particles of total masses $m=\kappa h/ac=2\kappa\cdot 137m_0$. This purely formal calculation is related to the physically meaningful investigation of Born and Green.[5] These authors obtain for the field mass of the electron $(3/2\pi^{\frac{1}{2}})e^2/ac^2$, and they derive the eigenvalues of κ from the transcendental equation $\kappa^k L_n{}^{k+1}(\kappa^2)=0$ where $L_n{}^{k+1}$ is the $(k+1)^{st}$ derivative of the Laguerre polynomial L_n.

[5] M. Born and H. S. Green, Proc. Roy. Soc. Edinburgh 62, 470 (1949); M. Born, Rev. Mod. Phys. 21, 463 (1949).

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Electron Bombardment Conductivity in Diamond. Part II*

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Previously published results of a study of electron bombardment conductivity in diamond have been revised by the use of an improved alternating field method of internal space-charge neutralization. In addition lower limits are set for the mobilities of electrons and positive holes at room temperature. Measurements have also been made of the decay of current due to internal space-charge fields which are in reasonable agreement with theory. Finally, a double-pulsing technique is used to provide a novel method to study the rates of release of positive holes and electrons from traps.

1. INTRODUCTION

RECENTLY the results were published of work on electron bombardment conductivity in diamond[1] in whic h two principal effects were observed:

(1) In a crystal which is free of space charge, some or all of the the internal charge carriers produced by the bombardment are trapped before traversing the crystal so that the initial observed current is a function of the field applied across the crystal.

(2) The trapped charges build up an internal space-charge field such as to oppose the applied field. This causes the observed current to vary with time with constant applied field.

Part I described a neutralization technique by which the two effects could be separated and it reported an analysis of the motion of electrons through a space charge free crystal. It is the purpose of the present paper to present:

(1) An analysis of the positive hole current as well as a reinvestigation of the electron current through the space-charge free crystal in the light of an improved technique for eliminating the effect of space charge on the measurement, Section 2.

(2) An analysis of the transient behavior of the current as affected by internal space charge, Section 3.

(3) A new method of studying the release of electrons or positive holes from traps, Section 4.

In Part I, the theory, based on work by Hecht[2] for photo-conductivity, was developed for the configuration shown in Fig. 1. A pulsed beam of electrons bombards a diamond crystal through a thin electrode mounted directly on the surface of the material and to which a current indicating device is connected. On the other face of the crystal is mounted a second electrode maintained at an elevated potential.

If now a step function bombarding current strikes a space-charge free crystal, the initial peak current passing through the crystal represents the current we would obtain if we could neglect the internal field set up by trapped electrons and positive holes. Under such conditions and with the assumptions listed, the voltage-current characteristic of the bombarded crystal could be described by an equation of the form:

$$\Delta=\Omega[1-\exp(-\Omega^{-1})], \tag{1}$$

where $\Delta=\delta/\delta_\infty$ is the normalized yield; δ is the observed current passing through the crystal divided by the bombarding current; δ_∞ is the yield δ for infinite applied crystal field; $\Omega=\omega/l$ is the normalized range; l is the thickness of the crystal; $\omega=vFT$ is the probable electron range; v is the electron mobility; F is the applied field across the crystal; and T is the probable time an electron would spend in a semi-infinite crystal before being trapped.

The principal assumptions involved in formulating the theory are that the traps are distributed homogeneously throughout the crystal and that the effects of internal space-charge fields are negligible. The other assumptions discussed in Part I are all reasonably well met in the present applications of the theory. Calculations have been made which indicate that a fairly wide distribution of trap densities can be tolerated without introducing an appreciable error in the use of this theory.

2. THE SPACE-CHARGE FREE CRYSTAL

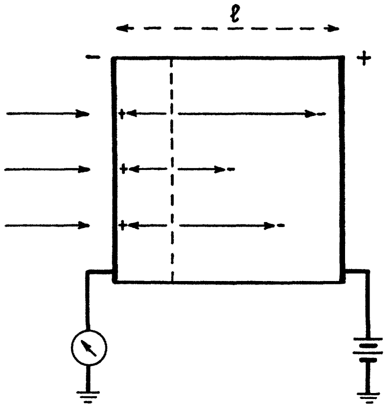
2.1 Determination of Yield

The experimental arrangement was similar to that described in Part I with an important difference. One difficulty that arose in the earlier work was that of

* A report of this work was given at the Congress of the Canadian Association of Physicists on June 1, 1949.

[1] K. G. McKay, Phys. Rev. 74, 1606 (1948) herein designated as Part I.

[2] K. Hecht, Zeits. f. Physik 77, 235 (1932).



$$Q_{OBS} = \frac{e}{\ell}\left[\Sigma\omega_- + \Sigma\omega_+\right]$$

FIG. 1. Illustration of principle of bombardment-induced conductivity.

determining whether or not there was really no net space charge in the crystal just before the occurrence of the current pulse we wished to examine.† This difficulty was overcome as follows: A 60-cycle sine wave was operated on so that the field applied across the crystal had the shape of the upper curve in Fig. 2. The middle line shows the relative position in time of the pulsed primary beam and the lowest line shows the corresponding current flow through the crystal as seen on the oscilloscope. The bombarding current was zero except during the pulses shown on Fig. 2. Starting on the left-hand side with a space-charge free crystal, the primary beam bombards the crystal for a few microseconds at the peak of the positive half-cycle of the crystal field. This causes electrons to travel through the crystal with the circuit arranged as in Fig. 1. At the end of the pulse the current through the crystal is somewhat reduced owing to the formation of an internal negative space charge due to trapped electrons. The crystal field is then reversed and at the peak of the negative half-cycle, a second or neutralizing pulse, possibly different both in length and amplitude from the first pulse, bombards the crystal. The positive holes produced by this pulse travel through the crystal initially under the influence of the applied field aided by the negative space-charge field. This current decreases as the space-charge field is neutralized by trapped positive holes. However, at the end of the second pulse, we do not know whether the crystal has been left with a net space-charge field or not. Consequently, we now reduce the applied field accurately to zero and, having established this condition, a third or test pulse bombards the crystal. If, as a result of the test pulse bombardment, there is any current flow through the crystal it will be due to an internal field. The general procedure was to observe the current flow through the crystal resulting from the test pulse and adjust the length of the neutralizing pulse until the observed current flow was reduced to zero. This was the condition in which only the primary pulse itself was seen since the amplifier is connected to the bombarded face of the crystal. Having established this condition, we can proceed to the next pulse that occurs at the peak of the positive half-cycle of the crystal field and be reasonably confident that the first wave of conduction electrons resulting from this pulse travels through a crystal which has no net space-charge field. By reversing the order of bombardment following the test pulse at zero field, the motion of positive holes rather than electrons can be studied for the "space-charge free" crystal.

