the transition region than in the n-region; the effective length of flow in the n-region, being L_p, is greater than the width of the transition region. Consequently, the variation of φ_p shown in Fig. 6(c) is seen to be reasonable. Similar considerations apply to φ_n. As is shown in Fig. 6(c), the application of $\delta\varphi$ does not alter $\varphi_p - \psi$ in the p-region nor $\varphi_n - \psi$ in the n-region. The

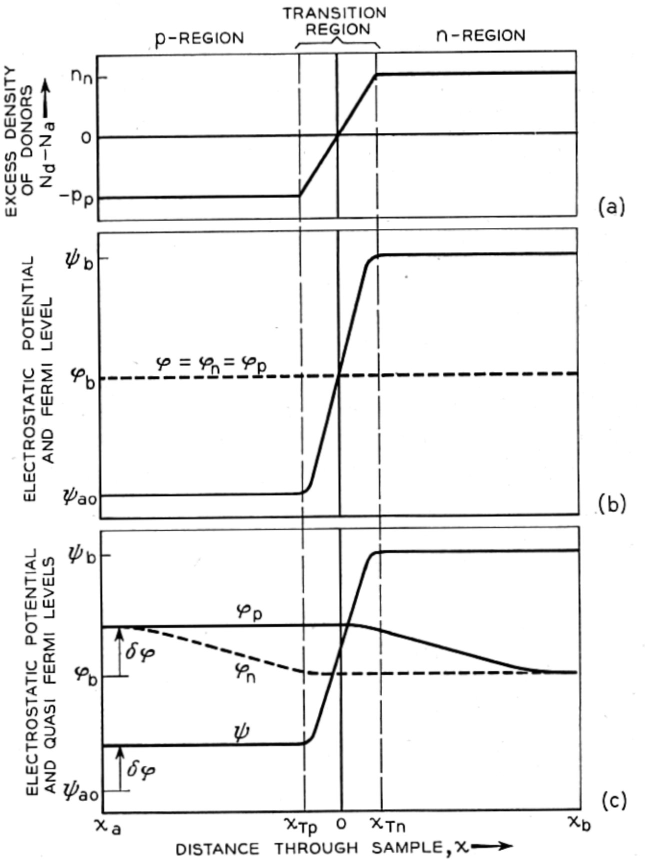

Fig. 6—Simplified model of a p-n junction.
(a) Distribution of donors and acceptors.
(b) Potentials for thermal equilibrium.
(c) Effect of $\delta\varphi$ applied potential in forward direction.

reason, as discussed in connection with (2.31), is that in these regions electrical neutrality requires an essentially constant value for the more abundant carrier. Hence the relationships between the φ's and ψ follow from (2.4).

The nature of the potential distribution in the transition region has no effect in the considerations just discussed. However, as shown in Section 2, the capacity of the transition region, which we shall denote by C_T in this section, does depend on the nature of the transition region and, consequently, on the value of K.

If the sizes of the p-region and n-region are large compared to the diffusion lengths, we may assume the current at x_a to be substantially I_p only and that at x_b, I_n only. The total current entering at x_a can be accounted for as doing three things: (1) neutralizing the electron current flowing into the p-region across x_{Tp}, (2) contributing to the charge in the transition region (this corresponds to the capacity discussed in Section 2) and (3) contributing a current flow to the right across x_{Tn}.

We have selected the hole current for analysis because the hole has a positive charge and the connection between the algebra and the physical picture is simplified. For the same reason, the text emphasizes forward current, although the equations are equally applicable to reverse currents. Nothing essential is left out by this process; since the sample as a whole remains uncharged, the current I is the same for all values of x and if I_p is known, then $I_n = I - I_p$ is also determined.

4.2 Solution for Hole Flow into the n-region

We shall calculate first the hole current $I_p(x_{Tn})$ flowing across x_{Tn}. It is readily evaluated as follows: The value of $p(x_{Tn})$ is given by

$$\begin{aligned} p(x_{Tn}) &= n_i e^{q(\varphi_b+\delta\varphi-\psi_b)/kT} \\ &= p_n e^{q\delta\varphi/kT} \end{aligned} \tag{4.1}$$

where p_n is the hole concentration in the n-region for thermal equilibrium. If we apply a small a-c. signal superimposed on a d-c. bias so that

$$\delta\varphi = v_0 + v_1 e^{i\omega t} \tag{4.2}$$

where v_1 is an a-c. signal, assumed so small that linear theory may be employed (i.e. $v_1 \ll kT/q$), then

