# ELEC4705 – Fall 2009

**Tom Smy**

## LECTURE 15
## The Bipolar Transistor

# Contents

## 15.1. Transistors – BJT and MOSFets

Transistors are devices which control a large current with a smaller current or an applied voltage. They are typically used for amplifying a signal or for digital control (on/off switching). There are two basic types:

- **Bipolar** structures which use a back to back diode structure.
- **FET** (field effect transistor) which is typically a surface controlled device (MOSFET).

## 15.2. BJT - Physical structure and band structure

The structure is a back to back diode (ie *npn* or *pnp*), as shown in figure 1. Two depletion regions are formed of exposed donors/acceptors with a large electric field in each causing band bending between the regions. There are three contacts an emitter, base, and collector. It is typically the base that is the controlling contact. Also figure 2 shows the band structure for the given npn transistor.

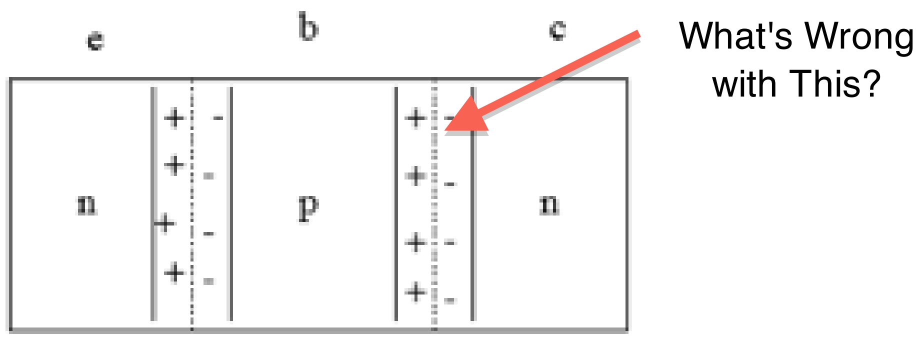



**Figure 1.** A Basic npn Bipolar Structure – note the mistake in the charge distribution!

### 15.2.1. Equilibrium

At equilibrium the fermi levels of all three regions must line up. There is no net current through either junction. The junction widths and built in voltages are simply calculated using the diode expressions. Across each junction there are two exactly equal drift and diffusive flows of both electrons and holes so that the total flow of both is zero. As with the diode the built in voltages across each junction are precisely that needed to produce equal and opposite flows of both electrons and carriers and guarantee that no current is flowing.

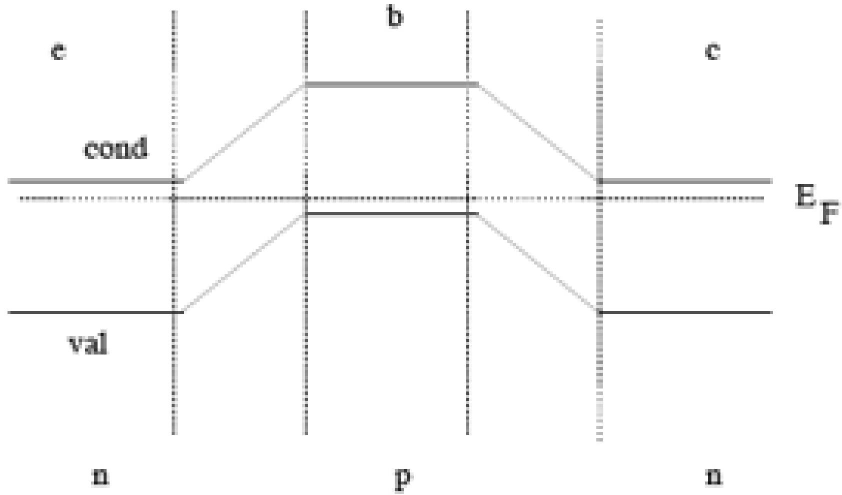
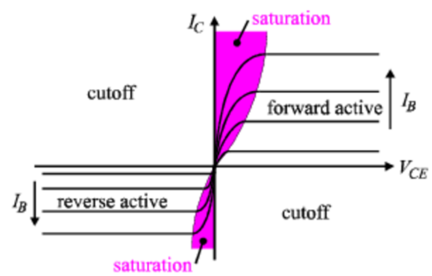



**Figure 2.** A npn band structure in equilibrium with no applied bias

## 15.3. Biasing the BJT

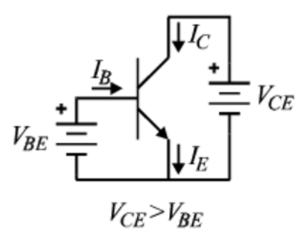
### BJT Regions of Operation

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




### 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



## 15.4. Forward Active

There are many ways of biasing a BJT but the primary use is as an amplifier when biased in forward active. We will use this case first as an example of the current transport in a BJT. In forward active the Base-emitter junction is forward biased by $V_{eb}$ and the base collector is reverse biased by $V_{cb}$. This results in the lowering of the barrier height between the emitter and the base and an increase in the barrier height between the base and collector as shown in figure 3.

