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Avalanche Effects in Silicon $p$–$n$ Junctions. I. Localized Photomultiplication Studies on Microplasmas*

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An improved experimental technique is described for the investigation of carrier multiplication in very small areas, particularly microplasmas. A light spot of a few microns diameter is positioned to cover a microplasma of comparable or smaller size and the multiplied photocurrent is measured as a function of reverse voltage.

When the size of the microplasma is much smaller than the light spot, then the multiplication as a function of voltage is dependent upon the characteristics of the microplasma in an upper voltage range just below the microplasma breakdown voltage. In a lower voltage range the microplasma has negligible effect on multiplication. By comparing for the upper and lower voltage ranges the behavior of the reciprocal of the multiplication factor as a function of voltage, it is possible to determine that the diameters of the area of the microplasma regions vary from less than one to more than $5 \mu$.

Multiplication factors as high as $10^6$ were measured. At high multiplication ($M > 100$), a deviation from the theoretically expected linear dependence of $1/M$ vs $V$ is observed. This deviation can be described by two effects: (1) the influence of the space charge of the multiplied carriers and (2) the pulsing mechanism of the microplasma. Because of this deviation, microplasma diameters of less than $1 \mu$ cannot be accurately determined.

Another consequence of the pulsing effect is an apparent negative resistance in the $V$–$I$ characteristic of a diode containing a microplasma. Dependence of the apparent negative resistance on load resistance, shunting capacity, and light intensity was investigated, and can be explained with the pulse model.

1. INTRODUCTION

P

REVIOUS investigations of avalanche breakdown in silicon $p$–$n$ junctions showed that there are at least two different kinds of avalanche breakdown. The first is characterized by a very small localized area of reduced breakdown voltage, the so-called microplasma. Microplasmas have been shown to be caused by imperfections in the crystal lattice. The second kind of breakdown, which occurs in the absence of imperfections, is distributed over the whole area and was first observed by Batdorf et al. The present two papers are devoted to new results on this subject, with the following paper hereafter referred to as II.

The present paper describes an improved experimental technique for the investigation of photomultiplication in very small areas, particularly microplasmas, and the results obtained. The most significant parameter in the avalanche region that can be experimentally measured is the multiplication factor $M$. The usual way of measuring $M$ is by measuring the multiplication of carriers generated by light or alpha particles within a diffusion length from the junction. The multiplication factor can then be obtained from the relation

$$M(V) = \frac{I(V)}{I_0},$$

where $I(V) =$ photocurrent at voltage $V$ and $I_0 =$ photocurrent at zero voltage.

By using a chopped beam of light of a very small diameter, it is possible to measure multiplication from point to point over the junction area for a shallow diffused junction in which photocarriers are able to diffuse to the junction. A different multiplication vs voltage curve is obtained when the light spot is focused on a microplasma than when it is focused on a region without imperfection.

The multiplication vs voltage data are evaluated by a method pointed out by Shockley. He finds that the voltage dependence of the multiplication at voltages approaching the breakdown voltage $V_B$ can be expressed by

$$1/M = (V_0 - V)(n/V_B),$$

where $n$ is a constant. This expression is in very good agreement with experimental data, provided the area in which multiplication occurs has a uniform breakdown voltage. If there is an area of significantly lower breakdown voltage, i.e., a microplasma, the multiplication law is altered. From the deviations in the multiplication characteristics, the ratio of light spot area to microplasma area can be determined.

The small light spot technique also permits deter-

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mination of the highest multiplication obtainable in a microplasma. It can be expected that as the applied voltage gets very close to the breakdown voltage, Eq. (2) will no longer apply because it requires \( \frac{1}{M} \) to become infinity for \( V = V_B \). With a small light spot, it is possible to measure extremely high values of multiplication.

As discussed in particular by Shockley\(^4\) the multiplication factor is linear in voltage. In the uniform region \( 1/M \) is given by Eq. (2), repeated below

\[
I = M I_o = (M_m a_m + M_u a_u) I_o,
\]

where \( M \) is the observed multiplication of the photocurrent.