$$p(x_{Tn}) = (p_n e^{qv_0/kt})(1 + (qv_1/kT)e^{i\omega t}).$$

We resolve this density into a d-c. component p_0 and an a-c. component $p_1 e^{i\omega t}$:

$$p(x_{Tn}) = p_n + p_0 + p_1 e^{i\omega t} \tag{4.3}$$

where

$$p_0 = p_n(e^{qv_0/kT} - 1) \tag{4.4}$$

$$p_1 = (qp_n v_1/kT)e^{qv_0/kT}. \tag{4.5}$$

So long as $p(x_{Tn}) \ll n_n$, the normal concentration of electrons in the

n-region, the lifetime τ_p and diffusion constant D for a hole will be substantially unaltered by $\delta\varphi$. Application of the hole-current equation to the hole density $p(x, t)$ gives

$$I_p = -qD\frac{\partial p}{\partial x}. \tag{4.6}$$

Combining this with the recombination equation

$$\frac{\partial p}{\partial t} = \frac{p_n - p}{\tau_p} - \frac{1}{q}\frac{\partial I_p}{\partial x} = \frac{p_n - p}{\tau_p} + D\frac{\partial^2 p}{\partial x^2} \tag{4.7}$$

leads to the solution

$$p = p_n + p_0 e^{(x_{Tn}-x)/\sqrt{D\tau_p}} + p_1 e^{i\omega t + (x_{Tn}-x)(1+i\omega\tau_p)^{1/2}/(D\tau_p)^{1/2}}. \tag{4.8}$$

The quantity $\sqrt{D\tau_p}$ is the diffusion length and is denoted by L_p. (We shall use subscript p for holes in the n-region and n for electrons in the p-region for both L and τ.)

When p is large compared to p_n, but small compared to n_n, the expression for p leads to the following formula for φ_p:

$$\varphi_p = \varphi_n + v_C - (kT/q)(x - x_{Tn})/L_p + v_1 e^{i\omega t - (x - x_{Tn})[(1+i\omega\tau_p)^{1/2}-1]/L_p}. \tag{4.9}$$

This shows that the d-c. part of φ_p varies linearly in the n-region, for large forward currents, and decreases by (kT/q) in each diffusion length L_p. The transition from this linear dependence to an exponential decay for φ_p comes when $\varphi_p - \varphi_n = (kT/q)$. This behavior of the d-c. part of φ_p is useful in connection with diagrams of φ_p versus distance. (See Sections 5 and 6.)

The solution just obtained for p gives rise to a current at x_{Tn} of

$$\begin{aligned} I_p(x_{Tn}) &= -qD\frac{\partial p}{\partial x} \\ &= qp_0 D/L_p + qp_1 De^{i\omega\tau}(1 + i\omega\tau_p)^{1/2}/L_p. \end{aligned} \tag{4.10}$$

The d-c. part is calculated by substituting (4.4) for p_0:

$$\begin{aligned} I_{p0}(x_{Tn}) &= (qp_n D/L_p)(e^{qv_0/kT} - 1); \\ &\equiv I_{ps}(e^{qv_0/kT} - 1) \end{aligned} \tag{4.11}$$

and the a-c. part is similarly obtained from (4.5) for p_1:

$$\begin{aligned} I_{p1}(x_{Tn}) &= (qp_n\mu/L_p)[e^{(qv_0/kT)}](1 + i\omega\tau_p)^{1/2} v_1 e^{i\omega t} \\ &\equiv (G_p + iS_p)v_1 e^{i\omega t} \equiv A_p v_1 e^{i\omega t} \end{aligned} \tag{4.12}$$

where A_p is called the admittance (per unit area) for holes diffusing into the n-region; its real and imaginary parts are the conductance and susceptance. For $\omega\tau_p$ small, the real term G_p is simply conductance per cm^2 of a layer L_p cm thick with hole conduction corresponding to the density $p_n + p_0$; it is also the differential conductance obtained by differentiating (4.11) in respect to v_0. For the case of zero bias this establishes the result quoted in Section 1 that the voltage drop is due to hole flow in the n-region where the hole conductivity is low.

In this section we have treated τ_p as arising from body recombination. In a sample whose y and z dimensions are comparable to L_p or L_n, surface recombination may play a dominant role. However, as we show in Appendix V, the theory given here may still apply provided appropriate values for τ_p and τ_n are used.