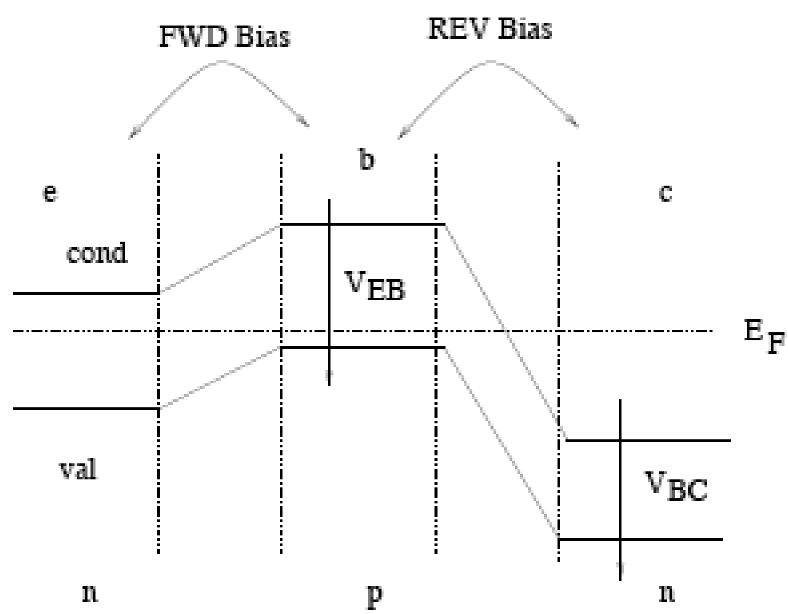



**Figure 3.** band structure for biased npn transistor

The lowering of the base emitter junction barrier height will unbalance the electron flows across that junction, causing a significant injection of minority carriers (electrons) into the $p-type$ base. This injection of electrons is exponentially related to the applied base-emitter voltage. At the collector junction the reverse bias provides a means to collect electrons that are present in the base near the junction. Any electron that is in the base near the collector junction will fall over the barrier and lower it's energy. This results in very low electron (minority) concentrations in the base at the collector junction. Figure 4 shows the electron transport in a npn transistor.

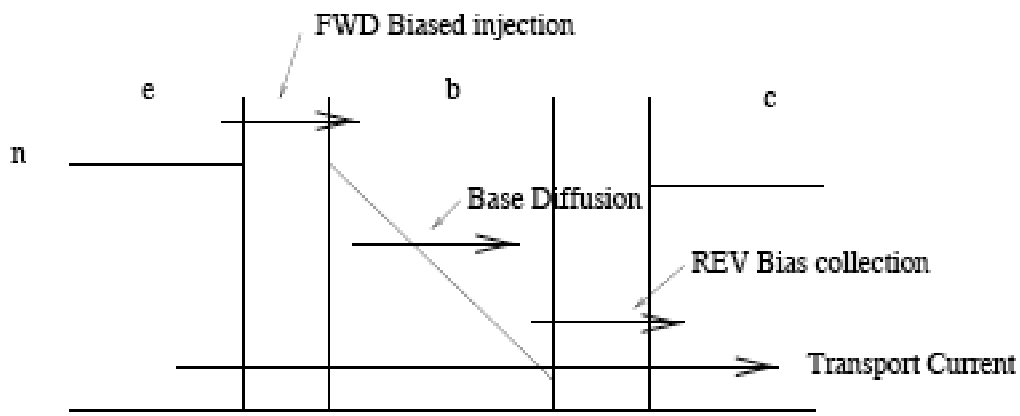
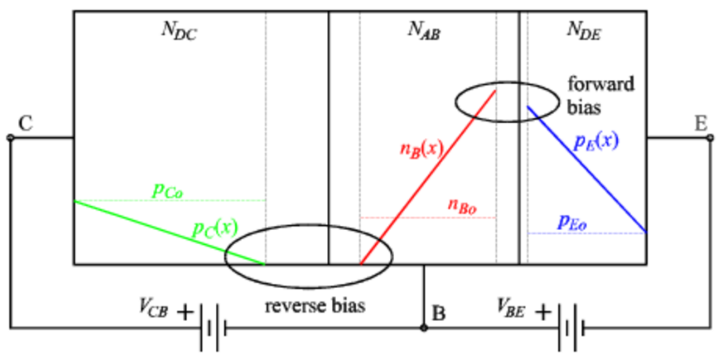



