Surface Leakage Current in Silicon Fused Junction Diodes*

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Summary—**The forward and reverse current of fused junction silicon diodes are compared with the predicted equations arising from a simplified model for surface leakage. It is found that analysis of the forward current in the "exponential" region leads to resolution of the contributions of the junction and the leakage path. The activation energies of the parameters describing these two contributions were determined; the former agrees with the value of the band gap. The implications and deficiencies of the model are discussed.**

Introduction

INVESTIGATIONS of surface properties of germanium and silicon, in the past few years, have led to the development of explanations of surface behavior in terms of the surface barrier, surface states, conductance in inversion regions, electronic transitions in surface recombination centers, and other phenomena.[1–4] Many of the investigations have centered on the behavior of "channels" on germanium surfaces, as influenced by the presence of different ambient gases.[5,6]

The purpose of this paper is to present a study of surface leakage currents from the point of view of their effect on device behavior. To do this, a comparison is made of experimental data with what seems to be the simplest possible theory.[7] The theory is based on a model which contains two elements: a leakage path on the surface of one side of a p-n junction, which is an electrical contact with the material on the other side of the junction, and a surface barrier separating the leakage path from the bulk region underneath. These seem to be the basic elements in surface leakage, and their reality is substantiated by experimental and theoretical information. To simplify the problem, it is assumed that the conductivity of the leakage path is a constant, and that the flow of current across the surface barrier is described by the simple diode equation. This is admittedly crude, but it avoids the complications introduced by the consideration of the distribution of surface states, and other details of the electronic structure of the surface which are incompletely understood.

The resulting equations are found to agree fairly well with the experiment, and provide explanations of many puzzling features of silicon diodes. Hence, the simplified theory seems to provide a useful first approximation to the behavior of junction diodes. The effects of further refinements will be discussed to some extent later.

Equations for Surface Leakage

The model for surface leakage is shown in Fig. 1. In addition to the junction current I_1 crossing the p-n junction, a leakage current I_2 crosses the surface barrier at all points x in which there is a bias, accumulates in the channel, and flows to the junction boundary ($x=0$). For purposes of deriving the equations, it is not necessary to stipulate which side of the p-n junction has the surface leakage path.

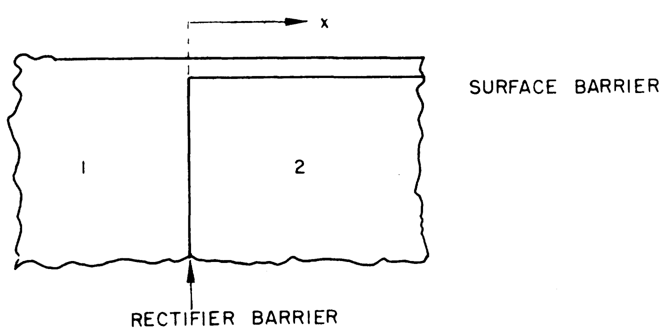

Fig. 1—Diagram of the model for surface leakage.

The change in voltage $V'(x)$ in the surface leakage path is given by Ohm's law:

$$dV'/dx = -I'/\sigma L \tag{1}$$

where I' is the cumulative current at distance x, σ is the two dimensional conductivity of the leakage path, and L is the width of the path at the distance x.

The diode equation describes the change in $I'(x)$ due to flow across the surface barrier:

$$dI'/dx = -I_sL[\exp(qV'/kT) - 1], \tag{2}$$

where I_s is the saturation current per unit area for the surface barrier. The boundary conditions are $I'=0$ at $x=\infty$, and $V'=0$ at $x=\infty$; the total leakage current I_2 is determined by the required value of I' at $x=0$, for a given $V'=V$ at $x=0$.

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[7] M. Cutler and H. M. Bath, "Surface leakage current in rectifiers," *J. Appl. Phys.*, vol. 25, p. 1440; November, 1954.

A solution for I_2 which is limited to the reverse direction can be obtained by assuming V' is large and negative. This was derived by Aigrain for a radial geometry.[8] For the one dimensional problem, with L independent of x, it is possible to derive a more complete solution by eliminating dx and integrating:

$$I_2^2 = I_L^2(e^v - v - 1), \tag{3}$$

where

$$I_L^2 = 2\sigma L^2 I_s kT/q. \tag{4}$$

We shall find it convenient to use v for qV/kT. It will be shown later that (3) is applicable also for radial geometry, if one has a forward bias.

