Electron Multiplication in Silicon and Germanium

K. G. McKAY AND K. B. McAFEE
Bell Telephone Laboratories, Murray Hill, New Jersey
(Received May 29, 1953)

Electron multiplication in silicon and germanium has been studied in the high fields of wide *p-n* junctions for voltages in the prebreakdown region. Multiplication factors as high as eighteen have been observed at room temperature. Carriers injected by light, alpha particles, or thermal-generation are multiplied in the same manner. The time required for the multiplication process is less than 2×10^{-8} second. Approximately equal multiplication factors are obtained for injected electrons and injected holes. The multiplication increases rapidly as "breakdown voltage" is approached. The data are well represented by ionization rates computed by conventional avalanche theory. In very narrow junctions, no observable multiplication occurs before Zener emission sets in, as previously reported. It is incidentally determined that the efficiency of ionization by alpha particles bombarding silicon is 3.6 ± 0.3 electron volts per electron-hole pair produced.

INTRODUCTION

ELECTRON multiplication in gases in the prebreakdown Townsend avalanche has been known for years; however, the corresponding charge multiplication in solids has not been as clearly recognized. The increased dark current observed in some insulators prior to breakdown has been attributed to strong field emission from the electrode[1] while current multiplication in semiconductors is normally caused by transistor action, i.e., the control of electron flow by the presence of positive holes or vice versa. The purpose of this paper is to describe experiments that demonstrate that charge carriers, injected into a *p-n* junction, can multiply under high field conditions. This multiplication appears to be an avalanche formation, and it occurs in both silicon and germanium. Previous measurements[2] of carriers injected by photons into very narrow germanium junctions have shown no charge multiplication. Subsequent measurements on those junctions of carriers injected either by photons or alpha particles have confirmed the earlier measurements, particularly in the prebreakdown region. For such junctions the slope of the current-voltage characteristic in the breakdown region is in essential agreement with the Zener theory of internal field emission.[3] The absence of multiplication is also implicit in the Zener theory.

The measurements to be described in the present paper were undertaken to examine in detail the portion of the current-voltage characteristic just below the "breakdown" or "voltage-limiting" region. The germanium junctions presently to be described differ in an important manner from those previously studied in having a broader space-charge region. The observation of charge carrier multiplication leads to the possibility of avalanche breakdown in broad junctions and Zener internal field emission in junctions which are too narrow to support appreciable multiplication.

[1] A. von Hippel, Phys. Rev. 54, 1096 (1938).
[2] McAfee, Ryder, Shockley, and Sparks, Phys. Rev. 83, 650 (1951).
[3] C. Zener, Proc. Roy. Soc. (London) 145, 523 (1934).

SAMPLE CHARACTERISTICS

Although current multiplication has now been observed in a large number of junctions, in the following we shall concentrate on just two particular crystals—one of silicon and one of germanium. The crystals were fabricated by pulling from the melt with the axis of the seed parallel to the 111 crystal direction. The melt at the start contained *p*-type impurity. Halfway through growth the *n*-type impurity was added. The units were cut from the crystals so that they were bisected by the *p-n* junction whose plane was normal to the rod axis. In all of the measurements to be considered here, the individual rods from a given crystal had essentially identical properties, so only one of each will be specified. The physical dimensions, donor and acceptor impurities, and the resistivities are given in Table I.

CURRENT-VOLTAGE CHARACTERISTICS

Figure 1 shows the room temperature current-voltage characteristics of the junctions plotted on a log-log scale. The germanium junction exhibits an excellent saturation characteristic followed by the now familiar breakdown region.[2] The silicon reverse characteristic does not saturate as well, and the reverse current is much larger than it should be, based on the observed forward current and Shockley's theory of the *p-n* junction. However, this seems typical of well-behaved silicon junctions, and McAfee has proposed that this is due to spontaneous electron-hole pair generation within the space-charge region itself. Shockley and Read have shown that this is theoretically possible.[4]

Figure 2 shows the breakdown regions on a greatly expanded voltage scale to permit a measurement of the

TABLE I. Samples characteristics.

