$$\Delta I_C = S_\beta \Delta\beta + S_T \cdot \Delta V_{BE}$$

$$\Delta I_C = \frac{I_C}{\beta_1} \times \frac{R_t + R_E}{R_t + (1+\beta_1)R_E} \Delta\beta - \frac{1}{R_E} \Delta V_{BE} \longrightarrow \boxed{\Delta I_C = \frac{\%۲}{R_E} + \frac{۲}{۵}} \quad \text{II}$$

$$R_t \ll (1+\beta)R_E \xrightarrow{\text{از سری قبل}} R_t = \frac{\beta_{min} \cdot R_E}{۱۰}$$

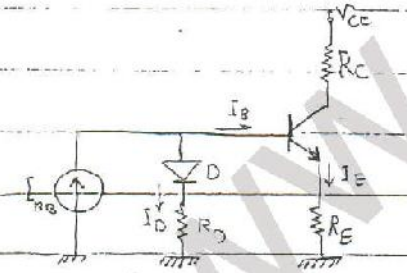
$$\text{I}, \text{II} \longrightarrow R_E = ۴۴\,\Omega, \ \boxed{R_E = ۷۲۵\,\Omega}$$

$$\longrightarrow R_t = ۲٫۹\,k\Omega, \quad I_{C_1} = ۵\,mA, \quad I_{C_2} = ۵٫۴۸\,mA$$

$$\longrightarrow ۵ < I_C < ۵٫۴۸$$

$$\longrightarrow ۵ < \frac{V_t - V_{BE}}{R_E + \frac{R_t}{\beta}} < ۵٫۴۸ \xrightarrow{\text{جبران حرارتی}} ۴٫۷ < V_t < ۴٫۹۲$$

$$\longrightarrow \boxed{\begin{array}{l} V_t = ۴٫۸\,V \\ R_b = ۲٫۸\,k\Omega \\ R_e = ۷۵۵\,\Omega \end{array}}$$



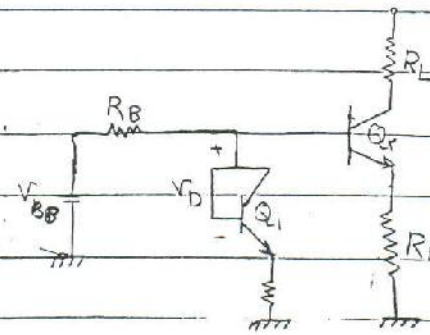
جبران اثر حرارتی:

$$\begin{cases} I_{BB} = I_D + I_B \\ V_D + R_D I_D = V_{BE} + R_E I_E \end{cases}$$

V_{BE} — I_{CBO} — β

$$\longrightarrow I_E = \frac{V_D - V_{BE} + I_{BB} R_D}{R_E + \frac{R_D}{1+\beta}}$$

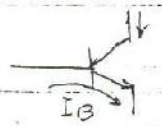
$$\frac{\Delta I_E}{\Delta T} = \frac{\frac{\Delta V_D}{\Delta T} - \frac{\Delta V_{BE}}{\Delta T}}{R_E + R_D/1+\beta} \longrightarrow \frac{\Delta V_D}{\Delta T} - \frac{\Delta V_{BE}}{\Delta T} = K$$

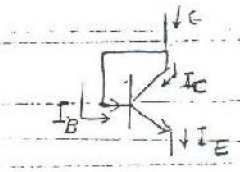


استفاده از ترانزیستور Q_1 به فرم رو برو بجای دیود مدار بالا

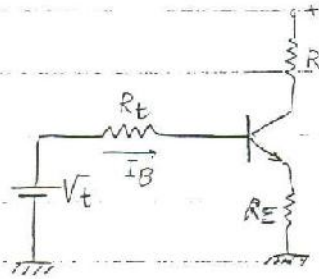
این مزیت را دارد که امپدانس ورودی ترانزیستور کم است

