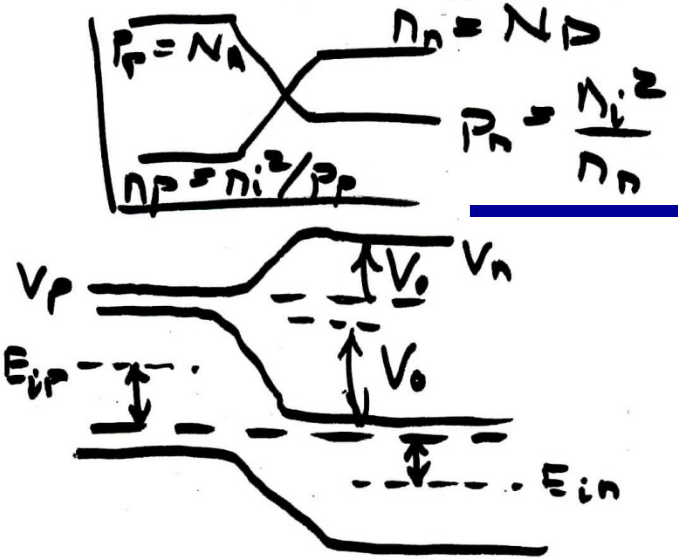
Final Exam Review

PN Junction

Contact Potential



$n_p p_p = n_i^2 = p_n n_n$
in equilibrium

$$V_0 = \frac{kT}{q} \ln \frac{N_A N_D}{n_i^2} \quad *$$

$$e^{qV_0/kT} = \frac{p_p}{p_n} = \frac{n_n}{n_p}$$

also $p_p = n_i \, e^{(E_{ip} - E_F)/kT}$

$n_n = n_i \, e^{(E_F - E_{in})/kT}$ $\qquad E_{ip} - E_{in} = qV_0$

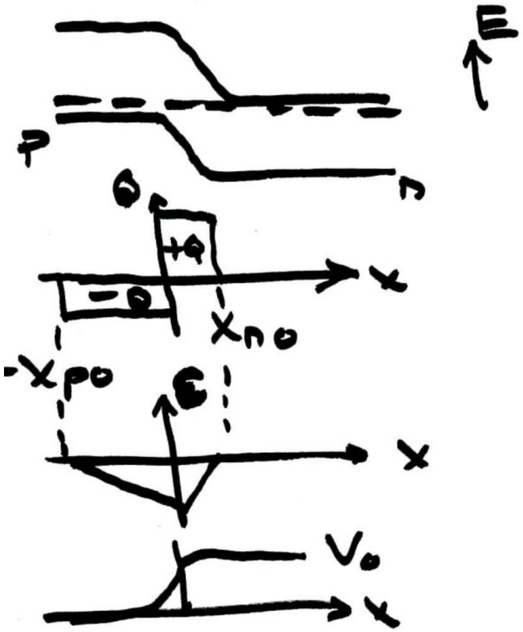
Space charge

$$X_{p0} N_A = X_{n0} N_D$$

$$W = \left[\frac{2\epsilon V_0}{q}\left(\frac{1}{N_A} + \frac{1}{N_D}\right)\right]^{1/2}$$

$$X_{n0} = \frac{W N_A}{N_A + N_D} \qquad X_{p0} = \frac{W N_D}{N_A + N_D}$$

$$\mathcal{E}_0 = q\frac{N_A X_{p0}}{\epsilon}$$



Bias

$$W = \left[\frac{2\epsilon}{q}(V_0 - V_f)\left(\frac{1}{N_A} + \frac{1}{N_D}\right)\right]^{1/2} \quad \text{forward}$$

$$= \left[\text{"} \quad (V_0 + V_r) \quad \text{"} \quad \text{"}\right]^{1/2} \quad \text{reverse}$$

$$\Delta p_n = p(x_{no}) - p_n = p_n\left(e^{qV/kT}-1\right)$$

$$\Delta n_p = n_p(x_{po}) - n_p = n_p\left(e^{qV/kT}-1\right)$$

$p_n < n_p$ if $N_D > N_A$

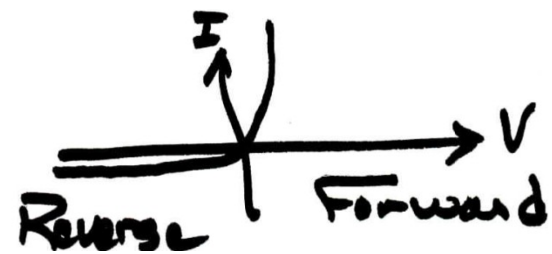
$$\delta n(x_p) = \Delta n\, e^{-x_p/L_n} = n_p\left(e^{qV/kT}-1\right)e^{-x_p/L_n}$$

$$\delta p(x_n) = \Delta p\, e^{-x_n/L_p} = p_n\left(e^{qV/kT}-1\right)e^{-x_n/L_p}$$

