97.398*, Physical Electronics, Lecture 16

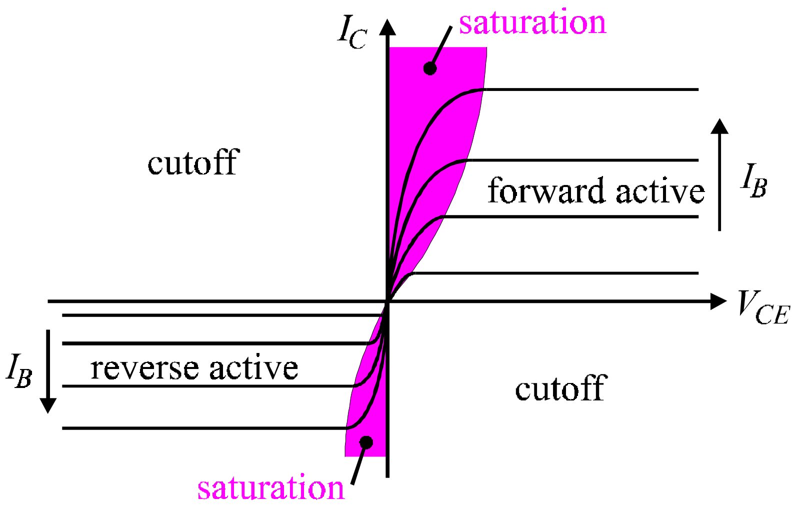
Bipolar Transistor Operation

Lecture Outline

- Last lecture discussed the structure and fabrication of a double diffused bipolar transistor
- Now examine current transfer in the bipolar structure in a qualitative way
  - Regions of operation: forward and reverse active, saturation and cutoff – definitions, minority carrier density and current flow from quantitative point of view
  - Calculate current components explicitly from minority carrier slopes (recall diffusion, lecture 7) – develop quantitative model equations next lecture
  - Transistor Action: the basic mechanism which makes a bipolar useful in amplification
- Next lecture will derive quantitative relationships

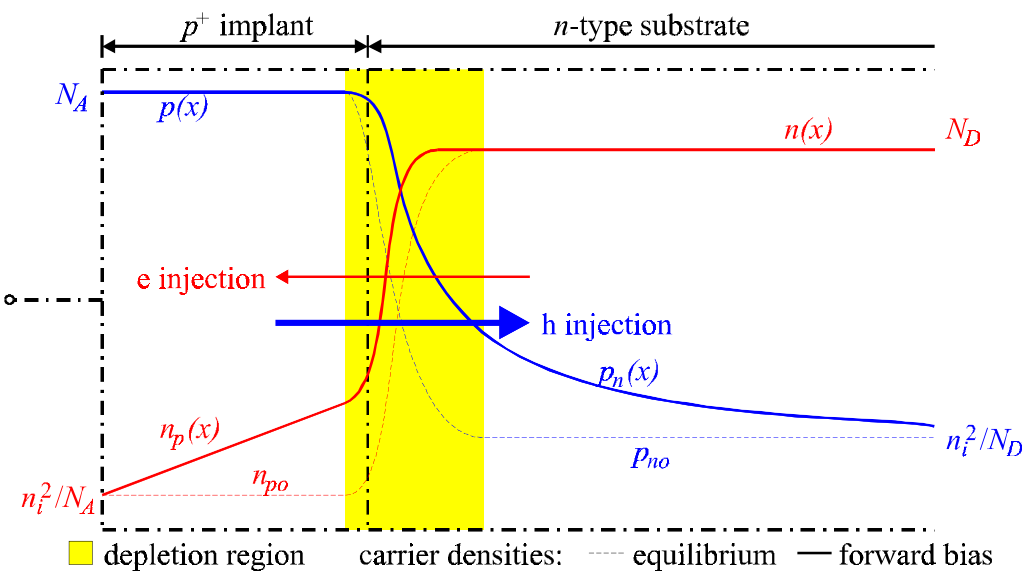
BJT Regions of Operation

- The bipolar transistor has four distinct regions of operation:
  - Forward Active
  - Reverse Active
  - Saturation
  - Cutoff



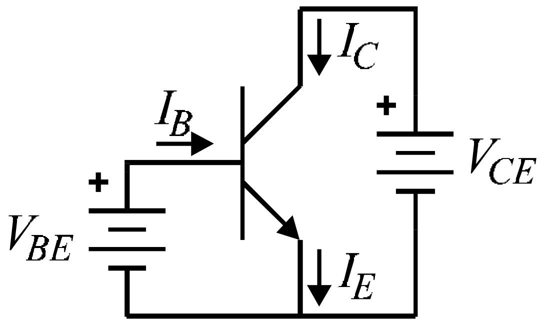
pn-Junction Review

- Recall that the boundary condition for the electron and hole minority densities at the depletion region edges were $n_{po}e^{qVD/kT}$ and $p_{no}e^{qVD/kT}$ respectively, and that the minority density variation with distance is linear for a neutral region which is short compared to the minority diffusion length



