Chapter 10. Bipolar junction transistor fundamentals

Invented in 1948 by Bardeen, Brattain and Shockley

Contains three adjoining, alternately doped semiconductor regions: Emitter (E), Base (B), and Collector (C)

The middle region, base, is very thin compared to the diffusion length of minority carriers

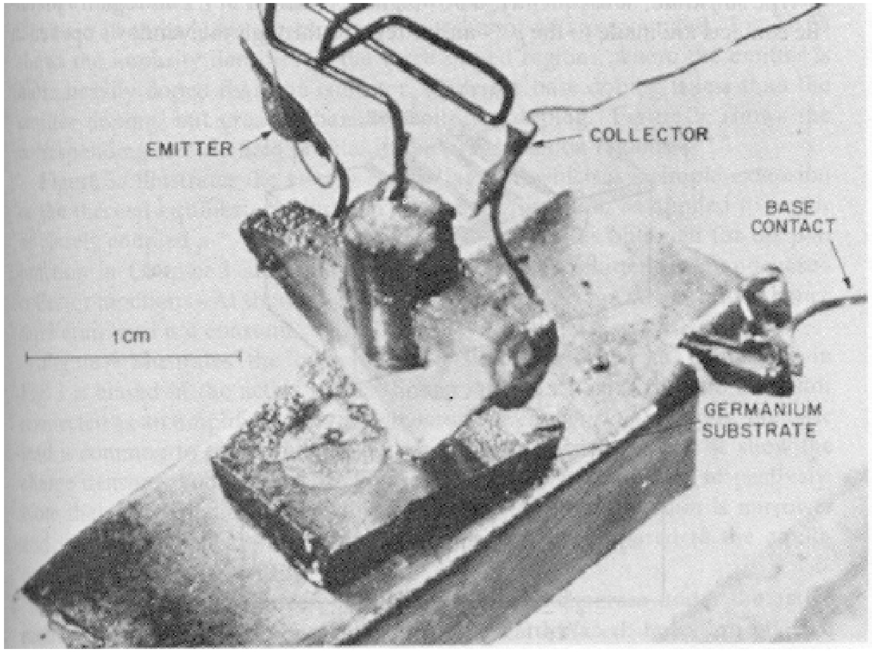
Two kinds: npn and pnp

BJT - General Introduction

- Who were the inventors of the transistor?
- Was the first practical working transistor an FET or BJT?
- What material was the first practical transistor made of? (Si or Ge?)
- The idea of a transistor was first proposed in 1926 by Julius Lilienfeld. Was this transistor a FET or BJT transistor?

First Working Transistor

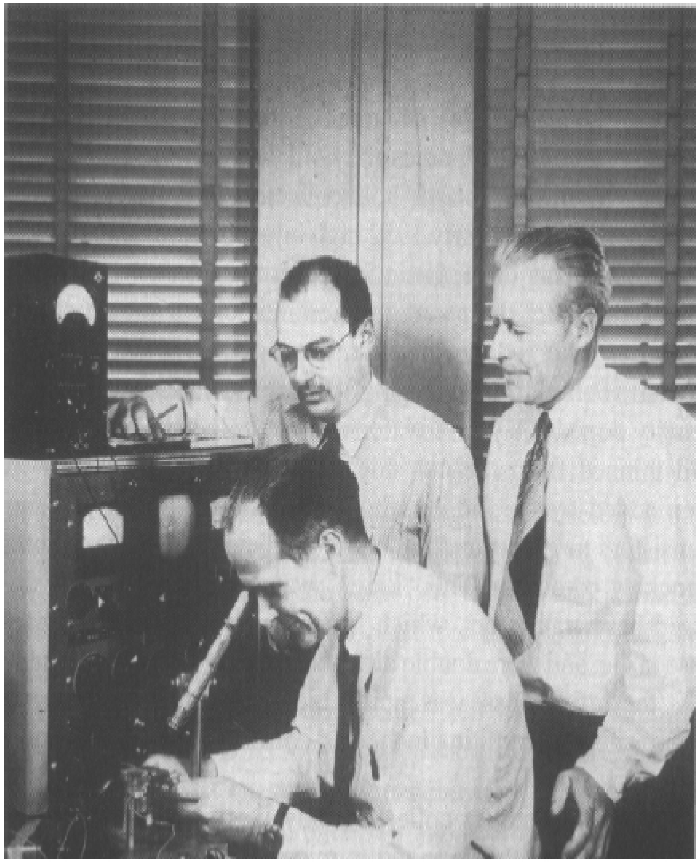
- Point contact transistor.
- Invented by John Bardeen and Walter Brattain in Bell Telephone Laboratories in December 1947.
- One month later, William Shockley developed the theory for the bipolar transistor.



Ref: J. Bardeen and W.H. Brattain, "The Transistor, A Semiconductor Triode", Reprinted in the Proceedings of the IEEE, vol. 86, no. 1, pp. 29-30, Jan 1998.

