Session 11: Solid State Physics

Bipolar Junction Transistor

Outline

- A
  - B
  - C
  - D
  - E
- F
  - G
- H
- I
- J

Introduction

In recent decades, the higher layout density and low-power advantage of CMOS technology has eroded the BJT's dominance in integrated-circuit products.

(higher circuit density → better system performance)

BJTs are still preferred in some integrated circuit applications because of their high speed and superior intrinsic gain.

✓ faster circuit speed

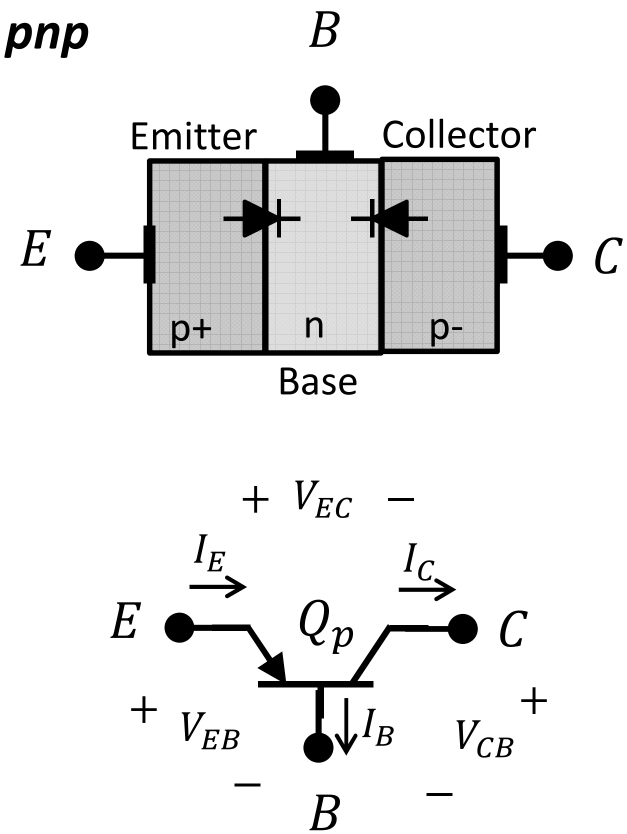
✗ larger power dissipation

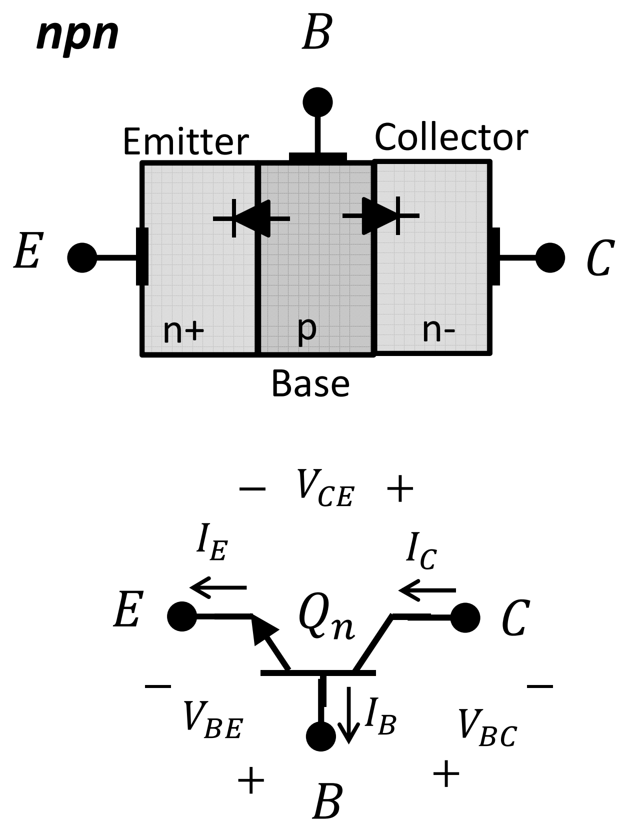
→ limits device density (~10^4 transistors/chip)

Si (npn, pnp) → SiGe HBT → GaAs (InSb) HBT

BJT Types and Definitions

The BJT is a 3-terminal device, with two types: PNP and NPN





Asymmetric!

Review: Current Flow in a Reverse-Biased pn Junction

1. I □□□□□□□□
2. □□□□□□□□□□
3. □□□□□□□
4. □□□□
5. □□□□□

- In a reverse-biased pn junction, there is negligible diffusion of majority carriers across the junction. **The reverse saturation current is due to drift of minority carriers across the junction and depends on the rate of minority-carrier generation close to the junction (within ~one diffusion length of the depletion region).**

  ⇒ We can increase this reverse current by increasing the rate of minority-carrier generation, *e.g.* by

  - optical excitation of carriers (*e.g.* photodiode)
  - electrical injection of minority carriers into the vicinity of the junction…

PNP BJT Operation (Qualitative)

1. I
2.
3.
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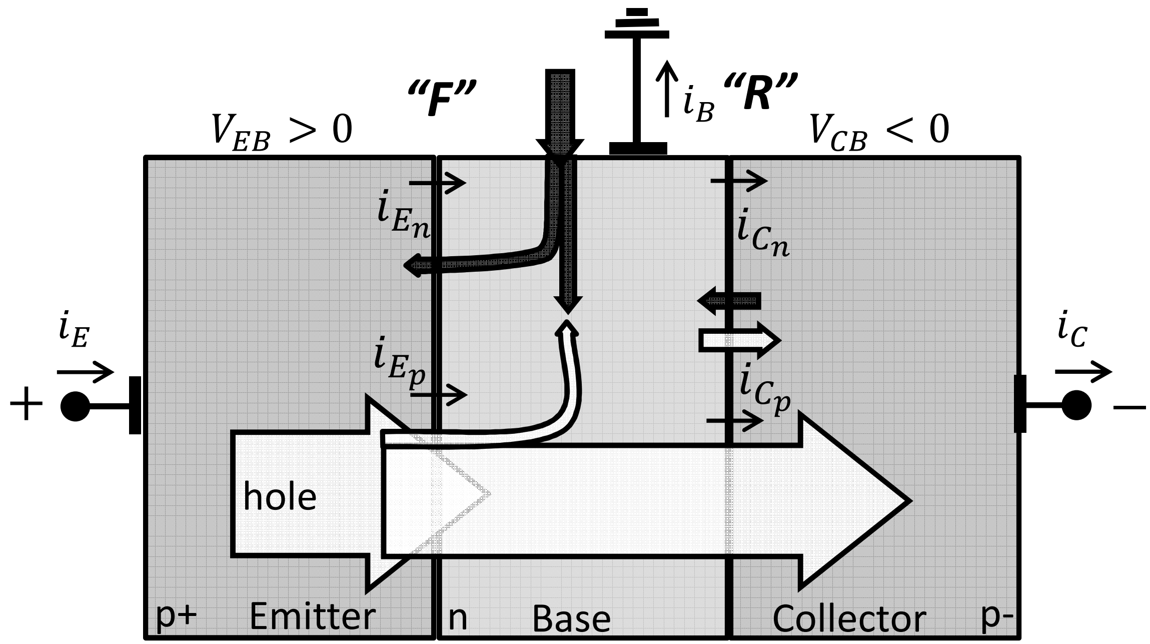
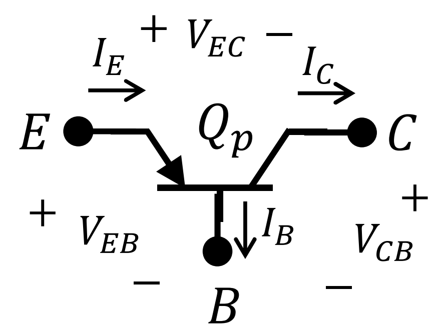
5.

A forward-biased "emitter" pn junction is used to inject minority carriers into the vicinity of a reverse-biased "collector" pn junction.

→ **The collector current is controlled via the base-emitter junction**





$$\beta \equiv \frac{i_C}{i_B}$$

To achieve high current gain:

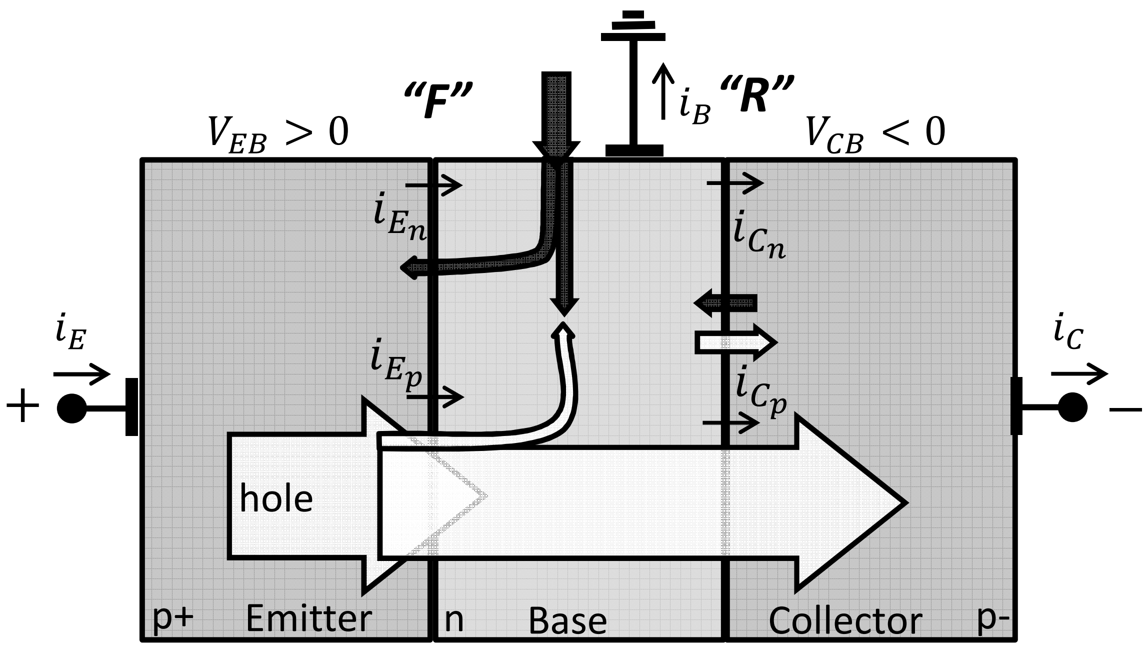
- The injected minority carriers should not recombine within the quasi-neutral base region
- The emitter junction current is comprised almost entirely of carriers injected into the base (rather than carriers injected into the emitter)

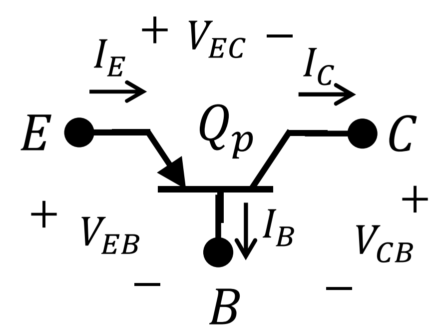
Base Current Components (Active Mode of Operation)

The base current consists of majority carriers supplied for

1. Recombination of injected minority carriers in the base
2. Injection of carriers into the emitter
3. Reverse saturation current in collector junction (Reduces $|I_B|$)

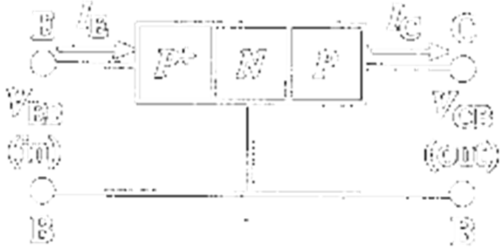
4. Recombination in the base-emitter depletion region



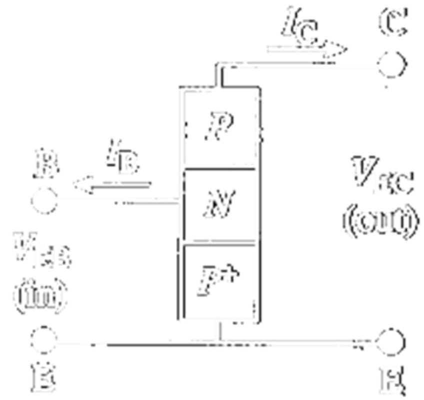


$$\beta \equiv \frac{i_C}{i_B}$$

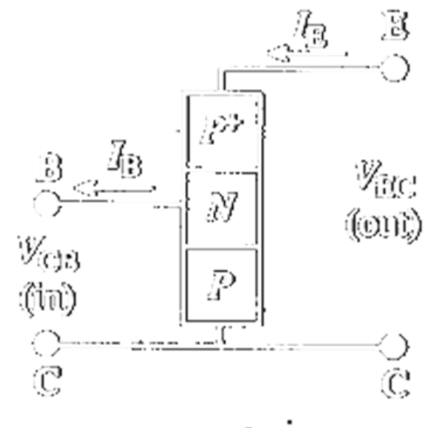
BJT Circuit Configurations



CB: Common Base

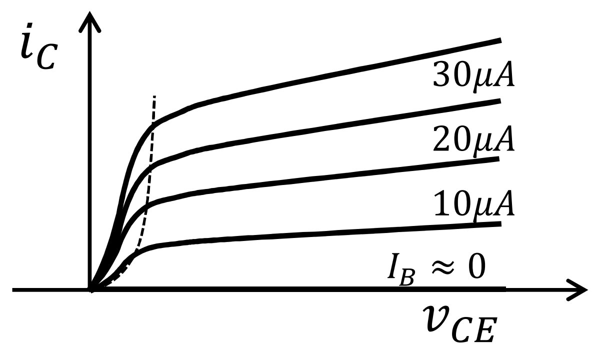


CE: Common Emitter



CC: Common Collector

Output Characteristics for Common-Emitter Configuration



BJT Modes of Operation

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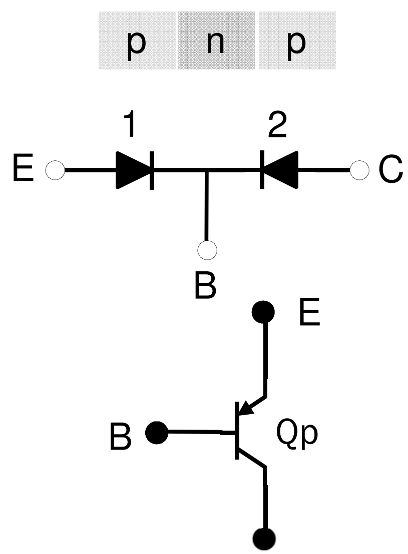

