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ECE606: Solid State Devices
Lecture 27: Introduction to Bipolar Transistors

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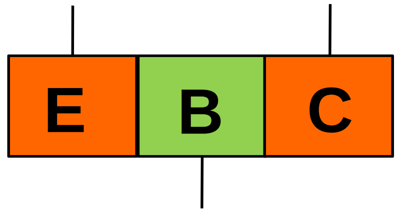
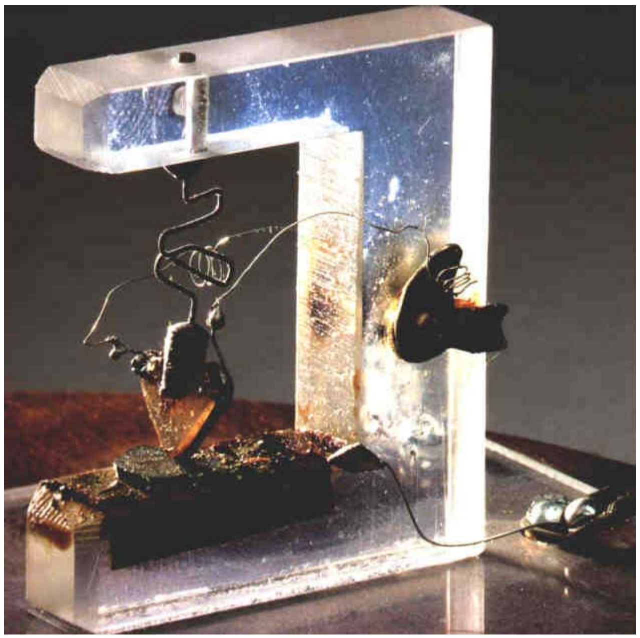
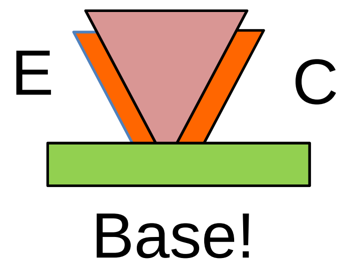
Background







Point contact **Germanium** transistor (your HW problem!)

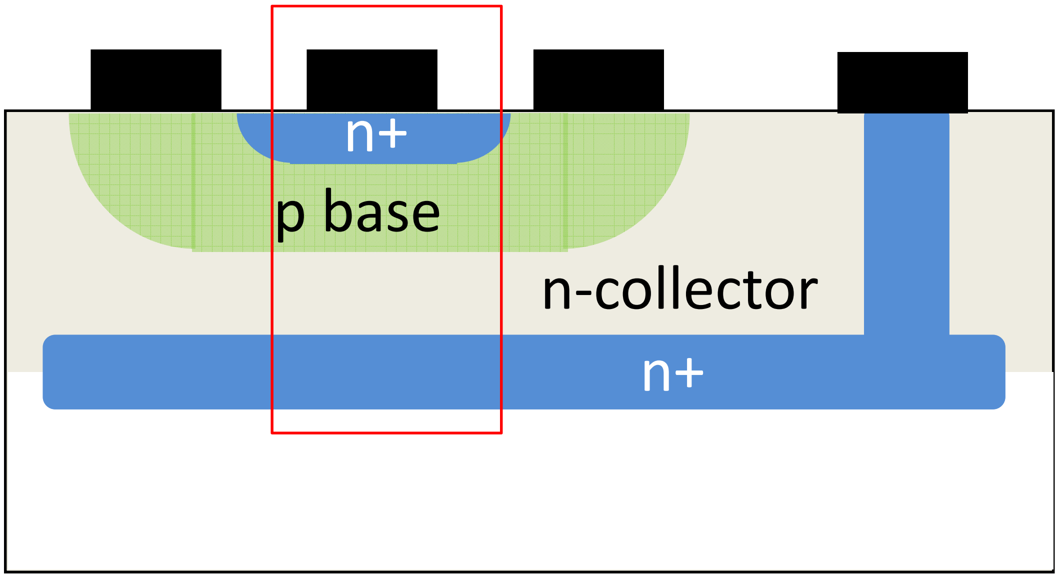
Ralph Bray from Purdue missed the invention of transistors.

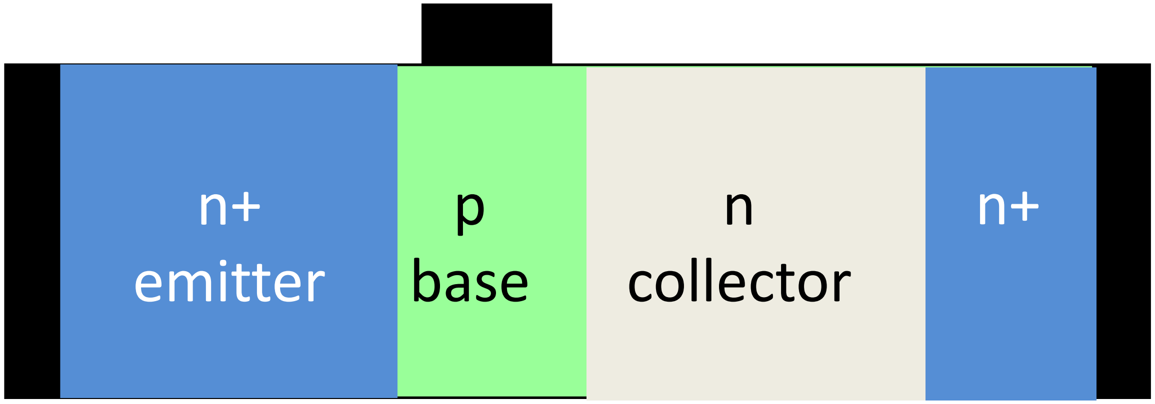
Transistor research was also in advanced stages in Europe (radar).