Forward Active Operation - Potentials

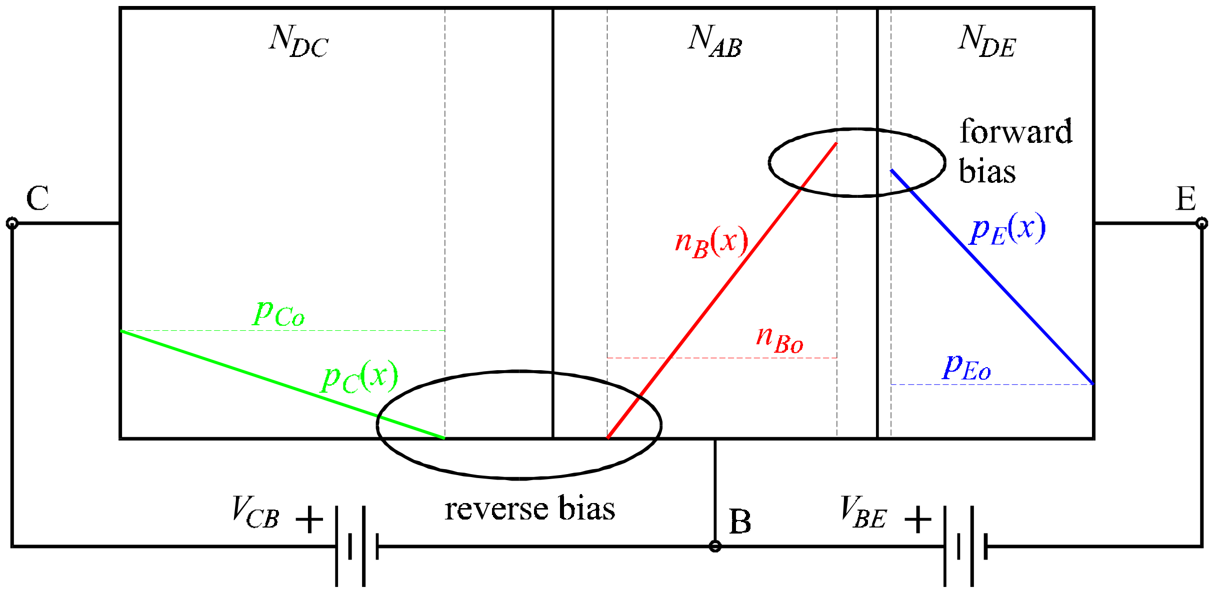
- When the base-emitter junction is forward biased and the base collector junction is reverse biased (implying $V_{CE} > V_{BE}$), the device is in the forward active region of operation



$V_{CE} > V_{BE}$

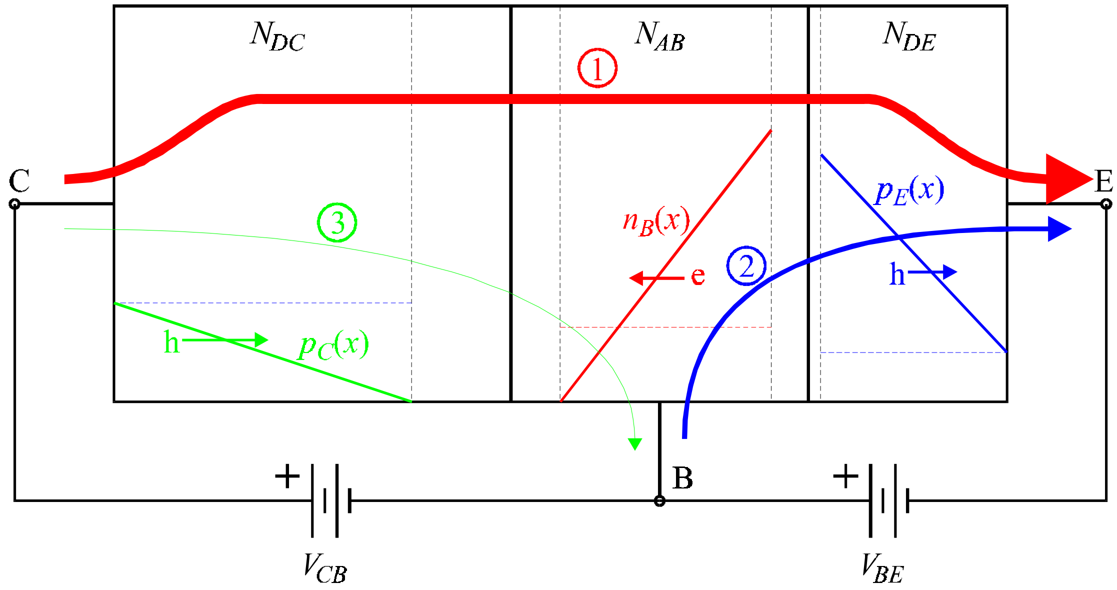
Forward Active Operation - Minority Carriers

- $V_{BE} > 0$ raises $p_E(x)$ and $n_B(x)$ at the BE depletion region edges
- $V_{BC} < 0$ lowers $p_C(x)$ and $n_B(x)$ at the BC depletion region edges
- Since all regions are short compared to the minority diffusion lengths, the minority densities change linearly over all regions