**Figure 4.** Electron Transport Current in a npn Transistor

## Forward Active Operation - Minority Carriers

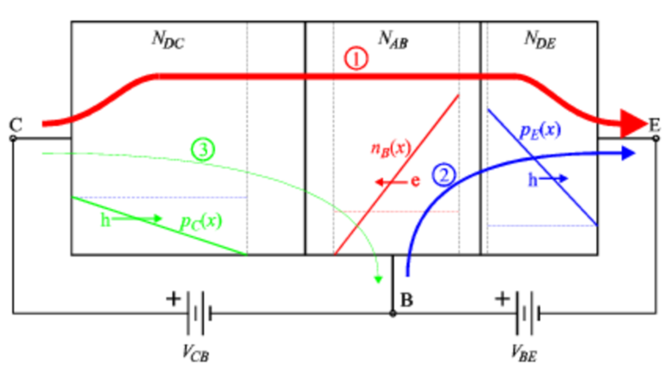
- $V_{BE} > 0$ raises $p_E(x)$ and $n_B(x)$ at the BE depletion region edges
- $V_{BC} < 0$ lowers $p_C(x)$ and $n_B(x)$ at the BC depletion region edges
- Since all regions are short compared to the minority diffusion lengths, the minority densities change linearly over all regions






## 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)



### 15.4.1. Forward Active

- Electrons are injected into the base at the emitter junction. Causing a high concentration of electrons in the base at that junction.
$$n \approx e^{qV_{be}/KT} \tag{15.1}$$
- Electrons are collected at the collector junction as they fall over into the collector region.
$$n \approx 0$$
- A diffusional transport current is present from the emitter junction through the base to the collector current. If the base is thin then electron distribution is linear.
$$J \approx e^{qV_{be}/KT} \tag{15.2}$$

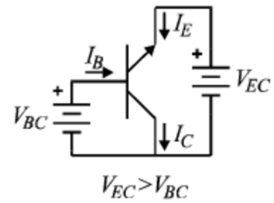
The net result of this is a transport current that is controlled by the base emitter current. The equation of this transport current is given by equation 15.3.
$$I_C = I_E = I_0 e^{qV_{be}/KT} \tag{15.3}$$
A closer analyses of the base emitter junction shows that there is a base current flowing that can be given by 15.4.
$$I_B \approx \frac{I_0}{\beta} e^{qV_{be}/KT} \tag{15.4}$$
where we have $I_C = \beta I_B$.

Notes:

- The collector current can be therefor controlled by a small base current.
- $\beta$ can be made large by choosing a good clean material and making the base width small (large diffusion current).
- This formula is only valid for forward active, but other modes of operation (cutoff, saturation, etc) can be understood in a similar manner.

# Reverse Active Region - Potentials

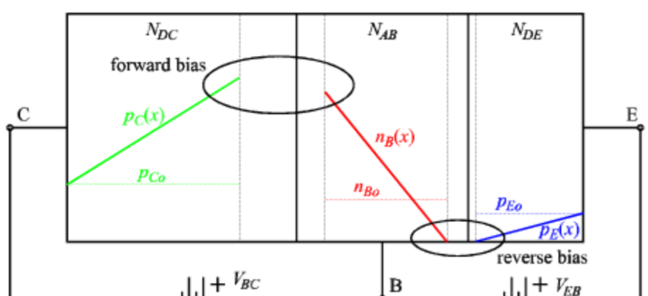
- When the base collector junction is forward biased and the base emitter junction is reverse biased (implying $V_{EC} > V_{BC}$), the device is in the reverse active region of operation
- Basically the forward active region with roles of emitter and collector reversed





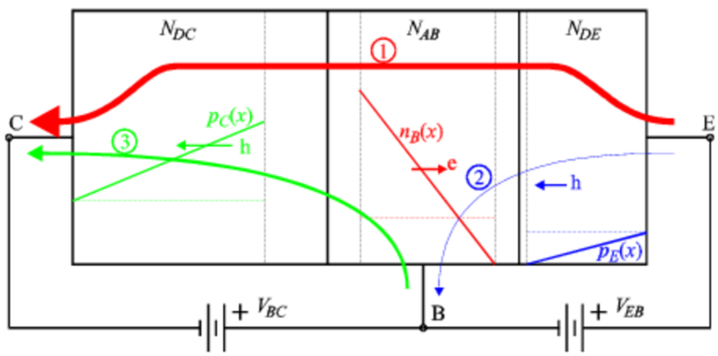

# Reverse Active Region - Minority Carriers

- 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

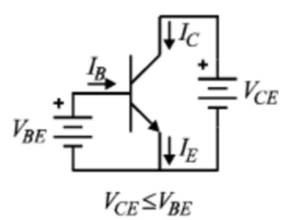
- Three current components in reverse active operation:
  - "Linking current" due to electron transport from emitter to collector (1)
  - small component due to injection of holes from emitter to base (2)
  - "Back injection" due to hole injection from base to collector (3)





