Equilibrium Currents Induced in Zincblende by Electron Bombardment of Negative Electrode

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The current induced in zincblende crystals when the negative electrode is bombarded by 5- to 900-volt electrons has been measured. The electrodes were evaporated copper films 0.02 or 0.05 micron thick. The experimentally observed ratio of the equilibrium bombardment-induced crystal current to the bombarding current (a) had values ranging from about 10^{-5} to 10^{-9}, (b) was independent of the magnitude of the bombarding current, (c) was proportional to the bombarding voltage raised to the nth power where n ranged from 2.0 to 2.6 for bombarding voltages up to 600 volts, (d) did not show a dependence on the crystal temperature, and (e) increased as the potential difference between the crystal electrodes was increased. A space charge in the crystal, apparently very near the bombarded electrode, had a major effect on the time variation of the bombardment-induced current and on the magnitude of its equilibrium value. The primary result of bombardment seems to be the emission of electrons into the crystal from the electrode. It does not appear to be necessary to assume that internal secondaries were a major source of conduction electrons.

I. INTRODUCTION

It has been shown by Wilson[1] that the electrons in a metal electrode on an insulating crystal ordinarily do not have sufficient energy to pass into the lowest unoccupied ("conduction") band of the crystal. If, however, the negative electrode is exposed to electron bombardment, some of the electrons in the metal may be excited to a sufficiently high energy so that they may pass into the crystal, where they can act as conduction electrons. Experimental observations of such bombardment-induced currents will be presented.[2]

Zincblende, which has energy bands[3] typical of insulating crystals, was chosen as a suitable insulating material. It is well known that zincblende crystals become conducting when exposed to ultraviolet illumination,[4] when exposed to 15-kilovolt electron or positive ion beams,[5] and when exposed to alpha-ray bombardment.[6] These results show that electrons excited to a normally unoccupied band can move through the zincblende lattice under the influence of an electric field; consequently, one would expect that this would also be true for the extra electrons which come into the crystal from the bombarded electrode.

Very thin copper electrodes were evaporated onto opposite faces of a zincblende crystal and, as is shown in Fig. 1, a small spot near the center of the negative electrode on the crystal surface was bombarded by a beam of 5- to 900-volt electrons. The resulting increase in the current through the crystal was measured. Bombardment was continued, sometimes for over an hour, until the bombardment-induced current reached a steady value.

Most of the experimental results will be expressed in terms of the ratio of the bombardment-induced crystal current to the bombarding current. This ratio, which will be designated by δ and called the "bombardment yield," is essentially the probability that a bombarding electron will cause an electron to pass through the crystal to the positive electrode. One may think of this as the product of four probabilities: P_1, the probability that a bombarding electron or its secondaries will pass through the bombarded electrode to the metal-crystal interface; P_2, the probability that these electrons will pass from the metal into the crystal; P_3, the probability that, for each electron coming into the crystal, a conduction electron will leave the space-charge layer near the bombarded electrode; and P_4, the probability that, for each electron leaving the space-charge layer, an electron will pass through the crystal into the positive electrode. When the bombarding voltage is large, one may need to multiply P_3 by a suitable factor to take into account the liberation of additional conduction electrons within the crystal.

Since P_2 depends on the electric field near the bombarded electrode, it is to be expected that space-charge changes in the crystal could have a marked effect on the bombardment yield. If an equilibrium bombardment-induced crystal current exists, the probabilities P_3 and P_4 must approach unity as a limit for equilibrium conditions. Consequently the equilibrium yield is, at least for small bombarding voltages, essentially equal to the product of probabilities P_1 and P_2, and is primarily a measure of the probability of electron emission into the crystal from the bombarded electrode.

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* The experimental work covered in this paper was completed while the author was in the Physics Department of the University of Minnesota.

[1] A. H. Wilson, Proc. Roy. Soc. **A133**, 458 (1931); **A134**, 277 (1931); **A136**, 487 (1932).

[2] M. Distad, Phys. Rev. **55**, 1146 (1939), paper No. 176.

[3] D. A. Wright, Proc. Phy. Soc. London **60**, 13 (1948); F. Seitz, J. Chem. Phys. **6**, 454 (1938); Y. Uehara, Bull. Chem. Soc. Japan **14**, 542 (1939).

[4] B. Gudden, R. Pohl and others. Summarized by A. L. Hughes and L. A. DuBridge, *Photoelectric Phenomena* (McGraw-Hill Book Company, Inc., New York, 1932), Chapter 8; and by F. C. Nix, Rev. Mod. Phys. **4**, 723 (1932).

[5] H. Lenz, Ann. d. Physik **77**, 449 (1925); **82**, 775 (1927); Physik. Zeits. **26**, 365 (1925); B. Gudden and R. Pohl, Physik. Zeits. **26**, 481 (1925).

[6] A. J. Ahearn, Phys. Rev. **73**, 524 (1948).