۳۵





$$h_{ie} = \frac{\eta V_T}{I_C} \qquad \frac{h_{ie}}{1+h_{fe}}$$



$$R_t = R_D \| R_B$$

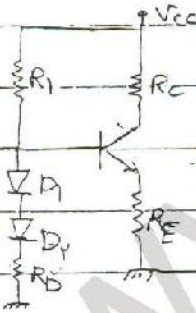
$$V_t = \frac{R_D V_{BB} + R_B V_D}{R_D + R_B}$$

$$V_t = R_t I_B + V_{BE} + R_E I_E$$

$$\longrightarrow I_E = \frac{(V_{BB} R_D + V_D R_B)/(R_B + R_D)}{R_E}$$

$$\longrightarrow \frac{\Delta I_E}{\Delta T} = \frac{1}{R_E}\left[\frac{\Delta V_D}{\Delta V_T}\cdot\frac{R_B}{R_B+R_D} - \frac{\Delta V_{BE}}{\Delta T}\right]$$

$$\frac{\Delta V_D}{\Delta T} = \frac{\Delta V_{BE}}{\Delta T} = -k \longrightarrow \frac{\Delta I_E}{\Delta T} = \frac{K}{R_E}\left[\frac{1}{1+\frac{R_B}{R_D}}\right]$$

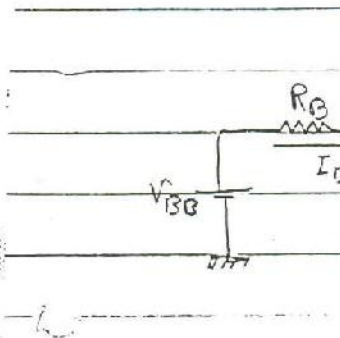


$$V_t = \frac{V_{CC} R_D + 2V_D R_B}{R_D + R_B}$$

$$R_t = R_D \| R_B$$

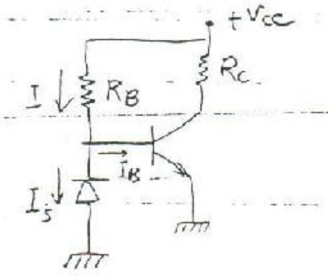
$$I_E = \frac{(V_{CC} R_D + 2V_D R_B)/(R_B + R_D) - V_{BE}}{R_E}$$

$$\frac{\Delta V_D}{\Delta T} = \frac{\Delta V_{BE}}{\Delta T} \longrightarrow \frac{\Delta I_E}{\Delta T} = 0 \longrightarrow R_B = R_D$$



$$\frac{\Delta I_E}{\Delta T} = 0 \longrightarrow \frac{\Delta V_{BE}}{\Delta T} = \frac{\Delta V_D}{\Delta T}$$ تمرین: با فرض اینکه

جبران اثر حرارتی I_{CBO} :

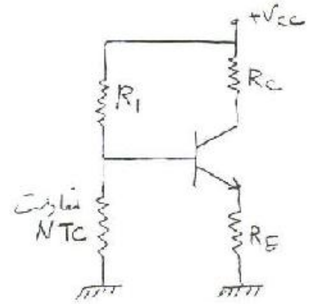


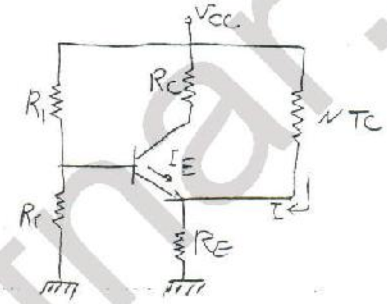
$$\begin{cases} I_C = \beta I_B + (1+\beta) I_{CBO} \\ I_C = \beta (I - I_S) + (1+\beta) I_{EBO} \end{cases}$$

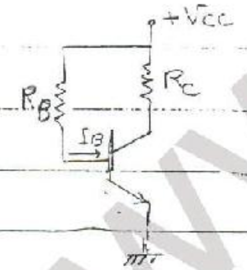
با فرض رفتار معادل دیود و ترانزیستور و β بزرگ

$$\longrightarrow \frac{\Delta I_C}{\Delta T} = -\beta \frac{\Delta I_S}{\Delta T} + (1+\beta) \frac{\Delta I_{CBO}}{\Delta T} \simeq 0 \quad , \quad \beta \gg$$

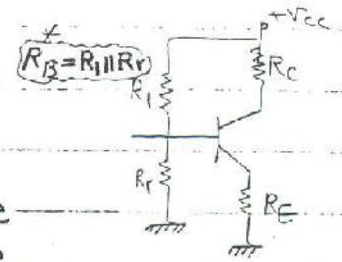
تثبیت کنندگی حرارتی با استفاده از مقاومت‌های NTC , PTC :







$$\Delta I_C = S_I \frac{\Delta I_C}{\Delta I_{CBO}} + \cdots$$



$$S_0 = \frac{\Delta I_C \text{ مدار بدون پایداری}}{\Delta I_C \text{ مدار پایدار}}$$

