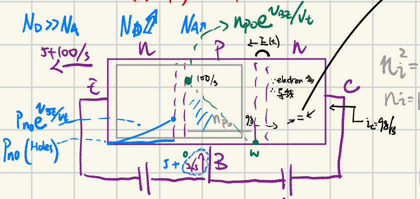
35 BJT:

Basic: Use of input voltage to control output current

E-B Junction

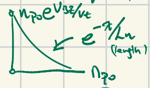
If Forward Bias, Injecting Electrons ($n \to P$) → in P, diffusing Electrons → in n, Collecting Electrons



V_{BE} (B高E低) V_{CB}

In npn, V_{BE} is forward, V_{CB} is reversed

when V_{BE} impose, 然后



base width: W → requires $W \ll L_n$

∵ 不能太宽

→ Eg. 100/s come in base, 98 go collector, cuz base is short

Tips

$L_n = \sqrt{D_n \tau_n}$ → lifetime

$N_A = 10^{15}$

$n_i^2 = P n$

$n_i = 10^{10}$

$n = 10^5 \ cm^{-3}$ → n_{po}

(thermal equilibrium, no impose)

$i_{drift} = q \mu_n n \vec{E}$

Modes of operation

	E-BJ	C-BJ	
(forward) Active	forward	Reverse	→ Amplification
(reverse Active)	Reverse	forward ~~Reverse~~	(接反了)
Cut off	Reverse	Reverse	
Saturation	forward	forward	

$$i_c = A_E q D_n \frac{dn}{dx}\Big|_W = \underbrace{A_E q D_n \frac{n_{po}}{W}}_{I_S} e^{V_{BE}/V_t}$$

$$i_c = I_S (e^{V_{BE}/V_t} - 1)$$

[V_{BE} → change, Then, i_c → change] } nonlinear

[V_{BE} → small signal] } linear

Active

In Active Mode:

(Base) i_B = (To supply the lost holes due to recombinat with the Injecting electrons) + (holes injecting from B to E, $A_E q D_p \frac{dp}{dx}\Big|_{x=0}$) → $P_{no} e^{V_{BE}/V_t} \cdot e^{-x/L_p}$

$(\Delta 面积)$ $\frac{A_E \frac{1}{2} \times n_{po} e^{V_{BE}/V_t} - 1 \cdot W}{\tau_n}$, n_{po}: $\frac{n_i^2}{N_D}$

$= A_E q \frac{D_p}{L_p} P_{no} (e^{V_{BE}/V_t} - 1)$ → small, P_{no}: $\frac{n_i^2}{N_D}$

Requirement: $n_{po} \gg P_{no}$ $(N_D \gg N_A)$

Width Base → Small

i_B Smaller than i_c

$$i_c = A_E q D_n \frac{n_{po}}{W} (e^{V_{BE}/V_t} - 1)$$

n_{po}: $\frac{n_i^2}{N_A}$

$$\frac{i_c}{i_B} = \beta$$

$$\beta = 1 \Big/ \left(\frac{1}{2}\frac{W^2}{D_n \tau_n} + \frac{D_p}{D_n}\left(\frac{N_A}{N_D}\right)\left(\frac{W}{L_p}\right)\right)$$

small　　small

$\beta = 100$ ↑ (gain ↑)

Common-Emitter (CE) Current Gain

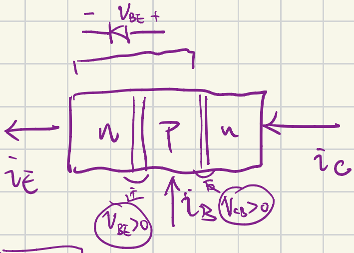
$$i_E = i_c + i_B$$

i_B → small

$$= i_c + \frac{i_c}{\beta} = i_c\left(1 + \frac{1}{\beta}\right) \Rightarrow i_c = \frac{\beta}{1+\beta} i_E$$

CB Common Base current gain

$$\alpha = \frac{i_c}{i_E} \approx 0.99$$

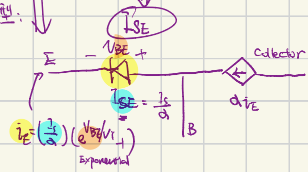


$(i_E \simeq i_C)$ $\quad i_E = i_C + i_B$

Active

$i_C = I_S(e^{v_{BE}/V_t} - 1)$, $\quad i_E = \frac{i_C}{\alpha} = \left(\frac{I_S}{\alpha}\right)(e^{v_{BE}/V_t} - 1)$

large Signal 模型：

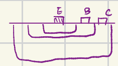


Tips

Concept：If Active mode 接反，

则不理想，因为两侧不相等 $\rightarrow \alpha = 0.1$

Prove：



Planor

$\beta = \frac{\alpha}{1-\alpha} \cong 0.1$ ([illegible])

Reverse ← (无gain)

α_R $\quad \beta_R$

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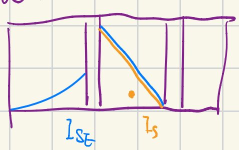
Active mode：



$$i_E = A_E q D_n \frac{n_{p0}}{W}(e^{v_{BE}/V_t} - 1) + A_E q D_p \frac{p_{n0}}{L_p}(e^{v_{BE}/V_t} - 1)$$

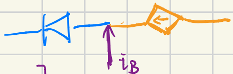
$$= \underbrace{\left(A_E q D_n \frac{n_{p0}}{W} + A_E q D_p \frac{p_{n0}}{L_p}\right)}_{I_{SE}}(e^{v_{BE}/V_t} - 1)$$

Slope

$$i_C = \underbrace{A_E q D_n \frac{n_{p0}}{W}(e^{v_{BE}/V_t} - 1)}_{100/s} - \underbrace{A_E q \frac{1}{2} \frac{W n_{p0}}{\tau_n}(e^{v_{BE}/V_t} - 1)}_{2/s \text{ lost hole}}$$

I_S

∵ 为了简单，neglect the lost hole in the base due to recombination

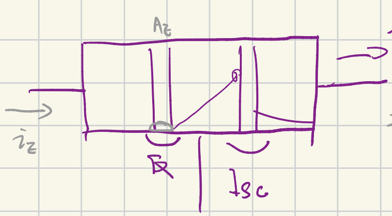


$\frac{I_S}{\alpha} = I_{SE}$

$i_C = \alpha i_E$

$\alpha \cong 0.99$

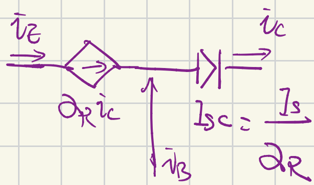
Reverse Active mode：



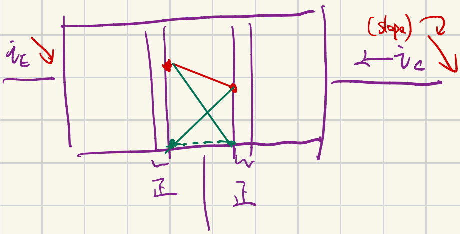
$i_C = I_{SC}(e^{v_{BC}/V_t} - 1)$

$i_E = \underbrace{A_E q D_n \frac{n_{p0}}{W}}_{I_S}(e^{v_{BC}/V_t} - 1) = \underset{(\text{small})}{\alpha_R} i_C$

model：



Saturation



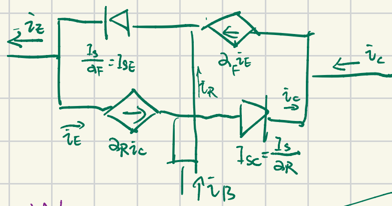
Ebers-Moll Model

可换成 linear 迭加: $n(v_{BE}, v_{BC}) = n(v_{BE}, 0) + n(0, v_{BC})$

浓度 — Forward — Reverse Active

$v_{BE} = 0.7$, $v_{BC} = 0.6$; $n(v_{BE},0)$: $v_{BE} = 0.7$; $n(0, v_{BC})$: $v_{BC} = 0.6$

$\downarrow i_C \qquad \downarrow i_C \qquad \downarrow i_C$



正, 反, 0 都可

可 Saturation → linear 相加

$$i_C = \alpha_F \frac{I_s}{\alpha_F}\left(e^{v_{BE}/V_t} - 1\right) - \frac{I_s}{\alpha_R}\left(e^{v_{BC}/V_t} - 1\right)$$

$$i_E = \frac{I_s}{\alpha_F}\left(e^{v_{BE}/V_t} - 1\right) - \alpha_R \frac{I_s}{\alpha_R}\left(e^{v_{BC}/V_t} - 1\right)$$

所有 model 都可描述

$$\begin{cases} i_C = I_s\left(e^{v_{BE}/V_t} - 1\right) + \frac{I_s}{\alpha_R} \quad \alpha_R \to 0.1 \\ i_E = \frac{I_s}{\alpha_F}\left(e^{v_{BE}/V_t} - 1\right) + I_s \end{cases}$$

← reverse leakage current

$$i_B = i_E - i_C = \frac{I_s}{\beta_R}\left(e^{v_{BC}/V_t} - 1\right) + \frac{I_s}{\beta_F}\left(e^{v_{BE}/V_t} - 1\right)$$

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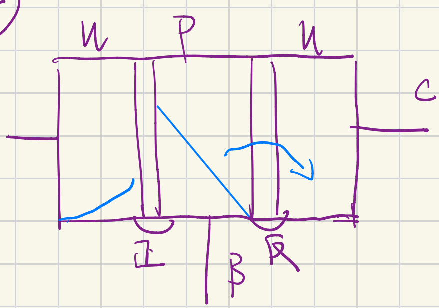
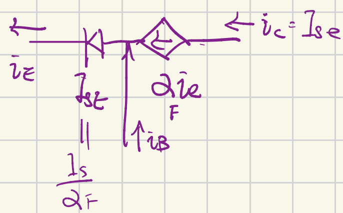
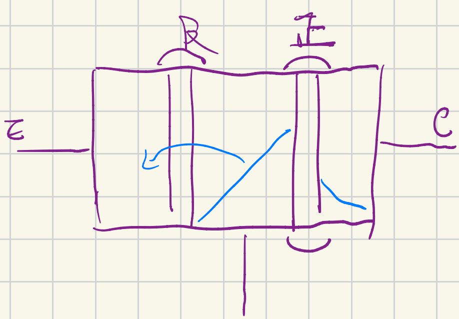
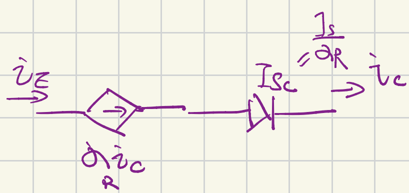


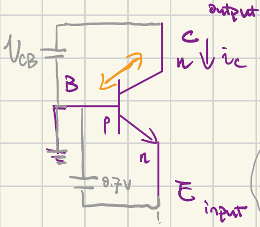
Active:





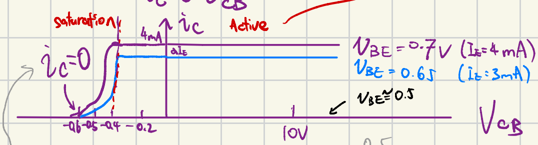


§ circuit symbol



C B output characteristic

$i_c \sim V_{CB}$



0.7   0.5

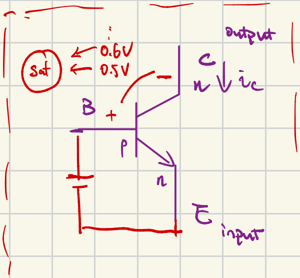
$$i_E = \frac{I_S}{\alpha_F}\left(e^{V_{BE}/V_t} - 1\right) - \alpha_R \frac{I_S}{\alpha_R}\left(e^{V_{BC}/V_t} - 1\right)$$

$$i_C = \alpha_F \frac{I_S}{\alpha_F}\left(e^{V_{BE}/V_t} - 1\right) - \frac{I_S}{\alpha_R}\left(e^{V_{BC}/V_t} - 1\right)$$

Eg.

$$\underbrace{i_C = I_S\left(e^{V_{BE}/V_t} - 1\right)}_{1mA} + \underbrace{\frac{I_S}{\alpha_R}}_{\text{small enough}} \rightarrow 10^{-12}A$$

(A pn junction does not become effectively forward biased until the voltage exceeds ~0.4V)



Active:

E-B Junction	C-B Junction
$V_{BE} = 0.6 \sim 0.8V$ $\cong 0.7V$ (forward)	Reverse + forward $\cancel{<0.5V}$ 太小正向不导通 负项正偏
Saturation: forward $V_{BE} = 0.7V$	forward (>0.5)

§ Ebers-Moll Model

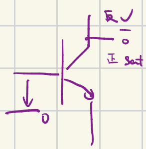
Eg. 5.1 the transistor has $\beta = 100$ and a $V_{BE} = 0.7V$ at $i_c = 1mA$ → find I_s

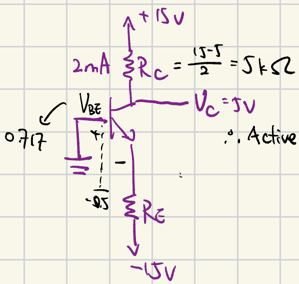
Design the circuit So that $I_C = 2mA$ & $V_C = 5V$

(? mode)

$\beta = \frac{I_C}{I_B}$ $\alpha = \frac{I_C}{I_E}$

$I_E = I_C + I_B$





∴ Active

① ∴ $i_c \cong I_s\left(e^{V_{BE}/V_t} - 1\right)$

② (Sol) $i_C = I_s e^{V_{BE}/V_t}$

③ $V_{BE} = V_t \ln \frac{I_C}{I_S}$

$0.7 = V_t \ln \frac{1}{I_S}$

④ $V_{BE} = V_t \ln \frac{2}{I_S} = V_t \ln\left(\frac{1}{I_S} \times 2\right) = \underbrace{V_t \ln \frac{1}{I_S}}_{0.7} + \overset{0.025}{V_t} \ln 2$

⑤ $= 0.717V$

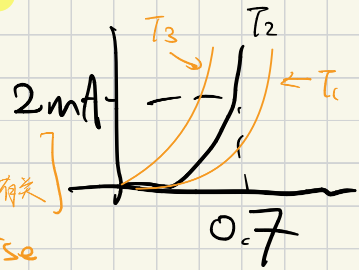
⑥ $I_E = \frac{I_C}{\alpha} = 2.02mA$

$R_E = \frac{-0.717 + 15}{2.02} \approx 7.07k\Omega$

Assume $V_{BE}=0.7\,V$, $\longrightarrow$ get 7.079

∴ 只要 active，就用 0.7

[$T_3 > T_2 > T_1$ ← $I_S(T)$
$T\nearrow \rightarrow I_S\nearrow$] ↖ I_S 与 T 有关



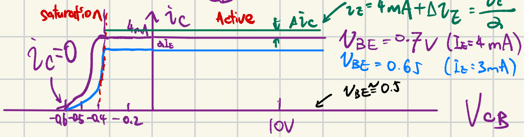
$\Delta V_{BE(on)} = -2mV/1°C$ rise

$I_S(T)\nearrow$

⇒ α, β

$\alpha = \dfrac{i_C}{i_E}$ ↘ total (large signal)

$i_C \sim V_{CB}$

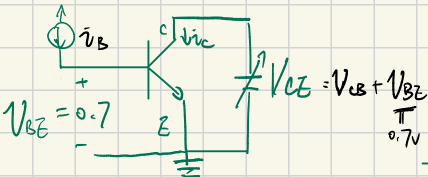


$\alpha_{ac} = \dfrac{\Delta i_C}{\Delta i_E}$ $\quad(\alpha = \alpha_{ac})$

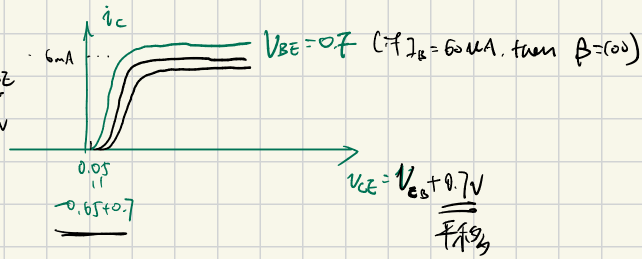
↳ small signal

$\beta_{ac} = \dfrac{\Delta i_C}{\Delta i_B}\Big|_{\text{at } V_{CE}} = \beta$

§ CE output characteristics



$i_B = \dfrac{1}{\beta}\left(e^{V_{BE}/V_t} - 1\right)$



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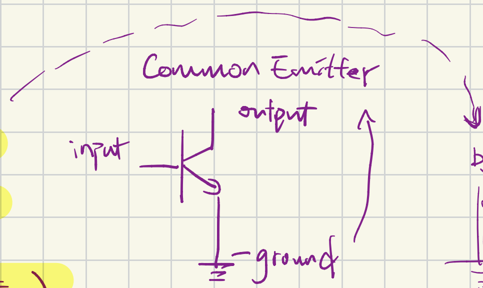
§ The CE output characteristic

Eber Moll equations

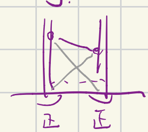
$$i_C = I_S\left(e^{V_{BE}/V_t} - 1\right) - \frac{I_S}{\alpha_R}\left(e^{V_{BC}/V_t} - 1\right)$$

$$i_E = \frac{I_S}{\alpha_F}\left(e^{V_{BE}/V_t} - 1\right) - I_S\left(e^{V_{BC}/V_t} - 1\right)$$

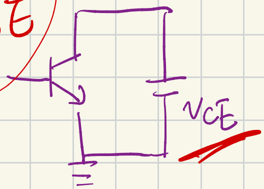
$$i_B = \frac{I_S}{\beta}\left(e^{V_{BE}/V_t} - 1\right) + \frac{I_S}{\beta_R}\left(e^{V_{BC}/V_t} - 1\right)$$

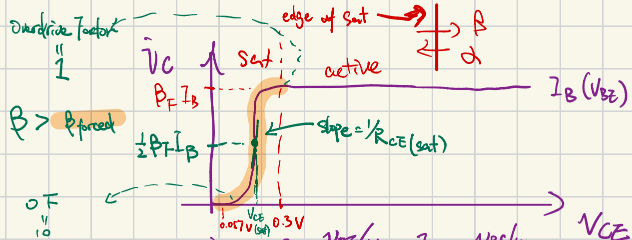


by:



V_{CE}





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

$$\frac{i_C}{i_B} = \frac{I_s e^{V_{BE}/V_t} - \frac{I_s}{\alpha_R} e^{V_{BC}/V_t}}{\frac{I_s}{\beta_F} e^{V_{BE}/V_t} + \frac{I_s}{\beta_R} e^{V_{BC}/V_t}}$$

→ for $i_C = 0$

$V_{CE} = V_t \ln\left(\frac{1}{\alpha_R}\right) = 0.057V$

$$= \frac{e^{V_{CE}/V_t} - \frac{1}{\alpha_R}}{\frac{1}{\beta_F} e^{V_{CE}/V_t} + \frac{1}{\beta_R}}$$

→ for a large V_{CE}

$i_C = I_B \beta_F$

$\beta_R = \frac{\alpha_R}{1-\alpha_R} = \frac{0.1}{0.9} = 0.11$, $\beta_F = 100$, $e^{V_{CE}/V_t} \gg \frac{\beta_F}{\beta_R} = 1000$

$V_{CE(EOS)} = 0.3V$

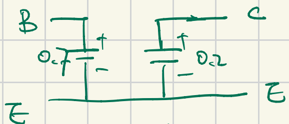
$0.057V \xrightarrow{\text{sat}} 0.3V$

$$\frac{1}{2}\beta_F = \frac{e^{V_{CE}/V_t} - \frac{1}{\alpha_R}}{\frac{1}{\beta_F} e^{V_{CE}/V_t} + \frac{1}{\beta_R}} \Rightarrow \frac{2}{\alpha_R} + \frac{\beta_F}{\beta_R} = e^{V_{CE}/V_t} \Rightarrow V_{CE(sat)} = V_t \ln\left(\frac{\beta_F}{\beta_R} + \frac{2}{\alpha_R}\right) = V_t \ln\left(\frac{100}{0.11} + \frac{2}{0.1}\right)$$

$= 0.173 V$

$\boxed{\text{If } V_{CE} \to \text{sat},\ V_{CE(sat)} = 0.2V}$

Sat.



(Sat) $I_{C(sat)} < \beta I_B$

$\left[\ \beta_{forced} \equiv \frac{I_{C(sat)}}{I_B} < \beta \Rightarrow \frac{\beta}{\beta_{forced}} \equiv \text{overdrive factor}\ \right]$

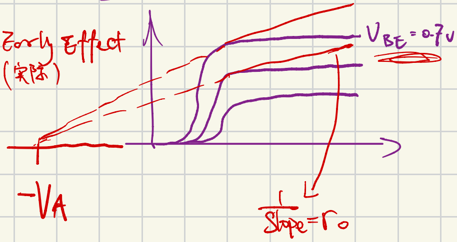
The greater the overdrive factor the deeper the transistor is driven into sat

Early Effect: CE

Eg.

