Chapter 12

Transistors

The BJT

The Bipolar Junction Transistor (BJT)

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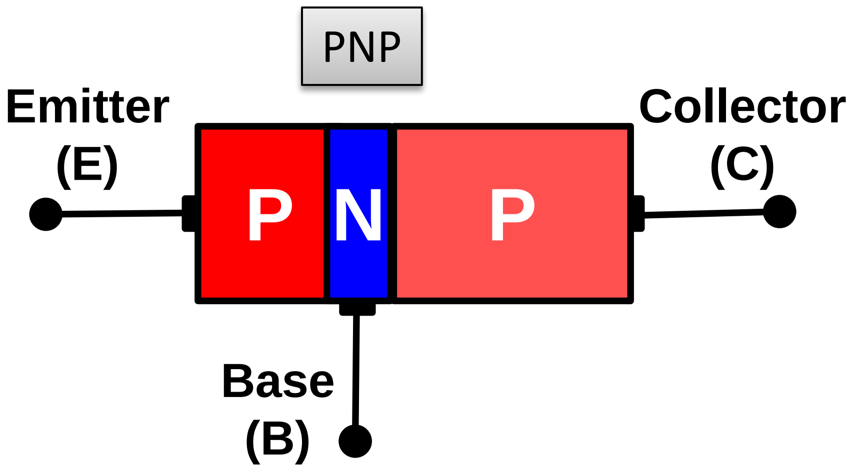
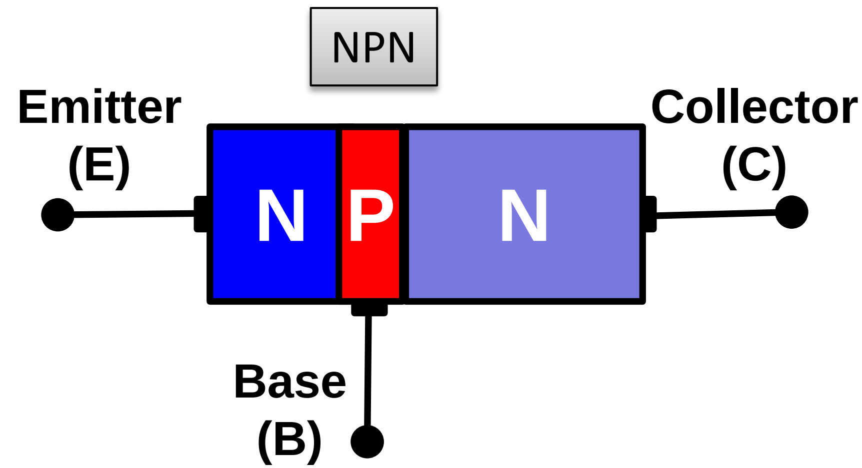
- This is an important class of transistor with a long history, especially for analogue applications. BJTs have a fundamentally different operating principle to FETs;
- The concept is to construct a 3-terminal device using either a PNP or an NPN arrangement of the doping in three adjacent regions of a semiconductor crystal;
- While FETs are ‘unipolar’ devices (i.e. either electrons or holes make up the current flow in the channel), BJTs are ‘bipolar’: both electrons and holes are involved in each type, although electrons dominate the current in an NPN and holes in a PNP.

A Short History of the BJT

- The original BJT was invented by Bardeen, Brittain and Shockley in Bell Labs on Christmas Eve in 1947;
- Early devices were made of Germanium and mostly PNP in kind but Silicon devices are found to give better high temperature performance (because of a higher bandgap);
- Electrons in Si have significantly higher mobility than holes, so NPN transistors tend to give better performance than PNP (e.g. by working at higher frequencies);
- Although bipolar transistors dominated the early ICs, they required special isolation measures to separate individual devices whereas MOS technologies with their intrinsic isolation, provide much higher packing densities in ICs.

