THE IDEAL DIODE VOLT-AMPERE CHARACTERISTIC

Much of the development in this section makes use of the depletion approximation and assumes a step junction device.

The diode at thermal equilibrium serves as a base upon which to build the concept of carrier flux and potential barriers. Indeed, when forward or reverse biases are applied, the changes in the potential barrier and carrier fluxes determine the current direction and its relative magnitude.

The energy band diagram under equilibrium condition is illustrated below, since $E_F$ is constant at thermal equilibrium, and $E_C$, $E_V$ changes when making transition from $P$- to $N$-type material; the slope of the energy band edges is proportional to the electric field $E$, therefore a negative slope yields a negative electric field in the depletion region. The carrier pyramids in the bulk regions of the figure crudely represent the energy distribution of the carrier densities as determined by the product of the density of states function and Fermi function. The majority and minority that are presented here, actually decreasing exponentially with increasing energy.
As shown on the figure, the electrons are drifting down the hill from left to right to a lower energy level, while the minority holes from the p-type are drifting down to a lower energy from right to left, and because the current in equilibrium condition must be zero for each type of carrier, holes can't build up on one end and so do electrons, therefor the current equations become

\[ J_P = J_{P\text{drift}} + J_{P\text{diff}} \]

\[ J_N = J_{N\text{drift}} + J_{N\text{diff}} \]

or

\[ J_P = q \mu_P \frac{PE - qD_P}{dP} \]

And

\[ J_N = q \mu_N nE + qD_N \frac{dn}{dx} \]

But as explained above, \( J = J_P = J_N = 0 \) under equilibrium, then we get

\[ J_{N\text{drift}} = -J_{N\text{diff}}, \text{ and } J_{P\text{drift}} = -J_{P\text{diff}}. \]

Expanding on the explanation, examine the carrier concentration on the two sides of a p-n junction. The majority carrier \( P \) may be \( 10^{16}/\text{cm}^3 \) and \( P \) on the n-side may be \( 10^5/\text{cm}^3 \), going from P to n the holes changes by \( 10^5/\text{cm}^3 \) therefore the slope will be very large \( (dP/dx) \) and causing the holes to diffuse from \( P \) to \( n \).
Finally, in the uniformly doped bulk region, $E_C - E_F$ is constant and, hence, the electric field is zero. Also, since $n = N_D$ in $n$- and $p = N_A$ in $p$-region, then $\frac{dn}{dx}$ and $\frac{dp}{dx}$ are zero, therefore the total current in bulk region is zero.

**Diode V-I Characteristics**

**a) Forward Bias, $V_A > 0$**

- Electron energy: $J_{n\text{drift}}$
- Hole energy: $J_{p\text{drift}}$
- Energy band diagram for forward bias $V > 0$ under equilibrium

**b) Reverse Bias, $V_A < 0$**

- $N$-bulk
- Energy band diagram for reverse bias at thermal equilibrium

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**Diode Structure Diagrams**

- $P$ and $n$ regions with Al contacts
- Diffusion and drift regions
- Bulk region
a) FORWARD BIAS, $V_A > 0$

The effect of applying $V_A$ to a p-n junction is that the potential hill energy barriers will be reduced by $qV_A$ from the equilibrium case and the difference between p-bulk and n-bulk energy levels become $q(V_{bi} - V_A)$, and as a result there will be an increase in the hole diffusion from p to n and electrons from n to p, while the drift electrons and drift holes remain the same.

The net effect of forward bias is a large increase in diffusion current components while the drift components are fixed near the equilibrium values, since the Fermi junction distributes the carriers nearly exponentially with increasing energy. Now the number of carriers able to diffuse increases exponentially with the reduction of the potential barriers, therefore the net forward bias current should increase exponentially with $V_A$.

b) REVERSE BIAS, $V_A < 0$

By applying a negative $V_A$, the p-bulk region and n-bulk region will be separated by $qV_A$ from the equilibrium case and the total shift become $q(V_{bi} - V_A)$, with $V_A < 0$ this will add up to $qV_{bi}$, the result is that there will be less electrons with enough energy to diffuse from n to p and also less holes to go from p to n, and therefore the hole diffusion current and electron diffusion current is reduced to less than its thermal equilibrium value. However the drift current components of hole and electron remain the same as its thermal value.
For $V_A > 0$ the source of holes at the metal-P material contact. To create a hole an electron must jump into the external circuit, the hole then moves to the right toward the junction, eventually diffuses across the depletion region and is injected into the n-region as a minority carrier. As a minority carrier the hole has a very limited lifetime and soon recombines with a majority carrier electron. This recombination in turn calls for an electron to flow from the n-region contact. This procedure continuous flow of carriers into and out of the semiconductor via the contacts.

Since the device has only two terminals, the total current through the diode must be a constant at each point:

$$J = \text{constant} = J_N(x) + J_P(x)$$
Therefore, if the minority carrier current density \( j_n(x) \) is known in
the n-bulk region the majority carrier current density \( j_p(x) \) is
also known from \( j_n(x) = j - j_p(x) \).

The same arguments is true for P-region when minority
carrier current density \( j_N(x) \) is known then the majority carrier
current density \( j_P(x) \) is known from \( j_P(x) = j - j_N(x) \).

