current required to change the potential distribution in the transition region is related to other hole currents is discussed in Section 4.1.

Under our assumptions, after the voltage $\delta\varphi$ is applied, a steady state is reached involving no current hence $\nabla\varphi_p = \nabla\varphi_n = 0$. Consequently, both φ_p and φ_n are constant and

$$\varphi_p - \varphi_n = \delta\varphi \tag{2.25}$$

since the holes are being supplied from a source at a potential $\delta\varphi$ higher than for the electrons.

We shall then have

$$p = n_i e^{q(\varphi_p - \psi)/kT} = n_1 e^{q(\varphi_1 - \psi)/kT} \tag{2.26}$$

$$n = n_i e^{q(\psi - \varphi_n)/kT} = n_1 e^{q(\psi - \varphi_1)/kT} \tag{2.27}$$

where

$$\varphi_1 = (\varphi_p + \varphi_n)/2, \quad \varphi_p = \varphi_1 + \delta\varphi/2, \quad \varphi_n = \varphi_1 - \delta\varphi/2 \tag{2.28}$$

and

$$n_1 = n_i e^{q\delta\varphi/2kT}. \tag{2.29}$$

Thus the effect of applying the potential $\delta\varphi$ in the pseudo-equilibrium case is equivalent to changing n_i to n_1 just as if the energy gap had been reduced by $q\delta\varphi$.

In the p-region, $n \ll p$ and so that $p = -ax$ is a good approximation. Similarly, in the n-region, we set $n = ax$. Hence we have in the p-region

$$\psi = \varphi_1 + (\delta\varphi/2) - (kT/q) \ln (-ax/n_i) \tag{2.30}$$

and in the n-region

$$\psi = \varphi_1 - (\delta\varphi/2) + (kT/q) \ln (ax/n_i). \tag{2.31}$$

Hence the effect of $\delta\varphi$ is to shift ψ in the p-region upwards by $\delta\varphi$ compared to ψ in the n-region. This is an example of the general result that $\psi - \varphi_p$ tends to remain constant at a given point in the p-region no matter what disturbances occur and $\psi - \varphi_n$ tends to remain constant in the n-region.

The Capacity for the Neutral Case $K \ll 1$

For the neutral case, we calculate the total number of holes, P, between x_a and x_b as a function of $\delta\varphi$. The charge of these holes is qP and the effective capacity is $q\, dP/d\,\delta\varphi$. As explained above, we are really interested in the change in number of holes in the transition region. However, the value of P is relatively insensitive to the location of the limits x_a and x_b so long as they lie in regions where the conductivity approaches the maximum values in the

p- and n-regions. In the following calculations, we shall consider a unit area of the junction so that values of P and of capacity are on a unit area bases.

The value of P is obtained by integrating $p\,dx$ making use of the neutrality condition to establish the functional relationship between p and x. The neutrality condition can be written as

$$ax = 2n_1 \sinh \frac{q(\psi - \varphi_1)}{kT} \equiv 2n_1 \sinh u \tag{2.32}$$

where $u \equiv q(\psi - \varphi_1)/kT$ and

$$p = n_1\, e^{q(\varphi_1 - \psi)/kT} \equiv n_1\, e^{-u} \tag{2.33}$$

$$n = n_1\, e^{+u} \tag{2.34}$$

so that the value of P can be obtained by changing variables from x to u:

$$\begin{aligned} P &= \int_{x_a}^{x_b} p\,dx = \int_{u_a}^{u_b} p(2n_1/a)\cosh u\,du \\ &= (n_1^2/a)\int_{u_a}^{u_b}[1 + e^{-2u}]\,du = (n_1^2/a)[u_b - u_a + (e^{-2u_a} - e^{-2u_b})/2] \end{aligned} \tag{2.35}$$

