

Electron transport properties of β -phase $\text{Co}_{0.50}\text{Ti}_{0.50}$ alloy films with various degrees of long range order

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Abstract. The influence of the structural disorder on the electron transport properties of $\text{Co}_{0.50}\text{Ti}_{0.50}$ alloy films in a temperature range of 4.2–300 K has been investigated at zero and 0.5 T of magnetic field. The disordered state in the alloy films was obtained by vapor quenching deposition onto substrates cooled by liquid nitrogen. The changes in the transport properties of the alloy films caused by the order-disorder structural transformation and the external magnetic field are explained by the analyses using various models for the electron transport in the disordered systems.

PACS. 72.15.Qm Scattering mechanisms and Kondo effect – 72.80.Ng Disordered solids – 73.61.At Metal and metallic alloys

1 Introduction

The electronic structures, physical properties and thermal stability of $3d$ transition metal compounds in connection with peculiarities of their crystalline structures have been a focus of many investigations during recent years. β -phase Co-Ti alloys have a CsCl-type (B2) crystal structure in a Ti concentration range of 49.5–54.2 at% at 873 K, and are stable up to the melting point (1508 K) [1]. The high stability of the alloys is closely related to a significant ionic character of the metallic bonding due to a substantial charge transfer from Ti to Co atoms. The nature of the high stability of CoTi compound was discussed in reference [2] in terms of band filling. The magnetic measurements and the spin-polarized linear-muffin-tin-orbital (LMTO) calculations of the perfectly ordered equiatomic CoTi alloy have shown that this compound is paramagnetic with no magnetic moment of the Co atoms [3,4]. It was also argued that such a magnetic behavior of CoTi compound arises from the specific local environment [3].

In contrast to the ordered state of CoTi alloy, the Co and Ti atoms can randomly occupy the sites of bcc lattice in the disordered state. It might be expected that this change in symmetry and basis of the unit cell itself leads to drastic changes in electronic energy structures (EES) and physical properties of this alloy. The electronic structure and some physical properties of B2-phase CoTi have been calculated several times [2,4–8]. The calculated density of states (DOS) for the ordered CoTi compound are

almost the same in all these publications; the DOS curve has two main peaks, separated by a deep minimum or pseudogap. The Fermi level of CoTi compound is located on the shallow plateau just above the pseudogap. The occupied bands are composed mainly of the Co d character, while the empty bands are dominated by the Ti d character with an admixture of the Co d character. Taking into account the characteristics of the states near the Fermi level, one can also expect that an influence of the structural disorder in Co-Ti alloy on the transport properties will be significant. Indeed, according to the results of the theoretical calculations of the DOS for the pseudobinary $\text{Co}(\text{Ti}_{1-x}\text{Al}_x)$ alloys with $0 < x < 1$, a significant increase in the DOS near the Fermi level was observed in comparison with the ordered state [4]. The same tendency should be observed for the equiatomic binary alloy.

We have already investigated the influence of the structural order-disorder transformation on various physical properties of the B2-phase Co-Al alloys [9–11] and Fe-Al alloys [12–14]. The observed significant changes in physical properties of these alloys were attributed to the appearance of the transition metal antistructure atoms (TM-ASA), resulting in a formation of magnetic clusters, and to a substantial increase of localized states near the Fermi level.

CoTi compound is stable up to the melting point, which impedes the formation of a significantly disordered state in this alloy even by quenching the molten alloy. It is well-known that thin film technology allows us to prepare metals and alloys in various metastable states which

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sometimes can not be obtained in the bulk materials. Therefore, it seems to us very attractive to apply thin film technology to obtain CoTi alloy in the disordered state for the purpose of studying various physical properties of the disordered CoTi alloy. A significant structural disorder and an arbitrary occupation of the sites of bcc lattice by the Co and Ti atoms change the local environment and create the Co-ASA or their clusters in CoTi alloy and, hence, cause some changes in the magnetic state of the alloy. The appearance of these magnetic clusters can be considered as additional scattering centers and their manifestation can be found by investigating the transport properties of the alloys in various states with different long-range order.

There are very few experimental studies of the transport properties of the equiatomic CoTi alloys. The temperature dependence of the resistivity of an as-cast bulk CoTi equiatomic alloy in a temperature range of 20–300 K was studied by Goff [15]. An indirect knowledge about the direct current (DC) conductivity of the ordered bulk CoTi equiatomic β -phase alloy can be obtained from the analyses of the optical measurements by Sasovskaya [16]. To the best of our knowledge, the effect of the structural disorder on the resistivity of CoTi alloy has not been investigated yet. Thus, the purpose of this paper is to obtain the equiatomic CoTi alloy in the disordered state and to study experimentally the influence of the structural order-disorder transformation on its transport properties.

This paper is organized as follows; Section 2 contains a brief description of the sample preparation and experimental details, the experimental results are shown in Section 3 and interpreted in Section 4, Section 5 summarizes and concludes the paper.

2 Experimental procedure

β -phase $\text{Co}_{0.50}\text{Ti}_{0.50}$ alloy was prepared by melting Co and Ti pieces of 99.99% purity in an arc furnace with a water cooled Cu hearth. In order to obtain the volume homogeneity the ingot was remelted twice and then annealed at 1300 K for 6 h. Any weight loss after the repeated melting and the heat treatment was not observed. In order to prepare the disordered alloy, the advantages of thin film technology were employed.

$\text{Co}_{0.50}\text{Ti}_{0.50}$ alloy films with a total thickness of about 100 nm and of 10×30 mm in dimensions were prepared by flash evaporation [17] of the crushed alloy powders of 80–100 μm in diameter onto glass, and single-crystalline Si and NaCl substrates simultaneously in a high vacuum conditions better than 5×10^{-5} Pa. The thin film samples deposited onto glass and Si substrates were mainly used for the measurements of the transport and magnetic properties, while those deposited onto NaCl substrates were used for the structural study.

The deposition rate was about 2 nm/s. Such a high deposition rate was chosen to reduce the volume contamination and oxidation of the films. An equiatomic ordered β -phase in these films was reached by the deposition onto heated substrates up to 730 K (state 1).

In order to obtain a disordered state in the film, a vapor quenching deposition technique was employed, where a chaos of gas phase is condensed onto substrates cooled down to 150 K by liquid nitrogen (state 2). All the films prepared at 150 K were cut into two parts and one set of halves was put into a vacuum chamber and annealed at 730 K for 45 min in a high vacuum of 1×10^{-5} Pa (state 3).

