with a phase-sensitive detector operating at 500 Hz. The data shown in Figs. 1 and 2 were obtained at the lowest temperature, about 0.4 K. At temperatures above about 0.7 K, splitting could not be observed, probably because of thermal broadening of the peak in $(dI/dV)_s$.

Here it is appropriate to comment on the influence of spin-orbit scattering. Generally a spin-orbit scattering rate, $1/\tau_{so}$, will lead to a broadening of the effects discussed above. If it is small enough ($\tau_{so}\Delta \gtrsim 1$), the two peaks in the tunneling conductance will be correspondingly broadened, but still well separated. If the scattering rate is large ($\tau_{so}\Delta \ll 1$), the two peaks are smeared into one which is of the type found in other pair-breaking situations. Thin aluminum films are known to have sufficiently small spin-orbit scattering[8,9] rates to make the splitting effect observable. However, Fig. 3(b) indicates that the broadening effect due to spin-orbit scattering[10] is not negligible and a detailed comparison between experiment and theory will be made in a future publication. Another cause for broadening of the density-of-states curves can be the effect of the magnetic field on the electron orbits. However, the estimated effect for the aluminum film under consideration is very small. The pair-breaking parameter with which one can calculate the broadening of the BCS type of density-of-states curves[6,11] is given by $\alpha = \frac{1}{2}[H/H_{c\parallel}{}^0(0)]^2$, where $H_{c\parallel}{}^0(0)$ is the critical field the film would have at $T=0$ if the field would act on the electron orbits only. One can estimate that $H_{c\parallel}{}^0(0)$ is 3.7 times bigger than the measured critical field $H_{c\parallel}{}^0(0)$, thus leading to rather small values for α.

Consistent with this reasoning is the fact that the order parameter $\Delta(H)$ was found not to vary significantly with H up to the highest fields, indicating that the films were in the paramagnetic limit.

In conclusion, we have observed splitting of the quasiparticle states of superconducting Al by a magnetic field. The magnitude of the splitting as well as the shape of the density-of-states curve are consistent with theory.

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Plastic Flow in Normal and Superconducting Indium*

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Changes in flow stress, which occur in indium at the transition from the normal to the superconducting states, have been studied in a series of experiments in which strain rate, state, and temperature are changed independently. The results are consistent with a simple theory which associates the changes in flow stress with changes in activation volume and thus with the nature of the interaction between moving dislocations and obstacles.

In recent experiments by Kojima and Suzuki,[1] by Pustovalof, Startsev, and Fomenko,[2] and by Alers, Buck, and Tittmann,[3] a difference in macroscopic flow stress between the normal and superconducting states in lead, niobium, and indium has been revealed and studied. In the experiments by Alers, Buck, and Tittmann[3] the chief characteristics of the change in flow stress are these:

(a) The flow stress is higher in the normal state by up to 5%. A small correction can be applied to the difference to take account of specimen work hardening.

(b) The difference in flow stress is independent of strain rate over a rate change factor of 50.

(c) The switch from superconducting to normal states, which is produced by a magnetic field, appears to stop the dislocation movement until the normal flow stress is reached.

(d) The change in flow stress is linearly dependent on $(T/T_c)^2$, where T is the temperature and T_c the critical temperature.

It would appear from these results that a theoretical model which relates the increase in flow stress to an increased electron-dislocation viscosity in the normal state is unrealistic, since the increase would be dependent on the average velocity of the dislocations and hence on the strain rate. As polstulated by Alers, Buck, and Tittmann, a model in which the dislocations are held up by obstacles for times greater than the flow times between obstacles would appear to be applicable. A simple model of thermally activated movement of dislocations past obstacles then gives the expression

$$kT \ln\{\dot{\epsilon}/\rho d b \nu_0\} = V(\sigma-\sigma_0)-U_0, \tag{1}$$

where ρ is the mobile dislocation density, b the Burger's vector, d the distance between obstacles, ν_0 the obstacle-barrier attempt frequency, V the activation volume, σ the flow stress, σ_0 a back stress due to piled-up dislocations which have passed a particular barrier, and U_0 the potential energy of the barrier.

This paper describes a number of experiments on indium which give new information on the nature of the changes in flow stress. The results are discussed in terms of Eq. (1). At a fixed temperature two different types of change can be impressed on the system, viz., the following:

(1) A change in strain rate $\dot{\epsilon}$ to $\dot{\epsilon}'$ at a fixed temperature. —If the strain rate is changed suddenly while the specimen is being pulled then it is assumed (a) that the dislocation population and geometry will not be altered, i.e., ρ, b, d, ν_0, and V will remain constant; (b) that the nature of the obstacles will remain unaltered, i.e., U_0 constant; (c) that the long-range stress due to piled-up dislocations will be unchanged, i.e., σ_0 constant. Under these conditions an observed change in flow stress from σ to σ' is associated with the increased strain rate from $\dot{\epsilon}$ to $\dot{\epsilon}'$ and the activation volume V is given, from Eq. (1), by

$$V = \frac{kT \ln(\dot{\epsilon}'/\dot{\epsilon})}{\sigma'-\sigma}. \tag{2}$$

In this way activation volumes can be found at different temperatures for the normal and superconducting states.