Shockley's Bipolar Transistors …

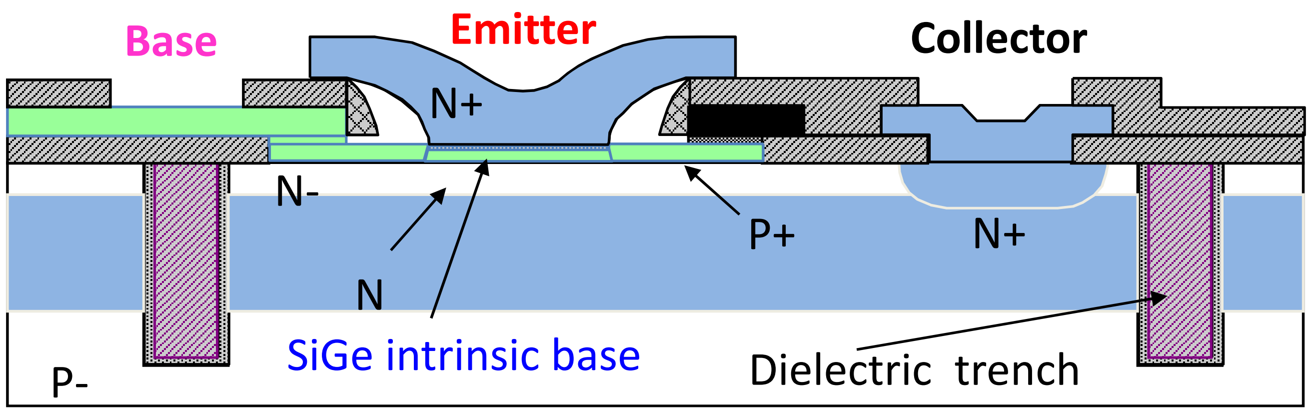
Double

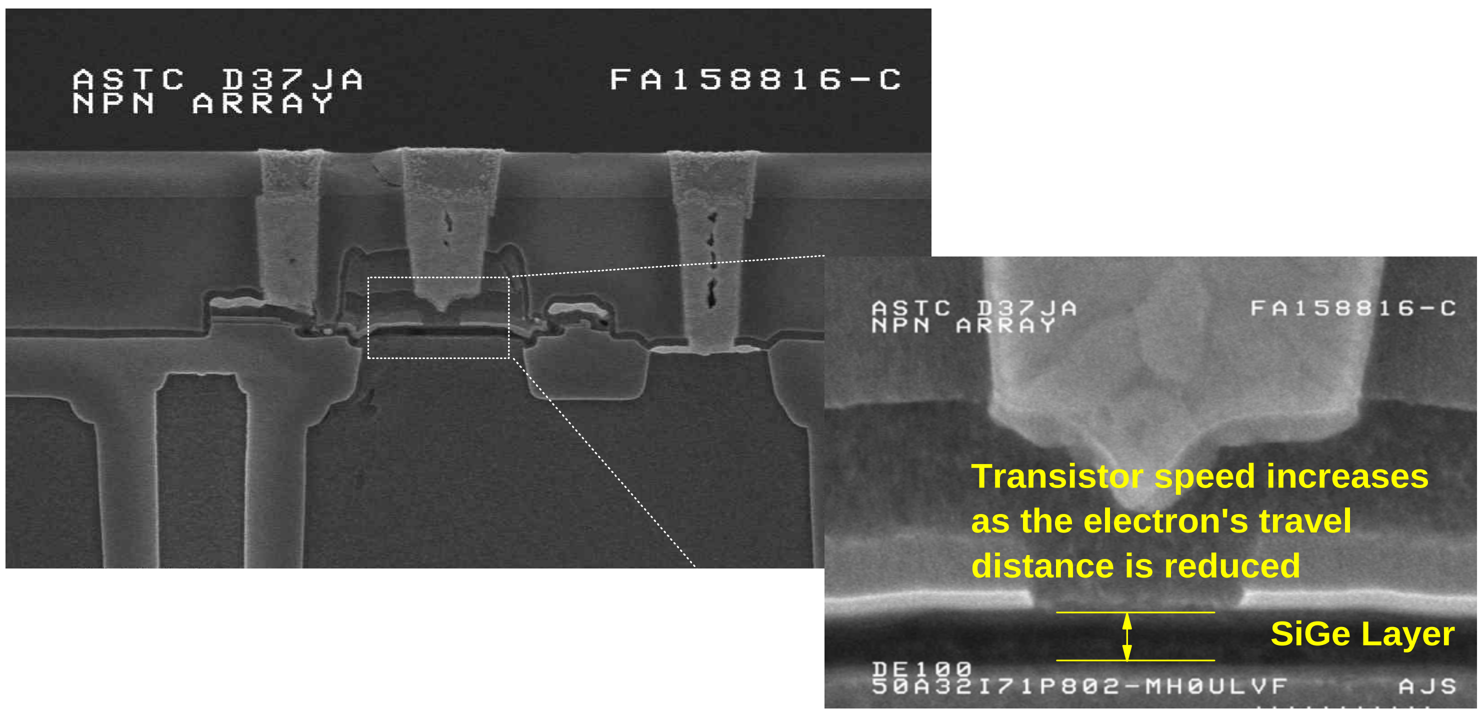
Diffused BJT



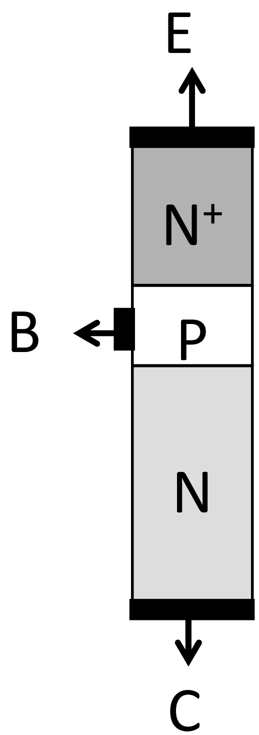


Modern Bipolar Junction Transistors (BJTs)





