difficulties encountered in the operation of this new instrument. We plan to measure a few more heavy masses and shall also attempt to improve our precision so as to reach in all cases the limit of one milli-mass-unit.

We wish to thank Dr. Joseph Slepian of the Westinghouse Research Laboratories for the loan of the Condon-Hipple magnet, Dr. L. G. Smith for many valuable suggestions during the early stages of this work, and Mr. A. Tuthill for his technical assistance. Thanks are also due to Dr. W. A. Higinbotham of our Electronics Division for the design of the timing equipment and to members of the Chemistry Department for much valuable advice.

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Electron-Hole Production in Germanium by Alpha-Particles

KENNETH G. McKAY
Bell Telephone Laboratories, Murray Hill, New Jersey

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The number of electron-hole pairs produced in germanium by alpha-particle bombardment has been determined by collecting the internally produced carriers across a reverse-biased $n-p$ junction. No evidence is found for trapping of carriers in the barrier region. Studies of individual pulses show that the carriers are swept across the barrier in a time of less than 2×10^{-8} sec. The counting efficiency is 100 percent. The energy lost by an alpha-particle per internally produced electron-hole pair is 3.0 ± 0.4 ev. The difference between this and the energy gap is attributed to losses to the lattice by the internal carriers. It is concluded that recombination due to columnar ionization is negligible in germanium.

INTRODUCTION

IN the theories of external secondary emission and of bombardment conductivity, it is desirable to know the actual number of electrons freed in a solid by a bombarding particle. The rate of loss of energy by the bombarding particle has been studied extensively by measurements of stopping power and treated theoretically by Bohr, Bethe, and others[1] for high energy particles. This energy loss is the result of electron excitation and ionization, lattice excitation, and nuclear displacement. Much of the energy may be lost in the production of high energy internal secondary electrons which, in turn, produce tertiaries and so forth. Consequently, only approximate estimates of the number of free electrons produced per bombarding particle can be obtained from theory. No satisfactory method has been devised to obtain this quantity experimentally for metals. For phosphors, the light output per incident particle can be measured but its interpretation in terms of a number of free electrons is complicated by the existence of nonradiative transitions. A better method, which has been used for certain insulators, is bombardment conductivity.[2] It is the purpose of this report to describe an accurate determination by this method of the average energy lost by an alpha-particle in producing one electron-positive hole pair in germanium. The use of germanium is predicated by the fact that it is a valence bonded crystal, with the same structure as diamond for which the average energy lost by an alpha-particle in producing one electron-positive hole pair has been measured.[3] Moreover, large single crystals of germanium of known composition and known electrical properties can now be prepared.

THEORY OF THE METHOD

Consider a rod of germanium of which one half is n-type and the other half p-type. If the n-type end is made positive with respect to the p-type end, the $n-p$ barrier will develop a very high resistance and virtually all of the voltage drop along the rod will be concentrated across the $n-p$ barrier. This can be crudely likened to a thin insulator separating two conductors. If the bombarding particles strike the barrier itself so that the resultant holes and electrons are produced in this high field region, they will be swept across the barrier, thereby registering in the external circuit and will eventually disappear in the main body of the germanium. Although the field is not constant throughout the barrier, that is irrelevant as long as trapping or recombination do not take place within the barrier, i.e., as long as the sum of the voltage drops traversed by a given electron-hole pair is substantially equal to the total voltage drop across the specimen. To date, no evidence has been observed for the existence of trapping or recombination within a well made $n-p$ barrier in germanium. Moreover, the injected current densities normally used are much too small to set up a space charge field which could perturb the barrier field appre-

[1] N. F. Mott and H. Massey, *Theory of Atomic Collisions* (Oxford University Press, London, 1934).

[2] Reviews of this work as applied to crystal counters have been published by R. Hofstadter, Nucleonics **4**, No. 4, 2 (1949); **4**, No. 5, 29 (1949); Proc. Inst. Radio Engrs. **38**, 726 (1950).

