ECE-305: Spring 2018
Bipolar Junction Transistors

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

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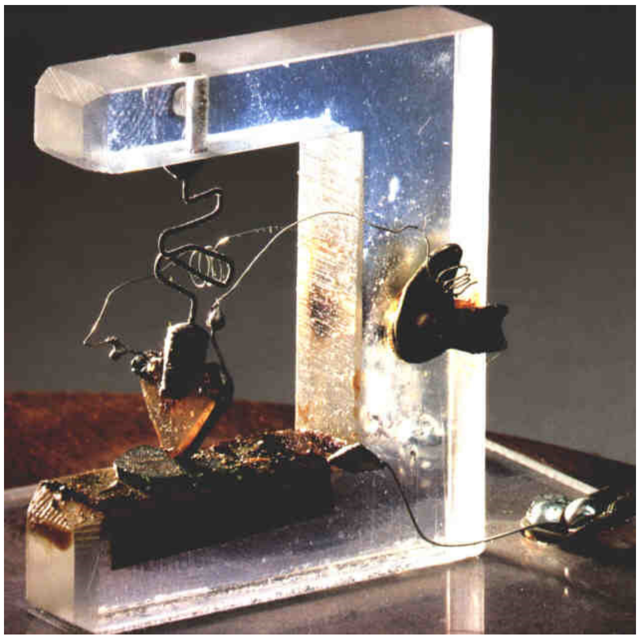
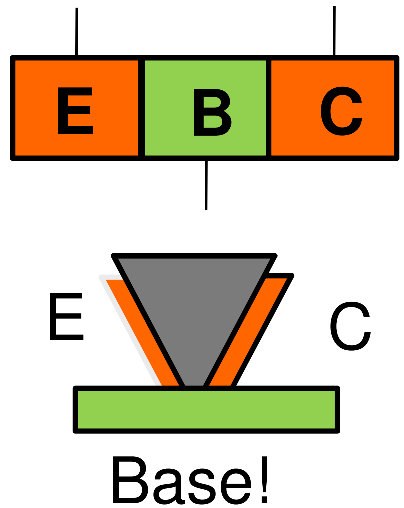
Outline

1) Introduction to Bipolar Junction Transistors
2) Definitions and conventions
3) Band diagram with and without biases
4) Forward active band-diagram
5) Currents in bipolar junction transistors
6) Conclusions

Background



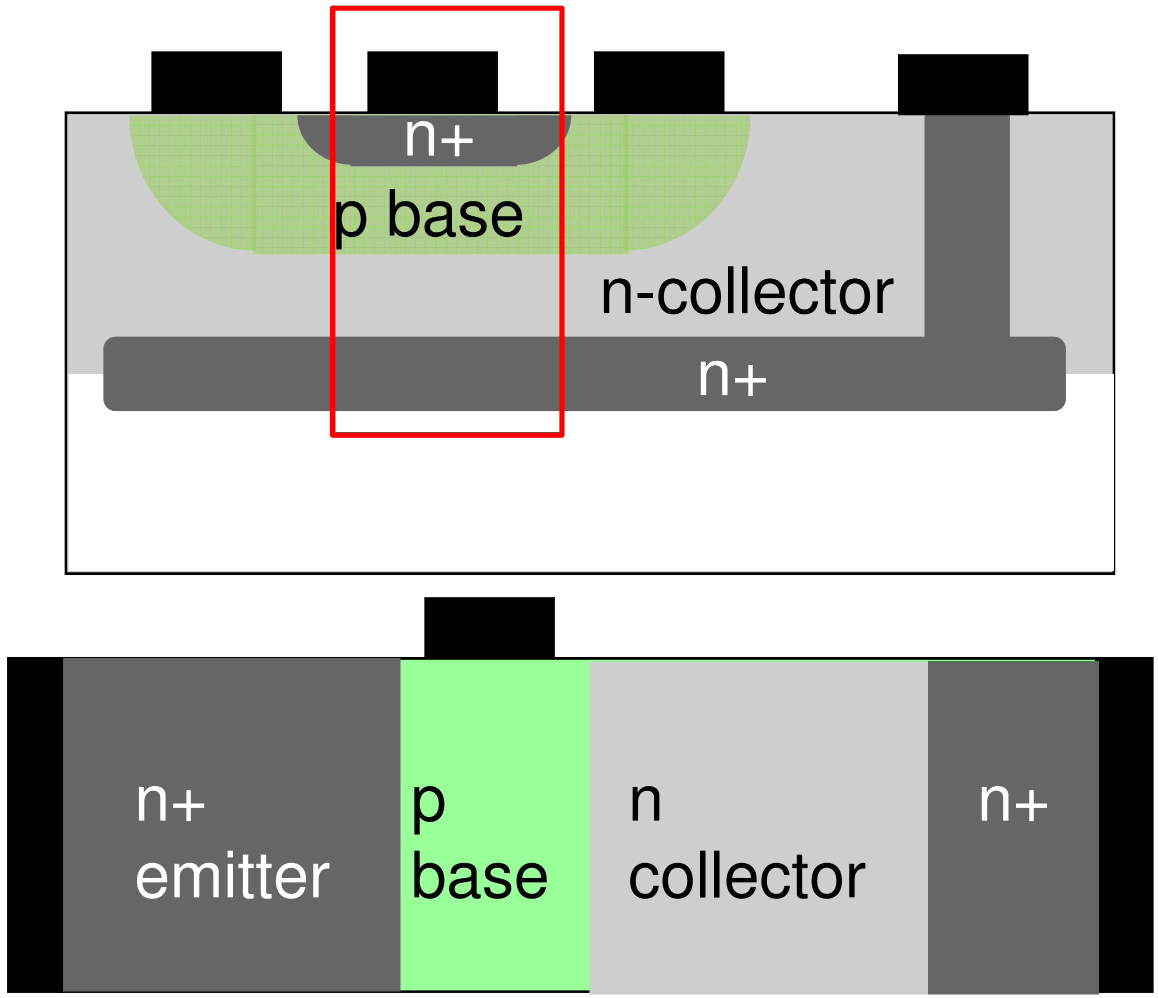


Point contact **Germanium** transistor (Bell Labs)

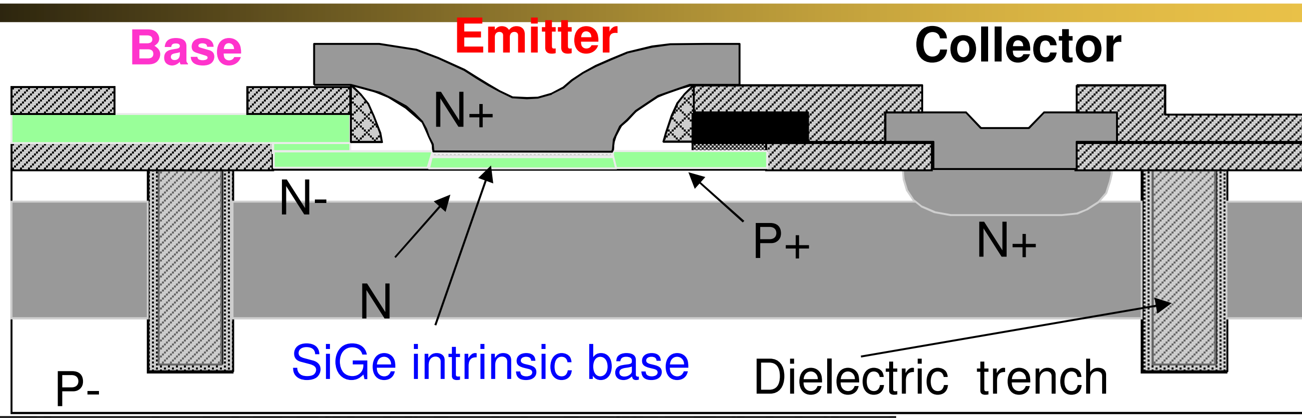
Shockley's Bipolar Transistors

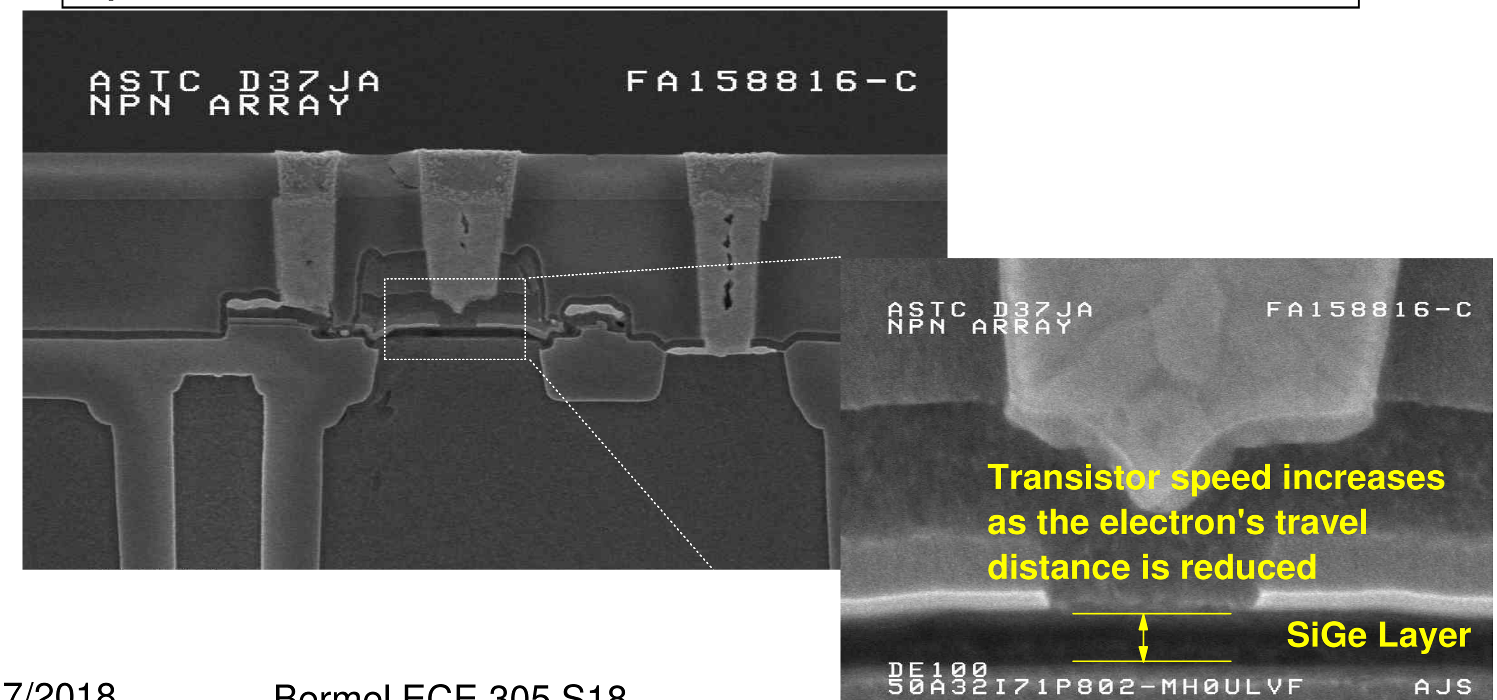
Double

Diffused BJT

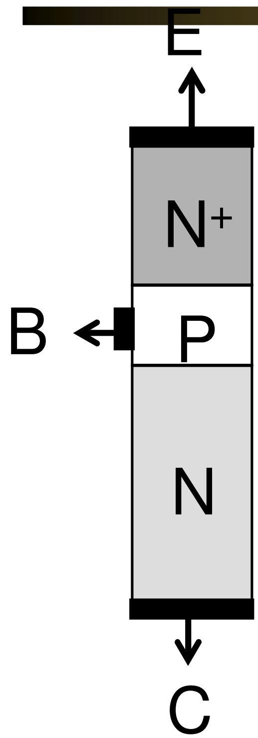


Modern Bipolar Junction Transistors (BJTs)