Symbols and Convention

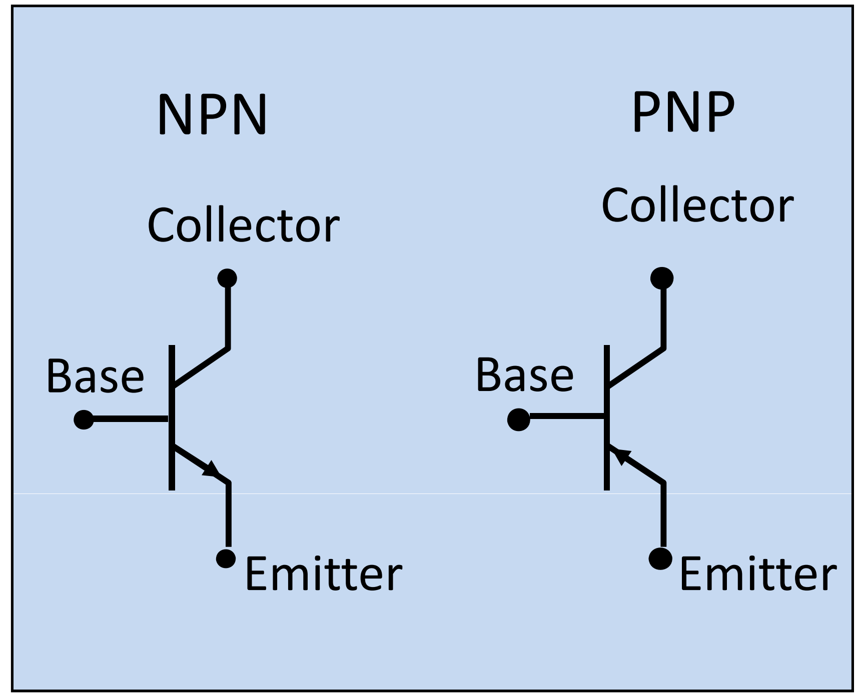


Poly emitter

Low-doped base

Collector doping optimization

Symbols



$$I_C+I_B+I_E=0$$

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

Outline

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

Topic Map

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

Band Diagram at Equilibrium

$$\nabla \bullet D = q\left(p - n + N_D^+ - N_A^-\right)$$

$$\frac{\partial n}{\partial t} = \frac{1}{q}\nabla \bullet \mathbf{J}_N - r_N + g_N$$

$$\mathbf{J}_N = qn\mu_N E + qD_N \nabla n$$

$$\frac{\partial p}{\partial t} = -\frac{1}{q}\nabla \bullet \mathbf{J}_P - r_P + g_P$$

$$\mathbf{J}_P = qp\mu_P E - qD_P \nabla p$$

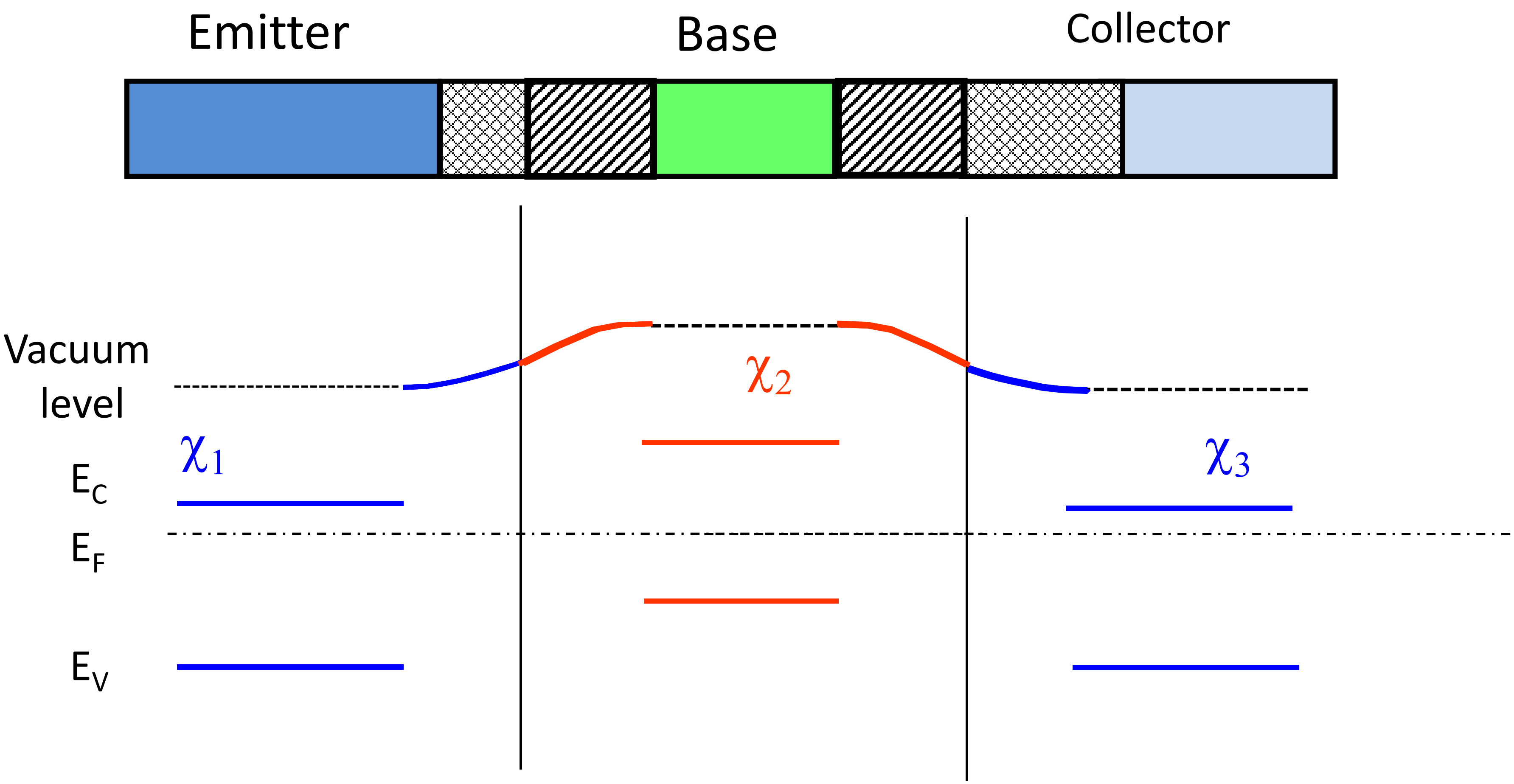
← **Equilibrium**

DC dn/dt=0

Small signal dn/dt ~ jωtn

Transient --- Charge control model

Band Diagram at Equilibrium



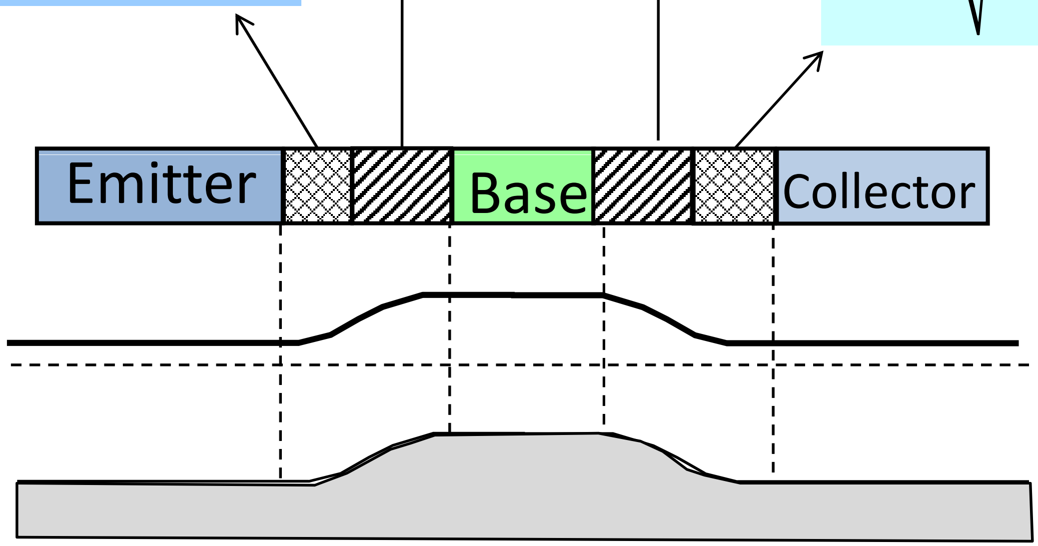
Electrostatics in Equilibrium

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

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

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

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



Outline

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Diode					
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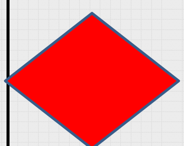
BJT/HBT					
MOS					