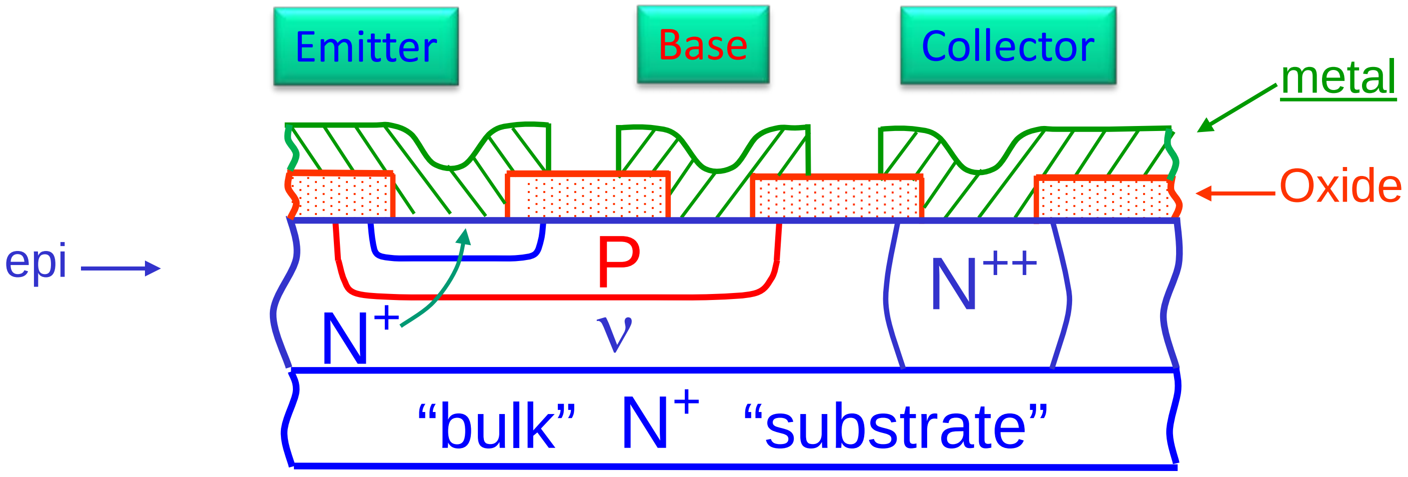
PNP and NPN Bipolar Transistors



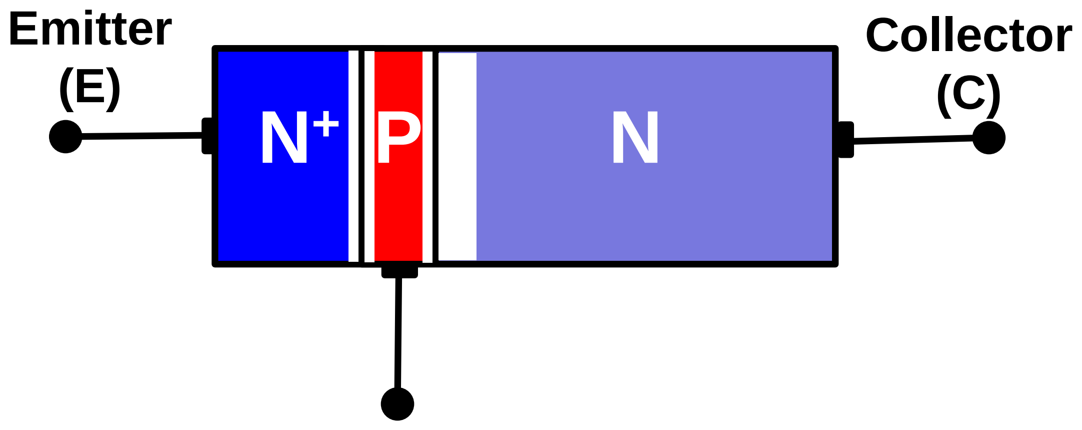


- The BJT is a logical extension of the PN junction involving the addition of a third doped region, so that the structure consists of two PN junctions;
- The two end regions are called the **Emitter** and **Collector**, and these are separated by a **thin Base** region. The fact that the Base width is small is critical to the operation of the BJT as **both PN junctions must be close enough to interact with each other**;
- In practice, the Emitter is usually more heavily doped than the Collector.

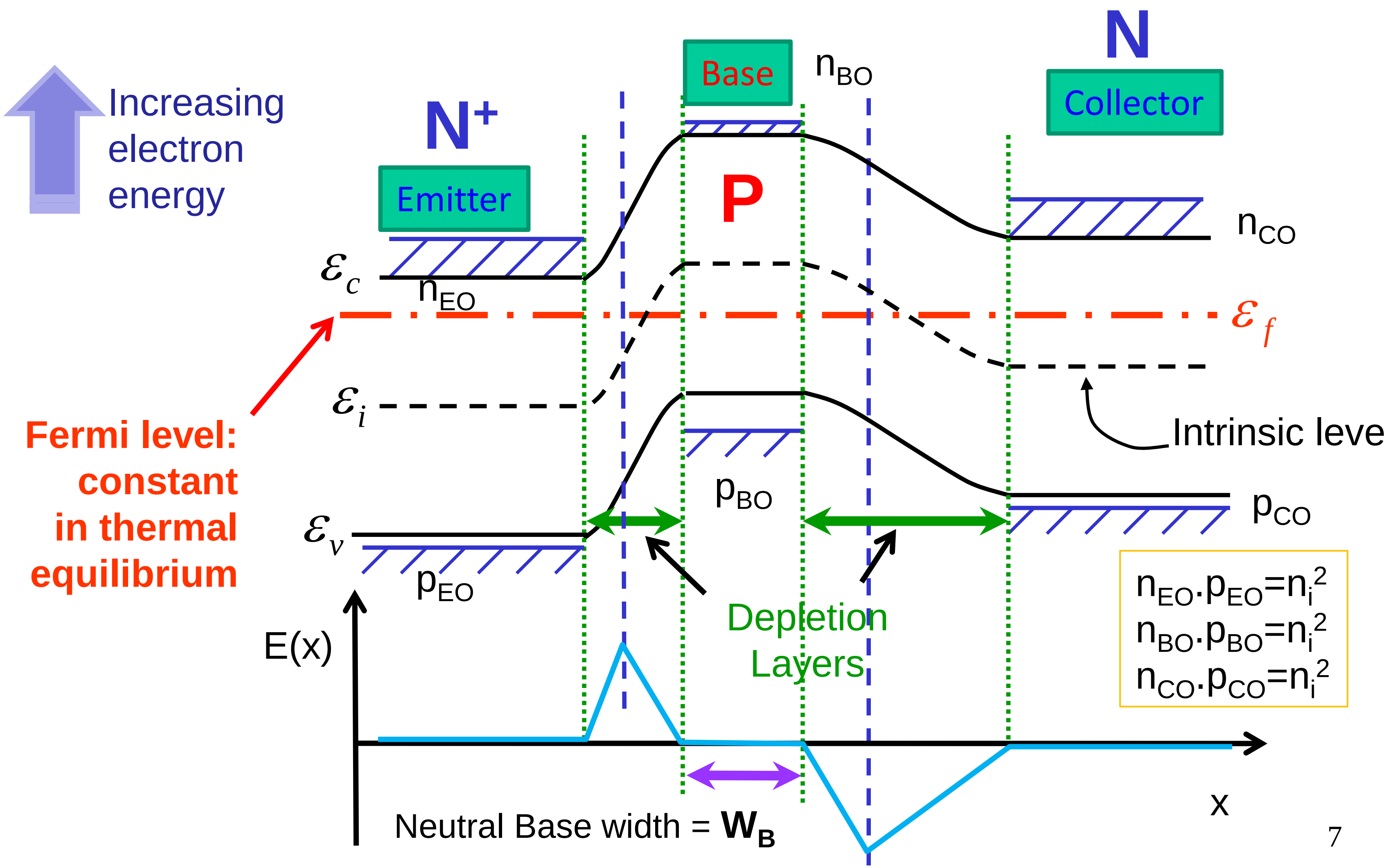
Practical….



