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Effect of lattice transformation on the pressure dependence of T_c of V_3Si single crystals*

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The superconducting transition temperature T_c has been measured under hydrostatic pressure up to 18 kbar on both transforming and nontransforming V_3Si single crystals. dT_c/dp was found to be always positive, but about 30% smaller for the nontransforming samples. The results are compared with predictions based on previous elastic-modulus measurements under pressure.

Samples of the high-temperature superconductor V_3Si may or may not undergo a cubic-to-tetragonal lattice transformation above the superconducting transition temperature T_c, depending on the sample conditions. However, they always exhibit a shear mode, $C_s = \frac{1}{2}(C_{11} - C_{12})$, softening with decreasing temperature. The softening is usually stronger for the transforming sample but is arrested below T_c.[1] The T_c of the transforming samples is slightly lower than that of the nontransforming ones. It was suggested that the high T_c of V_3Si was mainly caused by the lattice softening near T_c.[2] The pressure-enhanced superconductivity in this material was attributed to the possible pressure-induced lattice softening.[2] Several experiments have since been carried out on V_3Si subjected to pressure to search for pressure-induced lattice softening.[3–5]

Elastic-modulus studies of V_3Si single crystals showed that C_s for the transforming and nontransforming crystals behaves quite differently under hydrostatic pressure at low temperature. The pressure coefficient $\partial C_s/\partial p$ for the transforming sample[3] decreases to zero at about 90 K, reaches a minimum (− 0.05) at about 80 K, and finally becomes positive below 50 K. This indicates that the shear mode softens between 90 and 50 K, and achieves a maximum softness at about 80 K, but stiffens again at lower temperature under pressure. As for the nontransforming sample,[4] while $\partial C_s/\partial p$ becomes negative at about 90 K, it continues to decrease monotonically to a more negative value (− 5) down to 13.5 K. This represents a stronger softening of the shear mode under pressure all the way to very low temperature. From the elastic data, the elastic Grüneisen constants were calculated in the anisotropic Debye model for both the transforming and the nontransforming samples.[3] By using McMillan's formula, a much larger pressure effect (~16 times) on T_c of the nontransforming samples was predicted.[3]

Recently the pressure dependence of T_L of V_3Si single crystal was determined up to 18 kbar.[5] T_L was found to be suppressed by pressure, and an extrapolated critical pressure of 24 kbar was obtained for the complete stabilization of the high-temperature cubic phase down to the superconducting state. A close examination of previous high-pressure results on T_c of V_3Si[6] which was extended to 24 kbar reveals a deviation from linearity above 22 kbar. All these can be explained consistently in terms of the Labbe-Friedel model[7] based on the singular nature of the electron energy spectrum by taking into account the interband charge transfer under pressure.[5,8] However, the results are also consistent with suggestions by Testardi evoking pressure-induced lattice softening.[2] According to the latter, T_c should saturate and then decrease with higher pressure (> 24 kbar). This is apparently different from the prediction[3] that the nontransforming (or cubic) V_3Si should exhibit a larger pressure effect on its T_c according to the elastic data in spite of the fact that these elastic results seemed to support Testardi's model.

Although the hydrostatic pressure effect on T_c of V_3Si was previously studied by various workers,[6] the crystal structure in the superconducting state of the samples investigated has never been clear. In this experiment we examined the pressure dependence of T_c of V_3Si single crystals of known lattice structure at low temperature. The purpose was two-fold: (i) to test the predictions of a larger pressure effect on T_c for the nontransforming samples than for the transforming one,[3] and (ii) to examine indirectly the suggested high pressure (> 24 kbar) dependence of T_c.[2]

In view of the sensitive dependence of the elastic properties of V_3Si on the sample conditions, we investigated only samples on which elastic modulus studies were previously carried out. We have measured T_c of one transforming (No. 1)[3] and two nontransforming [Nos. 2 (Ref. 9) and 3 (Ref. 4)] V_3Si single-crystal samples under hydrostatic pressure up to 18 kbar. They were small bars (~0.6×1 ×4 mm) spark cut from bigger crystals. The big crystals were kindly supplied by Testardi (Nos. 1 and 2)[1,3] and Larsen and Ruoff (No. 3),[4] who had studied the elastic moduli on the crystals in great detail both under pressure (Nos. 1 and 3) and not under pressure (No. 2). The T_c's are 16.6 K for

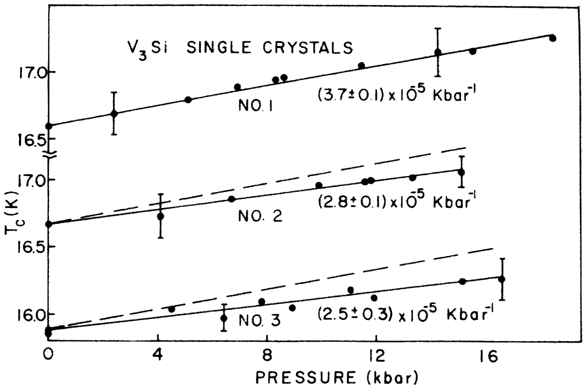

FIG. 1. Hydrostatic pressure dependence of T_c for the transforming sample No. 1 and nontransforming samples No. 2 and No. 3. The two dashed lines have the slope of sample No. 1.