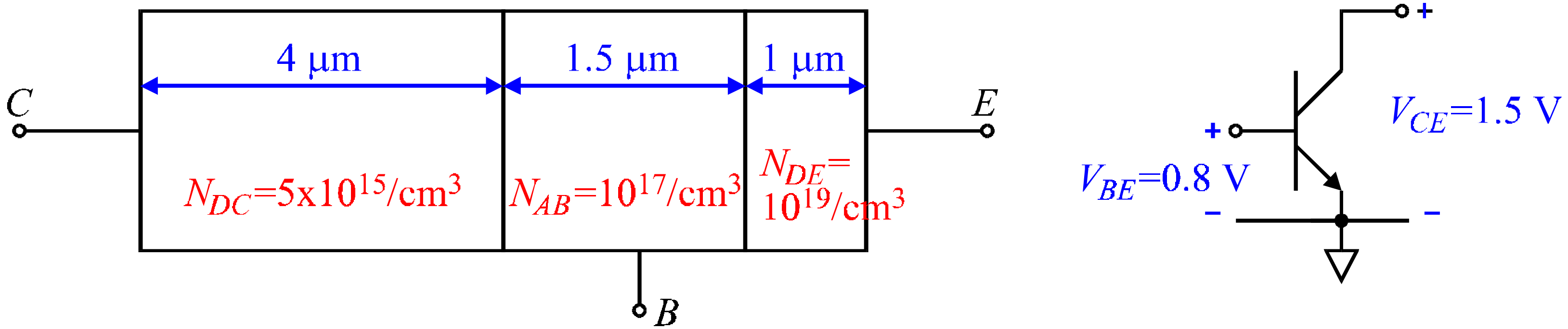
Forward Active Operation - Current Components

- Three current components in forward active operation, all of which can be characterised from the appropriate minority gradient:
  - "Linking current" due to electron transport from collector to emitter (1)
  - "Back injection" due to hole injection from base to emitter (2)
  - small component due to injection of holes from collector to base (3)



Example 16.1: Current Calculations

- Calculate the electron and hole current densities flowing across the base-emitter junction for the device structure and bias condition shown below, using only the boundary conditions and the diffusion equation. The neutral widths were calculated in an earlier example.



Example 16.1: Solution

- The required equations are the diffusion current density expressions

$$J_n = qD_n \frac{dn(x)}{dx} \qquad J_p = -qD_p \frac{dp(x)}{dx}$$

- and the minority carrier boundary conditions at the depletion edges of a *pn*-junction

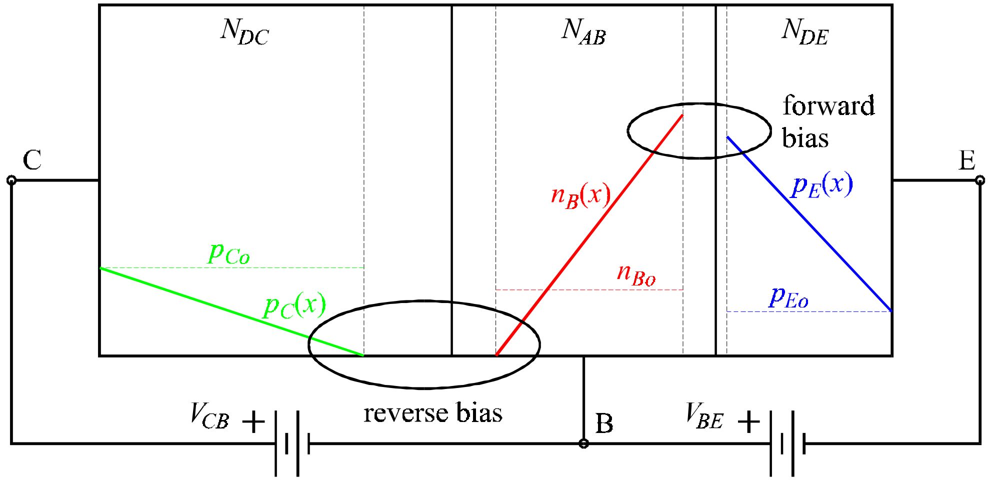
$$p_n\Big|_{\text{depl edge}} = p_{no} e^{qV_D/kT} \qquad n_p\Big|_{\text{depl edge}} = n_{po} e^{qV_D/kT}$$

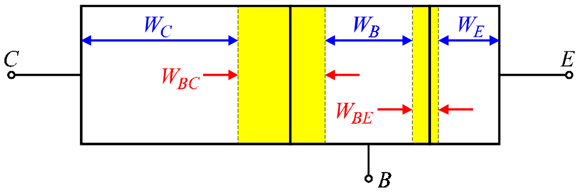
Example 16.1: Solution (con't)

- Applying these equations to the neutral emitter region gives

$$J_p = -qD_p \frac{dp(x)}{dx} = -qD_p \frac{p_{Eo} - p_{Eo} e^{qV_{BE}/kT}}{W_E}$$

$$= -1.6 \times 10^{-19} \cdot 12.2 \cdot \frac{21 - 21e^{0.8/0.026}}{10^{-4}} = 11.2 \text{ A / cm}^2$$