A block diagram of the equipment used is shown in Fig. 3. The amplifier, pulsers, and experimental tube are as described in Part I. To provide a comparison with previously measured values, the same area of the same diamond was bombarded. Measurements were made by recording all bombarding and resulting induced current pulses photographically. These were subsequently measured with the aid of a special coordinate scale which eliminated effects of oscilloscope distortion such as keystone effect, etc.

2.2 Analysis of Results

Before considering the actual results we must notice that the neutralizing procedure adopted establishes the condition for zero net space-charge in the crystal; it is still possible that even with this condition there are trapped in the crystal equal numbers of electrons and positive holes (assuming plane parallel geometry). If these are thermally released in the interval between the test pulse and the next pulse to be observed, and if the rate of escape for electrons is different from that for holes, it is possible that the crystal may acquire a net space-charge field by the time the principal pulse occurs. This was tested in several ways. First, the time between the test pulse and the principal pulse was varied from 4 to 16 msec. This was done for a crystal field well below saturation where any change in field would result in a pronounced change in yield. No difference could be observed in the amplitude or shape of

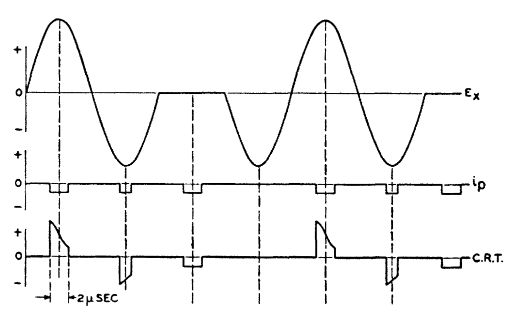


FIG. 2. Time relations between crystal field, bombarding current pulses, and induced conductivity pulses.

† Reference 1, Section 57.

the current resulting from the principal pulse. Second, two test pulses were used separated by 12 msec. In the interval between the test pulses, the crystal field was raised to a high value so that any electrons or holes which were released from traps would have a probability of greater than 0.5 of leaving the crystal. The second test pulse showed no trace of induced current nor was there any departure in the amplitude or shape of the principal pulse from its appearance when only one test pulse was used. From this we can conclude that once the crystal has been neutralized it remains neutralized as well as can be detected by this type of experiment.

If after neutralization, the crystal does contain large equal numbers of trapped electrons and holes, it is possible that owing to their different ranges, the holes

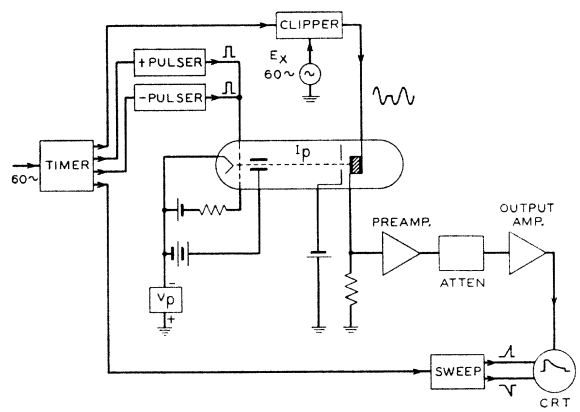


FIG. 3. Block diagram of experimental equipment.

will not be trapped at the same depths as the electrons. In that case sizable fields might exist inside the crystal although no space-charge field could be detected externally. Such a situation would probably affect the yield measurements. To test this, a d.c. source was incorporated into the circuit which generated the crystal field so that the principal pulse occurred at the same positive peak value each time but the neutralizing pulse could occur at different negative peak values. The test pulse, of course, always occurred with zero applied field. For a fixed positive voltage of 300 volts, the negative peak voltage was varied from 100 to 1200 volts. In each case, the pulse occurring at the negative peak voltage—the neutralizing pulse—was adjusted for proper neutralization. Under these circumstances there was no observable change in the amplitude or shape of the principal pulse representing electron flow through the crystal. This experiment was repeated with a reversal of the order of bombardment so that the principal pulse represented positive holes traversing the crystal. Again, no change in the principal pulse could be detected as the voltage at which the neutralizing pulse occurred was varied over the same range as that described above. The conclusion is that these experiments are completely insensitive to any effects due to a possible displacement of the center of gravity of trapped positive holes from the center of gravity of trapped electrons. This may be accounted for by an effective mobility of trapped charges through thermal release and subsequent retrapping or by the possibility that the neutralization process consists primarily of actual recombination between a positive hole and a trapped electron or vice versa rather than merely a trapping of both carriers in the same region.

In view of this insensitiveness to the crystal voltage at the onset of the neutralizing pulse, the investigation was extended to neutralization at zero applied field. Now we had simply a principal pulse at a positive applied crystal voltage followed by a neutralizing pulse at zero applied crystal voltage. It was found that if the neutralizing pulse was at least equal in duration and intensity to the principal bombarding pulse, the current wave form induced by the principal pulse was indistinguishable from that obtained by the conventional neutralizing procedure. These measurements were carried out for the full range of crystal fields that have been used (2000 to 20,000 volts/cm) and for several different pulse lengths.

