

## SEMICONDUCTOR PHYSICS

Electron Momentum:  $p = mv = \hbar k = \frac{h}{\lambda}$  Planck:  $E = h\nu = \hbar\omega$

Kinetic:  $E = \frac{1}{2}mv^2 = \frac{1}{2}\frac{p^2}{m} = \frac{\hbar^2}{2m^*}k^2$  (3-4) Effective mass:  $m^* = \frac{\hbar^2}{d^2E/dk^2}$  (3-3)

Total electron energy = P.E. + K.E. =  $E_c + E(\mathbf{k})$

Fermi-Dirac  $e^-$  distribution:  $f(E) = \frac{1}{e^{(E-E_f)/kT} + 1} \equiv e^{(E_f-E)/kT}$  for  $E \gg E_f$  (3-10)

Equilibrium:  $n_0 = \int_{E_c}^{\infty} f(E)N(E)dE = N_d f(E_c) = N_c e^{-(E_c-E_f)/kT}$  (3-15)

$N_c = 2\left(\frac{2\pi m_n^* kT}{h^2}\right)^{3/2}$   $N_v = 2\left(\frac{2\pi m_p^* kT}{h^2}\right)^{3/2}$  (3-16), (3-20)

$p_0 = N_v[1 - f(E_v)] = N_v e^{-(E_f-E_v)/kT}$  (3-19)

$n_i = N_c e^{-(E_f-E_i)/kT}$ ,  $p_i = N_v e^{-(E_i-E_f)/kT}$  (3-21)

$n_i = \sqrt{N_c N_v} e^{-E_i/2kT} = 2\left(\frac{2\pi kT}{h^2}\right)^{3/2} (m_n^* m_p^*)^{3/4} e^{-E_i/2kT}$  (3-23), (3-26)

Equilibrium:  $\frac{n_0}{p_0} = \frac{n_i}{p_i} = e^{(E_f-E_i)/kT}$  (3-25)  $n_0 p_0 = n_i^2$  (3-24)

Steady state:  $\frac{n}{p} = \frac{N_c}{N_v} e^{-(E_f-E_i)/kT} = \frac{n_i}{p_i} e^{(E_f-E_i)/kT}$  (4-15)  $np = n_i^2 e^{(E_f-E_i)/kT}$  (5-38)

$\mathcal{E}(x) = -\frac{dV(x)}{dx} = \frac{1}{q} \frac{dE_i}{dx}$  (4-26)

Poisson:  $\frac{d\mathcal{E}(x)}{dx} = -\frac{d^2V(x)}{dx^2} = \frac{\rho(x)}{\epsilon} = \frac{q}{\epsilon}(p - n + N_d^+ - N_a^-)$  (5-14)

$\mu \equiv \frac{q\bar{v}}{m^*}$  (3-40a) Drift:  $v_d \equiv \frac{\mu \mathcal{E}}{1 + \mu \mathcal{E}/v_s} \left\{ \begin{array}{l} = \mu \mathcal{E} \text{ (low fields, ohmic)} \\ = v_s \text{ (high fields, saturated vel.)} \end{array} \right.$  (Fig. 6-9)

Drift current density:  $\frac{I_x}{A} = J_x = q(n\mu_n + p\mu_p)\mathcal{E}_x = \sigma \mathcal{E}_x$  (3-43)

$J_n(x) = q\mu_n n(x)\mathcal{E}(x) + qD_n \frac{dn(x)}{dx}$

Conduction Current: drift diffusion (4-23)

$J_p(x) = q\mu_p p(x)\mathcal{E}(x) - qD_p \frac{dp(x)}{dx}$

$J_{\text{total}} = J_{\text{conduction}} + J_{\text{displacement}} = J_n + J_p + C \frac{dV}{dt}$

Continuity:  $\frac{\partial p(x,t)}{\partial t} = \frac{\partial \delta p}{\partial t} = -\frac{1}{q} \frac{\partial J_p}{\partial x} - \frac{\delta p}{\tau_p}$   $\frac{\partial \delta n}{\partial t} = \frac{1}{q} \frac{\partial J_n}{\partial x} - \frac{\delta n}{\tau_n}$  (4-31)

