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Avalanche Effects in Silicon $p$–$n$ Junctions. II. Structurally Perfect Junctions

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The fabrication of a planar guard ring diode which exhibits uniform microplasma-free breakdown is described. Discrepancies are discussed between the behavior of these junctions and those reported by Batdorf et al. and Chynoweth, including results showing extremely hard $V$–$I$ characteristics associated with uniform avalanche breakdown. Experimental evidence is presented which confirms Shockley’s theory in which the breakdown behavior is predicted from the Poisson distribution of impurities within the space-charge layer. The photomultiplication technique as described in Paper I is applied to uniform $p$–$n$ junctions. The linearity of $1/M$ vs $V$, as predicted by theory, was verified for values of $M$ between 1.6 and 500. For higher values, the multiplication curves deviate from a straight line. In this higher range they are in good agreement with the pulse-multiplication model developed in Paper I. Light emission patterns from these junctions are shown and a correlation between these patterns and crystal properties is discussed. The effects of resistivity striations in the silicon single crystals is shown to have a strong effect on breakdown areas and no effects of dislocations and oxygen on uniformity are found. From capacity and multiplication measurements a value for the breakdown field of $E_B = 445 \pm 25$ kV/cm was obtained for a 32-V junction.

1. INTRODUCTION

The mechanism of avalanche breakdown in $p$–$n$ junctions has been complicated by the fact that actual junctions studied usually have local defects producing regions in which avalanche breakdown occurs at voltages substantially below the voltage at which breakdown would occur for the same average impurity distribution in the junction in the absence of imperfections.

One of the most important defects is found at the intersection of the junction with the surface and, in general, if a device is made in which the junction is substantially uniform over its area then disturbances at the surface cause avalanche breakdown to occur there at a voltage which may be substantially lower than the breakdown voltage that would occur in the interior.

From a fundamental point of view, the uniform junction in which effects due to structural imperfections controlling the breakdown voltage are eliminated, is the junction of maximum theoretical interest.

Research at several places has been directed towards eliminating surface breakdown and producing uniform junctions. The most extensive publication of these results is a paper by Batdorf, Chynoweth, Dacey, and Foy. In this paper the authors succeed in fabricating junctions exhibiting far more uniform breakdown over large areas than have been reported previously. The authors also reach some interesting conclusions regarding the relationship of their work to previous work on avalanche breakdown. In particular, they conclude that it is extremely probable that previously investigated junctions had their effective breakdown voltage reduced by a factor of approximately 2, owing to the presence of microplasma generating regions. They suggest that the most important cause of these microplasmas are dislocations in the material.

The paper by Batdorf et al. provided valuable stimulus for the investigations reported in this paper. In particular, it is concluded in this paper that dislocations probably do not play an important role in producing microplasmas in many cases.

Improvements in experimental techniques since the time of the Batdorf paper have perhaps contributed to development of results which appear to be much more in line with those expected theoretically. In particular, improved guard ring structures have been made in which the effect of breakdown at the surface is substantially eliminated. In the work of Batdorf et al., the $p$–$n$ junctions obtained had very soft $V$–$I$ characteristics, an effect usually associated with surface leakages or metal precipitates within the junction. Junctions discussed in this paper appear to be much more perfect in this regard. The criterion for uniformity, used by Batdorf et al., of light emission spread uniformly over the junction area has also been observed in respect to these junctions.

It should be mentioned here that during our investigations it was found that in order to observe bulk breakdown patterns it was not necessary to eliminate microplasmas entirely. Microplasmas having a breakdown voltage close to the bulk breakdown voltage (not more than 2 V lower for a 30-V junction) do not interfere with the observation of uniform light emission except in the immediate vicinity of the microplasma.

Since the Batdorf et al. publication, a theory of statistical effects in $p$–$n$ junctions has been developed by Shockley. He finds that statistical distribution of donors and acceptors in the space-charge layer causes a certain degree of nonuniformity of breakdown even in a "uniform" junction due to fluctuations from point-to-point.