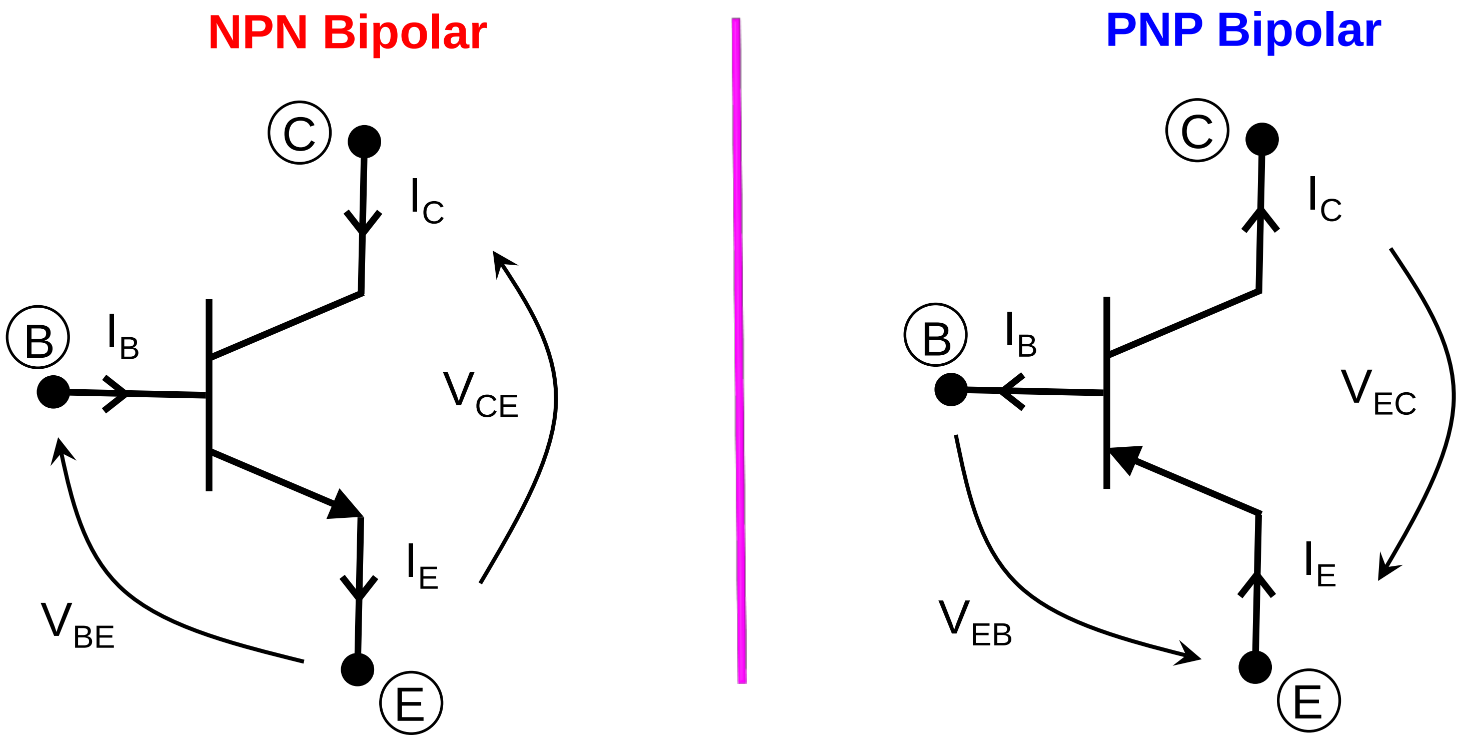
…. and Idealised NPN Structure



Energy Band Diagram for Ideal NPN Bipolar Transistor in Thermal Equilibrium



Circuit Schematic Symbols for BJT and Reference Senses (DC)



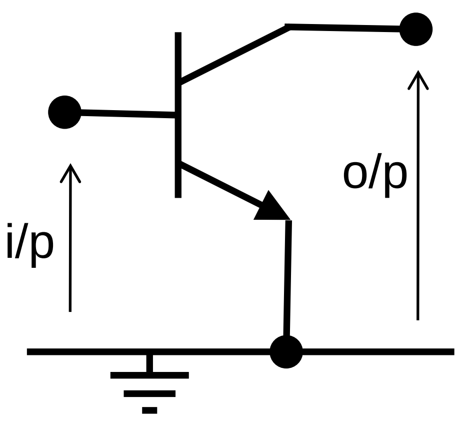
- Note that the position of the arrow indicates the Emitter and its direction distinguishes between NPN and PNP
- In both cases, KCL gives: $I_E = I_C + I_B$

Biasing Modes of the Ideal NPN Transistor

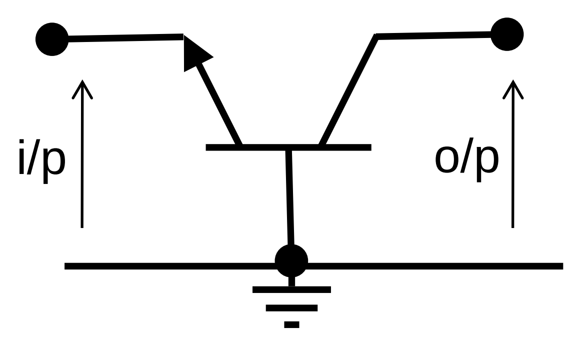
- The BJT has two closely-spaced PN junctions, so that in principle 4 biasing possibilities exist for the overall structure:
  - **Normal (or Forward) Active Mode:** Forward Bias the E/B junction and Reverse Bias the C/B junction. This is the arrangement normally used in signal amplifiers, for example;
  - **Saturation Mode:** *Forward* Bias *both* the E/B and B/C junctions. A high current can then flow from C→ E with a very small V_{CE}. The transistor approximates a closed switch (or could represent the digital logic state '0', for example);
  - **Cut-Off Mode*:*** *Reverse* Bias *both* the E/B and B/C junctions. The transistor is essentially an open-circuit from C→ E with a very small leakage current flowing. The transistor then approximates an open switch (or could represent the digital logic state '1', for example);
  - **Reverse Active Mode:** here we Reverse Bias the E/B junction and Forward Bias the B/C junction. This mode is normally avoided.

