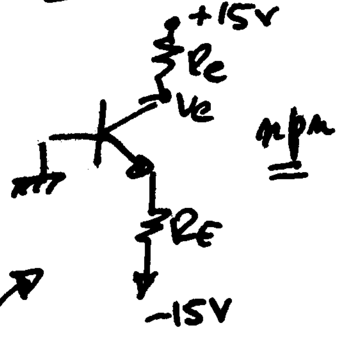
Complementi su Transistor.

- Esempi di polarizzazioni

① 2 tensioni: positive e negativa +, −



punto di lavoro in D.C

$V_E = -0{,}7\,V$ $R_E = \frac{-15+0{,}7}{I_c}$

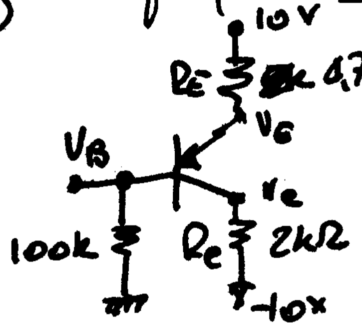
per $I_c = 2mA \Rightarrow R_E = 7k\Omega$

per avere dinamica $V_c \Rightarrow$ es: $5V \Rightarrow R_c = \frac{15-5}{2mA}$

$R_c = 5k\Omega$

BASE COMUNE

② pnp − emettitore comune − 2 tensioni (+)(−)



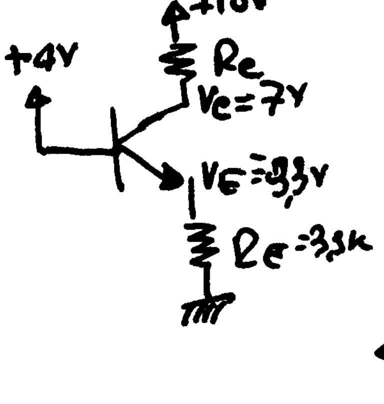
punto di lavoro in D.C.

$V_E = 0{,}7V$ si sceglie $I_c \approx 2mA \Rightarrow R_E = 4{,}7k$

$\Rightarrow$ dinamica $\sim 6V\,(V_c - V_E) \Rightarrow$

$R_c = \frac{4V}{2mA} = 2k\Omega$

③ BASE COMUNE − tensioni positive.



1) $V_E = 4V - 0{,}7V = 3{,}3V$

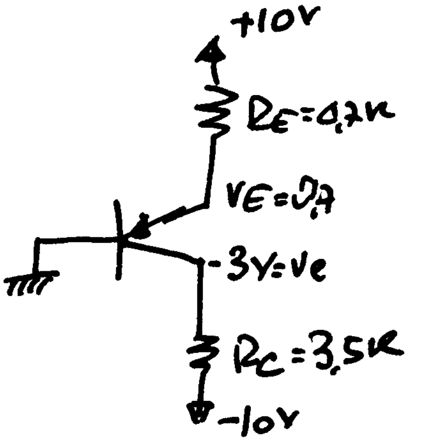
2) scelta di $I_c \sim I_E = 1mA$

3) $R_E = \frac{3{,}3V}{1mA} = 3{,}3k$

4) Scegliere dinamica $V_c = 7V \Rightarrow (V_c - V_E = 7V - 3{,}3$

5) $R_e = 3\,k\Omega$

BASE COMUNE 2 tensioni (+)/(−) pnp



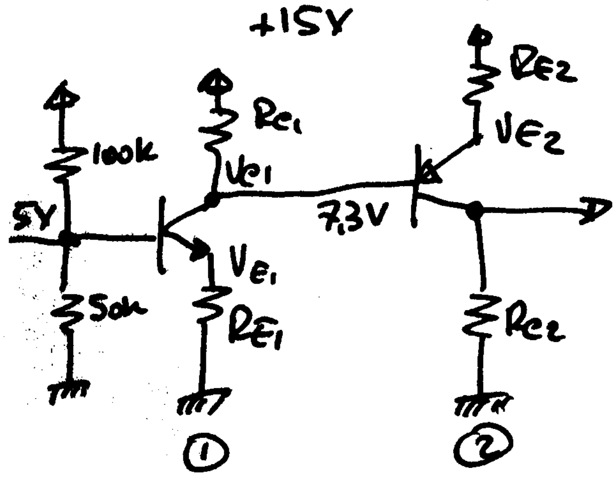
① $V_E = +0{,}7\,V$ ⇒ scelta di $I_C = 2\,mA$

② $R_E = \frac{(10-0{,}7)\,V}{2\,mA} = 4{,}7\,K$

③ dinamica 3,7 V

④ $R_C = \frac{(-10+3)\,V}{2\,mA} = \frac{7\,V}{2\,mA} = 3{,}5\,k$

Polarizzazione di due stadi a transistor, una tensione (+)



① $V_{E1} = 5V - 0{,}7V = 4{,}3\,V$

② scelta di $I_{E_1} = 1{,}5\,mA$

③ $R_{E1} = 3\,k\Omega$

④ Dinamica $(V_{C1} - V_{E1}) = (7{,}3 - 4{,}3\,V) = 3\,V$

⑤ $R_{C1} \doteq 5\,k\Omega$

⑥ $V_{E_2} = 8\,V$ ⑦ scelta $I_{C_2} = I_{E_2} = 3\,mA \rightarrow V_{E_2} = 8\,V$

⑧ $= R_{E_2} = \frac{15V - 8V}{3\,mA} = 2{,}7\,k\Omega$

⑨ dinamica $V_{CE_2} - V_{E_2} = -2\,V$

⑩ $V_{CE_2} = 6\,V$

⑪ $R_{C_2} = \frac{6\,V}{3\,mA} = 2\,k\Omega$

$g_m = \frac{\partial I_C}{\partial V_{BE}} = \frac{I_C}{V_T} = \frac{i_c}{v_{BE}}$ regime dinamico segnale sovrapposto al regime di polarizzazione in DC.

$i_b = \frac{i_c}{\beta} \Rightarrow i_b = \frac{1}{\beta} \frac{I_C}{V_T} v_{be}$

$i_b = \frac{g_m}{\beta} v_{be}$ $\quad r_\pi = \frac{v_{be}}{i_b} = \frac{\beta}{g_m} = \beta \cdot r_e$

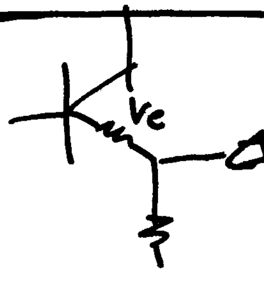
resistenza dinamica guardando nella base fra base ed emettitore.

talvolta $\beta \cdot r_e$ scritta come r_π.

$\Rightarrow \beta \cdot r_e$

$i_e \approx i_c \rightarrow i_e = \frac{I_E}{V_T} v_{BE}$

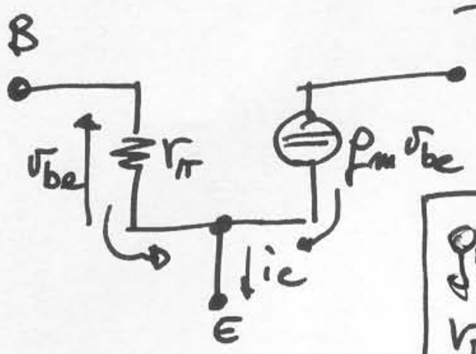
$r_e = \frac{v_{be}}{i_E} = \frac{V_T}{I_E} = r_e$ resistenza guardata nell'emettitore



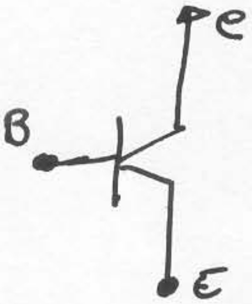
$\leftarrow \frac{V_T}{I_E} = r_e$

Rappresentazione elettrica del transistor.