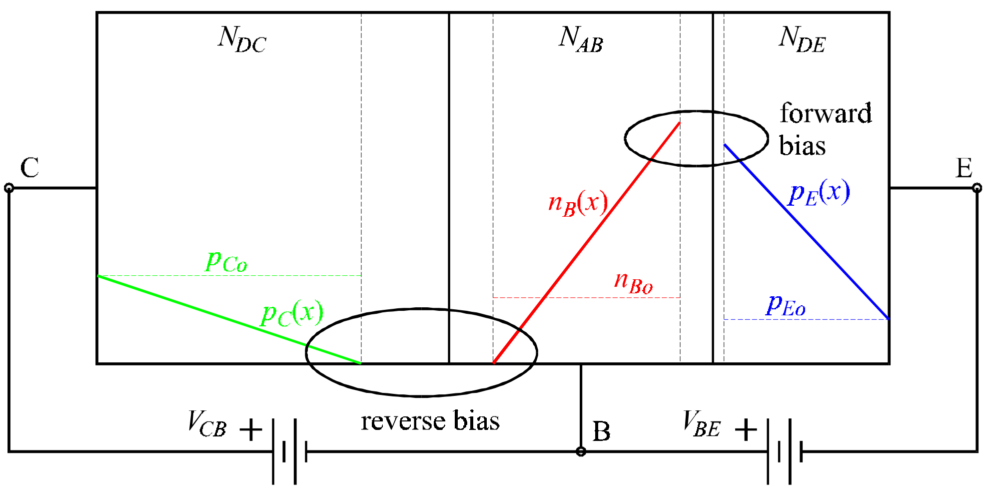


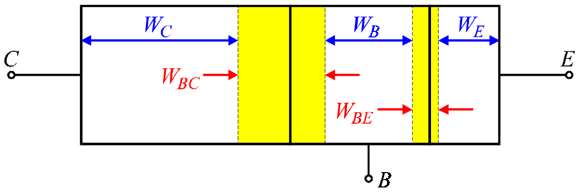
Example 16.1: Solution (con't)

- Applying the appropriate equations to the base neutral region with V_{BC} = -0.7V gives (note error in second gradient term in notes)

$$J_n = qD_n \frac{dn(x)}{dx} = qD_n \frac{n_{Bo}e^{qV_{BE}/kT} - n_{Bo}e^{qV_{BC}/kT}}{W_B}$$

$$= 1.6\times10^{-19}\cdot 34.9\cdot \frac{2.1\times10^{3}\cdot e^{0.8/0.026} - 2.1\times10^{3}\cdot e^{-0.7/0.026}}{1.4\times10^{-4}} = 2.28\times10^{3}\ \text{A / cm}^{2}$$

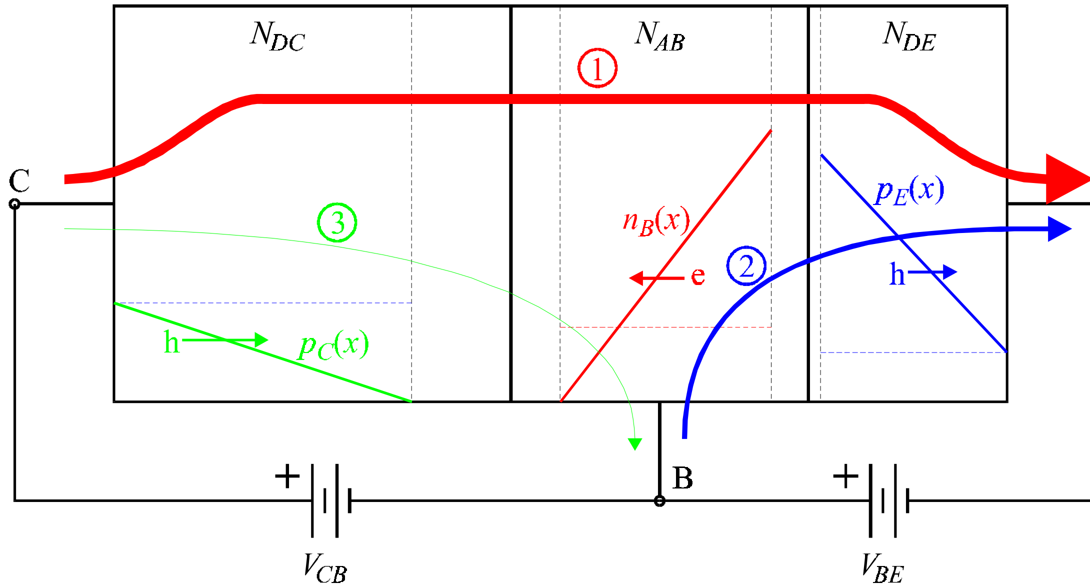




Example 16.1: Solution (con't)

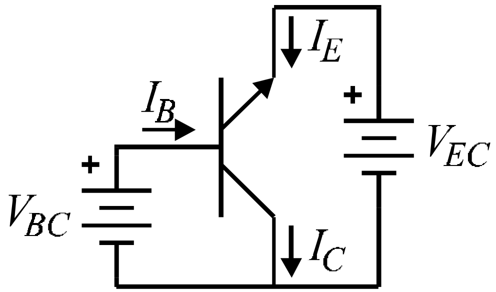
- Note that J_n, the electron injection (linking current) component, is much larger than J_p, the hole (back) injection component

