ECE-305: Spring 2018
Final Exam Review

Pierret, *Semiconductor Device Fundamentals* (SDF)
Chapters 10 and 11 (pp. 371-385, 389-403)

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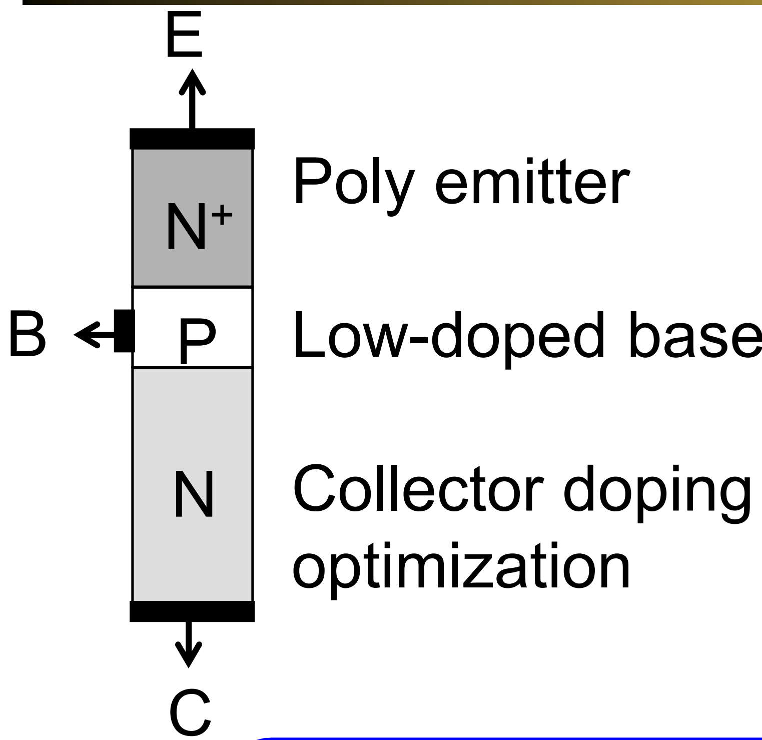
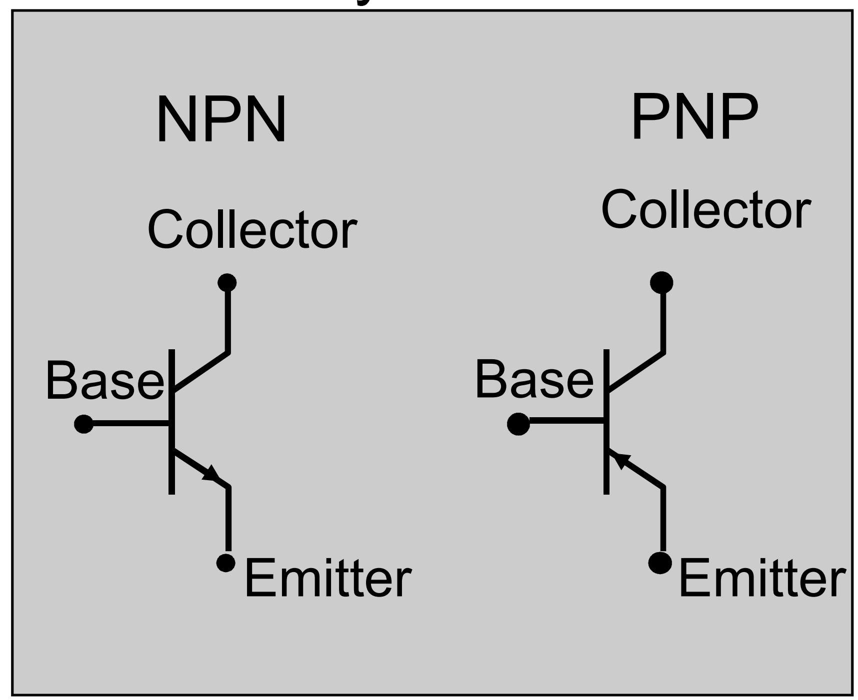
BJT Symbols and Conventions



Symbols



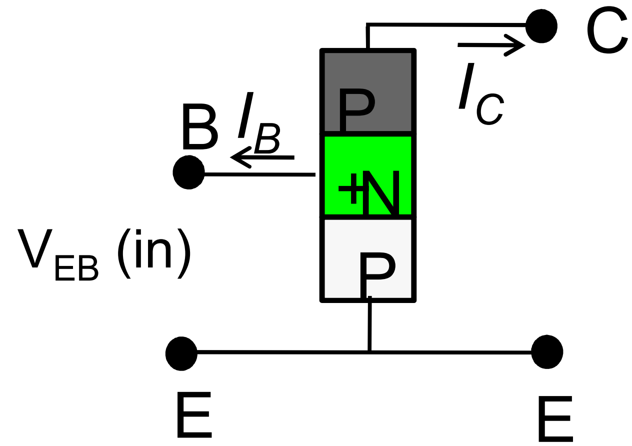
$$I_C+I_B+I_E=0$$

$$V_{EB}+V_{BC}+V_{CE}=0$$

BJT Current Gain

Common Emitter current gain ..