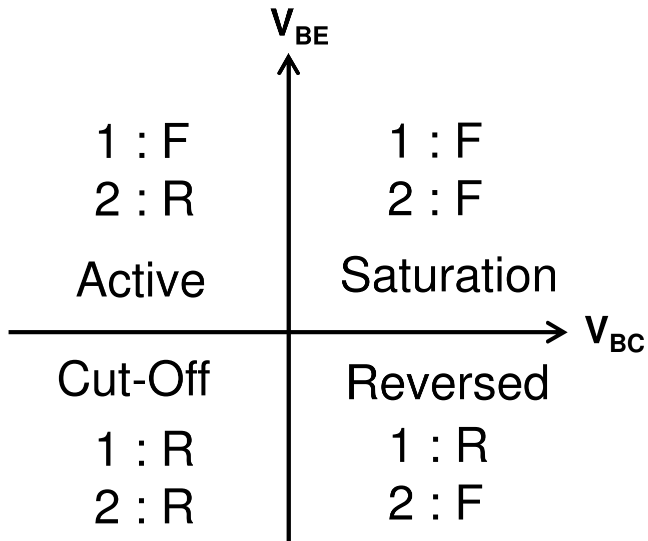

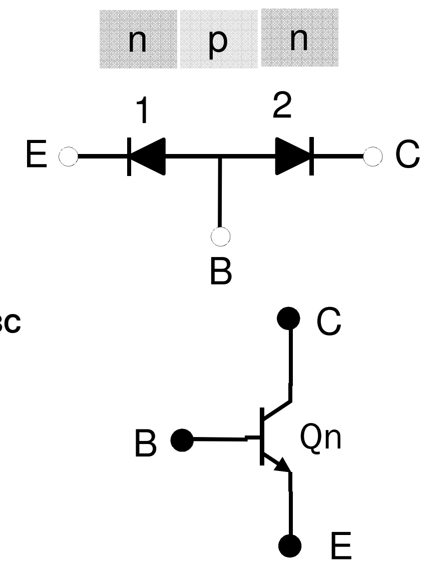

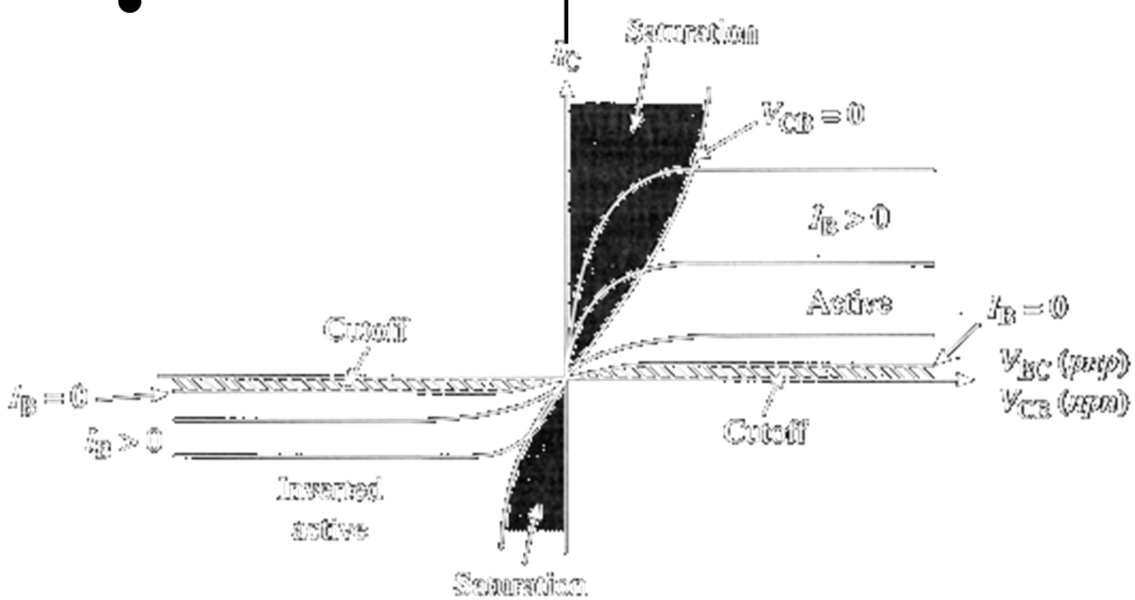

BJT Electrostatics

1. I
2.
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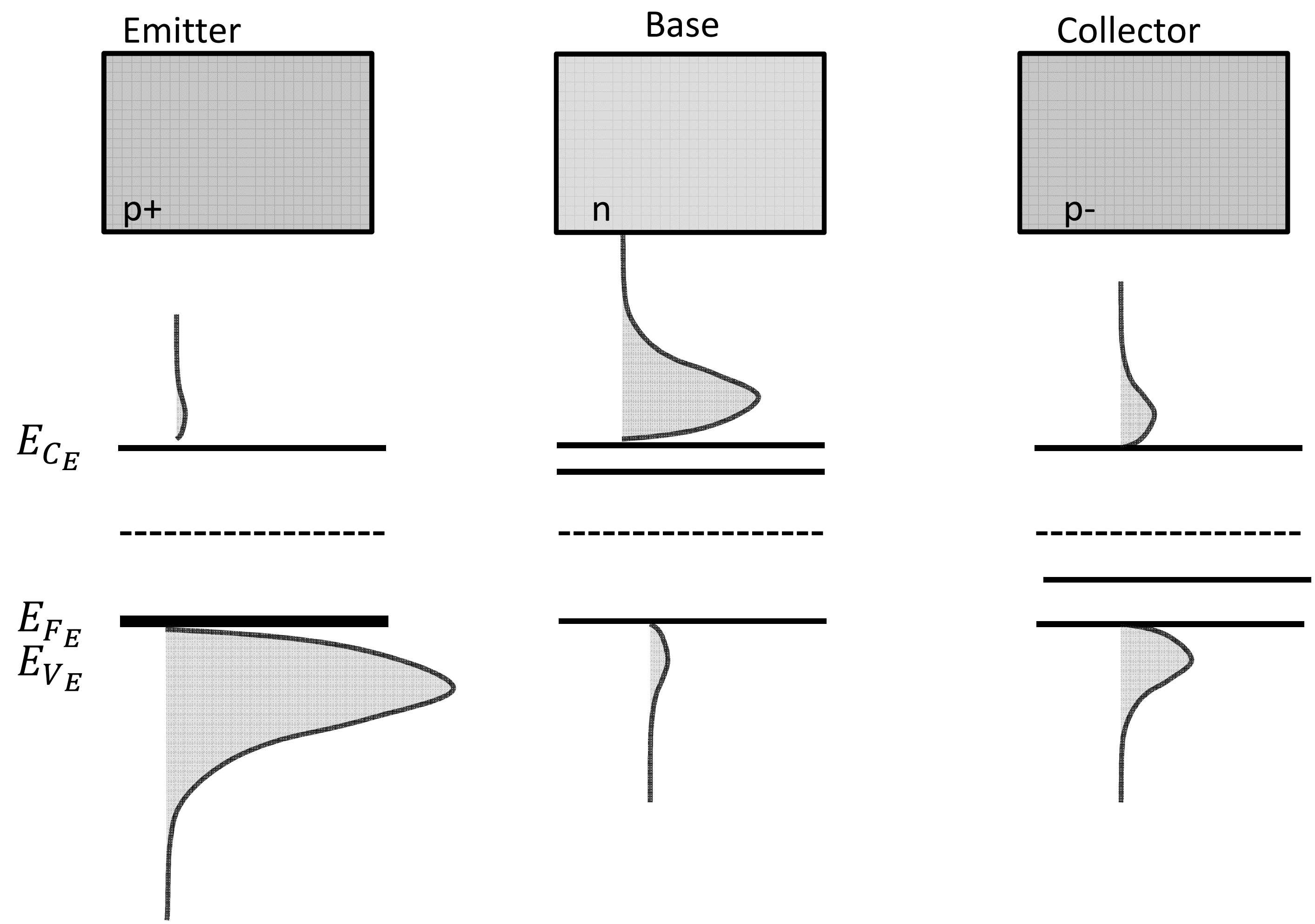
4.
5.

pnp



Under normal operating conditions, the BJT may be viewed electrostatically as two independent pn junctions

BJT Electrostatics

1. I
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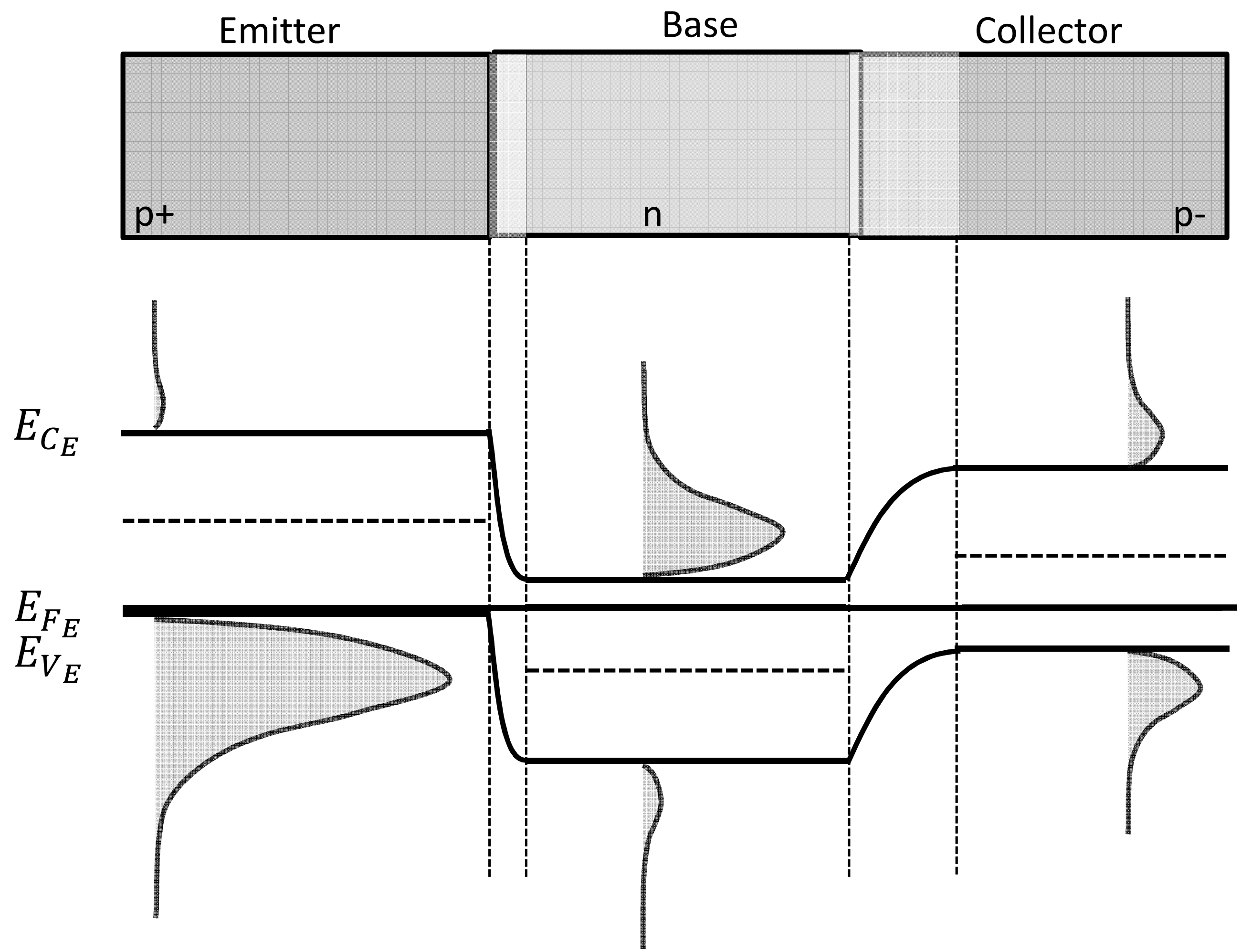
pnp



Under normal operating conditions, the BJT may be viewed electrostatically as two independent pn junctions

BJT Electrostatics

1. I
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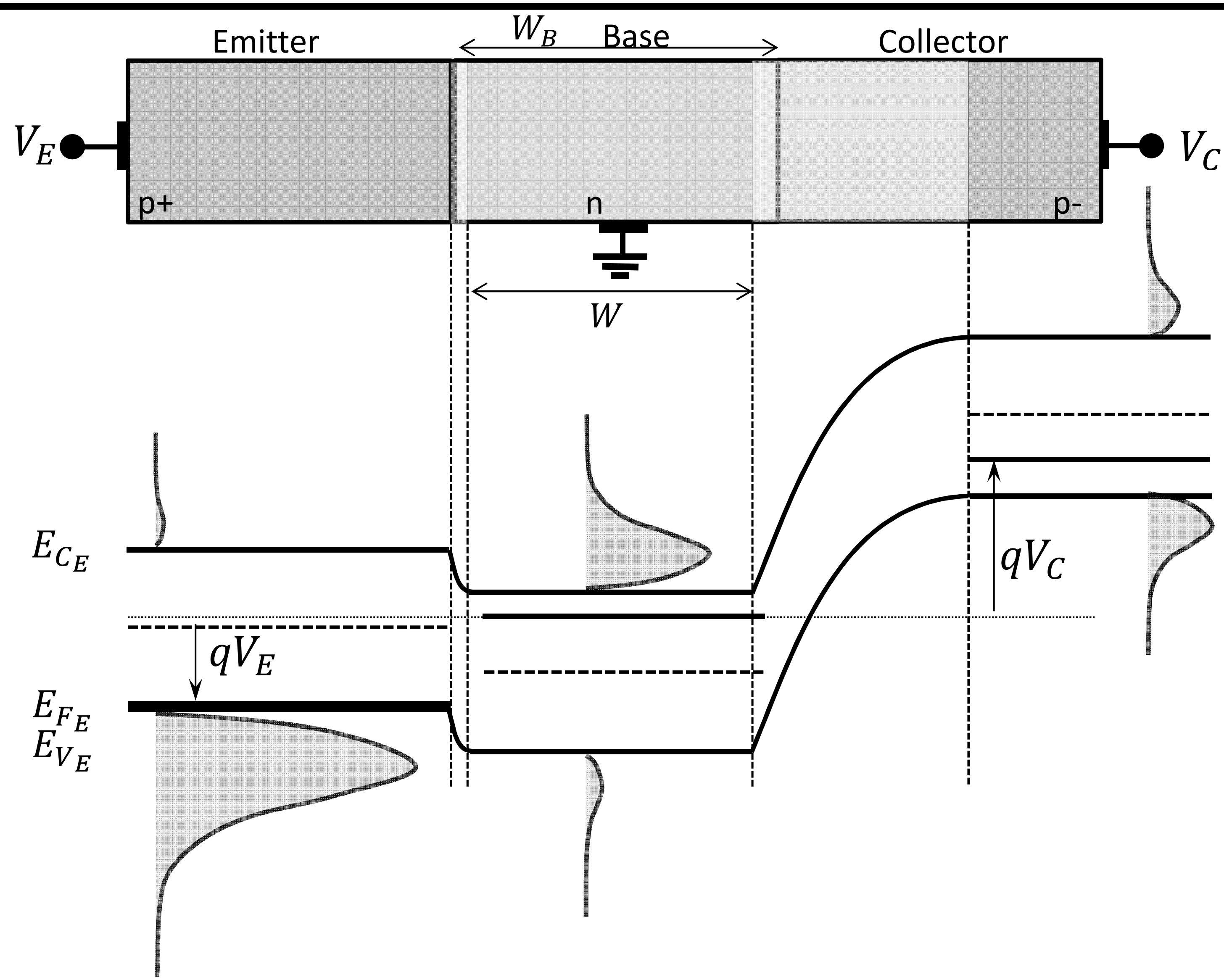
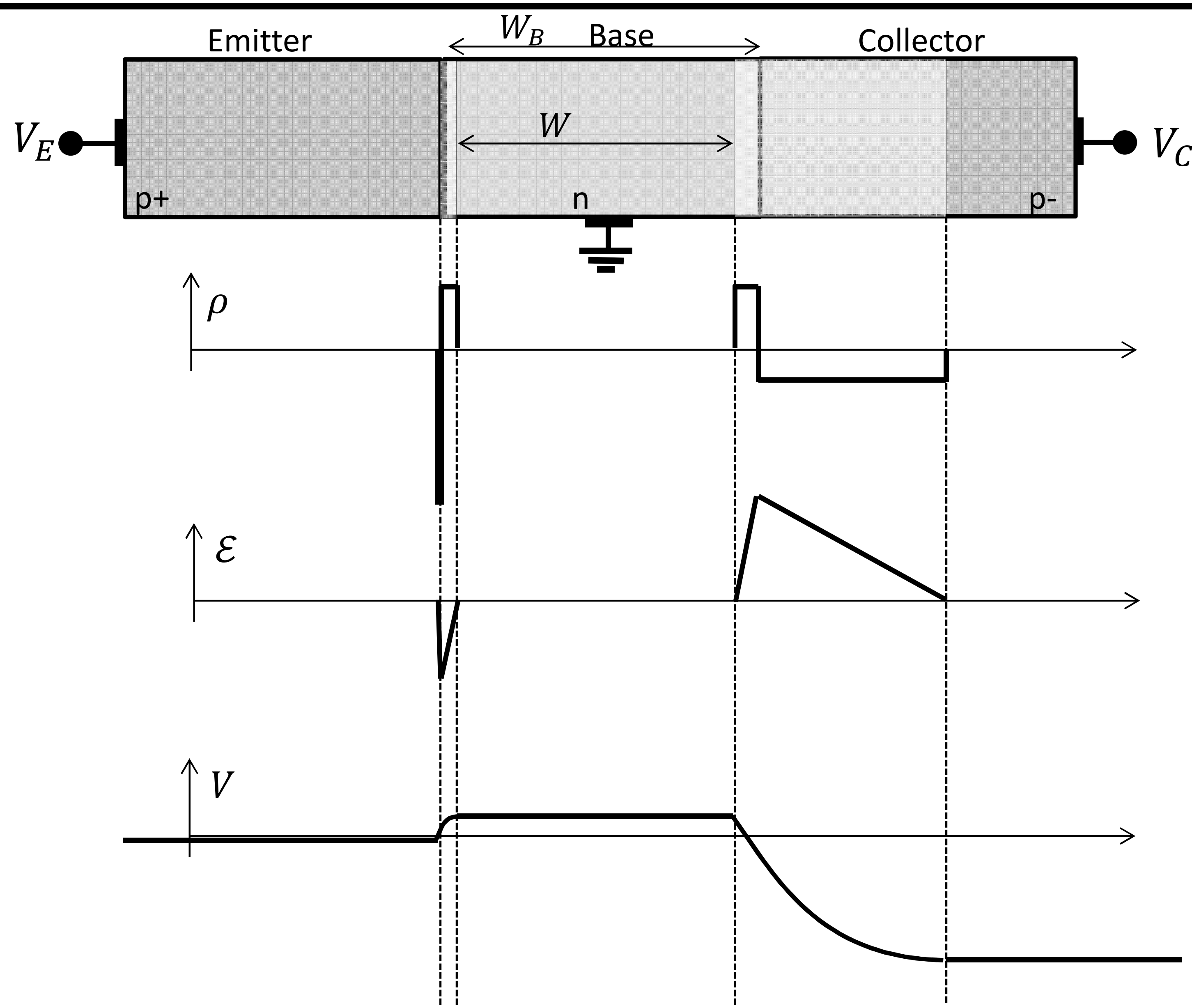
pnp



