Semiconductor devices

Thorbjørn Erik Køppen Christensen

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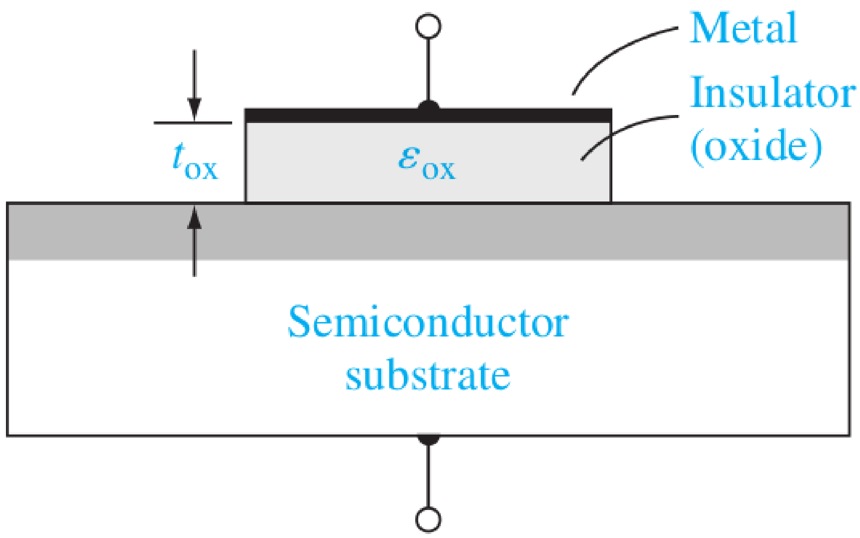
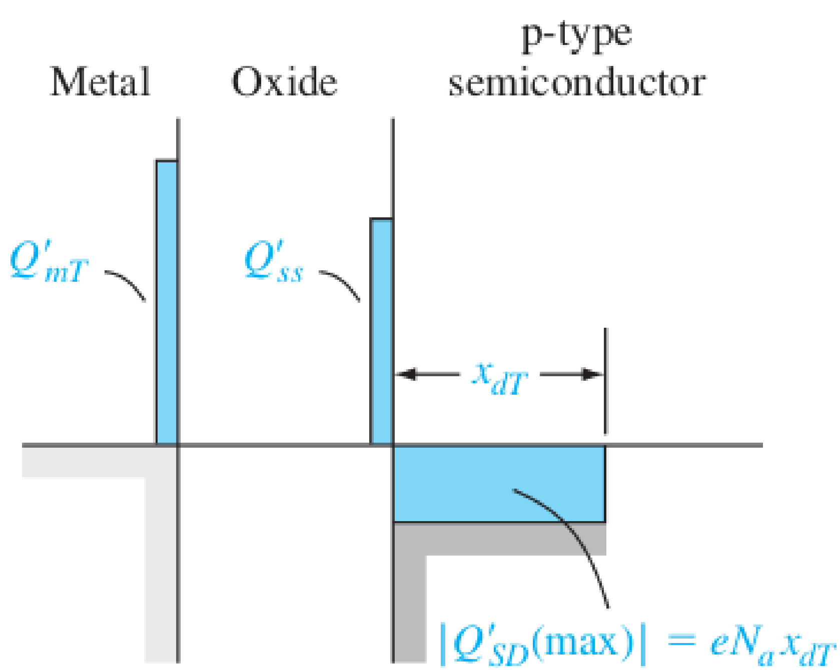
Part I

Fundamentals of the Metal-Oxide-Semiconductor Field-Effect Transistor (MOSFET)

1 The two-terminal MOS structure





The MOS structure is similar to that of the plate capacitor:

$$C = \frac{\epsilon}{d}$$
$$Q' = C'V$$
$$E = \frac{V}{d}$$

By applying either a positive or negative voltage to the p type semiconductor, one can create an accumulation or depletion layer, the thickness of this layer is interesting (here depletion layer)

$$\phi_{fp} = V_t \ln\left(\frac{N_a}{n_i}\right)$$
$$x_d = \sqrt{\frac{2\epsilon\phi_s}{eN_a}}$$

