

## Breakdown in Silicon

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The voltage-current, light multiplication, and small-signal ac impedance characteristics of reverse-biased silicon  $p$ - $n$  junctions are studied in the breakdown region. Two types of junctions are considered: a uniform diffused junction, and an alloyed junction specifically designed to contain only one region of localized breakdown (microplasma). The results for the single-microplasma junction are as follows: (i) The voltage-current characteristic, which describes the relations existing during the instant the microplasma is on, consists of a negative-resistance unstable region and a positive-resistance stable region. (ii) The multiplication characteristic indicates that the junction is most sensitive to light in the unstable

breakdown region. (iii) The small-signal ac impedance characteristic exhibits an inductive component of current in the unstable breakdown region.

The single-microplasma junction  $V$ - $I$  characteristic is compared with a previous theoretical prediction which discusses the mechanisms underlying the properties of a microplasma; an explanation of the multiplication and impedance characteristics of the single-microplasma junction in terms of these properties is indicated; and lastly, the behavior of a uniform junction, which contains many microplasmas, is explained in terms of the results obtained with a single-microplasma junction.

### INTRODUCTION

THE electrical properties of  $p$ - $n$  junctions in silicon have been studied both experimentally and theoretically over the complete operating range. The behavior with forward and small reverse bias is in essential agreement with theory. At a sufficiently high reverse bias, carriers crossing the junction will attain enough energy to cause ionizations. The junction behavior in this region is understood as a particular case of the Townsend avalanche process originally proposed for gaseous breakdown.<sup>1,2</sup> A further increase in reverse bias results in a nondestructive breakdown characterized by a current increase of many orders of magnitude at essentially constant voltage. This region is not particularly well understood in that the junction "breaks down" in tiny spots (microplasmas).<sup>3,4</sup> It has been observed that very narrow junctions in silicon (with breakdown voltages less than about 6 volts) behave in a manner qualitatively different from that described above.<sup>5</sup> We shall be concerned principally with higher voltage breakdown junctions. It is the purpose of this paper to present the results of some experiments on microplasmas which suggest a qualitative explanation of many junction properties in the breakdown region. We will consider, in particular, the voltage-current characteristic, the response to light (multiplication), and the junction impedance in the region of a few megacycles/second.

If it is supposed that the breakdown region is a simple extension of the avalanche region, it is possible to make simple calculations of the  $V$ - $I$  characteristic, as well as the multiplication *vs* current and the small-signal impedance characteristic. These calculations will not be done here since we shall show that the simple model is

too idealized to represent an actual junction. It is sufficient to say that the simple model predicts a linear increase in multiplication with current, and that the small-signal ac impedance should be inductive, with the inductive current increasing linearly with average current. We shall first present measurements of the  $V$ - $I$  characteristics of a uniform junction containing many microplasmas followed by similar measurements on a single-microplasma junction. We shall then relate the behavior of the single-microplasma junction to previous theoretical calculations of microplasma properties as well as present a qualitative explanation for the properties of uniform junctions. Finally we shall use these results to explain the multiplication and impedance characteristics encountered in both junctions.

### VOLTAGE-CURRENT CHARACTERISTIC

#### Uniform Junction

The type of diode used is shown in Fig. 1. These diodes, made by the gaseous diffusion techniques, were mounted on a ceramic header and sealed with a brass cap containing a window so that light multiplication measurements could be taken. They were chosen for their low (under  $\frac{1}{2}$  ohms) ohmic resistance and sharp (current change of six decades in a fraction of a volt) breakdown.

A schematic of the circuit used to obtain the  $V$ - $I$  characteristics is shown in Fig. 2. The voltage and current of the diode consists of a dc component and a

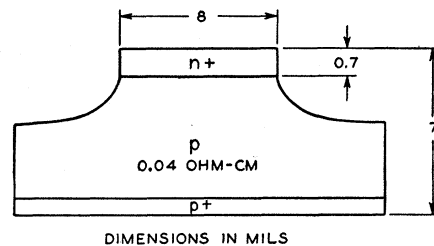


FIG. 1. Cross section of uniform junction.

<sup>1</sup> K. G. McKay and K. B. McAfee, Phys. Rev. **91**, 1079 (1953).

<sup>2</sup> K. G. McKay, Phys. Rev. **94**, 877 (1954).

<sup>3</sup> A. G. Chynoweth and K. G. McKay, Phys. Rev. **102**, 369 (1956).

<sup>4</sup> D. J. Rose, Phys. Rev. **105**, 413 (1957).

<sup>5</sup> A. G. Chynoweth and K. G. McKay, Phys. Rev. **106**, 418 (1957).

superimposed (positive or negative) pulse. The dc components are read on the microammeter and potentiometer; the pulsed components are found from oscilloscope measurement of the pulse voltage at two circuit points and a knowledge of the circuit parameters. The estimated 10% accuracy of the pulse measurements was checked by replacing the diode by a known resistance and measuring the pulsed voltage-current characteristic.

The results for a 2- $\mu$ sec pulse with a 50-cps repetition rate are compared with the dc characteristic in Fig. 3. In this case the dc current at zero pulse voltage (operating point) is 30  $\mu$ a. The pulse characteristics were also obtained at higher operating points (not shown), yielding a family of parallel lines intersecting the dc characteristic at the operating points. At currents below 100  $\mu$ a the two characteristics in Fig. 3 are similar, whereas at higher currents a pronounced deviation occurs. Since approximately the same results were obtained for a junction with one-fifth the area, this indicates that the deviation of the two modes of operation occurs at a specified current and not at a specified current density.

