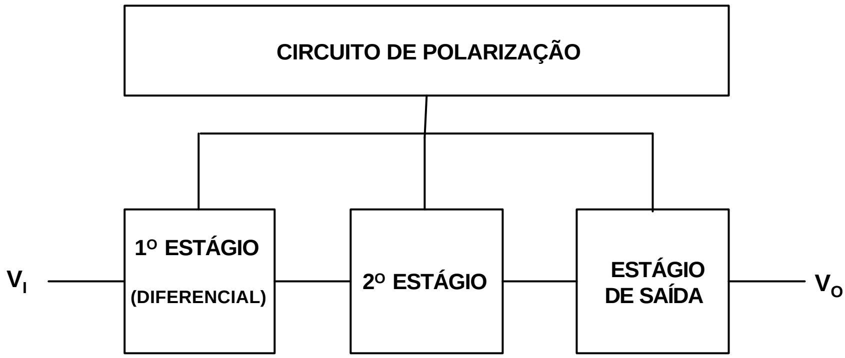
CAP. 1
AMPLIFICADORES DIFERENCIAIS E DE MÚLTIPLOS ESTÁGIOS

OBJETIVOS

- **Analisar a operação do amplificador diferencial**
- **Entender o significado de tensão de modo diferencial e de modo comum**
- **Determinar as características de pequenos sinais do amplificador diferencial**
- **Analisar e projetar amplificadores diferenciais com cargas ativas**
- **Analisar e projetar amplificadores com múltiplos estágios**

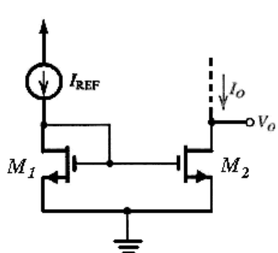
INTRODUÇÃO

DIAGRAMA EM BLOCOS



1.1 CIRCUITOS DE POLARIZAÇÃO

ESPELHO DE CORRENTE MOS



M_1 sempre saturado

$$I_{REF} = \frac{1}{2} k_n' \left(\frac{W}{L}\right)_1 (V_P - V_{SB})^2$$

M_2 saturado $(V_O \geq V_{GS} - V_t)$

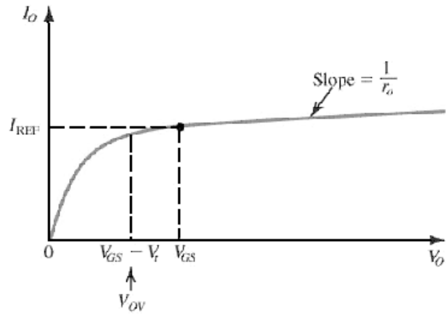
$$I_O = \frac{1}{2} k_n' \left(\frac{W}{L}\right)_2 (V_P - V_{SB})^2$$

$$\boxed{\frac{I_O}{I_{REF}} = \frac{(W/L)_2}{(W/L)_1}}$$

Efeito de V_O sobre I_O

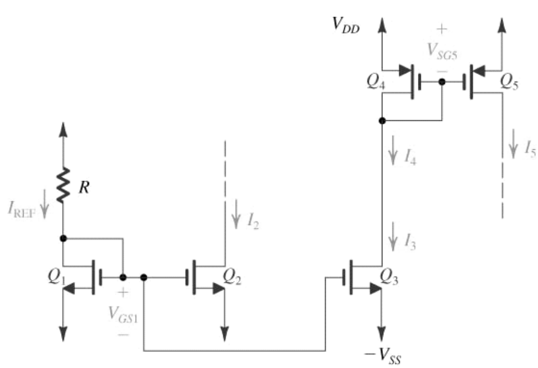
$$I_O = \frac{1}{2} k'_n \left(\frac{W}{L} \right)_2 \left(V_P - V_{SB} \right)^2 \left(1 + \frac{V_{DS_2}}{V_{A_2}} \right)$$

$$\boxed{\frac{I_O}{I_{REF}} = \frac{(W/L)_2}{(W/L)_1} \left(1 + \frac{V_O - V_{GS}}{V_{A_2}} \right)}$$

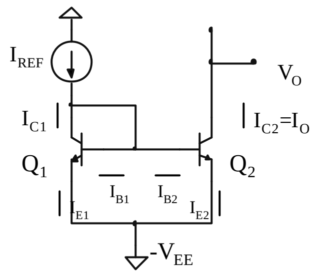


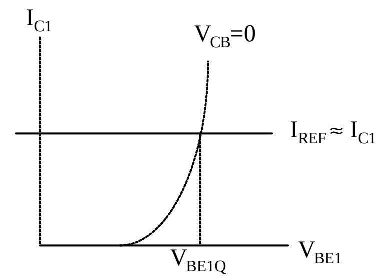
$$R_O = \frac{\Delta V_O}{\Delta I_O} = r_{o2} = \frac{V_{A2}}{I_O}$$

Circuito guia de corrente CMOS



ESPELHO DE CORRENTE COM TBJ





$Q_1 \equiv Q_2$

Q_2 na região ativa

Efeito Early desprezível

→ **$I_{C1} = I_{C2} = I_C$**

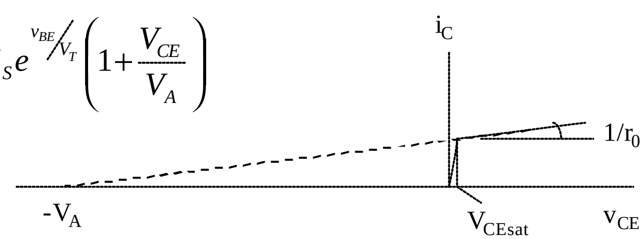
$I_{B1} = I_{B2} = I_B$

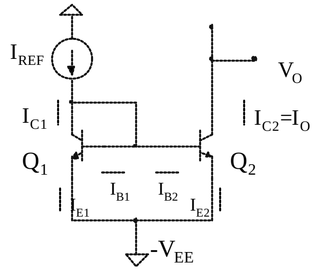
$$\frac{I_O}{I_{REF}} = \frac{1}{1+2/\beta} \quad \Rightarrow \quad \frac{I_O}{I_{REF}} \approx 1$$

Para β>>1

Considerando o efeito Early

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

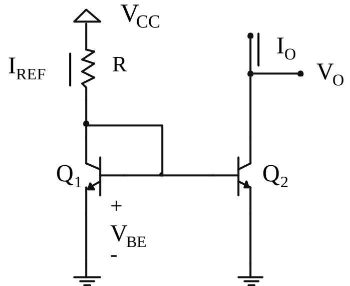




$$\frac{I_O}{I_{REF}} = \frac{1}{1+2/\beta} \times \frac{1+\dfrac{V_O+V_{EE}}{V_A}}{1+\dfrac{V_{BE}}{V_A}}$$

$$\frac{I_O}{I_{REF}} \approx \frac{1}{1+\dfrac{2}{\beta}} \times \left(1+\frac{V_O+V_{EE}-V_{BE}}{V_A}\right)$$