We have established by the above experiments that the neutralization procedure does indeed result in not only a space charge neutral crystal but also a crystal with a residual internal space charge which is too small to effect our measurements. Consequently we are now in a position to analyze the results obtained by the conventional neutralizing procedure described in Section 2.1. Measurements were made of the peak yield as a function of applied crystal field for bombarding voltages, V_p, of 5, 7, 10, and 14 kv with both electrons and positive holes as carriers. Throughout this series of measurements the primary bombarding current during both the principal and neutralizing pulse was held constant at 1.25×10^{-4} amp./cm². Some typical wave forms for electron carriers are shown in Fig. 4 and the corresponding wave forms for positive holes are shown in Fig. 5. The procedure followed was to measure all the values of peak yield, for, say electrons, and plot these as a function of applied field for each value of V_p. Each curve was then fitted as well as possible to the theoretical curve given by Eq. (1) by scaling the coordinates. It was found that only one scaling factor for the abscissas was needed to provide a best fit for each of the four curves obtained at different values of V_p, which is as it should be since the product (vT) is independent of the conduction current. A typical correlation between theory and experiment is shown in Fig. 6 for $V_p=10$ kv. Those for the other values of V_p were comparable to this although some showed a somewhat greater scatter in experimental points. Having established the scaling factor for the abscissas, the experimental values of applied voltage were transformed to Ω-values, and, by Eq. (1) to equivalent Δ-values. These values of Δ were plotted against the experimentally determined values of δ and the best

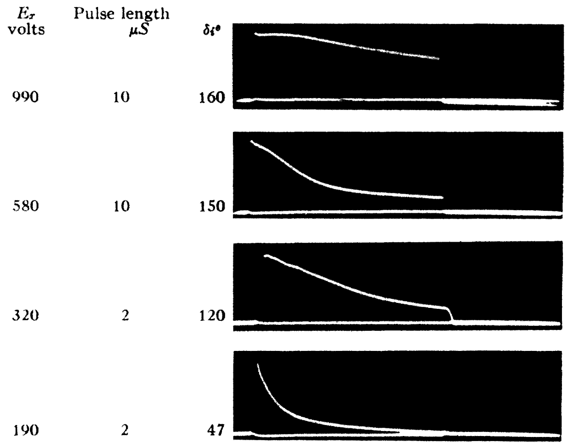


FIG. 4. Variation of δ_i^e with crystal voltage. $V_p = 10$ kv.

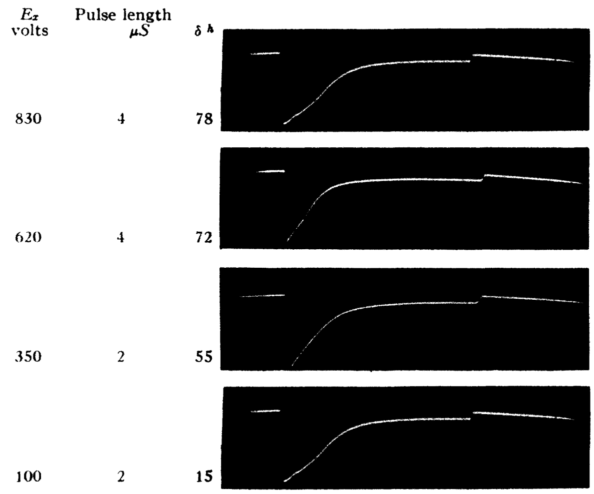


FIG. 5. Variation of δ_i^h with crystal voltage. $V_p = 10$ kv.

straight line fit used to determine the ordinate scaling factor, i.e., δ_∞, for each value of V_p.

The same procedure was carried out for the measurements on positive holes as carriers. Again, one abscissa scaling factor was adequate to give a best fit between theory and experiment for bombarding voltages of 5, 7, 10, and 14 kv. However, the product vT for positive holes was 55 percent of that for electrons signifying a difference in mobility or in probable free time before trapping or both. Experimentally, the approach to saturation for positive hole current was somewhat slower as a function of applied field. Approximately the same upper limit of applied field was used in both sets of measurements so that the largest values of Ω achieved for positive holes were less than those for electrons with a possible loss of accuracy in fitting the experimental points to the theoretical curve. A typical correlation is shown in Fig. 7, for $V_p = 10$ kv. Table I gives a summary of the results obtained from the values of the scaling factors for both electrons and positive holes.

If our picture of what is occurring is correct, there is another method of measuring the peak yield. Having established the proper condition for neutralization, the height of the trailing edge of the neutralizing pulse should represent current flow through a space-charge free crystal since the following test pulse tells us that the crystal is neutral. Actually this will only be true if there is no appreciable release of the neutralizing carriers from traps. Moreover, the trailing edge of the pulse is not quite as fast as the leading edge so that there is more experimental error in making the measurement than by the conventional method. Actual measurements of the yield were made in this manner and were found to agree within about 10 percent with those described. However, there was considerably more scatter and the data for electrons were worse than those for positive holes. This is to be expected in view of the data on release of carriers from traps to be presented in Section 4.

The wave forms of the type shown in Figs. 4 and 5 also supply information about the pulse rise time. If, for the moment, we neglect instrumental limitations, this rise time is essentially the time required to establish equality between the number of carriers being created by the primary electrons and the number being removed either by trapping or by arrival at the unbombarded electrode. It is assumed that such a condition can be achieved before the internal space charge field has become appreciable. If the rise time, T_R, is defined as the time taken for the pulse to rise from 10 to 90 percent of its final value, it can be shown for small values of Ω, where practically all of the carriers are ultimately trapped in the crystal with a probable trapping time equal to T, that $T_R/T \simeq 2\cdot 2$. As the applied field is increased this ratio decreases until T_R approaches a value determined by the transit time across the crystal. To use the rise time to determine T, it is desirable to use low field strengths such that $\Omega \ll 1$ and this is the region in which space-charge limitation becomes important. Owing to the finite rise time and the fact that the period of observation is limited by the onset of space-charge build-up, it is conceivable that the observed peak value may not represent the true yield as given by Eq. (1), but may be somewhat smaller. This means that the current begins to be reduced by the effect of the internal space-charge field before the current has reached its full value. This would be particularly true at low field strengths where the rate of build-up of trapped space charge is high and the rise time T_R is large. However, Wannier[3] has pointed out that if such a situation could be set up, it is probable that the current would be limited primarily by the space charge of the conduction current in the crystal itself so that these rise time considerations would not necessarily apply. It should be noted that if the space-

[3] G. H. Wannier (private communication).