The deviation of the dc characteristic from the pulsed characteristic is a result of heating. Since the junction is uniform except for statistical fluctuations of impurity density and other crystal imperfections such as dislocations, occlusions, etc., the breakdown voltage over every small element is essentially constant. Therefore, the increase in voltage of the dc characteristic of Fig. 3 is a reflection of the increase in breakdown voltage due to the heating of the wafer. If the wafer heats up in a non-uniform manner, then the breakdown voltage of the coolest part of the wafer must be increased sufficiently to give the result in Fig. 3. Therefore, the dc characteristic is determined by the thermal resistance of the wafer mount to the ambient surroundings. Assuming Chynoweth's<sup>5</sup> experimental result for the temperature coefficient of breakdown,

$$\beta' = \Delta V / (V \Delta T) = 5 \times 10^{-4} / ^\circ\text{C}, \quad (1)$$

we obtain at one-milliamper operating current

$$\Delta T = \Delta V / (\beta' V) = 20^\circ\text{C} \text{ for } \Delta V / V = 0.2 / 20, \quad (2)$$

or about one  $^\circ\text{C}/\text{mw}$  internal temperature rise. This

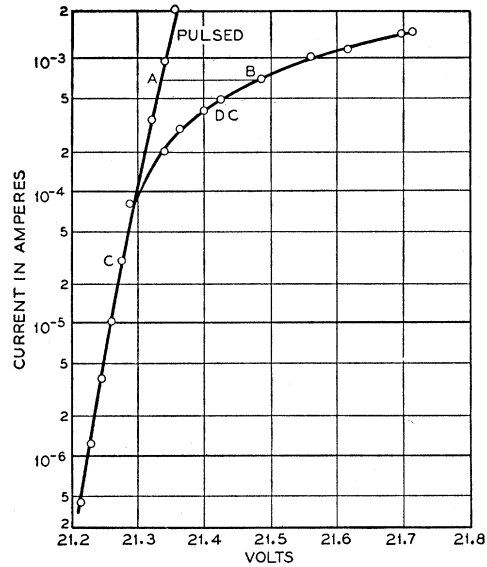


FIG. 3.  $V$ - $I$  characteristic for pulsed and dc operation in uniform junction, showing heating effect.

temperature rise is quite reasonable for the mount that was used.

As the pulse duration is increased, it becomes possible to observe the time constants for the thermal effect. When the current pulse is applied, the operating point moves suddenly from  $C$  to  $A$  (Fig. 3), and gradually from  $A$  to  $B$ . As the operating point moves from  $A$  to  $B$ , a voltage change is detected during time intervals ranging from  $10^{-5}$  to 1 sec (and possibly longer) with the greatest change occurring in time intervals of the order of  $10^{-2}$  seconds.

### Single-Microplasma Junction

A better understanding of the behavior of a uniform junction can be obtained if a single microplasma region is isolated and studied. To obtain a single microplasma it is necessary to have a junction in which breakdown is limited to an area of the same order of magnitude as the area of a single microplasma. According to Rose's<sup>4</sup> estimate, this is 500  $\text{\AA}$  in diameter. This is too small a diameter to isolate from a uniform junction. However, by a combination of the diffusion and alloying techniques in silicon, it is possible to obtain junctions which have a small region of high field and which conduct current in the breakdown region through a single microplasma.

Pearson<sup>6</sup> found that metal impurities on the silicon surface will initiate local melting and produce various melt patterns. In particular, for the  $\{100\}$  plane the pattern will be as shown in Fig. 4. For forming the single-microplasma junction, aluminum is used as the initiating impurity. A sufficient quantity is used to fill the cavity whose walls are formed by the four  $\{111\}$

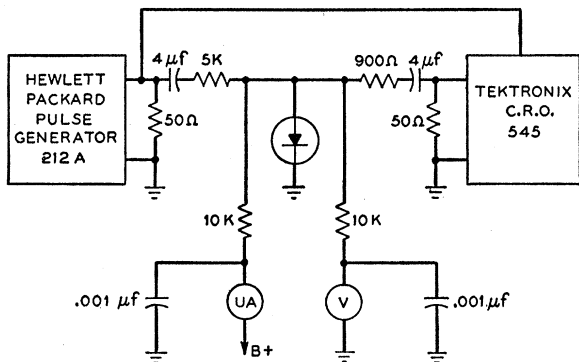


FIG. 2. Schematic of circuit used to obtain  $V$ - $I$  characteristic.

<sup>6</sup> G. L. Pearson, Acta Cryst. (to be published).

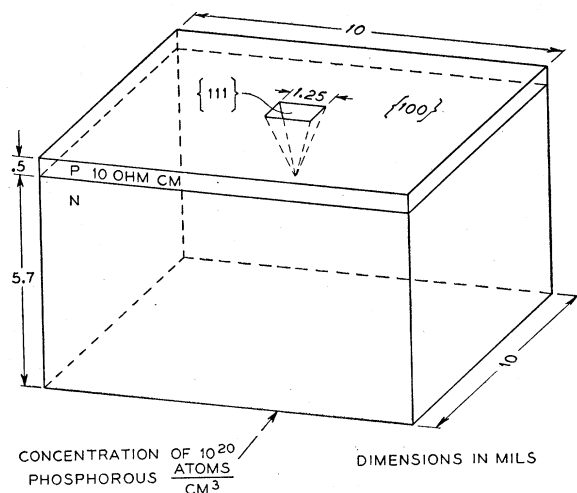


FIG. 4. Diagram of single-microplasma junction.

planes. The patterns could be observed by etching out the aluminum. Lines rather than points are quite often observed at the bottom of the cavity, indicating a rectangular rather than a square base. By changing the amount of aluminum in question, various-size squares and related depths of penetrations were obtained. The original 10 ohm-cm  $p$  material had phosphorus diffused in<sup>7</sup> from one side with an estimated surface concentration of  $10^{20}$  atoms/cm<sup>3</sup> to make a  $p$ - $n$  junction as shown in Fig. 4. The aluminum was then alloyed in from the  $p$  side to the desired depth of penetration. For the experiments considered, the conductivity was of the order of 0.04 ohm-cm at the maximum penetration.

