Letters to the Editor

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Irradiation of Graphite at Liquid Helium Temperatures

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IN a recent paper,[1] a model for the damage produced in graphite by particle bombardment was presented. This was based to a considerable extent on information obtained from neutron and proton irradiations at nominal liquid nitrogen temperatures; it was further postulated that the damage retained at this temperature represents essentially all the damage formed. This postulate implies that none of the damage centers move, or are altered, below liquid nitrogen temperatures and that irradiation at liquid nitrogen temperature does not affect the damage centers already formed. To verify this assumption, it is necessary to irradiate at still lower temperatures and the present note describes recent bombardments of graphite (type *AWG*) at liquid helium temperatures with 1.25-Mev electrons at integrated fluxes of about 20 and 40 microampere-hours. Following irradiation, the specimen was given one-minute annealing pulses at successively higher temperatures to room temperature and resistivity measurements made at 4°K following each annealing pulse. Two samples were irradiated, one showing a change of 7% in resistivity, the second a change of 4%. During the first run (7% change), the sample temperature was not observed during irradiation. There was some concern about possible specimen heating, so the second sample was irradiated with a reduced beam current and the temperature continuously monitored during irradiation; for the most part the temperature remained very close to 4°K, occasionally reaching a maximum of about 10°K. Because of the similarity of the two annealing runs, it is deduced that the sample temperature also remained low during the first run.

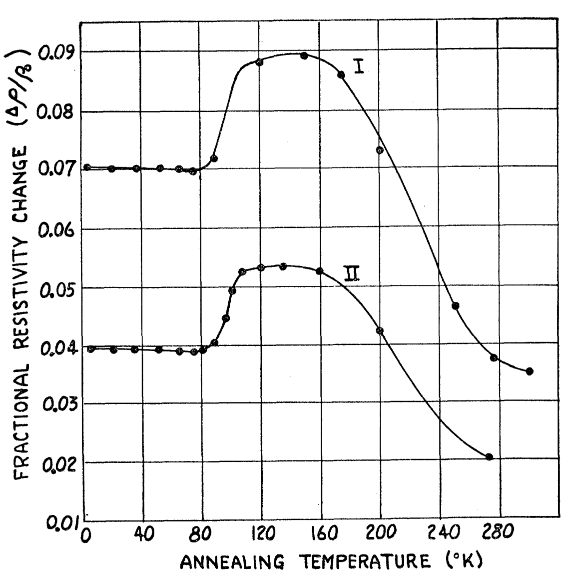

FIG. 1. Pulse annealing of two graphite samples irradiated at liquid helium temperature with 1.25-Mev electrons. Resistivity measured at 4°K.

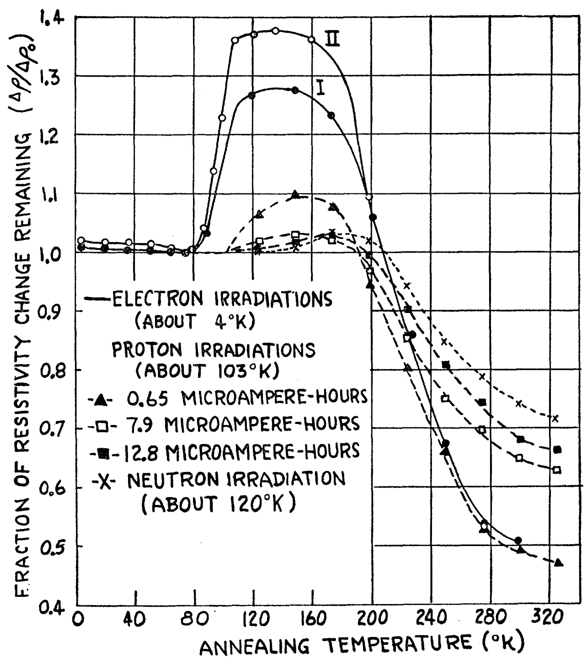

FIG. 2. Comparison of pulse annealing behavior with that observed in previous proton and neutron irradiations of graphite at the temperatures indicated. $\Delta\rho_0$ refers to the value at 78°K.

The two annealing curves are shown in Fig. 1. As can be seen, there is practically no effect below about 80°K. A small amount of annealing may take place, but is too small to warrant discussion, especially when compared to the striking behavior at higher temperatures. Note the abruptness of the annealing between 80°K and 110°K. The actual temperatures during the nominal "liquid nitrogen" irradiations were in the range of 103°K (cyclotron) to 125°K (Brookhaven Reactor), which are high enough that most of the annealing in the region 80°K–110°K must have taken place during irradiation. Figure 2 compares our results with those obtained previously by Deegan[2] following irradiation with protons and neutrons. The neutron irradiation corresponds approximately to 3×10^{18} fast neutrons per cm^2, while one microampere-hour is 2.3×10^{16} protons (8 Mev) per cm^2. The smaller peaks of the latter data are presumably due in part to the annealing at the higher irradiation temperatures, although there is also some dependence of the annealing behavior on the total exposure. On the basis of this comparison, it may be concluded that, although the assumption of reference 1 (that all the damage is retained at the nominal liquid nitrogen exposures) is not literally justified, probably no new type of damage center is introduced by the lower temperature irradiation. In other words, the previous annealing experiments revealed some of the behavior that we have reported, but not all of it. From the standpoint of radiation damage studies, it is of interest to note that, if the specimen temperature is carefully held below 80°K, a liquid nitrogen temperature irradiation is sufficient to inhibit all thermal annealing of the damage centers.

