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Internal Field Emission in Silicon *p-n* Junctions

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Internal field emission is believed to occur in narrow *p-n* junctions in silicon. This conclusion is based on the following observations: (i) as in wide junctions, the multiplication characteristic has a positive temperature coefficient whereas the reverse characteristic, unlike wide junctions, possesses a negative temperature coefficient; (ii) the forward and reverse currents are relatively insensitive to temperature; (iii) radiative transitions of energetic carriers in the high-field region result in the emission of visible light, the pattern of which shows that the current flows more or less uniformly through the whole extent of the junction but that the array of fewer and more intense light spots characteristic of avalanche breakdown is absent; (iv) the noise associated with the onset of avalanche breakdown is absent. It is concluded that in these narrow junctions the junction space charge field due to the built-in potential alone is sufficient to result in a rate of carrier generation much greater than that of the normal thermal processes. By assuming a reasonable form for the voltage dependence of the field-generated current, it proves possible to account qualitatively for the complex forward-bias characteristics of these junctions. The reverse characteristics show the onset of multiplication of field-emitted carriers at a reasonable threshold. Possible causes of the softness of the reverse characteristics are discussed.

INTRODUCTION

WHEN the reverse voltage applied to a *p-n* junction reaches a critical value, electrical breakdown occurs, as evidenced by the onset of an extremely rapid increase of the current with voltage. In early work on germanium and silicon, this breakdown was attributed to internal field emission, a process that had been considered theoretically by Zener in connection with breakdown in insulators.[1] This theory was extended by Shockley to semiconductors and it was apparently verified by analysis of the reverse characteristic of a low breakdown-voltage germanium *p-n* junction.[2] A feature of the experimental work was that the junction failed to exhibit any charge multiplication when biased at just below breakdown. Subsequent studies[3,4] of charge multiplication in reverse-biased junctions have demonstrated conclusively that charge multiplication should have been occurring at the fields thought to have been present. Furthermore, though the slope of the published curve in the Zener region agreed quite well with the theoretical prediction, subsequent measurements on a number of samples showed widely difference slopes.[5] Consequently, it is not certain that internal field emission was responsible for the breakdown characteristic. It is the purpose of this paper to present more solid evidence of the occurrence of internal field emission.

EXPERIMENTAL

The high field strengths required in order to observe the Zener effect exist in highly-doped silicon junctions where the junction width can be as little as 400 angstroms. These narrow junctions can be produced readily by diffusion techniques. The results described in this paper were obtained on units prepared from the same parent crystal and in the same manner that has been described in detail elsewhere.[6] Similar results have been obtained for other junctions formed from many different low-resistivity parent crystals. The junction formed by the diffusion of phosphorus into low-resistivity (about 0.007 ohm cm) *p*-type silicon slices occurred at a depth of 2 to 3 microns below the etch-polished crystal surface and had a cross-sectional area of about 0.1 cm^2. Nickel electrodes were applied to the crystal surfaces by an electroless plating technique, the electrode on the polished surface covering about half of the area.

The forward and reverse characteristics and the multiplication characteristic were plotted directly on an $X-Y$ paper recorder with the crystal at room temperature and again when it was immersed in liquid nitrogen. The multiplication characteristic was obtained by injecting carriers into the junction by light and plotting the photocurrent as a function of the reverse bias. Measurements of the variation of the junction capacity with reverse bias gave information about the field distribution inside the junction, its width, and the built-in potential. The techniques of these multiplication and capacity measurements have been described elsewhere.[4]

RESULTS

a. Multiplication

The multiplication factor, M, is defined as the ratio of the photocurrent at a given voltage to its constant value at small values of the reverse bias. In Fig. 1, M is plotted as a function of the applied bias voltage, V_a, as measured at room temperature and also, at that of liquid nitrogen. The curves were traced directly from the $X-Y$ recorder chart and are not smoothed data. It was verified that the multiplication characteristic was independent of the intensity of the light. Because of the extremely low dynamic impedance of these junctions at biases of more than 3 or 4 volts, it was not possible

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[1] C. Zener, Proc. Roy. Soc. (London) **145**, 523 (1934).

[2] McAfee, Ryder, Shockley, and Sparks, Phys. Rev. **83**, 650 (1951).

[3] K. G. McKay, Phys. Rev. **94**, 877 (1954).

[4] A. G. Chynoweth and K. G. McKay (to be published).

[5] E. M. Conwell, Proc. Inst. Radio Engrs. **40**, 1327 (1952).

[6] A. G. Chynoweth and K. G. McKay, Phys. Rev. **102**, 369 (1956).

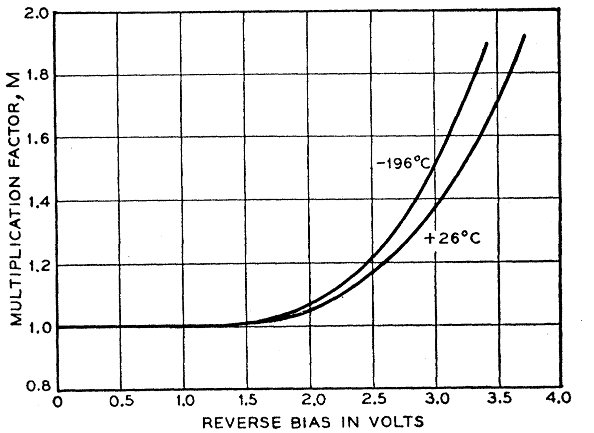

FIG. 1. The multiplication characteristics for a narrow junction at room temperature and at that of liquid nitrogen.

