Uniform Silicon $p-n$ Junctions. I. Broad Area Breakdown

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In terms of the convection current and ac voltage in the beam, the electromagnetic power flow is given by

$$\dot{P}_e = \frac{1}{2} \text{Re} \, \Phi^* F_e^* V.$$  \hspace{1cm} (B7)

It is readily confirmed that, just as for the sheet beam, the above expressions for $\dot{P}_e$ and $F_e$ satisfy the relation

$$\frac{\partial p}{\partial \beta} = p \beta F_e / \beta.$$  \hspace{1cm} (B8)

The time-average stored field energy in a single wave, per unit length of drift region, is given by

$$\bar{W}_e = \frac{1}{2} \pi \epsilon \int_{b}^{a} (E_e E_e^* + E_x E_x^*) \, dr.$$  \hspace{1cm} (B9)

which readily reduces to

$$\bar{W}_e = A \epsilon E E^*/ 4 \beta^2.$$  \hspace{1cm} (B10)

It should be noted that, for both types of thin beams treated here, the expressions for $\beta^2$ are restricted to small fixed values of $\beta$, the beam thickness in electronic wavelengths. It has been necessary to introduce a nominal beam thickness because $\beta$ relates to the plasma frequency $\omega_p$, which depends on the finite volume space-charge density $\rho_v$. Although neglect of the field variations across each beam has made the expressions for $\beta^2$ somewhat artificial, it has not made the beam models unrealistic for power balance computations.

**INTRODUCTION**

Chynoweth and McKay\(^4\) have shown that at avalanche breakdown in reverse-biased silicon p-n junctions, the breakdown current does not pass uniformly through the junction over the whole junction area. Instead, the current funnels through the junction at many very small spots. The locations of these spots can be seen (in shallow diffused junctions) since they emit visible radiation arising from recombinations of energetic electrons and holes. The mechanism of formation of these local breakdown spots has been considered by Rose\(^5\) who gave to them the name—microplasmas. These microplasmas are frequently unstable, giving rise to a characteristic form of noise.\(^5\)

\(^1\) A. G. Chynoweth and K. G. McKay, Phys. Rev. 102, 369 (1956).

Chynoweth and Pearson\(^6\) showed that these local avalanche breakdowns, or microplasmas, showed a strong tendency to form at points where edge dislocations passed through the space-charge region. Senitzky and Moll\(^7\) subsequently showed that if a gross field inhomogeneity was intentionally built into the junction, the breakdown could be initiated at this inhomogeneity and that higher breakdown currents were carried simply by an expansion of this breakdown area rather than by the formation of additional breakdown sites.

These various investigations suggested that attempts should be made to study avalanche breakdown in junctions as free as possible from field inhomogeneities and dislocations. This paper describes the breakdown behavior of such junctions which, furthermore, by virtue of a special geometry, were also free from edge effects. (Chynoweth and Pearson\(^6\) have previously shown that

\(^7\) B. Senitzky and J. L. Moll, Phys. Rev. 110, 612 (1958), and private communication.
if there are no dislocations in the junction, the next most favored sites for breakdown are around the periphery of the junction.) It is found that in these dislocation- and edge-free junctions the breakdown occurs not by way of microplasmas, but in a much more uniform manner over the whole junction area in what might be called a macroplasma. A detailed study of various avalanche breakdown phenomena in these uniform junctions forms the main topic of this paper. In the following paper the electron ionization rate as a function of field strength is determined from the multiplication data and discussed in detail.