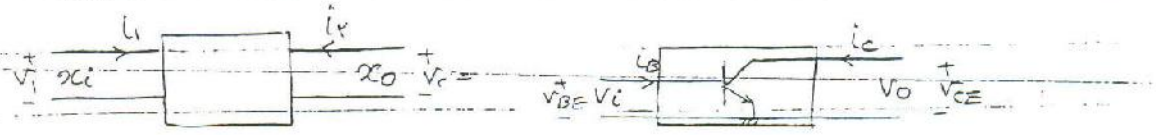
$$\frac{\Delta I_C}{\Delta I_{CEO}} \simeq 1 \longrightarrow I_C = \beta I_B + \overbrace{(1+\beta) I_{CBO}}^{I_{CEO}}$$

$$\rightarrow S_0 = \frac{1}{\left(\frac{R_B^* + R_E(1+\beta)}{R_B^* + R_E}\right)^{-1}} = \frac{R_E(1+\beta)}{R_B^* + R_E} \quad , \quad R_B^* \ll (1+\beta) R_E$$

$$\rightarrow S_0 = \frac{(1+\beta) R_E}{R_B^* + R_E}$$

$$S_0 = 1 + \frac{\beta R_E}{R_E + R_B} \quad , \quad \beta \gg$$

$$S_0 > 10$$



$$Z\ \text{امپدانس}\begin{cases} V_1 = Z_{11} i_1 + Z_{12} i_2 \\ V_2 = Z_{21} i_1 + Z_{22} i_2 \end{cases}$$

$$h\ \text{هیبرید}\begin{cases} V_1 = h_{11} i_1 + h_{12} V_2 \\ i_2 = h_{21} i_1 + h_{22} V_2 \end{cases}$$

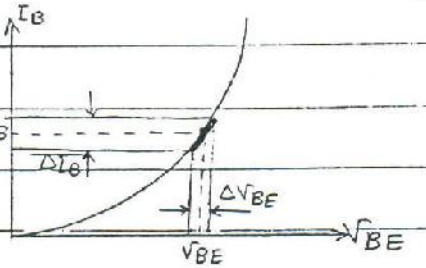
$$Y\ \text{ادمیتانس}\begin{cases} i_1 = y_{11} V_1 + y_{12} V_2 \\ i_2 = y_{21} V_1 + y_{22} V_2 \end{cases}$$

$$\begin{cases} Z_{11} = \dfrac{V_1}{i_1}\Big|_{i_2=0} & \text{امپدانس ورودی خروجی باز} \\ Z_{22} = \dfrac{V_2}{i_2}\Big|_{i_1=0} & \text{امپدانس خروجی ورودی باز} \\ Z_{12} = \dfrac{V_1}{i_2}\Big|_{i_1=0} & \text{امپدانس انتقالی معکوس} \\ Z_{21} = \dfrac{V_2}{i_1}\Big|_{i_2=0} & \text{امپدانس انتقالی مستقیم} \end{cases}$$

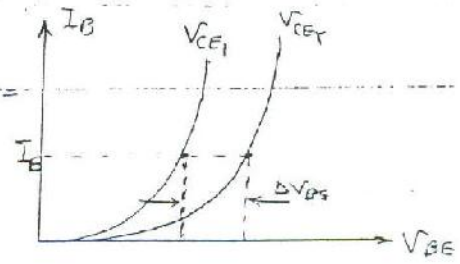
$$\begin{cases} y_{11} = \dfrac{i_1}{V_1}\Big|_{V_2=0} & \text{ادمیتانس ورودی} \\ y_{22} = \dfrac{i_2}{V_2}\Big|_{V_1=0} & \text{ادمیتانس خروجی} \\ y_{12} = \dfrac{i_1}{V_2}\Big|_{V_1=0} & \text{ادمیتانس انتقالی معکوس} \\ y_{21} = \dfrac{i_2}{V_1}\Big|_{V_2=0} & \text{ادمیتانس انتقالی مستقیم} \end{cases}$$