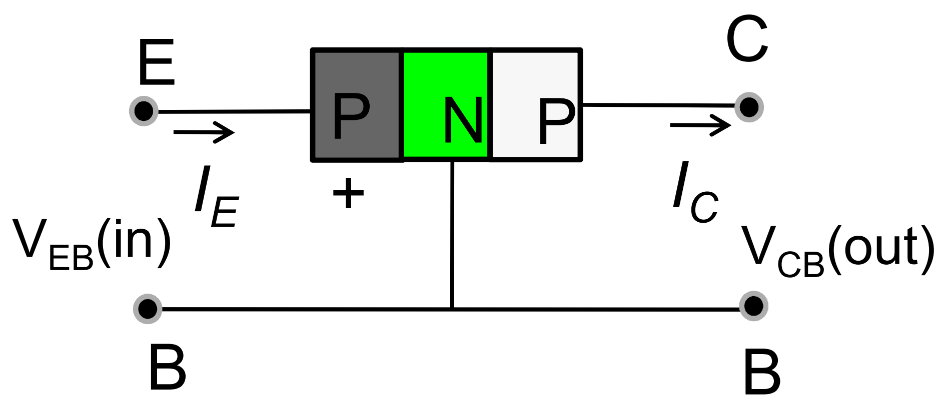
$$\beta_{DC} = \frac{I_C}{I_B}$$



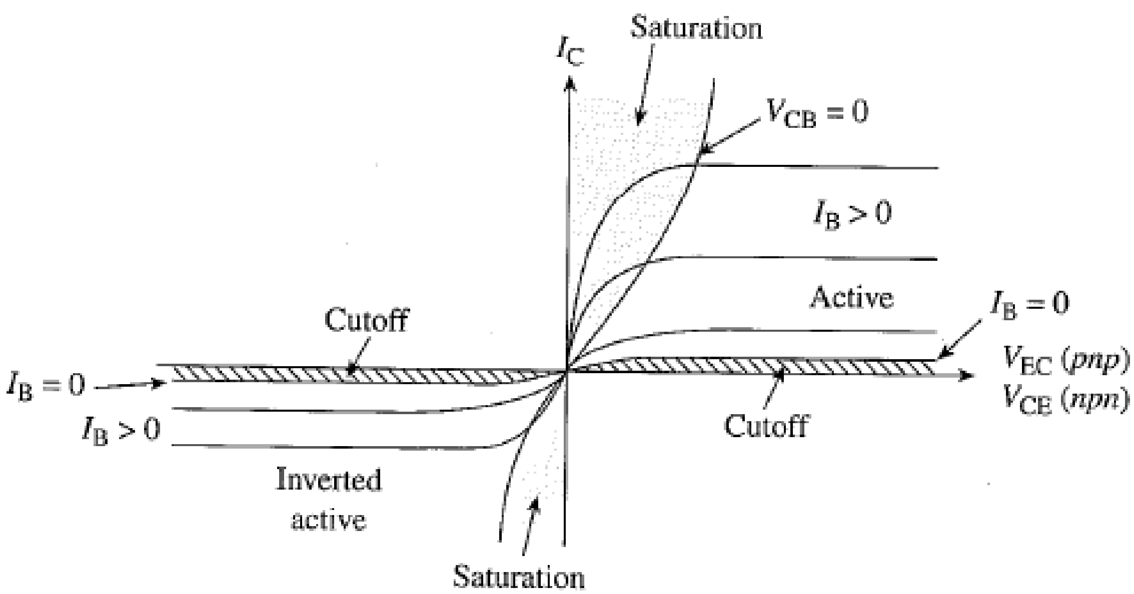
Common Base current gain ..

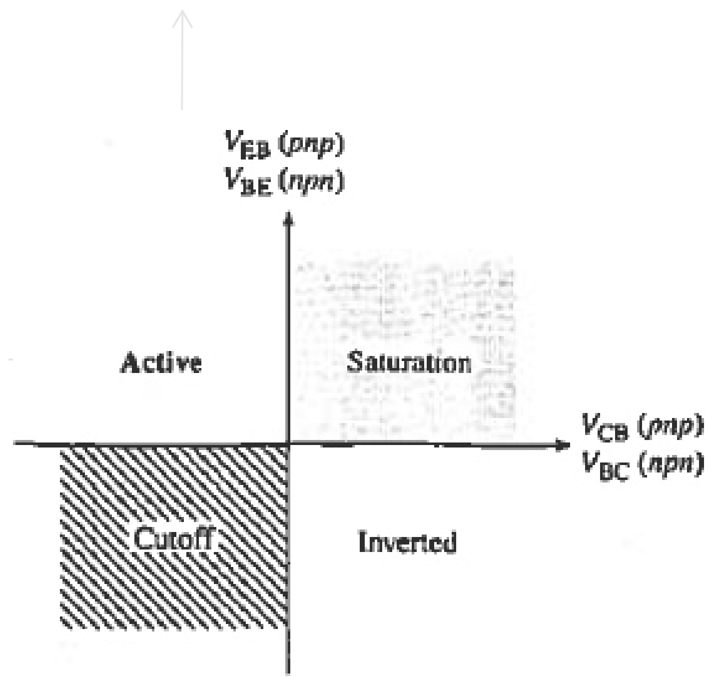
$$\alpha_{DC} = \frac{I_C}{I_E}$$

$$\beta_{DC} = \frac{I_C}{I_B} = \frac{I_C}{I_E - I_C} = \frac{\alpha_{DC}}{1 - \alpha_{DC}}$$

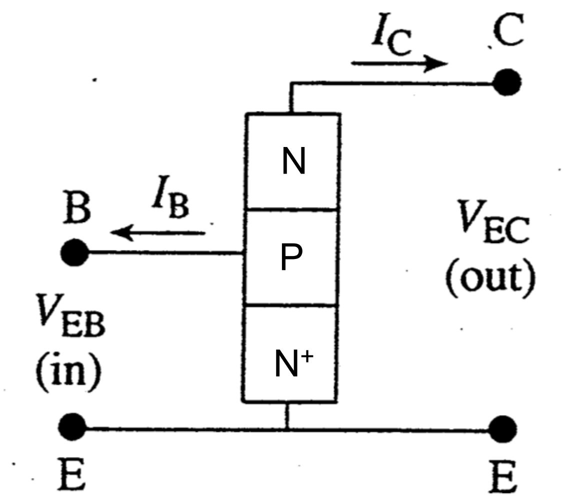


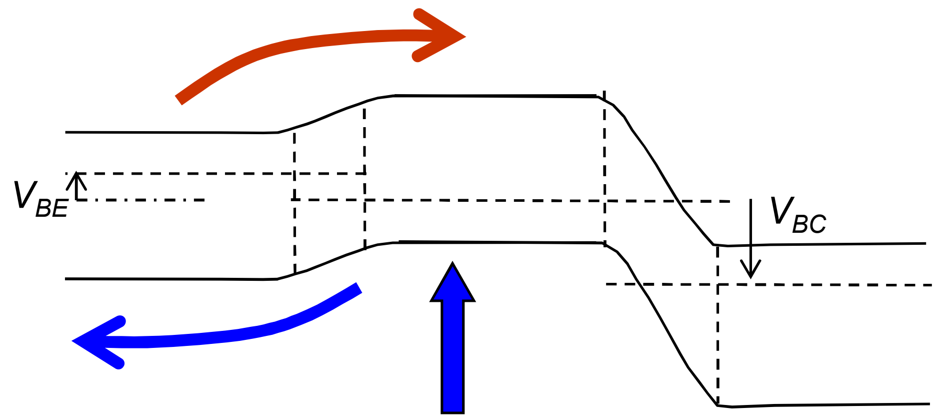
Current Gain





essence of current gain





Input → I_B ; Response ← V_{BE} → Input

$$I_B \approx \frac{qD_p}{W_E}\frac{n_{i,E}^2}{N_E}\left(e^{qV_{BE}\beta}-1\right)$$

$$I_E \approx \frac{qD_n}{W_B}\frac{n_{i,B}^2}{N_B}\left(e^{qV_{BE}\beta}-1\right)$$

