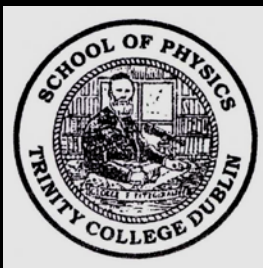
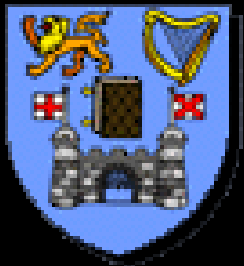


Semiconductor Devices - 2014

Lecture Course
Part of
SS Module PY4P03

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Diode Current Components

$$-\frac{p_n - p_{n0}}{\tau_a} + D_a \frac{\partial^2 p_n}{\partial x^2} - \frac{n_n - p_n}{n_n/\mu_p + p_n/\mu_n} \mathcal{E} \frac{\partial p_n}{\partial x} = 0$$

$$D = \frac{k_B T}{q} \mu = V_t \mu$$

$$D_a = \frac{n_n + p_n}{n_n/D_p + p_n/D_n}$$

Using Einstein's Relation

Ambipolar Lifetime

$$\tau_a = \frac{p_n - p_{n0}}{U} = \frac{n_n - n_{n0}}{U}$$

Ambipolar Diffusion Coeff.

$$-\frac{p_n - p_{n0}}{\tau_p} - \mu_p \mathcal{E} \frac{\partial p_n}{\partial x} + D_p \frac{\partial^2 p_n}{\partial x^2} = 0$$

Low Electric Field Approximation - 1D Diffusion Eq.

$$\frac{\partial^2 p_n}{\partial x^2} - \frac{p_n - p_{n0}}{D_p \tau_p} = 0$$

Small Injection Approximation ($D_p = D_n = D_a$)

Diffusion Limited Currents

Diffusion Exponent

$$L_p = \sqrt{D_p \tau_p}$$

Hole Diffusion Length

$$p_n - p_{n0} = p_{n0} \left(e^{qV_a/k_B T} - 1 \right) e^{-(x-x_n)/L_p}$$

$$J_p = -qD_p \frac{\partial p_n}{\partial x} \Big|_{x_n} = \frac{qD_p p_{n0}}{L_p} \left(e^{qV_a/k_B T} - 1 \right)$$

$$J_n = -qD_n \frac{\partial n_p}{\partial x} \Big|_{-x_p} = \frac{qD_n n_{p0}}{L_n} \left(e^{qV_a/k_B T} - 1 \right)$$

Partial currents of holes and electrons

This much survives on the other side of the diffusion tails

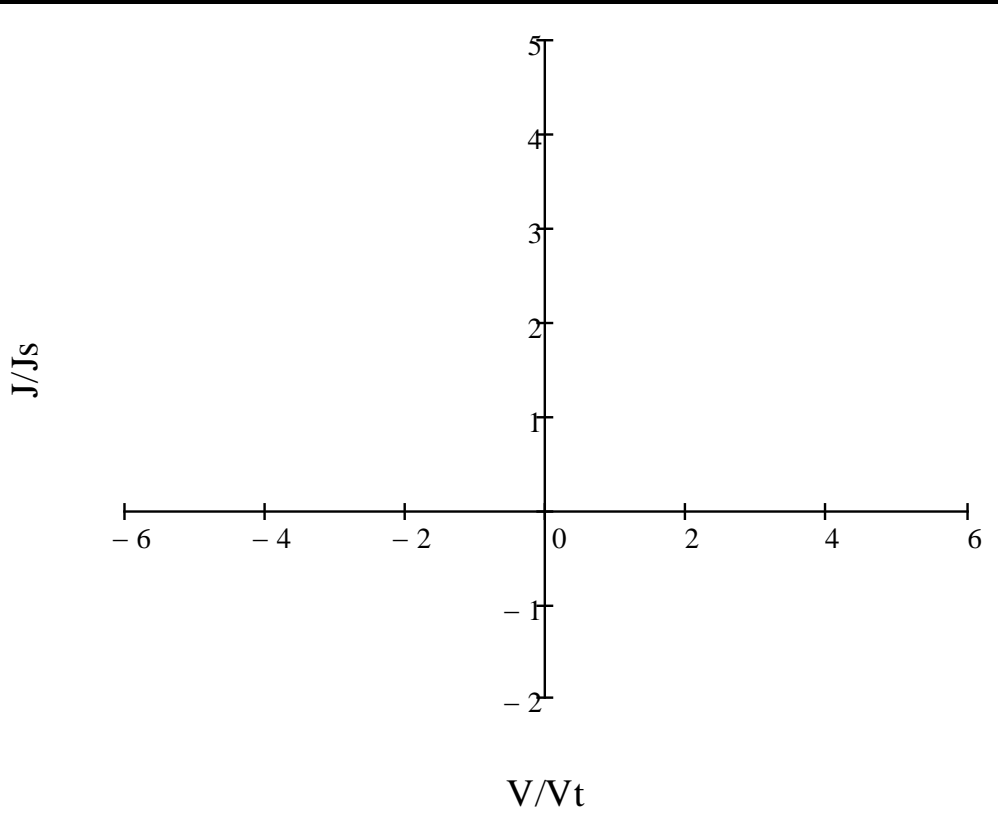
$$J_s = \frac{qD_p p_{n0}}{L_p} + \frac{qD_n n_{p0}}{L_n}$$

