minor axis and counter-rotating flow about the major axis. The diffusion is enhanced by a term in $dj_{\varphi-1}/dr$ which measures the shear of the magnetic field, and also by a term x_c which measures the outward shift of the plasma associated with the rotation.

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Pressure-Enhanced Superconductivity in V₃X Compounds*

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The superconducting transition temperature of the compounds V₃Si, V₃Ga, and V₃Ge is found to increase linearly with the application of hydrostatic pressure. This behavior is compared with predictions based upon measurements of the elastic moduli.

The superconducting transition temperature of the compounds V₃Si, V₃Ga, and V₃Ge have been raised by the application of hydrostatic pressure. This observation is compared with some interesting predictions regarding the strain dependence of the superconducting transition temperature for these compounds made in a recent note by Testardi, Kunzler, Levinstein, and Wernick.[1]

The samples studied were in the form of small sections (weight ~0.1 g) of arc-cast buttons, with the addition of a cylindrical sample 3 mm in diameter, 3 mm long, which was cut, by spark erosion, from a large single crystal of V₃Si.[2] Hydrostatic pressure was applied to the samples at room temperature with a 1:1 mixture of n-pentane and isoamyl alcohol as the transmitting fluid in a piston and cylinder arrangement using a cell technique similar to that described by Jayaraman et al.[3] A clamp technique was used to retain the pressure during cooling to the superconducting transition temperature. Thus, the only inhomogeneity in the pressure distribution is that which is introduced upon the freezing of the transmitting fluid and the thermal contraction during the subsequent cooling to the low temperature. Previous experience with this arrangement suggests that only slight deviation from a hydrostatic pressure environment results. The transition to the superconducting state was detected magnetically using an ac technique and a

measuring frequency of 130 cps. The temperature was determined by a germanium resistance thermometer which had been calibrated against the vapor pressures of liquid helium and hydrogen and the superconducting transition temperatures of lead and niobium. Pressures were determined relative to the superconducting transition temperature of tin or lead.[4] Room-temperature lattice-parameter determinations were made on filings taken from the polycrystal samples after the pressure measurements had been made.[5]

The zero-pressure T_c values, taken before the pressure measurements, and the room-temperature lattice parameters are listed in Table I. All quoted T_c values, both at zero and high pressure, are for the midpoint of the transition. The transition for the V₃Ge was sharp (~0.03°K wide), but the transitions for the V₃Ga and the polycrystal-

Table I. Lattice parameter, T_c, and $\partial T_c/\partial P$ for some V₃X compounds.

Compound	a^a (Å)	T_c (°K)	$\partial T_c/\partial P$ (10^{-5} °K bar^{-1})
V₃Si (single crystal)		16.85	3.7
V₃Si (polycrystal)	4.725	16.83	3.1
V₃Ga	4.816	13.87	1.0
V₃Ge	4.783	6.104	8.1

[a]Ref. 5.
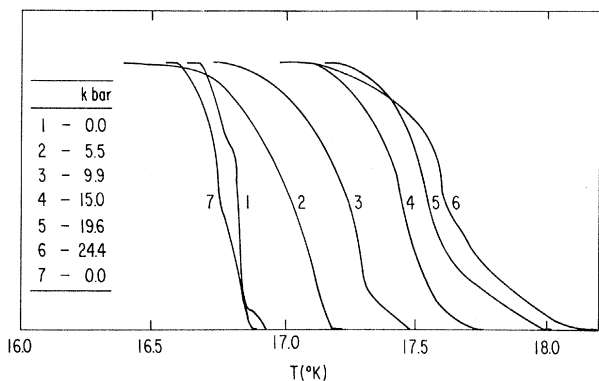
FIG. 1. Superconducting transition curves at various pressures for single crystal V_3Si.

line V_3Si were considerably broader (~0.25°K wide). The central portion of the transition for the V_3Si single crystal was sharp, but there was some high- and low-temperature structure to the transition (see Fig. 1). In the case of the V_3Ge and the V_3Ga the application of pressure did not produce any significant change in either the shape or the width of the transition. However, for the V_3Si the transition broadened (by a factor of ~2 at 20 kbar) for both the polycrystal and single-crystal sample, and in the latter case there was a change in the overall shape. This is illustrated in Fig. 1 where transition curves, recorded at various pressures, for the single crystal are shown. In spite of the broadening of the transition curve there can be no doubt of the general shift of the transition, as a whole, to higher tem-

perature. It may also be noted that upon removal of the maximum pressure the transition almost returns to its initial width.

The change of T_c as a function of pressure for the three compounds is shown in Fig. 2. In each case T_c is seen to increase linearly with pressure, with the greatest change occurring for the V_3Ge. The corresponding values of the pressure dependence of T_c are listed in Table I.