For the cases of practical interest, the value of p at $x = x_a$, denoted by p_a, and the value of n at $x = x_b$, denoted by n_b, will both be large compared to n_1. Consequently, we conclude that

$$u_a = -\ln(p_a/n_1) \text{ and } u_b = \ln n_b/n_1$$

are both larger than unity in absolute value but probably less than twenty for a reasonable variation of impurity between x_a and x_b. (For example for a change in potential of 0.2 volts such as would occur between p- and n-type germanium, u_a and u_b would each be about 4 in magnitude.) Hence we obtain for P,

$$\begin{aligned} P &= (n_1^2/2a)(2(u_b - u_a) + (p_a/n_1)^2 - (n_1/n_b)^2) \\ &\cong p_a^2/2a + (n_1^2/a)(u_b - u_a) \end{aligned} \tag{2.36}$$

where we have neglected $(n_1/n_b)^2$ which is $\ll 1$ and the negligible compared to $u_b - u_a$. The term $p_a^2/2a$ is simply the integrated acceptor-minus-donor density in the p-region, as may be seen as follows:

$$\int_{x_a}^{0} (N_a - N_d)\,dx = \int_{x_a}^{0} (-ax)\,dx = ax_a^2/2 = p_a^2/2a. \tag{2.37}$$

The second term in (2.36) is essentially the sum of the holes of the right of $x = 0$ plus the electrons to the left of $x = 0$, whose charge is also compensated by holes. The total number of holes can be expressed in terms of $\delta\varphi$ through the dependence of n_1 on $\delta\varphi$. The second term is thus

$$(n_1^2/a)[\ln(n_b/n_1) + \ln(p_a/n_1)] = (n_i^2/a)e^{q\delta\varphi/kT} \cdot [\ln(n_b p_a/n_i^2) - q\delta\varphi/kT] \qquad (2.38)$$

Hence for a small change $d\delta\varphi$ in $\delta\varphi$, the change in charge $dQ = q\,dP$ and the capacity C are given by

$$C = \frac{dQ}{d\delta\varphi} = \frac{q^2}{kT}\frac{n_1^2}{a}[\ln(n_b p_a/n_i^2) - (q\delta\varphi/kT) - 1]. \qquad (2.39)$$

This capacity can be reexpressed in terms of the difference in ψ between x_a and x_b: When $\delta\varphi = 0$, corresponding to the thermal equilibrium case, we have

$$p_a n_b = n_i^2 e^{q(\psi_b - \psi_a)/kT} \qquad (2.40)$$

Using this together with the definitions of L_D and L_a we obtain

$$C = \frac{\kappa[q(\psi_b - \psi_a - \delta\varphi)/kT - 1]\, e^{q\delta\varphi/kT}}{4\pi(2L_D^2/L_a)} \qquad (2.41)$$

In this expression ψ_a and ψ_b are the potentials when $\delta\varphi = 0$; so that

$$\psi_b - (\psi_a + \delta\varphi)$$

is thus the increase in potential in going from x_a to x_b when $\delta\varphi$ is applied.

For thermal equilibrium, $\delta\varphi = 0$ and, as discussed above, the term in $\psi_b - \psi_a$ will be about 10. Hence, using the definition $K = L_D/2L_a$, we have

$$C \cong \kappa/4\pi(4KL_D/10) \qquad (2.42)$$

For $K \ll 1$, the case for which this formula is valid, C will be the capacity of a condenser whose dielectric layer is much less than L_D thick.

Capacity for Space Charge Case, $K \gg 1$

As discussed in connection with (2.30) and (2.31), the applied potential $\delta\varphi$ reduces the increase ($= 2\psi_m$) in ψ between the p-region and the n-region by $\delta\varphi/2$ on each side of $x = 0$. This is accomplished by a narrowing of the space charge layer by δx_m on each side where (according to (2.20))

$$\delta\psi_m = -\delta\varphi/2 = 4\pi q a x_m^2 \delta x_m/\kappa \qquad (2.43)$$

The decrease in width δx_m brings with it an increase in number of holes $-ax\,\delta x_m$ per unit area of the junction on the p-side and an equal number of electrons on the n-side. Thus a charge of holes per unit area of $\delta Q = -qax_m\delta x_m$ must flow in from the left. The capacity per unit area is, therefore,

$$C = \delta Q/\delta\varphi = qax_m\delta x_m/\delta\varphi = \kappa/4\pi 2x_m \qquad (2.44)$$

corresponding to a condenser of thickness $2x_m$. It is evident that formula (2.44) will hold for a small change $d\delta\varphi$ superimposed on a large bias $\delta\varphi$ provided that $2x_m$ is the thickness of the space charge region under the conditions when $\delta\varphi$ is applied. If $\psi_{m.0}$ is the value of ψ for $\delta\varphi = 0$, then $\psi_m = \psi_{m.0} - \delta\varphi/2$; and C will vary as

$$C = \kappa[4\pi qa/3\kappa(\psi_{m.0} - \delta\varphi/2)]^{1/3}/8\pi \tag{2.45}$$

so that $1/C^3$ should plot as a straight line versus $\delta\varphi$ with slope

$$-(8\pi/\kappa)^3(3\kappa/8\pi qa) = -\frac{192\pi^2}{\kappa^2 qa}. \tag{2.46}$$