4.3 D-C. Formulae

The total direct hole current flowing in at x_a is I_{p0} plus the current required to recombine with electrons in the p-region. This latter current is, of course, equal to the electron current flowing into the p-region. This electron current, denoted by I_{n0} or $I_{n0}(x_{Tp})$, is obtained by the same procedure as that leading to (4.11) for I_{p0} except that bD replaces D and the subscripts of L and τ are now n. Combining the two currents leads to the total direct current:

$$I_0 = I_{p0} + I_{n0} = (qD)\left(\frac{p_n}{L_p} + \frac{bn_p}{L_n}\right)(e^{qv_0/kT} - 1) \tag{4.13}$$

for the direct current per unit area for applied potential v_0.[12] The algebraic signs are such that $I > 0$ corresponds to current from the p-region to the n-region in the specimen; $v_0 > 0$ corresponds to a plus potential applied to the p-end. The ratio of hole current to electron current across the transition region is

$$\begin{aligned}\frac{I_{p0}}{I_{n0}} &= \frac{p_n}{L_p}\cdot\frac{L_n}{bn_p} = \frac{p_p}{bn_n}\cdot\frac{\sqrt{bD\tau_n}}{\sqrt{D\tau_p}} \\ &= \frac{p_p}{bn_n}\sqrt{\frac{bn_n}{p_p}} = \sqrt{\frac{\sigma_p}{\sigma_n}}\end{aligned} \tag{4.14}$$

where we have used the relationships $n_n p_n = n_p p_p = n_i^2$ from (2.2) and $\tau_p n_n = \tau_n p_p = 1/r$ from (3.2) and (3.3). These results can be summarized by saying that the current flows principally into the material of higher re-

[12] For convenience we repeat the definitions here: $q \equiv$ magnitude of electronic charge; $D \equiv$ diffusion constant for holes; p_n and $n_n \equiv$ thermal equilibrium value of p and n, assumed constant throughout n-region ($x > x_{Tn}$); n_p and $p_p \equiv$ similar values for $x < x_{Tp}$; $L_p \equiv$ diffusion length $\equiv \sqrt{D\tau_p}$ for holes in n-region; $\tau_p \equiv$ lifetime of hole in n-region before recombination; b = electron mobility/hole mobility; L_n and τ_n similar in quantities for electrons in p-region; $\sigma_n = q\mu bn_n$ and $\sigma_p = q\mu p_p$ are the conductivities of the two regions.

sistivity. We can also say that the hole current depends only on the n-type material and vice versa. For a p-n junction emitter in a transistor with an n-type base, it is thus advantageous to use high conductivity p-type material so as to suppress an unwanted electron current.

For comparison with experiment, it is advantageous to express the values of p_n and n_p in terms of the conductivities σ_n and σ_p. If the conductivity of the intrinsic material is written as

$$\sigma_i = q\mu n_i(1 + b), \tag{4.15}$$

then, if $p_n \ll n_n$ and $n_p \ll p_p$, we find

$$q\mu p_n = b\sigma_i^2/(1 + b)^2\sigma_n \tag{4.16}$$

$$q\mu b n_p = b\sigma_i^2/(1 + b)^2\sigma_p . \tag{4.17}$$

Using these equations, we may rewrite (4.11) and a corresponding equation for electron current into the p-region so as to express their dependence on d-c. bias v_0 and the properties of the regions:

$$\begin{aligned} I_{p0}(v_0) &= \frac{b\sigma_i^2}{(1 + b)^2\sigma_n L_p} \cdot \frac{kT}{q}(e^{qv_0/kT} - 1) \\ &\equiv G_{p0}\frac{kT}{q}(e^{qv_0/kT} - 1) \\ &\equiv I_{ps}(e^{qv_0/kT} - 1) \end{aligned} \tag{4.18}$$

$$\begin{aligned} I_{n0}(v_0) &= \frac{b\sigma_i^2}{(1 + b)^2\sigma_p L_n} \cdot \frac{kT}{q}(e^{qv_0/kT} - 1) \\ &\equiv G_{n0}\frac{kT}{q}(e^{qv_0/kT} - 1) \\ &\equiv I_{ns}(e^{qv_0/kT} - 1). \end{aligned} \tag{4.19}$$

