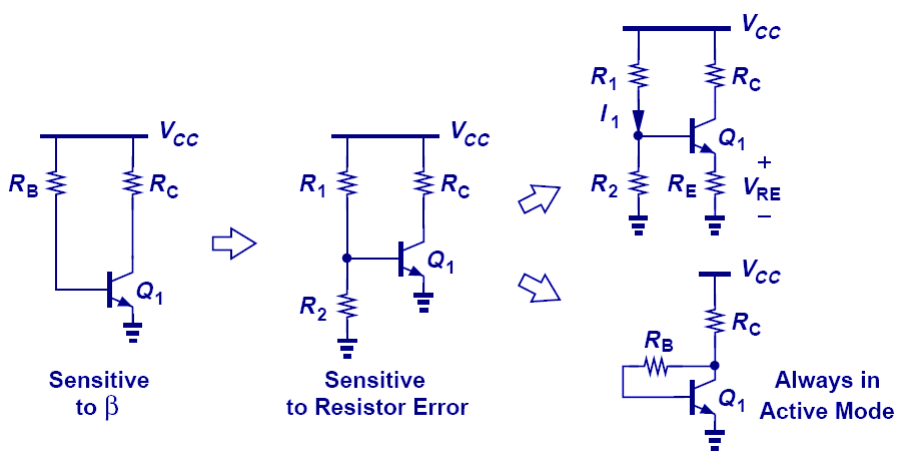
EE 530 Eletrônica Básica I

Transistores Bipolares
Amplificadores

Prof. Pedro Xavier

Resumo



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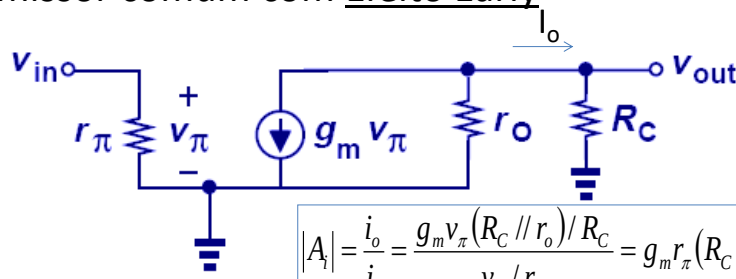
Amplificadores com o TBJ

- Emissor comum com Efeito Early



$$A_v = -g_m(R_C \parallel r_O)$$

$$R_{out} = R_C \parallel r_O$$

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

$$|A_i| = \frac{i_o}{i_i} = \frac{g_m v_\pi (R_C // r_o)/R_C}{v_\pi / r_\pi} = g_m r_\pi (R_C // r_o)/R_C$$

$$|A_i| = \beta \left(\frac{R_C r_o}{R_C + r_o} \right) \frac{1}{R_C}$$

$$|A_i| = \beta \left(\frac{r_o}{R_C + r_o} \right) \cong \beta$$

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Amplificadores com o TBJ

Passo a passo do processo de análise para pequenos sinais através dos modelos

1. Determina-se o Ponto de Operação P.O. cc (I_C).
2. Calcula-se os parâmetros de pequenos sinais $g_m = I_C/V_T$, $r_\pi = \beta/g_m$ e $r_e = V_T/I_E \cong 1/g_m$.
3. Substitui-se as fontes cc de tensão por um curto-circuito e as fontes cc de corrente por um circuito aberto.
4. Substitui-se o TBJ pelo modelo equivalente.
5. Analisa-se o circuito resultante para determinar as grandezas de interesse.