For steady state diffusion:  $\frac{d^2 \delta n}{dx^2} = \frac{\delta n}{D_n \tau_n} \equiv \frac{\delta n}{L_n^2}$   $\frac{d^2 \delta p}{dx^2} = \frac{\delta p}{L_p^2}$  (4-34)

Diffusion length:  $L \equiv \sqrt{D\tau}$  Einstein relation:  $\frac{D}{\mu} = \frac{kT}{q}$  (4-29)

## p-n JUNCTIONS

Equilibrium:  $V_0 = \frac{kT}{q} \ln \frac{p_p}{p_n} = \frac{kT}{q} \ln \frac{N_a}{n_i^2/N_d} = \frac{kT}{q} \ln \frac{N_a N_d}{n_i^2}$  (5-8)

$\frac{p_p}{p_n} = \frac{n_n}{n_p} = e^{qV_0/kT}$  (5-10)  $W = \left[ \frac{2\epsilon(V_0 - V)}{q} \left( \frac{N_a + N_d}{N_a N_d} \right) \right]^{1/2}$  (5-57)

One-sided abrupt  $p^+n$ :  $x_{n0} = \frac{WN_a}{N_a + N_d} \approx W$  (5-23)  $V_0 = \frac{qN_d W^2}{2\epsilon}$

$\Delta p_n = p(x_{n0}) - p_n = p_n(e^{qV/kT} - 1)$  (5-29)

$\delta p(x_n) = \Delta p_n e^{-x_n/L_p} = p_n(e^{qV/kT} - 1)e^{-x_n/L_p}$  (5-31b)

Ideal diode:  $I = qA \left( \frac{D_p}{L_p} p_n + \frac{D_n}{L_n} n_p \right) (e^{qV/kT} - 1) = I_0 (e^{qV/kT} - 1)$  (5-36)

Non-ideal:  $I = I_0' (e^{qV/nkT} - 1)$  (5-74)  
( $n = 1$  to  $2$ )

With light:  $I_{op} = qA G_{op}(L_p + L_n + W)$  (8-1)

Capacitance:  $C = \left| \frac{dQ}{dV} \right|$  (5-55)

Junction Depletion:  $C_j = \epsilon A \left[ \frac{q}{2\epsilon(V_0 - V)} \frac{N_d N_a}{N_d + N_a} \right]^{1/2} = \frac{\epsilon A}{W}$  (5-62)

Stored charge  
exp. hole dist.:  $Q_p = qA \int_0^\infty \delta p(x_n) dx_n = qA \Delta p_n \int_0^\infty e^{-x_n/L_p} dx_n = qAL_p \Delta p_n$  (5-39)

$I_p(x_n = 0) = \frac{Q_p}{\tau_p} = qA \frac{L_p}{\tau_p} \Delta p_n = qA \frac{D_p}{L_p} p_n (e^{qV/kT} - 1)$  (5-40)

$G_s = \frac{dI}{dV} = \frac{qAL_p p_n}{\tau_p} \frac{d}{dV} (e^{qV/kT}) = \frac{q}{kT} I$  (5-67c)

Long p<sup>+</sup>-n:  $i(t) = \frac{Q_p(t)}{\tau_p} + \frac{dQ_p(t)}{dt}$  (5-47)

### MOS-n CHANNEL

Oxide:  $C_i = \frac{\epsilon_i}{d}$  Depletion:  $C_d = \frac{\epsilon_s}{W}$  MOS:  $C = \frac{C_i C_d}{C_i + C_d}$  (6-36)

Threshold:  $V_T = \underbrace{\Phi_{ms} - \frac{Q_i}{C_i}}_{\text{Flat band}} - \frac{Q_d}{C_i} + 2\phi_F$  (6-38)

Inversion:  $\phi_s(\text{inv.}) = 2\phi_F = 2 \frac{kT}{q} \ln \frac{N_a}{n_i}$  (6-15)  $W = \left[ \frac{2\epsilon_s \phi_s}{qN_a} \right]^{1/2}$  (6-30)