$D/\mu = kT/q$ Einstein Relation

$L = [D\tau]^{1/2}$ Diffusion Length

$$I_{total} = I_p(x_n=0) + I_n(x_p=0)$$



$$= qA\frac{D_p}{L_p}\Delta p_n + qA\frac{D_n}{L_n}\Delta n_p$$

$$= I_o\left(e^{qV/kT}-1\right)$$ *Diode Equation*

applications

Rectifiers – Large gap, low doping, A large (R_s small), L small

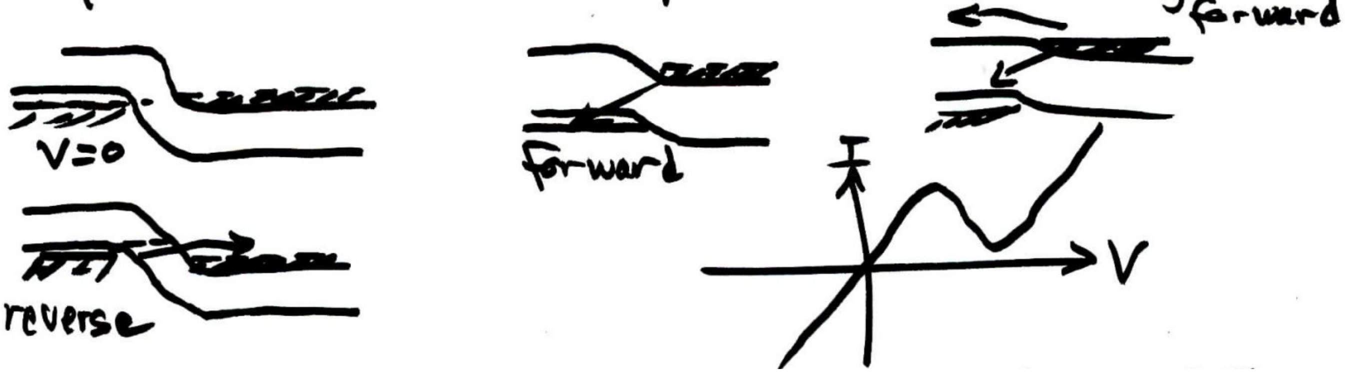
switching diodes – Very short τ_n, τ_p (but lower gain)

Breakdown Diode

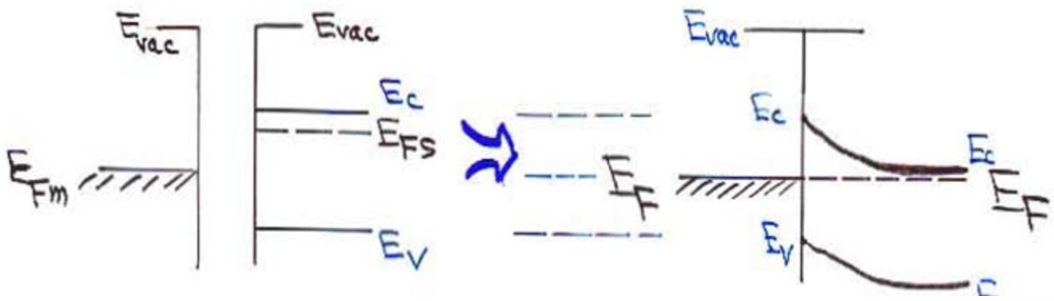
Varactor $V^{-1/2}$ for $V_r >> V_o$ (abrupt junction)

Tunnel Diodes

(Degenerate)



Schottky Barriers

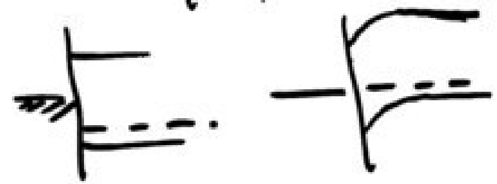


1. Join M and SC band structures by lining up vacuum levels E_{vac}^{metal} and E_{vac}^{SC}.
2. $\Phi_M = E_{vac} - E_F^{metal}$ stays the same after contact.
3. $\chi = E_{vac} - E_C$ stays the same at interface.
4. $E_C - E_F$ stays the same in the SC bulk
5. Line up E_F^{SC} with E_F^{metal}.
6. Curve $E_C - E_F$ to connect $E_C^{surface}$ and E_C^{bulk}
7. Curve valence band same way.
8. Schottky barrier $\Phi_{SB} = E_C^{surface} - E_F^{metal}$.
9. n-type band bending $qV_B = \Phi_{SB} - (E_C - E_F)$
10. $(E_C - E_F) = (E_C - E_i) - (E_F - E_i)$
11. $n = n_i e^{(E_F - E_i)}$

$$W = \sqrt{\frac{2\epsilon(V_0 - V)}{qN_D}} \qquad \epsilon = \epsilon_s \epsilon_0$$

(get from p-n eqn. for W)