Band Diagram with Bias

$$\nabla \bullet D = q\left(p - n + N_D^+ - N_A^-\right)$$

← **Non-equilibrium**

$$\frac{\partial n}{\partial t} = \frac{1}{q}\nabla \bullet \mathbf{J}_N - r_N + g_N$$

$$\mathbf{J}_N = qn\mu_N E + qD_N \nabla n$$

$$\frac{\partial p}{\partial t} = \frac{1}{q}\nabla \bullet \mathbf{J}_P - r_P + g_P$$

$$\mathbf{J}_P = qp\mu_P E - qD_P \nabla p$$

DC dn/dt=0

Small signal dn/dt ~ jωtn

Transient --- Charge control model

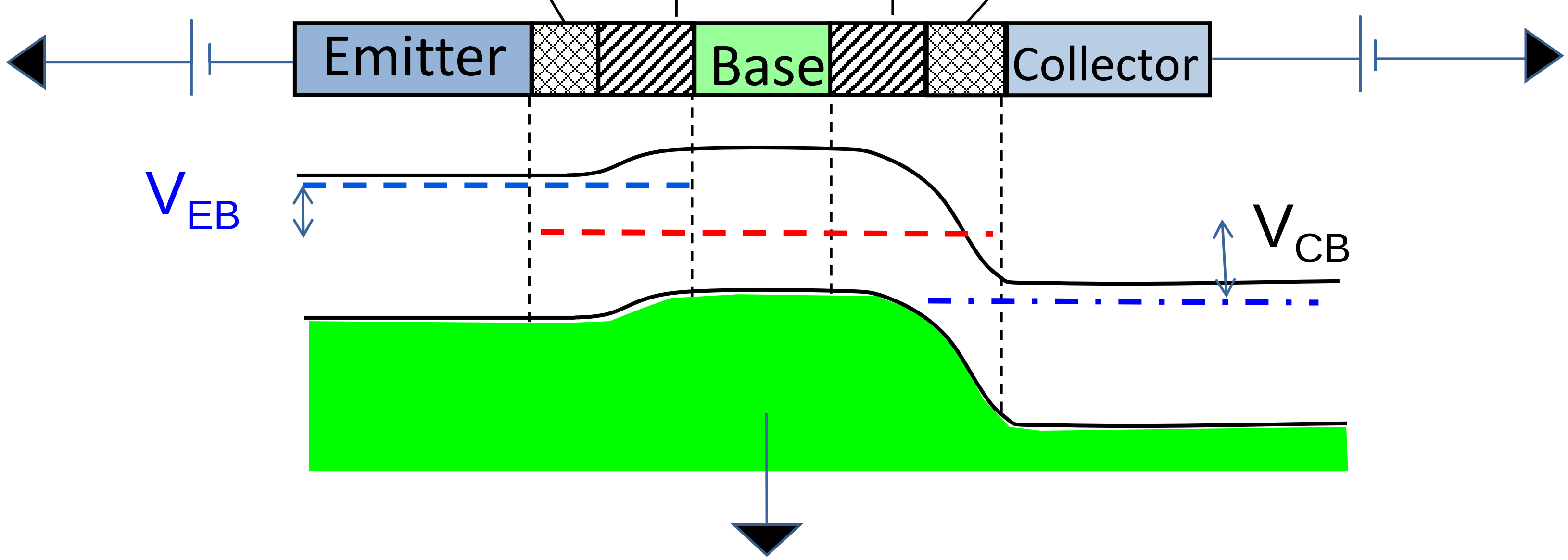
Electrostatics in Equilibrium

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

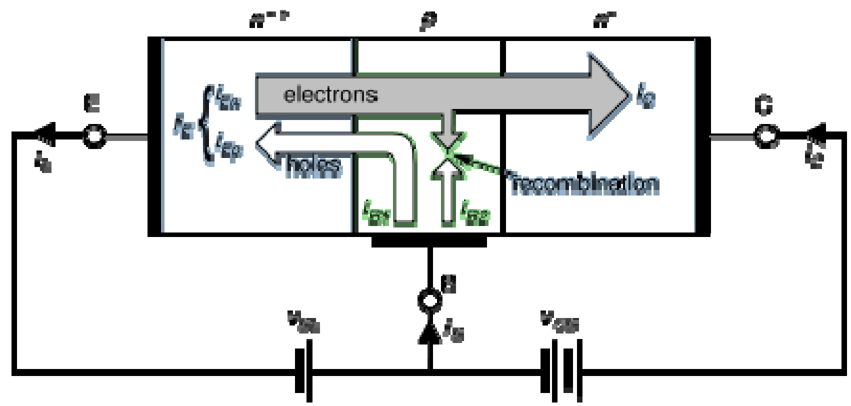
$$x_{p,BC} = \sqrt{\frac{2k_s\varepsilon_0}{q}\frac{N_C}{N_B\left(N_C+N_B\right)}\left(V_{bi}-V_{CB}\right)}$$

