combination are taken into consideration. For germanium, using the same radioactive source, a maximum voltage of 30 mv and a short-circuit current of 2×10^{-5} amp have been observed, giving a corrected multiplication of 1.9×10^{5}. Assuming the average energy of a beta particle from the $Sr^{90}-Y^{90}$ source to be 0.7 Mev, the cost in energy per charge carrier would be 3.7 ev for germanium and 4.7 ev for silicon.[3]

A single silicon junction used as a power generator has been found to have the following characteristics: From the 50-millicurie radioactive source, which has available about 200 microwatts of radioactive power, 0.8 microwatt of electrical power is delivered to a matched load of about 10 000 ohms. This represents a conversion efficiency of about 0.4 percent. Calculations indicate that a similar wafer of optimum thickness would give an efficiency of 2 percent.

Factors reducing the efficiency are bulk and surface recombination, backscattering, large bucking currents due to high I_0 and junction leakage, and energy absorption processes other than charge carrier production.

One of these wafers has been used as a generator to power completely a transistor audio-oscillator. Such a power supply has potentially a long life since $Sr^{90}-Y^{90}$ has a half-life of 20 years. However, radiation damage effects have been noted which may limit life. This is being investigated at present.

Appreciation is expressed to Dr. E. G. Linder and M. A. Lampert of these laboratories and to Professor M. G. White of Princeton University for many valuable discussions during the course of this work.

* This work was supported by the Components and Systems Laboratory, Wright Air Development Center, Air Research and Development Command, U. S. Air Force.
1 Ehrenberg, Lang, and West, Proc. Phys. Soc. (London) **A64**, 424 (1951).
2 Law, Mueller, Pankove, and Armstrong, Proc. Inst. Radio Engrs. **40**, 1352 (1952).
3 These values may be compared with the corresponding results obtained for α-particle bombardment by K. G. McKay and K. B. McAfee, Phys. Rev. **91**, 1079 (1953), *viz.*, 3.6±0.3 ev/electron-hole pair in Si and 2.94 ±0.15 ev/electron-hole pair in Ge.

Expansion of Copper Bombarded by 21-Mev Deuterons

William R. McDonell* and Henry A. Kierstead
Chemistry Division, Argonne National Laboratory, Lemont, Illinois
(Received November 13, 1953)

Tubes of copper have been bombarded with 21-Mev deuterons from the Argonne cyclotron, and we have measured the bending which resulted from the expansion of the copper on the bombarded side of the tubes. The tubes were about 16 in. long, $\frac{3}{32}$ in. to $\frac{3}{16}$ in. outside diameter and of wall thickness approximately equal to the range of the deuterons in copper (0.052 cm). Each tube was bent double at the center, annealed in vacuum for two hours above 400°C, fastened by means of the adjacent open ends in an evacuated target assembly, and cooled by passing water or liquid nitrogen through it. Both legs of a central 6-in. length of the folded tube were exposed to the deuteron beam. At frequent intervals during the bombardment, the cyclotron beam was turned off, and the deflection of the free end was measured against a fixed reference scale, by observation through a short-focus telescope and by use of a light beam reflected from mirrors attached to the tube and the reference.

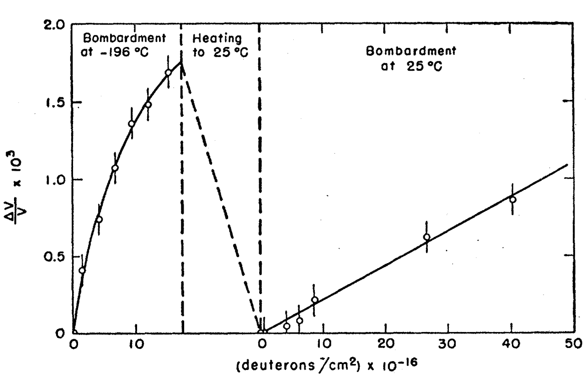

FIG. 1. Specific volume increase induced by deuteron bombardment.

The data from a typical run are plotted in Fig. 1. The ordinate is the fractional change in volume calculated from the observed deflections, assuming the expansion to be isotropic and uniform throughout the volume penetrated by the deuterons. A one percent volume change would produce a deflection of the tube of 2.4 mm. A deflection of about a centimeter was required to produce a small permanent set, whereas the total deflection observed in this run was of the order of a half millimeter. After the bombardment at −196°C, the sample was allowed to warm up to room temperature before bombardment at 25°C. During the warm-up, the expansion produced by the low-temperature bombardment was annealed. Techniques are being developed to study the annealing characteristics in more detail.