(2) A change of state at a fixed temperature. —In these experiments the change of state from superconducting to normal is produced by the application of a magnetic field. It would then appear reasonable to assume that ϵ, ρ, b, d, ν_0, T, and U_0 should remain unchanged and therefore, from Eq. (1), we obtain

$$(V_s-V_n)/V_n = (\sigma_n-\sigma_s)/(\sigma_s-\sigma_0), \tag{3}$$

where suffixes n and s indicate normal and superconducting values, respectively. As will be shown later, the experimentally determined values of $\sigma_n-\sigma_s$ should be normalized against the total elongation. Equation (3) suggests that a comparison of normalized values of $\sigma_n-\sigma_s$ as a function of T should be made with values of $(V_s-V_n)/V_n$ at different temperatures.

The specimens were cast, in split molds of high-purity graphite, as single crystals of similar but undetermined orientations, from Cominco 99.999% pure indium. Casting was done in a resistive furnace under an inert atmosphere. The tensile specimens were approximately 3 in. long and of $\frac{1}{4}$-in.-square cross section. They were held by V-faced split grips, giving a gauge length of approximately 2 in.

The specimens were pulled in a tensile-testing machine based on a design by Basinski[4] and built with the assistance of drawings supplied by Dr. Basinski and the National Research Council of Canada. With the present drive system the specimens can be strained at a variety of rates ranging from 2×10^{-3}/sec to 1×10^{-6}/sec, the usual rates being 10^{-4}/sec and 10^{-5}/sec. Within a particular range the strain rate may be suddenly altered by a factor of 10 by energizing suitable magnetic clutches in a gearbox. The load applied to the specimen is indicated by a precalibrated load cell, consisting of a carbon-steel ring on which are mounted four strain gauges. The electrical output from the strain bridge is suitably nulled and the out-of-balance signal amplified and used to drive the pen of a chart recorder. The paper chart is driven by a direct coupling from the drive shaft of the tensile tester and thus a direct plot of load versus elongation is achieved.

The cryostat for these experiments was rudimentary, consisting of a double glass Dewar system in which the temperature was altered by pumping through a monostat on the helium bath. A superconducting solenoid, with its axis along the length of the specimen, was used to drive the specimens into the normal state.

Starting with the specimen cooled down to T_c, the transition temperature (3.4°K for indium), the following sequence was repeated at a number of temperatures down to about 1.8°K. (1) The strain rate $\dot{\epsilon}$ was increased by a factor of 10 to $\dot{\epsilon}'$ and then reduced to its original value. (2) The specimen was driven normal by a magnetic field. (3) Procedure (1) was then repeated for the normal specimen. (4) The magnetic field was switched off and procedure (1) repeated for the superconducting specimen.

The chart record then gives values of $\sigma'-\sigma$ due to the increase in strain rate [used in Eq. (2)] and $\sigma_n-\sigma_s$ due to the change in state [used in Eq. (3)]. Between temperature changes the specimen was partially unloaded to minimize creep and then again brought up to the flow stress after temperature equilibrium had been established. Little or no change in flow stress was observed to accompany such a discontinuous change in temperature.

With these specimens loads are up to about 30 kg with change-of-state offsets of about 500 g at 2°K. The offsets with change-of-strain rate are about 25 and 60 g at 2 and 3.4°K, respectively. Loads and offsets are measured to about ±5 g.

In general the magnitude of the recorded load offset, corresponding to a change in flow stress, increased slowly as a function of total elongation. Since, within the range of values of load used, the total elongation was linearly proportional to total load, a particular offset can be normalized to a particular value of total elongation. The linearity is checked periodically during the course of an experiment by going back to 3.4°K.

Values of activation volume were obtained at different temperatures for the normal and superconducting states. The normalization procedure outlined above appears to successfully eliminate work-hardening changes since repeated experimental runs with several different specimens can all be reduced to a common plot. Values of V_n and V_s for a single specimen are shown as a function of temperature in Fig. 1. The activation volume V_n changes little below the transition temperature while V_s, on the other hand, increases rapidly.

Values of increase in flow stress with change of state, i.e., $\sigma_n-\sigma_s$, were obtained and for a single specimen these are plotted as a function of $(T/T_c)^2$ in Fig. 2. This plot was suggested by the work of Alers, Buck, and Tittmann[3] and is in

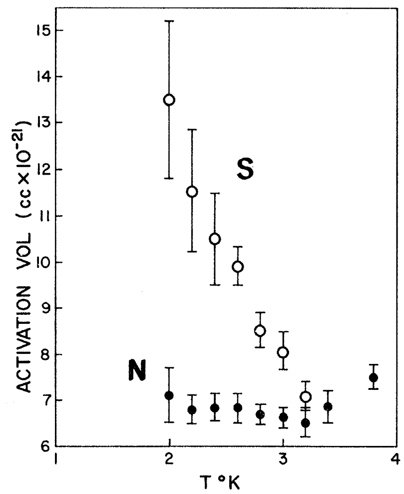

FIG. 1. Temperature dependence of the activation volume in the normal and superconducting state of indium. As the orientation of the tensile axis was not determined, the values of V were calculated using values of tensile stress, not resolved shear stress, and are thus only approximate. This only affects the absolute values of V_s and V_n, not their relative proportions.

agreement with their discovery of a linear relationship.