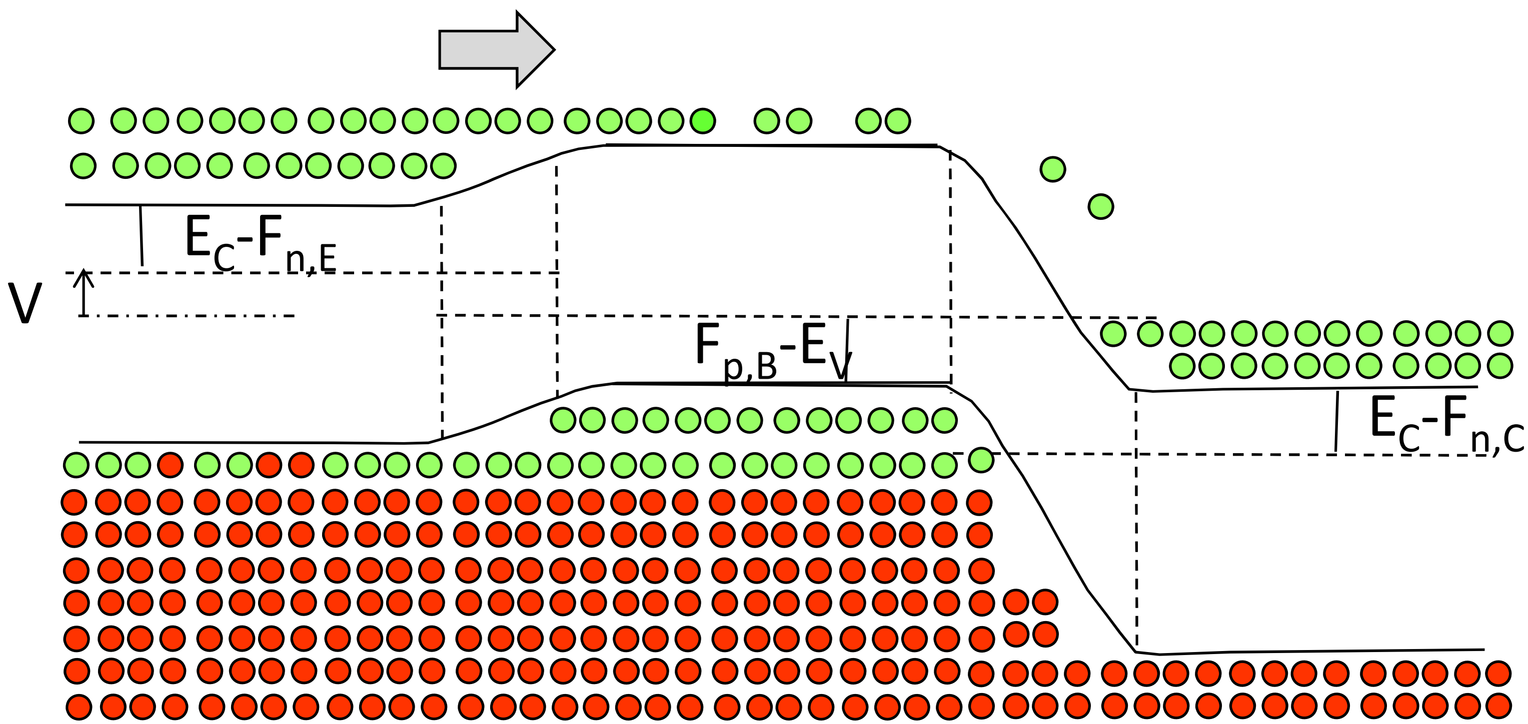
$$x_{n,E} = \sqrt{\frac{2k_s\varepsilon_0}{q}\frac{N_B}{N_E\left(N_B+N_E\right)}\left(V_{bi}-V_{EB}\right)}$$