X-ray fluorescence of the prepared samples confirmed their equiatomic composition. Structural analyses of the films were performed by using transmission electron microscopy (TEM). The resistivity measurements were carried out by the four-probe technique in a temperature range of 4.2–300 K with and without an external magnetic field of 0.5 T directed normally to the film plane.

3 Experimental results

The TEM patterns of the film deposited onto the substrate at 730 K exhibits a mixture of diffraction rings typical for bcc lattice and a series of additional superstructure rings which are attributed to the reflections from the (100), (111) and (210) atomic planes, as in references [10, 12]. The mean grain size is about 35 nm. This result shows that a stable phase of the superlattice with a high degree of long range order (η) is formed at our deposition conditions, even though η of state 1 (η_1) can not be estimated quantitatively.

Lowering the substrate temperature down to 150 K leads to the formation of a considerably disordered polycrystalline alloy films without any visible superstructure ring (state 2, $\eta_2 \sim 0$) also as in references [10,12] and the mean grain size is less than 5 nm. An annealing of these disordered films at 730 K for 45 min causes a recovery of the structural rings with prominent diffraction spots on them and an appearance of weak superstructural diffraction rings typical for the B2 structure. However, comparing with the ordered films, the intensity ratio of the superstructural diffraction rings to the structural ones is low. Therefore, it is clear that η_3 in such a film (state 3) is smaller than η_1 , but the mean grain size is slightly larger (about 50 nm). Thus, it can be concluded that such a deposition technique and additional heat treatment allow us to prepare a set of $\text{Co}_{0.50}\text{Ti}_{0.50}$ alloy films with various degrees of long range order: $\eta_1 \sim 1 > \eta_3 > \eta_2 \sim 0$.

Figure 1 presents the temperature dependences of the normalized resistivity for the $\text{Co}_{0.50}\text{Ti}_{0.50}$ alloy films with various degrees of long range order, revealing significantly different behavior depending on η . The details of these dependences at low temperatures (4.2–30 K) with zero and 0.5 T of magnetic field are shown in Figures 2–4. The ordered $\text{Co}_{0.50}\text{Ti}_{0.50}$ alloy films exhibit a typical metallic behavior with a positive temperature coefficient of resistivity (TCR) in the whole investigated temperature range and have a resistivity at room temperature (RT) of about 218 $\mu\Omega\text{cm}$. This value is significantly larger than the corresponding value calculated from the optical data [16] of the bulk ordered alloy (66.6 $\mu\Omega\text{cm}$) and much larger

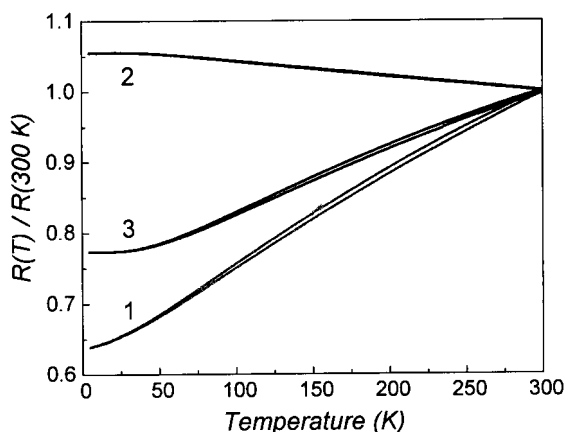


Fig. 1. Variation of the normalized resistivity with temperature (during both cooling and heating) for the ordered (1), partly disordered (3), and disordered (2) $\text{Co}_{0.50}\text{Ti}_{0.50}$ alloy film.

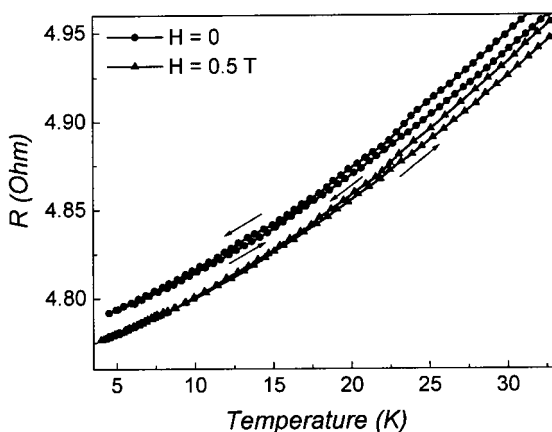


Fig. 2. Resistance of the ordered (state 1) $\text{Co}_{0.50}\text{Ti}_{0.50}$ alloy films as a function of temperature during both cooling and heating, measured at zero (circles) and 0.5 T (triangles) magnetic field.

than the results obtained by Goff for as-cast bulk alloys ($25\ \mu\Omega\text{cm}$) [15]. The reason for this significant discrepancy in resistivity between the ordered film and the bulk $\text{Co}_{0.50}\text{Ti}_{0.50}$ alloy samples can be explained by a finer grain structure of the films.

4 Interpretation

The usual expression for the temperature dependence of the resistivity of metals and alloys can be described by the Matthiessen rule $\rho(T) = \rho_0 + \rho_i(T)$, where ρ_0 is the temperature independent residual resistivity (mainly due to electron defect scattering without absorption or emission of phonons) and $\rho_i(T)$ is the so-called “ideal” resistivity provided by inelastic electron scattering. The “ideal” resistivity includes the electron-phonon, electron-electron and electron-magnon (for magnetic materials) scatterings. Each mechanism gives rise to a different power law T^α of the temperature dependence of resistivity.

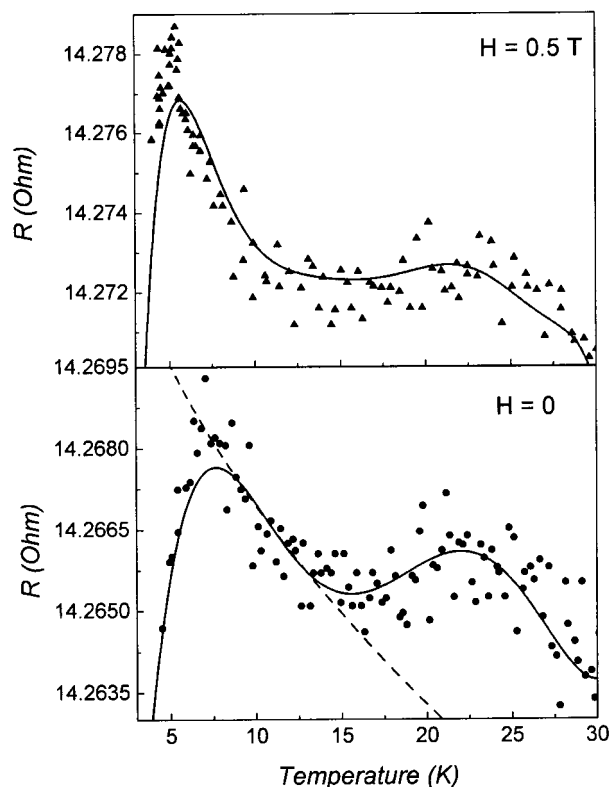


Fig. 3. Resistance of the disordered $\text{Co}_{0.50}\text{Ti}_{0.50}$ alloy films (state 2) as a function of temperature measured at zero (circles) and 0.5 T (triangles) magnetic field. Solid lines are least-square fits to the experimental data. Dashed line is a fit to the function $R = R_0 - b'T^{0.5}$ where R_0 and b' are constants.