Symbols and Conventions

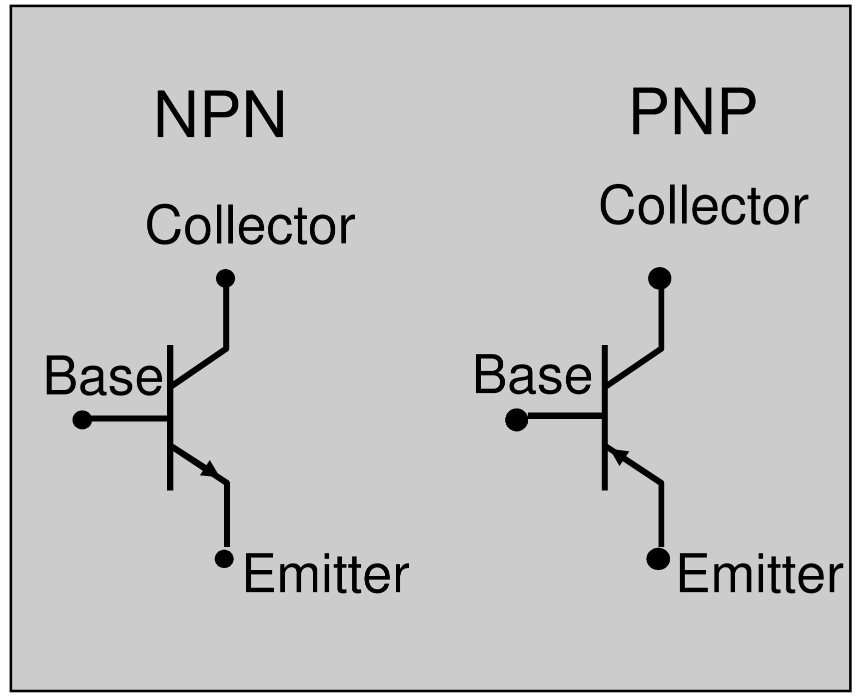


Poly emitter

Low-doped base

Collector doping optimization

Symbols

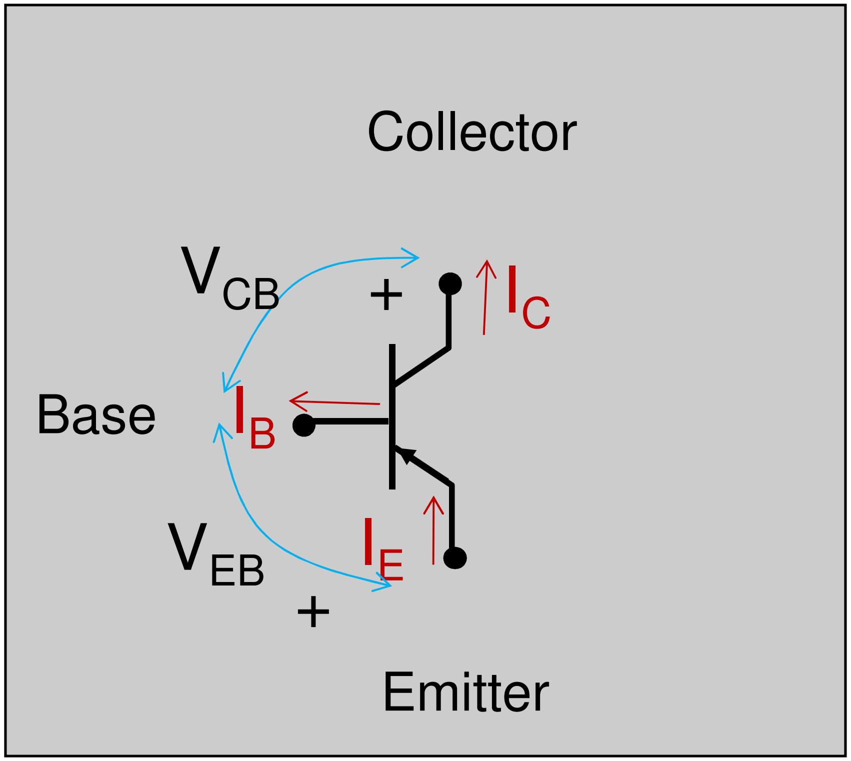


$$I_C+I_B+I_E=0$$

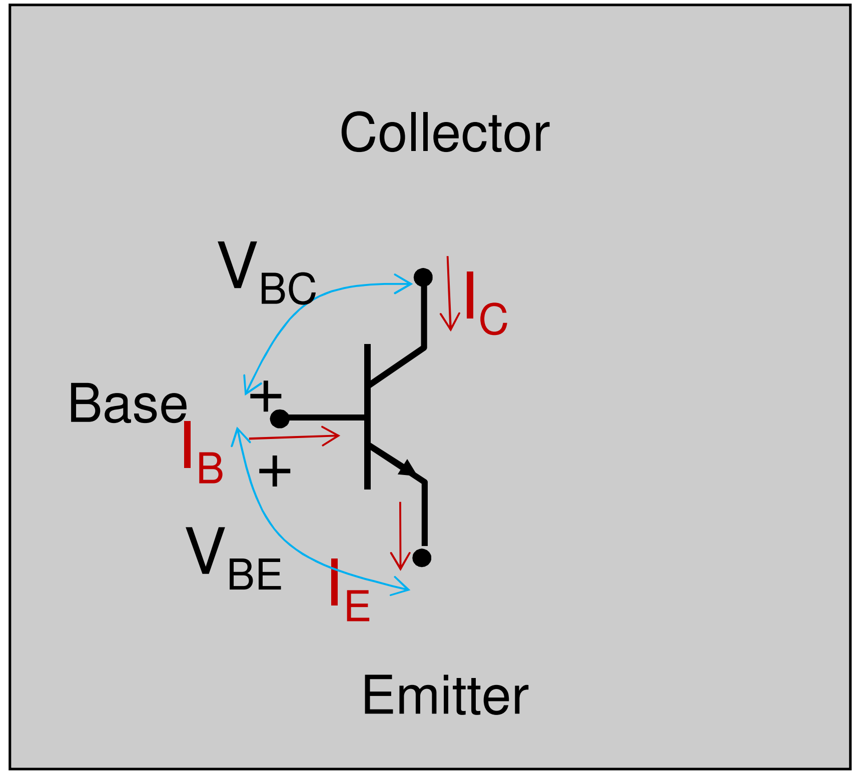
$$V_{EB}+V_{BC}+V_{CE}=0$$

Polarities

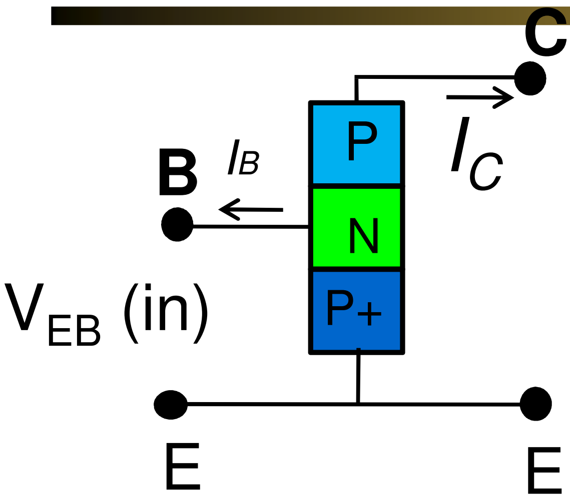
PNP Transistors

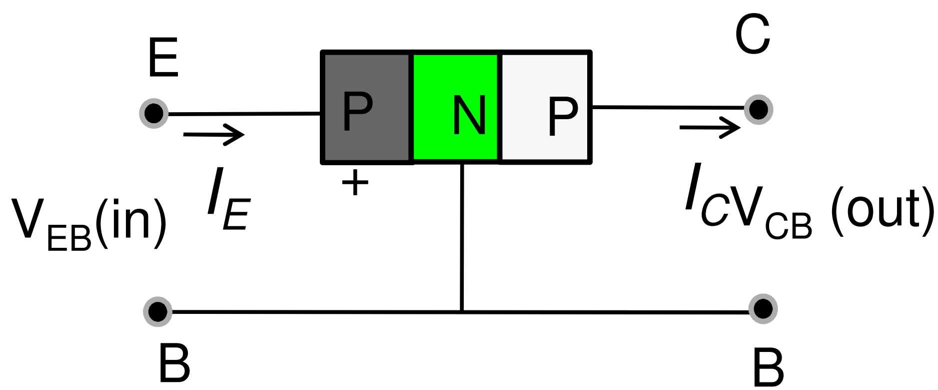


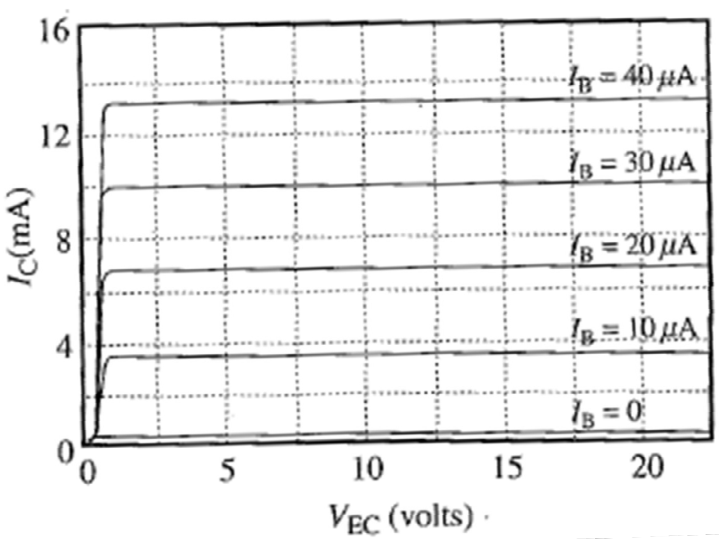
NPN Transistors

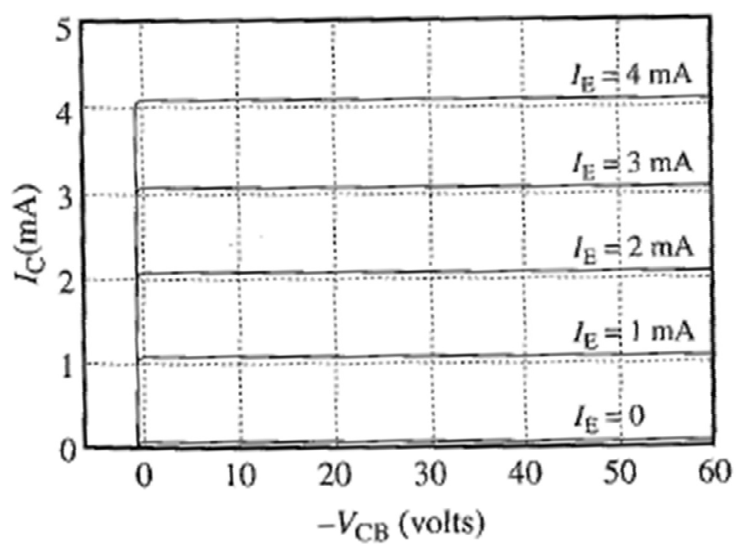


Configurations: Common Emitter/Common Base





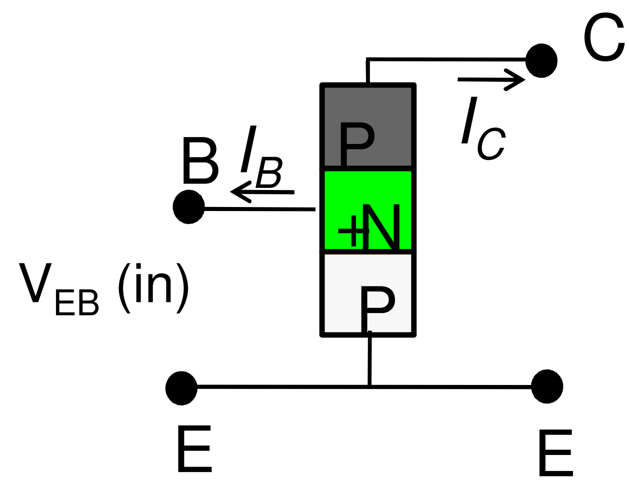




Current Gain

Common Emitter current gain ..