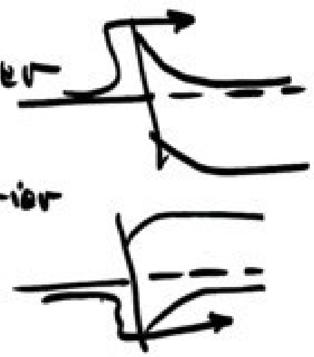
P=Type

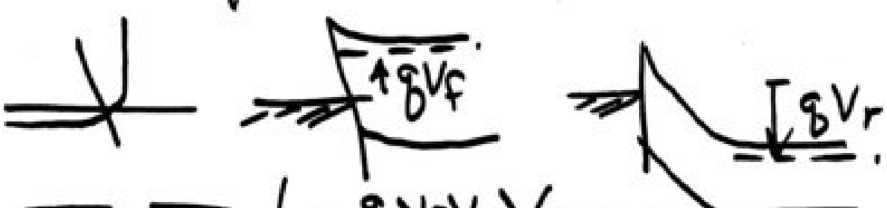


also

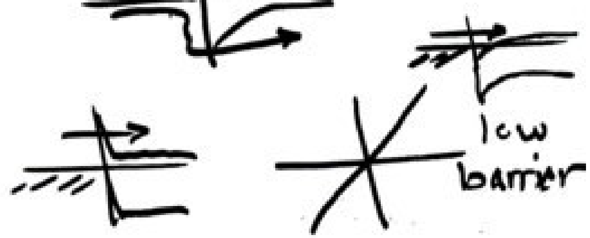
e barrier

h barrier

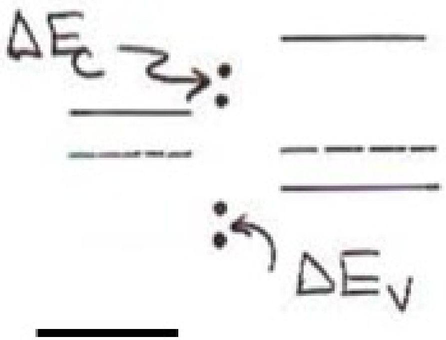




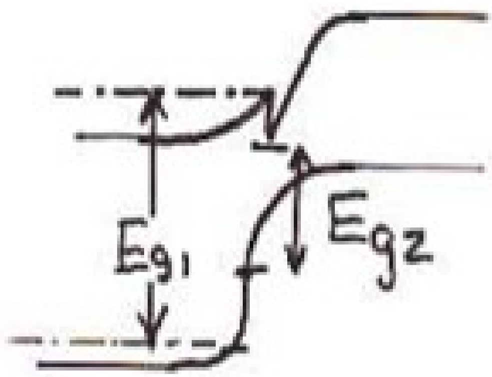
$$I = I_0\left(e^{q(V-V_0)/kT} - 1\right)$$



Heterojunctions

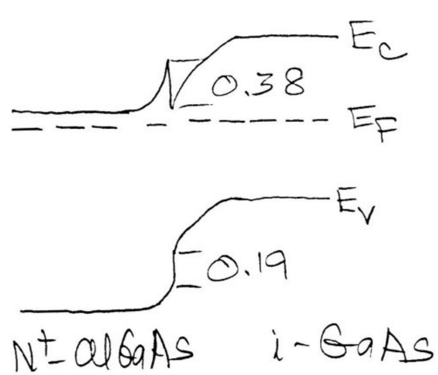


1. Align SC Fermi levels with bands flat.
2. Find x=0 based on N1 vs N2 doping.
3. N-type bends up. P-type bends down.
4. Insert ΔE_C and ΔE_V .
5. Use 2/3 – 1/3 Rule.
6. Connect E_C's . Connect E_V's.
7. Keep each band gap constant.
8. No notch for longer connection.

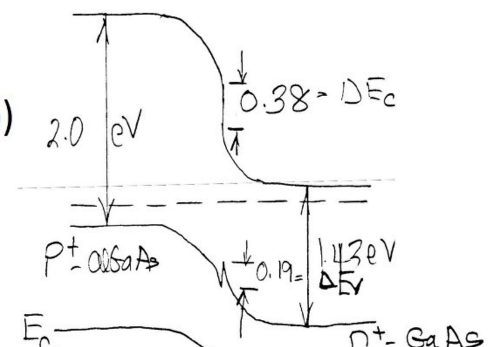


Examples

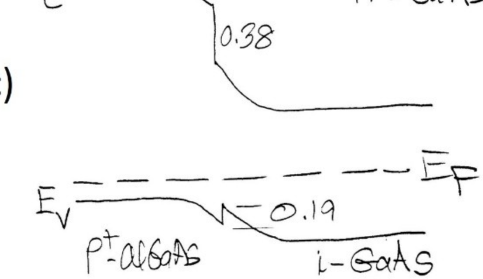
(a)



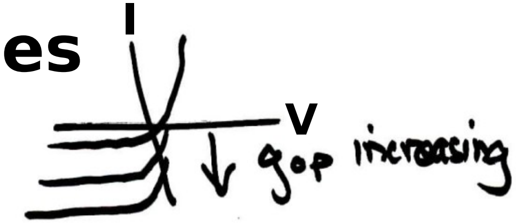
(b)



(c)

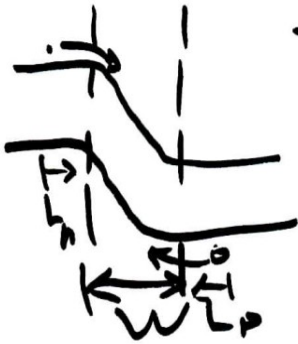


Photodiodes



$$V_{oc} = \frac{kT}{q}\ln\left[\frac{I_{op}}{I_{th}}+1\right]$$

for open circuit



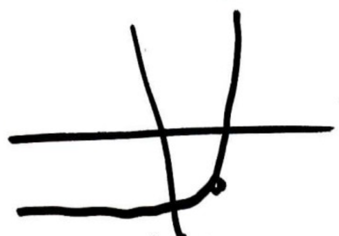
$$I_{op} = qAg_{op}(L_p+L_n+W)$$

$$I = qA\left(\frac{L_p}{\tau_p}p_n + \frac{L_n}{\tau_n}n_p\right)\left(e^{qV/kT}-1\right) - I_{op}$$

* $\frac{L}{\tau}=\frac{D}{L} \rightarrow L^2 = D\tau$; also $\frac{D}{\mu}=\frac{kT}{q}$ Einstein