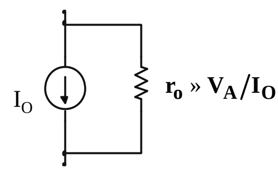
Uma fonte de corrente simples



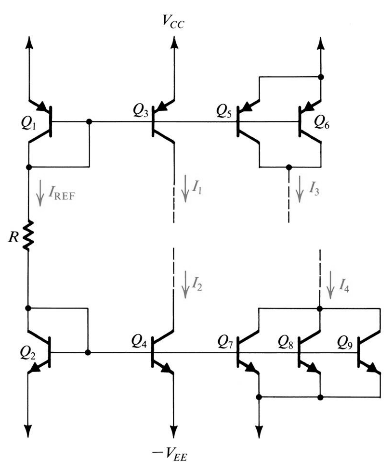
$$I_{REF} = \frac{V_{CC} - V_{BE}}{R}$$

$$I_O = \frac{1}{1+2/b} \cdot \left(1 + \frac{V_O - V_{BE}}{V_A}\right) \frac{V_{CC} - V_{BE}}{R}$$

Modelo equivalente CC,
válido para Q_2 na região ativa



Circuitos guias de corrente



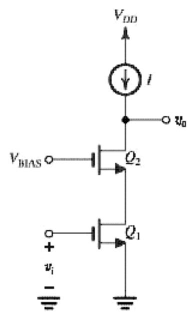
$$I_{REF} = \frac{V_{CC} + V_{EE} - V_{EB1} - V_{BE2}}{R}$$

Considerando todos os transistores idênticos e b **muito alto:**

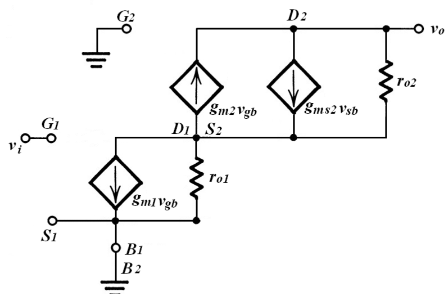
$$I_1 = I_2 = I_{REF}$$
$$I_3 = 2I_{REF}$$
$$I_4 = 3I_{REF}$$

1.2 AMPLIFICADOR CASCODE

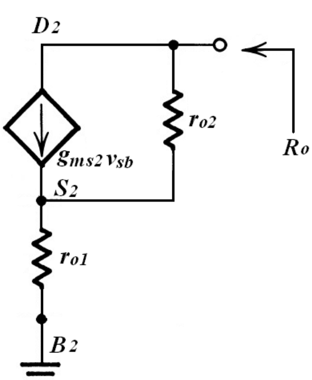
AMPLIFICADOR CASCODE MOS

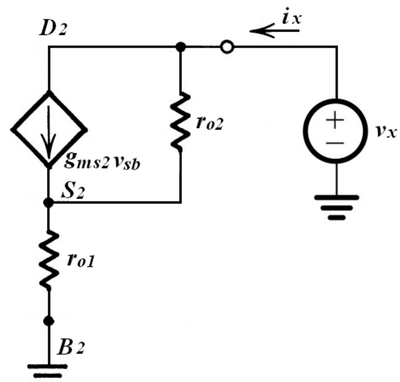


Modelo de pequenos sinais



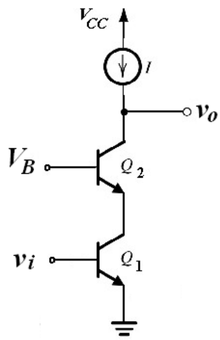
Modelo de pequenos sinais para determinação de R_o