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

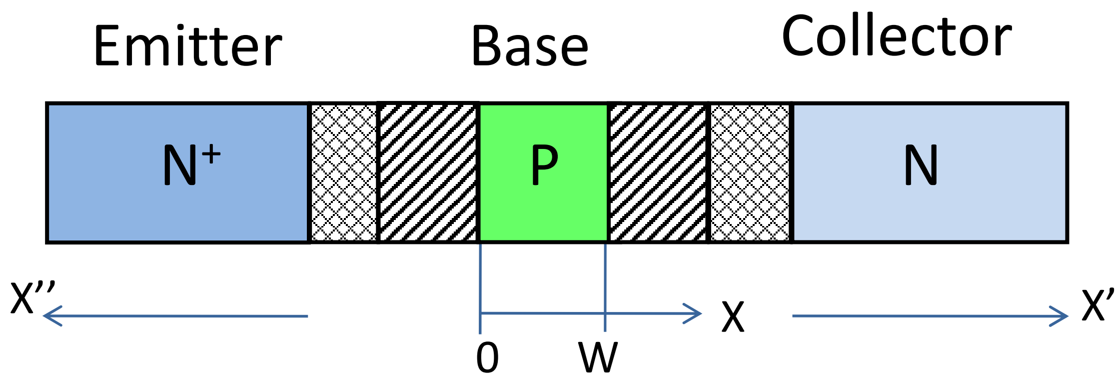


Current flow with Bias





Coordinates and Convention



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

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

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

Carrier Distribution in Base

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

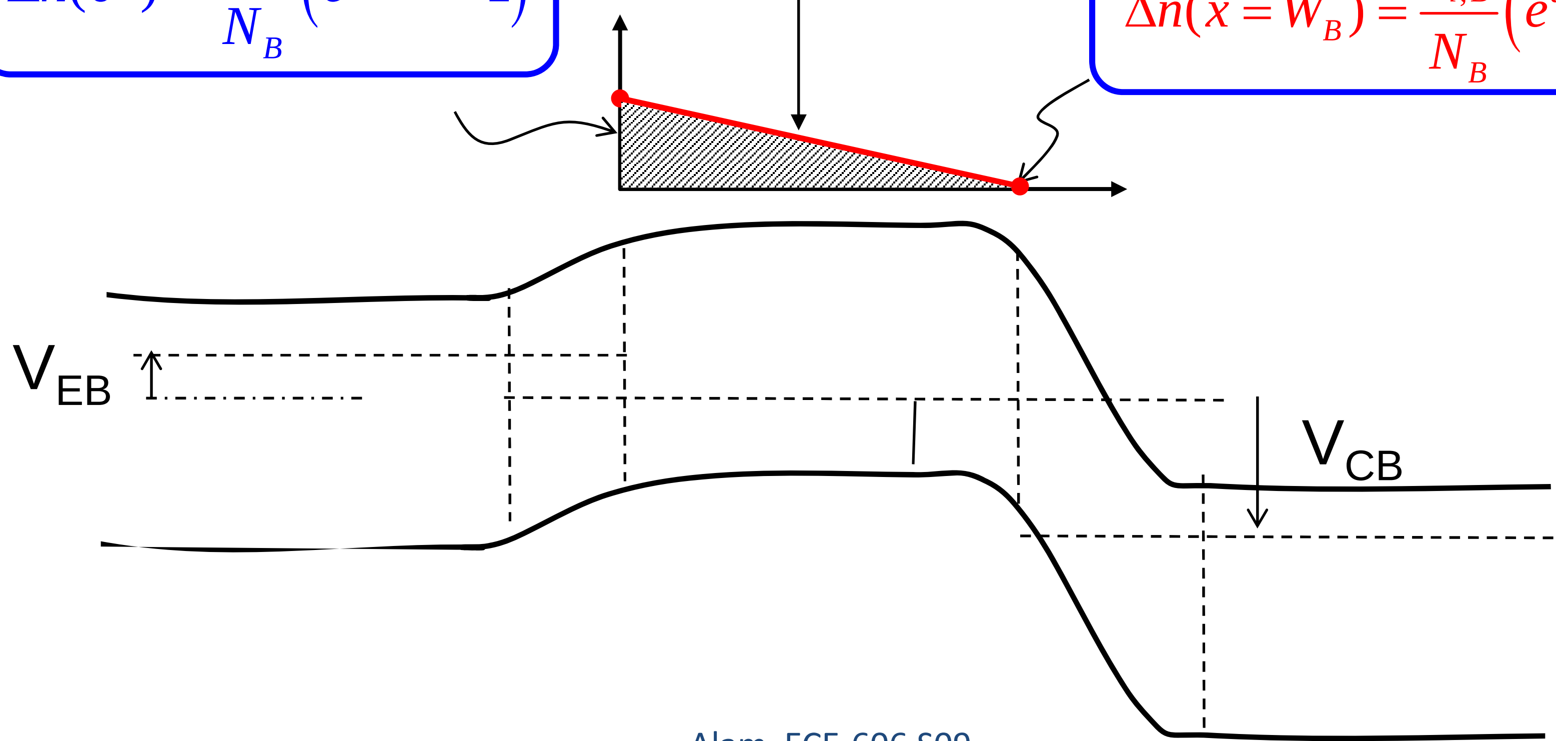
C

D

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

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

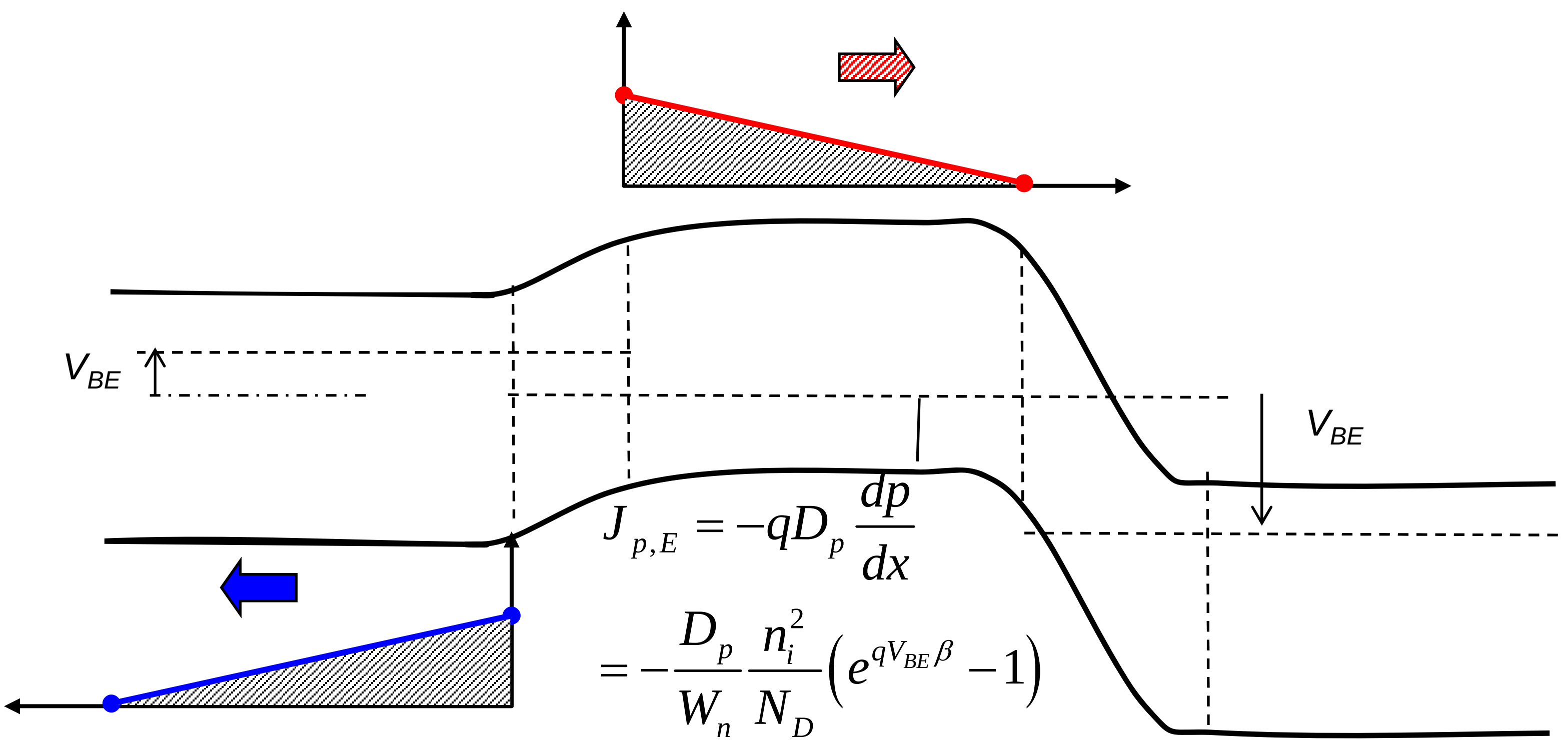
$$\Delta n(x = W_B) = \frac{n_{i,B}^2}{N_B}\left(e^{qV_{BC}\beta}-1\right)$$