modello π



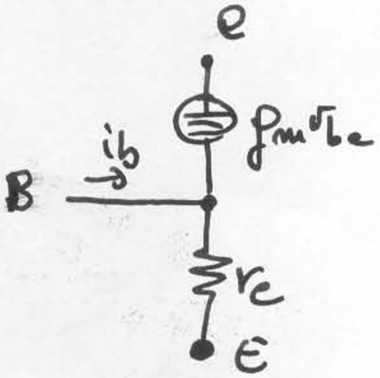
$$g_m = \frac{I_e}{V_T}$$
$$r_\pi = \beta \cdot g_m$$



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

$$= v_{be} \Big/ \left(\frac{r_\pi}{1+\beta}\right) = v_{be}/r_e$$

modello T



$$i_b = \frac{v_{be}}{r_e} - g_m v_{be} = \frac{v_{be}}{r_e}\left(1 - g_m r_e\right)$$

$$= \frac{v_{be}}{r_e}\left(1-\alpha\right) = \frac{v_{be}}{r_e}\left(1 - \frac{\beta}{\beta+1}\right)$$

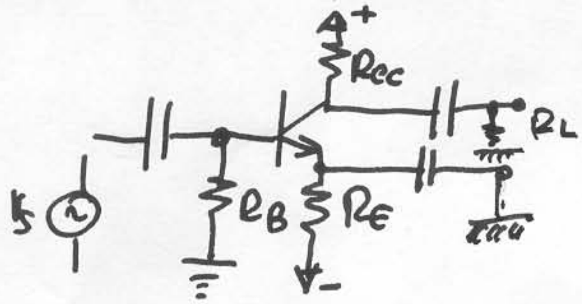
$$= \frac{v_{be}}{(\beta+1) r_e} = \frac{v_{be}}{r_\pi}$$

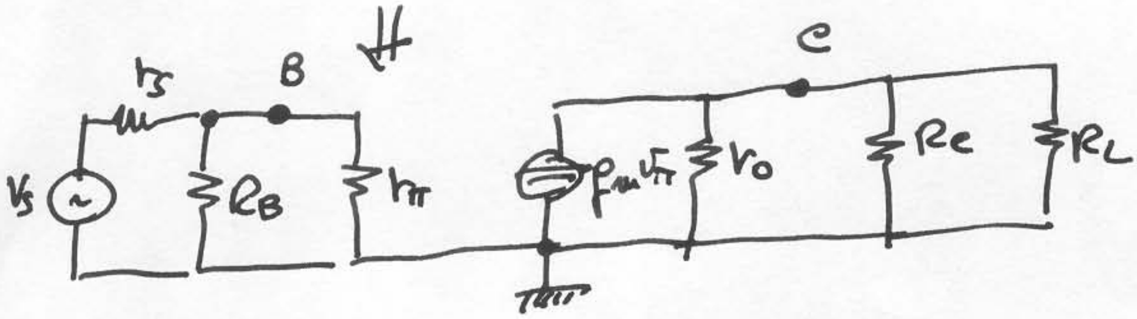
$$g_m = \frac{I_e}{V_T}$$

$$r_e = \frac{1}{g_m}$$

Configurazioni.

emitter comune.





$R_o = R_C \| r_o$

$R_i = R_B \| r_\pi$

$r_\pi = r_e \cdot \beta$

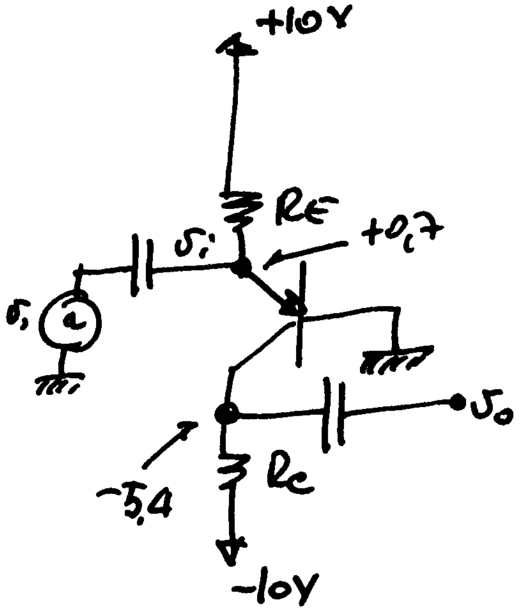
Z_{in} ⇒ moderate impedenza $(R_B \| r_\pi)$

transconduttanza g_m

Z_{out} ⇒ $R_C \| r_o$

base a massa - regime dinamico.

In D.C.

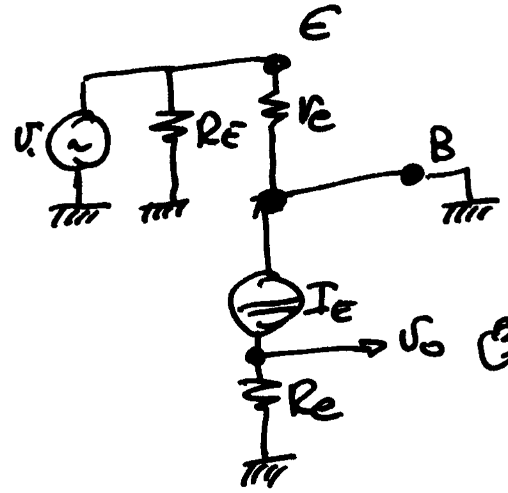


$R_E = 10K\Omega$ & $I_E = 0{,}93$

dinamica tra 0,7 e -5,4

$R_c \sim 5K\Omega$

modello:

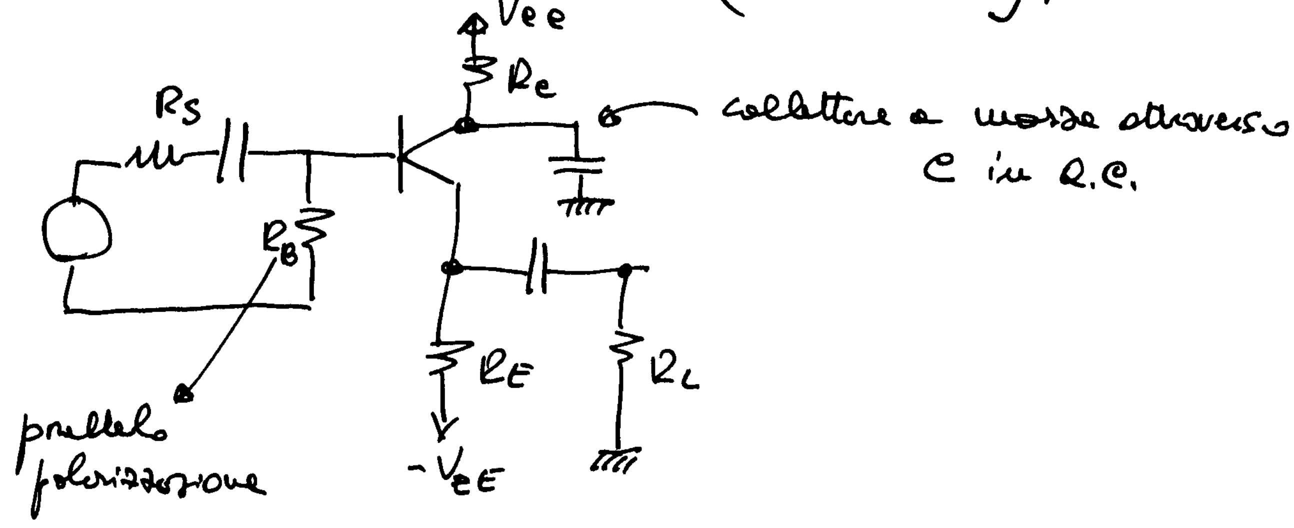


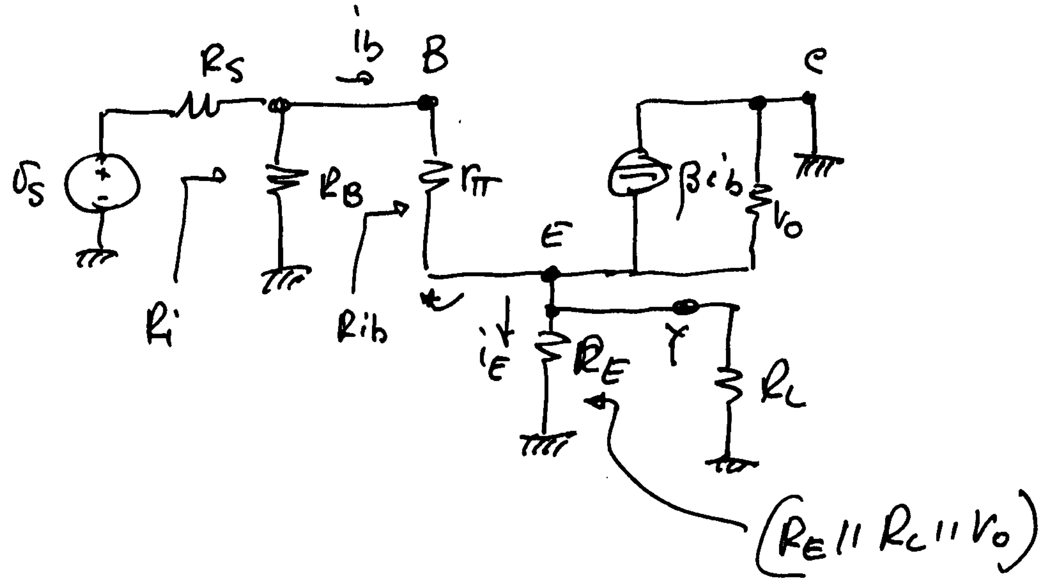
① $\frac{v_i}{R_E} \rightarrow 0$

② $\frac{v_i}{r_e} = i_e \sim I_e$

③ $v_o = \frac{v_i}{r_e} \cdot R_c$

Emitter Follower (analitico).

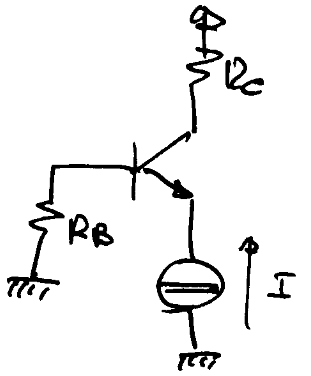




$$i_E = \beta i_b + i_b = i_b(\beta+1)$$

$$R_{ie} = \frac{r_\pi + (R_S \| R_B)}{\beta+1}$$

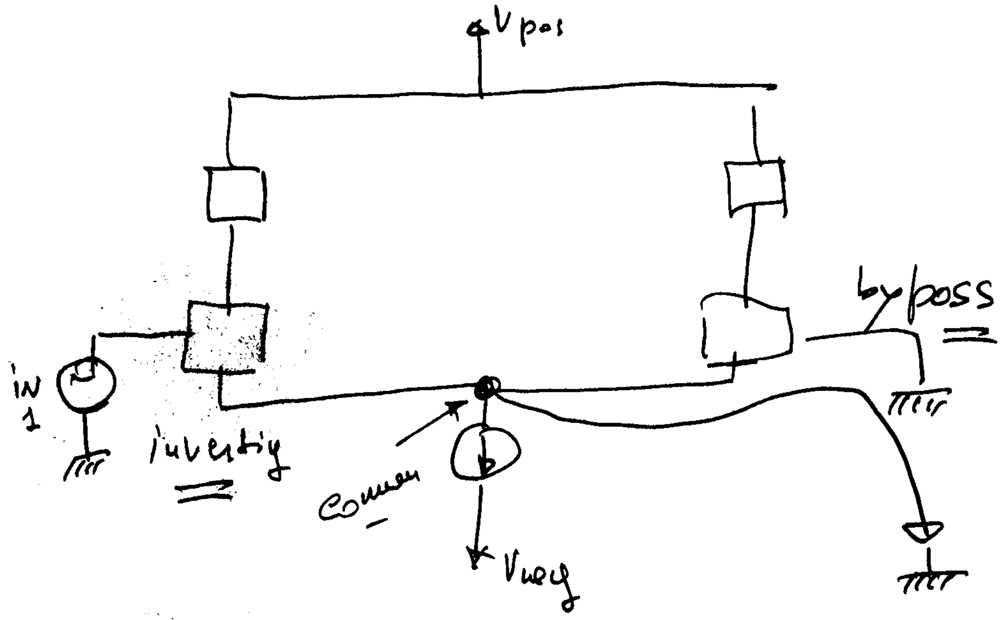
Complementi su amplificatori differenziali



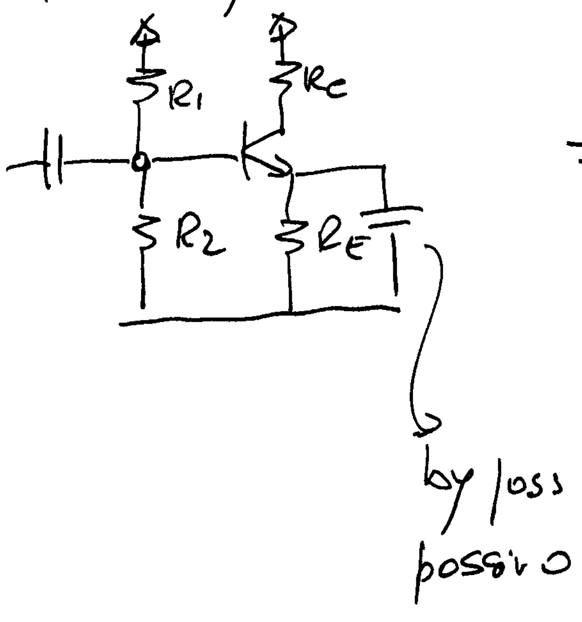
Polarizzando con un generatore di corrente

I non dipende da β e da R_B

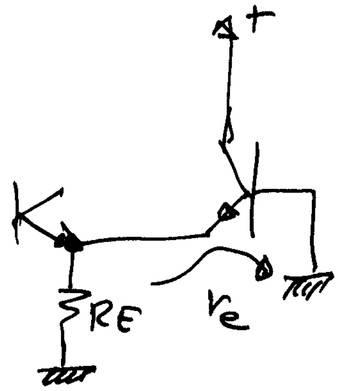
⇒ alta impedenza di ingresso.