TABLE I. Values of δ_∞ and vT obtained from correlation of theory and experimental points.

	Electrons		Positive holes	
V_p (kv)	δ_∞^e	$(vT)^e$(cm^2 volt^{-1})	δ_∞^h	$(vT)^h$(cm^2 volt^{-1})
5	31	8.3×10^{-6}	19	4.6×10^{-6}
7	76	8.3×10^{-6}	49	4.6×10^{-6}
10	190	8.3×10^{-6}	108	4.6×10^{-6}
14	480	8.3×10^{-6}	320	4.6×10^{-6}

charge field of the charges in motion were providing the principal limitation to the rise time for low values of applied field, we would have a situation analogous to that of the space-charge-limited diode where the current is dependent only on the field and is independent of the cathode temperature. We would therefore expect that for low fields the peak current through the crystal should be a function only of the field and should be independent of the bombarding voltage V_p. This is not observed to be the case. Even for very low applied fields, the peak current through the crystal increases as the bombarding current or the bombarding voltage increases although the relation is not linear over the region covered by the experimental data. It is conceivable that under these conditions, the current in the center of the bombarded region is actually space-charge-limited but the current around the periphery is not. This would result in a partially space-charge-limited current. However, the rise time would be characteristic of the current flow around the periphery and therefore it seems reasonable that the rise time measurements can be used to determine the magnitude of T. In the actual experiments, the input RC constant ranged from 5×10^{-10} sec. to 2×10^{-9} sec. which provides a negligible limitation to the rise time in comparison with the band width of the amplifier together with the finite rise time of the primary pulse itself. The observed rise time as set by all these factors was about 0.05 μsec. and was the same for all values of Ω and also the same for positive holes and electrons. Since a 40 percent change in rise time could be readily detected, it is probable that $T<0.02$ μsec. We can also conclude that the peak yields for low field strengths are suspect as they are likely to be too small, either through a transit time limitation or through a space-charge limitation of the conduction current itself.

2.3 Derived Constants

One rather surprising result, shown in Table I, is that δ_∞ for electrons is considerably greater than that for positive holes, while, on the basis of our simple theory, we would expect them to be equal. One possible explanation of this is that the trap distribution is such that part of the bombarded area has perhaps ten times the trap density for positive holes as the rest of the area. Over the range in field with which we have dealt, such an area would be almost opaque to positive holes and thus the holes would be trapped before they could move a sufficient distance to contribute appreciably to the observed current. This is a much more radical inhomogeneity in trap distribution than was considered in Section 1. The scatter in the experimental points and the relatively narrow range of Ω over which the measurements were made do not warrant fitting the points to a composite yield curve covering such inhomogeneities in trap density. Further evidence in support of this explanation of the disparity in the δ_∞ for electrons and that for positive holes will be presented in Section 3.

One important result that can be derived from the values of δ_∞ is the number of electron volts energy, φ, required to produce one internal secondary electron. The energy per primary electron which is dissipated in the diamond is equal to V_p minus the energy lost in penetrating the gold electrode. One method of obtaining φ is to plot V_p/δ_∞ against V_p, and extrapolate to large values of V_p. A more sensitive method is to plot $dV_p/d\delta_\infty$ against V_p. It is true that taking the slope of a curve with only four determining points is markedly dependent on the form of the smoothing and consequently

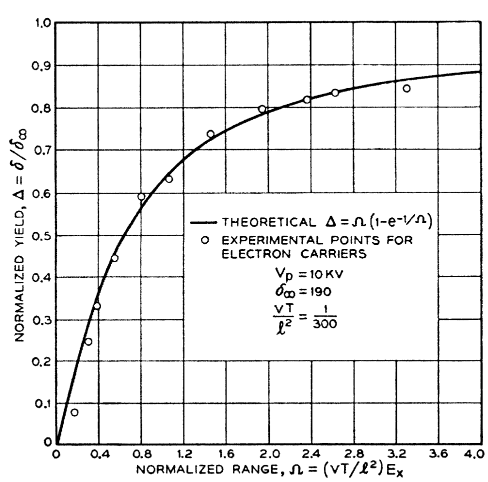


FIG. 6. Electron yield as a function of normalized range.

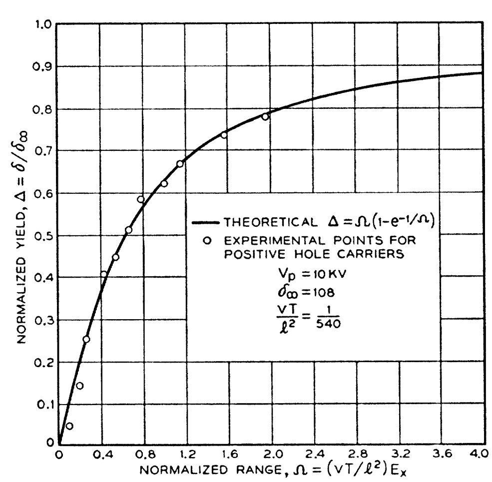


FIG. 7. Positive hole yield as a function of normalized range.

the results should be regarded with some caution. Figure 8 shows the result of such a plot. The lower curve is for electrons and the upper curve for positive holes. From this it can be concluded that φ is less than 13 volts and probably greater than 7 volts. The mean value of $\varphi=10$ volts is the same as the value determined by Ahearn on experiments with alpha-particles.[4] It will also be observed that in spite of the difference between δ_∞ for electrons and for positive holes, this plot suggests that they both extrapolate to approximately the same value of φ. It is tempting to speculate

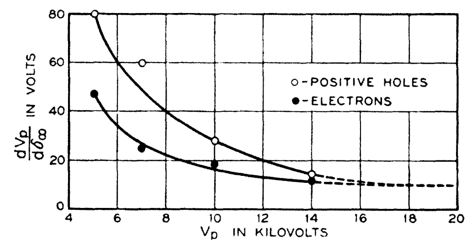


FIG. 8. Determination of primary energy required to produce one free electron or positive hole.

that this implies that the sections of the bombarded area which are "opaque" to positive holes lie very close to the surface but more accurate data are required before this could be concluded with any certainty.