The field should be highest at the point since that is the region of the highest charge concentration. The fact that breakdown does occur at the point was substantiated experimentally by etching away the aluminum and observing light emission<sup>3,8</sup> from the bottom of the cavity.

The question of whether more than one region is breaking down can be answered by means of oscilloscope observations.<sup>2</sup> If the diode is biased by a constant voltage source in series with a low (4-ohm) resistance and the pulses across the resistance are observed with a scope, the traces shown in Fig. 5 will result. As the average current is increased, the pulses increase in amplitude and duration until they are on continuously. A further current increase to one ma does *not* disclose any new pulses. It is also noted that for a given dc condition the pulse height is invariant, which would not be the case if two regions were breaking down simultaneously. We therefore conclude that there is only one localized breakdown region.

The conclusions drawn from the scope measurements were confirmed by another technique. The microplasma

pulses were amplified by broadband SKL Model 202D amplifiers and counted by a Hewlett Packard Model 524B counter. The result is the solid curve shown in Fig. 6. The dotted curve, for comparison, refers to a unit with more than one breakdown region. Considering the solid curve we see that at currents higher than 100  $\mu$ a the count drops to a value slightly above the amplifier background and stays at this level as the current is further increased.

The dc and pulsed characteristics are shown in Fig. 7. The rather abrupt change in the dc characteristic is noted at the transition between the unstable region (intermittent microplasmas) and stable region (sustained microplasmas). The pulsed characteristic is obtained in the stable region by techniques similar to those used on the uniform junction. Unlike the uniform junction, the pulsed characteristic shows only a *slight* deviation from the dc characteristic. The  $V$ - $I$  characteristic is *linear* in the stable region with a slope corresponding to a 1000-ohm resistance.

In the unstable region, the instantaneous current is either essentially zero, or approximately 100  $\mu$ a. The observed rate of transition from one current to another is limited by the time constants of the observing equipment, which has a bandwidth of about 50 Mc/sec. This fact is confirmed by an experiment which was performed in conjunction with A. Uhlir<sup>9</sup> of this laboratory and will be very briefly described here. A single-microplasma

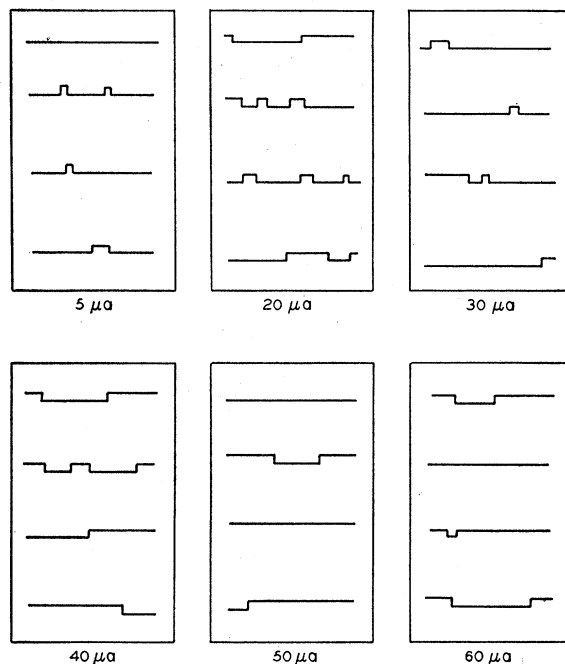


FIG. 5. Oscilloscope traces showing microplasma current pulses for different average currents. Four 5- $\mu$ sec sweeps are shown for each average current. Low resistance in series with unit.

<sup>7</sup> The diffusion was kindly performed by C. J. Frosch of the Bell Telephone Laboratories.

<sup>8</sup> R. Newman, Phys. Rev. **100**, 700 (1955).

<sup>9</sup> Uhlir, Moll, and Senitzky, Proc. Inst. Radio Engrs. (to be published).

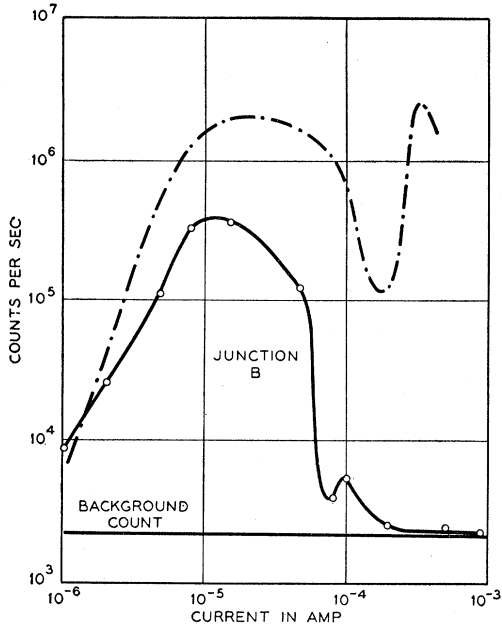


FIG. 6. Pulse count as a function of average current. Solid curve refers to single-microplasma junction and dotted curve to junction containing more than one microplasma.

diode, operated in the unstable region, was mounted in a 3-cm waveguide and the microwave power output from the guide was mixed with a 9300-Mc/sec signal and detected by a receiver with a 1-Mc/sec bandwidth. The receiver output consisted of randomly distributed pulses of roughly one- $\mu$ sec duration. When these pulses were compared with the current pulses (measured across a 50-ohm resistance) through the diode, it was found that the microwave pulses occurred at the leading edge of the microplasma pulse. From Fourier transform theory we have the approximate condition that  $\Delta\omega\Delta t=1$ , where  $\Delta t$  is the pulse rise time and  $\Delta\omega$  is the bandwidth of the Fourier transform. Applying this condition to our experiment, we find that the pulse rise time could be of the order of  $10^{-11}$  sec. This agrees with the requirement that the pulse rise time should be of the order of a transit time of a carrier across the junction which is roughly  $10^{-11}$  sec. The decay time of the microplasma current pulse is longer, for reasons to be discussed, and therefore will not result in microwave pulses.