BJT Electrostatics

pnp



BJT Performance Parameters (PNP)

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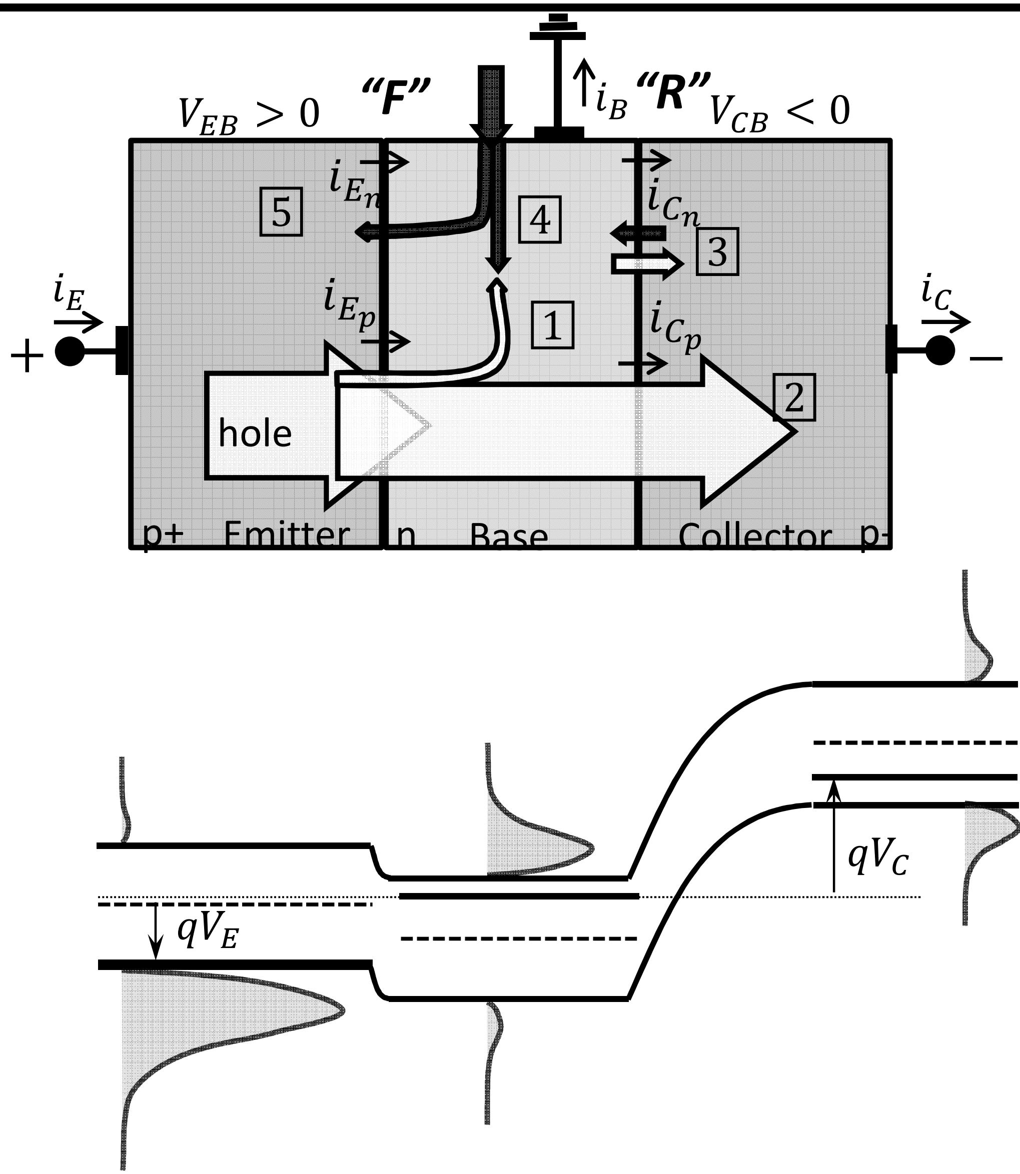


Emitter Efficiency:

$$\gamma \equiv \frac{i_{E_p}}{i_{E_p} + i_{E_n}}$$

$\boxed{5}$ ↘ relative to $\boxed{1+2}$

Base Transport Factor:

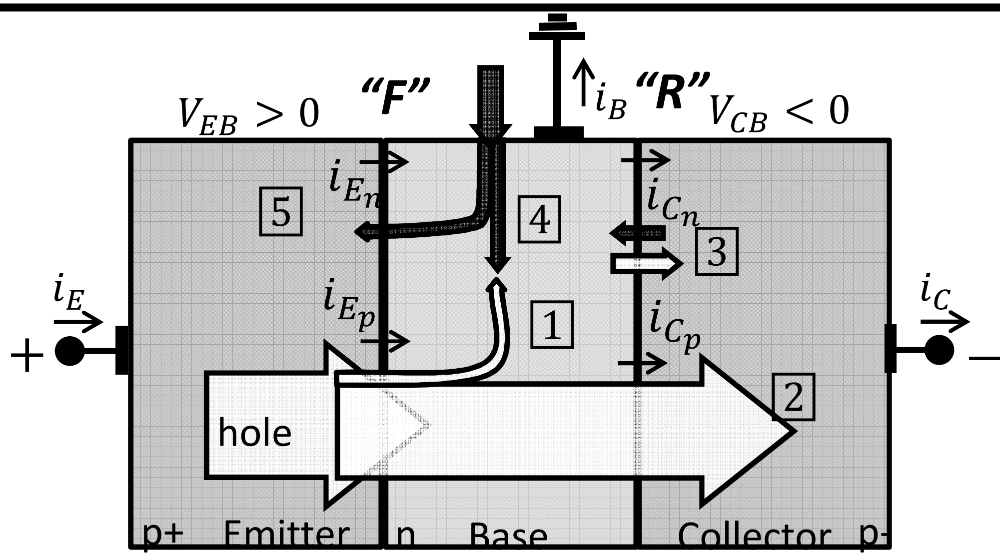
$$\alpha_T \equiv \frac{i_{C_p}}{i_{E_p}}$$

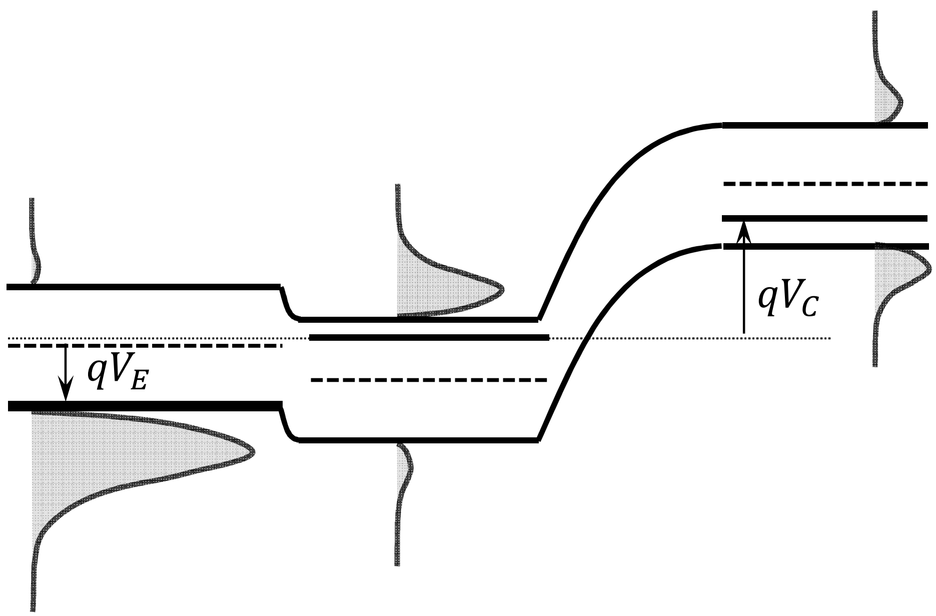
$\boxed{1}$ ↘ relative to $\boxed{2}$

Common-Base d.c. Current Gain:

$$\alpha_{dc} \equiv \gamma \, \alpha_T$$

Collector Current (PNP)





The collector current is comprised of:

2 Holes injected from emitter, which do not recombine in the base

3 Reverse saturation current of collector junction

$$I_C = \alpha_{dc} I_E + I_{CBO}$$

where I_{CBO} is the collector current which flows when $I_E = 0$

$$I_C = \alpha_{dc}(I_C + I_B) + I_{CBO}$$

$$I_C = \frac{\alpha_{dc}}{1-\alpha_{dc}} I_B + \frac{I_{CBO}}{1-\alpha_{dc}}$$

$$= \beta I_B + I_{CEO}$$

Notation (PNP BJT) , Assumptions

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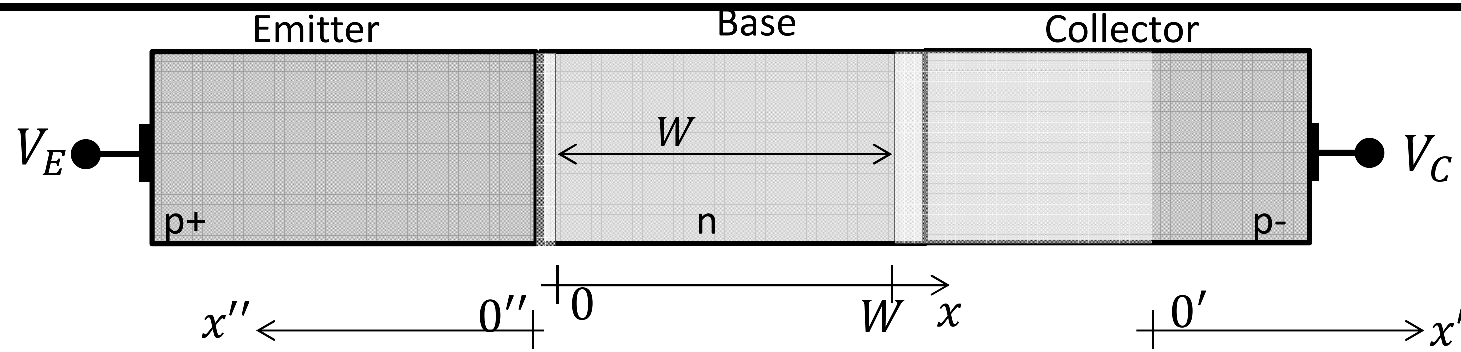

Notations:

$$N_{AE} = N_E \gg N_{DB} = N_B > N_{AC} = N_C$$

$$D_{nE} = D_E \qquad D_{pB} = D_B \qquad D_{nC} = D_C$$

$$L_{nE} = L_E \qquad L_{pB} = L_B \qquad L_{nC} = L_C$$

$$\tau_{nE} = \tau_E \qquad \tau_{pB} = \tau_B \qquad \tau_{nC} = \tau_C$$

$$n_{p0_E} = n_{E0} \qquad p_{n0_B} = p_{B0} \qquad n_{p0_C} = n_{C0}$$

Assumptions:

1) 1-D structure
2) $W \ll L_P$ and is constant
3) Like diode gen-rec in depletion region is negligible
4) Uniform doping + step junction
5) Low-level injection everywhere!