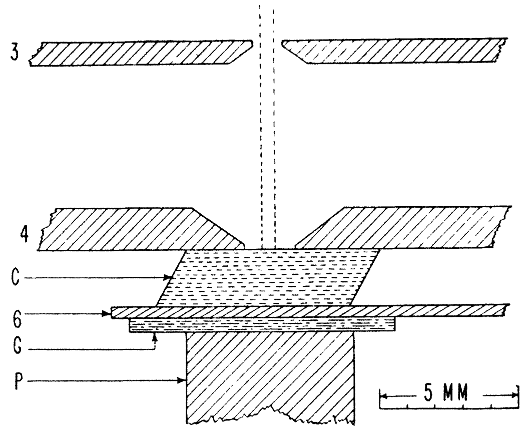

FIG. 1. Details of the crystal mounting. The electron beam, indicated by the vertical dashed lines, passes through the openings in electrodes 3 and 4 and strikes the thin evaporated copper film on the upper surface of the crystal (*C*). This conducting film is in contact with electrode 4 and completely covers the opening in it. Electrode 6 is in contact with the evaporated copper film on the lower face of the crystal (*C*) and is held in place by spring pressure acting on the plunger (*P*) and the glass plate (*G*).

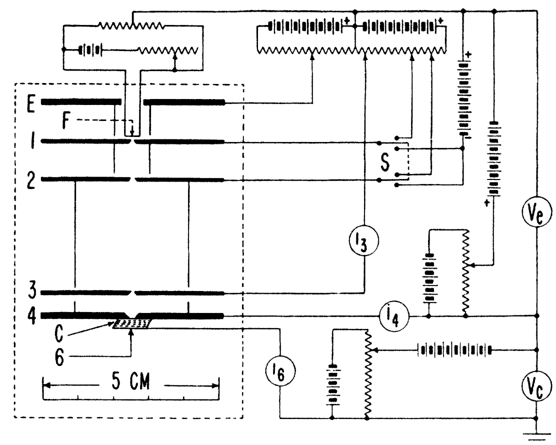

FIG. 2. The electron gun and associated electrical circuit. The electron gun, which is drawn to scale, consists of the tungsten filament *F* and electrodes *E*, 1, 2, 3, and 4 which are circular copper disks with attached spun copper shields. See Fig. 1 for details of the crystal mounting.

II. EXPERIMENTAL EQUIPMENT AND PROCEDURE

Natural yellowish-brown zincblende crystals[7] of Japanese origin were split into irregularly shaped plates to furnish the two transparent and only slightly colored samples which were used for the experimental work. The dimensions of crystal *A* were approximately $4\times5\times1.6$ mm and those of crystal *B* were $4\times4\times1.2$ mm, the large faces being natural cleavage faces without visible flaws in the central area where the electron beam would strike. The face which was to be exposed to electron bombardment was covered by a semi-transparent layer of evaporated copper whose thickness, as determined from its electrical properties,[8] was about 0.02 micron for crystal *A* and 0.05 micron for crystal *B*. An opaque layer of copper was evaporated onto the opposite face of each crystal.

The essential features of the electron-gun assembly are shown in Fig. 2. Electrons emitted from the tungsten filament (*F*) passed through the holes in the center of electrodes 1 to 4 and bombarded the thin copper film on the upper surface of the crystal (*C*) which was either crystal *A* or *B*. External Helmholtz coils furnished a magnetic field of 100 gauss directed along the axis of the tube. This collimated the electron beam. The diameter of the beam when it struck the crystal face was about 0.5 mm, the diameter of the opening in electrode 1, and appeared to be almost independent of the magnitude of the bombarding current. The bombarded area was only two percent of the total area of the evaporated electrode on the upper crystal face and about fifteen percent of the crystal surface area exposed to illumination from the filament. The crystal (*C*), electrode 6, and the lead to electrode 6 were enclosed in a metal shield (not shown on Fig. 2) which prevented stray electrons from reaching electrode 6.

The electron-gun assembly was enclosed in a Pyrex tube and a high vacuum was maintained in this tube. Unless specifically stated otherwise, a mixture of dry ice and acetone was placed around the Pyrex tube to cool the crystal to a temperature near that of dry ice. Heat from the filament warmed up the electron-gun assembly and the crystal temperature increased slowly for several hours after the filament was turned on. After completing the runs on crystal *A* and before crystal *B* was put in the electron-gun assembly, additional radiating sleeves (not shown in Fig. 2) were attached to each electrode disk to give better thermal contact with the Pyrex tube. While the maximum rise in the crystal temperature was probably of the order of 15°C for crystal *A*, it was apparently less than 5°C for crystal *B*.

The electrical circuit is shown in Fig. 2. Switch *S* was used to turn the electron beam off by applying a 45-volt retarding potential to electrodes 1 and 2. The potential of electrode 3 was kept at 0 to 3 volts positive with respect to the filament, thus maintaining electrode 3 at a relatively large negative potential with respect to electrode 4 so that most of the reflected and secondary electrons from the crystal electrode would return to electrode 4. A shunted Compton electrometer was used to measure the crystal currents for the early runs which will be designated as group *K* on Fig. 5. A vacuum-tube electrometer,[9] using a Western Electric D-96475 tube with input shunts ranging from 10^9 to 10^{11} ohms, was used for the remainder of the readings.

