BJT I-V Characteristics

EECS 320

Introduction to Semiconductor Devices

BJT I-V Characteristics

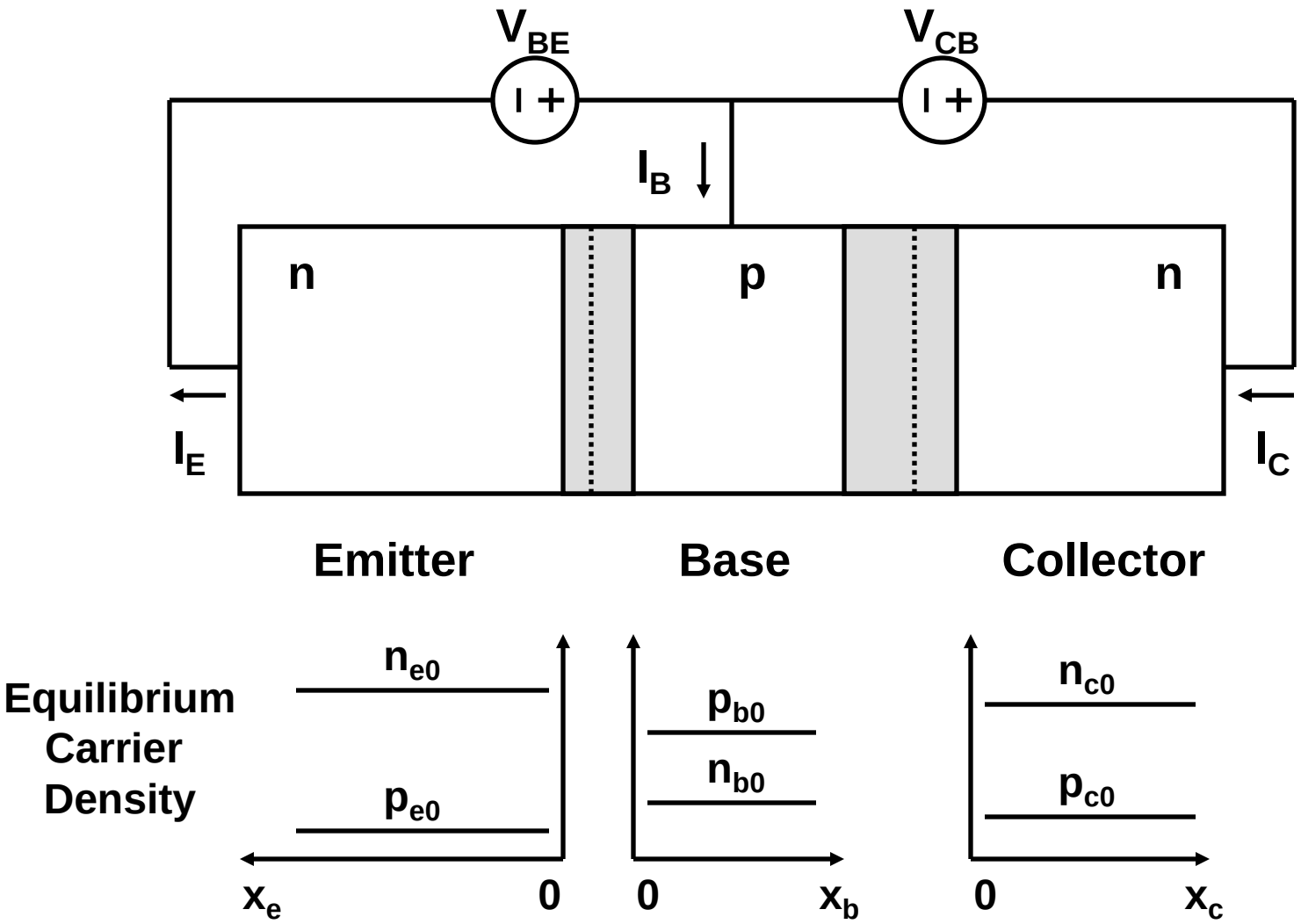
Goal: Develop I-V Relations

Approach: Determine current through solution of minority carrier diffusion equations

Similar assumptions to p-n diode analysis

- uniform doping, step junction
- steady state
- low-level injection
- no external generation
- no R-G in depletion regions
- "long" emitter and collector

Equilibrium Carrier Densities



Carrier Densities Under Bias

How do we determine the carrier density under bias?