The values of G_{p0} and G_{n0} (which are readily seen to be the values of the low-frequency, low-voltage ($v_0 < kT/q$) conductances) and the saturation reverse currents are given by

$$G_{p0} \equiv \frac{b\sigma_i^2}{(1 + b)^2\sigma_n L_p} \equiv \frac{q}{kT} I_{ps} \tag{4.20}$$

$$G_{n0} \equiv \frac{b\sigma_i^2}{(1 + b)^2\sigma_p L_n} \equiv \frac{q}{kT} I_{ns} \tag{4.21}$$

The expression for direct current then becomes

$$\begin{aligned} I_0(v_0) &= [G_{p0} + G_{n0}]\left(\frac{kT}{q}\right)[e^{qv_0/kT} - 1] \\ &= (I_{ps} + I_{ns})[e^{qv_0/kT} - 1]. \end{aligned} \tag{4.22}$$

4.4 Total Admittance

In order to calculate the alternating current, we must include the capacity of the transition region, discussed in Section 2. Denoting this by C_T, we then find for the total alternating current.

$$I_{ac} = (G_p + iS_p + G_n + iS_n + i\omega C_T)\, v_1 = A v_1 \tag{4.23}$$

where G_n and S_n are similar to G_p and S_p but apply to electron current into the p-region. The value of the hole and electron admittances can be expressed as

$$A_p = G_p + iS_p = (1 + i\omega\tau_p)^{1/2}\, G_{p0}\, e^{qv_0/kT} \tag{4.24}$$

$$A_n = G_n + iS_n = (1 + i\omega\tau_n)^{1/2}\, G_{n0}\, e^{qv_0/kT} \tag{4.25}$$

For low frequencies, such that ω is much less then $1/\tau_p$, we can expand $G_p + iS_p$ as follows:

$$G_p + iS_p = G_{p0}\, e^{qv_0/kT} + i\omega(\tau_p/2)G_{p0}\, e^{qv_0/kT} \tag{4.26}$$

Hence $(\tau_p/2)G_{p0}\, e^{qv_0/kT}$ behaves like a capacity.

It is instructive to interpret this capacity for the case of zero bias, $v_0 = 0$, for which we find:

$$C_p = \tau_p G_{p0}/2 = \tau_p q p_n \mu/2L_p = q^2 p_n L_p/2kT. \tag{4.27}$$

The last formula, obtained by noting that $\tau_p\mu = q\tau_p D/kT = qL_p^2/kT$, has a simple interpretation: qp_nL_p is the total charge of holes in a layer L_p thick. For a small change in voltage v, this density should change by a fraction qv/kT so that the change in charge divided by the change in v is $(q/kT)(qp_nL_p)$ which differs from C_p only by a factor of 2, which arises from the nature of the diffusion equation.

This capacity can be compared with $C_{T\ \mathrm{neut.}}$, discussed in Section 2, (see equation (2.39) and text for (2.42)) for germanium at room temperature as follows:

$$\frac{C_p}{C_{T\ \mathrm{neut.}}} = \frac{q^2 p_n L_p}{2kT} \cdot \frac{kTa}{10q^2 n_i^2} = \frac{p_n L_p a}{20 n_i^2}. \tag{4.28}$$

For a structure like Fig. 6(c), the excess of donors over acceptors reaches its maximum value, equal to n_n, at x_{Tn} leading to $n_n = ax_{Tn}$. Consequently $a = n_n/x_{Tn}$. Substituting this value for a in (4.28) and noting that $p_n n_n = n_i^2$ gives

$$\frac{C_p}{C_{T\ \mathrm{neut.}}} = \frac{L_p}{20 x_{Tn}} \tag{4.29}$$

As discussed at the beginning of this section, $L_p \doteq 6 \times 10^{-3}$ cm for holes in germanium. Hence if the transition region is 6×10^{-4} cm thick, the diffusion capacity C_p will dominate the capacitative term in the admittance.