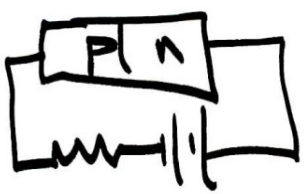
Reverse bias

Photodetector



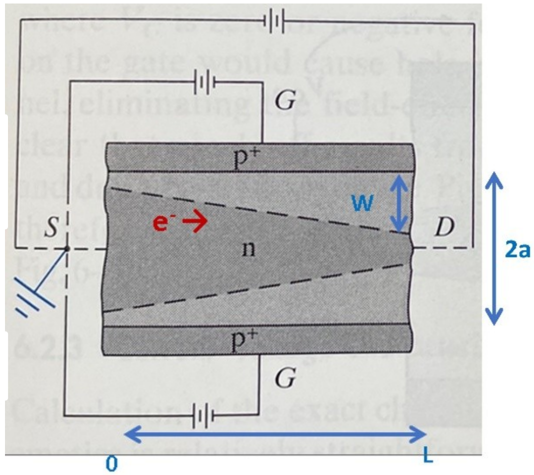
no bias

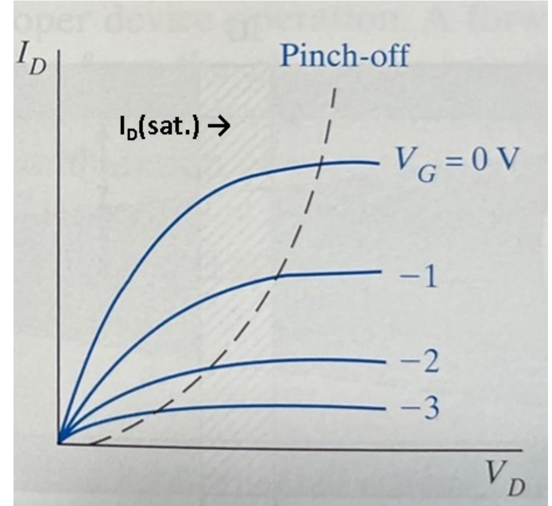
Solar cell



Like a battery

JFET





$$W(x=L) = \left[\frac{2\epsilon(-V_{GD})}{qN_d}\right]^{1/2}$$

V_{GD} is (−)
negative bias to G

$$V_p = -V_{GD}(\text{pinch-off}) = -V_G + V_D$$

$$V_p = \frac{qa^2N_d}{2\epsilon}$$

With negative V_G, need less V_D to reach pinch-off

$$I_D = G_0 V_p\left[\frac{V_D}{V_p} + \frac{2}{3}\left(\frac{-V_G}{V_p}\right)^{3/2} - \frac{2}{3}\left(\frac{V_D - V_G}{V_p}\right)^{3/2}\right]$$

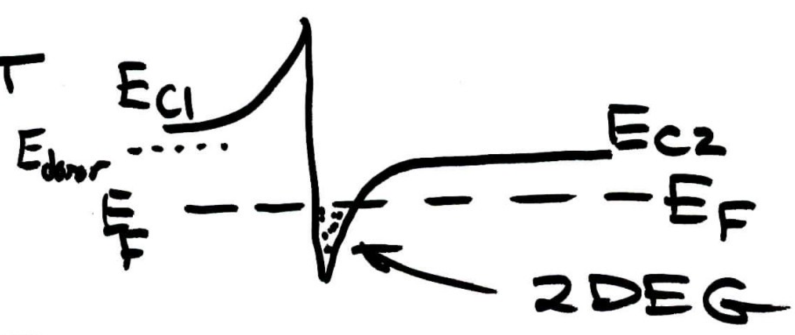
$$G_0 = \text{conductance} \equiv 2aZ/\rho L$$

$$I_D(\text{sat.}) = G_0 V_p\left[\frac{V_G}{V_p} + \frac{2}{3}\left(\frac{-V_G}{V_p}\right)^{3/2} + \frac{1}{3}\right]$$

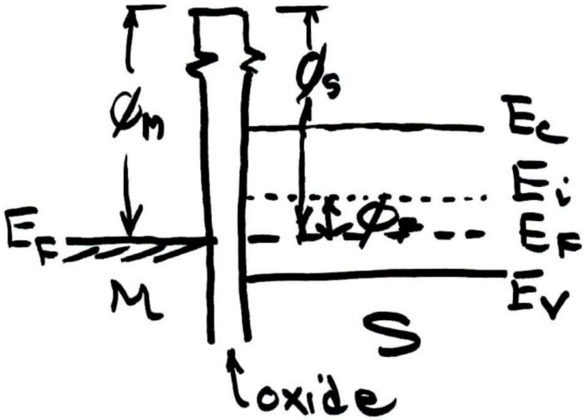
$g_m =$ mutual transconductance $\equiv \dfrac{\partial I_D}{\partial V_G}$