Configurations of the NPN Bipolar Transistor (Normal Active Mode)

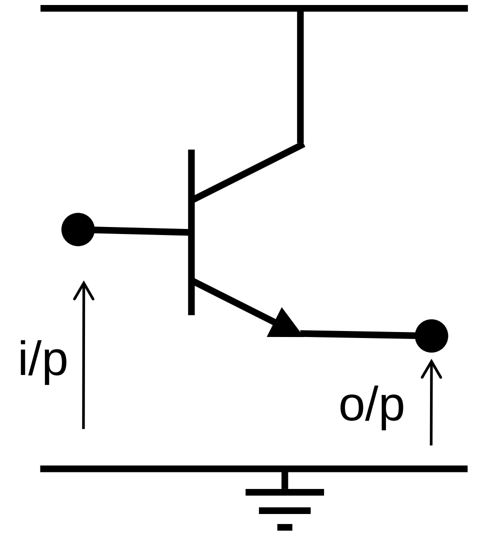
- If we operate the BJT as a signal amplifier in the Normal Active mode, for example, three connection configurations are possible:



Common Emitter (CE)

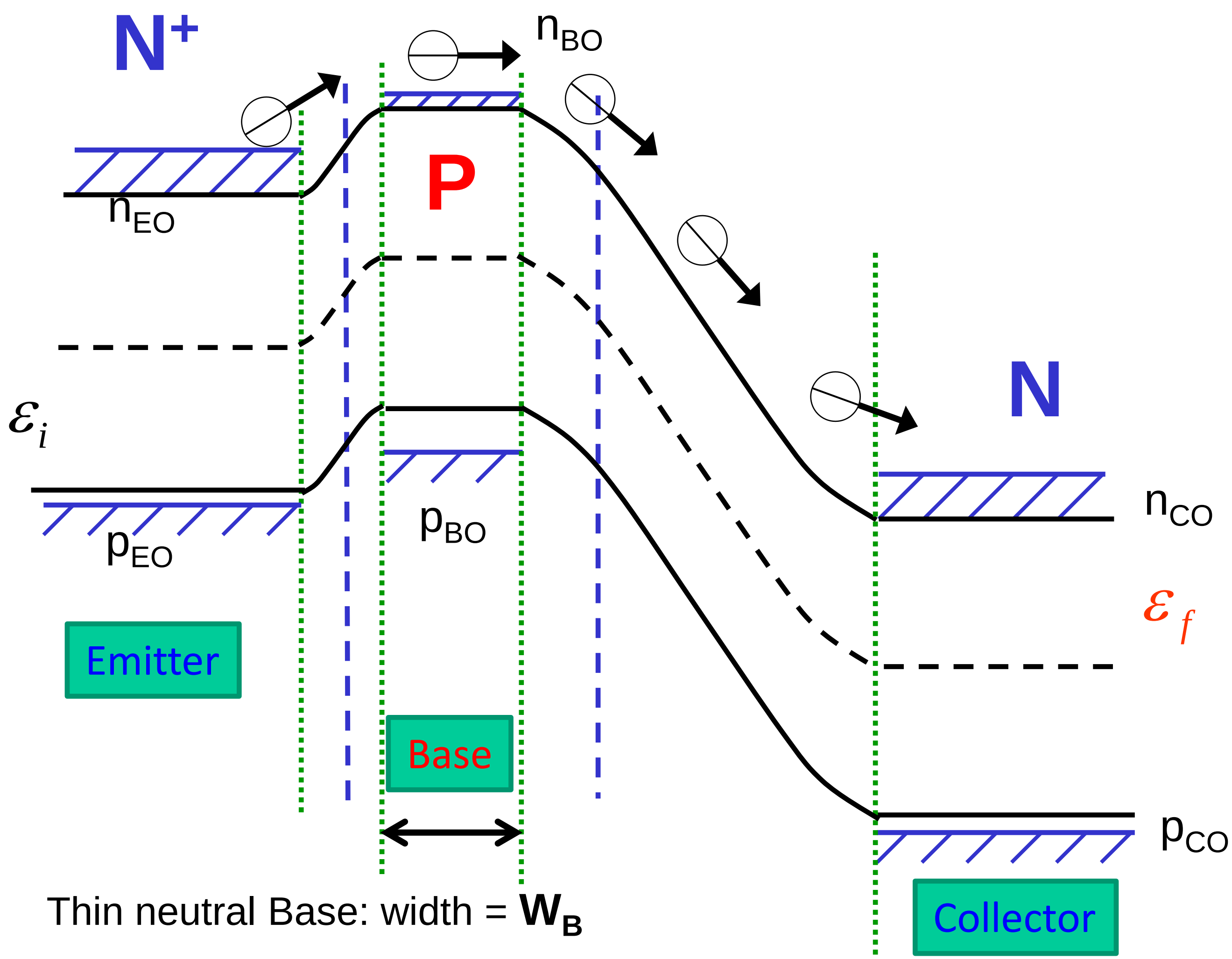


Common Base (CB)