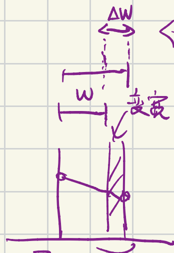
$i_E = 0$ open 反向

→ implement 3 equations



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

V_{CE}越大，V_{CB}越大



collector Junction depletion width widen

width ↑ ⇒ W ↓

$i_C = I_S\left(e^{V_{BE}/V_t} - 1\right)$

↳ $I_S = A_E q D_n \frac{n_{p_0}}{W} e^{V_{BE}/V_t}$

$\frac{1}{W - \Delta W} = \frac{1}{W\left(1 - \frac{\Delta W}{W}\right)} \doteq \frac{1}{W}\left(1 + \frac{\Delta W}{W}\right)$

$\because \Delta W \propto V_{CE} \Rightarrow \Delta W = \lambda' V_{CE} \rightarrow \doteq \frac{1}{W}\left(1 + \frac{\lambda'}{W} V_{CE}\right)$

(linear 关系)

$\frac{\lambda'}{W} = \frac{1}{V_A}$

$$i_C = I_S e^{V_{BE}/V_t}\left(1 + \frac{V_{CE}}{V_A}\right)$$

斜比去

$$\left(\frac{\partial i_C}{\partial V_{CE}}\right)\Bigg|_{\text{for a const } V_{BE}} \equiv r_o \leftarrow \frac{1}{\text{Slope}} = r_o$$

$$\left(\frac{I_C}{V_A}\right)^{-1} = \boxed{\frac{V_A}{I_C}}$$

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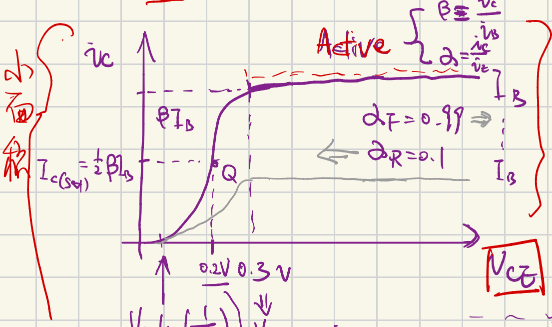
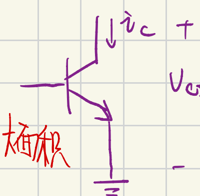
§ CE Common Emitter

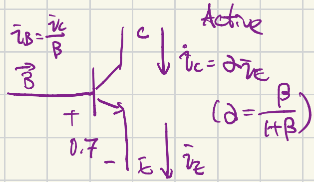


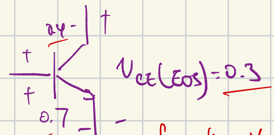


$I_{C(sat)} < \beta I_B$

$\beta_{forced} \equiv \frac{I_{C(sat)}}{I_B} < \beta$

The transistor is forced in "sat"





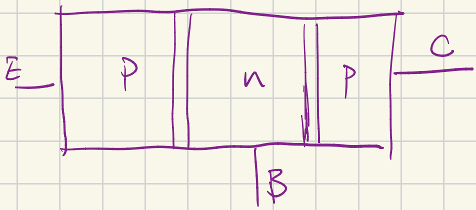
for active, $V_{CE} > 0.3$

$V_{CB} + V_{BE} > 0.3$

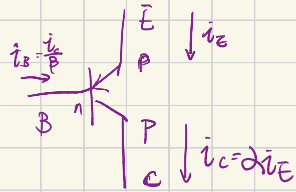
$$V_{CB} + \underbrace{V_{BE}}_{0.7} > 0.3 \Rightarrow V_{CB} > -0.4 \Rightarrow V_C - V_B > -0.4 \Rightarrow V_C > V_B - 0.4$$

§ PnP transistor

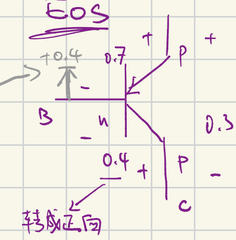
PnP / Amplifier



Active



Eos



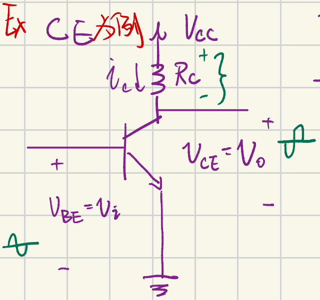
$0.3 = V_{EC}(Eos)$

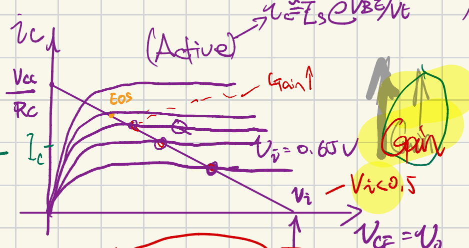
[for "Active"条件 $V_{CB} < 0.4$]

$\Rightarrow V_C - V_B < 0.4 \Rightarrow V_B + 0.4 > V_C$

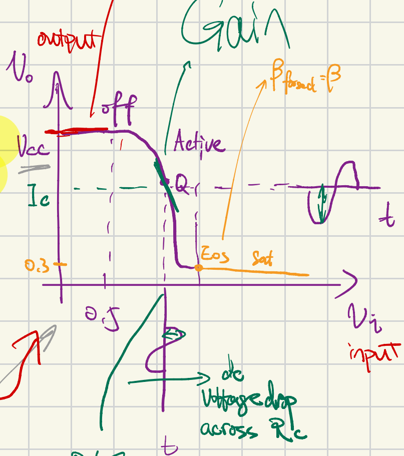
§ The BJT as an amplifier - as a switch

Ex CE为例





不影响



$V_o = V_{cc} - i_C R_C$ load line

Active: $V_o = V_{cc} - R_C I_S e^{V_i/V_t}$

ac gain = ↓ 微分

$$A_v = \frac{\partial V_o}{\partial V_i}\Big|_{V_i = 0.65} = -\frac{R_C I_C}{V_t} \Rightarrow \text{Voltage drop across } R_C$$

工作点 → slope 不同

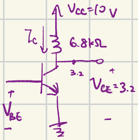
§5.2

A CE circuit using a BJT having $I_s = 10^{-15}A$, $R_C = 6.8k\Omega$, $V_{CC} = 10V$

变化量

导通 0.7 V_{BE}

a) $V_{BE} = ?$ for $V_{CE} = 3.2V$



Assume "Active"

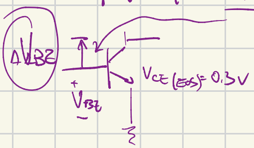
$I_C = I_S e^{V_{BE}/V_t} \Rightarrow V_{BE} = 690.8mV \Rightarrow 0.69 < 3.2$ Active ✓

$I_C = \frac{10-3.2}{6.8} = 1mA$

b) at this pt $\Rightarrow A_v = \frac{10-3.2}{V_t} = -272\ V/V$

c) find the positive increment in V_{BE} that drives the BJT to EOS

$\hookrightarrow V_{CE}(EOS) = 0.3$



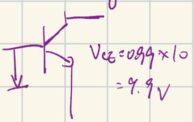
$I_C(EOS) = \frac{10-0.3}{6.8} = 1.617mA$

$\Delta V_{BE} = V_t \ln \frac{I_{C2}}{I_{C1}} = V_t \ln \frac{1.617mA}{1mA} = 12mV$

≙ 两差

d) find the negative increment in V_{BE} that drives BJT to within 1% of cut off (ie. $V_o = 0.99V_{CC}$)

1% cut off

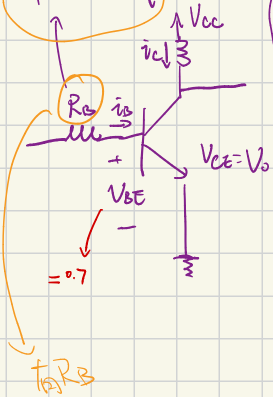


$I_C = \frac{10-9.9}{R_C} = 0.0147mA$

$\Delta V_{BE} = V_t \ln \frac{0.0147mA}{1mA} = -105.5mV$

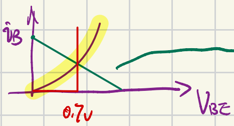
$V_{BE} - \Delta V_{BE} = 690.8mV - 105.5mV \approx 590mV$

Pratical



输入端

$i_B = \frac{i_C}{\beta} = \frac{i_S(e^{V_{BE}/V_t})}{\beta} \Rightarrow i_B$与$V_{BE}$有exponential关系



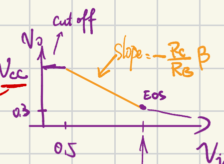
load line
$V_i = i_B R_B + V_{BE}$

think as ideal $\rightarrow i_B = \frac{V_i - 0.7}{R_B}$ ($V_{BE} = 0.7$)

-slope 关系

linear 关系

不导通 = Vcc



$0.7 + I_B(EOS) \cdot R_B$
$= 0.7 + \frac{R_B}{\beta}\left(\frac{V_{CC}-0.3}{R_C}\right)$

Assume "Active" $i_C = \beta i_B$

$\boxed{V_o} = V_{CC} - i_C R_C = V_{CC} - \beta \frac{\boxed{V_i} - 0.7}{R_B} R_C$

$I_C(EOS) = \frac{V_{CC} - 0.3}{R_C} \Rightarrow I_B(EOS) = \frac{I_C(EOS)}{\beta}$

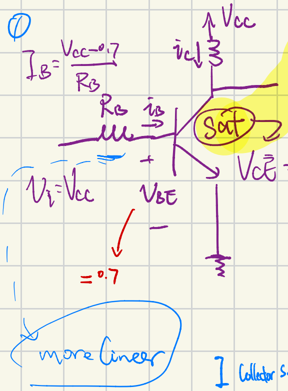
β很大

Slope: AC信号
放大倍数

Saturation

as a switch → $v_i = V_{CC}$ or 0

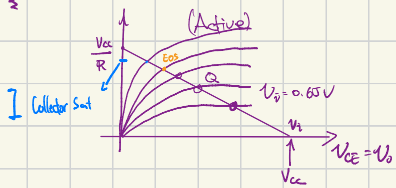
① $I_B = \frac{V_{CC}-0.7}{R_B}$



② $I_C(\text{sat}) = \frac{V_{CC}-0.2}{R_C}$

$$\beta_{\text{forced}} = \frac{I_C(\text{sat})}{I_B} = \frac{\frac{V_{CC}-0.2}{R_C}}{\frac{V_{CC}-0.7}{R_B}} \simeq \frac{R_B}{R_C} < \beta$$

The deeper the BJT is
The smaller the β_{forced} is



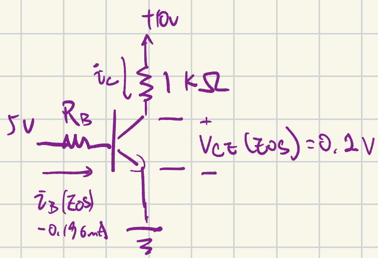
$\frac{\beta}{\beta_{\text{forced}}}$ = overdrive

