Lecture 16: Bipolar Junction Transistors (BJTs) I

- Announcements:
- HW#6 online soon and due Friday two weeks from now via Gradescope
- Lab#3 continues next week
  - Prelab due before lab next week
- Midterm 1 on Friday, Oct. 11
  - We have 7-9 p.m., 160 Kroeber Hall
  - For the review session, please post on Piazza specific problems you would like covered
- My Monday Office Hours will move to 5-6 p.m. on Oct. 14 and thereafter
- I am traveling today and will still be gone Monday, Oct. 7
  - This lecture is pre-recorded as will be the Monday lecture
  - I will be back on Wednesday, Oct. 9
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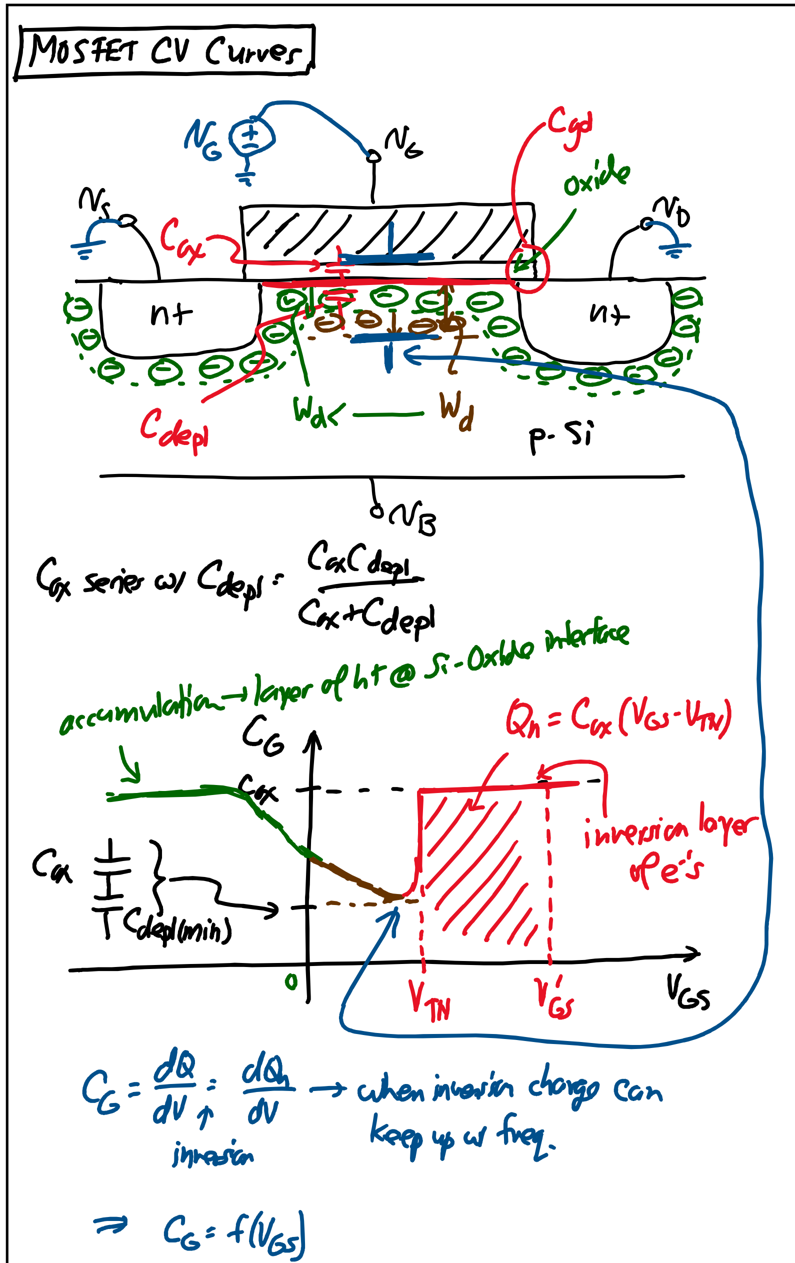
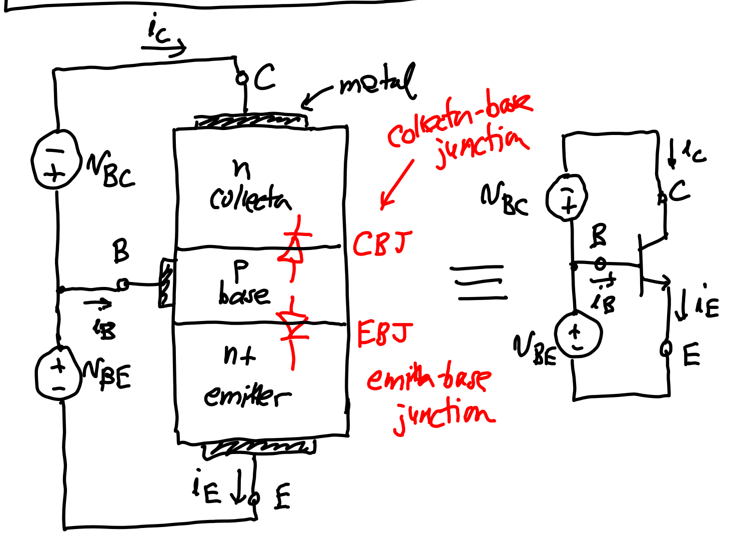
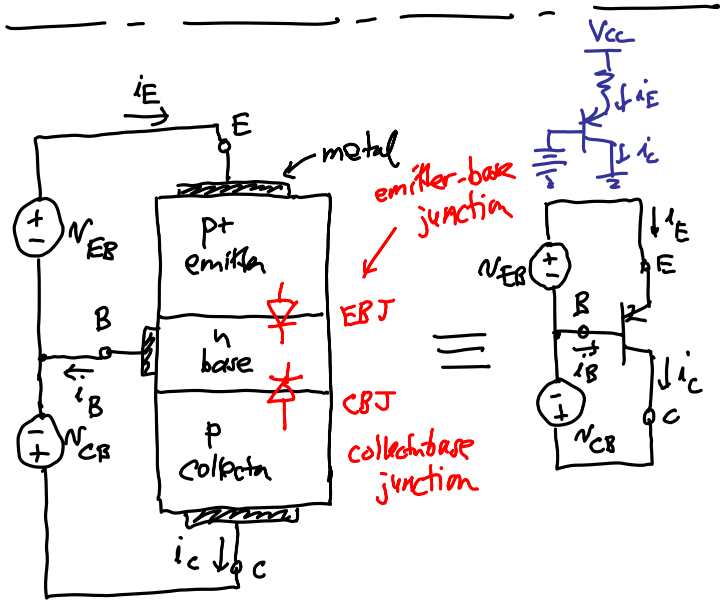
- Lecture Topics:
  - MOS CV Curve
  - Bipolar Junction Transistor (BJT)
    - Regions of Operation
    - Cutoff
    - Forward-Active
- -----------------------------------
- Last Time:
- Almost finished with MOS physics (for now)
- Now, finish it, then proceed with BJTs