The dc characteristic gives only a rough indication of the actual voltage required to sustain the microplasma at any specified current. Let us designate as the instantaneous current voltage characteristic the relations which exist during the time the microplasma is on. We see that the dc characteristic and the instantaneous characteristic merge at currents greater than  $100 \mu$ a (stable region). It is possible to obtain the instantaneous characteristics at currents less than  $100 \mu$ a as follows: A constant-voltage source is placed across the unit in series with a high (11 400-ohm) resistance and the

microplasma pulse currents<sup>10</sup> as well as the dc conditions are measured. Knowing the resistance it is a simple matter to obtain the instantaneous and dc characteristic shown in Fig. 8. It is necessary to follow this procedure since, for example, a direct connection of an oscilloscope across the diode, or the 11 400-ohm resistor, causes the diode to go into relaxation oscillations. This behavior arises because the diode has an internal negative resistance in the 0–100  $\mu$ a range and this in combination with the added capacity can oscillate. This was avoided in the technique used above by maintaining low capacity across the diode terminals. Only data in which the pulses show flat tops and (qualitatively) a reasonably wide distribution in pulse widths are used. Another effect of the negative resistance is to limit the range over which instantaneous data can be obtained.

The relation of the dc and instantaneous characteristic can be described by considering the source voltage at point *A* (Fig. 8) with the load line shown. This will be the operating point of the unit before the microplasma has switched on, *C* will be the operating point after it has switched, and *B* is the average voltage and current position which must lie on the same load line. The ratio of *AB* to *AC* is the duty cycle of the microplasma. As the source voltage increases, the dc curve also moves up at first but is eventually depressed by

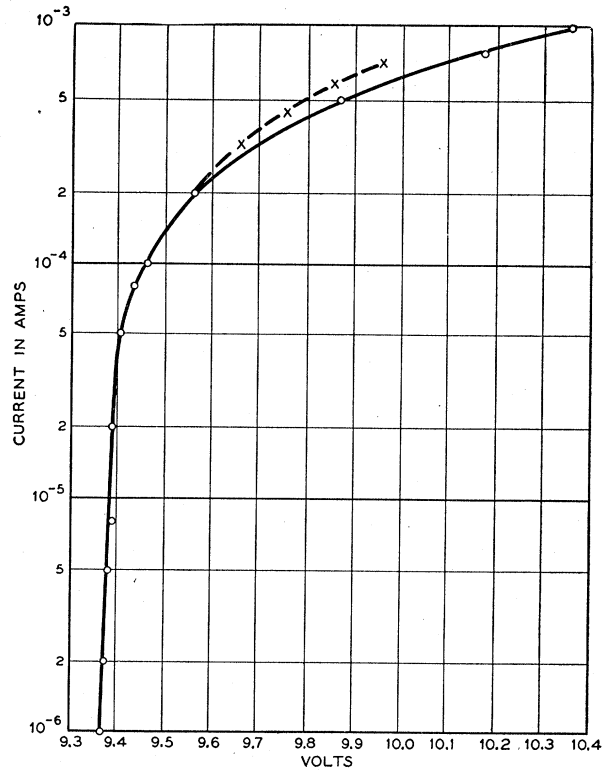


FIG. 7. *V-I* characteristic for pulsed (dotted curve) and dc (solid curve) operation in single-microplasma junction.

<sup>10</sup> The currents were measured across a 10-ohm resistance in series with the unit and the 11 400-ohm resistance.

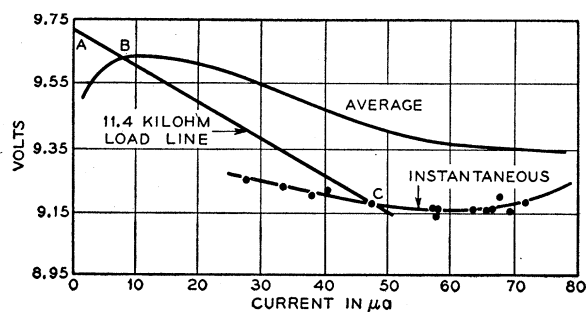


FIG. 8. Instantaneous and dc characteristic for single-microplasma junction.

the increase in duty cycle. This accounts for the undulations in the dc characteristic and shows why these are suppressed when the series resistance is low. Considering the instantaneous characteristic, we note that there is an indication of negative resistance at the low-current end and an agreement (as there should be) with the dc characteristic at the high-current end.

With the high resistance in series with the unit, the pulses shown in Fig. 9 are no longer rectangular as in Fig. 5. This is reasonable since the  $RC$  time constant, where  $C$  is the junction capacity, involves the low dynamic resistance of the microplasma itself on the pulse rise and the high external resistance of the circuit on the pulse decay. This would suggest that even with low series resistance the pulses would not have equal rise and decay times if observed with sufficiently fast sweeps. This is in agreement with the results obtained previously from the microwave measurements.

