Semiconductor Physics

1. Law of mass action: $n_0 p_0 = \ n_i{}^2$
2. Carrier concentrations in non-degenerate semiconductor

   $$n_0 = N_C \exp\left(-\frac{E_C - E_F}{kT}\right), \quad p_0 = N_V \exp\left(-\frac{E_F - E_V}{kT}\right)$$

   $$n_0 = n_i \exp\left(\frac{E_F - E_i}{kT}\right), \quad p_0 = n_i \exp\left(\frac{E_i - E_F}{kT}\right)$$

3. E field in a non-uniformly doped semiconductor: $E(x) = \frac{k_B T}{q N_A(x)} \frac{dN_A(x)}{dx}$
4. Drift current: $J_{drift} = q(n\mu_n + p\mu_p)E$
5. Diffusion current: $J_{diff} = q\left(D_n \frac{dn}{dx} - D_p \frac{dp}{dx}\right)$

pn Junction

6. Total depletion region width in a step junction: $x_D = \sqrt{\frac{2\varepsilon_s}{q}\left(\frac{1}{N_D} + \frac{1}{N_A}\right)(\phi_i - V_a)}$
   a. Depletion region width on the n-side: $x_n = \frac{N_A}{N_D + N_A} x_D$
   b. Depletion region width on the n-side: $x_p = \frac{N_D}{N_D + N_A} x_D$`
7. Capacitance: $C = \sqrt{\frac{q\varepsilon_s}{\left(\frac{1}{N_D} + \frac{1}{N_A}\right)(\phi_i - V_a)}} = \frac{\varepsilon_s}{x_D}$
8. Current: $J_{long} = qn_i^2\left(\frac{D_p}{L_p N_D} + \frac{D_n}{L_n N_A}\right)\left[\exp\left(\frac{qV_a}{kT}\right) - 1\right]$ for long-base diode

   $J_{short} = qn_i^2\left(\frac{D_p}{W_B' N_D} + \frac{D_n}{W_E' N_A}\right)\left[\exp\left(\frac{qV_a}{kT}\right) - 1\right]$ for short-base diode

MOS Device

9. Flat band voltage: $V_{FB} = \phi_M - \phi_s$
10. Surface potential: $\phi_s = \chi + \frac{E_g}{2} - k_B T ln\left(\frac{N_D}{n_i}\right)$ for n-type substrate

$$\phi_s = \chi + \frac{E_g}{2} + k_B T ln\left(\frac{N_A}{n_i}\right)$$ for p-type substrate.

11. $x_{Dmax} = \sqrt{\frac{4\varepsilon_s|\phi_p|}{qN_A}}$ where ϕ_p is the bulk potential in the quasi-neutral p-Si region.

12. Threshold voltage, $V_T = V_{FB} + 2\phi_p + \sqrt{\frac{4\varepsilon_s q N_A|\phi_p|}{C_{ox}}}$

MOSFET

13. Long-channel MOSFET

    a. Drain current before saturation: $I_D = \mu_n C_{ox}\frac{W}{L}\left[\left(V_G - V_T - \frac{V_D}{2}\right)V_D\right]$

    b. Saturation drain current : $I_D = \mu_n C_{ox}\frac{W}{2L}(V_G - V_T)^2$

    c. Transconductance: $g_{msat} = \frac{\partial I_D}{\partial V_G} = \mu_n C_{ox}\frac{W}{L}(V_G - V_T)$

    d. Saturation drain voltage: $V_{Dsat} = V_G - V_T$

14. Short channel MOSFET

    a. Saturation drain voltage: $V_{Dsat} = \frac{\varepsilon_{sat}L[V_G - V_T]}{\varepsilon_{sat}L + [V_G - V_T]}$ with $\varepsilon_{sat} = \frac{2\nu_{sat}}{\mu_{eff}}$

    b. Saturation drain current: $I_{Dsat} = WC_{ox}[V_G - V_T - V_{Dsat}]\nu_{sat}$

    c. Transconductance: $g_{msat} = W\nu_{sat}C_{ox}\frac{(V_G - V_T)(V_G - V_T + 2\varepsilon_{sat}L)}{(V_G - V_T + \varepsilon_{sat}L)^2}$

BJT

15. Collector current in npn BJT: $J_n = \frac{qD_n n_i^2}{x_B N_{AB}}\left[exp\left(\frac{qV_{BC}}{k_B T}\right) - exp\left(\frac{qV_{BE}}{k_B T}\right)\right]$

16. Base recombination current in npn BJT: $J_{rB} = \frac{q x_B n_i^2}{2\tau_n N_{AB}}\left[exp\left(\frac{qV_{BE}}{k_B T}\right) - 1\right]$

17. Hole current in emitter in npn BJT: $J_{pE} = \frac{qD_{pE} n_i^2}{L_{pE} N_{DE}}\left[exp\left(\frac{qV_{BE}}{k_B T}\right) - 1\right]$

18. Base transport factor: $\alpha_T = 1 - \frac{|I_{rB}|}{|I_{nE}|} = 1 - \frac{x_B^2}{2D_n\tau_n}$

19. Emitter injection efficiency: $\gamma = \frac{I_{nE}}{I_{nE}+I_{pE}} = \left[1 + \frac{x_B N_{AB} D_{pE}}{x_E N_{DE} D_{nB}}\right]^{-1}$

20. Common-base current gain: $\alpha = \frac{I_C}{I_E} = \alpha_F = \alpha_T \gamma$

21. Common-emitter current gain: $\beta = \frac{I_C}{I_B} = \beta_F = \frac{\alpha}{1-\alpha}$

22. Early effect

   a. $V_A = \frac{\int_0^{x_B} p\,dx}{p(x_B)} \left[\frac{\partial x_B}{\partial V_{CB}}\right]^{-1}$

   b. $\frac{\partial I_C}{\partial V_{CB}} = -\frac{I_C}{V_A}$