Resistivity studies on low-T_c $A15$ compounds

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We report the low- and high-temperature resistivity studies of $A15$ compounds that have a low electron-phonon coupling constant (λ). The results do not agree with the model proposed by Gurvitch recently. We suggest further investigations before one starts using the universal plot of λ vs $\rho(0)$, where $\rho(0)$ is the residual resistivity.

The resistivity $\rho(T)$ of $A15$ compounds has an unusual temperature dependence.[1-3] At high temperatures ($T > 200$ K) their $\rho(T)$ deviates from linearity in T that is expected of a normal metal. However, the real puzzle is their $\rho(T)$ behavior at low temperatures ($T < 0.1\Theta_D$, where Θ_D is the Debye temperature of the compound). The $\rho(T)$ of many $A15$ compounds with "high" superconducting transition temperature ($T_c > 15$ K) shows a T^2 dependence at this temperature range ($T_c < T < 0.1\Theta_D$). Further, by studying[4] a few low-T_c $A15$ compounds, it was concluded that the $\rho(T)$ of these compounds shows[5] a higher power-law dependence of $T(T^3 - T^5)$. Although there are many theories that try to account for this behavior, we have already pointed out[6] the inadequacy of some of these models.

Recently, Gurvitch[7] has speculated that there is a universal disorder-induced resistivity behavior of strongly coupled metals (with large electron-phonon coupling constant λ) at low temperatures ($T_c < T < 0.1\Theta_D$). According to Gurvitch,[7] the power-law behavior of $\rho(T)$ with temperature changes from T^n ($n = 3$-5) to a T^2 as disorder increases provided their λ is sufficiently large ($\lambda > 0.8$). He has also suggested that the physics of this effect is probably due to nonconservation of momentum in the electron-phonon scattering at low temperatures. Further, he adds that such a universal correlation allows independent estimates of λ. Although Gurvitch has carefully studied a large number of $A15$ compounds, we have already pointed out[8] an exception to his correlation.

Gurvitch has answered[9] most of our questions except the fact that the $\rho(T)$ data of Ti_3Sb does not agree with his model. In this Brief Report, we report new resistivity studies on Ti_3X (X = Au, Ir, and Pt) compounds whose resistivity behavior at low temperatures cannot be explained by his correlation. We also report the resistivity data of Cr_3Si from 8 to 300 K. These compounds are made by melting the individual constituents (purity 99.9%) in an arc furnance under a high-purity argon atmosphere. X-ray powder diffraction revealed that each sample is a single-phase $A15$ structure. Their structural and superconducting properties are given in Table I. The low-temperature resistivity can be written as

$$\rho(T) = \rho_0 + AT^n , \tag{1}$$

where ρ_0 is the residual resistivity and A and n are constants. The quality of the fit is determined by a parameter called percentage deviation (D) and it is given by the expression

$$D = 100\left[\sum_{i=1}^{N}\frac{\chi_i^2}{N}\right]^{1/2} , \tag{2}$$

where χ_i is given by

$$\chi_i = [\rho_i(\text{obs}) - \rho_i(\text{fit})]/\rho_i(\text{obs}) . \tag{3}$$

We have used a program called MINUITS developed by James[10] to fit Eq. (1) to our resistivity data. Here, ρ_0, A, and n are treated as variable parameters and their values are determined using an error analysis.[10] A log-log plot is given in Fig. 1 to guide the eye. The fitting analysis for the low-temperature resistivity data ($T_1 < T < T_2$) is given in Table II.

From this table we find, regardless of their T_c or λ, $\rho(T)$ of all Ti_3X (X = Au, Ir, and Pt) alloys show a T^2 dependence in this temperature range ($T_1 < T < T_2$). One can also see that the maximum value of λ of these compounds is less than 0.8 and should not show any T^2 dependence of $\rho(T)$ according to Gurvitch's correlation. Hence, we find that our experimental results are in contradiction with his idea. According to Gurvitch the T^2 term is traceable to momentum nonconservation in electron-phonon scattering at low temperatures. He found that the value of A in Eq. (1) is 5-10 times larger than the predicted value. He suggested that the high

TABLE I. Structural superconducting properties of some low-T_c $A15$ compounds.

Sample	Lattice constant (Å)	T_c (K)	$\rho_{300\,K}$ ($\mu\Omega$ cm)	$\frac{\rho_{300\,K}}{\rho_{8\,K}}$
Ti_3Au	5.095	· · ·	89.242	6.1
Ti_3Pt	5.029	0.48	91.361	7.2
Ti_3Ir	5.007	4.25	119.142	2.6
Cr_3Si (annealed at 900°C)	4.554	· · ·	66.128	54.2