### Discussion

The fundamental voltage-current characteristics in the unstable region are the instantaneous characteristics of the microplasma. As was previously mentioned, these characteristics show a negative resistance at the low-current end. The reason for a negative resistance of a microplasma in  $p$ -intrinsic- $n$  junctions has been discussed by Rose.<sup>4</sup> A very brief explanation follows: As the current increases in the intrinsic region, the peaking of the field at either end of the discharge (due to current space charge) makes it possible to have an increased multiplication with a decreased voltage. Thus, as the current is increased, the voltage decreases. At high enough current densities the ionization rate becomes less sensitive to field and a positive-resistance characteristic results. The difficulties involved in applying this mechanism to a highly doped  $p$ - $n$  junction (no intrinsic region) has also been discussed previously.<sup>4</sup>

Irrespective of the difficulties in explaining the negative resistance itself, the reasons given by Rose for the associated instability of the discharge seem plausible. If, owing to a statistical fluctuation, the current suddenly decreases, the voltage would have to increase to support the discharge. Sufficient capacity across the diode terminals to keep the voltage constant could

cause the discharge to extinguish. As the current increases, the probability of a large percentage fluctuation decreases; a positive-resistance region is reached in which the instability mechanism is inapplicable, and the discharge becomes stable as is seen experimentally.

One of the reasons for the positive resistance at the high-current end of the characteristic is the temperature increase in the microplasma region. Using the previously given value of  $\beta'$  and Rose's estimate for the relation between current and temperature in the microplasma,<sup>4</sup>

$$\Delta T/\Delta I = 1.2 \times 10^5 \text{ } ^\circ\text{C}/\text{amp}, \quad (3)$$

we obtain

$$\Delta V/\Delta I = (\beta' \Delta T)/\Delta I = 600 \text{ ohms for } V = 10 \text{ volts}, \quad (4)$$

which is of the right order of magnitude to account for the observed effect.

The above calculation relates the breakdown voltage to the temperature increase caused by the current through the microplasma. This calculation assumes that the 500- $\text{\AA}$  diameter of the microplasma remains constant with current, an assumption which is at present open to question. The thermal effect is not the only

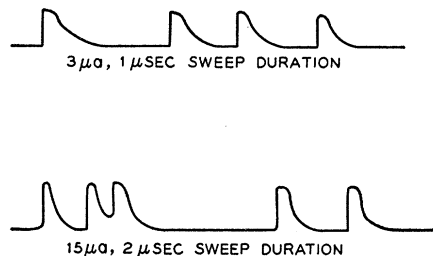


FIG. 9. Oscilloscope traces showing microplasma pulses for two average currents and sweep durations. High resistance in series with unit.

possible significant contribution to the positive resistance. There is some spreading resistance from the ends of the microplasma. In 0.04 ohm-cm material, the spreading resistance from a sphere of diameter of 500  $\text{\AA}$  is approximately 600 ohms so that this effect is comparable to the thermal effect.

Because of the size involved, the thermal time constants in the microplasma region are extremely short. Rose estimates  $10^{-10}$  sec. This is substantiated by two experimental facts: one is the flat tops observed on microplasma pulses, some of which are of the order of  $10^{-7}$ -sec duration, and the other is the close agreement in the stable region of the pulsed and dc characteristic in Fig. 7.

Considering the voltage-current characteristic for the uniform junction shown in Fig. 3, we note that the diode resistance at the high-current end is of the order of 300 ohms. Most of this resistance, as was previously pointed out, is due to the general heating of the wafer, with a time constant of the order of milliseconds. The pulsed characteristic for the uniform junction must be explained as the effect of many potential microplasmas

in parallel. When the voltage is suddenly increased, any one microplasma can turn on to about  $100 \mu a$ . At this point the voltage across the microplasma begins to increase so another one begins to conduct. Thus the slope of the pulsed  $V-I$  characteristic for the uniform junction must be determined by the statistical distribution of the breakdown voltage of all the small areas of the junction that are potential microplasmas.

**MULTIPLICATION CHARACTERISTICS**

Charge multiplication is defined on the basis of the avalanche theory of breakdown by McKay.<sup>1,2</sup> If carriers are injected into the junction by light, the multiplication can be experimentally obtained as the difference of two voltage-current characteristics; one with light on and the other with light off, normalized to the low-voltage value. This difference is conveniently obtained by the chopped-light technique (see Fig. 10) where an ac signal proportional to the difference is developed across  $R$  and fed into the phase-sensitive detector which is synchronized (450 cps) with the chopper. Since a

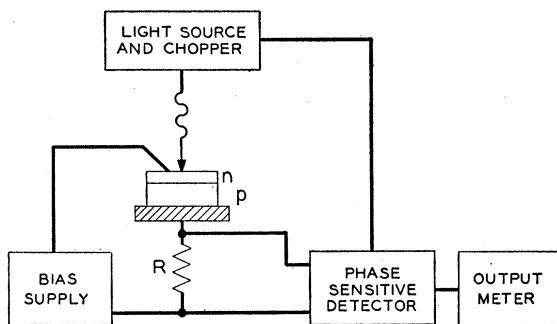


FIG. 10. Schematic for multiplication measurement.

current change at constant voltage is desired, the only requirement on the impedance of the external circuit is that it be less than the dynamic resistances of the two voltage-current characteristics. Consequently, as the multiplication is decreased,  $R$  may be increased to obtain more sensitivity.

Besides convenience, another reason for using chopped light arises from the temperature dependence<sup>11</sup> of the breakdown voltage. Light, focused on the junction from a 30-watt tungsten source, can cause sufficient heating within a period of several minutes to yield entirely erroneous results for the multiplication measurements. Because of the times involved, this difficulty is eliminated when a chopped-light technique is used.

McKay and McAfee<sup>1</sup> have investigated multiplication in silicon at relatively low values (1 to 20) and have made observations in the higher range of multiplication ( $M > 100$ ).<sup>12</sup> Our attention will be centered here on the range of high multiplication.