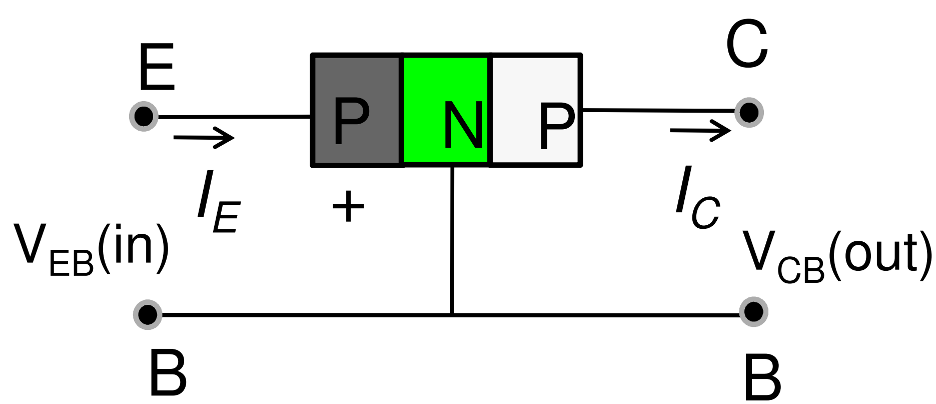
$$\beta_{DC} = \frac{I_C}{I_B}$$



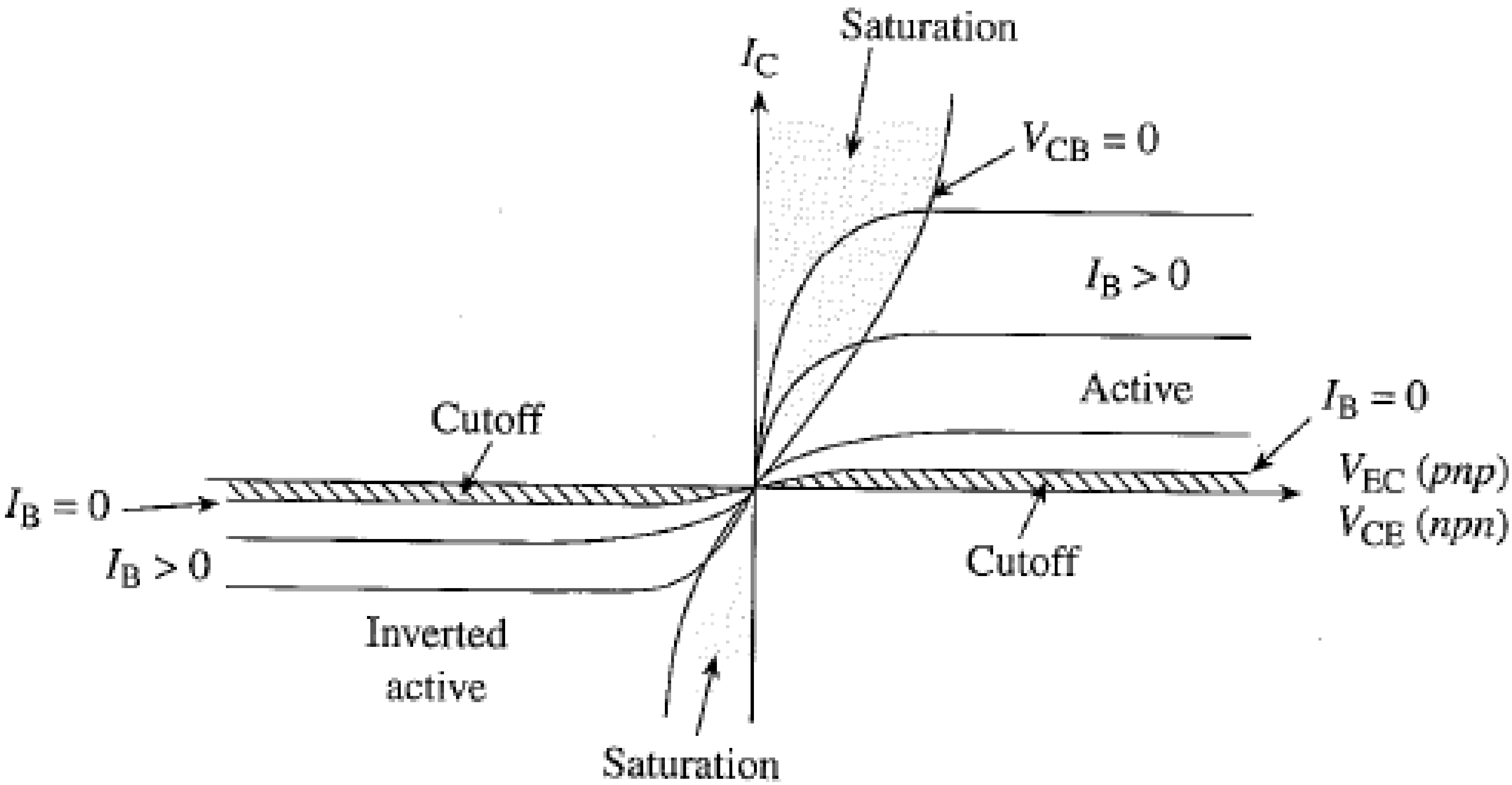
Common Base current gain ..

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

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



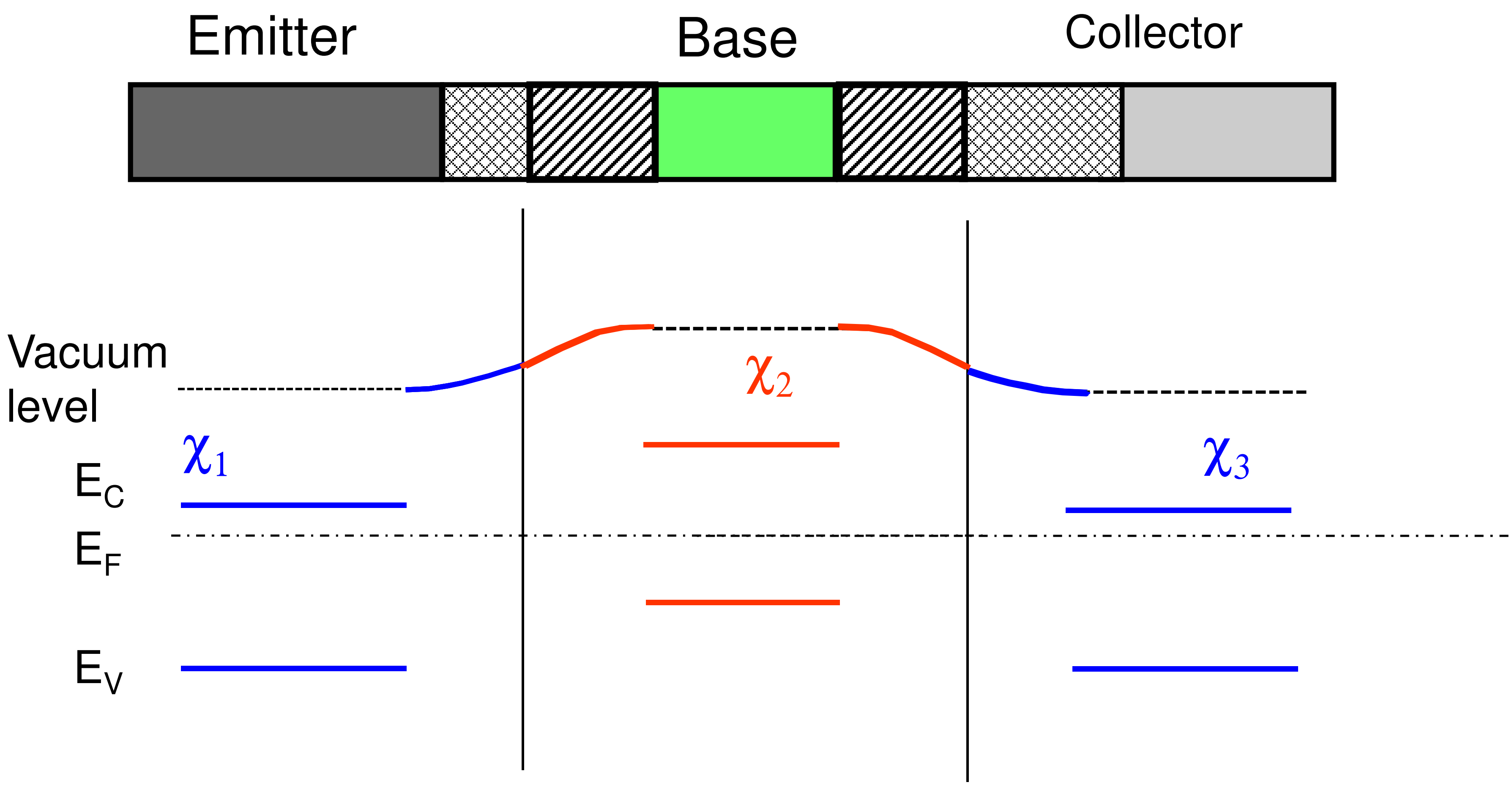
Current Gain



Topic Map

	Equilibrium	DC	Small signal	Large Signal	Circuits
Diode					
Schottky					
BJT/HBT	◆				
MOS					

Band Diagram at Equilibrium



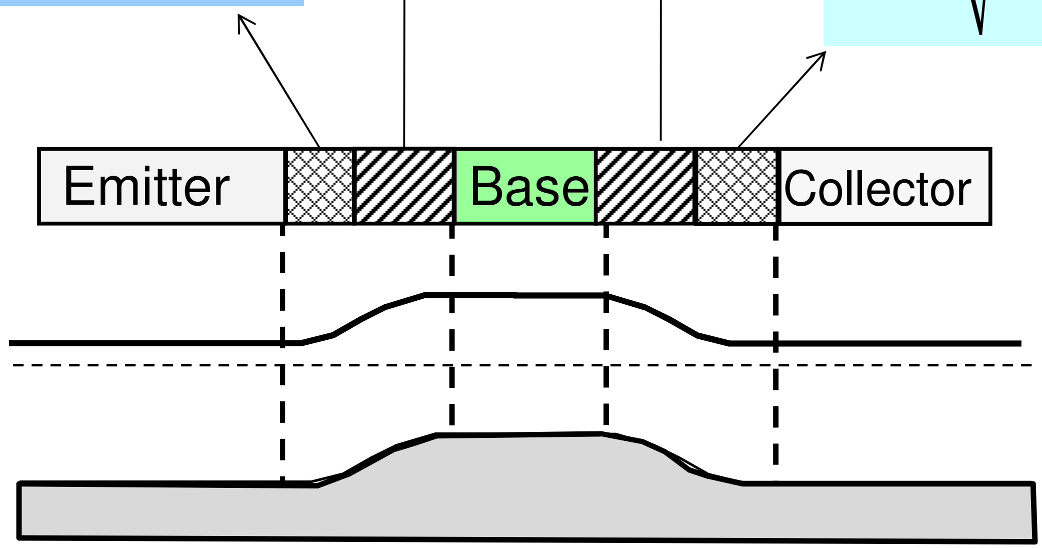
Electrostatics in Equilibrium

$$x_{p,BE} = \sqrt{\frac{2k_s\varepsilon_0}{q}\frac{N_E}{N_B\left(N_E+N_B\right)}V_{bi}}$$

$$x_{p,BC} = \sqrt{\frac{2k_s\varepsilon_0}{q}\frac{N_C}{N_B\left(N_C+N_B\right)}V_{bi}}$$

$$x_{n,E} = \sqrt{\frac{2k_s\varepsilon_0}{q}\frac{N_B}{N_E\left(N_B+N_E\right)}V_{bi}}$$

$$x_{n,C} = \sqrt{\frac{2k_s\varepsilon_0}{q}\frac{N_B}{N_C\left(N_C+N_B\right)}V_{bi}}$$



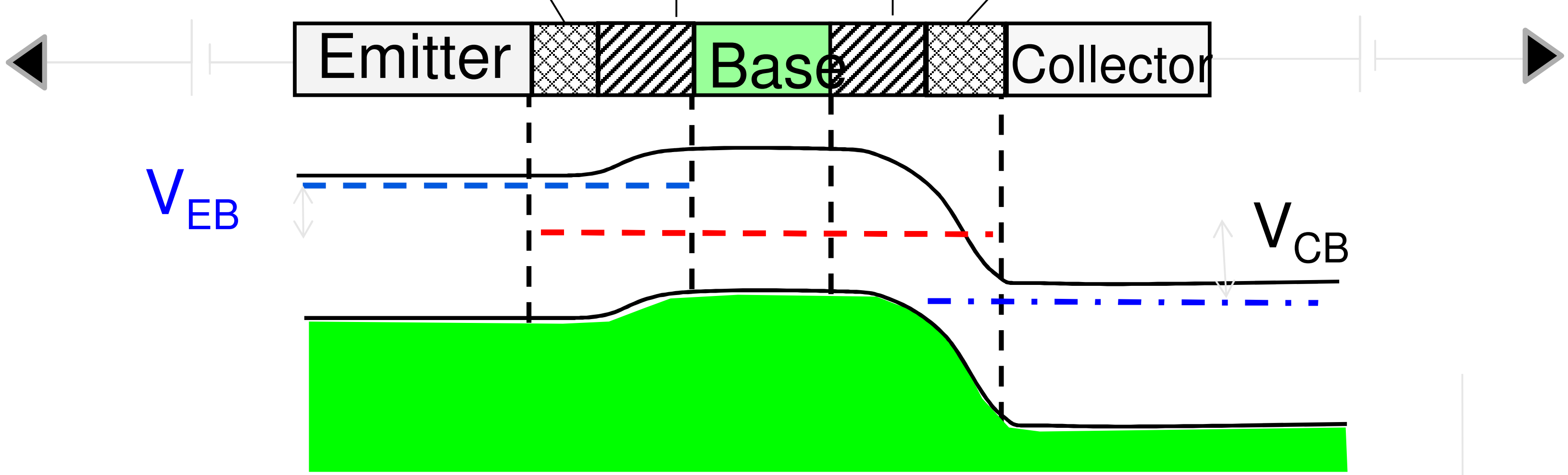
Electrostatics in Equilibrium

$$x_{p,BE} = \sqrt{\frac{2k_s\varepsilon_0}{q}\frac{N_E}{N_B\left(N_E+N_B\right)}\left(V_{bi}-V_{EB}\right)}$$

$$x_{p,BC} = \sqrt{\frac{2k_s\varepsilon_0}{q}\frac{N_C}{N_B\left(N_C+N_B\right)}\left(V_{bi}-V_{CB}\right)}$$

$$x_{n,E} = \sqrt{\frac{2k_s\varepsilon_0}{q}\frac{N_B}{N_E\left(N_B+N_E\right)}\left(V_{bi}-V_{EB}\right)}$$