BJT - General Introduction (Cont'd)

Inventors of the Transistor



Clockwise from left:
William Shockley (seated), John Bardeen and Walter Brattain

Ref: James M. Early, "Out to Murray Hill to Play: An Early History of Transistors", IEEE Trans. Electron Devices, vol. 48, no. 11, pp. 2468-2472, 2001.

[Read also: R.M. Warner, "Microelectronics: Its Unusual Origin and Personality", IEEE Trans. Electron Devices, vol. 48, no. 11, pp. 2457-2467, 2001.

Schematic representation of pnp and npn BJTs

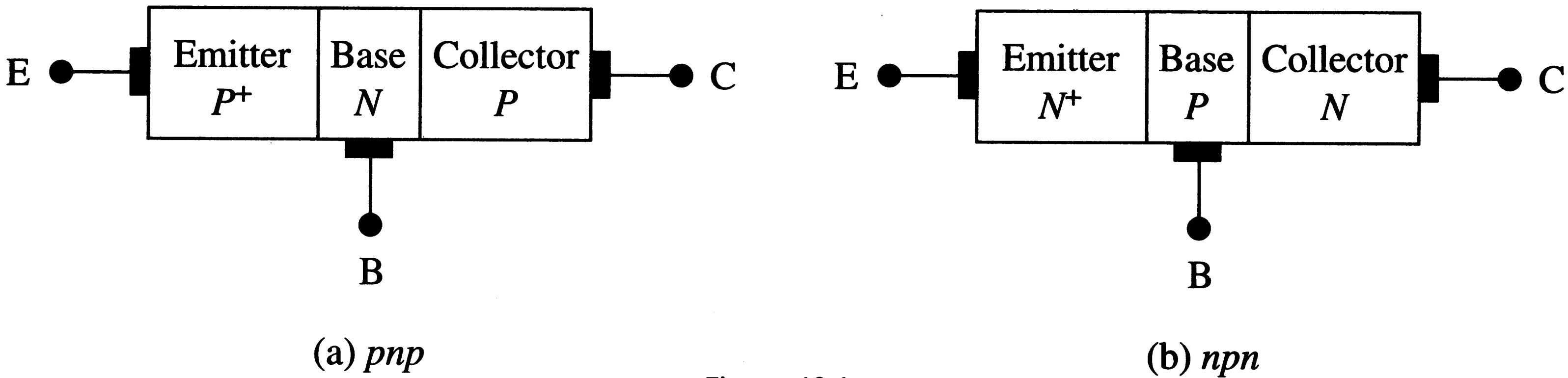
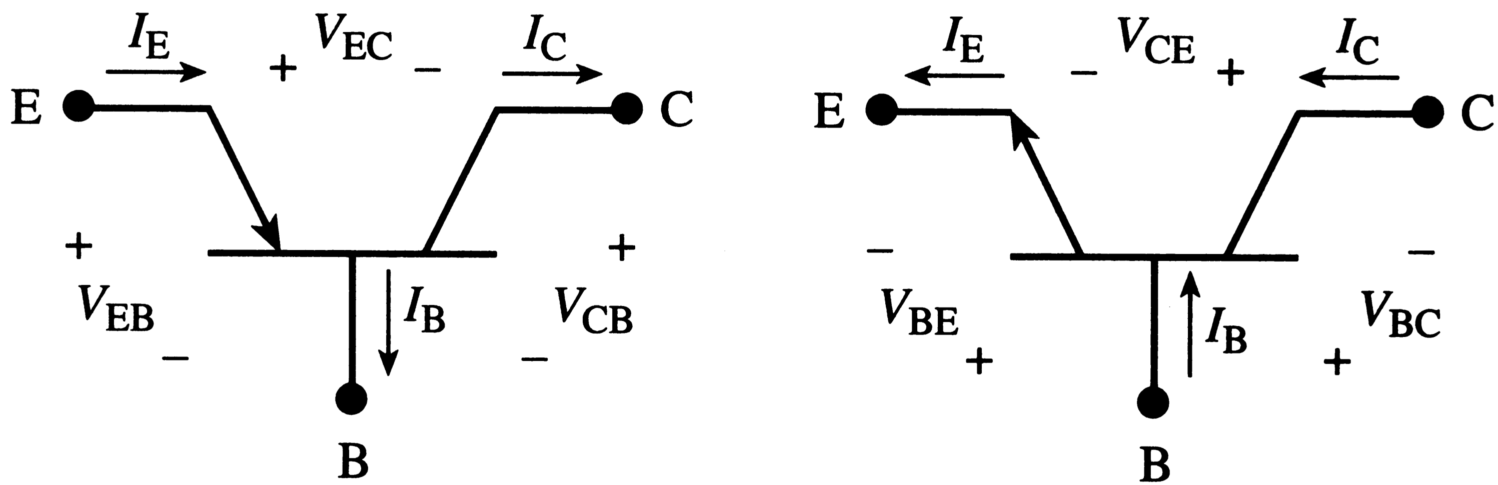


Figure 10.1

Emitter is heavily doped compared to collector. So, emitter and collector are not interchangeable.

