

ECE 305 Exam 4 Formula Sheet (Fall 2015)

You may remove these pages from the exam packet, and take them with you.

Physical Constants	Silicon parameters ($T = 300\text{ K}$)
$h/2\pi = \hbar = 1.055 \times 10^{-34}\text{ J}\cdot\text{s}$	$N_C = 3.23 \times 10^{19}\text{ cm}^{-3}$
$m_0 = 9.109 \times 10^{-31}\text{ kg}$	$N_V = 1.83 \times 10^{19}\text{ cm}^{-3}$
$k_B = 1.38 \times 10^{-23}\text{ J/K}$	$n_i = 1.1 \times 10^{10}\text{ cm}^{-3}$
$q = 1.602 \times 10^{-19}\text{ C}$	$K_S = 11.8$
$\epsilon_0 = 8.854 \times 10^{-12}\text{ F/m}$	$E_g = 1.12\text{ eV}; \chi = 4.03\text{ eV}$

Miller Indices: (hkl) {hkl} [hkl] <hkl>

Density of states $g_C(E) = \frac{(m_n^*)^{3/2} \sqrt{2(E-E_C)}}{\pi^2 \hbar^3}$

Fermi function $f(E) = \frac{1}{1+e^{(E-E_F)/kT}}$

Intrinsic carrier concentration $n_i = \sqrt{N_C N_V} e^{-E_g/2kT}$

Equilibrium carrier densities: $N_C = \frac{1}{4} \left(\frac{2m_n^* kT}{\pi \hbar^2} \right)^{3/2}$

$N_V = \frac{1}{4} \left(\frac{2m_p^* kT}{\pi \hbar^2} \right)^{3/2}$

$n_0 = N_C e^{(E_F-E_C)/kT} = n_i e^{(E_F-E_i)/kT}$

$p_0 = N_V e^{(E_V-E_F)/kT} = n_i e^{(E_F-E_i)/kT}$

Space charge neutrality: $p - n + N_D^+ - N_A^- = 0$

Law of Mass Action: $n_0 p_0 = n_i^2$

Non-equilibrium carriers: $n = N_C e^{(F_N-E_C)/kT}$ $p = N_V e^{(E_V-F_P)/kT}$ $np = n_i^2 e^{(F_N-F_P)/kT}$

Conductivity/resistivity: $\sigma = \sigma_n + \sigma_p = q(n\mu_n + p\mu_p) = 1/\rho$

Drift-diffusion current equations: $J_n = nq\mu_n \mathcal{E}_x + qD_n \frac{dn}{dx} = n\mu_n \frac{dF_n}{dx}$ $\frac{D_n}{\mu_n} = \frac{kT}{q}$

$J_p = pq\mu_p \mathcal{E}_x - qD_p \frac{dp}{dx} = p\mu_p \frac{dF_p}{dx}$ $\frac{D_p}{\mu_p} = \frac{kT}{q}$

Carrier conservation equations: $\frac{\partial n}{\partial t} = +\nabla \cdot \left(\frac{J_n}{q} \right) + G_n - R_n$

$\frac{\partial p}{\partial t} = -\nabla \cdot \left(\frac{J_p}{q} \right) + G_p - R_p$

Poisson's equation: $\nabla \cdot (\epsilon \mathcal{E}) = \rho$

SRH carrier recombination: $R = \Delta n / \tau_n$ or $R = \Delta p / \tau_p$

Minority carrier diffusion equation: $\frac{\partial \Delta n}{\partial t} = D_n \frac{\partial^2 \Delta n}{\partial x^2} - \frac{\Delta n}{\tau_n} + G_L$ $L_{D,n} = \sqrt{D_n \tau_n}$

PN homojunction electrostatics: $V_{bi} = \frac{kT}{q} \ln \left(\frac{N_D N_A}{n_i^2} \right)$ $\frac{d\mathcal{E}}{dx} = \frac{\rho(x)}{K_S \epsilon_0}$