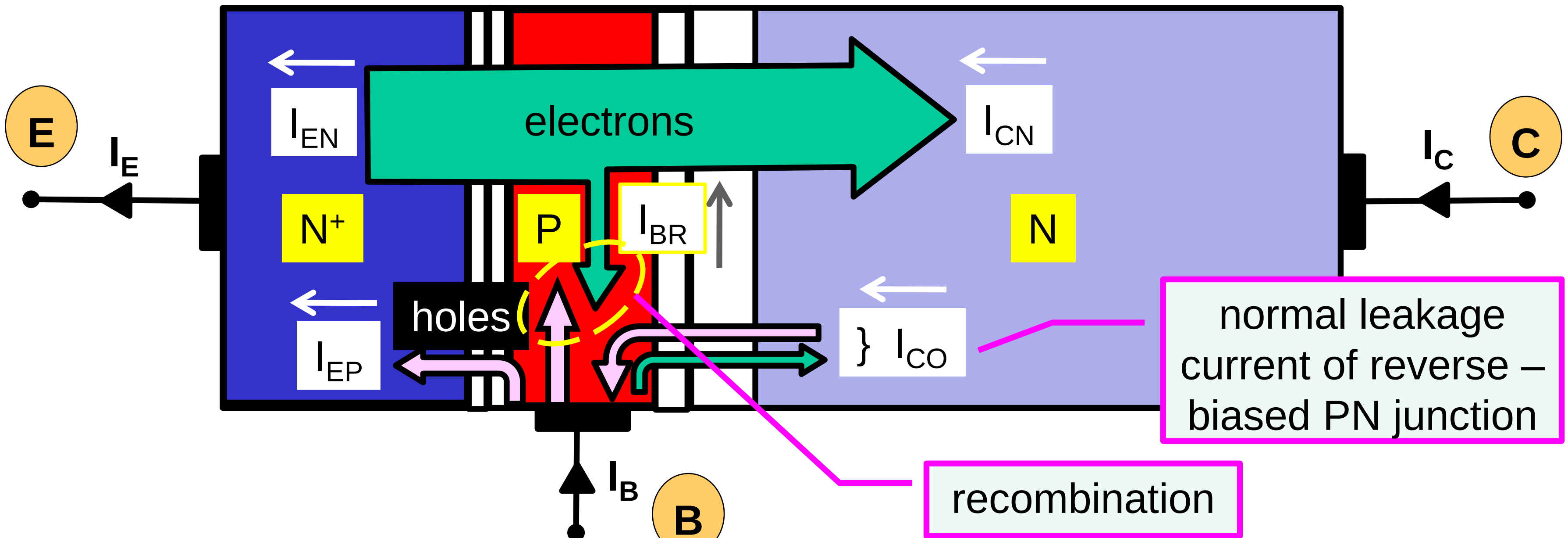


Common Collector (CC)

NPN Transistor in CB Configuration: Energy Band Diagram: Forward Active Mode



Current Components in CB NPN BJT Transistor: Forward Active Mode



- The primary mechanism is that a large number of electrons are injected across the Forward-Biased B/E junction, then they diffuse quickly across the narrow neutral base (where some are lost through recombination with the majority holes) before being collected by the favourable potential gradient created through reverse-biasing the B/C junction.

DC Current Equations for an NPN BJT

- We can write the following relations by inspection of the current components in the preceding slide:

$$\left.\begin{aligned} I_E &= I_{EP} + I_{EN} \\ I_C &= I_{CN} + I_{CO} \\ I_B &= I_{EP} + I_{BR} - I_{CO} \end{aligned}\right\}$$

Note: $I_E = I_C + I_B$ as required

- We define the Common Base DC Current Gain (α) as:

$$\alpha = \left[\frac{I_C - I_{CO}}{I_E}\right] = \frac{I_{CN}}{I_{EP} + I_{EN}}$$

- Ideally, this should be as close to 1 as possible. Now write:

$$\alpha = \frac{I_{CN}}{I_{EP} + I_{EN}} = \left[\frac{I_{CN}}{I_{EN}}\right] \cdot \left[\frac{I_{EN}}{I_{EP} + I_{EN}}\right] = \gamma \cdot B$$

Base Transport Factor and Emitter Efficiency

- We define the **Emitter Injection Efficiency (γ)** as:

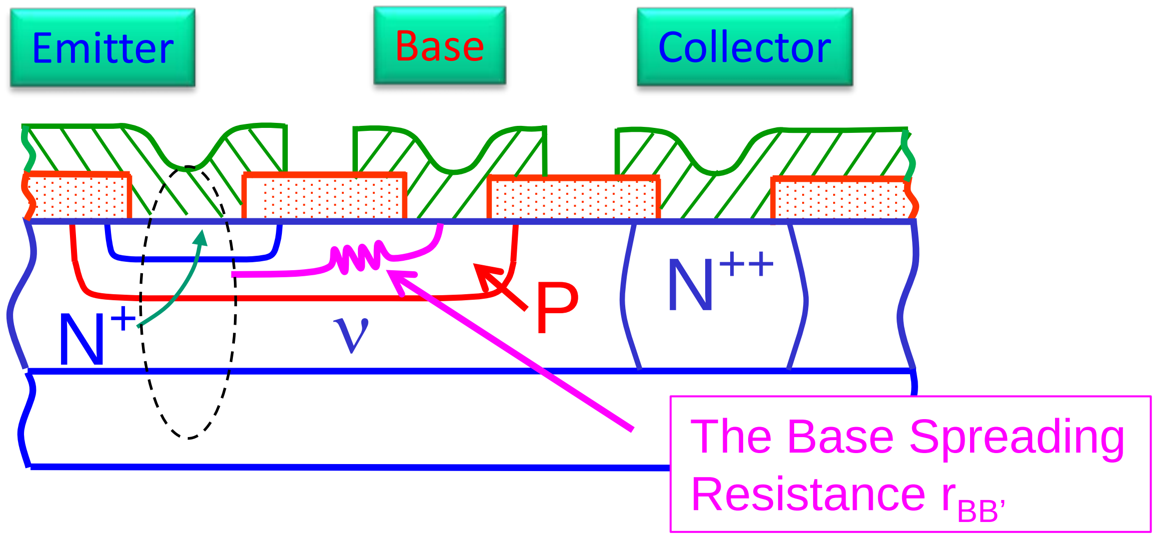
$$\gamma = \left[\frac{I_{EN}}{I_{EN} + I_{EP}} \right]$$

- While the **Base Transport Factor (B)** is defined as:

$$B = \left[\frac{I_{CN}}{I_{EN}} \right]$$

- In order to make α close to unity, both of these must be close to unity. To make γ close to 1, the Emitter must be much more heavily doped than the Base (which will tend to make I_{EP} small), while to make B close to 1, the Base region must be fabricated to be very narrow (in order to minimise recombination)

The Base Spreading Resistance $r_{BB'}$



- This refers to a significant parasitic resistance in the bipolar junction transistor, located between the metal Base contact (B) and the internal 'active' Base terminal (B'). It can be as high as 10s of Ohms;
- To make α near 1, it appears that we should (a) make W_B as small as possible and (b) make the Base doping as low as possible: both of these will tend to greatly increase $r_{BB'}$ and seriously degrade transistor performance: a classical design 'trade-off' in BJT design.