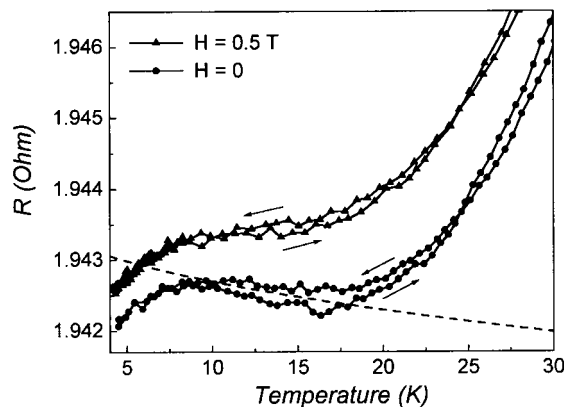


Fig. 4. Resistance of the $\text{Co}_{0.50}\text{Ti}_{0.50}$ alloy films with an intermediate degree of long range order (state 3) as a function of temperature during both cooling and heating, measured at zero (circles) and 0.5 T (triangles) magnetic field. Solid lines are only guides to the eyes. Dashed line is a fit to the function $R = R_0 - b'T^{0.5}$ where R_0 and b' are constants.

It was shown by Ptitsina *et al.* [18] that the electron-phonon interaction in the disordered (or dirty) systems is conducted mainly by two processes: the first is the so-called “pure” electron-phonon scattering and the second one is the inelastic scattering from the vibrating impurities. The temperature dependence of the electron-phonon scattering normalized with respect to the residual

resistivity can be written as similar to the Bloch-Grüneisen law [19]

$$\frac{\Delta\rho_{\text{e-ph}}(T)}{\rho_0} = \frac{1}{2} \frac{\pi\beta_1\tau}{\hbar(p_F u_l)^4} (k_B T)^5 \times \int_0^{\Theta_D/T} \frac{x^5 dx}{(e^x - 1)(1 - e^{-x})}. \quad (1)$$

The normalized temperature dependence of the resistivity caused by scattering on the electron-phonon-vibrating impurities can be written by [20]

$$\frac{\rho_{\text{int}}(T)}{\rho_0} = \left[2 \left(\frac{u_l}{u_t} \right) \beta_t - \left(1 - \frac{\pi^2}{16} \right) \beta_l \right] \frac{4\pi^2 k_B^2}{3E_F p_F u_l} \times T^2 \int_0^{\Theta_D/T} \frac{e^x (x-1) + 1}{(e^x - 1)^2} x dx, \quad (2)$$

where $\tau = \ell/v_F$ is the elastic transport time, u_l and u_t are the sound velocity of the longitudinal and transverse phonons, β_l and β_t are the constants of electron coupling with the longitudinal and transverse phonons, E_F and p_F are the Fermi energy and momentum, respectively, and Θ_D is the Debye temperature [21]. It follows from equations (1) and (2) that at low temperatures the resistivity is proportional to T^5 for the “pure” electron-phonon scattering, and is proportional to T^2 for the case of the electron scattering by the vibrating impurities.

Electron-electron scattering [22] also gives rise to a temperature exponent $\alpha = 2$, while the lowest power value $\alpha = \frac{3}{2}$ usually indicates a spin-mixing scattering with magnons in dilute ferromagnetic alloys [23]. The $T^{\frac{3}{2}}$ contribution to the initial part (at low temperatures) of the temperature dependence of resistivity was also observed for the noble-metal-host 3d-solute spin-glass alloys [24, 25] and interpreted in terms of the spin-diffusion theory [26].

In order to carry out the analyses of the experimental data more precisely, the experimental values of $\frac{R(T)}{R_{300\text{ K}}}$ for the ordered $\text{Co}_{0.50}\text{Ti}_{0.50}$ alloy film (state 1) and the film with an intermediate degree of long range order (state 3) were fitted by a function of $A + BT^5 F_1(T) + CT^2 F_2(T) + DT^{\frac{3}{2}}$. Here $R_{300\text{ K}}$ is the resistance at RT , A is the normalized residual resistance, B , C and D are fitting constants, $F_1(T) = \int_0^{\Theta_D/T} \frac{x^5 dx}{(e^x - 1)(1 - e^{-x})}$, and $F_2(T) = \int_0^{\Theta_D/T} \frac{e^x (x-1) + 1}{(e^x - 1)^2} x dx$. There are 5 parameters in this fitting procedure: A , B , C , D and also Θ_D in functions F_1 and F_2 . The chosen fit function allowed us to estimate the contributing portions of the most probable mechanisms of the electron scattering to the resistivity of the $\text{Co}_{0.50}\text{Ti}_{0.50}$ alloy films with different degrees of long range order. The resultant fitting parameters are presented in Table 1, and the obtained curves are shown in Figure 5. In Figure 5 we plot $\frac{\Delta\rho(T)}{\rho_0}$ -vs.- T , where $\Delta\rho(T) \equiv \rho(T) - \rho_0$ and $\rho_0 = A\rho_{300\text{ K}}$ is the residual resistivity obtained by fitting.