[7] A. J. Ahearn (see reference 6) found that a crystal from this lot was satisfactory as a crystal counter. He found, by spectrochemical analysis, that this crystal had 0.01 to 0.3 percent mercury impurity and less than 0.03 percent each of cadmium, copper, iron, and lead.

[8] A. Riede, Ann. d. Physik **45**, 881 (1914).

[9] M. Distad and J. H. Williams, Rev. Sci. Inst. **5**, 289 (1934).

The measured crystal currents ranged from 10^{-10} ampere to less than 10^{-14} amp.

The following voltages and currents were measured:

V_e = Electron bombarding voltage, the potential difference between electrode 4 and the midpoint of the filament (F) plus a small contact potential correction.

i_e = Electron bombarding current falling on the crystal electrode, essentially the same as i_4 on Fig. 2 except for minor corrections for the crystal current and secondary electrons collected on electrode 3.

V_c = Crystal voltage, the potential difference between electrodes 6 and 4 (considered positive when electrode 6 is positive with respect to electrode 4). The voltage V_c was +450 volts except where specifically stated otherwise.

i_6 = General expression for the current through the crystal to electrode 6 (considered positive when electrons flow from electrode 4 through the crystal to electrode 6). Currents i_b, (i_B+i_b), and (i_F+i_b) are special cases of i_6.

i_b = Background current through the crystal when the filament current is on and the electron beam is off.

i_B = Bombardment-induced current through the crystal. The total current through the crystal during electron bombardment is the sum of the two currents i_B and i_b.

i_F = Equilibrium or final value of the bombardment-induced crystal current i_B.

$\delta = i_B/i_e$, the bombardment yield.

$\delta_F = i_F/i_e$, the equilibrium or final bombardment yield.

The filament current, the crystal voltage (V_c), the bombarding voltage (V_e), and the voltage on electrode 3 were kept constant during and after each electron bombardment run. The voltages on electrodes 1 and 2 were adjusted when necessary to keep the bombarding current (i_e) constant during a run and, through switch S, to turn the electron beam on and off. The input to the vacuum-tube electrometer was short-circuited when the electron beam was turned either on or off, and the first reading of the crystal current was taken not earlier than twenty seconds after the change had been made. The large time-constant of the vacuum-tube electrometer made earlier readings impractical.

The example given in Fig. 3 shows the observed crystal current for a set of runs for which the bombarding voltage was small. Starting with a relatively small dark current, the crystal current abruptly increased

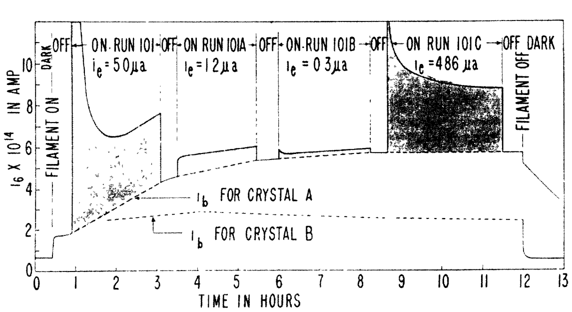

FIG. 3. The observed crystal current (i_6) for a set of runs on crystal A. The bombarding voltage (V_e) was 45 volts and the crystal voltage (V_c) was +450 volts for all runs, but the bombarding current (i_e) was different for each run as is indicated on the figure. The shaded areas represent the bombardment-induced current. "OFF" and "ON" refer to the electron beam.

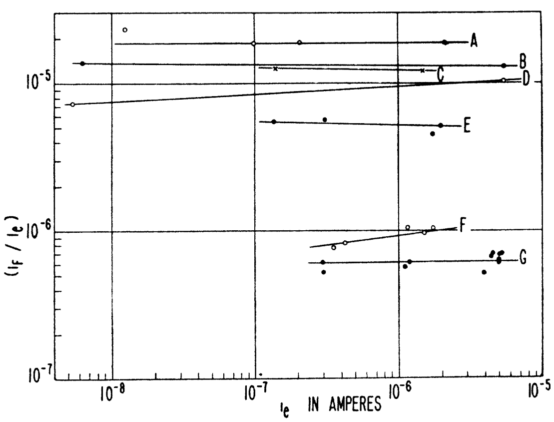

FIG. 4. Dependence of the equilibrium bombardment yield (i_F/i_e) on the bombarding current (i_e). The bombarding voltage (V_e) was 450 volts for groups A and D, 600 for B, 900 for C, 270 for E, 150 for F, and 45 for G. The actual (i_F/i_e) values for group G were a hundred times smaller than those plotted. The crystal voltage (V_c) was +450 volts for all runs.

when the filament current was turned on at 0.4 hour. This increase represents the photo-conduction current produced by illumination from the filament. When the electron beam was turned on at 0.9 hour, the crystal current jumped to about 2.4×10^{-12} amp., which is off the graph. The crystal current decreased rapidly, reaching a minimum at 2.0 hours, and then increased slowly until the electron beam was turned off at 3.1 hours. The bombardment-induced current (i_B) at any given time is represented on this figure by a vertical line from the top to the bottom of the shaded area. The current i_B was essentially constant for the last half hour, and the equilibrium current i_F is represented by the right-hand edge of the shaded area. Although the crystal current was still increasing at the end of the first run, this increase was caused by the increase in the background current (i_b) as indicated by the upper dashed line. The slow rise in i_b was a consequence of the slow increase in crystal temperature produced by heat from the filament. The lower dotted line shows that the rise in i_b was much smaller for crystal B because the temperature rise was much smaller. One can see that the bombardment-induced current reached an equilibrium value more rapidly for the second and later runs shown on Fig. 3.