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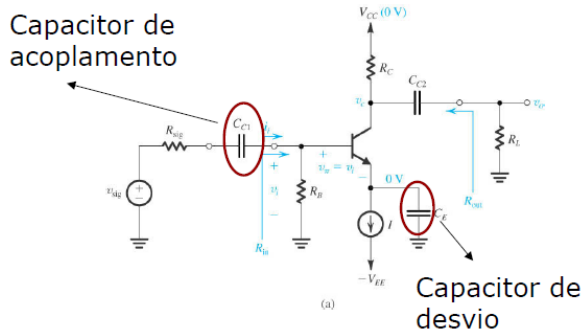
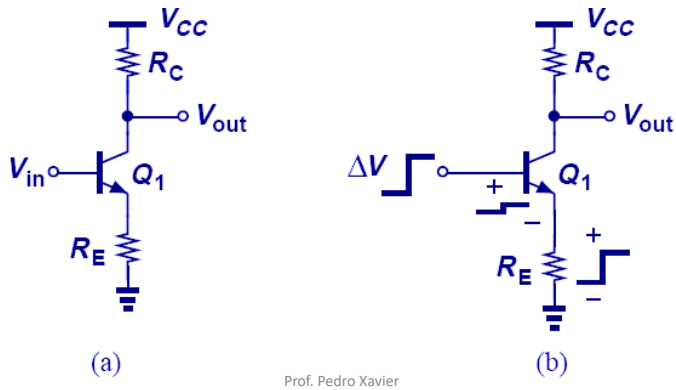
Amplificadores

- Neste curso, consideramos o capacitor como um curto circuito na análise de pequenos sinais.



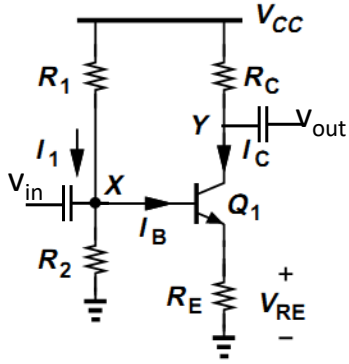
Amplificadores com o TBJ

- Emissor comum com degeneração de emissor
  - Menor ganho ($\Delta V_{BE} \neq \Delta V$)
  - Maior linearidade



Calcule A_v, R_{in} e R_{out}

- V_{CC}=10V; R_C=1 kΩ; R_1=10 kΩ; R_2=1 KΩ; β=100;
- I_S=10^{-6} A; V_T=25 mV; R_E=20 Ω



Ponto de operação determinado na aula passada:
I_C=3,3840 mA

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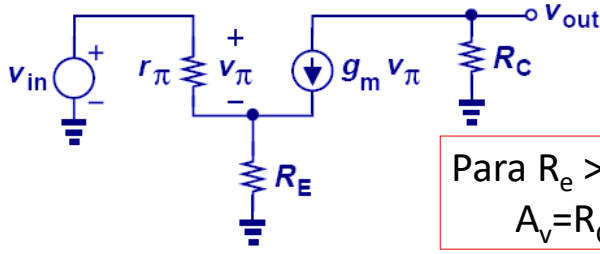
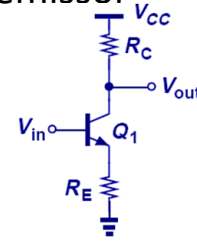
Amplificadores com o TBJ

- Emissor comum com degeneração de emissor





Para $R_e >> 1/g_m$:
A_v=R_C/R_E

$$v_{out} = -g_m v_\pi R_C$$

Linearização

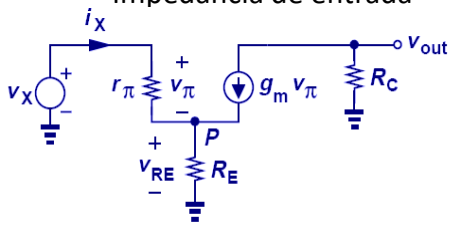
$$v_{in} = v_\pi + (g_m v_\pi + \frac{v_\pi}{r_\pi})R_E \Rightarrow v_{in} = v_\pi\left[1 + (g_m + \frac{1}{r_\pi})R_E\right]$$

$$A_v = \frac{v_{out}}{v_{in}} = -\frac{g_m R_C}{1 + g_m R_E} \Rightarrow A_v = -\frac{R_C}{\frac{1}{g_m} + R_E}$$

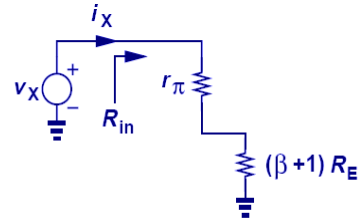
$$r_\pi = \beta/g_m \gg 1/g_m$$

Amplificadores com o TBJ

- Emissor comum com degeneração de emissor
  - Impedância de entrada



(a)