<sup>11</sup> G. L. Pearson and B. Sawyer, Proc. Inst. Radio Engrs. 40, 1348 (1952).

<sup>12</sup> K. G. McKay, Bell Telephone Laboratories (private communication).

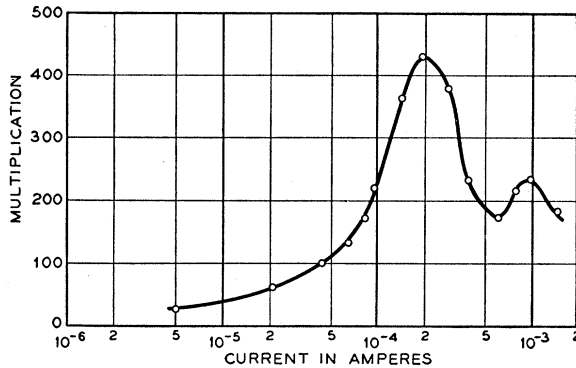


FIG. 11. Multiplication for uniform junction.

The results for a uniform junction are shown in Fig. 11 where the multiplication is plotted for currents ranging from  $50 \mu a$  to 2 ma. These curves vary widely from unit with respect to the location and magnitudes of the peaks; nevertheless certain properties are common to all units, namely, the initial increase of multiplication with current in accordance with the simple model which results in multiplication proportional to current, and then the drastic oscillations in the multiplication vs current curve with several peaks in the measured range. The reasons for this behavior will be considered later.

The multiplication for a single-microplasma junction shown in Fig. 12 first increases and then, at  $100 \mu a$ , decreases to nearly its prebreakdown value and remains constant at this level as the current is increased to one ma. As was mentioned previously, the multiplication in the breakdown region is considered to be proportional

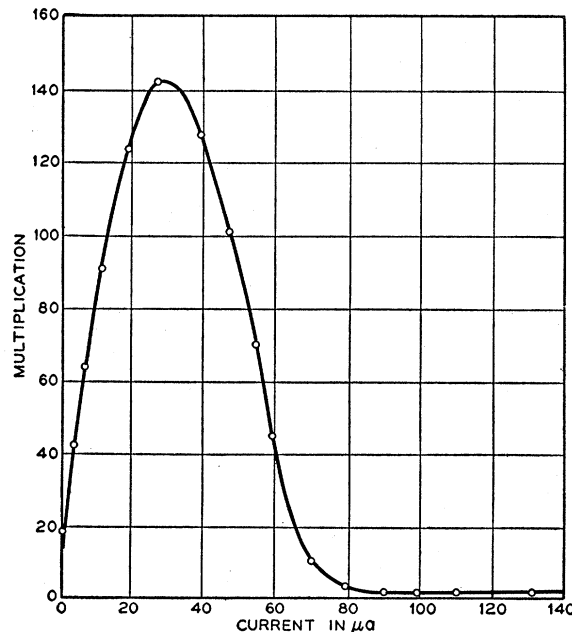


FIG. 12. Multiplication for single-microplasma junction.

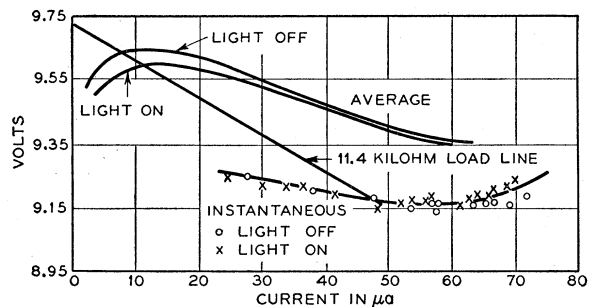


FIG. 13. Instantaneous and dc characteristic showing the effects of light on single-microplasma junction.

to the difference between two characteristics: one with light on and the other with light off. The actual multiplication for any single carrier crossing the junction must be very high at the high dc currents. It is not possible, however, to measure this multiplication. Both the heating effect and the spreading resistance appear in the  $V-I$  characteristic and have the same effect on the multiplication data as the addition of 1000 ohms in series with the junction. The significant fact of these data is that the junction is strongly sensitive to light in the unstable region and has the same relatively low sensitivity in the stable region as in the prebreakdown region. It is difficult, even in the unstable region, to relate the multiplication measurement to actual multiplication of a single carrier, since the primary effect of the light is to trigger more pulses and leave the pulse amplitude unchanged. It would be more appropriate to consider the photosensitivity of the junction in terms of the number of microplasma pulses triggered by the light.

The multiplication characteristics shown in Fig. 12 can be interpreted in terms of the instantaneous characteristics. From Fig. 13 we see that the light does not affect the instantaneous characteristic but it does have a pronounced effect on the duty cycle. Let us for the

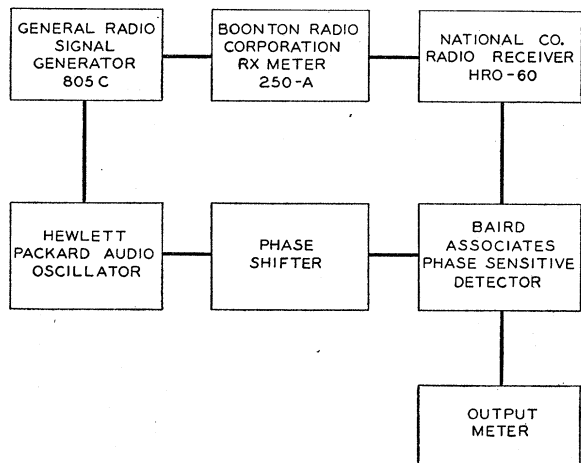


FIG. 14. Block diagram for impedance measurements.

present assume that the number of microplasma pulses is proportional to the number of chance carriers that appear in the localized breakdown region. This proportionality is reduced at long pulse durations where there is a high probability that the carriers enter the region when the pulse is on. Further, if we make the assumption that the pulse duration is unaffected by the light, then at low duty cycles, the ratio of the dc current with the light on to that with light off should be dependent on the ratio of the photocurrent to the reverse saturation current. The current difference of the two characteristics will increase with the source voltage because the average pulse duration increases. This increase will continue until the number of pulses becomes insensitive to the number of carriers and the multiplication will decrease.