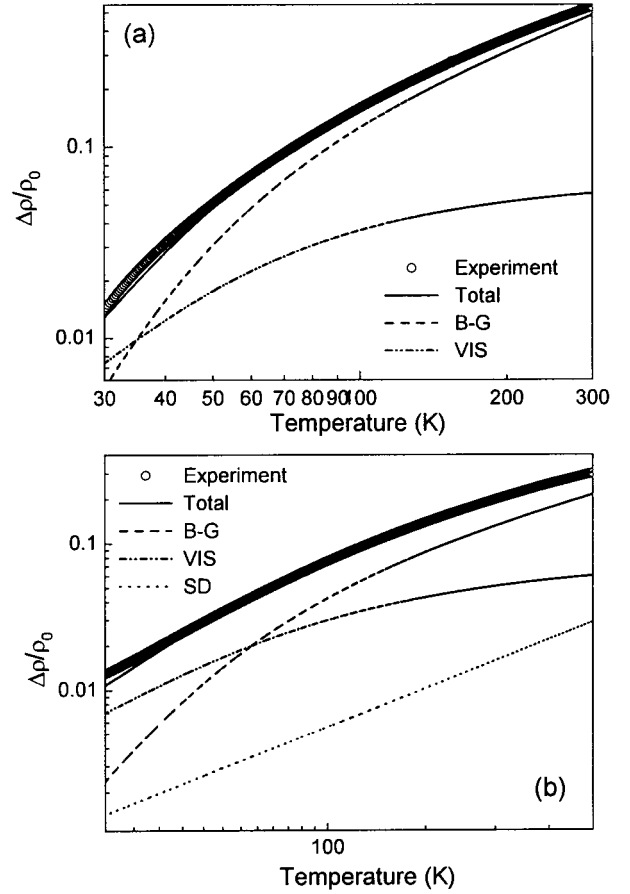


Fig. 5. The normalized experimental temperature dependence of the resistivity (circles), $\frac{\Delta\rho(T)}{\rho_0}$ -vs.- T , for the $\text{Co}_{0.50}\text{Ti}_{0.50}$ alloy films in the (a) ordered and (b) intermediate states together with the resultant fitting curves (solid lines) obtained by taking into account various mechanisms of electron scattering: electron-phonon described by equation (1) (dashed, B-G), electron-phonon-vibrating impurities described by equation (2) (dashed-dotted, VIS), and the spin-diffusive mechanism of scattering (dotted, SD).

It is seen that the resistivity of the ordered $\text{Co}_{0.50}\text{Ti}_{0.50}$ alloy films (state 1) originates mainly from the electron-phonon scattering (the modified Bloch-Grüneisen function, Eq. (1)) with a Debye temperature of 297 K, since the electron-phonon-vibrating impurity term (Eq. (2)) is relatively small and the spin-diffusive term is negligible (coefficient D for the ordered state is smaller by seven orders of magnitude than that for the films with an intermediate degree of long range order). The partial disorder (transition from state 1 to 3) leads to a noticeable increase in the residual resistivity of the alloy (compare A for both states in Tab. 1). According to reference [21], in the films with a large residual resistance, the electron-phonon-vibrating impurity scattering can exceed the resistance contribution by the electron-phonon interaction even at high temperatures (near RT). The detailed analysis of the electron-phonon-impurity interference has been done by Reizer and Sergeev [20]. This mechanism, being combined with the elastic electron scattering and

Table 1. Fitting parameters to the $\frac{R(T)}{R_{300\text{ K}}}$ data for two states of the $\text{Co}_{0.50}\text{Ti}_{0.50}$ alloy films.

Alloy state	Fit range (K)	A	B (10^{-13}K^{-5})	C (10^{-6}K^{-2})	D ($10^{-6}\text{K}^{-1.5}$)	Θ_D (K)
1	30-300	0.656	7.68	5.75	~ 0	297
3	40-300	0.769	2.15	2.69	5.58	346

electron-phonon scattering, generates a variety of interference processes. The partial disorder increases the contribution of such kind of scattering to the total resistivity of the $\text{Co}_{0.50}\text{Ti}_{0.50}$ alloy films: compare the ratio of coefficient B and C for these states in Table 1 (also see Fig. 5).

In contrast to the ordered state of alloy, the spin-diffusive term plays an important role in the total resistivity of the $\text{Co}_{0.50}\text{Ti}_{0.50}$ alloy films with an intermediate degree of long range order. This result allows us to presume the existence of a spin-glass state in such a film at the temperatures of Figure 5. According to our magnetization study using VSM, the ordered $\text{Co}_{50}\text{Ti}_{50}$ alloy films are not ferromagnetically ordered, at least, above 100 K [27]. Neither the disordered state in the $\text{Co}_{50}\text{Ti}_{50}$ alloy film is ferromagnetically ordered at 300 K, but a decrease of temperature down to 100 K leads to the appearance of a small magnetic moment in this alloy film [27]. We attributed such a change in the magnetic state of the disordered alloy to the appearance of the Co-ASA, resulting in the formation of magnetic clusters which begin to couple ferromagnetically below 100 K. It is clear that the higher the degree of long range-order, the less the Co-ASA and/or their clusters appear. The number of these clusters, if any, in the $\text{Co}_{50}\text{Ti}_{50}$ alloy films with an intermediate degree of long-range order (state 3) is not enough to be coupled ferromagnetically, and the spin-diffusive scattering, which follows the $T^{\frac{3}{2}}$ law, is observed in addition to the two kinds of the electron-phonon scattering.

The structural disorder in the $\text{Co}_{0.50}\text{Ti}_{0.50}$ alloy films (transition from state 1 to state 2) leads to the change in sign of the TCR from positive to negative (as seen in Fig. 1) as well as a significant increase in resistivity. The temperature dependence of the resistivity for the $\text{Co}_{0.50}\text{Ti}_{0.50}$ alloy film with η_2 comes in between the ordered and disordered ones.

The existence of the negative TCR for the disordered (or highly resistive) metallic alloys is a well-known phenomenon. A threshold residual resistivity of $\rho_{\max} = \sigma_{\min}^{-1} = 150\ \mu\Omega\text{cm}$, which divides the positive and negative TCR regimes, has often been treated as the universal boundary [28]. This so-called Mooij criterion determines whether a material can have the negative TCR or not. However, Tsuei [29] has shown that this value is not universal, but depends on the characteristics of material and can vary from 30 to 500 $\mu\Omega\text{cm}$. There are two main expressions for the estimation of the minimum metallic conductivity. According to Mott and Koveh [30] σ_{\min} for highly resistive alloys can be evaluated by $\sigma_{\min} \simeq 0.03e^2/\hbar a$ where a is the crystal lattice constant, while Logan's criterion [31] of the minimum metallic conductivity was obtained by taking into account the interplay

between Anderson localization and dephasing mechanism and was expressed as $\sigma_{\min} \simeq 0.23\ e^2/\hbar a$. If the lattice constant of the bulk ordered equiatomic alloy is used for the investigated films (*i.e.* $a = 2.999\ \text{\AA}$), the threshold resistivity for the $\text{Co}_{0.50}\text{Ti}_{0.50}$ alloy films turns out to be about 550 $\mu\Omega\text{cm}$ according to the Logan's criterion. The obtained numerical estimation is in an excellent agreement with our experimental data; the resistivity of the ordered $\text{Co}_{0.50}\text{Ti}_{0.50}$ alloy film at RT is equal to $\rho_{293\text{ K}(\text{ord})} \approx 218\ \mu\Omega\text{cm}$ and the TCR is positive, while the disordered state is characterized by $\rho_{293\text{ K}(\text{disord})} \approx 625\ \mu\Omega\text{cm}$ and the negative TCR.