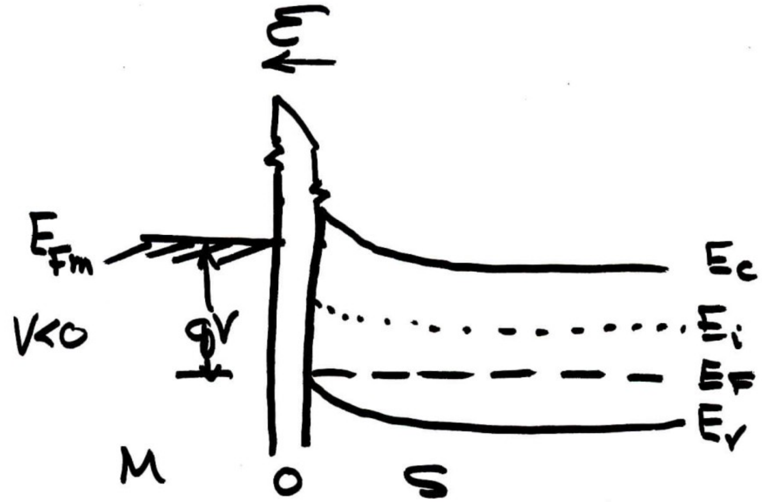
$$g_m(\text{sat.}) = \frac{\partial I_D(\text{sat.})}{\partial V_G} = G_0 \left[1 - \left(-\frac{V_G}{V_P}\right)^{1/2}\right]$$