to extend these measurements to values of M higher than about 2. However, it is apparent that within this range a given amount of multiplication occurs at a lower voltage as the temperature is decreased and there is no reason why this behavior should not occur for all values of M. Thus, if breakdown were caused solely by multiplication leading to the avalanche condition, the breakdown voltage, V_B, would drop with temperature. This is consistent with the results obtained by McKay[3] for junctions with higher breakdown voltages. McKay found that the temperature dependence of the avalanche breakdown *voltage* for linear-gradient junctions can be described approximately by

$$V_{BT}=V_{B0}[1+\beta'(T-T_0)],$$

where the temperature coefficient, β', has the value $+6.7\times10^{-4}$/°C. From multiplication plots such as Fig. 1 for a number of junctions, the average value found for β' at the higher values of M was, approximately, $+5.0\times10^{-4}$/°C, which is regarded as in reasonable agreement with the above value. It was established that all the narrow junctions with which the present paper is primarily concerned showed positive temperature coefficients for the multiplication characteristics, the coefficient being defined by $(1/V_a)(dV_a/dT)$ for a given value of the multiplication.

For these junctions, when $M=2$, the maximum field in the junction is of the order of 10^6 volts/cm. Furthermore, the temperature coefficient for the breakdown *field* for a linear-gradient junction is $\beta=\frac{2}{3}\beta'\simeq3.3\times10^{-4}$/°C. McKay gave a plot of β *versus* field indicating that β was constant over the range $2.5\times10^5<E<5\times10^5$, while at larger fields β was tentatively shown as dropping to zero at $E=10^6$ volts/cm. This drop was based on a single determination of β (at $E=10^6$ volts/cm) from the rectification characteristics. As will be shown below, this leads to erroneous results for these narrow junctions. The present experiments show, therefore, that β remains roughly constant over the range $2.5\times10^5<E<10^6$ volts/cm.

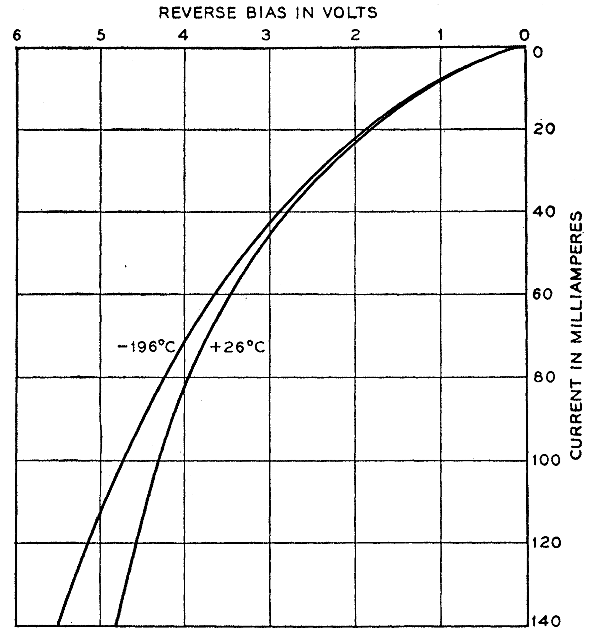

FIG. 2. The reverse characteristics for a junction classed as having a soft reverse characteristic.

b. Rectification

Unlike the multiplication characteristics, the way in which the rectification characteristic depended on temperature varied among junctions with different breakdown voltages. The reverse and forward characteristics for one of the junctions classed as having a low value for V_B are shown in Figs. 2 and 3. The characteristics were obtained by dc methods which allowed currents of up to about 250 ma to be drawn without significant heating of the units. Qualitative studies of the characteristics at higher currents were made by using a low duty-cycle pulser which had an output impedance of one ohm. The markedly soft nature of the reverse characteristic was maintained up to at least 1 amp, thus making it impossible to define V_B with any certainty. It was shown that for all values of the bias, the current dropped slightly with the crystal temperature while the breakdown voltage increased.

The semilogarithmic plots of the forward currents shown in Fig. 3 are unusual in several respects: The normal theory for rectification leads to an expression

$$I=I_s[\exp(eV/kT)-1],$$

where I_s is the thermally generated saturation current, e is the electronic charge, k is Boltzmann's constant, T is the absolute temperature, and V is the applied voltage, being positive for the forward direction. In the forward direction at room temperature the unity term can be neglected when compared with the exponential

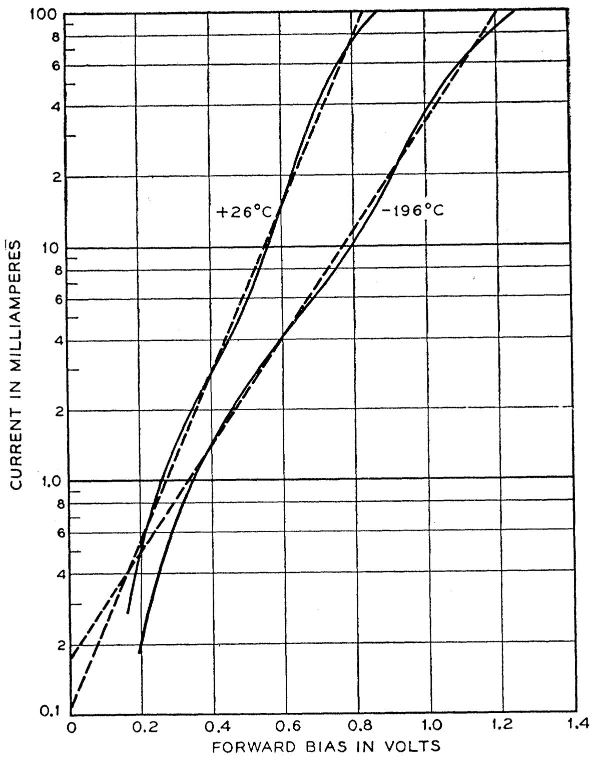

FIG. 3. Semilogarithmic plots of the forward characteristics for the junction whose reverse characteristics are shown in Fig. 2.

term for $V > 0.1$ volt. Thus a semilogarithmic plot should be a straight line of gradient (e/kT) and intercept I_s. Usually, I_s drops rapidly with the temperature while according to the rectifier equation, the slope of the plot increases as the temperature is reduced. From Fig. 3 it is clear that the junction in question does not follow the expected behavior; the plots wobble about a straight line in a way that was very reproducible, qualitatively, from crystal to crystal. Furthermore, extrapolating to zero voltage the straight lines which the curves tend to follow indicates that, for this particular junction, I_s is largely insensitive to temperature while the slope decreases instead of increasing. These observations will be discussed later.