“Game Plan” for I-V Derivation

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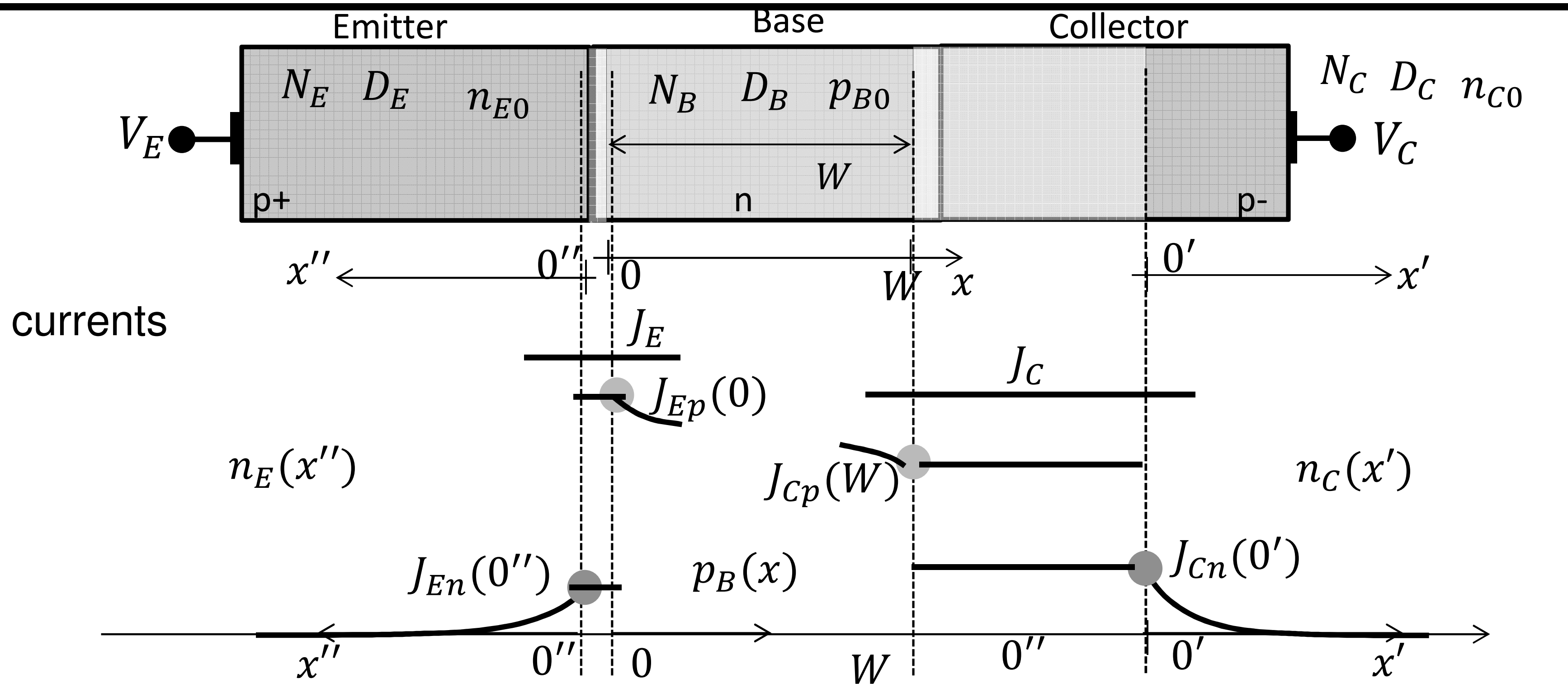

$I_{Ep}(0)$ $\quad$ $I_{En}(0'')$ $\qquad\qquad$ $I_{Cp}(W)$ $\quad$ $I_{Cn}(0')$

$$I_E = -qAD_B \left.\frac{d\Delta p_B}{dx}\right|_{x=0} - qAD_E \left.\frac{d\Delta n_E}{dx''}\right|_{x''=0''} \qquad I_C = -qAD_B \left.\frac{d\Delta p_B}{dx}\right|_{x=W} + qAD_E \left.\frac{d\Delta n_E}{dx''}\right|_{x'=0'}$$

minority-carrier diffusion equation (different set of B.C. for each region)

minority-carrier diffusion currents at depletion region edges

Minority Carriers

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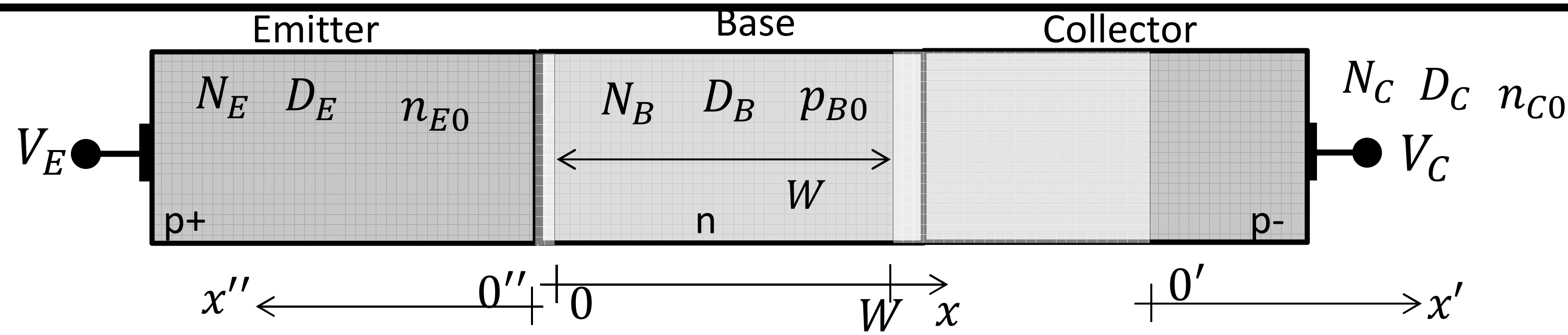

Carriers: Steady-State solution is:

$$\frac{d^2\Delta n_p}{dx^2} = \frac{\Delta n_p}{D_n \tau_n} \qquad \left(L_n = \sqrt{D_n \tau_n}\right)$$

$$\Delta n_E(x'') = E_1 e^{x''/L_E} + E_2 e^{-x''/L_E}$$

$$\Delta p_B(x) = B_1 e^{x/L_B} + B_2 e^{-x/L_B}$$

$$\Delta n_C(x'') = C_1 e^{x'/L_C} + C_2 e^{-x'/L_C}$$

$$\Delta n_E(0'') = n_{E0}\left(e^{qV_{EB}/kT} - 1\right)$$

$$\Delta p_B(0) = p_{B0}\left(e^{qV_{EB}/kT} - 1\right)$$

$$\Delta p_B(W) = p_{B0}\left(e^{qV_{CB}/kT} - 1\right)$$

$$\Delta n_C(W) = n_{C0}\left(e^{qV_{CB}/kT} - 1\right)$$

Minority Carriers – Active

1. I
2.
3.
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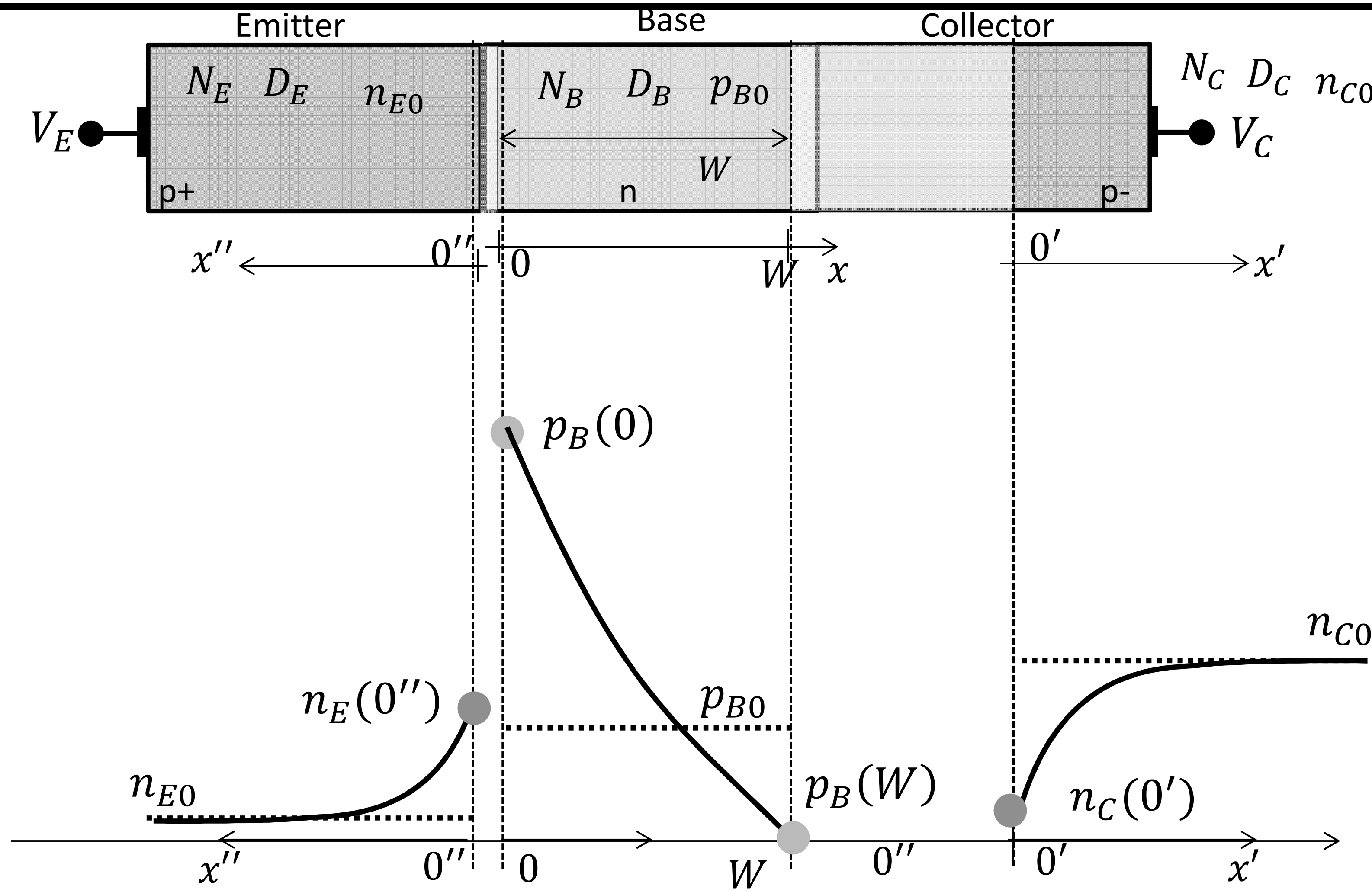
5.



Active: forward reverse

Minority Carriers – Saturation

1. I
2.
3.
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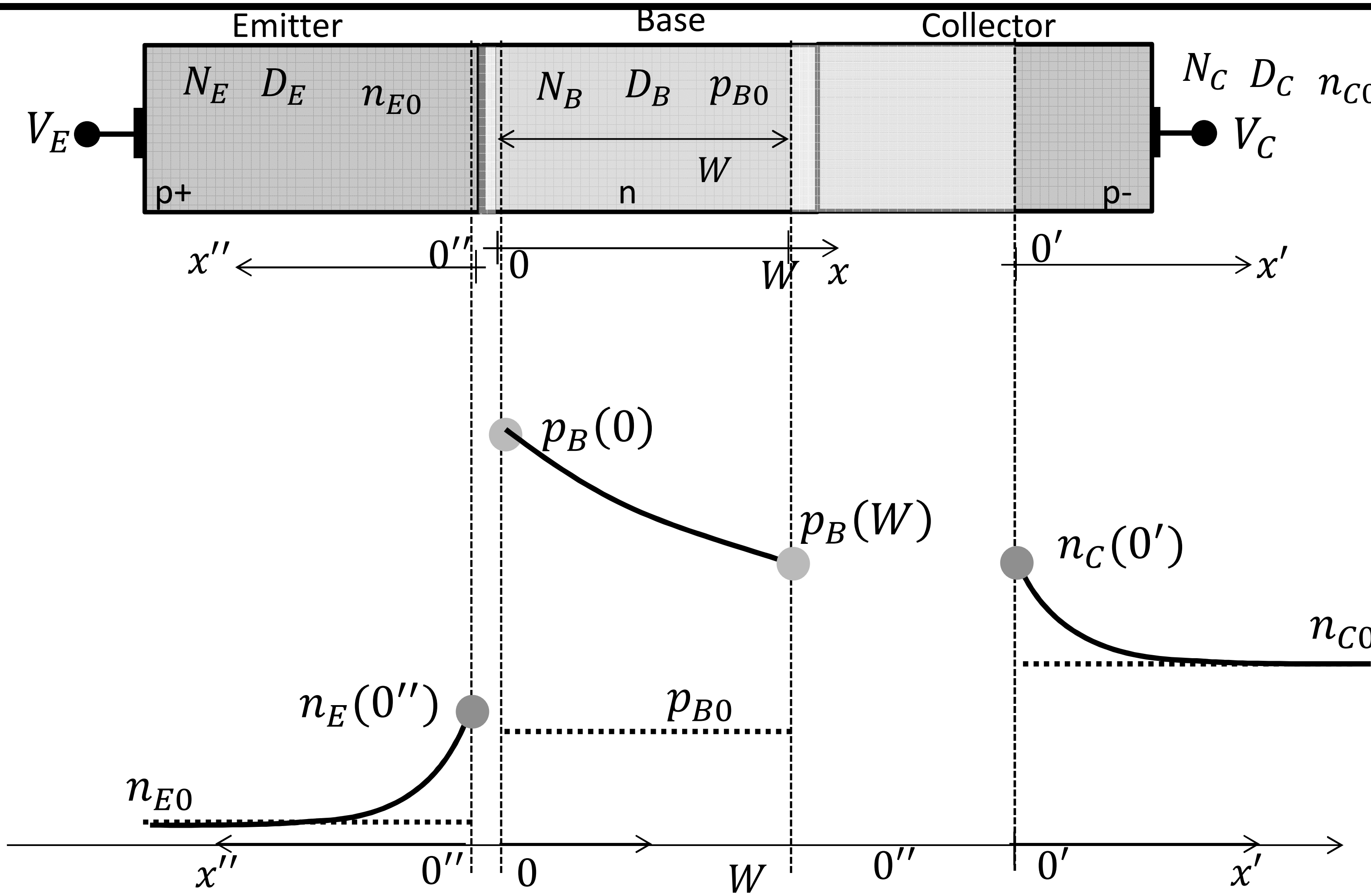

Saturation: forward forward

Minority Carriers – Cut-off

1. I
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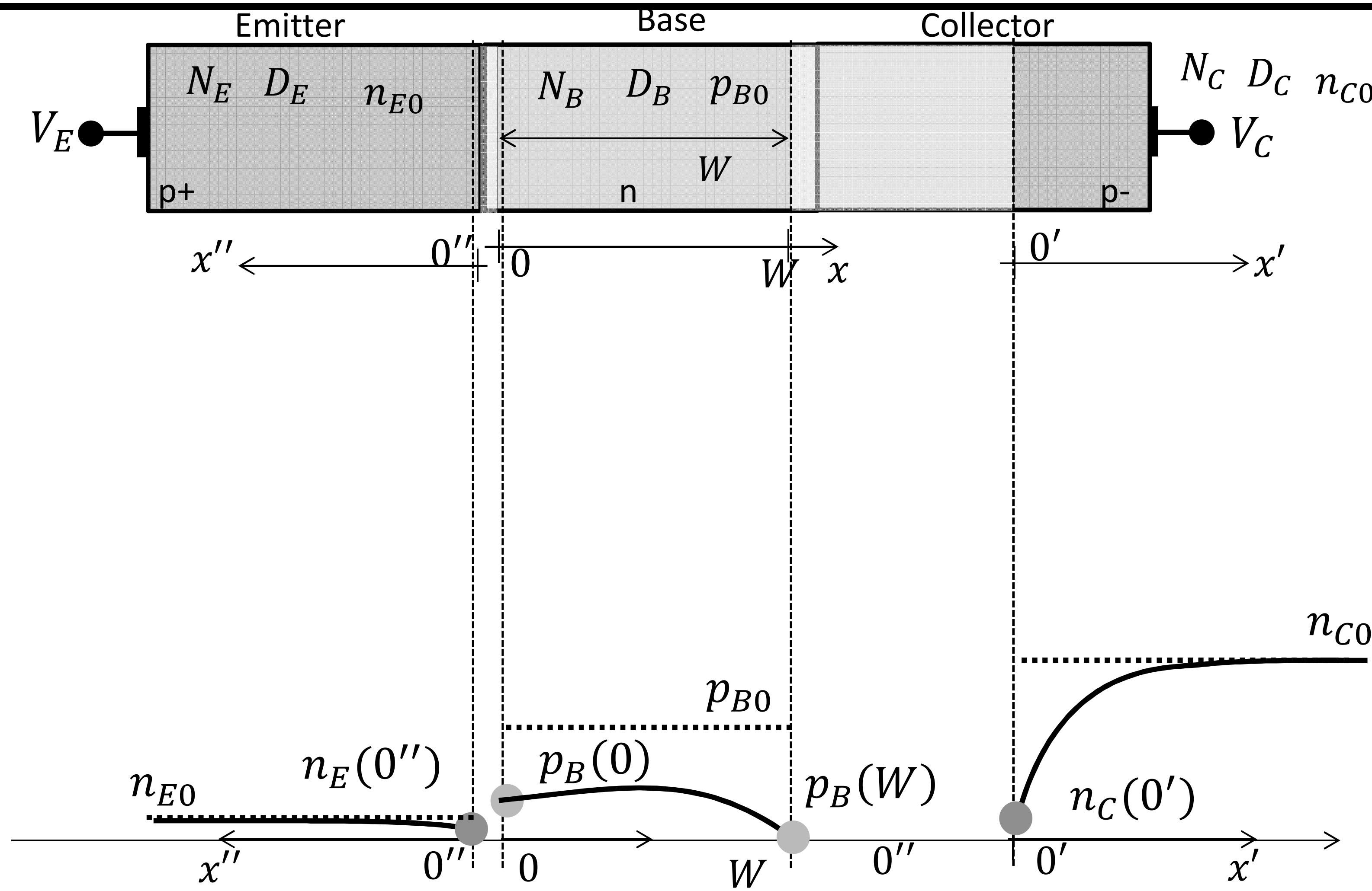

Cut-off: reverse reverse

Ideal BJT!