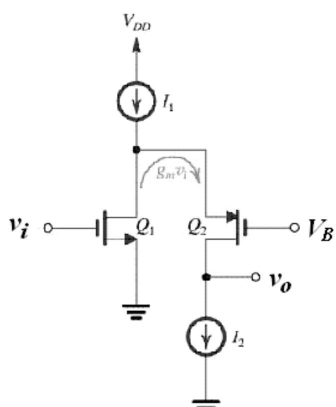


AMPLIFICADOR CASCODE TBJ

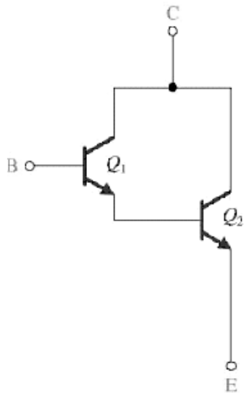
Ex.: Determinar a resistência de saída



AMPLIFICADOR "FOLDED" CASCODE

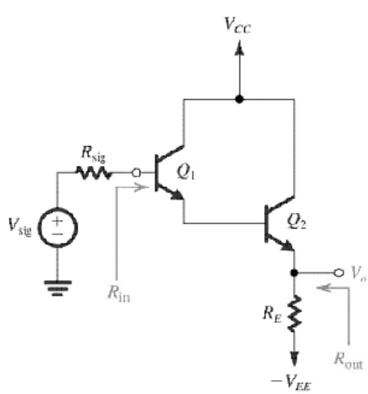


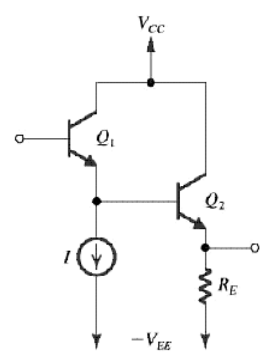
1.3 CONFIGURAÇÃO DARLINGTON



Mostre que $b_D = b_1 b_2$

Seguidor de tensão usando a Configuração Darlington

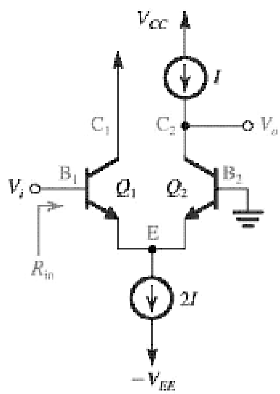




Fonte *I* para garantir b_1 *elevado*

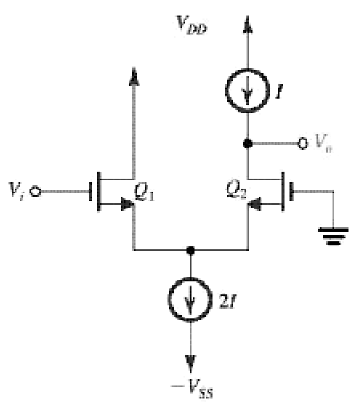
1.4 CONFIGURAÇÃO CC-BC e DC-GC

Coletor comum – base comum



Análise

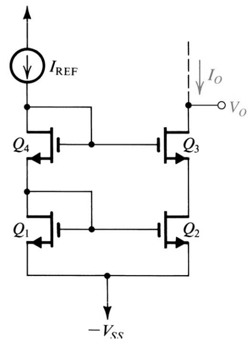
Dreno comum – porta comum



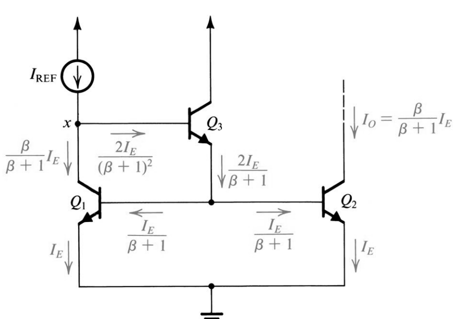
Análise

1.5 Circuitos Melhorados de Espelhos de Corrente

Espelho cascode MOS



Espelho de corrente com compensação da corrente de base



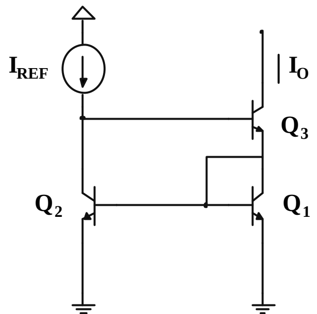
$$I_{REF} = \left(\frac{b}{b+1} + \frac{2}{(b+1)^2} \right) I_E$$

$$I_o = \frac{b}{b+1} I_E$$

$$\frac{I_O}{I_{REF}} = \frac{1}{1 + 2/\left(b^2 + b\right)}$$

$$\frac{I_O}{I_{REF}} \cong \frac{1}{1 + 2/b^2}$$

Espelho de corrente de Wilson



$$\frac{I_O}{I_{REF}} = \frac{1}{1+2/\left(b^2+2b\right)}$$

$$\frac{I_O}{I_{REF}} \cong \frac{1}{1+2/b^2}$$

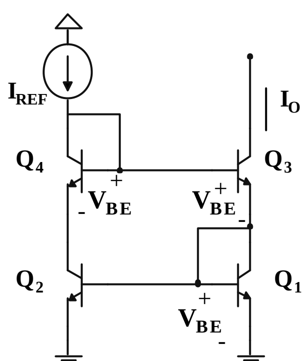
A vantagem deste espelho de corrente é sua maior resistência de saída R_O

$$R_O = b\,\frac{r_o}{2}$$

Problema: erro devido ao efeito Early

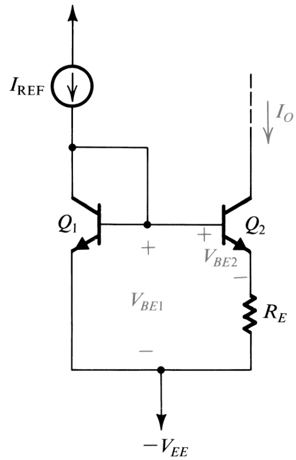
$$V_{CE1} = V_{BE}$$
$$V_{CE2} = 2V_{BE}$$

Espelho de corrente de Wilson melhorado



$$V_{CE1} = V_{CE2} = V_{BE}$$

Fonte de corrente de Widlar



$$V_{BE1} = V_{BE2} + R_E I_O$$

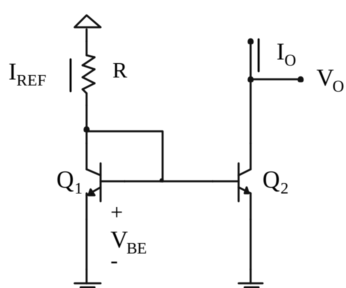
$$V_{BE1} = V_T \ln \frac{I_{REF}}{I_S}$$

$$V_{BE2} = V_T \ln \frac{I_O}{I_S}$$

$$R_2 I_O = V_T \ln \frac{I_{REF}}{I_O}$$

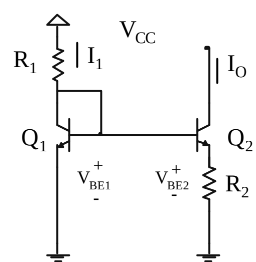
Exemplo: V_{CC}=10V; I_O=10mA

a) **Fonte de corrente simples**
Assumindo V_{BE}=0.6V



$$R = \frac{10 - 0.6}{10\mu A} = 940\,k\Omega$$

b) **Fonte de corrente de Widlar**
Escolhendo I_{REF}=1mA



$Q_1 \equiv Q_2$

$$\mathbf{R_1 \; @ \; \frac{10 - 0.7}{1} = 9.3KO}$$

$$\mathbf{R_2 = \frac{25mV}{10mA} \ln \frac{10^3}{10} = 11.5KO}$$

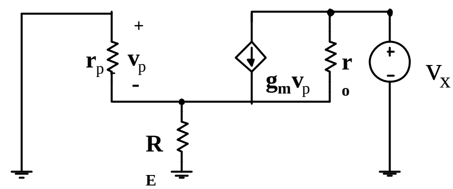
Resistência de saída da fonte de corrente de Widlar

$$v_x = -v_\pi - \left(g_m + \frac{1}{R'_E} \right) v_\pi r_o$$

$$i_x = g_m v_\pi - \left(g_m + \frac{1}{R'_E} \right) v_\pi$$

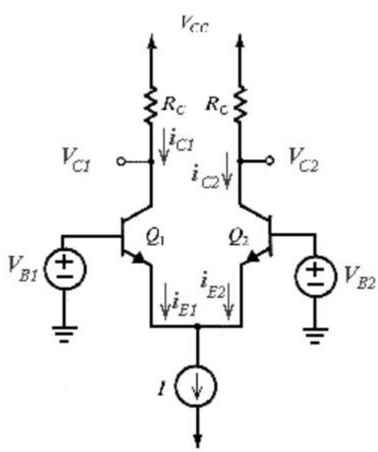
$$R_O \equiv \frac{v_x}{i_x} = \frac{\left(g_m + \frac{1}{R'_E} \right) r_o}{\frac{1}{R'_E}}$$