However, different physical mechanisms of the electron scattering can also provide the growth of the resistivity with decreasing temperature. The highly comprehensive analyses of the temperature dependence of the resistivity for $\text{Co}_x\text{Ga}_{1-x}$ and $\text{Co}_2(\text{Ga}_{2-x}\text{Fe}_x)$ alloys were performed by Whittle and coworker [32,33], Cywinski [34], and Ochiai and Brittain [35,36]. These alloys also contain magnetic and nonmagnetic atoms and have the same crystalline structure as CoTi alloy. It was shown that the TCR for $\text{Co}_x\text{Ga}_{1-x}$ alloys is changed from the positive to negative value if x changes from 0.48 to 0.52 and then to the positive value again for $x = 0.6$. Such a behavior of the resistivity for the crystalline alloys is also accompanied by the appearance of the resistivity minimum (for the alloys with a positive TCR) or by the additional exponential growth of the resistivity (for the alloys with a negative TCR) in the low temperature region. In general, Whittle and Cywinski have explained the temperature dependence of the resistivity for these alloys using the model of Markowitz [37] developed for highly resistive alloys.

This model takes into account the higher-order phonon scattering processes by incorporating the temperature-dependent Debye-Waller factor into the usual expression for the resistivity. According to this model, the TCR becomes negative if the ratio of the residual resistivity ρ_0 to the temperature dependent part ρ_1 in the total resistivity, ρ_0/ρ_1 , is about 50 or higher. For some values of this ratio the model also predicts a linear dependence of ρ on T at high temperatures ($T \gg \Theta_D$) and the existence of the resistivity minimum at $T_{\min} = 0.18\Theta_D$. Such an approach does not concern with the nature of the residual resistivity and can be applied to the crystalline as well as amorphous alloys.

Cywinsky and Whittle have connected the nature of high resistivity of the investigated crystalline bulk $\text{Co}_x\text{Ga}_{1-x}$ alloys with the peculiarities of their electronic band structure, and explained the resistivity minimum (or the exponential growth of resistivity) at low temperatures by hopping conductivity or tunneling between

the localized states. In contrast to them, Ochiai and Brittain concluded that the resistivity minimum in such an alloy has the magnetic origin and is attributed to the magnetic scattering on the spin clusters in the reentrant spin glass state.

According to the results of our previous study [27] the structural order-disorder transition leads to a drastic change in the real part of the dielectric function ε_1 in the low energy part of the spectra ($h\nu \lesssim 1$ eV), where the optical absorption is mainly due to free electrons. While the ordered $\text{Co}_{0.50}\text{Ti}_{0.50}$ alloy has large negative ε_1 in low energy region, which is typical for the ordinary metals, the structural order-disorder transition changes ε_1 to be a positive value. This reflects a significant variation in one of the important parameters of free carriers, the plasma frequency or, equivalently, the effective mass. According to the Drude formula, the real part of the dielectric function in the low energy region is given by

$$\varepsilon_1 = 1 - \frac{\Omega_P^2}{\omega^2 + \gamma^2}, \quad (3)$$

where Ω_P is the plasma frequency of free electrons, γ is the effective relaxation frequency of free charge carriers, which contains all possible scattering mechanisms, and ω is the angular frequency of the incident light. The plasma frequency, Ω_P , is given again by

$$\Omega_P^2 = \frac{4\pi N e^2}{m^*}, \quad (4)$$

where N is the charge carrier concentration and m^* is the effective mass of the charge carrier. Since N does not change appreciably upon the order-disorder transformation, m^* becomes the dominant factor whose enhancement leads to a reduction in Ω_P . The reduction of Ω_P is due to the dispersionless band near the Fermi level which is ascribed to the increased disorder. This statement can also be supported by an evaluation of the changing tendency of the DC conductivity of the CoTi alloy films, by using the optical data. Indeed, the optical conductivity due to free carriers can be expressed as

$$\sigma = \frac{\Omega_P^2 \gamma}{4\pi(\omega^2 + \gamma^2)}. \quad (5)$$

This gives us the DC conductivity, σ_{DC} , when $\omega = 0$ and σ_{DC} is determined by two parameters, *i.e.* Ω_P^2 and γ . Thus, the DC resistivity can be written as

$$\rho_{\text{DC}} = \sigma_{\text{DC}}^{-1} = \frac{4\pi\gamma}{\Omega_P^2}. \quad (6)$$

It was shown earlier [38] that the structural disorder in the equiatomic CoGa alloy leads to a significant increase in resistivity and this increase is mainly due to a significant decrease in Ω_P . Notice that γ increases insignificantly. Therefore, it can be assumed that the same regularity is also observed for the CoTi alloy films and the increase in resistivity for the disordered $\text{Co}_{0.50}\text{Ti}_{0.50}$ alloy films is also caused mainly by the reduced Ω_P .

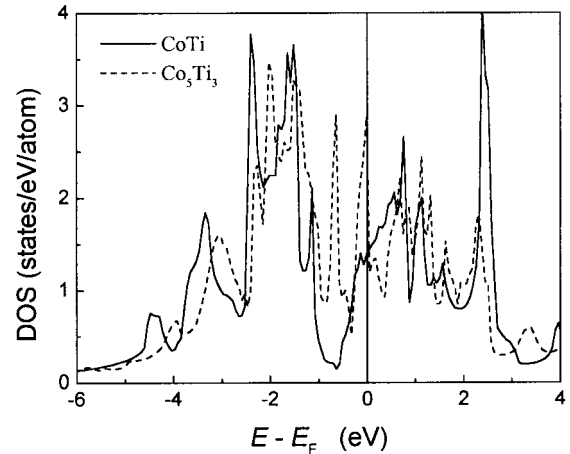


Fig. 6. The calculated DOS curves for the equiatomic CoTi (solid line) and Co_5Ti_3 (dashed line). The Fermi level is located at the zero of energy.