The rectification characteristics obtained for a junction with a somewhat higher breakdown voltage (crystal O) are shown in Figs. 4 and 5. The reverse characteristics are not as soft as for the lower voltage unit. When the temperature is lowered, the reverse current drops at moderate values of the bias but then increases more rapidly and actually crosses over the room temperature characteristic, thus leading to a breakdown voltage lower than it had at room temperature. The forward characteristics shown in Fig. 5 this time indicate that I_s has dropped somewhat with the temperature while the general slope has remained more or less the same.

Measurements on junctions with breakdown voltages in the range 7 to 15 volts indicated that as the breakdown voltage increased, the current at which the crossover point in the reverse characteristics occurred decreased. In units with a breakdown of 10 volts or more, the current at which the crossover occurred was very small while V_B, which was sharply defined, possessed a positive temperature coefficient. Furthermore, the forward characteristics behaved qualitatively, though still not quantitatively, as expected from the rectifier equation.

The results relating to the rectification characteristics as well as the capacity and multiplication measurements are summarized in Table I for several units. It is to be emphasized that for very soft characteristics it is impossible to define a sharp breakdown voltage and instead, the junctions are classified according to the reverse bias required to produce a certain current density. The first two rows give the values of the reverse bias required to produce current densities of 1.0 and 0.1 amp/cm^2. The ratio of these two biases is called the softness ratio, recorded in the third row. The columns of the table are arranged in the order of decreasing softness ratio, that is, increasing hardness of the breakdown characteristic. The units used in these experiments, though made from the same parent crystal, had their junctions lying in different crystallographic planes; these are recorded in row 4. The temperature coefficient of the reverse bias required to produce a current density of 1.0 amp/cm^2 is given in row 5. Rows 6 and 7 show the values of I_s determined from the semilogarithmic plots of the forward characteristic at room and liquid nitrogen temperatures, while rows 8 and 9 give their average slopes. In row 10 is recorded the junction width at zero applied voltage as determined from the capacity measurements at room temperature.

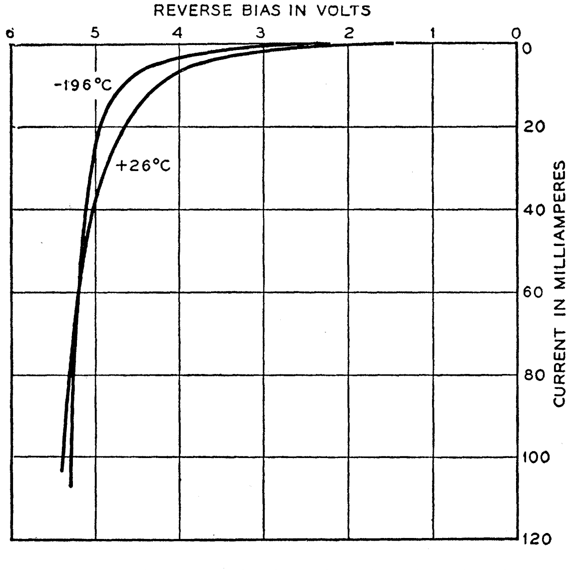

FIG. 4. Reverse characteristics for a junction classed as having a somewhat harder characteristic than that shown in Fig. 2.

Finally, row 11 shows the temperature coefficient for the multiplication characteristics as measured at $M=2$.

Though there is a fair amount of scatter in the results recorded in Table I, some definite trends can be established: The increasing hardness of the characteristic is paralleled by (i) an increase in the breakdown voltage, (ii) a decrease in the saturation current while its temperature coefficient increases from about zero towards positive values, and (iii) an increase in the average slope of the forward characteristic while the change of the slope with temperature progresses from an appreciable positive temperature coefficient towards zero. (Units with higher breakdown voltages show this coefficient eventually going negative, that is, the slope increases with a decrease in the temperature.) The table shows further that there is no obvious correlation between the breakdown voltage and the junction width in these units; measurements of the latter are equal to within experimental error. Also, the temperature coefficient of the multiplication characteristic shows no obvious trends, is in all cases positive, and scatters around the value of $+0.0005$ deg C^{-1}.

c. Absence of Avalanche Breakdown Phenomena

Previous published work has shown that a silicon junction carrying a high current at avalanche breakdown emits visible light and in particular, the light arises only at highly localized breakdown regions, or microplasmas.[6] McKay has shown[3] that the electrical noise associated with the onset of avalanche breakdown arises because the microplasmas carry the current intermittently; that is, they are continuously switching on and off. While they are on they carry a constant current of about 100 μa, and this figure is constant for the whole range of junction widths and breakdown voltages (i.e., $V_B>6.5$ volts) over which avalanche breakdown occurs.