Crystal	Length cm	Width cm	Donor	Acceptor	$\bar{\rho}_n$ ohm-cm	$\bar{\rho}_p$ ohm-cm
Ge	1	0.1	Arsenic	Gallium	0.0066	0.27
Si	1	0.1	Phosphorus	Boron	0.024	0.006

[4] W. Shockley and W. T. Read, Jr., Phys. Rev. 87, 835 (1952).

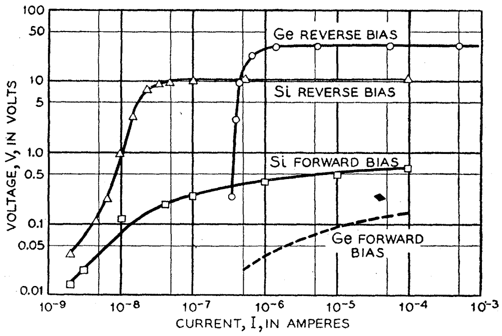

FIG. 1. Current *vs* voltage characteristics for the germanium and silicon p-n junctions.

slope $d(\ln V)/d(\ln I)$ in this region. The measured slopes for the germanium and silicon junctions, respectively, are 0.0013 and 0.00070. These slopes are at least a factor of ten smaller than those predicted by Shockley's modification of the Zener theory of internal field emission.[2]

CAPACITY-VOLTAGE CHARACTERISTICS

Figure 3 shows the variation of junction capacitance as a function of applied reverse voltage V as measured on an audio-frequency bridge. From the capacity per unit area, C/A, we obtain the effective width W of the space-charge region simply through the relation

$$W=\frac{\kappa}{4\pi C/A},$$

where κ = dielectric constant = 16 for germanium and 12 for silicon. However, additional information can be derived from the functional form of the capacity variation with voltage. If we increase the voltage in Fig. 3 by the built-in voltage ($2\psi_i$) for applied voltage equal to zero, we find that $\log(C/A)$ *vs* $\log(V+2\psi_i)$ yields a good straight line. For both the germanium and silicon junctions, the slope of that line is given by $C\sim(V+2\psi_i)^{-\frac{1}{3}}$, which is the relationship derived for a linear gradient of impurity concentration across a junction.[5] The growth processes for both junctions were

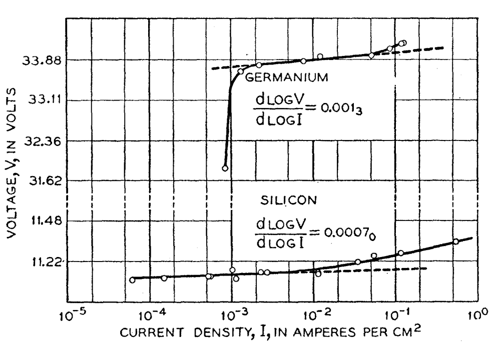

FIG. 2. Enlarged I/V characteristics, showing the details in the breakdown region.

[5] W. Shockley, Bell System Tech. J. **28**, 435 (1949).

such that a near-linear gradient was to be expected. The capacity variation confirms this expectation and permits the assertion that the electric field is a maximum at the center of the junction and decreases parabolically with distance from the center. The maximum field is

$$E_{\max}=1.5E_{\mathrm{Av}}=1.5(V+2\psi_i)W^{-1}.$$

Figures 4 and 5 show W and $E_{\max}$ plotted as a function of V as obtained from these relations. These data serve to establish the basic electrical features of these junctions.

PHOTOENHANCEMENT

It has been demonstrated by Goucher[6] that when light falls on a germanium reverse-biased p-n junction, unit quantum yield is obtained and that, within wide limits, this is independent of the bias voltage. Our measurements show significant departures from this relation as the bias voltage approaches breakdown. The measurements were made by measuring the voltage and current through a nonilluminated junction