Near breakdown, the reciprocal of the multiplication factor is linear in voltage. In the uniform region \( 1/M \) should vary as shown in Fig. 2. For voltages substantially below \( V_m \), the multiplication should be dominated by the uniform region on which most of the light falls. As the avalanche breakdown \( V_m \) is approached, the microplasma region dominates and, for voltages quite close to \( V_m \), this domination is so pronounced that \( M \) is determined largely by the microplasma region. Accordingly, we may write

\[
1/M_m = (V_m - V) n_u/V_u,
\]

As discussed in particular by Shockley\(^4\) the multiplication factor for two regions having different breakdown voltages, as in the case represented by Eq. (3) should vary as shown in Fig. 2. For voltages substantially below \( V_m \), the multiplication should be dominated by the uniform region on which most of the light falls. As the avalanche breakdown \( V_m \) is approached, the microplasma region dominates and, for voltages quite close to \( V_m \), this domination is so pronounced that \( M \) is determined largely by the microplasma region. Accordingly, we may write

\[
M = M_m a_m
\]

for \( V \) in the neighborhood of \( V_m \).

The approximation (7) can be used to interpret experimental data of the sort shown in Fig. 3 in order to obtain the factor \( a_m \). This is done by noting that in accordance with approximations (7) and (6) we may write for the slope on Fig. 2 the value

\[
-d(1/M)/dV = n_m/V_m a_m.
\]

If \( n_m \) and \( V_m \) do not differ by large factors from \( V_u \) and \( n_u \), then the slope of the \( 1/M \) line of Fig. 3 will be

1. **THEORY**

2. **Estimates of the Sensitive Area of a Microplasma Region**

In this section, we consider how experimental data on multiplication factor vs voltage can be interpreted in order to estimate the size of the region in which the multiplication factor is especially large. For this purpose, we use a model in which it is assumed that the junction area can be divided into two regions. One is a uniform region in which the multiplication factor is \( M_u \). The other region, which is potentially a microplasma region, is much smaller and has a lower breakdown voltage and higher multiplication factor denoted by \( M_m \).

We assume, as shown in Fig. 1, that the illumination falls in a circle on the specimen, the circle having a diameter \( D_L \) and a corresponding area \( A_L \). Under the experimental conditions of interest in this study, \( D_L \) is much larger than the diameter \( D_m \) of the local region having the lower breakdown voltage. The fraction of the light area that falls upon the local region is denoted by \( \alpha_m \):

\[
\alpha_m = D_m^2/D_L^2 \ll 1.
\]

The last inequality applies to the cases of particular interest in which the area of the microplasma region is small compared to the area of the light spot.

When a current of photocarriers \( I_o \) is generated uniformly over the area \( A_L \), then a fraction \( \alpha_m \) of this current flows across the junction in the microplasma region and a fraction \( \alpha_u \) flows across in the uniform region. (Evidently, \( \alpha_m + \alpha_u = 1 \).) The total current flowing across the junction is then given by

\[
I = M I_o = (M_m a_m + M_u a_u) I_o,
\]

Fig. 1. Area of light spot compared with area of local low breakdown or microplasma region.

Fig. 2. Approximate dependence of multiplication factors upon voltage for two regions.
larger than the slope for the uniform case by a factor \(1/a_m\). Thus the difference in slope between the uniform curve and the microplasma curve can be used to interpret the area of the microplasma region, provided that the area of the light spot itself is known.

This analysis can be carried out more precisely as follows: the ratio \(S\) of the slopes of the characteristic for the composite junction is compared with the extrapolation of the uniform area curve according to Eqs. (5) and (6). This ratio should be

\[
S = [d(1/M)/dV] + [d(1/M_a)/dV] = \left(\frac{n_m}{V_m a_m}\right) \left(\frac{V_u a_u}{n_u}\right).
\]

This equation can be solved for \(a_m\) yielding

\[
a_m/a_u = n_m V_u/n_u V_m S = V_u/V_m S.
\]

In this equation, the only quantity which cannot be determined from data like that of Fig. 3 is \(n_m\). However, if the lowering of breakdown voltage for the microplasma region from that of the uniform region is not large, then it is probable that the value for \(n_m\) will be approximately equal to \(n_u\). In most of the cases, especially for small microplasmas, the value of \(a_u\) is close to unity and, therefore, negligible as a factor. Accordingly, Eq. (10) may be used to estimate \(a_m\).