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References:


point of the density of impurities. There is always one location having the lowest breakdown voltage. In a step junction without compensation of impurities this point breaks down 0.7 V below the average breakdown voltage. Shockley's theory permits calculation of the $V-I$ characteristic of a junction with bulk avalanche breakdown effect.

Results obtained by application of the photomultiplication technique (described in Paper I) to uniform $p-n$ junctions are also reported. A combination of this photomultiplication technique and the diffusion techniques for uniform junctions leads to new knowledge about many aspects of the avalanche process.

Experimental proof of the principles used in Paper I for the determination of microplasma areas is obtained by measuring $1/M$ vs voltage on uniform junctions up to their breakdown voltages. In Paper I it was also established that the upper limit of multiplication in a microplasma is closely related to the noise effect generally found in microplasmas. A similar noise effect is present in uniform junctions. It is of interest to determine whether the limitations as derived for microplasmas are the same for uniform junctions. Light spots as large as the expected area of uniform breakdown voltage can be used and because this permits operating at higher current levels, the accuracy of the measurements is considerably increased.

In the junctions observed it appears that in addition to statistical fluctuations of the donors and acceptors there are systematic fluctuations lying in parallel layers in the crystal. Observations of light emission near breakdown voltage enables a detection of small concentration differences from region to region in the crystal. These striations are observed in all crystals studied and are discussed in Sec. 4.1.

Localized multiplication studies make it possible to determine fluctuations of the bulk breakdown voltage in a uniform diode. By means of this technique it can be decided whether the striated light emission is really caused by striations in breakdown voltage.

Another matter of interest is the value of the breakdown field in uniform junctions. Batdorf et al. found an increase of breakdown voltage by a factor of about 2 in their uniform junction compared to a similar diode containing microplasmas. They, therefore, concluded that the breakdown field in a junction free from defects is considerably higher than was previously thought. The results to be presented here do not confirm this conclusion and indicate a breakdown field closer to the original measurements than that measured by Batdorf and co-workers.

2. EXPERIMENTAL

2.1. Guard Ring

A different type of guard ring than the one described by Batdorf et al. was used in this investigation (Fig. 1). The guard ring was made by a deep phosphorus diffusion penetrating to a depth of 11.0 μ; the active junction by a shallow phosphorus diffusion of 0.6-μ depth. A planar construction was used for the guard ring to reduce leakage current and to improve stability.

2.2. Diffusion Technique

Considerable effort was required to develop a diffusion technique that resulted in a low microplasma content of the diodes. The technique that finally was evolved gave about 10 percent of microplasma-free diodes in the successful runs. The rest of the devices had microplasmas with breakdown voltages high enough to permit observation of uniform breakdown. It should be noted, however, that some diffusion runs failed completely with no obvious change of the procedure. It was found that most microplasmas originate from surface effects. Therefore, it was necessary to start with a clean and crystallographically perfect silicon surface and avoid contamination and corrosion during the diffusion procedure. Three different surface treatments were evaluated: mechanical polishing, chemical polishing, and electrolytic polishing. The results of this evaluation showed that electrolytic polishing provided the best surface for fabricating diodes with uniform breakdown.

The sequence of diffusion steps is listed in Table I. Prior to the first step, oxidation, the slices were electropolished and thoroughly cleaned in solvents.

Standard photoresist techniques were used after steps 1, 3, and 4 to obtain the desired geometry. Helium...
was used as carrier gas during the phosphorus predeposits in a conventional 2-zone furnace because less inert gases led to chemical reactions and pitting of the silicon surface. Pits introduced in this way have a high probability of becoming sites of microplasmas. This result is contrary to the report of other investigators who found that oxidizing atmospheres were preferable. In the experiments described here, oxidizing ambients affected the uniformity of doping adversely at the low temperatures used. The pitting effect could also be observed when carrier gas or furnace tubes were not kept absolutely dry. Diffusion of the active diode area was done by the technique of multiple predeposition. In this technique the slices are alternately doped and cleaned by removing the SiO$_2$-$P_2$O$_5$ glass with a solution containing HF to achieve more uniform doping. A slow etch (8 parts NH$_4$F:1 part HF) was chosen here in order to preserve the oxide on top of the guard ring junction. This is possible because the $P_2$O$_5$-$SiO_2$ dissolves much faster than SiO$_2$. After three such predeposition steps the areas for the evaporated and alloyed gold contacts as shown in Fig. 1 were etched out. Care was taken to insure that the $n^+$ layer was removed from the back of the slice to avoid interference of light emission observation and electrical characteristics by injection effects.