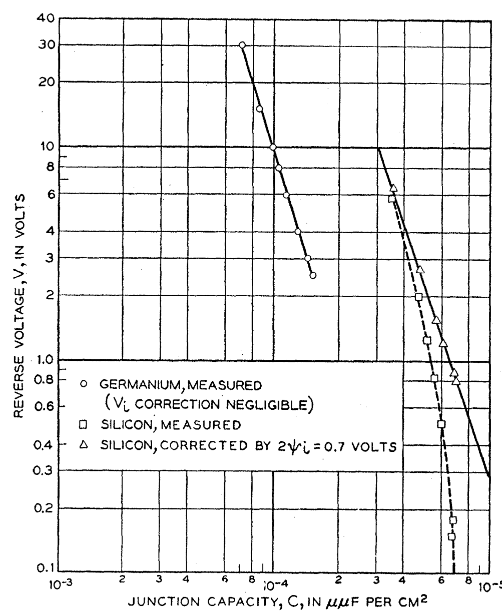

FIG. 3. Measured variation of junction capacity with applied voltage.

with a type K potentiometer. The junction was then illuminated, the junction voltage readjusted to the previous value, and the new current determined. The change in current was ascribed to photoconduction. Figure 6 shows a plot of photocurrent *vs* applied voltage for the silicon junction. The light was filtered by a monochromator and wavelengths above and below the long-wave limit for silicon were used. By normalizing the photocurrents at low voltages where the induced

[6] Goucher, Pearson, Sparks, Teal, and Shockley, Phys. Rev. **81**, 637 (1951).

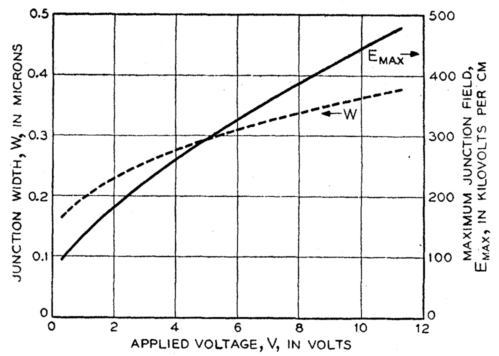

FIG. 4. Variation of junction width W and maximum junction field E_{max} with applied voltage V for the silicon junction

currents are very nearly voltage-independent, we see that the yield curves are essentially independent of exciting wavelength. Moreover, the normalized curves are independent of the intensity of the light over the measured range of 100:1. The photo yield curves for the germanium junction were very similar in shape to those for silicon if the voltage scale was multiplied everywhere by about a factor of three. To check the absolute yield, a light spot of a known intensity was used on the germanium junction. At a low reverse bias of 3 volts this yielded a quantum efficiency of 0.65. An estimate of the width of the light spot, together with the diffusion lengths in the sample, corrects this to approximately unity quantum yield. At a bias of 33.9 volts, the photocurrent had increased by a factor of ten to give an apparent quantum yield of 6.5 and a corrected yield of about 10.

It is of importance to know whether the photo-enhancement at high voltages is the same for injected holes as for injected electrons. This was determined by scanning the junction in a direction parallel to the sample axis with a small spot of light. This is essentially the same as the technique described by Goucher[6] to measure diffusion lengths. The two solid curves of Fig. 7 are typical of the germanium sample. The light spot was small enough to guarantee that when scanning on the n side we were indeed injecting holes into the barrier and not electrons generated by scattered light over the p side. The two curves are essentially identical

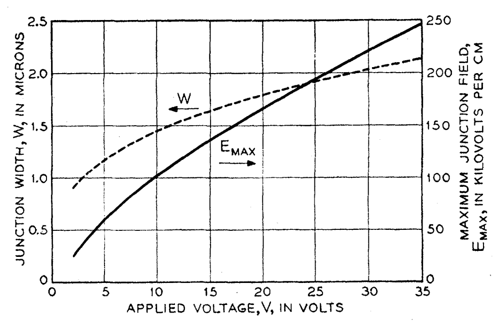

FIG. 5. Variation of junction width W and maximum junction field E_{max} with applied voltage V for the germanium function.

in shape and, if normalized to the same maximum current, are alike. The same is true of curves measured at other biases. If multiplication of injected electrons did occur and multiplication of injected holes did not occur, the yield at the higher bias would follow the lower curve on the n side and the upper curve on the p side as shown by the dotted line. This is clearly not the case.