Saturation Current

$$J = J_p + J_n = J_s \left(e^{qV_a/k_B T} - 1 \right)$$

The Total Current

The Ideal World and Its Imperfections



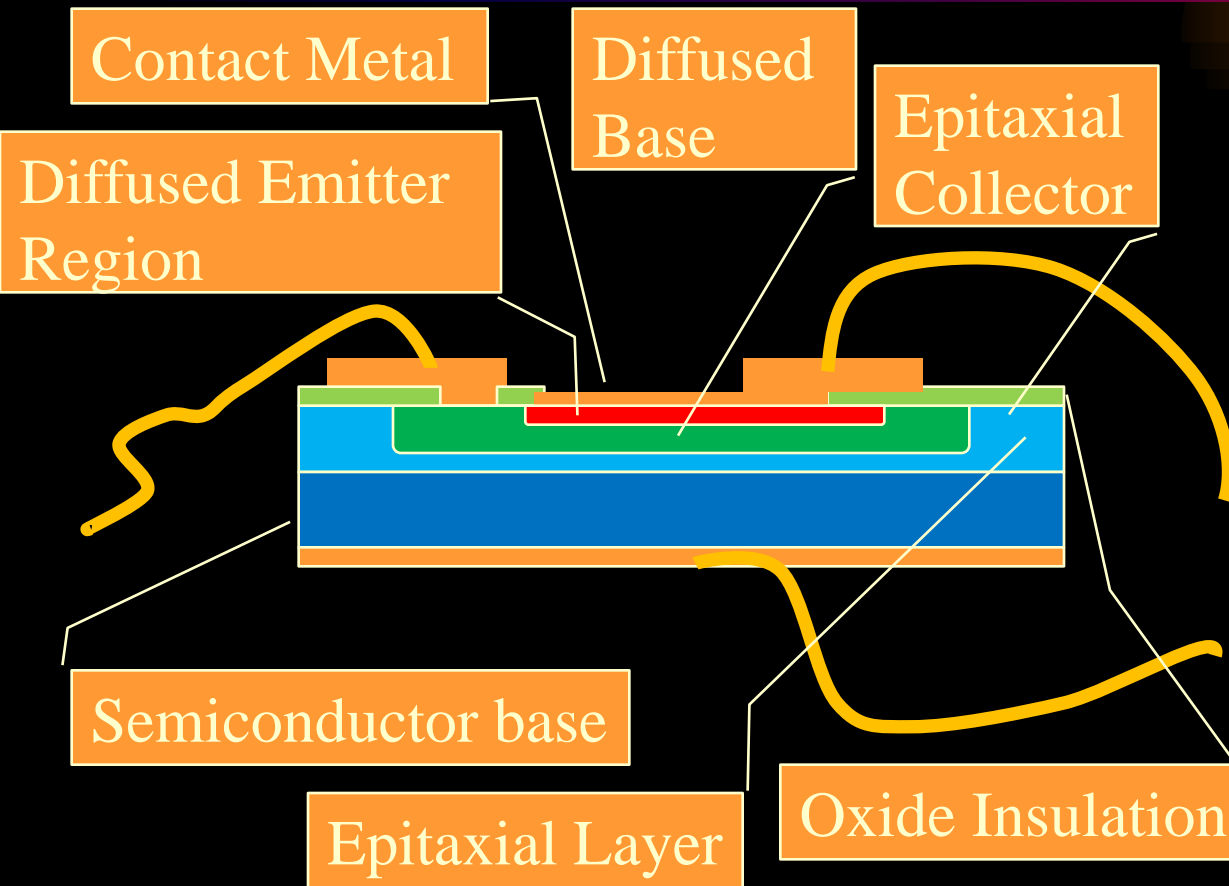
$$\frac{J}{J_s} = \left(e^{V_a/\eta V_t} - 1 \right)$$