How can we determine the current voltage relationships?

Boundary Conditions

Excess Minority Carrier Densities At Depletion Region Edges:

$$\Delta p_e(x_e = 0) = p_{e0}\left[\exp\left(qV_{BE}/kT\right) - 1\right]$$

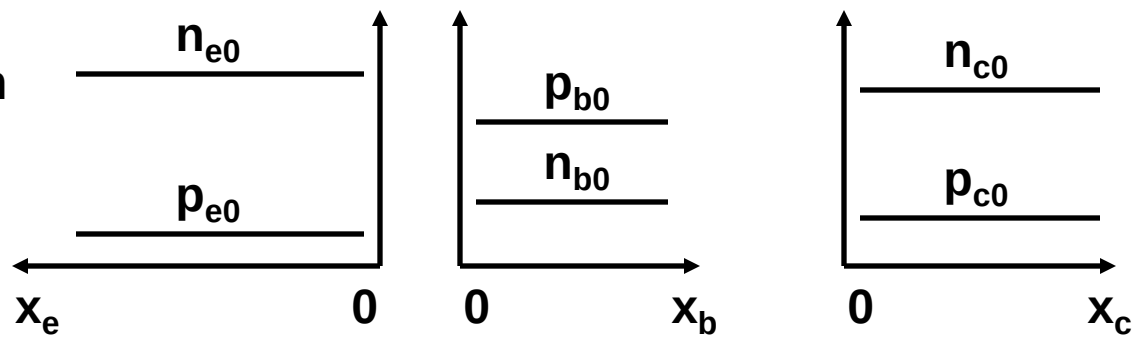
$$\Delta n_b(x_b = 0) = n_{b0}\left[\exp\left(qV_{BE}/kT\right) - 1\right]$$

$$\Delta n_b(x_b = W_{bn}) = n_{b0}\left[\exp\left(-qV_{CB}/kT\right) - 1\right]$$

$$\Delta p_c(x_c = 0) = p_{c0}\left[\exp\left(-qV_{CB}/kT\right) - 1\right]$$

These are the boundary conditions used to solve continuity eqns

Equilibrium Carrier Density



Minority Carrier Density

Excess minority carriers in base:
(solving minority carrier diffusion equation in steady-state, G=0)

Contribution from BE junction

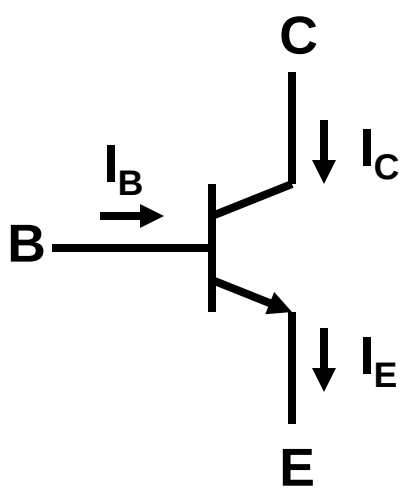
$$\Delta n_b(x_b) = \frac{n_{b0}}{\sinh(W/L_b)} \left\{ \begin{array}{l} \sinh\left(\frac{W - x_b}{L_b}\right)\left[\exp\left(\frac{qV_{BE}}{kT}\right) - 1\right] \\ + \sinh\left(\frac{x_b}{L_b}\right)\left[\exp\left(-\frac{qV_{CB}}{kT}\right) - 1\right] \end{array} \right\}$$