The base width is small compared to the minority carrier diffusion length. If the base is much larger, then this will behave like back-to-back diodes.

BJT circuit symbols



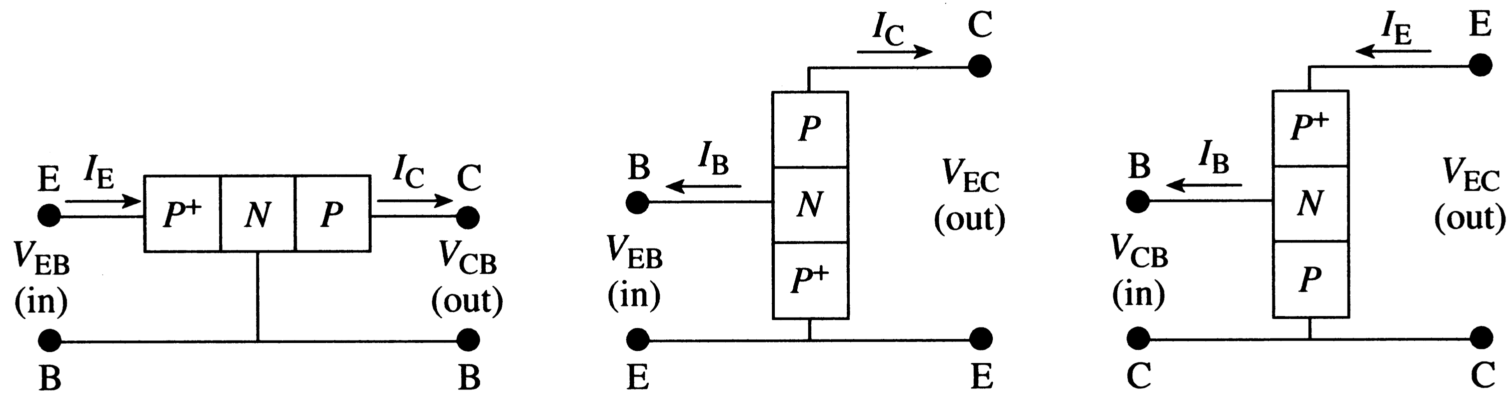
(a) *pnp* (b) *npn*

Figure 10.2

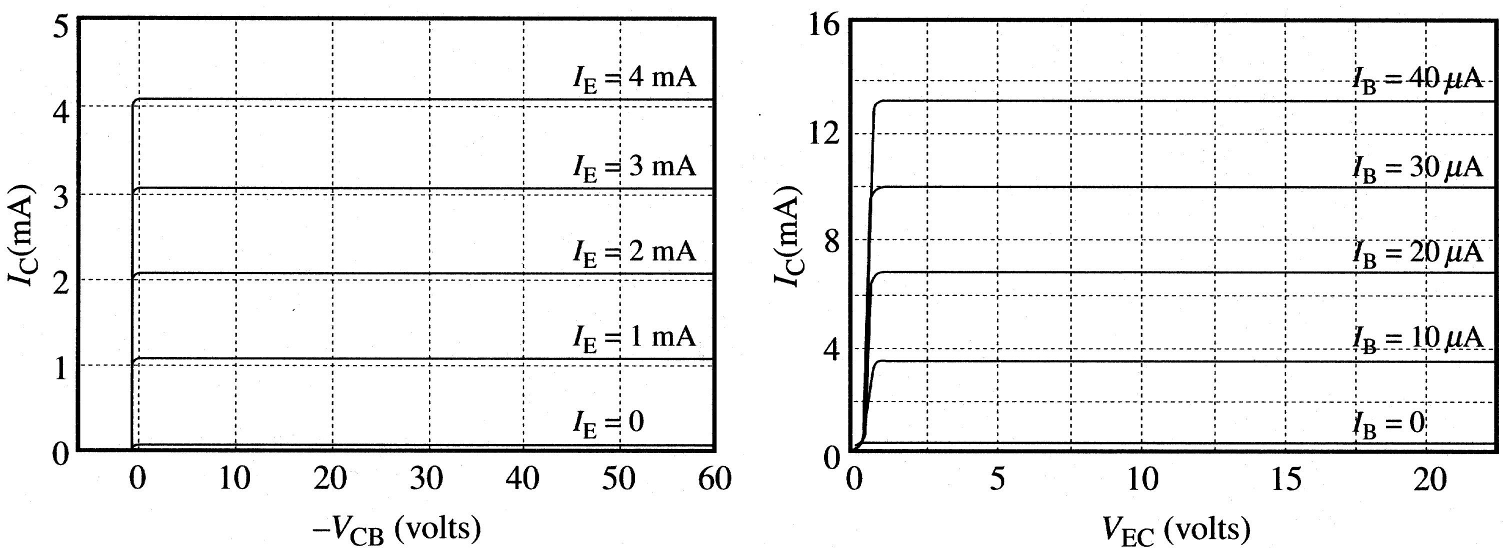
$I_E = I_B + I_C$ and $V_{EB} + V_{BC} + V_{CE} = 0$ $V_{CE} = -V_{EC}$

As shown, the currents are positive quantities when the transistor is operated in forward active mode.

