Lecture 18

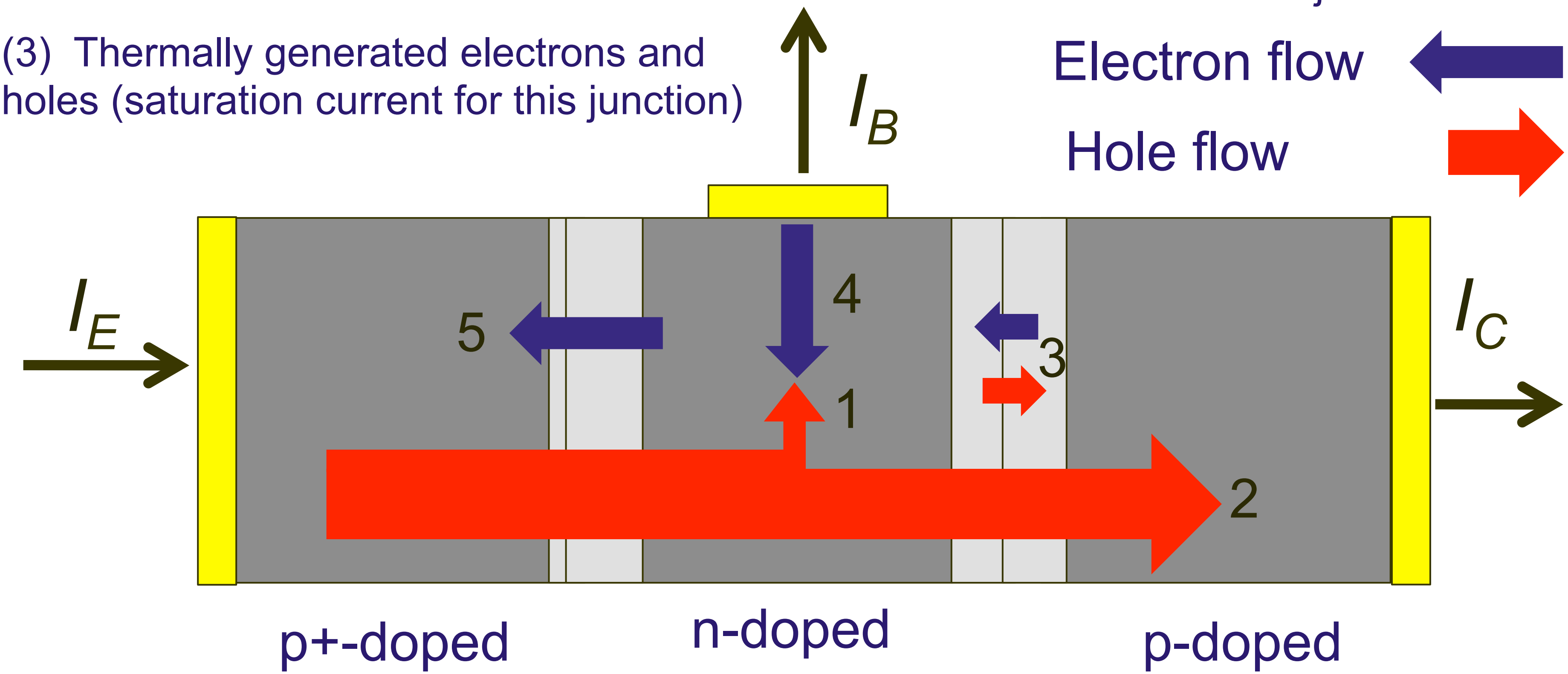
- Bipolar Junction Transistor
- Operation – Bias and Currents
- Current gain
- Application as amplifier
- Characteristics, Load Line