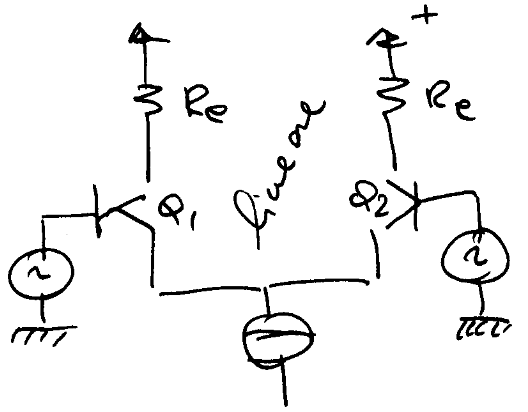
Esempio di by-pass

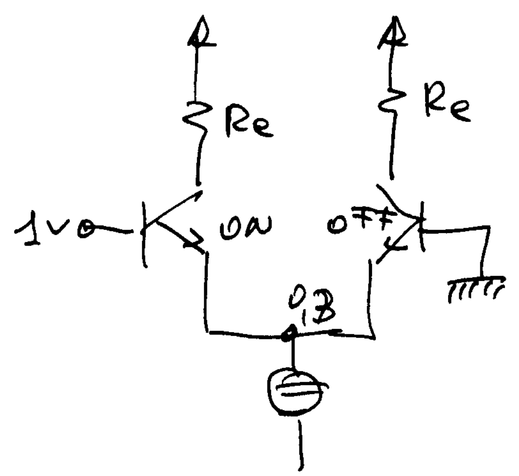


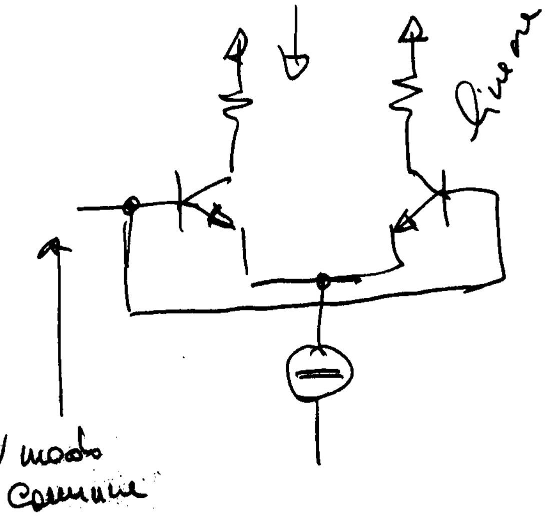
⇒

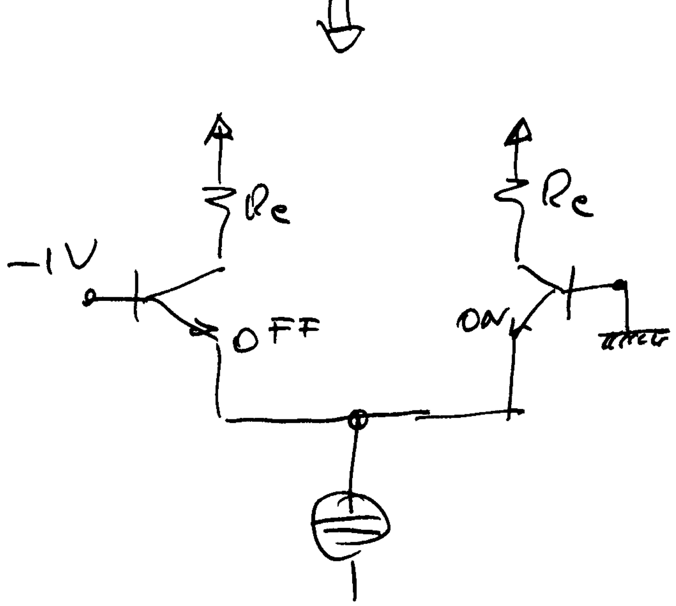


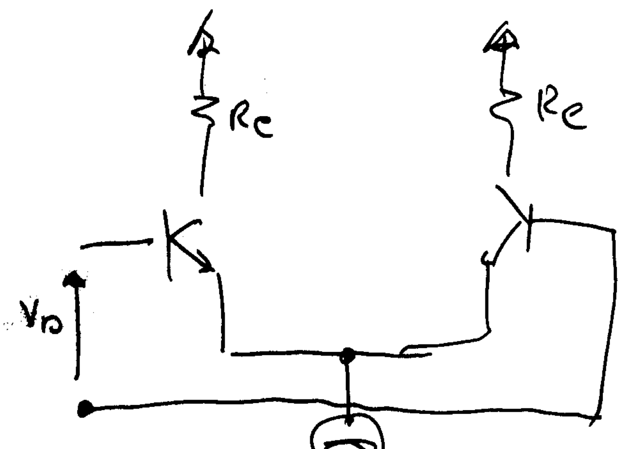
Configurazioni











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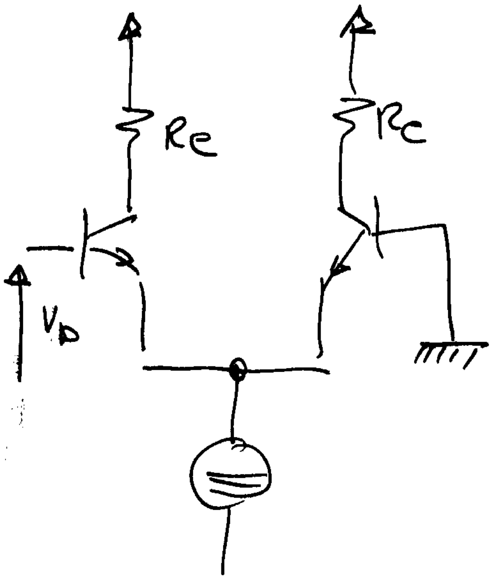
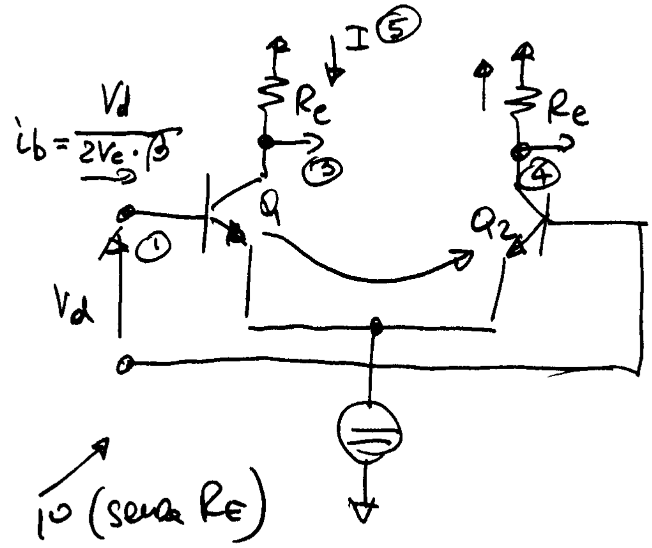


$V_{BE_1} = V_{BE} + \frac{V_d}{2}$ / $V_{BE_2} = V_{BE_2} - \frac{V_d}{2}$



① $Z_{in} = 2r_e \cdot h_{fe}$

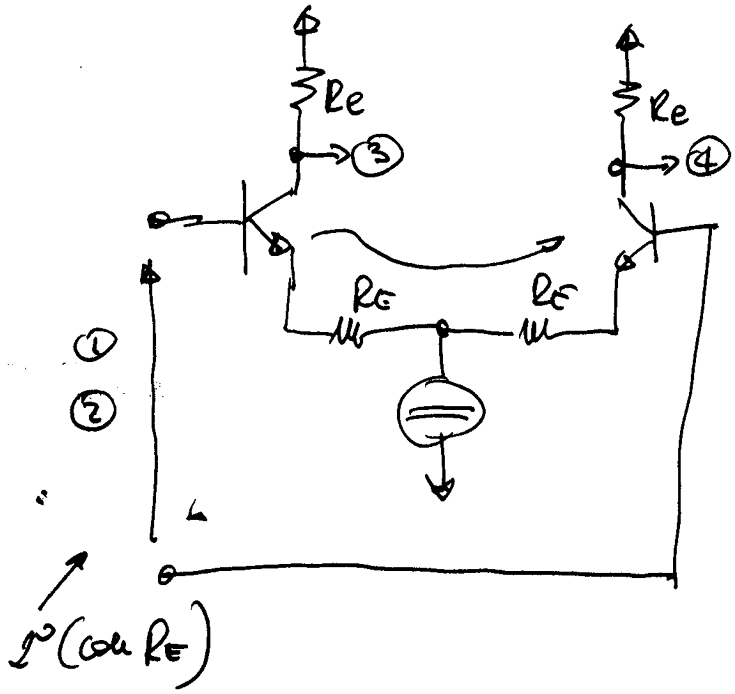
② $I_e = \frac{v_d}{2r_e}$

③ $= -\frac{R_e}{2r_e} \cdot v_D$ ← $-\frac{1}{2} g_m R_c$ ↑ G diff.

④ $= \frac{R_e}{2r_e} \cdot v_d$ ← $\frac{1}{2} g_m R_e$

⑤ $= I_e = g_m \frac{v_d}{2} = \frac{v_d}{2r_e}$

Con R_E



① $Z_{in} = 2(r_e + R_E) \cdot h_{fe}$

② $i_b = v_D / 2(r_e + R_E) \cdot h_{fe}$

③ $-\frac{R_e}{2(r_e + R_E)} \cdot v_D$ ↑ G diff.

