ANISOTROPY OF THE SUPERCONDUCTING ENERGY GAP IN PURE AND IMPURE TIN

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(Received November 6, 1961)

Anderson's[1] theory of dirty superconductors predicts that the energy gap, which is expected to be anisotropic in pure superconductors, will become isotropic when enough impurity is added that the scattering frequency, $1/\tau$, becomes greater than the energy gap frequency, ω_g. In order to test this prediction experimentally, we have used the far-infrared techniques developed by Richards and Tinkham[2] to investigate the absorptivity of single-crystal surfaces of pure and impure tin over a frequency range spanning the energy gap. Our results give the first spectroscopic evidence for the anisotropy of the superconducting energy gap, and confirm Anderson's ideas about dirty superconductors.

The experiment was performed by observing the far-infrared power reaching a bolometer after it made many reflections from the walls of a nonresonant cavity. Two of the cavity walls were 2.5- by 7-cm slabs of single-crystal tin whose surfaces had been carefully electropolished. The fractional change in power detected by the bolometer when the superconductivity was destroyed by a magnetic field, $(P_S-P_N)/P_N$, was measured over the wavelength range $3\text{ mm} > \lambda > 0.5\text{ mm}$ at the temperature $T = 0.32\,T_c$. $(P_S-P_N)/P_N$ is of the order of five percent at low frequencies where the superconductor is essentially lossless, and drops to zero at frequencies high enough to cause excitations across the energy gap. The sharp decrease in $(P_S-P_N)/P_N$, which marks the onset of absorption in the superconductor, is a measure of the energy gap.

For our pure samples, estimates based on the theory of the anomalous skin effect indicate that the electrons which are effective in interacting with unpolarized electromagnetic waves of our frequencies (which are higher than the range of validity of the extreme anomalous limit) lie in a band about 30° wide around the Fermi surface, parallel to the surface of the tin, and displaced somewhat from the equator of the Fermi surface. We measure the energy gap averaged over this band so that in the presence of an anisotropic gap, the absorption edge is smeared out.

In Fig. 1, we show the broad absorption edges obtained by measuring three different orientations of pure tin. Because of the large anisotropy within the effective band of electrons, it is not possible to give an accurate gap value for each orientation. Figure 1 does show, however, that the mean gap for the (110) plane is larger than for (001) or (100). This is in qualitative agreement with the anisotropy inferred from ultrasonic attenuation measurements[3,4] which also average the gap over a band around the Fermi surface.

As might be expected from the complicated Fermi surface of tin, the anisotropy of the gap cannot be represented by an ellipsoid. Since tin has two equivalent axes at right angles in the (001) plane, such a model predicts a sharp absorption edge for an (001) surface. In Fig. 1, however, we see that this absorption edge is smeared out even more than those for the (100) and (110) surfaces.

In impure samples with $\omega_g\tau < 1$, as a result of the short mean free path, electrons over the whole Fermi surface interact with the electro-

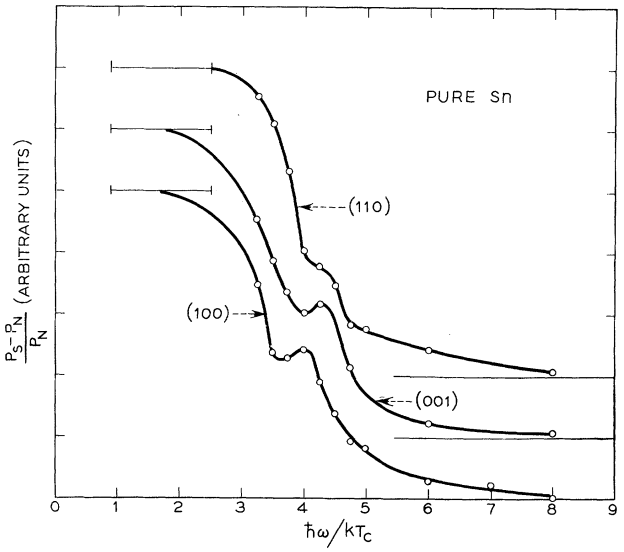

FIG. 1. Frequency dependence, for (110), (001), and (100) planes of pure tin, of the fractional difference between the power reaching the bolometer in the superconducting and normal states. These curves are normalized for display purposes so that the ordinate of the lowest frequency point is the same for all of them, and then displaced to prevent overlapping. The horizontal bar indicates the approximate bandwidth of the lowest frequency point. The bandwidth for the other points was approximately 10%.

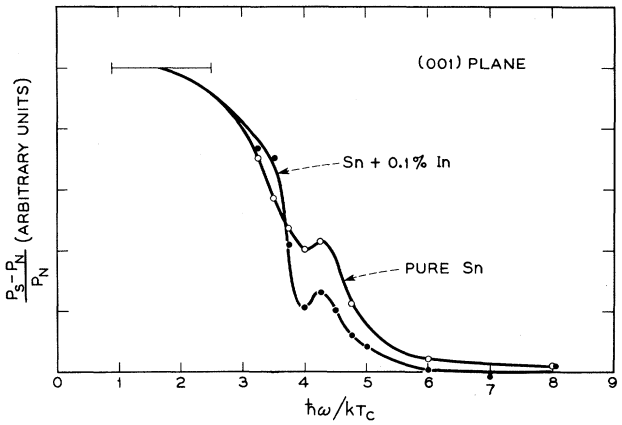

FIG. 2. Frequency dependence, for the (001) plane of pure and impure tin, of the fractional difference between the power reaching the bolometer in the superconducting and normal states. The bandwidths and normalization are the same as in Fig. 1.

magnetic field. Thus, if the gap anisotropy were unaffected in the dirty superconductor, the addition of impurity would smear out the absorption edge even further. The absorption edges for pure and impure (001) tin surfaces in Fig. 2 show, however, that the absorption edge in the impure sample is sharper, not broader than that in the pure sample.

The marked steepening of the absorption edge for tin with 0.1% indium ($\omega_g\tau \approx 0.9$) compared to that for pure tin ($\omega_g\tau \approx 250$) experimentally verifies Anderson's prediction that the energy-gap anisotropy disappears when $\omega_g\tau \lesssim 1$. Other results not shown indicate no further steepening of the absorption edge with added indium and also confirm that the shape and position of the absorption edge for tin with 0.1% indium is essentially independent of crystalline orientation, as would be expected whether or not the gap anisotropy disappeared.

Electron tunneling experiments[5,6] and previous infrared energy gap measurements[2] did not show effects of the anisotropy in tin. However, the sample preparation was such that these were probably experiments on dirty superconductors. We believe that the dirty-superconductor mechanism explains the absence of anisotropy effects in these experiments. We also feel that our results lend considerable support to Masuda's interpretation of his nuclear relaxation experiments.[7]

All of the absorption edges measured show structure in the form of a bump at $\hbar\omega \approx 4.2kT_c$. This structure may be related to that found by Ginsberg, Richards, and Tinkham[8] for lead and mercury. There is one important difference, however, since the tin structure is at a higher frequency than the mean energy gap, while that for lead and mercury is at a lower frequency. At present there is no satisfactory explanation of this structure for any of these metals.

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