- The ‘ideal’ dependence is NOT valid even for the ‘best’ diodes at room temperature and arbitrary bias.
- The voltage activation scale is ηV_t and not V_t .
- In most cases the ‘ideality factor’ is closer to 2 rather than 1, because of large recombination/generation current components.
- Large currents ‘kick-in’ above V_{bi} (say 0.5 V), however most approximations fail soon above that.
- Reverse bias saturation is not perfect in practice – eventually ionisation breakdown.

Some Remarks on Diodes

- In practical applications, two parameters are of great importance – forward voltage drop and reverse leakage current.
- In view of its smaller band gap $E_g(\text{Ge}) \sim 0.7 \text{ eV}$, compared to $E_g(\text{Si}) \sim 1.1 \text{ eV}$, Ge diodes have higher reverse bias leakage currents (deep recombination).
- However, for Ge the forward voltage drop is lower as $V_{\text{bi}}(\text{Ge}) \sim 0.3 \text{ V}$, and this implies lower internal losses and therefore less overall heating – often important in high-power circuits.
- The difference is also important in ‘clipping’ circuits – i.e. overdrive and distortion pedals – *for the guitar players out there, it makes a real difference.*

Epitaxial Bipolar Transistor



Recipe

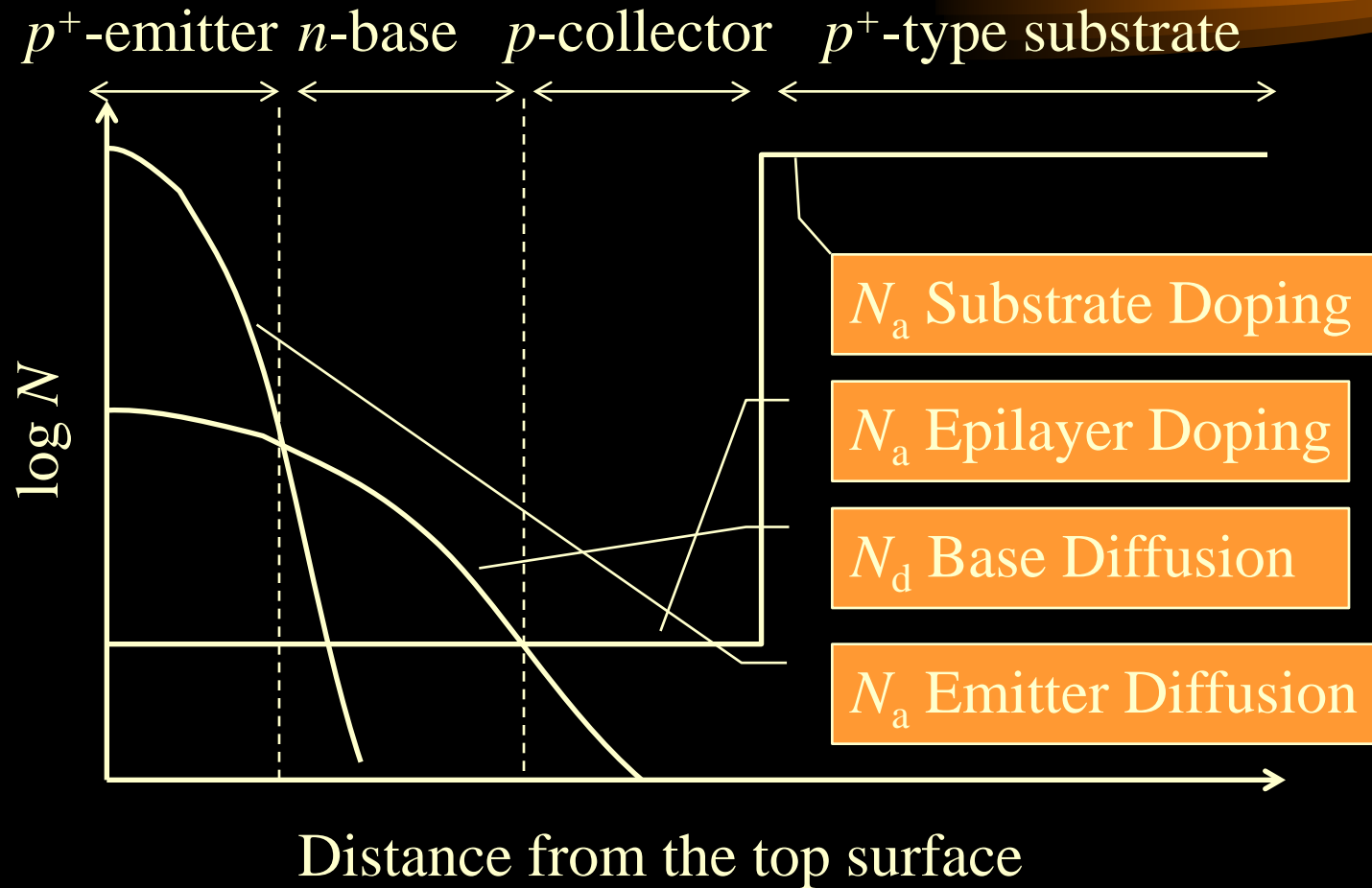
- ...
- Grow an epilayer
- Oxidize
- Diffuse from a limited source
- Diffuse from a constant source
- ...