Sat $\beta_{\text{forced}} = \frac{i_C(\text{sat})}{i_B} < \beta$

(40)

Ex 5.3 β in the range of 50 to 150

find R_B that results in sat, with an overdrive factor of at least 10



(EOS)

$i_C(\text{EOS}) = \frac{10-0.2}{1k\Omega} = 9.8\,mA$

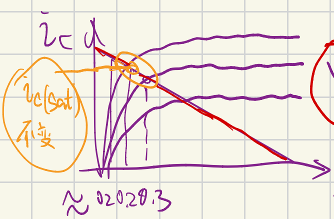
$i_B(\text{EOS}) = \frac{i_C(\text{EOS})}{\beta} = \frac{i_C(\text{EOS})}{50} = 0.196\,mA$

↓

挑最小 ∵ 要 worst case 也 Sat

Sat 后 i_C 不再增加

50 也 saturate



$V_{BE}(I_B)$

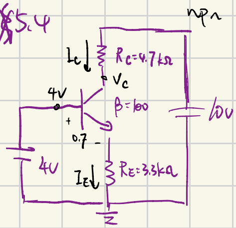
(要越 Sat， I_B 要增加 → $R_B\downarrow$ → $I_B\uparrow$)

$0.196mA \times 10 = 1.96mA = i_B$

$\beta_{\text{forced}} = \frac{9.8}{1.96} = 5$

$\frac{\beta}{\beta_{\text{forced}}} = \frac{50}{5} = 10$ ✓

Ex 5.4



Find all node voltage & branch currents

(sol) Assume "Active"

$I_E = \dfrac{4-0.7}{3.3} = 1mA$

$I_C = \alpha I_E = \dfrac{\beta}{1+\beta} I_E = 0.99\,mA$

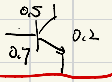
$V_C = 10 - I_C R_C = 10 - 0.99 \times 4.7 = \underline{5.3V}$

$5.3 > 4 \rightarrow$ Reverse $\rightarrow$ Active ✓

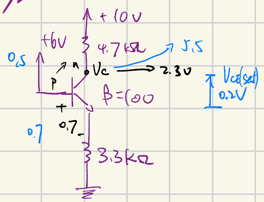
$I_B = \dfrac{I_C}{\beta} = \dfrac{0.99}{100}$

Tips: 判断是否 V_{CB} reverse

① 比大小：$V_C > 4V - 0.5V$



Ex 5.5



Assume "Active"

$I_E = \dfrac{6-0.7}{3.3} = 1.6\,mA$

$I_C = \alpha I_E = 1.58\,mA$

$V_C = 10 - 1.58 \times 4.7 = 2.5V$

$\left.\begin{array}{l} 6V - 0.5V = 5.5 \\ 5.5 > 2.5 \end{array}\right\}$ not "Active"

Saturation:

$V_C = 6 - 0.5 = 5.5$

$I_C = \dfrac{10-5.5}{4.7k} = 0.96\,mA$

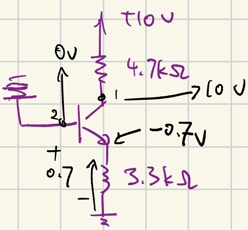
$I_E = 1.6\,mA$

$I_B \cancel{=} \dfrac{I_C}{\beta}$

$I_B = I_E - I_C = 1.6 - 0.96 = \underline{0.64\,mA}$

$\beta_{forced} = \dfrac{0.96}{0.64} = 1.5 < \beta = 100$

Ex. 5.6



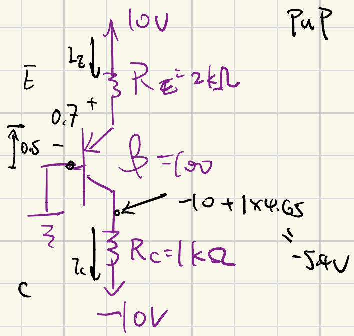
Assume "Active"

$\because V_B < V_E$ $\therefore$ current goes node $-0.7V$ Not "Active"

Cut off

node 1 = 10　node 2 = 0　all current = 0

Ex 5.7



PnP

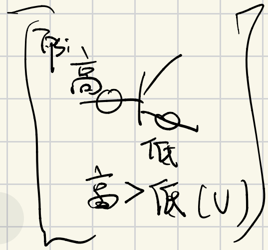
Assume "Active"

$I_E = \frac{10-0.7}{2} = 4.65\,mA$

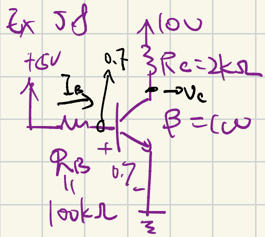
$I_C = \alpha I_E \approx 4.65\,mA$

$\because 0 + 0.5 > -5.4V \rightarrow$ Reverse

$\therefore$ "Active"



Ex 5.8



Assume "Active"

$I_B = \frac{5-0.7}{100} = 0.043\,mA$

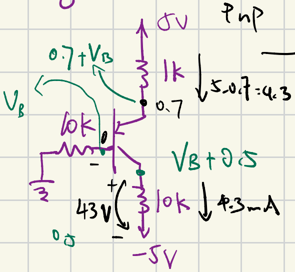
$I_C = \beta I_B = 4.3\,mA$

$V_C = 10 - 4.3\times2 = 1.4V$

$1.4 > 0.7 \rightarrow$ Reverse $\rightarrow$ Active

$1.4 - 0.5 = 0.9 \geq 0.7$

Ex 5.9



→ do Assume : Base should smallest ≥ 0

→ do Assume "Sat"

$I_E = \frac{5-(V_B+0.7)}{1}$

$I_C = \underbrace{\frac{V_B+0.5+5}{10}}_{\text{Collector}} + \underbrace{\frac{V_B}{10}}_{\text{base}}$

Solve $V_B = 3.13$

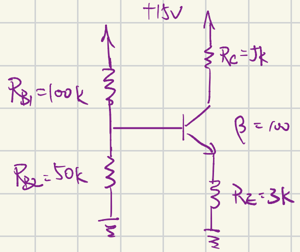
$I_C = 0.86\,mA$

$I_B = 0.31\,mA$

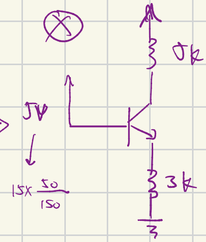
$I_E = I_C + I_B$

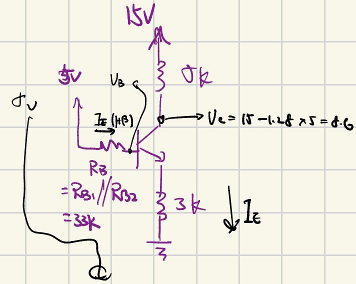
$\beta_{forced} = \frac{0.86}{0.31} = 2.8 < \beta$

5.10



$\Rightarrow$





Assume "active"

$5 = \frac{I_E}{1+\beta}\times 33 + 0.7 + I_E\cdot 3$

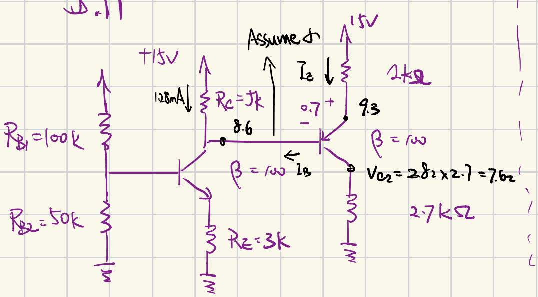
$\Rightarrow I_E = 1.29mA \Rightarrow I_C = 1.28mA$

$V_C = 15-1.28\times5 = 8.6V$

$V_B = 1.29\times3+0.7 = 4.57V$

$8.6V > 4.57V \rightarrow$ 集>基 $\rightarrow$ 反 $\rightarrow$ active

5.11



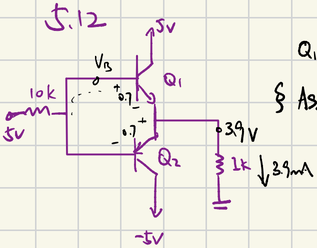
后面会 affect 前面

Assume $I_B \ll I_C$ → 为后便于 Assume $I_B \ll I_C$ 很小

$$\begin{cases} I_E = \frac{15-9.3}{2k} = 2.85mA \\ I_C = \alpha I_E = 2.82mA \\ I_B = \frac{I_C}{\beta} = 0.0282mA \end{cases}$$

} Assume ✓

5.12



Q_1 and Q_2 Can't be conducting Simultaneously

§ Assume Q_1 "on" Q_2 "off"

$5 = I_B\cdot10 + 0.7 + I_B(1+\beta)\cdot 1 \Rightarrow I_B = 0.039mA$

$V_B = 5 - 10\times0.039 = 4.6V$

Assume ✓

Tips

$I_C = \frac{\beta}{1+\beta}I_E$

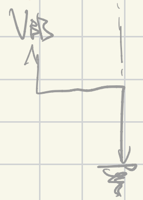
$I_C = \beta I_B = \frac{\beta}{1+\beta}I_E$

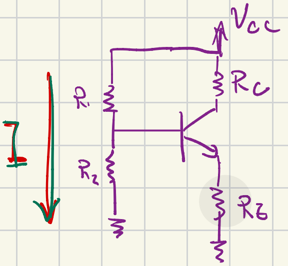
$I_E = I_B(1+\beta)$

(41)

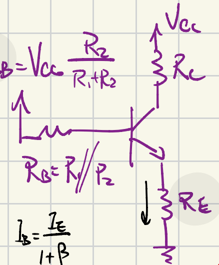
§5.5 Biasing in BJT amplifier circuit

Biasing (拉闸栗)





$\Rightarrow$ $V_{BB} = V_{cc}\frac{R_2}{R_1+R_2}$



$\frac{2}{3}R$ $\quad I_B = \frac{I_E}{1+\beta}$

$\frac{I_E}{1+\beta}$

$V_{BB} = I_B R_B + V_{BE} + I_E R_E$

$$I_E = \frac{V_{BB} - V_{BE}}{R_E + \frac{R_B}{1+\beta}}$$

V_{BE} & $\beta \Rightarrow$ BJT 有关

$$\Delta I_E = \frac{\partial I_E}{\partial V_{BE}}\Delta V_{BE} + \frac{\partial I_E}{\partial \beta}\Delta\beta$$

越小 越小

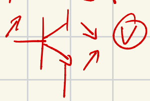
dc stability ↑

(Adding R_E can reduce the sensitivity of I_E against V_{BE} and β)

Tips: ②

(if $V_{BB}\uparrow \Rightarrow I_B\uparrow, I_C\uparrow, I_E\uparrow$)