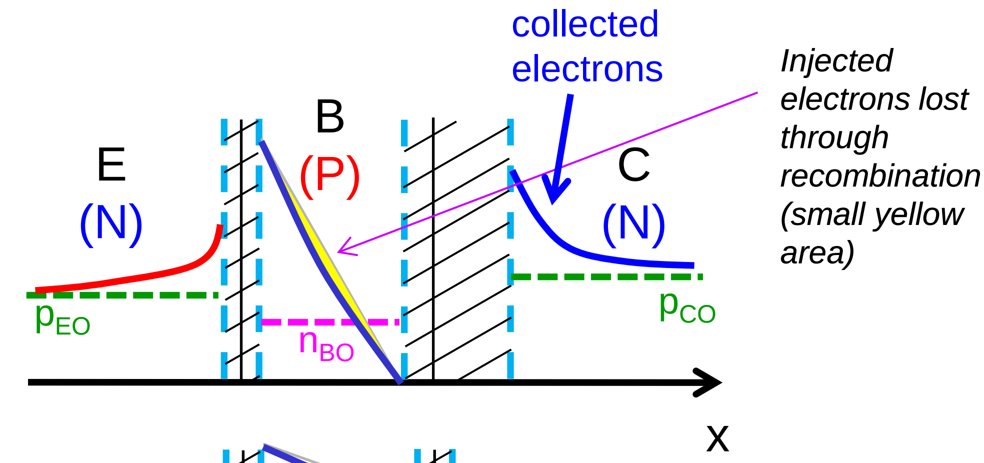
2014/2015

The remaining slides will not be examined

Carrier Distributions in BJT in Different Bias Modes

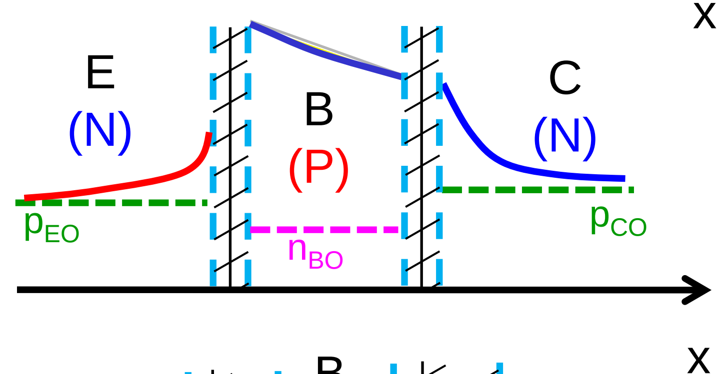
- **Forward Active Mode:**

  (E/B) forward biased;
  (B/C) reverse biased



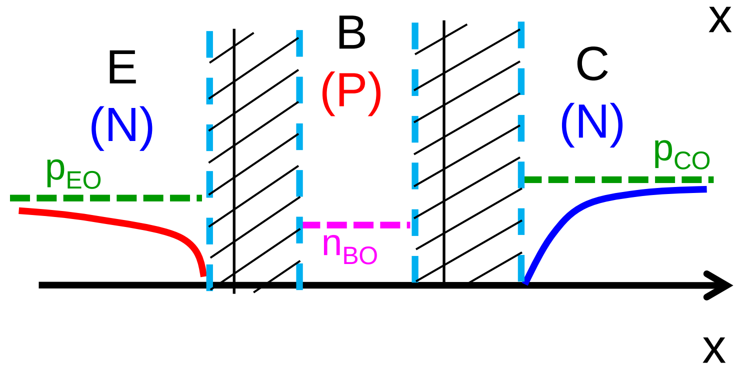
- **Saturation Mode:**

  (E/B) forward biased;
  (B/C) forward biased



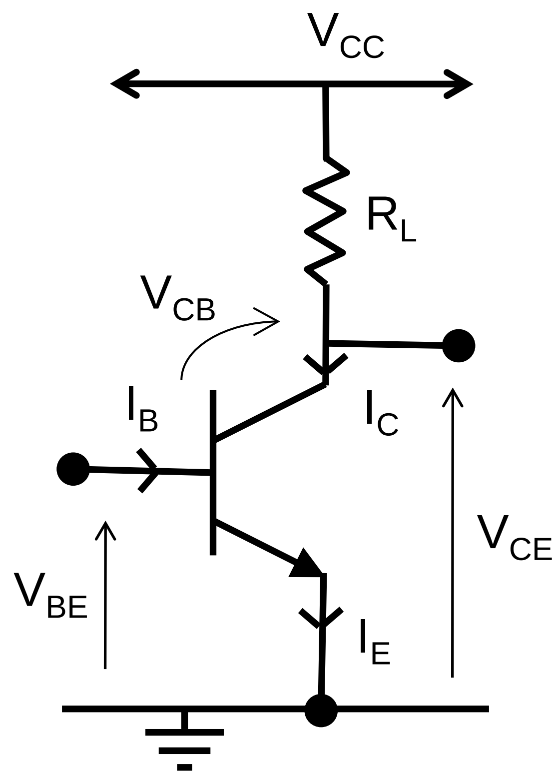
- **Cut-Off Mode:**

  (E/B) reverse biased;
  (B/C) reverse biased

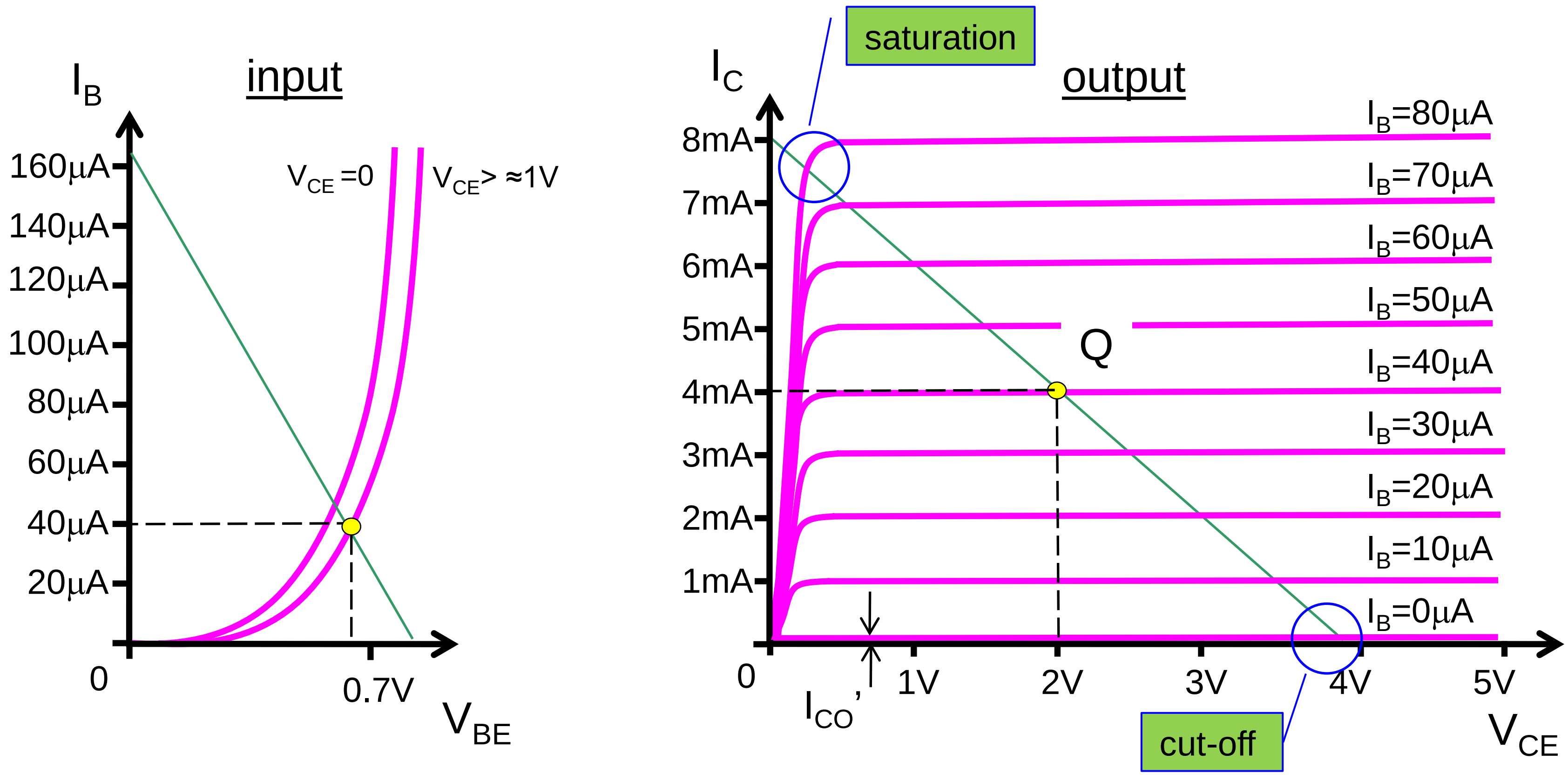


Common Emitter (CE) Configuration

- This is the most commonly used arrangement of the BJT, offering a good combination of current gain, voltage gain and therefore also power gain:



CE Static or DC Characteristics of BJT