Features

- Building block
- Provides gain
- Current-control device
- Bipolar device

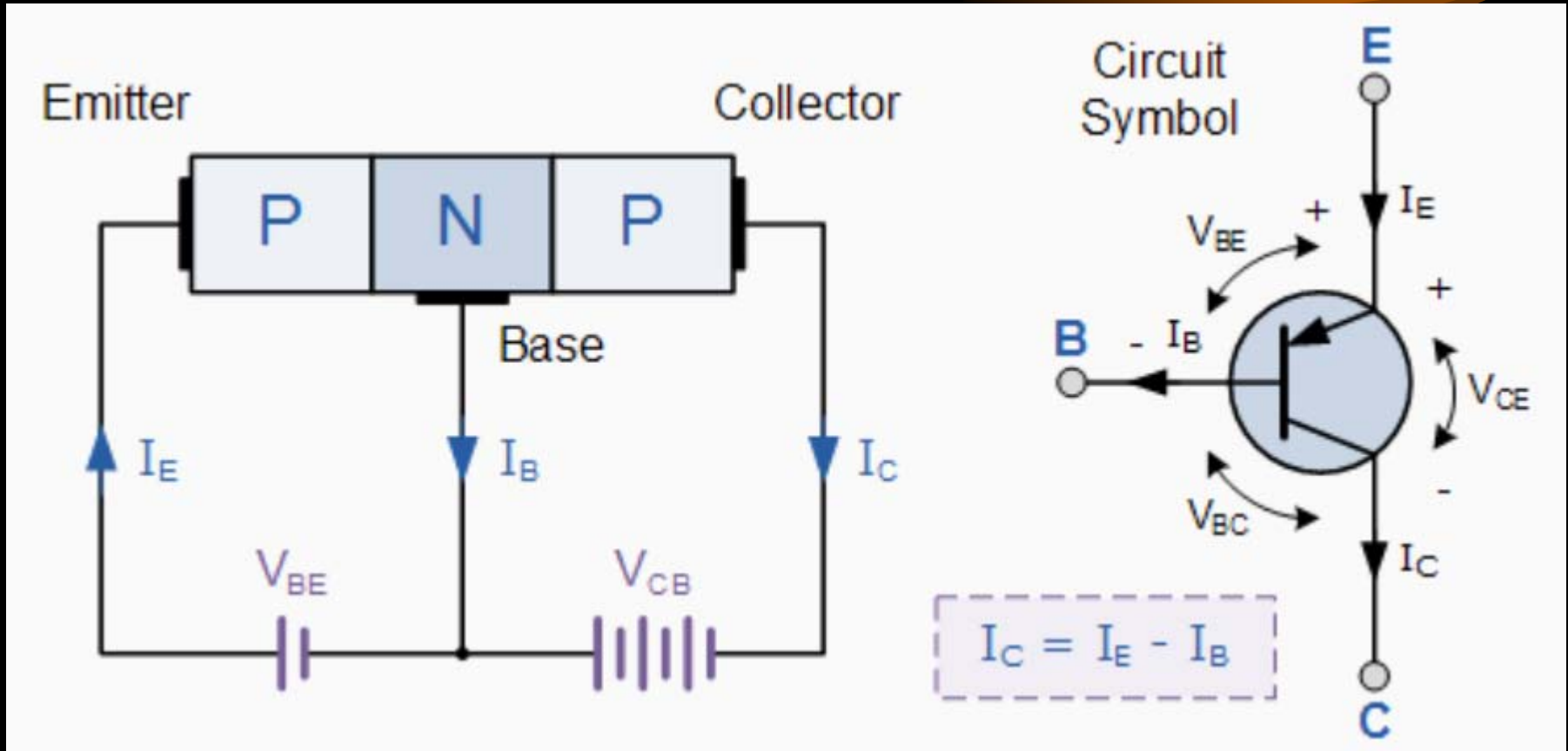
- Usually the base is created thin, in order to achieve high current and power gain
- The secondary junction formed (say nn^+) is normally perfectly ohmic

Bipolar Transistor – Doping Profile



- Two distinct diffusion steps have to be performed – diffusion from a finite source (with or without drive-in) and constant source
- Obviously, it would be easier to realize the n - p - n on an n -wafer.

