NONLINEAR EFFECTS IN ULTRASONIC ABSORPTION IN SUPERCONDUCTING INDIUM

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The absorption of ultrasound in high-purity single crystalline indium is studied. A strong nonlinear dependence of the absorption on the amplitude of the sound is observed in the superconducting state. The results are in qualitative agreement with the Granato-Lücke model for the amplitude-dependent absorption of ultrasound at dislocations.

RECENTLY, experiments on the study of ultrasonic absorption in lead[1, 2] have led to the discovery of a new sound absorption mechanism in the superconducting state. A strongly marked nonlinearity appears in the sound absorption below the critical temperature. This nonlinearity is so great that for sufficiently high sound amplitudes the attenuation in the superconductor does not differ from the attenuation in the normal metal.

We have observed similar effects in indium. The absorption of longitudinal sound at 115, 160, and 210 Mc/sec has been investigated in single crystals of indium with orientations (100), (110), and (111). As the source material, we used indium of quality In-000 with a purity of 99.995%. The specimens were first prepared in the required shape and orientation by the method described in [3]. They had the shape of cylinders with a diameter of 11 mm and a thickness of 6 mm. The measurements were carried out in the temperature range 4.2–1°K.

Figure 1 shows the dependence of the difference in the absorption in the normal and superconducting states on the relative amplitude of the ultrasonic wave for different temperatures. At not very low temperatures, it is evident that there is a certain amplitude threshold above which the absorption begins to have a nonlinear character. The application of a magnetic field sufficient for disruption of superconductivity at the given temperature removed the amplitude dependence for all achievable amplitudes of the sound wave.

It was pointed out in [2, 4] that all these phenomena are apparently explained by the fact that in the superconducting state specific conditions are created which lead to the appearance of an amplitude-dependent ultrasonic absorption at dislocations, even at such low temperatures. A model mechanism for such absorption was suggested by Granato and Lücke.[5] The dislocation is likened to a string rigidly attached at the nodes of the dislocation chain and coupled by the Cottrell binding force with pinning points which can be impurities, vacancies, and other point defects. When variable deformation of amplitude greater than the threshold of breakaway of the dislocation from the pin is applied, the motion of the dislocation is of a hysteresis type and an additional absorption proportional to the area of the hysteresis loop arises. The theory gives the following expression for the amplitude-independent part of the damping decrement:

$$\Delta_h = \frac{C_1}{\varepsilon}\exp\left(-\frac{C_2}{\varepsilon}\right).$$

Here C_1 and C_2 are constants that depend on the material, orientation of the specimens, and the density of dislocations, and ε is the amplitude of the deformation.

According to Mason,[4] the damping action of the electron gas surrounding the dislocation is large in the normal state. Therefore, the threshold for breakway of the dislocations is not reached for the sound wave amplitudes used and the amplitude-dependent absorption is absent. On going to the superconducting state, the viscosity of the electron gas decreases sharply as the number of normal electrons decreases and the breakaway stress is correspondingly decreased, which leads to the appearance of an amplitude dependence in the sound absorption at those same amplitudes. As is seen in Fig. 1, such threshold effects actually occur.

It follows from the formula given above that a graph plotted in the coordinates $\ln(\Delta_h\varepsilon)$ and ε^{-1} (the Granato-Lücke coordinates) should yield straight lines. In the experiments described, the damping decrement was not measured, but rather

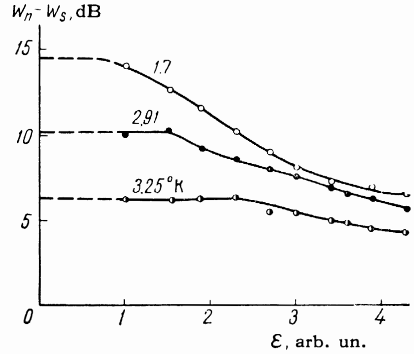

FIG. 1. Dependence of the ultrasonic absorption on the amplitude of the sound field for various temperatures. $\nu = 210$ Mc/sec; $q \perp (100)$.

the additional absorption connected with this mechanism and in the presence of amplitude dependence these quantities cannot be regarded as identical. Nevertheless, an attempt was made to construct experimental curves in the Granato-Lücke coordinates. Instead of the decrement, we used everywhere simply the additional absorption ΔW which appears as a consequence of the mechanism discussed. The quantity ΔW is obtained from graphs similar to that shown in Fig. 1, by subtraction of the value $W_n - W_s$ for a given amplitude from the limiting value for an amplitude close to zero. As is seen from Fig. 2, with appropriate choice of this limiting value, the experimental points lie very closely along a straight line. The slope of these lines decreases with decrease in temperature. The slopes of the straight lines are also somewhat different for the different frequencies. The intercept of the straight lines on the abscissa axis (which determines $\ln C_1$) changes sharply with change in temperature, with the value of C_1 changing several fold.

The annealing of one of the specimens at a temperature of 140°C for a period of 12 hours with subsequent slow cooling to liquid nitrogen temperatures did not lead to any appreciable change in the character of the absorption. This shows that the bulk of the total dislocation density are growth dislocations.

In conclusion, we note that attempts to determine the value of the energy gap and its anisotropy

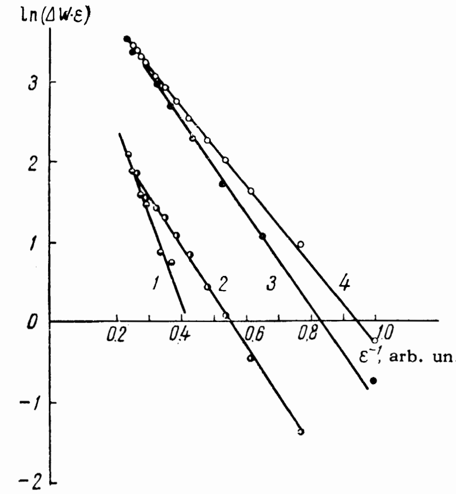

FIG. 2. Dependence of the additional absorption of ultrasound on the amplitude in Granato-Lücke coordinates: curve 1 – $\nu = 210$ Mc/sec; $T = 3.25$°K; 2 – $\nu = 115$ Mc/sec; $T = 3.25$°K; 3 – $\nu = 210$ Mc/sec, $T = 1.7$°K; 4 – $\nu = 115$ Mc/sec, $T = 1.665$°K, $q \perp (100)$.

at very low amplitudes of the sound field lead to a much higher value of the energy gap. For a sound propagation vector $\mathbf{q} \perp (111)$, the value of $2\Delta(0) \sim 4.5\ \kappa T_c$ is obtained, and for $\mathbf{q} \perp (100)$, (110), we get $2\Delta(0) \sim 5.4\ \kappa T_c$.

Further research will be directed toward the study of the possibilities of separation of the electronic part of the absorption in its pure form and to the determination of the anisotropy of the energy gap.

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