In addition to the holes which flow to account for the change in ψ_m, the concentration of holes in the n-region will be increased by a factor $\exp(q\delta\varphi/kT)$. However, this increase does not lie in the transition region; we shall consider it later, in Section 4, in connection with a-c. admittance.

Comparison of the Two Capacities

It is instructive to compare the two capacities just derived. We suppose that for one value of n_i we have $K \gg 1$ so that the space charge solution is good. For this case we choose $x_a = -x_m$ and $x_b = +x_m$ so as to bound the space charge layer. We then imagine n_i to be increased, either by raising the temperature or by applying a potential difference $\delta\varphi$. The capacity then changes from

$$C_{\text{sp. chg.}} = \kappa/8\pi x_m \text{ to } C_{\text{neut.}} = 5\kappa/8\pi KL_D \tag{2.47}$$

(i.e., from (2.44) to (2.42)) so that the ratio is

$$\frac{C_{\text{neut.}}}{C_{\text{sp. chg.}}} = \frac{5x_m}{KL_D} \tag{2.48}$$

For $K < 1$, this ratio is large, both because of K in the denominator and because $x_m > L_a$ so that $x_m/L_D > L_a/L_D = 1/2\,K$.

In Section 4.4 we shall compare these capacities with that due to diffusion of holes and electrons beyond the transition region.

2.4 The Abrupt Transition

For completeness we shall consider the case in which the impurity concentration changes abruptly from p_p to n_n at $x = 0$. For this case the potential in the space-charge layer will be of the parabolic type discussed by Schottky, the potentials varying as

$$\psi = (2\pi/\kappa)q\, p_p(x - x_p)^2 + \text{constant}, \qquad x < 0 \tag{2.49}$$

$$\psi = -(2\pi/\kappa)q\, n_n(x - x_n)^2 + \text{constant}, \qquad x > 0 \tag{2.50}$$

where $x_p < 0$ and $x_n > 0$ are the ends of the space-charge layer in the p- and n-regions. The gradient of potential at $x = 0$ must be equal for the two layers leading to

$$-p_p x_p = n_n x_n \tag{2.51}$$

so that if the total width of the space charge layers is $W = x_n - x_p$, it follows that

$$x_p = -n_n W/(n_n + p_p) \text{ and } x_n = p_p W/(n_n + p_p). \tag{2.52}$$

The potential difference across the layer, which is $\psi_b - \psi_a$ is

$$\psi_b - \psi_a = (2\pi q/\kappa)(p_p x_p^2 + n_n x_n^2) = [2\pi q\, p_p n_n/\kappa(p_p + n_n)]W^2 \tag{2.53}$$

If $p_p \gg n_n$ this reduces to

$$\psi_b - \psi_a = 2\pi q\, n_n W^2/\kappa \tag{2.54}$$

the formula given by Schottky, which should be appreciable in this case, for which all the voltage drop occurs in the n-region.

The capacity for the abrupt transition will be

$$C = \kappa/4\pi W \tag{2.55}$$

where W is obtained by solving (2.53). For this case $(1/C)^2$ should plot as a straight line versus $\psi_b - \psi_a$:

$$\frac{1}{C^2} = [8\pi(p_p + n_n)/\kappa q\, p_p\, n_n](\psi_b - \psi_a). \tag{2.56}$$

3. General Conclusions Concerning the Junction Characteristic

In this section we shall consider direct current flow through the junction and shall derive the results quoted in Fig. 1 relating the current distribution to the characteristics of the junction. We shall suppose that holes and electrons are thermally generated in pairs at a rate g and recombine at a rate rnp so that the net rate of generation per unit volume is

$$(\text{net rate of generation}) = g - rnp,$$

which vanishes at equilibrum. Obviously, $g = rn_i^2$. If relatively small concentrations δp and δn of holes and electrons are present in excess of the equilibrium values, the net rate of generation is

$$\delta\dot{p} = \delta\dot{n} = g - r(n + \delta n)(p + \delta p) = -rn\delta p - rp\delta n \tag{3.1}$$