(b)

$$V_A = \infty$$

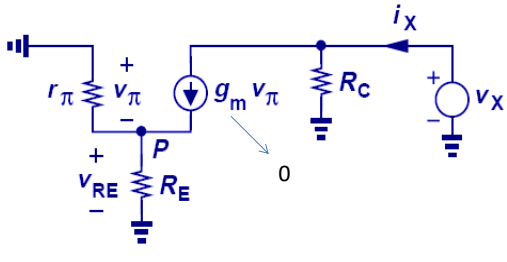
$$v_X = r_\pi i_X + R_E i_E$$

$$v_X = r_\pi i_X + R_E(1+\beta) i_X$$

$$R_{in} = \frac{v_X}{i_X} \Rightarrow \boxed{R_{in} = r_\pi + (\beta+1)R_E}$$

Amplificadores com o TBJ

- Emissor comum com degeneração de emissor



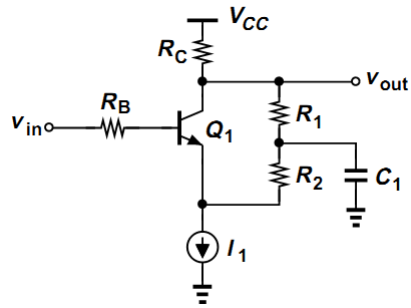
(a)

$$V_A = \infty$$

$$\boxed{R_{out} = \frac{v_X}{i_X} = R_C}$$

Exercício

- Assuma que C_1 é alto, despreze o efeito Early e calcule R_{in}, R_{out} e A_v



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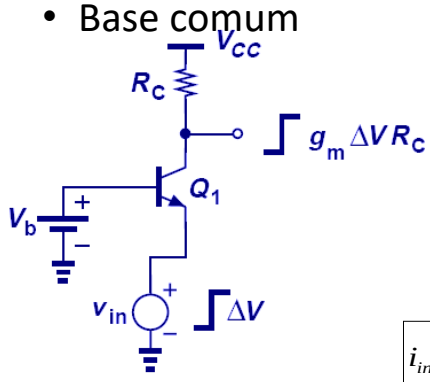
Amplificadores com o TBJ

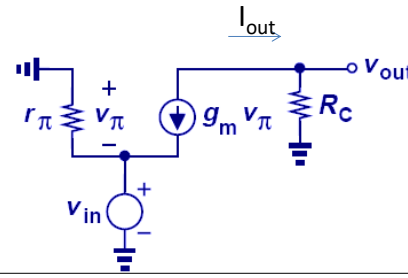
- Emissor comum com degeneração de emissor

Recalcular os ganhos e impedâncias considerando o efeito Early.

Amplificadores com o TBJ

- Base comum



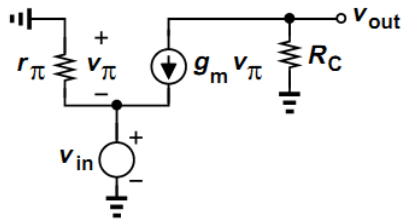


$$v_{in} = -v_\pi$$
$$v_{out} = -g_m v_\pi$$
$$A_v = g_m R_C$$

$$i_{in} = -i_e = -(\frac{v_\pi}{r_\pi} + g_m v_\pi) = -v_\pi(\frac{1}{r_\pi} + g_m)$$
$$i_{in} = -v_\pi(\frac{g_m}{\beta} + g_m) = -v_\pi g_m(\frac{1}{\beta} + 1)$$
$$i_{in} = -v_\pi g_m(\frac{\beta+1}{\beta}) | i_{out} = -g_m v_\pi$$
$$A_i = \alpha$$