Since there is no generation or recombination inside the
depletion region, then if the minority carrier diffusion current is
known at the edges of the depletion region, then it is known
throughout the depletion region, and hence at the other edge
of the depletion region, therefore,

\[
\begin{align*}
\left. j_p \right|_{\text{depletion}} &= \left. j_n \right|_{\text{depletion}} = -qD_n \frac{dn}{dx} \bigg|_{x=x_n} \quad \text{in n-region} \\
\left. j_N \right|_{\text{depletion}} &= \left. j_P \right|_{\text{depletion}} = qD_p \frac{dp}{dx} \bigg|_{x=-x_P} \quad \text{in P-region}
\end{align*}
\]

And the total current is simply

\[
j = j_p(x_n) + j_N(-x_P)
\]

Because \( j_N(x_n) = j_N(-x_P) \),

\[
j_N = q\mu_n n e + qD_N \frac{dn}{dx} = 0
\]

Then \( e = \frac{-D_N}{\mu_n} \frac{dn/dx}{n} = -\frac{KT}{q} \frac{dn/dx}{n} \)

\[
V_i = V_{bi} - V_A = -\int_{-x_p}^{x_n} e \, dx = -\int_{-x_p}^{x_n} \frac{KT}{q} \frac{dn/dx}{n} \ln n(x_n)
\]

\[
V_{bi} - V_A = \frac{KT}{q} \ln \frac{n_n(x_n)}{n_p(-x_P)} \quad \text{Therefore} \quad \frac{n_n(x_n)}{n_p(-x_P)} = e
\]

\[
n_p(-x_P) = n_n(x_n) e^{-q(V_{bi}-V_A)/KT}
\]

But under equilibrium

condition \( V_{bi} = \frac{KT}{q} \ln \left( \frac{n_0 P_0}{n_i^2} \right) \Rightarrow -q(V_{bi} - V_A)/KT = \frac{n_i^2}{n_0 P_0} \)
Combining the above equations, yields
\[ n_p(-x_p) = n_m(x_m) \frac{n_m^2}{n_p^0 P_0^0} \frac{q V_A / kT}{e} = \frac{n_m^2}{n_p^0 P_0^0} e^{\frac{q V_A / kT}{P_0^0}} \]

remembering that \( n_m(x_m) = n_m^0 \) and \( \frac{n_m^2}{P_0^0} = n_p^0 \)
then we get:
\[ n_p(-x_p) = n_p^0 e^{\frac{q V_A / kT}{P_0^0}} \]

and the injected electron concentration at the boundary \(-x_p\) is:
\[ \Delta n_p(-x_p) = n_p^0 (e^{\frac{q V_A / kT}{P_0^0}} - 1) \]

because \( \Delta n(-x_p) = n_p(-x_p) - n_p^0 \)

For the hole concentration at the edges of the depletion region
\[ P_n(x_m) = P_n^0 e^{\frac{q V_A / kT}{P_0^0}} \]
\[ \Delta P_n(x_m) = P_n^0 (e^{\frac{q V_A / kT}{P_0^0}} - 1) \]

For long-base diode \( \Delta n_p(-\infty) = 0 \) and \( \Delta P_n(\infty) = 0 \)

**Derivation for the Ideal Diode Equation:**

To solve the minority carrier diffusion equations, we select two coordinate systems as illustrated below.

To solve the minority carrier diffusion equations, we select two coordinate systems as illustrated below.

Using the boundary condition \( \Delta P_n(\infty) = A_1 e^\infty + A_2 e^{-\infty} = A_1 e^\infty + 0 = 0 \)
then \( A_1 \) must be zero. \( A_1 = 0 \), then
\[ \Delta P_n(0^+) = P_n^0 (e^{\frac{q V_A / kT}{P_0^0}} - 1) = A_2 \]

\[ \Delta P_n(x') = A_1 e_{\text{LP}} + A_2 e_{\text{LP}} \]

the solution is:

\[ \Delta P_n(x') = \frac{\Delta P_n(\infty)}{L^2} = \frac{\Delta P_n(0^+)}{L^2} \]
Therefore the solution for $\Delta P_n(x)$ is
\[
\Delta P_n(x) = P_n(\frac{qV_A}{kT} - 1) e^{-x/L_p}
\]

or
\[
P_n(x') = P_n + \Delta P_n(x')
\]
\[
P_n(x') = P_n + P_n(\frac{qV_A}{kT} - 1) e^{-x'/L_p}
\]

Also for P-hulk region
\[
\eta_p(x) = \eta_p(\frac{qV_A}{kT} - 1) e^{-x/L_N}
\]

and finally the hole current, and the electron current can be calculated as:
\[
J_p(x') = -qD_p \frac{d\Delta P_n}{dx'} = -qD_p P_n(\frac{qV_A}{kT} - 1)(-1) e^{-x'/L_p}
\]

AND
\[
J_N(x'') = qD_N \frac{d\eta_p}{dx''} = qD_N \eta_p(\frac{qV_A}{kT} - 1) e^{-x''/L_p}
\]

and the total current density is
\[
\mathbf{j} = J_p(x') + J_N(x'') = J_p(x_m) + J_N(-x_p)
\]

\[
\mathbf{j} = q\left[\frac{D_N}{L_N} \eta_p + \frac{D_p}{L_p} P_n\right] \left(\frac{qV_A}{kT} - 1\right)
\]

then the total current $I = A \cdot \mathbf{j}$ where $A$ is the area of junction.

\[
I = qA \left[\frac{D_N}{L_N} \eta_p + \frac{D_p}{L_p} P_n\right] \left(\frac{qV_A}{kT} - 1\right)
\]

but $\eta_p = \frac{n^2_p}{N_A}$ and $P_n = \frac{n^2_e}{N_D}$, then

\[
I = qA n^2_p \left[\frac{D_N}{L_N N_A} + \frac{D_p}{L_p N_D}\right] \left(\frac{qV_A}{kT} - 1\right)
\]

if we assume $I_0 = qA n^2_p \left[\frac{D_N}{L_N N_A} + \frac{D_p}{L_p N_D}\right]$, then

\[
I = I_0 \left(\frac{qV_A}{kT} - 1\right)
\]