This is equivalent to saying that excess holes in an n-type semiconductor, and excess electrons in a p-type semiconductor, respectively, have lifetimes τ_p and τ_n given by

$$\delta\dot{p} = -\delta p/\tau_p = -rn\delta p \text{ or } \tau_p = 1/rn = p/g \tag{3.2}$$

and

$$\delta\dot{n} = -\delta n/\tau_n = -rp\delta n \text{ or } \tau_n = 1/rp = n/g. \tag{3.3}$$

We shall have occasion to use this interpretation later. (We later consider the modifications required when surface recombination occurs, Section 4.2, Appendix V, and the effect of a localized region of high recombination rate, Section 4.6, Appendix III.)

In principle, the steady-state solution can be obtained in terms of the three potentials ψ, φ_p and φ_n. These must satisfy three simultaneous ordinary differential equations, which we shall derive. As discussed in Section 2, we consider all donors and acceptors to be ionized so that Poisson's equation becomes

$$\frac{d^2\psi}{dx^2} = -\frac{4\pi q}{\kappa}\left(ax + n_i e^{q(\varphi_p-\psi)/kT} - n_i e^{q(\psi-\varphi_n)/kT}\right) \tag{3.4}$$

an equation in which the unknowns are the three functions φ_p, φ_n and ψ. The total current density, from left to right, is

$$I = I_p + I_n = -q\mu\left[p\,\frac{d\varphi_p}{dx} + bn\,\frac{d\varphi_n}{dx}\right]. \tag{3.5}$$

The elimination of p and n by equation (2.4) results in an equation involving the three unknown functions and I. The divergence of hole current, equal to the net rate of generation of holes, is

$$\begin{aligned}\frac{dI_p}{dx} &= -q\mu p\left[\frac{q}{kT}\left(\frac{d\varphi_p}{dx}\right)^2 - \frac{q}{kT}\frac{d\psi}{dx}\frac{d\varphi_p}{dx} + \frac{d^2\varphi_p}{dx^2}\right]\\ &= q(g - rnp) = qg(1 - e^{q(\varphi_p-\varphi_n)/kT}),\end{aligned} \tag{3.6}$$

with p in the second term given by (2.4) so that (3.6) is also an equation for the three unknown functions. The equation for dI_n/dx can be derived from the last two and adds nothing new. These three equations can be used to solve for $d^2\psi/dx^2$, $d^2\varphi_p/dx^2$ and $d\varphi_n/dx$ in terms of lower derivatives and I. They thus constitute a set of equations sufficient to solve the problem provided that physically meaningful boundary conditions are imposed. We shall not, however, deal directly with these equations; the main reason for deriving them was to show that the problem in question is, in principle, completely formulated. Instead of attempting to solve the equations, we shall discuss certain general features of the solutions for φ_p and φ_n, using approximate methods, and in this way bring out the essential features of the theory of rectification.