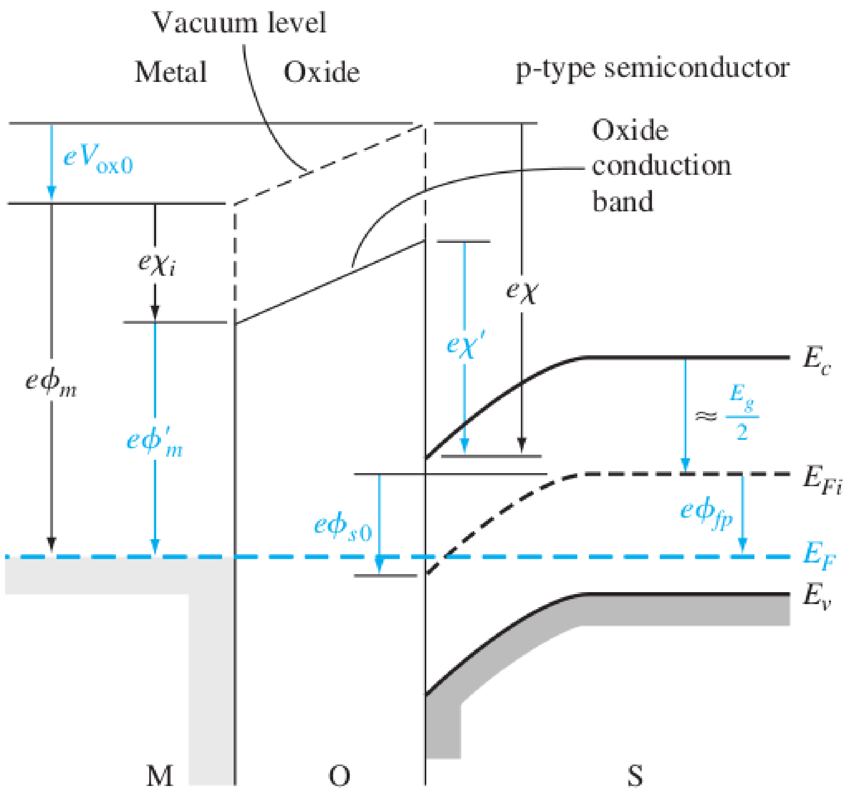
ϕ_s is the surface potential: difference between E_{Fi} at bulk and surface, the inversion threshold is when $\phi_s = -2\phi_{fp}$ and inversion occurs, it's the threshold voltage where the space charge region doesn't become larger, but more electrons can still go in the conducting band:

$$x_{dT} = \sqrt{\frac{4\epsilon\phi_{fp}}{eN_a}}$$

Same holds for n types, (change N_a with N_d.- Now one can find the surface charge density:

$$n = n_i \exp\left[\frac{E_F - E_{Fi}}{kT}\right]$$
$$n_s = n_i \exp\left[\frac{\phi_{fp} + \Delta\phi_s}{V_t}\right] = \underbrace{n_i \exp\left(\frac{\phi_{fp}}{V_t}\right)}_{n_{st}} \exp\left(\frac{\Delta\phi_s}{V_t}\right) \quad \Delta\phi_s > 2\phi_{fp}$$

1.1 Work function difference



(b)

contact and (b) energy band diagram through the

$$e\phi'_m + eV_{ox0} = e\chi' + \frac{E_g}{2} - e\phi_{s0}e\phi_{Jfp}$$

$V_{ox}0$ is the potential drop across the oxide, ϕ'_m the modified metal work function

$$V_{ox0} + \phi_{s0} = -\left[\phi'_m - \left(\chi' + \frac{E_g}{2e} + \phi_{fp}\right)\right]$$

The metal semiconductor workfunction is then:

$$\phi_{ms} \equiv \left[\phi'_m - \left(\chi' + \frac{E_g}{2e} + \phi_{fp}\right)\right]$$

$$\phi_{ms_{np}} = \pm\left(\frac{E_g}{2e} - \phi_{fp}\right)$$

1.2 Flat-band voltage

The flat band voltage is the gate voltage that leads to no band bending.