Amplificadores com o TBJ

- Base comum
  - Impedância de entrada



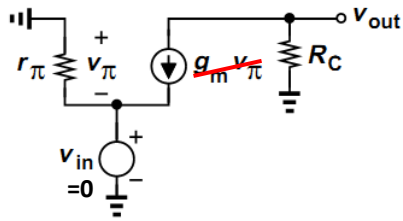
$$i_{in} = -v_\pi g_m(\frac{\beta+1}{\beta})$$

$$v_{in} = -v_\pi$$

$$R_{in} = \frac{\alpha}{g_m} \cong \frac{1}{g_m}$$

Amplificadores com o TBJ

- Base comum
  - Impedância de Saída



$$R_{out} = R_C$$

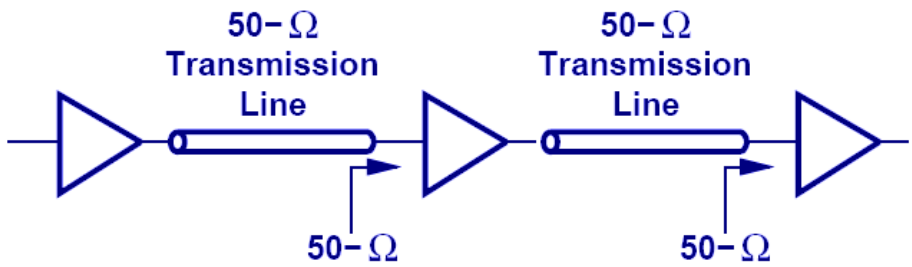
Com efeito Early

$$R_{out} = R_C \,//\, r_o$$

$$A_v = g_m R_C \,//\, r_o$$

Amplificadores com o TBJ

- Base comum
  - Utilizado para casamento de impedâncias



Exercício

- Projete um amplificador BC de forma que amplifique (ganho máximo) a saída de um termômetro (V_{term}=600mV, temperatura ambiente).

$$V_{CC} = 1.8\ \text{V}, I_C = 0.2\ \text{mA}, I_S = 5 \times 10^{-17}\ \text{A}, \text{and } \beta = 100$$

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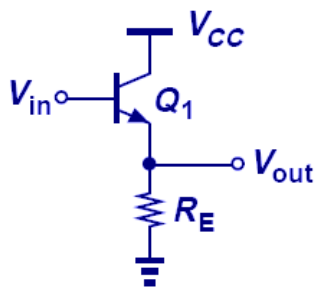
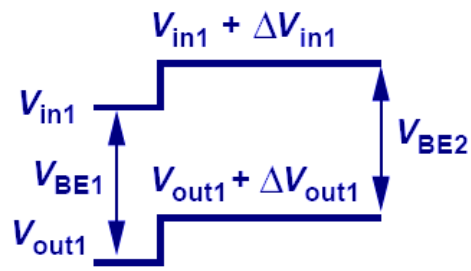
Amplificadores com o TBJ

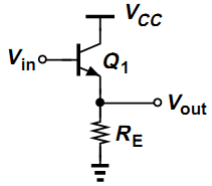
- Coletor comum (Seguidor de Emissor)

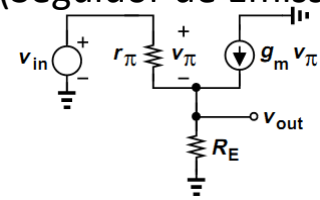




Amplificadores com o TBJ

- Coletor comum (Seguidor de Emissor)

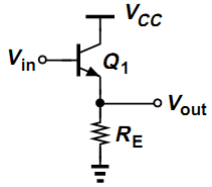


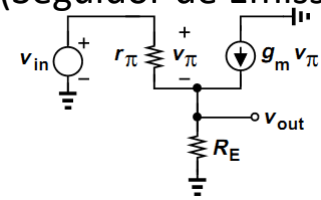


PARA CASA: Calcule A_v, R_{in} e R_{out}

Amplificadores com o TBJ

- Coletor comum (Seguidor de Emissor)





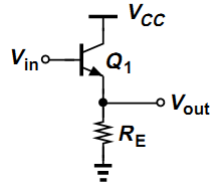
$$v_{out} = R_E\left(\frac{v_\pi}{r_\pi} + g_m v_\pi\right) = R_E v_\pi\left(\frac{1}{r_\pi} + g_m\right) = R_E v_\pi\left(\frac{1}{r_\pi} + \frac{\beta}{r_\pi}\right) \Rightarrow v_\pi = \frac{v_{out}}{R_E\left(\frac{1}{r_\pi} + \frac{\beta}{r_\pi}\right)}$$