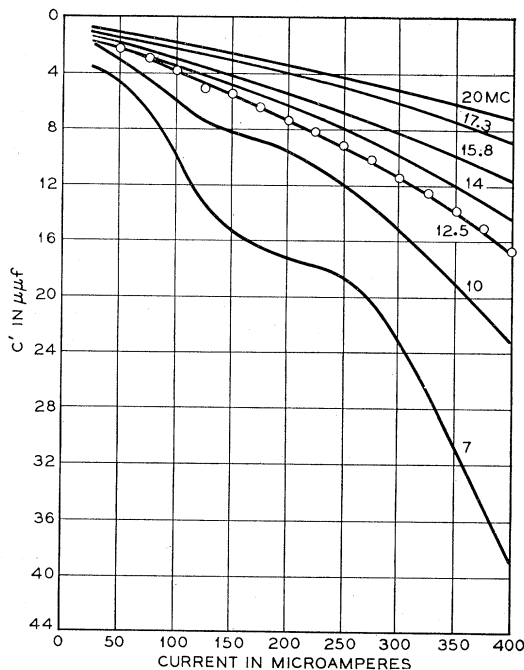


FIG. 15.  $C'$  vs current for uniform junction for a limited current range.

The assumption that the number of microplasma pulses is proportional to the number of carriers appearing in the junction is verified as follows: The junction is illuminated by a source whose intensity is measured by the photocurrent induced in the junction in the pre-breakdown region. The number of pulses in the breakdown region is counted by a technique previously described. The pulse count, as a function of average current, has a broad maximum extending from approximately 5 to 20 microamperes. The decrease in count at the lower currents is partly due to the inability of the amplifiers to pass the extremely short pulses encountered. The maximum count is then plotted against photocurrent and a linear relation is found over a three-decade range in pulse count.

The multiplication characteristic for the uniform junction in Fig. 11 is seen to be a superposition of several individual microplasma characteristics. Since more than one microplasma is involved in the uniform junction, a given light intensity will trigger more pulses and the multiplication will be greater.

**IMPEDANCE CHARACTERISTICS**

To make rf impedance measurements independent of signal amplitude, signals of the order of 10 mv or less had to be applied across the diode. At these signal levels, obtaining a satisfactory null indication in a bridge measurement with breakdown noise present required the use of the detection scheme shown in Fig. 14. The bridge element of the *RX* meter receives a signal from an audio (450 cps) modulated signal generator. The

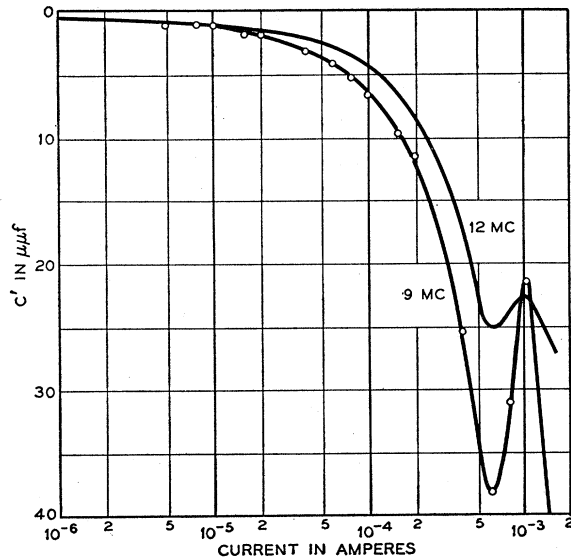


FIG. 16.  $C'$  vs current for uniform junction for an extended current range.

bridge unbalance is then detected by the radio receiver and the phase-sensitive detector.

Writing the diode admittance as

$$Y = 1/R + j\omega C, \tag{5}$$

the two quantities  $R$  and  $C$  can be measured on the bridge. Before breakdown the term  $1/R$  is negligible and  $C$ , the displacement current capacity, is  $7.4 \mu\mu\text{f}$  for the uniform junction. After breakdown it is found that the conductance becomes significant and the susceptance, after going through zero, becomes negative. The above expression can then be rewritten as

$$Y = 1/R + j\omega(C - C'), \tag{6}$$

where the terms  $(C - C')$  and  $R$  are measured directly on the bridge. The results will be left in these terms since an equivalent circuit which represents this phenomenon over the entire range has not been found,

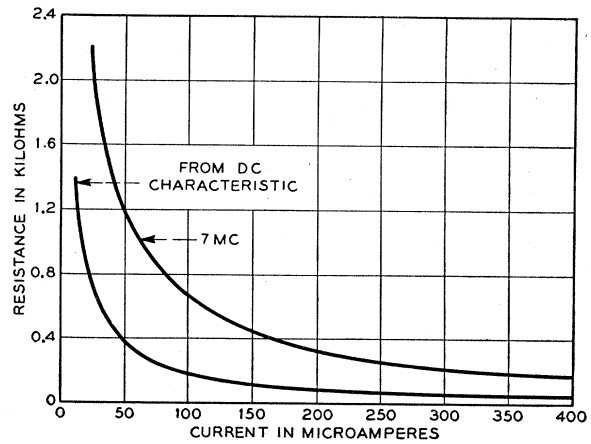


FIG. 17. Resistance vs current for uniform junction, showing resistance at 7 Mc/sec and resistance obtained from Fig. 3.

although for a limited range (frequency and current) the frequency dependence could be somewhat reduced by using an equivalent parallel-inductance representation. For the uniform junction it is noted in Fig. 15 that at low frequencies where  $C' > C$  the current is inductive, and as the frequency is increased and  $C' < C$  the current becomes capacitive. At currents of the order  $500 \mu\text{a}$ ,  $C'$  begins to decrease and goes through a minimum as shown in Fig. 16. Again the remarks made about the multiplication data are applicable here; the shape and position of the peaks vary from unit to unit but the general characteristics at low currents are similar.

