VE320 Intro to Semiconductor Devices

Chapter 7

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② e⁻ in potential field

③ e in periodic potential field

④ concentration of electrons and holes

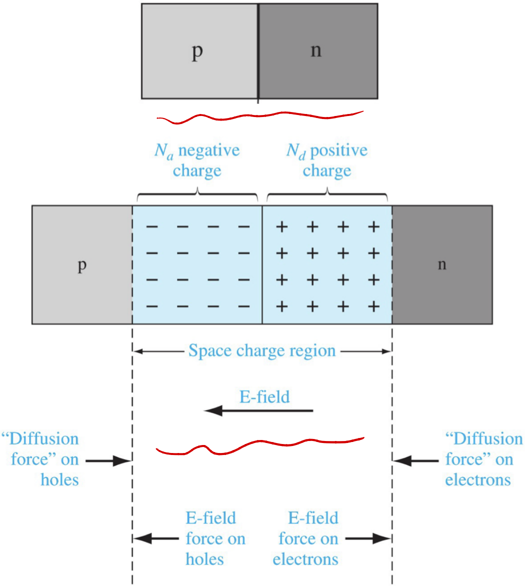
E_F E_{Fi}

⑤ current density — drift — diffusion

⑥ concentration of e and holes change w.r.t. t and x

⑦ pn junction.

Structure of pn Junction



Energy-band Diagram

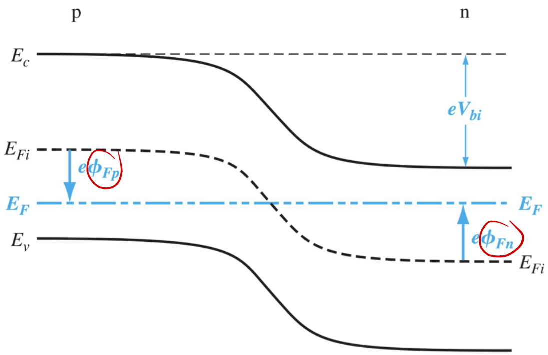


Figure: Energy-band diagram of a pn junction in thermal equilibrium

Built-in Potential Barrier

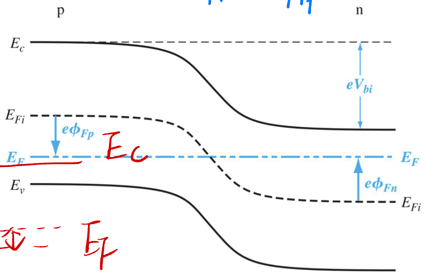
N_{a2} N_{d2}

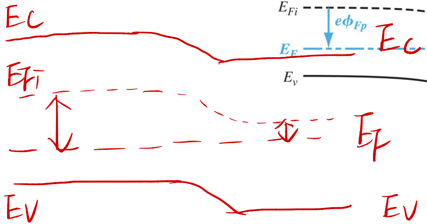
$n_0 = n_i \exp\left(\frac{E_F - E_{Fi}}{kT}\right) = n_i \exp\left(\frac{-e\phi_{Fn}}{kT}\right)$

ϕ_{Fn}, ϕ_{Fp}.

$N_a = N_{a2} - N_{d2}$

P P





N_{a1} N_{d1}

$N_d = N_{d1} - N_{a1}$

net concentration

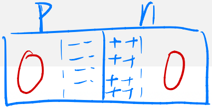
$$V_{bi} = |\Phi_{Fn}| + |\Phi_{Fp}|$$

$$= \frac{kT}{e} \ln\left(\frac{N_a N_d}{n_i^2}\right) = V_t \ln\left(\frac{N_a N_d}{n_i^2}\right)$$

V

where $V_t = kT/e$ is the thermal voltage.

