PROPAGATION OF MICROWAVE PHONONS IN GERMANIUM

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Recent work has shown that there is an appreciable electronic contribution to the shear elastic constant C_{44} in heavily doped n-type germanium.[1,2] The electronic contribution is of the relaxation type; it depends on the redistribution of electron population in the several valleys of the germanium conduction band when the crystal is strained. Therefore, one can anticipate that relaxation dispersion and absorption will be present if the elastic constant is measured in an appropriate frequency range.[3] This communication reports the observation of large anelastic absorption associated with the electronic redistribution at a frequency near 10^{10} cycles/sec.

The microwave phonons were generated and detected by spin wave-phonon interactions in thin films of Ni-Fe alloy evaporated onto an end of the germanium specimens.[4] It is possible to generate both longitudinal and transverse phonons by this technique.[5] Details of the method of excitation of microwave phonons will be published separately. All the measurements were made at 4.2°K. The phonon frequency was 8.9 kMc/sec.

The germanium specimens were oriented single-crystal bars, 0.1 inch square and varying in length from 1 to 2 cm. Two kinds of germanium were studied, one, "pure," containing less than 10^{14} donors/cm^3, and the other, "heavily doped," containing more than 10^{19} arsenic donors/cm^3. Two types of crystallographic orientation were also used for each kind of germanium, one in which the direction of phonon propagation was a [110] direction and another in which the direction of propagation was a [100] direction. There were five types of waves which could be studied, three (two transverse and one longitudinal) in the [110] specimens but only two in the [100] specimens, the two transverse waves being degenerate.

The experiment consisted of generating a pulse of phonons at one end of the specimen by applying a pulse of microwave power to the Ni-Fe film in an appropriate cavity and observing the delayed pulses of power returned to the cavity by elastic waves which had been reflected from the far end of the specimen one or more times. Two kinds of results were obtained. One is the deduction of the velocity of sound from the observed transit time. Since the elastic constants of germanium are known, this allows identification of the elastic polarization mode of the wave.[1,6] The other kind of result is that certain of the five possible elastic wave types are greatly attenuated and are not observed to propagate in heavily doped germanium.

The results are summarized in Table I. The first columns identify the waves and display the elastic constant which determines the velocity of the wave. The last columns show whether the wave was observed to propagate in each kind of germanium.

The interesting feature of the results is that, although all of the waves can be propagated in pure germanium, only those waves whose elastic constant does not contain C_{44} can be propagated in heavily doped germanium. This is exactly the prediction of the theory of the electronic contribution to the elastic constants of germanium. The waves whose elastic constant contains C_{44} destroy the degeneracy of the valleys and are attenuated by the electronic relaxation absorption. There is no electronic effect associated with the waves whose elastic constant does not involve C_{44}.

These results are reasonable in the light of the quantitative theory of absorption of elastic waves by electronic relaxation. The wave dynamical theory of Weinreich et al.[7] and the phenomenological theory of Kittel[8] show that the elastic energy flow

Table I. Propagation of 8.9-kMc/sec phonons in germanium.

Wave			Propagation in Ge	
Propagation	Polarization	Elastic constant	Pure	Heavily doped
[110]	[110]	$\frac{1}{2}(C_{11}+C_{12}+2C_{44})$	yes	no
[110]	[001]	C_{44}	yes	no
[110]	[110]	$\frac{1}{2}(C_{11}-C_{12})$	yes	yes
[100]	[100]	C_{11}	yes	yes
[100]	[001]	C_{44}	yes	no

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*

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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