Bipolar Transistor Current flow Summary

(1) Injected holes lost to recombination in n-type base

(2) Injected holes which reach the reverse biased collector junction

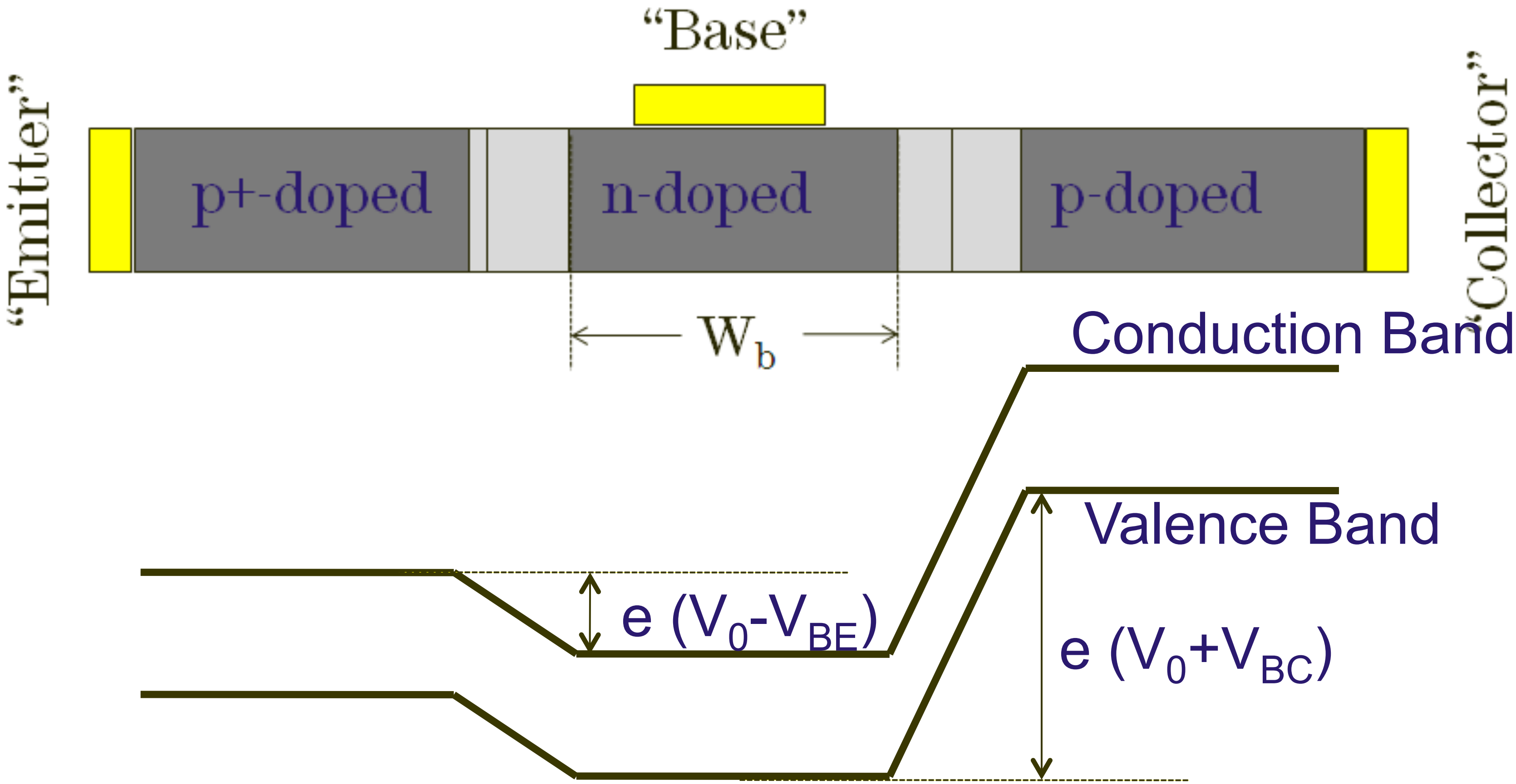
(3) Thermally generated electrons and holes (saturation current for this junction)



(4) Electrons supplied to replace those lost by recombination with holes in the base