[3] A. J. Ahearn, Phys. Rev. **73**, 1113 (1948); K. G. McKay, Phys. Rev. **77**, 816 (1950).

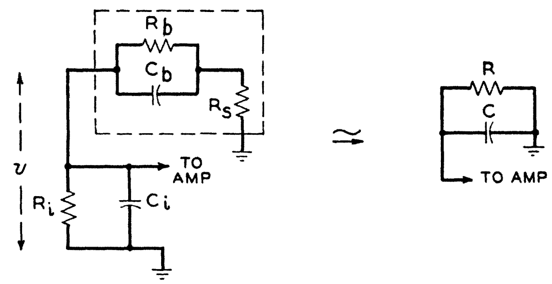

FIG. 1. Equivalent circuit of $n-p$ germanium crystal and amplifier input.

ciably. Thus a germanium $n-p$ barrier has precisely the properties of an ideal insulator for bombardment conductivity. The geometry described has the attractive property that voltage probe measurements can be made along the entire length of the specimen. Thus it can be established that essentially all of the applied voltage is indeed concentrated across the $n-p$ barrier.

It might appear that any rectifying contact to germanium would serve as well as an $n-p$ junction. This is not so because it is known from transistor characteristics that a point contact, acting as a collector, exhibits a current multiplication which depends on its previous history. Thus if we bombard the barrier region around a point contact, the maximum observed charge may be several times the total charge of electrons (or holes) generated in the bulk germanium by the bombarding particle. Unfortunately we usually do not know the amplification factor of the point contact barrier so we cannot thus determine the intrinsic work of ionization in the germanium. No such current multiplication has been observed for a normal $n-p$ barrier. Photoconductivity measurements have demonstrated a quantum yield of unity for such a barrier.[4] Moreover, the theory of the $n-p$ barrier, which has been well-substantiated by experiment, nowhere suggests the possibility of current multiplication.[5]

Figure 1 shows the equivalent circuit of the germanium crystal and the amplifier input as used in these experiments. R_b, C_b represent the constituents of the barrier impedance, R_i, C_i those of the amplifier input, and R_s the series resistance of the body of the germanium. By applying a reverse bias to the barrier, we can ensure that $R_b \gg R_s$ and thus neglect R_s completely. The equivalent circuit then reduces to a simple parallel RC circuit, where $R=R_bR_i(R_b+R_i)^{-1}$ and $C=C_i+C_b$. The time taken to sweep the carriers out of the barrier region is short compared with the RC relaxation time, so that this action is equivalent to the production of an impulse current across the barrier layer, resulting in a peak voltage across the barrier of $v=Q/C$ where Q is the effective charge transported across the barrier. The limitations imposed by the noise spectrum and capacity of the barrier have been discussed previously.[6]

TABLE I. Forbidden energy gap width E_G and average work of ionization ϵ for various solids.

Solid	$-\epsilon$ ev	E_G ev	ϵ/E_G	$\epsilon-E_G$ ev
Diamond[a]	10	~6	~1.7	~4
Germanium	3.0	0.72	4.2	2.3
AgCl[b]	7.6	4.88	1.6	2.7
AgBr[b]	5.8	3.95	1.5	2.4
CdS[c]	5–10	2.37	2–4	2–7

[a] See reference 3.
[b] See reference 2.
[c] Dr. Kallmann in a private communication stated that pulses had been observed with CdS corresponding to $\epsilon=5$ ev in which probably no secondary processes were involved.

EXPERIMENTAL TECHNIQUE

A number of specimens have been used in this work but, since they have all been similar although by no means identical, it will suffice to describe the salient features of one. This is a rod 2 cm long and of square cross section 1 mm wide. It is a single crystal in the middle of which occurs the barrier which is normal to the length of the crystal.[7] The ends of the crystal were sandblasted and then rhodium plated to provide low resistance ohmic electrical contacts. Probe measurements made along the length of the germanium showed that, with several volts reverse bias applied to the crystal, the total voltage drop across the two contacts and across the main body of the germanium was less than 0.3 percent of the voltage drop across the barrier. This justifies the neglect of R_s in the equivalent circuit. The current-voltage characteristic, which was essentially the same as published curves for well behaved $n-p$ junctions,[4] verified the results of the probe measurements.