④ $\frac{R_e}{2(r_e + R_E)} \cdot v_D$

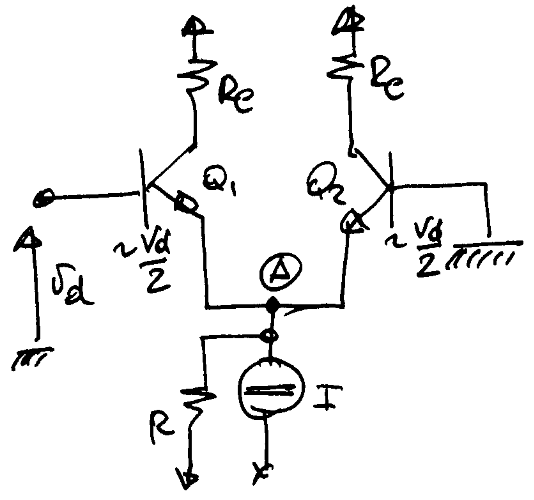
⑤ $I_e = \frac{v_D}{2r_e + 2R_E}$

③ o ④ uscite single ended

Uscita differenziale (fra i collettori).

- 1° caso senza R_E ⇒ $-\frac{1}{2} g_m R_e - \frac{1}{2} g_m R_e = \boxed{-g_m \cdot R_e}$

- 2° caso con R_E $-\frac{R_e}{2(r_e + R_E)} - \frac{R_e}{2(r_e + R_E)} = -\frac{R_c}{r_e + R_E}$

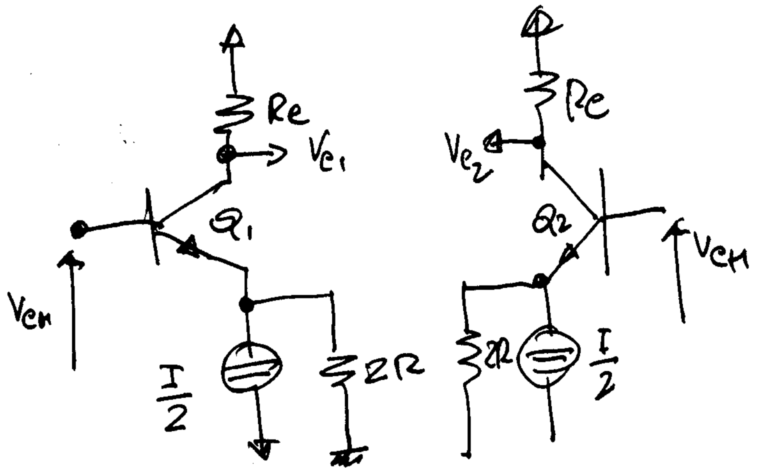


differenziale usato in modo non complementare

⇒ tensione in (A) non rigorosamente 0 ⇒ ma se $R \to \infty$ o $R >> r_e$ V_d è ancora diviso in parti uguali alle 2 giunzioni

⇒ quasi come differenziale.

Modo comune (stesso segnale alle basi).



$$v_{e1} = v_{cm} = \frac{R_c}{2R + r_e}$$

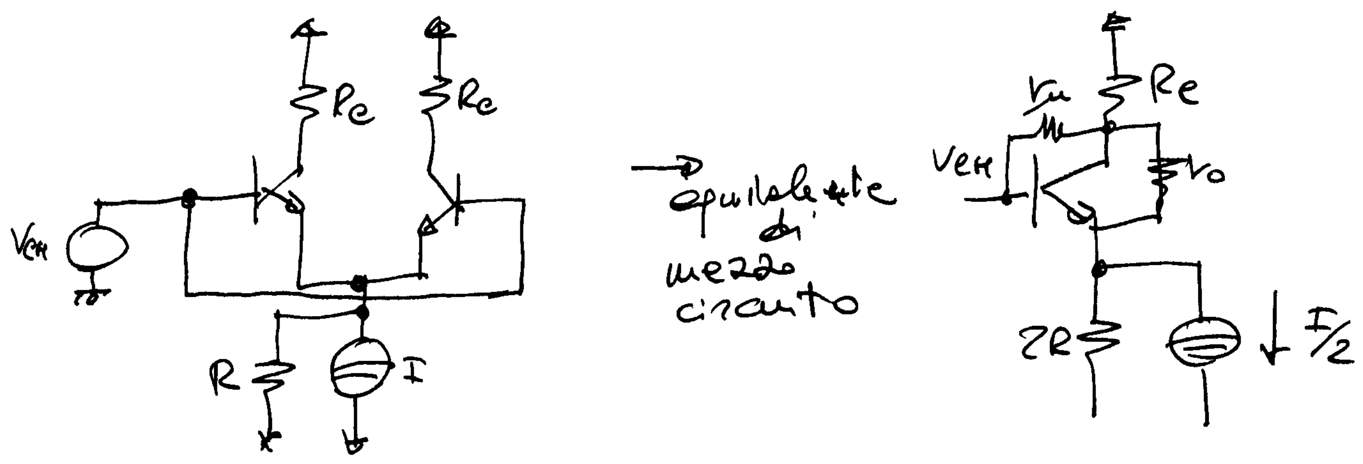
$$\approx \frac{R_c}{R}$$

ora: $A_{CM} = \frac{R_c}{2R}$

$$A_d = \frac{1}{2} g_m R_c$$

$$CMRR = \left| \frac{A_d}{A_{CM}} \right| = g_m \cdot R$$

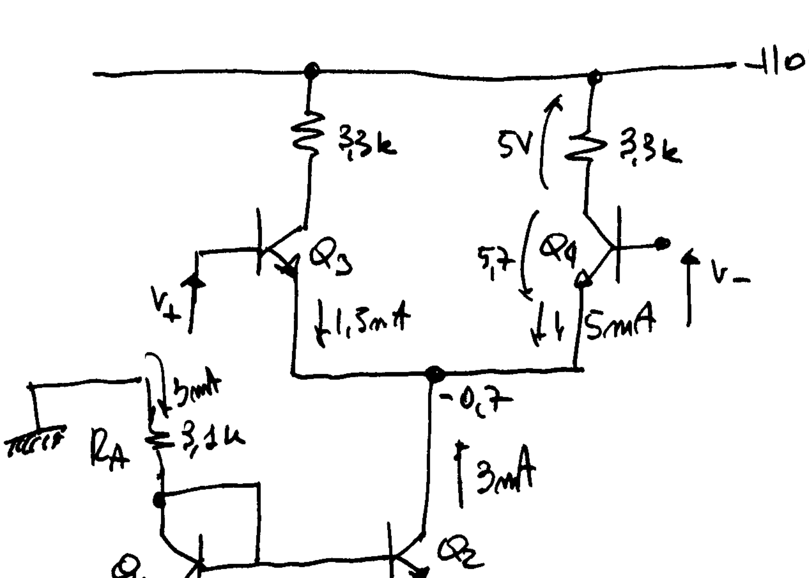
Zin (modo comune)



guadagno common mode piccolo → 0 ⇒ segnale al collettore 0

$$2R_{in} = r_\mu \parallel [h_{fe} \cdot 2R] \parallel [h_{fe} \cdot r_o]$$

Differenziale con carico attivo su emettitore.



$$R_A = \frac{-0{,}7 - (-10V)}{3mA} = 3{,}1\,k\Omega$$

(scelta)