Bipolar Junction Transistors (BJT's)



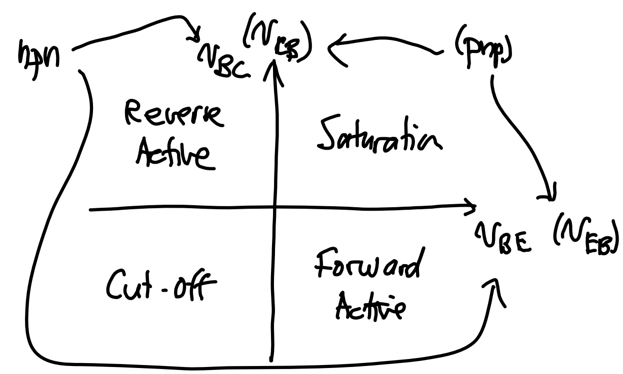


Regions of BJT Operation

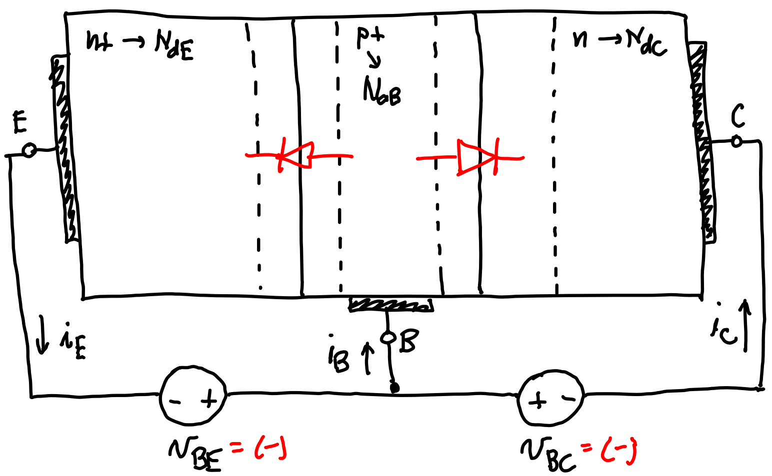
F ← forward bias, R ← reverse bias

EBJ	CBJ	Mode
R	R	Cutoff (both diodes off)
F	R	Forward Active (widely used in analog amplifiers)
R	F	Reverse Active
F	F	Saturation