$$J_n = 2.28 \times 10^3 \text{ A / cm}^2 \qquad J_p = 11.2 \text{ A / cm}^2$$



Reverse Active Region - Potentials

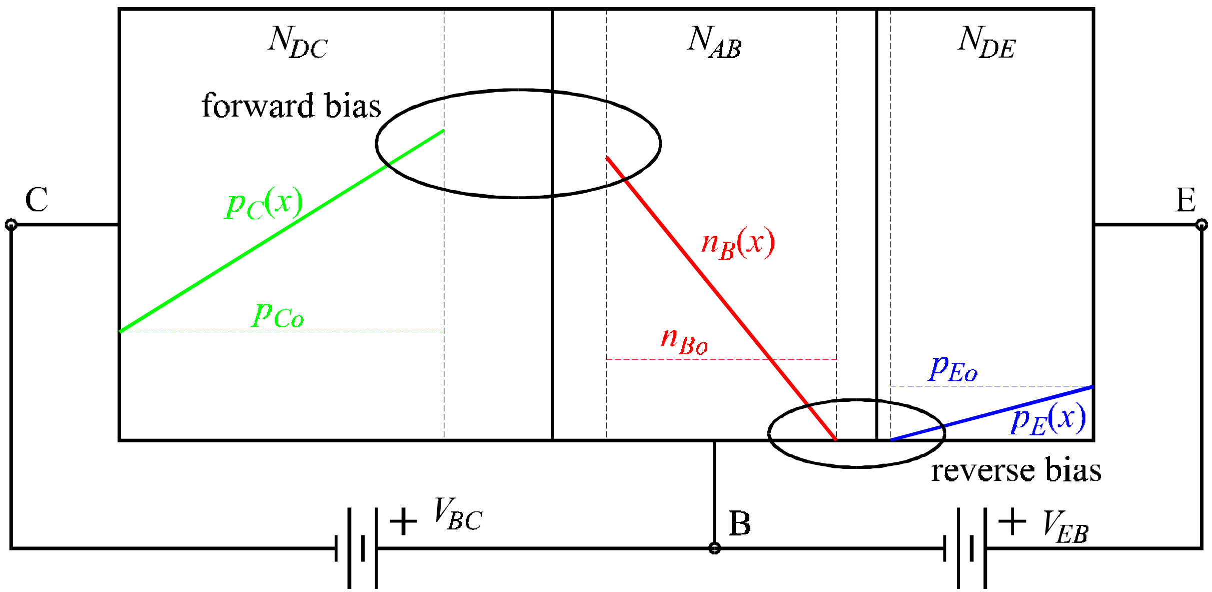
- When the base collector junction is forward biased and the base emitter junction is reverse biased (implying $V_{EC} > V_{BC}$), the device is in the reverse active region of operation
- Basically the forward active region with roles of emitter and collector reversed



$V_{EC} > V_{BC}$

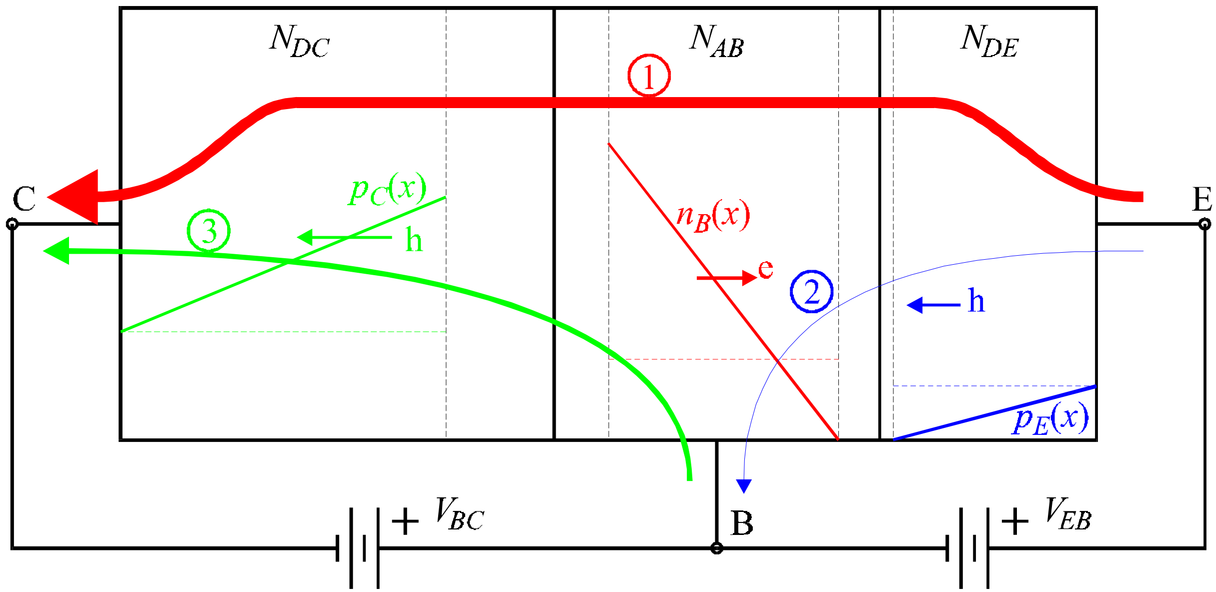
Reverse Active Region - Minority Carriers

- Similar distributions to forward active, with bias (forward/reverse) of base-collector and base-emitter junctions reversed
- Note that potentials are mislabeled in notes



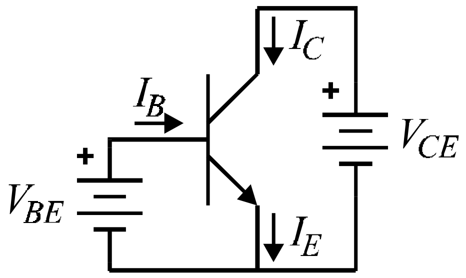
Reverse Active Region - Current Components

- Three current components in reverse active operation:
  - "Linking current" due to electron transport from emitter to collector (1)
  - small component due to injection of holes from emitter to base (2)
  - "Back injection" due to hole injection from base to collector (3)