Although A_p simulates a conductance and capacitance in parallel at low frequencies, its high-frequency behavior is quite different. In Fig. 7 the

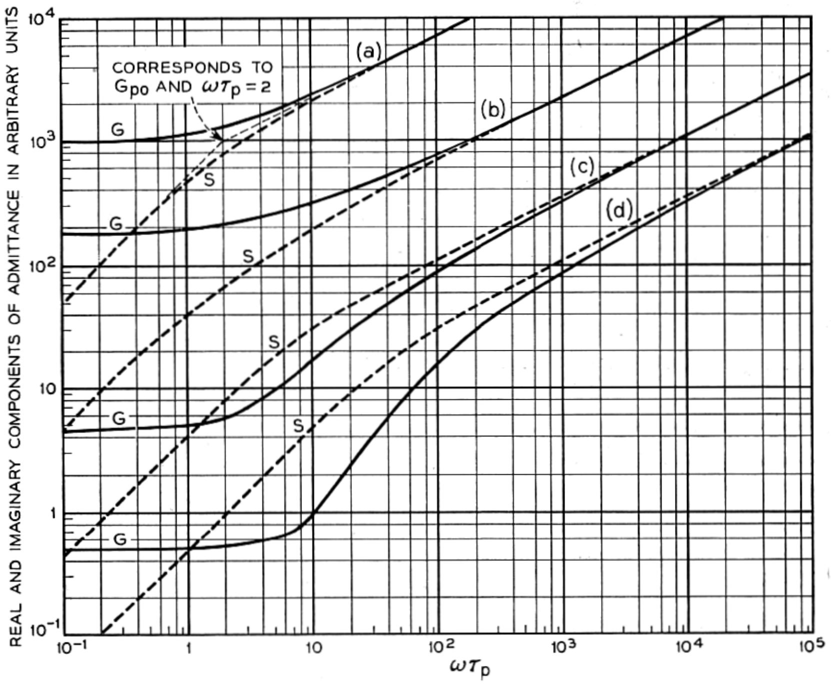

Fig. 7—Real, G, and imaginary, S, components of admittance for hole flow into n-region.
(a) $10^3 A_p/G_{po} = 10^3(1 + i\omega\tau_p)^{1/2}$ corresponding to uniform n-region.
(b) $10^2 \times$ Formula of Appendix III, corresponding to layer of high recombination rate in front of n-region. This causes G to exceed S at higher frequencies than for (a).
(c) $10 \times$ Equation (4.33), corresponding to a retarding field in the n-region, with $L_r = L_p/\sqrt{10}$.
(d) Equation (4.33) with $L_r = L_p/10$.

behavior of $(1 + i\omega\tau_p)^{1/2} = A_p/G_{p0}$, is shown. For high frequencies G_p and S_p are equal:

$$G_p = S_p = \sqrt{\tau_p/2}\, G_{p0} \sqrt{\omega} = \frac{b\sigma_i^2 \sqrt{\omega}}{(1 + b)^2 \sigma_n \sqrt{2D}} \tag{4.30}$$

Thus for high frequencies the admittance is independent of τ_p and is determined by the diffusion of holes in and out of the n-region. The three straight asymptotes have a common intersection at the point G_{p0}, $\omega\tau = 2$ on Fig. 7, a fact which is useful in estimating the value of τ from such data.

For large ω, S_p varies as $\omega^{1/2}$ as shown in (4.30) whereas S_T is ωC_T. Hence at very high frequencies C_T will dominate the admittance. At very high frequencies C_T itself will have a frequency dependence; however, for the assumptions on which the treatment of this section is based, the relaxation time for the transition region τ_T is much less than τ_p. This is a consequence of the fact that, although diffusion of holes into the transition region is required for the charging of C_T, the distance is relatively short, being in fact only that fraction of the width $x_{Tn} - x_{Tp}$ of the transition region in which ψ rises by kT/q; in germanium this will be about one-tenth of $x_{Tn} - x_{Tp}$. Since diffusion times vary as (distance)^2, the ratio of the times is

$$\frac{\tau_T}{\tau_p} = \frac{(x_{Tn} - x_{pn})^2}{100L_p^2}. \tag{4.31}$$

Hence if $L_p > x_{Tn} - x_{pn}$, τ_T will be much less than τ_p.[13]

4.5 *Admittance Due to Hole Flow in a Retarding Field*

In Appendix II we treat the case in which a potential gradient, due to changing concentration for example, is present in the n- and p-regions. This tends to prevent holes from diffusing deep in the n-region and for this reason the n-region acts partly like a storage tank for holes under a-c. conditions, thus enhancing S_p compared to G_p in A_p. If the electric field is $-d\psi/dx = kT/qL_r$, where L_r is the distance required for an increase of kT/q of potential (i.e. a factor of e increase in n_n), then the value of A_p is

$$A_p = [q\mu p_n/L_p] \frac{(2L_r/L_p)(1 + i\omega\tau_p)}{1 + [1 + (1 + i\omega\tau_p)(2L_r/L_p)^2]^{1/2}} \tag{4.32}$$

For $\omega\tau_p > 1$, this admittance is largely reactive provided $2L_r/L_p$ is sufficiently small.