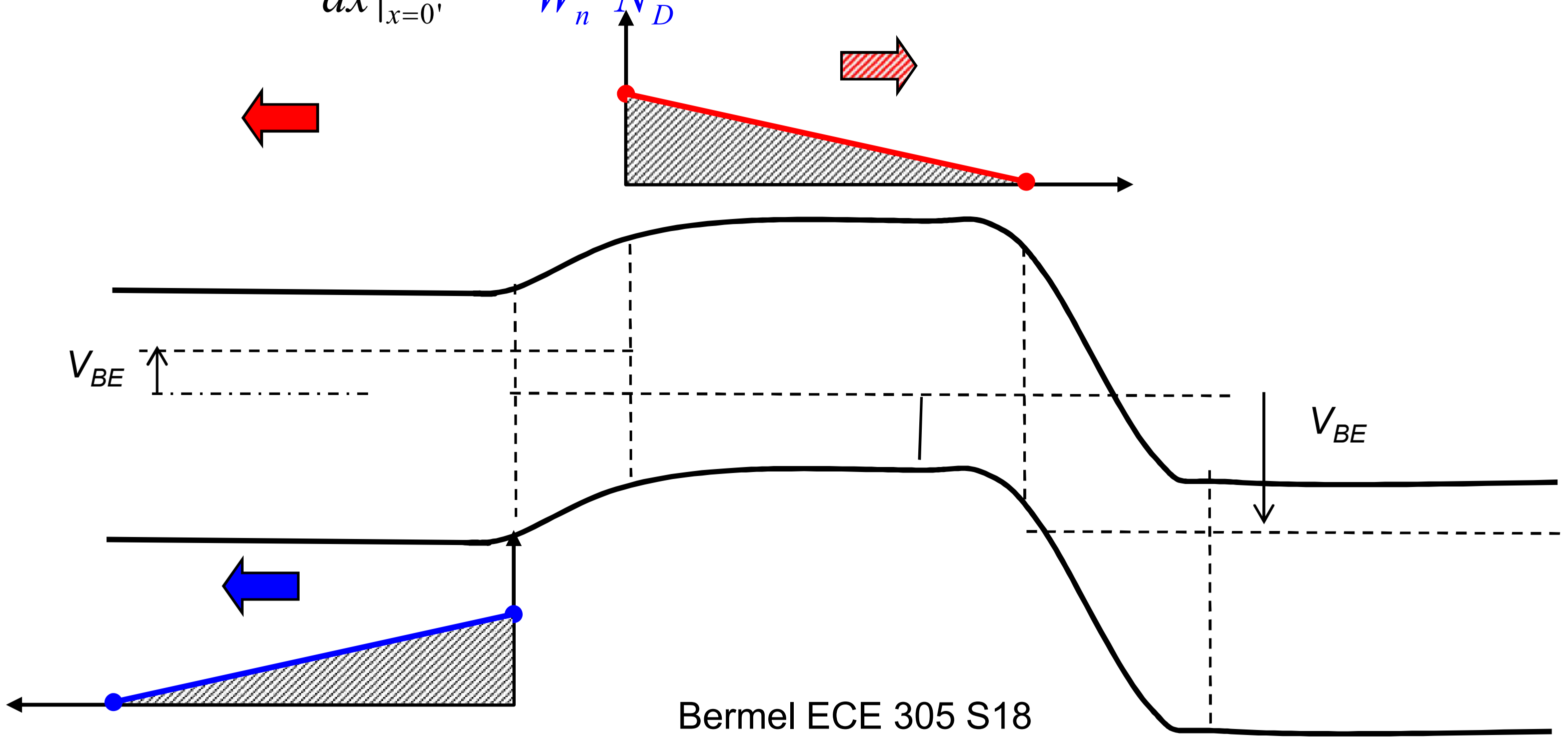
Response

Emitter Current

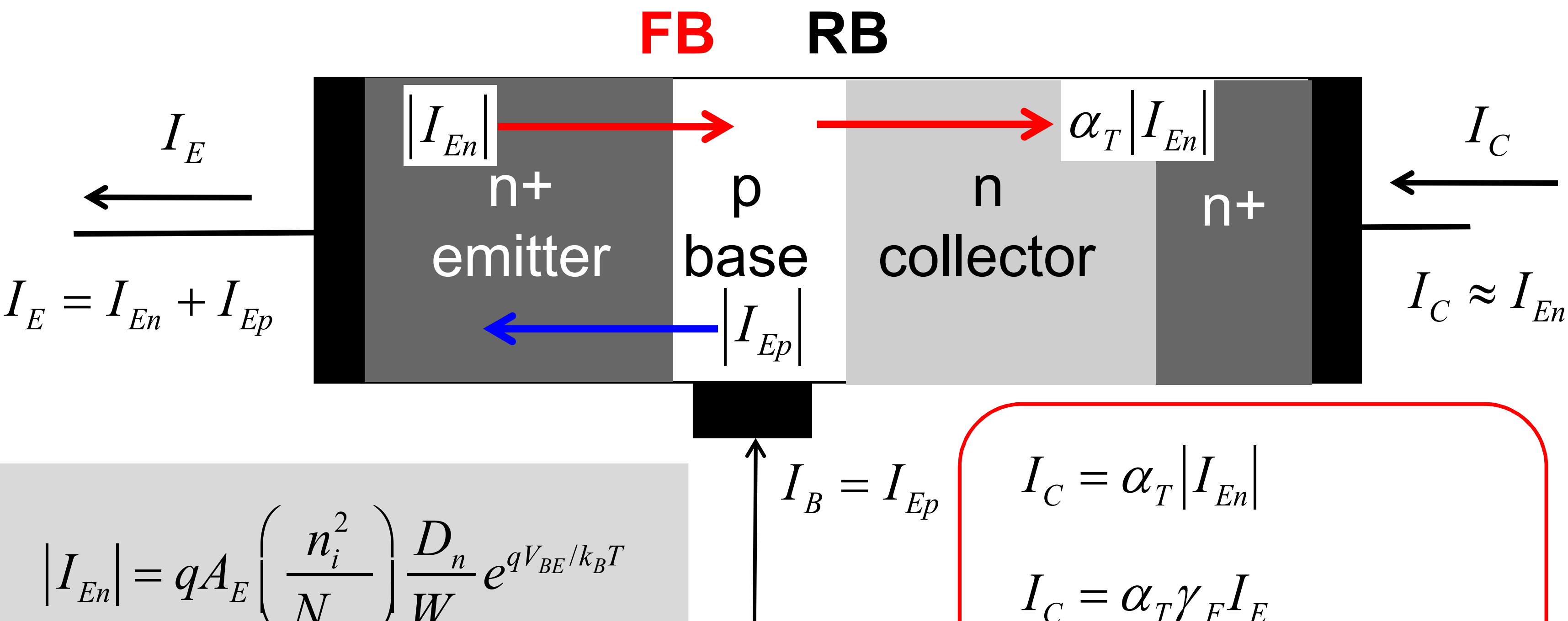
$$J_{n,E} = qD_n \left.\frac{dn}{dx}\right|_{x=0} = -\frac{qD_n}{W_B}\frac{n_{i,B}^2}{N_B}\left(e^{qV_{BE}/k_BT}-1\right)+\frac{qD_n}{W_B}\frac{n_{i,B}^2}{N_B}\left(e^{qV_{BC}/k_BT}-1\right)$$

$$J_{p,E} = -qD_p \left.\frac{dp}{dx}\right|_{x=0'} = -\frac{D_p}{W_n}\frac{n_i^2}{N_D}\left(e^{qV_{BE}\beta}-1\right)$$

$$J_E = J_{p,E} + J_{n,E}$$



collector current: forward active region



$$|I_{En}| = qA_E \left(\frac{n_i^2}{N_{AB}} \right) \frac{D_n}{W_B} e^{qV_{BE}/k_B T}$$

$$|I_{Ep}| = qA_E \left(\frac{n_i^2}{N_{DE}} \right) \frac{D_p}{W_E} e^{qV_{BE}/k_B T}$$