- Suppose, for example, V_{CC}=4V and R_L = 500Ω, And suppose also that the Base bias circuit produces I_B=40μA. Then we get the output (green) DC load line shown on the RHS graph (note: 4V/500Ω = 8mA) and also the DC operating point or Q-point as shown (i.e. V_{CEO}=2V, I_{CO}=4mA)

Common Emitter DC Current Gain

- We define the CE DC current gain (β or sometimes h_{FE}) as:

$$\beta = h_{FE} = \left[\frac{I_C - I_{CO}^{'}}{I_B}\right] \Rightarrow \quad I_C = \beta \cdot I_B + I_{CO}^{'}$$

- Earlier we saw:

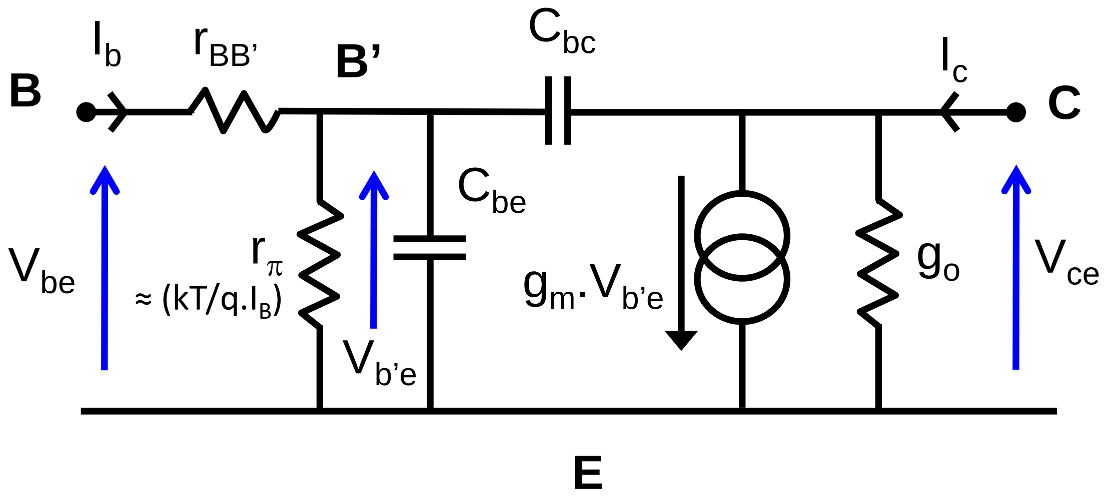
$$\begin{aligned} I_C &= \alpha \cdot I_E + I_{CO} \\ &= \alpha \cdot (I_C + I_B) + I_{CO} \\ \Rightarrow \quad I_C &= \frac{\alpha \cdot I_B}{1-\alpha} + \frac{I_{CO}}{1-\alpha} \end{aligned}$$