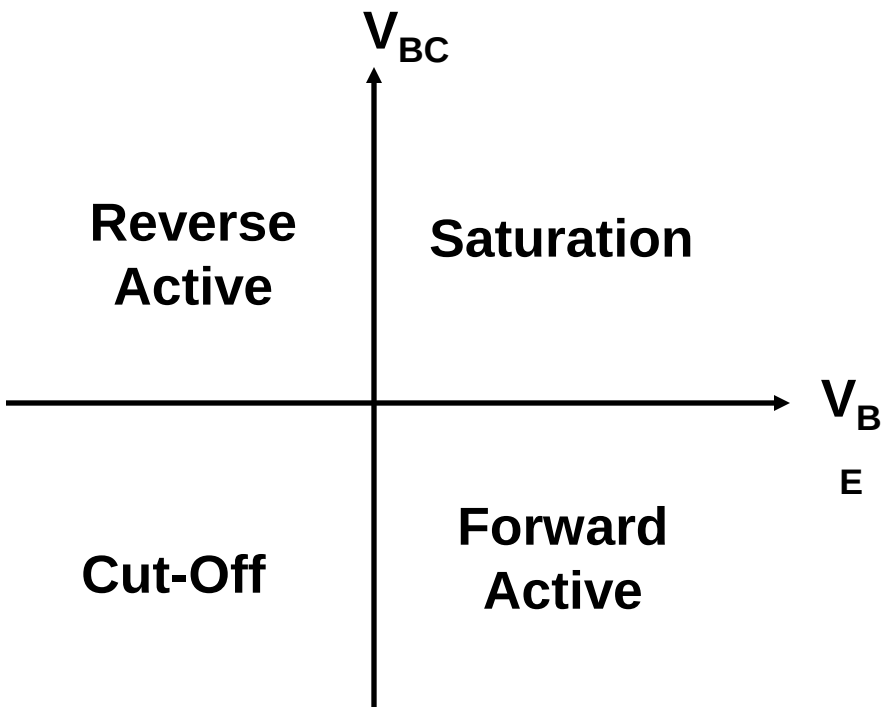
Contribution from CB junction

Minority carriers in emitter and collector same as p-n diode

Minority Carrier Densities

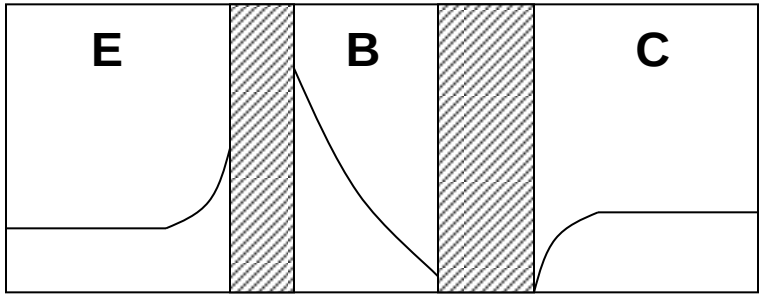
Sketch the minority carrier densities for each region of operation in a npn BJT