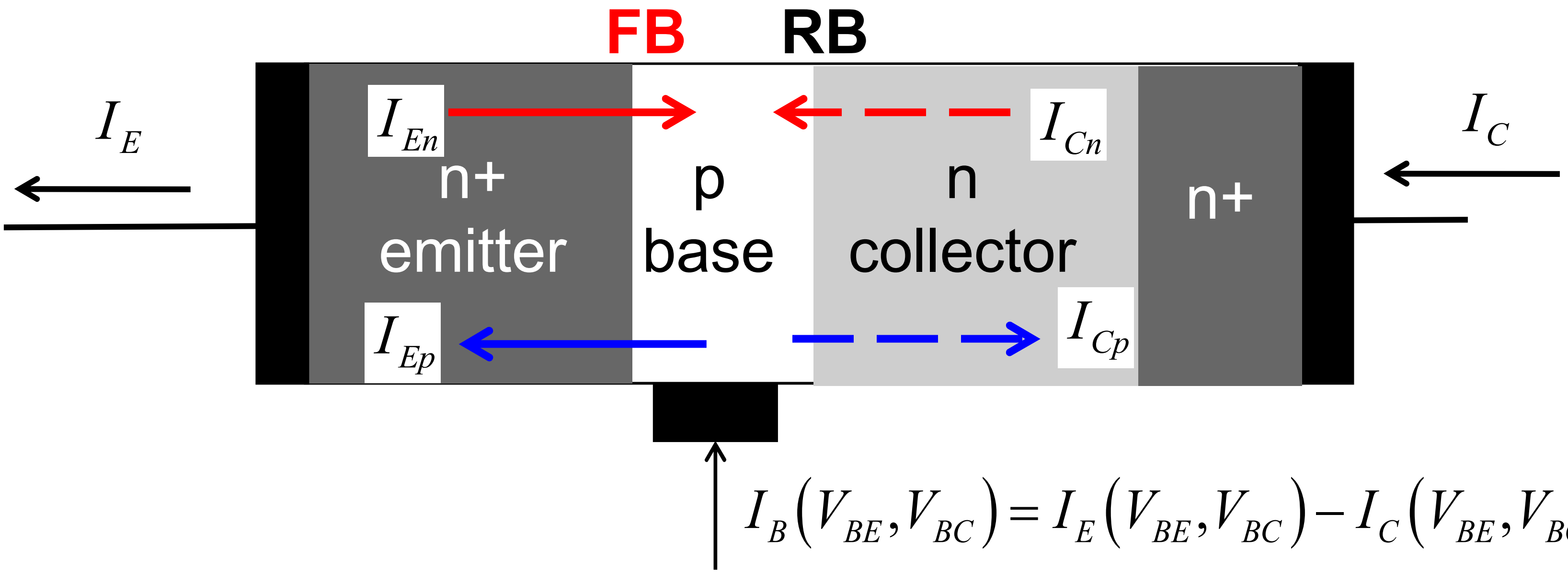
$$I_C = \alpha_T |I_{En}|$$

$$I_C = \alpha_T \gamma_F I_E$$

$$I_C = \alpha_F I_{F0} \left(e^{qV_{BE}/k_B T} - 1 \right)$$

$$\alpha_F = \alpha_T \gamma_F$$

Ebers-Moll model



$$I_B(V_{BE},V_{BC}) = I_E(V_{BE},V_{BC}) - I_C(V_{BE},V_{BC})$$

$$I_C(V_{BE},V_{BC}) = \alpha_F I_{F0}\left(e^{qV_{BE}/k_BT} - 1\right) - I_{R0}\left(e^{qV_{BC}/k_BT} - 1\right)$$

$$I_E(V_{BE},V_{BC}) = I_{F0}\left(e^{qV_{BE}/k_BT} - 1\right) - \alpha_R I_{R0}\left(e^{qV_{BC}/k_BT} - 1\right)$$

Ebers-Moll model

$$I_C\left(V_{BE,}V_{BC}\right)=\alpha_F I_{F0}\left(e^{qV_{BE}/k_BT}-1\right)-I_{R0}\left(e^{qV_{BC}/k_BT}-1\right)$$

$$I_E\left(V_{BE},V_{BC}\right)=I_{F0}\left(e^{qV_{BE}/k_BT}-1\right)-\alpha_R I_{R0}\left(e^{qV_{BC}/k_BT}-1\right)$$

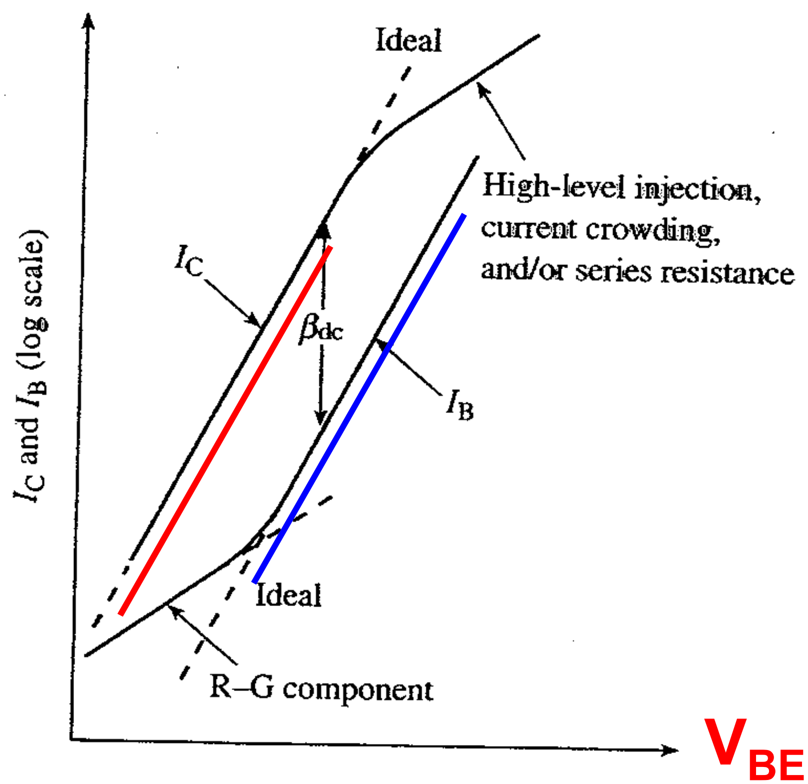
$$\alpha_F=\alpha_T\gamma_F \qquad I_{F0}=qA_E\left(\frac{n_i^2}{N_{AB}}\right)\frac{D_n}{W_B}+qA_E\left(\frac{n_i^2}{N_{DE}}\right)\frac{D_p}{W_E}$$

$$\alpha_R=\alpha_T\gamma_R \qquad I_{R0}=qA_E\left(\frac{n_i^2}{N_{AB}}\right)\frac{D_n}{W_B}+qA_E\left(\frac{n_i^2}{N_{DC}}\right)\frac{D_p}{W_C}$$

$$\alpha_F I_{F0}=\alpha_R I_{R0}$$

Gummel Plot and Output Characteristics

$$\frac{I_C}{A} = -\frac{qD_n}{W_B}\frac{n_{i,B}^2}{N_B}(e^{qV_{BE}/kT}-1)+\frac{qD_n}{W_B}\frac{n_{i,B}^2}{N_B}(e^{qV_{BC}/kT}-1)$$