3. RESULTS

3.1. Electrical Characteristics

A typical $V-I$ characteristic of a microplasma-free junction, measured with separate contacts for voltage and current, to eliminate contact resistance, is shown in Fig. 2. The characteristic is extremely hard with a current rise of four decades within 0.1 V. Variation of breakdown voltage of the microplasma-free diodes within one slice was less than 0.5 V. The forward characteristics of these diodes were similar to previously measured curves on junctions containing microplasmas. This is to be expected because a small defect like a microplasma does not have significant influence on the current flow across a junction in forward direction.

The temperature dependence of the characteristic is given in Fig. 3 where the same junction was measured at different temperatures. For the avalanche condition we derive from these curves a temperature coefficient of 0.024 V/C° which is in agreement with previous measurements of junctions with the same breakdown voltage.

3.2. Multiplication Measurements

The multiplication in a reverse biased $p-n$ junction is actually a function not only of the voltage but also of the location at which the photon generates the hole-electron pair. The two simplest cases to consider may be referred to as pure hole multiplication and pure electron multiplication where the incident carriers upon the junction are either entirely holes or entirely electrons. These correspond to cases in which the photon is absorbed just outside the space-charge layer of the $p-n$ junction on either the $n$ or $p$ side, respectively, so that the minority carrier of the hole-electron pair is sure to reach the space-charge layer and be drawn across. It is not practical to produce such highly localized generation; however, it is experimentally practical to approach this condition by using two drastically different distributions of hole-electron pair generation. This difference is produced by varying the wavelength of the light.

For the $p-n$ junctions studied in this paper, the light falls upon a very thin diffused $n^+$ region. If very short wavelength light is used (3200 to 5800 Å) then the absorption coefficient is at least as large as $7 \cdot 10^4$ cm$^{-1}$, (reference 12), so that the hole-electron pairs generated tend chiefly to be restricted to a layer about 0.5 μ thick, a small fraction of the carriers are generated in

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11 The filter used in this experiment was checked over a wide range of wavelength to make sure that no light outside the above mentioned range was transmitted.
the space-charge layer, the width of which for this junction varies from about 0.4 \( \mu \) at 2 V to 1.4 \( \mu \) at the maximum voltage of over 30 V. (The capacity measurements leading to these conclusions are discussed in subsection 3.4.) It is evident that for this case the carriers entering the space-charge layer, and becoming multiplied, are predominantly holes. The multiplication curve for this case is the upper curve of Fig. 4. Because the ionization rate for holes is much smaller than for electrons it can be expected that the high multiplication range of this curve is influenced by electron multiplication. Therefore, the striking linearity of the curve may be only accidental.

It should be noted that a spurious apparent multiplication effect can occur as a result of the widening of the space-charge layer with a reverse bias. This results in a reduction of the distance through which carriers must diffuse in order to find the field in the \( p-n \) junction. From Fig. 4 it is seen that increasing the voltage from 2 to 4 V results in an apparent multiplication increase of only 1%. Since the widening of the space-charge layer varies less rapidly than the first power of the voltage, depending upon the distribution of unbalanced chemical charge near the junction, one can conclude that at most an apparent increase in multiplication of the order of 3% can arise from this cause over the entire voltage range of observation.