$$R_O = R'_E + \left(1 + g_m R'_E\right) r_o$$



$$R_O \cong (1 + g_m R'_E) r_o$$

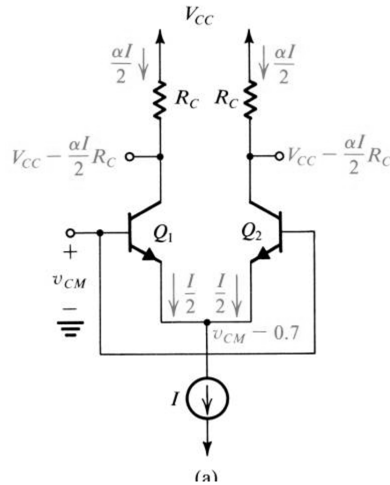
1.6 PAR DIFERENCIAL



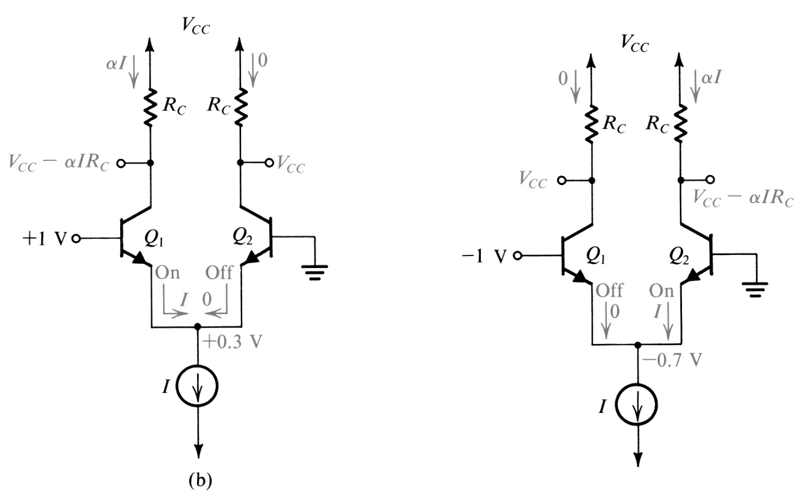
CONSIDERAÇÕES

- **Fonte de corrente ideal**
- **Transistores e resistores casados**
- **Transistores na região ativa**
- **Resistência de saída do TBJ infinita**

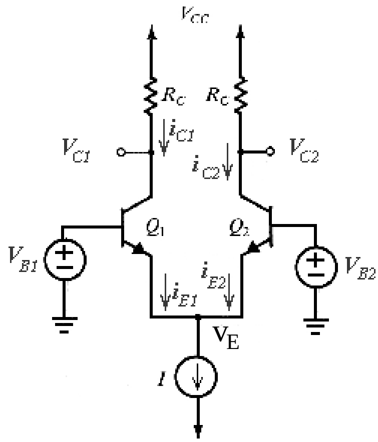
TENSÃO DE MODO COMUM



OPERAÇÃO COM GRANDES SINAIS



Análise de grandes sinais



$$i_{E1} = \frac{I_S}{a} e^{(v_{B1} - v_E)/V_T}$$

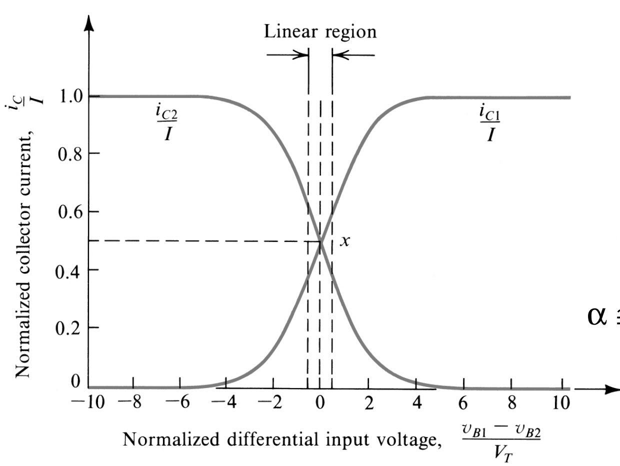
$$i_{E2} = \frac{I_S}{a} e^{(v_{B2} - v_E)/V_T}$$

$$I = i_{E1} + i_{E2} = \frac{I_S}{a} e^{-\frac{v_E}{V_T}} \left(e^{\frac{v_{B1}}{V_T}} + e^{\frac{v_{B2}}{V_T}} \right)$$

$$\frac{i_{E1}}{I} = \frac{1}{e^{(v_{B2} - v_{B1})/V_T}}$$

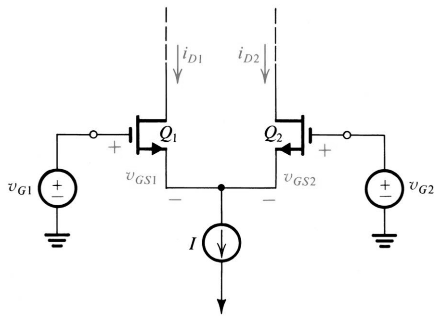
$$\frac{i_{E2}}{I} = \frac{1}{e^{(v_{B1} - v_{B2})/V_T}}$$

CARACTERÍSTICA DE TRANSFERÊNCIA



$\alpha \cong \mathbf{1}$

1.6.2 PAR DIFERENCIAL COM TRANSISTOR MOS



Q_1 º Q_2
Q_1 e Q_2 saturados
Fonte de corrente ideal
V_A ® ¥

$$v_{G1} - v_{G2} = v_{GS1} - v_{GS2} = v_{id} \quad (1)$$

$$i_{D1(2)} = \frac{1}{2} k_n' \frac{W}{L} \left(v_{GS1(2)} - V_t \right)^2 \quad (2)$$

$$i_{D1} + i_{D2} = I \quad (3)$$

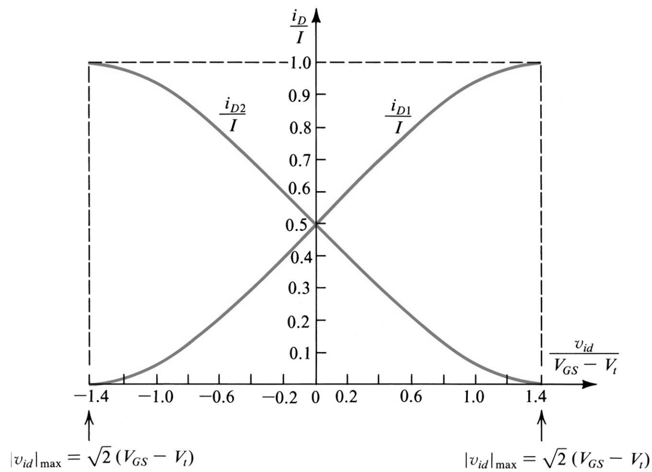
Combinando as equações 1, 2 e 3 e considerando que no ponto quiescente

$$i_{D1} = i_{D2} = \frac{I}{2} \qquad v_{GS1} = v_{GS2} = V_{GS}$$

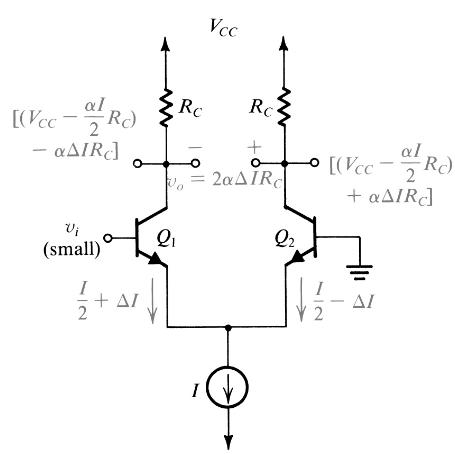
tem-se

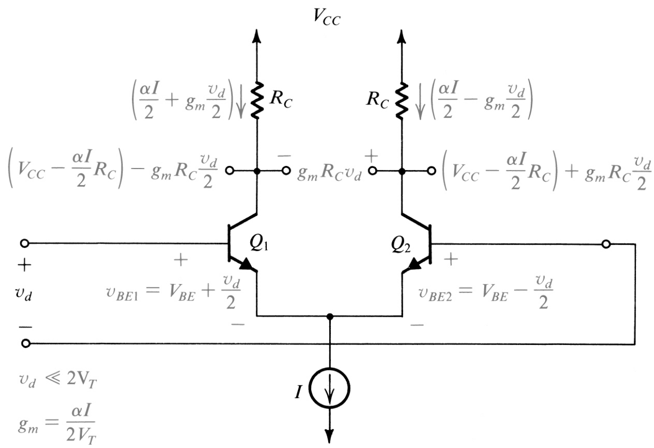
$$i_{D1(2)} = \frac{I}{2} \pm \frac{I}{\left(V_{GS} - V_t \right)} \frac{v_{id}}{2} \sqrt{1 - \left(\frac{v_{id}/2}{V_{GS} - V_t} \right)^2}$$

