THE PN-JUNCTION UNDER FORWARD AND REVERSE BIAS

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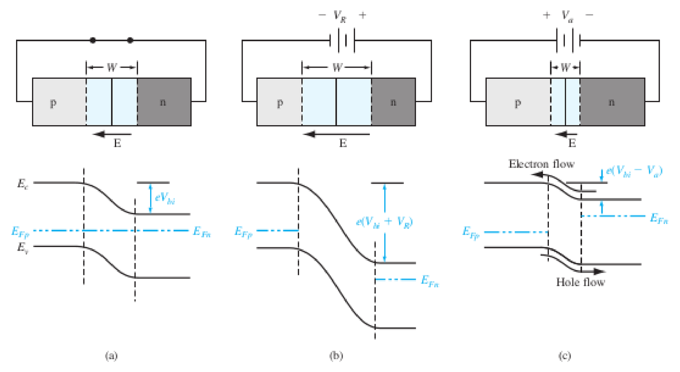
The pn-junction diode

pn junction current



- The abrupt depletion layer approximation applies. The space charge regions have abrupt boundaries, and the semiconductor is neutral outside of the depletion region.
- The Maxwell–Boltzmann approximation applies to carrier statistics.
- The concepts of low injection and complete ionization apply.
- – The total current is a constant throughout the entire pn structure.
  - The individual electron and hole currents are continuous functions through the pn structure.
  - The individual electron and hole currents are constant throughout the depletion region.

$$
\begin{aligned}
V_{bi} &= V_t \ln\left(\frac{N_a N_d}{n_i^2}\right) \\
\frac{n_i^2}{N_a N_d} &= \exp\left(-\frac{eV_{bi}}{kT}\right) \\
n_{n0} &\approx N_d \\
n_{p0} &\approx \frac{n_i^2}{N_a} \\
n_{p0} &= n_{n0} \exp\left(-\frac{eV_{bi}}{kT}\right)
\end{aligned}
$$

n_n is the majority carrier electrons, n_p is the concentration of minority carrier electrons.

$$
\begin{aligned}
n_p &= n_{p0} \exp\left(\frac{eV_a}{kT}\right) \\
p_n &= p_{n0} \exp\left(\frac{eV_a}{kT}\right)
\end{aligned}
$$

Minority carrier distribution

$$
\begin{aligned}
\frac{\partial(\delta p_n)}{\partial t} &= D_p \frac{\partial^2(\delta p_n)}{\partial x^2} - \mu_p E \frac{\partial \delta p_n}{\partial x} + g' - \frac{\partial p_n}{\tau_{p0}} \\
\frac{d^2 \delta p_n}{dx^2} - \frac{\delta p_n}{L_p^2} &= 0 \qquad (x > x_n), L_p^2 = D_p \tau_{p0} \\
\frac{d^2 \delta n_p}{dx^2} - \frac{\delta n_p}{L_n^2} &= 0 \qquad (x > x_n), L_n^2 = D_n \tau_{n0} \\
p_n(x_n) &= p_{n0} \exp\left(\frac{eV_a}{kT}\right) \xrightarrow[x \to \infty]{} p_{n0} \\
n_p(-x_p) &= n_{p0} \exp\left(\frac{eV_a}{kT}\right) \xrightarrow[x \to -\infty]{} n_{p0} \\
\delta p_n(x) &= p_n(x) - p_{n0} = A e^{\frac{x}{L_p}} + B e^{-\frac{x}{L_p}} \\
&= p_{n0}\left[\exp\left(\frac{eV_a}{kT}\right) - 1\right] \exp\left(\frac{x_n - x}{L_p}\right) \\
\delta n_p(x) &= n_p(x) - n_{p0} = C e^{\frac{x}{L_n}} + D e^{-\frac{x}{L_n}} \\
&= n_{p0}\left[\exp\left(\frac{eV_a}{kT}\right) - 1\right] \exp\left(\frac{x_p - x}{L_n}\right) \\
p &= p_0 + \delta p = n_i \exp\left(\frac{E_{Fi} - E_{Fp}}{kT}\right) \\
n &= n_0 + \delta n = n_i \exp\left(\frac{E_{Fn} - E_{Fi}}{kT}\right)
\end{aligned}
$$

At the space charge edge:

$$
\begin{aligned}
n_0 p_n(x_n) &= n_0 p_{n0} \exp\left(\frac{V_a}{V_t}\right) = n_i^2 \exp\left(\frac{V_a}{V_t}\right) \\
np &= n_i^2 \exp\left(\frac{E_{Fn} - E_{F_p}}{kT}\right)
\end{aligned}
$$

