BJT

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Bipolar Junction Transistors

- Bipolar
  - Device operation depends on the injection and collection of minority carriers.
    - electrons and holes
- Invented in 1948 by Bardeen, Bratain, and Shockley at Bell Telephone Labs (Lucent)
- Small and one can integrate transistors with C, R, and L elements on a chip.
- Note: Tubes still good for sustained high power operation.

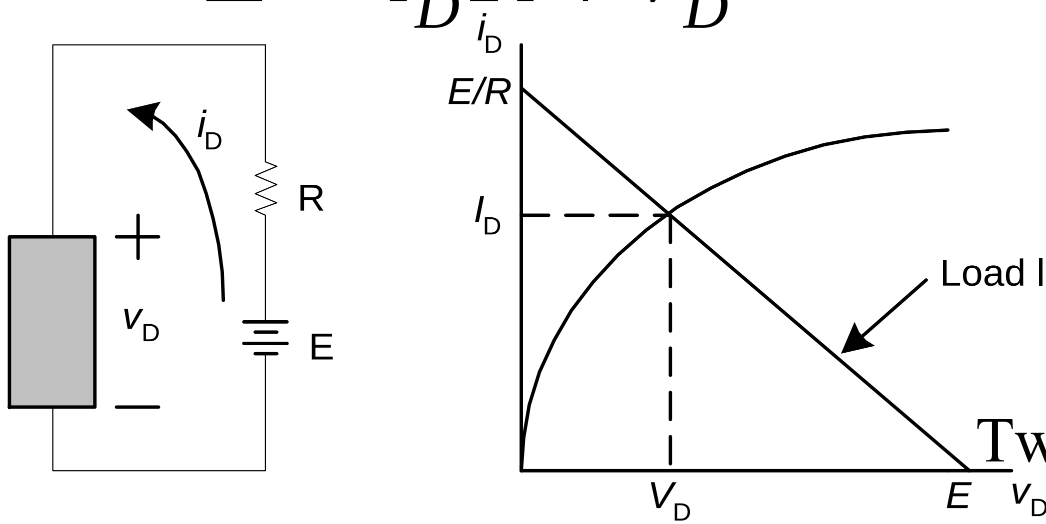
Bipolar Junction Transistors

- Based on:
  - one forward biased p^{++}/n^{+} junction and one reversed biased n^{+}/p junction or
  - one forward biased n^{++}/p^{+} junction and one reversed biased p^{+}/n junction
- Three terminal device
  - small changes in a control current cause large changes in the controlled current (gain)
  - Can be switched from on to off and back.

Load line

- Helps us pick a Q point with a non-linear device (diodes, BJTS, MOSFETS) and a linear device (resistor).

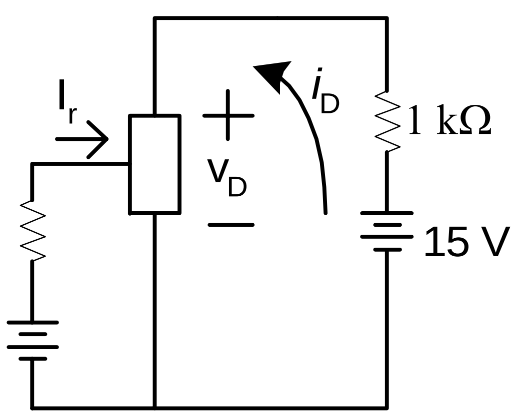
$$E = i_D R + v_D$$

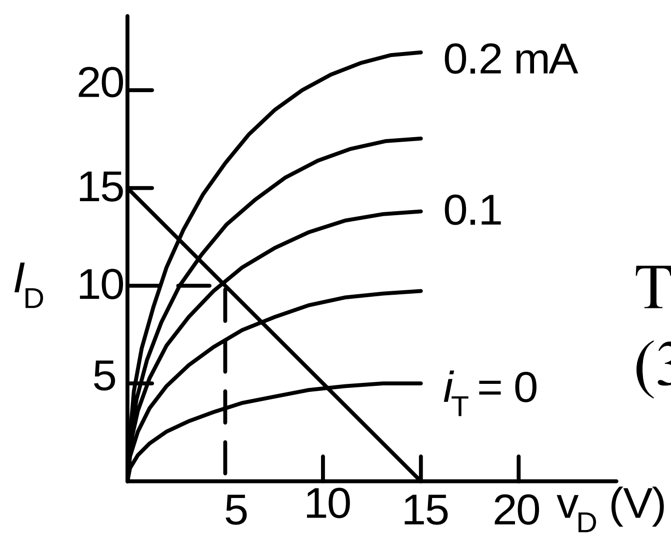


Two Terminal

Load line

$$E = i_D R + v_D$$



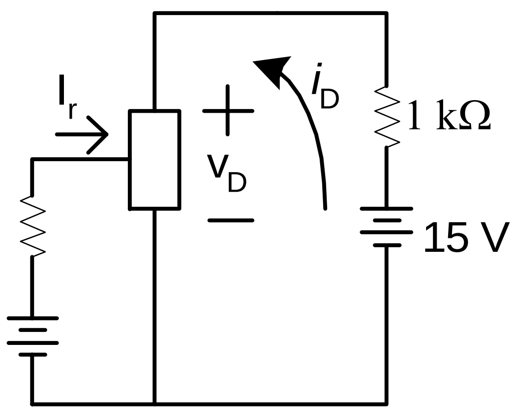


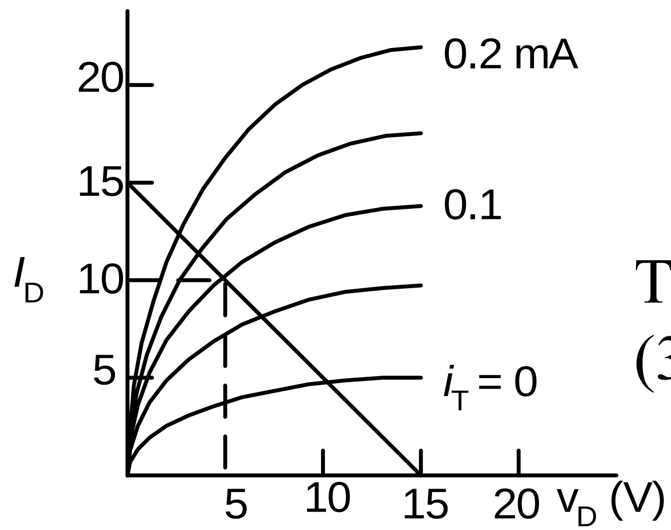
Three Terminal
(3-D PLOT)

Switching

What is i_D, v_D in the off state (i_T=0mA)?