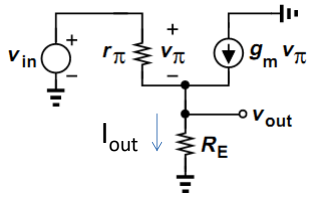
$$v_{in} = v_{out} + v_\pi = v_{out} + \frac{v_{out}}{R_E\left(\frac{1}{r_\pi} + \frac{\beta}{r_\pi}\right)} = v_{out}\left(1 + \frac{1}{\frac{R_E}{r_\pi}(1+\beta)}\right) = v_{out}\left(1 + \frac{r_\pi}{R_E(1+\beta)}\right)$$

$$\frac{v_{out}}{v_{in}} = \frac{1}{1 + \frac{r_\pi}{\beta+1}\cdot\frac{1}{R_E}} = \frac{1}{\frac{(\beta+1)R_E + r_\pi}{(\beta+1)R_E}} = \frac{(\beta+1)R_E}{(\beta+1)R_E + \frac{\beta}{g_m}} \Rightarrow \boxed{\frac{v_{out}}{v_{in}} \approx \frac{R_E}{R_E + \frac{1}{g_m}}}$$

Amplificadores com o TBJ

- Coletor comum (Seguidor de Emissor)





$$i_{out} = \frac{v_\pi}{r_\pi} + g_m v_\pi = v_\pi\left(\frac{1}{r_\pi} + g_m\right)$$

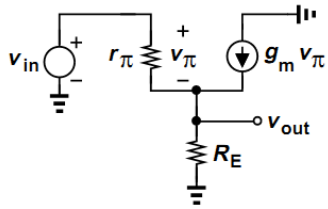
$$i_{in} = \frac{v_\pi}{r_\pi}$$

$$\frac{i_{out}}{i_{in}} = \frac{v_\pi\left(\frac{1}{r_\pi} + g_m\right)}{\frac{v_\pi}{r_\pi}} = r_\pi\left(\frac{1}{r_\pi} + g_m\right) = 1 + \frac{g_m}{r_\pi}$$

$$\frac{i_{out}}{i_{in}} = 1 + \frac{\beta / r_\pi}{r_\pi} \Rightarrow \boxed{\frac{i_{out}}{i_{in}} = 1 + \beta}$$

Amplificadores com o TBJ

- Coletor comum (Seguidor de Emissor)
  - Impedância de entrada



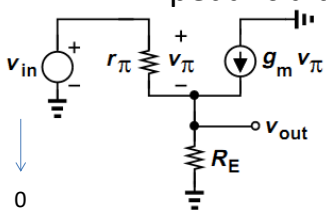
$$v_{in} = v_\pi + R_E(i_{in} + g_m v_\pi) = r_\pi i_{in} + R_E(i_{in} + g_m r_\pi i_{in})$$

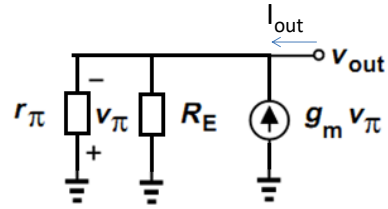
$$v_{in} = r_\pi i_{in} + R_E i_{in}(1 + g_m r_\pi) = i_{in}\left[r_\pi + R_E(1 + g_m r_\pi)\right]$$

$$\boxed{R_{in} = \frac{v_{in}}{i_{in}} = r_\pi + R_E(1 + \beta)}$$

Amplificadores com o TBJ

- Coletor comum (Seguidor de Emissor)
  - Impedância de saída





$$i_{out} = \frac{v_{out}}{R_E // r_\pi} - g_m v_\pi = \frac{v_{out}}{R_E // r_\pi} + g_m v_{out} = v_{out}\left(\frac{1}{R_E // r_\pi} + g_m\right)$$

$$i_{out} = v_{out}\left(\frac{R_E + r_\pi}{R_E r_\pi} + \frac{\beta}{r_\pi}\right) = v_{out}\left(\frac{R_E + r_\pi + \beta R_E}{R_E r_\pi}\right) = v_{out}\frac{R_E(\beta+1) + r_\pi}{R_E r_\pi}$$

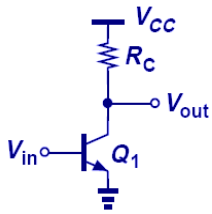
$$i_{out} \cong v_{out}\frac{R_E + r_\pi/\beta}{R_E r_\pi/\beta} \Rightarrow \boxed{\frac{v_{out}}{i_{out}} \cong R_E // \frac{r_\pi}{\beta} = R_E // \frac{1}{g_m}}$$

Amplificadores com o TBJ

- Coletor comum (Seguidor de Emissor)

Recalcular os ganhos e impedâncias considerando o efeito Early.