2.2. Maximum Multiplication of a Microplasma Region

In this section we deal with the theory of the multiplication of photocurrents in devices operating in the voltage range where microplasmas form. This situation differs in a significant way from the lower voltage range discussed in Sec. 2.1. In that case, each photon falling in a given region was assumed to produce an additional photon. In the voltage range where microplasmas form, the situation is very different. The microplasma switches on to a more or less fixed current, and when in this on condition it is not appreciably affected by an additional photon. On the other hand, when the microplasma is turned off, a photon in the microplasma region may well cause it to switch on again.

We discuss a theory of how a microplasma region should behave so far as multiplying photocurrent is concerned. This theory is based on a model for the microplasma which is in general agreement with experimental findings on microplasma behavior.9,10 The theory permits prediction of how the behavior of the diode will depend upon the level of illumination falling on the region of the microplasma, and leads to ways in which experimental measurements can be obtained to interpret various aspects of the process. These predictions also constitute tests of the validity of the model.

The high multiplication voltage range where microplasmas form is divided for purposes of discussion in two parts: (1) the upper voltage range of saturated pulse current at very high multiplication; and (2) the transition voltage range comprising the onset of the pulse mechanism.

The upper voltage range (1) is described by three constants:

- \(I_1\) = microplasma current in on condition,
- \(\tau_1(V)\) = average time that the microplasma is on,
- \(\tau_0(V)\) = average time that the microplasma is off.

Let \(f_1\) denote the fraction of the time that the microplasma is on. Evidently, \(f_1 = \tau_1/\left(\tau_1 + \tau_0\right)\). If \(f_1\) is small, then the effect of the carriers produced by the photocurrent is to cause the microplasma to switch on more than it would do in their absence. This results in an increase in the photocurrent, which can be interpreted as multiplication. When \(f_1\) increases, the fraction of carriers arriving when a pulse is on will also increase. Those carriers will not be multiplied. This enters into the multiplication law as follows:

\[
M(V) = \left(I(V)/I_0\right) = \left(I_1 f_1/q N_0\right) = \left(I_1/q N_0\right) N \tau_1,
\]

where \(I(V)\) = average current measured at applied voltage \(V\), \(I_0\) = photocurrent at low voltage, \(q\) = charge on the electron, \(N_0\) = total number of photocarriers injected per second within the illuminated region, \(N\) = number of pulses per second, \(N_0\), and \(\tau_1\) are related by a formula derived for the case of a discharge in an ionization counter, which is very similar to the one treated here,11 and states that \(N\) the number of pulses generated is equal to the potential number
Fig. 5. Photocurrent $I_0$ when 2-$\mu$m light spot is moved across the edge of a broken diode.

$N_0$ times the fraction of the time $1/(1+N_0 \tau_1)$ that the microplasma is off and waiting:

$$N = N_0/(1+N_0 \tau_1).$$

If the area of the microplasma is only a fraction $a_m$ of the light spot area, this equation is modified by reducing the potential number of pulses to $a_m N_0$:

$$N = a_m N_0/(1+a_m N_0 \tau_1).$$

The photocurrent approaches a limiting maximum value when $a_m$ approaches unity. From (1) the corresponding limiting value of $M$ is:

$$M_{lim} = I_1/q N_0.$$  

This limiting $M$ is dependent on light intensity through $N_0$, and increases with decreasing intensity.

The theory for the transition voltage range (2) differs from the upper voltage range (1) in that in keeping with observations on the oscilloscope no constant pulse current is assumed. This range can best be described by a high multiplication $M^*$ for each carrier initiating a pulse and a relaxation time $\tau_1$ during which multiplication takes place. Both $M^*$ and $\tau_1$ are increasing functions of the voltage. No other carriers can be multiplied during this time.

The average current is represented by

$$\bar{I} = NM^* q.$$  

From Eqs. (11), (13), and (15) we obtain

$$M = \frac{NM^* q}{N_0 q} = M^* N_0 \frac{a_m}{1+a_m N_0 \tau_1}$$

or

$$\frac{1}{M} = \frac{1}{a_m M^*} \frac{I_0 \tau_1}{q} = \frac{1}{a_m M^*} \frac{I_0 \tau_1}{q},$$

where

$$I^* = q/\tau_1.$$  

Equation (17) can be transformed into Eq. (11) by letting $M^* q = I_1 \tau_1$.