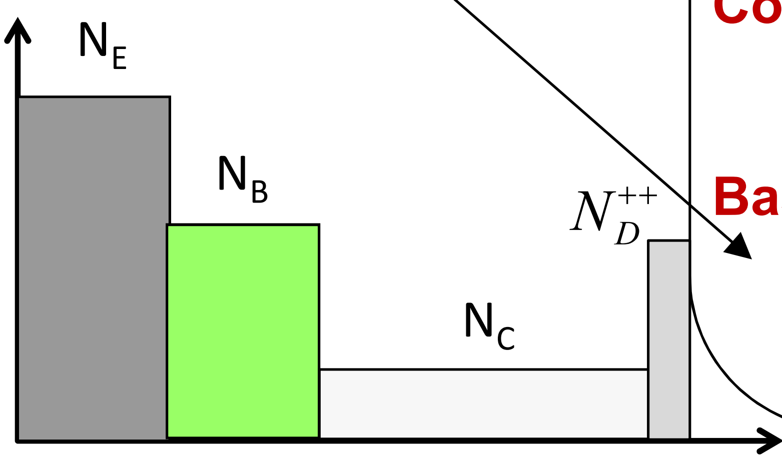
$$\frac{I_B}{A} = \frac{qD_p}{W_E}\frac{n_{i,E}^2}{N_E}(e^{qV_{BE}/kT}-1)$$

$$\beta_{DC} = \frac{I_C}{I_B}$$

$\beta_{DC} \longrightarrow$ Common emitter Current Gain

maximizing gains in BJTs

$$\beta_{dc} \approx \frac{D_n}{W_B}\frac{W_E}{D_p}\frac{n_{i,B}^2}{n_{i,E}^2}\frac{N_E}{N_B}$$



Emitter doping: As high as possible without *band gap narrowing*

Base doping: As low as possible, without *current crowding, Early effect*

Collector doping: Lower than base doping *without Kirk Effect*

Base Width: As thin as possible without *punch through* (~1 mm in '50s, 200 Å now)

How to make better Transistor

$$\beta \approx \frac{D_n}{W_B} \cdot \frac{W_E}{D_p} \frac{n_{i,B}^2}{n_{i,E}^2} \frac{N_E}{N_B}$$

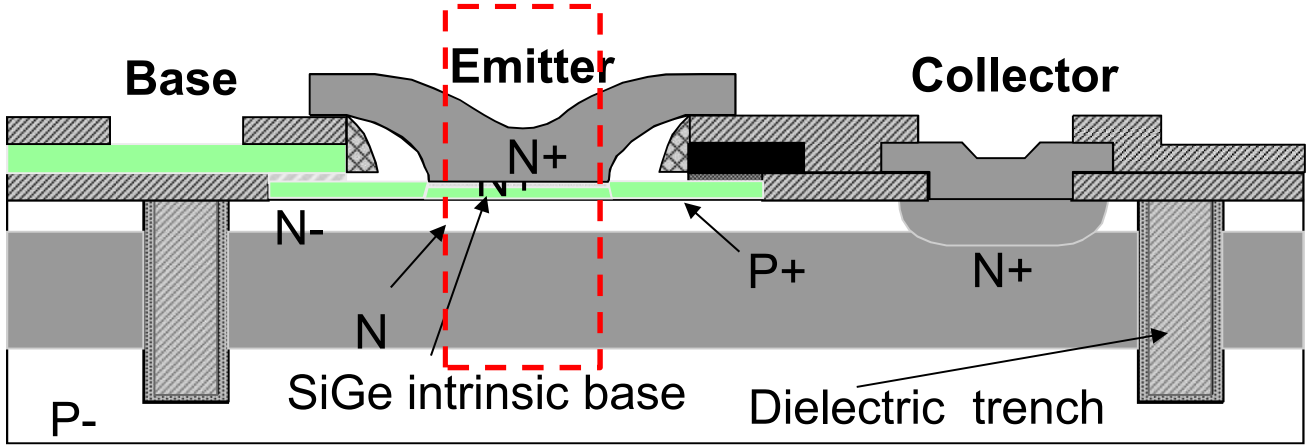
Graded Base transport

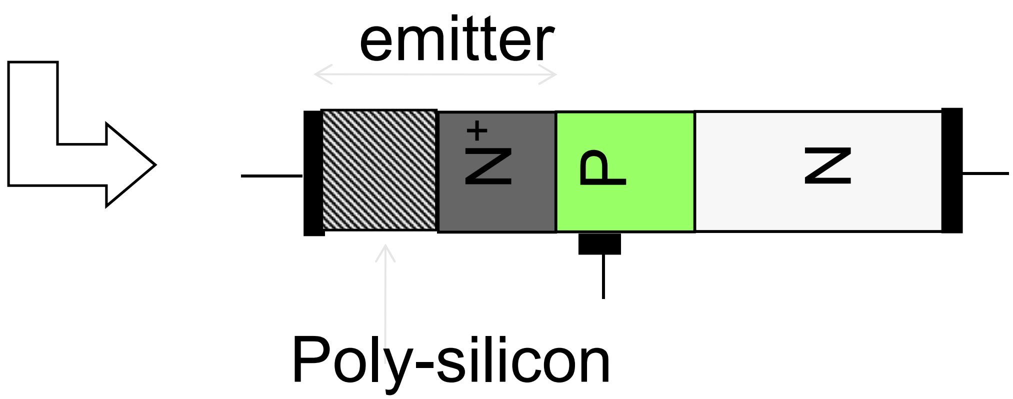
Polysilicon Emitter

Classical Shockley Transistor

Heterojunction Bipolar Transistor

poly-silicon HBT emitter





SiGe HBT applications

1) **optical fiber communications**

   -40Gb/s…….160Gb/s

2) **Wideband, high-resolution DA/AD converters and digital frequency synthesizers**

   -military radar and communications

3) **Monolithic, millimeter-wave IC's (MMIC's)**

   -front ends for receivers and transmitters

future need for transistors with
1 THz power-gain cutoff freq.

New equations on equation sheet

Bipolar transistors: (assuming NPN, short emitter, base, and collector)
Ebers-Moll Equations:

$$I_C(V_{BE},V_{BC}) = \alpha_F I_{F0}\left(e^{qV_{BE}/k_BT}-1\right) - I_{R0}\left(e^{qV_{BC}/k_BT}-1\right)$$

$$I_E(V_{BE},V_{BC}) = I_{F0}\left(e^{qV_{BE}/k_BT}-1\right) - \alpha_R I_{R0}\left(e^{qV_{BC}/k_BT}-1\right)$$

$$I_{F0} = qA\left(\frac{D_{nB}}{W_B}\frac{n_i^2}{N_{AB}} + \frac{D_{pE}}{W_E}\frac{n_i^2}{N_{DE}}\right)$$

$$I_{R0} = qA\left(\frac{D_{nB}}{W_B}\frac{n_i^2}{N_{AB}} + \frac{D_{pC}}{W_C}\frac{n_i^2}{N_{DC}}\right)$$

$$\alpha_F = \gamma_F \alpha_T$$

$$\alpha_R = \gamma_R \alpha_T$$

$$\alpha_F I_{F0} = \alpha_R I_{R0}$$

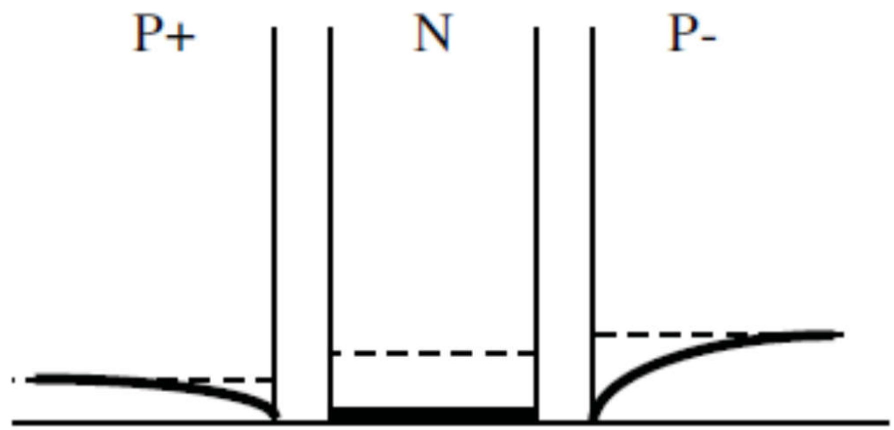
$$\gamma_F = \frac{I_{En}}{I_{En}+I_{Ep}} = \frac{1}{1+\frac{D_{pE}}{D_{nB}}\frac{W_B}{W_E}\frac{N_{AB}}{N_{DE}}}$$