Collector and Emitter Electron Current

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

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



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

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

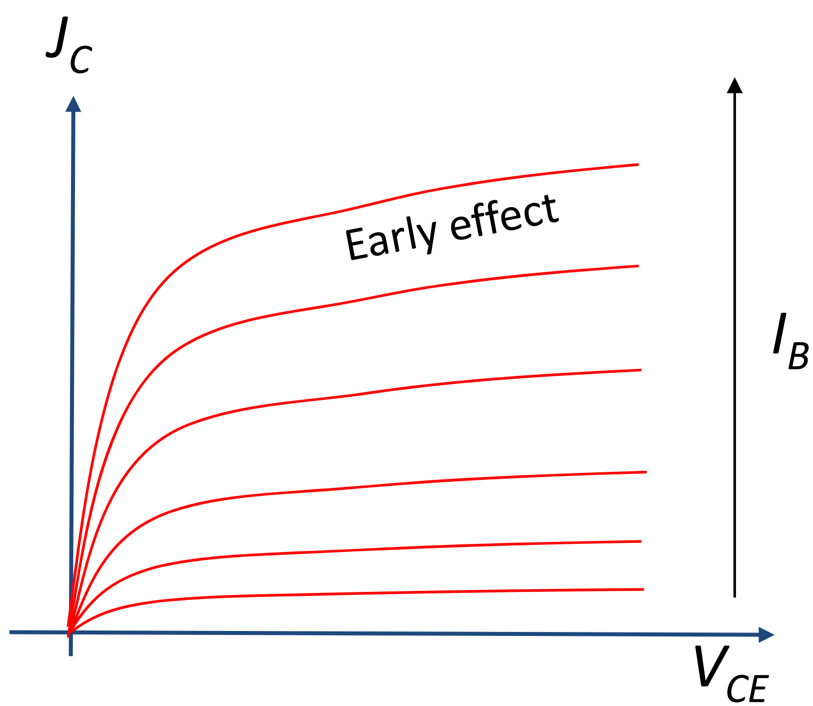
Current-Voltage Characteristics

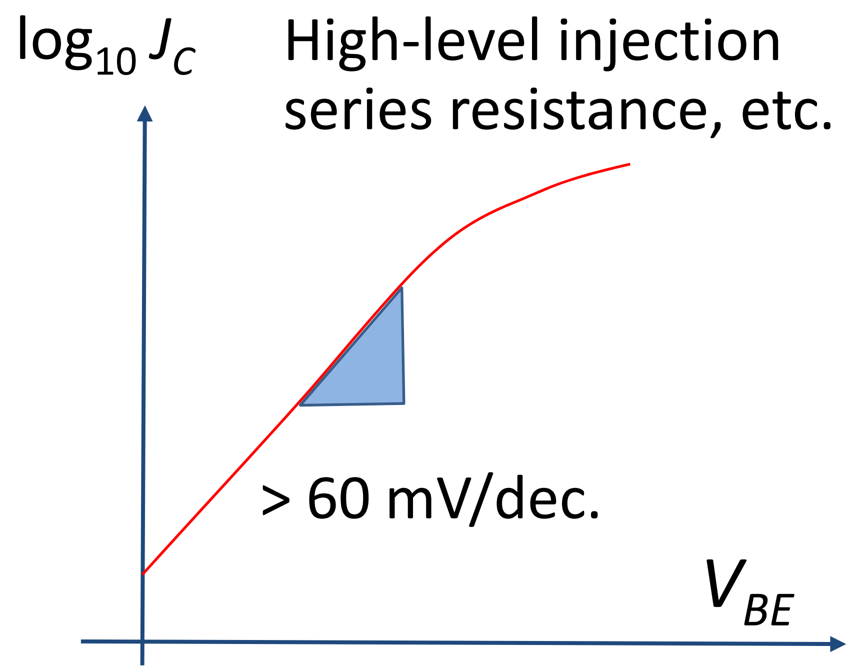
Normal, Active Region

EB: Forward biased

BC: Reverse biased

$$J_{n,C} = -\frac{qD_n}{W_B}\frac{n_{i,B}^2}{N_B}\left(e^{qV_{BE}\beta}-1\right)+\frac{qD_n}{W_B}\frac{n_{i,B}^2}{N_B}\left(e^{qV_{BC}\beta}-1\right)$$





Have you seen this figure before?

Outline

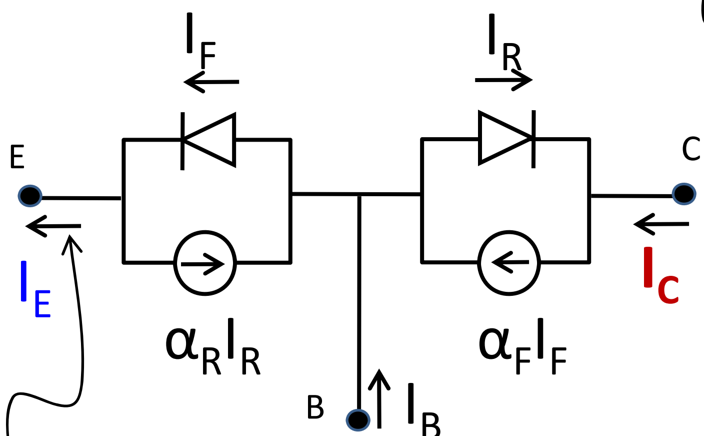
1) Equilibrium and forward band-diagram
2) Currents in bipolar junction transistors
3) **Ebers Moll model**
4) Conclusions

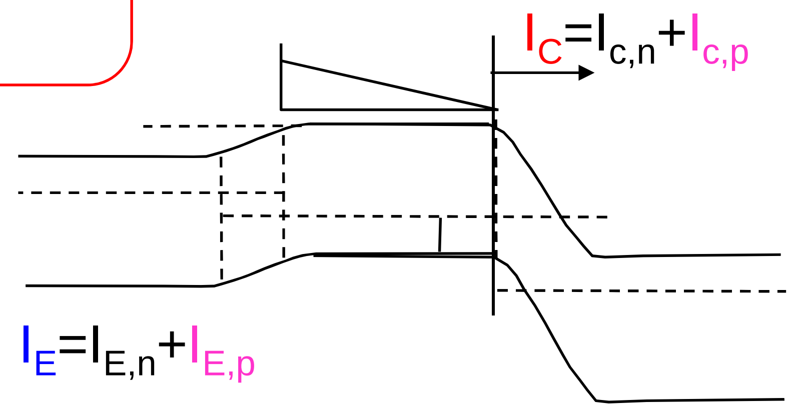
Ebers Moll Model

Hole diffusion in collector

$$I_C = -A\frac{qD_n}{W_B}\frac{n_{i,B}^2}{N_B}\left(e^{qV_{BE}\beta}-1\right) + A\left[\frac{qD_n}{W_B}\frac{n_{i,B}^2}{N_B} + \frac{qD_p}{W_C}\frac{n_{i,C}^2}{N_C}\right]\left(e^{qV_{BC}\beta}-1\right)$$

$$\equiv \alpha_F I_{F0}\left(e^{qV_{BE}\beta}-1\right) - I_{R0}\left(e^{qV_{BC}\beta}-1\right)$$