This is also confirmed by our theoretically calculated DOS using the LMTO method for the equiatomic CoTi and Co_5Ti_3 alloys. For Co_5Ti_3 alloy the electronic structures were calculated using a defect-specified supercell method [39]. As the Ti concentration decreases, a very sharp peak in the DOS curve near the Fermi level grows (see Fig. 6), indicating an easier localization of the states near the Fermi level and an increase of m^* . The same is true for Co-Al [13] and Fe-Al [14] alloys. This is another manifestation of the localization of the states near the Fermi level upon the order-disorder transformation.

Figure 7 presents the temperature dependence of the resistivity for the disordered $\text{Co}_{0.50}\text{Ti}_{0.50}$ alloy films in a wide temperature range. The temperature dependence is quite linear in the range from RT to 100 K, and below this range a significant deviation from the straight line is observed. To our mind, the linear $R(T)$ dependence with a negative TCR for the disordered state of alloy can be explained by the Markowitz model taking into account the higher-order phonon scattering processes [37]. The origin of the deviation (a decrease in resistivity) could be connected to an appearance of the long-range magnetic ordering near 100 K. Noninteracting magnetic moments of the Co-ASA and/or their clusters play a role of the spin-dependent scattering centers at high temperature (above 100 K) and below 100 K they are coupled ferromagnetically, which reduces the scattering. This assumption agrees well with the results of our previous magnetization measurements using VSM.

Another rather interesting feature of the influence of the structural disorder on the transport properties of the $\text{Co}_{0.50}\text{Ti}_{0.50}$ alloy films is the appearance of the resistivity minimum at $T_{\text{min}}=15\text{--}16$ K for the completely and partially disordered alloys (states 2 and 3, respectively) (see Figs. 3 and 4, respectively). Since the $R(T)$ of the ordered $\text{Co}_{0.50}\text{Ti}_{0.50}$ alloy film (state 1) does not show any peculiarity at least above 4 K (see Fig. 2), it is clear that the observed resistivity minimum originates from the structural disordering. For the disordered $\text{Co}_{0.50}\text{Ti}_{0.50}$

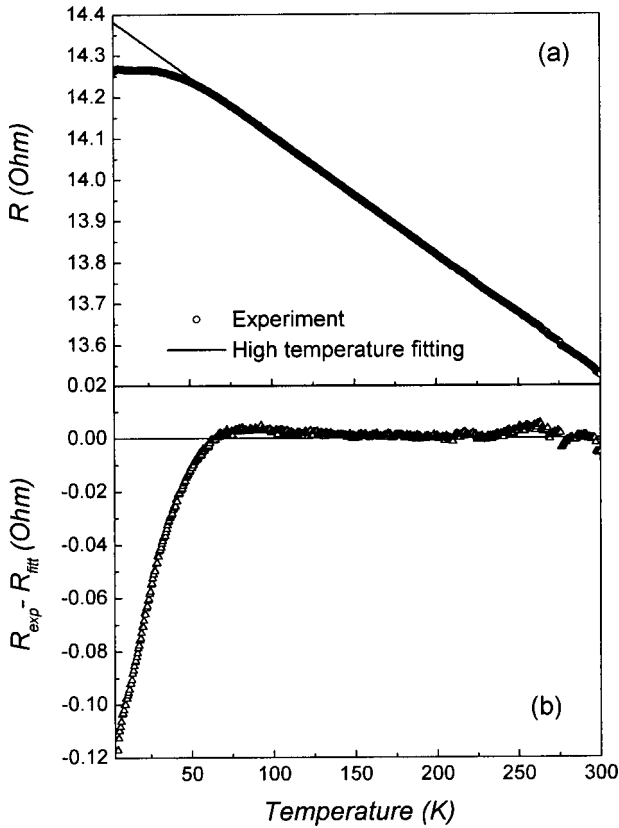


Fig. 7. Fitting of the experimental temperature dependence of the resistivity for the disordered $\text{Co}_{0.50}\text{Ti}_{0.50}$ alloy films (state 2) to the function $R = R_0 - b''T$ where R_0 and b'' are constants (a) and the deviation of the experimental $R(T)$ from a straight line (b).

alloy film (state 2) below T_{\min} , the resistivity increases and then decreases with decreasing temperature, producing a low-temperature resistivity maximum at $T_{\max} = 7.7$ K. For the $\text{Co}_{0.50}\text{Ti}_{0.50}$ alloy film with an intermediate degree of long range order (state 3), $T_{\max} = 10$ K. The depths of the resistivity minimum, defined by $(\rho_{\max} - \rho_{\min})/\rho_{\max}$, for states 2 and 3 are equal to 0.00016 and 0.0006, respectively.

We also investigated the effect of the magnetic field on the nature of the resistivity minimum. The relative shifts between the $R(T, H)$ and $R(T, H = 0)$ curves are caused by the usual magnetoresistive contributions (see Figs. 2-4). These contributions are rather small; about -0.4% for the ordered state, and about $+0.05\%$ for states 2 and 3. It was found that for the ordered $\text{Co}_{0.50}\text{Ti}_{0.50}$ alloy film the magnetic field did not affect the shape of the low temperature part of the $R(T)$ dependence (see Figs. 2), while for the completely or partially disordered $\text{Co}_{0.50}\text{Ti}_{0.50}$ alloy film this effect was noticeable (see Figs. 3 or 4, respectively). When an external magnetic field of 0.5 T was applied, the resistivity maximum for the disordered $\text{Co}_{0.50}\text{Ti}_{0.50}$ alloy film (state 2) became higher and shifted toward the low temperature side, and the depth of the resistivity minimum decreased (see Fig. 3).

Apparently, the resistivity extremum (minimum or maximum) appears as a result of an interplay among several mechanisms of scattering. The usual electron-phonon scattering, local spin density fluctuations and electron-magnon scattering make a positive contribution to resistivity, *i.e.*, they lead to an increase in resistivity with temperature, while hopping or tunneling conductivity, Kondo-effect and quantum corrections to conductivity due to the electron-electron interactions in the presence of weak localization are negative.

Because the structural disorder in the CoTi alloy films can lead to the appearance of the Co-ASA as well as the Ti-ASA, the former ones and/or their clusters can carry magnetic moments and can be considered as magnetic scattering centers responsible for the resistivity growth with decreasing temperature. For example, the appearance of the resistivity minimum for a very similar alloy system, FeTi alloys, was explained by Ikeda [40] in the framework of Kondo effect [41]. As aforementioned, however, the disordered state in the $\text{Co}_{0.50}\text{Ti}_{0.50}$ alloy film is ferromagnetically ordered at best below 100 K, and therefore the Co-ASA or their clusters could not be considered as independent scattering centers.

