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The electrical resistivity of Ti–Zr–Ni quasicrystals in the interval 1.3–300 K

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Abstract

The resistivity of rapidly quenched quasicrystalline ribbons $Ti_{41.5}Zr_{41.5}Ni_{17}$, $Ti_{53}Zr_{27}Ni_{20}$ and $Ti_{45}Zr_{38}Ni_{17}$ are investigated in the interval 1.3–300 K. The "metallic" behaviour of the resistance is found at $T > 20$ K. Such behaviour is connected with electron–phonon s–d scattering. The beginning of superconducting transition in $Ti_{41.5}Zr_{41.5}Ni_{17}$ is found out at $T < 1.6$ K. There is shallow minimum of $\rho(T)$ close by 20 K.

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Keywords: The electrical resistance; Temperature; Icosahedral quasicrystals; s–d transitions

1. Introduction

For temperature dependence of electrical resistivity of the quasicrystalline superconductors: Al–Zn–Mg [1]; Al–Cu–Mg, Al–Cu–Li [2]; Ti–Zr–Ni [3] is characteristic the positive derivative $d\rho/dT > 0$ in a wide interval of temperature and relatively small value of resistivity $-\rho \leqslant 200\ \mu\Omega\,\mathrm{cm}$.

However, in [4] for rapidly quenched quasicrystal alloys of Ti–Zr–Ni system (amorphous, disordered icosahedral and icosahedral + Laves phase samples) was observed $d\rho/dT < 0$ in the interval 10–300 K.

Therefore it is represented interesting to investigate a kind of temperature dependence of electrical resistivity of the Ti–Zr–Ni quasicrystals in a wide interval of temperature on monophase samples of a high degree of perfection.

From the phase diagram of Ti–Zr–Ni system [5] follows, that in this system the stable icosahedral phase has the composition $Ti_{41.5}Zr_{41.5}Ni_{17}$. For this structure the rapid quenching can give monophase samples of rather perfect structure.

In the present Letter we have prepared the monophase samples of the composition $Ti_{41.5}Zr_{41.5}Ni_{17}$, have studied their structure and investigated tempera-

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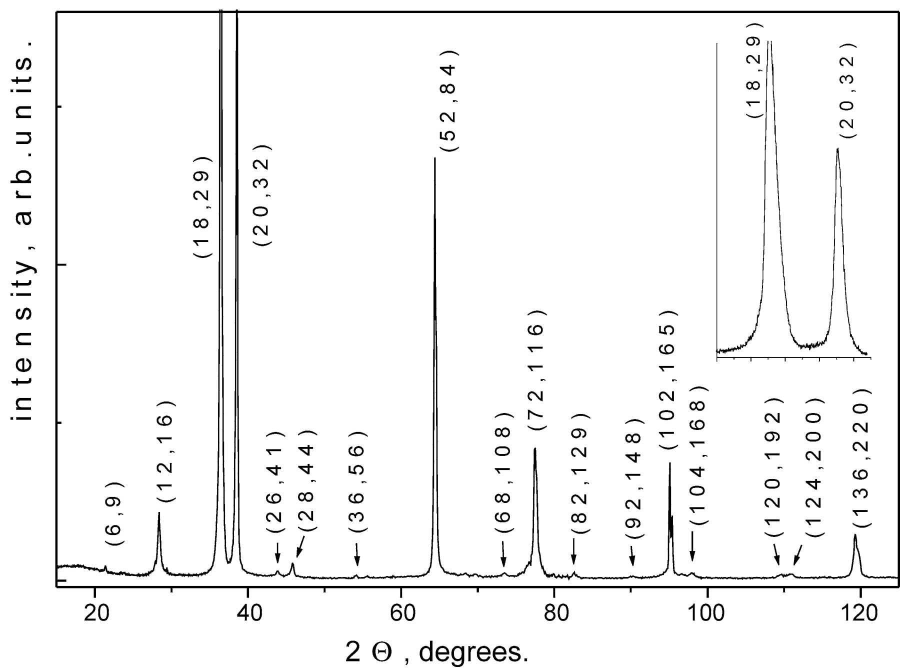

Fig. 1. XRD pattern of the $Ti_{41.5}Zr_{41.5}Ni_{17}$ icosahedral quasicrystal. In the inset the interval $35^\circ \leqslant 2\theta \leqslant 40^\circ$ is shown.

ture dependence of their electrical resistivity in the interval 1.3–300 K. We give also the $\rho(T)$ dependences for the quasicrystals $Ti_{53}Zr_{27}Ni_{20}$ and $Ti_{45}Zr_{38}Ni_{17}$ which superconductivity was described in [3].

2. Experiment

2.1. Samples preparation

The thin ribbons were obtained by melt spinning in inert atmosphere [3]. The linear speed of the disk surface at quenching made about 20 m/s. The control of the element structure which has been carried out by the method of X-ray fluorescence, has shown, that the structure of samples $Ti_{41.5}Zr_{41.5}Ni_{17}$ deviates from nominal no more, than on 0.5%. The measurements are carried out on the nonannealed samples.