Figure 2 is a simplified schematic of the circuit used. One end of the crystal is grounded and the other end feeds to the input of a preamplifier. Bias is supplied through a shunt resistor of the same order of magnitude as the barrier resistance. The preamplifier output goes to a slave sweep which is triggered by individual pulses larger than a predetermined magnitude, and also to an attenuator which is calibrated to an accuracy of better than 0.1 db. The attenuator contains a coaxial cable delay line which delays the signal pulse by 0.17 μsec enabling the sweep to start adequately before the arrival of the signal at the main amplifier. The over-all band width of the system is about 35 megacycles/sec and the maximum available gain is 110 db.

The calibrating circuit consists of a pulser which generates a flat-topped pulse with a rise time of 0.01 μsec. The output is fed through an attenuator to a small condenser C_c that is connected to the preamplifier input. The leading edge of the calibrating pulse, when applied to condenser C_c, provides an impulse current

[4] Goucher, Pearson, Sparks, Teal, and Shockley, Phys. Rev. **81**, 637 (1951).
[5] W. Shockley, *Electrons and Holes in Semiconductors* (D. Van Nostrand Company, Inc., New York, 1950), p. 309.
[6] K. G. McKay, Phys. Rev. **76**, 1537 (1949).
[7] G. K. Teal and J. B. Little, Phys. Rev. **78**, 647 (1950).

or quantity of charge to the input circuit of the amplifier. As long as R_s is negligible, this is entirely equivalent to the production of an impulse current across the barrier by one alpha-particle. By comparing the photographed pulses due to alpha-particle bombardment with the calibrating pulse, a direct measurement of the charge collected per individual bombarding alpha-particle is obtained.

The alpha-particle gun provides a collimated beam of alpha-particles from polonium. The maximum beam width striking the sample is 3.5×10^{-3} cm. This is somewhat wider than the barrier width which is expected to be approximately 5×10^{-4} cm at a few volts reverse bias. However, this is compensated for by the effect of diffusion. As long as the total time taken to collect all of the holes or electrons at the barrier by diffusion is much shorter than the *RC* decay constant or the recombination lifetime, the maximum pulse height will be the same as if all of the carriers were produced in the barrier itself. In these experiments, the *RC* decay constant was always greater than 5 μsec and the recombination lifetime was greater than 50 μsec as determined from photoconductivity measurements.[4] If the carriers are created at a distance of 10^{-3} cm from the barrier, 90 percent of the carriers will be collected by the barrier in a time of less than 0.5 μsec. This should guarantee fairly uniform pulse heights. All measurements were made in a vacuum of better than 10^{-2} mm Hg to eliminate any effects due to air ionization. At no time during the experiments did the temperature of the germanium exceed room temperature by more than 5°C.

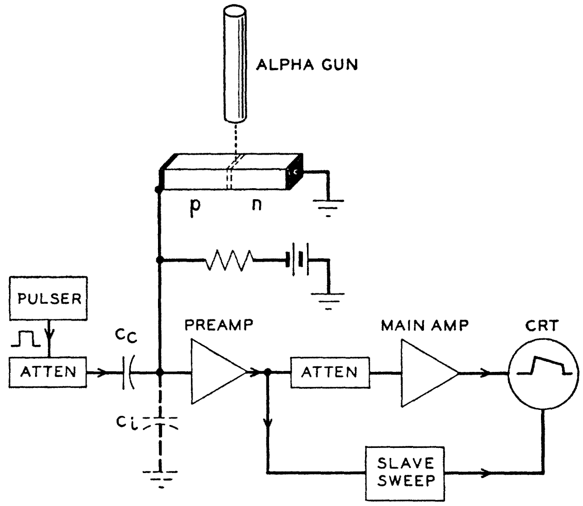

FIG. 2. Schematic of experimental equipment.