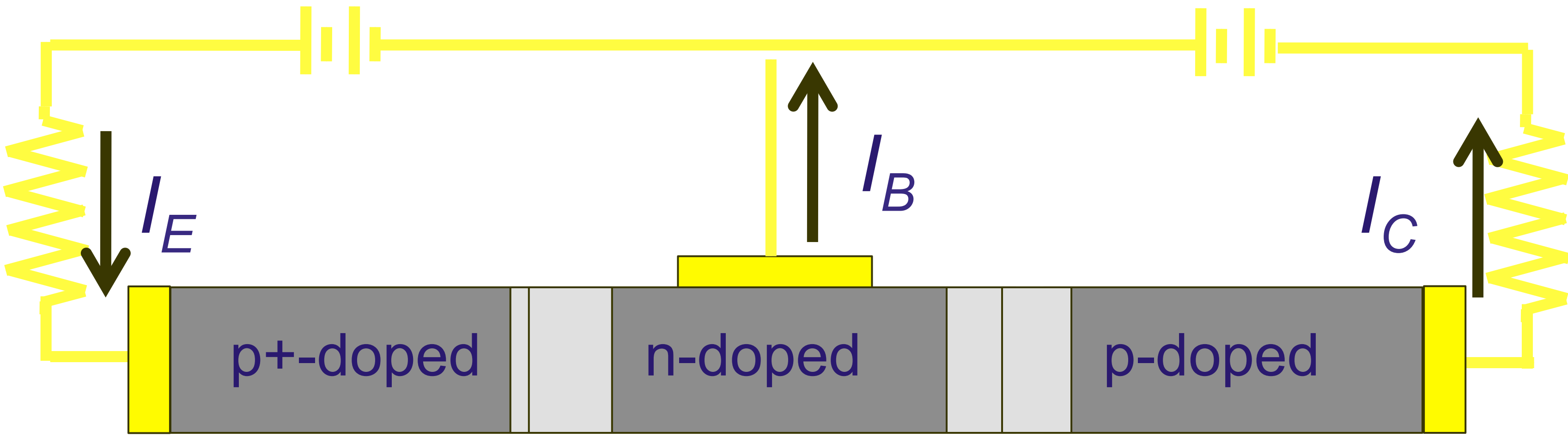
(5) Electrons injected across the forward biased emitter junction