Saturation Region - Potentials

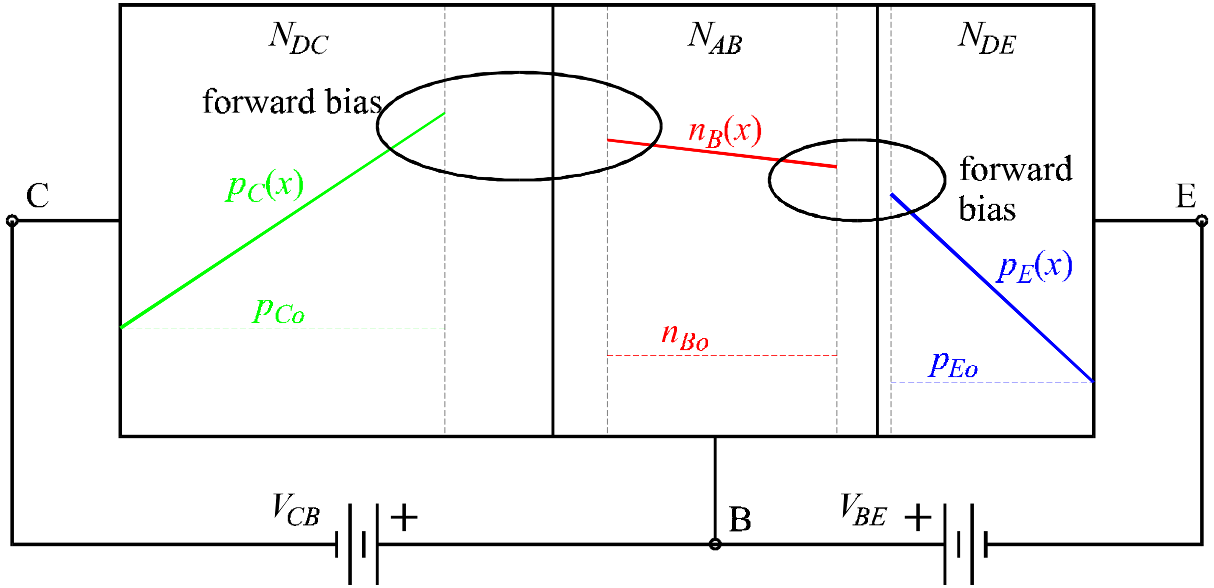
- The saturation region of operation is characterised by forward bias potentials on both the base-emitter and base-collector junctions (implying $V_{BE} \geq V_{CE}$)



$V_{CE} \leq V_{BE}$

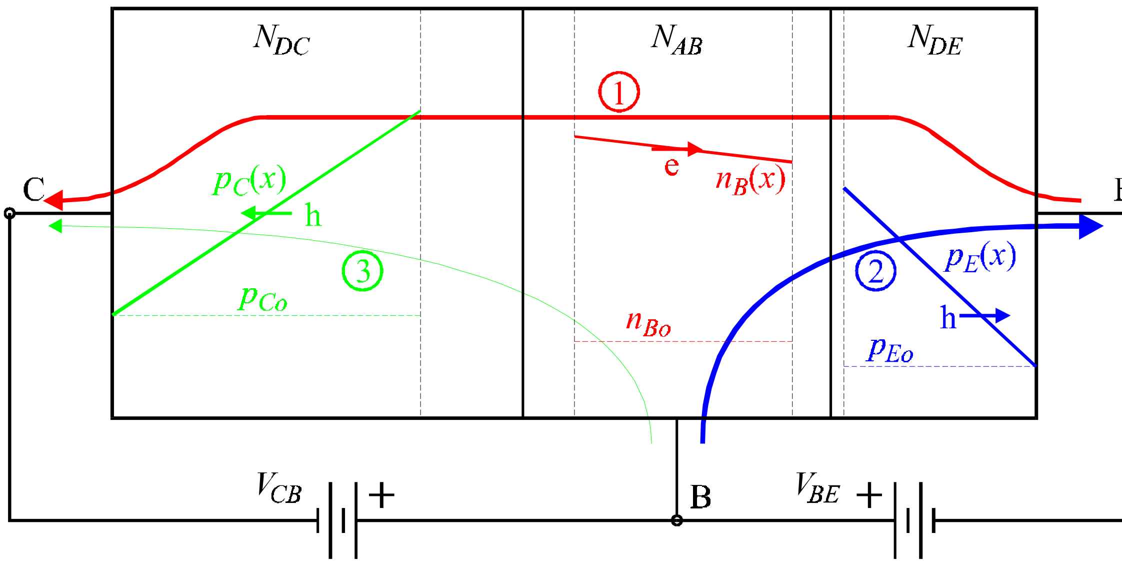
Saturation Region - Minority Carriers

- With both junctions forward biased, the minority carrier densities are raised above their equilibrium values throughout the device
- The values of $n_B(x)$ on either side of the neutral base region ($n_{Bo}e^{qVBE/kT}$ and $n_{Bo}e^{qVBC/kT}$) determine the slope of $n_B(x)$ - depending on the relative values of V_{BE} and V_{BC}, the slope may be +ve, -ve or zero