The total current is the sum of the junction component I_1 and leakage components I_2:

$$I = I_j(e^v - 1) \pm I_L(e^v - v - 1)^{1/2}, \tag{5}$$

where the plus and minus signs are taken, respectively, for forward and reverse bias. I_j is the saturation current for the junction.

The qualitative difference in the behavior of the two functions of v is of interest. Fig. 2 shows plots on a log-log scale of $(e^v - 1)$ and $(e^v - v - 1)^{1/2}$. The ordinate is converted to current by shifting each set of curves vertically by the amount log I_j or log I_L. In the reverse direction, the leakage component increases as $(-V)^{1/2}$, whereas the junction component becomes constant at a low reverse bias (about 0.1 volt). On the other hand, the junction component increases as exp (qV/kT) in the forward direction, whereas the leakage component increases as the square root of this function, exp $(qV/2kT)$. It is clear that for any ratio of values of I_j and I_L, the junction component will ultimately be dominant, given a large enough forward bias, and the leakage component will be significant at a large enough negative bias. The limits of validity of these equations, within the constraints of the model, are, in the forward direction, at currents large enough to give a base voltage drop ($\gtrsim$0.1 ma), and at a reverse bias large enough to lead to a junction breakdown.

For purposes of discussion, we shall present also the solution for the length of the leakage path, that is, the distance x_1 in which the voltage and current drop essentially to zero. This is obtained by substituting the solution for $I'(V')$, which is of the same form as $I_2(V)$ in (3), back into (1), and integrating. This gives

$$x_1 = \pm \frac{1}{2} \lambda \int_{qV/kT}^{\pm 1} (e^v - v - 1)^{-1/2} dv, \tag{6}$$

where

$$\lambda = (2kT\sigma/qI_s)^{1/2}. \tag{7}$$

The upper limit in the integral of (6) was chosen arbitrarily, since V approaches zero asymptotically with increasing x, and reaches zero only at $x = \infty$.

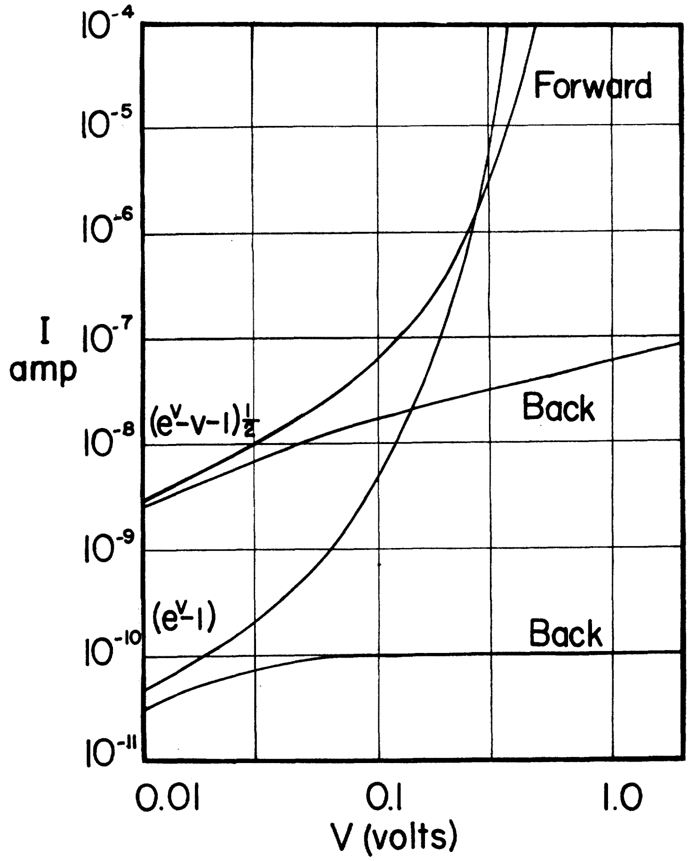

Fig. 2—Plots of theoretical junction and leakage current components for $I_j = 10^{-10}$ a, $I_L = 10^{-8}$ a.