Operational Bias – p+-n-p

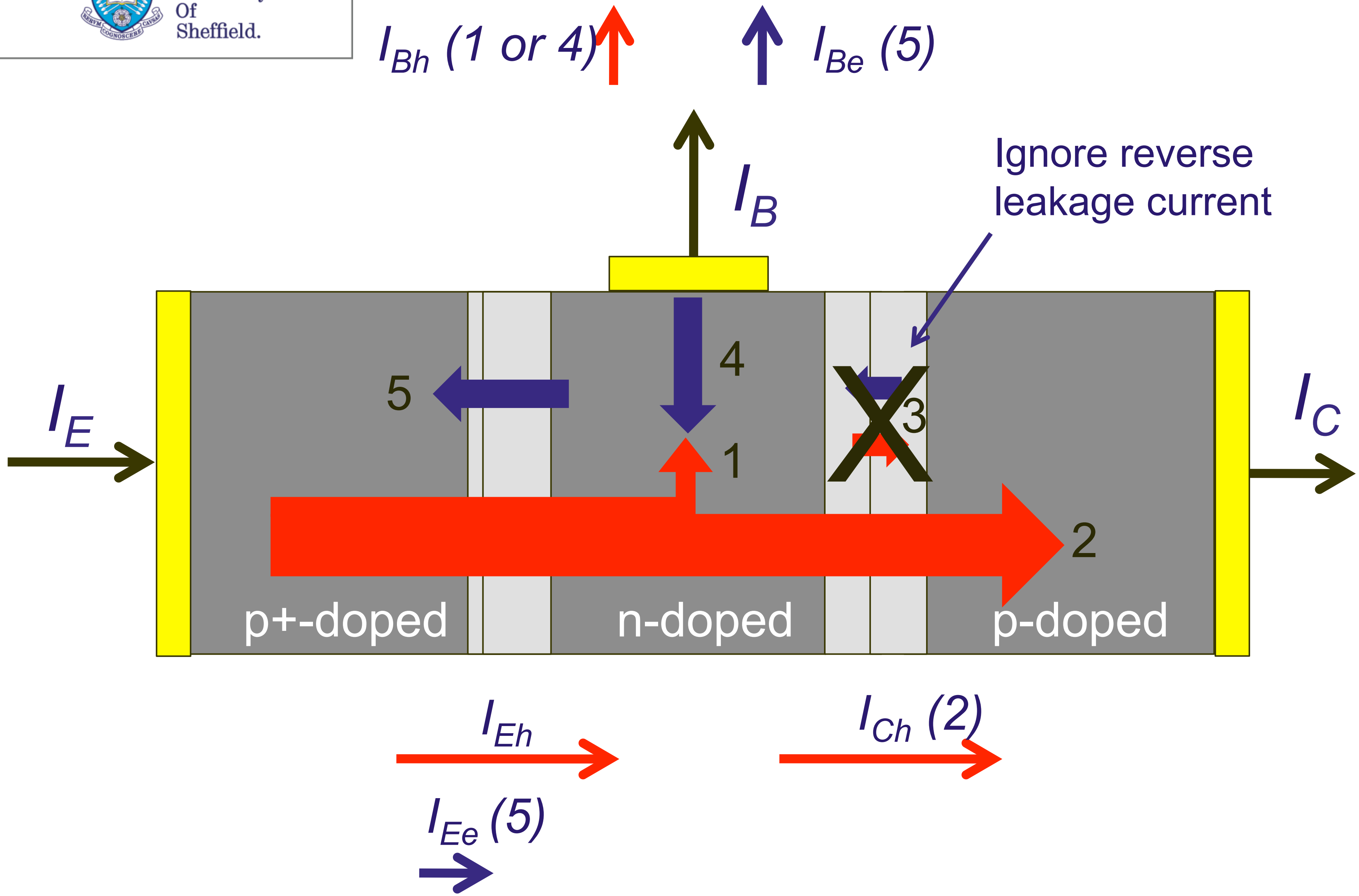


V_{BE} determines Emitter and hence Collector current

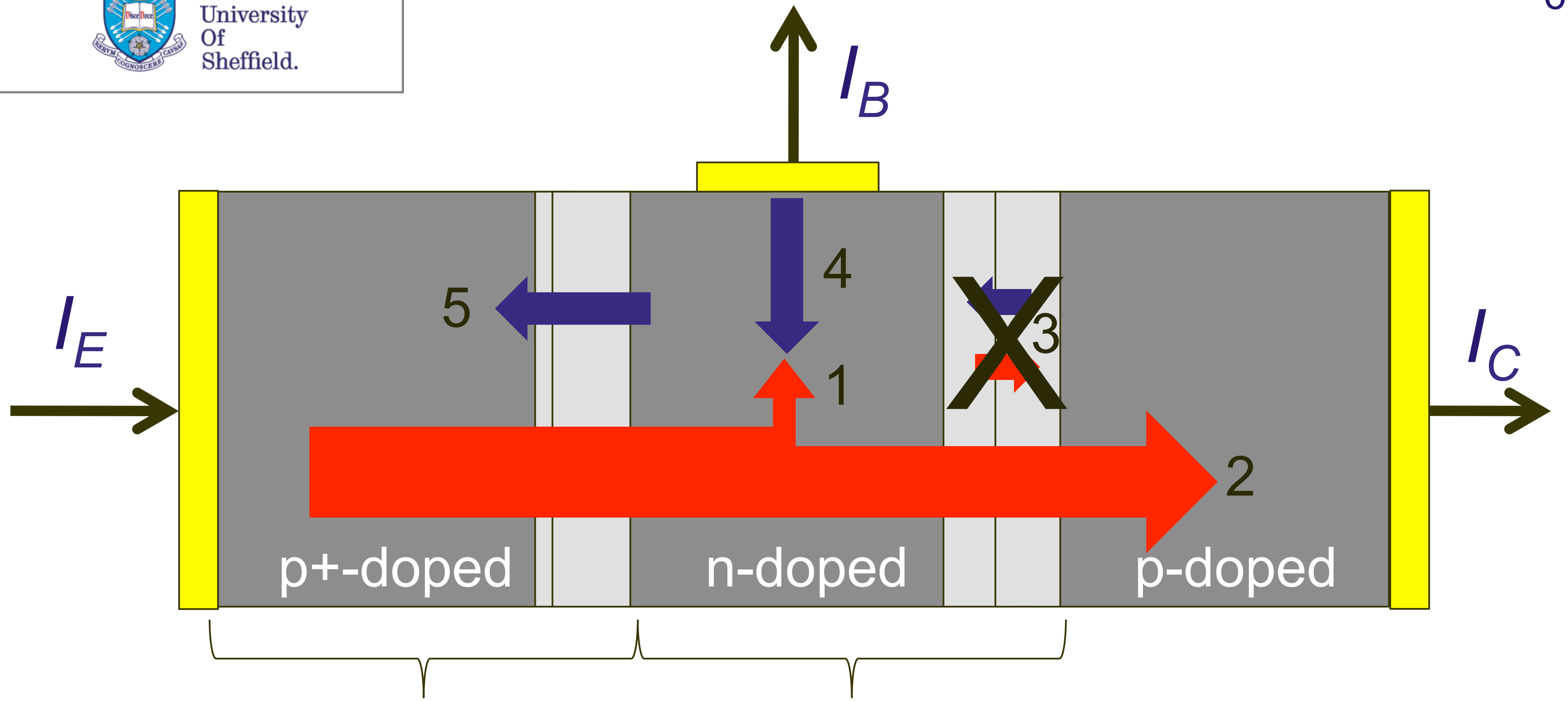
Terminal Currents



- Ideally $I_E \approx I_C$ and I_B is small
- Amplification is from comparing I_B to I_E or I_C
- We can derive relationships for ratios of these three currents



I_{Bh} (1 or 4)
I_{Be} (5)
I_B
Ignore reverse leakage current
I_E
I_C
5
4
1
3
2
p+-doped
n-doped
p-doped
I_{Eh}
I_{Ch} (2)
I_{Ee} (5)



I_C=B I_{Eh}

Emitter efficiency
- fraction of emitter current due to holes (or electrons in n^+-p-n devices)

$$\gamma = \frac{I_{Eh}}{I_{Ee} + I_{Eh}}$$

B - **Base transport factor** – fraction of holes from the emitter which reach the collector

For a high gain transistors both need to be very close to 1

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Terminal Currents (2)

Ratio of I_E and I_C $$\frac{I_C}{I_E} = \frac{BI_{Eh}}{I_{Ee} + I_{Eh}} = B\gamma = \alpha \approx 1$$

