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Temperature dependence of electrical resistivity of deformed and undeformed V-rich V_3Si single crystals

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The electrical resistivity $\rho(T)$ of V-rich V_3Si single crystals ($T_c \simeq 11.4$ K) was measured from 4.2 to 300 K along the directions of [1 0 0] and [1 1 1] before and after plastic deformation at 1573 K. Anisotropy of $\rho(T)$ was observed although V_3Si has the cubic A15 structure. Plastic deformation does not affect the normal-state $\rho(T)$ behaviour but changes the normal–superconducting transition width ΔT_c. At low temperatures ($T_c < T \lesssim 40$ K), $\rho(T)$ varies approximately as T^n where $n \simeq 2.5$ and this behaviour does not contradict the $\rho(0)$–λ "phase-diagram" plot proposed by Gurvitch, where λ is the electron–phonon coupling constant and $\rho(0)$ is the residual resistivity.

1. Introduction

The electrical resistivity $\rho(T)$ of A15 compounds as a function of temperature has been considerably studied because of their anomalous temperature dependence of $\rho(T)$ (electrical resistivity at temperature T) [1–3] and a relatively high superconducting transition temperature T_c. $\rho(T)$ for a normal metallic system shows a linear temperature dependence at high temperatures and it shows a $T^n (n = 3–5)$ temperature dependence at low temperatures. However, $\rho(T)$ for A15 compounds deviates from a linear temperature dependence, reaching a saturation value at high temperature. Furthermore, at low temperature, many A15 superconducting compounds with a transition temperature of $T_c > 15$ K show a T^2 dependence of $\rho(T)$, but a few low-T_c A15 compounds such as Mo_3Ge and Nb_3Sb show a higher power-law dependence $T^n (n = 3–5)$ [1, 2, 4, 5].

Considerable progress towards understanding their anomalous behaviour of $\rho(T)$ and the relation between their superconductive properties and $\rho(T)$ was recently achieved. However, the $\rho(T)$ behaviour especially at low temperature has not as yet been fully explained [3, 6]. Gurvitch [7, 8] has suggested that the appearance of the T^2 temperature dependence of $\rho(T)$ depends on a combination of strong electron–phonon coupling and a disorder-induced effect. He has demonstrated that at low temperature there is a new universal transition in the resistivity behaviour of strongly coupled superconductors. Chiara *et al.* [9] reported that the results for their good stoichiometric V_3Si multilayered films ($T_c \simeq 16$ K) agreed with Gurvitch's idea, but some exceptions were pointed out by Ramakrishnan and co-workers [3, 6, 10].

In A15 compounds, it is well known that lattice defects considerably influence both the normal-state resistivity and the transition temperature [11]. The effect of disordering on $\rho(T)$ was reported in irradiated Nb_3Sn, V_3Si, Nb_3Pt and Nb_3Al [1, 2]. Caton and Viswanathan [2] reported that the resistivity of irradiated V_3Si at low temperatures shows a T^2 dependence. In this paper, we report the temperature dependence of the electrical resistivity of V-rich off-stoichiometric V_3Si single crystals with the A15 structure. The effect of high-temperature plastic deformation on $\rho(T)$ of these crystals is also presented.

2. Experimental procedure

The master ingot of V_3Si was prepared by melting high-purity V and Si in a plasma-arc furnace. Rods of 7 mm diameter and 80 mm length were cut from the ingot by spark machining. A single crystal was grown from these rods by the floating zone method, using a single-crystal growth apparatus NEC SC-35HD with an optical heat source at a growth rate of 1.4 mm ks^{-1} under a high-purity argon gas flow. The chemical composition of the crystal was analysed by energy-dispersive X-ray analysis. The A15 structure was confirmed by X-ray powder diffraction patterns. Small precipitates of vanadium-rich solid solution were observed by scanning electron microscopy but their volume fraction was too small to make a significant contribution to the resistivity.

Oriented compression samples with dimensions about 2 mm × 2 mm × 6 mm were cut from the single crystal by spark machining. Compression tests were carried out at a nominal strain rate of 1.7×10^{-4} s^{-1}

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TABLE I Sample characterization for V-rich V_3Si

Chemical composition (at % Si)	Lattice constant (nm)	T_c (K)	$\rho(300)^a$ ($\mu\Omega$ m)		$\rho(300)/\rho(T_c)^a$	
			[1 0 0]	[1 1 1]	[1 0 0]	[1 1 1]
22.1	0.4731	11.4	0.71	0.82	2.1	2.4

[a] $\rho(300)$ and $\rho(T_c)$ are the resistivities at 300 K and just above T_c, respectively.

at 1573 K in a vacuum of $\sim 7 \times 10^{-3}$ Pa. The samples oriented near [1 0 0] and [1 1 1] were compressed to about 5 and 10% of plastic strain, respectively.