$$\begin{aligned} V_{ox0} + \phi_{s0} &= -\phi_{ms} \\ V_g &= \Delta V_{ox} + \Delta\phi_s = (V_{ox} - V_{ox0}) + (\phi_{s0} - \phi_{s0}) \\ &= V_{ox} + \phi_s + \phi_{ms} \end{aligned}$$

For flaatband

$$\begin{aligned} Q'_m + Q'_{ss} &= 0 \\ V_{ox} &= \frac{Q'_m}{C_{ox}} \\ V_{ox} &= \frac{-Q'_{ss}}{C_{ox}} \\ V_G = V_{FB} &= \phi_{ms} - \frac{Q'_{ss}}{C_{ox}} \end{aligned}$$

Threshold Voltage

$$\begin{aligned} Q'_{mT} + Q'_{ss} &= |Q'_{SD}(\max)| \\ |Q'_{SD}(\max)| &= eN_a x_{dT} \\ V_G &= V_{ox} + \phi_s + \phi_{ms} \end{aligned}$$

at threshold $V_G = V_{TN}$

$$\begin{aligned} V_{TN} &= V_{xoT}02\phi_{fp} + \phi_{ms} \\ V_{oxT} &= \frac{Q'_{mT}}{C_{ox}} \\ &= \frac{1}{C_{ox}}\left(|Q'_{SD}(\max)| - Q'_{ss}\right) \\ V_{TN} &= \frac{1}{C_{ox}}\left(|Q'_{SD}(\max)| - Q'_{ss}\right) + \phi_{ms} + 2\phi_{fp} \\ &= \frac{t_{ox}}{\epsilon_{ox}}\left(|Q'_{SD}(\max)| - Q'_{ss}\right) + \phi_{ms} + 2\phi_{fp} \\ &= \frac{|Q'_{SD}(\max|}{C_{ox}} + V_{FB} + 2\phi_{fp} \end{aligned}$$

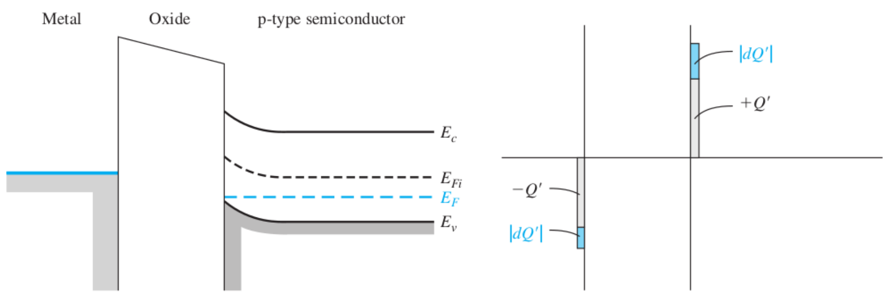
The same can be done with an n type conductor

$$V_{TP} = \frac{t_{ox}}{\epsilon_{ox}}\left(-|Q'_{SD}(\max)| - Q'_{ss}\right) + \phi_{ms} + 2\phi_{fn}$$

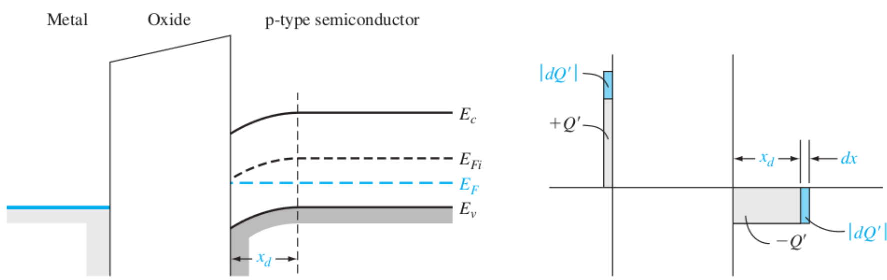
with

$$\phi_{ms} = \phi'_m - \left(\chi' + \frac{E_g}{2e} - \phi_{fn}\right)$$
$$|Q'_{SD}(\max)| = eN_d x_{dT}$$
$$x_{dT} = \sqrt{\frac{4\epsilon_s \phi_{fn}}{eN_d}}$$
$$\phi_{fn} = V_t \ln\left(\frac{N_d}{n_i}\right)$$