3. EXPERIMENTAL TECHNIQUE

3.1. Preparation of Samples

The diodes used for this investigation were $n^+ p$ diffused planar guard ring diodes having a junction depth in the active region of approximately 0.6 $\mu$m and a bulk breakdown voltage of 30 V. The junction is close enough to the surface to permit light emission observation and adjustment of a small light spot on a microplasma. The diffusion technique for planar guard ring avalanche diodes is described in the paper II of this series.

3.2. Optical and Mechanical Arrangement

The optical arrangement was designed to permit positioning of very small light spots (1-25 $\mu$m diameter) on microplasma regions. This technique has also been used by Kikuchi but only with light spots of 70-$\mu$m diameter. If one wants to determine the size of a microplasma, however, then it is necessary to use light spots not more than about 20 times larger in area than the microplasma itself.

The photocurrents generated by such small light spots range from $10^{-9}$ to $10^{-12}$ A, which is two to three orders of magnitude smaller than the dark current of the diode. Therefore, the light beam was chopped and the diode current passed through a narrow band filter tuned to the chopping frequency.

Figure 4 shows the optical and mechanical arrangement. The light source is a high pressure mercury arc lamp with an arc diameter of 0.3 mm. The beam is chopped at a frequency of 390 cps. The small light spot is obtained by focusing a small opening in a metal foil (hole sizes ranging from 10 to 400 $\mu$m) through a microscope objective onto the microplasma. Intensity of the light can be varied in reproducible steps by an iris diaphragm.

All the measurements were made with blue light obtained from a blue filter with a transmission range of 3200 to 5800 A. Thus more than 80% of the light was absorbed within 0.5 $\mu$m, from the surface, a condition that was chosen for two reasons: (1) Nearly no light is being absorbed in the space-charge region, a condition that was chosen for two reasons: (1) Nearly no light is being absorbed in the space-charge region. Therefore, the measurement will not be significantly affected

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$^{12}$ No transmission of the filter in the infrared has been found.
by changes in the photocurrent due to changes in space-charge layer width at different voltages. (2) Predominantly holes are being used as primary carriers. This is necessary because of the difference of ionization coefficient for holes and electrons which leads to a nonlinear dependence of \(1/M\) vs voltage for electrons.

With the optical arrangement described, light spots with a diameter of 10 \(\mu\) or more can be produced and used for measurement. For smaller light spots, non-uniform distribution of light over the area due to scattering, diffraction, and multiple reflection has to be considered. In order to determine the distribution of light intensity in the spot it would be desirable to have a point or line detector of dimensions small compared to the light spot. Such detectors were not available. Instead a straight edge of sharp resolution was formed by cracking a silicon slice with a diffused layer and measuring photocurrent as the light spot traversed the slice across the edge. The resulting curve for photocurrent vs position is shown in Fig. 5. The two points on either side of the largest drop in current were separated by a motion of 2.5 \(\mu\). Exposing a photographic film by shining the light spot on it showed a bright center about 1.4 \(\mu\) in diameter. It can be seen in Fig. 5 that most of the photocurrent is generated within a small region corresponding to the 1.4-\(\mu\) center part. On the basis of this information the photocurrent density in the center region of the light spot is assumed to be the same as if the \(3.9 \times 10^{-10}\) A of Fig. 5 were uniformly spread over a circle of 2-\(\mu\) diameter.

The adjustment of a very small light spot has to be accurate and stable at least within 0.2 \(\mu\) during the duration of the measurements discussed in Sec. 4.2, which sets rather stringent requirements for the mechanical arrangement. The smallest light spot giving useful quantitative results was found to be 2 \(\mu\) wide.