ALPHA-BOMBARDMENT CONDUCTIVITY

The measurements described above are all dc measurements; they cannot ascertain the time scale at

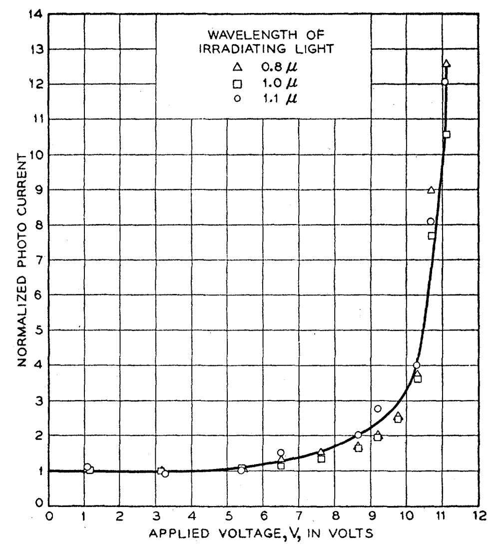

FIG. 6. Variation of photocurrent with applied junction voltage for light of various frequencies illuminating the silicon junction. The ordinate scales have been normalized by setting the photocurrent equal to unity at low voltages.

which the enhancement takes place. In particular, they cannot distinguish between essentially instantaneous multiplication in the junction and a form of transistor action established by an n-p-n-p structure. It was thus desirable to measure the time scale of the action and to study the enhancement by using an entirely different form of current injection. These objectives were achieved by bombarding the junction with alpha particles from polonium and measuring the charge produced per alpha particle. The charge pulse is transformed to a voltage pulse, amplified on a wide-band, high-gain amplifier and displayed on an oscilloscope. The details of the equipment have been published previously.[7] It should be noted that an absolute determination of charge is obtained in this measurement.

Figure 8 shows the variation of the charge collected in units of e, the charge on an electron, as a function of applied voltage for both silicon and germanium junctions. The three sets of points for silicon were taken on three different junctions of somewhat different dimen-

[7] K. G. McKay, Phys. Rev. 84, 829 (1951).

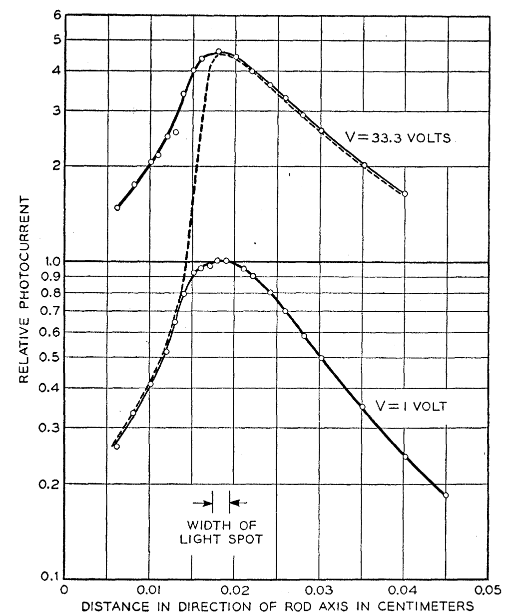

FIG. 7. Photoresponse of the germanium junction as a function of distance from junction of light spot for two different values of applied voltage. The dotted curve represents the expected response if holes injected by light did not multiply in junction.

sions which were cut from the same single crystal. The dots and squares correspond to measurements taken by photographing the oscilloscope traces and carefully measuring the negatives. The circles and crosses correspond to visual observations of the oscilloscope and thus are not as accurate. Thus within the accuracy

