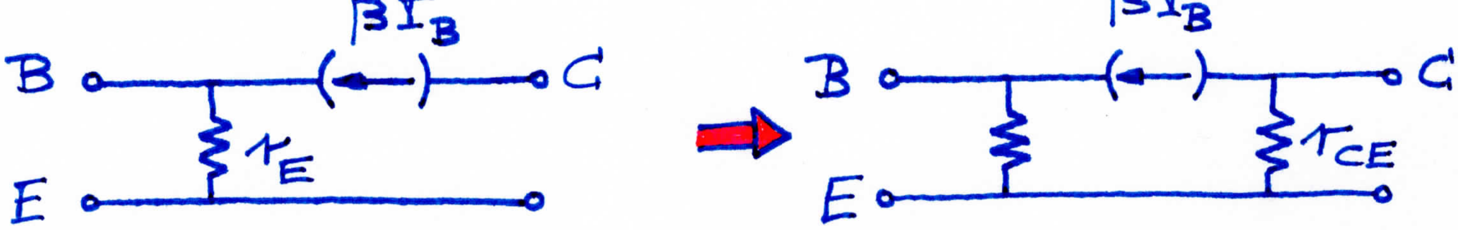
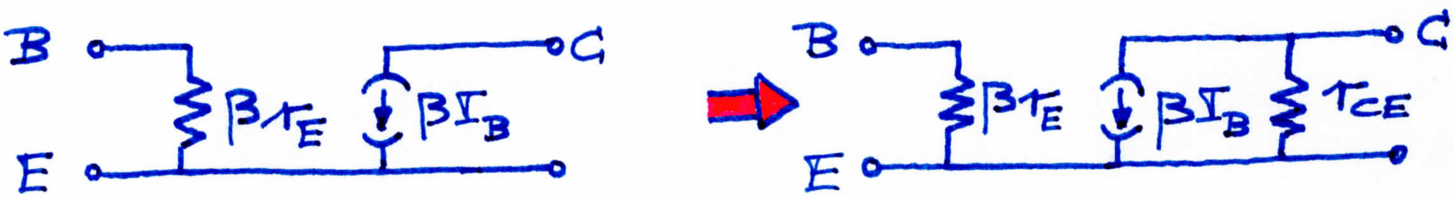
Non-idealities of BJTs

Ideal BJT $\Rightarrow$ Infinite output impedance

Real BJT $\Rightarrow$ Finite output impedance

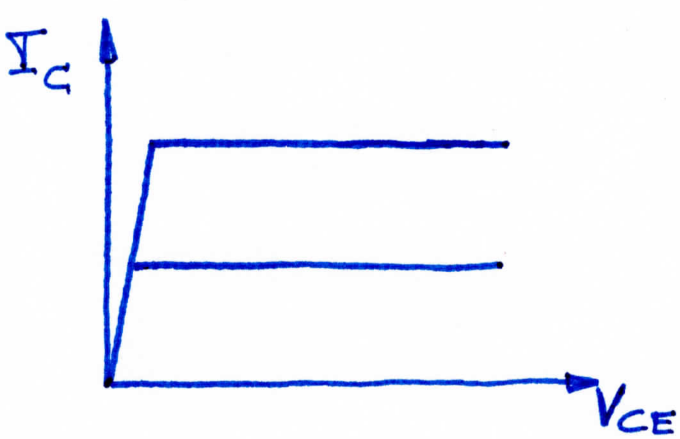
Recall:



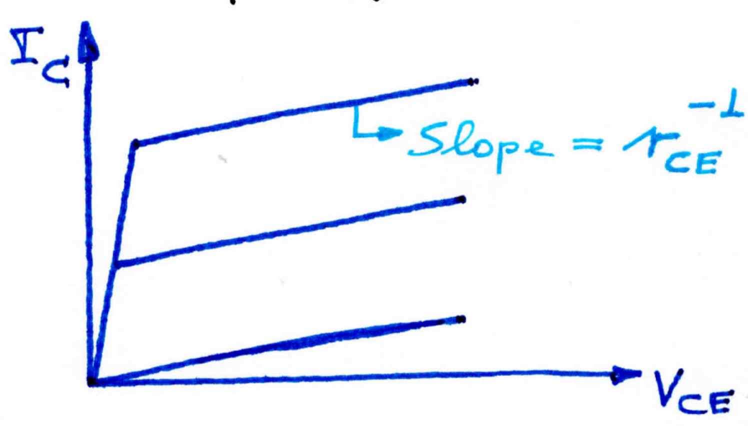


Ideal | Real

$\Rightarrow$ Output characteristic of BJT:

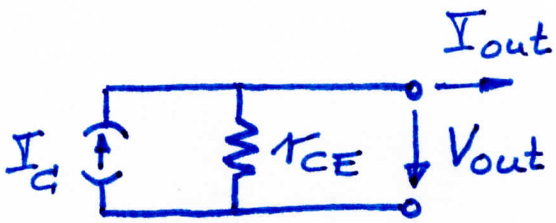


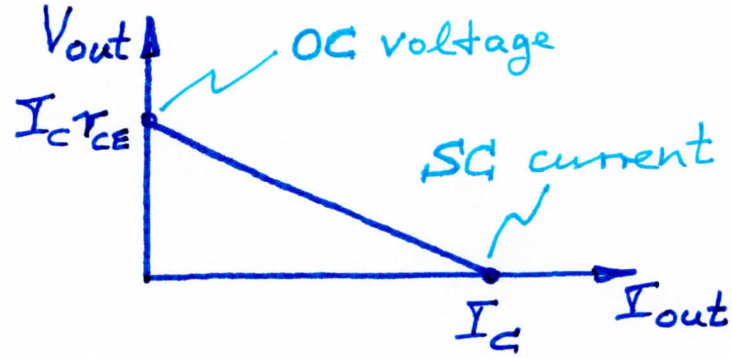
Ideal



Real

Exercise Consider the following circuit





What is the output impedance ("looking in") of the circuit ?

Solutions:

① Recall from other courses

$$r_{out} = \underline{\underline{r_{CE}}}$$

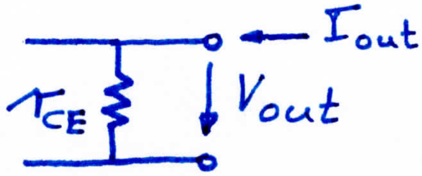
② Intuitive answer

$-(\rightarrow)-$ has infinite impedance

$$\Rightarrow \quad r_{out} = \underline{\underline{r_{CE}}}$$

③ **Superposition theorem** : We apply V_{out} (= stimulus) and obtain I_{out} (= effect). When applying the superposition theorem, we consider, seperately, each stimulus and set all other stimuli to zero.

The circuit then becomes

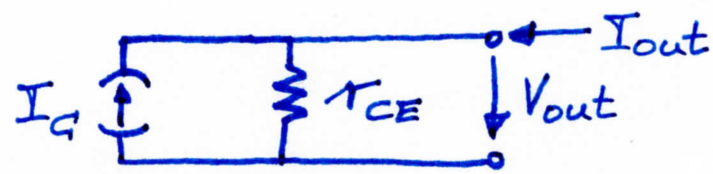


Ohm's law

$$r_{out} = \frac{V_{out}}{I_{out}} = \underline{\underline{r_{CE}}}$$

4 Let us take into account all sources

$\Rightarrow$ Most complex method $\Rightarrow$ Should give same result



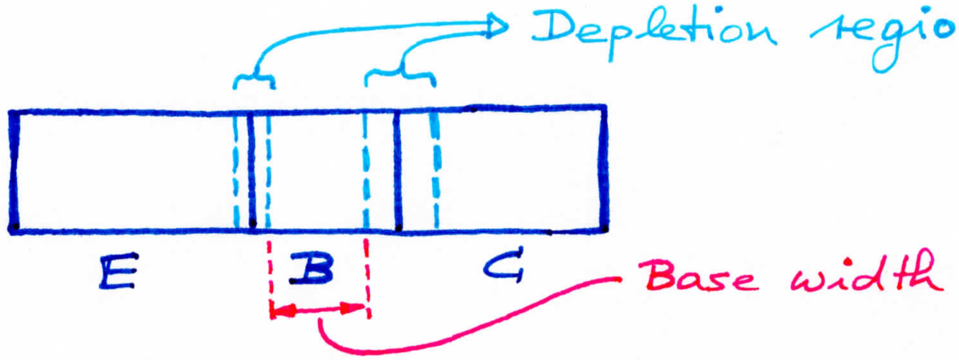
$$\Rightarrow \quad V_{out} = (I_C + I_{out})\, r_{CE}$$

$$r_{out} = \frac{dV_{out}}{dI_{out}} = \frac{d}{dI_{out}} V_{out} = \frac{d}{dI_{out}} (I_C + I_{out})\, r_{CE}$$

$$= \underline{\underline{r_{CE}}}$$

Conclusion: Methods above agree and show that r_{CE} is the output impedance of the transistor