Samples with dimensions about 0.5 mm × 0.5 mm × 6 mm for resistivity measurements were cut from the deformed samples and the single crystal by spark machining. The electrical resistivity $\rho(T)$ was measured from 4.2 to 300 K by a standard d.c. four-probe technique with a current of 5 mA along the direction near [1 0 0] and [1 1 1] with and without plastic strain.

3. Results and discussion

Table I shows the characterization of the V-rich V_3Si single crystals studied. Fig. 1 shows the resistivity data of undeformed samples as a function of the temperatures from 4.2 to 300 K. The $\rho(T)$ curve shows a negative deviation from its linear temperature dependence at high temperatures ($T > 150$ K). This behaviour is similar to that reported for several A15 compounds including V_3Si [2, 4, 12], Chevrel phases [13], and several silicides [12, 14]. Gurvitch [15] related these phenomena to the shortness of the conduction electron mean free path.

Although V_3Si has the cubic A15 structure and the electrical resistivity is thought to be independent of orientation, $\rho(T)$ along the [1 1 1] direction is slightly higher than that along the [1 0 0] direction. A similar anisotropy of resistivity in a cubic system was also reported in $CoSi_2$ [16]. The anisotropy observed in our samples should not be attributed to an intrinsic origin. Jurisch *et al.* [17] pointed out that there was a possibility of compositional fluctuations along the crystal growth axis. Although a significant compositional fluctuation along the growth direction was not detected by means of energy-dispersive X-ray analysis, the anisotropy of $\rho(T)$ observed here may arise from a very small compositional fluctuation. But, at the same time, it should be noted that Ullrich *et al.* [18] mentioned that the symmetry of a cubic V_3Si crystal was lowered by dislocations, and Paufler *et al.* [19] observed that needle-shaped subgrains were distributed parallel to the direction of crystal growth. Inhomogeneous distribution of dislocations and point defects caused by off-stoichiometry may also be responsible for the anisotropy of $\rho(T)$.

Fig. 2 shows the normal–superconducting transition behaviour of the samples for the [1 0 0] direction before and after deformation. Although neither the normal-state $\rho(T)$ behaviour nor the offset transition temperature changes very much after deformation, the onset transition temperature shifts to a higher temperature. The sample deformed parallel to [1 1 1] shows a similar behaviour. Mahajan *et al.* [20] observed no effect of high-temperature plastic deformation on the superconducting transition temperature for [1 1 0] deformed crystals. The V_3Si crystals are deformed by {1 0 0}⟨0 1 0⟩ slip systems [20] and even after dislocations pass through the crystals, stress relief and atomic reordering are allowed in the cooling process

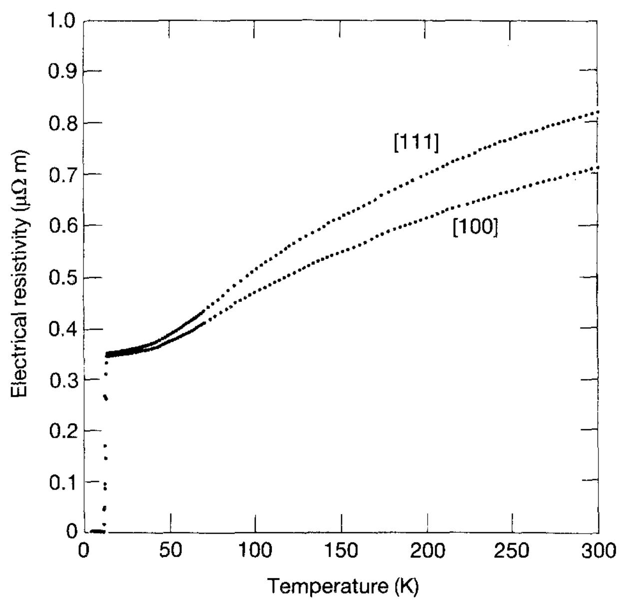

Figure 1 Resistivity of undeformed V-rich V_3Si as a function of temperature and crystallographic direction.

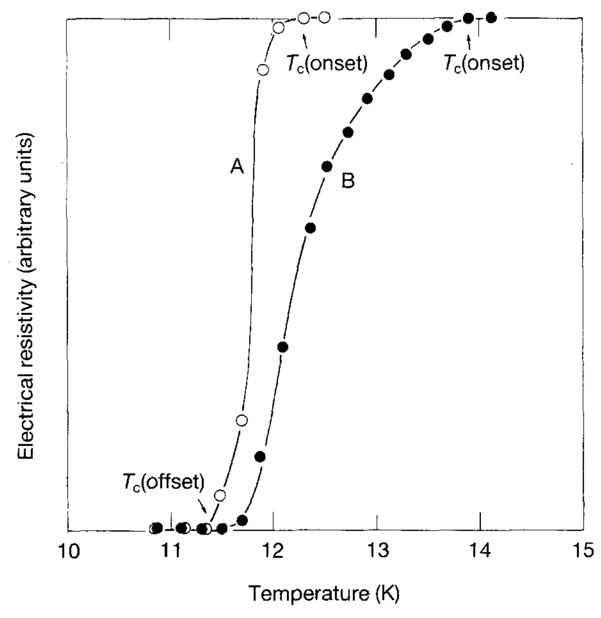

Figure 2 Normal–superconducting transition behaviour of V-rich V_3Si before and after deformation for [1 0 0] direction. A and B show the results of the undeformed sample and the sample deformed ~5%, respectively.

after deformation. Therefore, the offset transition temperature T_c is independent of the plastic deformation at high temperatures.