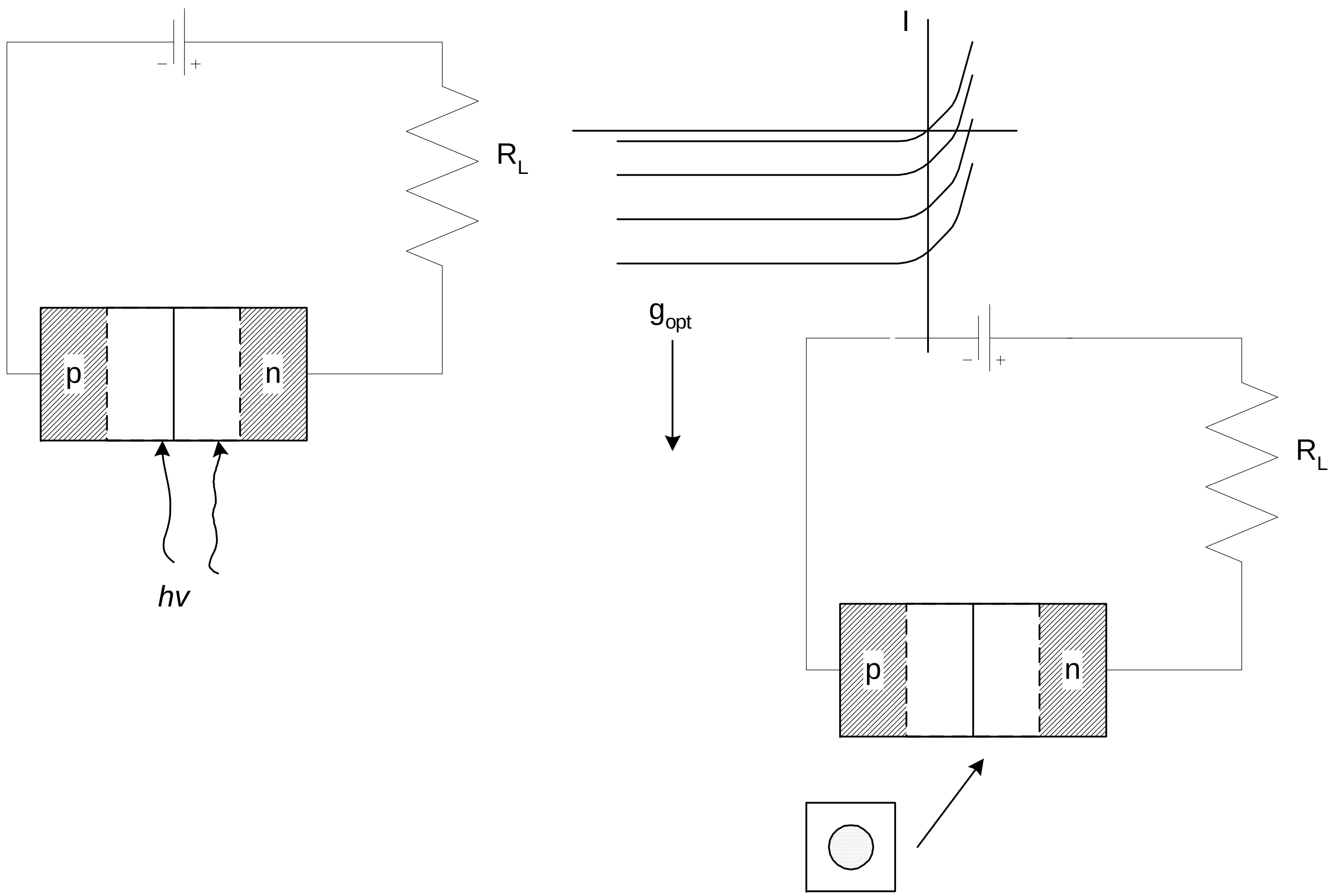
What is i_D, v_D in the on state (i_T=2mA)?



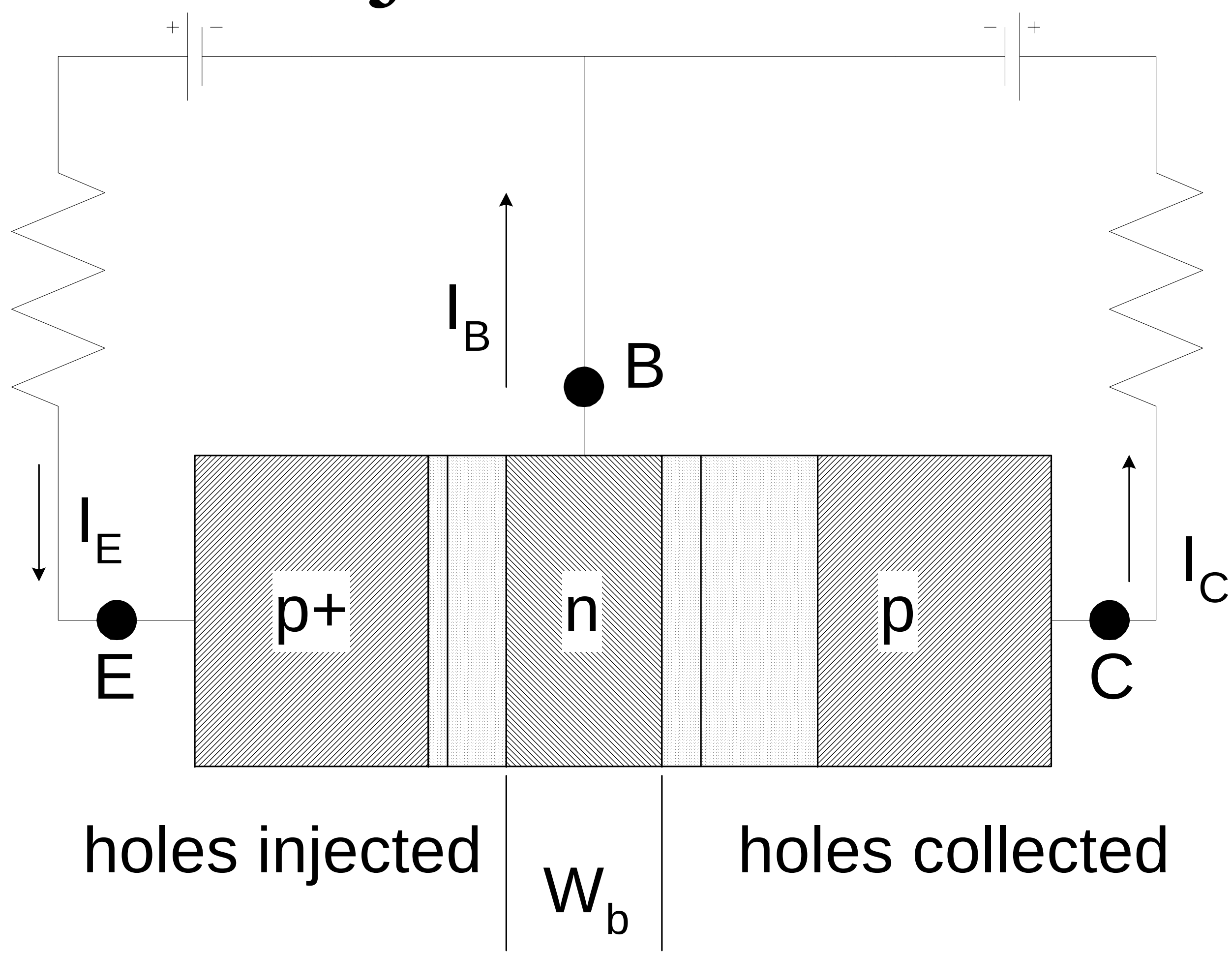


Three Terminal
(3-D PLOT)

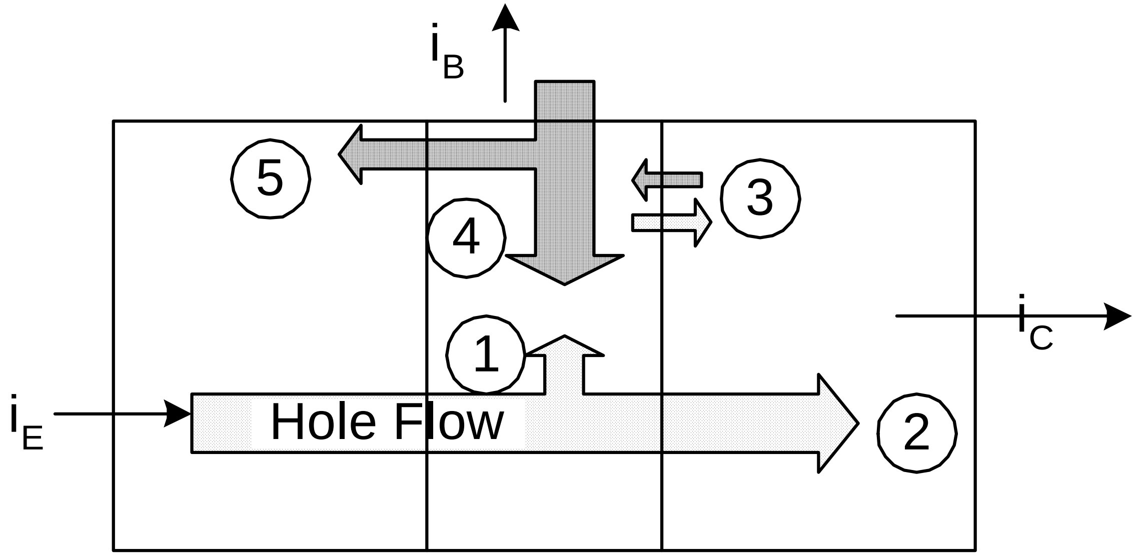
Hole injector



Hole injector and collector



Hole and electron current



1) injected holes lost to recombination
2) holes reaching the reversed biased CB junction
3) thermally generated EHP
4) electrons supplied the base contact (recombines with holes)
5) electrons injected across the forward biased EB junction