α is the **current transfer ratio** between the emitter and collector and is slightly less than 1 i.e. ~0.99

Base current $$I_B = I_{Ee} + (1 - B)I_{Eh}$$

Ratio of I_B and I_C (**current gain**) $$\frac{I_C}{I_B} = \frac{BI_{Eh}}{I_{Ee} + (1 - B)I_{Eh}}$$

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Terminal Currents (3)

Expand by using previous equations and divide top and bottom by total emitter current

$$\frac{I_C}{I_B} = \frac{BI_{Eh}}{I_{Ee} + (1\text{-}B)I_{Eh}} = \frac{B\left(I_{Eh}/I_{Ee} + I_{Eh}\right)}{\left(I_{Ee}/I_{Ee} + I_{Eh}\right) + (1 - B)\left(I_{Eh}/I_{Ee} + I_{Eh}\right)}$$

Cancel terms and then substitute for γ

$$\frac{I_C}{I_B} = \frac{B\left[{I_{Eh}}\big/{(I_{Ee} + I_{Eh})}\right]}{1\text{-}B\left[{I_{Eh}}\big/{(I_{Ee} + I_{Eh})}\right]} = \frac{B\gamma}{1 - B\gamma} = \frac{\alpha}{1 - \alpha} \equiv \beta$$

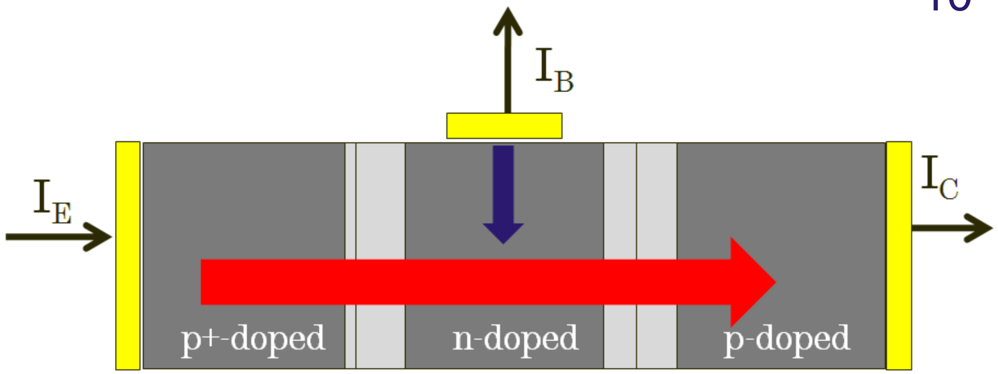
- β is the **current gain** or current amplification factor
- Since $B\gamma = \alpha \sim 1$, β can be large (typically up to 100)