Early effect $\Rightarrow$ Base width modulation



BE depletion region is thin (forward bias)

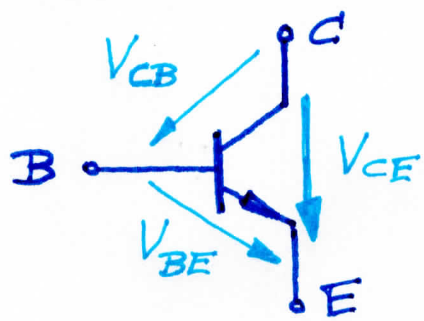
CB depletion region is thick (reverse bias)

$V_{CE} \uparrow \Rightarrow V_{CB} \uparrow \Rightarrow$ Reverse bias increases

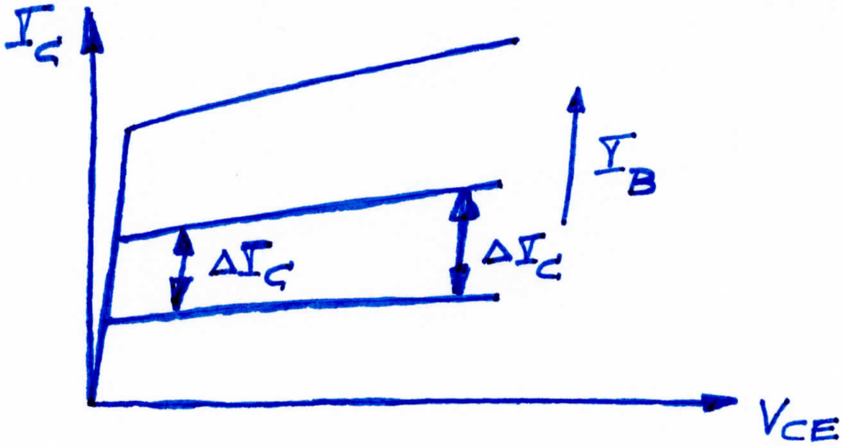
$\Rightarrow$ Neutral base width becomes thinner $\Rightarrow \alpha \uparrow$

$\Rightarrow \beta \uparrow \Rightarrow$ Amplification increases with V_{CE} !

Recall:



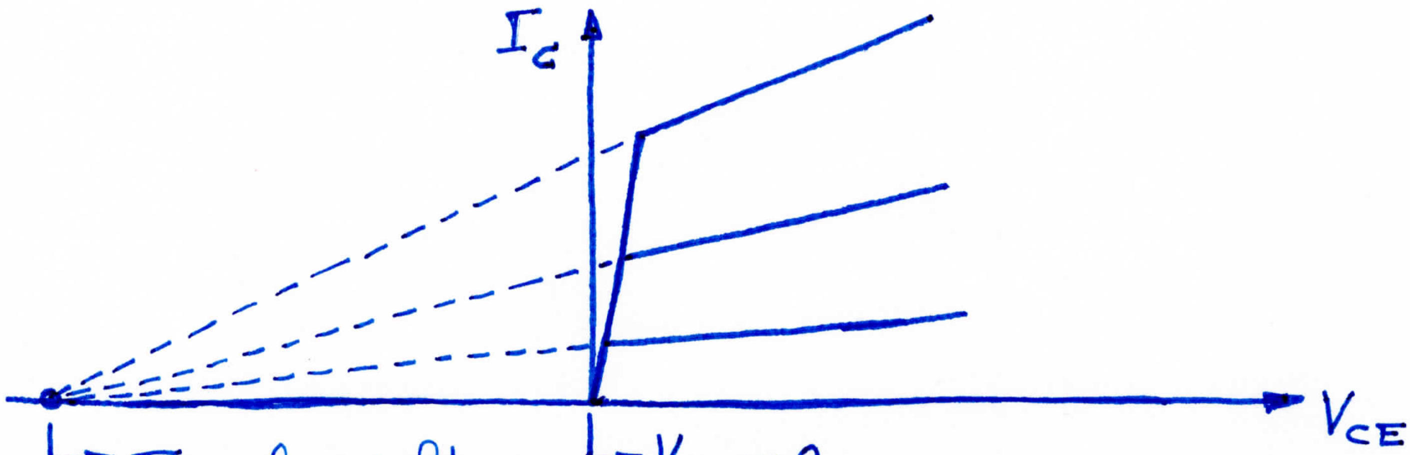
Output characteristic of BJT



$$\Rightarrow \beta = \frac{\Delta I_C}{\Delta I_B}$$

$\hookrightarrow$ increases with V_{CE} due to base width modulation

Early found the following fact



⇒ Extending the IV traces leads to one common point ⇒ Early voltage point $V_{Early} \approx -10V$ to $-100V$ (sometimes the "−" sign is omitted.

Recall:

$$I_E = I_o \, e^{V_{BE}/V_t}$$ (Diode eqn. for forward direction)

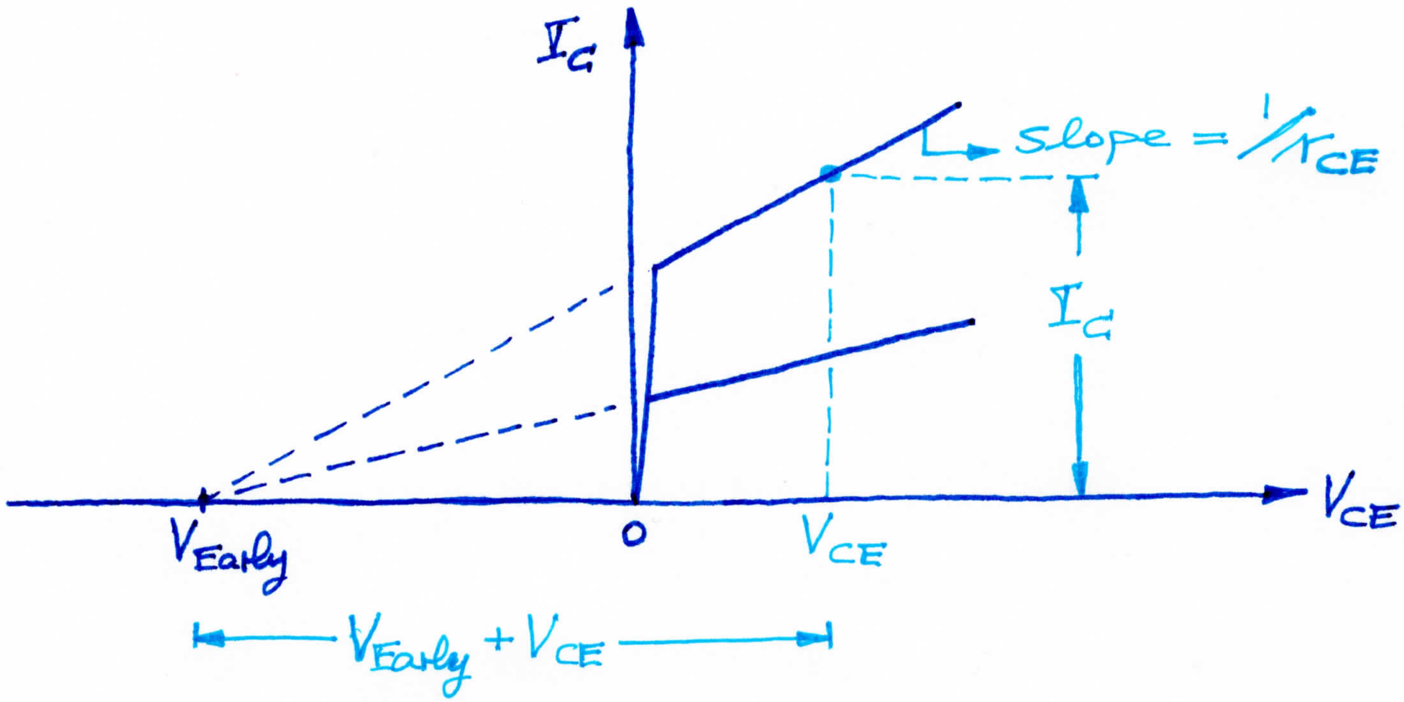
$$I_C = \alpha I_E = \alpha I_o \, e^{V_{BE}/V_t}$$