Electric Field



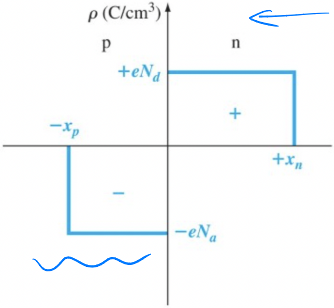


Figure: space charge density

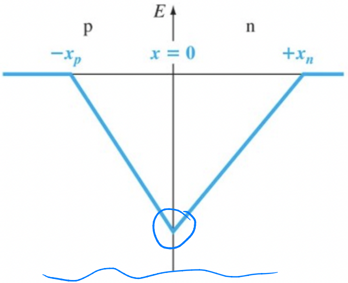


Figure: electric field

$$\rho(x) = \begin{cases} -eN_a, & -x_p \leq x \leq 0 \\ +eN_d, & 0 \leq x \leq x_n \end{cases}$$

$$\frac{d^2\Phi(x)}{dx^2} = -\frac{\rho(x)}{\epsilon_s} = -\frac{dE(x)}{dx} \quad (\epsilon_s : \text{Dielectric constant})$$

Electric Filed

$E(x=-x_p)=0$

$E(x=x_n)=0$

$$E(x) = \begin{cases} -\dfrac{eN_a}{\epsilon_s}(x+x_p), & -x_p \le \quad x \le \quad 0 \\ -\dfrac{eN_d}{\epsilon_s}(x_n - x), & 0 \le \quad x \le \quad x_n \end{cases}$$

When x = 0:

$$\boxed{N_a x_p = N_d x_n}$$

$$\begin{cases} x_p = \dfrac{N_d x_n}{N_a} \\ x_n = \dfrac{N_a x_p}{N_d} \end{cases}$$

Maximum electric field intensity at x=0:

$$E_{\max} = -\frac{eN_a x_p}{\epsilon_s} = -\frac{eN_d x_n}{\epsilon_s}$$

$\longleftarrow$

Suppose $\Phi(x) = 0$ when $x = -x_p$:

$$\Phi(x) = \begin{cases} \dfrac{eN_a}{2\epsilon_s}(x + x_p)^2, & -x_p \leq \quad x \leq \quad 0 \\ \dfrac{eN_d}{\epsilon_s}(x_n \cdot x - \dfrac{x^2}{2}) + \dfrac{eN_a}{2\epsilon_s}x_p^2, & 0 \leq \quad x \leq \quad x_n \end{cases}$$

When $x = x_n$, the potential is the same as the built-in potential barrier:

$$V_{bi} = |\Phi(x = x_n)| = \frac{e}{2\epsilon_s}(N_d x_n^2 + N_a x_p^2)$$

Space Charge Width

$$
\begin{cases}
x_n = & \left[\dfrac{2\epsilon_s (V_{bi})}{e} \left(\dfrac{N_a}{N_d} \right) \left(\dfrac{1}{N_a + N_d} \right) \right]^{1/2} \\
x_p = & \left[\dfrac{2\epsilon_s (V_{bi})}{e} \left(\dfrac{N_d}{N_a} \right) \left(\dfrac{1}{N_a + N_d} \right) \right]^{1/2}
\end{cases}
$$

The total depletion region:

$$
\begin{aligned}
W &= x_n + x_p \\
&= \left[\frac{2\epsilon_s (V_{bi})}{e} \left(\frac{N_a + N_d}{N_a N_d} \right) \right]^{1/2}
\end{aligned}
$$

Reverse Bias

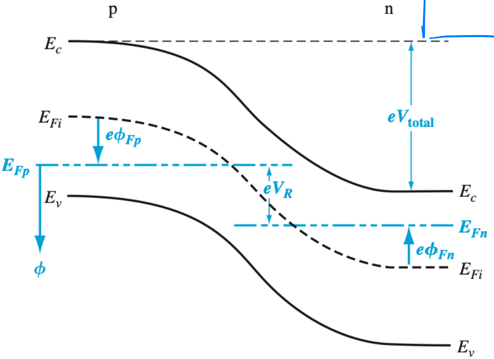
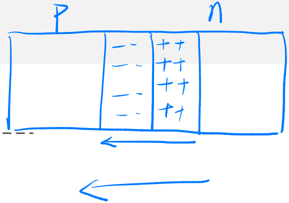