Base Current

- Three components:
  - Recombination of injected holes with electrons in the base
  - Some electrons will be injected into the emitter
  - Some are swept into the reversed biased base collector junction (created by thermal generation)

Base Current

- We would like our base current (control current) to be smaller than our controled current (I_C).
- $W_b << L_p$ (by design)

Amplification

$$i_C = Bi_{Ep}$$

$$\gamma = \frac{i_{Ep}}{i_{En} + i_{Ep}}$$

$$\frac{i_C}{i_E} = B\left(\frac{i_{Ep}}{i_{En} + i_{Ep}}\right) = B\gamma \equiv \alpha$$

$$i_B = i_{En} + (1 - B)i_{Ep}$$

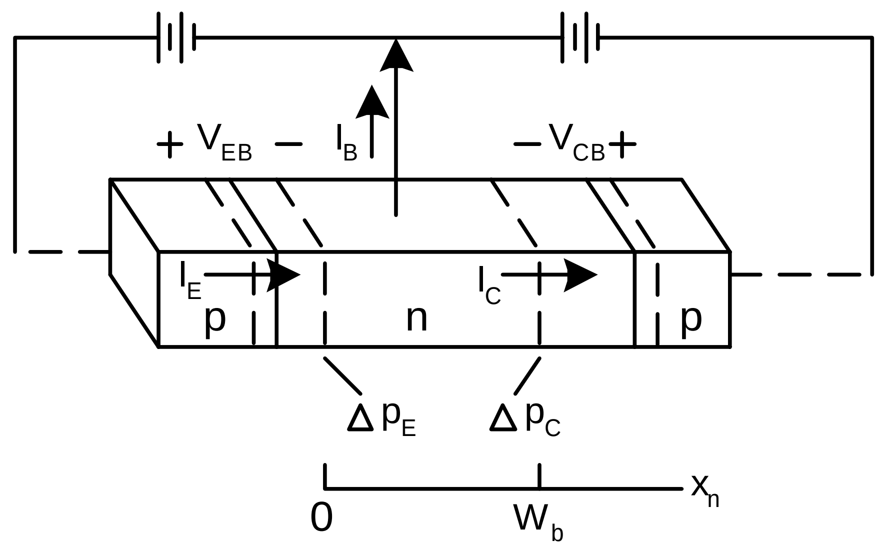
$$\frac{i_C}{i_B} = \frac{B\gamma}{1 - B\gamma} = \frac{\alpha}{1 - \alpha} \equiv \beta$$

$$\frac{i_C}{i_B} = \beta = \frac{\tau_p}{\tau_t}$$

Terminal Currents, I_C, I_B and I_E

- Assumptions: (pnp BJT)
  - Holes diffuse from emitter to collector; drift is negligible.
  - The emitter current is made up entirely of holes ($\gamma=1$).
  - The collector saturation current is very small.
  - The active areas, have the same areas
  - All currents and voltages are in the steady state.

Minority carrier distributions



Minority carrier distributions

$$\Delta p_E = p_n\left(e^{qV_{EB}/kT} - 1\right) \quad (1)$$

$$\Delta p_C = p_n\left(e^{qV_{CB}/kT} - 1\right) \quad (2)$$

Assume:

1) $V_{EB} >> kT/q$

2) $V_{CB} << 0$

1 and 2 reduce to

$$\Delta p_E = p_n e^{qV_{EB}/kT} \quad (3)$$

$$\Delta p_C = -p_n \quad (4)$$

Minority carrier distributions

$$\frac{\mathrm{d}^2 \delta p(x_n)}{dx_p^2} = \frac{\delta p(x_n)}{L_p^2} \qquad (5)$$

The general solution is

$$p(x_n) = C_1 e^{x_n / L_p} + C_2 e^{-x_n / L_p} \qquad (6)$$

We need to use boundary conditions to

solve for C_1 and C_2 :

B.C.1

$$\delta p(x_n = 0) = \mathrm{C}_1 + \mathrm{C}_2 = \Delta p_E$$

B.C.2

$$p(x_n = W_b) = C_1 e^{W_b / L_p} + C_2 e^{-W_b / L_p} = \Delta p_C$$

Minority carrier distributions

Solving for C_1 and C_2 :

$$C_1 = \frac{\Delta p_C - \Delta p_E e^{-W_b/L_p}}{e^{W_b/L_p} - e^{-W_b/L_p}} \qquad (7)$$

$$C_2 = \frac{\Delta p_E e^{W_b/L_p} - \Delta p_C}{e^{W_b/L_p} - e^{-W_b/L_p}} \qquad (8)$$

Minority carrier distributions

$$\delta p(x_n) = \Delta p_E \frac{e^{W_b/L_p} e^{-x_n/L_p} - e^{-W_b/L_p} e^{x_n/L_p}}{e^{W_b/L_p} - e^{-W_b/L_p}} \quad (9)$$

for $\Delta p_C = 0$

Terminal currents

Now we know the minority carrier distrabution in the base
we can calulate emitter and collector currents at each depletion edge.
From chapter 4 :

$$\mathrm{I_p} = -qAD_p \frac{d\delta p(x_n)}{dx_n} \qquad (10)$$

Evaluated at $\mathrm{x_n} = 0$ give the hole componant of the emitter current.

$$\mathrm{I_{Ep}} = I_p(\mathrm{x_n} = 0) = \mathrm{qA}\frac{\mathrm{D_p}}{\mathrm{L_p}}(C_1 - C_2) \qquad (11)$$

Terminal currents

I_C at $x_n = W_b$ is made up of entirely holes.

$$I_C = I_p(x_n = W_b) = qA\frac{D_p}{L_p}(C_2 e^{-W_b/L_p} - C_1 e^{W_b/L_p}) \quad (12)$$

Terminal currents

I_C at $x_n = W_b$ is made up of entirely holes.

$$I_{Ep} = qA\frac{D_p}{L_p}\left(\Delta p_E \mathrm{ctnh}\frac{W_b}{L_p} - \Delta p_C \mathrm{csch}\frac{W_b}{L_p}\right) \quad (13)$$

$$I_C = qA\frac{D_p}{L_p}\left(\Delta p_E \mathrm{csch}\frac{W_b}{L_p} - \Delta p_C \mathrm{ctnh}\frac{W_b}{L_p}\right) \quad (14)$$

Terminal currents

I_B can be found by summing the currents at the node.