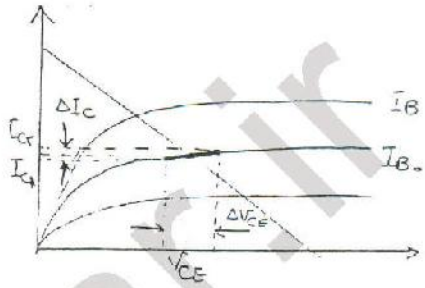
$$\begin{cases} h_{11} = \dfrac{V_1}{i_1}\Big|_{V_2=0} & \text{امپدانس ورودی} \ (h_{ie}) \\ h_{22} = \dfrac{i_2}{V_2}\Big|_{i_1=0} & \text{ادمیتانس خروجی} \ (h_{oe}) \\ h_{12} = \dfrac{V_1}{V_2}\Big|_{i_1=0} & \text{بهره ولتاژ انتقالی معکوس} \ (h_{re}) \\ h_{21} = \dfrac{i_2}{i_1}\Big|_{V_2=0} & \text{بهره جریان انتقالی مستقیم} \ (h_{fe}) \end{cases}$$

$$h_{11} = h_{ie} = \frac{\Delta V_{BE}}{\Delta I_B}\Big|_{V_{CE}\ \text{ثابت}}$$

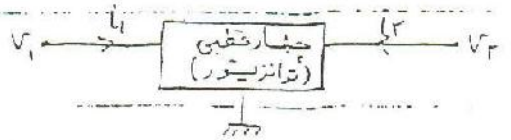


$$h_{11} = h_{re} = \left.\frac{\Delta V_{BE}}{\Delta V_{CE}}\right|_{I_B \text{ ثابت}}$$





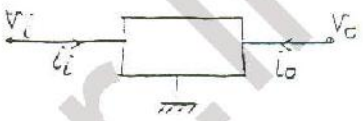
مدار هیبرید:



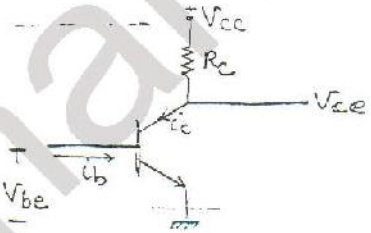
پارامترهای h

$$\begin{cases} V_1 = h_{11} i_1 + h_{12} V_2 \\ i_2 = h_{21} i_1 + h_{22} V_2 \end{cases}$$

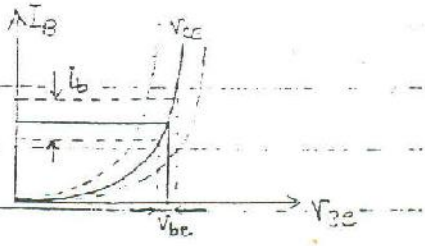
$$\begin{cases} V_i = h_{ie} i_i + h_{re} V_o \\ i_o = h_{fe} i_i + h_{oe} V_o \end{cases}$$

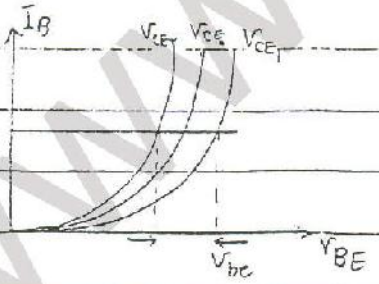


$$\begin{cases} V_{be} = h_{ic} i_b + h_{re} V_{ce} \\ i_c = h_{fe} i_b + h_{oe} V_{ce} \end{cases}$$