Característica de transferência normalizada do par diferencial MOS

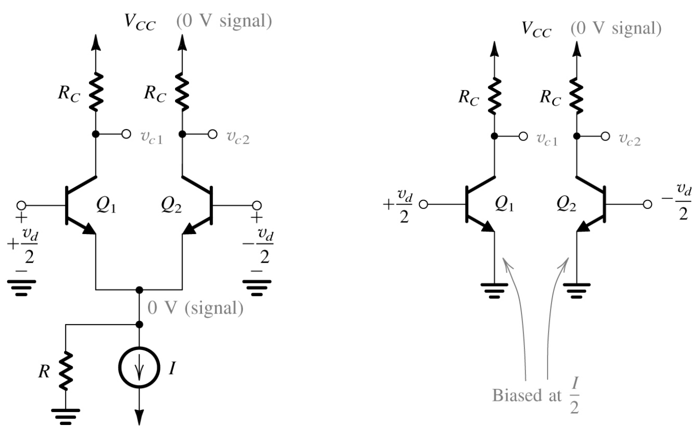


1.6.3 OPERAÇÃO COM PEQUENOS SINAIS

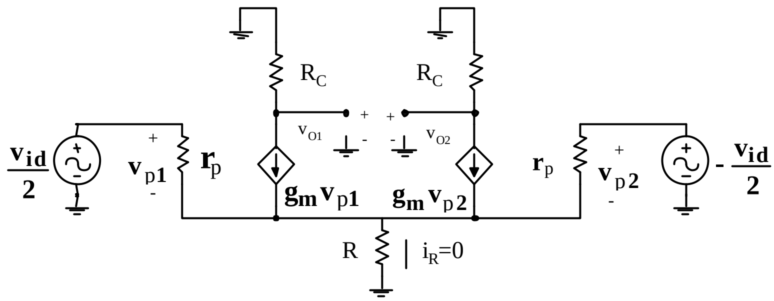




SEPARAÇÃO DO AMPLIFICADOR DIFERENCIAL EM DUAS METADES



CIRCUITO EQUIVALENTE DE PEQUENOS SINAIS

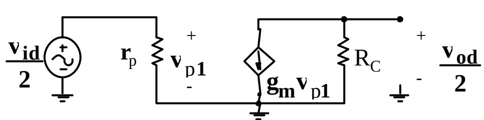


$$v_{od} = v_{o1} - v_{o2}$$

$$v_{o1} = \frac{v_{od}}{2} \qquad v_{o2} = -\frac{v_{od}}{2}$$

Análise de pequenos sinais

Ganho de modo diferencial



$$A_d = \frac{V_{od}}{V_{id}} = -g_m R_C$$

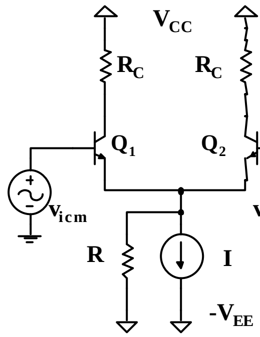
$$g_m = \frac{I_C}{V_T} = \frac{aI}{2V_T}$$

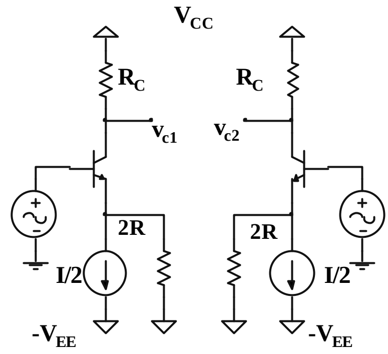
Obs.: Se a saída tomada for simples o ganho diferencial será:

$$A_d = \frac{V_{o1}}{V_{id}} = -\frac{1}{2} g_m R_C$$

Ganho de modo comum

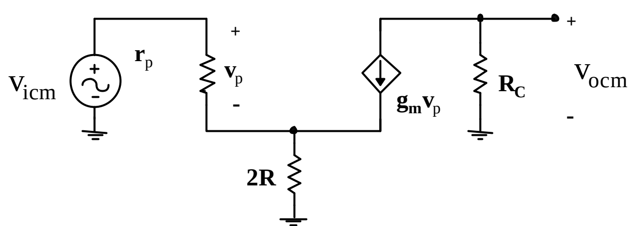
$$A_{cm} = \frac{V_{ocm}}{V_{icm}}$$





$v_{c1} = v_{c2} = v_{ocm}$

Meio circuito equivalente AC para análise de modo-comum



$$A_{cm} = \frac{v_{ocm}}{v_{icm}}$$

$$A_{cm} = -\frac{g_m R_C}{1 + 2 g_m R\left(1 + \frac{1}{b}\right)} \cong -\frac{a R_C}{2R}$$

CMRR: razão de rejeição de modo comum

$$CMRR = \left|\frac{A_d}{A_{cm}}\right| = \frac{1}{2}\left[1 + 2g_m R\left(1 + \frac{1}{b_o}\right)\right] \approx g_m R$$

$$CMRR\big|_{dB} = 20\log\left|\frac{A_d}{A_{cm}}\right|$$

Os sinais de entrada contêm usualmente uma componente de modo diferencial e uma de modo comum

$$v_{id} = v_1 - v_2$$

$$v_{icm} = \frac{v_1 + v_2}{2}$$

$$v_o = A_d v_{id} + A_{cm} v_{icm}$$

Resistência de entrada de modo diferencial

$$R_{id} = \left.\frac{v_{id}}{i_b}\right|_{v_{icm}=0} = 2r_p$$

Resistência de entrada de modo comum

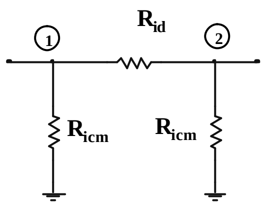
$$R_{icm} = \left.\frac{v_{icm}}{2i_b}\right|_{v_{id}=0} = \frac{1}{2}\left[r_p + 2R(b+1)\right]$$