In the narrow junctions reported in this paper, neither noise pulses nor a comparable array of light spots could be observed. This suggests that the high currents in the reverse direction are produced by a mechanism other than avalanche breakdown

Light emission was observed, however, though quite different in its spatial distribution to the avalanche case. Instead of a number of bright red spots appearing through the crystal surface, there was a very faint and more or less uniform red glow, visible to the dark-adapted eye at current densities of more than 2 amp/cm^2. A photograph of the emission is shown in Fig. 6; the exposure time was about 100 times that required for the previously published photographs of light emission from a junction in avalanche breakdown. The photograph suggests that the light is coming from a vast number of small spots and, from a rough estimate of the spot density, the actual current per spot was less than 10 μa, a value much smaller than that observed under avalanche breakdown conditions.

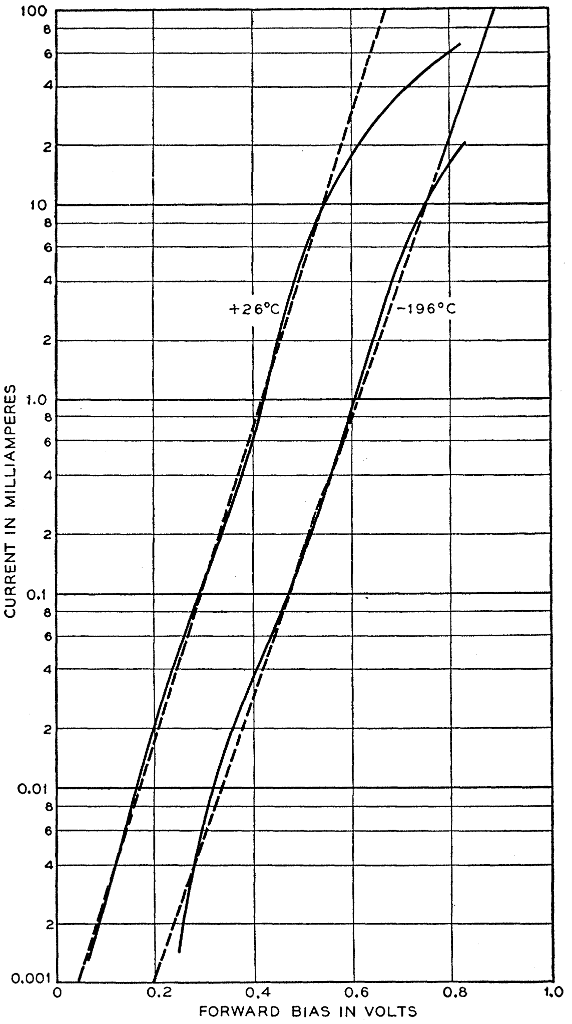

Fig. 5. Semilogarithmic plots of the forward characteristics for the junction whose reverse characteristics are shown in Fig. 4.

The fact that the light emission is approximately uniform over the whole area of the junction offers direct proof that most of the current is flowing uniformly through the junction rather than being confined to the surface layers by some spurious process. This conclusion was strengthened further by the fact that etching the junction edges of the units did not alter appreciably their rectification characteristics.

d. Fields Present in the Junction

It is necessary to consider whether the estimated fields in the junctions are sufficient to produce internal field emission. Capacity *versus* reverse bias studies were made of several of the junctions which showed that the field distribution inside the junction was very close to parabolic. From Table I, high currents were produced when $(V_a+V_i)\sim 6$ volts. The junction width for such a net bias was about 740 A, giving a maximum field

TABLE I. Data on the rectification and multiplication characteristics for a series of narrow *p-n* junctions.

Crystal	*N*	*J*	*E*	*I*	*R*	*K*	*P*	*L*	*D*	*M*	*H*	*O*
Reverse bias (room temp.) (at 1.0 amp/cm^2)	4.1	4.9	4.2	4.6	4.7	4.8	5.2	5.4	6.5	5.6	5.8	5.4
(at 0.1 amp/cm^2)	0.7	1.1	1.1	1.7	2.4	2.8	3.2	3.5	4.4	3.8	4.0	4.1
Softness ratio	5.85	3.72	3.91	3.07	1.96	1.60	1.64	1.55	1.48	1.47	1.45	1.32
Crystallographic plane	110	100	111	111	111	100	110	110	110	100	110	100
$10^4\times\frac{1}{V_B}\left(\frac{dV_B}{dT}\right)$, (°C)$^{-1}$	−5.4	−2.6	−4.1	−4.8	−3.8	−2.6	−3.3	−1.6	0	−0.8	−3.7	0
I, μa/cm^2 (room temp.)	6000	2800	1730	210	100	89	170	56	66	57	77	5.7
(N_2 temp.)	6000	2500	1520	85	20	27	98	12	5.2	12	2.5	0.4
$\frac{d(\ln I)}{dV}$, forward (room temp.)	5.7	7.2	7.8	10.5	12.8	12.1	13.8	12.4	12.1	13.7	11.2	18.7
(N_2 temp.)	4.1	5.5	5.6	8.2	10.5	9.0	9.7	9.4	12.1	11.7	11.8	16.8
Junction width, zero bias (angstroms)	441	415	415	445	378	396	400	398	400	398	411	400
$10^4\times\frac{1}{V_a}\left(\frac{dV_a}{dT}\right)$, (°C)$^{-1}$ (multiplication)	+2.8	+4.6	+8.9	+5.0	+4.9	+4.6	+4.9	+2.9	+5.7	···	+4.1	+3.5

$E_M \simeq 1.2\times10^6$ volts/cm. This figure is close to the value of 1.4×10^6 volts/cm predicted theoretically by Shockley's equation for silicon.[2] Also significant is that even at zero applied bias, the built-in potential results in maximum fields of about 4×10^5 volts/cm. Departures from perfect plane-parallel geometry of the space charge region (because of local fluctuations in impurity concentrations) could well result in zero-bias fields of perhaps 6×10^5 volts/cm. Thus, even at zero bias, the field conditions present in the junctions may be capable of producing some internal field emission.