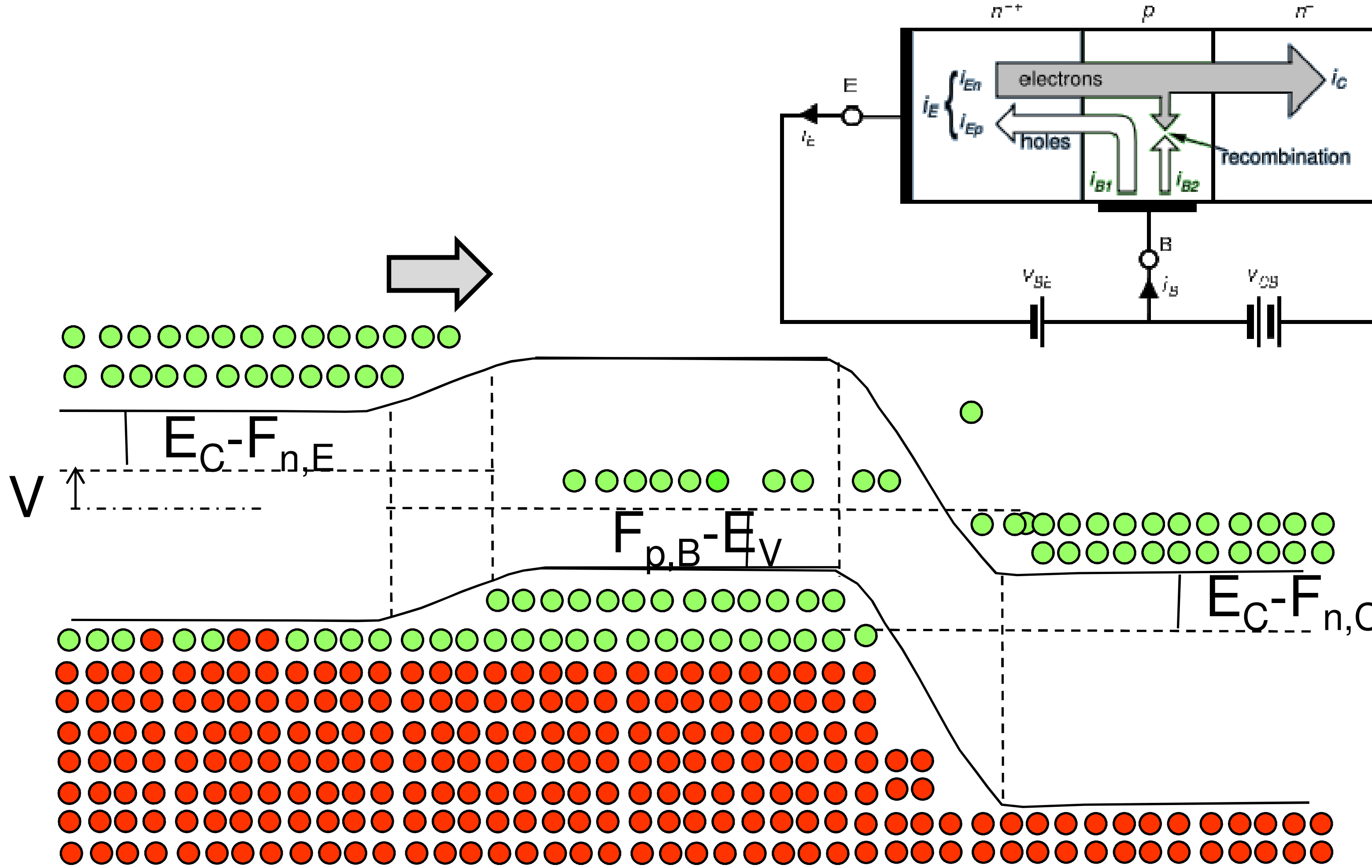
$$x_{n,C} = \sqrt{\frac{2k_s\varepsilon_0}{q}\frac{N_B}{N_C\left(N_C+N_B\right)}\left(V_{bi}-V_{CB}\right)}$$



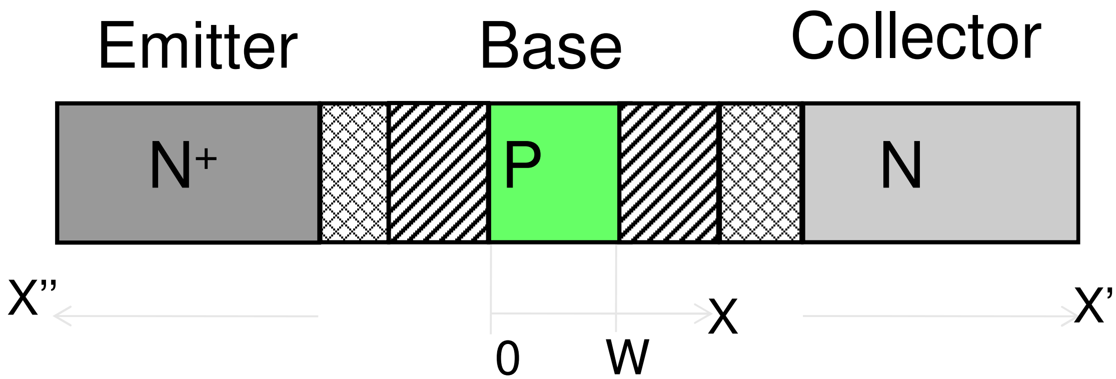
Topic Map

	Equilibrium	DC	Small signal	Large Signal	Circuits
Diode					
Schottky					
BJT/HBT		◆			
MOS					

Current flow with Bias



Coordinates and Convention



$$N_E = N_{D,E} \qquad N_B = N_{A,B} \qquad N_C = N_{D,C}$$

$$D_E = D_P \qquad D_B = D_N \qquad D_C = D_P$$

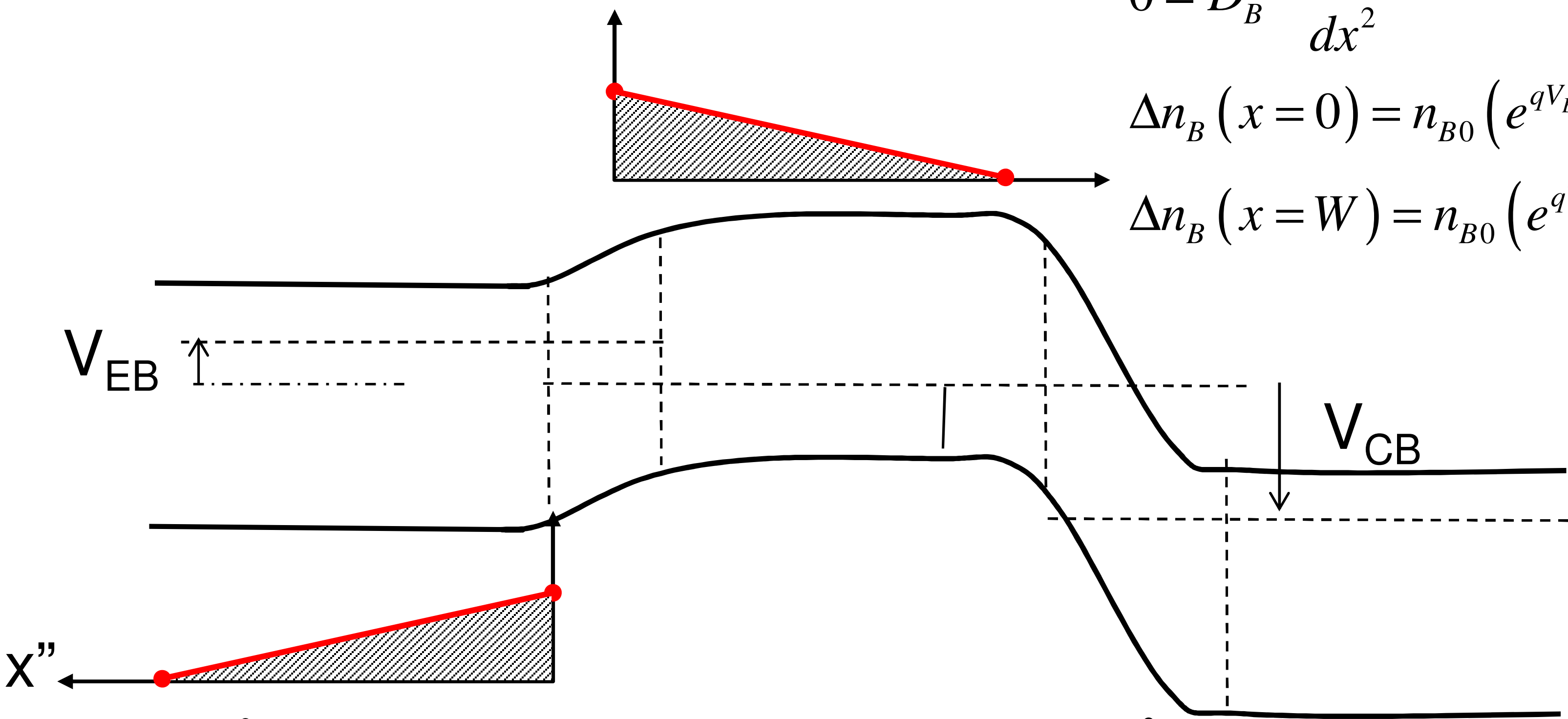
$$n_{E0} = n_{p0} \qquad p_{B0} = p_{n0} \qquad n_{C0} = n_{n0}$$

Carrier Distribution in Base

$$0 = D_B \frac{d^2 \Delta n_B}{dx^2}$$

$$\Delta n_B\left(x=0\right) = n_{B0}\left(e^{qV_{BE}/k_BT} - 1\right)$$

$$\Delta n_B\left(x=W\right) = n_{B0}\left(e^{qV_{BC}/k_BT} - 1\right)$$



$$0 = D_E \frac{d^2 \Delta p_E}{dx^2}$$

$$\Delta p_E\left(x''=W_E\right) = 0$$

$$\Delta p_E\left(x''=0\right) = p_{E0}\left(e^{qV_{BE}/k_BT} - 1\right)$$

$$0 = D_C \frac{d^2 \Delta p_C}{dx^2}$$

$$\Delta p_C\left(x'=W_C\right) = 0$$

$$\Delta p_C\left(x'=0\right) = p_{C0}\left(e^{qV_{BC}/k_BT} - 1\right)$$

Carrier Distribution in Base

$$\Delta n_B(x) = Ax + B = C\left(1 - \frac{x}{W_B}\right) + D\left(\frac{x}{W_B}\right)$$

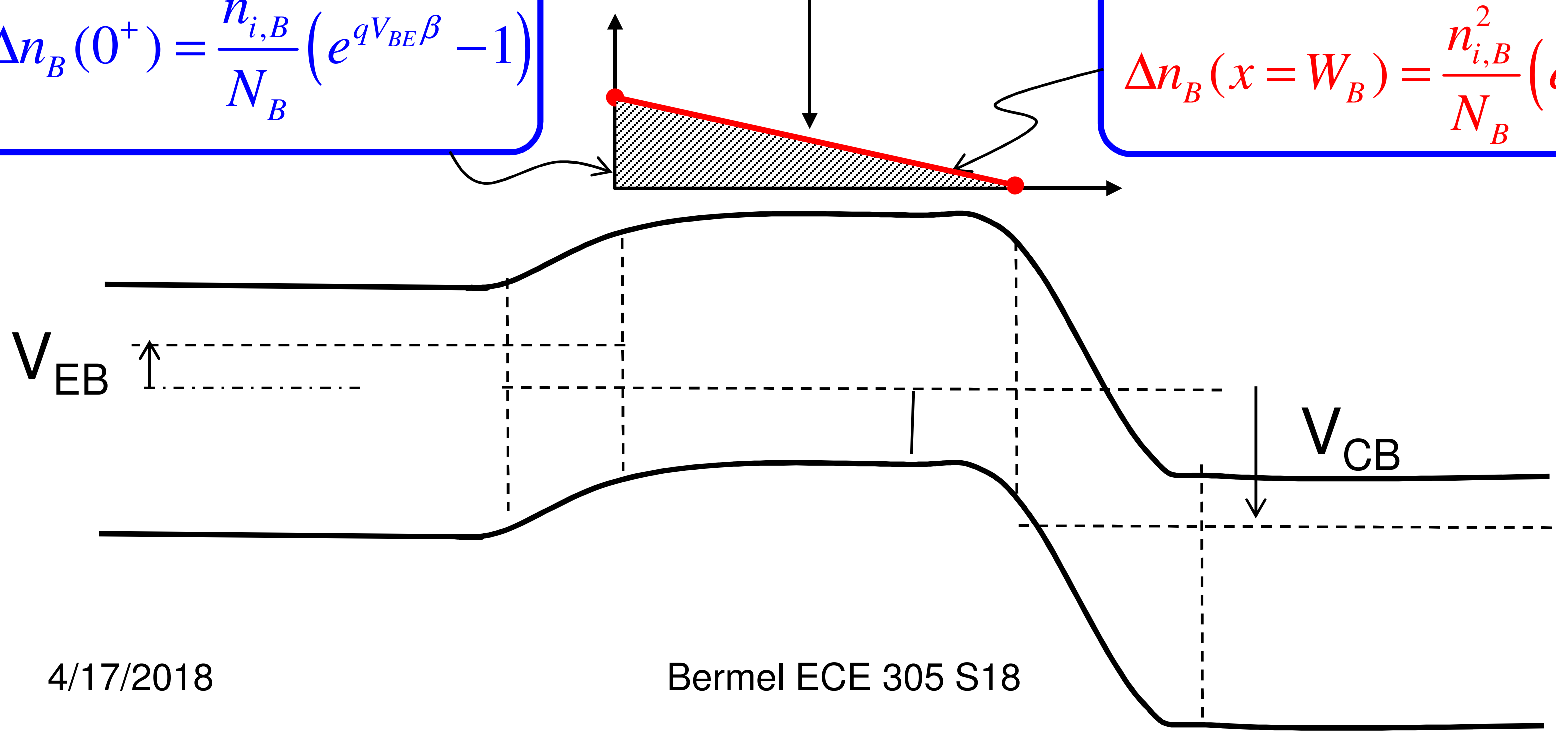
C

D

$$\Delta n_B(x) = \frac{n_{i,B}^2}{N_B}\left(e^{qV_{BE}\beta} - 1\right)\left(1 - \frac{x}{W_B}\right) + \frac{n_{i,B}^2}{N_B}\left(e^{qV_{BC}\beta} - 1\right)\left(\frac{x}{W_B}\right)$$