We have examined the nature of the observed resistivity minimum for the completely and partially disordered $\text{Co}_{0.50}\text{Ti}_{0.50}$ alloy film (states 2 and 3) by fitting the experimental $R(T)$ curves. It was shown by Altshuler and Aronov [42] that the quantum corrections to conductivity due to the electron-electron interactions in the presence of weak localization can be expressed as $\Delta\rho \equiv \rho(T) - \rho_0 \approx -b\sqrt{T}$ where b is constant. Even though the temperature range for fitting is rather narrow, it is seen in Figures 3 and 4 that there is a reasonable agreement between experimental and fitting curves in $T_{\max} \leq T \leq T_{\min}$. It should be also mentioned here that the variable-range hopping conductivity (as one of the possible candidates for the explanation of the resistivity growth with decreasing temperature) gives a much worse agreement between experimental and fitting curves.

The decrease in resistivity below 7.7 and 10 K for the $\text{Co}_{0.50}\text{Ti}_{0.50}$ alloy films of state 2 and 3, respectively, can result from, for example, magnetic ordering [43] (as typically observed at very low temperatures for heavy fermion systems) or by a superconductive transition. Since the completely disordered $\text{Co}_{0.50}\text{Ti}_{0.50}$ alloy film is ferromagnetically ordered at these temperatures, the reasoning connected with a superconductive transition looks more plausible. $\text{Co}_x\text{Ti}_{1-x}$ alloys exhibit superconducting transitions at 1.4–4.0 K for $0.05 \leq x \leq 0.20$ [44]. The formation of the Ti-ASA and their clusters in the disordered state of $\text{Co}_{0.50}\text{Ti}_{0.50}$ alloy is a rather probable source for the superconducting currents, because the crystalline β -Ti has a temperature of the superconductive transition, T_c , of 4–6 K [44]. The superconductive fluctuations, *i.e.*, the Cooper pairs with a small correlation length and a short lifetime, can also exist above T_c for the disordered superconductors. There are basically two types of contributions to resistivity; one from the current carried by the superconducting fluctuations (Aslamasov-

Larkin term [45]), and the other from the scattering of normal electrons by the superconducting fluctuations (Maki-Thomson term [46]). It was shown by Johnson and Tsuei [47] that, for the temperature-dependent fluctuation, the resistivity decays as

$$\frac{\Delta\rho_{sc}}{\rho_{4.2\text{ K}}} = -c \exp(-f\sqrt{t})$$

where $t = (T - T_c)/T_c$, f is a measure of the free-energy difference between the normal and superconducting states, and c is a constant. It is clearly seen that the magnetic field lowers the resistivity maximum for the completely disordered $\text{Co}_{0.50}\text{Ti}_{0.50}$ alloy film (state 2) by about 2 K. It is well-known that the magnetic field reduces T_c .

Figure 8 presents the simulation results of the temperature dependence of resistivity near the resistivity minimum in the presence of the superconductive transition at two different temperatures. The resistivity minimum in the $R(T)$ dependence was modelled by two competitive mechanisms of the electron scattering, *i.e.*, the electron-vibrating impurity scattering and the quantum corrections to the electron-electron interactions in the presence of weak localization, which follow T^2 and $-T^{0.5}$ laws, respectively. The abrupt superconductive transition at different temperatures was simply approximated by a function of $-A \exp[(T_c - T)/T]$ for different T_c , where A is a constant and T_c is the temperature of the superconductive transition. A comparison of the experimental and the modelled data (see Figs. 3 and 8, respectively) reveals clearly the similarities between them. Therefore, it can be concluded that the abrupt decrease in resistivity is caused by the superconductive transitions in the β -Ti regions (the Ti-rich Co-Ti alloy regions) which appear as a consequence of the structural disordering. The detailed magnetic measurements at low temperatures of the investigated $\text{Co}_{0.50}\text{Ti}_{0.50}$ alloy film are in progress to provide additional information supporting the conclusions made on the basis of the present resistivity measurements.

5 Summary

1. The disordered state in the $\text{Co}_{0.50}\text{Ti}_{0.50}$ alloy films was obtained by means of vapor quenching deposition onto glass substrates cooled by liquid nitrogen.
2. The loss of the translational invariance in the disordered state increases the resistivity (about 3 times at RT in comparison with the ordered state) and leads to a change from the positive to negative TCR.
3. The observed temperature dependence of the resistivity for the disordered $\text{Co}_{0.50}\text{Ti}_{0.50}$ alloy films are explained by the partial localization of the electronic states near the Fermi level.
4. It was established that the electron-phonon and the electron-phonon-vibrating impurity scattering are the main contributions to the resistivity of the ordered and partially ordered $\text{Co}_{0.50}\text{Ti}_{0.50}$ alloy films: while, for the ordered state of alloy, the main contribution originates from the electron-phonon scattering, the partial

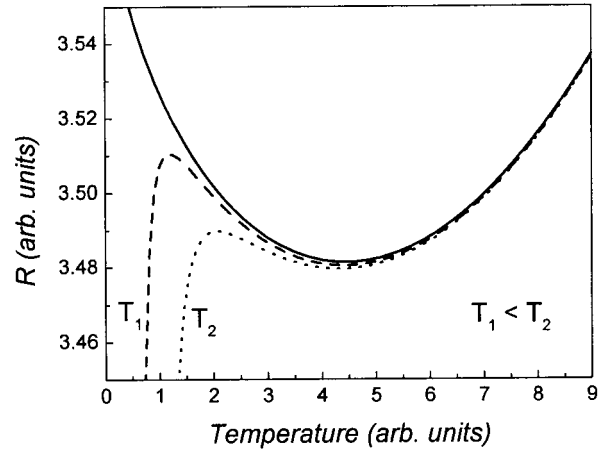


Fig. 8. Modelled temperature dependence of resistivity near the resistivity minimum in the absence of the superconductive transition (solid line) and in the presence of the superconductive transitions at two temperatures: T_1 (dashed line) and T_2 (dotted line). $T_1 < T_2$.

structural disordering enhances the role of the electron-phonon-vibrating impurity mechanism and makes the spin-diffusive scattering rather noticeable. The origin of the latter one is connected with the appearance of the Co-ASA in the partially ordered state of alloy.