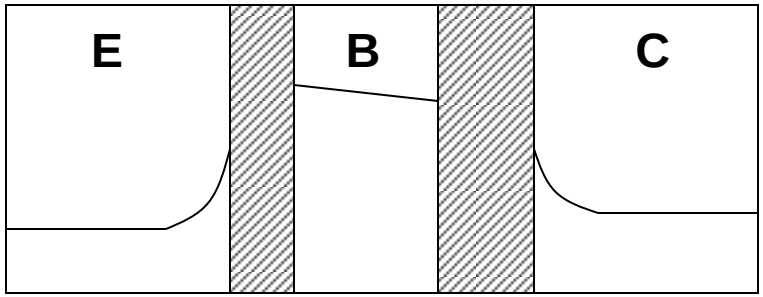


Minority Carrier Densities

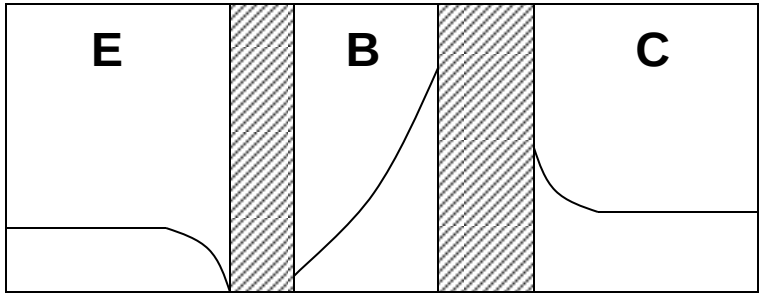
Forward Active



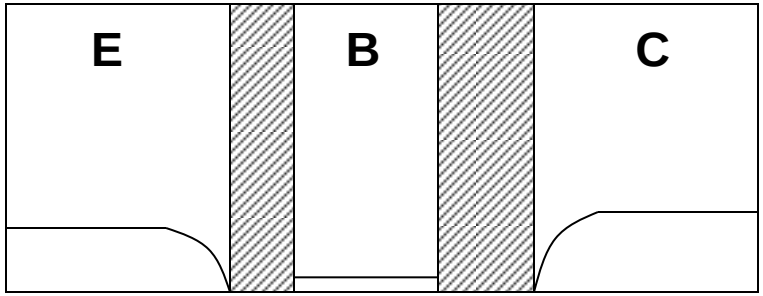
Saturation



Reverse Active



Cutoff



Current Equations

Assumptions

- **Depletion approximation**
- **Drift current independent of electric field**
- **Device current due to diffusion current – minority carrier injection or extraction**

$$I_n = qAD_n \frac{d\Delta n(x)}{dx} \qquad I_p = -qAD_p \frac{d\Delta p(x)}{dx}$$

Emitter Current

Current due to electron and hole injection

$$I_{En} = \frac{qAD_b n_{b0}}{L_b \sinh(W/L_b)} \left\{ \cosh\left(\frac{W}{L_b}\right)\left(e^{qV_{BE}/kT} - 1\right) - \left(e^{-qV_{CB}/kT} - 1\right) \right\}$$

$$I_{Ep} = \frac{qAD_e p_{e0}}{L_e}\left(e^{qV_{BE}/kT} - 1\right)$$

$$I_E = I_{En} + I_{Ep}$$

Collector Current

Similarly for collector:

$$I_{Cn} = \frac{qAD_b n_{b0}}{L_b \sinh(W/L_b)} \left\{ \left(e^{qV_{BE}/kT} - 1\right) - \cosh\left(\frac{W}{L_b}\right)\left(e^{-qV_{CB}/kT} - 1\right) \right\}$$

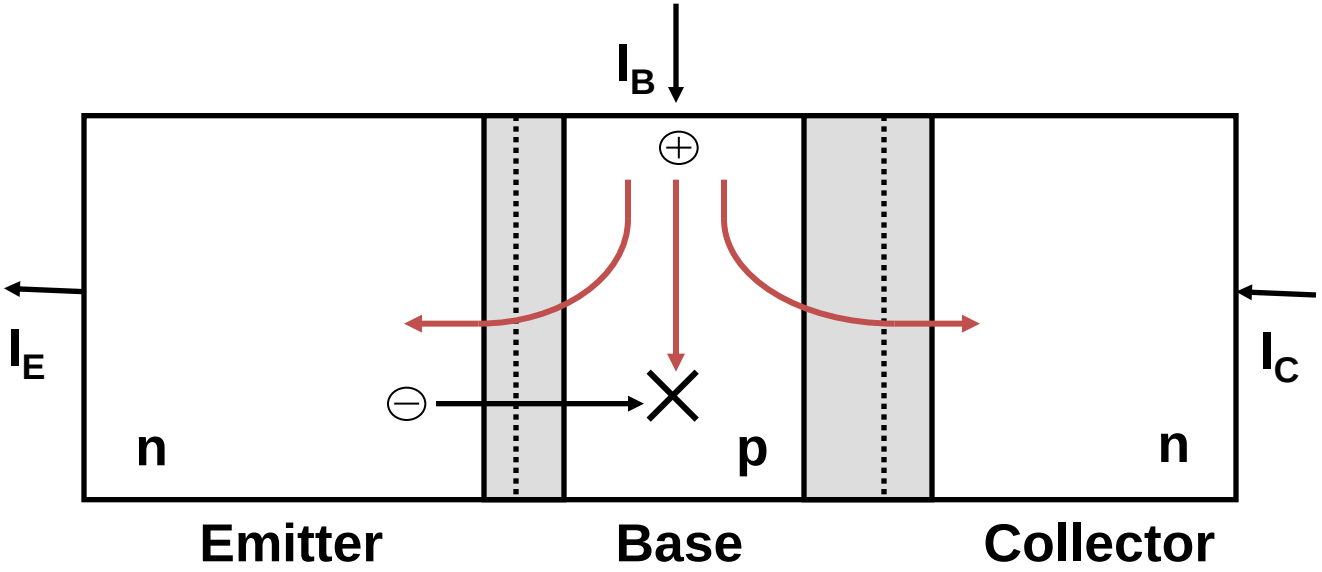
$$I_{Cp} = -\frac{qAD_c p_{c0}}{L_c}\left(e^{-qV_{CB}/kT} - 1\right)$$