1. I
2.
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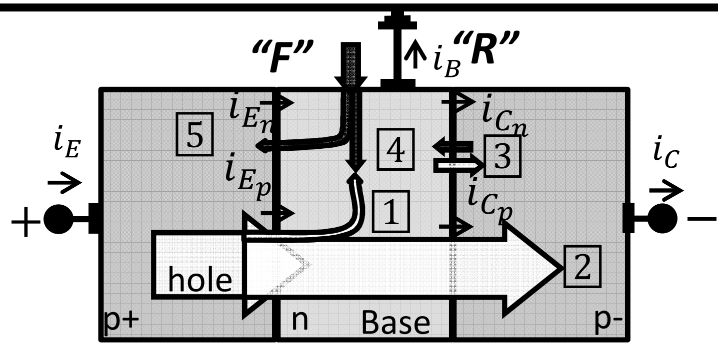
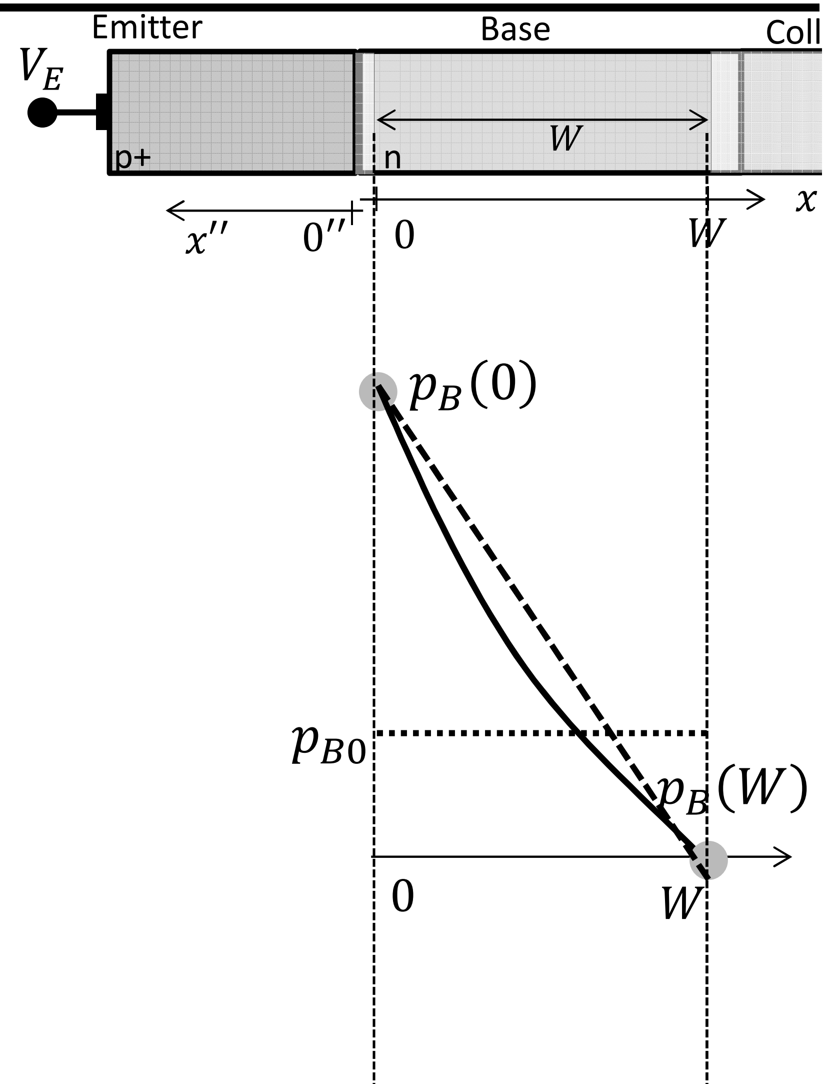




$W \ll L_B$ ([1] = 0)

$$\Delta p_B(x) = B_1 e^{x/L_B} + B_2 e^{-x/L_B} \cong B_1' + B_2' x$$

$$\Delta p_B(x) = \Delta p_B(0) - \left[\frac{\Delta p_B(0) - \Delta p_B(W)}{W}\right] x$$

where
$$\begin{cases} \Delta p_B(W) = p_{B0}(e^{qV_{CB}/kT} - 1) \\ \Delta p_B(0) = p_{B0}(e^{qV_{EB}/kT} - 1) \end{cases}$$

Current Equations - IE

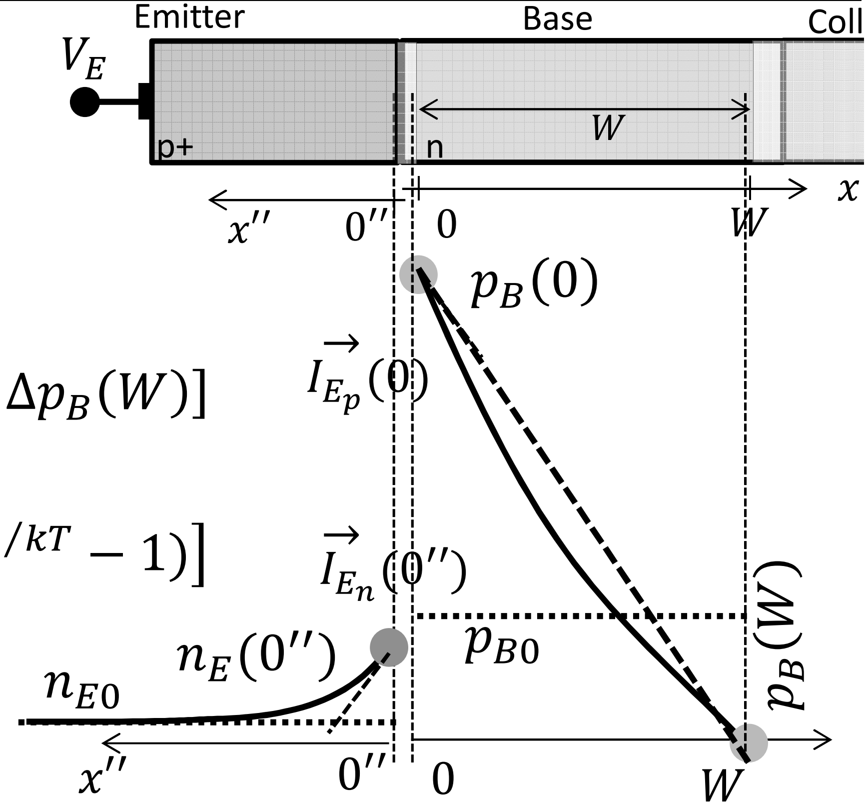
1. I
2.
3.
4.
5.

$$I_{E_n}(0'') = -qAD_E \left.\frac{d\Delta n_E}{dx''}\right|_{x''=0''}$$

$$= -qA\frac{D_E}{L_E}n_{E0}\left(e^{qV_{EB}/kT}-1\right)$$

$$I_{E_p}(0) = -qAD_B \left.\frac{d\Delta P_B}{dx}\right|_{x=0} = qA\frac{D_B}{W}[\Delta p_B(0) - \Delta p_B(W)]$$

$$= qA\frac{D_B}{W}p_{B0}\left[\left(e^{qV_{EB}/kT}-1\right) - \left(e^{qV_{CB}/kT}-1\right)\right]$$



$$I_E = I_{E_p}(0) + I_{E_n}(0'') =$$

$$= qA\left\{\frac{D_B p_{B0}}{W} + \frac{D_E n_{E0}}{L_E}\right\}\left(e^{qV_{EB}/kT}-1\right) - qA\frac{D_B p_{B0}}{W}\left(e^{qV_{CB}/kT}-1\right)$$

Dominant term

Current Equations – IC , IB

1. I
2.
3.
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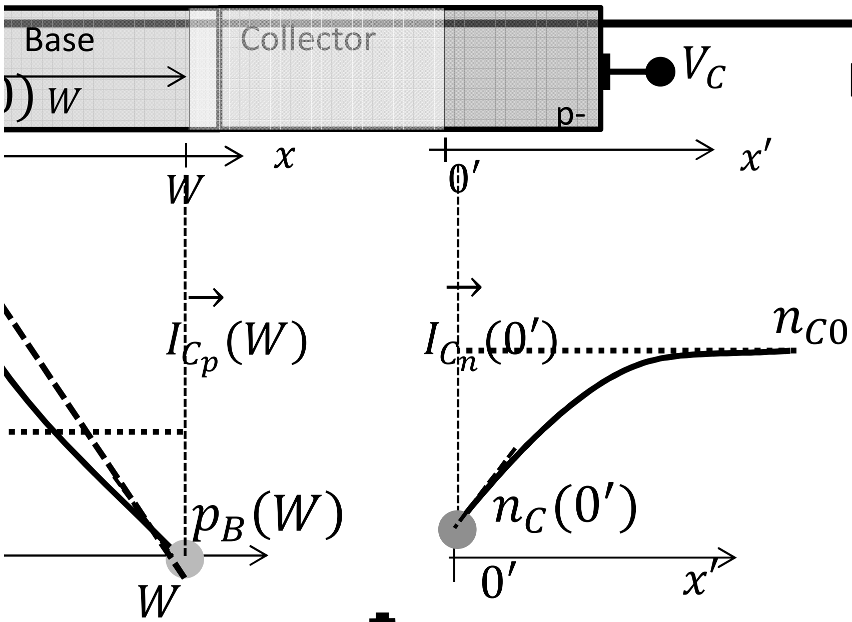
5.



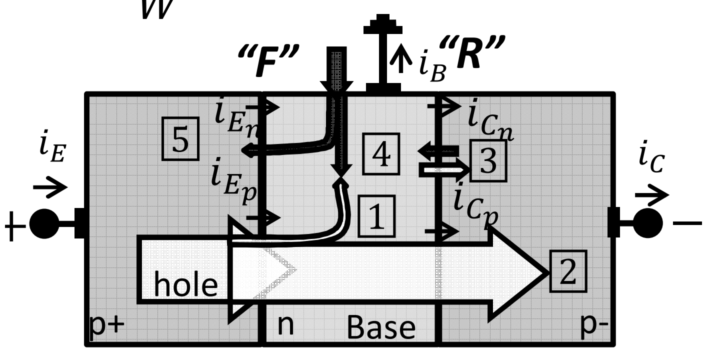
No recombination in Base $\quad I_{E_p}(0) = I_{C_p}(W)$

$$I_{C_n}(0') = -qA\frac{D_C n_{C0}}{L_C}\left(e^{qV_{CB}/kT} - 1\right)$$

$$I_C = I_{C_p}(W) + I_{C_n}(0')$$

$$= qA\frac{D_B p_{B0}}{W}\left(e^{qV_{EB}/kT} - 1\right)$$

$$-qA\left\{\frac{D_C n_{C0}}{L_C} + \frac{D_B p_{B0}}{L_B}\right\}\left(e^{qV_{CB}/kT} - 1\right)$$



$$I_B = I_E - I_C = \underbrace{qA\frac{D_B n_{E0}}{L_E}\left(e^{qV_{EB}/kT} - 1\right)}_{\boxed{5}} + \underbrace{qA\frac{D_C n_{C0}}{L_C}\left(e^{qV_{CB}/kT} - 1\right)}_{\boxed{3}}$$

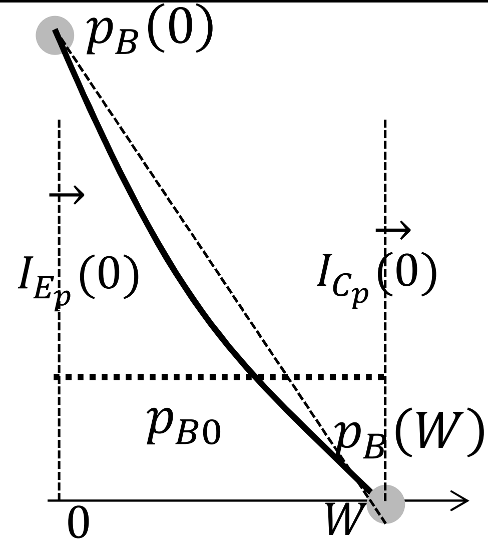
$\boxed{5}$ usually > $\boxed{3}$

Considering Recombination in Base

1. I
2.
3.
4.
5.

$$\Delta p_B(x) = B_1 e^{x/L_B} + B_2 e^{-x/L_B}$$

$$\begin{cases} \Delta p_B(W) = p_{B0}(e^{qV_{CB}/kT} - 1) \\ \Delta p_B(0) = p_{B0}(e^{qV_{EB}/kT} - 1) \end{cases}$$



$$\Delta p_B(x) = p_{B0}(e^{\frac{qV_{EB}}{kT}} - 1)\frac{\sinh\frac{W-x}{L_B}}{\sinh\frac{W}{L_B}} + p_{B0}(e^{\frac{qV_{CB}}{kT}} - 1)\frac{\sinh\frac{x}{L_B}}{\sinh\frac{W}{L_B}}$$

$$I_E = qA\left[\frac{D_E n_{E0}}{L_E} + \frac{D_B p_{B0}}{L_B}\coth\frac{W}{L_B}\right]\left(e^{\frac{qV_{EB}}{kT}} - 1\right) - qA\frac{D_B p_{B0}}{L_B}\,(e^{\frac{qV_{CB}}{kT}} - 1)\frac{1}{\sinh\frac{W}{L_B}}$$

$$I_C = qA\frac{D_B p_{B0}}{L_B}\,(e^{\frac{qV_{EB}}{kT}} - 1)\frac{1}{\sinh\frac{W}{L_B}} - qA\left[\frac{D_B p_{B0}}{L_B}\coth\frac{W}{L_B} + \frac{D_C n_{C0}}{L_C}\right](e^{\frac{qV_{CB}}{kT}} - 1)$$

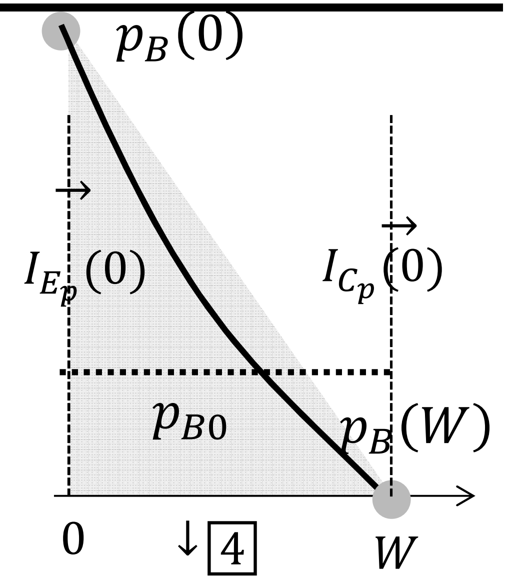
$$I_B = I_E - I_C$$

1. I
2.
3.
4.
5.

Quasi-Ideal BJT!

$$I_{B2} = \frac{\Delta Q_B}{\tau_B} = \frac{qA}{\tau_B}\int_0^W \Delta p_B(x)dx = \frac{qA}{2\tau_B}W\big(\Delta p_B(0) + \Delta p_B(W)\big)$$

$$= \frac{qAWp_{B0}}{2\tau_B}\Big((e^{\frac{qV_{EB}}{kT}} - 1) + (e^{\frac{qV_{CB}}{kT}} - 1)\Big)$$



Valid for all regions of operation!

