# Lecture #18

## ANNOUNCEMENTS

- Lowest quiz score will be dropped for each student
- No Discussion and Office Hours next week
- Design Project will be posted online tomorrow

## OUTLINE

The Bipolar Junction Transistor

- Gummel numbers
- Charge-control model
- Base transit time

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# Current Formulas for NPN BJT

**Long Emitter and Long Collector:**

$$I_E = qA\left[\left(\frac{D_E}{L_E} p_{E0} + \frac{D_B}{L_B} n_{B0} \frac{\cosh(W/L_B)}{\sinh(W/L_B)}\right)\left(e^{qV_{BE}/kT} - 1\right) - \left(\frac{D_B}{L_B} n_{B0} \frac{1}{\sinh(W/L_B)}\right)\left(e^{qV_{BC}/kT} - 1\right)\right]$$

$$I_C = qA\left[\left(\frac{D_B}{L_B} n_{B0} \frac{1}{\sinh(W/L_B)}\right)\left(e^{qV_{BE}/kT} - 1\right) - \left(\frac{D_C}{L_C} p_{C0} + \frac{D_B}{L_B} n_{B0} \frac{\cosh(W/L_B)}{\sinh(W/L_B)}\right)\left(e^{qV_{BC}/kT} - 1\right)\right]$$

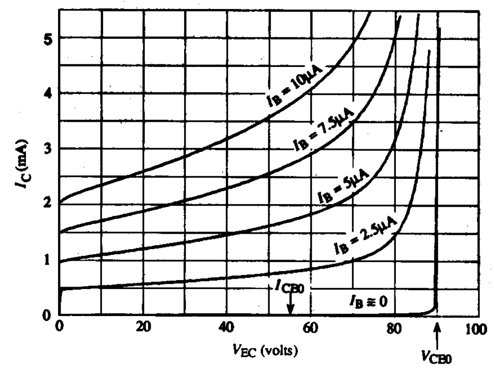
**Short Emitter and Short Collector:**

$$I_E = qA\left[\left(\frac{D_E}{W'_E} p_{E0} + \frac{D_B}{L_B} n_{B0} \frac{\cosh(W/L_B)}{\sinh(W/L_B)}\right)\left(e^{qV_{BE}/kT} - 1\right) - \left(\frac{D_B}{L_B} n_{B0} \frac{1}{\sinh(W/L_B)}\right)\left(e^{qV_{BC}/kT} - 1\right)\right]$$

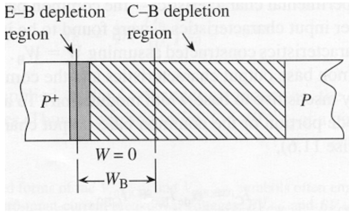
$$I_C = qA\left[\left(\frac{D_B}{L_B} n_{B0} \frac{1}{\sinh(W/L_B)}\right)\left(e^{qV_{BE}/kT} - 1\right) - \left(\frac{D_C}{W'_C} p_{C0} + \frac{D_B}{L_B} n_{B0} \frac{\cosh(W/L_B)}{\sinh(W/L_B)}\right)\left(e^{qV_{BC}/kT} - 1\right)\right]$$

# Review: BJT Breakdown Mechanisms

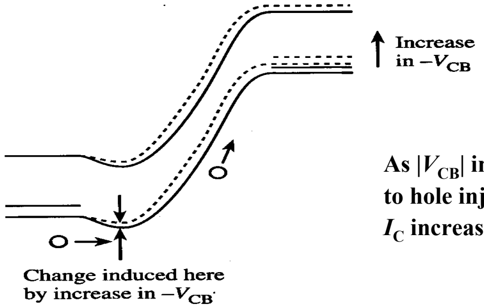
- In the common-emitter configuration, for high output voltage $V_{CE}$, the output current $I_C$ will increase rapidly due to one of two mechanisms:
  - – punch-through
  - – avalanche



# Review: Punch-Through



**E-B and E-B depletion regions in the base touch, so that $W = 0$**

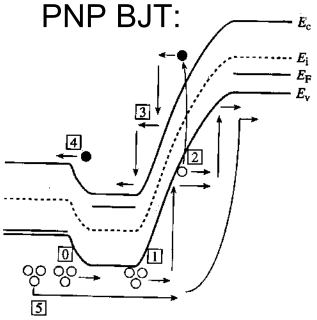


**As $|V_{CB}|$ increases, the potential barrier to hole injection decreases and therefore $I_C$ increases**

# Review: Avalanche

- Holes are injected into the base, then collected by the B-C junction
  - Some holes in the B-C depletion region have enough energy to generate EHP [1]
  - The generated electrons are swept into the base [3], then injected into the emitter [4]
  - Each injected electron results in the injection of $I_{Ep}/I_{En}$ holes from the emitter into the base [0]