Eq. (6) can be integrated numerically, but it suffices for our purpose to consider two approximations:

$$x_1 = \lambda e^{-v/2} \qquad \text{for } v \gg 0 \tag{8}$$

$$x_1 = \lambda(-v - 1)^{1/2} \qquad \text{for } v \ll 0 \tag{9}$$

One sees that x_1 becomes small rapidly with an increasing forward bias, and increases as the square root of reverse bias. Its magnitude is characterized by the distance parameter λ. It is apparent then, that as one increases the forward bias, not only is the leakage current less important compared to the junction current, but the leakage path becomes negligibly small; it is biased out. Since one can use one-dimensional equations even with radial geometry, provided that x_1 is small compared to the radius of the junction, the solution in equations (3) and (5) is valid in the forward direction for radial geometry. In this case, L is the circumference. We note here, for later reference, that the radial solution in the reverse direction predicts that I_2 will increase with increasing bias more rapidly than is indicated by (3).[8]

It should be recognized that changes in the "length" x_1 of the leakage path, as predicted by this model, would occur instantaneously on application of a bias. Phenomena involving time dependent changes would require that σ or I_s be functions of time.

[8] P. R. Aigrain, "Phenomena of rectification and transistance in germanium," *Ann. Phys.*, vol. 7, p. 140; January–February, 1952.

Experimental Results

The data reported here were obtained by extensive measurements of four silicon diodes, which were chosen at random from some production samples. The diodes were made by fusion on n-type silicon. The resistivities ranged between 0.3 and 10 ohm-cm. All of them showed the same qualitative behavior. Less extensive measurements on other silicon-fused junction diodes, including some prepared at another laboratory, also showed results similar to the ones reported here. Table I shows the pertinent data for the four diodes and the constants computed by analysis of the current voltage curves, measured at a number of temperatures, in the light of (5). The analysis is described in the following paragraphs.

TABLE I

Diode number	Probable resistivity range ohm-cm	I_j at 25°C 10^{-15} a	I_L at 25°C 10^{-10} a	Activation energy for I_j ev	Activation energy for I_L ev
1	1–2	5.7	1.0	1.25	0.61
2	4–10	5.6	1.5	1.25	0.64
3	2.5–5	11.8	1.8	1.26	0.64
4	0.3–0.8	3.2	1.0	1.27	0.61

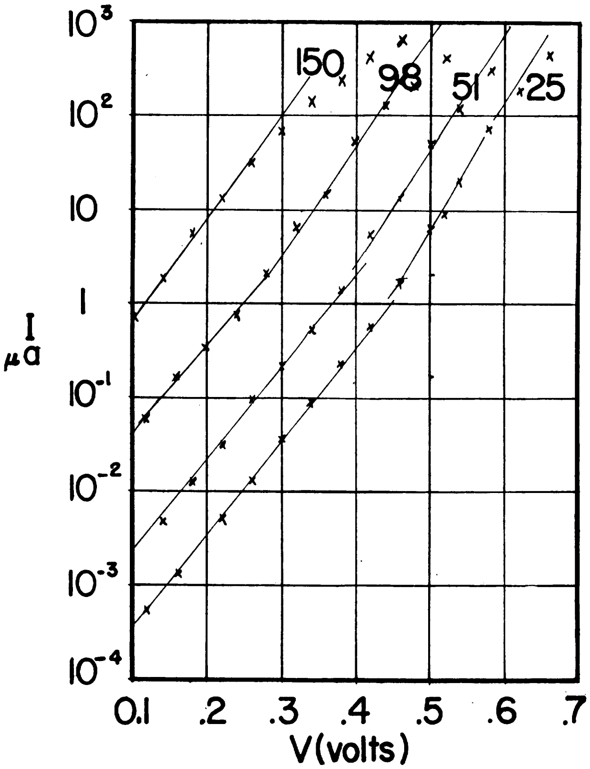

Fig. 3—Plots of ln$I$ vs V for diode no. 3 at 25°C., 51°C., 98°C., and 150°C.

Fig. 3 shows forward current plots for one of the diodes of log I vs V. When data are obtained with sufficient accuracy, (V is measured by means of a potentiometer) the curve shows a distinct break between two straight line regions. The lower part has a slope somewhat larger than $q/2kT$, and the upper part has a slope somewhat smaller than q/kT. The effect of the voltage drop in the base becomes apparent where the current is larger than 10^{-4} amperes. The curves are consistent with (5), and suggest that the two parts correspond, respectively, to the leakage current and the junction current. Rather than extrapolate to obtain the values of I_L and I_j, a more accurate procedure is used, as follows.