Ideal pn junction current

$$
\begin{aligned}
J_p(x_n) &= -eD_p \left.\frac{dp_n(x)}{dx}\right|_{x=x_n} \\
J_p(x_n) &= -eD_p \left.\frac{d\delta p_n(x)}{dx}\right|_{x=x_n} \\
&= \frac{eD_p p_{n0}}{L_p}\left[\exp\left(\frac{eV_a}{kT}\right) - 1\right] \\
J_n(-x_p) &= \frac{eD_n n_{p0}}{L_n}\left[\exp\left(\frac{eV_a}{kT}\right) - 1\right] \\
J &= \underbrace{\left[\frac{eD_p p_{n0}}{L_p} + \frac{eD_n n_{p0}}{L_n}\right]}_{J_s}\left[\exp\left(\frac{eV_a}{kT}\right) - 1\right]
\end{aligned}
$$

Generation-recombination currents and high-injection levels

$$
R = \frac{C_n C_p N_t (np - n_i^2)}{C_n(n + n') + C_p(p + p')}
$$

Reverse bias:

$$
\begin{aligned}
R &= \frac{-C_n C_p N_t n_i^2}{C_n n' + C_p p'} \\
&= \frac{-n_i}{\frac{1}{N_t C_p} + \frac{1}{N_t C_n}} \\
&= \frac{-n_i}{2\tau_0} \qquad \tau_0 = \frac{\tau_{p0} + \tau_{n0}}{2} \\
J_{gen} &= \int_0^w eG\, dx = \frac{en_i W}{2\tau_0} \\
J_R &= J_s + J_{gen}
\end{aligned}
$$

Forward bias:

$$
\begin{aligned}
R &= \frac{np - n_i^2}{\tau_{p0}(n + n') + \tau_{n0}(p + p')} \\
n &= n_i \exp\left[\frac{E_{Fn} - E_{Fi}}{kT}\right] \\
p &= n_i \exp\left[\frac{E_{Fi} - E_{Fp}}{kT}\right]
\end{aligned}
$$

figure 8.13

$$
eV_a = (E_{Fn} - E_{Fi}) + (E_{Fi} - E_{Fp})
$$

At the space charge region center:

$$
\begin{aligned}
\frac{eV_a}{2} &= E_{Fn} - E_{Fi} = E_{Fi} - E_{Fp} \\
n &= n_i \exp\left[\frac{eV_a}{2kT}\right] \\
p &= n_i \exp\left[\frac{eV_a}{2kT}\right] \\
R_{max} &= \frac{n_i}{2\tau_0} \frac{\exp\left(\frac{eV_a}{kT}\right) - 1}{\exp\left(\frac{eV_a}{kT} + 1\right)}
\end{aligned}
$$

ignoring the ones ($V_a \gg kT/e$)

$$
\begin{aligned}
&= \frac{n_i}{2\tau_0} \exp\left(\frac{eV_a}{2kT}\right) \\
J_{rec} &= \int_0^{''} eR\, dx = ex' \frac{n_i}{2\tau_0} \exp\left(\frac{eV_a}{2kT}\right) \\
&= \underbrace{\frac{eWn_i}{2\tau_0}}_{J_{r0}} \exp\left(\frac{eV_a}{2kT}\right) \\
J &= J_{rec} + J_D \\
J_D &= J_s \exp\left(\frac{eV_a}{kT}\right) \\
\ln J_{rec} &= \ln J_{r0} + \frac{V_a}{2V_t} \\
\ln J_D &= \ln J_s + \frac{V_a}{2V_t} \\
I &= I_s \left[\exp\left(\frac{V_a}{nV_t}\right) - 1\right]
\end{aligned}
$$

This n is not n but the ideality factor, now for high level injection:

$$
\begin{aligned}
np &= n_i^2 \exp\left(\frac{V_a}{V_t}\right) \\
(n_0 + \delta n)(p_0 + \delta p) &= n_i^2 \exp\left(\frac{V_a}{V_t}\right) \\
\delta n \delta p &\approx n_i^2 \exp\left(\frac{V_a}{V_t}\right) \\
\delta n = \delta p &\approx n_i^2 \exp\left(\frac{V_a}{2V_t}\right) \\
I &\propto \exp\left(\frac{V_a}{2V_t}\right)
\end{aligned}
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