If the bombarding voltage (V_e) was less than 30 volts, it was necessary to continue bombardment for over three hours before the bombardment-induced current reached a steady value; but less than an hour was sufficient if V_e was greater than 150 volts. When the bombarding voltage was large, the background current (i_b) was usually negligibly small compared to the equilibrium bombardment-induced current (i_F). The current i_F was as much as two thousand times larger than i_b.

III. BACKGROUND CURRENT

A typical value for the equilibrium dark-current was 6×10^{-15} amp.[9a] Superimposed on this was a charging current which was inversely proportional to the time the voltage V_c had been on the crystal.[10] In a typical case this charging current had a value of 2×10^{-13} amp. at half a minute after the voltage had been put on the crystal and became negligibly small after about thirty minutes. A reverse polarization current, comparable in magnitude to the charging current, was observed when the crystal voltage was subsequently reduced to zero. Fluctuations arising from these effects were minimized by keeping the crystal voltage (V_c) steady for an hour before and during all bombardment runs.

The background current (i_b) was both a dark current and a photo-conduction[4] current resulting from the illumination from the filament. The current i_b was approximately proportional to the crystal voltage (V_c), had almost the same magnitude for positive and negative V_c, and was zero when V_c was zero. It was markedly dependent on the crystal temperature and on the illumination from the filament.

Electron bombardment had no apparent effect on either the time variation or the magnitude of the background current (i_b) when the equilibrium bombardment-induced current (i_F) was less than twenty times larger than i_b. When i_F was more than fifty times larger than i_b, a small temporary increase in i_b was usually observed just after the electron beam was turned off. For example, in an extreme case where i_F was 1700 times larger than i_b, the crystal current was 6×10^{-14} amp. at two minutes after the electron beam had been turned off, and within ten minutes the background current had returned to its normal value of 4×10^{-14} amp. In all cases the magnitude of the temporary increase in the background current was very small in comparison to the magnitude of the bombardment-induced current.

The useful life of the crystals was abruptly terminated by the onset of dielectric breakdown.[11] At first there were only occasional surges in the crystal current and normal bombardment-induced currents were observed during the quiet intervals. Within a few days the fluctuations became so large and so frequent that it was impossible to obtain accurate readings. Crystal A was used for over three months, but crystal B showed signs of breakdown after only three weeks. The maximum externally applied fields, when the crystal voltage (V_c) was 450 volts, were 2800 volt/cm for crystal A and 3750 volt/cm for crystal B. These are below the limits set by Lenz[5] for avoiding rapid breakdown, namely

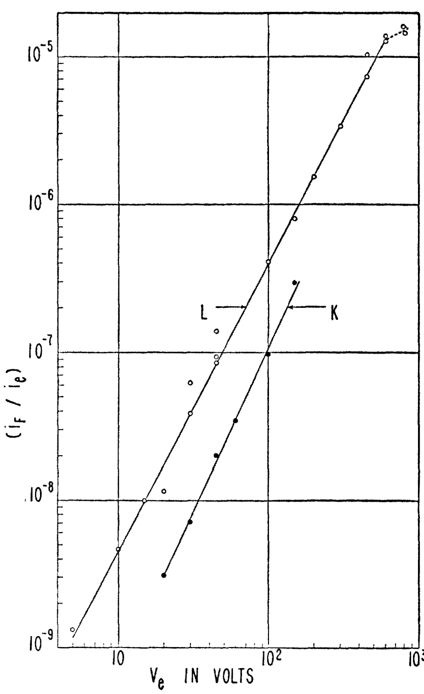

FIG. 5. Dependence of the equilibrium bombardment yield (i_F/i_e) on the bombarding voltage (V_e) for runs using crystal A. The crystal voltage (V_c) was +150 volts for group K and +450 volts for group L.

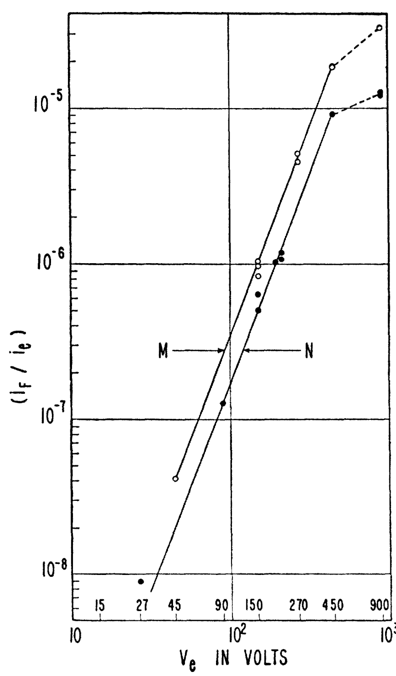

FIG. 6. Dependence of the equilibrium bombardment yield (i_F/i_e) on the bombarding voltage (V_e) for runs using crystal B. Group M gives the results for the earlier runs and group N those for the later runs. The crystal voltage (V_c) was +450 volts for both groups.