The abscissa scaling factors may also be used to determine some other solid state properties of the diamond. It was shown that $T\leq 2\times 10^{-8}$ sec. for both electrons and positive holes. Thus from vT in Table I we can conclude that the mobility for electrons must be greater than 400 cm²/volt-sec. and for positive holes must be greater than 200 cm²/volt-sec. On the other hand, Klick and Maurer[5] have recently concluded from Hall effect measurements that the electronic mobility in diamond at room temperature is 900 cm²/volt-sec. which is not contradicted by the result derived above. If we use Klick and Maurer's value, we obtain for the electrons $T\simeq 10^{-8}$ sec. Now the trap density N_t is given by

$$N_t=1/T\sigma u,$$

where u is the thermal velocity of the electrons and σ is the trapping cross section.

If we assume a trapping cross section of 10^{-16} cm², we obtain a trap density of 10^{17}/cm³ or somewhat less than one trap per million atoms.

In comparing these results with the preliminary data published in Part I, we see that the values of (vT) are now more consistent and slightly higher. It was necessary in the earlier paper to use values of vT which varied by a factor of two to obtain a reasonable fit to Eq. (1) for electron carriers produced by the different bombarding voltages. The earlier value of δ_∞ for $V_p=14$ kv was considerably higher than that now obtained and much of that may be ascribed to the earlier method of neutralization together with the relatively few points used to define the yield curve. However, actual yields were observed for $V_p=14$ kv which were slightly in excess of the value of δ_∞ now obtained. This may have been due to inaccurate attenuator calibration (a complete recalibration accompanied the present measurements) or it is possible that there had been a change in the surface structure of the crystal, either in the electrode or in the diamond itself, in the elapsed time interval between the two sets of measurements.

3. BOMBARDMENT CONDUCTIVITY UNDER SPACE-CHARGE CONDITIONS

In a recent paper,[6] R. R. Newton set up the equations governing the flow of current through the crystal as a function of time, in which he included the build-up of internal space-charge fields due to trapped electrons and the subsequent release of trapped electrons, but neglected diffusion terms and space-charge effects due to the charges in motion. Newton defines the region in which free electrons and positive holes are being produced in equal numbers as the plasma layer. In this paper it was concluded that if the applied field was sufficiently high, all of the electrons produced in the plasma layer would initially be drawn out into the body of the crystal and the current would then fall off due to a reduction in the range of these electrons owing to the build-up of the opposing internal space-charge field. In this time region the current, as a function of time, must fall off more rapidly than an exponential and probably the second derivative of the current is negative for small times. Using a power series method, Newton developed approximate solutions for small time and could thus predict the initial rate of decay of the current. However, when the field across the plasma layer becomes sufficiently low, trapping and recombination in the plasma layer become important and the current of electrons leaving the plasma layer is no longer a constant. The subsequent current flow will then be determined primarily by conditions in the plasma layer and by the thermal release of trapped electrons. Newton concluded that the current-time curve should have an inflection point when the field across the plasma layer becomes very small. By assuming that the inflection point should occur when the field across the plasma layer equals zero, the time for the appearance of the inflection point was also calculated. The only parameters used in these calculations are derived from experimental data obtained solely from the space-charge free crystal.

It is evident that if there is no appreciable release of trapped electrons within the time of 1 μsec. or less, the initial slope will not be influenced appreciably by the release of trapped electrons. Consequently, Newton's theory can be tested by neglecting release of trapped

[4] A. J. Ahearn, Phys. Rev. **73**, 1113 (1948).
[5] C. C. Klick and R. J. Maurer, Phys. Rev. **76**, 179 (1949).
[6] R. R. Newton, Phys. Rev. **75**, 234 (1949).

electrons and calculating $-(1/\delta_\infty^2)(di/dt)_{t=0}$ as a function of Ω where i is the observed current. This was done using the values of δ_∞, (vT) and bombarding current density given in Section 2.2. The dielectric constant was taken as $K=5.68$. The result, plotted as a function of Ω ($\Omega=\lambda^{-1}$ in Newton's paper), is shown as the solid curve in Fig. 9. The experimental points for $V_p=5$, 7, 10, and 14 kv are also plotted and the agreement both as to the shape of the curve and its absolute magnitude is quite satisfactory particularly since the expression for the theoretical curve contains no adjustable parameters.

The experimental curves for higher field strengths clearly show an inflection point, e.g., see the upper two traces in Fig. 4. Figure 10 shows a comparison between the calculated time τ_i, to reach the inflection point and the experimentally determined values for different values of V_p. The calculated curve again neglects release of trapped electrons and in this case the product $\delta_\infty\tau_i$ should be a unique function of δ_∞. It will be seen that the theory predicts the proper form of the variation of $\tau_i\delta_\infty$ with field strength but is too low in absolute magnitude by a factor of approximately two. The only cause that Newton postulates for the existence of an inflection point, as opposed to an abrupt fall of current to zero, is the release of trapped electrons and the inclusion of this factor will indeed increase the magnitude of the calculated values bringing them more in agreement with the experimental points. However, in this case $\delta_\infty\tau_i$ is no longer a unique function of Ω because, for a given value of Ω, when δ_∞ is small, τ_i is

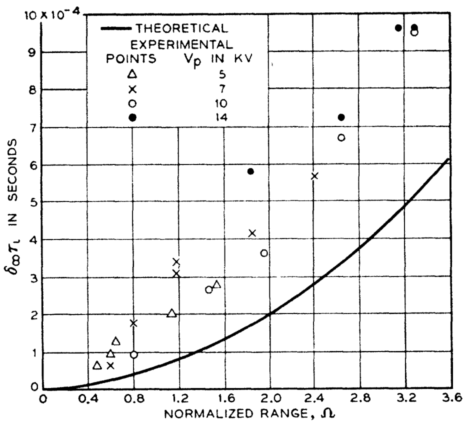


FIG. 10. τ_i, the time to reach the inflection point for electron carriers as a function of normalized range.