The behavior of the resistance is noted in Fig. 17. As the frequency decreases from 7 Mc/sec to 200 kc/sec, the resistance decreases to the characteristic which is the slope of the pulsed curve in Fig. 3. The resistance increases over the entire current range as the frequency is increased from 7 to 20 Mc/sec, but at no point is this increase greater than 30%.

The behavior of the impedance for the single-microplasma junction is shown in Fig. 18. The inductive current first increases and then decreases, so that above  $100 \mu\text{a}$  the current drawn is mainly capacitive and approaches its value in the prebreakdown region.

The inductance of the single microplasma shown in Fig. 18 is a direct result of the mechanism of the dis-

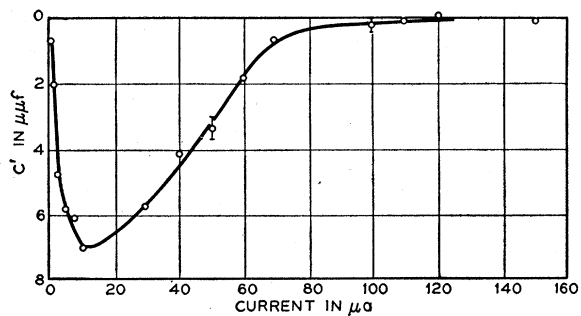


FIG. 18.  $C'$  vs current for single-microplasma junction.



charge. A qualitative explanation of this characteristic follows: assume that the breakdown voltage is suddenly applied. The current will not increase until a chance carrier enters the junction and triggers the microplasma. In general there will be a lag between the current and the voltage, which will be a function of such factors as the operating point on the instantaneous characteristic, the temperature, and the degree of illumination. Since the measurement involves the average inductance, the significant variable will be the average lag of the current with voltage. As the pulse duration increases, the inductive current will increase; but when the pulse duration is sufficient, a voltage increase will not trigger any new pulses and the lag between voltage and current will disappear. Thus the inductive current would be expected to go through a maximum and then go to zero when the microplasma becomes stable, as is shown in Fig. 18. The same characteristic would be expected to

go through several maxima for the uniform junction, as is shown in Fig. 16.

#### CONCLUSION

Although the detailed mechanism of localized breakdown in silicon is not fully understood, the terminal characteristics of a single microplasma suffice to give a qualitative explanation for some of the terminal characteristics of *p-n* junctions in this region.

#### ACKNOWLEDGMENTS

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## Birefringence Caused by Edge Dislocations in Silicon

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A calculation is given of the intensity distribution in a beam of plane polarized or circularly polarized infrared light after transmission through a crystal of silicon containing a single-edge dislocation or a simple tilt boundary. It is apparent that care must be taken to differentiate between an edge dislocation and the region around the extremum of an inclusion, since both give similar intensity contours, the only difference being one of absolute magnitude.

### 1. INTRODUCTION

BOND and Andrus<sup>1</sup> (referred to as B.A. in the sequel) have recently successfully utilized photoelastic methods to investigate the stress distribution in the immediate neighborhood of an edge dislocation in silicon. The purpose of this paper is to calculate the expected intensity distribution near a single-edge dislocation and a simple tilt boundary in silicon when plane-polarized or circularly polarized infrared light is used. We are then in a position to criticize certain of the theoretical results and experimental conclusions quoted by B.A. In Sec. 2, we consider the single-edge dislocation. The intensity distribution around an edge dislocation has been given by B.A. where it appears, however, to have suffered an anomalous reflection about the slip-plane (compare Fig. 2 with Fig. 1 of their paper). The simple tilt boundary is discussed in Sec. 3, and, as might be expected, the intensity near such a boundary falls off exponentially with distance from the boundary; by a suitable choice of the type and density of the discrete edge dislocations within the tilt boundary, the results of this last section can, of course,

be used to estimate the intensity distribution near a simple twin interface.<sup>2</sup> In both the latter sections, the analysis is carried out using the *isotropic* elastic approximation. Finally, in Sec. 4, a brief discussion of the various numerical magnitudes is given.

### 2. SINGLE-EDGE DISLOCATION

We erect a system of orthogonal Cartesian coordinates  $x_i$  ( $i=1, 2, 3$ ) in the crystal, such that  $x_1$  is parallel to the slip direction, and  $x_2$  is normal to the glide plane. The strains around a positive edge dislocation, of strength  $b$ , situated at the origin are then

$$\begin{aligned} e_{11} &= -\frac{Ax_2}{r^4} [x_1^2(3-2\nu) + x_2^2(1-2\nu)], \\ e_{22} &= \frac{Ax_2}{r^4} [x_1^2(1+2\nu) - x_2^2(1-2\nu)], \\ e_{12} &= \frac{2Ax_1(x_1^2 - x_2^2)}{r^4}, \end{aligned} \quad (1)$$

<sup>1</sup> W. L. Bond and J. Andrus, Phys. Rev. **101**, 1211 (1956).

<sup>2</sup> R. Bullough, Proc. Roy. Soc. (London) **A241**, 568 (1957).