### 3.3. Electrical Arrangement

The electrical arrangement permitting multiplication measurements and microplasma pulse observations on the same diode is shown in Fig. 6. The reverse bias is measured at the diode terminals shown as \(V\). The chopped photocurrent passes through the load resistance \(R_b\) leading to an ac voltage. This ac signal is amplified by a low-noise, low-level preamplifier and passed through two narrow bandpass filters. Each filter consists of an amplifier stage with a double-T network having frequency-dependent feedback. Simultaneous observations of the amplitude and frequency of an oscillator signal on the oscilloscope makes it possible to adjust the center frequency of the bandpass filter to the chopper frequency within 0.2 cps at 390 cps, provided that the power line frequency driving the synchronous motor of the chopper is sufficiently stable. The bandwidth was adjustable from 0.5 to 10 cps, and was normally chosen between 2 and 4 cps.

The noise of the load resistance \(R_b\) is critical. For the detection of very small photocurrents \(R_b\) should be as high as possible. For high values of \(R_b\) the noise voltage at the amplifier input is proportional to \((R_b)^3\) and is larger than the amplifier noise. The ac signal from the photocurrent is proportional to \(R_b\). Therefore, the signal-to-noise ratio is proportional to \((R_b)^4\). The useful size of \(R_b\) is limited by the shunting capacity of the diode and its voltage dependence. In order to eliminate the voltage dependence of the diode capacity, the load resistance \(R_b\) has to be small in comparison to \(1/\omega C_{40}\), where \(\omega\) is the chopper frequency and \(C_{40}\) the diode capacity at zero bias. Good results have been obtained with \(R_b = 100 000\) \(\Omega\).

Other sources of error are the instability of the mercury arc lamp, pick-up noise and preamplifier noise, nonlinearity of preamplifier and filters, and the readings of \(I_b\) and \(M I_b\) on the oscilloscope. For a light spot of 5-\(\mu\) diameter and a photocurrent \(I_b > 10^{-10}\) A, the error in the measured multiplication factor \(M\) is estimated to be <5%.

For microplasma noise observations the load resistance \(R_b\) is changed to a value of 100 \(\Omega\). The voltage drop across \(R_b\) due to the microplasma pulses is amplified by the two broad band amplifiers and observed on an oscilloscope.

The average current through the diode can be meas-
ured as a voltage drop $V_I$ across a 100-$\Omega$ resistor in series with the diode.

4. RESULTS

4.1. Microplasmas and $V-I$ Characteristics

The $V-I$ characteristic in the breakdown region of a diode with several microplasmas is shown in Fig. 7. Breakdown of the first four microplasmas can be readily seen. It should be noted that the $V$ and $I$ values of Fig. 7 are average values and that in the negative resistance regions the diode is carrying current in pulses. (See Sec. 5.1 for a detailed discussion.) Between currents corresponding to two microplasmas there is always a straight part of the $V-I$ characteristic, representing the resistance of those microplasmas that are in the on condition. From Fig. 7, the resistance of the first three microplasmas is found to be of the order of $10^6$ $\Omega$ per microplasma, in keeping with values expected for space-charge effects.4

(The microplasma No. 4 in Fig. 7 was observed to emit yellow light rather than red, suggesting that it was very near or actually at the surface of the silicon slice. Its breakdown voltage is unstable and it does not behave like a regular microplasma. This type of microplasma was not studied in detail in the present investigation.)

The exact shape of the characteristic in the negative-resistance breakdown region of the $V-I$ characteristic is strongly dependent on load resistance, shunting capacity (including diode capacity), and light intensity. In Fig. 8, several $V-I$ characteristics are plotted for a diode with several load resistances and the single fixed total capacity of 350 pF. In Fig. 9 the same plot is given for the single fixed load resistance of 100 000 $\Omega$ and several capacitance values. Figure 10 shows the dependence on light intensity for a load resistance of 10 k$\Omega$ and a shunting capacity of 350 pF. Increasing light intensities have qualitatively the same result as increasing capacity. For higher light intensities the negative part in the $V-I$ characteristic disappears. Because of this dependence the observation of the negative part in the $V-I$ characteristic is only possible on microplasmas with low pulse repetition rate. A discussion of these results is given in Sec. 5.1.