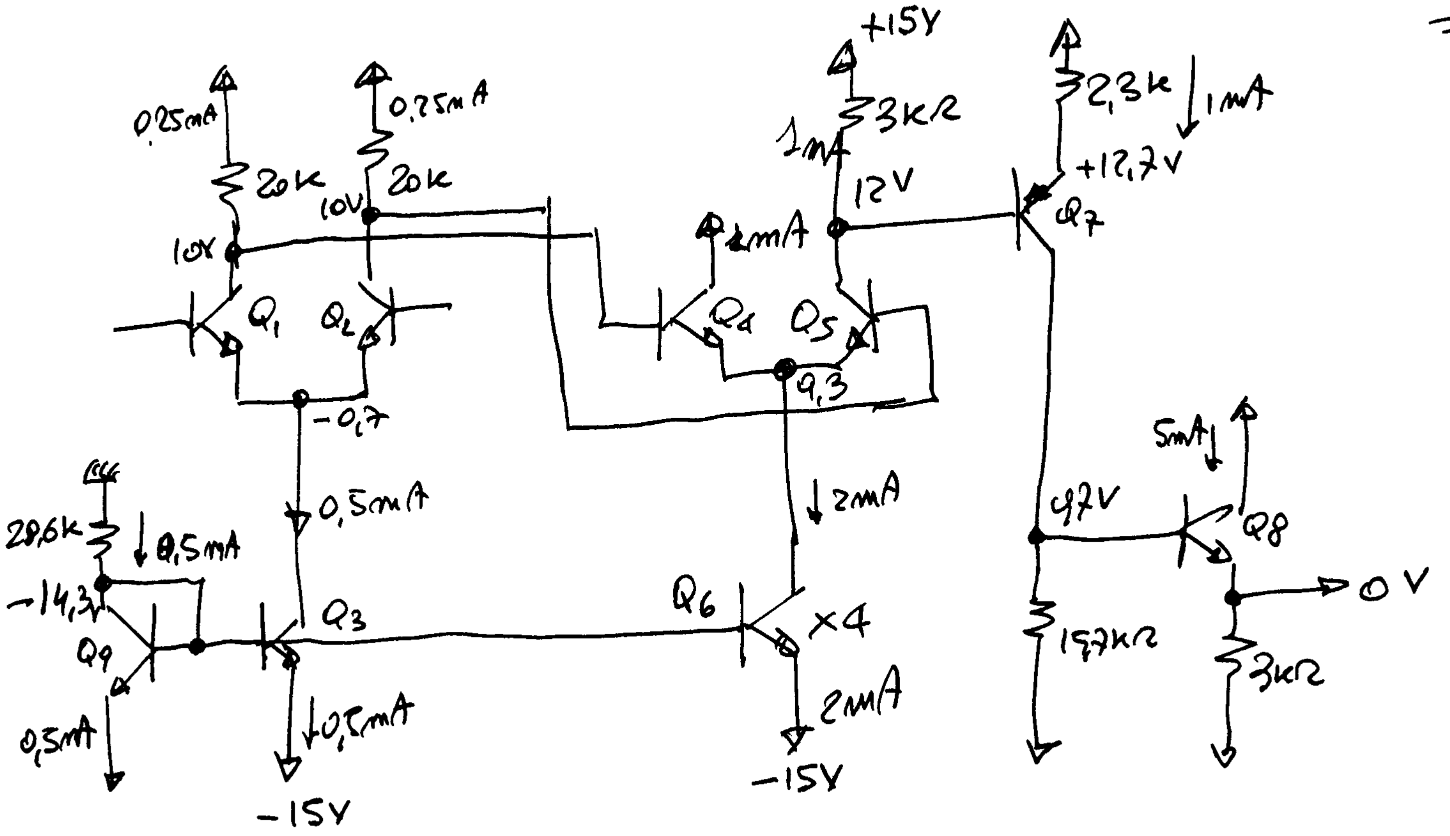
$I_{C1} = I_{C2} = 1{,}5\,mA$

$R_{C1} = R_{C2} = 3{,}3\,k\Omega$

$P_{Q_1} = 0{,}7 \times 3mA = 0{,}2\,mW$

$P_{Q_2} = 3mA(-0{,}7 - (-10V)) \sim 28\,mW$

$P_{Q_3} = P_{Q_4} = (1{,}5mA \times 5{,}7V) = 8{,}6\,mW$



in Q_9 0,5mA ⇒ anche Q_3 = 0,5mA ⇒ Q_6 = 2mA

in coppia (Q_1 e Q_2) ⇒ 0,5mA in Q_1/Q_2 0,25mA

collettori Q_1 e Q_2 = $(15V - 0{,}25 \times 20)$ = **+10V**

Q_4 e Q_5 emitters = 9,3V Q_6 fornisce 2mA

Q_4 e Q_5 polarizzato con 1mA. Collettore di Q_5

$[15 - 1 \times 3] = +12V$ → Emettitore Q_7 = 12,7V e

corrente di emettitore di Q_7 = $(15 - 12{,}7)/2{,}3k = 1mA$

Corrente di collettore di Q_7 = 1mA, tensione di

collettore = $[-15 + 1 \times 15{,}7] = 0{,}7V$ → Emettitore di

Q_8 = 0V → corrente $[0 - (-15)]/3$ = **5mA**

Dissipazioni: su +15V.

$0{,}25mA + 0{,}25mA + 1mA + 1mA + 1mA + 5mA = 8{,}5mA$

$P^+ = (15 \times 8{,}5) = 127{,}5 mW$

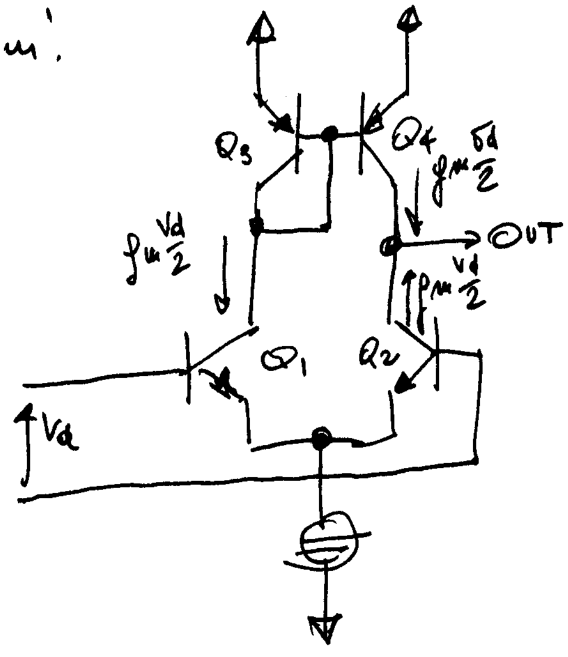
su −15V

$0{,}5mA + 0{,}5mA + 2mA + 1mA + 5mA = 9mA$

$P^- = (15V \cdot 9) = 135 mW.$

$I_B(Q_1, Q_2) = 0{,}25mA / \underset{h_{fe}}{100} = 2{,}5\mu A$

Nei chip sostituzione resistenze con elementi attivi
– meno occupazione su silicio. → carichi passivi
→ carichi attivi. ⇒ alte resistenze → alti
guadagni.



$G = \frac{g_m R_o}{2}$

⇒ altissimo.

Stesso circuito pag. 12

In generale:

1) alta impedenza di ingresso ⇒ evitare perdite di segnale
2) primo stadio ⇒ alto CMRR (abbattimento comune)
3) Stadi intermedi ⇒ alto guadagno. (single ended)
4) bassa impedenza di uscita (emitter).

1° stadio: differenzial-in / differential out Q_1 e Q_2
polarizzati da Q_3

2° stadio: differenziale, ma uscita single-ended da Q_5
Q_4 e Q_5 polarizzato da Q_6

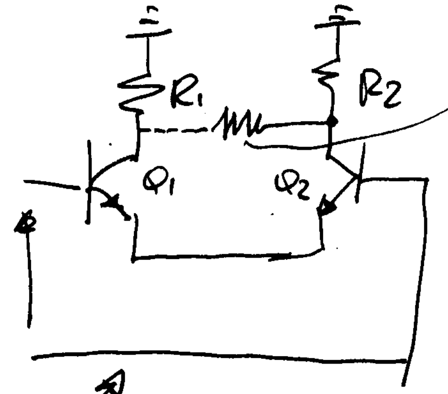
3° stadio emitter Q_7 per guadagno. (per migliorare guadagni sostituire resistenze con carichi attivi).
Q_7 anche shift di livello per dinamica

Z_{in_1} : Q_1 e Q_2 a $0{,}25mA$ ⇒ $r_{e1}, r_{e2} = \frac{25\Omega}{0{,}25} = 100\Omega$

per $h_{fe} = 100$ $Z_{in} = 2 r_e \cdot h_{fe} = 20k\Omega$.