e. Temperature Dependence of Reverse Characteristic

From what is already known about the multiplication processes in silicon *p-n* junctions, a positive temperature coefficient for the multiplication characteristic is not unreasonable, even for the narrowest junctions. The factors that determine the voltage V_a, that must be applied to produce a given amount of multiplication, are: (i) the built-in voltage, V_i, (ii) the energy, V_L, lost by the carrier to the lattice while traversing the space charge region of width W, and (iii) the energy, V_0, that a carrier must have to produce secondary electron-hole pairs. The temperature dependence of V_a is determined by the combined effects of the temperature variations of V_i, V_L, W, and V_0. Considering these individually and combining them, we conclude that the observed decrease in V_a with temperature requires that the energy lost to the lattice by the carriers in crossing the junction decreases by a few tenths of a volt on cooling to liquid nitrogen temperature. This could be accounted for by an increase of 10% to 20% in the carrier mean free path between inelastic collisions, which is regarded as quite reasonable.

A prediction of the temperature coefficient for internal field emission is much more difficult. The theory has yet to be formulated in terms of the energy band structure of silicon.[7] Moreover, our experimental conditions are considerably different from those that would normally be assumed for a theoretical model. At best it can be concluded that the temperature dependence of the field required to produce a given emission current will be small with either sign possible for the temperature coefficient.

f. Evidence of Internal Field Emission

The above experiments show that these narrow junctions behave quite differently from the wider junctions that exhibit avalanche breakdown. The basic experimental facts are: (i) as the breakdown voltage is lowered the temperature coefficient of V_B decreases from positive values, goes through zero, and becomes appreciably negative while the temperature coefficient of the multiplication characteristic is at all times positive and independent of the breakdown voltage, and (ii) a large decrease in the temperature results in a relatively small change in the magnitude of the reverse and forward currents. From (i), it follows that if breakdown were caused solely by multiplication leading to the avalanche condition, V_B would decrease with temperature for all values of V_B, contrary to the observations. From (ii), it is concluded that the carriers responsible for the large currents at low biases are not activated thermally. In particular, they are not generated at recombination centers throughout the space charge

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[7] G. H. Wannier, Phys. Rev. **100**, 1227 (1955). See also, Phys. Rev. **101**, 1835 (1956).

region.[8] As the reverse bias increases, the junction width increases as $(V_a+V_i)^{\frac{1}{3}}$ whereas the observed current increases as $(V_a+V_i)^m$, where m lies between 1 and 3. Furthermore, the fact that M is truly unity over a fairly wide range of the reverse bias and that at all biases it is independent of the light intensity indicates that there is a negligible enhancement of the diffusion current due to the voltage gradient produced by the current flow in the bulk of the crystal. Estimates of the current density required to produce a sufficient field in the low-resistivity material were orders of magnitude higher than the reverse currents actually present. The light emission pattern and the etching experiments show that spurious surface effects at the edges of the junction are not responsible for the large currents and, therefore, that the rectification characteristics are those of the junction in the interior of the crystal. Finally, the noise associated with the onset of avalanche breakdown was absent entirely from these narrow junctions. It is concluded that the only hypothesis consistent with the above experimental observations is that the high currents are generated mainly by internal field emission.

g. Effect of Internal Emission on Forward and Reverse Characteristics

Having concluded that we are dealing with internal field emission, let us consider in detail its effect on the forward and reverse characteristics.

Forward Characteristics

We now ascribe the abnormally high values of I_s and the complex forward characteristics to internal field emission occurring at zero or even small forward-applied biases. However, though the field may be sufficient, there is the additional condition that carriers must be able energetically to make transitions between the initial and final states. The fact that the built-in potential is approximately equal to the energy gap shows this to be possible at zero bias, as then the Fermi level runs through the top of the valence band on the p side and the bottom of the conduction band on the n side of the junction. At small forward biases, transitions can occur only from filled levels in the forbidden region though it is reasonable to suppose that there is a sufficient density and spread of such levels (on account of the high state of degeneracy of the crystal) to enable appreciable field emission at forward biases of up to a few tenths of a volt.

Let us assume some reasonable form for the dependence of the internal field emission current on the potential across the junction. Shockley's equation for the emission current, I_E, has the form:

$$I_E=a(V_i-V)\exp[-n/(V_i-V)],$$

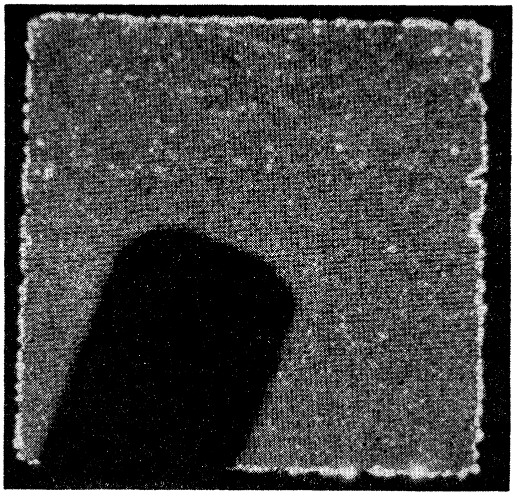

FIG. 6. Photograph of the visible light emission from a narrow junction at a net current density of about 2 amp/cm².

where a and n are dimensional constants, and (V_i-V) is the potential across the junction if V is positive for forward biases. Certainly, this equation is, at best, a poor approximation to the present experimental situation but it has the essential feature of any expression for the emission current, namely, that I_E increases very rapidly as the potential is increased from zero. The current I_E should be added to the thermally generated current, I_s, in the rectifier equation which now becomes:

$$I=\{I_s+a(V_i-V)\exp[-n/(V_i-V)]\}\times[\exp(eV/kT)-1]. \quad (1)$$

Experimentally, the drop-off in the current at high forward bias is caused by the voltage drop at the contacts and in the body of the silicon becoming appreciable. Also, for $V<0.06$ volt, the semilogarithmic plot will show a large drop in the current because of the neglect of unity compared to $\exp(eV/kT)$. Thus, a theory must account for the shape of the semilogarithmic plot over the range $0.06<V<0.6$ volt. As V increases over this range, the slope of the plot at first decreases and then increases.