(Remeber we assumed $\gamma = 1$.)

$$I_B = I_E - I_C = qA\frac{D_p}{L_p}\left(\left(\Delta p_E + \Delta p_C\right)\tanh\frac{W_b}{2L_p}\right) \qquad (15)$$

Approximations of the terminal currents

If $\Delta p_C = -p_n$ and $-p_n$ is small the I_E, I_B, and I_C equation can be reduced to:

$$I_E \cong qA\frac{D_p}{L_p}\Delta p_E \operatorname{ctnh}\frac{W_b}{L_p} \cong qA\frac{D_p}{L_p}\Delta p_E\left(\frac{1}{W_b/L_p}+\frac{W_b/L_p}{3}\right) \quad (16)$$

$$I_C \cong qA\frac{D_p}{L_p}\Delta p_E \operatorname{csch}\frac{W_b}{L_p} \cong qA\frac{D_p}{L_p}\Delta p_E\left(\frac{1}{W_b/L_p}-\frac{W_b/L_p}{6}\right) \quad (17)$$

$$I_B \cong qA\frac{D_p}{L_p}\Delta p_E \tanh\frac{W_b}{L_p} \cong qA\frac{D_p}{L_p}\Delta p_E\frac{W_b}{2L_p} = \frac{qAW_b\Delta p_E}{2\tau_p} \quad (18)$$

Approximations of the terminal currents

I_B can be found by charge analysis

If the hole distrabution in the base is linear then the charge due to holes in the area under the triangle.

$$Q_p = \frac{1}{2} qA\Delta p_E W_b \qquad (19)$$

If the stored charge must be replaced every τ_p

$$I_B = \frac{Q_p}{\tau_p} = \frac{qAW_b\Delta p_E}{2\tau_p} \qquad (20)$$

Current Transfer

γ, for an applied forward voltage on the CE junction how much current is due to holes, divided by the total current?

$$\gamma = \left[1 + \frac{W_b n_n \mu_n^p}{L_n^p p_p \mu_p^n} \right]^{-1} \qquad \text{(21a)(note: pnp)}$$

$$\gamma = \left[1 + \frac{W_b p_p \mu_p^n}{L_p^n n_n \mu_n^p} \right]^{-1} \qquad \text{(21b)(note: npn)}$$

B, what is the ratio of injected electrons that make it to the collector?

$$B = \frac{I_C}{I_{Ep}} = \operatorname{sech} \frac{W_b}{L_p} = 1 - \frac{{W_b}^2}{2{L_p}^2} \qquad \text{(22a)(note: pnp)}$$

$$B = \frac{I_C}{I_{En}} = \operatorname{sech} \frac{W_b}{L_n} = 1 - \frac{{W_b}^2}{2{L_n}^2} \qquad \text{(22a)(note: npn)}$$

$$\alpha = B\gamma \qquad (23)$$

$$\beta = \frac{\alpha}{1 - \alpha} \qquad (24)$$

Example of B, γ, α, and β

An abrupt Si BJT has the following properties at 300K:

Emitter	Base	Collector
$Na=10^{18}cm^{-4}$	$Nd=10^{15}cm^{-3}$	$Na=10^{14}cm^{-3}$
$\tau_n=1x10^{-6}s$	$\tau_p=.1x10^{-6}s$	$\tau_n=1x10^{-6}s$
$A=10^{-4}cm^2$	$A=10^{-4}cm^2$	$A=10^{-4}cm^2$
$L_E=10x10^{-4}cm$	$L_B=10x10^{-4}cm$	$L_C=300x10^{-4}cm$

Calculate B, γ, α, and β for the forward and reverse active mode

Generalized biasing

- The equations we developed last time were for DC and forward active, (normal active).
- We assumed normal active biasing and equal areas of the EB junction and BC junction.

Generalized biasing

- What would occur if we reversed biased the EB junction and forward biased the CB junction?
- What would occur if the areas of the two junctions were not the same?

Generalized biasing

- Two equations, Two unknowns

$$I_E = I_{EN} + I_{EI} = I_{ES}\left(e^{qV_{EB}/kT} - 1\right) - \alpha_I I_{CS}\left(e^{qV_{CB}/kT} - 1\right)$$

$$I_C = I_{CN} + I_{CI} = \alpha_N I_{ES}\left(e^{qV_{EB}/kT} - 1\right) - I_{CS}\left(e^{qV_{CB}/kT} - 1\right)$$

Generalized biasing

- Two equations, Two unknowns

$$I_E = \alpha_I I_C + (1 - \alpha_N \alpha_I) I_{ES} \left(e^{qV_{EB}/kT} - 1 \right) \text{ (CS E.)}$$

$$I_C = \alpha_N I_E - (1 - \alpha_N \alpha_I) I_{CS} \left(e^{qV_{CB}/kT} - 1 \right) \text{(CS E.)}$$

$$I_E = \alpha_I I_C + I_{EO} \left(e^{qV_{EB}/kT} - 1 \right)$$

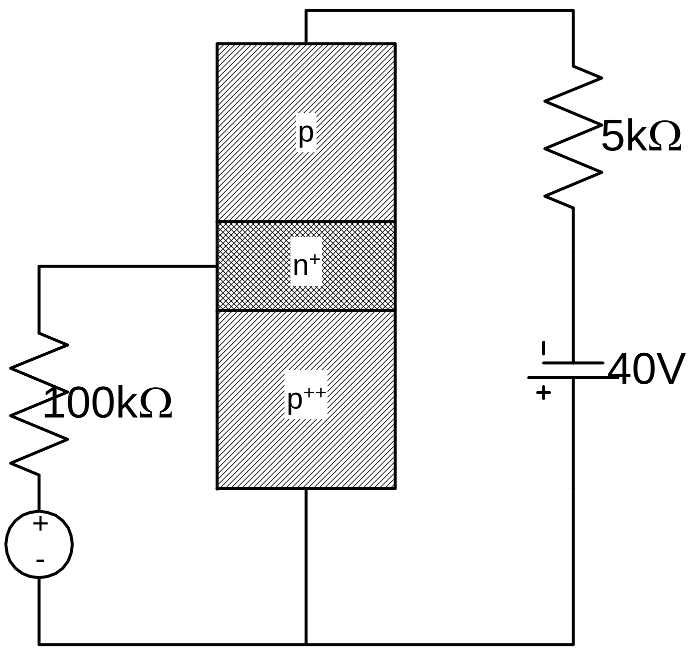
$$I_C = \alpha_N I_E - I_{CO} \left(e^{qV_{CB}/kT} - 1 \right)$$

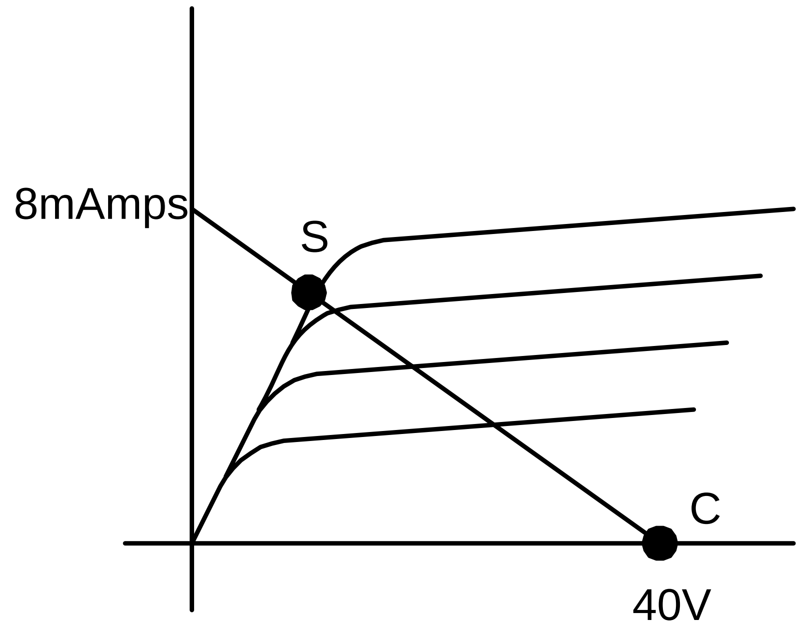
Switching

- We would like two states
  - that can be switched from one to the other and back in as little time as possible time.
  - that can be controlled with as little energy transfer as possible.
  - that does not use energy when not switching.

Switching

- In the BJT these two states are:
  - Cutoff (small i_B, small i_C, large $-V_{CE}$)
  - Saturation (large i_B, large i_C, small $-V_{CE}$)





Switching

- Cutoff
  - The emitter base junction is not forward biased, therefor it is not injecting holes
  - The collector base junction is reversed biased therefor only I_{gen} flows (supplied by the base current). Note if I_{gen} is flowing we are using a small amount of power in this state.