$\Rightarrow$ push BJT into "Sat"



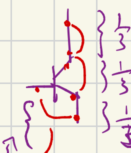
$\therefore$ V_{BB} 不能太大

① I_E 稳定 $\begin{cases} V_{BB} \gg V_{BE} \\ R_E \gg \frac{R_B}{1+\beta} \end{cases}$ $\Rightarrow$ $I_E = \frac{V_{BB}}{R_E}$ independence of BJT

与电晶体相关

Rule of thumb for Design $\begin{cases} 0.\ I_C R_C \approx \frac{1}{3}V_{cc} \\ .\ V_{CE} \approx \frac{1}{3}V_{cc} \\ .\ V_B \approx \frac{1}{3}V_{cc} \end{cases}$

① $I = 0.1 I_E \sim 1 I_E$



$R_E \gg \frac{R_B}{1+\beta}$ $\longrightarrow$ R_E 在 1/3 段时可决定，∴ 要决定 R_B

$\Downarrow$

$\frac{\frac{1}{3}V_{cc}}{I_E} \gg \frac{\frac{2}{3}R}{\beta}$ $\quad R//2R \quad \frac{V_{cc}}{3I}$ $\Rightarrow I_E \ll \beta I \Rightarrow I \gg \frac{I_E}{\beta}$

偏压稳定性

(to avoid the attenuation of the input signal)

the smaller I ↓ the better

(neglect $I_B \Rightarrow V_{cc} \times \frac{R_2}{R_1+R_2} = \frac{1}{3}V_{cc} \Rightarrow R_1 = 2R_2$)

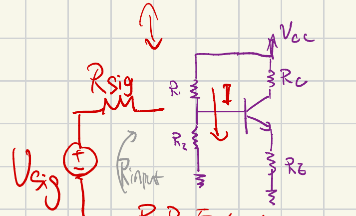
$I = \frac{V_{cc}}{3R}$

很大

$I \gg 0.01 I_E$

$I = 0.1 I_E$ or $1 I_E$

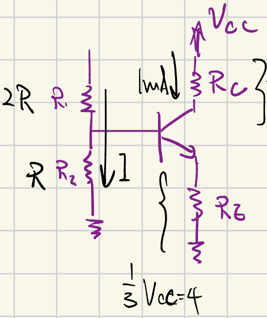
⇕

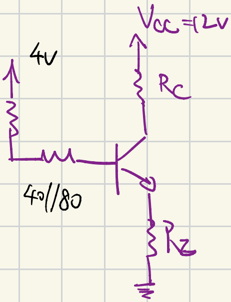


R_1, R_2 需够大

才能让分压进入电路

($I\downarrow, R\uparrow$)





Bias by R_E, V_{BB}, R_B

Design to have $I_E = 1mA$

for $V_{CC}=12V$, $\beta=100$

(sol)

$R_C = \frac{4}{1} = 4k\Omega$

$R_E = \frac{4-0.7}{1mA} = 3.3k\Omega$

neglect I_B:

$4 = \frac{R_2}{R_1+R_2}\cdot 12$, $I = \frac{12}{3R} = 0.1 I_E \Rightarrow R = 40k\Omega$

let $I = 0.1 I_E$ (if $I=1$, $I_E = 4k, 8k$)

Consider $I_B \neq 0$

$$I_E = \frac{4-0.7}{3.3k + \frac{40//80}{1+\beta}} = 0.93mA \rightarrow 1mA$$

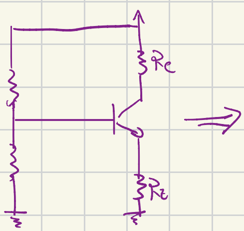
go 3k

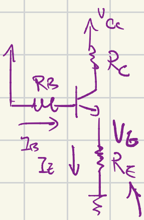
电流换算

② 偏压电路

Biasing in BJT amplifier

$(I_E = (1+\beta) I_B)$





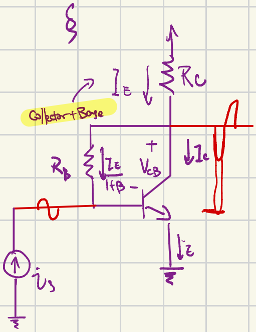
$[\beta\uparrow \Rightarrow I_E\uparrow \Rightarrow V_E\uparrow \Rightarrow V_{BE}\downarrow \Rightarrow I_E\downarrow]$ $I_C\downarrow$

Provide dc biasing stability

偏压稳定性

$I_E = \frac{V_{BB}}{R_E}$

§

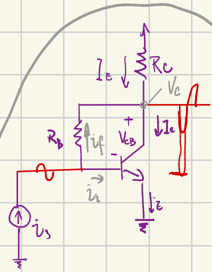


$I_E = \frac{V_{cc}-V_{BE}}{R_C + \frac{R_B}{1+\beta}}$

V_{BE}, β dep on BJT

If $R_C \gg \frac{R_B}{1+\beta} \Rightarrow I_E = \frac{V_{cc}}{R_C}$ indep of BJT

R_B不能太小 ∵ $V_{CB}\downarrow = I_B R_B\downarrow \Rightarrow$ Output Voltage Swing $\downarrow$



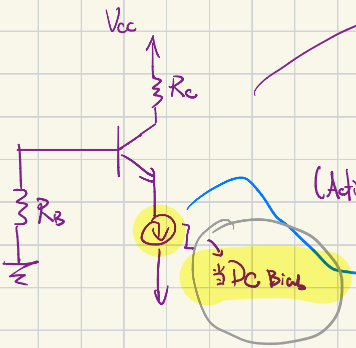
$\beta\uparrow \Rightarrow I_C\uparrow (I_E\downarrow) \Rightarrow V_C\downarrow \Rightarrow i_i\downarrow \Rightarrow I_E\downarrow$

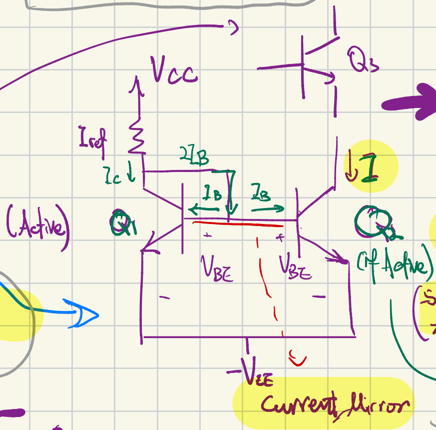
$(i_f\uparrow)$

(Tips: R_B不能过大OR过小)

个电压 **Bias by Current Source**

§ Biasing Using a current Source





$I_{ref} = \frac{V_{cc} - V_{BE} - (-V_{EE})}{R}$

if $V_{cc} + V_{EE} \gg V_{BE}$

$I_{ref} = \frac{V_{cc} + V_{EE}}{R}$

(与电晶体无关) indep of BJT

$Q_1 = Q_2$ Perfect matched

很 stable

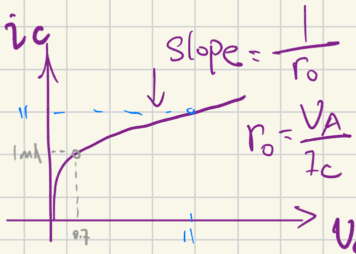
$\therefore I_{ref} = I_c + 2I_B$

$= I_c + 2\frac{I_c}{\beta} \Rightarrow I\left(1 + \frac{2}{\beta}\right) \approx I_c = I$

①

$\because V_{BE}$相等(Q_1 & Q_2), β一样 $\therefore I_c$就会一样

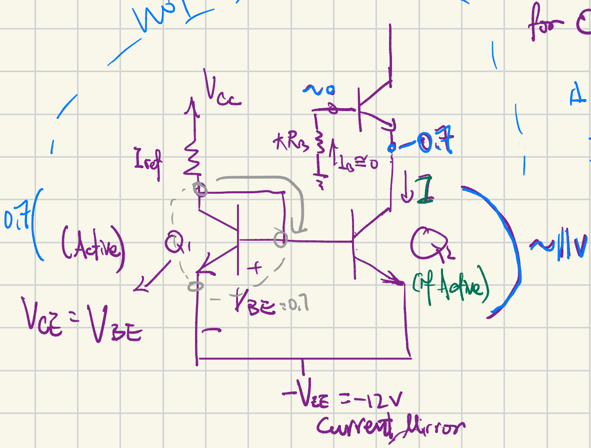
$$\frac{I}{I_{ref}} = \frac{1}{1 + 2/\beta}, \text{ if } \beta \gg 2 \Rightarrow I \doteq I_{ref}$$



$r_o = \frac{V_A}{I_C}$

电晶体一定会有Early Effect

not same Anymore



for Q_1, $V_{CE} = V_{BE}$

$\Delta I = \frac{11 - 0.7}{r_o}$ ← 电压 slope

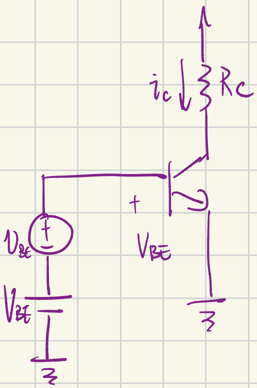
$I = I_{ref} + \Delta I$ ← (considering Early Effect)

① $I_c = I_s e^{V_{BE}/V_T}$

$\therefore V_{BE}$一样(BJT一样)

§ 5.6 Small-signal operation & models

π mode CE



amplification (Active)

V_{BE}可很小

$$i_C = I_S e^{v_{BE}/V_T} = I_S e^{(V_{BE}+v_{be})/V_T} = \underbrace{I_S e^{V_{BE}/V_T}}_{I_C\ (\text{DC信号})} e^{v_{be}/V_T}$$

$$= I_C\left(1+\frac{v_{be}}{V_T}\right) \quad \text{small signal Approximation.}$$

$v_{be} \ll V_T$ ($v_{be} \lesssim 10mV$)

$$= \underbrace{I_C}_{DC} + \underbrace{\underbrace{\left(\frac{I_C}{V_T}\right)}_{\text{放大倍数}} v_{be}}_{i_c\ (AC)} \rightarrow \therefore\ i_c = g_m v_{be}$$

$$g_m \equiv \frac{I_C}{V_T}$$

(transconductance)

AC信号放大决定于

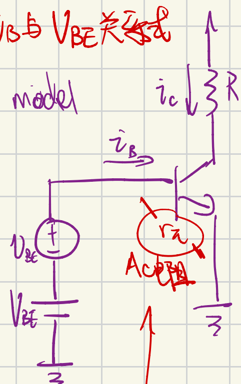
($\because$ 为model, $\therefore$ V_{BE}可不加Resistor)

Eg. for $I_C = 1mA$, $g_m = 40\ mA/V$ (电流放大大) 大
(much larger than MosFet)