$W = \sqrt{\frac{2K_S \epsilon_0 V_{bi}}{q} \left(\frac{N_A + N_D}{N_A N_D} \right)}$ $x_n = \left(\frac{N_A}{N_A + N_D} \right) W$ $x_p = \left(\frac{N_D}{N_A + N_D} \right) W$ $\mathcal{E}(0) = \sqrt{\frac{2qV_{bi}}{K_S \epsilon_0} \left(\frac{N_A N_D}{N_A + N_D} \right)}$

PN diode current: $\Delta n(0) = \frac{n_i^2}{N_A} (e^{qV_A/kT} - 1)$ $\Delta p(0) = \frac{n_i^2}{N_D} (e^{qV_A/kT} - 1)$

$J_D = J_o (e^{qV_A/kT} - 1)$ $J_o = q \left(\frac{D_n n_i^2}{L_n N_A} + \frac{D_p n_i^2}{L_p N_D} \right)$ (long) $J_o = q \left(\frac{D_n n_i^2}{W_p N_A} + \frac{D_p n_i^2}{W_n N_D} \right)$ (short)

Non-ideal diodes: $I = I_o (e^{q(V_A - IR_s)/kT} - 1)$ $J_{gen} = -q \frac{n_i}{2\tau_o} W$

Photovoltaics: $V_{oc} = \frac{nkT}{q} \ln \left(\frac{J_{sc}}{J_o} \right)$ $J_{PV} = J_o (e^{qV_A/kT} - 1) - J_{sc}$

Small signal model: $G_d = \frac{I_D + I_o}{kT/q}$ $C_J(V_R) = \frac{K_s \epsilon_o A}{\sqrt{\frac{2K_s \epsilon_o V_{bi}}{q N_A}}} = A \sqrt{\frac{q K_s \epsilon_o N_A}{2V_{bi}}}$ $C_D = G_d \tau_n$

MS diode properties: $qV_{bi} = |\Phi_M - \Phi_S|$ $\Phi_{BP} = \chi + E_G - \Phi_M$ $\Phi_{BN} = \Phi_M - \chi$

$J_D = J_o (e^{qV_A/kT} - 1)$ $J_o = A^* T^2 e^{-\Phi_B/kT}$ $A^* = \frac{4\pi q m^* k_B^2}{h^3} = 120 \frac{m^*}{m_o} \frac{A}{\text{cm}^2 \cdot \text{K}^2}$

MOS capacitors: $W = \sqrt{\frac{2K_s \epsilon_o \phi_s}{q N_A}} \text{ cm}$ $\epsilon_s = \sqrt{\frac{2q N_A \phi_s}{K_s \epsilon_o}} \frac{V}{\text{cm}}$

$Q_B = -q N_A W (\phi_s) = -\sqrt{2q K_s \epsilon_o N_A \phi_s} \frac{C}{\text{cm}^2}$

$V_G = V_{FB} + \phi_s + \Delta\phi_{ox} = V_{FB} + \phi_s - \frac{Q_s(\phi_s)}{C_{ox}}$

$C_{ox} = K_o \epsilon_o / x_o$

$V_{FB} = \Phi_{ms}/q - Q_F/C_{ox}$

$C = C_{ox} / \left[1 + \frac{K_o W (\phi_s)}{K_s x_o} \right]$

$V_T = -Q_B(2\phi_F)/C_{ox} + 2\phi_F$

$Q_n = -C_{ox}(V_G - V_T)$

MOSFETs: $I_D = -W Q_n(y=0) \langle v_y(y=0) \rangle$

$I_D = \frac{W}{L} \mu_n C_{ox} (V_{GS} - V_T) V_{DS}$

$I_D = W C_{ox} v_{sat} (V_{GS} - V_T)$

Square Law (for $V_{GS} \geq V_T$): $I_D = \begin{cases} \frac{W}{L} \mu_n C_{ox} [(V_{GS} - V_T) V_{DS} - V_{DS}^2/2], & 0 \leq V_{DS} \leq V_{GS} - V_T \\ \frac{W}{2L} \mu_n C_{ox} (V_{GS} - V_T)^2, & V_{DS} \geq V_{GS} - V_T \end{cases}$