Let S represent the slope $d(\ln I)/dV$. Then, from Eq. (1), the sign of (dS/dV) behaves as that of the expression:

$$-a\left[\frac{2n}{(V_i-V)}+1\right]+\frac{n^2I_s}{(V_i-V)^3}\exp[n/(V_i-V)]. \quad (2)$$

Now V_i is of the order of a volt so that as V increases from 0.06 to 0.6 volt, the exponential term will increase by several orders of magnitude on account of the value of n. Thus, it is possible for (dS/dV) to be negative when V is small while gradually becoming positive as V increases, in agreement with the experimental behavior.

In comparing Eq. (1) more closely with experiment, it is permissible to neglect I_s compared with the field

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[8] E. M. Pell and G. M. Roe, J. Appl. Phys. **27**, 768 (1956); Also, Noyce, Sah, and Shockley, Bull. Am. Phys. Soc. Ser. II, **1**, 382 (1956).

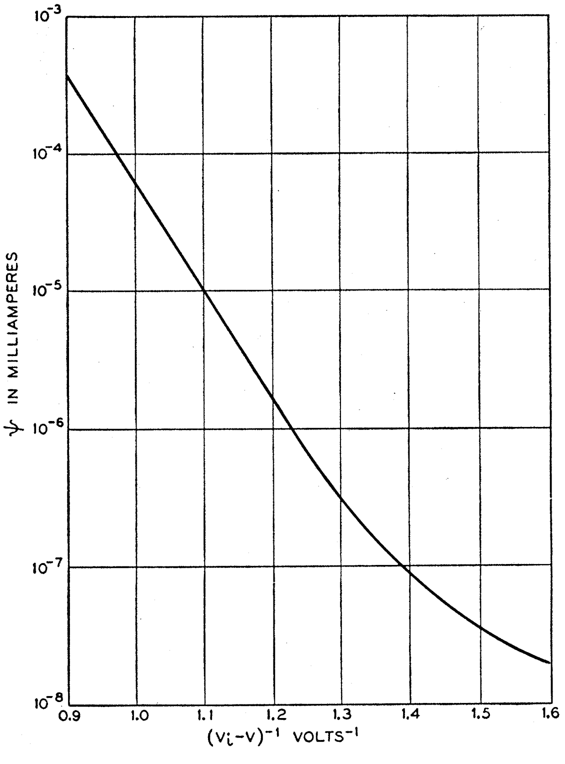

FIG. 7. Plot obtained from the room temperature forward characteristic of Fig. 5 showing the effect of carrier generation by field emission. In the absence of field emission, the quantity, ψ, would be independent of the forward bias, V.

emission current at low values of V. Then, letting

$$\Psi=I/[\exp(eV/kT)-1],$$

one has

$$\ln\Psi=\ln a+\ln(V_i-V)-n/(V_i-V).$$

Thus, a plot of $\ln\Psi$ *versus* $(V_i-V)^{-1}$ should be a straight line because the variation in $\ln(V_i-V)$ is negligible compared with that of $n/(V_i-V)$. A plot of $\ln\Psi$ *vs* $(V_i-V)^{-1}$ is given in Fig. 7 for the room temperature data of Fig. 5. The plot shows a slight curvature rather than being straight; this curvature is probably a result of the above approximations and departures of the field emission current from the assumed analytic form. Notable is the fact that the curve is monotonic rather than showing any trace of the wobble present in the $\ln I$ *versus* V plots. From the slope of the curve in Fig. 7 at small forward bias, n was found to be about 22 volts. For junctions with softer reverse characteristics (and presumably higher fields for a given value of V) somewhat higher values were found for n. From the intercept at $V=0$, $[1/(V_i-V)\simeq 0.91]$, the value of the coefficient a was 2×10^3 amp cm^{-2} volt^{-1}.

From the inflection point in Fig. 5, we can use expression (2) to obtain a value for the thermally generated current I_s. Although rather inaccurate, this does yield the right order of magnitude.

Equation (1) indicates that at small values of the forward bias the slope of the $\ln I$ *versus* V plots is given approximately by $[(e/kT)-n/V_i^2]$. At room temperature, $e/kT\simeq 38$. Then, the slope should be about 38–18 = 20, which is consistent with the average value quoted for crystal 0 in Table I.

Thus, the addition to the rectifier equation of a component representing a field generated current with a reasonable form for its voltage dependence can account for the complex structure of the $\ln I-V$ plots and their abnormally small slopes.