CE Stage



A_V:elevado
A_i :elevado
R_{in}: média
R_{out}: alta

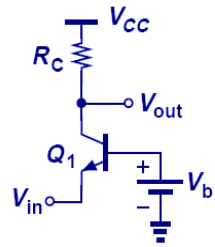
$$A_v = -g_m R_C$$

$$A_i = -\beta$$

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

$$R_{out} = R_C$$

CB Stage



A_V:elevado
A_i < 1
R_{in}: baixa
R_{out}: alta

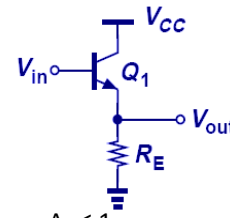
$$A_v = g_m R_C$$

$$A_i = \alpha$$

$$R_{in} \cong \frac{1}{g_m}$$

$$R_{out} = R_C$$

Follower



$A_V \leq 1$
A_i :elevado
R_{in}: muito alta
R_{out}: muito baixa

$$A_v \approx \frac{R_E}{R_E + \frac{1}{g_m}}$$

$$A_i = 1 + \beta$$

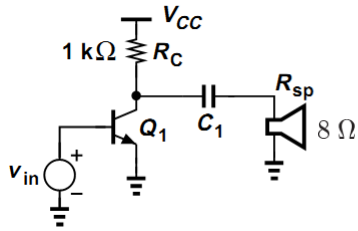
$$R_{in} = r_\pi + R_E(1+\beta)$$

$$R_{out} \cong R_E \,//\, \frac{1}{g_m}$$

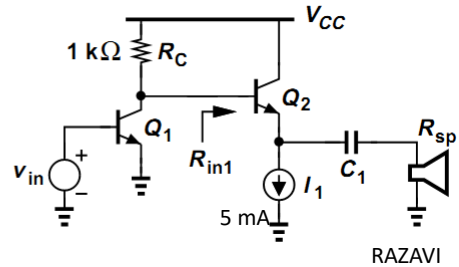
Exercício

- Determine o ganho

$\beta = 100, V_A = \infty$



A_V sem alto falante =20



RAZAVI

A_{V1} sem SEGUIDOR DE EMISSOR=20

Fontes de figuras da aula

- Aula do prof. Fabiano Fruett
- Introdução à física dos semicondutores (H.A. Mello)
- Fundamentos da microeletrônica (Razavi)
- Microeletrônica (Sedra)

Sugestão de estudo

- Razavi, Cap. 5
- Sedra/Smith cap. 4 seções 4.9 até 4.11 e 4.13 até 4.15

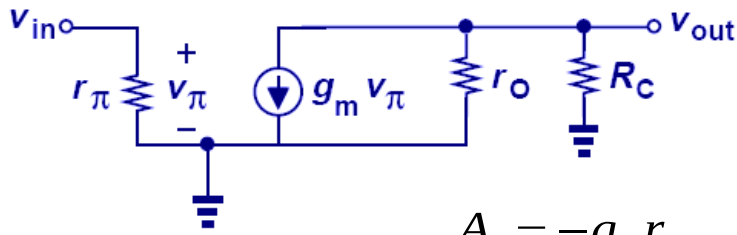
  Exercícios e problemas correspondentes

Para saber mais:

Paul R. Gray e Robert G. Meyer, Analysis and Design of Analog integrated Circuits, John Wiley & Sons

Amplificadores com o TBJ

- Emissor comum com Efeito Early
  - GANHO INTRÍNSECO (RC →∞)



$$A_v = -g_m r_O$$

$$|A_v| = \frac{V_A}{V_T}$$