large and thus would be considerably affected by release of trapped electrons. On the other hand, for large δ_∞, τ_i is small and should be relatively independent of such a release of trapped electrons. On examining the experimental points there does not appear any consistent trend in the discrepancy between theory and experiment of the values of $\delta_\infty\tau_i$ as a function of V_p. From this we can conclude that release from traps does not play a significant role in determining the position of the inflection point in these experiments. The relatively minor disagreement between the absolute values may be due merely to the approximations involved such as the assumption of plane parallel geometry, homogeneous trap distribution, etc., or it may be necessary to examine

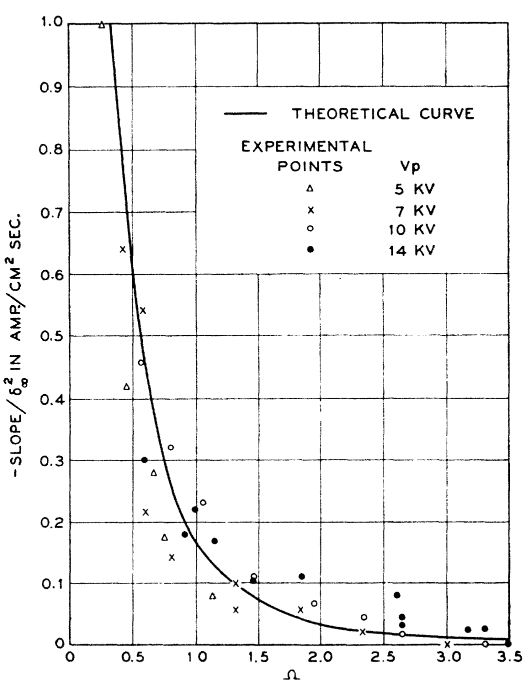


FIG. 9. Initial rate of decay of electron current through crystal as a function of normalized range.

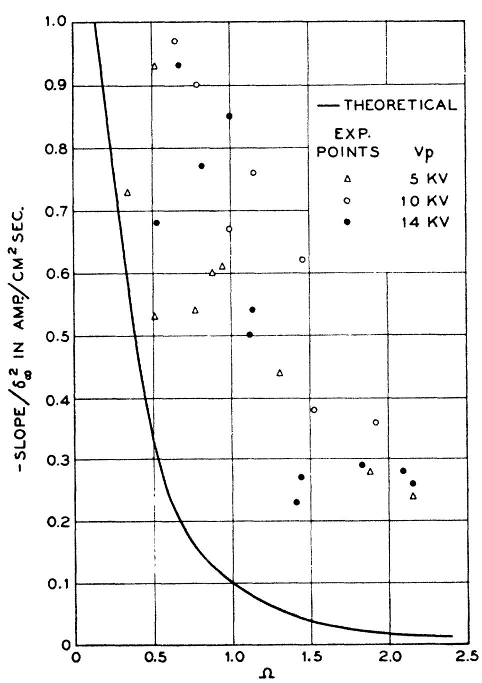


FIG. 11. Initial rate of decay of positive hole current through crystal as a function of normalized range.

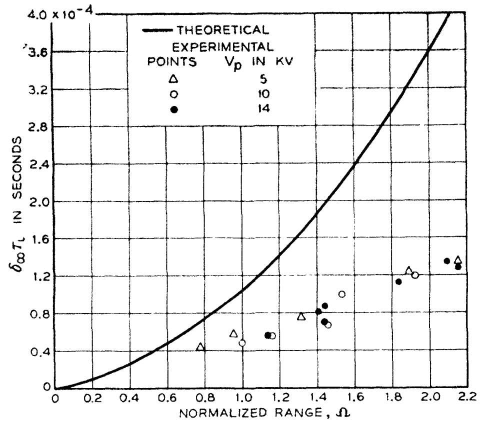


FIG. 12. τ_i, the time to reach the inflection point for positive hole carriers as a function of normalized range.

the behavior of the plasma layer in detail before resolving this difference.

The same type of comparison between theory and experiment can be carried out for positive holes merely by recalculating the theoretical curves using the appropriate data for positive holes as determined in Section 2.2. Figure 11 shows the comparison between theory and experiment for the initial rate of decay of current divided by δ_∞^2 as a function of Ω. In spite of the rather large scatter in the experimental points, it is evident that the correlation between theory and experiment is not nearly as good as the corresponding correlation for electrons. However, we are using the value of δ_∞ for positive holes that was derived in Section 2.2 for the space-charge free crystal and it was suggested there that the value was too low because of some high trap density regions in the bombarded area. A positive hole which cannot move appreciably before being trapped will not contribute to the value of δ_∞ but it will contribute to the space-charge field. Consequently we should use a much larger value of δ_∞ in this comparison. If in Fig. 11 we use the value of δ_∞ determined for electrons, we find that the agreement between theory and experiment is good for low values of Ω. For larger values of Ω the theoretical curve would have to be modified to include regions coexisting with different values of Ω. As stated in Section 2.2 the accuracy of the data does not warrant such a modification although various plausible arrangements have been set up which correlate the theory and experiment within the experimental error.

Further evidence to support this thesis is shown in Fig. 12 where the calculated curve for $\delta_\infty \tau_i$ is compared with the experimentally determined points for positive holes. Again, release from traps have been neglected. Here the experimental points lie below the theoretical curve but if we put in the value of δ_∞ for electrons rather than that for holes, the agreement is fairly good for low Ω while the same modified theory considered above will produce fairly good agreement for high Ω.

4. MULTIPLE PULSE BOMBARDMENT

An extension of the pulsing technique described in Section 2.1 has been made which is a novel approach to the problem of thermal release from traps. Starting with a space-charge neutralized crystal, a positive voltage is applied and an "initial" pulse of current bombards the crystal just as before. The trailing edge of the observed pulse represents the current which flows through the crystal under the combined influence of the applied field and the internal space-charge field which exists at that instant. If the applied field is held constant and, after a few microseconds the crystal is again bombarded with a primary current pulse equal in magnitude to the first pulse, the height of the leading edge of the current resulting from the second or "test" pulse‡ should be exactly the same as the height of the trailing edge of the "initial" pulse provided there has been no change in the internal space-charge field during the intervening time interval Δt. Presumably the only way in which this field could change during the unbombarded interval is through the thermal release of trapped electrons and their subsequent removal from the crystal under the influence of the existing field. If this process does take place, the negative space-charge field will decrease in magnitude during the unbombarded interval and the peak test pulse current will be greater than the height of the trailing edge of the initial pulse. The extent of the difference will be a function of the length of the unbombarded time interval.