The dependence of A_p upon ω is shown in Fig. 7 for two values of L_r/L_p. The plot shows the real and imaginary parts of

$$A_p/[2q\mu p_n L_r/L_p^2] = \frac{(1 + i\omega\tau_p)}{1 + [1 + (1 + i\omega\tau_p)(2L_r/L_p)^2]^{1/2}} \tag{4.33}$$

for $L_p/L_r = 10^{1/2}$ and $L_p/L_r = 10$, the two curves being relatively displaced vertically by one decade. The second value implies that the field keeps the holes back so that they penetrate only $\frac{1}{10}$ their possible diffusion length in no field. It is seen that for this case the storage effect is very pronounced and the susceptance S is much larger than G for high frequencies.

The function $(1 + i\omega\tau_p)^{1/2}$, discussed earlier, corresponds to the limiting case of (4.32) for $L_r = \infty$.

[13] In Appendix IV an analytic treatment of C_T is given.

4.6 The Effect of a Region of High Rate of Generation

There is evidence that imperfections, such as surfaces and cracks, add materially to the rate of generation and recombination of holes and electrons. If there is a localized region of high recombination rate in the transition region, there will be a pronounced modification of the admittance characteristics. In Fig. 8(a) such a layer is represented at $x = 0$. In Fig. 8(b) the customary plot of φ_p and φ_n versus x is shown. If we neglect the effect of the series resistance terms denoted by R_1 in Section 3, the change $\delta\varphi$ will

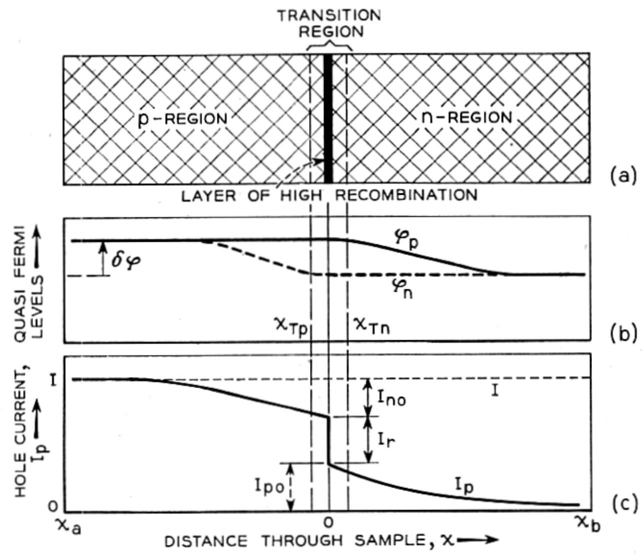

Fig. 8—The effect of a localized layer of high recombination rate on the junction characteristic.
(a) Location of layer of high recombination rate.
(b) Quasi Fermi levels.
(c) Distribution of hole current showing rapid change at layer of high recombination rate.

occur in the p-region for φ_n and in the n-region for φ_p. The hole current flowing into the n-region will thus be the same as before and will be given by equation (4.11) or (4.18) and denoted by $I_{p0}(\delta\varphi)$. Similarly, the electron current will be $I_{n0}(\delta\varphi)$. In the layer we shall suppose that there is a rate of generation of hole electron pairs equal to g_a per unit area of the layer and a rate of recombination proportional to $r_a np$ per unit area. We suppose, furthermore, that the layer is so thin that n and p are uniform throughout the layer. The net rate of generation is thus

$$g_a - r_a np = g_a [1 - e^{q(\varphi_p - \varphi_n)/kT}] \tag{4.34}$$

since for equilibrium conditions the rates balance so that $r_a n_i^2 = g_a$. The net hole current recombining in the layer per unit area is thus

$$I_r(\varphi_p - \varphi_n) = qg_a\,[e^{q(\varphi_p - \varphi_n)/kT} - 1] \tag{4.35}$$

There must, therefore, be a discontinuous decrease of hole current across the layer. The total hole current flowing in at $x = x_a$, which is also the total current I, thus does three things: for $x < x_{Tp}$, it combines with $I_{n0}(\delta\varphi)$; for $x_{Tp} < x < xT_n$, it combines with electrons at rate $I_r(\delta\varphi)$; for $x > x_{Tn}$, it flows into the n-region in amount $I_{p0}(\delta\varphi)$. This leads to

$$I = I_{n0}(\delta\varphi) + I_{p0}(\delta\varphi) + I_r(\delta\varphi). \tag{4.36}$$

In other words the layer of high recombination acts like a rectifier in parallel with $I_{n0}(\delta\varphi) + I_{p0}(\delta\varphi)$. The frequency characteristic of $I_r(\delta\varphi)$, however, will be independent of frequency and will contribute a pure conductance to the admittance of the junction.