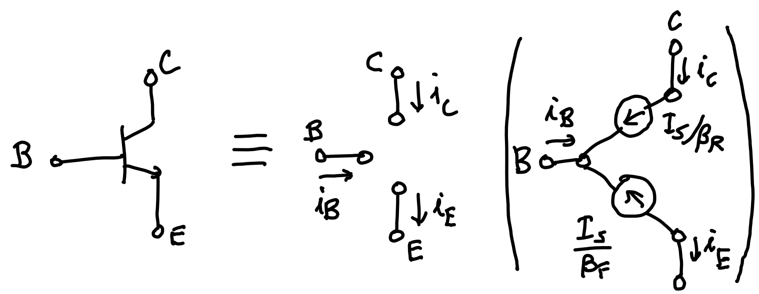
⇒ Or graphically:



① Cutoff Region: (npn transistor)

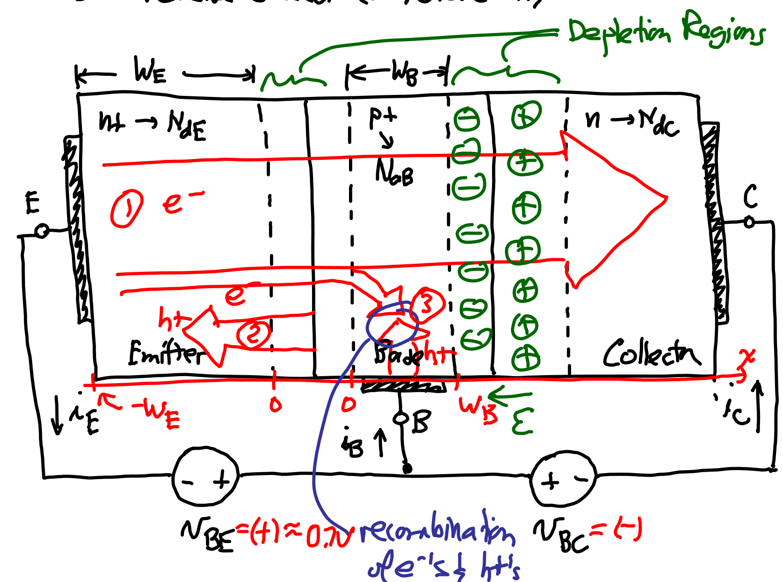


⇒ Both diodes reverse-biased
↳ No current flows.
$i_B = 0,\ i_C = 0,\ i_E = 0$

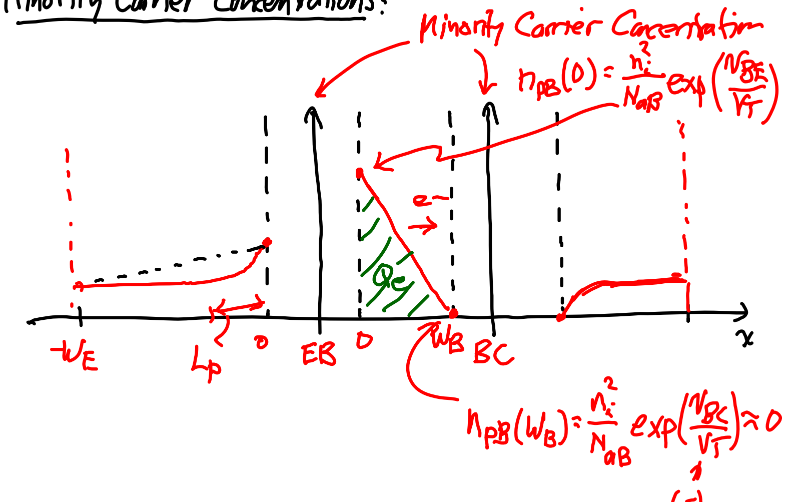


② Forward-Active Region: (npn transistor)

BEJ forward-biased (i.e., diode on)
BCJ reverse-biased (i.e., diode off)



Minority Carrier Concentrations:



BEJ Forward-Biased:

⇒ get diffusion current as in diode

⇒ forward-biasing of a BJT → three current components:

① e⁻'s injected from emitter to base:

$$I_{nB} = -A J_{nB}^{diff}$$

② h⁺'s injected from base to emitter:

$$I_{pE} = -A J_{pE}^{diff}$$

③ recombination of e⁻'s & h⁺'s in the base

$$I_{rB} \propto \exp\left(\frac{V_{BE}}{V_T}\right)$$

$$i_C = I_{nB} = ①$$

$$i_E = I_{nB} + I_{pE} + I_{rB} = ① + ② + ③$$

$$i_B = I_{pE} + I_{rB} = ② + ③$$

Diffusion Current:

$$I_{nB} = -A J_{nB}^{diff} = -A q D_{nB} \frac{dn_p(x)}{dx}$$

(A: cross-sectional area; D_{nB}: diffusion constant for e⁻'s in base; $n_p(x)$: e⁻ conc. in p-type region)

$$= -qAD_{nB} \frac{[n_{pB}(W_B) - n_{pB}(0)]}{W_B} \rightarrow *$$

Current Formulations

①: $I_{nB} = -A J_{nB}^{diff} = -A q D_{nB} \frac{dn_p(x)}{dx}$

(A: cross-sectional area; D_{nB}: diffusion constant for e⁻'s in base; $\frac{dn_p(x)}{dx}$: slope of minority carrier concentration)

$$* \quad = -qAD_{nB} \frac{[n_{pB}(W_B) - n_{pB}(0)]}{W_B}$$

$$n_{pB}(W_B) = \frac{n_i^2}{N_{aB}} \exp\left(\frac{V_{BC}}{V_T}\right) \approx 0$$

$$n_{pB}(0) = \frac{n_i^2}{N_{aB}} \exp\left(\frac{V_{BE}}{V_T}\right)$$

$$\boxed{I_{nB} = qAD_{nB} \frac{n_i^2}{N_{aB} W_B} \exp\left(\frac{V_{BE}}{V_T}\right) = ①}$$

$$\boxed{i_C = ① = I_S \exp\left(\frac{V_{BE}}{V_T}\right)}$$

②: $I_{pE} = A J_{pE}^{diff} = qAD_{pE} \frac{dp_n(x)}{dx}$

(D_{pE}: diffusion constant for h⁺'s in emitter; $\frac{dp_n(x)}{dx}$: slope)

$$= qAD_{pE} \frac{[p_{nE}(0) - p_{nE}(-W_E)]}{W_E} \quad *$$

(W_E for a short emitter; (or L_p) for long emitter)

$$p_{nE}(0) = \frac{n_i^2}{N_{dE}} \exp\left(\frac{v_{BE}}{V_T}\right)$$

$$p_{nE}(-W_E) \cong 0$$

*

$$I_{pE} = qAD_{pE}\frac{n_i^2}{N_{dE}W_E}\exp\left(\frac{v_{BE}}{V_T}\right) = ②$$

make emitter doping large to reduce

③: $I_{rB} = \frac{Q_e}{\tau_b}$ ← Q_e: minority carrier charge in the base; τ_b: minority carrier lifetime in base

$$= \frac{1}{\tau_b}\left[\frac{1}{2} n_{pB}(0) W_B qA\right]$$

area under the minority carrier (e^-) charge curve

$$\therefore I_{rB} = \frac{1}{2}\frac{n_i^2 W_B qA}{N_{aB}\tau_b}\exp\left(\frac{v_{BE}}{V_T}\right) = ③$$

Define. Forward Current Gain $= \beta_F$

$$\beta_F = \frac{i_C}{i_B} = \frac{①}{③+②} = \frac{\frac{qAD_{nB}n_i^2}{N_{aB}W_B}}{\frac{1}{2}\frac{n_i^2 W_B qA}{N_{aB}\tau_b} + \frac{qAD_{pE}n_i^2}{N_{dE}W_E}}$$

$$\therefore \beta_F = \left[\frac{W_B^2}{2\tau_b D_{nB}} + \frac{D_{pE}W_B N_{aB}}{D_{nB}W_E N_{dE}}\right]^{-1}$$

To maximize β_F, want:

① W_B = small

② $N_{dE} \gg N_{aB}$ $\xrightarrow{\text{leads to}}$ $D_{pE} \ll D_{nE}$

③ τ_b = large → base Si should be free of impurities/defects to prevent recombination of e^-'s & h^+'s

→ This is why emitter is n^+.