BJT circuit configurations and output characteristics



(a) Common base (b) Common emitter (c) Common collector

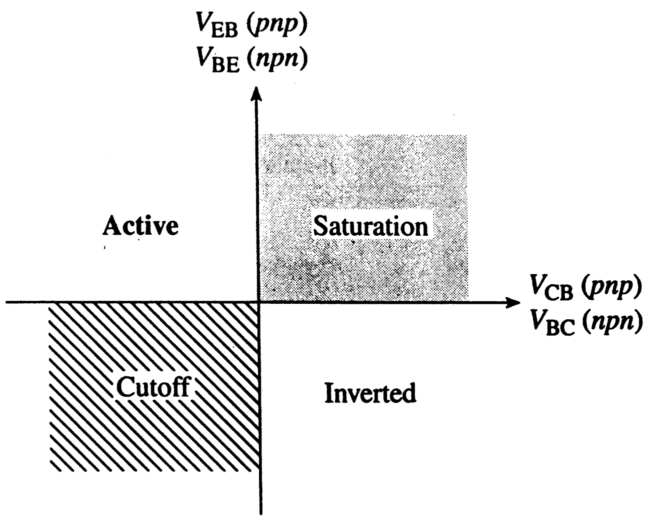


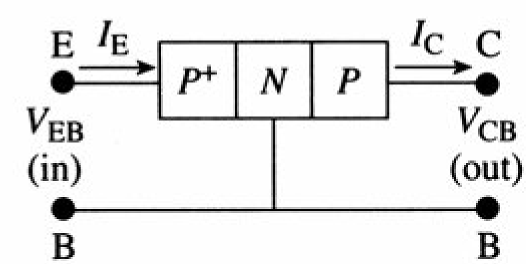
(a) Common base (b) Common emitter

BJT biasing modes

Table 10.1 Biasing Modes.

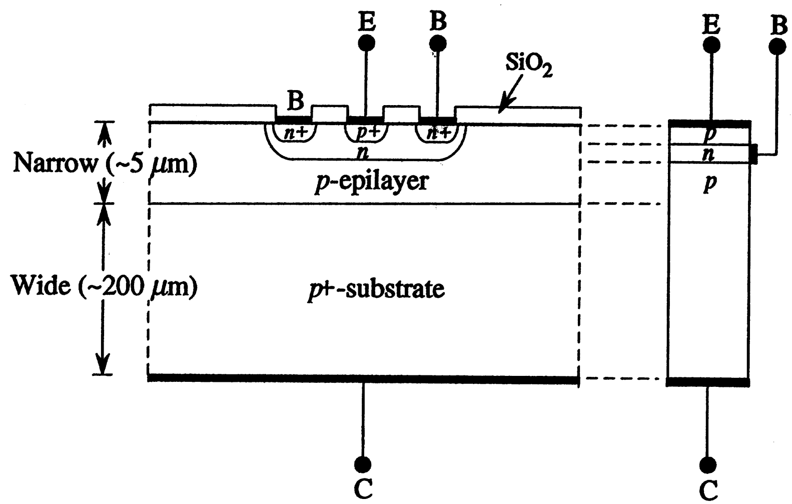
Biasing Mode	*Biasing Polarity E–B Junction*	*Biasing Polarity C–B Junction*
Saturation	Forward	Forward
Active	**Forward**	**Reverse**
Inverted	Reverse	Forward
Cutoff	Reverse	Reverse



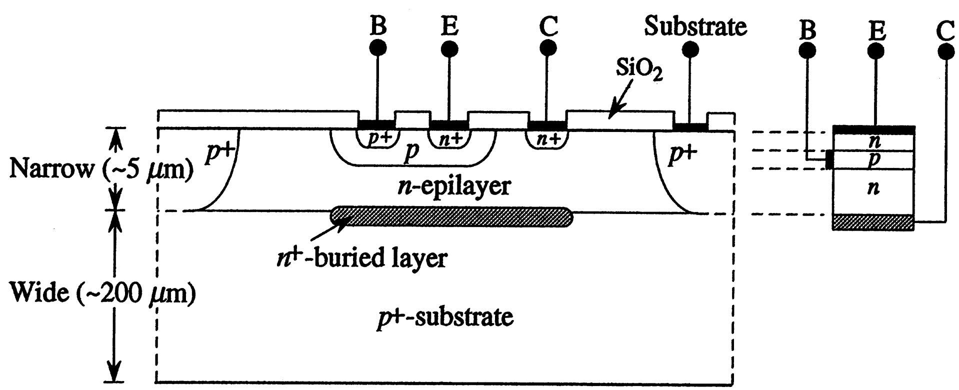


(a) Common base

Cross sections and simplified models of discrete and IC npn BJTs



(a)



(b)