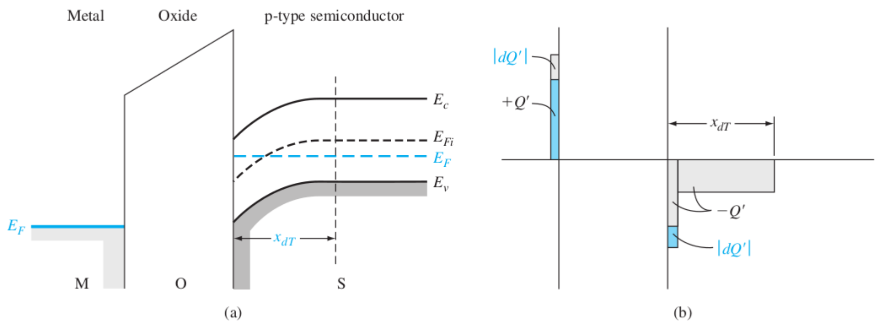
2 Capacitance-voltage characteristics

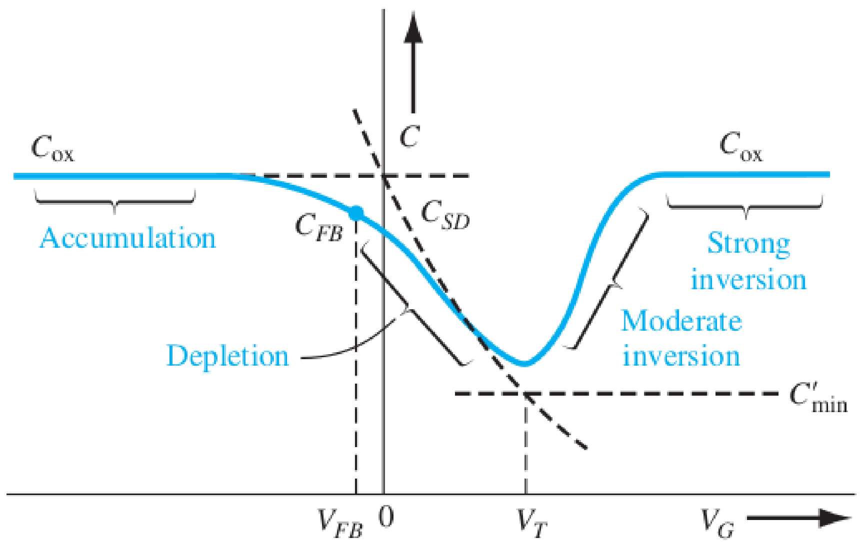


(a) (b)



(a) (b)


Metal
Oxide
p-type semiconductor
E_c
E_{Fi}
E_F
E_v
E_F
x_{dT}
M
O
S
(a)
$|dQ'|$
$+Q'$
x_{dT}
$-Q'$
$|dQ'|$
(b)


C
C_{ox}
Accumulation
C_{FB}
C_{SD}
Depletion
Strong inversion
Moderate inversion
C'_{min}
V_{FB}
0
V_T
V_G

$$C = \frac{dQ}{dV}$$

dQ is the magnitude of differential change in charge

$$
\begin{aligned}
C'(acc) &= C_{ox} = \frac{\epsilon_{ox}}{t_{ox}} \\
\frac{1}{C'(depl)} &= \frac{1}{C'_{ox}} + \frac{1}{C'_{SD}} \\
C'(depl) &= \frac{C_{ox}C'_{SD}}{C_{ox} + C'_{SD}} \\
&= \frac{C_{ox}}{1 + \frac{C_{ox}}{C'_{SD}}} \\
&= \frac{\epsilon_{ox}}{t_{ox} + \frac{\epsilon_{ox}}{\epsilon_s} x_d} \\
C'_{\min} &= \frac{\epsilon_{ox}}{t_{ox} + \frac{\epsilon_{ox}}{\epsilon_s} x_{dT}} \\
C'(inv) &= C_{ox} = \frac{\epsilon_{ox}}{t_{ox}} \\
C'_{FB} &= \frac{\epsilon_{ox}}{t_{ox} + \frac{\epsilon_{ox}}{\epsilon_s}\sqrt{V_t \frac{\epsilon_s}{eN_a}}}
\end{aligned}
$$