An effective multiplication for electrons can be obtained by using relatively long wavelength light. The wavelength used in the study ranged from short infrared to 6600 Å. This light has an absorption coefficient smaller than 2 \( \times \) 10^3 cm\(^{-1}\) as reported in reference 12. The penetration of this light is probably much larger than a diffusion length of minority electrons in the \( p \)-type body. If this diffusion length is larger than the width of the space-charge layer, then the carriers being multiplied consist predominantly of electrons diffusing to the space-charge layer from the \( p \)-type region. Again, the effect of widening the space-charge layer can be estimated to produce an apparent multiplication in-
crease of only 3% at most, as deduced from the variations between 2 and 4 V in Fig. 4. This is consistent with the conclusion based on the fact that the diffusion length for electrons in the $p$ region is probably approximately 20 $\mu$, whereas the maximum width of the space charge layer is approximately 1.4 $\mu$.

3.3. Light Emission and Study of Striations

The technique used of the observation and photography of light emission has been described in a previous paper. In Fig. 5 light emission of two typical diodes is shown. One immediately notices striations of light emission approximately 50 $\mu$ wide. These striations could be found in most of the devices investigated, in float zone as well as Czochralski grown crystals from different suppliers. They can be distinguished from ordinary microplasmas as can be seen in Fig. 6 showing both effects in one and the same diode. The difference in brightness is even more striking with direct observation. The hardness of the high speed film that has to be used for photography suppresses such difference in intensity.

The correlation of those striations within slices cut from different crystals was investigated by mapping the directions of the striations in all the diodes on a slice. Two such maps are depicted in Figs. 7 and 8. Figure 7 was obtained on a crystal grown by the float zone technique, Fig. 8 on an oxygen-free, dislocation-free crystal, grown by the Dash technique. Both crystals were cut perpendicular to the pull direction. The same pattern of concentric rings was found on every crystal investigated, including Czochralski grown crystals. A different but also correlated pattern can be found on slices cut parallel to the pull axis (Fig. 9). Here the striations are concave towards the seed end of the crystal with the curvature of the striations varying slightly for different crystals. The width and distance of the stria-

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tions seem to be strongly dependent on crystal growing conditions, as is indicated by investigations presently being carried out in this laboratory. Although the light emission from these junctions is not absolutely uniform all over, they are uniform as compared with junctions containing microplasmas and for convenience we refer to these striated junctions as "uniform" junctions.

Striations were also found in boron-diffused $p^+n$ junctions (see Fig. 10). Due to the less advanced stage of boron diffusion techniques more microplasmas are present in this diode.

At high magnification [Fig. 11(a)] the light emitting spots in the striations can be resolved. They are statistically varying in size and brightness and do not have sharp outlines. Sometimes they occur in clusters separated by dark areas [Fig. 11(b)].

Quantitative information on the variation of breakdown voltage from place to place in the structurally perfect $p-n$ junctions can be used to interpret the variations in concentration which produce them. The method of analysis consists of measuring multiplication in small local regions, scanning the light spot across the striations. The light spot used was 6 $\mu$ in diameter, and photomultiplication curves were obtained at a series of locations along a line perpendicular to the striations at

12.2-$\mu$ increments. The breakdown voltage for each location was extrapolated from $1/M$ vs $V$ curves (Fig. 12). In order to obtain this curve, it is only necessary to measure the last portion of the $1/M$ curve close to the breakdown voltage for each point. The accuracy of the $V_n$ values was $\pm 0.05$ V. A photograph of the same diode with the line of scanning is given in Fig. 13.

Glowing areas are closely correlated to areas of low breakdown voltage as indicated in Fig. 12. The difference of breakdown voltage between the bright and the
dark areas is of the order of 0.2 V, except at one point having a considerably higher breakdown voltage than the rest of the diode. At the right side of the plot in Fig. 12 there is a considerable scatter of the points. This may be due to the fact that this area has a rather irregular distribution of breakdown voltage, which is also indicated by the somewhat irregular light emission pattern. A slight rise of average breakdown voltage from the left to the right edge of the diode is noticeable. This effect might be caused by a small temperature change during the measurement.

In order to account for the variations in breakdown voltage, it can be assumed that there are fluctuations in the level of the p-type doping through the crystal. From the observed difference of the order of 0.5 V at an average voltage of 31.8 V, the variation of doping level in the underlying p-type material is 1.5%.