Due to Early effect, eqn. is modified

$$I_C = \alpha I_o \, e^{V_{BE}/V_t} \underbrace{\left(1 + \frac{V_{CE}}{V_{Early}}\right)}_{\text{Addition due to Early effect}}$$

Recall: Output impedance of BJT = r_{CE}

BJT output characteristic with Early effect:



Inspection of the figure reveals

$$\boxed{\text{Slope} = \frac{1}{r_{CE}} = \frac{I_C}{V_{Early} + V_{CE}}}$$

Solve for V_{Early} yields

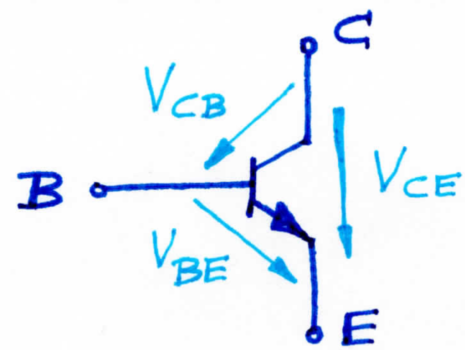
$$V_{Early} = \underbrace{I_C\, r_{CE}}_{= r_{out} \text{ of BJT}} - V_{CE}$$

Breakdown of CB junction at high V_{CE} values

Recall:

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

$V_{BE} \to 0.7V$

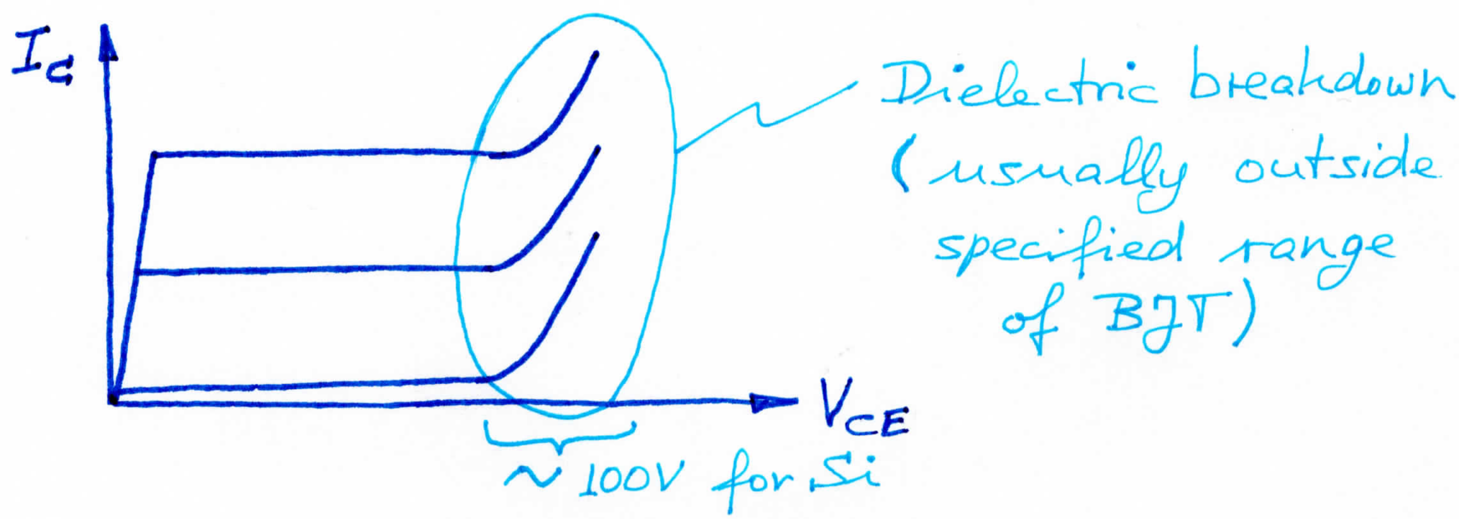


When $V_{CE}\uparrow \Rightarrow V_{CB}\uparrow$

$\Rightarrow$ Reverse bias of CB diode increases

$\Rightarrow$ At some point $\Rightarrow$ Dielectric breakdown

BJT output characteristic



Materials options

Ge Si GaAs SiC GaN C

$\longrightarrow$ Increase in breakdown field

$\Rightarrow$ Some semiconductors are better than Si