At the present time, we do not wish to discuss the annealing mechanism in the 80–110°K region except to point out that presumably it is due either to a release of trapped electrons or a decomposition of interstitial clusters, both of which will increase the resistivity in graphite.

We wish to express our appreciation to T. G. Berlincourt for much invaluable discussion and assistance. In addition we wish to acknowledge discussions with D. B. Bowen and the help of H. Kenworthy and L. Bienvenue in performing the irradiations.

[1] G. R. Hennig and J. E. Hove, "Interpretation of Radiation Damage in Graphite," presented at the International Conference on the Peaceful Uses of Atomic Energy in Geneva on August 15, 1955 (unpublished).
[2] G. E. Deegan (unpublished).

Superconductivity at Millimeter Wave Frequencies*

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THE interesting phenomenon of superconductivity discovered by Onnes[1] in 1911 is still incompletely understood. London[2] has emphasized that somehow the superconducting electrons must fall into a quantum state of long-range order, a "macroscopic quantum state." The discovery of the isotopic effect[3] and the theories of Fröhlich[4] and Bardeen[5] have linked superconductivity to the zero-point vibrational energies of the atoms and have thus indicated a possible mechanism for a superconducting quantum state. The postulate of a superconducting quantum state implies an energy gap of the order of kT_c between the superconducting and the normal state. The substances for which superconductivity occurs in the easily workable temperature range of 2° to 5°K might, therefore, have a quantum gap corresponding to absorption frequencies of the order of 40 to 100 kMc/sec. Previous superconductivity measurements[6] of Sn up to frequencies of 36 kMc/sec failed to reveal an energy gap, although measurements[7] in the infrared region indicate that Sn is not superconducting at optical frequencies. The development[8] at Duke University of refined millimeter wave techniques for the 1- to 5-mm region has made possible investigations in the

(a)

(b)

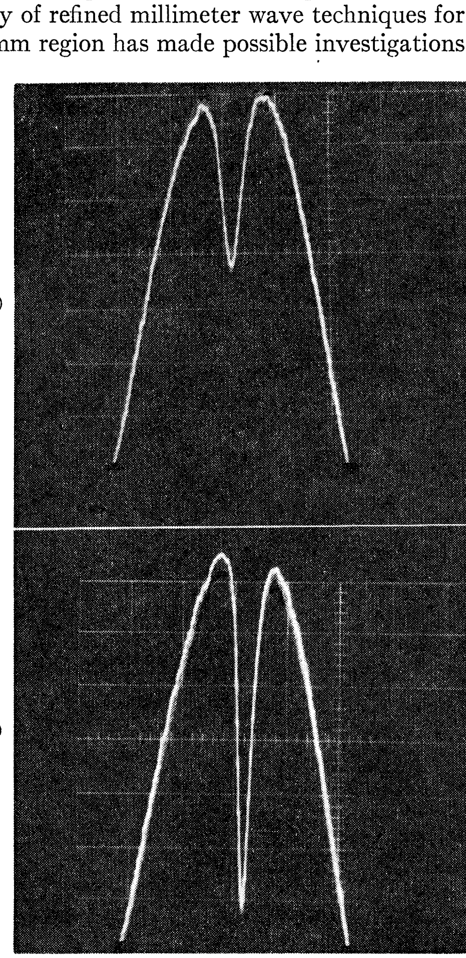

FIG. 1. Cathode-ray display of a resonance curve of a tinplated cylindrical cavity operating in TE_{011} mode at 4-mm wavelength and at 2.6°K; (a) with magnetic field applied to prevent superconductivity, (b) without magnetic field.

frequency range where the supposed energy gap might be measured for several substances including Sn, Al, and Cd. We have consequently undertaken a study of these metals. The rather suggestive preliminary results obtained for Sn will be briefly described here.

For Sn, $kT_c/h=77$ kMc/sec. Measurements have been made at wavelengths of 2, 2.5, 3, and 4 mm (77 kMc/sec to 150 kMc/sec). Superconductivity, but with some residual resistance, has been observed at all these frequencies for temperatures well below T_c. See, for example, Fig. 1. However, at temperatures not far below