However. In Practical, we have Consider R (信号源一般都会配有电阻)

求i_B与V_{BE}关系式

π model



一般都有input端电阻

①

$$i_B = \frac{i_C}{\beta} = \frac{1}{\beta}(I_C + i_c) = \underbrace{\frac{I_C}{\beta}}_{I_B} + \underbrace{\frac{g_m}{\beta} v_{be}}_{i_b}$$

$$i_b = \frac{g_m}{\beta} v_{be}$$

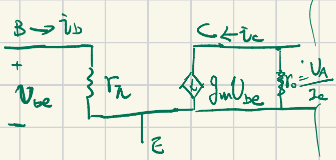
input 端电阻电流

$$\boxed{\text{Define}: r_\pi \equiv \frac{v_{be}}{i_b} = \frac{\beta}{g_m}}$$

(Ac 电阻)

$$r_\pi = \frac{\beta}{\frac{I_C}{V_T}} = \frac{V_T}{\left(\frac{I_C}{\beta}\right)} = \frac{V_T}{I_B}$$

② hybrid-π model (small signal)
(适合小信号 model)

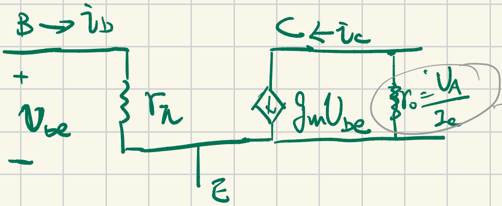


π-model

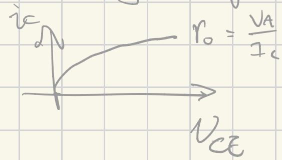
② hybrid-π model (small signal) 大信号无 model

只有小信号有model

Input 端在 i_B，求 i_B current



consider Early Voltage



§ T-model

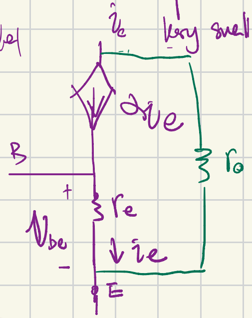
input 端在 i_E，求 i_E current。

$$i_e = i_c + i_b = g_m v_{be} + \frac{v_{be}}{r_\pi} = \left(g_m + \frac{1}{r_\pi}\right) v_{be}$$

Define: $$\left[\, r_e = \frac{v_{be}}{i_e} = \frac{1}{g_m + \frac{1}{r_\pi}} = \frac{r_\pi}{1 + \underbrace{g_m r_\pi}_{\beta}} = \frac{r_\pi}{1+\beta} = \frac{V_t}{(1+\beta) I_B} = \boxed{\frac{V_t}{I_E}} \,\right]$$

r_e ← very small

T-model



$$g_m = \frac{\beta}{r_\pi}$$

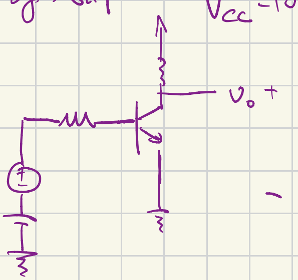
$$r_e = \frac{V_t}{I_E}$$

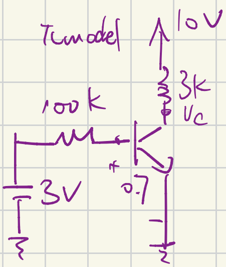
$$r_\pi = \frac{V_t}{I_B}$$

---

§ Eg. 5.14

$V_{CC} = 10V$ $\beta = 100$ find v_o / v_i





$$I_B = \frac{3 - 0.7}{100} = 0.023mA$$

$$I_C = \beta I_B = 2.3mA$$

$$V_C = 10 - 2.3 \times 3 = 3.1V$$

C-BJ reverse bias → Active

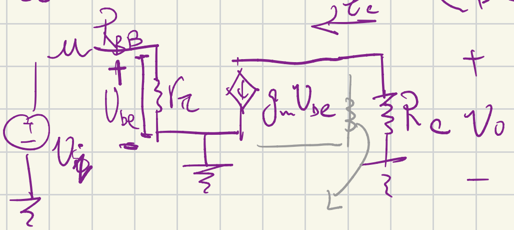
$g_m = \frac{I_C}{V_t} = \frac{2.3}{0.025} = 92\ mA/V$

$g_m = i_C$ 对 v_{BE} 微分

$r_\pi = \frac{\beta}{g_m} = \frac{100}{92} = 1.09\ k\Omega$

Ac Signal:

(Dc 电压源接地)



$v_o = -i_c R_c = -g_m v_{be} R_c$

$v_{be} = v_i \cdot \frac{r_\pi}{R_{BB}+r_\pi}$

若有 r_o

$r_o = \frac{V_A}{I_C} = \frac{230V}{2.3mA}$

Answer: $\frac{v_o}{v_i} = -\frac{r_\pi}{R_{BB}+r_\pi} \cdot g_m R_c$

$= -3.04\ V/V$ (放大)

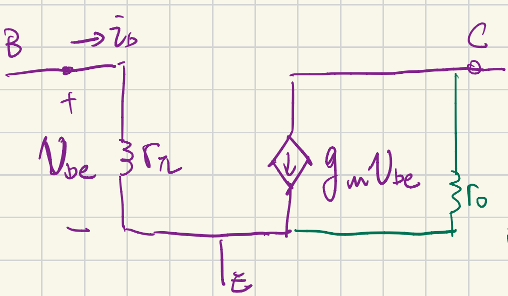
比较小：R_{BB} 太大，r_π 太小有，增益被吃掉了

---

③

§ Small-signal Model

π-model



$i_C = I_S e^{v_{BE}/V_t}$

$g_m = \left.\frac{\partial i_C}{\partial v_{BE}}\right|_{I_C} = \frac{I_C}{V_t} \Rightarrow i_c = g_m v_{be}$

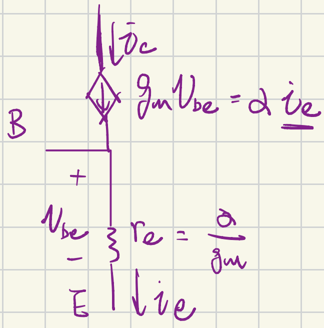
$r_\pi = \frac{V_t}{I_B}$

若 keep $r_o = \frac{V_A}{I_C}$

在此 AC model 中，虽然 AC current 方向会不同

但，在此只假设一个方向

T model



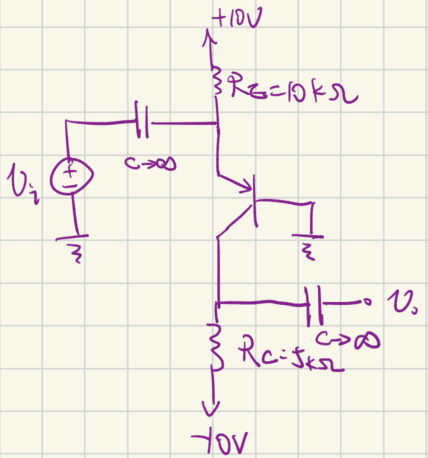
$$r_e = \frac{r_\pi}{1+\beta} = \frac{V_T}{I_E}$$

$$g_m v_{be} = \alpha \frac{v_{be}}{r_e} \Rightarrow \frac{1}{g_m} = \frac{r_e}{\alpha}$$

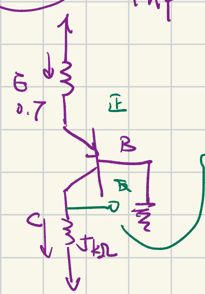
$$r_e = \frac{\alpha}{g_m}$$

Eg. 5.16

$\alpha = 0.99 \quad \beta = 100$



DC:



$I_E = \frac{10-0.7}{10} = 0.93\,mA$

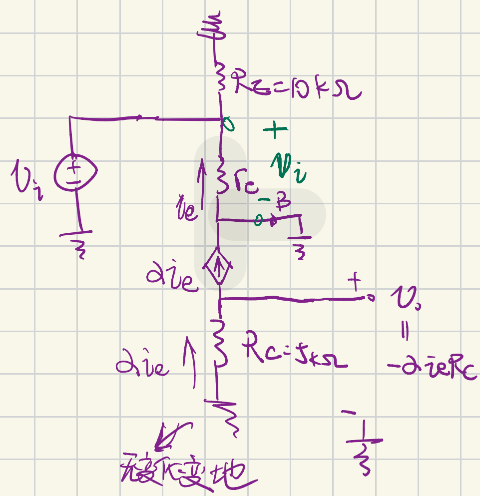
$I_C = 0.92\,mA$

$\rightarrow 0.92 \times 5 - 10 = -5.4\,V$

$0 > 0.54\,V \rightarrow$ active

求AC:

$$r_e = \frac{V_T}{I_E} = \frac{25mV}{0.93mA} = 27$$



$$i_e = -\frac{v_i}{r_e}$$

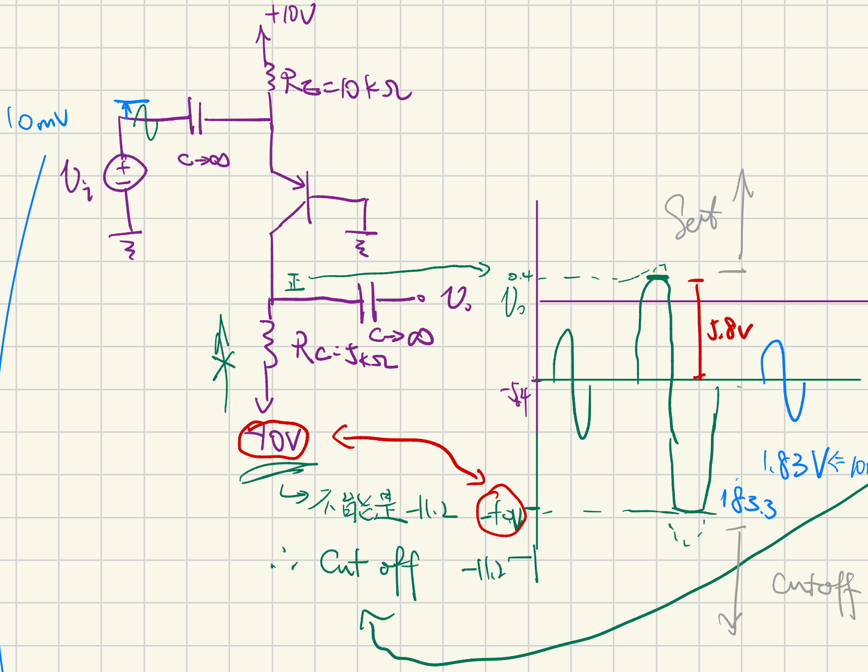
$$v_o = -\alpha\left(-\frac{v_i}{r_e}\right)R_C$$

$$\frac{v_o}{v_i} = \alpha\frac{R_C}{r_e} = 183.3$$

找到 v_i, v_o 等式

$I_{Collect}$ 与 $I_{Emitter}$ 方向一致

Small Signal Approximation



$\frac{5.4+0.4}{2}$

positive swing = 5.8V

negative swing = −11.2V

Cut off = 4.6

$$i_c = I_s e^{(V_{BE}+v_{be})/V_t} = I_s e^{V_{BE}/V_t} e^{v_{be}/V_t} \cong I_c \left(1+\frac{v_{be}}{V_t}\right)$$