Softness of Reverse Characteristic

Probably, several factors contribute towards the softness of the reverse characteristic. The multiplication characteristics show that $M=1$ up to reverse biases of about 1.5 volts. Yet even over this range, the reverse current grows rapidly with the voltage. It has been shown above that considerable carrier generation by internal field emission is possible even at $V_a=0$ in which case, the current will certainly increase with V_a right from $V_a=0$. The way in which I increases with V_a will be very complex. For zero or small reverse bias, the top of the valence band on the p side will be only slightly higher than the bottom of the conduction band on the n side, so that only a few electrons in the valence band on the p side will be available for the emission transition. This situation is shown diagrammatically in Fig. 8 for a highly idealized field distribution. As the bias is increased, the number of such available electrons will increase also. In the lower part of Fig. 8 is sketched the field distribution in the junction. It is apparent that

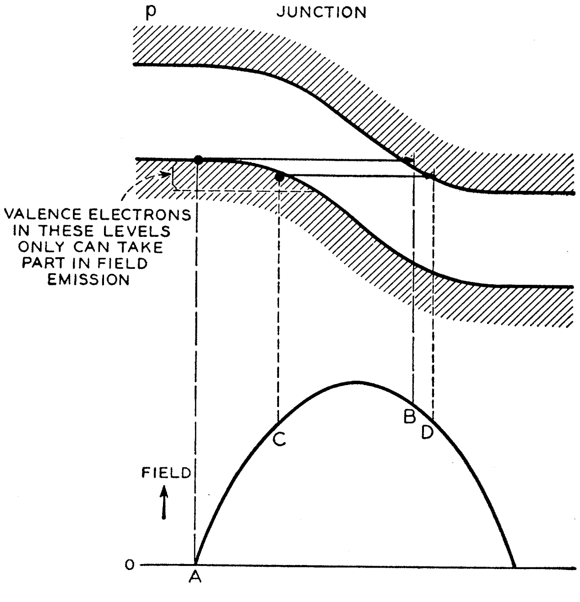

FIG. 8. Diagram showing the dependence of the effective field promoting the transition of an electron from the valence band to the conduction band on the initial position of the electron in the space charge region.

the average field responsible for the transition will vary according to the position of the electron in the valence band and this situation also will vary with the reverse bias. Hence, the reverse characteristic will appear softer than that predicted by the theoretical equation which is derived for the case of a uniform field.

Probably, another important cause of the softness is that local fluctuations in impurity concentrations will result in corresponding fluctuations in the field strength. At $V_a=0$, only a few sites may be emitting but as V_a increases, the increasing current will be carried by an increasing number of emission sites; the total emission current is not likely to be carried at one or a few sites only because the spreading resistance would give rise to a self-limiting voltage drop as soon as the current becomes appreciable. Thus, the spreading resistance at each emission site also helps to prevent the rapid increase of current with voltage dictated by the usual expression for the field emission current.

Onset of Multiplication in the Reverse Characteristic

In Fig. 9 is shown a log-log plot of the current *versus* the reverse bias. For applied biases in the range 1 to 3 volts the plot is straight, but at about 3.6 volts a more rapid increase in the current sets in. When plotted in this way, the reverse characteristics for most of the crystals showed this breakover at about the same applied voltage. The breakover occurred at about the same bias at both room temperature and that of liquid nitrogen. The slopes of the straight-line portion varied considerably from crystal to crystal, reflecting variations in the softness of the characteristic.

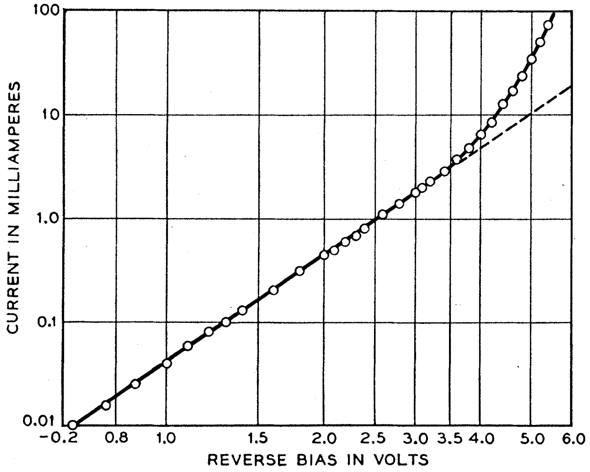

FIG. 9. A log-log plot of the reverse characteristic showing the onset of multiplication of field-emitted carriers at a reverse bias of about 3.6 volts.

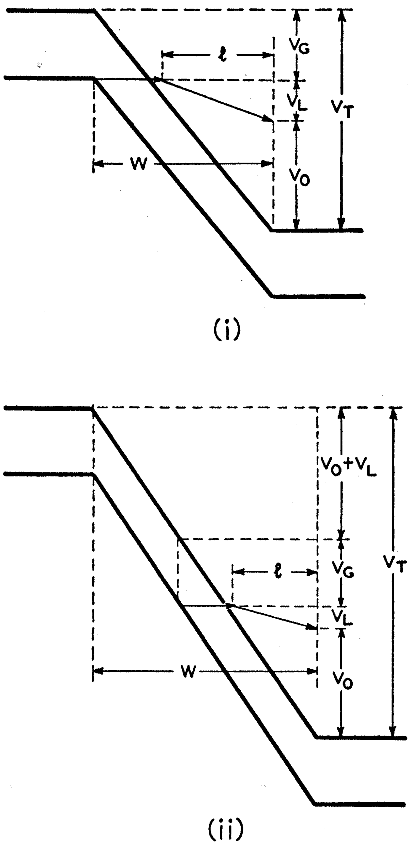

FIG. 10. Diagrams illustrating the method by which upper and lower estimates can be made of the applied bias required for field-emitted carriers to acquire sufficient energy to produce electron-hole pairs just before leaving the junction (i) for carriers emitted at the edge of the junction; (ii) for carriers emitted in the high-field region at the center of the junction.