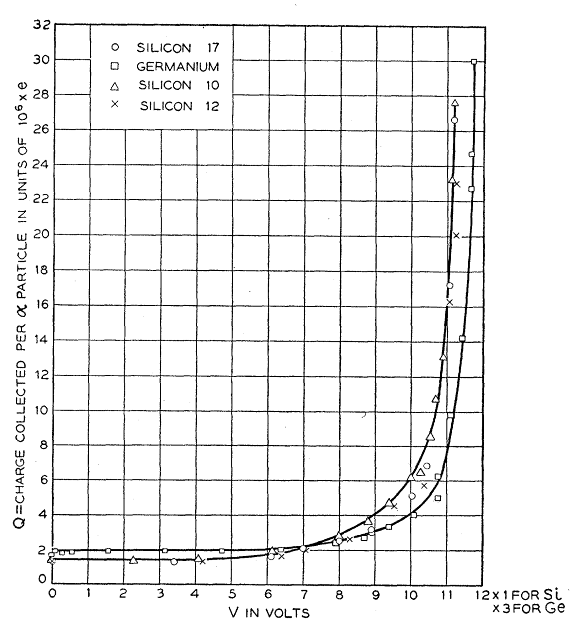

FIG. 8. Charge Q collected per alpha particle incident on junction of applied voltage. Data are shown for three separate silicon junctions and the germanium junction. Silicon No. 10 is the junction used in all other figures.

of the visual measurements there is no significant difference between the three sets of points for silicon. As will be shown later, these results agree with the photoenhancement measurements.

The absolute yield values are of interest. The low field yield for germanium was 1.80×10^6 electronic charges per polonium alpha particle. This gives for the efficiency of ionization, $\epsilon=2.94\pm0.15$ ev/pair, where ϵ is defined as the energy of the bombarding particle divided by the number of electron hole pairs produced per particle. This value for ϵ compares well with the previously determined value of $\epsilon=3.0\pm0.3$ ev/pair as measured on several other germanium junctions in the low field region.[7] The corresponding value for silicon is $\epsilon=3.6\pm0.3$ ev/pair, for which a value has not previously been published.

By examining the individual pulses on a fast sweep, the pulse rise times could be studied. As previously described,[7] the rise time corresponds to the total time that the induced current is flowing across the junction. Careful studies were made on both silicon and germanium of the pulse rise times throughout the voltage ranges shown on Fig. 8. For all voltages, including those where the charge enhancement was greater than 15, pulses were observed with a rise time that was characteristic of the amplifier, i.e., the actual pulse rise time must be less than 0.02 μsec.

NORMALIZED YIELD CURVES

Figure 9 sums up the previous results. The photo yields and alpha-bombardment yields have been normalized to unity at low biases where they are voltage independent. The normalized voltage$=V/V_b$ where V_b, the breakdown voltage, is obtained from the current-voltage characteristics shown in Fig. 2. It should be emphasized that the normalizing voltage has not been determined simply by the voltage at which the charge enhancement became very large. The normalized curves are similar for the two junctions although showing a real difference for $0.6<$normalized voltage<0.95.

Another source of carriers which are injected into the junction is the saturation current itself, derived from the spontaneous thermal generation of electron-hole pairs. According to the previous results, this current also be multiplied in the high field region. If the linear portion of the saturation current in Fig. 1 is extrapolated to higher voltages and the difference between this and the actual current is plotted against normalized voltage, the result is a plot which follows the curves of Fig. 9. The multiplication so obtained is indeed somewhat less than that obtained by deliberate carrier injection. This is to be expected since the dc reverse current is made up partly of a volume current and partly of surface leakage which is strongly dependent on previous surface treatment. However, this result means that for these junctions, the "soft" knee observed in the transition from the saturation region to the breakdown region, as shown in Fig. 1, can be attributed to multiplication in the junction of the saturation current.[8]

DISCUSSION

The experimental evidence that has been presented can be used to establish the following characteristics of the observed process:

(1) The agreement obtained in photoyield *versus* voltage with different values of the incident wavelength (Fig. 6) is sufficient to show that multiplication takes place in the same amount regardless of the depth within the semiconductor at which the charge carriers are produced. The longer wavelengths employed gave a penetration depth[9] for the light many times the dimensions of the sample while the shorter wavelength produced most of its charge carriers in the region near the surface.

The agreement, shown on Figs. 6 and 9, between the yield curves for various wavelengths of light together with those for alpha-bombardment conductivity, rules out the possibility that the increased induced current can result merely from an enhanced rate of production of carriers by the bombarding particle in the high field region.

(2) The absolute measurements of quantum yield both with light and with alpha bombardment, show that charge multiplication is really taking place in the junction.