3.5. Capacitance Measurements

Capacitance measurements, necessary for obtaining the breakdown field, are complicated by the presence of the guard ring whose capacitance is an unwanted addition, with a different voltage dependence, to the capacitance of the active diode. In order to determine the guard ring capacitance so that it could be subtracted from the total, diodes having only guard rings were diffused at the same time and on the same material as the complete diodes, and their capacitance measured. (An alternative would have been to diffuse diodes without guard ring, but it was found that certain changes of resistivity occur during guard ring diffusion. Therefore, it was decided to choose the present method which is as close as possible to the actual conditions.) Both guard ring only and guard ring diode measurements were plotted, and the guard ring data subtracted from the combined data. The three curves are shown in Fig. 15. The built-in voltage of 0.7 V has been added to the applied
2.3. There is a discrepancy between the conclusions that they represent spherical surfaces can only be caused by resistivity striations in the crystals. From the shape of striation patterns we can draw inference from the measurement error of the individual curves and was approximately ±3% at breakdown.

The capacitance vs voltage characteristic of the active diode region follows closely a law of the form $V C n_e = \text{constant}$, where $n_e = 2.0 - 2.3$. There is a discrepancy between these measurements and the capacitance calculated from diffusion parameters. The expected capacity from the diffusion is about 30% higher. The effect observed is as if some degree of compensation were occurring immediately under the junction for a distance of a few microns. The compensation seems to be limited to the surface of the material because it was not detectable by four point probe measurements on the back side of a slice containing completed diodes.

The mechanism of this effect has not yet been adequately explained, but for purposes of this paper one may take the measured capacitance as accurately representing the actual space-charge layer width, and from this data the field distribution may be calculated.

4. DISCUSSION

4.1. Light Emission Patterns

The striation patterns in Figs. 7–9 are obviously correlated with the original single crystals used for diffusion. If they were caused by inhomogeneous doping during diffusion, one would not expect them to result in a uniform pattern over the whole slice. The difference in light emission can further be only interpreted as a difference in breakdown voltage. In the absence of lattice imperfections such differences in breakdown voltage can only be caused by resistivity striations in the crystals. From the shape of striation patterns we can draw the conclusions that they represent spherical surfaces concave towards the pull direction, and the axis of rotation approximately coinciding with the pull axis. The most convincing interpretation of these hemispheres is that they delineate surfaces of solidification during crystal growth. Multiplication measurements give the result that the variation in doping causing the striations is of the order of 1%. Small temperature variations during crystal growth may cause variations of growth rate and thus small deviations of the doping level can be introduced. It should be pointed out, however, that the distance between striations is generally much smaller than the length of crystal pulled during one rotation. Therefore, the resistivity striations cannot be caused by a stable temperature gradient across the crucible, a condition that has been shown previously to be conducive to formation of striations. The details of the process by which the striations discussed here originate are at present unknown. Neither is it known whether they are caused by small fluctuations of the concentration of the added dopant (i.e., boron) or large variations of a compensating impurity, although the latter possibility is less likely. If the striations are caused by fluctuations of growth rate, then the distribution coefficient of the impurity plays an important part. For boron we expect small fluctuations because its distribution coefficient is close to one. All the other impurities should have more pronounced striations if the crystals are grown under the same conditions. This seems to be the case. For instance $p^n$ junctions diffused into phosphorus doped silicon have much narrower, more pronounced striations (Fig. 10).

Shockley's breakdown theory can be checked by investigation of the areas of the little light emitting volume elements. Shockley assumes those breakdown spots to be cubes of the dimension of the space-charge layer. This is only an approximation, but the actual size of these spots can be expected to be not too different from the space-charge layer width.

Figure 16 gives the statistical distribution of diameters of light spots as obtained on a photograph. It can be noted that the most frequent diameter is 1 μ, which is rather close to the depletion layer width of 1.4 μ of this junction. Figure 16 deviates from an ideal statistical distribution. This is not surprising, considering that the real distribution may be distorted by uneven exposure of spots of varying brightness by the photographic film. It is of interest to note that the same technique, used on a picture of a uniform junction published by Batdorf et al., gives an average diameter of 5 μ, indicating that they had a wider space-charge layer.