PNP BJT:



→ For each EHP created in the C-B depletion region by impact ionization, $I_{Ep}/I_{En}+1>\beta_{dc}$ additional holes flow into the collector
*i.e.* carrier multiplication in C-B depletion region is internally amplified

$$\boxed{V_{CE0}=\frac{V_{CB0}}{(\beta_{dc}+1)^{1/m}}}$$

where $V_{\mathrm{CB0}}$ = reverse breakdown voltage of the C-B junction

$$2\le m\le 6$$

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# Base Gummel Number

Base Gummel number $G_B \equiv \int_0^W \frac{n_i^2}{n_{iB}^2}\frac{N_B}{D_B}dx$

= total integrated base dopant dose (atoms/cm$^2$) divided by $D_{\mathrm{B}}$

For a uniformly doped base with negligible band-gap narrowing,

$$G_B=\frac{N_B W}{D_B}$$

$$I_C\cong\frac{qn_i^2A}{G_B}\left(e^{qV_{EB}/kT}-1\right)$$

# Emitter Gummel Number w/ Poly-Si Emitter

Emitter Gummel number $G_E \equiv \int_0^{-W_E'} \frac{n_i^2}{n_{iE}^2} \frac{N_E}{D_E} dx + \frac{n_i^2 N_E(-W_E')}{n_{iE}^2(-W_E')S_p}$

where $S_p = D_{E\text{poly}}/W_{E\text{poly}}$ is the ***surface recombination velocity***

For a uniformly doped emitter,

$$G_E = N_E \frac{n_i^2}{n_{iE}^2}\left(\frac{W_E'}{D_E} + \frac{1}{S_p}\right)$$

$$I_B \cong \frac{qn_i^2 A}{G_E}\left(e^{qV_{EB}/kT} - 1\right)$$

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# Charge Control Model

A PNP BJT biased in the forward-active mode will have excess **minority-carrier charge $Q_B$** stored in the quasi-neutral base:

$$\Delta p_B(x,t) = \Delta p_B(0,t)\left(1 - \tfrac{x}{W}\right)$$

$$Q_B = qA\int_0^W \Delta p_B(x,t)dx = \frac{qAW\Delta p_B(0,t)}{2}$$

$$\frac{dQ_B}{dt} = i_B - \frac{Q_B}{\tau_B}$$

# Base Transit Time $\tau_t$

$$Q_B = qA\int_0^W \Delta p_B(x,t)dx = \frac{qAW\Delta p_B(0,t)}{2}$$

$$i_c = -qAD_B \left.\frac{\partial \Delta p_B(x,t)}{\partial x}\right|_{x=W} = \frac{qAD_B\Delta p_B(0,t)}{W} = \frac{Q_B}{W^2/2D_B} = \frac{Q_B}{\tau_t}$$

$$\tau_t \equiv \frac{W^2}{2D_B}$$

- time required for minority carriers to diffuse across the base
- sets the switching speed limit of the transistor

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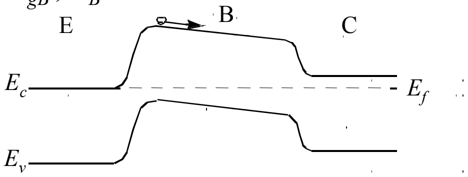
# Relationship between $\tau_t$ and $\tau_B$

$$\tau_B \cong \beta_{dc}\tau_t$$

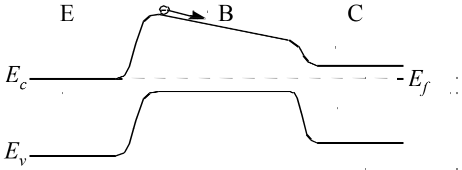
# Drift Transistor: Built-in Base Field

The base transit time can be reduced by building into the base a drift field that aids the flow of electrons.

- Fixed $E_{gB}$, $N_B$ decreases from emitter end to collector end.



- Fixed $N_B$, $E_{gB}$ decreases from emitter end to collector end.



$$\mathcal{E} = \frac{1}{q}\frac{dE_C}{dx}$$