Switching

- Saturation
  - i_B is large so many holes are being injected into the base, so many holes in fact that the base starts to become p-type and the collector base junction stops being reversed biased.
  - Note i_C and i_B are large in this on state thus dissipated a lot of power even when not switching. **This limits the amount of BJTs that can be integrated on a die .**

Switching

- Turn on Transient

$$i_B = \frac{Q_b(t)}{\tau_p} + \frac{dQ_b(t)}{dt}$$

For a step response:

$$\frac{I_B}{s} = \frac{Q_b(s)}{\tau_p} + sQ_b(s)$$

$$Q_b(t) = I_B \tau_p \left(1 - e^{-t/\tau_p}\right)$$

$$t_s (\text{when } Q_b(t)/t_s = I_C) = \tau_p \ln\left(\frac{1}{1 - I_C/\beta I_B}\right) (\text{CS E.})$$

Switching

- Turn off Transient

$$t_{sd} = \tau_p \ln\left(\frac{\beta I_B}{I_C}\right) \text{(CS E.)}$$

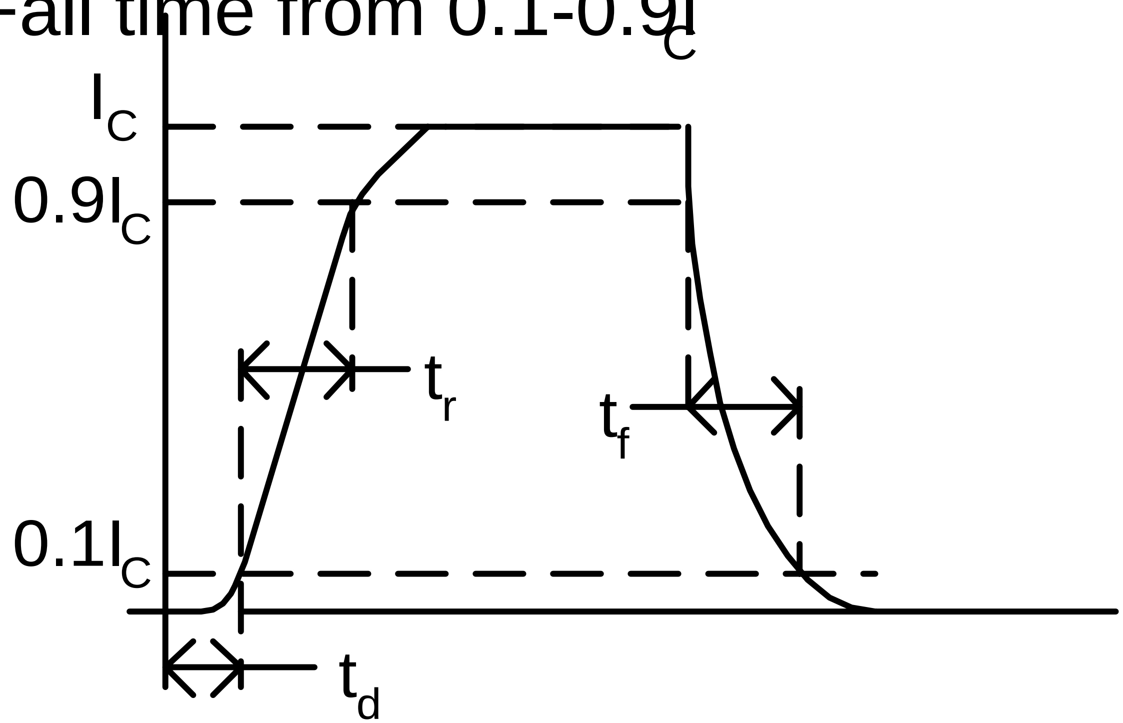
- Note: oversaturation decreases t_s and increases $t_{sd.}$
- One can drive the device into cutoff by applying a negative current which forces the stored charge out, rather than letting decay.

Switching

t_d — Delay time while junction capacitance is charging

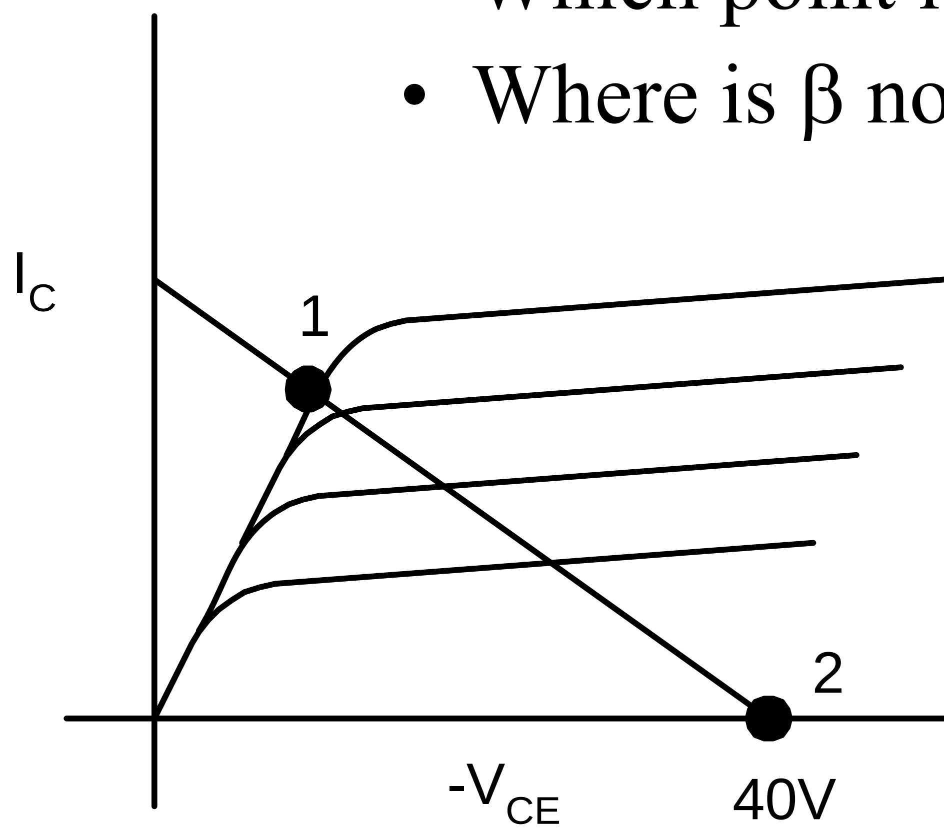
t_r — Rise time from 0.1-0.9I_C

t_f — Fall time from 0.1-0.9I_C



Quiz #6

- Which point is in cutoff?
- Which point is in saturation?
- Where is β not equal I_c/I_b?



BJT: Second order effects

- Drift in the base region
- Base narrowing
- Avalanche breakdown
- Injection level: Thermal effects
- Base Resistance and emitter crowding