$$\Delta n_B(0^+) = \frac{n_{i,B}^2}{N_B}\left(e^{qV_{BE}\beta} - 1\right)$$

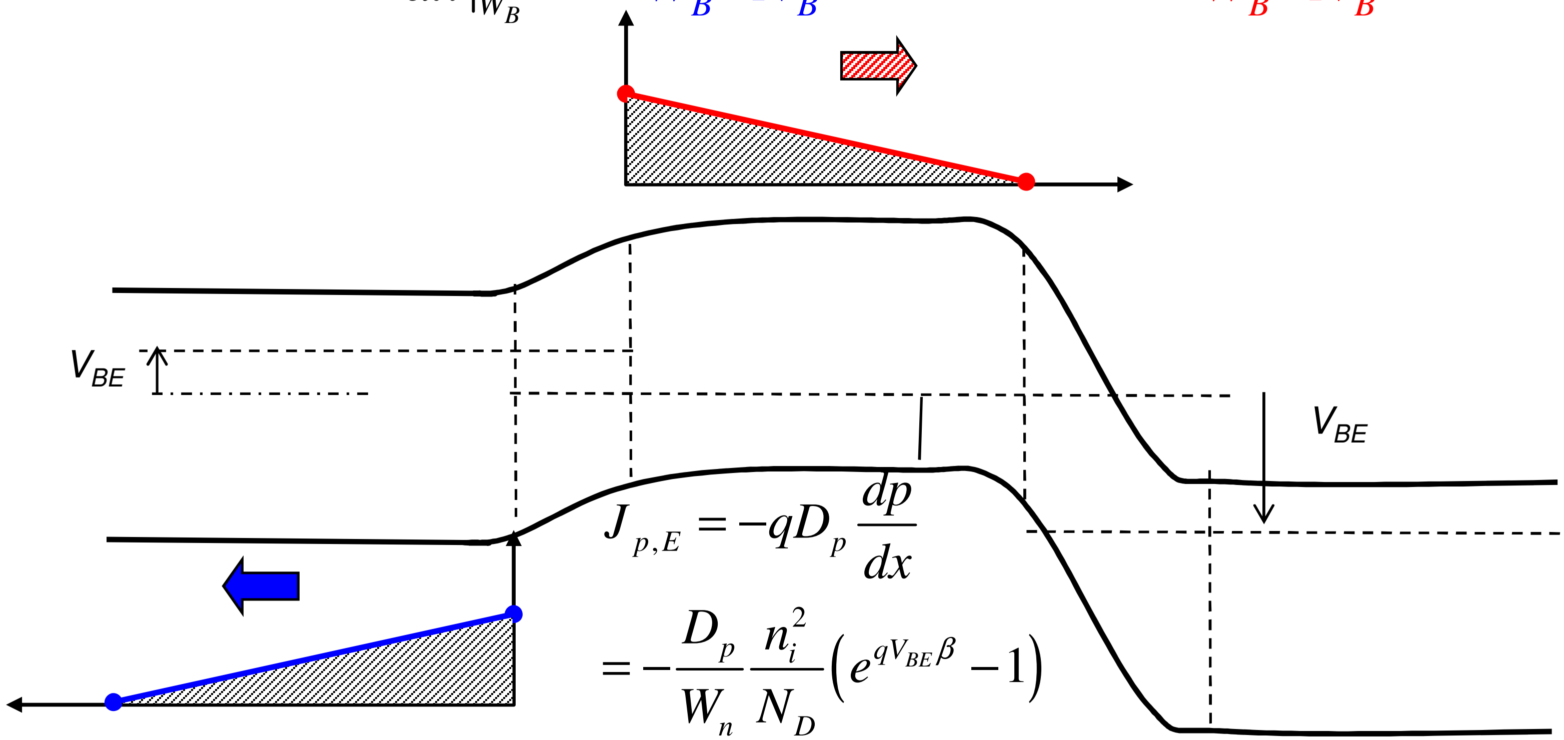
$$\Delta n_B(x = W_B) = \frac{n_{i,B}^2}{N_B}\left(e^{qV_{BC}\beta} - 1\right)$$



Collector Electron Current

$$\Delta n_B(x) = \frac{n_{i,B}^2}{N_B}\left(e^{qV_{BE}/k_BT} - 1\right)\left(1 - \frac{x}{W_B}\right) + \frac{n_{i,B}^2}{N_B}\left(e^{qV_{BC}/k_BT} - 1\right)\left(\frac{x}{W_B}\right)$$

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



$$J_{p,E} = -qD_p\frac{dp}{dx}$$

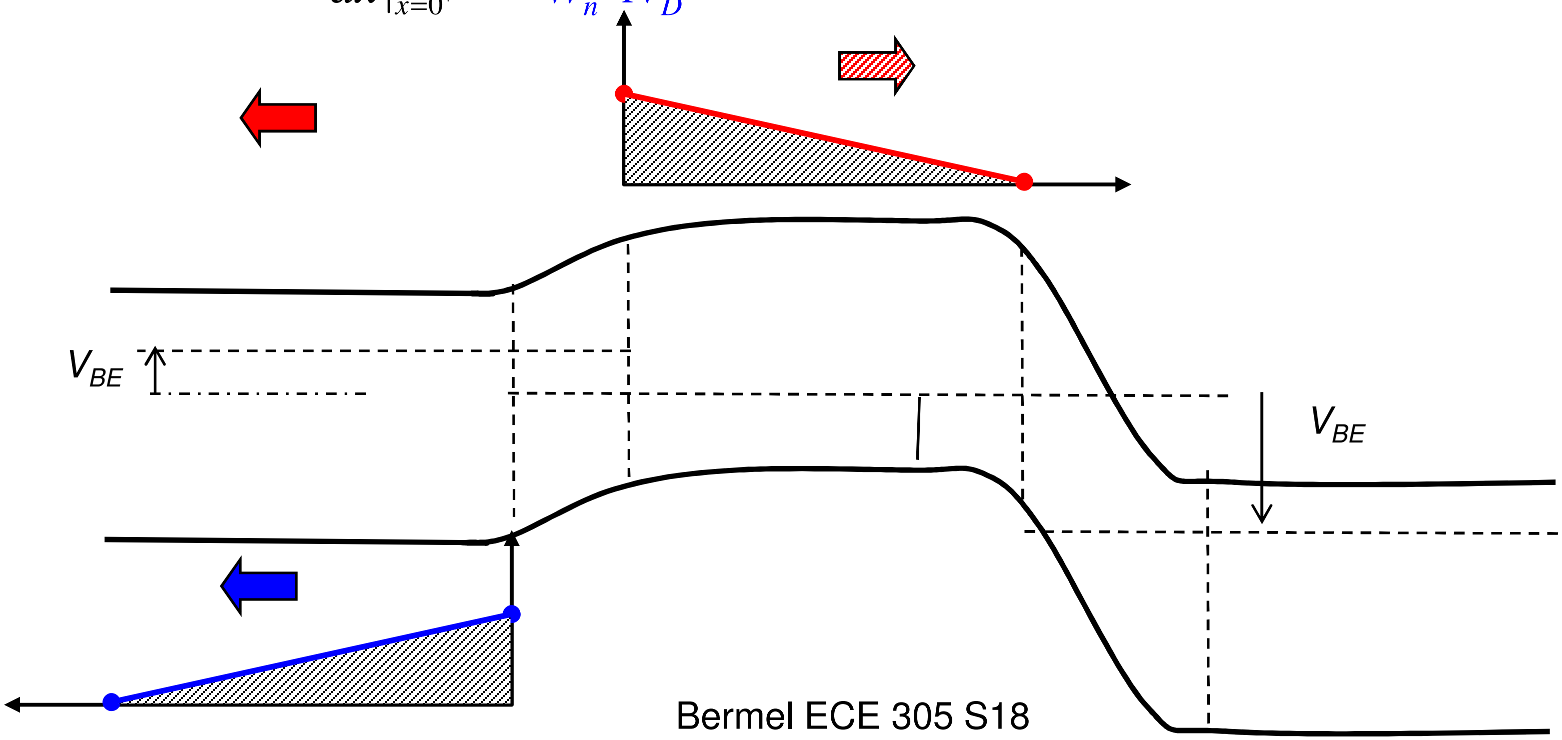
$$= -\frac{D_p}{W_n}\frac{n_i^2}{N_D}\left(e^{qV_{BE}\beta} - 1\right)$$

Emitter Current

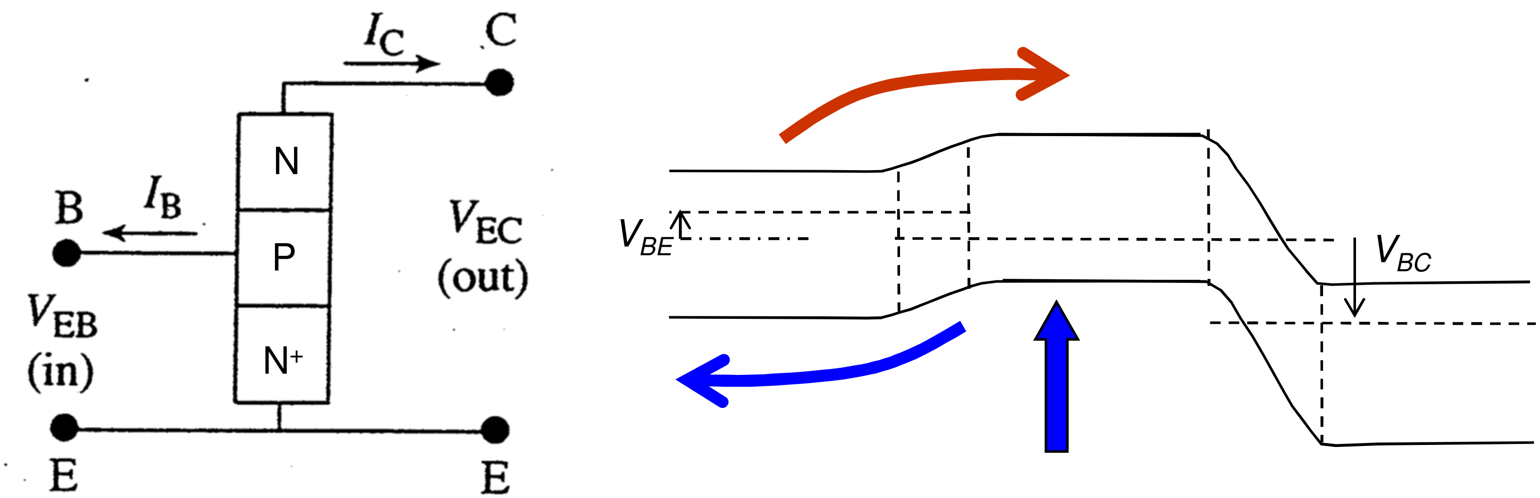
$$J_{n,E} = qD_n \left.\frac{dn}{dx}\right|_{x=0} = -\frac{qD_n}{W_B}\frac{n_{i,B}^2}{N_B}\left(e^{qV_{BE}/k_BT}-1\right)+\frac{qD_n}{W_B}\frac{n_{i,B}^2}{N_B}\left(e^{qV_{BC}/k_BT}-1\right)$$

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

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



essence of current gain



Input → Response → Input

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

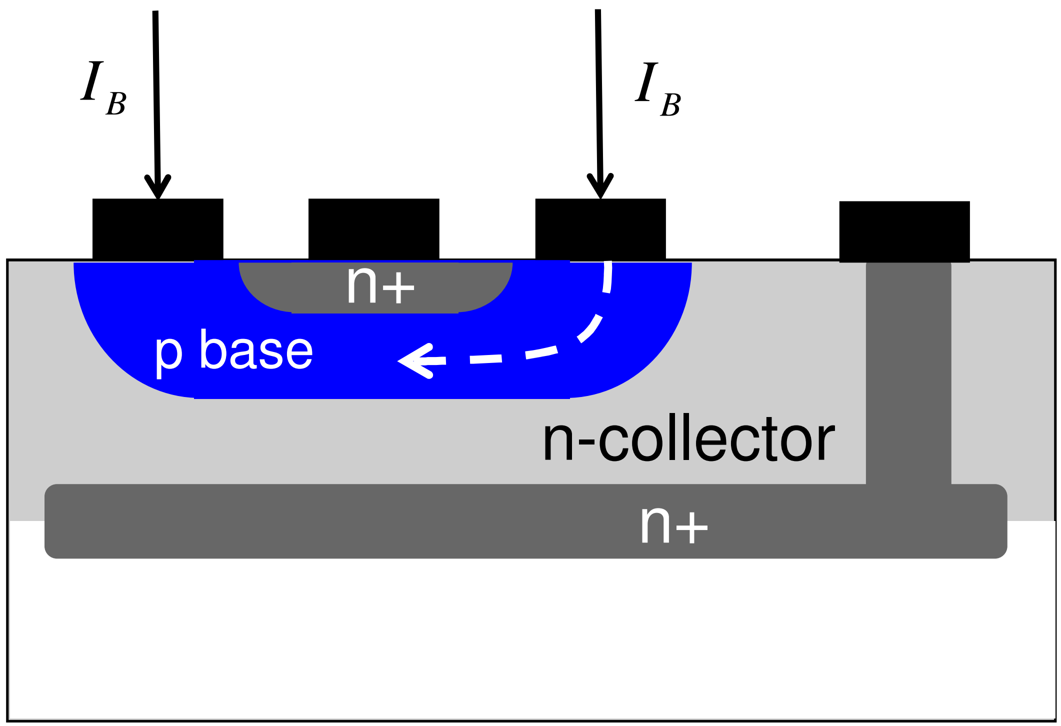
$$I_E \approx \frac{qD_n}{W_B}\frac{n_{i,B}^2}{N_B}\left(e^{qV_{BE}\beta}-1\right)$$