Figure 10.6

Electrostatic variables for a pnp BJT at equilibrium

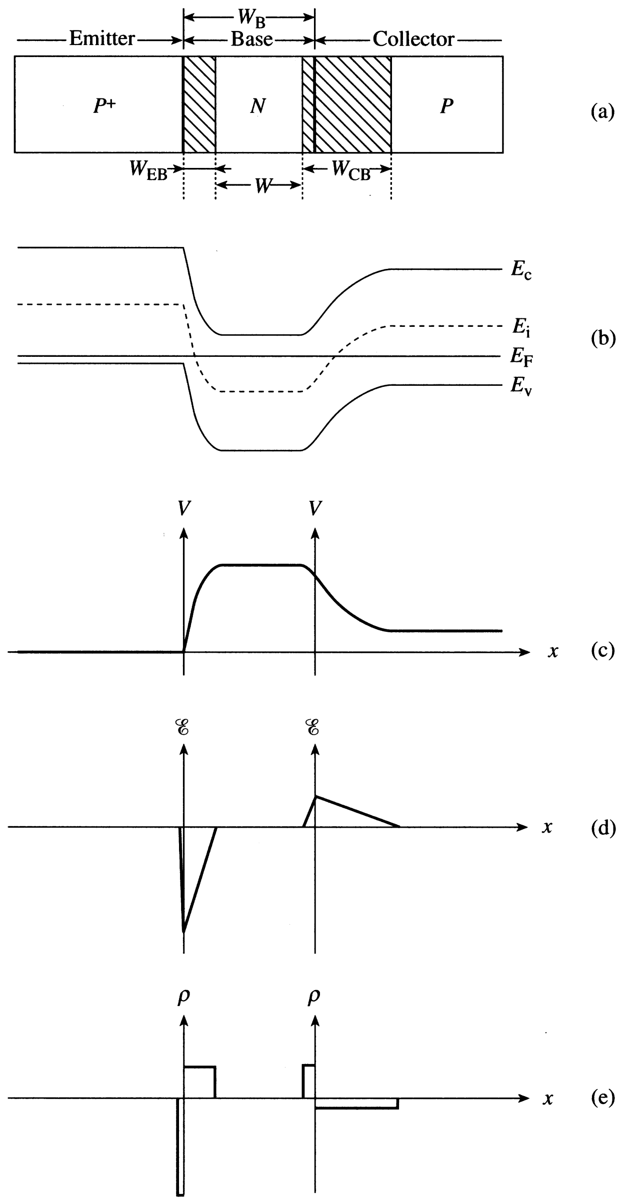


Figure 10.7

$$V = -\frac{1}{q}\left(E_C - E_{ref}\right)$$

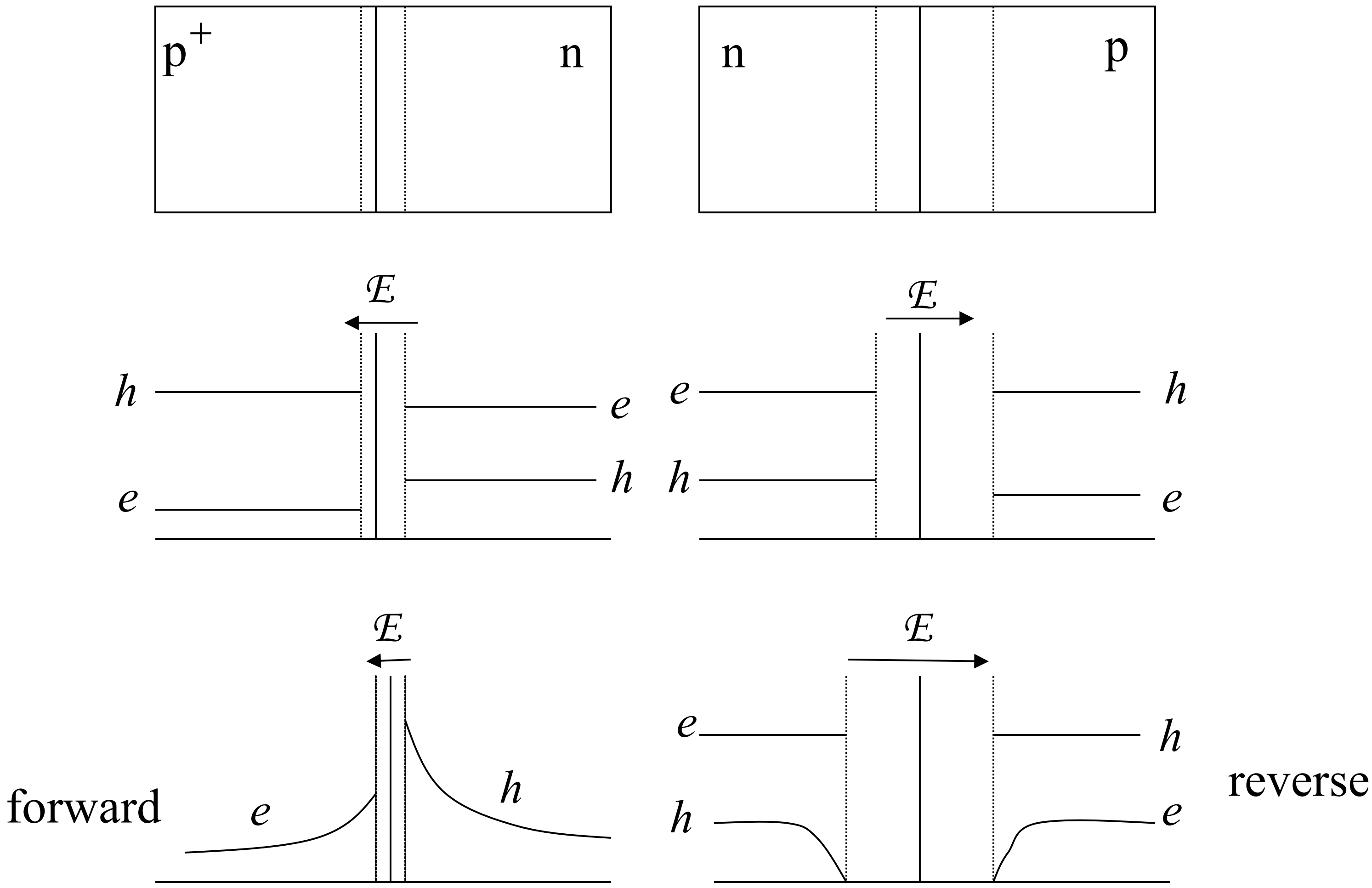
$$\mathcal{E} = \frac{1}{q}\frac{dE_C}{dx} = \frac{1}{q}\frac{dE_i}{dx}$$

