the electron–magnon interaction should increase by a factor of

$$\frac{(T_{\min})_2}{(T_{\min})_1} = \left(\frac{A_2 + A_4 + A_6}{A_4 + A_6}\right)^{2/3}$$

in agreement with the experimental results. Thus, in the case of the investigated alloys the shift of $T_{\min}$ increased on reduction in the magnetic susceptibility due to the spin glass transition at T_f (Ref. 3). The existence of the shift related to the reduction in $\Delta\sigma^{e-m}$ was also responsible for the observed correlation between the values of $T_{\min}$ and T_f.

We thus found that the power-law increase in ρ of the investigated alloys at temperatures $T \approx 30$–100 K was due to the quantum interference contribution of the electron–phonon interaction, due to the electron–magnon contribution and, obviously also due to the umklapp processes involving the 3d electrons.

We shall conclude by considering the linear temperature dependences $\rho(T)$ found for the investigated alloys at $T \approx 100$–300 K. It is clear from the preceding analysis that the interference mechanisms of the scattering of conduction electrons appeared at lower temperatures and, consequently, in this temperature range the usual phonon scattering mechanism was active. However, since at lower temperatures the interference effects were governed by the contributions of the s and d electrons, we could expect that their role to be significant at higher temperatures.

Inclusion of the s and d electrons allows us to write down the electrical resistivity in the form

$$\rho(T) \propto \left(\frac{v_s S_s}{\omega_{ss} + \omega_{sd}} + \frac{v_d S_d}{\omega_{dd} + \omega_{ds}}\right)^{-1} \frac{T}{\theta^2}, \tag{17}$$

where

$$\omega_{ss} \propto b_{ss} p_s \nu_s(\varepsilon_F), \quad \omega_{dd} \propto b_{dd} p_d \nu_d(\varepsilon_F),$$
$$\omega_{sd} \propto b_{sd} p_{sd} \nu_d(\varepsilon_F), \quad \omega_{ds} \propto b_{sd} p_{sd} \nu_s(\varepsilon_F)$$

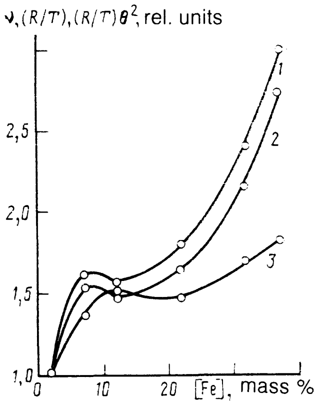

FIG. 8. Composition dependence of the slopes of the straight lines R/T (curve 1), of the normalized slopes of the straight lines $R/T\theta^2$ (curve 2) and of the density of the electron states $\nu(\varepsilon_F)$ (curve 3).

if $T \gg \theta$. Here, v_s and v_d are the velocities of electrons in the relevant valley of the Fermi surface; s is the Fermi surface area; ω is the frequency of intravalley and intervalley collisions of electrons with phonons; b_p is the matrix element of the electron–phonon interactions (p_s and p_d are the dimensions of the Fermi surface sheets and p_{sd} is the distance between them in the **p** space).

Since we have $v_s \gg v_d$ and, consequently, $\nu_d \gg \nu_s$, it follows from Eq. (17) that

$$\rho \propto \frac{\nu(\varepsilon_F)}{v_s s_s} \frac{T}{\theta^2}, \qquad (18)$$

i.e., the composition dependence of the slope of the straight lines $\rho(T)$ of the investigated alloy should be governed primarily by the composition dependence of the density of states.

Figure 8 shows the experimental values of the slopes of the dependences $\rho(T)$ and the data on the density of the electron states obtained from measurements of the specific heat of the investigated alloys.[9] For convenience of comparison, these quantities are normalized to the corresponding values for an alloy with the minimum value and characterized by $c_{\mathrm{Fe}} = 0.02$. We can see that the composition dependences of the quantities being compared are qualitatively similar. Some discrepancy may be the result of simplifying assumptions made in the derivation of Eq. (18).

It therefore follows that the linear dependence $\rho(T)$ observed for the investigated alloys at $T \approx 100$–300 K is due to the phonon mechanism of the scattering of conduction electrons involving both s and d carriers.

4. CONCLUSIONS

Our analysis of the experimental dependences $\rho(T)$ of Ni–Cr–Fe alloys shows that the low-temperature characteristic features of the electrical resistivity and magnetoresistance can be explained by quantum effects of the electron–electron interaction and weak localization of electrons, respectively. It is shown above that the low-temperature branch of the minimum of ρ is formed primarily by the "heavy" $3d$ electrons, whereas the magnetoresistance appears because an external magnetic field disturbs the conditions of localization of the "light" $4s$ electrons.

In the region where ρ rises with temperature in accordance with a power law, the main contribution is due to the quantum interference effects of the electron–electron and also the electron–magnon interactions and obviously due to the umklapp processes involving the $3d$ electrons. The major change in the electron–magnon contribution at the temperature T_f of the transition to the low-temperature spin glass phase shifts the temperature of the minimum of the resistivity ρ toward higher temperatures and this accounts for the correlation between $T_{\min}$ and T_f exhibited by the investigated alloys.

The linear dependence of ρ on T at $T \approx 100$–300 K is due to the phonon mechanism of the scattering of conduction electrons involving both the s and d carriers. The magnitude of the resistivity is proportional to the density of the electron states.

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1) In this investigation all the expressions of the quantum interference theory are given for the three-dimensional case when $L_1, L_2, L_3 \gg L_\varphi$; here, L_1, L_2, and L_3 are the dimensions of the sample and L_φ is the characteristic dephasing length of electrons.

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