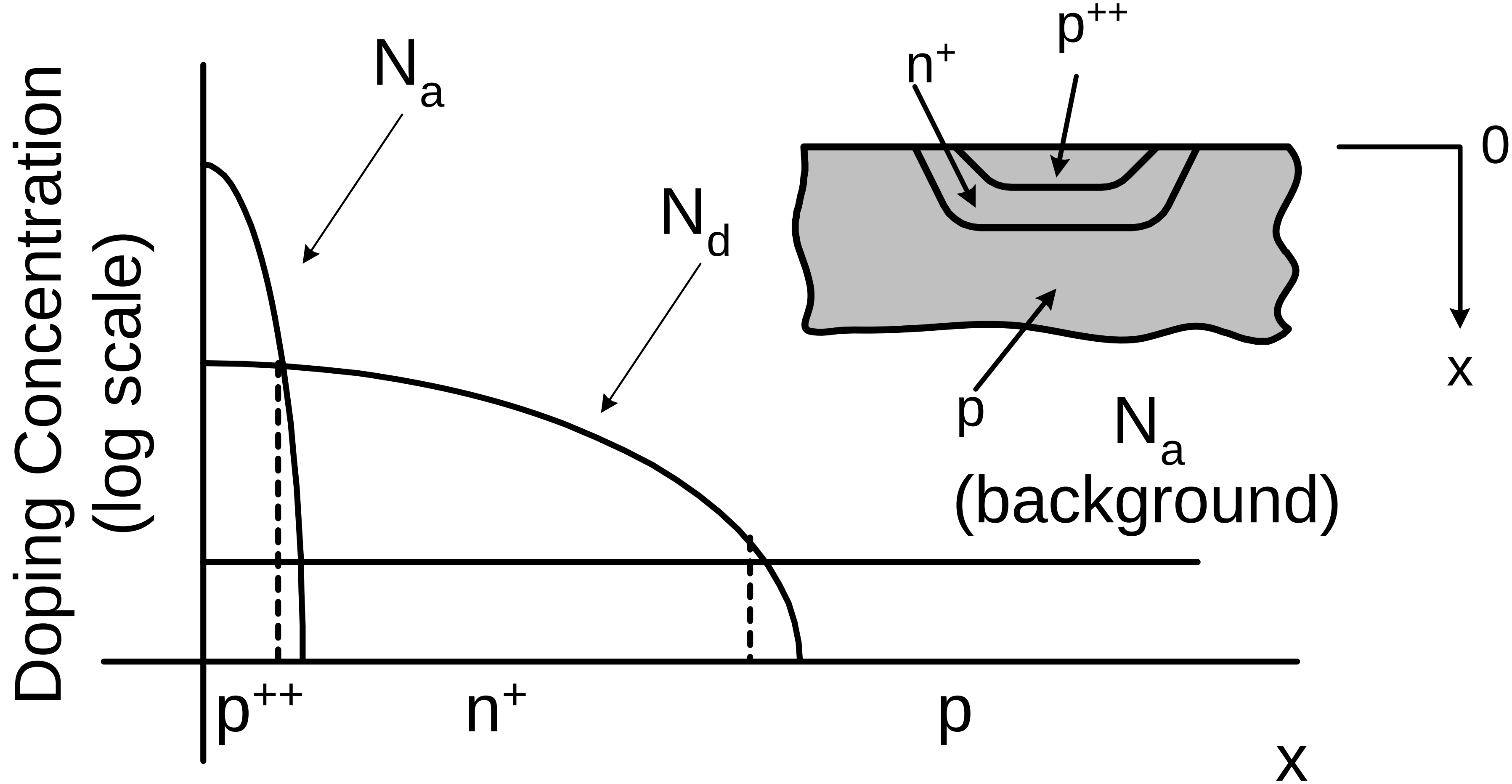
Drift in the base region

- In a double diffused BJT, there exists a region of changing doping concentration
  - This causes an electric field which speeds up the holes across the base.
  - This caused the base transit time to be halved for the case of a exponential doping profile.

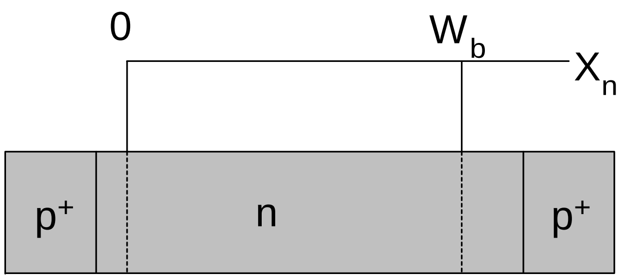
$$B = 1 - \frac{W_b^{\ 2}}{2L_p^{\ 2}} \text{(Uniform doping in base)}$$

$$B = 1 - \frac{W_b^{\ 2}}{4L_p^{\ 2}} \text{(Non - Uniform doping in base)}$$

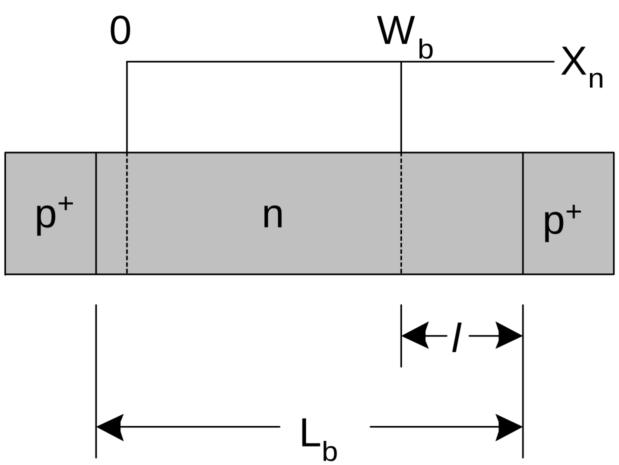
Drift in the base region



Base width narrowing (Early Effect)