The described shape of solidification interfaces indicates that the prevailing cooling mechanism is by radiation, which is expected for silicon (melting point 1420°C). Crystals cooled by heat conduction exhibit the opposite curvature of solidification interfaces.

4.2. Current–Voltage Characteristic

The reverse characteristic in Fig. 2 is typical of a large number of diodes measured. In comparison with the characteristic published by Batdorf et al., extreme hardness is evident. The reason why Batdorf et al. did not obtain hard characteristics is not known and may have to do with their technique of junction fabrication. The hardness of the uniform junctions also permitted the observation of noise effects. Reverse currents before the onset of avalanche breakdown varied within one order of magnitude from device to device and are conjectured to consist to a considerable part of surface leakage in spite of the oxide coverage of the junctions. This can be demonstrated by plotting the product of leakage current and junction capacity versus voltage. This product should be constant if the reverse current were generated in the space-charge layer by centers not affected by variations in the electric field. In our devices, however, it increases with voltage. Leakage current at a fixed voltage increases with temperature with an activation energy of 0.62 eV.

It was not possible to verify Shockley’s theoretical current–voltage characteristic due to two obstacles. In the lower current range the pulse mode of the current with the ensuing exponential dependence of pulse length on current interferes with the measurement and in the high-current range the distribution of breakdown voltages is distorted due to the presence of striations.

4.3. High Multiplication Range

The deviation of the $1/M$ curves shown in Fig. 14 from a straight line, the saturation of $M$ at a value dependent on light intensity, the observation of noise in the high multiplication region, and the temperature dependence of avalanche voltage, all indicate that multiplication in uniform diodes is governed by the same processes as observed in microplasmas.

Little experimental information about the noise pulses in uniform diodes was obtained in this investigation but it is likely that the underlying mechanism is very similar to that in microplasmas. This is indicated by the fact that the pulse-multiplication theory developed in Paper I for microplasmas is in general agreement with measurements on uniform junctions.

4.4. Breakdown Field and Ionization Coefficient

It is interesting to compare ionization coefficients measured during this investigation with previous results. The logarithm of ionization coefficient was plotted versus the reciprocal field, a presentation introduced by Chynoweth. For computation of the maximum field $E_m$ from the capacity data, the following relationship was used.

$$E_m = \left[\frac{n_c}{(n_c-1)}\right] E = \left[\frac{n_c}{(n_c-1)}\right] V/W,$$

where $n_c$ = exponent in the capacitance law (see Sec. 3.4) and $E$ = average field in the junction = $V/W$.

In the Appendix it is shown that this relation holds for every impurity distribution following a power law.

It was noted that the present data for the ionization rates of electrons in uniform junctions are within the same range as previously measured data on junctions containing imperfections. This is not very surprising, since, as has been pointed out before, microplasmas are a localized phenomenon limited in their influence on the $1/M$ curves to voltages near their local breakdown.

The results just discussed do not confirm Chynoweth’s data on uniform junctions which are much lower than all the other measurements. It might be worth noticing that the capacity data in Chynoweth’s paper, indicating a junction width of 1 μ and a continuously graded distribution throughout the voltage range cannot be reconciled with a diffusion giving a junction depth of 0.1–0.2 μ as is claimed for the same uniform junction. It is not impossible that a compensation effect similar to that described in this paper interfered with the measurement. If the bulk concentration underneath the active junction is lowered considerably, then the capacity of the guard ring is no longer negligible. All these effects may have contributed to the discrepancy between the measurements in reference 20 and all the other measurements.