Hence: $\begin{cases} I_E = I_{E\,ideal} \\ I_C = I_{C\,ideal} - I_{B2} \\ I_B = I_{B\,ideal} + I_{B2} \end{cases}$

$$I_{B_{ideal}} = qA\frac{D_B n_{E0}}{L_E}\left(e^{\frac{qV_{EB}}{kT}} - 1\right) + qA\frac{D_C n_{C0}}{L_C}(e^{\frac{qV_{CB}}{kT}} - 1)$$

$$I_B = qA\left[\frac{\overset{\sim 10}{D_B}\,\overset{\sim 10^2}{n_{E0}}}{L_{E\sim 25\mu}} + \frac{\overset{\sim 1.5\mu}{W}\,\overset{\sim 10^4}{p_{B0}}}{2\tau_{B\sim 1\mu}}\right]\left(e^{\frac{qV_{EB}}{kT}} - 1\right) + qA\left[\frac{D_C n_{C0}}{L_C} + \frac{Wp_{B0}}{2\tau_B}\right](e^{\frac{qV_{CB}}{kT}} - 1)$$

$\boxed{5}$ $\sim 4 \times 10^5$ $\sim 7.5 \times 10^5$ $\boxed{4}$

Quasi-Ideal BJT!

1. I
2.
3.
4.
5.

$$I_B = qA\left[\frac{D_B n_{E0}}{L_E} + \frac{W p_{B0}}{2\tau_B}\right]\left(e^{\frac{qV_{EB}}{kT}} - 1\right) + qA\left[\frac{D_C n_{C0}}{L_C} + \frac{W p_{B0}}{2\tau_B}\right]\left(e^{\frac{qV_{CB}}{kT}} - 1\right)$$

$D_B \sim 10$, $n_{E0} \sim 10^2$, $W \sim 1.5\mu$, $p_{B0} \sim 10^4$, $L_E \sim 25\mu$, $\tau_B \sim 1\mu$

$\boxed{5}$ $\quad \frac{D_B n_{E0}}{L_E} \sim 4 \times 10^5 \quad \frac{W p_{B0}}{2\tau_B} \sim 7.5 \times 10^5 \quad$ $\boxed{4}$

$$I_C = qA\left[\frac{D_B p_{B0}}{W} - \frac{W p_{B0}}{2\tau_B}\right]\left(e^{\frac{qV_{EB}}{kT}} - 1\right) - qA\left[\frac{D_C n_{C0}}{L_C} + \frac{W p_{B0}}{2\tau_B}\right]\left(e^{\frac{qV_{CB}}{kT}} - 1\right)$$

$\frac{D_B p_{B0}}{W} \sim 7 \times 10^8 \quad \frac{W p_{B0}}{2\tau_B} \sim 7.5 \times 10^5$

Hence:
$$\begin{cases} I_E \cong I_{E_{ideal}} \\ I_C \cong I_{C_{ideal}} \\ I_B \cong I_{B_{ideal}} + I_{B2} \end{cases}$$

CB: Common Base

1. I
2.
3.
4.
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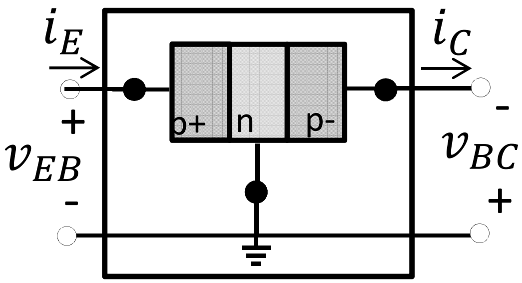
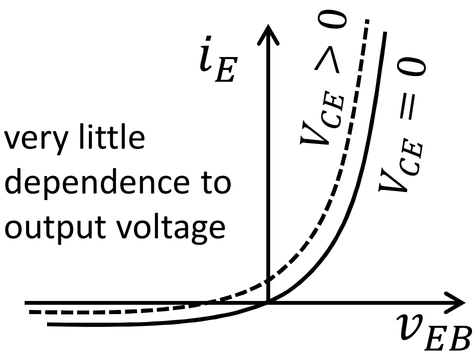
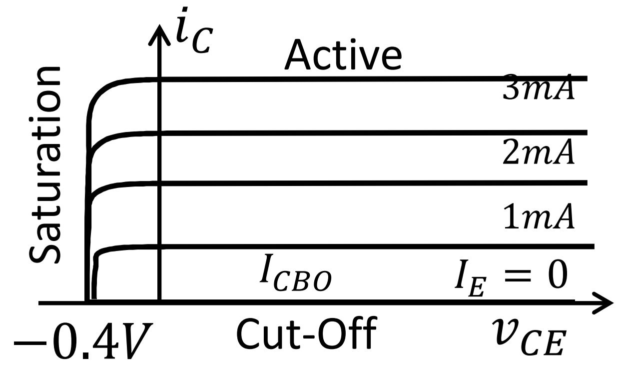


Input Characteristic



Output Characteristic

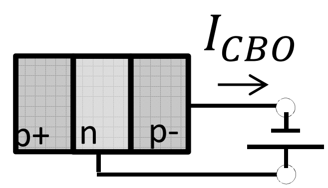


Ideal: $\alpha_T = 1 \quad \rightarrow \alpha_{dc} = \frac{I_C}{I_E} = \gamma = \frac{I_{E_p}}{I_E} = \dfrac{\frac{D_B p_{B0}}{W}}{\frac{D_B p_{B0}}{W} + \frac{D_E n_{E0}}{L_E}} = \dfrac{1}{1 + \frac{D_E}{D_B}\frac{N_{DB}}{N_{AE}}\frac{W}{L_E}}$ ↑↑

Non ideal: $\alpha_T = \frac{I_{C_p}}{I_{E_p}} = \frac{1}{\cosh\frac{W}{L_B}} \cong \frac{1}{1 + \frac{1}{2}\left(\frac{W}{L_B}\right)^2} \quad \rightarrow \alpha_{dc} = \alpha_T \gamma$

I_{CBO} Leakage current of BC diode

Determined by n_{C0} as $n_{C0} \gg p_{B0}$



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CE: Common Emitter

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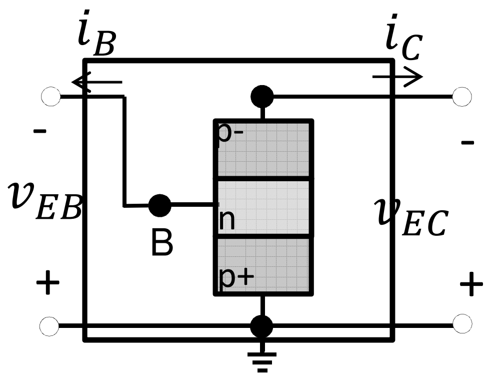
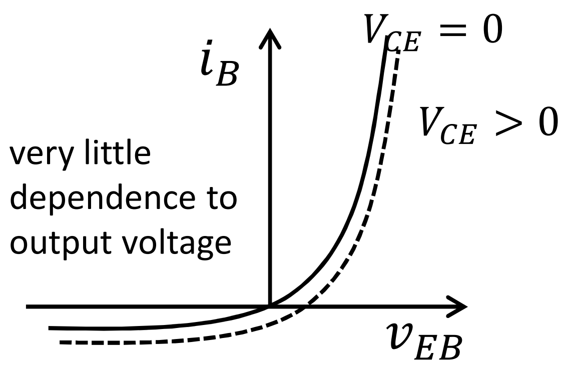
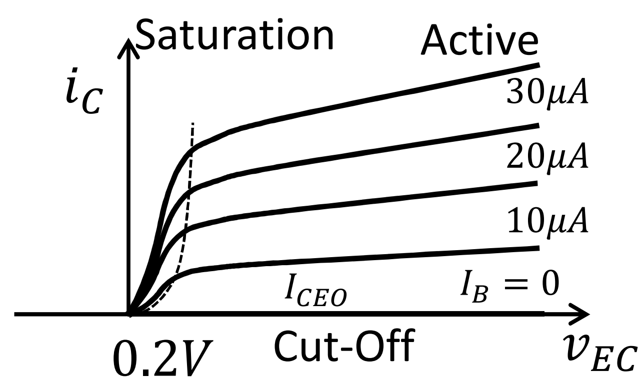


Input Characteristic



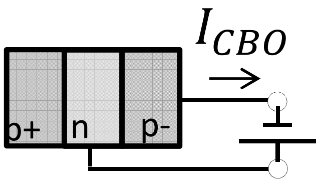
Output Characteristic



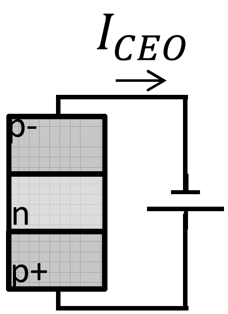
$$\left.\begin{matrix} W \ll L\_C \\ V_{CB} < 0 \\ V_{EB} > 0 \end{matrix}\right\} \rightarrow \begin{cases} I_C \approx qA \dfrac{D_B p_{B0}}{W} \; e^{\frac{qV_{EB}}{kT}} \\ I_B \approx qA \dfrac{D_E n_{E0}}{L_E} \; e^{\frac{qV_{EB}}{kT}} \end{cases} \rightarrow \beta_{dc} = \frac{I_C}{I_B} = \frac{D_B}{D_E} \cdot \frac{p_{B0}}{n_{E0}} \cdot \frac{L_E}{W} \downdownarrows$$

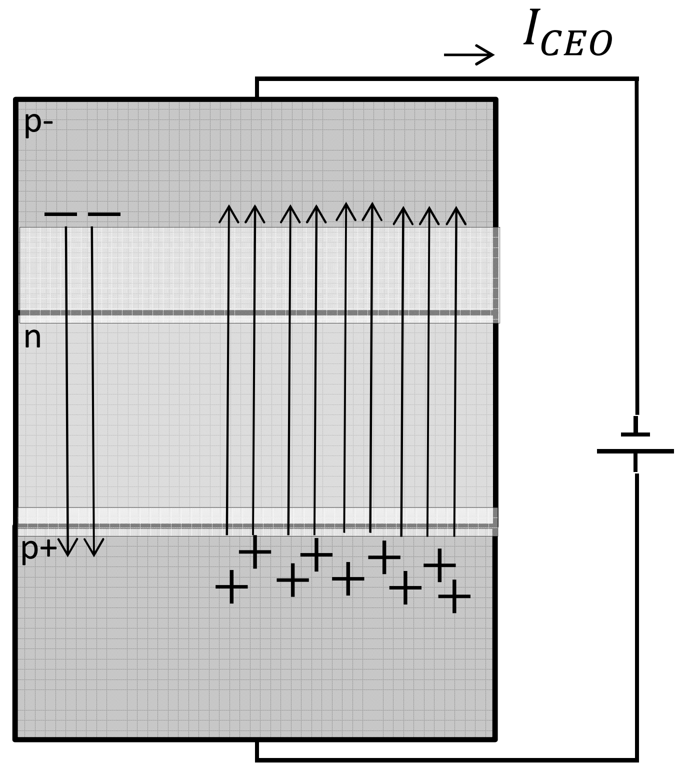
$$\frac{N_{AE}}{N_{DB}} \upuparrows$$

ICEO and ICBO



$$I_{CEO} \gg I_{CBO}$$





$$I_{CEO} = I_{C_n} + I_{C_p} = I_{CBO} + \beta_{dc} I_{CBO}$$

Ebers-Moll Equations

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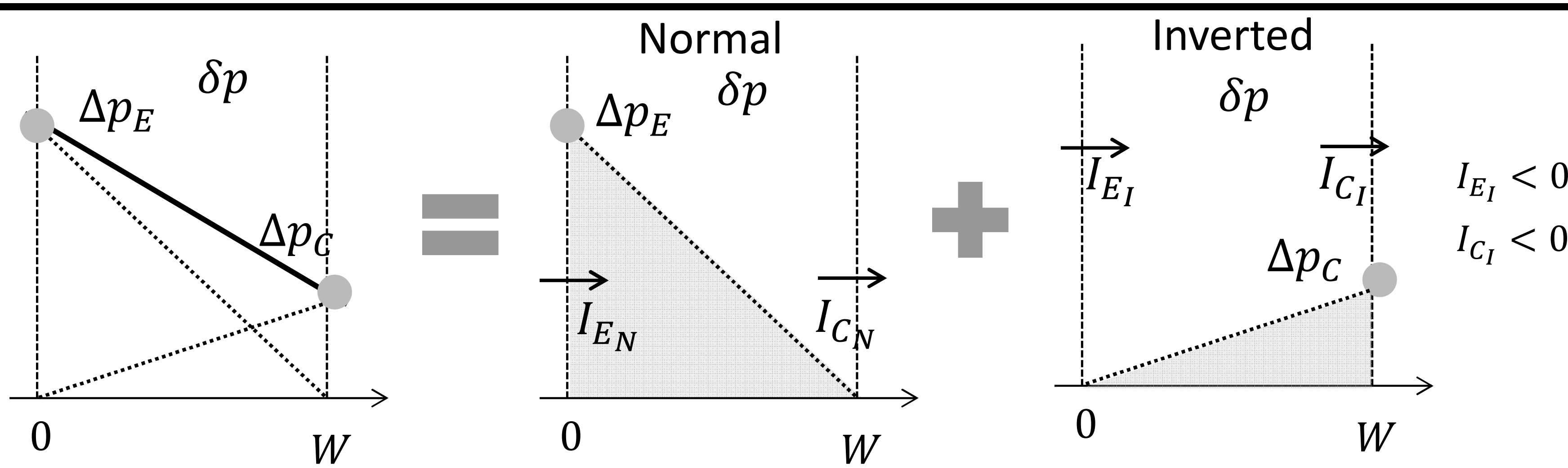

$$(\Delta P_C = 0) \xrightarrow{\text{Normal}} I_{E_N} = a\Delta p_E \;;\; I_{C_N} = b\Delta p_E$$

$$(\Delta P_E = 0) \xrightarrow{\text{Inverted}} I_{E_I} = -b\Delta p_C \;;\; I_{C_I} = -a\Delta p_C$$

$$\begin{cases} a = qA\frac{D_B}{L_B}\coth\frac{W}{L_B} \\ b = qA\frac{D_B}{L_B}\operatorname{csch}\frac{W}{L_B} \end{cases}$$

$$\begin{cases} I_E = I_{E_N} + I_{E_I} = a\Delta p_E - b\Delta p_C \\ I_C = I_{C_N} + I_{C_I} = b\Delta p_E - a\Delta p_C \end{cases} \xrightarrow[\alpha_I \equiv I_{C_I}/I_{E_I}]{\alpha_N \equiv I_{C_N}/I_{E_N}} \begin{cases} I_E = I_{ES}\left(e^{\frac{qV_{EB}}{kT}} - 1\right) + \alpha_I I_{C_I} \\ I_C = \alpha_N I_E - I_{CS}\left(e^{\frac{qV_{CB}}{kT}} - 1\right) \end{cases}$$

$$\begin{cases} I_{E_N} = I_{ES}\left(e^{\frac{qV_{EB}}{kT}} - 1\right) \;;\; \Delta p_C = 0 \\ I_{C_I} = I_{CS}\left(1 - e^{\frac{qV_{CB}}{kT}}\right) \;;\; \Delta p_E = 0 \end{cases}$$