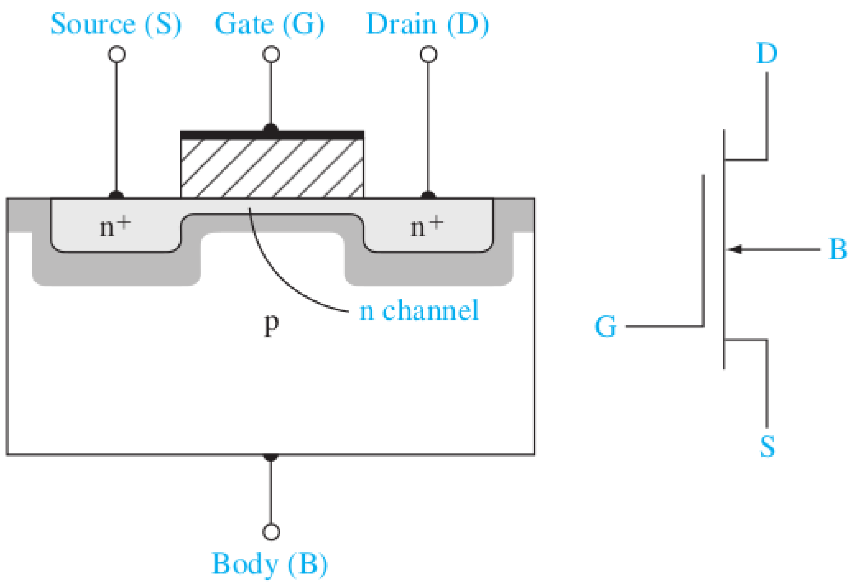
2.1 Frequency effects

Two sources of electrons changing the charge density of the inversion layer: Diffusion of minority carrier electrons and thermal generation of electron hole pairs inside the space charge region.

2.2 Fixed oxide and interface charge effects

$V_{FB} = \phi_{ms} - \frac{Q'_{SS}}{C_{ox}}$ This can move and smear out the C-V curve

3 The basic MOSFET operation



There are four MOSFET types: n and p types and each can be in either enhancement(auto off) mode and depletion(auto on).

$$\begin{aligned}
I_d &= g_d V_{DS} \\
g_d &= \frac{W}{L}\mu_n |Q'_n| \\
V_{DS}(sat) &= V_{GS} - V_T
\end{aligned}$$

for an n-chanel type in depletion

$$\begin{aligned}
I_D &= \frac{W\mu_n C_{ox}}{2L}\left[2\left(V_{GS}-V_T\right)V_{DS}-V_{DS}^2\right] \\
&= \frac{k'_n}{2}\frac{W}{L}\left[2\left(V_{GS}-V_T\right)V_{DS}-V_{DS}^2\right] \\
&= K_n\left[2\left(V_{GS}-V_T\right)V_{DS}-V_{DS}^2\right]
\end{aligned}$$

When the transistor is biased in the saturation region

$$\begin{aligned}
I_D &= \frac{W\mu_n C_{ox}}{2L}\left(V_{GS}-V_T\right)^2 \\
&= \frac{k'_n}{2}\frac{W}{L}\left(V_{GS}-V_T\right)^2 \\
&= K_n\left(V_{GS}-V_T\right)^2
\end{aligned}$$

Part II

Optical devices

4 Optical absorption

$$\lambda ? \frac{c}{\nu} = \frac{hc}{E}$$

When light goes thorugh a solar cell, if $E_{textup} < E_g$ The light is not absorbbed, otherwise an electron is forced into the conduting band.

$$E_{ads} = \alpha I_v(x)dx$$

Is the energy adsorbed pr time. Iv is the photon flux, α the adsorption coeficcient., from fig 14.2

$$I_\nu(x+dx) - I_\nu(x) = \frac{dI_\nu(x)}{dx} \cdot dx = -\alpha I_\nu(x)dx$$
$$\frac{dI_\nu(x)}{dx} - \alpha I_\nu(x)$$