EXPERIMENTAL RESULTS

Figure 3 shows a photograph of 16 alpha-pulses striking around the barrier. The observed spread in pulse heights agrees well with that calculated from the known beam width of the alpha-particle gun. The lower trace is that of the calibrating pulse. The maximum pulse height was taken as that best representing the maximum utilization of the carriers. The experiment has been repeated with seven samples of germanium from different sources and of resistivities ranging from 1 ohm cm to 20 ohm cm. The maximum pulse heights obtained from these different samples agree within 5 percent. Varying the bias across the junction from 0.3 to 15 volts showed no observable trend and the variations observed in maximum pulse height were no greater than the error involved in measuring up the photographs. The intensity calibration of the alpha-particle source was good only to within 25 percent, owing principally to uncertainty in the diameter of the beam defining aperture, but within that accuracy, the counting efficiency was 100 percent, i.e., every alpha-particle that strikes the germanium is registered. The alpha-pulses with the steepest rise time were exact replicas of the calibrating pulses within the accuracy to which the pulses could be superimposed. This indicates that in both cases the rise times are set by the transient response of the amplifier. From this we can set an upper limit to the length of time required to sweep all the holes and electrons across the barrier as 0.02 μsec. For the biases used, the effective barrier width is of the order of 5×10^{-4} cm with applied fields across the barrier of the order of 10^4 volts/cm. In such a strong field, it is probable that the low field value of mobility is no longer valid but it appears safe to assume that the carriers should traverse the barrier with a velocity of at least 10^7 cm/sec. Hence if there are no short time trapping effects in the barrier, the time taken for the carriers to traverse the barrier should be less than 10^{-10} sec. This is certainly not contradicted by the upper limit of 2×10^{-8} sec set by the experiment.

The final value for the charge collected per incident alpha-particle is $Q=1.77\times10^6e$, where e is the charge of an electron. According to Seitz,[8] less than 0.1 percent of the energy of an alpha-particle is given up to sources other than the liberation of electrons. Consequently we are justified in dividing Q/e into the initial energy of the

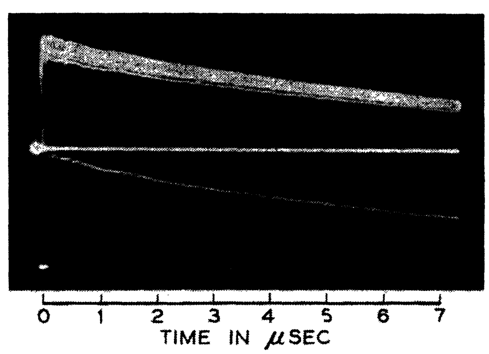

FIG. 3. Photograph of pulses from sixteen alpha-particles striking the $n-p$ barrier.

[8] F. Seitz, Disc. Faraday Soc. (No. 5) 271 (1949).

alpha-particle to determine the average energy lost by an alpha-particle in producing one electron-hole pair. Defining this quantity as ϵ, the work of ionization, and taking the energy of a polonium alpha-particle as $E_\alpha = 5.298$ Mev, we have

$$\epsilon = E_\alpha \frac{e}{Q} = 3.0 \pm 0.4 \text{ ev.}$$

It was previously reported[9] that for germanium $\epsilon = 5.6$ ev. This was an erroneous value owing to an intermittent fault in the calibrating circuit. The fact that the charge collected per alpha does not agree with the value previously obtained for a point contact rectifier[6] is irrelevant since the latter depends on the previous treatment of the point contact.