$Q_d = -qN_a W_m = -2(\epsilon_s q N_a \phi_F)^{1/2}$  (6-32) At  $V_{FB}$ :  $C_{FB} = \frac{C_i C_{\text{debye}}}{C_i + C_{\text{debye}}}$

Debye screening length:  $L_D = \sqrt{\frac{\epsilon_s kT}{q^2 p_0}}$  (6-25)  $C_{\text{debye}} = \frac{\sqrt{2} \epsilon_s}{L_D}$  (6-40)

Substrate bias:  $\Delta V_T = \frac{\sqrt{2\epsilon_s q N_a}}{C_i} (-V_B)^{1/2}$  (n channel) (6-63)

$I_D = \frac{\bar{\mu}_n Z C_i}{L} \left\{ (V_G - V_{FB} - 2\phi_F - \frac{1}{2}V_D)V_D - \frac{2}{3} \frac{\sqrt{2\epsilon_s q N_a}}{C_i} [(V_D + 2\phi_F)^{3/2} - (2\phi_F)^{3/2}] \right\}$  (6-50)

$I_D = \frac{\bar{\mu}_n Z C_i}{L} [(V_G - V_T)V_D - \frac{1}{2}V_D^2]$  (6-49)

Saturation:  $I_D(\text{sat.}) = \frac{1}{2} \bar{\mu}_n C_i \frac{Z}{L} (V_G - V_T)^2 = \frac{Z}{2L} \bar{\mu}_n C_i V_D^2(\text{sat.})$  (6-53)

$g_m = \frac{\partial I_D}{\partial V_G}$  ;  $g_m(\text{sat.}) = \frac{\partial I_D(\text{sat.})}{\partial V_G} = \frac{Z}{L} \bar{\mu}_n C_i (V_G - V_T)$  (6-54)

For short L:  $I_D = ZC_i(V_G - V_T)V_s$  (6-60)

Subthreshold slope:  $S = \frac{dV_G}{d(\log I_D)} = \frac{kT}{q} \ln 10 \left[ 1 + \frac{C_d + C_{it}}{C_i} \right]$  (6-66)

### BJT-p-n-p

$I_{Ep} = qA \frac{D_p}{L_p} \left( \Delta p_E \text{ctnh} \frac{W_b}{L_p} - \Delta p_C \text{csch} \frac{W_b}{L_p} \right)$  (7-18)  $\Delta p_E = p_n (e^{qV_{EB}/kT} - 1)$   
 $\Delta p_C = p_n (e^{qV_{CB}/kT} - 1)$  (7-8)

$I_C = qA \frac{D_p}{L_p} \left( \Delta p_E \text{csch} \frac{W_b}{L_p} - \Delta p_C \text{ctnh} \frac{W_b}{L_p} \right)$

$I_B = qA \frac{D_p}{L_p} \left[ (\Delta p_E + \Delta p_C) \tanh \frac{W_b}{2L_p} \right]$  (7-19)

$B = \frac{I_C}{I_{Ep}} = \frac{\text{csch } W_b/L_p}{\text{ctnh } W_b/L_p} = \text{sech} \frac{W_b}{L_p} \approx 1 - \left( \frac{W_b^2}{2L_p^2} \right)$  (7-26)

(Base transport factor)

$\gamma = \frac{I_{Ep}}{I_{En} + I_{Ep}} = \left[ 1 + \frac{L_p^n n_n \mu_n^p}{L_n^p p_p \mu_p^n} \tanh \frac{W_b}{L_p} \right]^{-1} \approx \left[ 1 + \frac{W_b n_n \mu_n^p}{L_n^p p_p \mu_p^n} \right]^{-1}$  (7-25)

(Emitter injection efficiency)

$\frac{i_C}{I_E} = B\gamma \equiv \alpha$  (7-3)

$\frac{i_C}{I_B} = \frac{B\gamma}{1 - B\gamma} = \frac{\alpha}{1 - \alpha} \equiv \beta$  (7-6)

$\frac{i_C}{I_B} = \beta = \frac{\tau_p}{\tau_n}$  (7-7)

(Common base gain)

(Common emitter gain)

(For  $\gamma = 1$ )