Response

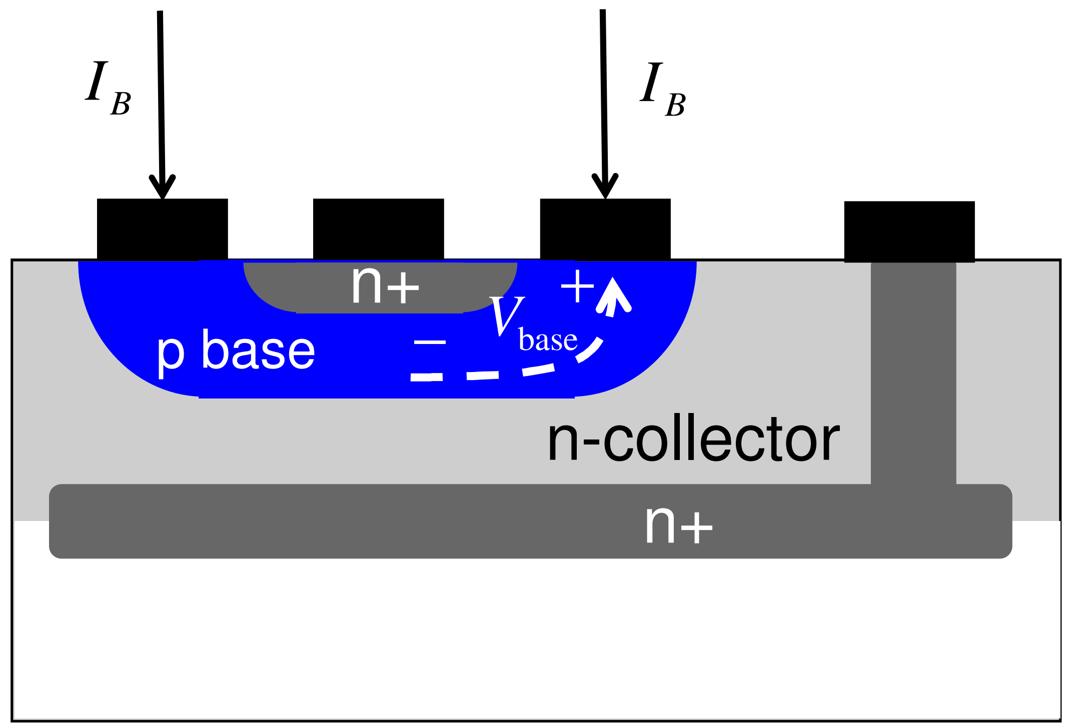
Outline

1) Equilibrium and forward band-diagram
2) Currents in bipolar junction transistors
3) **Ebers Moll model**
4) Conclusions