4.2. Multiplication Measurements on Microplasmas

Since it was desirable to check the light spot technique for area determination with another independent measurement, initial measurements were made on a very large microplasma. These microplasmas are very rare and their origin is unknown. The one used in this investigation was found by chance during observations of light emission at reverse breakdown. It had a clearly defined and measurable diameter which increased with increasing current [Fig. 11 (a)-(c)]. The photographs
show a dark spot in the center of the big microplasma. It does not seem possible to explain the difference in light intensity as due to voltage drops in the diffused layer produced by reverse current. At a current of 1 mA we have calculated this voltage drop to approximately 8 mV. This is much less than the inaccuracy of 100 mV in the measurement of the breakdown voltage (Fig. 12). We believe, therefore, that the dark center is caused by a slightly higher breakdown voltage.

There are two independent ways of measuring variation of breakdown voltage across the microplasma: (1) Assuming the applied voltage is equal to the breakdown voltage at the edge of the light emission, we can plot the radius of the light emission vs applied voltage, or equivalent to this, the breakdown voltage \( V_B \) vs distance. (2) The local breakdown voltage can be determined by scanning the microplasma with a 2- \( \mu \) light spot and extrapolating the \( 1/M \) curves. The two curves in Fig. 12 are obtained by the two techniques. The agreement is very satisfactory. The multiplication technique gives a curve somewhat lower than indicated by the light emission. This is to be expected, because multiplication is dominated by the lowest breakdown voltage within the light spot region.

In order to determine the reliability of this method of area measurement, light spots of different sizes were used to measure \( 1/M \) vs \( V \) curves on this microplasma. The results are shown in Fig. 13. In Fig. 14 the breakdown region is expanded. Microplasma areas as determined by Eq. (10) are shown in Table I for microplasma (a).

Results for two other microplasmas of medium and small size are also shown in Table I. It can be noted, particularly for the small microplasma (c), that different light spot sizes lead to different microplasma diameters. The \( 1/M \) curves from which the values for microplasma (c) are obtained are shown in Fig. 15. All \( 1/M \) values are independent of light intensity in the range used for the area calculations. It can be noted

### Table I. Evaluation of microplasma diameters.

<table>
<thead>
<tr>
<th>Microplasma No.</th>
<th>( D_L(\mu) ) (diam of light spot)</th>
<th>( D_m(\mu) ) (diam of micropl.)</th>
<th>( a_m ) (area ratio)</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>8</td>
<td>4.8</td>
<td>0.35</td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>4.8</td>
<td>0.17</td>
</tr>
<tr>
<td></td>
<td>24</td>
<td>5.0</td>
<td>0.05</td>
</tr>
<tr>
<td></td>
<td>56</td>
<td>6.1</td>
<td>0.01</td>
</tr>
<tr>
<td></td>
<td>168</td>
<td>18.3</td>
<td>0.001</td>
</tr>
<tr>
<td>b</td>
<td>8</td>
<td>2.8</td>
<td>0.1</td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>2.6</td>
<td>0.05</td>
</tr>
<tr>
<td>c</td>
<td>2</td>
<td>0.9</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>1.4</td>
<td></td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>2.1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>3.1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>24</td>
<td>6.3</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 14. Expanded breakdown region of a 5- \( \mu \) microplasma for different light spot diameters.
that these curves do not change in slope in proportion to the light spot area, and also show a shift in extrapolated breakdown voltage. The reasons for this behavior is discussed in Sec. 5.2.

5. DISCUSSION OF RESULTS

5.1. V–I Characteristic

The breakdown region of the V–I characteristic (Figs. 8–10) can be qualitatively explained with a model proposed by Champlin. Champlin’s model in its simplest form is described by three constants: a breakdown voltage \( V_B \), a time \( \tau_0 \), and a current \( I_1 \). If the voltage is below \( V_B \), the microplasma is off and carries negligible current. If the voltage rises above \( V_B \), the microplasma waits on the average for a time \( \tau_0 \) and then switches on and carries current \( I_1 \). If the voltage drops below \( V_B \), the microplasma at once switches off.