Current Gain, β

The expression for the current gain, β, indicates that we need the E-B current to consist mainly of majority carriers from the emitter (defined by the emitter efficiency γ - need p^+>>n in a p^+-n-p device or n^+>>p in a n^+-p-n device) and that most of these majority carriers reach the collector without recombining in the base (defined by base transport factor, B – length of the base, L_B, must be much smaller than the minority carrier diffusion length, W_h (holes in this case))

e.g. if γ = 0.98, B = 0.95, current gain, β = 0.98x0.95/(1-0.98x0.95) ~ 13.5
if γ = 0.99, B = 0.995, current gain, β = 0.99x0.995/(1-0.99x0.995) ~ 66

Origin of Gain
(current injection picture)

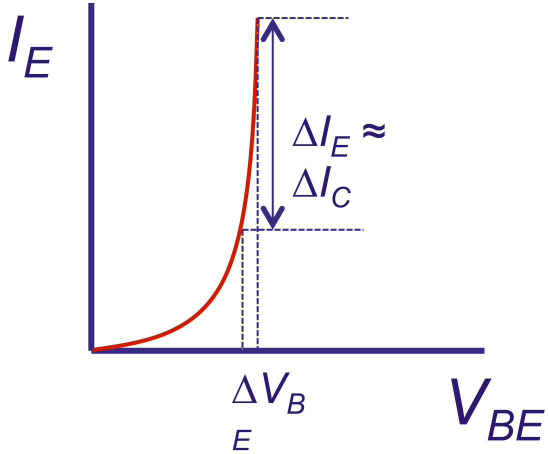


- In a similar way to gate bias controlling the output current in a FET so the E-B bias controls the collector current – a small ΔV_{BE} can control a large ΔI_C

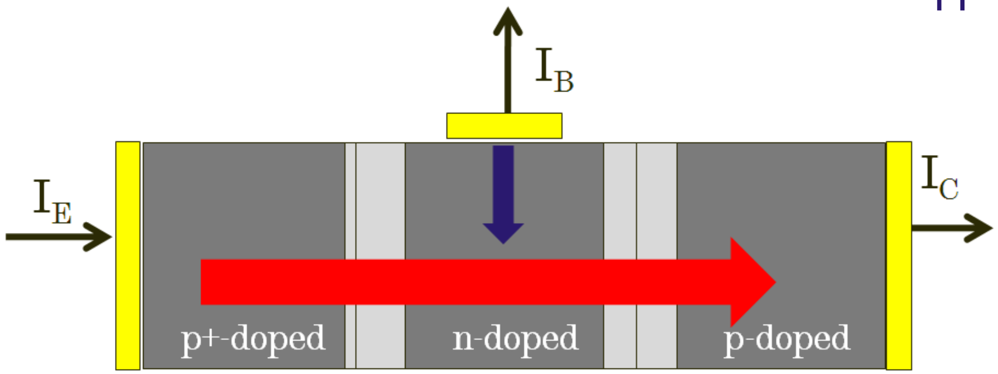
- Hence voltage gain = $(\Delta I_C R_L)/\Delta V_{BE}$ where R_L is the load resistor in the collector circuit

- Usually we use current gain = $\dfrac{I_C}{I_B}$ and I_B depends on V_{BE}

- Transconductance $\quad g_m = \dfrac{\Delta I_C}{\Delta V_{BE}}$



Origin of Gain
(charge balance picture)