(3) The rise-time measurements of the pulses produced by alpha particles show that this multiplication takes place in a time that is less than 2×10^{-8} second. Moreover, the values so obtained agree with those observed in the dc measurements. From this we conclude that the multiplication is not merely a consequence of a hook mechanism resulting from an *n-p-n-p* structure or a complex of traps such as are invoked in secondary photoconductivity. Rather, we conclude that we have *true* multiplication taking place in the high field of the barrier. Further evidence that the barriers studied are not pathological is obtained from the completely normal current-voltage characteristics of Fig. 1, the capacity-voltage characteristic of Fig. 3, and the diffusion length characteristic of Fig. 7. Moreover, the fact that such multiplication has been observed in many junctions rules out a mere freak configuration of impurities.

(4) In the diffusion length curves of Fig. 7, the holes or electrons that reach the barrier from a light spot a given distance from the barrier, remain essentially constant irrespective of the barrier voltage. Thus, the fact that the entire curve is unchanged in shape by

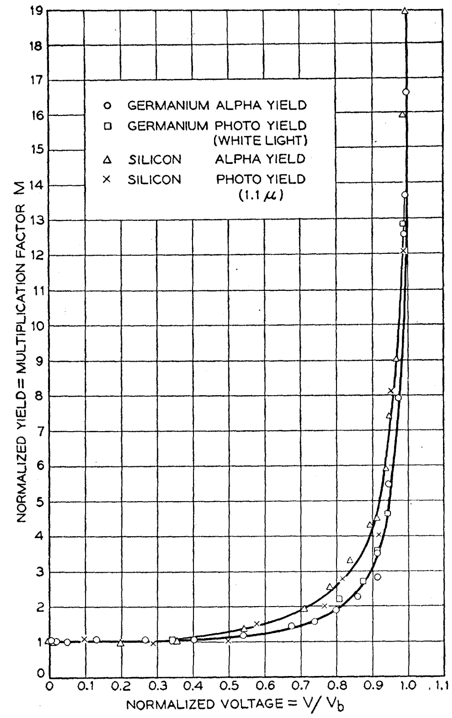

FIG. 9. Normalized yield curves of alpha bombardment and of photoconductivity for the silicon and germanium junctions from Fig. 8 and Fig. 6. Ordinate normalization was obtained by setting photo or alpha yield equal to unity for small applied voltage. Abscissa normalization was obtained by dividing the applied voltages by the breakdown voltages from Fig. 2.

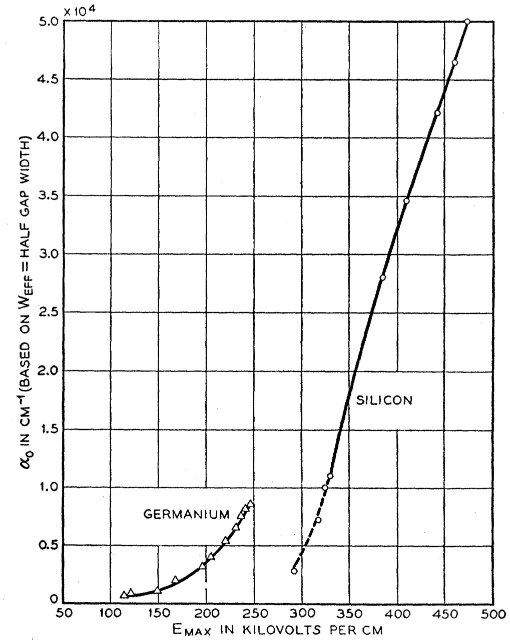

FIG. 10. Calculated ionization coefficients for germanium and silicon.

[8] Another method of carrier injection is by a point emitter. A point contact was set down 0.025 cm from the *p-n* junction in the *p* region of the germanium junction. Using the latter as collector in a conventional transistor circuit, the resultant current multiplication α of the injected electrons was measured. The variation in α with junction voltage showed essentially the same characteristic as that exhibited by the photoenhancement and the alpha-bombardment conductivity.

[9] H. Briggs, Phys. Rev. **77**, 727 (1950).

multiplication implies that both electrons and holes multiply at approximately the same rate. A correction term has been added to the diffusion equation to estimate the effect of applied field upon motion of the injected carriers. Using the measured resistivities this contribution proves to be negligible when compared with the diffusion term.

(5) The good agreement between the voltage at which the multiplication becomes very large and the onset of breakdown suggests that the two are closely connected.