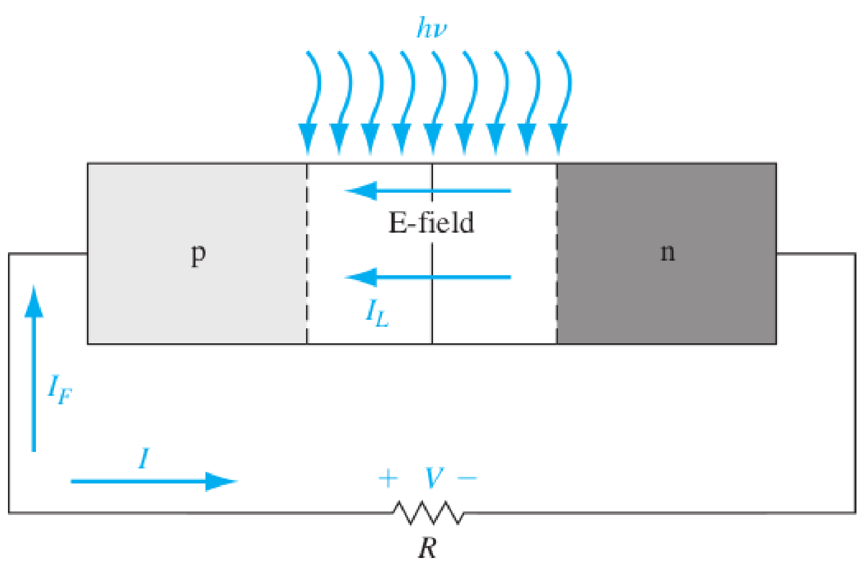
Initially $I_\nu(0) = I_{\nu 0}$

$$I_\nu(x) = I_{\nu 0} e^{-\alpha x}$$

Electron–Hole pair generation:

$$g' = \frac{\alpha I_\nu(x)}{h\nu}$$

5 Solar cells



A solar cell is a pn junction, with no voltage apllied. Consider a pn junction with a load:

$$I = I_L - I_F = I_L - I_S \left[\exp\left(\frac{V}{V_t}\right) - 1\right]$$

Where I_L is the photocurrent generated by the junction sweeping out the electrons generated in the space charge region, I_F is the forward bias generated by I_L going over the resistor. There are two limiting cases, Short circuit ($R = 0$, $V = 0$):

$$I = I_{SC} \qquad = I_L$$

And $R \to \infty$

$$\begin{aligned}
I = 0 &= I_L - I_S \left[\exp\left(\frac{V}{V_t}\right) - 1\right] \\
V_{OC} &= V_t \ln\left(1 + \frac{I_L}{I_S}\right) \\
P = IV &= I_L V - I_{_S} \left[\exp\left(\frac{V}{V_t}\right) - 1\right] V \\
\frac{dP}{dV} &= 0 = I_L - I_{_S} \left[\exp\left(\frac{V_m}{V_t}\right) - 1\right] V - I_S \frac{V_m}{V_t} \exp\left(\frac{V_m}{V_t}\right) \\
1 + \frac{I_L}{I_S} &= \left(1 + \frac{V_m}{V_t}\right) \exp\left(\frac{V_m}{V_t}\right)
\end{aligned}$$

The efficiency in solar cells is:

$$\begin{aligned}
\eta &= \frac{P_m}{P_{in}} \times 100\,\% \\
&= \frac{I_m V_m}{P_{in}} \times 100\,\% \\
\text{fillfactor} &= \frac{I_m V_m}{I_{SC} V_{OV}} \approx 0.7 - -0.8
\end{aligned}$$

To increase efficiency the solar cells multiple band gaps must be used. The real efficiency $\approx 10\,\% - -15\,\%$

5.1 Nonuniform absorption effects:

$$\text{number of adsorped photons} = \alpha \Phi_0$$

$$G_L = \alpha(\lambda)\Phi_0(\lambda)\left[1 - R(\lambda)\right] e^{-\alpha(\lambda)x}$$