[illegible]1，2次方拿掉

$i_c = \left(\frac{I_c}{V_t}\right) v_{be}$ linear

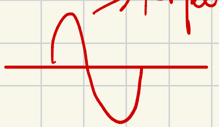
Small Signal Approximation

$v_{be} \ll V_t$

$v_{be} \leq 10mV$

Consider the linearity

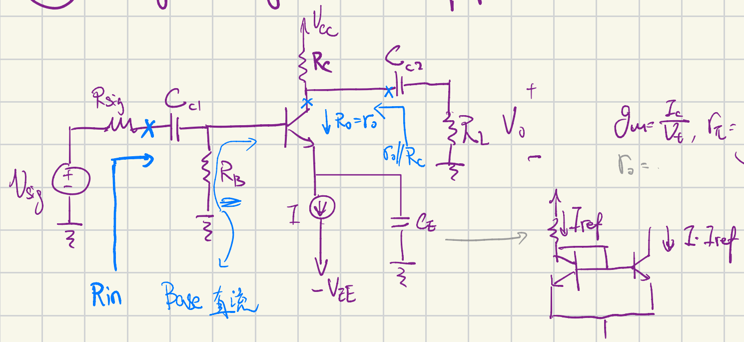
>10mV small signal not linear



→ Perfect Sin/cos

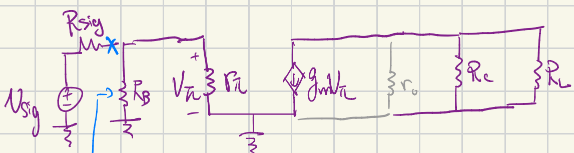
(44) Single-stage BJT amplifiers

AC signal + DC



$g_m = \frac{I_C}{V_t}$, $r_\pi = \frac{\beta}{g_m} = \frac{V_t}{I_B}$

$r_o =$

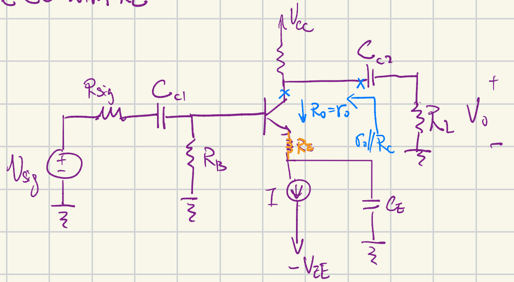


$R_{in} = R_B // r_\pi$

$V_o = -g_m V_\pi (r_o // R_C // R_L)$

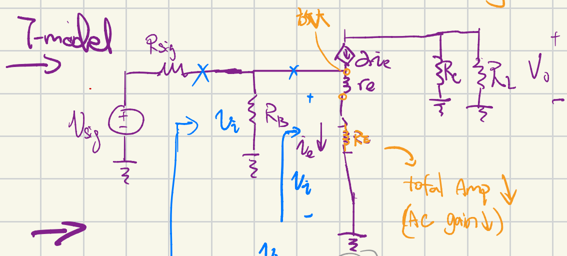
$V_\pi = V_{sig} \frac{R_{in}}{R_{sig}+R_{in}}$

the CE with RE



R_E → 增加直流偏压稳定性 (provides a dC biasing stability)

T-model →



total Amp ↓ (AC gain ↓)

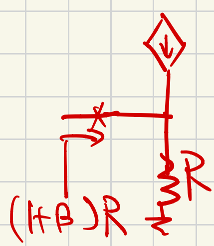
R_{in} $\frac{v_i}{i_b} = \frac{i_e(r_e+R_E)}{i_b} = (1+\beta)(r_e+R_E)$

$R_{in} = R_B // (1+\beta)(r_e+R_E)$

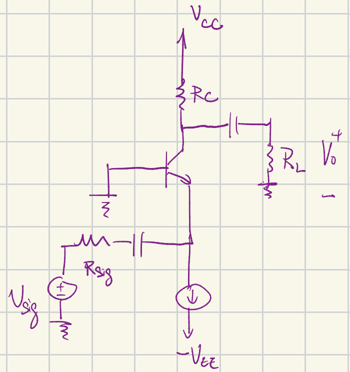
$V_o = -\alpha\, i_e (R_C // R_L)$

$i_e = \frac{v_i}{r_e+R_E}$ ← $v_i = V_{sig}\frac{R_{in}}{R_{sig}+R_{in}}$

$$\Rightarrow \underbrace{\frac{V_o}{V_{sig}}}_{\text{total Amplifier}} = -\alpha \frac{(R_C//R_L)}{r_e+R_E}\cdot\frac{R_{in}}{R_{sig}+R_{in}}$$

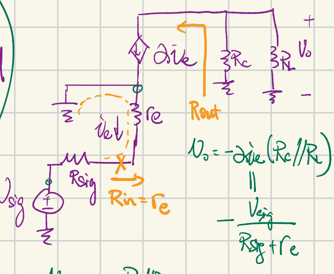


§ the CB



T-model ⟹

neglect r_o



$$v_o = -\alpha i_e (R_C // R_L)$$
$$\qquad \| $$
$$-\frac{V_{sig}}{R_{sig}+r_e}$$

$\because r_e = \frac{r_\pi}{1+\beta} = \frac{V_t}{I_E}$

$r_\pi = \frac{V_t}{I_B} \sim$ K ~ 10K

$$\frac{v_o}{v_{sig}} = \alpha \frac{R_C // R_L}{R_{sig}+r_e}$$

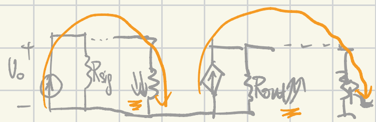
$R_C // R_L$ → output resistance

$R_{sig}+r_e$ → input resistance

$\therefore R_{in} = r_e$ ↓ very small

R_{out} ↑↑ very big

从Current 角度看, unity-gain current Amplifier



{ — 与 R_{sig} & R_{out} 无关 (Perfect current Amplifier)

low input resistance

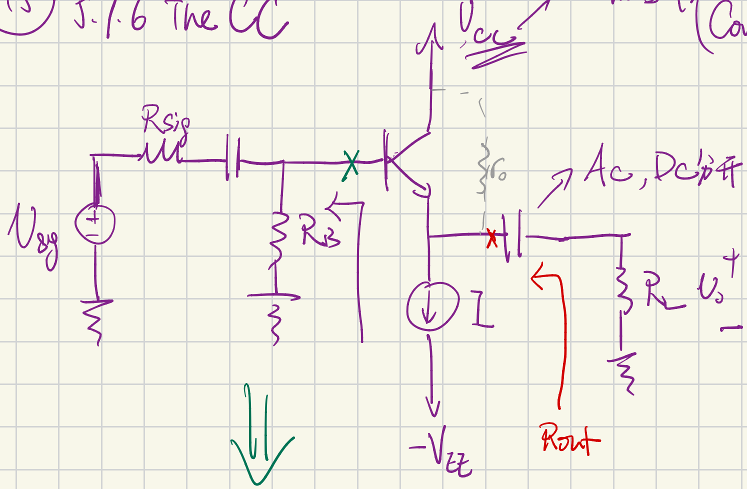
high output resistance

(45) 5.7.6 The CC (Common Collector)

B → E
in out

V_{CC} → AC 信号中为地

Ac, Dc 分开



T-model

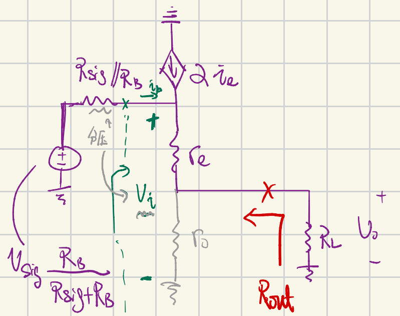
Emitter follower

relatively high input resistance

(voltage gain ≈ 1)

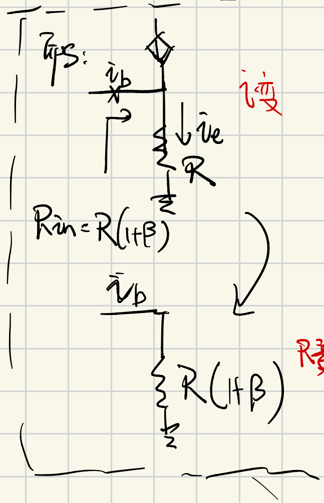
$$V_o = V_i \frac{(r_o // R_L)}{r_e + (r_o // R_L)} \cong V_i$$

$\frac{V_t}{I_E} \Rightarrow$ very small



$$R_{in} = \frac{V_{in}}{i_b} = \frac{V_{in}}{i_e}(1+\beta)$$

$$= (r_e + (r_o // R_L))(1+\beta)$$



$$V_i = V_{sig} \frac{R_B}{R_{sig}+R_B} \cdot \frac{(1+\beta)(r_e + r_o // R_L)}{(R_{sig}//R_B) + (1+\beta)(r_e + r_o // R_L)}$$

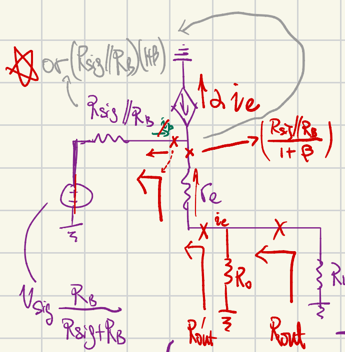
substitute V_o

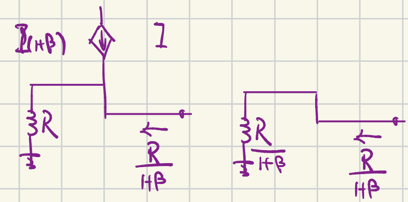
$$\therefore \frac{V_o}{V_{sig}} = \frac{R_B}{R_{sig}+R_B} \times \frac{(1+\beta)(r_o // R_L)}{(R_{sig}//R_B) + (1+\beta)(r_e + r_o // R_L)} \cong 1$$

$$= \frac{R_B}{R_{sig}+R_B} \times \frac{(r_o // R_L)}{\frac{(R_{sig}//R_B)}{1+\beta} + (r_e + r_o // R_L)} \cong 1$$