Figure 13 is a composite photograph showing a series of such pulses. In each case we have started with a neutralized crystal; the initial pulse which is 6 μsec. long is produced and then, a certain time later, the test pulse occurs. The complete experiment is then repeated with a different time interval between the end of the initial pulse and the onset of the test pulse. In Fig. 13 the different unbombarded time intervals Δt expressed in microseconds are: 0.05, 5, 10, 15, 20, 25, and 30. The first interval which is barely resolved produces no appreciable change but in all subsequent intervals the

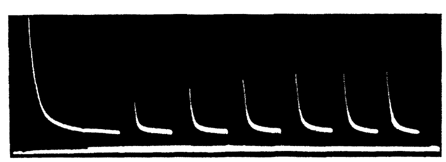


FIG. 13. Release of trapped electrons. Initial pulse length = 6 μsec. Test pulse length = 4 μsec. at 5 μsec. intervals.

peak test pulse current increases regularly with increasing time interval. These measurements were all made with $V_p = 14$ kv and an applied field which corresponded to $\Omega = 1.84$. A set of similar measurements was made for initial pulse lengths of 2 and 10 μsec. Let ψ be the ratio of the peak current in the test pulse

‡ Note that the term "test pulse" as used here does not have the same connotation as in Section 2.

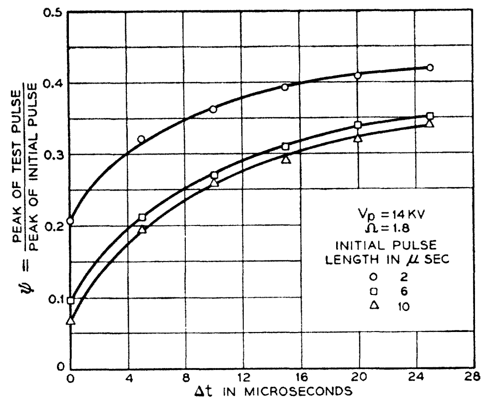


FIG. 14. ψ = peak of test pulse divided by peak of initial pulse as a function of Δt, the time interval after the end of the initial pulse.

to the peak current in the initial pulse. (The peak current in the initial pulse cannot be determined directly from Fig. 13 owing to amplifier compression.) The results of these measurements expressed in terms of ψ are shown in Fig. 14. It is evident that the interpretation of these curves in terms of a quantitative determination of the actual number of traps present of a given trap depth is rather complicated. The motion of released electrons changes the space-charge field which in turn alters the observed current but the region in which we are working is one in which the field across the plasma layer is important and, lacking information about the current-field characteristics of the plasma layer, we cannot make a direct quantitative analysis of the data. However, we can make a crude calculation which is applicable to small values of the effective field where the yield varies approximately linearly with the field.

Let n_s equal the number of electrons initially trapped in shallow traps, i.e., at the end of the initial pulse; n_d equal the number of electrons initially trapped in deep traps; and $n_e(t)$ equal the number of electrons initially trapped which have escaped from the crystal. Then $\psi = [F_0 - K_1(n_s + n_d - n_e(t))]/F_0$, where F_0 is the applied field and K_1 is a constant.

Let the probability of release of a trapped electron from a shallow trap be $1 - e^{-t/\tau}$ and the probability of that electron then escaping from the crystal be P. Then the total number of electrons which have escaped from the crystal at time t is

$$n_e(t) = Pn_s(1 - e^{-t/\tau}),$$

where we neglect the effect of electrons which, having been released, are retrapped in shallow traps and subsequently are released and escape from the crystal. Then

$$\psi = 1 - (K_1/F_0)[n_s + n_d - Pn_s(1 - e^{-t/\tau})].$$

If we assume that P is essentially independent of t, at least in comparison with $e^{-t/\tau}$, we have that

$$\ln(d\psi/dt) = K_2 - (t/\tau).$$

Although in these experiments we begin with a high value of Ω, the effective value of the field when operating in the space-charge-controlled region is small so that even such a crude calculation may be a fair approximation. Figure 15 shows a semilog plot of $d\psi/dt$ as a function of t for various initial pulse lengths. We expect some variation from linearity near $t=0$ since we have neglected the finite length of the initial pulse. Nevertheless, the data do indicate that the main contribution to the increased height of the leading edge of the test pulses comes from traps with a $\tau \simeq 10$ μsec. Mott and Gurney[7] give an approximate relation between the half-life and the trap depth which gives for τ,

$$\tau = \frac{h^3 e^{E/kT}}{1.386\pi m\sigma(kT)^2(6\pi)^{\frac{1}{2}}},$$

where E is the depth of the trap below the conduction band and σ is the capture cross section of the trap for thermal electrons. Assuming that $\sigma \sim 10^{-16}$ cm^2, we find that for $\tau = 10$ μsec., $E \simeq 0.28$ ev at room temperature. If we assume that this trap consists of a hydrogenic orbit, the ionization energy will be approximately $10\kappa^{-2} \simeq 0.3$ ev where κ is the dielectric constant. This may be merely a coincidence but it does suggest a possible mechanism for this type of trap.

Measurements have been made with longer intervals between the initial and test pulses. Owing to instrumental limitations, the results were rather qualitative. However, it was demonstrated that electrons were being released from traps many milliseconds after the initial pulse. It seems unlikely that this can be accounted for by successive retrapping in shallow traps

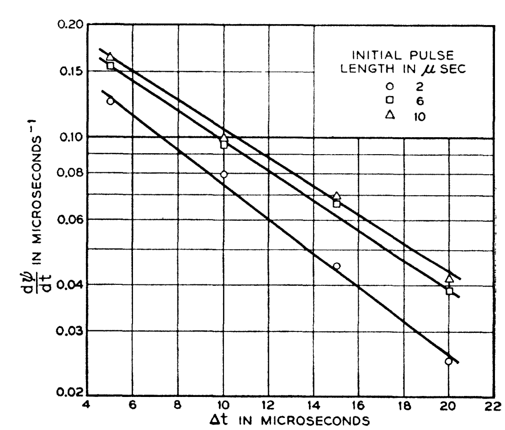


FIG. 15. $d\psi/dt$ as a function of Δt to determine rate of thermal release from traps.