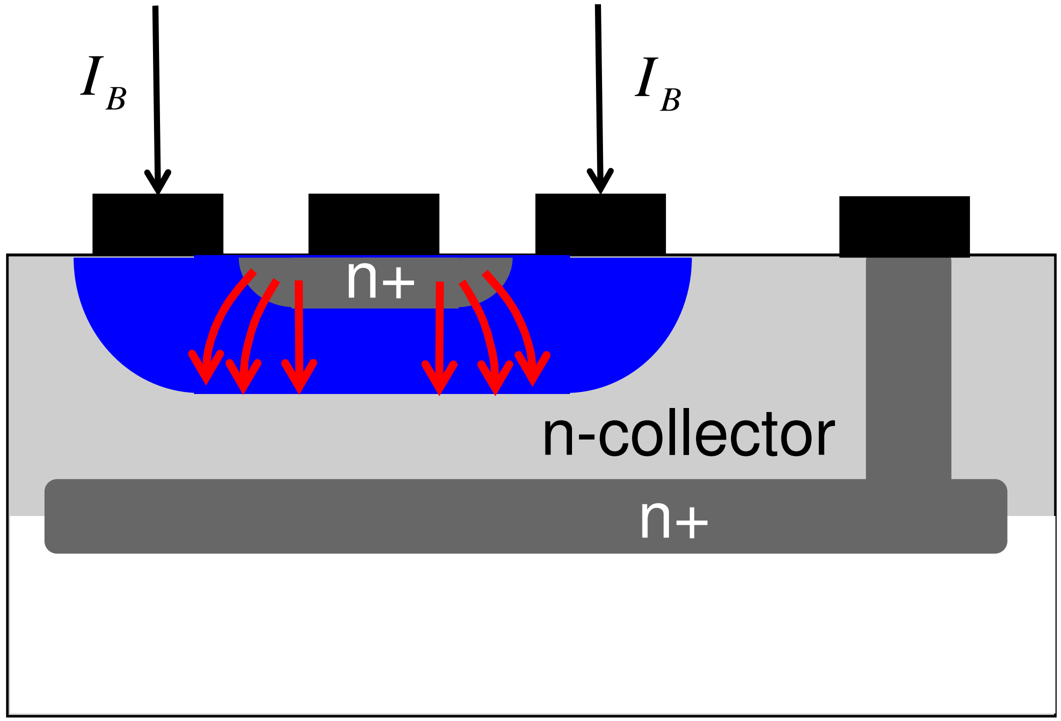
emitter current crowding



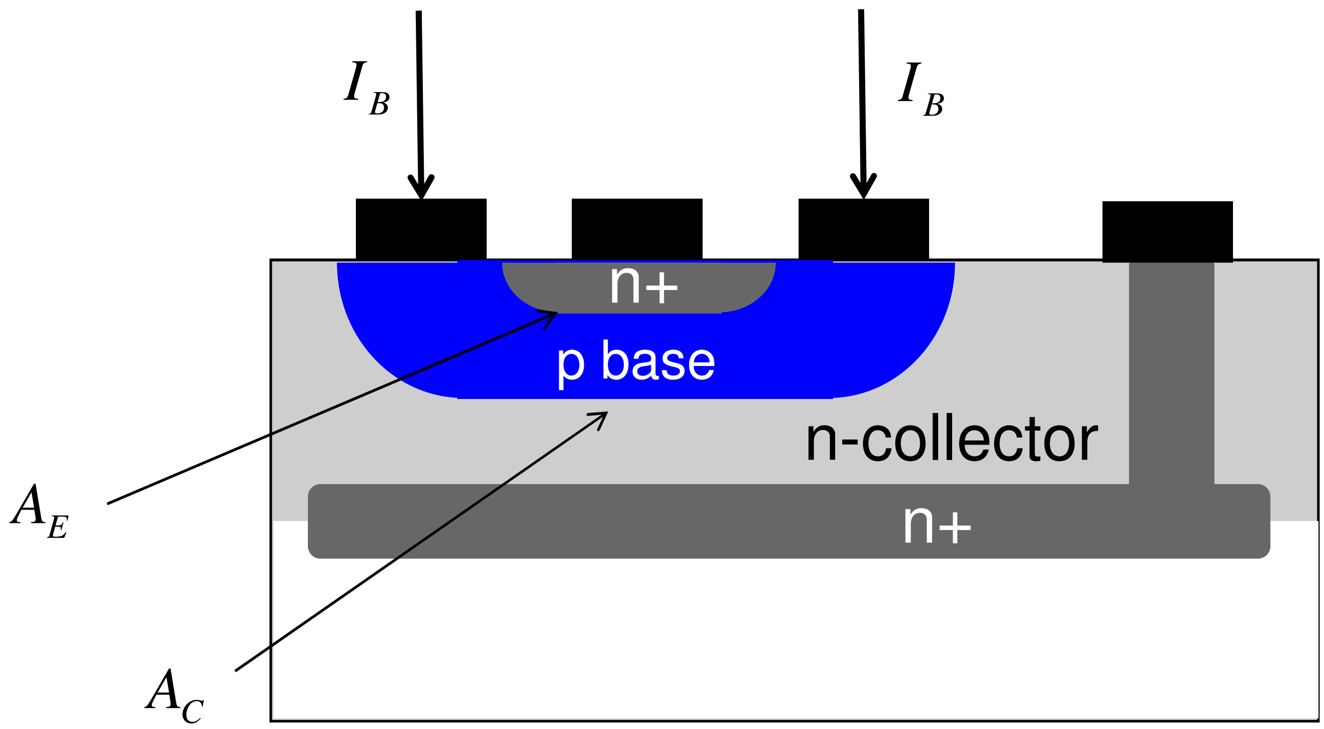
emitter current crowding



emitter current crowding

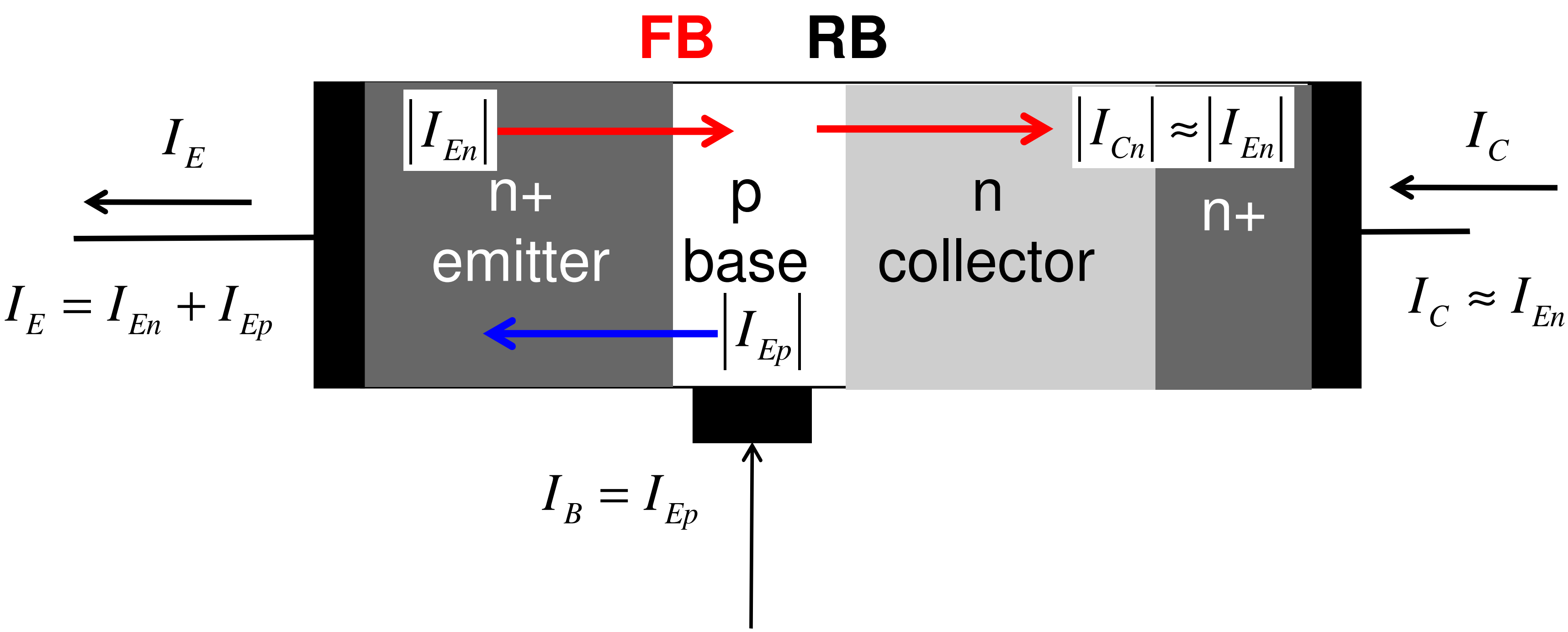


emitter and collector areas

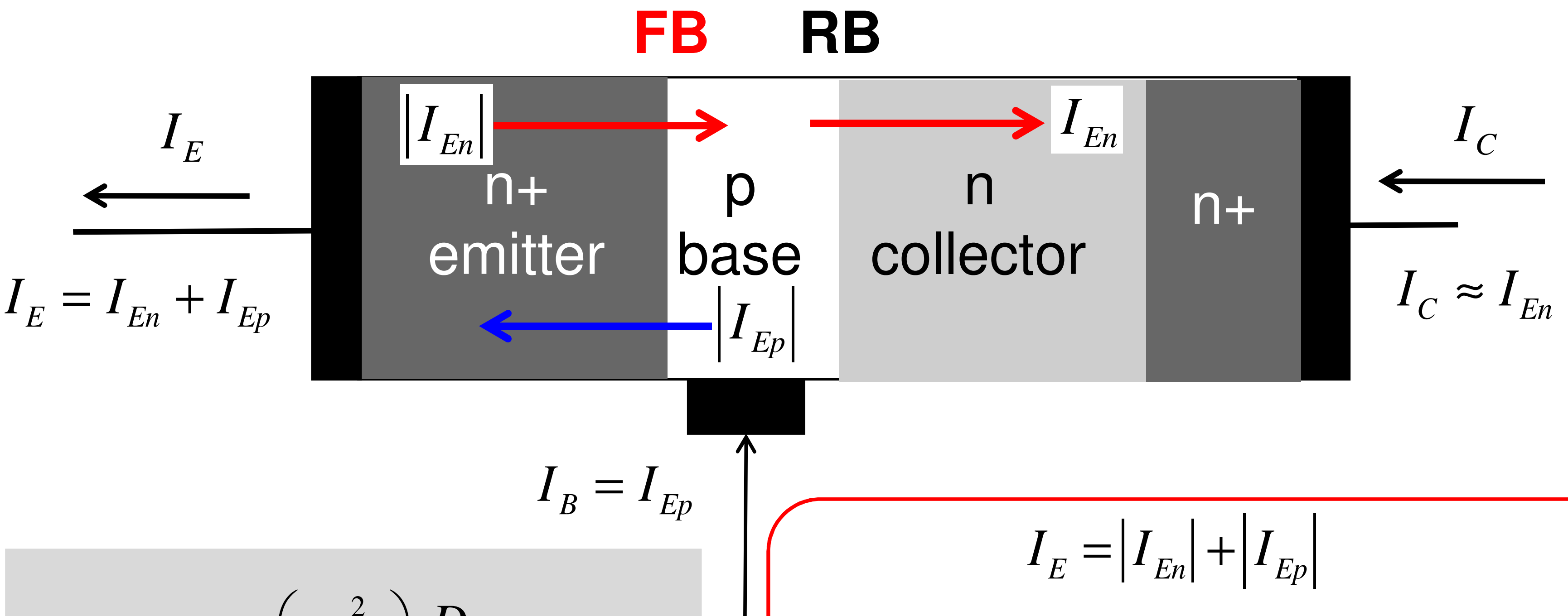


$$A_C >> A_E$$

forward active region



emitter current: forward active region



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

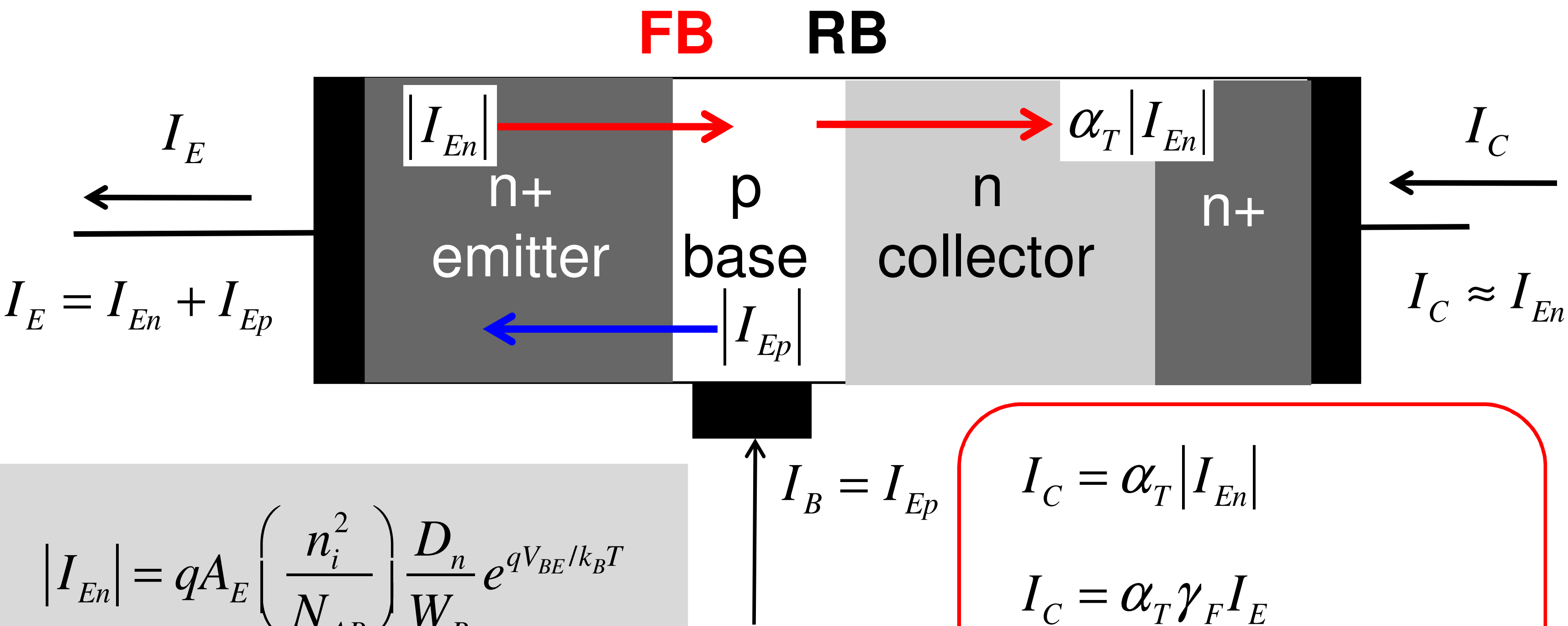
$$\left|I_{Ep}\right| = qA_E\left(\frac{n_i^2}{N_{DE}}\right)\frac{D_p}{W_E}e^{qV_{BE}/k_BT}$$

$$I_E = \left|I_{En}\right| + \left|I_{Ep}\right|$$

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

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

collector current: forward active region



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

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

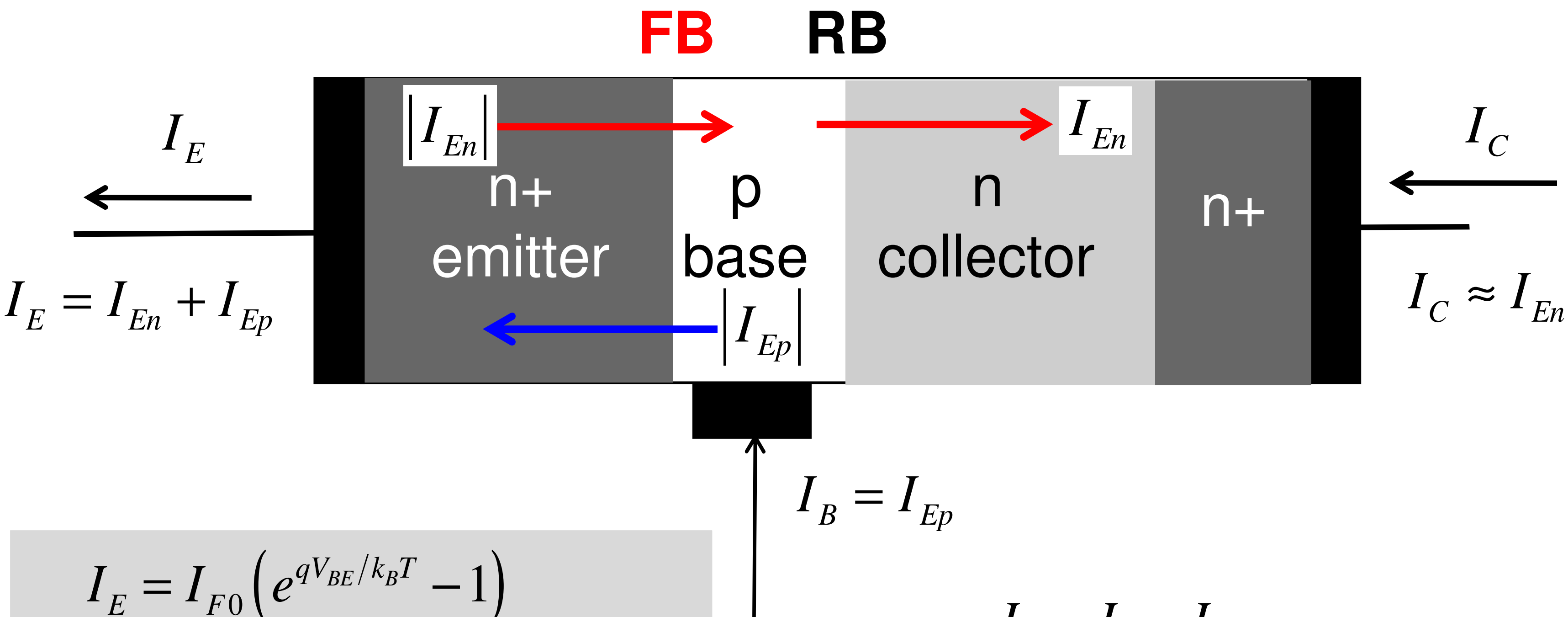
$$I_C = \alpha_T |I_{En}|$$

$$I_C = \alpha_T \gamma_F I_E$$

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

$$\alpha_F = \alpha_T \gamma_F$$

base current: forward active region



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

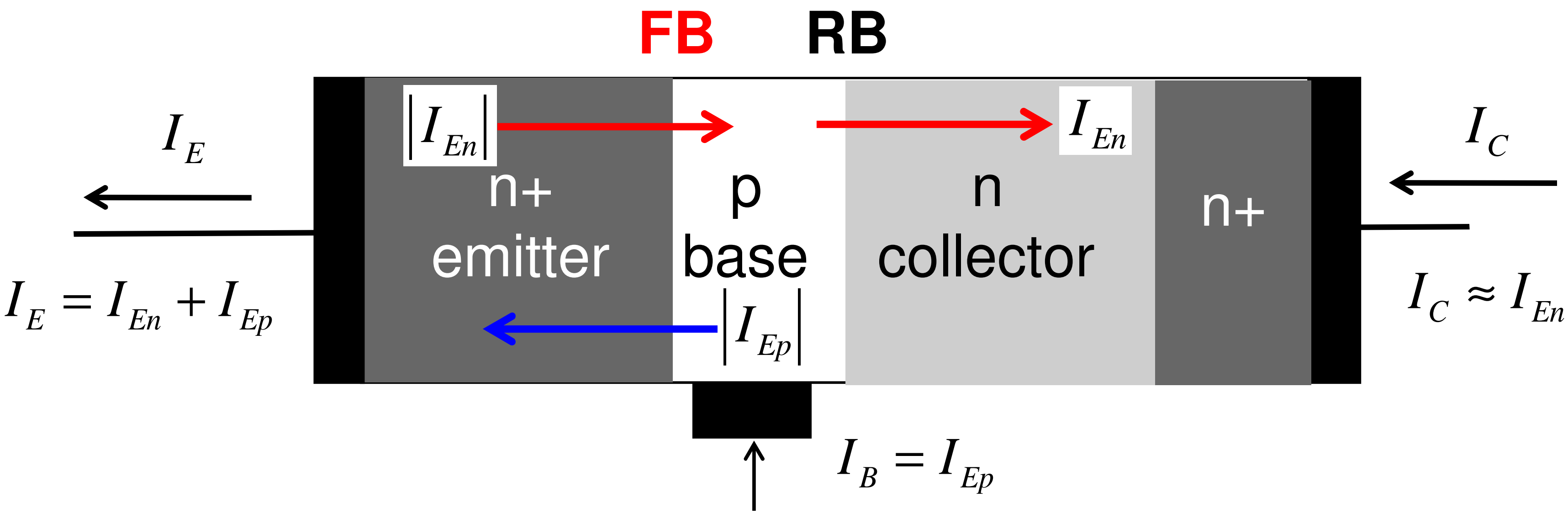
$$I_C = \alpha_F I_{F0}\left(e^{qV_{BE}/k_BT} - 1\right)$$