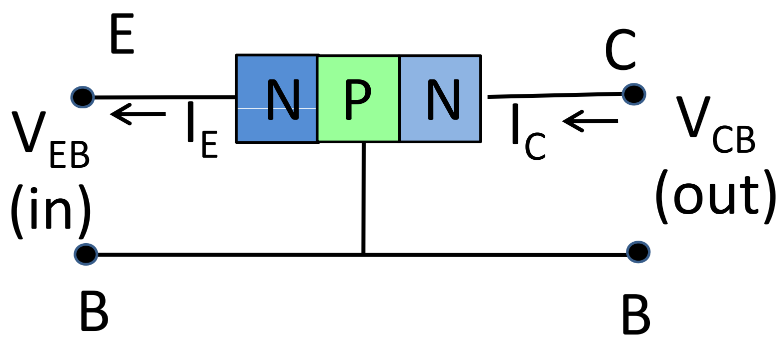
$$I_F = I_{F0}\left(e^{qV_{BE}\beta}-1\right)$$

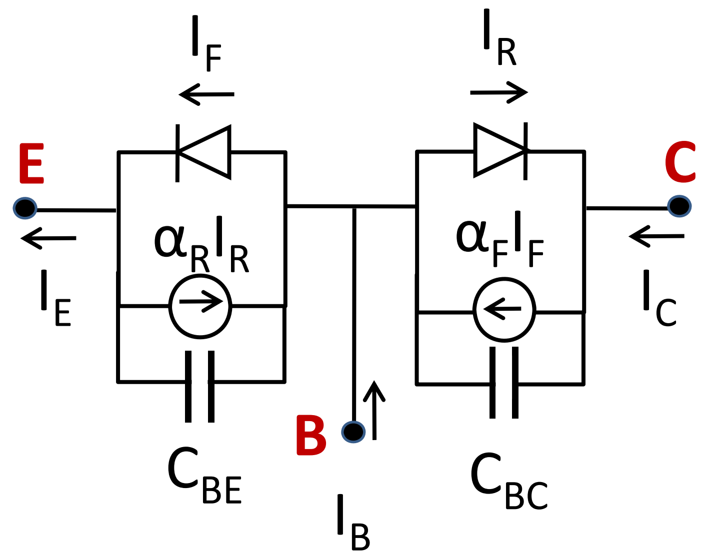
$$I_R = I_{R0}\left(e^{qV_{BC}\beta}-1\right)$$

$$I_E = -A\left[\frac{qD_p}{W_E}\frac{n_{i,E}^2}{N_E} + \frac{qD_n}{W_B}\frac{n_{i,B}^2}{N_B}\right]\left(e^{qV_{BE}\beta}-1\right) + A\frac{qD_n}{W_E}\frac{n_{i,B}^2}{N_B}\left(e^{qV_{BC}\beta}-1\right)$$

$$\equiv I_{F0}\left(e^{qV_{BE}\beta}-1\right) - \alpha_R I_{R0}\left(e^{qV_{BC}\beta}-1\right)$$

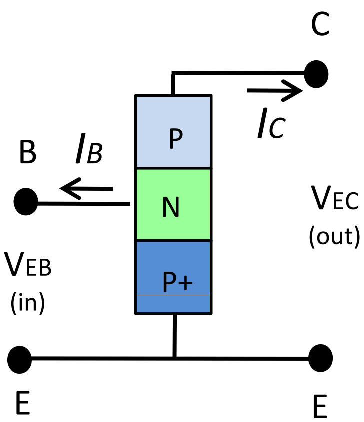
Common Base Configuration

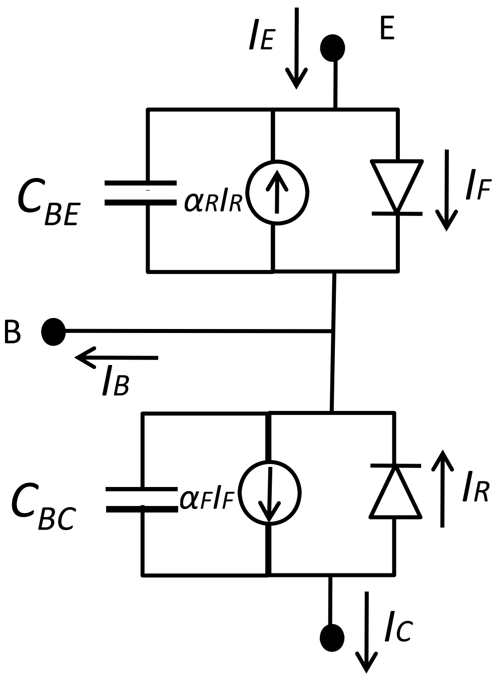


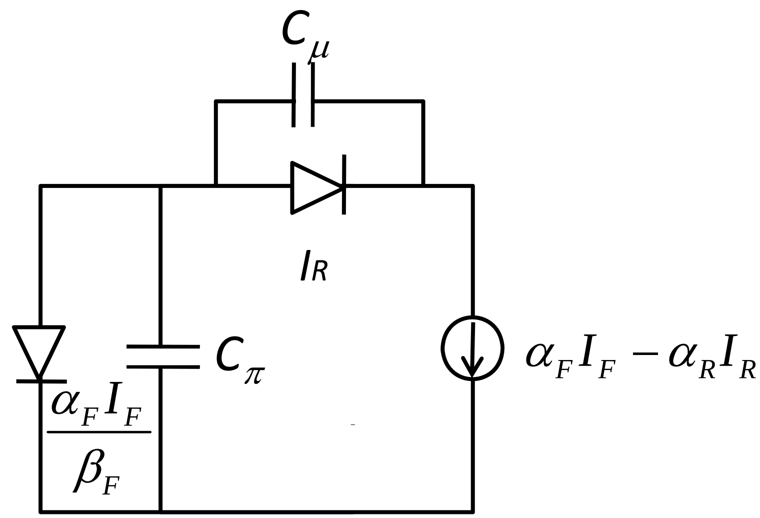


How would the model change if this was a Schottky barrier BJT?

Common Emitter Configuration







$$\frac{\alpha_F I_F}{\beta_F} = \frac{\alpha_F I_F}{\frac{\alpha_F}{1-\alpha_F}} = (1-\alpha_F) I_F = I_B$$

This is a practice problem …

Conclusion

- The physics of BJT is most easily understood with reference to the physics of junction diodes.
- The equations can be encapsulated in simple equivalent circuit appropriate for dc, ac, and large signal applications.
- Design of transistors is far more complicated than this simple model suggests.
- For a terrific and interesting history of invention of bipolar transistor, read the book "Crystal Fire".