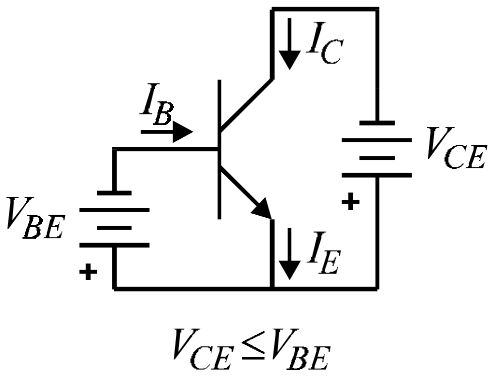
Saturation Region - Current Components

- Three current components in saturation operation:
  - "Linking current" due to electron transport (1) - can be from emitter to collector ($V_{BE} < V_{BC}$), collector to emitter ($V_{BE} > V_{BC}$), or zero ($V_{BE} = V_{BC}$)
  - component due to injection of holes from base to emitter (2)
  - component due to injection from base to collector (3)



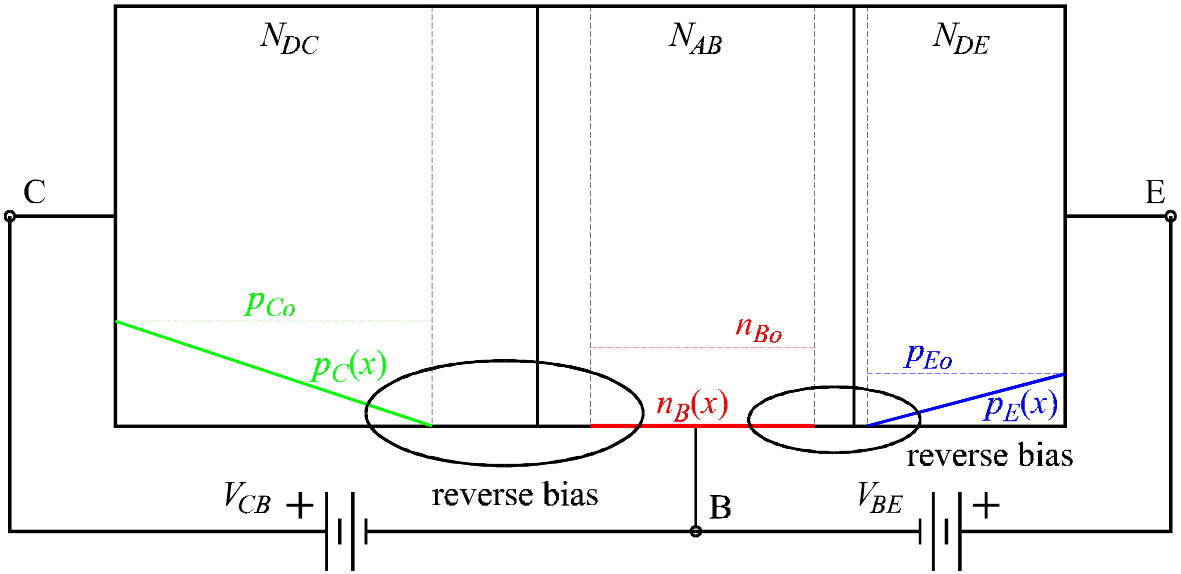
Cutoff Region - Potentials

- When both junctions are reverse biased (implying V_{BE} negative and $V_{BE} \geq V_{CE}$) the device is in the cutoff region of operation



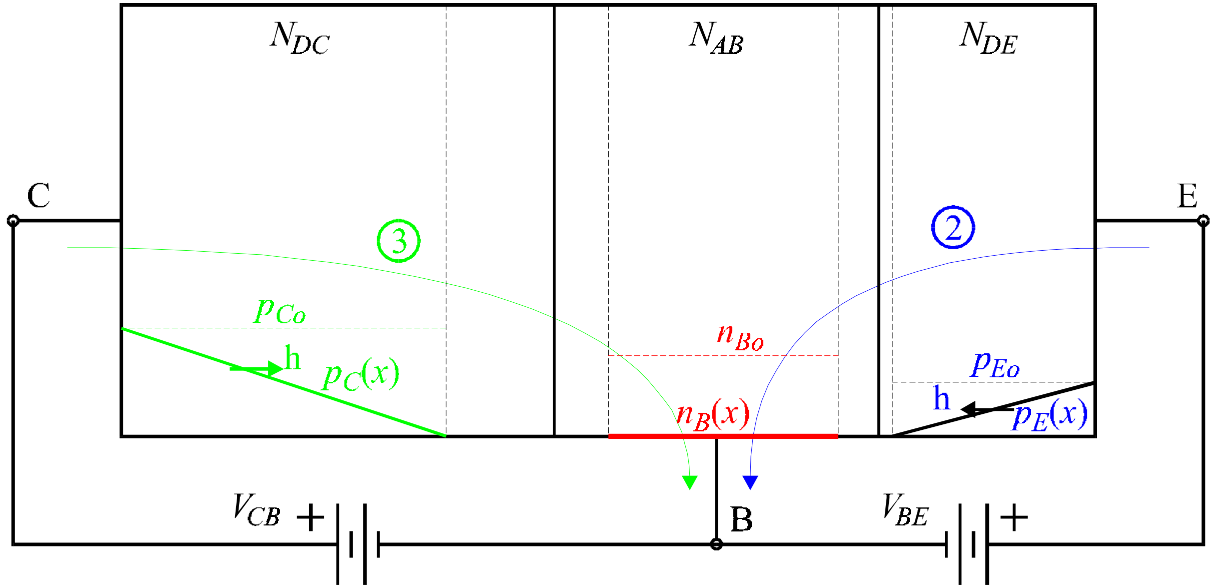
Cutoff Region - Minority Carriers

- With V_{BE} and V_{BC} reverse biased, the minority carrier densities are small at all depletion region edges
- This implies that $n_B(x)$ is zero over the entire neutral base region, since the distribution must be linear