6 Photoluminescence and Electroluminescence

Electrons And holes can recombine in many ways, through doners/accepters, inbetween them nand through traps. As well as directly. The emmision range is:

$$I(\nu) \propto \nu^2 (h\nu - E_g)^{\frac{1}{2}} \exp\left[-\frac{h\nu - E_g}{kT}\right]$$

Efficiency:

$$\eta_q = \frac{R_r}{R}$$

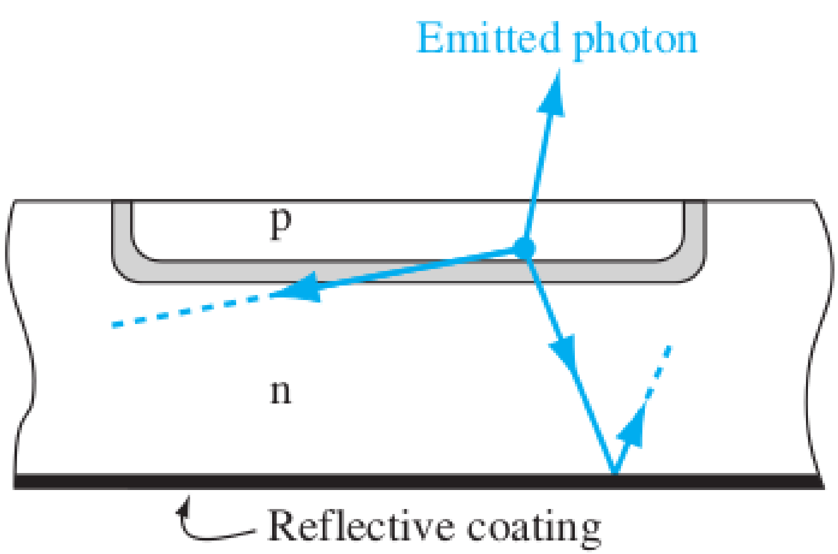
R_r is the radiating recombination rate

$$= \frac{\tau_{nr}}{\tau_{nr} + \tau_r}$$

τ_{nr} is nonradiative and τ_r is radiative

$$R_r = Bnp$$

7 Light emitting diodes



$$\lambda = \frac{hc}{E_g}$$

With applied voltage, minority excess carriers are injected and spewt to the natural area. If it's direct band to band light is emitted. (Ga is on p side). Internal quantum efficiency is the fraction of diode current that produces luminecence. three components are important:

$$
\begin{aligned}
J_n &= \frac{eD_n n_{p0}}{L_n}\left[\exp\left(\frac{V}{V_t}\right)-1\right] \\
J_p &= \frac{eD_p p_{n0}}{L_p}\left[\exp\left(\frac{V}{V_t}\right)-1\right] \\
J_r &= \frac{en_i W}{2\tau_0}\left[\exp\left(\frac{V}{2V_t}\right)-1\right] \\
\gamma &= \frac{J_n}{J_n+J_p+J_R}
\end{aligned}
$$

γ is the injection efficiency, now use a n^+p diode to make J_n largest

$$
\begin{aligned}
R_r &= \frac{\delta n}{\tau_r} \\
R_{nr} &= \frac{\delta n}{\tau_{nr}} \\
R = R_r + R_{nr} &= \frac{\delta n}{\tau} = \frac{\delta n_r}{\tau_r} + \frac{\delta n_{nr}}{\tau_{nr}} \\
\eta &= \frac{R_r}{R_r+R_{nr}} = \frac{\tau}{\tau_r} \\
\eta_i &= \gamma\eta
\end{aligned}
$$

External quantum efficiency: The fraction of generated photons that are *emitted*

$$\Gamma = \left(\frac{\bar{n}_2-\bar{n}_1}{\bar{n}_2+\bar{n}_1}\right)^2$$

Is the Fresnel loss, and describes the light lost through reflaction ($\bar{n}_1$ refraction index of air, $\bar{n}_2$ of the semiconductor). The critical angle:

$$\Theta_c = \sin^{-1}\left(\frac{\bar{n}_1}{\bar{n}_2}\right)$$