$$V_{CB} = 0$$

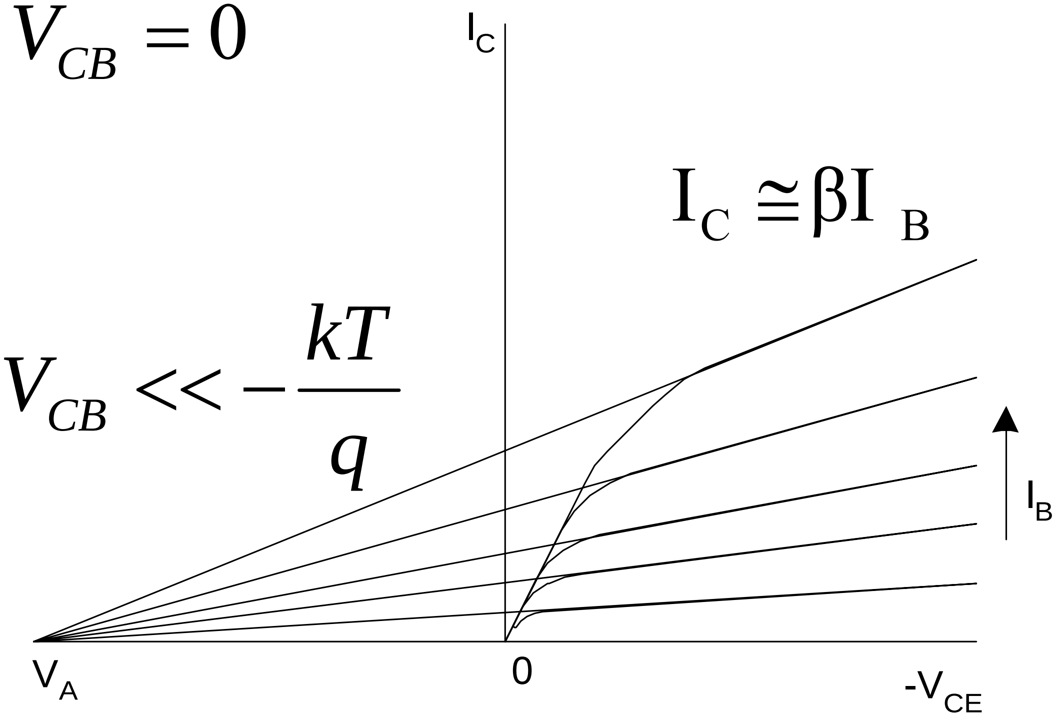


$$V_{CB} << -\frac{kT}{q}$$

$$W_b = L_b - l$$

$$l \alpha \sqrt{V_{BC}}$$

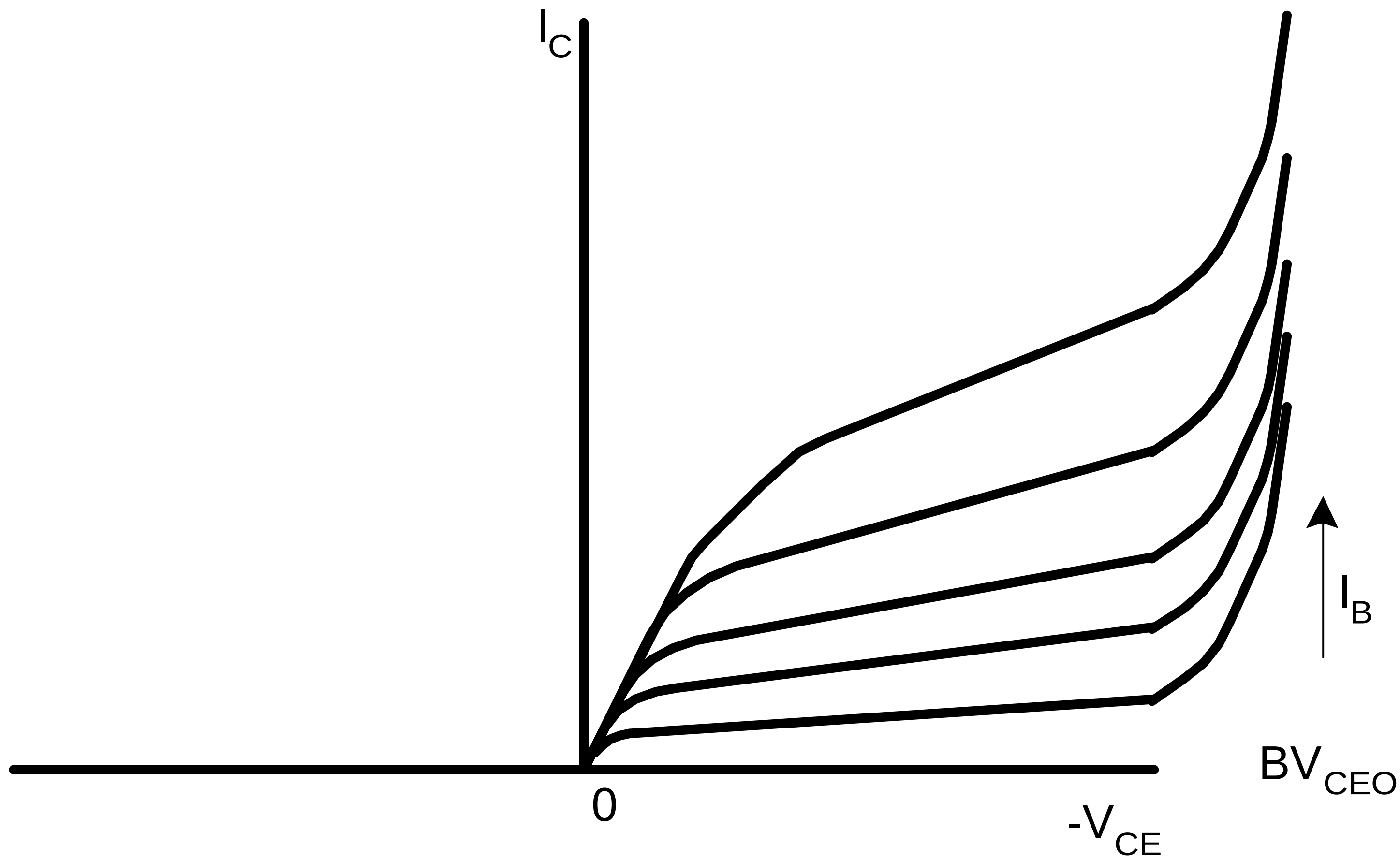
$$I_C \cong \beta I_B$$



Avalanche breakdown

- The collector base junction is under reverse bias. At extreme reverse bias this junction can breakdown due to avalanche. In CE biasing this injects more electrons into the base which causes more holes to be injected to the emitter. If too much power is being dissipated by the CB junction it will burn out.

Avalanche breakdown



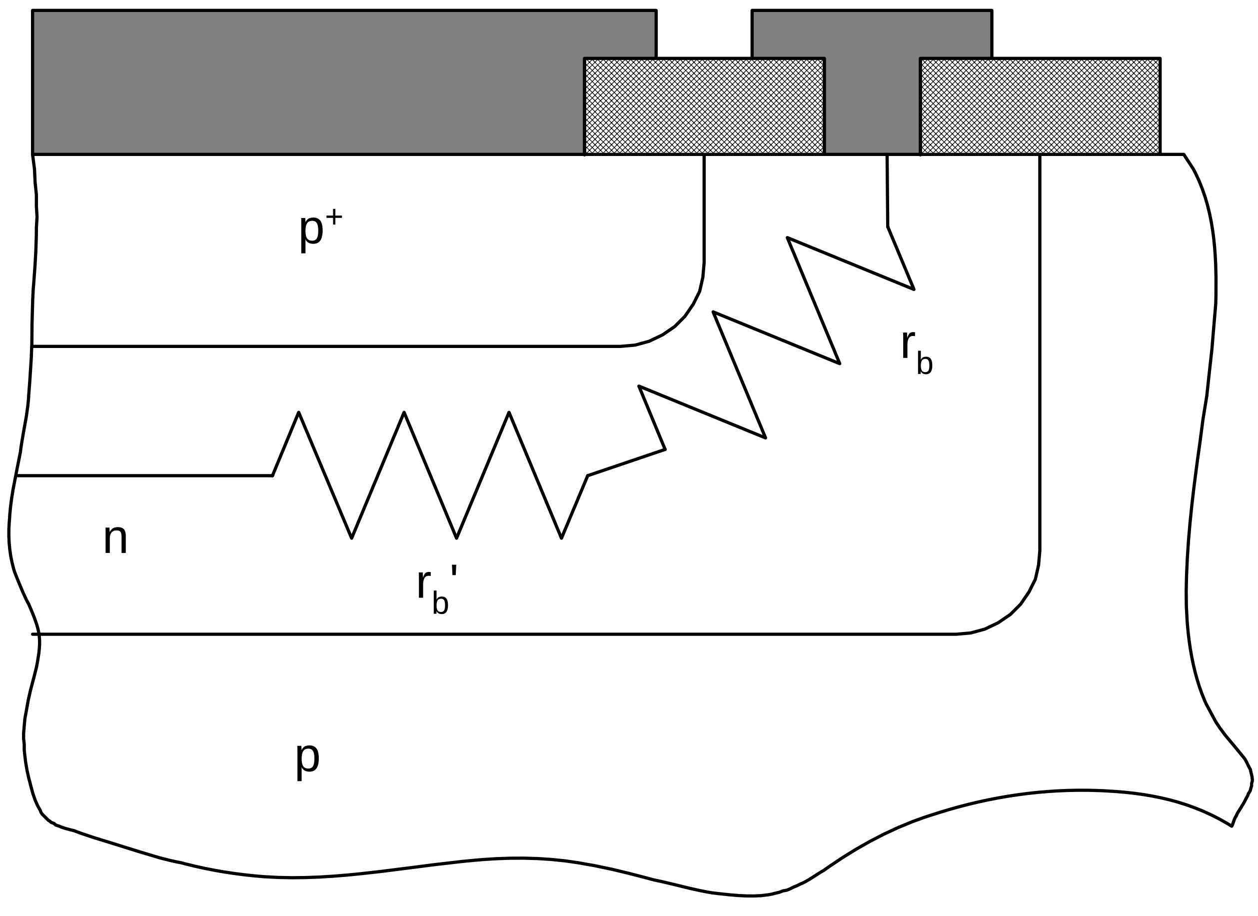
Injection level: Thermal effects

- Minority carrier lifetime increases directly with temperature.
- Mobility decreases with temperature ($T^{-3/2}$)
- This results in the diffusion length increasing and thus the gain increasing
- This can cause more current to flow which increases the temperature which increases the lifetime, which increases the gain etc…
- This is called thermal runaway. You lose control of the collector current and the device burns out.