$$I_C = I_{Cn} + I_{Cp}$$

What is the base current?

Base Current

Contributors To Base Current



- **Hole injection into emitter**
- **Hole injection into collector (reverse bias)**
- **e-h recombination in base**

BJT Simplified Relationships

For $W \ll L_B$

$$\gamma_e = \frac{1}{1 + \frac{D_E}{D_B}\frac{N_B}{N_E}\frac{W}{L_E}}$$

$$\alpha_T = \frac{1}{1 + \frac{1}{2}\left(\frac{W}{L_B}\right)^2}$$

$$\alpha_{dc} = \frac{1}{1 + \frac{D_E}{D_B}\frac{N_B}{N_E}\frac{W}{L_E} + \frac{1}{2}\left(\frac{W}{L_B}\right)^2}$$

$$\beta = \frac{1}{\frac{D_E}{D_B}\frac{N_B}{N_E}\frac{W}{L_E} + \frac{1}{2}\left(\frac{W}{L_B}\right)^2}$$

What does $W \ll L_B$ mean?

PNP BJT

We have developed expressions for I-V and figures of merit for the npn BJT

How do things change for pnp?

R-G In Depletion Region

For BJT in Common Emitter Configuration

$$J_{scr} = q\frac{n_i x_d}{2\tau_{nr}} e^{qV_{BE}/2kT}$$

SCR in BE depletion region
Significant in fwd bias, but significance decreases at large fwd bias

Similar expression for BC depletion region, however insignificant for rev bias junction

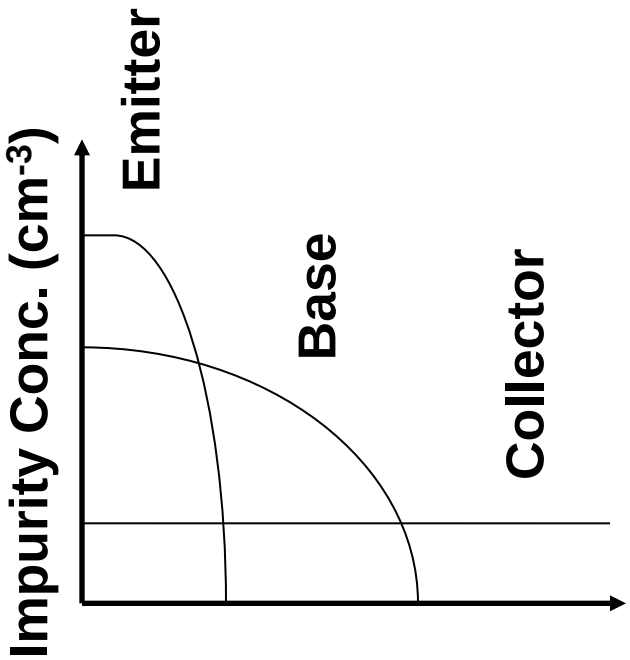
Revise Emitter and Base Current Expressions

$$I_E = I_{En} + I_{Ep} + I_{SCR}$$

$$I_B = I_E - I_C = \left(I_{En} + I_{Ep} + I_{SCR}\right) - \left(I_{Cn} + I_{Cp}\right)$$