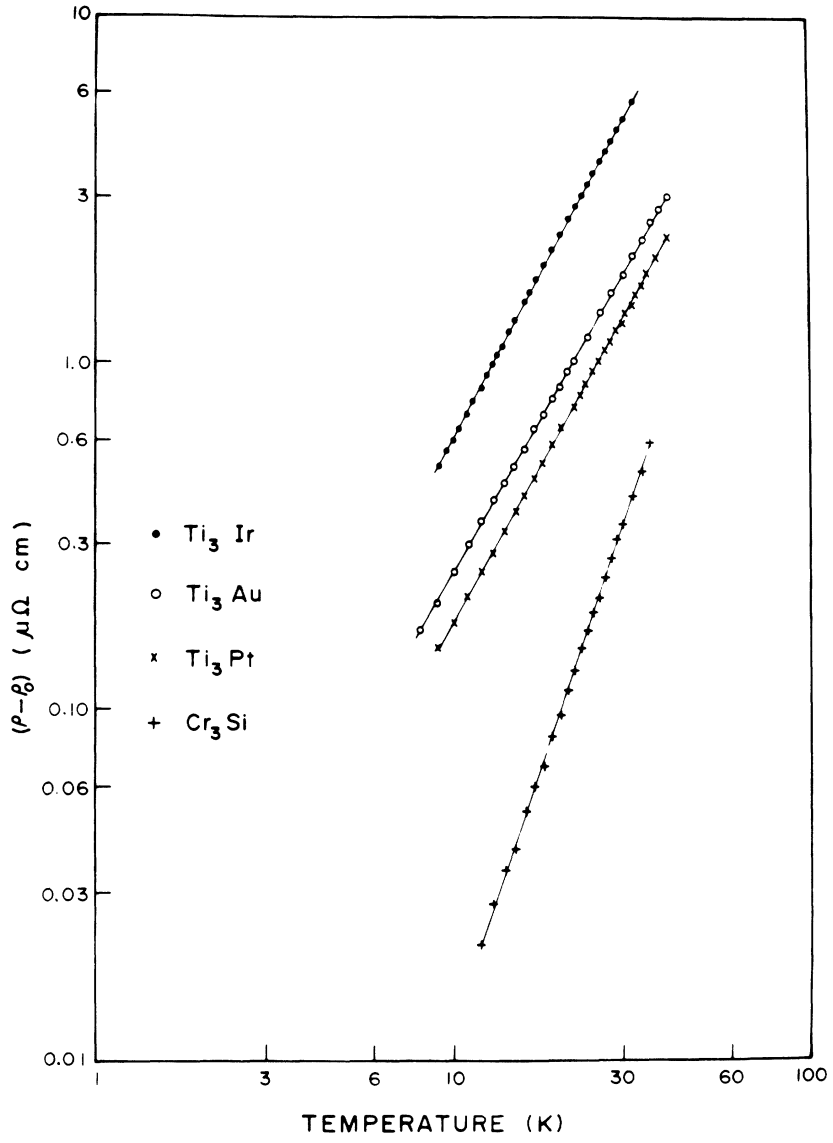

FIG. 1. A log-log plot of resistivity vs temperature of low-T_c $A15$ compounds at low temperatures.

values of λ promote the transition (T^n to T^2) at lower values of ρ_0 and also stated that the value of λ was not addressed in the theoretical analysis.

However, in the recent work of Al'tshuler,[11] the kinetic properties of conduction electrons are considered at low temperatures where the wavelength of the thermal phonons exceeds the electron mean-free path for elastic collisions with the impurities. Since the impurities influence the electron-phonon interaction, the usual kinetic equation is not valid and also Matthiessen's rule is violated. According to Al'tshuler, the modified kinetic equation yields a T^2 dependence of resistivity when $T > (\Theta_D/\mu\tau)$ where μ is the chemical potential and τ is the impurity lifetime of the electron. Such power-law dependence was obtained

TABLE II. Resistivity analysis of low-T_c $A15$ compounds.

Sample	$\rho(0)$ ($\mu\Omega$ cm)	A	n	T_1 (K)	T_2 (K)	D	λ	Θ_d[a] (K)
Ti_3Au	14.45	1.74×10^{-3} $\mu\Omega$ cm/K^2	1.95	8	40	0.13	· · ·	385
Ti_3Pt	12.50	2.40×10^{-3} $\mu\Omega$ cm/K^2	1.95	8	40	0.12	0.39	376
Ti_3Ir	49.45	5.6×10^{-3} $\mu\Omega$ cm/K^2	2.00	8	32	0.13	0.65	238
Cr_3Si	1.24	0.6×10^{-5} $\mu\Omega$ cm/K$^{3.2}$	3.21	8	40	0.32	· · ·	670

[a]Data taken from Ref. 12.