If one divides both sides of (5) by the leakage current function, one obtains for the forward direction

$$I(e^v - v - 1)^{-1/2} = I_L + I_j[(e^v - 1)/(e^v - v - 1)^{1/2}]. \quad (6)$$

The left-hand expression, computed from experimental data, plotted against the bracketed function in the second term on the right should be a straight line with slope I_j and intercept I_L. Fig. 4 shows a plot of this sort for a silicon diode at room temperature. Table I includes the room temperature values of I_L and I_j.

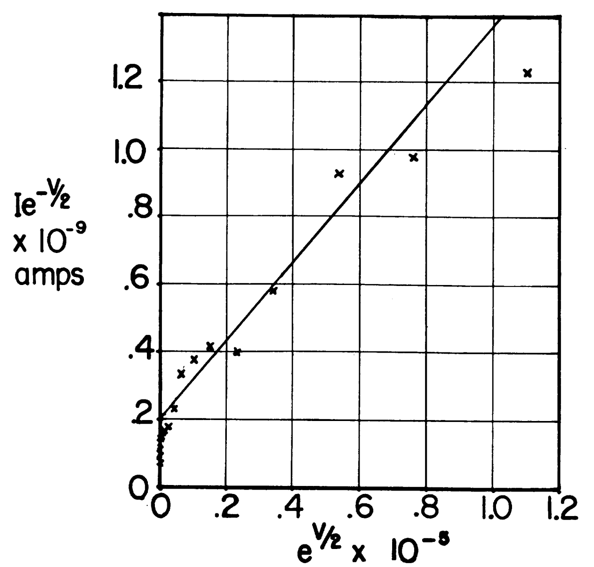

Fig. 4—Linear plot for analysis of I_j and I_L for diode no. 3 at 25°C. $I_j = 1.18 \times 10^{-14}$ a, $I_L = 1.8 \times 10^{-10}$ a.

Fig. 5 (next page) shows plots of ln I_L and ln I_j as functions of $1/T$. It was found, for all diodes examined in this way, that the I_j points fell very well on a straight line with a slope that corresponds to an activation energy near 1.26 ev. When correction is made for the anticipated dependence of I_j on T^3 the slope was 1.20 ev; this is in fair agreement with the width of the forbidden band in silicon.

The points for I_L lie on a straight line, but with larger deviations than I_j. The data for different diodes seem to show a similar deviation from a straight line, so that it seems likely that they represent a curve rather than scatter about a straight line. (It may be a linear plot with a break. The data are insufficient to tell.) The slope of the curve corresponds to an activation energy of 0.62 ev.

So far, the discussion of the experimental results has indicated good agreement with theory. There are further

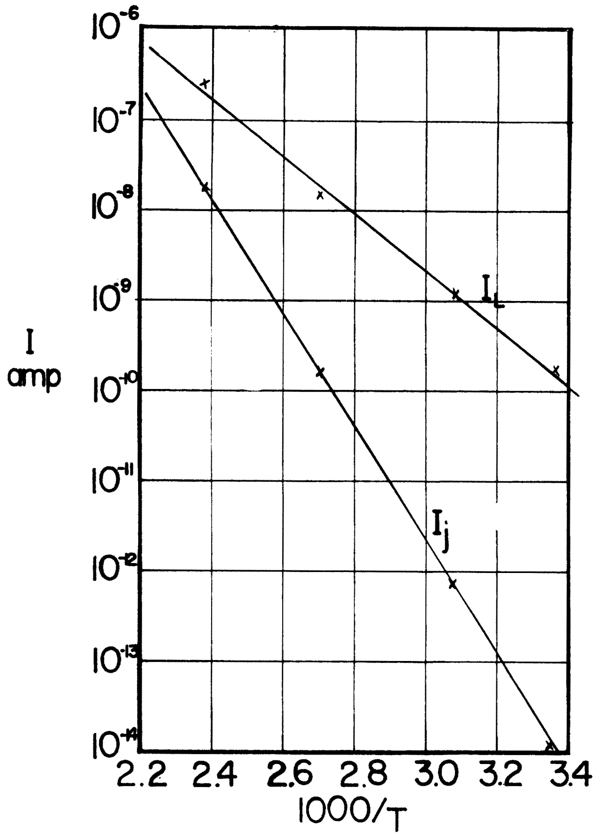

Fig. 5—Activation energy plots of I_j and I_L for diode no. 3.

observations which contain greater ambiguity. The data for low voltages, when plotted in Fig. 4, should all fall at the intercept, since $(e^v-1)(e^v-v-1)^{-1/2}$ is negligible on this scale, and $I(e^v-v-1)^{-1/2}$ should be constant and equal to I_L. It is not constant, however, and $I(e^v-v-1)^{-1/2}$ shows a steady decrease to a value of the order of one third of the extrapolated value of I_L. This is another way of saying that at these voltages the junction component of the current is negligible, and the leakage component is observed to deviate from the form of (3). However, in view of the fact that I changes by many orders of magnitude, whereas the change in $I(e^v-v-1)^{-1/2}$ is relatively small, (3) seems to be a good first-order approximation.