DISCUSSION

Table I summarizes most of the data now available on the work of ionization in various solids. Diamond and germanium are of particular interest as they are both valence bonded crystals with the same crystal structure, yet the forbidden energy gaps differ by almost an order of magnitude. The results show that ϵ is not simply proportional to E_G. Let us consider briefly the energy loss mechanisms. The bombarding particle can lose energy in the following ways: (1) Direct excitation of lattice vibrations or direct nuclear collisions. Seitz[8] has shown that less than 0.1 percent of the energy of an alpha-particle is lost this way. (2) Production of high energy electrons which subsequently leave the crystal carrying their energy with them. Secondary emission data suggests this is a very inefficient process. (3) X-ray production and subsequent emission. This also appears energetically inefficient. (4) Exciton production with subsequent recombination. The agreement between the wavelength dependence of the infrared absorption and the photoconductive yield in germanium argues against any appreciable production of excitons which do not subsequently decompose[10] and Seitz has inferred that an exciton would probably be unstable at room temperature in diamond.[11] (5) Production of electron-hole pairs. These may be produced with sufficient energy on the average to produce tertiaries, etc. Competing with the process of tertiary production will be losses due to lattice excitation by the internally produced carriers.

It appears reasonable to assume that number (5) assimilates essentially all of the energy of the alpha-particle in germanium or diamond. Then $\epsilon - E_G$ represents the excess energy which is transferred to the lattice by the internally produced electrons and holes. In the materials listed in Table I, this quantity shows a certain degree of constancy. To derive values for $\epsilon - E_G$ theoretically requires not only a treatment of the collision process but also a detailed picture of the electron-lattice interaction over a wide range of electron energies. To date, this has not been done. However, the data suggest that energy losses to the lattice do play a considerable role and they appear to be more or less independent of the width of the energy gap E_G.

Although this work has been solely concerned with alpha-particle bombardment, it should be noted that the values of ϵ obtained from alpha-bombardment and electron bombardment for diamond agree within the experimental error. Apparently the same is true for CdS.[12] It is reasonable, therefore, to expect that a value of approximately $\epsilon = 3.0$ ev should be realized for electron bombardment in germanium. Moore and Herman[13] reported a value of $\epsilon = 5$ ev for 10-kv electrons bombarding germanium. Their published data indicates that they had not yet reached saturation, i.e., their published values of ϵ may be too high. Thus the extent of the agreement is quite encouraging. Moreover, this agreement is obtained in spite of the great difference in density of charges produced by electrons as compared with alpha-particles. This suggests that immediate recombination between holes and electrons produced by alpha-particles, does not occur in germanium when a field is present. (This is in contrast with the columnar ionization problem in gaseous ionization chambers.) Actually many of the alpha-particles do not strike the barrier at all but produce holes and electrons in the field free region immediately adjacent to the barrier and the carriers then diffuse to the barrier. In this case the same number of carriers are made available per alpha as when the alpha-particle strikes the barrier. Thus, even in field free germanium, recombination due to density of induced carriers, is negligible within the limits studied.

ACKNOWLEDGMENT

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[9] K. G. McKay, Phys. Rev. **82**, 329 (1951).
[10] F. S. Goucher and H. B. Briggs (private communication).
[11] F. Seitz, Phys. Rev. **76**, 1376 (1949).

[12] This is not true for alkali halides. H. Witt, Z. Physik **128**, 442 (1950) reported a value of $E_\alpha e/Q = 600$ ev for alpha-bombardment of NaCl at a field strength of 1.5×10^5 volts/cm without reaching a saturation with respect to field strength. This is compared with a value of 60 ev for beta-particles in KCl under similar conditions by H. U. Harten, Z. Physik **126**, 619 (1949). Witt attributes the difference to strong recombination of electrons produced by alpha-particles.
[13] A. R. Moore and F. Herman, Phys. Rev. **81**, 472 (1951).

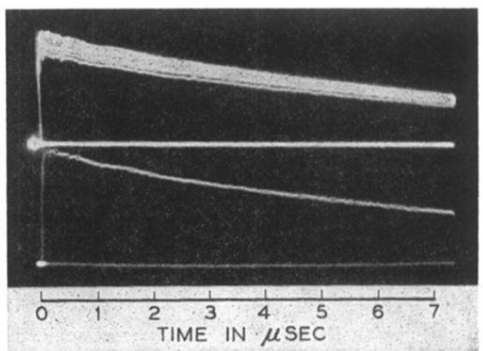

FIG. 3. Photograph of pulses from sixteen alpha-particles striking the $n-p$ barrier.