Surprisingly, in spite of the obvious interest in the A15 superconducting compounds due to the high T_c values which are found amongst them, relatively little has been done to study the effect of uniform compression upon the transition temperature. Undoubtedly this was due to the discouraging results, from the point of view of raising the transition temperature, which were obtained in the initial investigations. Measurements to 2 kbar on V_3Si and V_3Ga, in the form of layers formed on the surface of vanadium wires, have been made by Müller and Saur[6] by means of the ice-bomb technique. They reported a decrease of T_c for both compounds. Weger, Silbernagel, and Greiner[7] studied the effect of both uniaxial and hydrostatic stress on the T_c of single-crystal V_3Si up to ~0.5 kbar. They found that a stress applied along the [100] direction rapidly lowered T_c (-5×10^{-4} °K bar^{-1}), while a stress applied along the [111] direction had very little effect upon T_c. Furthermore, they noted that for a hydrostatic stress (applied with helium gas) of ~0.4 kbar there was no detectable shift of the
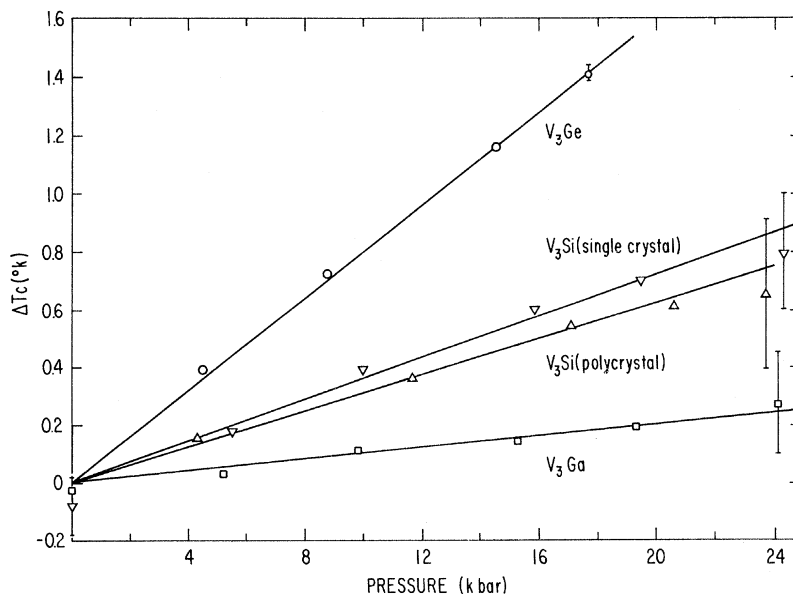

FIG. 2. The change of T_c as a function of pressure for some V_3X compounds. The data points represent the shift in the midpoint of the transition curve. The vertical bars indicate the width of the transition.

transition (to within $\pm 0.05°K$). More recently Neubauer[8] has examined under hydrostatic pressure (using a transmitting medium very similar to that in the present investigation) several A15 compounds including V_3Si, for which he also finds T_c increases under pressure.

In view of the observations of Weger, Silbernagel, and Greiner we would explain the discrepancy between the present observations (and those of Neubauer) and those of Müller and Saur as being due to poorer hydrostatic pressure conditions in the latter workers' experimental arrangement. The nature of the samples which they employed could lead to quite considerable stress at the boundary between the wire and the surface layer. Furthermore, it is questionable as to how accurately hydrostatic is the pressure that is produced by the ice-bomb arrangement.[9] From the data of Weger, Silbernagel, and Greiner we estimate that a 10% inhomogeneity in the pressure would be sufficient to account for the decrease in T_c of V_3Si observed by Müller and Saur. It may be further noted that the change of T_c ($\sim 0.02°K$) which we would expect at the hydrostatic pressure applied by Weger, Silbernagel, and Greiner lies well within their quoted resolution.

Testardi et al.[1] have expanded T_c as linear and quadratic functions of strain, which may be expressed for volume strain in the cubic case[10] as

$$T_c(\Delta V) - T_c(0) = \Gamma_1 \frac{\Delta V}{V_0} + \frac{1}{6}(\Delta_{11} + 2\Delta_{12})\left(\frac{\Delta V}{V_0}\right)^2, \quad (1)$$

where $\Gamma_i = \partial T_c / \partial \epsilon_i$, $\Delta_{ij} = \partial^2 T_c / \partial \epsilon_i \epsilon_j$, and $\bar{\epsilon}$ is the linear strain. From measurements of the temperature dependence of the elastic moduli above and below T_c they estimate for V_3Si, $\Delta_{11} = -24$, $\Delta_{12} = -5$, $|\Gamma_1| < 50$, and for V_3Ge $\Delta_{11} = 9.4$, $\Delta_{12} = -1.8$, $|\Gamma_1| < 45$, where Γ_1 is in units of $°K$ and Δ_{ij} in units of $10^4 °K$. Substituting these values into (1) leads to the prediction that T_c will decrease for V_3Si (and for V_3Ga from a scaling of the elastic data taken on polycrystal material) and increase for V_3Ge under a uniform reduction of volume. In addition a strong quadratic dependence of T_c upon volume change is expected because of the very large values of Δ_{ij}.