Figure: Energy-band diagram of a pn junction under reverse bias



$$V_{\text{total}} = |\Phi_{Fn}| + |\Phi_{Fp}| + V_R = V_{bi} + V_R$$

W and E

$V_{bi} \to \underline{V_{bi} + V_R}$

$$W = \left[\frac{2\epsilon_s(V_{bi} + V_R)}{e}\left(\frac{N_a + N_d}{N_a N_d}\right)\right]^{1/2}$$

$$E_{\text{max}} = -\left[\frac{2e(V_b i + V_R)}{\epsilon_s}\left(\frac{N_a N_d}{N_a + N_d}\right)\right]^{1/2}$$

$$E_{\text{max}} = \frac{-2(V_{bi} + V_R)}{W}$$

Junction Capacitance

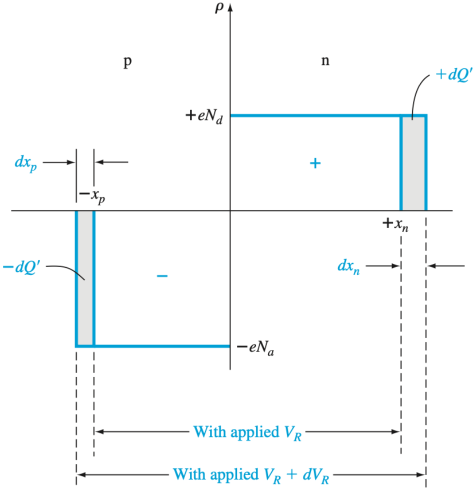
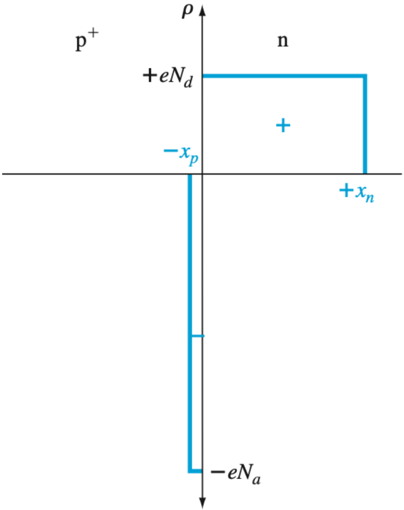


Figure: Change of depletion region width with a change in reverse-bias voltage

Junction Capacitance

$$
\begin{aligned}
C' &= \frac{dQ'}{dV_R} \\
&= eN_d \frac{dx_n}{dV_R} \\
&= \left[\frac{e\epsilon_s N_a N_d}{2(V_{bi}+V_R)(N_a+N_d)} \right]^{1/2} \\
&= \frac{\epsilon_s}{W}
\end{aligned}
$$

One-sided Junction



$N_a \gg N_d$

$x_n \gg x_p$

$W \simeq x_n$

Figure: One-sided p^+n junction

One-sided Junction

$$W \approx \left[\frac{2\epsilon_s(V_{bi} + V_R)}{eN_d}\right]^{1/2}$$

$$C' \approx \left[\frac{e\epsilon_s N_d}{2(V_{bi} + V_R)}\right]^{1/2}$$

$$\left(\frac{1}{C'}\right)^2 = \frac{2(V_{bi} + V_R)}{e\epsilon_s N_d}$$

V_{bi}

One-sided Junction

$$W \approx \left[\frac{2\epsilon_s(V_{bi} + V_R)}{eN_d}\right]^{1/2}$$

$$C' \approx \left[\frac{e\epsilon_s N_d}{2(V_{bi} + V_R)}\right]^{1/2}$$

$$\left(\frac{1}{C'}\right)^2 = \frac{2(V_{bi} + V_R)}{e\epsilon_s N_d}$$