The V–I characteristics of Figs. 8–10, as discussed in Sec. 4.1, correspond to average values of the current and the voltage applied to the diode. The occurrence of the negative resistance portion of the V–I characteristic may be understood in terms of Champlin’s model as follows: If the average current flowing through \( R_B \) in Fig. 6 is \( I_1 \) or a little more, the diode is on all the time at a voltage \( V_B \) so that \( V \) and \( I \) on the V–I characteristic are \( V_B \) and \( I_1 \). Suppose, however, that the average current passed through \( R_B \) is \( I_1/2 \); then the diode is on about half the time. When it is on it discharges the shunting capacitor (discussed in Sec. 4.1) to the voltage \( V_B \) and then turns off. After it turns off, the voltage then rises at a rate of \( I_1/2C \) for an average length of time \( \tau_0 \) and then turns on. Thus it is evident that for an average current \( I = I_1/2 \) the average voltage \( \bar{V} \) is higher than \( V_B \) and thus higher than for \( I = I_1 \). Hence the two average currents \( I_1/2 \) and \( I_1 \) are connected by a decreasing voltage portion of the V–I characteristic corresponding to a negative resistance. This negative resistance, however, arises only as a result of the measurement of the average dc characteristic of a discontinuous pulse process. In this respect the negative resistance of a microplasma is fundamentally different from a real negative resistance as can be found in gas discharges and three- or four-layer diodes.

5.2. Multiplication Measurements

The results of the area measurements given in Sec. 4.2 show that reliable measurements of the microplasma diameter are only obtained when the area of the light spot is not too large compared to the microplasma area. The higher the ratio of light spot to microplasma area, the higher the multiplication in the microplasma has to be in order to become noticeable in the measured photocurrent.

For high multiplications we observe a deviation in \( 1/M_m \) vs \( V \) from a straight line. Recent experiments indicate that this deviation is due to at least two effects: (1) At medium multiplications \( (50 < M_m < 1000) \) the deviation is independent of light intensity and may be caused by the space charge of the multiplied carriers; (2) at high multiplications \( (10^3 < M_m < 10^6) \) the influence of the microplasma pulse mechanism as discussed in Sec. 2.2 exceeds the space-charge effects. This failure...
of $1/M_m$ to go to zero according to the linear law is another limit in addition to the experimental limitations for the size determination of very small microplasmas, and can be shown to cause the apparent shift in breakdown voltage for microplasma $(c)$ shown in Fig. 15. For very small microplasmas this deviation of $1/M_m$ starts at a relatively small total multiplication $M$. Determination of the microplasma area by the two slopes of the $1/M$ curves is of course only permissible as long as $1/M$ is linear in voltage. For Fig. 15 the area of the microplasma is so small compared to the light spot area that this deviation becomes effective and thus accounts for the shift of the multiplication curves.

Confirmation that the above explanation of the behavior of Fig. 15 is correct is obtained by verifying that changes in apparent $V_B$ and microplasma diameter are expected when the deviation of $1/M_m$ vs $V$ from a linear law is reached. The verification consists of using the measured behavior for microplasma $(c)$ for the 2-$\mu$ light spot to calculate correctly the behavior for the 24-$\mu$ light spot. The photocurrents for the microplasma and for the surrounding area are additive, independent of how $1/M_m$ changes with voltage. Therefore, when the $1/M$ curve for a small light spot on a microplasma is known, the curve for a much bigger light spot area can be calculated. This additive property is illustrated in Fig. 16 using data from Fig. 15. Curve A is repeated from the 2-$\mu$ curve of Fig. 15 and curve C from the 24-$\mu$ curve. The triangles are points calculated from Eq. (4) of the multiplication one would expect from the large spot, using $a_m = (2/24)^3$, $M_m$ from curve A, and $M_u$ from the straight part corresponding to the uniform area of curve C at voltages below those shown in Fig. 16. Curve D is obtained by applying the same procedure to the ideal curve B.

Results obtained by the localized photomultiplication technique show that various sizes of microplasmas exist. Diameters of these microplasmas range from 5 $\mu$ to much smaller than 1 $\mu$. A comparison of these findings with previous results is of interest. Rose\textsuperscript{13} estimates theoretically a diameter of 0.05 $\mu$ for a microplasma, a value which is also used by Senitzky and Moll\textsuperscript{12} to explain their experimental results. Goetzberger and Stephens\textsuperscript{3} on the other hand found values between 0.09 and 0.7 $\mu$. Microscopic observation of microplasmas reveals that most of them are too small to be resolved (<0.8 $\mu$). Results of this investigation show that the previous data are not necessarily contradictory because microplasmas can obviously occur in a wide variety of sizes. The reason for this variation is at present unknown but is not unexpected if the microplasma action depends on charge trapping mechanisms or on structural defects of the sort proposed by Shockley.\textsuperscript{4}