From the determinations of activation volume, values of the ratio $(V_s-V_n)/V_n$ were calculated for each temperature. If one assumes that $(\sigma_s-\sigma_0)$ remains unaffected by a small change in temperature, then this ratio should, according to Eq. (2), have the same temperature dependence as that found for $\sigma_n-\sigma_s$, i.e., linear with $(T/T_c)^2$. The agreement is shown in Fig. 3 with the error bars indicating the appreciable uncertainties in the ratio determinations due to the scatter in measurements of activation volume.

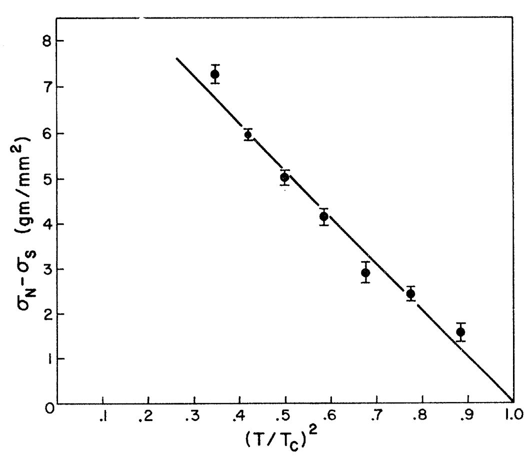

FIG. 2. Temperature dependence of the difference in flow stress between the normal state σ_n and the superconducting state σ_s for an indium specimen.

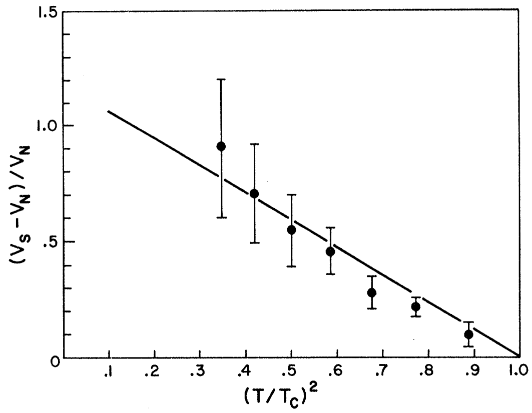

FIG. 3. Temperature dependence of the ratio $(V_s - V_n)/V_n$ [Eq. (3)] for an indium specimen.

In a separate series of experiments we varied the strain rates over a factor of 200 and observed no significant dependence of difference in flow stress $\sigma_n - \sigma_s$ on strain rate, thus confirming the observation made by Alers, Buck, and Tittmann.[3]

The results of these experiments thus imply that, in looking for an explanation of the observed changes in flow stress between the normal and superconducting states in a metal, attention should be directed to a model in which the activation volumes change. Since the pinning mechanism for dislocations by obstacles must be at least partially electrical in nature it is perhaps reasonable to expect that the activation volume should change with electronic configuration at temperatures below T_c in the superconducting state but remain constant in the normal state.

Preliminary experiments on lead indicate that a similar behavior is found in this case, and we hope to report on this shortly.

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Amorphous Semiconductors as Undulatorily Graded Band-Gap Systems*

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We propose as a model of some amorphous semiconductors a system with undulations in composition or structure on a scale within the range of validity of the graded band-gap concept. Electronic states well within allowed bands are determined by perturbative analysis; states near band edges, by a modification of an effective-mass analysis. Localized states are obtained and the band edge identified as the locus of classical turning points of the effective mass functions.

The theoretical analyses of electronic structure of amorphous solids have been previously based on models involving only short-range order.[1] These analyses have predicted insensitivity of electronic properties to doping[2] and absence of an energy gap, replaced by a mobility gap.[3] The observed optical properties do not for some materials support the latter[4] and exceptions to the former have been reported.[5] There is experimental evidence that some amorphous solids are characterized by structural and/or compositional inhomogeneities on a scale of approximately 100 Å.[6,7] This scale is just within the range of validity of the concept of a graded band gap,[8] and we therefore propose a model amorphous semiconductor involving intermediate-range order on the scale in which substance A smoothly grades to substance B, not monotonically as with the usual graded band-gap system, but undulating in composition with a mean period of the order of 100 Å. A and B may be different substances or different structures of the same substance.

The theory of graded materials employs the virtual crystal approximation on a local basis where the potential from the statistical distribution of constituents A and B at position $\vec{r}$ is re-