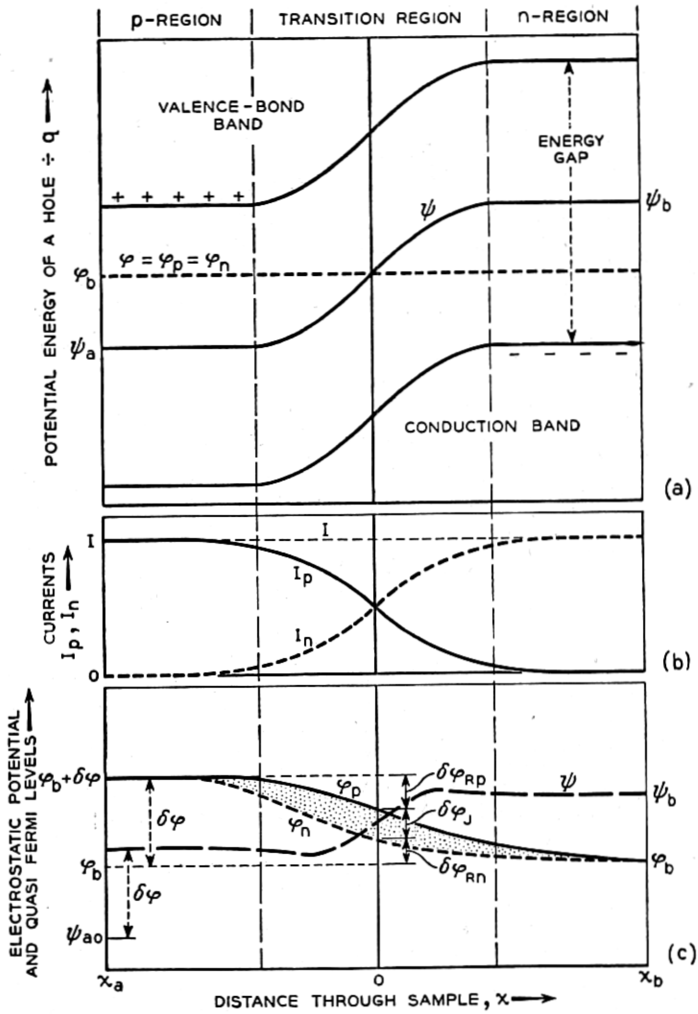

Fig. 5—Potential and current distributions for forward current in *p-n* junctions.
(a) *p-n* junction under equilibrium conditions.
(b) Division of current between holes and electrons.
(c) Distribution of potentials for forward current flow showing how the potential $\delta\varphi$ applied at x_a changes φ_p, φ_n and ψ.

In Fig. 5 we represent a general situation which may be used to illustrate the nature of the resistance of the junction. Part (a) corresponds to thermal equilibrium and shows the potential distribution and Fermi level in accordance with the scheme used in Fig. 2. Part (b) shows the current distribution for a forward current I from left to right and (c) shows the corresponding potential distribution and values of φ_n and φ_p, the total applied potential being $\delta\varphi$. Recombination prevents the hole current from penetrating far into the n-region, the depth of penetration being described by the diffusion length $L_p = \sqrt{D\tau_p} = \sqrt{Dp_n/g}$, where p_n is the hole concentration in the n-region. The electron current similarly is limited by $L_n = \sqrt{bD\tau_n} = \sqrt{bDn_p/g}$. (Diffusion lengths are evaluated for particular models of the junction in Section 4.) Far from the junction, therefore, the hole and electron concentrations have their normal values and consequently $\varphi_p = \varphi_n$ and $\varphi_p - \psi$ has its normal value. This accounts for the equal displacement $\delta\varphi$ for all three curves at $x = x_a$. The curves for φ_p and φ_n have a continuous downward trend which produces the currents

$$I_p = -q\mu p \frac{d\varphi_p}{dx} \quad \text{and} \quad I_n = -qb\mu n \frac{d\varphi_n}{dx}. \tag{3.7}$$

The area between the φ_p and φ_n curves has a special significance: This difference is related to the excess rate of recombination and the integral of this rate over the entire specimen must be sufficient to absorb the hole current $I_p = I$ entering at x_a so that the entire current at x_b is carried by electrons. In terms of $\varphi_p - \varphi_n$ and equation (3.6) we obtain

$$\begin{aligned} I = I_p(x_a) - I_p(x_b) &= \int_{x_a}^{x_b} - dI_p \\ &= gq \int_{x_a}^{x_b} (e^{q(\varphi_p - \varphi_n)/kT} - 1)\, dx. \end{aligned} \tag{3.8}$$

From (3.8) we conclude that if g is increased indefinitely for a specified current I, then $\varphi_p - \varphi_n$ must approach zero. For this case, in which the rate of recombination and generation is very high, $\varphi_p = \varphi_n$ and

$$I = I_p + I_n = -q\mu(p + bn)\, d\varphi_p/dx \tag{3.9}$$

and

$$\delta\varphi = -\int_{x_a}^{x_b} d\varphi_p = I \int_{x_a}^{x_b} dx/q\mu(p + bn) \equiv IR_0, \tag{3.10}$$

where R_0 is simply the integral of the local resistivity corresponding to densities p and n. For smaller values of g, I does not divide in the ratio $p{:}bn$ and $\varphi_p \neq \varphi_n$ and $\delta\varphi > IR_0$.[10]