5.3. Multiplication in the High Voltage Range where Microplasmas Form

Very high multiplication factors could be obtained by using a 6-$\mu$ light spot in the center region of the large 5-$\mu$ microplasma ($a_m$ is within the limits of the error). From Eq. (17) it follows that $1/M$ varies linearly with $I_0$ at constant voltage. This is the case as can be seen in Fig. 17 where $1/M$ is plotted vs $I_0$ with $V$ as parameter. The slope of those lines is $\tau_1/M^*\hat{q}$, the intercept with the ordinate is $1/M^*$. Both $M^*$ and $\tau_1$ increase with increasing voltage. Therefore, the curves in Fig. 17 change slope and move downward as voltage is increased. In Fig. 18 the logarithms of $M^*$ and $\tau_1$ are plotted vs voltage. The curves are linear over three decades in $M^*$ and two decades in $\tau_1$, indicating an exponential dependence on voltage in the

*\textsuperscript{13} D. J. Rose, Phys. Rev. 105, 413 (1957).
breakdown range.\textsuperscript{14} $M^*$ and $\tau_1$ can, therefore, be expressed by
\begin{align}
M^* &= M_0^* e^{V/V_M} \\
\tau_1 &= \tau_0 e^{V/V_r}.
\end{align}

The dependence of $\tau_1$ on $M^*$ is given by
\[\tau_1 = \text{const.} \cdot (M^*)^{V_M/V_r}.
\]

From Fig. 18 we obtain $V_M = 0.0145$ V, $V_r = 0.0204$ V, $V_M/V_r = 0.71$. From measurements on a uniform diode (see paper II) we found a similar exponential dependence of $M^*$ and $\tau_1$ on $V$ with $V_M/V_r = 0.67$.

### 5.4. Extrapolated Breakdown Field

By extrapolation of the $1/M$ curve to zero, it is possible to arrive at the bulk breakdown voltage. This measurement can be made either by measuring multiplication at a microplasma free part of the diode or by using a light spot extending over both a microplasma and a uniform area. In the first case multiplication can only be measured up to the breakdown voltage of the first microplasma. Shunting of the diode by this microplasma prevents measurement at higher voltages. If the light beam is adjusted to the microplasma with the lowest breakdown voltage, the full $1/M$ curve can be measured. The resulting extrapolated breakdown voltage is the same in both cases provided the measurements are taken at points not too distant from each other. From the extrapolated breakdown voltage the extrapolated breakdown field can be calculated. Breakdown fields obtained this way check with those measured on uniform diodes which occurred on the same slice of silicon but did not have microplasmas. For those the $1/M$ curve is straight to within 0.1 V or less of $1/M = 0$ and extrapolation to $1/M = 0$ on the straight line can be made with an accuracy of about ±0.05 V (these results are discussed more fully in Paper II of this series). Plots of $1/M$ vs voltage for different microplasmas also serve to show how far below the bulk breakdown voltage the microplasmas occur. Thus one can obtain information about the quality of diodes produced on a slice by a given procedure.

### 6. CONCLUSIONS

It has been shown that localized photomultiplication measurement in conjunction with plotting the reciprocal multiplication factor as suggested by Shockley\textsuperscript{4} is a valuable tool for the investigation of $p$-$n$ junctions. It is possible to determine the area of localized low breakdown spots, in particular of microplasmas, provided the ratio of light spot area to microplasma area is not too large. This limitation can be explained by a deviation from the linear $1/M$ law at high multiplication due to the space-charge effect of the multiplied carriers, and eventually a saturation of the multiplication factor at a value which is dependent on light intensity. The pulsing mechanism causes discontinuities and, under certain conditions, an apparent negative resistance in the $V-I$ characteristic.

A technique is available to correlate microplasma breakdown voltage by extrapolation of $1/M$ plots to zero $1/M$. Thus conclusions related to the perfection of the junction can be drawn. The technique described proved very valuable in the development of diffusion processes for microplasma-free junctions reported in Paper II of this series.

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