One possible model of the multiplication process is that the production of an electron-hole pair by an incident electron can take place anywhere in the high field region of the barrier rather than at one singular point or on one singular plane. In that case we have a situation analogous to that of a gas discharge in which the walls and electrodes act only as sinks for charge carriers and both electrons and ions can ionize. This is the Townsend β process.[10] It can be shown[11] that for equal rates of ionization of electrons and positive holes and for a uniform field, we have simply

$$\alpha_0 = (1 - M^{-1})/W_{\text{eff}}, \tag{1}$$

where α_0 = the rate of ionization, i.e., the number of electron-hole pairs produced by a carrier per cm path traveled in the direction of the field, M = the observed multiplication factor, and W_{eff} = the effective barrier width.

Actually the field distribution across the barrier is parabolic as determined from the capacity-voltage measurements. However, at this stage it is reasonable to assume a uniform field and an effective barrier width. The effective barrier width W_{eff} was chosen as one-half the actual barrier width as determined from capacity measurements, and the effective "uniform" field was taken equal to the maximum field existing at the center of the junction. For a given applied voltage, values of W and E_{max} were obtained from Figs. 4 and 5 and values of M from Fig. 8. Inserting these in Eq. (1), we get the values of α_0 shown in Fig. 10. These show that although the multiplication is a rapidly varying function of the field, no such violent variation is required of the rates of ionization. It should be observed that the use of Eq. (1) does not depend critically on the assumption that the ionization rates for electrons and holes are equal.

Although insufficient data are available to deduce values of α_0 theoretically, at least it can be shown that the values obtained are not unreasonable. The collision cross section for electron-hole pair production is not known as a function of the energy of an exciting electron or hole. However, the alpha-bombardment measurements set an upper limit to the minimum energy E_{min} required for pair production, while the energy gap E_G sets a lower limit. (If the lattice interaction is neglected, the lower limit will be $2E_G$.) Thus for germanium 0.7 ev$<E_{\text{min}}<$2.9 ev and for silicon $1.1<E_{\text{min}}<3.6$ ev. Shockley's theory of hot electrons in germanium[12] makes plausible the existence of electrons of several volts energy for fields of greater than 10^5 volts/cm. The reciprocal of α_0 is the mean free path for pair production in the direction of the applied field. The minimum value of α_0^{-1} obtained for silicon was 2000A corresponding to a barrier width $W=3750$A and an applied voltage of 11 volts. Thus sufficient energy is available within a mean free path α_0^{-1} to make pair production possible.

Using the measured values of α_0 for germanium, we can compute the expected multiplication for the narrow junctions in which the voltage limiting region was identified with Zener emission in an earlier publication.[2] For the highest voltages used, the calculated multiplication is less than 3 percent and hence negligible. This agrees with the experimental data. Thus it appears that, for very narrow junctions, appreciable multiplication can occur at very high fields and, before such fields are reached, internal field emission sets in. However, for wider junctions, the multiplication factor M may become infinite for fields below those required for field emission.

The junctions studied in the present work do not appear to be in any way unusual; they are uniform and well-behaved. It should be noted here that multiplication has been observed in junctions at least ten times as wide as these. Consequently the junction width and the impurity concentration do not appear to be critical. It is evident that although these experiments do not concern the region of breakdown itself, they must be taken into account in any theory of breakdown for these semiconductors.

ACKNOWLEDGMENT

We wish to express our appreciation to many of our colleagues at the Bell Telephone Laboratories who have contributed to this work. In particular we wish to acknowledge many stimulating discussions with W. Shockley who initiated the research. Thanks are also tendered to M. Sparks for his contributions to these studies. The crystals were grown by E. Buehler and R. Mikulyak. Valuable technical assistance was rendered by Miss C. Peffer and H. C. Meier.

[10] L. B. Loeb, *Fundamental Processes of Electrical Discharge in Gases* (John Wiley and Sons, Inc., New York, 1939).

[11] We are grateful to D. J. Rose for bringing Eq. (1) to our attention and for many helpful suggestions concerning the applicability of gas discharge theory to the present work.

[12] W. Shockley, Bell System Tech. J. **30**, 990 (1951).