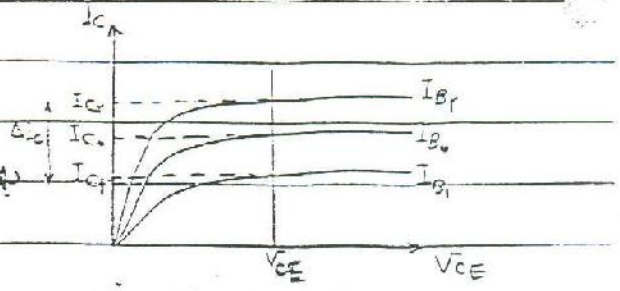


$h_{ie} = \left.\frac{V_{be}}{i_b}\right|_{V_{ce}=0}$ امپدانس ورودی



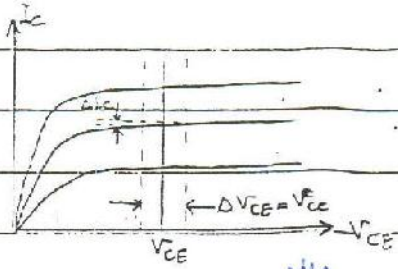


$h_{re} = \left.\frac{V_{be}}{V_{ce}}\right|_{i_b=0}$ بهره ولتاژ معکوس

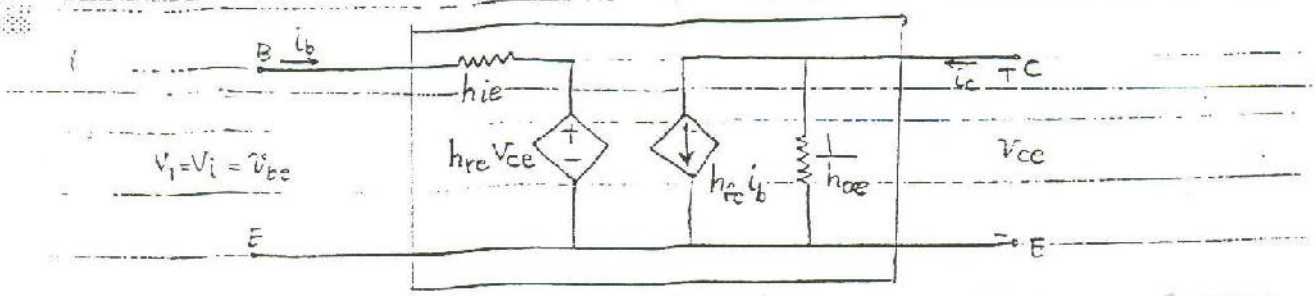


$h_{fe} = \left.\frac{i_c}{i_b}\right|_{V_{ce}=0}$ بهره جریان مستقیم

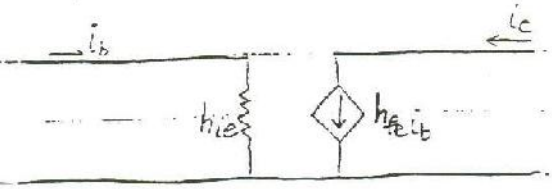
$$\begin{cases} i_b = \Delta I_B = I_{B_2} - I_{B_1} \\ i_c = \Delta I_C = I_{C_2} - I_{C_1} \end{cases}$$



$h_{oe} = \left.\frac{i_c}{V_{ce}}\right|_{i_b=0}$ ادمیتانس خروجی

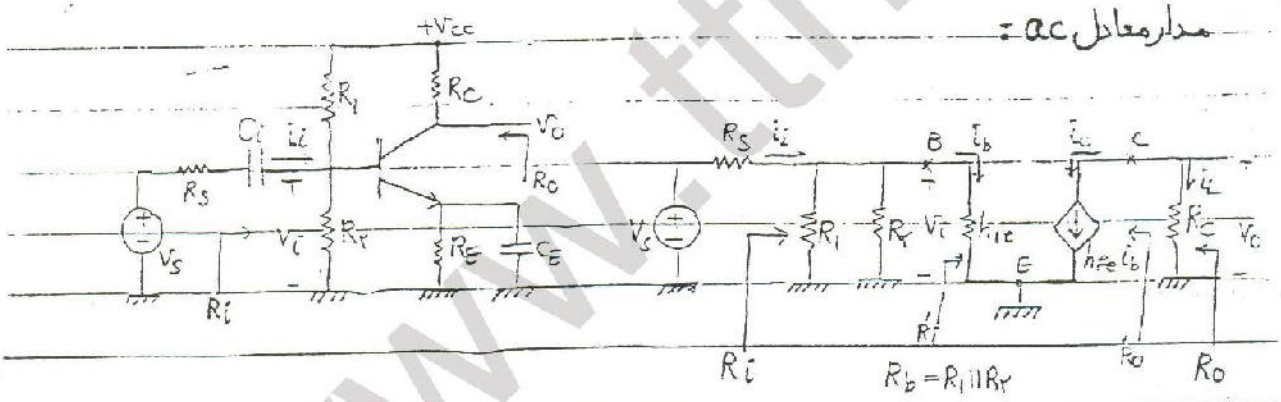


مدل هیبرید C.E (دقیق)



مدل تقریبی

مدار معادل ac :



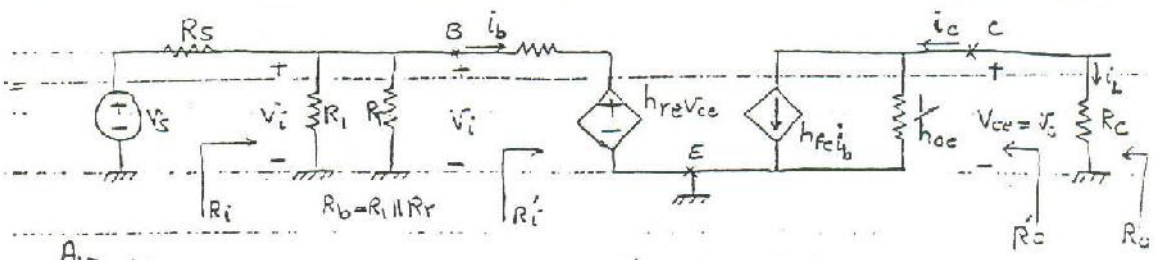
$A_i = \frac{i_L}{i_i}$ گین جریان $\quad A_V = \frac{V_o}{V_i}$ گین ولتاژ