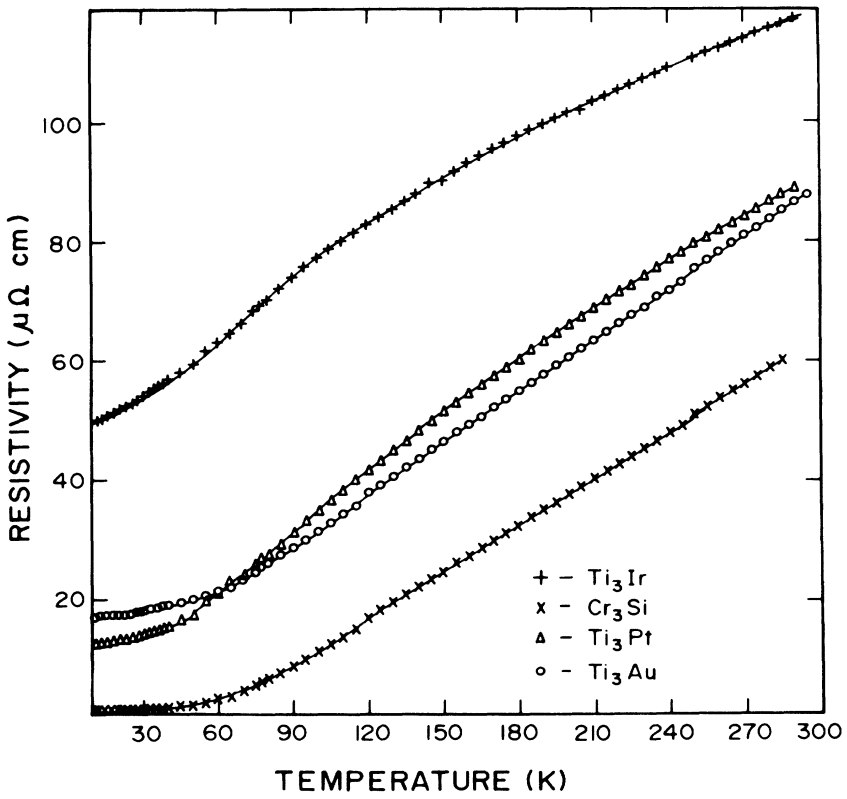

FIG. 2. Temperature dependence of resistivity of low-T_c $A15$ compounds.

without any assumption on the actual value of λ. However, one does not know whether this is the only mechanism operating at low temperatures which is responsible for the apparent T^2 behavior of $\rho(T)$. Also it is not very clear from this theory, why the $\rho(T)$ of other low-T_c compounds [including that of Cr_3Si where $\rho(T) \sim T^{3.2}$] shows a different power law at these temperatures. A log-log plot of the low-temperature resistivity with temperature is shown in Fig. 1. The overall resistivity curves for all these samples are shown in Fig. 2. Although $\rho(T)$ of Ti_3Ir shows a deviation from linear temperature dependence at high temperatures, the resistivities of Cr_3Si and Ti_3Au (which are nonsuperconducting down to 10 mK with very low λ) do not show such distinct deviation.

Finally, Gurvitch[7] has pointed out the importance of spin-fluctuation effects in the estimate of λ in certain vanadium compounds. Although it is true that these effects are important in vanadium-based $A15$ compounds,[12] we believe the contributions from this effect are negligible in low-T_c $A15$ Ti_3X compounds. Previous studies indicate[12,13] that the values of the densities of states for $A15$ Ti_3X compounds are low and this combined with the susceptibility studies[14] show the contribution from spin fluctuation is too small to account for the T^2 dependence of $\rho(T)$ at low temperatures.

In conclusion, we would like to point out that it may be premature to completely believe the plot given by Gurvitch to estimate λ of strongly coupled metals based on the resistivity analysis. One needs further experimental data on various other compounds (non-$A15$ compounds with large and small λ) to verify this universality at low temperatures.

[1]M. Gurvitch, A. K. Ghosh, B. L. Gyorffy, H. Lutz, O. F. Kammerer, J. S. Rosner, and M. Strongin, Phys. Rev. B **22**, 128 (1980).

[2]R. Caton and R. Viswanathan, Phys. Rev. B **25**, 179 (1982).

[3]P. B. Allen, in *Superconductivity in d and f Band Metals,* edited by M. B. Maple (Plenum, New York, 1980), p. 128.

[4]M. Gurvitch, A. K. Ghosh, B. L. Gyorffy, H. Lutz, O. F. Kammerer, J. S. Rosner, and M. Strongin, Phys. Rev. Lett. **41**, 1616 (1978).

[5]M. Gurvitch, Ref. 3, p. 317.

[6]S. Ramakrishnan, A. K. Nigam, and Girish Chandra, Phys. Rev. B **34**, 6166 (1986).

[7]M. Gurvitch, Phys. Rev. Lett. **56**, 647 (1986).

[8]S. Ramakrishnan and Girish Chandra, Phys. Rev. Lett. **57**, 1961 (1986).

[9]M. Gurvitch, Phys. Rev. Lett. **57**, 1962 (1986).

[10]F. James, computer code MINUITS (CERN program library D 506, Geneva, Switzerland, 1971).

[11]B. L. Al'tshuler, Zh. Eksp. Teor. Fiz. **75**, 1330 (1978) [Sov. Phys. JETP **48**, 670 (1978)].

[12]J. L. Staudenmann, B. DeFacio, L. R. Testardi, S. A. Werner, R. Flukiger, and J. Muller, Phys. Rev. B **24**, 6446 (1981).

[13]A. Junod, R. Flukiger, and J. Muller, J. Phys. Chem. Solids **37**, 27 (1976); A. Junod (private communication).

[14]D. I. Bardos, R. M. Waterstrat, T. J. Rowland, and J. B. Darby, Jr., J. Low Temp. Phys. **3**, 509 (1970).