EXPERIMENTAL

The present experiments have been done with a special junction geometry that avoids surface breakdown. Furthermore, as the junctions had small areas and were made in relatively low-dislocation density material, many junctions were obtained which were free from dislocations. The junction geometry, which is shown in Fig. 1, was obtained as follows: The junctions were made on \( p \)-type silicon of about 0.2- to 0.3-ohm-cm resistivity. Small areas, which were later to be the active junction areas, were masked by the oxide masking process\(^8\) and the remainder of the surface was diffused with a phosphorus donor diffusion with the surface concentration controlled so as to produce not an \( n \)-type layer, but merely a net \( \pi \)-type (lightly \( p \)-doped) layer. The oxide mask was then removed with hydrofluoric acid and the entire surface phosphorus diffused again, this time with a heavy concentration of phosphorus in the form manner over the whole junction area in what is known as a macroplasma. A detailed study of various avalanche breakdown phenomena in these uniform junctions forms the main topic of this paper. In the following paper the electron ionization rate as a function of field strength is determined from the multiplication data and discussed in detail.

![Diagram](image)

**Fig. 1.** The geometry of the edge-free junctions used in the present studies.


The experiments consisted primarily in compiling information on: (i) the visible light emission patterns, (ii) the reverse bias characteristics, (iii) capacitance vs bias behavior, (iv) the multiplication characteristics, (v) the integrated light emission vs bias, and (vi) the occurrence of microplasma noise. Throughout most of this paper results will be given for two junction samples; the properties of one are typical of the seven uniform junctions studied while the other junction (which was prepared at the same time and in the same way) exhibits some very informative anomalies. The two samples will be referred to as the smooth and the bumpy junctions.

RESULTS

(i) Light Emission Patterns

Figure 2 shows two photographs of the visible light emission patterns of smooth junctions in avalanche breakdown. The only differences between the two units are that they were made in separate diffusion runs and that different methods were used for making contact to the \( n^+ \)-type layer. In Fig. 2(a) contact was made by a wire to a small antimony-doped gold-alloyed island whereas in Fig. 2(b) contact was made via an annular ring instead of to an island. Both units had identical breakdown voltages.

The appearances of the light patterns in Fig. 2 especially Fig. 2(b) are both quite different from the patterns observed previously in large area junctions.\(^1\) The latter generally consist of random arrays of highly localized intense light spots whereas in the present junctions, though there is a tendency for the light to appear in spots [e.g., Fig. 2(a)], the spots are very much more diffuse and much weaker. In Fig. 2(b) the light emission pattern is particularly uniform, probably as a result of more perfect diffusion during fabrication. It should be noted that the breakdown voltages of these new junctions were 44 v, putting them well out of range of internal field emission breakdown mechanisms (previous work has shown that silicon junctions breaking down at less than about 6 v do so mainly by internal field emission and that this too is accompanied by a quite uniform light emission pattern\(^9\).

Figure 3 shows the light emission pattern of the bumpy junction, a junction which showed some interesting anomalies in its electrical properties. It will be noted that there are two bright local spots of light near the periphery of the junction while the immediate neighborhood of these spots is dark. Away from this region, however, the light from the rest of the junction appears similar to that for the smooth junction of Fig. 2(a) and noticeably much fainter and more diffuse.

than the light from the two bright spots. The two light spots appear similar to those representing microplasmas in earlier junctions and in the following sections, conclusive evidence will be presented to show that these two light spots do indeed represent microplasmas.

From previous work it is known that microplasmas, such as those in Fig. 3, tend to occur at imperfections such as dislocations passing through the junction. It is tentatively concluded, therefore, that the junctions represented by Fig. 2 are relatively free from defects which strongly promote the formation of microplasmas, and that the space-charge regions of these junctions have a closer resemblance to plane parallel geometry than has hitherto been obtained. The absence should be noted, also, of the high concentration of light around the junction periphery which is usually present in junctions whose edges are exposed.

There still remains, however, a tendency towards a spotty distribution of the light emission suggesting that even in these "smoother" junctions there can persist a slight tendency towards microplasma formation. Further evidence will be presented which supports this interpretation, but it should be emphasized here that this slight residual tendency towards microplasma formation will not detract from the main conclusion to be drawn, which is: junctions such as those in Figs. 2(a) and 2(b) are free from defects that cause the formation of the microplasmas which figured in earlier avalanche breakdown studies and as a consequence, the breakdown properties of these new junctions are radically different.