Equilibrium Carrier Densities

Base typically formed (in Si) using implant/diffusion fabrication processes



Our assumptions of uniform doping not true

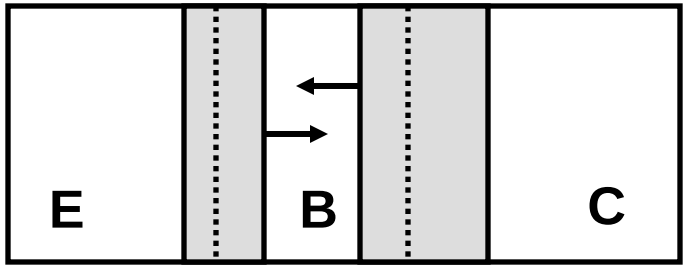
Base current dependent on charge stored in base

$$I_B \approx \frac{Q_B}{\tau}$$

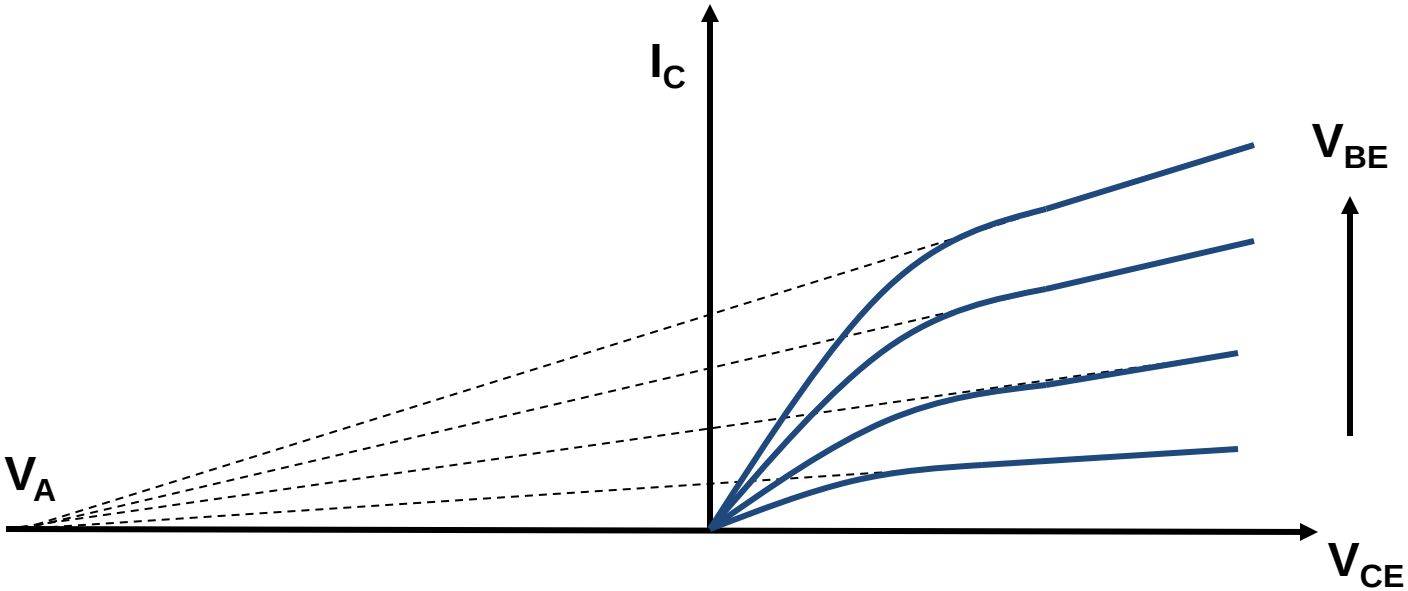
Base-Width Modulation

Early effect

Base width changes with bias

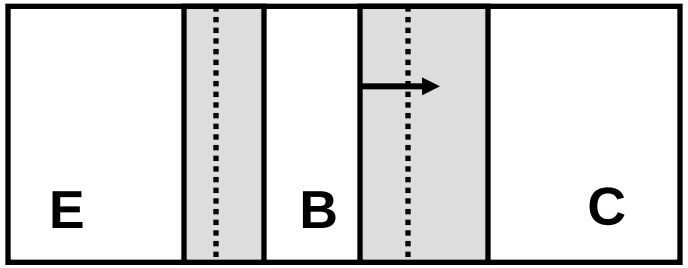


- In FA, significant change in collector current with bias
- Analogous to channel length modulation in FET