$$\alpha_T = \frac{I_{Cn}}{I_{En}} = \frac{1}{1+\frac{1}{2}\left(\frac{W_B}{L_{nB}}\right)^2}$$

$$\beta_F = \frac{\alpha_F}{1-\alpha_F}$$

$$\alpha_F = \frac{\beta_F}{1+\beta_F}$$

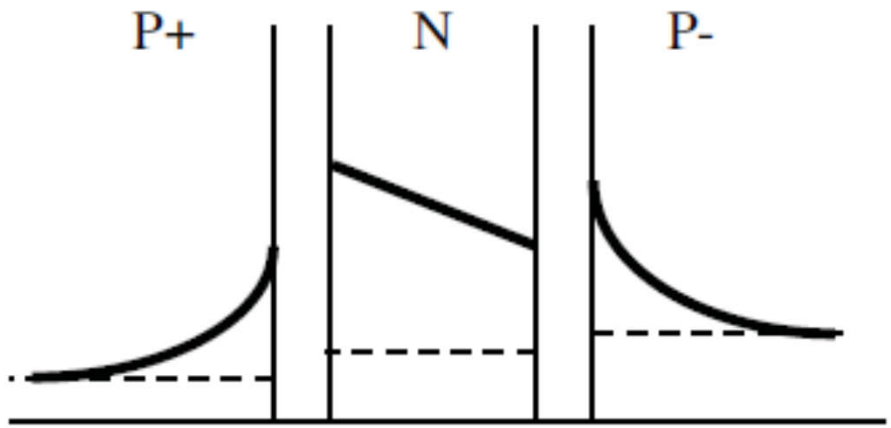
Practice Question 1



Region of Operation:

A. Forward Active
B. Inverse Active
C. Pinchoff
D. Saturation
E. Cutoff

Practice Question 2



Region of Operation:

A. Forward Active
B. Inverse Active
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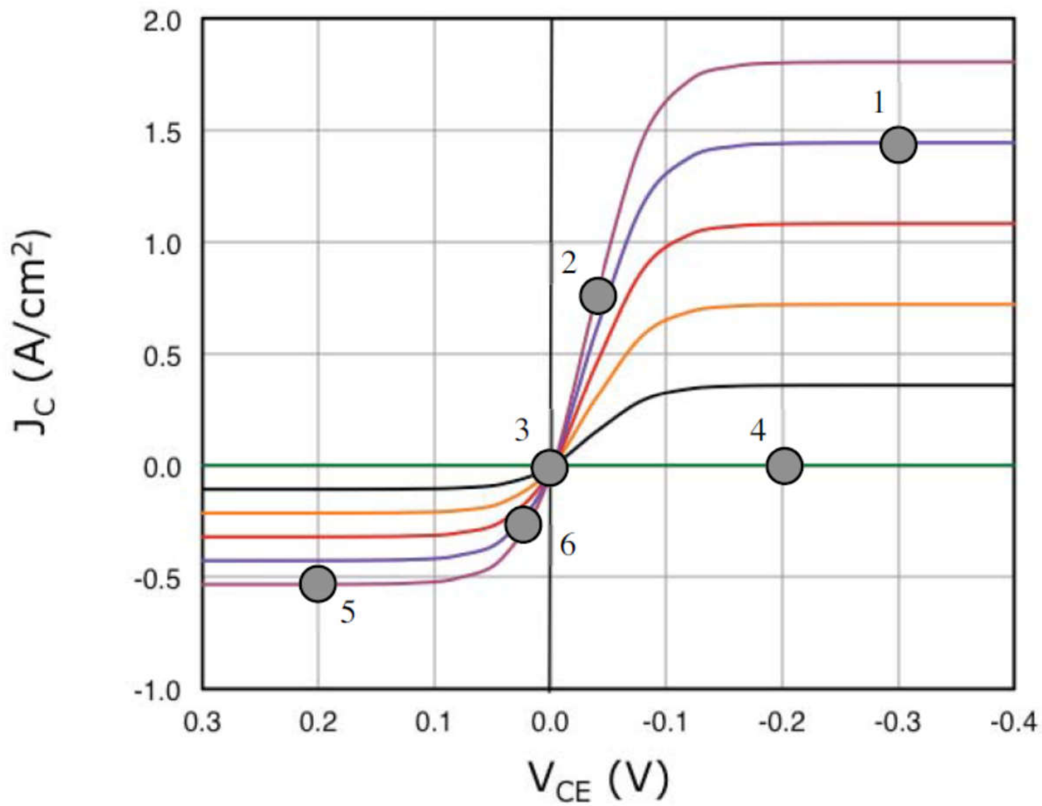
Practice Question 3



Region of Operation:

A. Forward Active: ___

B. Inverse Active: ___

C. Pinchoff : ___

D. Saturation : ___

E. Cutoff : ___

Practice Question 4

A narrow-base pnp BJT is operated as a diode by using the emitter and base terminals and leaving the collector terminal open. Using the Ebers-Moll model, obtain an equation for the open-circuit collector-base voltage as a function of the emitter current. Express your answer in terms of the Ebers-Moll parameters I_{FO}, I_{RO}, α_F, and α_R.

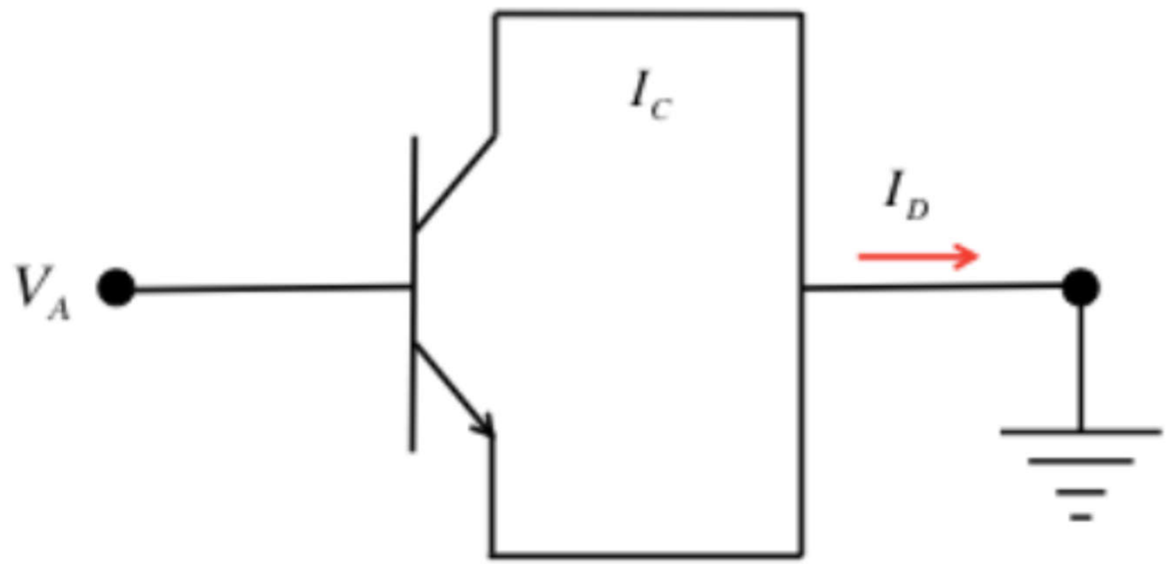
Practice Question 5

Which of the following would reduce “base width modulation” (i.e. the Early effect) and, therefore, increase the output resistance?

a) Increasing the emitter doping.
b) Increasing the collector doping.
c) Increasing the base width.
d) Increase the emitter thickness.
e) Decrease the base doping.