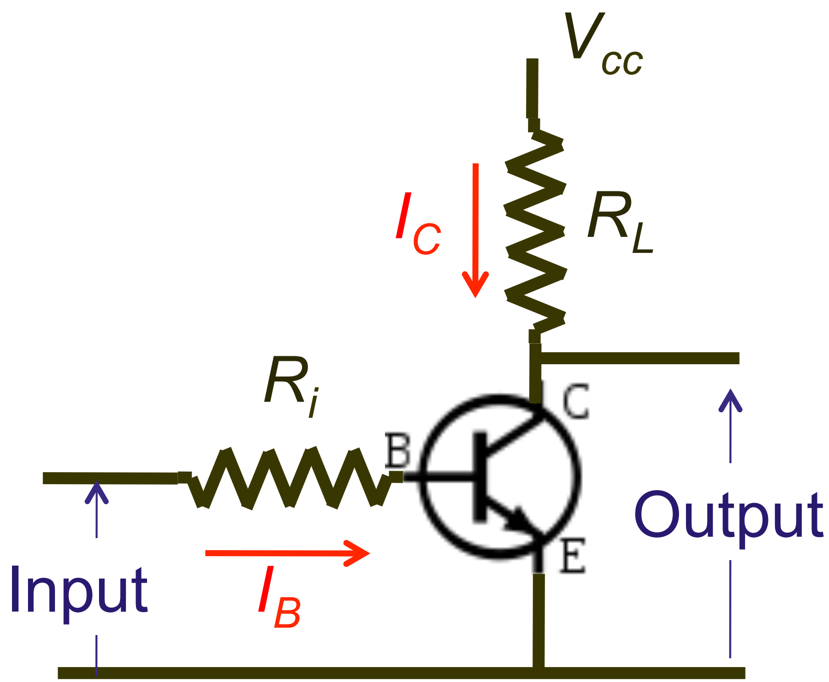


Assumes emitter efficiency $\gamma = 1$

• The base must remain neutral – i.e. the free carrier density equals donor atom density
• Excess holes injected into the base spend a short time there – they transit the base by diffusion in a time τ_t (base transit time)
• To maintain neutrality while there are excess holes in the base an equal number of balancing excess electrons enter the base from the contact
• On average these excess electrons last for the same time as the lifetime of the holes in the base i.e. τ_p
• For each electron entering the base to balance the excess holes, $\tau_p / \tau_t = \beta$ holes pass from emitter to collector i.e. get β holes traversing the base for every electron entering from the contact → current gain

Common Emitter Amplifier

(Up to now we have looked at common-base connection)



The base emitter is in ~forward bias so gives $V_{BE} \sim V_0$

Input voltage varies I_B

$\Delta I_C = \beta\, \Delta I_B$

Important characteristics are V_{CE} , I_C , and I_B

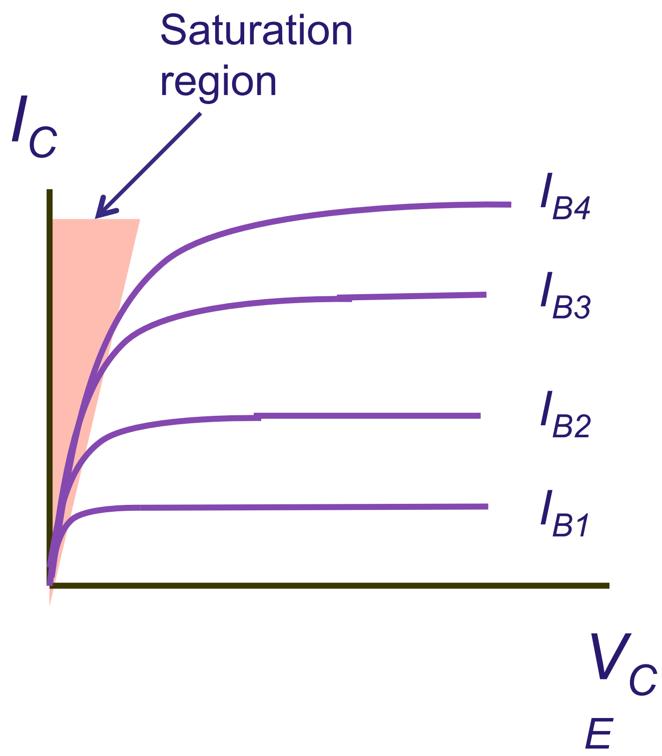
Characteristics (common emitter connection)