[7] N. F. Mott and R. W. Gurney, *Electronic Processes of Ionic Crystals* (Oxford University Press, London, 1940), p. 108.

and suggests that we are dealing with at least two types of traps and possibly more.

The same experiments have been repeated for positive holes. Within the experimental error, no release of positive holes can be observed in times up to 16 msec., which is as far as the measurements were carried. The value of the crystal field between initial and test pulses did not affect this although in some cases it was negative for all of the Δt and in some cases positive for most of the time. We could probably detect a 10 percent release of trapped holes. Consequently, the release time constant for these traps must be greater than 100 msec. This confirms our expectation that the traps for electrons and traps for positive holes should exhibit quite different behavior.

All of the double-pulsing experiments have been performed at room temperature. It would certainly be of great interest to study this as a function of temperature. Nevertheless, the results obtained so far are of considerable interest. Newton[6] suggested that the current-time curves of Section 3 would have a negative second time derivative as long as the thermal release rate from traps was zero, i.e., there would be no inflection point. However, we have shown that the thermal release rate for positive holes is completely negligible on any microsecond time scale at room temperature. We have also shown in the previous section that the positive hole current has a well-defined inflection point which occurs over quite a wide range of experimental conditions and evidently occurs when the field across the plasma layer is very small. Moreover, the measurements of the time to reach the inflection point, τ_i, for electrons show that, for a given crystal field, $\delta_\infty \tau_i$ is independent of δ_∞ over a range of more than 10:1. This would not be so if the release of electrons from traps played a significant role in determining the inflection point.

We may conclude that the thermal release of trapped charges is not necessary to produce an inflection point although its position undoubtedly should be influenced by any significant release of trapped charges. Two other possibilities may account for the existence of a current following the inflection point: An inhomogeneous trap distribution could result in the current being cut off in some sections but still persisting in others in a process analogous to the operation of a variable μ-vacuum tube. The other possibility is that as the internal field approaches its final value, edge effects begin to play a role and some of the electrons move through regions of the crystal which are not subtended by the bombarded area. Either or both of these mechanisms could account for the observed behavior and further experiments are required to distinguish between them.

5. CONCLUSIONS

This investigation has clearly demonstrated that it is possible to make quantitative measurements of the behavior of mobile electrons and positive holes, produced by electron bombardment, in an insulating crystal and to fit the results into the framework of a simple theory for the space-charge free crystal. The theory does not attempt to describe the processes involved in detail but predicts merely the over-all current-voltage characteristic of the crystal under certain specific conditions. The experimental results are reasonably consistent and nowhere contradict the theory except for cases where the restrictions pertaining to the theory have been violated. This should not be interpreted as ruling out the existence of more complex processes than have been considered here.

The studies of the bombardment conduction current flowing under internal space charge conditions enable us to deal with the specific behavior in more detail. Here certain postulates are made concerning the nature of the internal fields and the behavior of the charge carriers in those fields. The good agreement between theory and experiment serves not only to specify more completely the actual mechanism but also to point up the fact that this establishes at least a sound beginning to the understanding of current flow through an insulator under the influence of space-charge fields.

The measurements of release of trapped electrons demonstrate a new method of studying this aspect of electron-solid interaction. The method is, at present, rather crude but it has a big advantage over studies of this process by the decay of luminescence in that the released electron does not have to emit light subsequent to its release in order to be detected. Moreover, the measurements serve to present in further detail the processes involved in bombardment conductivity.

I wish to express my thanks to Addison H. White for his constant encouragement during the course of the work and for his constructive criticism of the manuscript.

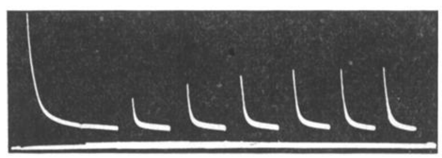


FIG. 13. Release of trapped electrons. Initial pulse length = 6 μsec. Test pulse length = 4 μsec. at 5 μsec. intervals.

E_x volts	Pulse length μS	δ_i^e
990	10	160
580	10	150
320	2	120
190	2	47

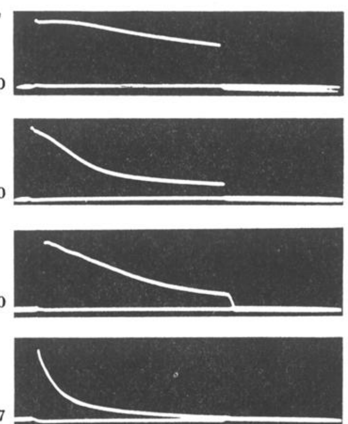


FIG. 4. Variation of δ_i^e with crystal voltage. $V_p = 10$ kv.

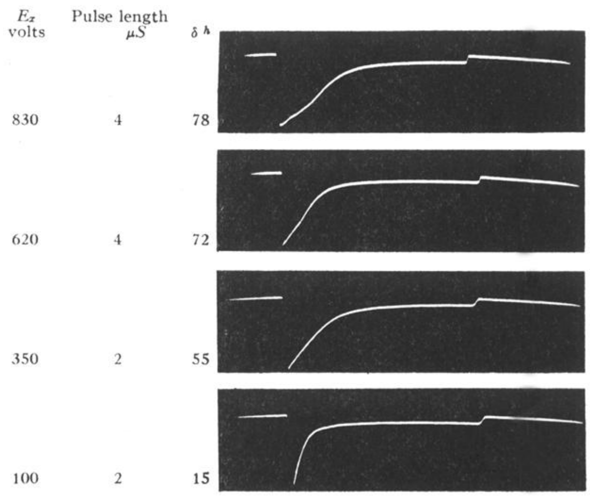


FIG. 5. Variation of δ_i^h with crystal voltage. $V_p = 10$ kv.