Practice Question 6

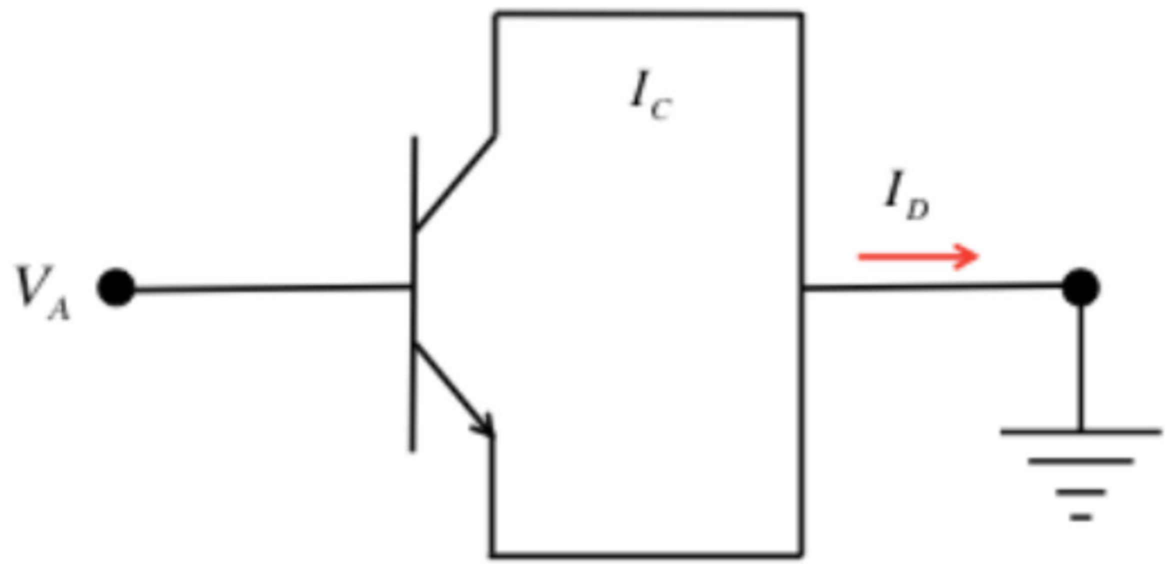
Consider the transistor circuit below



What is the region of operation for this transistor if the base voltage V_A is positive?

Practice Question 7

Write down the Ebers-Moll equations for the transistor circuit below:



Fall 2015: Multiple Choice

1 (8 points). Which of the following would increase the collector breakdown voltage in a BJT?

a. Increasing the emitter doping
b. Increasing the base doping
c. Increasing the collector doping
d. Decreasing the collector width
e. Decreasing the collector doping

Fall 2015: Multiple Choice

2 (8 points). How are the PN junctions biased in the forward active region of an NPN BJT?

a. Base-collector: forward biased   Emitter-base: forward biased
b. Base-collector: forward biased   Emitter-base: reverse biased
c. Base-collector: reverse biased   Emitter-base: forward biased
d. Base-collector: reverse biased   Emitter-base: reverse biased
e. Base-collector: forward biased   Emitter-base: biased in breakdown

Fall 2015: Multiple Choice

3 (8 points). What would be considered good values for α_{dc} and β_{dc}, respectively, in a BJT?

a. 0.1 and 0.11

b. 0.5 and 1

c. 0.99 and 99

d. 3 and 1.5

e. 20 and 1.052

Fall 2015: Multiple Choice

4 (8 points). For large gain in a bipolar transistor, the emitter doping must be …. ?

a. Larger than the base doping only
b. Smaller than the base doping only
c. Larger than the collector doping only
d. Larger than both base and collector doping
e. It does not matter

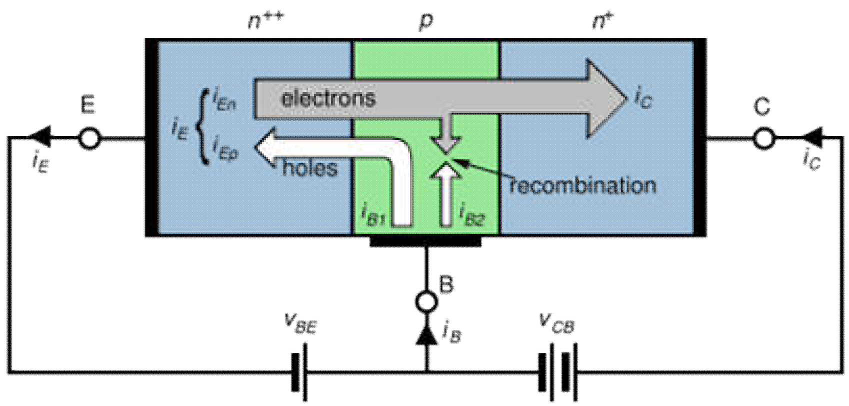
Fall 2015: Multiple Choice

5 (8 points). How can a heterojunction bipolar transistor be designed to improve β_{dc}?

a. Low bandgap material in the base region
b. Low bandgap material in the emitter region
c. High electron affinity material in the base region
d. Low breakdown voltage material in the collector region
e. High bandgap material in the base region

Fall 2015: Part II

Consider the NPN BJT made of silicon, depicted below. Assume that it is in the forward active region, with $IC=10$ μA, doping concentrations $N_{D,E}$=10^{18}/cm^3, $N_{A,B}$=10^{17}/cm^3, and $N_{D,C}$= 10^{16} /cm^3; thicknesses W_E=0.5 μm, W_B=0.25 μm, and W_C=2 μm; and diffusion constants $D_{p,E}$=2 cm^2/s, $D_{n,B}$=20 cm^2/s, and $D_{p,C}$=12 cm^2/s, and L_b=1 μm . The cross-sectional area A=1 μm^2. Assume that recombination within the BJT is small (i.e., diffusion lengths are much larger than the thicknesses of each layer).