Z_{in} Q_4 e Q_5 ⇒ $r_{e4} = r_{e5} = 25\Omega$ ⇒ $Z_{in_2} = 5k\Omega$

→ Calcolo guadagno 1° stadio.

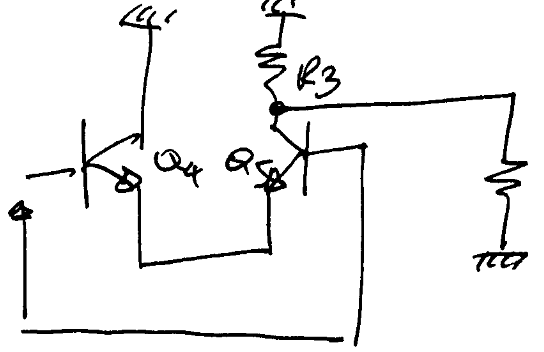


r_{i2} = impedenza di ingresso 2° stadio differenziale

schema equivalente 1° stadio.

$$A_1 = \frac{[R_{i2} \| (R_1+R_2)]}{r_{e1}+r_{e2}} = \frac{[5k \| 40k]}{200\Omega} = 224$$

guadagno 2° stadio: schema equivalente



uscita single-ended

R_{i3} = resistenza di ingresso di Q_7

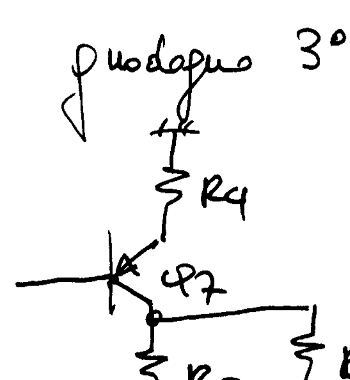
$= h_{fe}(R_4 + r_{e7})$

$= 100 \cdot (23k + 25\Omega)$

$= 234,8k\Omega$

$$A_2 = \frac{(R_3 \| R_{i3})}{r_{e4}+r_{e5}} = \frac{3k\Omega \| 234,8k}{50\Omega} \cong 60$$

guadagno 3° stadio: schema equivalente



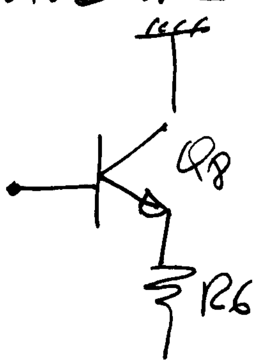
$R_{i4} = h_{fe} \cdot (r_{e8} + R_6) = 100(5\Omega + 3k) = \underline{303,5k}$

$\frac{25\Omega}{5} + 3k$

$$A_3 = \frac{R_5 \| R_{14}}{r_{e7} + R_4} = \frac{15{,}7k \,\|\, 303{,}5k}{2{,}325k} = 6{,}4$$

A_4 guadagno questo stadio

circuito equivalente

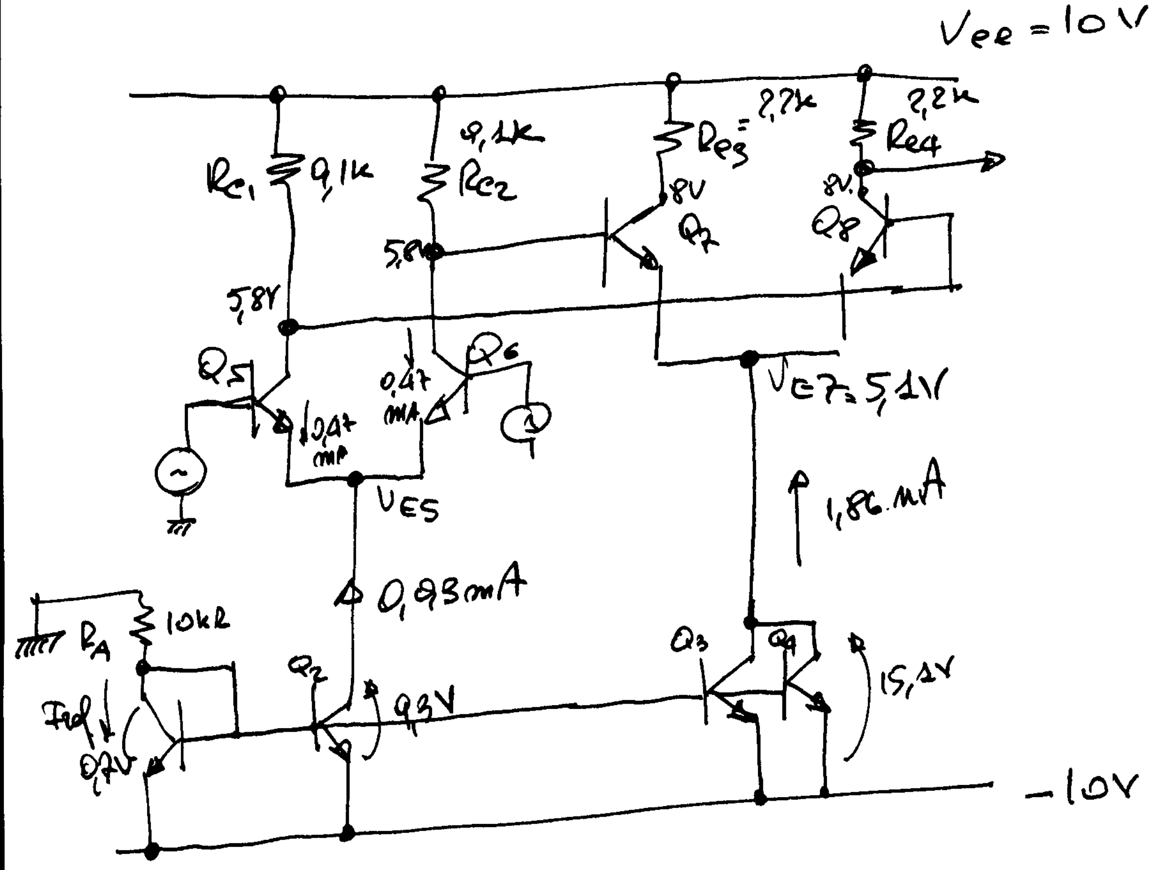


$$A_4 = \frac{R_6}{R_6 + r_{e8}} = \frac{3000}{3000+5} \simeq 1$$

$$A = A_1 \cdot A_2 \cdot A_3 \cdot A_4 = \underline{8513}$$

$$Z_{OUT} = R_6 \,\|\, \left[r_{e8} + \frac{R_5}{h_{fe}} \right] \rightarrow 15252$$

Altro esempio: semplice coppia di differenziali in cascata → rudimentale "operazionale"



① $I_{ref} = \dfrac{-0{,}7-(-10V)}{10k\Omega} = 0{,}93mA$ (portante)

$0{,}93 \nearrow Q_5 = 0{,}47mA$, $\searrow Q_6 = 0{,}47mA$ $\Rightarrow V_{ES} = -0{,}7V \Rightarrow V_{CEQ_2} = 9{,}3V$

$V_{cQ_5} = 5{,}8V$ (Dinamico) $= V_{c\,Q_6} \Rightarrow R_{c1} = R_{c2} = 9{,}1\,k$

$V_{E7} = 5{,}1V \Rightarrow V_{cQ_7} = 8V = V_{cQ_8} = 8V$ (Dinamico)
⇑ criticità!