This discrepancy extends into the reverse bias region, where $-I$ should vary, theoretically, as $(-v-1)^{1/2}$. Fig. 6 shows a typical plot of the forward and reverse branch of $\ln I$ vs $\ln V$. It is seen that the slope of the reverse branch is usually smaller in magnitude than 0.5, and is not generally constant. This deviation cannot be explained by the fact that radial geometry exists instead of linear geometry, since the former would lead to a slope that is larger in magnitude than 0.5. The deviations are probably the result of deficiencies in the theoretical model, and will be discussed later.

The magnitude of the leakage current is of interest. The value at room temperature is of the order of 10^{-8} a. The reverse current, at any bias, represents the product of the saturation current density for the surface barrier and the area over which the leakage path extends at the bias. There is evidence that the length of the path in silicon is very short.[9] But even if it had the magnitude of the dimensions of the diode, the surface saturation current density is too large to be accounted for by generation of minority carriers in the bulk. The conclusion, then, is that the surface barrier is low enough so that the emission of majority carriers from the top of the barrier is dominant.

It is of interest to compare the measured values of I_j with the theoretical junction saturation current $q(D_p/L_p)p_0A$. The value of A is $1\text{–}2\times10^{-3}$ cm^2, and the resistivities are known only to a factor of 2 or 3. Using these numbers, it is found that τ_p must be at least the order of milliseconds. This is undoubtedly large by a factor of 100, indicating that the measured I_j are smaller than the theoretically expected ones by factors of ten or more.

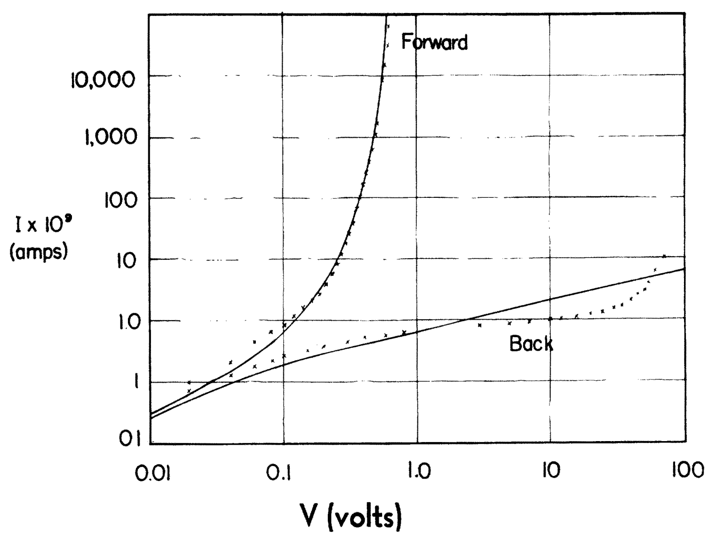

Fig. 6—Experimental points and theoretical curve for diode no. 1 at room temperature. The equation of the theoretical curve is $I=5.7\times10^{-15}(e^v-1)+1.0\times10^{-10}(e^v-v-1)^{1/2}$.

Conclusion

The general agreement with experiment, noted above, shows that the model is a useful first approximation for understanding and analyzing surface leakage currents in silicon diodes. The observed discrepancies, on the other hand, indicate the need for refinements in the model.

The improved model should take into account the dependence of the surface conductivity on the field, and the possible change in σ and I_s with bias, as the result of shifts in the field at the surface. It is known that the conductance of an inversion layer decreases if one has a larger field at the surface. This is in the proper direc-

[9] R. Gudmundsen (personal communication). His observations were made with an optical microprobe. He found that the leakage path is on the n-type side.

tion to account for the apparent decrease in I_k with decreasing forward bias. McWhorter and Kingston have derived the equation for leakage current in the reverse direction where I_s is constant but σ is inversely proportional to V.[5] The shape of this theoretical curve seems to be closer to the experimental ones, but it cannot be fitted accurately.