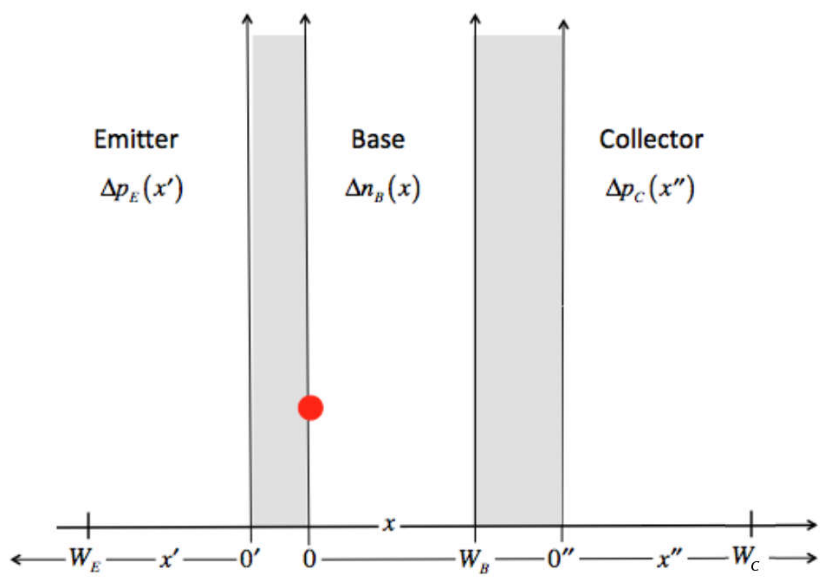


a) What is the emitter injection efficiency γF?
b) What is the base transport factor αT?
c) What is the common base current gain αDC?
d) What is the emitter gain βF (aka βdc)?
e) What is the forward saturation current density $IF0$?

Fall 2015: Part III

Consider the crystalline silicon-based bipolar junction transistor (BJT) depicted below. The shaded regions represent the depletion regions, while white regions may be treated as having zero electric field (in the depletion approximation). Assume that the doping concentrations $N_{D,E}$=10^{18}/cm^3, $N_{A,B}$=10^{17}/cm^3, and $N_{D,C}$= 10^{16} /cm^3. Assume $L_D \gg W_E$ and $L_D \gg W_C$.

a) Sketch the excess minority carrier concentrations (in all white regions) in forward active mode biasing.



Fall 2015: Part III

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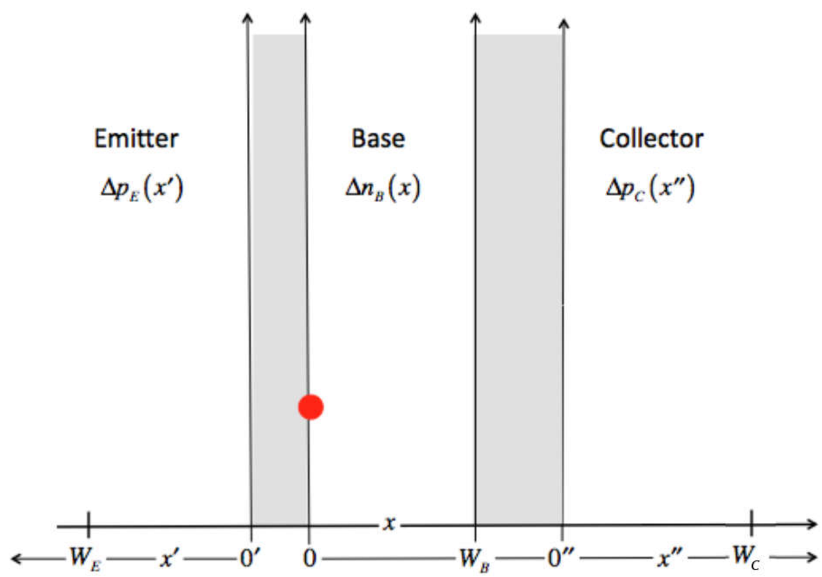
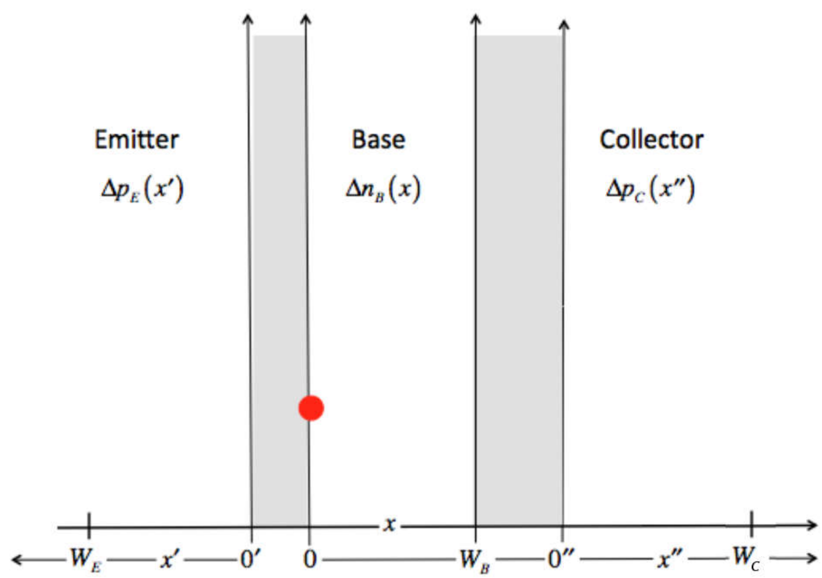
b) Sketch the excess minority carrier concentrations (in all white regions) in inverted mode biasing.



Fall 2015: Part III

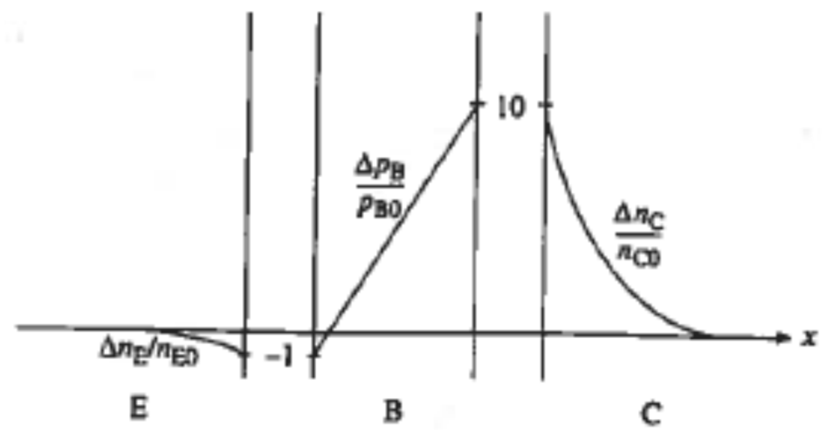
Consider the crystalline silicon-based bipolar junction transistor (BJT) depicted below. The shaded regions represent the depletion regions, while white regions may be treated as having zero electric field (in the depletion approximation). Assume that the doping concentrations $N_{D,E}$=10^{18}/cm^3, $N_{A,B}$=10^{17}/cm^3, and $N_{D,C}$= 10^{16} /cm^3. Assume $LD \gg WE$ and $LD \gg WC$.

c) Sketch the excess minority carrier concentrations (in all white regions) in cutoff mode biasing.



Fall 2015: Part III

(Questions d and e are based on the following information) The minority carrier concentrations in the quasineutral regions of a pnp BJT are given in the diagram below.



d) Estimate the sign of the collector-base and emitter-base biases, and deduce the operating mode of this BJT.

e) Calculate the magnitude of the collector-base bias V_{CB}.

Thank you for taking ECE 305

Good luck on your Final Exams!