Bloch function for the bottom of the conduction band, normalized to one in unit volume.

The pertinent point which we wish to make is that it is necessary to include the fact that $u_0^2(r_N)$ (the square amplitude, at the nucleus, of the appropriately normalized Bloch function) is of the order of 10^2 in evaluating $\psi_F^2(r_N)$ for use in hyperfine interaction calculations. When this is not done, i.e., if it is assumed that $\psi_F^2(r_N)=f^2(r_N)$, the estimated interaction, and thus the F-center resonance width, are small by several orders of magnitude.

With this in mind the writer has used the results of the KS calculation together with Hartree-Fock calculations[4] for sodium and potassium to estimate the F-center absorption width. The former is used to obtain $f(r_N)$ and the latter to obtain an approximation to $u(r_N)$ in terms of the ratio of the corresponding atomic orbital at the nucleus to its value at the outer maximum. The results pertaining to the interaction at one of the six metal ion nuclei surrounding the vacancy (for the F-center ground state) are: KCl, $f^2=1.4\times10^{21}$ cm^{-3}, $u^2(r_N)=5.4\times10^2$; NaCl, $f^2=2.2\times10^{21}$ cm^{-3}, $u^2(r_N)=3\times10^2$. This leads to theoretical resonance widths, by use of the methods discussed by Kittel, of 58 oersteds and 280 oersteds, respectively. These are to be compared with experimental values of 54 and 162 oersteds.[3] The agreement is quite satisfactory.

In view of these conclusions it appears that the possibly misnamed "continuum model" can give a reasonable picture of the F center. In discussing charge concentration and energy levels the point emphasized in this letter is not important; however, if detail within the unit cell is significant, a more careful consideration of the role of the cell-periodic part of the wave function is required. A more detailed discussion of the KS calculations is in preparation, and some of these points will be considered at greater length therein. In closing, the writer wishes to express his appreciation to Professor C. Kittel and Professor F. Seitz for their interest and comments on this subject.

* This work was supported in part by the U. S. Office of Naval Research.
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The Wavelength of Scattered Radiation

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(Received September 23, 1953)

THREE sets of observations have been reported on the red shift of monochromatic Hg lines scattered in liquids and gases under different conditions.

In early experiments on the scattering of monochromatic Hg lines passing through water, on which were impressed uhf waves,[1] the writer found that at certain critical frequencies of the uhf field the envelope of the Rayleigh lines was shifted toward the red by 0.06A. At these frequencies practically all the light was scattered from the direction of the primary beam. Sircar[2] has also observed that at absorption frequencies of the electromagnetic waves impressed on the cell, excessive scattering may occur in the higher alcohols.

Cabannes[3] observed a similar red shift in radiation scattered at 90° by gases and liquids. In his case no electric field was applied. Recently Singh[4] has made observations on the scattering of light by CCl_4 in an electrostatic field. He has observed that in the Rayleigh scattering of the primary Hg lines the wings of the Rayleigh lines are shortened and the Rayleigh lines themselves shifted toward the red. Subsequent work[5] has led him to believe that the magnitude of the displacement toward the red does not appear to depend on the strength of the applied field up to nearly 1500 v.

In view of these observations and of the failure of present-day theories to account for them, it seems imperative to re-examine the basic principles of the theories of radiation and of molecular scattering. Furthermore, extreme caution should be exercised in deriving any conclusions based on absolute values of the wavelength of radiation to insure that the lines are not shifted because of scattering similar to that described above.

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The Electron-Voltaic Effect in *p-n* Junctions Induced by Beta-Particle Bombardment*

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(Received November 3, 1953)

MEASUREMENTS have been made of the electron-voltaic effect[1] resulting from the bombardment of $p-n$ junctions with beta particles originating from a 50-millicurie $Sr^{90}-Y^{90}$ radioactive source. Alloy-type junctions[2] about $\frac{1}{4}$ cm^2 in area on germanium or silicon wafers were bombarded from the face opposite the one into which the alloying had proceeded. The wafers used were no more than a diffusion length thick. The voltage and current which such a device exhibits is similar to that arising from a photovoltaic cell except that in the present case the carriers are produced to a much greater extent throughout the volume of the semiconductor. Making certain simple assumptions regarding the operation of the generator, the expression for the maximum (open-circuit) voltage V of this device is

$$V=\frac{kT}{e}\ln\left(\frac{I_s}{I_0}+1\right),$$

where k is Boltzmann's constant, T the absolute temperature, e the electronic charge, I_0 the reverse saturation current, and I_s the short-circuit current produced by the bombardment. For best results the reverse saturation current of the junction should be low and the diffusion length for minority carriers in the semiconductor should be large.

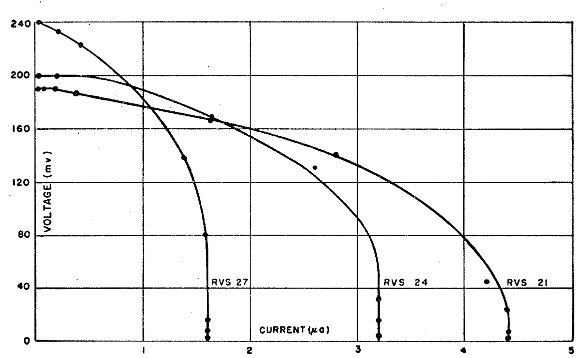

FIG. 1. Current *vs* voltage of various silicon units.

Figure 1 shows typical current *versus* voltage curves for silicon $p-n$ junctions. A maximum open-circuit voltage of 250 mv and a short-circuit current of 10^{-5} amp have been observed in silicon. From the short-circuit current, the multiplication of the beta current (which is 3.2×10^{-10} amp) can be computed. A multiplication of 1.5×10^5 is obtained for silicon if corrections for wafer thickness compared to beta depth of penetration and surface recombination 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.

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Expansion of Copper Bombarded by 21-Mev Deuterons

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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.

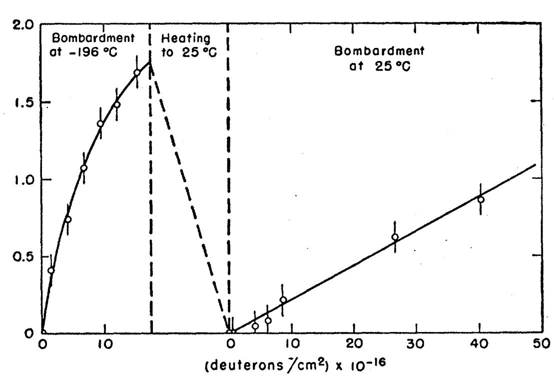

Fig. 1. Specific volume increase induced by deuteron bombardment.

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.

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The Hall Effect in Bismuth at 1.4°K*

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(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

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

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