Base Resistance and emitter crowding

- There is an incremental voltage drop along the emitter base junction.
  - This causes the emitter base junction to be unevenly biased
  - The outside edges of the junction are more forward biased than the center of the junction
  - This causes most of the carriers to be injected at the edges
  - Thus you want a long perimeter to area ratio or many stripes for high frequency operation because this extra resistance slows down the charging time of the EB and CB junctions

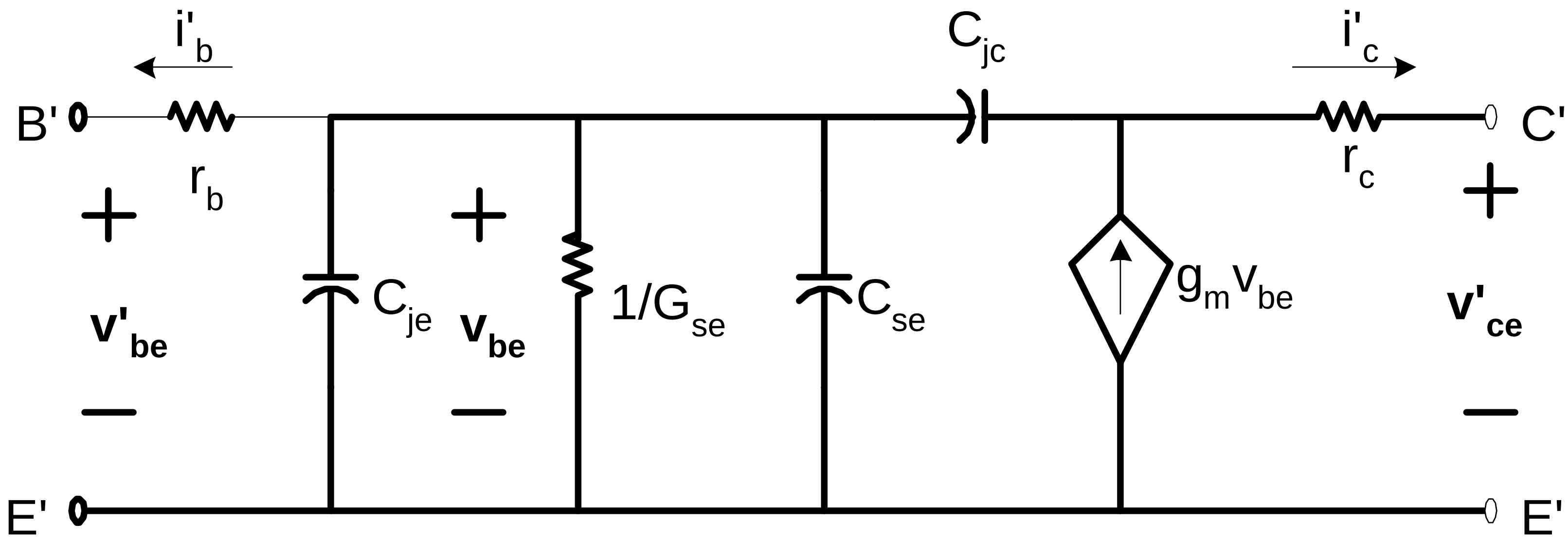
Base Resistance and emitter crowding



Frequency limit of transistors

- Capacitance and charging times
- Transit time effects
- High frequency transistors

Capacitance and charging times



$$f_T = \frac{1}{2\pi\tau_d}$$

$$\tau_d = \tau_E + \tau_{WC} + \tau_t$$

Capacitance and charging times

$$\tau_d = \tau_E + \tau_{WC} + \tau_t$$

$$\tau_E = r_e(C_e + C_c + C_p) = \frac{kT}{qI_E}(C_e + C_c + C_p)$$

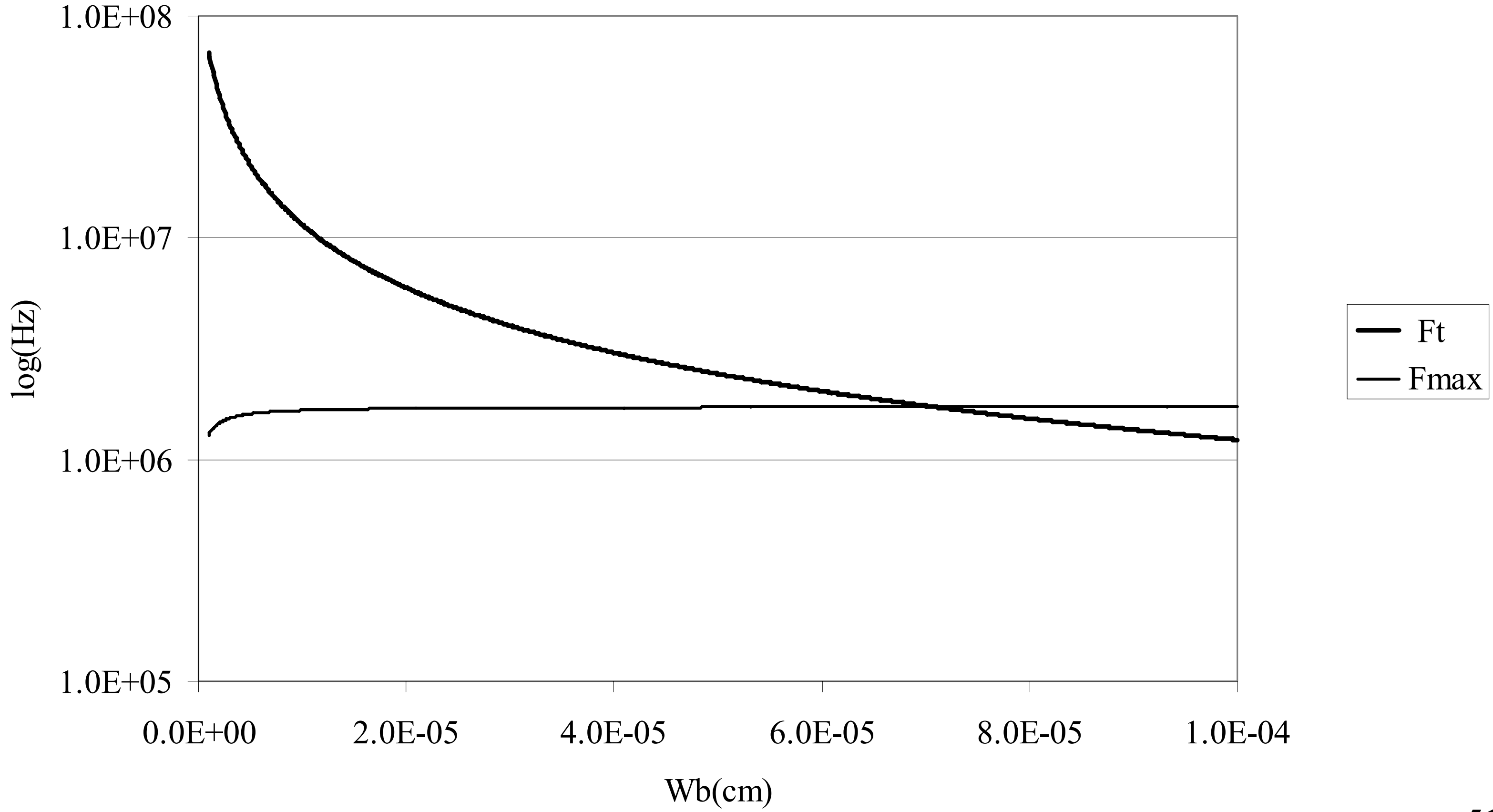
$$\tau_{WC} = \frac{W_{CB}}{2\langle v_s \rangle}$$ Here, W_{CB} is the length of the CB depletion width.

$$\tau_t = \frac{W_B{}^2}{2D}$$

Capacitance and charging times

$$f_{\max} = \left(\frac{f_T}{8\pi R_B C_c} \right)^{\frac{1}{2}}$$

$$f_T = \frac{1}{2\pi\tau_d}$$



High-frequency transistors

- Bottom line:
  - Every region of the device has a resistance associated with it which leads to a RC time delay.
  - At high frequencies even wires and leads have inductances and capacitances.