5. The appearance of the low-temperature resistivity minimum for the disordered $\text{Co}_{0.50}\text{Ti}_{0.50}$ alloy films can be explained by the quantum corrections to the electron-electron interactions in the presence of weak localization.
6. The abrupt decrease in resistivity of the disordered $\text{Co}_{0.50}\text{Ti}_{0.50}$ alloy films at very low temperatures is explained by the superconductive transition in the Ti-ASA regions or the Ti-rich Co-Ti alloys which are induced by the structural disordering.

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References

1. *Binary Alloy Phase Diagrams*, edited by T.B. Massalski, Vol. I (American Society for Metals, 1986), p. 1100.
2. J.M. Zhang, G.Y. Guo, *J. Phys. Cond. Matter* **7**, 6001 (1995).
3. K. Endo, I. An, A. Shinogi, *J. Phys. F* **7**, L99 (1977).
4. A. Jezierski, G. Borstel, *Physica B* **205**, 397 (1995).
5. J.Y. Rhee, B.N. Harmon, D.W. Lynch, *Phys. Rev. B* **54**, 17385 (1996).
6. D.A. Papaconstantopoulos, D.J. Nagel, *Int. J. Quantum Chem. S5*, 515 (1971).
7. R. Eibler, J. Redinger, A. Neckel, *J. Phys. F* **17**, 1533 (1987).

8. V.Y. Yegorushkin, N.I. Fedyanova, *Alloys of Rare Metals with Special Physical Properties* (Nauka, Moscow, 1983), p. 24.
9. Y.P. Lee, K.W. Kim, Yu.V. Kudryavtsev, J.Y. Rhee, Phys. Rev. B **59**, 546 (1999).
10. Yu.V. Kudryavtsev, Y.P. Lee, K.W. Kim, J. Appl. Phys. **83**, 1575 (1998).
11. J.Y. Rhee, K.W. Kim, Yu.V. Kudryavtsev, Y.P. Lee, J. Korean Phys. Soc. **35**, 5518 (1999).
12. Yu.V. Kudryavtsev, V.V. Nemoshkalenko, Y.P. Lee, K.W. Kim, J. Appl. Phys. **82**, 5043 (1997).
13. J.Y. Rhee, Yu.V. Kudryavtsev, K.W. Kim, Y. P. Lee, Jpn. J. Appl. Phys. **38**, 6401 (1999).
14. J.Y. Rhee, Phys. Rev. B (submitted).
15. J.F. Goff, J. Appl. Phys. **39**, 2208 (1968).
16. I.I. Sasovskaya, Fiz. Metal. Metalloved. **69**, 75 (1990) [Sov. Phys. Phys. Met. Metall. **69**, 72 (1990)].
17. *Handbook of Thin Film Technology*, edited by L.I. Maissel, R. Glang (McGraw Hill Hook Co., 1970).
18. N.G. Ptitsina, G.M. Chulkova, K.S. Il'in, A.V. Sergeev, F.S. Pochinkov, E.M. Gershenson, M.E. Gershenson, Phys. Rev. B **56**, 10 089 (1997).
19. B.L. Altshuler, Zh. Eksp. Teor. Fiz. **75**, 1330 (1978) [Sov. Phys. JETP **48**, 670 (1978)].
20. M.Yu. Reizer, A.V. Sergeev, Zh. Eksp. Teor. Fiz. **92**, 2291 (1987) [Sov. Phys. JETP **65**, 1291 (1987)].
21. K.S. Il'in, N.G. Ptitsina, A.V. Sergeev, G.N. Gol'tsman, E.M. Gershenson, B.S. Karasik, E.V. Pechen, S.I. Krasnosvobodtsev, Phys. Rev. B **57**, 15623 (1998).
22. B. Loegel, F. Gautier, J. Phys. Chem. Solids **32**, 2723 (1971).
23. D.L. Mills, A. Fert, I.A. Cambell, Phys. Rev. B **4**, 196 (1971).
24. P.J. Ford, J.A. Mydosh, Phys. Rev. B **14**, 2057 (1976).
25. S. Chakraborty, A.K. Majumdar, Phys. Rev. B **53**, 6235(1996).
26. N. Rivier, K. Adkins, J. Phys. F **5**, 1745 (1975).
27. Y.P. Lee, K.W. Kim, J.Y. Rhee, Y.V. Kudryavtsev, V.V. Nemoshkalenko, Phys. Rev. B **60**, 867 (1999).
28. J.H. Mooij, Phys. Status Solidi (a) **17**, 521 (1973).
29. C.C. Tsuei, Phys. Rev. Lett. **57**, 1943 (1986).
30. N.F. Mott, M. Koveh, Adv. Phys. **34**, 329 (1985).
31. D.E. Logan, P.G. Wolynes, Phys. Rev. B **36**, 4135(1987).
32. G.L. Whittle, G.C. Fletcher, P.E. Clark, R. Cywinski, J. Phys. F **12**, 303 (1982).
33. G.L. Whittle, P.E. Clark, R. Cywinski, J. Phys. F **10**, 1775 (1980).
34. R. Cywinski, J. Phys. F **9**, L29 (1979).
35. Y. Ochiai, J.O. Brittain, J. Phys. F **10**, 1187 (1980).
36. Y. Ochiai, J.O. Brittain, Phys. Lett. A **73**, 347 (1979).
37. D. Markowitz, Phys. Rev. B **15**, 3617 (1977).
38. Y.V. Kudryavtsev, I.V. Lezhnenko, I.N. Mishchenko, Phys. Metal **9**, 68 (1987) (in Russian).
39. Y.M. Gu, L. Fritsche, J. Phys. Cond. Matter **4**, 1905 (1992).
40. K. Ikeda, Phys. Status Solidi (b) **62**, 655 (1974).
41. J. Kondo, Prog. Theor. Phys. **32**, 37 (1964).
42. B.L. Altshuler, A.G. Aronov, Zh. Eksp. Teor. Fiz. **77**, 2028 (1979) [Sov. Phys. - JETP **50**, 968 (1979)].
43. T. Hiraoka, T. Nobata, R. Hara, G. Nakamoto, M. Kurisu, J. Magn. Magn. Mater. **177-181**, 383 (1998).
44. E.W. Collins, *A Source Book of Ti-Alloys Superconductivity* (Plenum Press, New York and London, 1983), p. 511.
45. L.G. Aslamasov, A.I. Larkin, Phys. Lett. A **26**, 238 (1968).
46. S. Ami, K. Maki, Phys. Rev. B **19**, 1403 (1979).
47. W.L. Johnson, C.C. Tsuei, Phys. Rev. B **13**, 4827 (1976).