Ebers-Moll Equations

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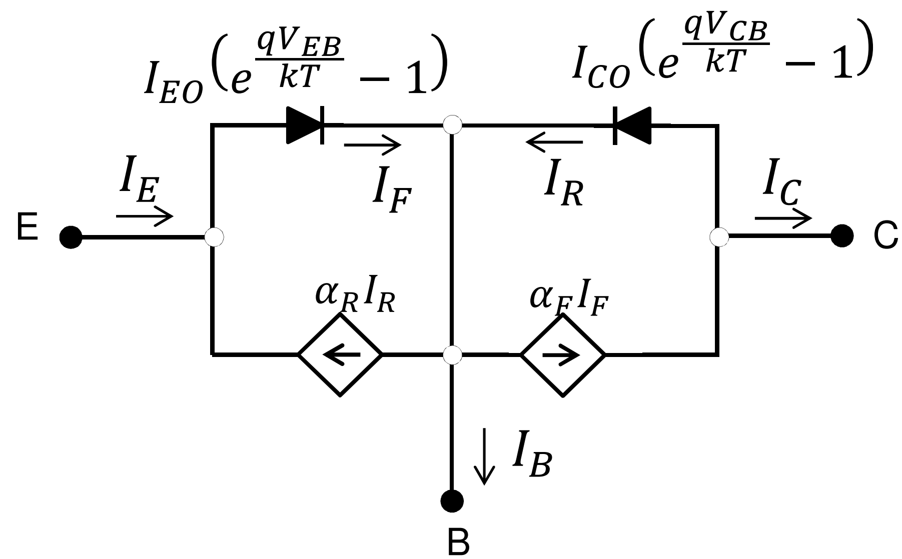
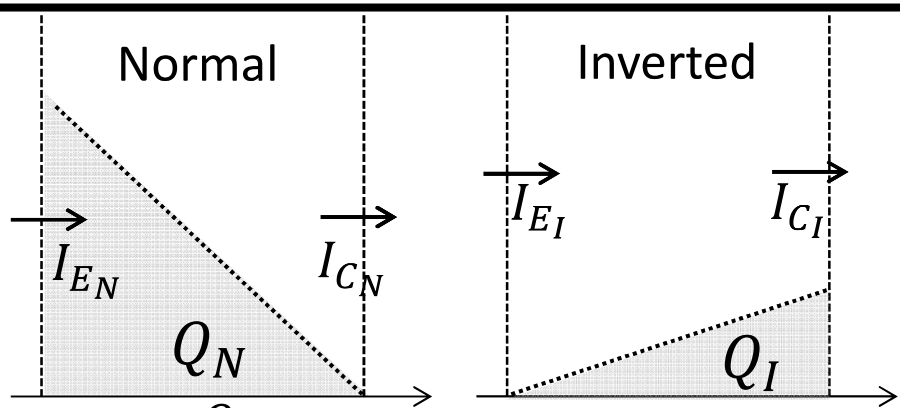
$$\begin{cases} I_E = I_{ES}\left(e^{\frac{qV_{EB}}{kT}} - 1\right) + \alpha_I I_{C\,I} \\ I_C = \alpha_N I_E - I_{CS}\left(e^{\frac{qV_{CB}}{kT}} - 1\right) \end{cases}$$

$$\begin{cases} I_E = \alpha_I I_{C\,I} + I_{EO}\left(e^{\frac{qV_{EB}}{kT}} - 1\right) \\ I_C = \alpha_N I_E - I_{CO}\left(e^{\frac{qV_{CB}}{kT}} - 1\right) \end{cases}$$



Charge Control Analysis



$$I_{C_N} \equiv \frac{Q_N}{\tau_{t_N}}$$

$$I_{E_N} = I_{C_N} + \frac{Q_N}{\tau_{p_N}}$$

$$I_{E_I} \equiv -\frac{Q_I}{\tau_{t_I}}$$

$$I_{C_I} = I_{E_I} - \frac{Q_I}{\tau_{p_I}}$$

Small-signal model

$$\begin{cases} i_E = Q_N\left(\frac{1}{\tau_{p_N}} + \frac{1}{\tau_{t_N}}\right) - \frac{Q_I}{\tau_{t_I}} + \frac{dQ_N}{dt} \\ i_C = \frac{Q_N}{\tau_{t_N}} - Q_I\left(\frac{1}{\tau_{p_I}} + \frac{1}{\tau_{t_I}}\right) - \frac{dQ_I}{dt} \\ i_B = \frac{Q_N}{\tau_{p_N}} + \frac{Q_I}{\tau_{p_I}} + \frac{dQ_N}{dt} + \frac{dQ_I}{dt} \end{cases}$$

Generally:

$$\begin{cases} I_E = I_{E_N} + I_{E_I} = Q_N\left(\frac{1}{\tau_{p_N}} + \frac{1}{\tau_{t_N}}\right) - \frac{Q_I}{\tau_{t_I}} \\ I_C = \frac{Q_N}{\tau_{t_N}} - Q_I\left(\frac{1}{\tau_{p_I}} + \frac{1}{\tau_{t_I}}\right) \end{cases}$$

$$\alpha_N \equiv I_{C_N}/I_{E_N} = \frac{\tau_{p_N}}{\tau_{t_N} + \tau_{p_N}}$$

$$\alpha_I \equiv I_{C_I}/I_{E_I} = \frac{\tau_{p_I}}{\tau_{t_I} + \tau_{p_I}}$$

$$I_{B_N} = \frac{Q_N}{\tau_{p_N}} \qquad \beta_N \equiv \frac{I_{C_N}}{I_{B_N}} = \frac{\tau_{p_N}}{\tau_{t_N}}$$

$$I_B = I_{B_N} + I_{B_I} = \frac{Q_N}{\tau_{p_N}} + \frac{Q_I}{\tau_{p_I}}$$

Transient Response

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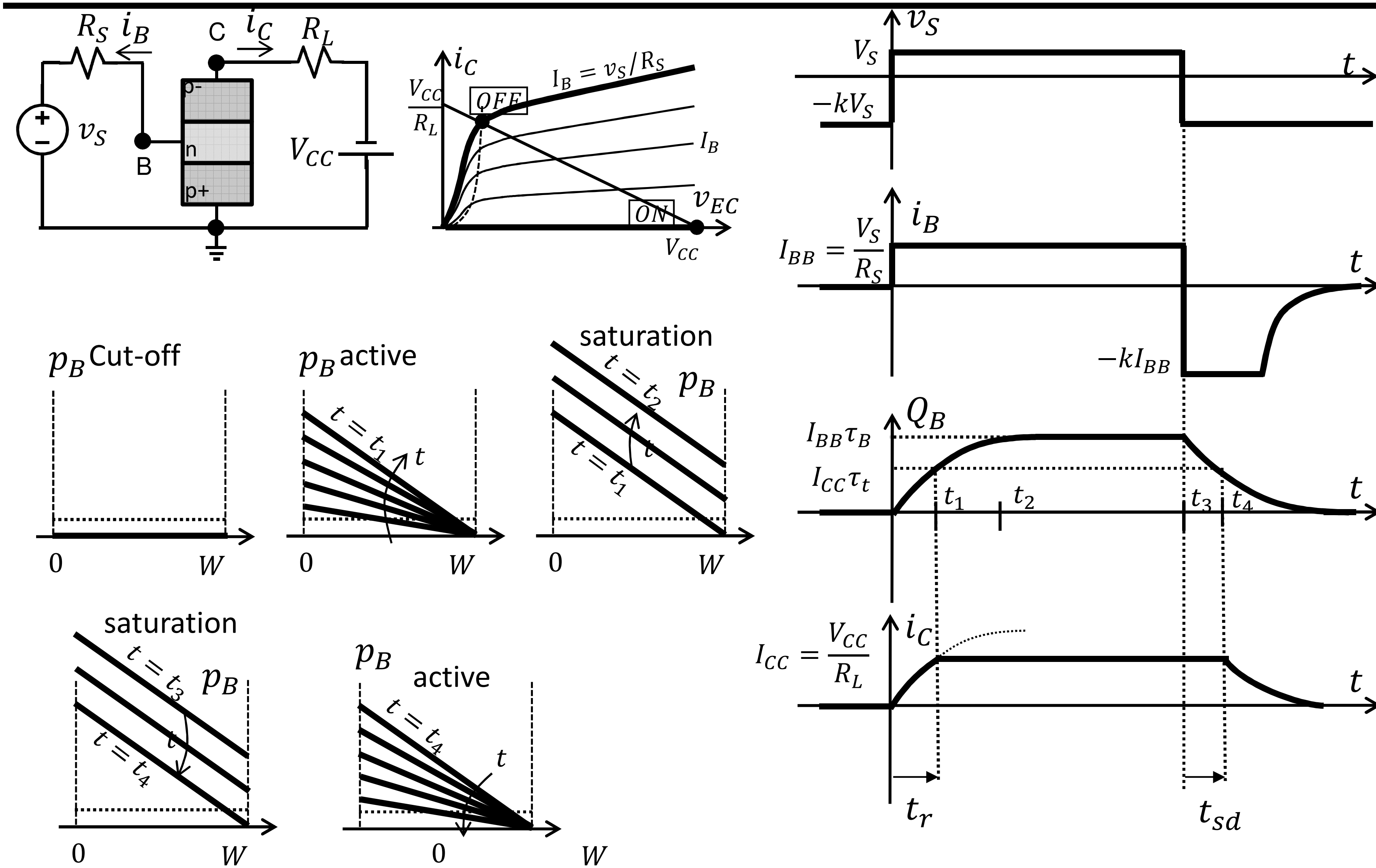

Base Transient Time

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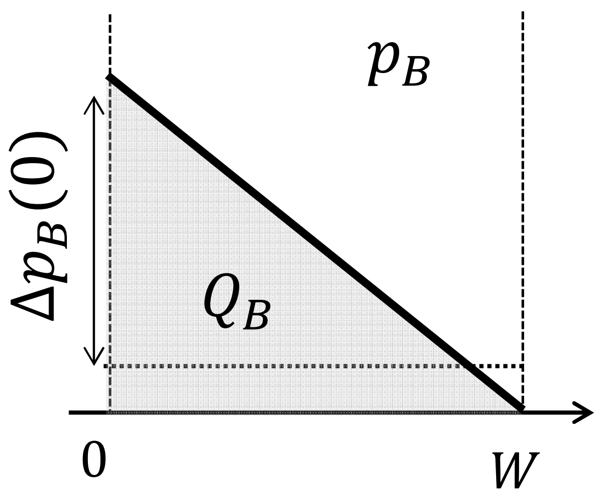
active



$$I_C = -qAD_B \left.\frac{\partial \Delta p_B}{\partial x}\right|_{x=W}$$

$$= qAD_B \frac{\Delta p_B(0,t)}{W}$$

$$= qAD_B \frac{2Q_B}{qAW^2}$$

$$Q_B = qA\frac{W\Delta p_B(0)}{2}$$

$$I_C = \frac{Q_B}{(W^2/2D_B)} = \frac{Q_B}{\tau_t}$$

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

Turn ON

Turn-on:

$$i_B = \frac{V_S}{R_S} = I_{BB}$$

$$\frac{dQ_B}{dt} = I_{BB} - \frac{Q_B}{\tau_B} \qquad \rightarrow Q_B(t) = I_{BB}\tau_B + Ae^{-t/\tau_B}$$

I.C.: $\quad Q_B(0) = 0 \qquad \rightarrow Q_B(t) = I_{BB}\tau_B\left(1 - e^{-t/\tau_B}\right)$

$$\rightarrow \begin{cases} i_C(t) = \dfrac{Q_B(t)}{\tau_t} = \dfrac{I_{BB}\tau_B}{\tau_t}\left(1 - e^{-t/\tau_B}\right) & 0 < t \le t_1 \\ i_C(t) = I_{CC} = \dfrac{V_{CC}}{R_L} & \end{cases}$$

$$i_C(t_r) = I_{CC} \quad \rightarrow t_r = \tau_B \ln\left(\frac{1}{1 - \frac{I_{CC}}{I_{BB}}\frac{\tau_t}{\tau_B}}\right)$$

Turn OFF

Turn-off:

$$\frac{dQ_B}{dt} = -kI_{BB} - \frac{Q_B}{\tau_B} \qquad \to Q_B(t) = -kI_{BB}\tau_B + Ae^{-t/\tau_B}$$

I.C.:

$$Q_B(0)\Big|_{turnOFF} = Q_B(\infty)\Big|_{turnON} = I_{BB}\tau_B$$

$$\to Q_B(t) = I_{BB}\tau_B\left((1+k)e^{-t/\tau_B} - k\right)$$

$$\to \begin{cases} i_C(t) = I_{CC} & t_3 < t \le t_4 \\ i_C(t) = \dfrac{Q_B(t)}{\tau_t} = \dfrac{I_{BB}\tau_B}{\tau_t}\left((1+k)e^{-t/\tau_B} - k\right) & t > t_4 \end{cases}$$

$$t_{sd} = t_4 - t_3 \ \to t_{sd} = \tau_B \ln\left(\frac{1+k}{\frac{I_{CC}}{I_{BB}}\frac{\tau_t}{\tau_B} + k}\right)$$

Non-Ideal BJT

Deviations from Ideality:

1. Base width modulation (Early effect)
2. Punch-through
3. Avalanche Breakdown
4. Geometrical effects
5. Generation-Recombination in depletion regions
6. High-level injection

Base Width Modulation

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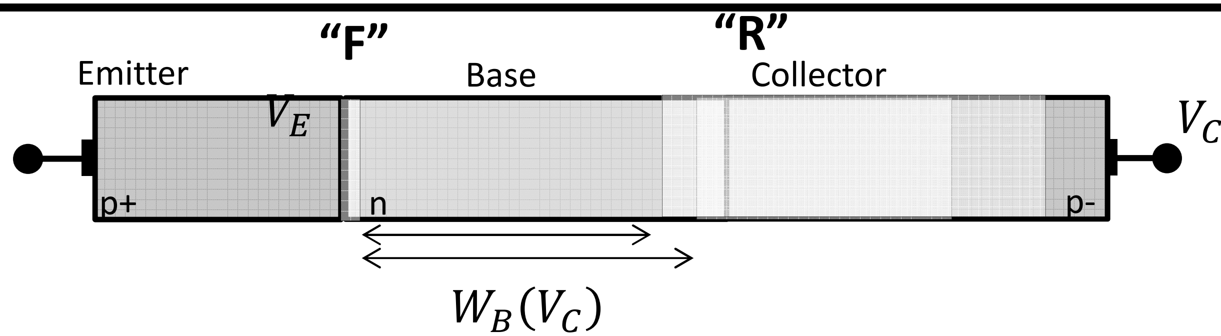
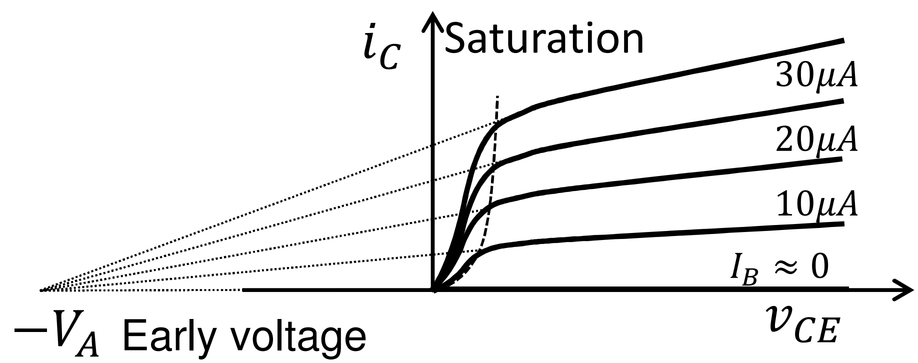