HEMT

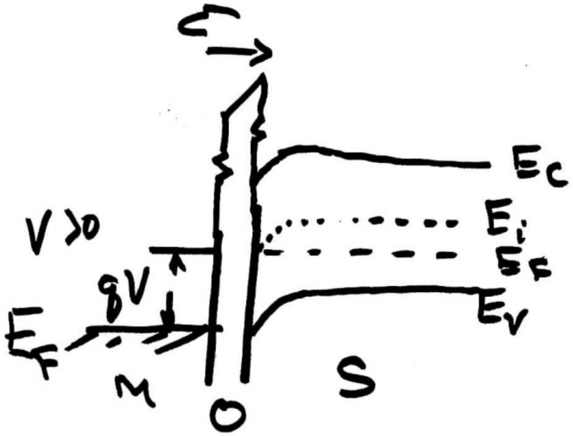


MOSFET





Accumulation



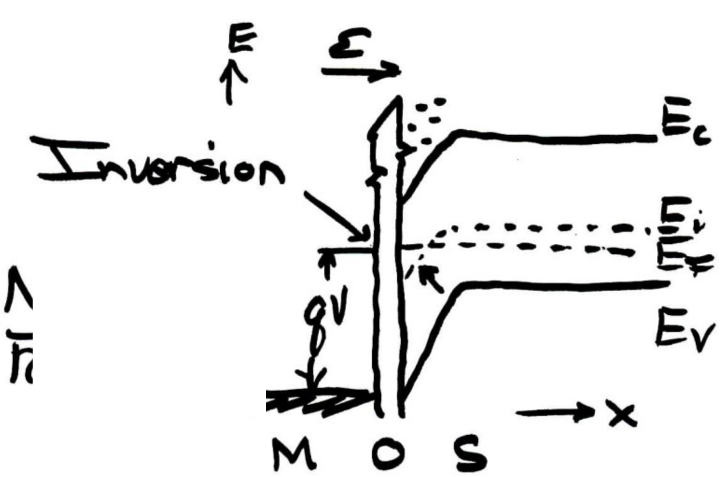
Depletion

Positive voltage to metal

$$\mathcal{E}(x) = \frac{1}{q}\frac{dE_i}{dx}$$

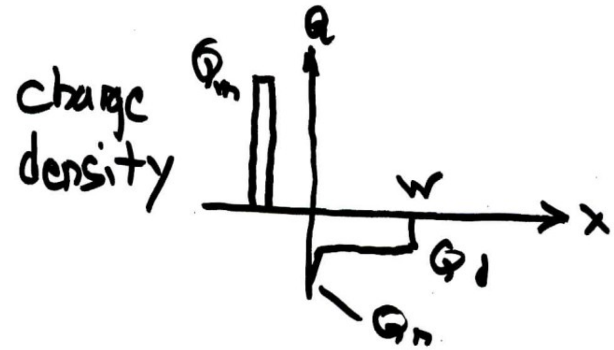
$$P = n_i e^{(E_i - E_F)/kT}$$

$$\phi_s(\text{inverted}) = 2\phi_F = \frac{2kT}{q}\ln\frac{N_a}{n_i}$$



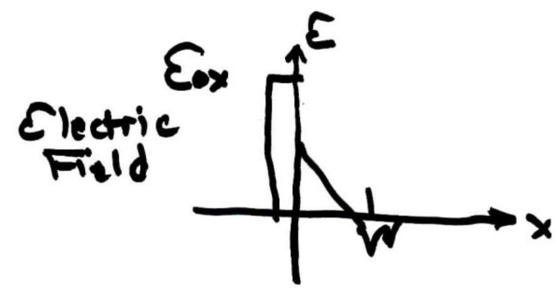
$$\rho = q(N_d^+ - N_a^- + p - n)$$

$$Q_m = -Q_s = \underbrace{qN_aW}_{Q_d} - Q_n$$



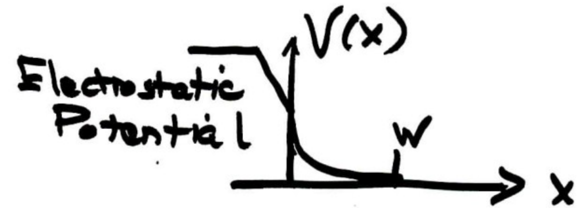
$$V = V_i + \phi_s$$

$$V_i = -\frac{Q_s d}{\epsilon_i} = -\frac{Q_s}{C_i}$$



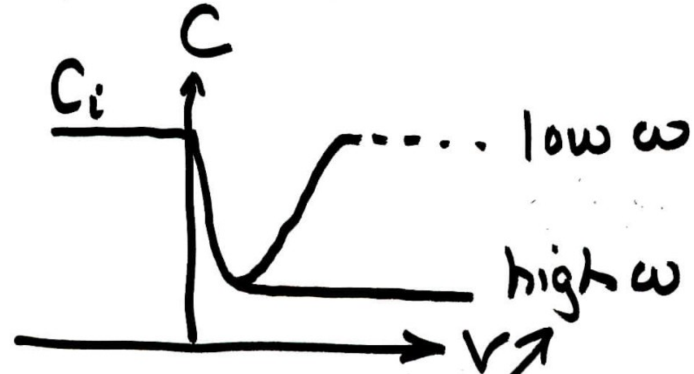
$$W = \left[\frac{2\epsilon_s\phi_s}{qN_a}\right]^{1/2}$$ like p^+-n junction

$$W_m = \left[\frac{2^2\epsilon_s kT\ln(N_a/n_i)}{q^2 N_a}\right]^{1/2}$$



$$W_m = \left[\frac{2^2 \epsilon_s kT \ln(N_a/n_i)}{q^2 N_a} \right]^{1/2}$$

$$V_T = -\frac{Q_d}{C_i} + 2\phi_F$$



$$C_i = \frac{\epsilon_i}{d} \qquad C_d = \frac{\epsilon_s}{W} \qquad C = \frac{C_i C_d}{C_i + C_d}$$

Real MOS Transistors

$$\Phi_{ms} = \phi_M - \phi_s \neq 0 \qquad V_{FB} = \Phi_{ms} - \frac{Q_i}{C_i}$$

$$\phi_F = \frac{kT}{q} \ln \frac{N_a}{n_i}$$

$$W_m = 2\left[\frac{\epsilon_s \phi_F}{q N_a}\right]^{1/2}$$

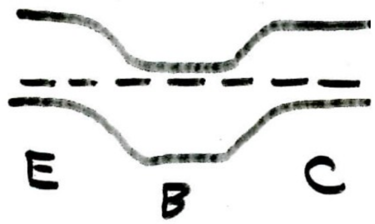
$$C_i = \frac{\epsilon_i}{d}$$

$$Q_D = -q N_a W_m$$

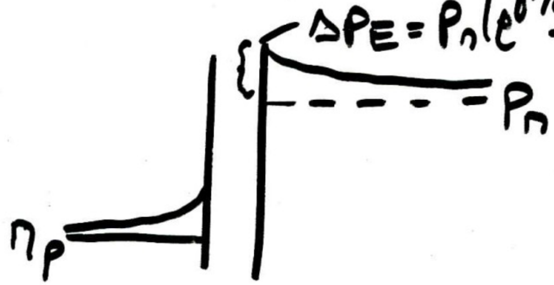
$$C_d = \frac{\epsilon_s}{W_m} \qquad C_{min} = \frac{C_i C_d}{C_i + C_d}$$

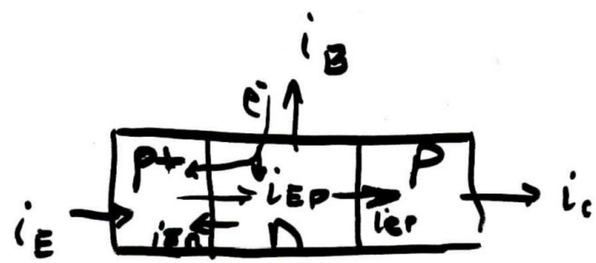
$$V_T = \Phi_{ms} - \frac{Q_i}{C_i} - \frac{Q_d}{C_i} + 2\phi_F$$

Bipolar Junction Transistor



"on": E in forward bias (lower the barrier), C in reverse bias (sweep out all carriers)





$$i_E = i_{Ep} + i_{En}$$

$$\frac{i_{Ep}}{i_{En}+i_{En}} = \gamma \qquad i_c = B\, i_{Ep}$$

Emitter Injection Efficiency

Base Transport Factor

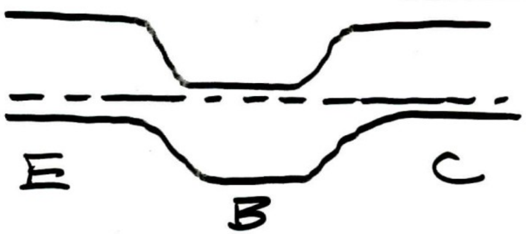
$B\gamma = \alpha$ Current Transfer Ratio

$\beta = \frac{\alpha}{1-\alpha}$ Base-to-collector current amplification factor (gain)

Hope $\alpha \sim 1$

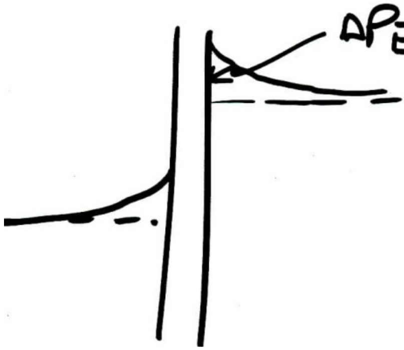
Know how to calculate ΔP_E and ΔP_C. You need it for I_E, I_C, and I_B.