Structure and Operation



http://www.electronics-tutorials.ws/transistor/tran_3.html

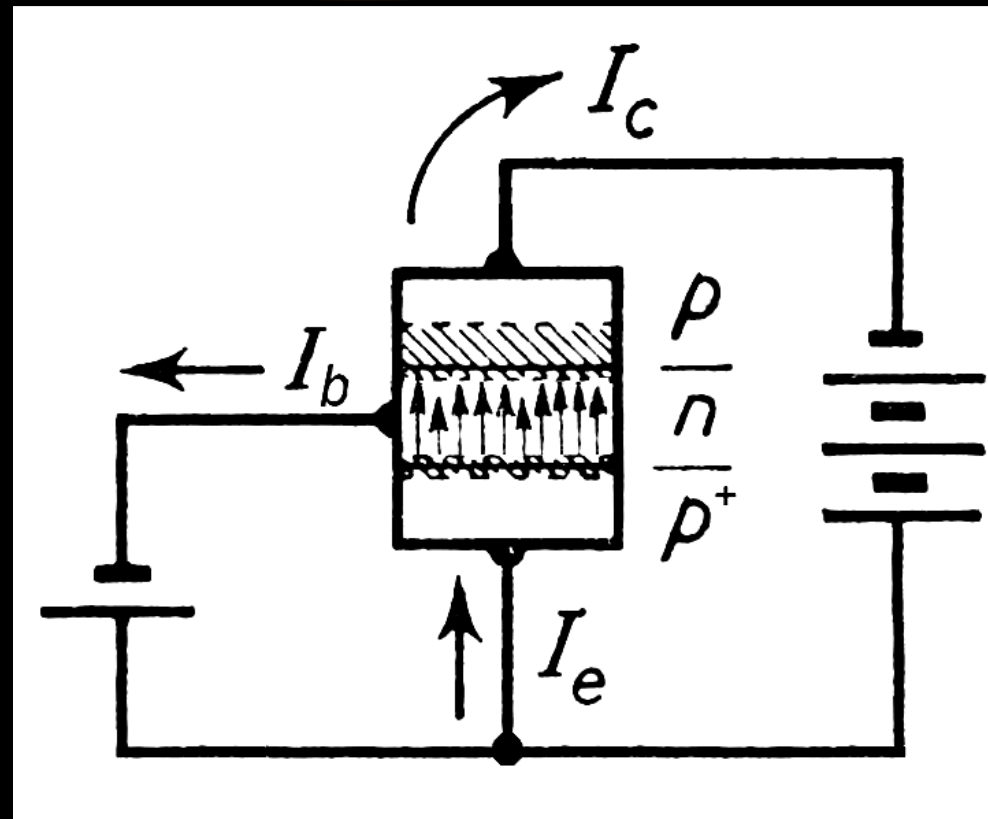
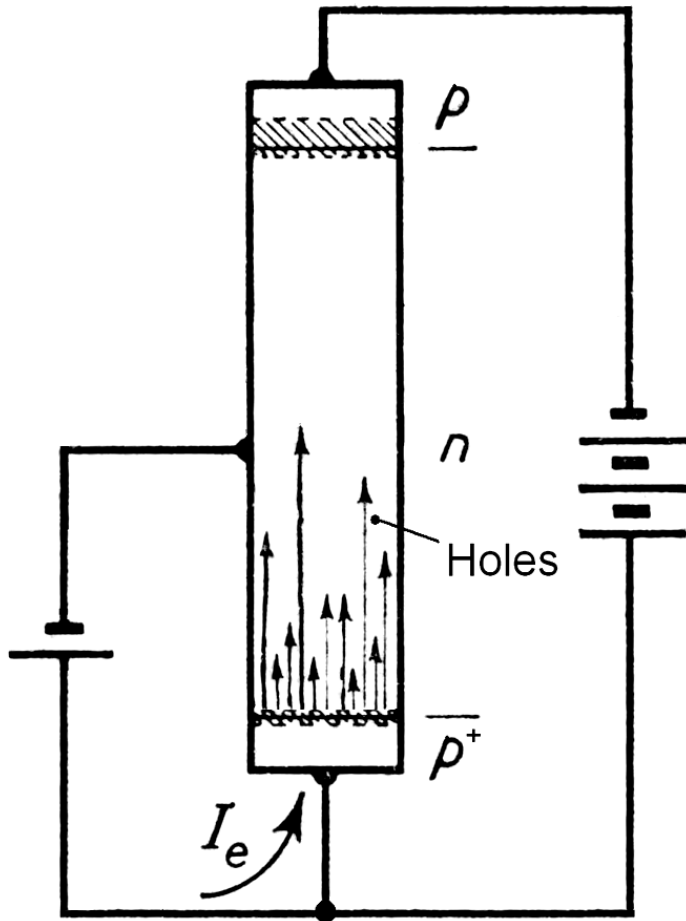
- Note the bias conventions and the correspondence to the circuit symbol. The *n-p-n* version is the same up to a sign change.
- Note, that in normal operation $I_B < I_C$.

Notes on BJT's

- The first commercial solid state amplifier (1947)
- Nowadays 'almost obsolete' – replaced primarily by FETs.
- Still used, however, in some high-power and high speed applications.
- Modern BJT's use epitaxial, planar construction.
- Two flavours $p-n-p$ and $n-p-n$. The underlying physics is the same. However the $n-p-n$ ones can be somewhat faster. *Why?*
- The amplification is due to the flow of minority carriers into the base region.