$V_{cQ_4} = 15{,}1V \Rightarrow I_c(Q_3 \| Q_4) = 1{,}86\,mA$

$I_c(Q_7) = 0{,}93mA = I_c(Q_8) = 0{,}93mA$

$\Rightarrow R_{c3} = 2{,}2K = R_{c4} = 2{,}2\,k$

Calcolo potenze:

$P_{Q_1} = I_{E1} \cdot V_{CE1} = (0{,}93\,mA)(0{,}7\,V) = 0{,}65\,mW$

$P_{Q_2} = I_{E2} \cdot V_{CE2} = (0{,}93\,mA)(9{,}3\,V) = 8{,}7\,mW$

$P_{Q_3} = P_{Q_4} = I_{E3} \cdot V_{CE3} = (0{,}93\,mA)(15{,}4) = 14\,mW$

$P_{Q_5} = P_{Q_6} = I_{E5} \cdot V_{CE5} = (0{,}47\,mA)(6{,}5\,V) = 3\,mW$

$P_{Q_7} = P_{Q_8} = I_{C7} \cdot V_{CE7} = (0{,}93\,mA)(2{,}9\,V) = 2{,}7\,mW$

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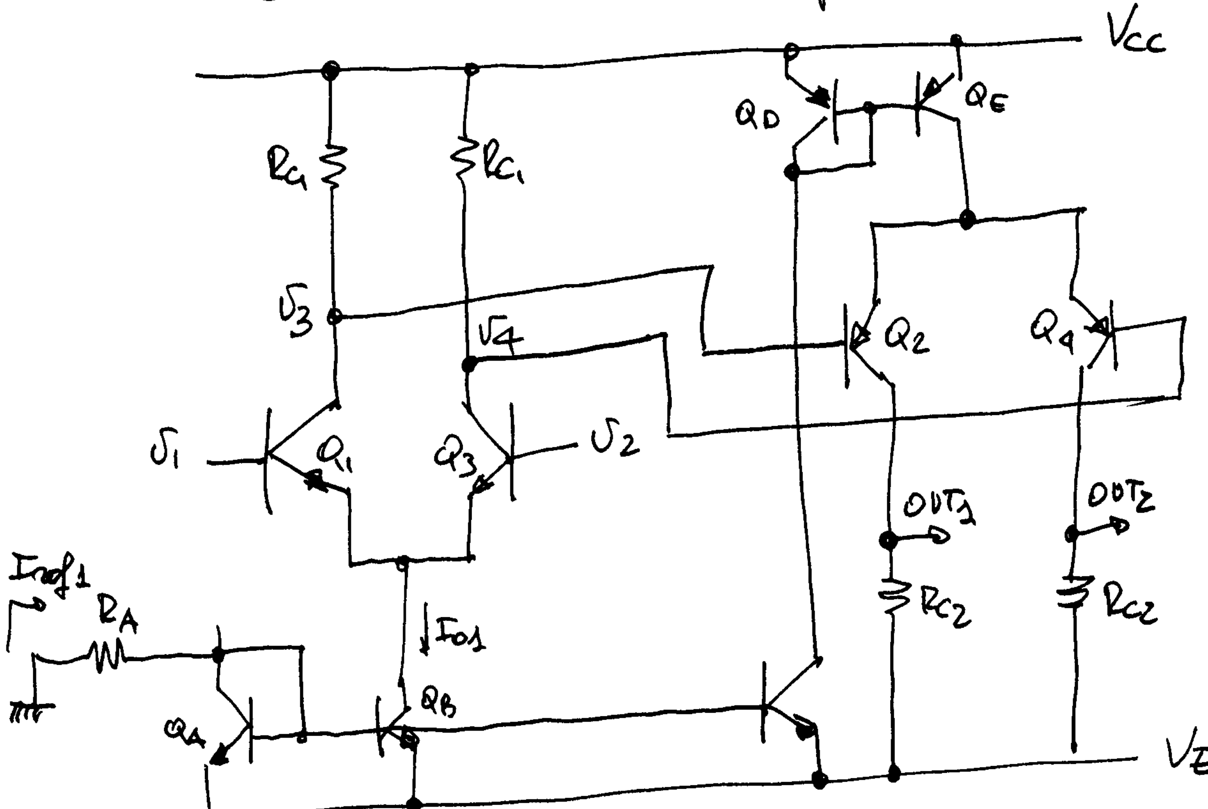
altro Esercizio completo. 2 stadi differenziali



Q_1 e Q_3 npn e Q_2, Q_4 pnp (forniscono il D.C. shifting per guadagno in dinamica)

$Q_A \rightarrow Q_E$ "settano" le correnti in $Q_1 \rightarrow Q_4$

Ricordiamo che:

$A_{dm-se} = \pm g_m \frac{R_C}{2}$ differential-mode e single ended

$A_{CM-SE} \cong \frac{R_C}{2R_o}$ common mode single ended
R_o resistenza inversa di coda del carico attivo

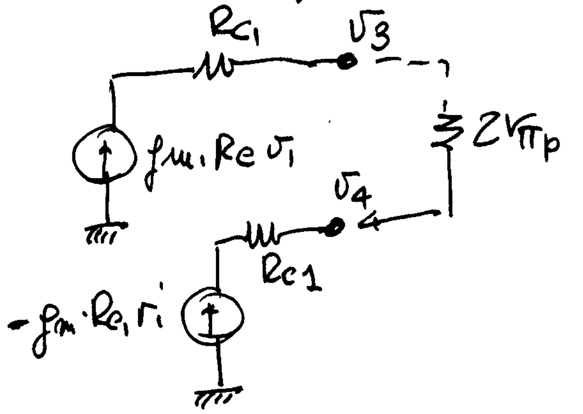
$r_{in-dm} = 2h_{fe} \cdot r_e$ resistenza di ingresso - differential mode

$r_{in-cm} \cong 2h_{fe} \cdot R_o$ altissima sia R_o = resistenza inversa carico attivo di "coda"

$r_{out \cdot se} = R_C$

A_{dm-se1} = guadagno differenziale single ended.

⇒ circuito equivalente Q_1 e Q_3



$A_{dm-se1} = g_m R_{C1} \frac{2r_{\pi p}}{2r_{\pi p} + 2R_{C1}} \cdot g_m R_{C2}/2$

↑ 1° stadio differenziale

↑ 2° stadio single ended

A_{dm-se2} idem per simmetria del differenziale ed uguali transistori.

A_{cm} → prodotto modo comune.

$$= \frac{R_{C2}}{2R_{oE}} \cdot \frac{R_{C1}}{2R_{oB}} \cdot \frac{2h_{fe} r_{oE}}{2h_{fe} r_{oE} + R_{C1}}$$

↑ R_o inversa di Q_E 2° stadio

↑ R_o inversa di Q_B 1° stadio

↑ fattore di attenuazione dovuto all'impedenza del 2° stadio Q_4, Q_E R_o alta fattore ~ 1

$$CMRR = \frac{(g_{m2}R_{C2})(g_{m1}R_{C1})/2}{(R_{C2}/2R_{oE})(R_{C1}/2R_{oB})} \cdot \frac{r_{\pi p}}{r_{\pi p}+R_{C1}} \cdot \frac{2\beta_o R_{oE}+R_{C1}}{2\beta_o R_{oE}}$$

$$= \frac{g_{m2}\, g_{m1}\, r_{\pi p}\, (2\beta_o R_{oE}+R_{C1}) R_{oB}}{(r_{\pi p}+R_{C1})\beta_o} = \frac{g_{m1} R_{oB}(2\beta_p R_{oE}+R_{C1})}{r_{\pi p}+R_{C1}}$$

essendo $g_{m2} \cdot r_{\pi p} = \beta_{op}$

e $R_{oE} >> R_{C1}$ e $r_{\pi p} \sim R_{C1}$

$$CMRR = \frac{g_{m1} R_{oB}(2\beta_{op} R_{oE})}{r_{\pi p}+R_{C1}} \sim g_{m1} g_{m2} R_{oB} R_{oE}$$

CMRR in uscita dell'ordine di $(g_m R_o)^2$