Quyen *et al.* [21] reported that the T_c of V_3Si showed a strong compositional dependence, and this may be due to lattice defects formed by the compositional deviation from stoichiometry; the excess V or Si of off-stoichiometry produces a decrease or increase in T_c, respectively. Dislocations may act as sites to annihilate and trap lattice defects, and suppress the effect of lattice defects caused by excess V of off-stoichiometry. A rearrangement of lattice defects around dislocations would locally improve the superconductivity and cause the increase of the onset transition temperature.

The resistivity at low temperatures can be written as

$$\rho(T) = \rho_0 + AT^n \qquad (1)$$

where ρ_0 is the residual resistivity extrapolated to zero Kelvin and A and n are constants. The fitting analysis is achieved by minimizing the error S of a least-square fit. S is given by

$$S = \sum_{i=1}^{N} [\rho_i(T)_{\mathrm{meas}} - \rho_i(T)_{\mathrm{fit}}]^2 \qquad (2)$$

where N is the number of data points in the fitted region. The quality of the fit is determined by a parameter R defined as

$$R = \left(S \Big/ \sqrt{\sum_{i=1}^{N} [\rho_i(T)_{\mathrm{meas}}]^2} \right)^{1/2} \qquad (3)$$

Table II shows the fitting analysis for the resistivity of the undeformed sample oriented parallel to [1 0 0] in the temperature range $T_c < T \lesssim 40$ K. The n values of all the samples, with and without plastic strains for both directions, are equal to 2.5 ± 0.2.

Gurvitch [7, 8] pointed out that a universal transition in the resistivity behaviour of strongly coupled superconductors could exist in the temperature range between T_c and $0.1\Theta_D$, where Θ_D is the Debye temperature. He suggested that the electron–phonon coupling λ could be estimated by using a $\rho(0)$–λ "phase-diagram" plot. In our data, the V-rich V_3Si samples have $n \simeq 2.5$, $T_c \simeq 11.4$ K and a residual resistivity $\rho_0 \simeq 0.34$ μΩ m. Considering $n \simeq 2.5$, that is in the T^3–T^2 transition region, we obtain electron–phonon coupling $\lambda \simeq 1$ from his plot [8]. Gurvitch mentioned that it is disputed whether $\lambda \simeq 1$ or $\lambda \simeq 2$ in V_3Si; he suggested $\lambda \simeq 2$ using both his calculation and his $\rho(0)$–λ plot [7, 8]. But in our data, even using his $\rho(0)$–λ plot, we obtain $\lambda \simeq 1$ in V-rich V_3Si. Of course, our sample is V-rich and $T_c \simeq 11.4$ K, which is lower than the highest values $T_c \simeq 17$ K obtained for a stoichiometric composition, so the λ value may be lower than that of stoichiometric V_3Si. Therefore, we consider that the result that $n \simeq 2.5$ for our V-rich V_3Si samples does not contradict Gurvitch's plot.

TABLE II Resistivity analysis of undeformed V-rich V_3Si single crystal for [1 0 0] direction in the temperature range $T_c < T \lesssim 40$ K

ρ_0 (μΩ m)	A (μΩ m $K^{-2.5}$)	n	S (μΩ^2 m^2)	R
0.34	1.62×10^{-6}	2.5	1.50×10^{-4}	0.003 16

4. Conclusions

1. Anisotropy of $\rho(T)$ for V-rich V_3Si single crystals was observed. $\rho(T)$ along the [1 1 1] direction was slightly higher than that along the [1 0 0] direction. This anisotropy may arise not only from fluctuations of composition but also from dislocations and from point defects caused by off-stoichiometry.

2. The $\rho(T)$ behaviour in the normal state and the offset transition temperature did not change very much after plastic deformation, but a slight increase of the onset transition temperature was observed for both directions. This increase would be due to local atomic rearrangement around dislocations.

3. At low temperatures between T_c and 40 K, $\rho(T)$ for V-rich V_3Si ($T_c \simeq 11.4$ K) varies approximately as T^n where $n \simeq 2.5$. This $\rho(T)$ behaviour does not contradict the $\rho(0)$–λ "phase-diagram" plot proposed by Gurvitch.

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