[9a] This included leakage currents across the sides of the crystal. The measured background and total crystal currents also included the very small surface leakage current. It had no effect, however, on the observed bombardment-induced crystal current because this was the difference between the total and the background currents.

[10] See also Paper No. 182, M. Distad, Phys. Rev. 55, 1147 1939).

[11] B. Gudden and R. Pohl, Zeits. f. Physik **6**, **248** (1921).

5 kv/cm at room temperature and 20 kv/cm at liquid air temperature.

IV. EQUILIBRIUM BOMBARDMENT YIELD

The observed values for the *equilibrium* bombardment yield were relatively reproducible in spite of variations in the background current, in the previous bombardment history, and in the time variation of the bombardment-induced current. Once equilibrium had been reached, the yield was observed to have a steady value for hours of continuous bombardment.

The dependence of the equilibrium yield ($\delta_F = i_F/i_e$) on the bombarding current (i_e) is shown in Fig. 4, the bombarding voltage (V_e) being kept constant for each group. Groups A to D show that as much as a thousandfold change in i_e had only a relatively small effect on the observed δ_F for large V_e. The four points on the plotted line for group G, which are the most reliable readings in this group, give the results for the runs shown on Fig. 3 and lead to the same conclusion for small V_e. On the whole, the data on Fig. 4 show that the equilibrium bombardment-induced current was proportional to the bombarding current to within the experimental errors.

The dependence of the equilibrium yield (δ_F) on the bombarding voltage (V_e) is shown by Figs. 5 and 6 for the runs on crystals A and B respectively. In each case most of the observed values fell on a straight line on the log-log graph to within the experimental error for V_e up to 600 volts. This indicates that

$$\delta_F = (i_F/i_e) = KV_e^n, \tag{1}$$

where n is the slope of the lines in Figs. 5 and 6 and K is a constant which is dependent on the crystal voltage (V_c) and on the thickness of the bombarded electrode.[11a] The measured values of n are 2.2 for group K, 2.0 for group L, and 2.6 for groups M and N. It is to be noted that the results agree with the simple relation given by Eq. (1) for as much as a ten-thousandfold change in δ_F. Group L includes data for V_e as small as 5 volts and a detectable bombardment-induced current was observed when V_e was 3 volts.

The experimental δ_F values for V_e greater than 600 volts fall below the line passing through the observations for smaller V_e on Figs. 5 and 6. This deviation from the behavior for smaller V_e was greater than the experimental error for these particular runs and was not due to progressive changes in the properties of the bombarded electrode.

The equilibrium yield (δ_F) increased as the crystal voltage (V_c) was increased. Comparison of the plotted lines for groups K and L on Fig. 5 indicates that increasing V_c from +150 to +450 volts increased δ_F by a factor ranging from 3.4 to 5.6, the larger increase being associated with smaller bombarding voltages. No similar data were obtained on crystal B except for one observation (when V_e was 100 volts) that showed only a sixfold increase in δ_F when V_c was increased from +50 to +450 volts. There was no indication of a saturation of δ_F with increasing V_c.

The available experimental evidence, although somewhat meager, does not indicate any dependence of the equilibrium bombardment yield (δ_F) on the crystal temperature. Changes in crystal temperature which increased the background current by a factor of two or more had no marked effect on δ_F. This was checked for bombarding voltages (V_e) ranging from 45 to 900 volts. In addition, two temperature runs were made, for which V_e was 10 volts and the crystal voltage (V_c) was +150 volts, going from the temperature of dry ice to room temperature. Although the background current increased by a factor of 38, the observed δ_F did not change by more than ten percent, which was less than the estimated experimental error for these particular runs. A later run with V_e equal to 45 volts and V_c equal to +450 volts indicated similar results, but in

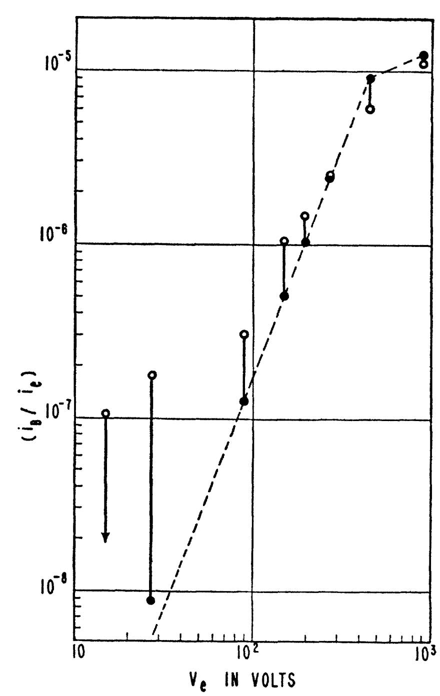

FIG. 7. Total change in the observed bombardment yield (i_B/i_e) as a function of the bombarding voltage (V_e) for typical runs on crystal B without previous bombardment. The open circles are the "first readings" which were taken from a half to four minutes after the electron beam was turned on. The solid dots represent final or equilibrium values. The crystal voltage (V_c) was +450 volts for all runs. The run for V_e equal to 15 volts was stopped before equilibrium was attained.