It is clear from the present measurements that the predicted behavior for the T_c of V_3Si and V_3Ga is contrary to that observed. Specifically, for V_3Si we estimate from (1) that at 20 kbar T_c is expected to decrease by $\sim 7°K$, where it is found to have increased by $\sim 0.7°K$.[11] Using the values of $\partial T_c / \partial P$ given in Table I and taking the

bulk modulus to be 1760 kbar,[12] we calculate values for Γ_1 of 55 and $140°K$ for V_3Si and V_3Ge, respectively. Thus, the value of Γ_1 for V_3Si lies just at the upper limit quoted by Testardi et al.,[1] but the value for V_3Ge exceeds their upper limit by a factor of 3. Furthermore, the data presented in Fig. 2 show no indication of the proposed strongly quadratic dependence of T_c upon strain.[11] If the slight deviation from linearity in the pressure dependence of T_c for V_3Si above 20 kbar is taken to be evidence of a quadratic contribution (and in view of the broadening of the transition this should be done with caution), the corresponding value for the quadratic contribution would be at least two orders of magnitude smaller than that predicted in Ref. 1. In the case of the V_3Ge, in view of the linearity of the pressure dependence of T_c, a similar reduction would place an upper limit on the quadratic contribution.

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conceivable that a quadratic strain dependence of T_c in combination with an elastic behavior which is close to quadratic could still result in a linear dependence of

T_c upon pressure.

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Wavelength Modulation Spectrum of Copper

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The wavelength modulation spectrum of Cu is presented at 7°K in the range of 2.0 $\leq \hbar\omega \leq 6.0$ eV. The band structure of Cu calculated by the empirical pseudopotential method is used to compute the imaginary part of the dielectric function $\epsilon_2(\omega)$ and the logarithmic derivative of the reflectivity, $R'(\omega)/R(\omega)$. Good agreement between theory and experiment is obtained at the absorption edge and at higher energies using the one-electron approximation if dipole matrix elements are calculated from wave functions including core contributions rather than the pseudowave functions. The transitions causing the structure in $R'(\omega)/R(\omega)$ are identified.

Recent advances in optical derivative spectroscopy have helped significantly in obtaining detailed knowledge about the band structure of semiconductors.[1] Applications of this technique to metals, however, have been scarce. There have been measurements of the electroreflectance of Ag and Au,[2] but there is some uncertainty[3] associated with the interpretation of these results. Thermoreflectance and piezoreflectance[4] have yielded valuable information about noble-metal band structure, and in the case of piezoreflectance the deformation potentials of Cu were measured. In this Letter, we present the wavelength modulation spectrum of Cu from 2.0 to 6.0 eV taken at 7°K. To our knowledge, this is the first application of wavelength modulation spectroscopy to metals at low temperatures. Our derivative spectrum of Cu shows clearly better resolution than those obtained by other methods. The experimental setup was described briefly elsewhere.[5] The Cu sample used in our measurements was the same single crystal used in cyclotron resonance experiments by Kip, Langenberg, and Morre.[6] After electropolishing the surface, the sample was quickly transferred to the low-temperature Dewar to avoid surface contamination. The sample temperature could be varied easily from 7 to 300°K. Here, for the sake of clarity, we present in Fig. 1 only the

Cu-derivative spectrum taken at 7°K. We have also measured the normal reflectivity spectrum of Cu which agrees well with that of Gerhardt.[4]

The origin of most of the structure in the measured derivative spectrum of Cu can be determined using the theoretical band structure of Cu, calculated by the empirical pseudopotential method.[7] In the calculation we used four form factors for the local pseudopotential and four other pa-
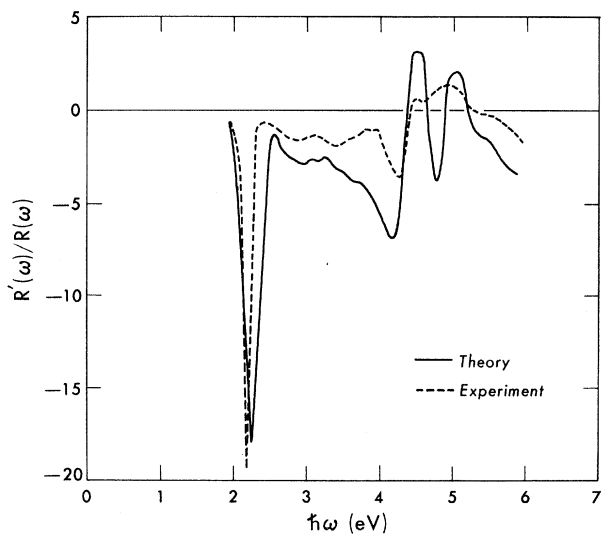

FIG. 1. The measured $R'(\omega)/R(\omega)$ at $T = 7°K$ and the calculated $R'(\omega)/R(\omega)$.