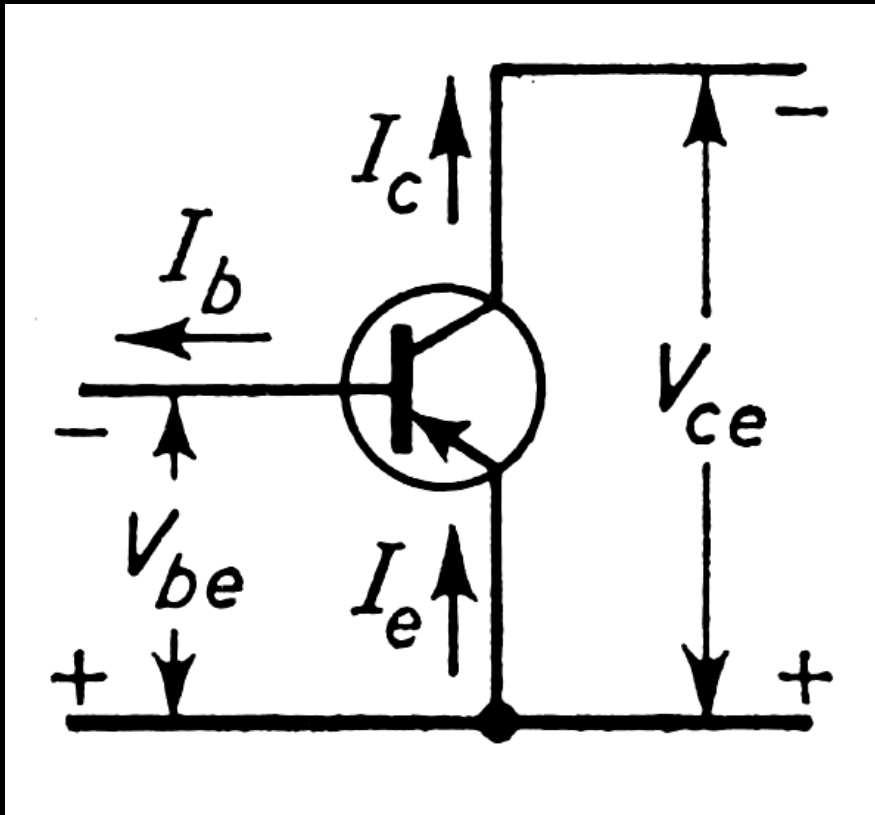
From Two Diodes to a Transistor

Common emitter configuration



- Two diodes in opposition do not make a transistor. The minority carriers will recombine before reaching the build-in field region of the second junction.