- Early voltage at y-intercept



Base Pushout – Kirk Effect

At high injection, minority charge in base comparable to B-C space charge

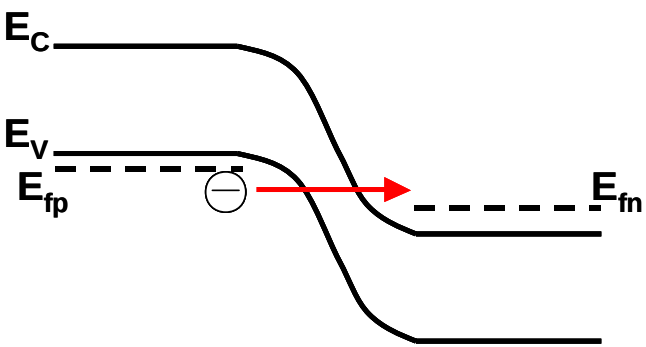


- B-C depletion region decreased
- Base width increased
- Opposite effect of Early effect

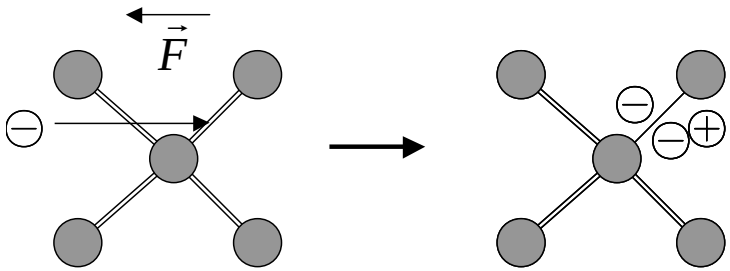
Breakdown In BJT

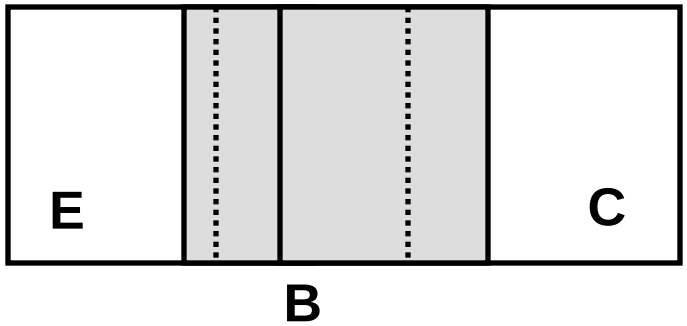
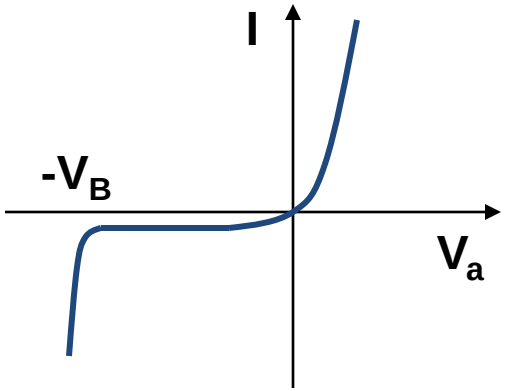
Diode Reverse Breakdown

Tunneling



Avalanche



Punch-through

Base fully depleted