- By direct comparison:

$$\beta = \left(\frac{\alpha}{1-\alpha}\right) \qquad I_{CO}^{'} = \left(\frac{I_{CO}}{1-\alpha}\right)$$

- e.g.: $\alpha = 0.99$ means that $\beta \approx 100$ (generally, $\beta >> 1$)

Small-Signal Equivalent Circuit of BJT in CE Configuration at Bias Pt. Q



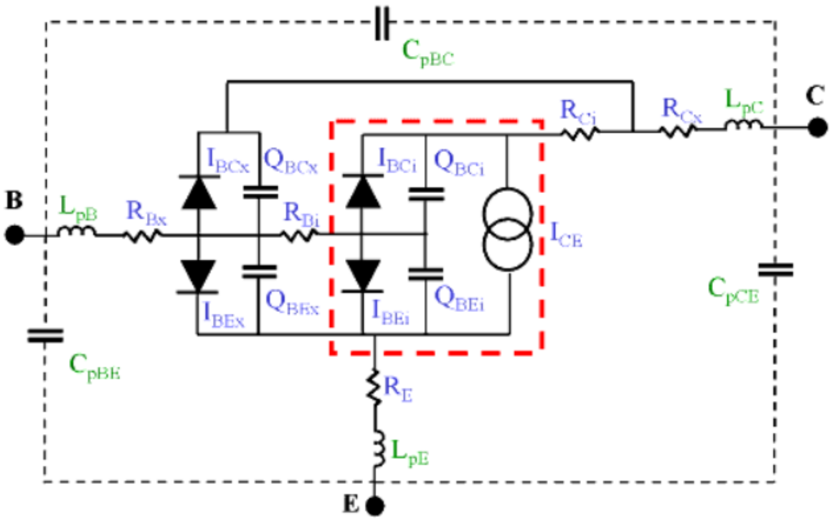
- This called the **Hybrid-Π** Equivalent Circuit model of the BJT;
- Other forms exist, for example equivalent circuits based on the hybrid or h-parameters

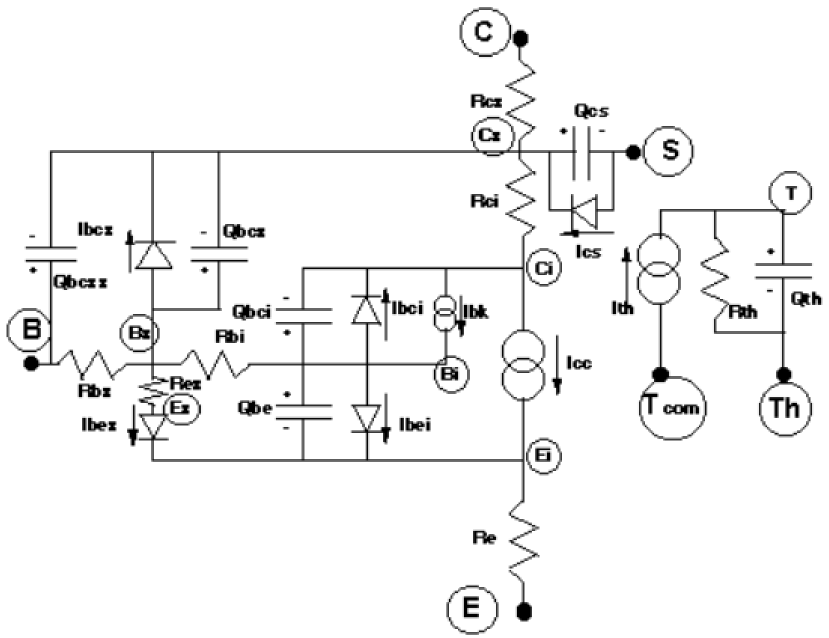
Large-Signal BJT Models

- Various large-signal models exist for the BJT, but the details are not given here. The earliest is the Ebers-Moll model, but this has been superseded by the still quite widely-used Gummel-Poon model
- More recent BJT nonlinear equivalent circuit models include MEXTRAM (Philips) and VBIC. For further details, see textbooks or web references.
- Some examples of BJT large-signal equivalent circuit models are given in the following slide.

Examples of BJT Large-Signal Models

For information only – do not remember!





End of SSE1 Course 2014/2015

Format of SSE1 Final Examination 2014

- Two-Hour Exam, **12.00-14.00 on Tuesday, 16th December** in the RDS, Shelbourne Hall;
- Note that format of examination varies regularly (if you are reviewing past papers);
- Numerical answers to past Examination Papers are provided in a file on Blackboard *(Past_Paper_Answers_2014)*
- There will be a total of FIVE Questions, with Question 1 compulsory. You should attempt any THREE of the Remaining FOUR Questions;
- Question 1 has 8 short parts in multiple-choice format <u>covering the entire course</u>. Each correct answer is awarded 5 Marks, each incorrect answer -1 Mark, no answer 0 Marks, (maximum 40 Marks)….

Format of SSE1 Final Examination 2014

- The FIRST of the remaining FOUR Questions (each worth 20 Marks), is based on material covered in Chapters 1-5;
- The SECOND of these FOUR Questions is a descriptive Question with multiple parts (i.e. 4 parts do any 3) based on the entire course, including Chapter 6;
- The THIRD and FOURTH of these remaining FOUR Questions are based entirely on material covered since the Mid-Term Test, i.e. Chapters 7-12, inclusive;
- A list of physical constants and useful formulas will be provided as part of the Examination Paper;
- Final examination accounts for 80% of total assessment;
- If you are having problems when revising a topic, come and see me!