$$\alpha_F = \alpha_T \gamma_F$$

$$I_B = I_E - I_C$$

$$I_B = \left(1 - \alpha_F\right) I_{F0}\left(e^{qV_{BE}/k_BT} - 1\right)$$

summary: forward active region



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

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

$$I_B = \left(1 - \alpha_F\right) I_{F0}\left(e^{qV_{BE}/k_BT} - 1\right)$$

$$\alpha_F = \alpha_T \gamma_F$$

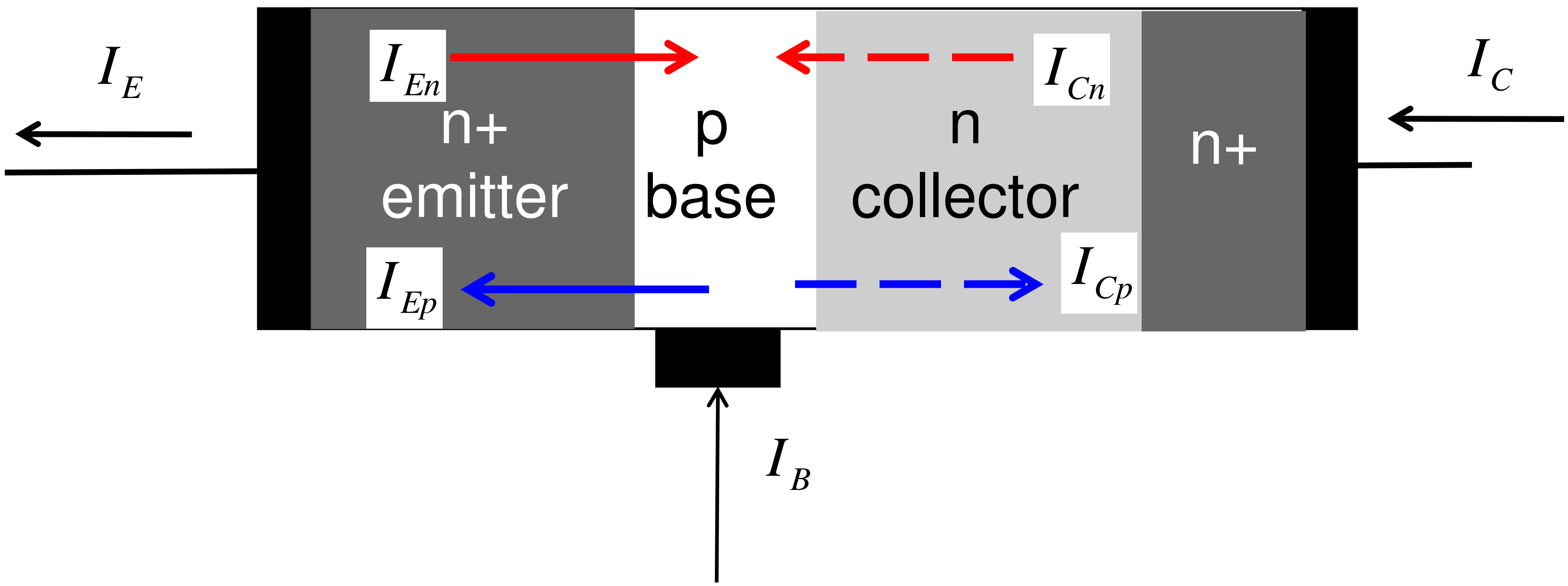
$$I_{F0} = qA_E\left(\frac{n_i^2}{N_{AB}}\right)\frac{D_n}{W_B} + qA_E\left(\frac{n_i^2}{N_{DE}}\right)\frac{D_p}{W_E}$$

Ebers-Moll model

Question:

How do we describe the BJT in **any** region of operation?

emitter-base junction (the **forward** diode)



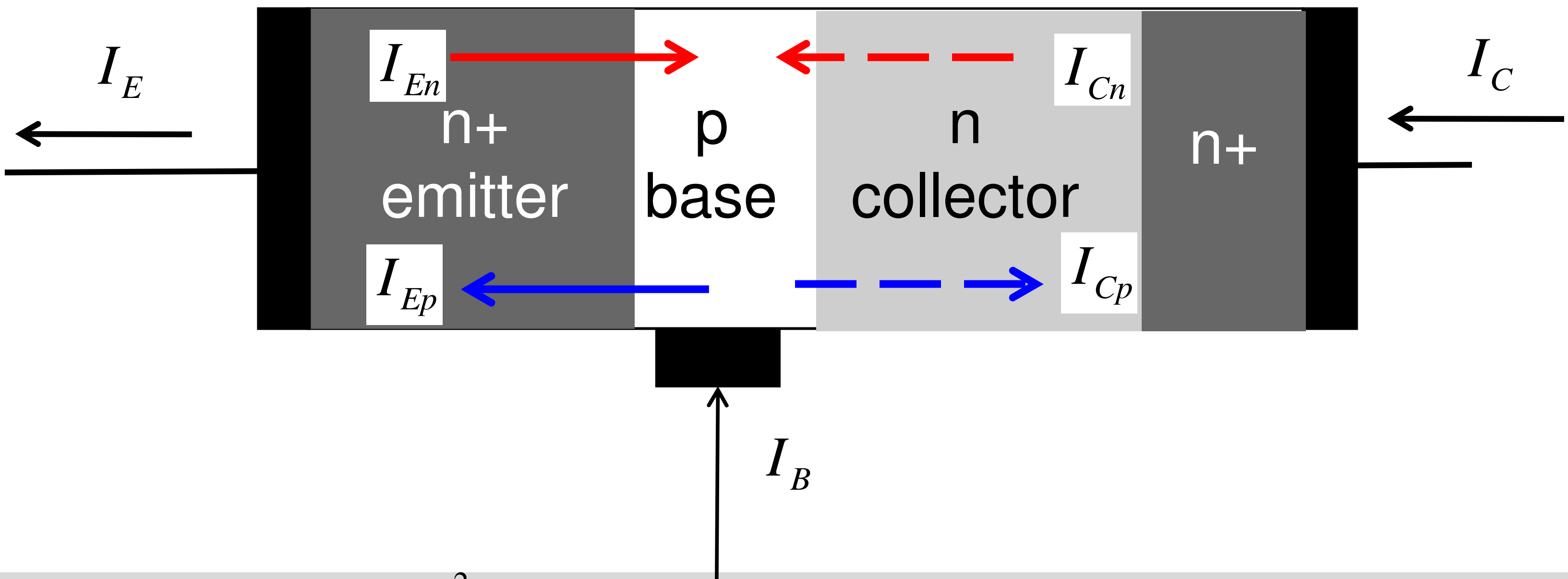
$$I_{En} = -qA \frac{D_n}{W_B} \frac{n_i^2}{N_{AB}} \left(e^{qV_{BE}/k_B T} - 1 \right)$$

$$I_{Ep} = -qA \frac{D_p}{W_E} \frac{n_i^2}{N_{DE}} \left(e^{qV_{BE}/k_B T} - 1 \right)$$

$$I_E(V_{BE}) = -I_{En}(V_{BE}) - I_{Ep}(V_{BE})$$

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

Base-collector junction (the **reverse** diode)



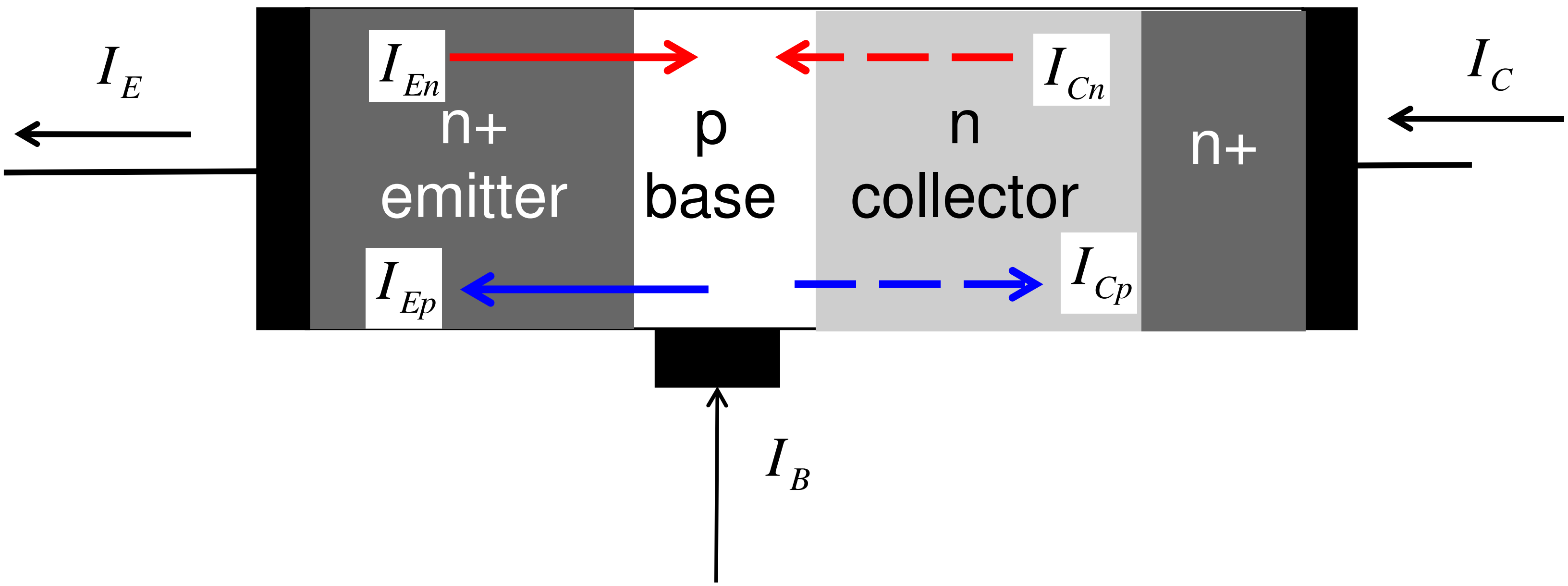
$$I_{Cn}(V_{BC}) = qA\frac{D_n}{W_B}\frac{n_i^2}{N_{AB}}\left(e^{qV_{BC}/k_BT} - 1\right)$$

$$I_C(V_{BC}) = -\left[I_{Cn}(V_{BC}) + I_{Cp}(V_{BC})\right]$$

$$I_{Cp}(V_{BC}) = qA\frac{D_p}{W_C}\frac{n_i^2}{N_{DC}}\left(e^{qV_{BC}/k_BT} - 1\right)$$

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

Both junctions….

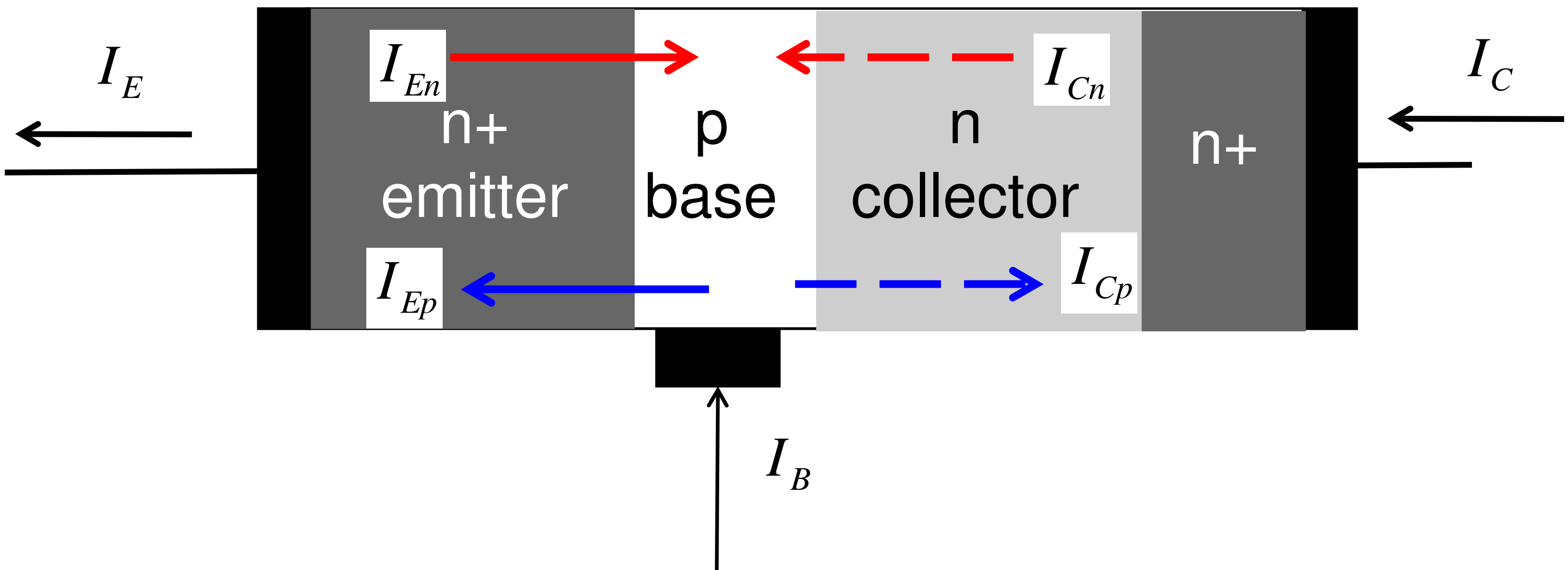


$$I_C\left(V_{BC}\right) = -I_{R0}\left(e^{qV_{BC}/k_BT} - 1\right)$$

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

But….
The two junctions are coupled!

Ebers-Moll model



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

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

Ebers-Moll model

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

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

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

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

See Pierret SDF, Chapter 11, sec. 11.1.4

Conclusion

- Bipolar junction transistor (BJT) physics is most easily understood as an extension of junction diode behavior
- The equations can be encapsulated in a simple equivalent circuit, appropriate for dc applications
- It is important to remember the definitions and conventions, so that we can recall them in various situations.
- Being able to draw the band-diagram for arbitrary bias conditions in a key skill, which will be on the final exam
- For a terrific and interesting history of invention of bipolar transistor, read the book, *Crystal Fire*