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Temperature dependence of electrical resistivity of vanadium, platinum, and copper

D. B. Poker and C. E. Klabunde
Solid State Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee 37830

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The electrical resistivities of V, Pt, and Cu (resistance ratios of 387, 7192, and 2047, respectively) were measured in the temperature range 6–327 K, and were analyzed following the theories of Bloch-Grüneisen and Wilson. An excellent fit to the data was obtained over the entire temperature range. The low-temperature (6–12 K) data were analyzed for the existence of a quadratic temperature dependence; the V and Pt exhibited quadratic temperature dependences with coefficients of 370 and 110 $\mathrm{f\Omega\,m\,K^{-2}}$, respectively. The data did not support the use of a quadratic term over the entire temperature range.

Early theoretical calculations by Block and Grüneisen, Mott, and Wilson of the scattering mechanisms for electrons have been extensively used in analyzing the electrical resistivity of metals.[1] Recent improvements in the refining of vanadium have led to the production of specimens significantly purer than previously available. In this paper we report measurements of electrical resistivity of such a vanadium specimen, as well as of copper and platinum, as a function of temperature, and the data are analyzed in terms of this scattering theory. The low-temperature data (6–12 K) were also analyzed to determine the existence of a term quadratic in temperature.

EXPERIMENT

The electrical resistance of wire specimens (0.25 mm diameter by 42 mm long) of V, Cu, and Pt was measured by standard precision potentiometric techniques, using soldered potential contacts for Cu and Pt samples and spot-welded contacts for the V. Temperature was measured in the range of 6–327 K using a copper-Constantan thermocouple having a liquid-helium reference junction. The thermocouple was calibrated in liquid helium and at the ice point. The residual error emf observed with both junctions in He was subtracted from all the readings, and the remaining signals were scaled by the constant factor (1.000 665) required to make the He-to-ice point interval agree with the tables.[2] The residual resistance ratio ($R_{273}/R_{3.6}$) of the V specimen was 387. The accompanying Cu and Pt specimens had a nominal purity of 99.999%, and their resistance ratios were 2047 and 7192, respectively.

RESULTS

In applying the theoretical model initiated by Bloch and Grüneisen to the electrical resistivity of metals, one may use the formula

$$\rho=\rho_0+\rho_{ee}T^2+\rho_{sd}T^3\frac{J_3(\Theta/T)}{7.212}+\rho_{ss}T^5\frac{J_5(\Theta/T)}{124.14}\ , \tag{1}$$

where

$$J_N(\Theta/T)=\int_0^{\Theta/T}\frac{x^N\,dx}{(e^x-1)(1-e^{-x})}\ .$$

The second term, which represents direct electron-electron scattering, has received recent attention in the low-temperature analysis of some metals. The last two terms represent, respectively, inter- and intraband scattering of electrons from the conduction band. Analyses of these terms are available elsewhere.[1] While this identification of the ρ_{sd} and ρ_{ss} terms has been disputed,[3] their use as interpolation functions is still valuable for comparing temperature variation of data.

Our data were anlayzed using Eq. (1) over the entire temperature range, with the Debye temperature, Θ, included as an adjustable parameter. A relative-least-squares criterion was used for fitting, and estimated errors were obtained by varying each parameter in turn until the fit was worse by one standard deviation.

The inclusion of the ρ_{ee} term in Eq. (1) when fitting over the entire temperature range, 6–327 K, was not supported by the data. No significant improvement in the fit resulted when ρ_{ee} was included, whereas none of the other terms could be deleted without drastically affecting the fit. Furthermore, changing the upper temperature limit for the fit caused the values of ρ_{ee} to fluctuate, taking on small positive and negative values. For these reasons, the ρ_{ee} term was left out of Eq. (1) for the high-temperature analysis.

The fit for copper was made without a ρ_{sd} term. When a ρ_{sd} term was included, a small negative term resulted, which was considered unphysical. The

TABLE I. Electrical resistivity parameters for copper, platinum, and vanadium.