Cutoff Region - Current Components

- Only two current components in saturation operation - “linking current” is zero because gradient of $n_B(x)$ is zero
  - small component due to injection of holes from emitter to base (2)
  - small component due to injection from collector to base (3)

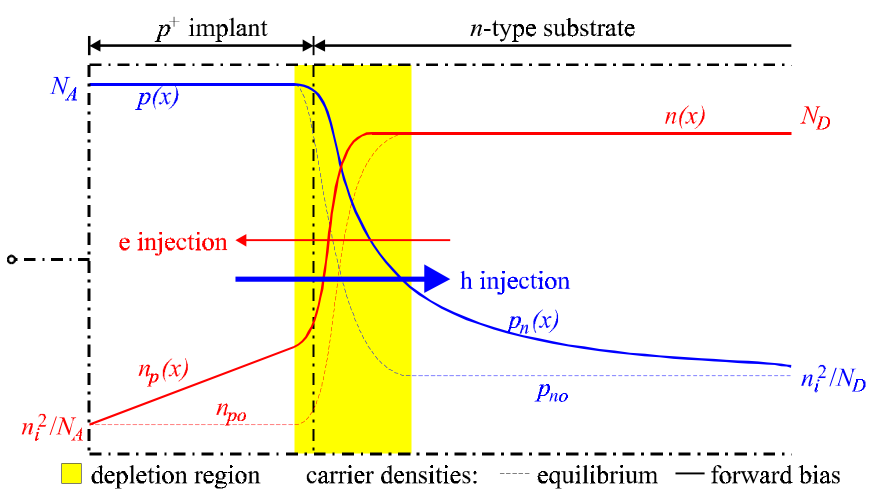


pn-Junction - Current Components

- Recall ideal diode equation saturation current density for p^+n diode

$$J_S\Big|_{p^+n} = \frac{qD_n n_{po}}{w_p} + \frac{qD_p p_{no}}{L_p}$$

- When one doping is much higher than the other, injection into the more lightly doped side dominates (equilibrium density much higher)

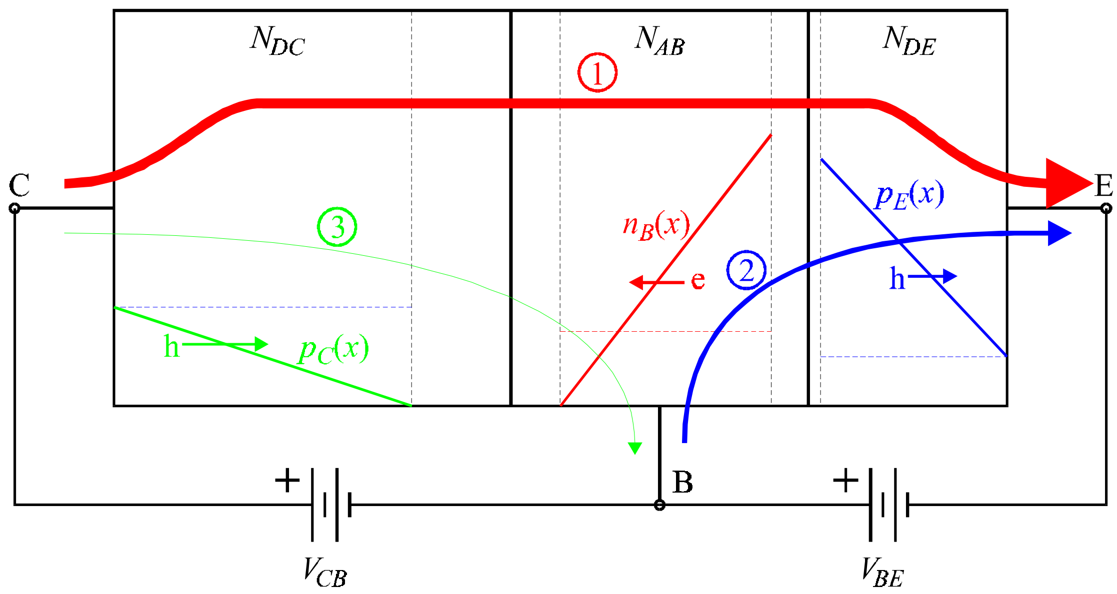


Transistor Action

- The term transistor action refers to the control of the large collector-emitter (linking) current by the smaller base (back injection) current in forward active operation, the origin of "current gain" in a BJT
- Two features of the device are essential for transistor action
  - a narrow base, which forces all electrons injected from the emitter to travel across the base neutral region to the collector
  - a high emitter doping compared to the base doping, making base (electron) injection the dominant term

Transistor Action in Forward Active Operation

- Current components across base-emitter junction are related by relative doping
- Large collector to emitter current controlled by small (back injection) base current due to requirement for relation across BE junction
- Narrow base prevents flow of injected electrons out base lead



Lecture Summary

- This lecture has introduced the fundamental current components in the bipolar structure for each region of operation
- Current components calculated explicitly from minority carrier slopes using diffusion relationship from diode
- Transistor action identified – narrow base and highly doped emitter allow control of large collector to emitter linking current with small base to emitter back injection component