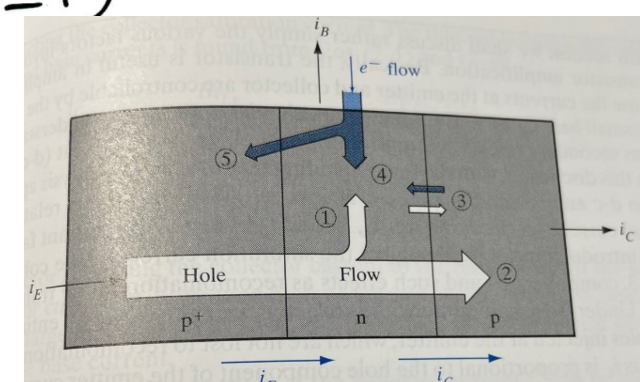
BJT



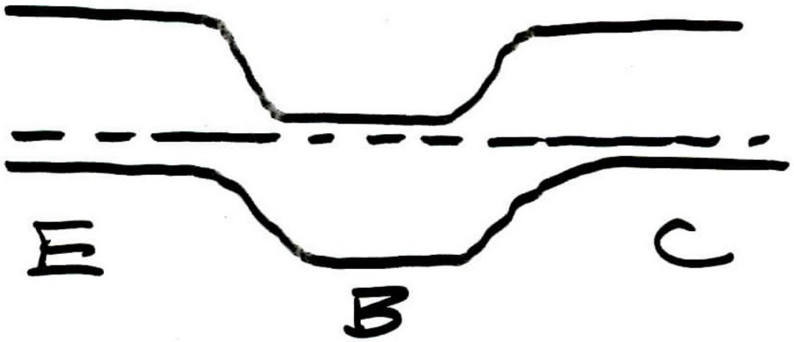
"on" — lower E-B barrier; C in reverse: sweep out carriers

$\Delta P_E = P_n(e^{qV/kT} - 1)$



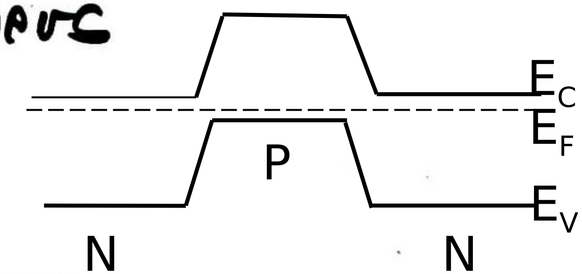


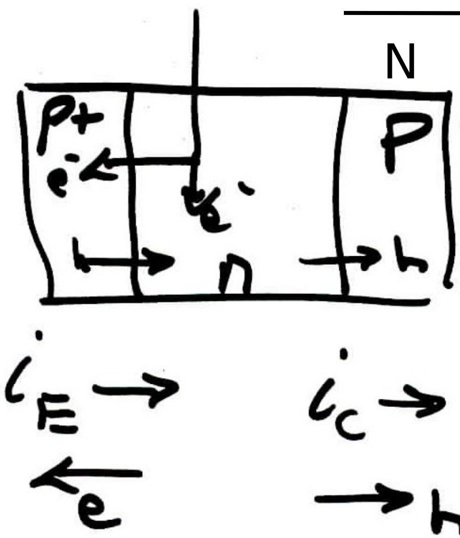
BJT



"on" — lower E-B barrier; C in reverse: sweep out carriers

$$\Delta P_E = P_n\left(e^{qV/kT} - 1\right)$$

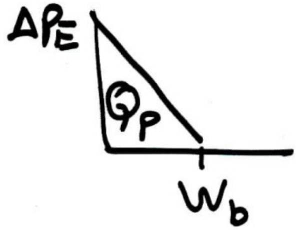




$$I_{Ep} = q\frac{AD_p}{L_p}\left(\Delta P_E \operatorname{ctnh}\frac{W_b}{L_p} - \Delta P_C \operatorname{csch}\frac{W_b}{L_p}\right)$$

$$I_{Cp} = q\frac{AD_p}{L_p}\left(\Delta P_E \operatorname{csch}\frac{W_b}{L_p} - \Delta P_C \operatorname{ctnh}\frac{W_b}{L_p}\right)$$

$$I_B = I_E - I_C = q\frac{AD_p}{L_p}\left[(\Delta P_E + \Delta P_C)\tanh\frac{W_b}{2L_p}\right]$$



$$Q_p = \frac{1}{2} q A W_b \Delta P_E$$ replaced every τ_p

so $$I_B = \frac{Q_p}{\tau_p} = \frac{1}{2} q \frac{A W_b \Delta P_E}{\tau_p}$$

$$\gamma = \frac{I_{Ep}}{I_{Ep} + I_{En}} \qquad B = \frac{I_C}{I_{Ep}} \qquad \alpha = B\gamma \qquad \beta = \frac{\alpha}{1-\alpha}$$

$$\gamma = \left[1 + \frac{L_p^n}{L_n^p}\frac{n_n}{p_p}\frac{\mu_n^p}{\mu_p^n}\tanh\frac{W_b}{L_p}\right]^{-1} \simeq \left[1 + \frac{W_b}{L_n^p}\frac{n_n \mu_n^p}{p_p \mu_p^n}\right]^{-1}$$

$$B = \operatorname{Sech}\frac{W_b}{L_p}$$

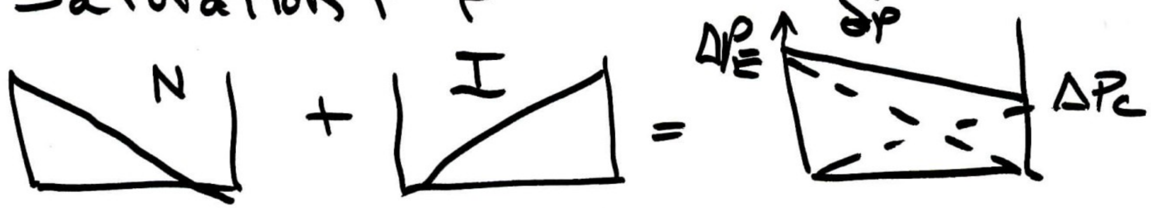
Sech y ~ 1Ctnh y ~1/y   Csch y ~ 1/y   Tanh y ~

p-n-p coupled diodes

V_{EB} V_{CB}

4 options:

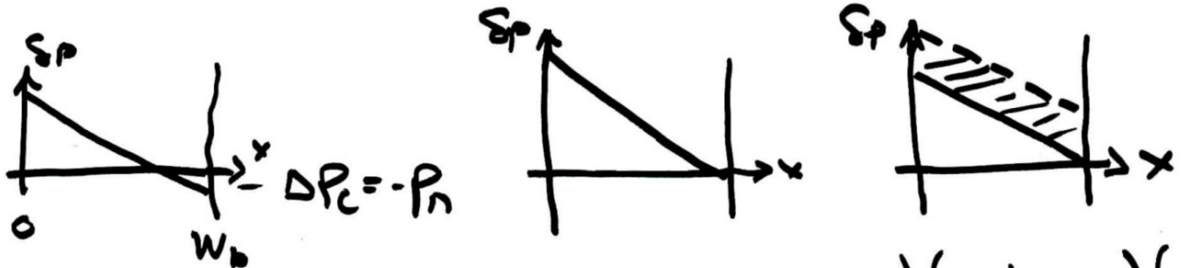
Normal	F	R
Inverted	R	F
Cutoff	R	R
Saturation	F	F



Both F-biased

$$I_{Ep} = qA\frac{D_p}{L_p}\left(\text{emitter diode} - \text{collector diode}\right)$$

$$I_{Cp} = \quad '' \quad \left(\quad '' \qquad '' \quad \right)$$



$V_{EB}>0$ F, $V_{CB}<0$ R

$V_{EB}>0$ F, $V_{CB}=0$ 0 — onset of saturation

$V_{EB}>0$ F, $V_{CB}>0$ F — oversaturation (excess charge)

$$Q_p \equiv \Delta P_E \frac{W_b}{2} \cdot q A$$

Current = charge replaced per second

$$= q A \frac{\Delta P_E W_b}{2 \tau_p}$$

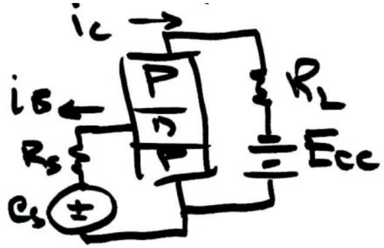
Charge Control Approximation

Transit time across the base often limits high frequency.

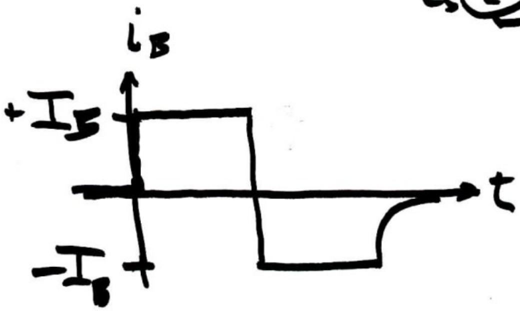
$$\beta \simeq \frac{\operatorname{csch} W_b/L_p}{\tanh W_b/2L_p} = \boxed{\frac{2L_p^2}{W_b^2}} = \frac{2D_p\tau_p}{W_b^2} \equiv \frac{\tau_p}{\tau_t}$$

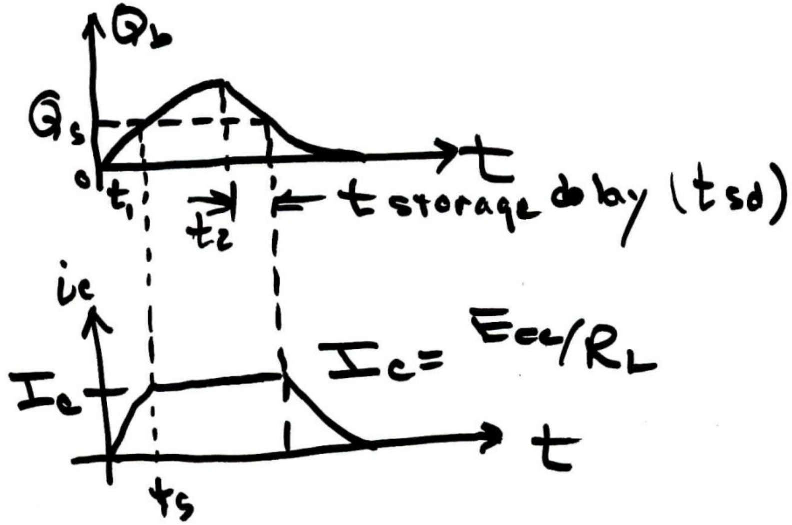
$$\tau_t = \boxed{\frac{W_b^2}{2D_p}}$$

Switching



→ V_{CE} — 0 range





$I_C = \beta I_B$

increase i_B to increase i_C but not above saturation

i_C fixed by V_{CC} and R_L

(can only draw so much current)

Early Effect (base narrowing)