$$\frac{d\mathcal{E}}{dx} = \frac{\rho}{\varepsilon}$$

ρ = charge density
$\varepsilon = K_s \varepsilon_o$

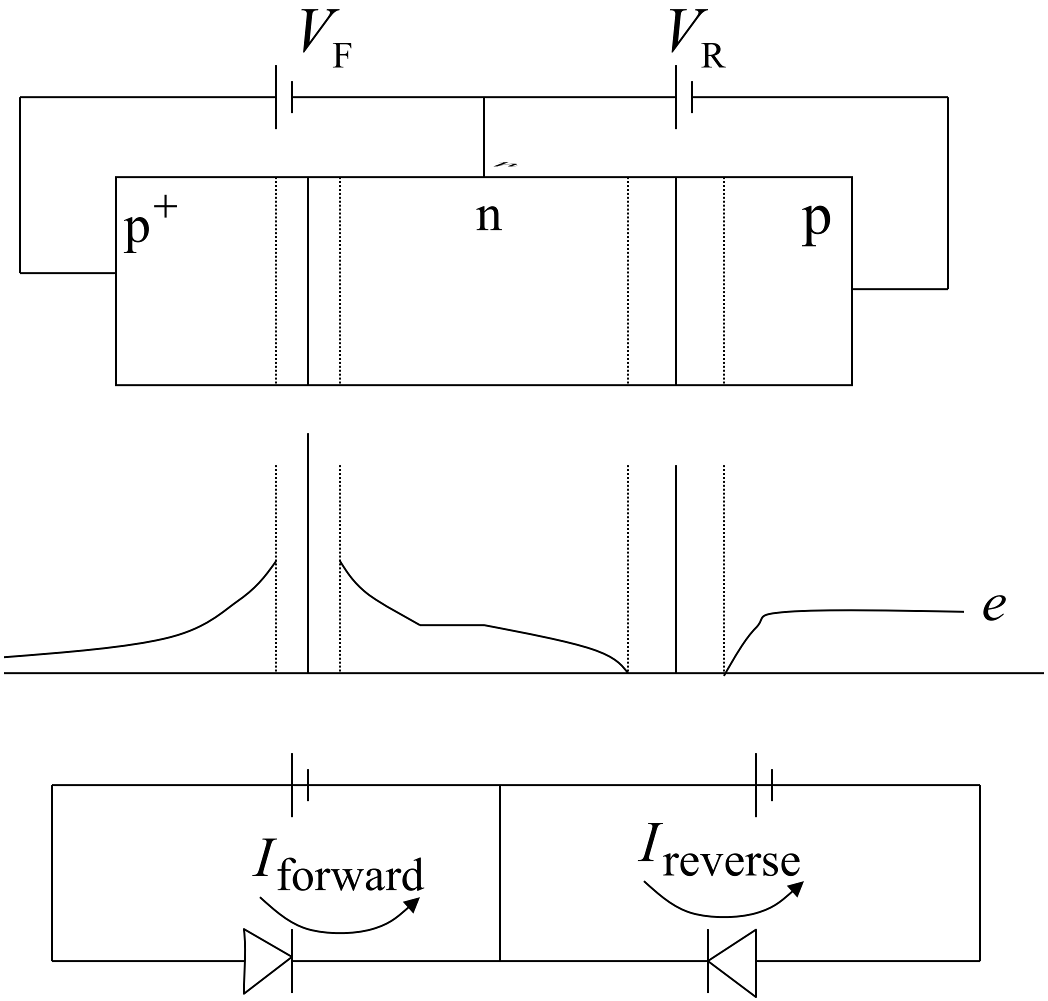
Qualitative discussions of operation

Consider two diodes, one forward biased and one reverse biased.



