is attenuated with an absorption coefficient,

$$\alpha = (\omega^2\tau/v)(\Delta C/C). \quad (1)$$

Here v is the wave velocity, $(\Delta C/C)$ is the fractional change in the elastic constant due to the electronic effect, and τ is the relaxation time for the restoration of statistical equilibrium among the electrons. The derivation of Eq. (1) assumes that $\omega\tau$ is small compared to unity. There are two contributions to τ, namely, intervalley scattering and diffusive spatial redistribution.[7] The diffusive relaxation time can be estimated from the sample mobility and the Einstein relation. The mobility of electrons in germanium with 3×10^{19} cm^{-3} donors is about 300 cm^2/volt sec.[9] Using the Einstein relation for degenerate statistics[10] gives $D = 10$ cm^2/sec. The diffusive relaxation time, $v^2/\omega^2 D$, thus is about 2×10^{-12} sec for 10-kMc/sec phonons. The intervalley scattering time is not known, but must be greater than 2×10^{-14} sec, the total electronic momentum relaxation time as determined from the mobility. Taking $\Delta C_{44} = 0.05$,[1] it is found from Eq. (1) that 10 cm$^{-1} < \alpha < 10^3$ cm^{-1}. Thus, the absorption coefficients predicted by the electronic theory readily account for our failure to observe waves whose propagation involves C_{44} in heavily doped germanium.

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ENERGY GAP AND CRITICAL FIELD OF SUPERCONDUCTING MOLYBDENUM OBTAINED BY ULTRASONIC MEASUREMENTS*

Norman H. Horwitz and Henry V. Bohm
Department of Physics, Wayne State University, Detroit, Michigan
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Superconductivity was recently discovered in pure molybdenum by Geballe, Matthias, Corenzwit, and Hull.[1] Using ultrasonic measurements, we have obtained a value of 114 ± 5 oersteds for H_0, the critical field at absolute zero. Measurements of the ultrasonic attenuation as a function of temperature give a value of $3.5 \pm 0.2\ kT_c$ units for $2\epsilon_0$, the energy gap at absolute zero.

The molybdenum sample which we examined was a single crystal prepared by electron-beam zone refining.[2] The residual resistivity ratio, $\rho_{273°K}/\rho_{4.2°K}$, for this sample is about 450.[3] 239-Mc/sec longitudinal pulses were propagated along the [100] crystallographic direction. Efficient coupling of the rf signal to the transducer was accomplished with a tunable sample holder. Details of our equipment will be described elsewhere.[4]

Our cryostat employed magnetic cooling to obtain temperatures from 1.1°K down to about 0.5°K. About five minutes were required for this system to come to equilibrium at the low temperature after demagnetization. As the sample slowly warmed, the echo pulse amplitude was recorded as a function of temperature. With low power input and a good vacuum in the salt tube, the sample drifted back to the bath temperature in about two hours.

The transition temperature was determined from the sharp discontinuity in the pulse-height versus temperature curve which occurred as the sample went into the normal state. Using this criterion, a transition temperature of 0.92 $\pm$ 0.01°K was obtained. In the measurements of Geballe et al. the transition temperature was determined by observing the change in resonant frequency of a coil surrounding the sample. They obtained a transition temperature of 0.98°K for their sample of highest purity. The lower transition temperature for our sample suggests that

it may be less pure than the best examined by Geballe et al.

The Bardeen-Cooper-Schrieffer (BCS) theory[5] and the more detailed work on ultrasonic attenuation in superconductors by Tsuneto[6] give the following relation between the temperature-dependent energy gap and the ultrasonic states:

$$\alpha_s/\alpha_n = \frac{2}{\exp[\epsilon(t)/kT_c]+1}, \qquad (1)$$

where $\epsilon(t)$ is one half the energy gap, and α_s and α_n are the attenuation in the superconducting and normal states, respectively. When the pulse-amplitude versus temperature data are analyzed using Eq. (1), the graph of $\epsilon(t)/kT_c$ versus reduced temperature shown in Fig. 1 is obtained. This plot gives a superconducting energy gap $2\epsilon_0 = 3.5 \pm 0.2\ kT_c$.

The critical-field values were obtained by observing the reduction in echo pulse height as the magnetic field transverse to the direction of sound propagation was slowly increased. The sample was considered to have returned to the normal state when the pulse amplitude fell to the value observed in the normal state, and further small incremental changes in the field produced no further effect. During the time of a field measurement the drift in temperature was negligible. Successive determinations of the critical field were thus obtained as the sample slowly warmed back to the temperature of the bath. The results of these measurements are shown in Fig. 2. Extrapolation of the H_c versus T^2 curve to 0°K yields the value of $H_0 = 114$ oersteds. We estimate the error in this determination to be ±5 oersteds.

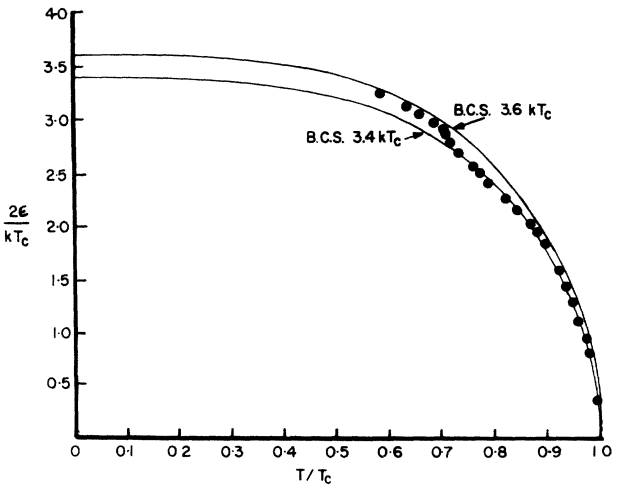

FIG. 1. Variation of $\epsilon(t)$ for molybdenum data using Eq. (1) compared with theoretical variation assuming $2\epsilon_0 = 3.4\ kT_c$ and $2\epsilon_0 = 3.6\ kT_c$.

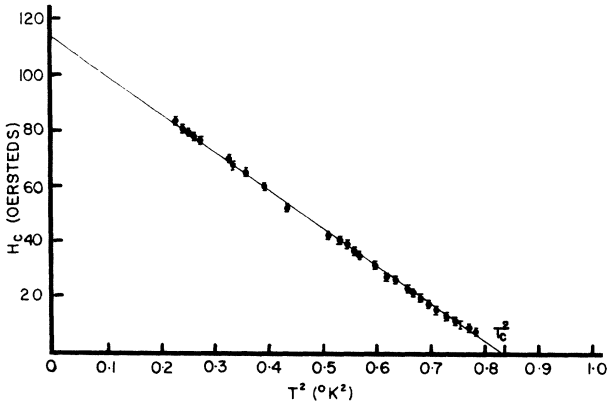

FIG. 2. Critical magnetic-field data for molybdenum. Solid curve is best straight line through experimental points.

We have tested the validity of the above criterion for a determination of H_0 by checking the critical field of a single crystal of pure zinc with sound propagated along the $[\bar{1}2\bar{1}0]$ axis. For this metal these measurements yielded a value of $H_0 = 55 \pm 3$ oersteds. This compares with the value of $H_0 = 52.5$ gauss obtained by Goodman and Mendoza[7] from susceptibility measurements on a polycrystalline sample.

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