(ii) Reverse Characteristics

Figures 4 and 5 show the room-temperature reverse characteristics for a typical smooth junction and the bumpy junction, respectively. The smooth junction has a smooth though somewhat soft characteristic and it breaks down at about 44 v, (as did all the other junctions to within ±1 v). Prepared in a similar way and using similar base material, the bumpy junction has the same breakdown voltage, at 44 v. But there are some very noticeable anomalies at intermediate biases. The reverse characteristic enters sharply into what appears to be a breakdown at 22.5 v. This breakdown characteristic enters a load-line form, from 23 to 24 v, whose slope is about $3 \times 10^4$ ohm. Centered between 24.5 and 25 v there is another rapid increase in current before the characteristic enters another load-line form. The heights of the first and second bumps in the reverse

Fig. 2. Visible light emission pattern from smooth junctions at avalanche breakdown. The junctions used for (a) and (b) were from different batches and had different methods of making electrical connections to the n-type layer.

Fig. 3. Visible light emission pattern from the bumpy junction at avalanche breakdown.
characteristic are roughly 30 and 25 \( \mu A \), respectively. These magnitudes are roughly as expected for the formation of microplasmas.\(^9\) The final load line represents a load of about \( 2 \times 10^4 \) ohm. As only one bumpy junction was available, it cannot be concluded for certain whether the relatively low current at reverse biases less than 20 v was typical of bumpy junctions, though there seems no good reason why it should be.

(iii) Capacitance Measurements

For the smooth junctions, the capacitance \( C \) closely followed a law of the form, \( C^n V = \text{constant} \), with \( n = 3 \), for all biases \( V \), up to a bias close to breakdown. Thus, these junctions can be regarded as linear impurity gradient junctions with, consequently, parabolic field distributions. The capacitative behavior of the bumpy junction was similar up to the onset of the breakdown, described above, at which point the junction became too "lossy" to enable meaningful capacitance measurements to be made. From the capacitance measurements, the width constant of the smooth junction (the width of the space-charge region for a total potential drop of 1 v) was \( 3.2 \times 10^{-6} \) cm.

(iv) Multiplication Characteristics

The method of obtaining the multiplication curve has been described previously.\(^{10}\) The multiplication curves obtained for the smooth junctions were virtually identical and that shown in Fig. 6 is a typical example. In Fig. 6, \( M \) increases smoothly to a sharp peak at a bias close to 44 v. This peak was found to be insensitive to

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Fig. 4. Reverse characteristic of a smooth junction.

Fig. 5. Reverse characteristic of the bumpy junction: (a) showing the whole curve, (b) showing that portion of the curve corresponding to the formation of two microplasmas.
the circuit load as long as the latter was small. There are two possible causes of such a peak: (i) it can result from a falling dynamic impedance of the junction compared with that of the bulk of the crystal, or (ii) as Senitzky and Moll have shown, it can arise if breakdown brings on the formation of microplasmas. When the microplasma is on all the time (at biases slightly greater than required for microplasma instability) it is current saturated and deliberately injecting a few more carriers does not lead to an enhanced current; hence the measured \( M \) drops. It is not known for certain which (if either) of these two hypotheses is responsible for the peak at 44 v though if it is the second hypothesis, this would support the conclusion that there is a slight tendency towards microplasma formation close to 44 v.