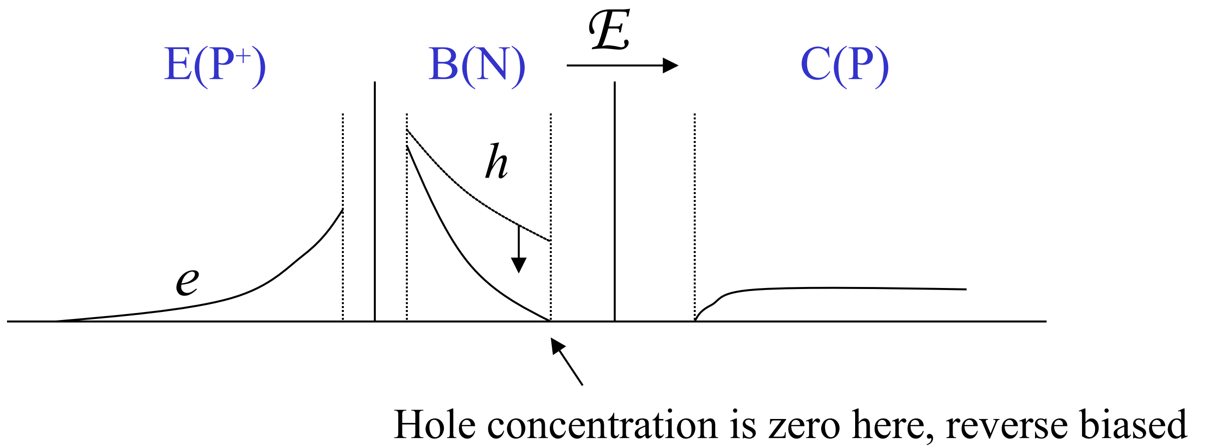
Qualitative discussion of transistor action

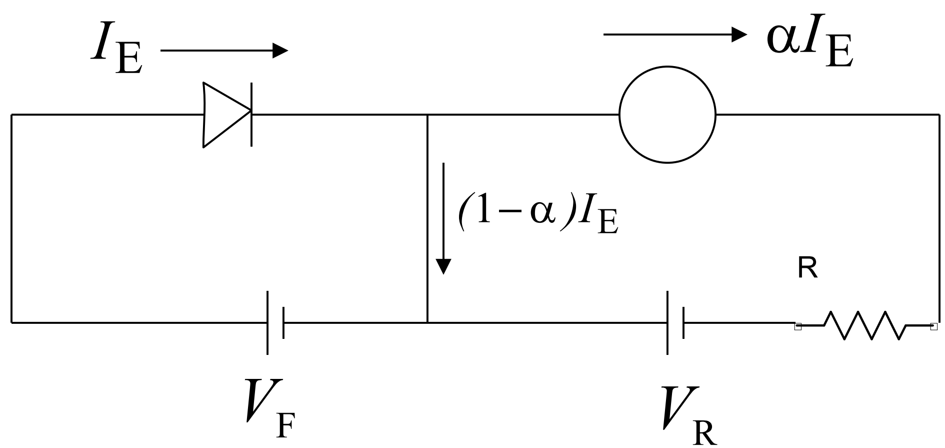
Combine the two diodes!