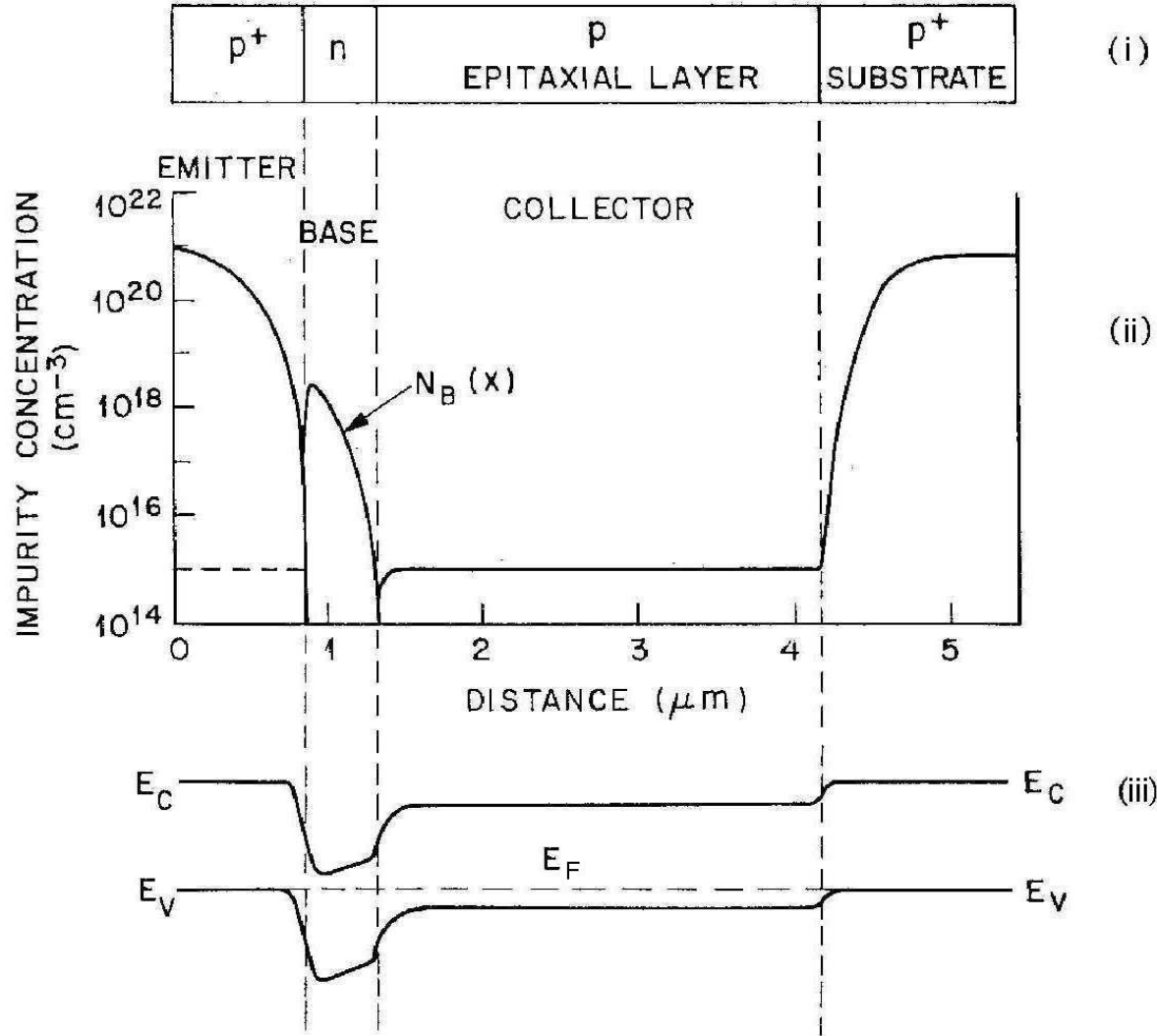
Focus on Common Emitter



- Why is power gain so important?
- Where is the power coming from? DC and AC operation.
- Why is the transistor called a 'transistor'?

- The base-collector junction is usually made physically larger than the emitter-base one, for the geometric collection efficiency.
- The collector and emitter currents are almost equal and large.
- The input (base) current is small.
- $I_c/I_b > 10^2$ in most 'modern' bipolar transistors.
- For practice – think about all three connection options – common base, common emitter and common collector. Which ones have current gain? Which ones have voltage gain?

Actual Impurity Concentration Profiles



- (i) Cross-sectional view of a diffused bipolar transistor.
(ii) Net impurity distribution in transistor.
(iii) Corresponding band diagram in thermal equilibrium.

- (i) • Role of the concentration gradients.
- (ii) • Build-in fields as large as $100 \text{ mV}/\mu\text{m}$
- Minority carrier drift and diffusion.
- Minority carrier recombination losses.
- (iii) • Minority carrier transit times – can gain orders of magnitude.

Base Transit Time

- The hole drift velocity v_p in the base is given by $v_p = \mu_p E_b$, where the hole mobility $\mu_p = 0.05 \text{ m}^2 \text{ V}^{-1} \text{ s}^{-1}$ in silicon.
- The transit time τ_b across the base, width w_b , is approximately:

$$\tau_b = \frac{w_b}{v_p} = \frac{w_b}{\mu_p E_b} = \frac{1.10^{-6}}{0.05 \times 0.2.10^6} = 1.10^{-10} \text{ s} = 100 \text{ ps}$$

for a base width w_b of $1 \text{ } \mu\text{m}$ (and neglecting diffusion).

- Frequency responses ($\approx 1/(2\pi\tau_b)$) up to the GHz region can be expected – depending on the circuit.
- Much faster special BPTs exist, as will be seen later.

Thanks and Acknowledgements



Thank You Very Much for Your Attention!