It is worth noting that the certain features of the behavior of I_2 as given in (3) are probably general ones, and independent of the details or degree of refinement of the model. These consist in the facts that I_2 varies, in the forward direction, roughly as exp. $(qV/2kT)$, and in the back direction as some power of qV/kT. This can be deduced from considerations that follow.

In the general case, σ in (1) and I_s in (2) may be functions of the bias V' at any point. Therefore, one derives the following equation instead of (3):

$$I_2^2 = \frac{2kT}{q} L^2 \int_0^v \sigma(y) I_s(y)(e^y - 1) dy, \tag{7}$$

where the variable of integration y is qV'/kT. It is clear that if σ and I_s are slowly varying functions of V', then I_2 could be expressed as

$$I_2 = F(v)e^{v/2}. \tag{8}$$

$F(v)$ will change slowly with v, compared to $e^{v/2}$; it could be interpreted as roughly corresponding to I_L of (4), with the values of σ and I_s appropriate for that value of v.

In the reverse direction, on the other hand, the exponential term in the integral is not significant, and the dependence of σ and I_s on V' will play an important part in the nature of the integral:

$$I_2 = -G(v) \tag{9}$$

where G will be a relatively slowly varying function of v.

If one grants that the above model is necessary and sufficient in its basic elements to explain the behavior of silicon diodes, then several implications are indicated, which are of interest in developing a more comprehensive understanding of what may have been considered as diverse phenomena.

1) The discrepancy of the behavior of reverse currents and their dependence on temperature with the theory for p-n junctions was one of the main instigating reasons for this work. The conclusions are self-evident and consist in a dissociation of the observed phenomena from the predictions of simple p-n junction theory.

2) The fact that the surface leakage current may constitute most or all of the current, has important implications in the study of noise. The "$1/f$" power dependence of noise observed in back currents of diodes has long been associated with surface phenomena. The obvious procedure, of dividing the observed current into junction and surface components, and separating the noise contributions of the two, is being approached in recent work in this field.

3) As the length of the leakage path is increased by decreasing the bias, the area of the effective junction is increased. This would cause the capacitance of the diode to decrease less rapidly than what is predicted by p-n junction theory. The importance of this effect will depend on the relative magnitude of the area of the effective leakage path (x_1L) and that of the junction. This effect is probably negligible in silicon, which seems to have a small leakage path. It may, however, be significant in germanium.

4) The possibility that the leakage path may be on the regrown region of a fused junction is an important consideration in device fabrication. If this happens, the impedance of the surface leakage path will have a maximum value, achieved when the bias is sufficient to cause the effective path x_1 to extend across the entire regrown region. Since the latter may be very small, this could seriously limit the reverse impedance of a diode.

The current-voltage curves which were observed in a number of silicon diodes prepared by fusion on p-type material seem to be affected by this limitation. A typical such curve is shown in Fig. 7. It is noted that $I(v)$ becomes linear in the neighborhood of the origin over a large range of voltage, compared to kT/q. The fact that the impedance does continue to increase in the reverse direction, even though it does so slowly compared to n-type diodes, can be explained, as before, by a decrease in the conductivity of the leakage path. If this explanation is correct, of course, one concludes that the leakage in silicon is on the n-type surface. This conclusion has been substantiated by observations noted.[9]

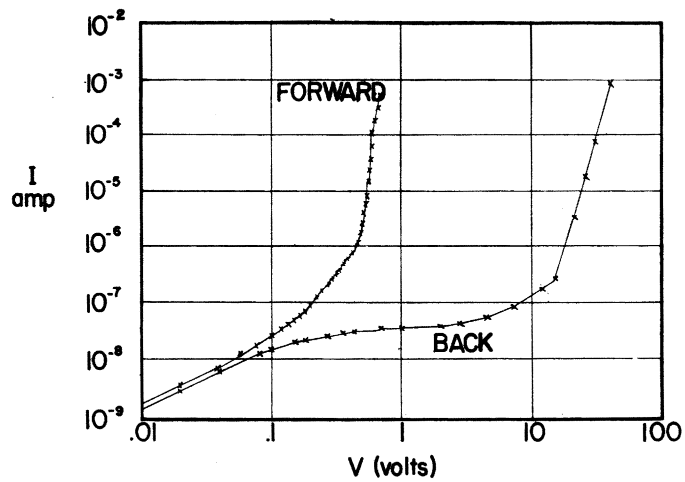

Fig. 7—Experimental curve for p-type silicon diode.

ACKNOWLEDGMENT

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