No transistor action

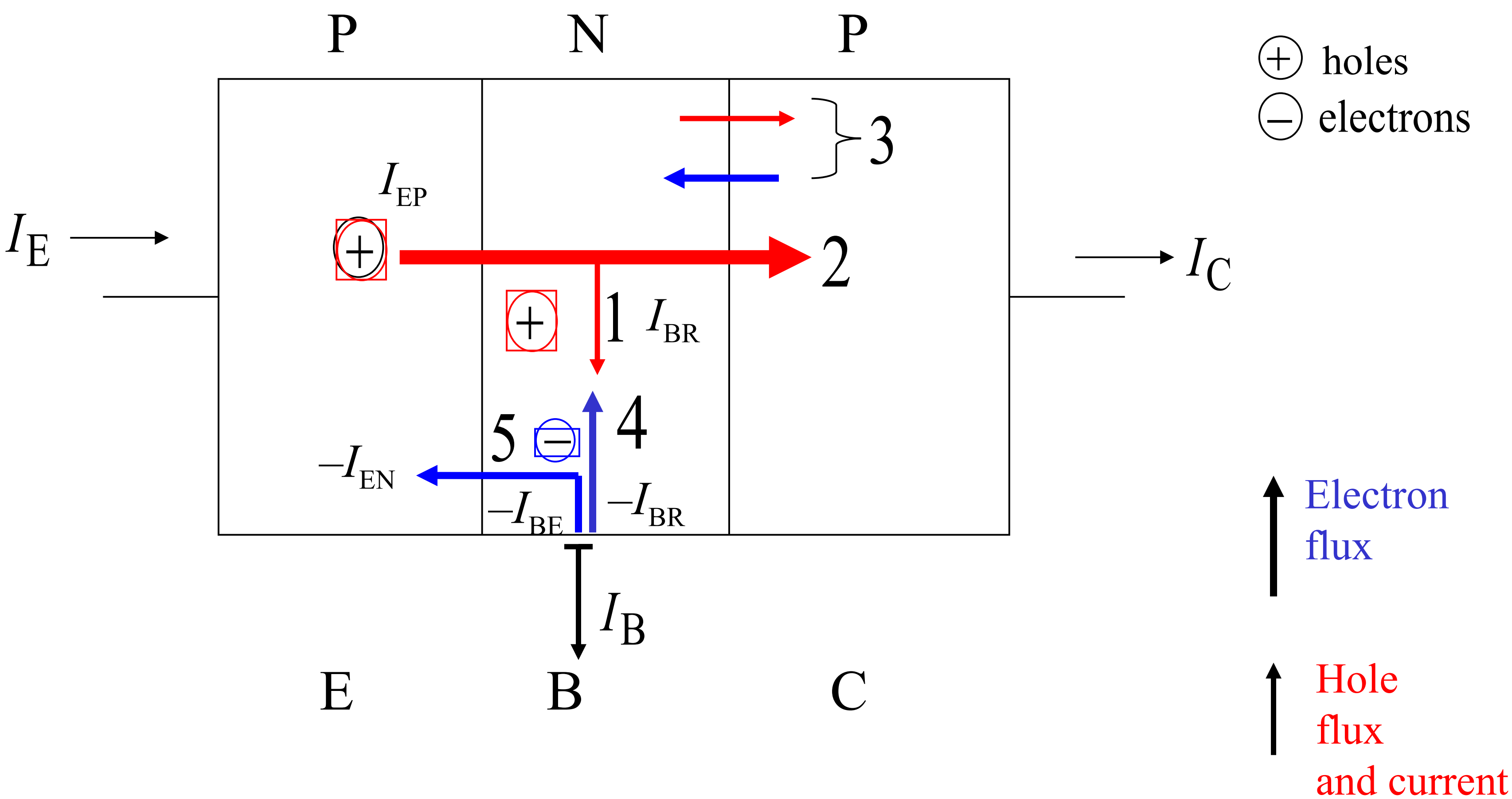
Consider very thin base width: Transistor action





The collector current I_C is almost equal to I_E, and collector current is controlled by the E-B junction bias. The loss, i.e. $\alpha < 1$ corresponds to the recombination of holes in base.

PNP under forward active mode



$$I_E = I_{EP} + I_{EN} = 1 + 2 + 5$$

$$I_B = I_{BR} + I_{BE} = I_{BR} + I_{EN} = -(4 + 5)$$

$$I_C = I_{EP} - I_{BR} = 2$$

Current components

1 = hole current lost due to recombination in base, I_{BR}

2 = hole current collected by collector, $\sim I_C$

1 + 2 = hole part of emitter current, I_{EP}

5 = electrons injected across forward biased E-B junction, $(-I_{BE})$; same as electron part of emitter current, $-I_{EN}$

4 = electron supplied by base contact for recombination with holes lost, $-I_{BR}$ (= 1)

3 = thermally generated e & h making up reverse saturation current of reverse biased C-B junction. (generally neglected)

Performance parameters (Consider pnp)

Neglect the reverse leakage (electron) current of C-B junction

Emitter efficiency:

$$\gamma = \frac{I_{EP}}{I_{EP} + I_{EN}} = \frac{I_{EP}}{I_E}$$

Fraction of emitter current carried by holes.
We want γ close to 1.

Base transport factor:

$$\alpha_T = \frac{I_C}{I_{Ep}}$$

Fraction of holes collected by the collector.
We want α_T close to 1.

Common base dc current gain:

$$I_C = \alpha_T I_{EP} = \alpha_T \gamma I_E = \alpha_{dc} I_E$$

$$\alpha_{dc} = \alpha_T \gamma$$

Note that α is less than 1.0 but close to 1.0 (e.g. $\alpha = 0.99$)

Performance parameters (Consider pnp)

Common emitter dc current gain, β_{dc}:

$$I_C = \beta_{dc} I_B$$

But,

$$I_C = \alpha_{dc} I_E = \alpha_{dc}(I_C + I_B)$$

$$I_C = \left(\frac{\alpha_{dc}}{1-\alpha_{dc}}\right) I_B$$

$$\beta_{dc} = \frac{\alpha_{dc}}{1-\alpha_{dc}} = \frac{\alpha_T \gamma}{1-\alpha_T \gamma}$$

Note that β is large (e.g. $\beta = 100$)

For npn transistor, similar analysis can be carried out. However, the emitter current is mainly carried by electrons.

Example: $\gamma = \dfrac{I_{EP}}{I_{EP} + I_{EN}}$ etc.