We shall next give an approximate treatment for the case in which $\delta\varphi_J$ (J for junction), the value of $\varphi_p - \varphi_n$ at $x = 0$, is an appreciable fraction of

[10] A general proof that $\delta\varphi > IR_0$ is given in Appendix I.

the total voltage drop. For this purpose we treat $\varphi_p - \varphi_n$ as constant over a range of integration from $x = -L_n$ to $x = +L_p$ obtaining

$$\begin{aligned} I &= gq(L_n + L_p)[e^{(q\delta\varphi_J/kT)} - 1] \\ &= I_s[e^{(q\delta\varphi_J/kT)} - 1] \end{aligned} \tag{3.11}$$

where

$$I_s = gq(L_n + L_p) \tag{3.12}$$

is the current density corresponding to the total rate of generation of hole-electron pairs in a volume $L_n + L_p$ thick. We next consider $\delta\varphi_{Rp} + \delta\varphi_{Rn}$ shown in Fig. 5c, where, as the subscript R implies, these are thought of as resistive terms and are given by the integrals

$$\delta\varphi_{Rp} + \delta\varphi_{Rn} = -\int_{x_a}^{0} d\varphi_p - \int_{0}^{x_b} d\varphi_n = \int_{x_a}^{0} I_p\, dx/q\mu p + \int_{0}^{x_b} I_n\, dx/q\mu bn.$$

The denominators are both approximately $q\mu(p + bn)$ which occurs in the integral for R_0. Furthermore, for most of the first range $I_p = I$ and for most of the second $I_n = I$. Near $x = 0$, I_p or I_n must be at least $I/2$. Hence it is evident that $\delta\varphi_{Rp} + \delta\varphi_{Rn}$ cannot be much less than IR_0. We shall represent it by IR_1 where $R_0 < 2R_1 < 2R_0$.

In terms of R_1 and I_s, the relationship between current and voltage becomes

$$\delta\varphi = \delta\varphi_{Rp} + \delta\varphi_{Rn} + \delta\varphi_J = R_1 I + \frac{kT}{q}\ln\left(1 + \frac{I}{I_s}\right). \tag{3.13}$$

This corresponds to an ideal rectifier in series with a resistance R_1. The junction will, therefore, be a good rectifier if the second term represents a much higher resistance.

We shall compare the two resistances for the case corresponding to $K \ll 1$. For this case, we have $p = -ax$ and $n = +ax$ except in the narrow range $|x| < L_a = n_i/a$. The integral R_0 can be approximated by integrating dx/σ for x outside of the range $\pm L_a$ using the approximation $\pm ax$ for p and n and approximating the integral from $-L_a$ to $+L_a$ by $2L_a/\sigma$ (intrinsic). This procedure gives

$$\begin{aligned} R_1 &= \int_{L_a}^{-x_a} dx/q\mu ax + \frac{2L_a}{q\mu n_i(1 + b)} + \int_{L_a}^{x_b} dx/q\mu bax \\ &= \frac{L_a}{q\mu n_i}\left(1 + \frac{1}{b}\right)\ln\,(x_b/L_a) \end{aligned} \tag{3.14}$$

where it is supposed that $-x_a \doteq x_b$ and that $ln\,(x_b/L_a)$ is large compared to $2/(b + 2 + 1/b)$. The evaluation of L_p and L_n for use in I_s is more involved since τ_p and τ_n are both functions of x. We shall obtain an approximate self-consistent diffusion length by assuming that the holes diffuse, on the average, to just such a depth, L_p, that in uniform material of the type found at L_p, their diffusion length would also be L_p. At a depth L_p, the value of n is aL_p so that by (3.2), τ_p is $1/raL_p = n_i^2/gaL_p$. Thus we write

$$L_p^2 = D\tau_p = Dn_i^2/gaL_p. \tag{3.15}$$

We can solve the equation (3.15) for L_p and a similar one for L_n and insert the results in equation (3.13). For small I this gives

$$\begin{aligned}\delta\varphi/I = R_1 + (kT/qI_s) = \frac{L_a}{q\mu n_i}\left(1 + \frac{1}{b}\right)\ln(x_b/L_a) \\ + kT/(q^2 g^{2/3}(DL_a n_i)^{1/3}(1 + b^{1/3})).\end{aligned} \tag{3.16}$$

It is seen that for g large, the second term, corresponding to the rectifying resistance, becomes small. For this case, as discussed above, $\varphi_p = \varphi_n$ and the exact integral for R_0 should be used and the junction will give poor rectification.