We believe these data constitute evidence for a bombardment-induced volume expansion in copper, presumably due to the production of vacancy and interstitial atoms. In fact, the initial rate of expansion in the low-temperature run is in general accord with the expansion estimated using Seitz's theory[1] for the number of displacements and the simple assumption that each displacement produces a volume change of the order of one atomic volume. The tenfold lower expansion rate in the room temperature bombardment is ascribed to thermal annealing during the run. The marked decrease in rate after extended bombardment may be due to thermal and deuteron annealing.

A more thorough investigation of this expansion is in progress.

We are indebted to O. C. Simpson for suggesting this experiment and for many helpful discussions. The cooperation of John P. FitzPatrick, Warren J. Ramler, and the other members of the cyclotron group is gratefully acknowledged.

* Employee of E. I. du Pont de Nemours Company, Inc., on loan to Argonne National Laboratory.
1 F. Seitz, Discussions Faraday Soc. **5**, 271 (1949).

The Hall Effect in Bismuth at 1.4°K*

J. M. Reynolds, T. E. Leinhardt, and H. W. Hemstreet
Physics Department, Louisiana State University, Baton Rouge, Louisiana
(Received November 9, 1953)

The dc Hall voltage has been measured as a function of magnetic field in a single crystal of bismuth at 1.4°K. The crystal was grown in vacuum from Johnson, Matthey bismuth (lot No. 4900) by the Bridgman method. The ratio of its electrical resistance at 4.2°K to that at room temperature was 5×10^{-3}. The crystal was in the form of a right parallelepiped with dimensions 25.5 by 7.5 by 0.88 mm. It rested in a Dewar flask in direct contact with liquid helium and oriented so that its large face was perpendicular to the direction of the magnetic field. A current of 9.6 ma passed along the length of the sample, and potential probes contacted the sample on the sides along a line mutually perpendicular to the direction of the current and magnetic field. The orientation of the axes in the crystal were such that the current was very nearly along a binary axis and the trigonal axis was about 25° from the direction of the field.

The Hall voltage is taken to be

$$V_H=\tfrac{1}{2}[V(B)-V(-B)], \quad (1)$$

where $V(B)$ and $V(-B)$ are measured potentials on the Hall probes. These values are shown in Fig. 1 as a function of the magnetic field. The size of the points gives the probable error. Oscillations in the Hall voltage with field are quite apparent at the fields shown here while at lower fields they were too small to

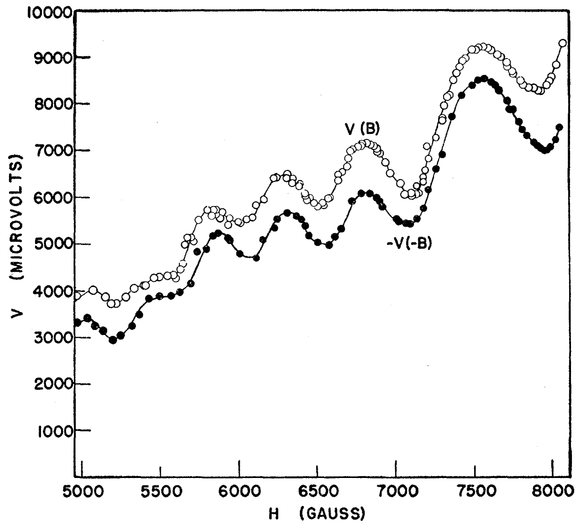

FIG. 1. The potentials observed on the Hall probes.

be observed. In somewhat qualitative experiments Gerritsen, de Haas, and van der Star[1,2] have found evidence of oscillations in bismuth at 14°K and 20°K. The Hall voltage, computed from these curves according to Eq. (1), was used to compute the Hall coefficient. In Fig. 2 the Hall coefficient is plotted against the reciprocal of the field. To examine the periodicity of the oscillations in $1/H$, the $1/H$ values corresponding to successive maxima and minima in the Hall coefficient are plotted against their corresponding integers (Fig. 3). Within the accuracy of the measurements, the Hall coefficient is seen to be periodic in $1/H$, as are the magnetic susceptibility[3] and the magnetoresistance.[4]

Measurements on the Hall effect in bismuth are in progress at more suitable axis orientations and at different temperatures.