[11a] The difference in yield values for groups M and N on Fig. 6 was caused by an increase in the thickness of the bombarded electrode by matter evaporated from the filament when it was accidentally operated for a short time at a higher than normal temperature. Within each group, however, checks were made to determine that progressive changes in the crystal electrode did not have a major effect on the yield values. For example, except for group K, the same bombarding voltage was used for the first and last readings in each group and in each case the yield values agreed to within ten percent.

this case the onset of dielectric breakdown made accurate measurements impossible.

V. TIME VARIATION OF THE BOMBARDMENT YIELD

The bombardment yield (δ) varied with the bombardment time and, except for some of the earlier runs on crystal A, asymptotically approached its equilibrium value without any intermediate maxima or minima. The direction and magnitude of the change in δ were a function of the bombarding voltage (V_e) and of the previous bombardment history. Omitting a detailed discussion of the time variation, our attention will be confined to those aspects which indicate the general nature of the space-charge changes and their influence on the equilibrium crystal currents.

We will first consider the behavior, as shown in Fig. 7, for typical runs on crystal B when it had not been previously bombarded for at least twelve hours. These show that the bombardment yield (a) *increased* to its equilibrium value for V_e greater than 270 volts, (b) showed practically no time variation when V_e was about 270 volts, and (c) decreased to its equilibrium value for V_e less than 270 volts.

It is to be noted that for V_e less than 270 volts the ratio of the "first" to the final yield values[12] was larger for smaller bombarding voltages, and that the ratio had values as large as twenty. Even larger values were observed on crystal A, the "first" yield value for run 101 on Fig. 3 being seventy times larger than the equilibrium value.

The time variation of the yield (δ) for the second and subsequent runs on a given day was influenced by the previous bombardment history. The effect was relatively small for bombarding voltages (V_e) greater than 300 volts, but was quite pronounced for V_e less than 200 volts. If we let V_e' be the bombarding voltage for the preceding run, and t_0 be the time the electron beam was off between the runs, and confine our attention to the cases where the preceding run had been continued long enough for δ to have reached its equilibrium value, then the following indicate the general tendencies for V_e less than 200 volts:

(a) V_e' equal to V_e: The first reading of δ was considerably smaller and δ decreased to its equilibrium value in a shorter time than for runs without previous bombardment. The effect of previous bombardment was pronounced for t_0 of 30 minutes and was present even for much larger values of t_0. The same effect was observed even if the bombarding current was different for the two runs (as is shown in Fig. 3).

(b) V_e' greater than V_e: δ decreased with time and, at least for V_e' in the range from 200 to 270 volts, previous bombardment had only a slight effect on the time variation of δ if V_e was considerably smaller than V_e'.

(c) V_e' less than V_e: δ *increased* to its equilibrium value if the beam had not been off too long. For example, this was observed when V_e' was 90 volts, V_e was 150 volts, and t_0 was 20 minutes.

VI. DISCUSSION OF SPACE-CHARGE EFFECTS

The time variation of the yield appeared to be caused by a bombardment-induced space charge in the crystal which, by changing the field near the bombarded electrode, changed the probability of electron emission from the electrode into the crystal.[12a] We will consider this space charge to be superimposed on any space charges which may have existed in the crystal before the start of bombardment. The results shown on Fig. 7 indicate that the polarity of the bombardment-induced space charge was a function of the bombarding voltage (V_e), being positive for large V_e (i.e., over 270 volts for crystal B) and negative for small V_e.

The equilibrium yield was found to be independent of the magnitude of the bombarding current. This indicates that the equilibrium density of the bombardment-induced space charge was probably also independent of the magnitude of the bombarding current. The time-variation characteristics discussed in the preceding section indicate that the equilibrium density of the negative space charge, which is associated with small bombarding voltages (V_e), apparently increased in magnitude as V_e was decreased.[12b] A similar consistent trend was not observed for the positive space charge associated with large V_e, a larger space-charge effect being observed when V_e was 450 volts than when V_e was either 270 or 900 volts. Since the equilibrium yield did not show a dependence on the crystal temperature, it appears, as a first approximation, that the equilibrium density of the space charge was not dependent on the crystal temperature.

The dependence of the time-variation characteristics on the previous bombardment history shows that the negative bombardment-induced space charge persisted for tens of minutes after the cessation of electron bombardment. This space charge apparently was very close to the bombarded electrode because it had practically no effect on the background current, but

[12] The actual *initial* values of δ, which were not measured, probably were very different from the "first" readings plotted on Fig. 7. It may be true for zincblende, as K. G. McKay, Phys. Rev. 74, 1606 (1948), found for diamond, that large changes in the bombardment-induced current take place during the first few microseconds of bombardment.