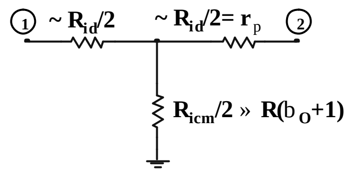
As correntes de pequenos sinais que fluem quando tensões diferenciais e de modo comum são aplicadas são

$$i_{b1} = \frac{v_{id}}{R_{id}} + \frac{v_{icm}}{R_{icm}}$$

$$i_{b2} = -\frac{v_{id}}{R_{id}} + \frac{v_{icm}}{R_{icm}}$$

Circuito equivalente de pequenos sinais para entrada de um amplificador diferencial diferencial

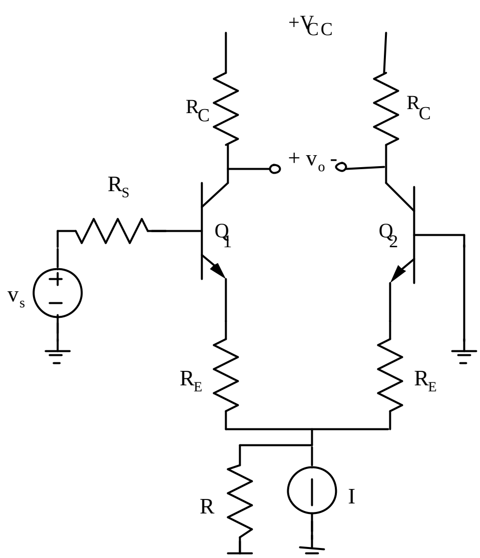




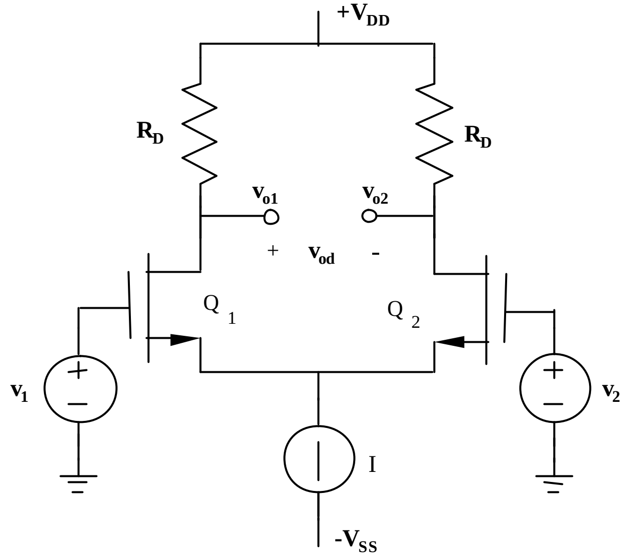
Modelo π **Modelo T**

Exemplo

V_{CC} = 15 V
R_C = 10 kΩ
R_E = 150 Ω
R = 200kΩ
I = 1 mA



1.6.4 OPERAÇÃO COM PEQUENOS SINAIS DO AMP. DIF. MOS



Operação em pequenos sinais do amp. dif. MOS

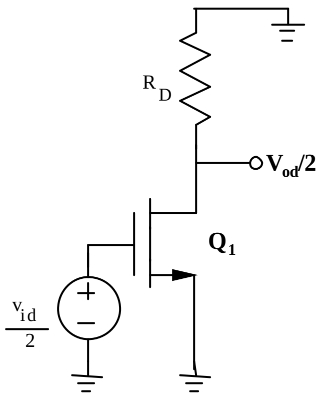
$$i_{D1(2)} = \frac{I}{2} \pm \frac{I}{(V_{GS} - V_t)} \frac{v_{id}}{2} \sqrt{1 - \left(\frac{v_{id}/2}{V_{GS} - V_t} \right)^2}$$

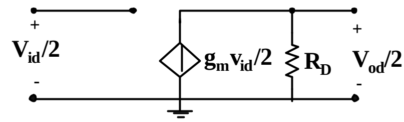
$$\frac{v_{id}}{2} << (V_{GS} - V_t)$$

$$i_{D1(2)} = \frac{I}{2} \pm \frac{I}{(V_{GS} - V_t)} \frac{v_{id}}{2}$$

$$i_d = g_m \frac{v_{id}}{2}$$

Ganho de modo diferencial



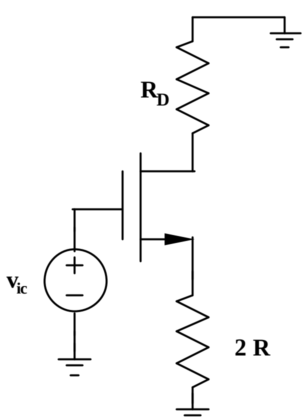


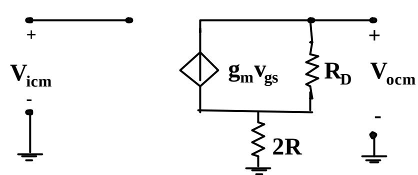
$$A_d = \frac{v_{od}}{v_{id}} = -g_m R_D$$

Considerando saída simples:

$$A_d = \frac{v_{od}}{v_{id}} = -\frac{1}{2} g_m R_D$$

Ganho de modo comum (considerando saída simples)





$$A_{cm} = -\frac{R_D}{2R}$$

CMRR (considerando saída simples)

$$CMRR = g_m R$$

Resistência de entrada de modo diferencial

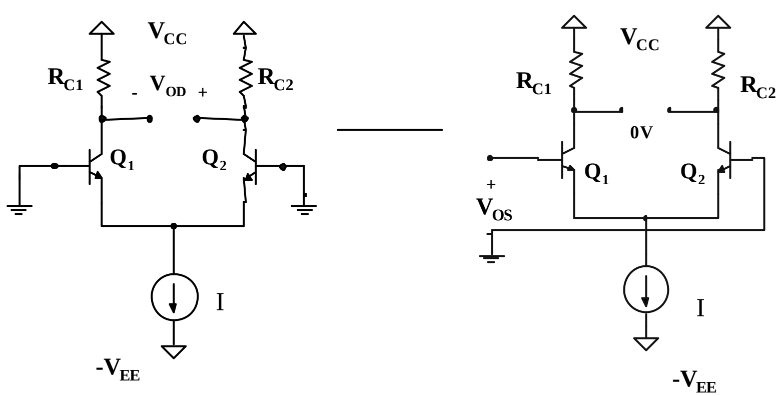
$$R_{id} = \infty$$

Resistência de entrada de modo comum

$$R_{icm} = \infty$$

1.6.5 CARACTERÍSTICAS NÃO IDEAIS DO AMPLIFICADOR DIFERENCIAL

Tensão de offset (V_{OS})