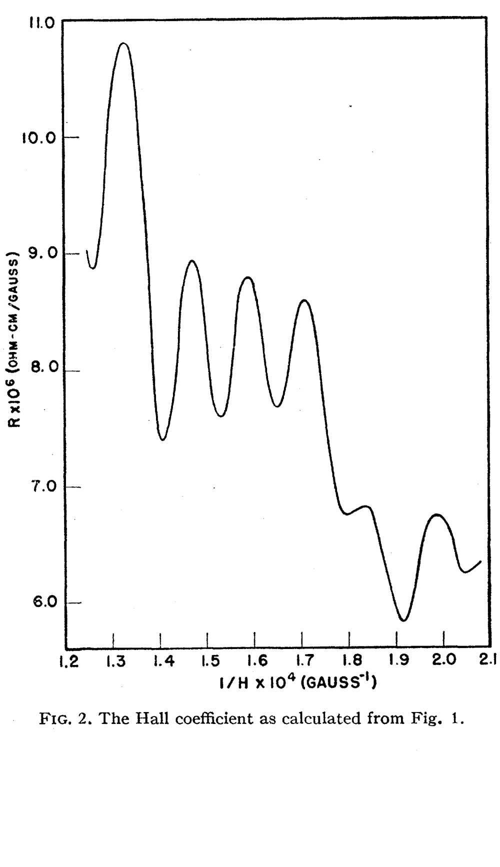

FIG. 2. The Hall coefficient as calculated from Fig. 1.

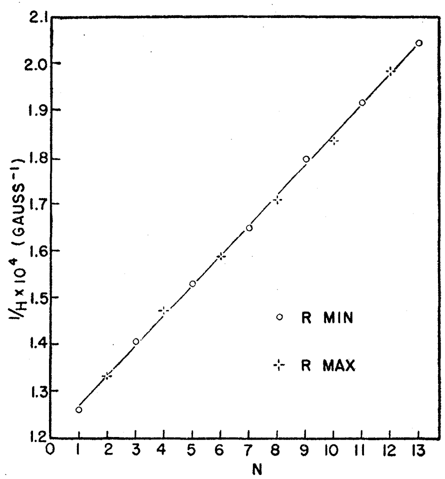

FIG. 3. Values for H^{-1} for which maxima and minima in the Hall coefficient occur, plotted against their corresponding integers.

These will be reported later with a more detailed comparison with the de Haas-van Alphen effect. Also, efforts are being made in this laboratory to interpret the oscillations in the Hall effect in terms of the Peierls, Blackman, and Landau theory of oscillations in the number of "de Haas-van Alphen electrons."

We wish to thank Professor George Jaffé, Professor J. S. Levinger, and Mr. E. G. Grimsal for their illuminating discussions.

* Supported by the National Science Foundation.

1 A. N. Gerritsen and W. J. de Haas, Physica 7, 802 (1940).
2 Gerritsen, de Haas, and van der Star, Physica 9, 241 (1942).
3 D. Shoenberg, Proc. Roy. Soc. (London) A170, 341 (1939).
4 P. B. Alers and R. T. Webber, Phys. Rev. 91, 1060 (1953).

Absolute Intensity of Water-Vapor Absorption at Microwave Frequencies

T. F. ROGERS
Air Force Cambridge Research Center, Cambridge, Massachusetts
(Received October 26, 1953)

MEASUREMENTS have shown that the Van Vleck-Weisskopf modification of the Lorentz equation for a microwave collision-broadened electromagnetic absorption line[1] describes the general structure of such a line and predicts its relative intensity out to frequencies removed from resonance by several times the half-width.[2] Using this modified equation, Van Vleck[3] compared theoretical and measured[4] absolute absorption values in the water-vapor spectrum in the region of the $5_{-1}-6_{-5}$ electric-dipole rotational transition at 13.48 mm and found that the measured values were higher than predicted by some 20 percent near resonance. This disagreement could be reconciled with the assumption of a higher absorption contribution—about a factor of 4—by the sum of the low-frequency wings of all other rotational H_2O lines. He concluded, therefore, that the modified equation perhaps predicted too low an absorption value at frequencies remote from resonance. An increased value of the effective dipole moment has since been measured[5] for this particular transition; this permits a small increase in the theoretical value, but at least a 10 percent discrepancy remains. During a calculation of the complete cm-mm water-vapor absorption spectrum (to be reported later), other possible reasons for the higher measured absorption have been explored and their influence calculated.

Dennison's[6] table of energy levels predicts only one additional line for $\lambda > 1$ mm; this 2_2-3_{-2} transition gives rise to a line at 1.63 mm, and Van Vleck included the effect of this line in his