[12a] The runs discussed in the preceding section gave results which were qualitatively consistent and quantitatively reproducible to a degree that made it seem unlikely that changes in the transmissivity of the bombarded electrode were the primary cause of the time variation for these runs. Some of the earlier runs on crystal A did have an erratic behavior which was ascribed to variations in the properties of the bombarded electrode, but the time variation for these runs has not been considered in this paper.

[12b] This is suggested by the observation that the ratio of the "first" to final yield values, as shown on Fig. 7, had larger values for smaller V_e when V_e was less than 270 volts. It is more definitely shown by the experimental observation that the yield *increased* with time when V_e was larger than the bombarding voltage for the preceding run (V_e'), and decreased if V_e was smaller than V_e'.

had a very pronounced effect on the bombardment yield.[12c]

One can think of the bombardment-induced space charge as being composed of both a negative space charge consisting of trapped electrons and a positive space charge formed by the ionizing action of the electrons coming into the crystal. It is quite possible that the equilibrium density of the negative space charge is relatively independent of the bombarding voltage (V_e), while the equilibrium density of the positive space charge probably increases as V_e is increased. Thus the negative space charge would predominate for small V_e, the magnitude of the net space charge would decrease as V_e was increased, and the positive space charge could predominate for large V_e. The effect of thermal or photoelectric action on the rate of liberation of electrons from traps and on the neutralization of the positive space charge was apparently so small that it did not have a major effect on the equilibrium magnitude of the bombardment-induced space charge.

VII. DISCUSSION OF RESULTS

The maximum externally applied fields, 3750 volt/cm for crystal B, were such that it was unlikely[13] that electrons would travel 1.2 mm (or 1.6 mm) through the crystal without being temporarily trapped at some imperfection or flaw. One might expect that this would build up a negative space charge distributed throughout the body of the crystal and that the resulting space charge would cause a decrease in the background current after the cessation of bombardment, but no such effect was observed.[13a] Apparently either the density of available traps was small or, as seems more probable, the rate of liberation of electrons from these traps by thermal or photoelectric action of the illumination from the filament was large. It seems, at least under semi-equilibrium conditions, that an electron has a relatively high probability of eventually passing through the crystal once it gets past the space-charge layer near the bombarded electrode.

It is quite possible, however, that the presence of inhomogeneities is the explanation for the apparent absence of a negative space charge in the body of the crystal. Ahearn and Wannier[14] have suggested that the current through the crystal may be carried principally along conducting channels. Using this concept, one may assume that the electrons coming into the crystal as a consequence of bombardment would pass through the lattice until they reached one or more of the conducting channels, and that they would then pass along these channels to the positive electrode. Bombardment-induced changes in the space charge—even if they extended for some distance into the crystal—would have only a relatively small effect on the background current if the bombardment-induced current was carried by only a relatively small fraction of the total number of conducting channels. Although inhomogeneities undoubtedly existed, the available information is insufficient to determine the extent to which they affected the space-charge formation in the crystal and the conduction processes through the crystal.

The effect of surface irregularities makes it difficult to determine the probability of electron transmission through the bombarded electrode. The bombardment yield values for the "first readings" on Fig. 7 for a 0.05-micron copper electrode are about an order of magnitude smaller than the transmissivities observed by Becker[15] for electrons passing through 0.04-micron nickel foils when he did not include transmitted secondaries with energies less than four electron volts. The dependence on bombarding voltage is, to a crude approximation, similar in the two cases. This indicates, if one assumes that nickel and copper have similar transmission properties, that the bombardment yield is probably of the same order of magnitude as the crudely estimated transmissivity of the bombarded electrode.[16]

The large bombardment yields observed by McKay[12] in diamond, and by others[17] in other substances, yields which were considerably greater than unity, were ascribed to the production of a large number of internal secondaries by each bombarding electron. The currents observed by Lenz[5] when he exposed a zincblende crystal to electron beams, with bombarding voltages ranging from 5 kv to 15 kv, also appear to have been caused principally by the liberation of conduction electrons and holes within the crystal. In the experiments described in this paper, some of the electrons entering the crystal probably had sufficient energy to produce internal secondaries. If these secondary electrons were free to move through the crystal, the bombardment yield could be considerably greater than the probability

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[12c] Only two percent of the total electrode area was exposed to electron bombardment. If the space charge were very close to the bombarded electrode and covered an area equal to that of the bombarded spot, its effect on the bombardment-induced electron emission into the crystal could be large and, at the same time, its effect on the total background current after the cessation of bombardment could be small.

[13] B. Gudden and R. Pohl, Zeits. f. Physik. **17**, 331 (1923), found that a field of about 10 kv/cm was required to saturate the primary photoconduction current through a typical zincblende crystal which was 1.3 mm thick.

[13a] Instead of a decrease, the passage of very large bombardment-induced crystal currents produced a small temporary increase in the background current after the cessation of bombardment. This seems to indicate that there was a small temporary increase in the density of electrons trapped in the body of the crystal, and that the observed increase in the background current was caused by the subsequent liberation of the trapped electrons by thermal or photoelectric action.

[14] Informal discussion. See G. H. Wannier, Phys. Rev. **76**, 438 (1949) and D. D. Pant, Proc. Ind. Acad. Sci. **19A**, 329 (1944).