V_{OS} é a tensão que deve ser aplicada à entrada de modo que a tensão na saída seja igual a zero

$$V_{OS} = \frac{V_{OD}}{A_d}$$

V_{OS} **é devida ao descasamento nos resistores e nos transistores**

ANÁLISE

1) Descasamento nos resistores e transistores casados

$$R_{C1} = R_C + \frac{\Delta R_C}{2} \qquad V_{C1} = V_{CC} - \left(\frac{aI}{2}\right)\left(R_C + \frac{\Delta R_C}{2}\right)$$

$$R_{C2} = R_C - \frac{\Delta R_C}{2} \qquad V_{C2} = V_{CC} - \left(\frac{aI}{2}\right)\left(R_C - \frac{\Delta R_C}{2}\right)$$

$$V_{OD} = V_{C2} - V_{C1} = a\,\frac{I}{2}\,\Delta R_C$$

$$V_{OS} = \frac{V_{OD}}{A_d} = \frac{a\,(I/2)\Delta R_C}{g_m R_C} \qquad |V_{OS}| = V_T\,\frac{\Delta R_C}{R_C}$$

2) Descasamento nos transistores e resistores casados

$$I_{S1} = I_S + \frac{\Delta I_S}{2} \qquad I_{E1} = \frac{I}{2}\left(1 + \frac{\Delta I_S}{2I_S}\right)$$

$$I_{S2} = I_S - \frac{\Delta I_S}{2} \qquad I_{E2} = \frac{I}{2}\left(1 - \frac{\Delta I_S}{2I_S}\right)$$

$$V_{OD} = a\,\frac{I}{2}\,\frac{\Delta I_S}{I_S}\,R_C \qquad |V_{OS}| = V_T\,\frac{\Delta I_S}{I_S}$$

$$V_{OS} = \sqrt{\left(V_T\,\frac{\Delta R_C}{R_C}\right)^2 + \left(V_T\,\frac{\Delta I_S}{I_S}\right)^2}$$

$$V_{OS} = V_T\sqrt{\left(\frac{\Delta R_C}{R_C}\right)^2 + \left(\frac{\Delta I_S}{I_S}\right)^2}$$

Correntes de polarização de offset de entrada

$$I_{B1} = I_{B2} = \frac{I/2}{b+1}$$

Perfeitamente simétrico

Descasamento em b

$$I_{OS} = \left| I_{B1} - I_{B2} \right|$$

Corrente de offset

$$b_1 = b + \frac{\Delta b}{2} \qquad b_2 = b - \frac{\Delta b}{2}$$

$$I_{B1} = \frac{I}{2}\frac{1}{b+1+\frac{\Delta b}{2}} \cong \frac{I}{2}\frac{1}{b+1}\left(1-\frac{\Delta b}{2b}\right)$$

$$I_{B2} = \frac{I}{2}\frac{1}{b+1-\frac{\Delta b}{2}} \cong \frac{I}{2}\frac{1}{b+1}\left(1+\frac{\Delta b}{2b}\right)$$

$$I_{OS} = \frac{I}{2(b+1)}\frac{\Delta b}{b}$$

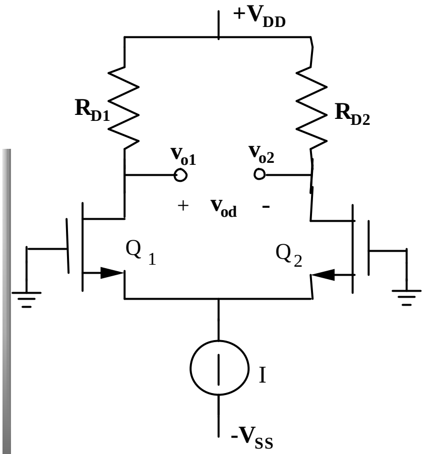
Correntes de polarização I_B

$$I_B \equiv \frac{I_{B1}+I_{B2}}{2} = \frac{I}{2(b+1)}$$

$$I_{OS} = I_B \frac{\Delta b}{b}$$

Exercício: Para um amplificador diferencial com TBJ utilizando transistores com b=100, com casamento máximo de 10%, e casamento de áreas de 10% ou melhor, e resistores de coletor com casamento de 2% ou melhor, encontre os valores de V_{OS}, I_B e I_{OS}. A corrente de polarização CC é de 100 mA.

Tensão de *offset*



Descasamento em R_D, W/L e V_t

1. Descasamento em R_D

$$R_{D1} = R_D + \frac{\Delta R_D}{2}$$

$$R_{D2} = R_D - \frac{\Delta R_D}{2}$$

$$V_{OD} = \frac{I}{2}\Delta R_D$$

Dividindo pelo ganho $g_m R_D$

$$|V_{OS}| = \frac{V_{GS} - V_t}{2}\frac{\Delta R_D}{R_D}$$

2. Descasamento em W/L

$$\left(\frac{W}{L}\right)_1 = \frac{W}{L} + \frac{\Delta(W/L)}{2}$$

$$\left(\frac{W}{L}\right)_2 = \frac{W}{L} - \frac{\Delta(W/L)}{2}$$

$$I_{D1} = \frac{I}{2}\left(1 + \frac{\Delta(W/L)}{2(W/L)}\right)$$

$$I_{D1} = \frac{I}{2}\left(1 - \frac{\Delta(W/L)}{2(W/L)}\right)$$

$$|V_{OS}| = \frac{V_{GS} - V_t}{2}\frac{\Delta(W/L)}{(W/L)}$$

3. Descasamento em V_t

$$V_{t1} = V_t + \frac{\Delta V_t}{2}$$

$$V_{t2} = V_t - \frac{\Delta V_t}{2}$$

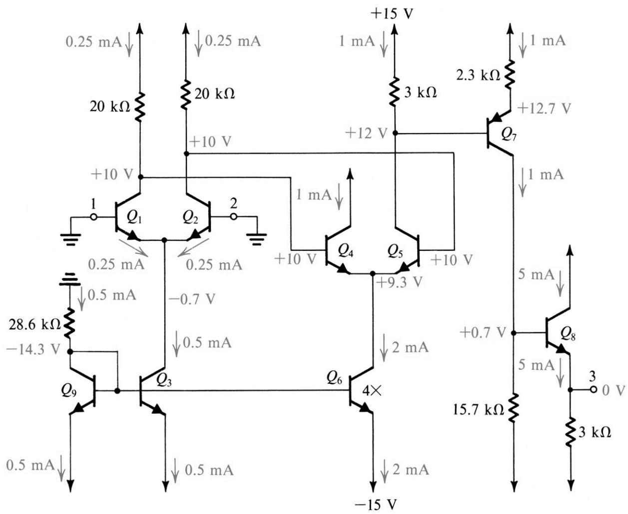
$$I_{D1} = \frac{1}{2}k_n'\frac{W}{L}(V_{GS} - V_t)^2\left(1 - \frac{\Delta V_t}{V_{GS} - V_t}\right)$$

$$I_{D2} = \frac{1}{2}k_n'\frac{W}{L}(V_{GS} - V_t)^2\left(1 + \frac{\Delta V_t}{V_{GS} - V_t}\right)$$