R_B可取很大 ≈ 1   small ≈ 1

V → → → V





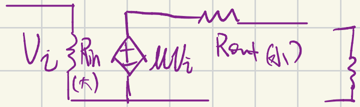
$$R_{out}' = \frac{R_{sig}//R_B}{1+\beta} + r_e$$

$$R_{out} = \left(\frac{R_{sig}//R_B}{1+\beta} + r_e\right) // r_o$$

very small

a very small output resistance

等效模型

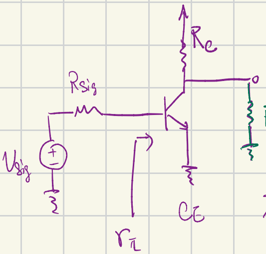


Perfect Voltage Amp (Ideal)

DC/AC 电压 导通

(信号源 & L 影响 输出)

$V_{in} \to V_{out}$



$V_o = -g_m R_c V_{be}$

$V_{be} = V_{sig} \dfrac{r_\pi}{R_{sig} + r_\pi}$

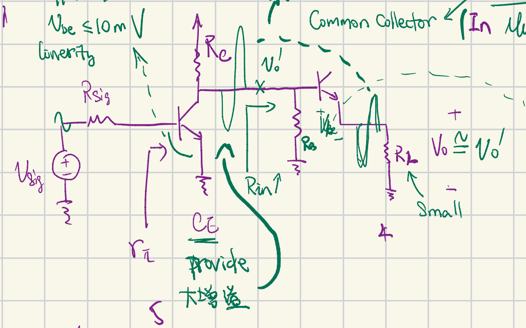
$\dfrac{V_o}{V_{sig}} = -g_m R_c \dfrac{r_\pi}{R_{sig}+r_\pi}$ (会受到 R_L 非常大)

$R_c \to (R_c \| R_L)$ small

Small-signal approximation
$V_{be} \leq 10\,mV$
Linearity

2 follow

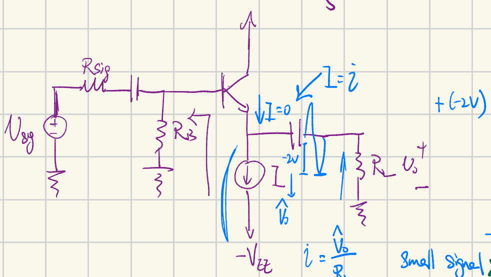
Common Collector ← (In Multiple stage) the last stage



$V_o \cong V_o'$

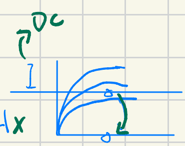
3 only small fraction of the input signal across V_{be}
⇒ linearity

分压, (大R 对小R)



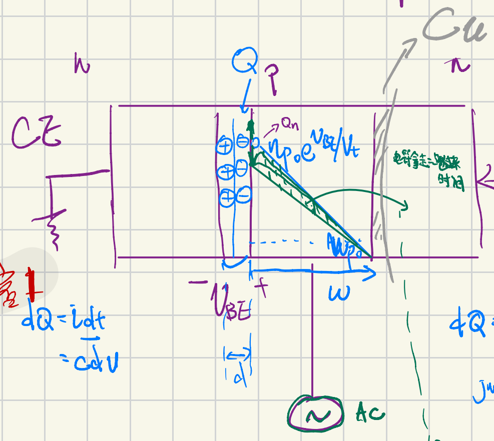
The peak output Voltage $\hat{V}_o = I R_L$

DC 被大 AC 电压影响



I < small signal ⇒ cut off

§ 5.8, The BJT Internal Capacitances of High-f Mode



$$i_c = AqD_n \frac{dn}{dx} = AqD_n \frac{n_{p0}e^{V_{BE}/V_t}}{W}$$

电容1

$dQ = i\,dt$

$= C\,dV$

Capacitance

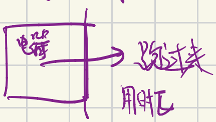
$$dQ = C_{je} \cdot dV_{BE}$$

junction CE

$$C_{je} = \frac{dQ}{dV_{BE}} = \frac{\epsilon_s}{d} \quad (需要时间)$$

Tips:

电流：电荷对时间的变化



∴ 电荷 ÷ τ = 电流

$Q \div \tau = I$

$$Q_n = A\frac{1}{2}q\,n_{p0}e^{V_{BE}/V_t}\,\frac{W^2}{W}\frac{D_n}{D_n}$$

$$= i_c\left(\underbrace{\frac{W^2}{2D_n}}_{\tau_{Forward}}\right)$$

电容2

$$dQ_n = \tau_F \cdot di_c = \tau_F\, g_m\, dV_{BE}$$

$\Downarrow$

$i_c = g_m V_{be}$

$$\Rightarrow C_{de} = \frac{dQ_n}{dV_{BE}} = \tau_F\, g_m$$

diffusion

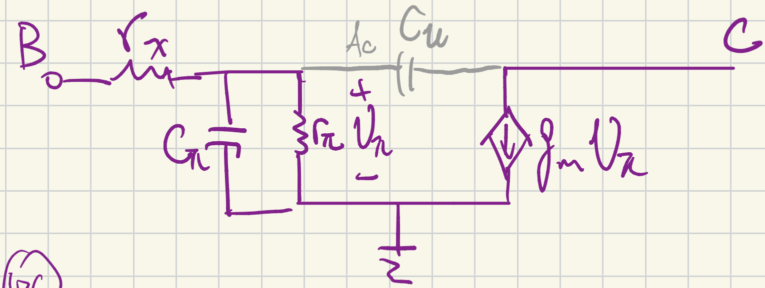
Total: $dQ = dQ + dQ_n$

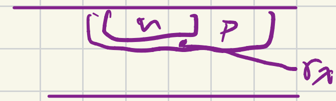
$$= C_{je} \cdot dV_{BE} + C_{de} \cdot dV_{BE}$$

$$= (C_{je} + C_{de}) \cdot dV_{BE}$$

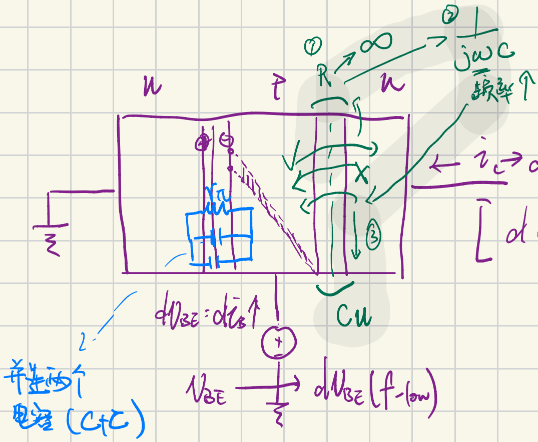
并联

Model





(46)



$i_c \to di_c = g_m dV_{BE}$

(total) $dQ = dQ + dQ_n$

$= \underline{(C_{je} + C_{de})} dV_{BE}$

$\| \; C_\pi$

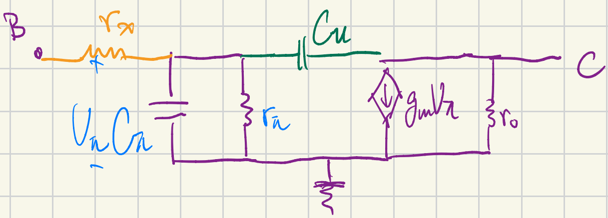
$\left[dQ = C_{je} \cdot dV_{BE}, \quad dQ_n = C_{de} \cdot dV_{BE} \right.$

$C_{je} = \frac{\varepsilon_s}{d}$

$C_{de} = g_m \tau_F$

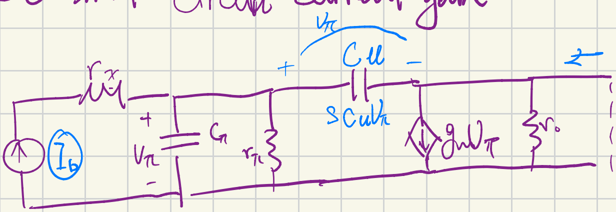
base transit time

$\tau_F = \frac{W}{2D_n} \sim pF$



§ A figure of merit

CE short-circuit current gain

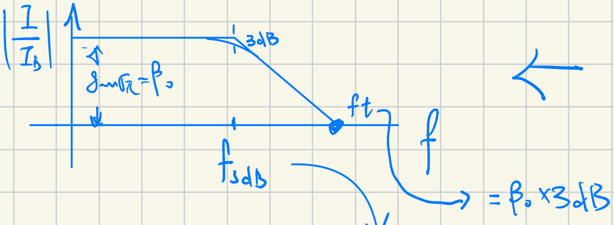


Assume $g_m \gg sC_\mu$

$I = g_m V_\pi - \underline{sC_\mu} \doteq g_m V_\pi$

ignore

$$\frac{I}{I_b} = \frac{g_m}{\frac{V_\pi}{r_\pi} + s(C_\pi + C_\mu) V_\pi}$$



$$= \frac{g_m r_\pi}{1 + s r_\pi (C_\pi + C_\mu)}$$

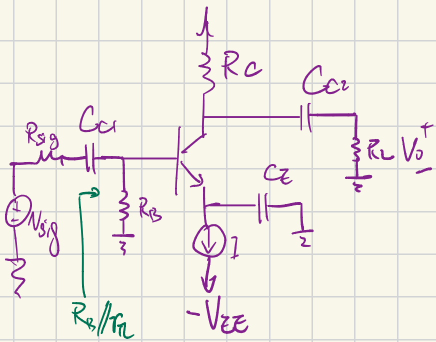
$s \to j\omega$

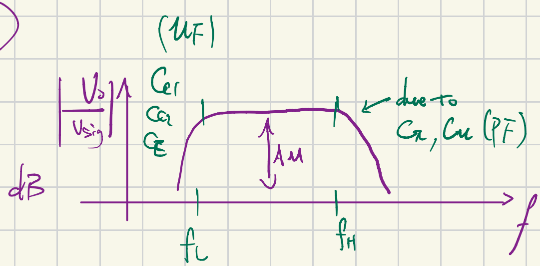
$$f_{3dB} = \frac{\omega_{3dB}}{2\pi} = \frac{1}{2\pi r_\pi (C_\pi + C_\mu)}, \quad f_t\,(增益=1时) = \frac{g_m r_\pi}{2\pi r_\pi (C_\pi + C_\mu)}$$

$$= \frac{g_m}{2\pi (C_\pi + C_\mu)}$$

Eg.

frequency response of the CE





$$A_M = -g_m (r_o // R_C // R_L) \times \frac{(R_B // r_\pi)}{R_{sig} + (R_B // r_\pi)}$$