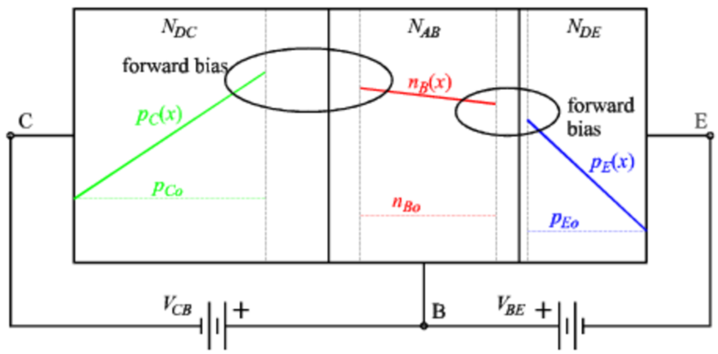

# Saturation Region - Potentials

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



## Saturation Region - Minority Carriers

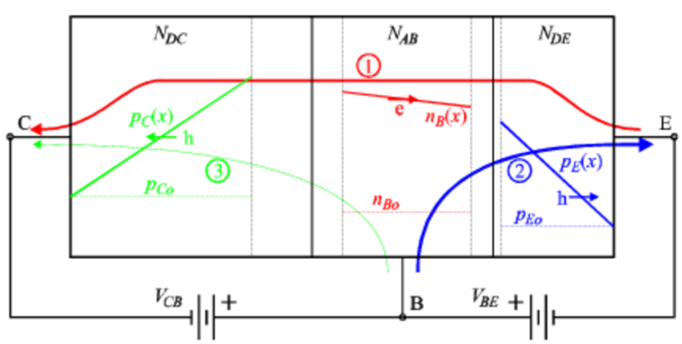
- With both junctions forward biased, the minority carrier densities are raised above their equilibrium values throughout the device
- The values of $n_B(x)$ on either side of the neutral base region ($n_{Bo}e^{qVBE/kT}$ and $n_{Bo}e^{qVBC/kT}$) determine the slope of $n_B(x)$ - depending on the relative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





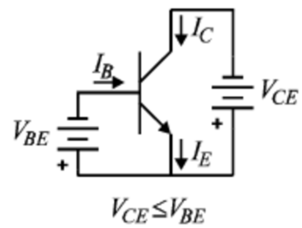

## Saturation Region - Current Components

- 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

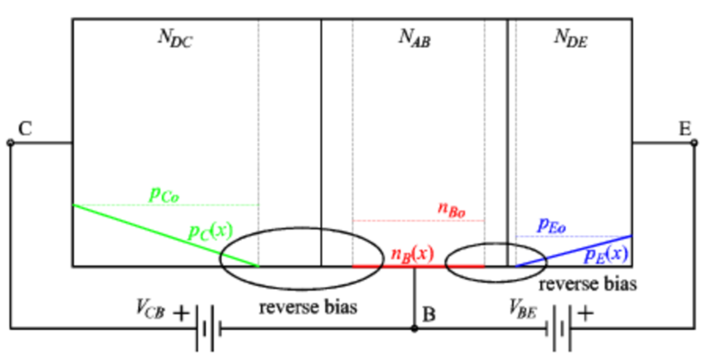
- When both junctions are reverse biased (implying $V_{BE}$ negative and $V_{BE} \geq V_{CE}$) the device is in the cutoff region of operation





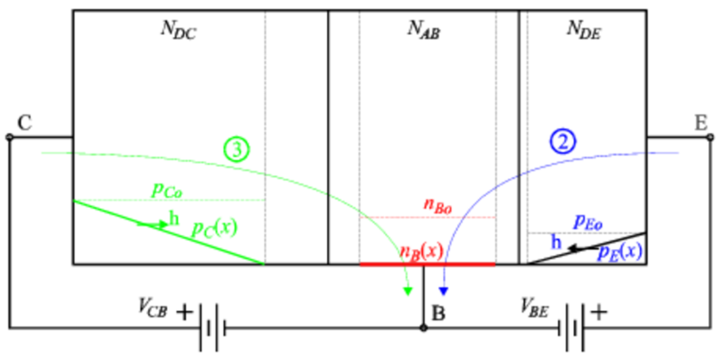

## Cutoff Region - Minority Carriers

- 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)



## 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