The multiplication curve for the bumpy junction is shown in Fig. 7. This curve was taken in the same way as for the smooth junction, using unfiltered tungsten light for injecting the carriers. The multiplication curves for the two junctions superimpose on each other almost exactly up to a reverse bias of about 35 v and, as did the smooth junction, the bumpy junction shows a multiplication peak at a bias of about 44 v. However, there are two noticeable bumps on the multiplication curve for the bumpy junction at biases of about 21 and 24 v. To within experimental error, these multiplication peaks coincide, biaswise, with the two rapid increases in current in the reverse characteristic which were ascribed to the formation of microplasmas. The discussion given in the previous paragraph regarding the observation of a peak in the multiplication characteristic again applies here. (The multiplication and reverse characteristics were taken several weeks apart and it seems that during this time there was a small drift from 21- to 22.5-v bias for one of the bumps. This drift, which may have been caused by channel formation or diffusion processes, is irrelevant for the purposes of this paper.)

As seen from Fig. 8, the multiplication characteristic for the smooth junction was essentially independent of the light intensity; the injection rates for the two curves differed by more than three orders of magnitude. For the bumpy junction, however, the magnitudes of the multiplication bumps are enormously enhanced at the lower light intensity while the background multiplication curves do not superimpose (Fig. 9). Again, this can be explained by the fact that the current through the microplasma can reach a saturation value.

\((v)\) Integrated Light Emission vs Current and Bias

To determine the total light emission as a function of current and bias, the units were mounted directly in front of a cooled photomultiplier with an S1 spectral response and the number of photons incident per second were counted using conventional counting techniques. It is not known if there is any shift in the spectral distribution of the light with bias at the smaller currents.
so that the data presented in Figs. 10–12 should be interpreted with this caution in mind. Figure 10 shows the light intensity $L$ vs the current $I$ for the smooth junction, over most of the range the results can be expressed by $L \propto I^n$, with $n$ close to $\frac{1}{3}$. At the highest currents the measured light intensity increases less rapidly with current, an effect which may have been partly explained by pulse pile-up in the counting equipment. However, some curious structure is evident in the curve for currents between 80 $\mu$A and 1 mA. For the smooth junction this current range corresponded to a bias range of from 39 to 40 v. Thus, the structure occurs only when fairly close to full breakdown.

The light intensity vs current for the bumpy junction is shown in Fig. 11 and there are some differences to be noted between it and Fig. 10. From the reverse characteristics, interpolation shows that the lowest measurable light intensities occur at the onset of breakdown of the first microplasma so that the whole of the linear portion of the curve in Fig. 11 can be taken to represent light from the microplasmas that appear at about 21- and 24-v bias. Over this range the light varies close to linearly with the total current, which is in agreement with earlier findings. The structure shown in Fig. 11 is remarkably similar to that of Fig. 10 only it occurs not close to the final breakdown, but in the narrow bias range in which the two microplasmas are formed (as can readily be determined by cross-interpolating between the light-current and voltage-current characteristics). Over this bias range the light intensity varies with the bias as shown in Fig. 12. There is no doubt that the two humps in the light vs current or bias for the bumpy junction correspond to the occurrence of the two microplasmas and, in Fig. 12, it will be seen that there is even some similarity in the shapes of the humps. It is easy to imagine a base line, as suggested by the dotted lines of the figures, and starting from this base line, the light intensity shows an initial rapid increase with current, then a leveling off, followed by a second rise to a final peak before falling back towards the base line.

In view of the definite correlations between the humps in Figs. 11 and 12 and the formation of microplasmas, and the similarities between the humps in Figs. 10 and 11, it again appears that there is a tendency towards microplasma formation close to 44 v in the smooth junction.

(vi) Microplasma Noise

A search was made for the characteristic noise that accompanies microplasma formation using the method described elsewhere. For the smooth junction there was no evidence of any such noise throughout the whole bias range—the upper bias limit to this survey occurred well into breakdown and was determined by either the excessive shot noise at high breakdown currents, by the low dynamic impedance of the junction, or by the limited bandwidth of the circuit (10 Mc). These combined effects may have masked any microplasma noise occurring in the smooth junctions when well into breakdown. For the bumpy junction there were two very strong displays of microplasma noise centered at about 20 and 23 v, respectively. This is unambiguous evi-
dence of microplasma formation at these voltages, which, from Fig. 12, are seen to coincide, roughly, with the onset of the first upswing of light output for the two microplasmas, respectively, as the bias is increased. Throughout most of the remaining bias range over which the light output bumps are prominent, the microplasmas were in the stable rather than the noisy state.