	Vanadium	Platinum	Copper
$\rho_{273.15}(\mathrm{n\Omega\,m})$	193.6	95.9	15.5
$\rho_0(\mathrm{p\Omega\,m})$	505 ±20	13.6 ± 3	7.6 ± 0.3
$\rho_{sd}\left(\frac{\mathrm{f\Omega\,m}}{\mathrm{K}^3}\right)$	30.9 ± 1.7	17.0 ± 3	. . .
$\rho_{ss}\left(\frac{\mathrm{a\Omega\,m}}{\mathrm{K}^5}\right)$	13.7 ± 0.7	68.2 ± 5	2.38 ± 0.1
Θ_D (K)	367 ±4	215 ± 5	338 ± 3
$(\chi^2)^{1/2}$	1.2%	2.5%	1.2%

remaining parameters are listed in Table I. The value of $\rho_{273.15}$ for V was experimentally determined, while the values for Pt and Cu are from Meaden.[4]

While the data over the entire temperature range could not be adequately fit when a ρ_{ee} term was included, the possibility of a term proportional to T^2 at low temperature was considered. The quadratic temperature dependence has been seen in some materials,[5] and is of interest in the case of V because of recent work investigating the role of enhanced electron-electron scattering[6] and spin fluctuations[7] on electrical properties. Possibilities for the source of a ρ_{ee} term which disappears at high temperatures have been suggested by Pinski, Allen, and Butler.[3]

The data were fit to the function $\rho=\rho_0+aT^2+bT^N$ from 6–12 K. The parameters did not vary strongly as a function of the upper limit of temperature, but the best results were obtained with a limit of 12 K. The results are listed in Table II, and are shown in Fig. 1 for the case where $N=5$. For all three elements, a good fit was obtained for values of N near 5. The quadratic temperature dependence, represented by the vertical intercept, was negligible for copper, but was significant for vanadium and platinum.

TABLE II. Low-temperature fit to $\rho=\rho_0+aT^2+bT^N$.

	Vanadium	Platinum	Copper
$\rho_0(\mathrm{p\Omega\,m})$	494	13.6	7.6
$a\left(\frac{\mathrm{f\Omega\,m}}{\mathrm{K}^2}\right)$	370	110	3
$b\left(\frac{\mathrm{a\Omega\,m}}{\mathrm{K}^N}\right)$	54	105	5.4
N	5.05	5.04	4.61
$(\chi^2)^{1/2}$	0.02%	0.34%	0.15%

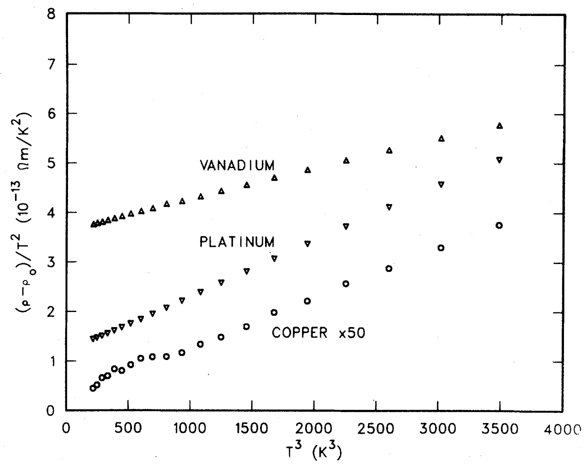

FIG. 1. $(\rho-\rho_0)/T^2$ vs T^3. The vertical intercept represents the quadratic temperature dependence of resistivity.

The coefficient of the T^2 term in Pt is 110 $\mathrm{f\Omega\,m\,K^{-2}}$, comparable to but less than, the results of others. Azarbar and Williams[8] report a value of 150 $\mathrm{f\Omega\,m\,K^{-2}}$ below 15 K, while Uher, Lee, and Bass[9] report values between 130 and 170 $\mathrm{f\Omega\,m\,K^{-2}}$ below 1 K.

Recently, Tsai *et al.*[10] published measurements of the resistivity of vanadium ($R=1760$) between 2 and 300 K, and fit the data with Eq. (1). Our values for ρ_{ss} and ρ_{sd} are larger than theirs, but this is mainly due to their restriction of Θ to a constant value of about 380 K. In the high-temperature limit, when corrected for differences in the values of Θ, the values of ρ_{ss} differ by 25%, while the values of ρ_{sd} differ by only 4%. They obtained a value for ρ_{ee} of 130 $\mathrm{f\Omega\,m\,K^{-2}}$, which is only about one-third as large as our result. However, our result was obtained from a fit to only the low-temperature data, below 12 K.

Our results indicate that the resistivities of V and Pt contain a quadratic temperature dependence at low temperatures, with the value for Pt comparable to those reported previously. Our results do not support the inclusion of a ρ_{ee} term over the entire temperature range.

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