[15] A. Becker, Ann. d. Physik **84**, 779 (1927); **2**, 249 (1929).

[16] The observed bombardment yields are, however, very much smaller than one would estimate from the results of H. Katz, Physik. Zeits. **38**, 981 (1937) and Ann. d. Physik **33**, 160 (1938), on 0.1-micron silver foils.

[17] E. S. Rittner, Phys. Rev. **73**, 1212 (1948); L. Pensak, Phys. Rev. **75**, 472 (1949); F. Ansbacher and W. Ehrenberg, Nature **164**, 144 (1949).

of electron transmission through the bombarded electrode and into the crystal.[17a] The degree to which internal secondaries contributed conduction electrons to the crystal current is uncertain because the transmission probabilities are not known with sufficient accuracy, but the observed yields were so small that it does not appear necessary to assume that internal secondaries were a major source of the electrons making up the bombardment-induced crystal current.[18]

We have seen that certain factors, such as crystal temperature and illumination from the filament, which had a pronounced effect on the dark conductivity and on the photoconductivity of the crystal, seemed to have little or no effect on the bombardment yield. This emphasizes the observation that the magnitude of the yield was primarily determined by factors, such as space charge and bombarding voltage, which affected the probability of electron emission from the bombarded electrode into the crystal. It has also been observed,[19] but not discussed in this paper, that there was no detectable bombardment-induced current for large negative crystal voltages (bombardment of positive electrode) when the bombarding voltage was 150 volts or less. It appears that the "conductivity" of the crystal was not the major limiting factor, but that the bombardment yield was primarily a measure of the probability of electron emission into the crystal.

VIII. SUMMARY

Equilibrium bombardment-induced crystal currents were observed when the negative electrode on a zinc-blende crystal was exposed to bombardment by 5- to 900-volt electrons. The crystal temperature was near that of dry ice for most of the runs. The equilibrium yield, which was the ratio of the bombardment-induced crystal current to the bombarding current, (a) had values ranging from about 10^{-5} to 10^{-9}, (b) was independent of the magnitude of the bombarding current, (c) was proportional to the bombarding voltage raised to the nth power where n ranged from 2.0 to 2.6 for voltages up to 600 volts, (d) did not show a dependence on the crystal temperature, and (e) increased as the crystal voltage was increased. The yield did not depend on the magnitude of the background current. Only large bombardment-induced currents had an effect on the background current.

The time variation of the yield indicated that a bombardment-induced space charge, apparently very close to the bombarded electrode, had a marked effect on the yield. This space charge was positive for large bombarding voltages (i.e., over 270 volts for crystal *B*), and negative for small voltages. The equilibrium density of the space charge was independent of the magnitude of the bombarding current and of the crystal temperature, but depended on the bombarding voltage. The equilibrium magnitude of the negative space charge was greater for smaller bombarding voltages.

The primary result of bombardment seems to be the emission of electrons into the crystal from the electrode. Once these electrons get past the space charge near the surface, they apparently have a high probability of passing through the crystal into the positive electrode under equilibrium conditions. It does not appear to be necessary to assume that internal secondaries were a major source of conduction electrons.

The writer wishes to express his appreciation to Professor J. T. Tate who in 1934 first suggested the possibilities in an investigation of this type, to Professor J. W. Buchta who was the faculty adviser for the later part of the work at the University of Minnesota, and to Professor E. L. Hill who also generously gave his time to discuss the results.

[17a] The rate of positive space-charge formation was so small, particularly after a few minutes of bombardment, that the resulting secondaries probably were only a small part of the total bombardment-induced crystal current.

[18] N. Bloembergen, Physica **11**, 343 (1945), who bombarded a silver chloride crystal with short pulses of 10- to 500-volt electrons and was unable to detect a bombardment-induced crystal current, concluded that the yield was less than 0.05 percent of what one might expect from crystal-counter experiments with high energy electrons. In this particular case it also appears that internal secondaries were not an effective source of conduction electrons when the bombarding voltage was small.

[19] M. F. Distad, *Summaries of Ph.D. Theses* (University of Minnesota, Minneapolis, Minnesota), Vol. II (1943), p. 191.

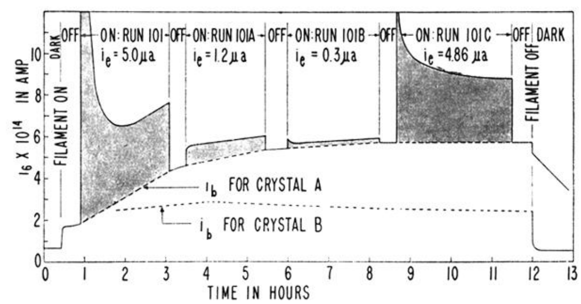

FIG. 3. The observed crystal current (i_6) for a set of runs on crystal A. The bombarding voltage (V_e) was 45 volts and the crystal voltage (V_c) was +450 volts for all runs, but the bombarding current (i_e) was different for each run as is indicated on the figure. The shaded areas represent the bombardment-induced current. "OFF" and "ON" refer to the electron beam.