DISCUSSION

There is abundant evidence in the foregoing that the reverse bias behaviors of the smooth and bumpy junctions are very similar except as regards the phenomena occurring in the bumpy junction associated with the formation of the two microplasmas between 20- and 25-v bias. The junctions possess similar bulk breakdown voltages, basic multiplication characteristics that superimpose satisfactorily, and generally similar light emission patterns.

That the two anomalies in the properties of the bumpy junction are caused by microplasma formation is also very clear. We have (i) the light emission patterns revealing two intense spots of light, qualitatively very similar to those seen in the earlier work in which, as in the present work, they were definitely correlated with the occurrence of the characteristic microplasma noise, (ii) these two intense light spots forming at the same biases at which sudden increases in the reverse current take place, and the magnitudes of these current increases being roughly as expected for microplasma formation, and (iii) along the first region, at least, of rapidly increasing current through the microplasma, the light intensity varying linearly with the current (assuming no spectral shift taking place). In addition, there is a considerably enhanced multiplication accompanying microplasma formation. This enhanced multiplication is saturated by relatively low light intensities as is to be expected if the light need only inject a relatively small number of carriers to keep the microplasmas in more or less sustained operation. Finally, there is the evidence of the load lines. Senitzky and Moll have considered two sources of this load impedance; thermal effects and the spreading resistance associated with a microplasma, assuming that the cross-sectional area of the microplasma remains constant (diameter equal to about 500 A) as the current is increased. The impedance due to heating in the microplasma is given by

\[ \Delta V/\Delta I = (\Delta V/V) \cdot (V/\Delta V) = \beta' \cdot (\Delta T/\Delta I), \]

where \( \beta' \) is the temperature coefficient of the breakdown voltage \( V \) and the change in temperature \( \Delta T \), caused by a change \( \Delta I \) in the current has been given by Rose\(^2\) as about \( 10^7 \) °C/amp. Thus, for \( V \approx 20 \) v, and \( \beta' = 7 \times 10^{-4}/°C \), we have \( (\Delta V/\Delta I) \approx 1400 \) ohms. This is considerably smaller than the value determined experimentally, namely, about \( 3 \times 10^4 \) ohms. If the experimental value is taken, therefore, to represent mainly spreading resistance, it predicts a diameter for the microplasma of 500 A (the bulk material having a resistivity of about 0.3 ohm-cm) which is in excellent agreement with earlier estimates.\(^2\)

It should be noted that the thin \( n \)-type layer on the surface of these junctions cannot be the controlling spreading resistance. In particular the macroplasma glow pattern does not arise through microplasma formation being, in general, thwarted by the resistance of the surface layer. These conclusions are drawn from Fig. 3 where it is clear that the current passing through the microplasmas has to pass by regions of the junction which are emitting a glow pattern. However, it is also obvious that the large current through the microplasmas causes a sufficient potential drop in their immediate neighborhood to inhibit breakdown there (the dark area surrounding the microplasmas).

The natures of the crystal imperfections responsible for the two microplasmas in the bumpy junction are
not known at present; obvious possibilities are dislocations, or impurity segregations. It is obvious, however, that if there were many more microplasma-inducing defects present, (as is generally the case where no special efforts to eliminate the defects have been made) the apparent breakdown voltage of the junction would be in the range between 20 and 25 v rather than at the breakdown voltage of 44 v observed in the junctions free from these defects. It is illuminating to note that a breakdown voltage of about 25 v, the measured width constant of \( 3 \times 10^{-4} \) cm, and the material resistivity of 0.3 ohm-cm, are all in very good agreement with the curves that were given by McKay empirically relating the breakdown voltage to the resistivity and to the width constant. Thus, it is plausible to interpret the 44-v breakdown in these junctions rather than those at 20 to 25 v as being closer to the value for an undistorted silicon p-n junction, and that the lower breakdown voltages usually observed are brought about by defects in the junction structure which strongly promote microplasma formation. In particular, it is believed that the smooth junctions more closely approximate the idealized situation of a space charge region with plane parallel geometry and with uniform energy gap than any junctions hitherto investigated by the authors.