The breakdown field $E_B$ is calculated from experimental data by the following equation:

$$E_B = n_c/(n_c-1)C\left[(V_B+V_c)/eA\right],$$

where $\left[\frac{n_c}{(n_c-1)}\right]C = 41.85 \pm 1.2$ pF, $V_B = 32.3 \pm 0.3$ V = extrapolated breakdown voltage, $V_c = 0.7$ V = built-
in voltage, $\epsilon = (1.11 \pm 0.04) \times 10^{-12}$ F/cm, and $A = 0.283 \pm 0.003 \text{ mm}^2/\text{area of the shallow junction}$. Because of the great accuracy with which the breakdown voltage can be determined from the experimental data given in Fig. 4, a more accurate value for the breakdown field in silicon can now be given than was hitherto possible. This value is

$$E_B = 445 \pm 25 \text{ kV/cm for } V_B = 32 \text{ V}.$$ 

The extrapolated breakdown field for electrons is

$$E_B = 425 \pm 25 \text{ kV/cm for } V_B = 30 \text{ V}.$$ 

The breakdown field found in this investigation differs from the breakdown field of $5.9 \times 10^5 \text{ V/cm}$ given by Chynoweth\(^\text{20}\) for $V_B = 44 \text{ V}$.

The electrical breakdown characteristic, the light emission from discontinuous spots, and the size of the light emitting spots are in agreement with this theory. The $V$-$I$ characteristic is only described in approximation due to a noise effect that was discovered to be present in uniform junctions. Light emission from uniform junctions was found to be very sensitive to the distribution of impurities in the substrate crystals. Striations of light emission delineating surfaces of solidification were found to be present even in crystals thought to be uniformly doped. A typical variation of 1.5% of doping was found across the striations. It is hoped that further work with uniform avalanche breakdown will point out ways to avoid those striations and make really uniform junctions.

### 5. CONCLUSIONS

It has been shown that it is possible to produce microplasma-free, bulk avalanche breakdown in silicon. This confirms earlier results by Batdorf et al. In disagreement with Batdorf et al., it was found that uniform $p-n$ junctions can be made with extremely hard characteristics. From the fact that uniform junctions could be made on Czochralski grown, as well as float zone crystals it can be concluded that dislocations, as well as oxygen content do not necessarily cause microplasmas. Most microplasmas encountered in this investigation seem to originate from surface contamination. Neither can it be said that microplasmas lower breakdown voltage to about half its value, as stated in reference 1. In this investigation it was found that microplasmas have breakdown voltages ranging up to very close to the bulk breakdown voltage.

Measurements of ionization coefficients and breakdown field were found to be in general agreement with many previous measurements on junctions with microplasmas.\(^{21,22}\) They disagree with measurements published by Chynoweth\(^\text{20}\) for uniform junctions which give fields about 30% larger than those reported here.

Experimental results are in agreement with the consequences of Shockley's theory in which statistical distribution of impurities within the space-charge layer is regarded as influencing the electric field and distribution of breakdown voltage over the junction area.

**APPENDIX. RELATION BETWEEN MAXIMUM AND AVERAGE FIELDS**

The capacitance $C$ of the junctions described in this paper is experimentally found to depend on reverse voltage $V$ (applied plus built-in) according to

$$C \propto V.$$ 

Since $C$ is related to the space-charge layer width $W$ by

$$C = \frac{f}{W},$$

this law can be written

$$V = K W^{n_e}.$$ 

The average field is, using (A1)

$$\bar{E} \approx V/W = KW^{n_e-1}. \quad (A2)$$

The maximum field $E_m$ is determined by first calculating $Q$, the total charge/cm$^2$ in the junction. Then from Poisson’s equation, $E_m = Q/\epsilon$.

The capacitance is defined such that a voltage increment $dV$ results in a charge increment $dQ = C dV$. From (A1), $dV = n_eKW^{n_e-1}dW$, and using $C = \epsilon/W$, the total charge is

$$Q = \int_v^0 C dV = n_eK \epsilon \int_0^W W^{n_e-2}dW$$

$$= \left[ \frac{n_e}{(n_e-1)} \right] K \epsilon W^{n_e-1}. \quad (A3)$$

The maximum field is thus $E_m = Q/\epsilon = n_eKW^{n_e-1}/(n_e-1)$, so that from (A2) the ratio of maximum to average field is:

$$\frac{E_m}{\bar{E}} = \frac{n_e}{(n_e-1)}. \quad (A4)$$