2.2. Structure of samples

Structure of samples was investigated by XRD-method with use of the monochromatic K_α-Cu radiation. The indexing of the reflections was made according to a technique [6–8]. XRD-spectrum of dispersion for samples $Ti_{41.5}Zr_{41.5}Ni_{17}$ was shown in Fig. 1. The general view of a picture of diffraction is similar earlier observed for i-phase in alloys of the given system [3].

The analysis of Fig. 1 confirms the monophase nature of samples $Ti_{41.5}Zr_{41.5}Ni_{17}$ as extraneous phases are not found out. All system of reflections without passing is described by icosahedral indexes (N, M) with one three-dimensional quasilattice constant d_0, or quasicrystalline parameter $a_q = d_0/2\sqrt{2+\tau}$. The set of reflections (N, M) confirms the formation of i-phase with structure of P-type. Reflections from accompanying phases, such as Laves phase, a solid solution, etc. was not observed. Absence of reflection (600) between reflections $(18, 29)$ both $(20, 32)$ i-phase and absence of doubletity of lines $(52, 84)$ confirms the absence of W-phase (crystal-approximant).

The quasicrystalline parameter has been calculated on reflections position located at the large corners of diffraction, and has been defined more precisely by a method of extrapolation. The diffraction survey of the strongest reflections $(18, 29)$ and $(20, 32)$ in

Table 1

	$Ti_{41.5}Zr_{41.5}Ni_{17}$ (No. 1)	$Ti_{41.5}Zr_{41.5}Ni_{17}$ (No. 3)	$Ti_{45}Zr_{38}Ni_{17}$ (No. 4)	$Ti_{53}Zr_{27}Ni_{20}$ (No. 2)
Phase composition	i-QCs	i-QCs	i-QCs + traces of Laves-phase	i-QCs + traces of α-Ti(Zr)
a_q (Å)	5.209	5.206	5.188	5.163
The coherence length (Å)	550	550	300	250
ρ_0 (μΩ cm)	272	188	208	186
c_3 (μΩ cm)	19.2	13.6	13.0	15.9
θ (K)	270	307	411	283
a	0.44	0.50	0.75	0.38
T_c (K)	< 1.4	< 1.4	< 1.4	1.94

the mode of ω-scanning of the sample (swing curve) give $\Delta\omega = 2$–$5°$, that testifies to the presence of a monocrystal-type texture. According to raster electronic microscopy the microstructure of a sample is polycrystalline with the average crystallite size about 5 μm. The coherence length was determined on the diffraction lines width by way of approximation with use of a diamond powder as the standard.

The quasicrystalline parameters and the coherence lengths are given in Table 1.

2.3. Measurement of resistance

The resistivity was measured by usual four-probe method. The current and potential contacts were pasted by electrically conductive silver epoxy EPO-TEK H20E. The sample and Fe–Ro thermometer of resistance was mounted on the massive copper block. Thermal contact to the block was provided by the grease "Apiezon". Measurements of resistance were carried out in a stationary mode. The analog temperature regulator stabilized temperature of the massive copper block with accuracy near 0.001 K.

3. Results and discussion

Experimental results are plotted in Fig. 2 and Table 1. There are the following characteristic features of the temperature dependence of the electrical resistivity of investigated quasicrystals:

(1) All investigated samples are superconductors. In [3] we observed full superconducting transition ($\rho = 0$) for the sample with composition $Ti_{53}Zr_{27}Ni_{20}$ whereas for samples $Ti_{45}Zr_{38}Ni_{17}$ the sharp resistance fall that testifies about the beginning of superconducting transition was revealed. For samples with the composition $Ti_{41.5}Zr_{41.5}Ni_{17}$ the sharp falling of resistance also is revealed at $T < 1.6$ K (see Table 1 and inset to Fig. 2). The temperature decrease ~ 0.3 K causes the decrease of resistivity $\sim 15\%$. There is no other mechanism, except of superconducting transition which could provide such sharp falling of resistivity. We shall note for comparison, that a cooling of the samples from room temperature up to liquid helium temperature cause the resistivity decrease ~ 2–3%;

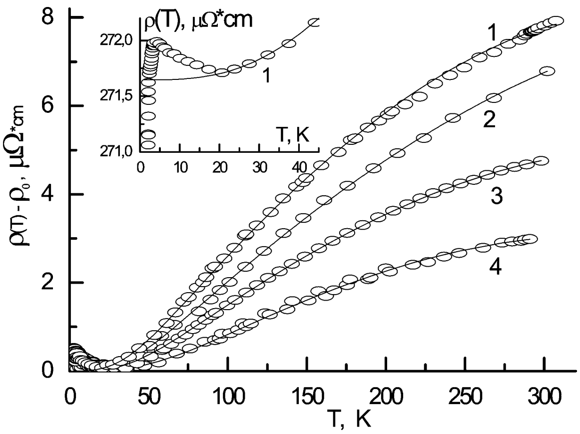

Fig. 2. The temperature dependences of resistivity of Ti–Zr–Ni icosahedral quasicrystals: $Ti_{41.5}Zr_{41.5}Ni_{17}$ (Nos. 1, 3); $Ti_{45}Zr_{38}Ni_{17}$ (No. 4); $Ti_{53}Zr_{27}Ni_{20}$ (No. 2). Solid lines are approximations according to (1). In the inset is shown the beginning of the superconducting transition for $Ti_{41.5}Zr_{41.5}Ni_{17}$.