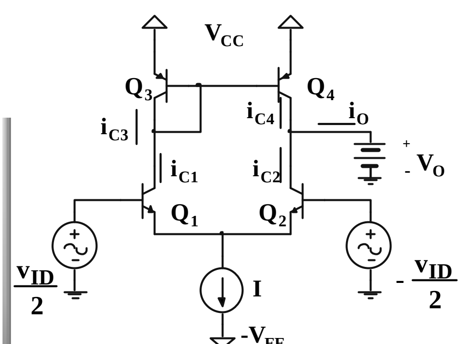
$$\Delta I = \frac{I}{2}\left(\frac{\Delta V_t}{V_{GS} - V_t}\right)$$

$$|V_{OS}| = \Delta V_t$$

Exemplo 6.3 – Sedra Smith (p. 484)



1.7 O AMPLIFICADOR DIFERENCIAL COM CARGA ATIVA



$Q_1 \cong Q_2$ e $Q_3 \cong Q_4$

V_o é tal que Q_2 e Q_4 operam na região ativa

I_B desprezível

$$i_{C1} = \frac{I}{2} + g_m \frac{v_{id}}{2}$$

$$i_{C2} = \frac{I}{2} - g_m \frac{v_{id}}{2}$$

$$i_{C1} = i_{C3} = i_{C4}$$

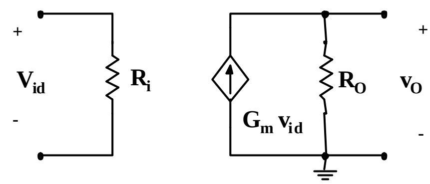
$$i_O = i_{C4} - i_{C2} = g_m v_{id}$$

Transcondutância em curto-circuito

$$G_m \equiv \frac{i_o}{v_{id}} = g_m$$

Ganho de tensão em circuito aberto

Modelo para pequenos sinais



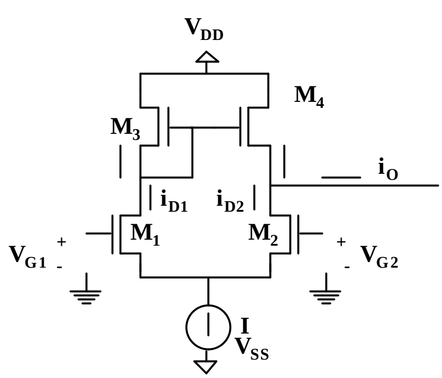
$$\frac{v_o}{v_{id}} = G_m R_o$$

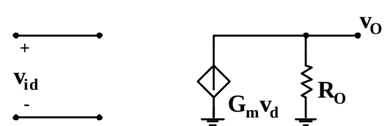
$$R_o = r_{o2} // r_{o4}$$

$$r_{o2(4)} = \frac{V_{An(p)}}{I/2} \qquad g_m = \frac{I/2}{V_T}$$

$$A_{vo} = \frac{1}{V_T\left(\frac{1}{V_{An}} + \frac{1}{V_{Ap}}\right)}$$

Amplificador diferencial CMOS com carga ativa



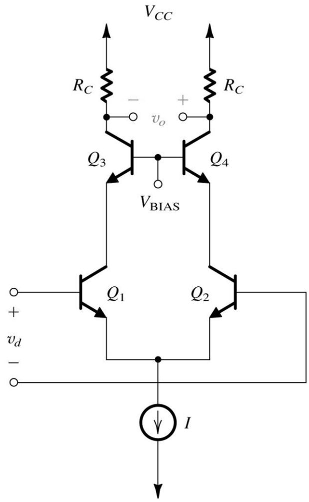


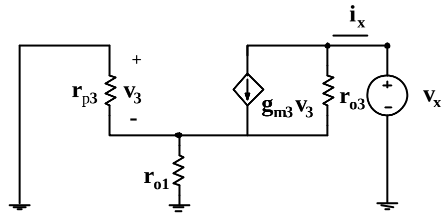
$$A_v \equiv \frac{v_o}{v_{id}} = G_m R_o$$

$$G_m \equiv \frac{i_o}{v_{id}} = g_m$$

$$R_o = r_{o2} // r_{o4}$$

Amplificador diferencial cascode

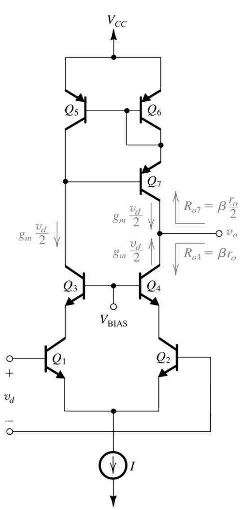




$$R_o = r_{o3}\left(1 + g_m r_{\pi 3}\right) = r_{o3}\left(1 + \beta_3\right)$$

$$R_o \cong \beta_3 r_{o3}$$

Amplificador diferencial cascode com carga ativa espelho de Wilson

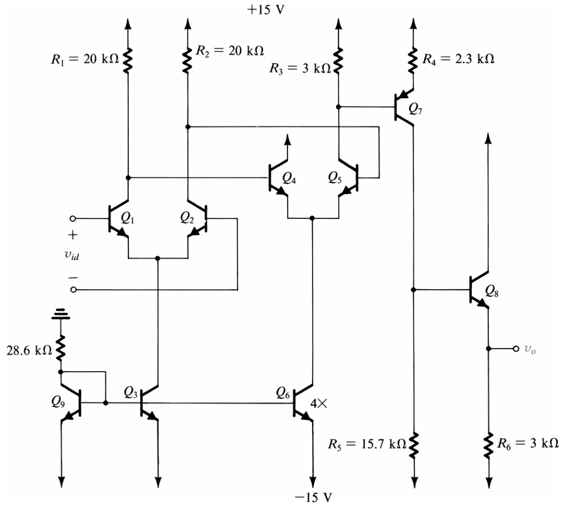


Exercício:

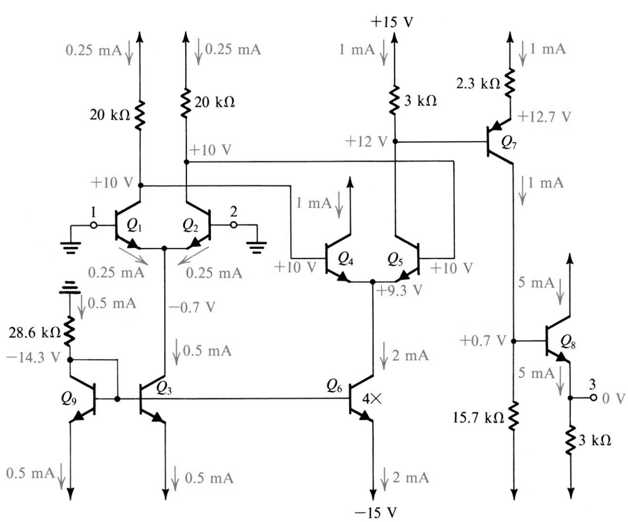
Para o amplificador da figura determine R_i, G_m, R_o e o ganho de tensão em circuito aberto.

Dados: I = 0,2 mA
b = 200
V_A = 100 V

1.8 AMPLIFICADOR OPERACIONAL BIPOLAR



Exemplo 6.3 – Sedra Smith (p. 484)



1.9 AMPLIFICADOR OPERACIONAL CMOS