If the layer is considered to have finite width, however, it will exhibit frequency effects just as does I_p in the n-region. In Appendix III, we treat a case in which the layer is a part of the n-region itself but has a recombination time different from the main layer. If the time is shorter, a large amount of the hole current may recombine in this layer. For high frequencies, the current may not penetrate the layer, in which case the admittance for hole current is determined by the thin layer rather than by the whole n-type region. A case of this sort is shown in Fig. 7. In this case the thickness of the layer is $\frac{1}{3}$ of its diffusion length and in it the lifetime of a hole τ_ℓ is $\frac{1}{9}$ the value τ_p in the main body of the n-region. The hole current will thus be restricted to this layer when the diffusion distance $\sqrt{D/\omega}$ is less than the layer thickness $(\frac{1}{3})\sqrt{D\tau_\ell}$; this corresponds to $\omega\tau_\ell > 9$ or $\omega\tau_p > 81$. The presence of the high rate of combination in the layer is evidenced by the tendency of G to be greater than S at high frequencies. If the layer were infinitely thin, as discussed above, it would simply add a constant conductance to the admittance.

4.7 Patch Effect in p-n Junctions

If there are localized regions of high recombination rate, a "patch effect" may be produced in an n-p junction. As an extreme example, suppose the value of g_a for the layer just considered is allowed to become very large; then the recombination resistance may become small compared to R_1 in Section 3 and the junction will become substantially ohmic. If the region of high rate of recombination is relatively small compared to the area of the rest of the junction, then the behavior of the junction as a whole may be regarded as being that due to two junctions in parallel. Over most of the area, the currents will flow as if the patch were not present so that one component of the current will be that due to the uniform junction. In addition there will be current due to recombination and generation in the patch. The series resistance to the patch will be relatively high due to the constriction of the current paths. On the other hand, the value of $I_r(\delta\phi)$ associated with the patch may be very high. Hence the current due to the patch will be that of a low impedance ideal rectifier in series with a high resistance; and if the ratio of impedances is high enough, such a series combination amounts essentially to an ohmic leakage path. Thus patches in the *p-n* junction will tend to introduce leakage paths and destroy saturation in the reverse direction.

An extreme example of a region of high rate of recombination would be a particle of metal making a non-rectifying contact to both *p*- and *n*-type germanium. Since holes and electrons are essentially instantly combined in a metal, the boundary condition at the metal surface would be equality of φ_p and φ_n. This would mean that near the metal particle, φ_p and σ_n could not differ by $\delta\varphi$, the condition required, over some parts of the junction at least, in order for ideal rectification to occur.

A common source of imperfection in *p-n* junctions arises from dirt or fragments on the surface which overlap the junction. Even if these do not actually constitute a short circuit across the junction, they may furnish patches of the sort discussed here and modify the junction characteristic.

4.8 Final Comments

Another possible cause for frequency effects may be found in the trapping of holes or electrons.[14] When an added hole concentration is introduced into an *n*-region, a certain fraction of the holes will be captured by acceptors and later re-emitted or else recombined with electrons while trapped. Investigation of this process is given in Appendix VI. One interesting result is that the trapping of holes in a uniform *n*-region cannot produce an effective susceptance (i.e. $i\omega C$) in excess of the conductance, as can a retarding field.

Finally it should be remarked that important and significant variations of the conductivity in the *p*- and *n*-regions may be produced by hole or electron injection. Under these conditions, when the hole concentration approaches n_n, $\psi - \varphi_n$ will vary. Under these conditions R_1 may be appreciably altered. These factors favor the *p-n* junction as a rectifier since they lead to a reduction of series resistance under conditions of forward bias and thus tend to improve the rectification ratio.

[14] Frequency dependent effects in Cu_2O rectifiers have been explained in this way by J. Bardeen and W. H. Brattain, personal communication.