(2) For all investigated samples the shallow minimum of $\rho(T)$ (less than 0.5% from the general level of resistivity) is observed near to 20 K. The increase of resistivity at decrease of temperature below 20 K can be connected to effects of weak localization coupled with the enhanced electron–electron interaction [9];

(3) To the right of the minimum "the metal" behaviour of the resistivity, $d\rho/dT > 0$, is observed, and linear dependence of resistivity is absent even at the highest of the investigated temperatures. Taking that into account, we approximated the $\rho(T)$ dependence by following formula

$$\rho(T) = \rho_0 + c_3 \cdot \left(\frac{T}{\theta}\right)^3 \cdot J_3^*\left(\frac{\theta}{T}\right), \tag{1}$$

$$J_n^*\left(\frac{\theta}{T}\right) = \int_a^{\theta/T} \frac{x^n e^x}{(e^x - 1)^2}\, dx. \tag{2}$$

The first term in (1) is residual resistivity; the second term is caused by interband s–d transitions because of electron–phonon scattering [10,11]. The absence of linear dependence of resistivity even in vicinity of θ we have described by introduction of nonzero lower limit in Debye integral (2) which is not calculated here from 0, but from some value, $a = (\hbar\pi V)/(k_B T l_e)$, where l_e is the mean free path of electrons, V—the sound velocity. The point is that phonons do not scatter the electrons with l_e smaller than phonon wave length; therefore the area of integration for single-phonon processes is narrowed up to $X_{\min} = (\pi/(l_e q_D))(\theta/T) \leqslant X \leqslant (\theta/T)$ [12–14].

Eq. (1) approximates the temperature dependent part of resistivity at $T > 20$ K with the mean error not worse 3% at values of the parameters resulted in Table 1.

Numbers of samples in the table correspond to the numbers of curves in Fig. 2.

Values of parameters c_3 and θ under the order of magnitude correspond to observable in metals [15]. The values of resistivity are close to the data [1,2,16]. The variations of ρ_0 can be connected with a deviation of the samples form from correct.

Above mentioned values of electric resistivity and character of temperature dependence of resistivity of the samples Ti–Zr–Ni correspond to type (a) on classification [9], that is temperature dependence of resistivity of this system is determined by mean free path of electrons.

The icosahedral quasicrystals Ti–Zr–Ni, as well as others quasicrystalline superconductors, Al–Zn–Mg, Al–Cu–Mg, Al–Cu–Li, belong to the TC-class of quasicrystals for which are characteristic high, in comparison with the MI-class, values of electronic concentration ($e/a \geqslant 2.1$) and ratio of the quasilattice constant, d_0, to average atomic diameter, d ($d_0/d \geqslant 1.75$) [17].

According to [4] for rapidly quenched alloys—amorphous $Ti_{44}Zr_{19}Ni_{37}$, disordered icosahedral $Ti_{53}Zr_{26}Ni_{21}$ and icosahedral $Ti_{47}Zr_{33}Ni_{20}$ + Laves-phase—a derivative $d\rho/dT < 0$. Comparison of our data and the data [4] shows, that for icosahedral quasicrystals the increase of structural perfection of samples of Ti–Zr–Ni system (TC-type) leads to the change of the sign of temperature derivative, that is to the "metall-like" temperature dependence of resistance as opposed to MI-type where improvement of the samples quality results in increase of resistance and absolute size of a negative temperature derivative [17].

It is possible to assume, that "metall-like" temperature dependence of the resistance of icosahedral quasicrystals of TC-type is caused, first of all, by comparative high concentration of the conduction electrons.

4. Conclusions

Temperature dependences of the resistivity of investigated icosahedral quasicrystals of Ti–Zr–Ni systems with various composition and structural perfection in an interval 1.4–300 K are qualitatively similar.

The attributes of superconducting transition in $Ti_{41.5}Zr_{41.5}Ni_{17}$ are found out at $T < 1.6$ K.

In area $T < 20$ K the decrease of resistivity is observed at increase of temperature that can be connected to effects of weak electron localization.

In the area $T > 20$ K the temperature dependence of resistivity show the "metal" behaviour ($d\rho/dT > 0$). This dependence are caused by electron–phonon s–d scattering the efficiency of which decreases because of small length of electron free path. This reduction of scattering efficiency results in the appreciable curvature of $\rho(T)$ dependence up to the highest of the investigated temperatures.

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