The breakover point is taken to represent the onset of multiplication of the current generated by internal field emission. As the multiplication characteristics show, multiplication of carriers injected at the edge of the junction should start at about $V_a=1.2$ volts though, in general, there was no perceptible deviation from the straight line at this bias. As the energy diagram shown in Fig. 10 indicates, a somewhat higher bias will be required to produce multiplication of field-emitted carriers and that this bias will depend on the site of the emission. Upper and lower limits can be estimated for the value of this bias as follows: A carrier, after being field-excited from the valence band to the conduction band by a horizontal transition, will produce multiplication if it gains sufficient energy to produce an electron-hole pair before it leaves the high-field region of the junction. This situation is represented diagrammatically in Fig. 10 for two cases: where the field emission occurs (i) right at the edge of the junction and (ii) in the region of highest field symmetrically across the center of the junction. For simplicity the field is considered as uniform throughout the space charge region. After arriving in the conduction band the carrier is accelerated by the field up to an energy V_0, the energy required to produce an electron-hole pair by collision. This acceleration takes place over a distance l over which the carrier loses an amount of energy, V_L, in inelastic collisions with the lattice. Previous experiments[4] have found V_0 to be 2.3 ev, while for carriers being accelerated towards the multiplication threshold energy, $V_L = 5\times 10^4 l$ ev. The width of the junction, W, is given approximately by $W = W_1 \times V^{\frac{1}{3}}$, where V is the potential across the juuction and W_1 is its width at $V=1$ volt, $\sim 4\times 10^{-6}$ cm. At $V=6$ volts (well above the observed multiplication threshold), $W \simeq 7\times 10^{-6}$ and because $l<W$, as can be seen by inspection of Fig. 10, V_L is certainly less than 0.3 ev over the bias range of interest. Since $V_L \ll V_0$, the small errors in estimating V_L that arise from the above assumption of uniform field are quite negligible for the purpose of estimating V_T, the total potential across the junction at the onset of multiplication. Inspection of the figures shows, then, that in case (i),

$$V_T = V_G + V_L + V_0 = 1.1 + (\sim)0.2 + 2.3 \simeq 3.6 \text{ volts},$$

where V_G is the width of the energy gap; and for case (ii),

$$V_T = V_G + 2V_L + 2V_0 = 1.1 + (\sim)0.3 + 4.6 \sim 6.0 \text{ volts}.$$

To obtain the applied bias required to produce the onset of multiplication the built-in voltage ($V_i = 1.1$ volts) should be subtracted from these values. The applied biases so obtained for cases (i) and (ii) are then 2.5 and 4.9 volts, respectively, bracketing the experimental value of 3.6 volts. It is concluded, therefore, that the observed onset of a more rapidly increasing current represents multiplication produced by carriers originally field-excited from sites in the valence band between the junction edge and center.

Hardening of Reverse Characteristics

From the above results it is apparent that internal field emission rather then multiplication dominates the breakdown characteristic in very narrow junctions. In very wide junctions, breakdown occurs by the avalanche process before the field gets sufficiently high to produce appreciable internal field emission. An intermediate situation may exist with both processes occurring side by side in junctions of intermediate width. Reverse characteristics which seem to fit this picture are frequently observed. At low voltages the current shows a gentle increase with V_a but at a well-defined value of the bias (called the hardening point) the current increases rapidly with the voltage, leading into a sharply-defined breakdown. It is significant from the point of view of the above argument that junctions with $V_B <$ about 7 volts rarely show hardening points, the characteristic being dominated throughout by field emission. Also, hardening points are uncommon in junctions with $V_B >$ about 40 volts.

CONCLUSIONS

The experiments on very narrow silicon *p-n* junction described in this paper have demonstrated that the high fields in the space charge region result in considerable internal field emission from zero bias on up to the highest reverse biases attainable. Further, at zero bias, the field is sufficient to produce an emission current orders of magnitude greater than that generated in the usual manner by thermal activation. The dominance of field emission results in considerable modification to the rectification characteristic. It imparts considerable softness to the reverse characteristic; it is to be expected that the conditions determining the softness of the breakdown characteristic vary considerably from junction to junction and, thus, the wide scatter in the slopes of the characteristics previously reported[5] is not surprising. Also, the field emission process results in a negative temperature coefficient for the breakdown voltage as distinct from the positive coefficient found for the case of avalanche breakdown. The forward characteristic is made complex by the superposition of the two carrier generation processes, thermal and field emission; the detailed explanation of the temperature dependence of the forward characteristic has not been attempted here.

It cannot be determined from the experiments described here whether emission is occurring at impurity levels alone or from both impurities and the valence band. Emission from impurities is an attractive hypothesis in that the reverse current at a particular spot would be prevented from increasing too rapidly with voltage by the rate at which the impurities can be replenished. It might also be possible to explain at least part of the temperature dependence of the rectification characteristics by this mechanism. The fact that the forward characteristics indicate field emission still occurring at forward biases of up to 0.4 volt suggests that emission from impurity levels is important.

From the present results it is not possible to determine any significant correlation between the junction characteristics and the crystallographic plane in which the junction was formed.

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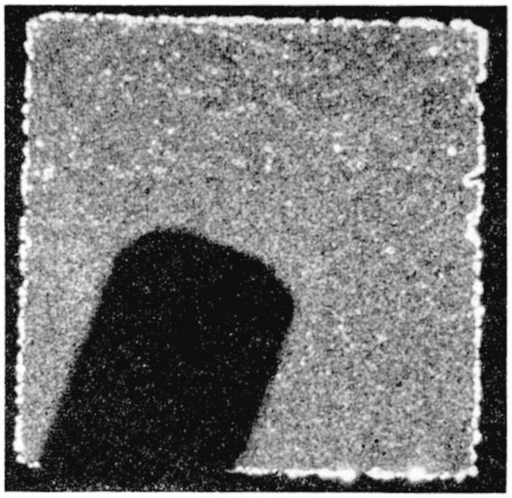

FIG. 6. Photograph of the visible light emission from a narrow junction at a net current density of about 2 amp/cm².