[The light emission pattern of Fig. 2(a) suggests that there still persists a slight tendency towards microplasma formation at the 44-v breakdown, even in the smooth junctions. This interpretation is supported by the results of the measurements of the light intensity vs the current. On the other hand, however, the junctions which gave light emission patterns such as that of Fig. 2(b) had the same breakdown voltage, yet showed no evidence whatever of any fine spotiness in their light emission patterns, thereby supporting the conclusion that the 44-v breakdown is close to the true value for these silicon junctions.]

The details of the light intensity vs current and bias curves are puzzling at this stage. It has been proposed that the linear dependence of the light intensity on the current for microplasma emission can be explained by an increasing duty cycle while the microplasma is in the unstable condition and by a cross-sectional area that is proportional to the current in the stable phase, the current density being assumed constant. However, it is clear from Fig. 11 that over a brief range of current the light intensity increases at a very rapid rate after which it returns to a roughly linear increase before eventually entering a "negative" region where the intensity actually drops as the current increases. This behavior is somehow related to the occurrence of the microplasmas in the bumpy junction while Fig. 10 shows that similar behavior may be occurring in the smooth junction close to breakdown. It would seem that the short rapid increase of light with current requires a corresponding increase in current density through the microplasma but what could bring this about is not obvious. Rough estimates show that at the currents involved there is little likelihood of pinch effects. The fact that the light output increases rapidly for a very small increase in current shows that the rapid increase is not caused by the initiation of secondary effects such as internal field emission or internal photoelectric effects. There remains the possibility that these anomalies arise in microplasmas when the injected charge densities become comparable with the existing space charge densities, so causing considerable distortions in the field distribution in the junction. Rough estimates of charge densities show that this condition may have been reached at currents greater than about 100 \( \mu A \). The four-thirds power dependence of the light intensity on the current for the smooth junction is also unexplained at present though it may arise from a spectral shift in the emitted light as the reverse bias is increased, or if there is a substantial "leakage" current that does not produce light emission. The latter would be in line with the observation that the reverse current for low reverse bias is usually much greater in the smooth junctions then in the single bumpy junction studied. Further work is needed to understand these various effects.

**CONCLUSIONS**

The relatively uniform light emission patterns, the higher breakdown voltages, the smooth multiplication curves and the absence of pronounced microplasma phenomena for the "smooth" junctions all seem to show that the space-charge regions of these junctions resemble the ideal plane parallel geometry more closely than those of any other junctions similarly investigated before. When some microplasmas are present, as in the reported "bumpy" junction, they occur at the breakdown voltages previously thought appropriate for the resistivity of the base material, they are accompanied by the characteristic microplasma noise, they give rise to large irregularities in the multiplication characteristics and sudden increases of current in the reverse characteristics, and they exhibit spreading resistances which are consistent with microplasmas of about 500-A diameter.

Thus, it is concluded that microplasmas are not a necessary accompaniment of avalanche breakdown in silicon. If a junction is free from field or lattice inhomogeneities, such as are introduced by dislocations, there may be no microplasmas formed. If there are such local inhomogeneities, however, they make breakdown locally much easier, so giving rise to the current concentrations which are called microplasmas. In particular, it has been found that in silicon junctions made from 0.3-ohm-cm material, the presence of a sufficient number of inhomogeneities, probably dislocations, lowers the breakdown voltage to about half of its value for uniform junctions. Almost all earlier data pertaining to breakdown voltages will apply to junctions containing very many dislocations.

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