sample No. 1, 16.7 K for No. 2, and 15.9 K for No. 3. The resistance ratios between room temperature and 20 K are 26 for sample No. 1, 16 for No. 2, and 7 for No. 3. This is consistent with the previous observation that only samples with a resistance ratio larger than ~25 will structurally transform.[1] Calorimetric checks[10] were also done on samples No. 1 and No. 2. A lattice transformation was observed in No. 1 at 21.6 K at zero pressure, but no transformation was detected in No. 2 above its T_c up to 18 kbar, in agreement with previous studies.[5] The superconducting transition was detected by a standard ac inductance bridge operating at 10 Hz. The hydrostatic pressure environment was provided by a clamp technique[11] using a pressure medium consisting of a fluid mixture of 1 : 1 *n*-pentane and isoamyl alcohol. The pressure experienced by the sample at low temperature was determined by a superconducting Pb manometer situated next to the sample.

T_c was found to be enhanced linearly by the application of hydrostatic pressure up to 18 kbar for all three V_3Si samples, as shown in Fig. 1. The general shape of the transition is similar for all samples. The vertical bar represents the width of the transition, which varies from ~0.2 K at 1 bar to ~0.4 K at 18 kbar. The dot stands for the midpoint of the transition. The values of dT_c/dp are $+(3.7\pm0.1)\times10^{-5}$ Kbar^{-1} for the transforming sample (No. 1), and $+(2.8\pm0.1)\times10^{-5}$ and $+(2.5\pm0.3)\times10^{-5}$ Kbar^{-1} for the nontransforming samples (No. 2 and No. 3, respectively). According to results of Smith,[12] dT_c/dp of V_3Si increases with its T_c (assuming no crystallographic difference), which may reflect the impurity level and the strain state of the sample. Here samples No. 1 and No. 2 were from the same source (Bell Labs) and thus should have the same starting impurities. In addition, T_c was higher for No. 2. Therefore the ~30% difference between the values of dT_c/dp of No. 1 and No. 2 must be associated with the structural transformation. In other words, dT_c/dp is larger for the transforming V_3Si than for the nontransforming one. The small difference in dT_c/dp between No. 2 and No. 3 may be caused by the difference in impurity levels of these two samples as evidenced by the much lower T_c of sample No. 3.

Clearly pressure has a smaller effect on T_c of No. 3 than on T_c of No. 1, in strong contrast with the prediction[3] that dT_c/dp for No. 3 would be about 16 times that for No. 1. This disagreement may be attributed to the neglect of the dispersion of the phonon energy spectrum and thus the overestimation of the contribution of the long-wavelength phonon modes obtained from the elastic measurements.[3] Judging from the low T_c of sample No. 3, it is also possible that the stronger softening of C_s under pressure at low temperature is characteristic of a higher impurity level. The smaller positive value of dT_c/dp of the nontransforming or the cubic V_3Si suggests that T_c of a transforming sample would not saturate at ~24 kbar. Instead it would keep on increasing after the cubic phase is stabilized beyond 24 kbar, although at a slower rate, reflecting the different responses to pressure of the electron energy spectra of V_3Si in its cubic and tetragonal states. The present data also partially explain the large divergences of dT_c/dp previously observed by other workers.[6]

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[1] For reviews, see L. R. Testardi, in ***Physical Acoustics***, edited by W. P. Mason and R. N. Thurston (Academic, New York, 1973), Vol. 10.

[2] L. R. Testardi, Phys. Rev. B 5, 4342 (1972).

[3] P. F. Carcia, G. R. Barsch, and L. R. Testardi, Phys. Rev. Lett. 27, 944 (1971); P. R. Carcia and G. R. Barsch, Phys. Status Solidi (to be published).

[4] R. E. Larsen and A. L. Ruoff, J. Appl. Phys. 44, 1021 (1973).

[5] C. W. Chu and L. R. Testardi, Phys. Rev. Lett. 32, 766 (1974).

[6] T. F. Smith, Phys. Rev. Lett. 25, 1483 (1970); H. Neubauer, Z. Phys. 226, 211 (1969).

[7] J. Labbe and J. Friedel, J. Phys. (Paris) 27, 153 (1966); 27, 303 (1966).

[8] C. S. Ting and A. K. Ganguly (report of work prior to publication); G. R. Barsh and D. A. Rogowski (report of work prior to publication).

[9] L. R. Testardi and T. B. Bateman, Phys. Rev. 154, 402 (1967).

[10] For the technique, see C. W. Chu and G. S. Knapp, Phys. Lett. A 46, 33 (1973).

[11] C. W. Chu, T. F. Smith, and W. E. Gardner, Phys. Rev. Lett. 20, 198 (1968).

[12] T. F. Smith, J. Low Temp. Phys. 6, 171 (1972).