It is also instructive to consider L_a as a variable. Increasing L_a corresponds to making the transition from p to n more gradual. It is evident that varying L_a changes the two terms of (3.16) in opposite directions so that there will be an intermediate value of L_a for which the resistance of the junction is a minimum. As L_a approaches zero, however, the second term should be modified: If we imagine that in the transition region the concentration $(N_d - N_a)$ varies only over a finite range, bounded by fixed values n_n and p_p in the n- and p-regions, then it is clear that the limiting values of L_p and L_n should be given not by (3.15) but by $\sqrt{D\tau_p}$ and $\sqrt{bD\tau_n}$ where τ_p and τ_n are evaluated in the n-region and p-region. This leads to a limiting value for I_s, which is given in equation (4.11) of the following section. In the range for which (3.16) applies, however, the interesting result holds that widening the transition region initially decreases the resistance by furnishing a larger volume in which holes and electrons may combine or be generated.

The condition that $\delta\varphi_J$ dominate the resistance is that the second term of (3.16) be much larger than the first. This leads to the inequality

$$1 \ll \frac{kT}{q^2 g^{2/3}(DL_a n_i)^{1/3}} \cdot \frac{q\mu n_i}{L_a} = (Dn_i/gL_a^2)^{2/3} = (L_{pi}/L_a)^{4/3} \tag{3.17}$$

where we have neglected various factors involving b, which are nearly unity, and $\ln(x_b/L_a)$ (which must be about 4 for Ge since the conductivity at x_b is about exp(4) times the intrinsic conductivity). The quantity

$$L_{pi} = (Dn_i/g)^{1/2} \tag{3.18}$$

is the diffusion length for holes in the intrinsic region. The inequality states that the diffusion length must be much larger than L_a. This is equivalent to the previous statement that the hole current must penetrate the n-region for the rectifier to have a good characteristic. (If a local region of high recombination is present in the transition region, this result just quoted need not apply. See Section 4.6.)

If the hole current penetrates deeply into the n-region and R_1 is negligible, then we can conclude that the current-voltage characteristic will fit the ideal formula. For these assumptions $\delta\varphi_{Rp}$ on Fig. 5 will be small and the principal change in φ_p will occur relatively deep in the n-region, at least beyond the transition region. So long as the hole concentration introduced in the n-region is much smaller than n_n, the hole current into the n-region will be a linear function of the value of p at the right edge of the transition region, being zero when p equals p_n, the equilibrium value of p. This leads at once to a hole current proportional to $p - p_n$ and since the shift of φ_p in respect to ψ at the edge of transition region is $\delta\varphi$, $p - p_n$ is equal to $p_n(\exp(a\delta\varphi/kT)-1)$. (These ideas are discussed in detail in Section 4.) A similar relationship will hold for electrons entering the p-region; hence the total current will vary as $\exp(q\delta\varphi/kT)-1$. This is a theoretical rectification formula[11] giving the maximum rectification for carriers of charge q.

4. Treatment of Particular Models

4.1 Introduction and Assumptions

In this section we shall deal chiefly with good rectifiers so that the IR drop, discussed in connection with R_1 in Section 3, is negligible. We shall deal chiefly with the case for which the transition region is narrow compared to the diffusion length; consequently, there is little change in I_p in traversing the transition region. In Fig. 6(a) we consider a hypothetical junction in which the properties are uniform outside the transition region. The division of the specimen into three parts as shown is seen to be reasonable for germanium: In n-type germanium, the diffusion constant for holes is about 40 cm^2/sec and the lifetime is greater than 10^{-6} sec so that the diffusion distance is $L_p = \sqrt{D\tau_p} > 6 \times 10^{-3}$ cm. This is much greater than most transition regions.

The major drop in φ_p must occur to the right of the transition region. This follows from our assumptions: First, we may neglect the IR drop in the p-region; hence φ_p is substantially constant from $x = x_a$ to $x = x_{Tp}$. Second, the decrease in φ_p is much less in the transition region than in the n-region; this follows from two considerations: the resistance for hole flow is lower in

[11] C. Wagner, *Phys. Zeits.* 32, 641–645 (1931).