$$I_E \cong I_{E_p} = qA\frac{D_B p_{B0}}{W} e^{qV_{EB}/kT}$$

$$V_{CB} \nearrow \longrightarrow W \searrow \longrightarrow I_E \nearrow$$



Show that

HW: $$V_A = \frac{qN_B W}{C_{jC}}$$

Active: $$i_C = I_S e^{\frac{v_{BE}}{nV_T}}(1 + \frac{v_{CE}}{V_A})$$

Punch Through

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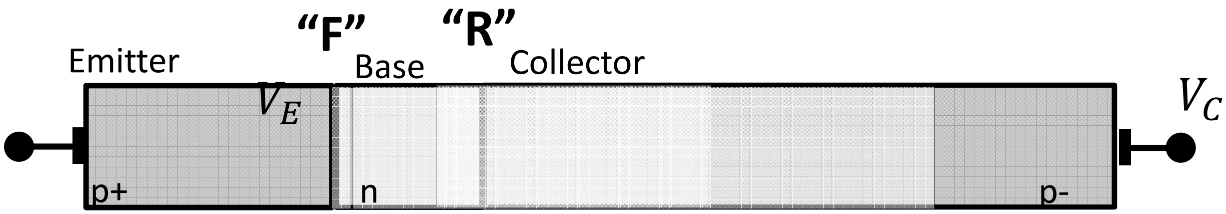
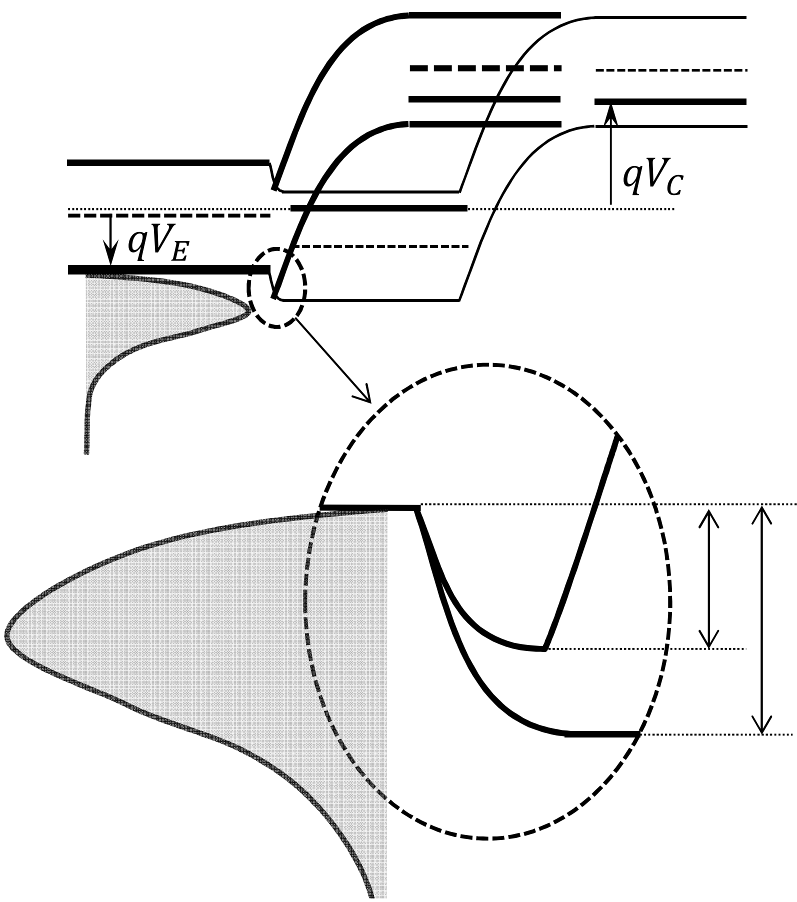
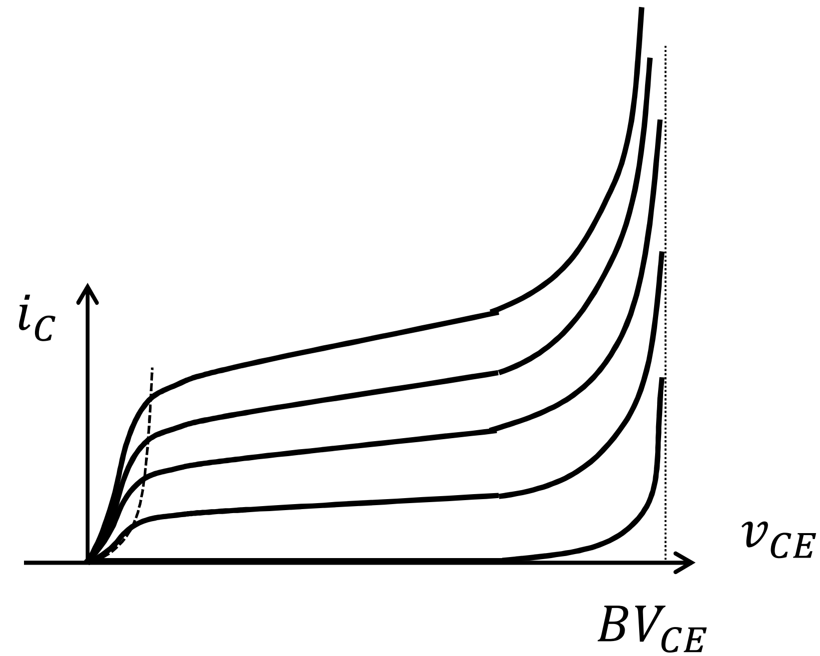
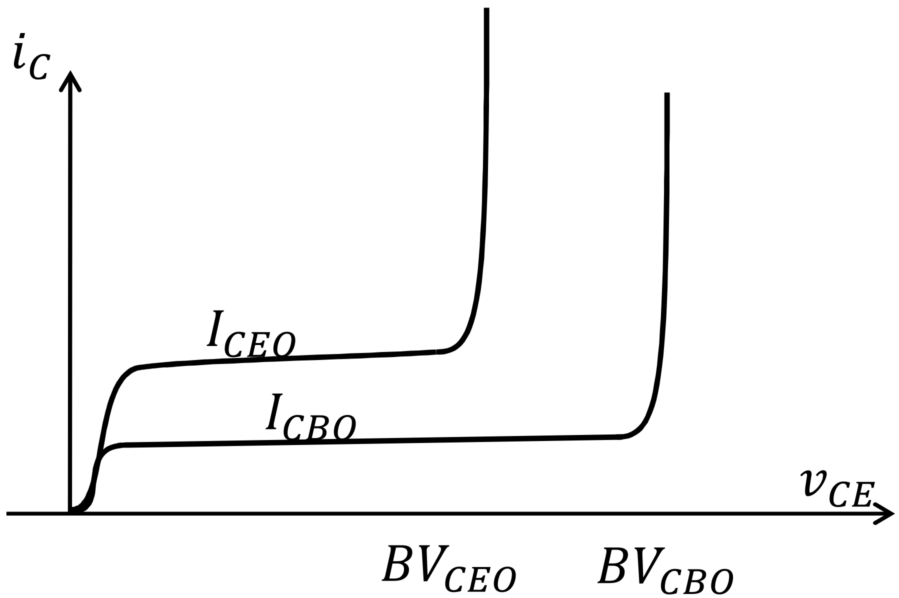






Avalanche Breakdown



$$BV_{CEO} = \frac{1}{\beta^{1/m}} BV_{CBO} \qquad m \sim 4$$

Geometry Considerations

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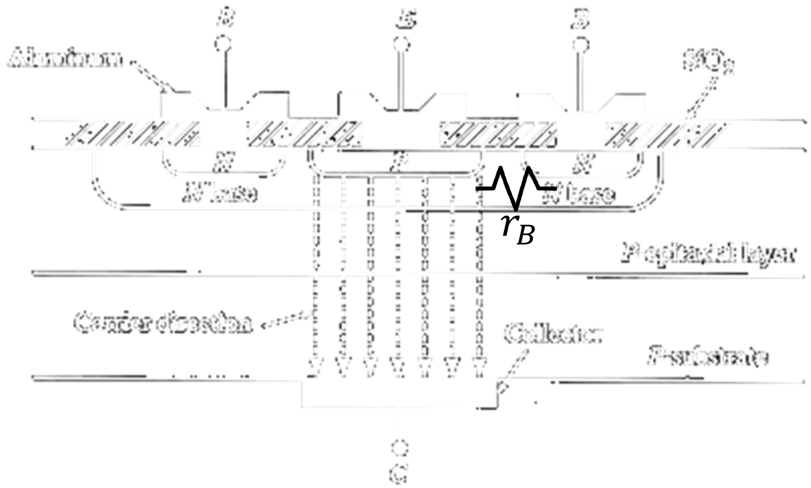
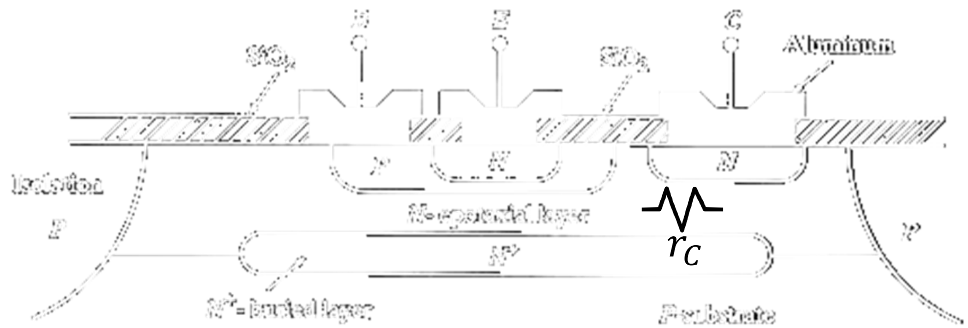
p-n-p Individual device



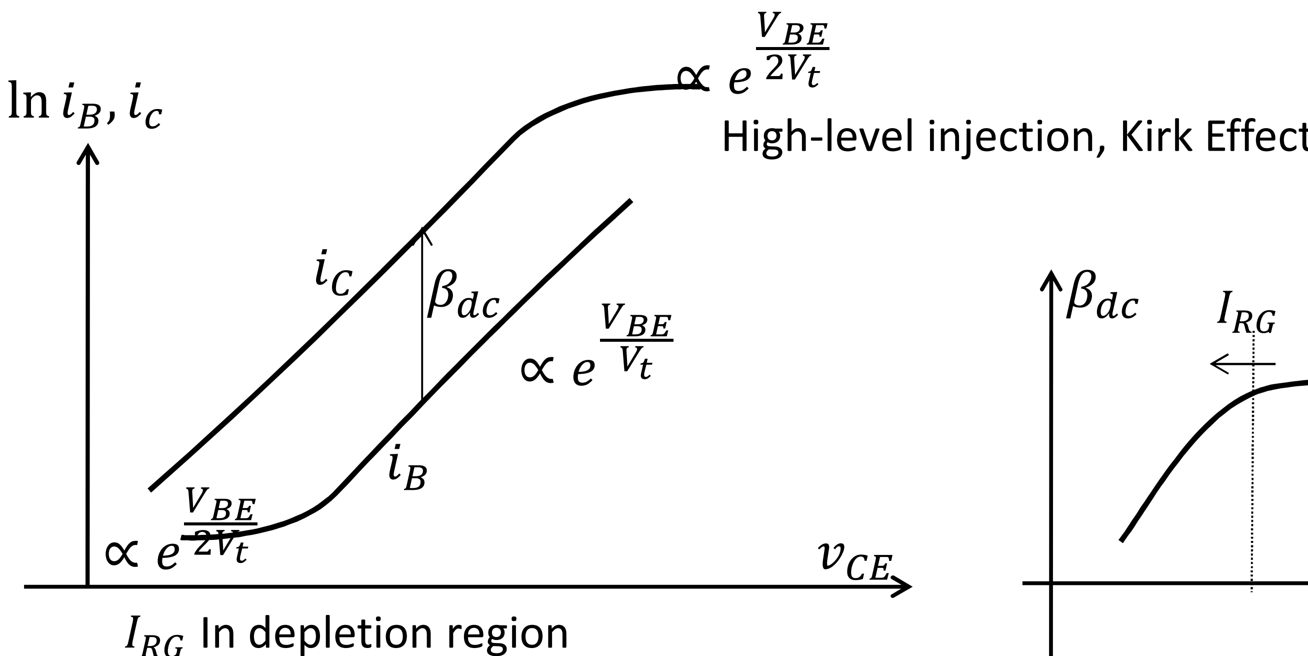
n-p-n Integrated circuit BJT

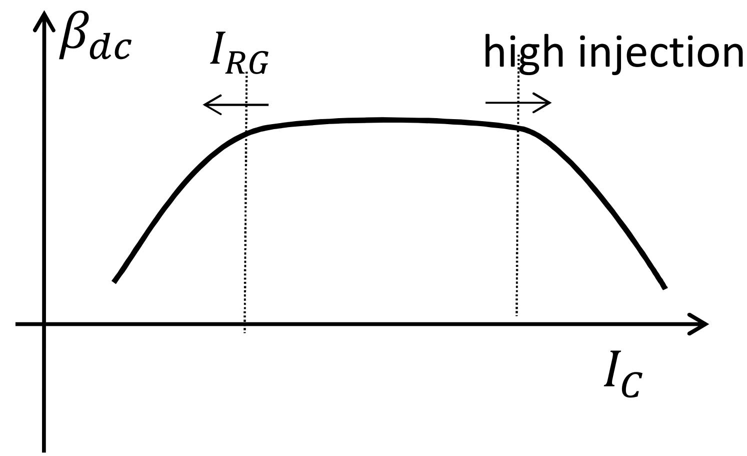


Current Crowding

G-R in Depl. Region , High-level injection

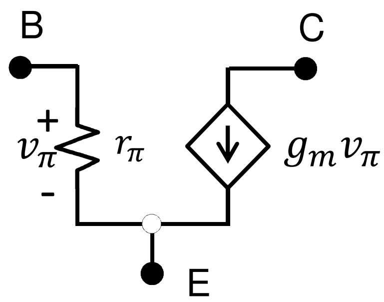
p-n-p Individual device





Small-Signal Model

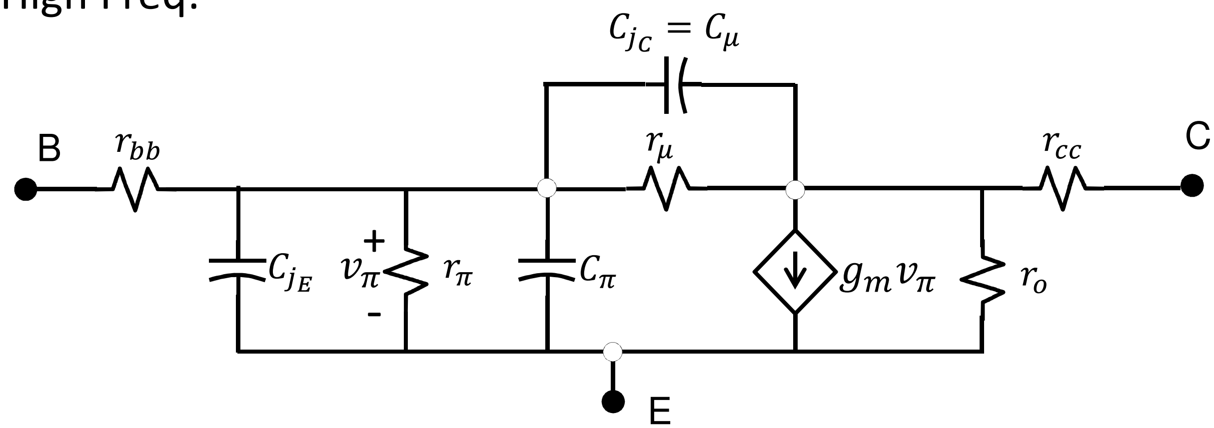
Low Freq:



$$g_m = \frac{I_C}{V_t} = \frac{I_C}{kT/q}$$

$$r_\pi = \frac{\beta_F}{g_m} = \beta_F . r_m$$

High Freq:



$$r_o = \frac{I_C}{V_A}$$

$$C_\mu = \frac{C_{\mu 0}}{\left(1 - \frac{V_{CB}}{V_{CB0}}\right)^m}$$

$$C_{j_E} = \frac{C_{j_{E0}}}{\left(1 - \frac{V_{EB}}{V_{EB0}}\right)^m}$$

$$C_D = \tfrac{1}{2} G_0 \tau_p$$

$$C_\pi = \frac{I_E}{kT/q} \tau_t = g_m . \tau_t$$