$$V_{CE} = V_{CB} + V_{BE}$$

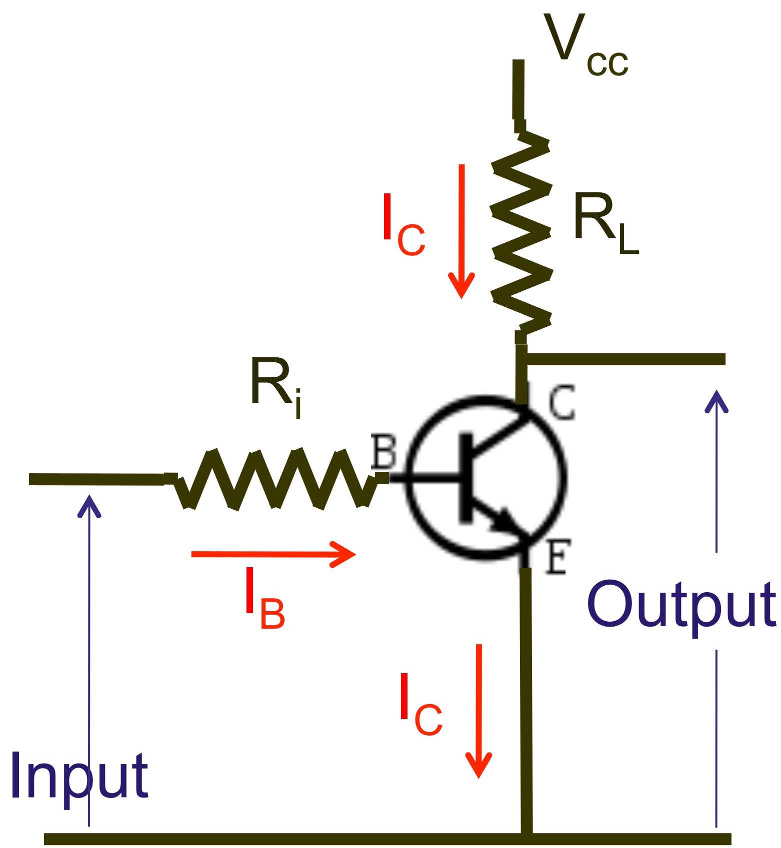
- Saturation region (note: different from FET!) – both junctions in forward bias and $V_{CB} \approx V_{BE}$ and V_{CE} small

- Remainder of region is “normal operation” where emitter-base forward biased and base-collector reverse biased

$$\Delta I_C = \beta \Delta I_B$$



Common Emitter Amplifier (2)



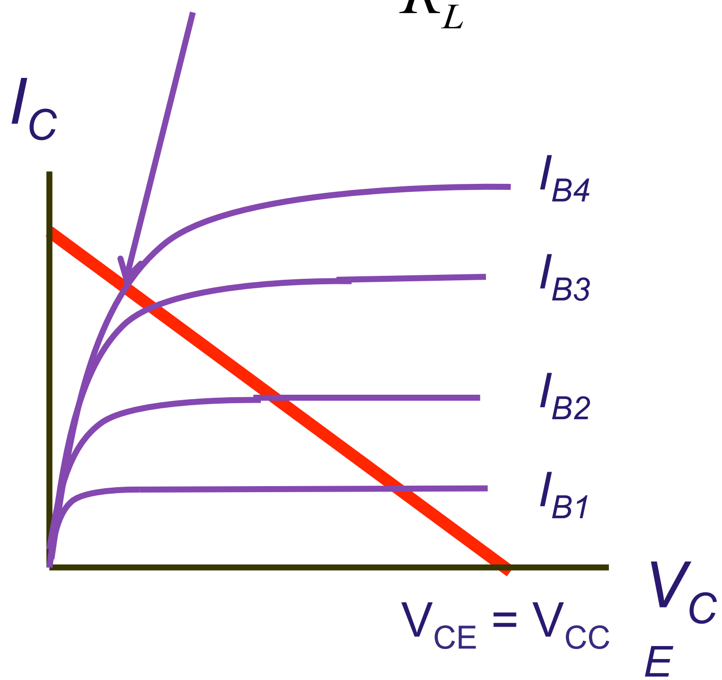
$$V_{CC} = I_c R_L + V_{CE}$$

What are the bias extremes?

- I_C=0 - device "off" → $V_{CE} = V_{CC}$
- V_{CE}=0 - device "on" → $I_c = \dfrac{V_{CC}}{R_L}$

Load Line

$$I_c \approx \frac{V_{CC}}{R_L}$$



Summary

- In bipolar transistors output (collector) current is controlled by injection from the emitter-base junction

- Current gain is affected by nature of emitter-base doping and the thickness of the base

- The common-emitter configuration acts as a current amplifier