$$A_V = \frac{V_o}{V_i} = \frac{-R_C i_c}{h_{ie} i_b} A_i' \rightarrow A_V = \frac{h_{fe} \cdot R_o}{h_{ie}} = \frac{R_o}{R_i'} A_i'$$

$$A_i = \frac{i_L}{i_i} = \frac{-i_c}{i_b} \times \frac{i_b}{i_i} = -h_{fe} \times \frac{R_b}{R_b + h_{ie}} \rightarrow A_i = -h_{fe} \frac{R_b}{R_b + h_{ie}}$$

$$R_i = \frac{V_i}{i_i} = R_1 \| R_2 \| (R_i') = R_1 \| R_2 \| \left(\frac{V_i}{i_b}\right) = R_1 \| R_2 \| h_{ie} \rightarrow R_i = R_1 \| R_2 \| h_{ie}$$

$$R_o = \left.\frac{V_o}{i_o}\right|_{V_s = 0} = R_o' \| R_C = \infty \| R_C = R_C \rightarrow R_o = R_C$$



$$A_V = \frac{V_o}{V_i} \rightarrow \begin{cases} V_o = -R_c \cdot i_c = -R_c (h_{fe} i_b + V_o h_{oe}) \\ V_i = h_{ie} i_b + h_{re} V_{ce} = h_{ie} i_b + h_{re} V_o \end{cases}$$

$$\rightarrow A_V = \frac{-h_{fe} \left(R_c \| \frac{1}{h_{oe}}\right)}{h_{ie} - h_{re} h_{fe} \left(R_c \| \frac{1}{h_{oe}}\right)}$$

$$R_i = \frac{V_i}{i_i} = R_1 \| R_2 \| R'_i = R_1 \| R_2 \| \frac{V_i}{i_b} = R_1 \| R_2 \| R'_i$$

$$\rightarrow R'_i = h_{ie} - h_{re} h_{fe} \left(R_c \| \frac{1}{h_{oe}}\right)$$

$$\rightarrow R_i = R_1 \| R_2 \| \left(h_{ie} - h_{re} h_{fe} \left(R_c \| \frac{1}{h_{oe}}\right)\right)$$

$$A_i = \frac{i_c}{i_b} \quad , \quad A_V = \frac{R_o}{R'_i} \times A_i$$

$$A_i = \frac{i_c}{i_b} = \frac{i_c}{h_{fe} i_b} \times \frac{h_{fe} i_b}{i_b} = \frac{\frac{1}{h_{oe}}}{\frac{1}{h_{oe}} + R_c} \times h_{fe} \rightarrow A_i = \frac{\frac{1}{h_{oe}}}{\frac{1}{h_{oe}} + R_c} \cdot h_{fe}$$

$$A_{i_s} \triangleq \frac{i_c}{i_i} = \frac{i_c}{i_b} \times \frac{i_b}{i_i} = A_i \times \frac{R_b}{R_b + R'_i} \rightarrow A_{i_s} = A_i \frac{R_b}{R_b + R'_i}$$

$$R_o = \left.\frac{V_o}{i_o}\right|_{V_s = 0} = R_c \| R'_o$$

$$R'_o = \left.\frac{V_o}{i_c}\right|_{V_s = 0} \quad , \quad i_c = h_{fe} i_b + V_o h_{oe} \quad , \quad i_b = \frac{-h_{re} V_o}{h_{ie} + R_s \| R_b} = i_b (h_{ie} + R_s \| R_b)$$

$$\rightarrow Y_o = \frac{1}{R'_o} = h_{oe} \frac{h_{fe} h_{re}}{h_{ie} + R_s \| R_b}$$

مثال عددی: $R_C = 1k\Omega$, $R_S = 100\Omega$, $R_b \gg h_{ie}$

$h_{fe} = \beta = 50$, $h_{ie} = 1100\Omega$, $h_{re} = 2.5 \times 10^{-4}$, $h_{oe} = 25\mu S$

$\rightarrow \frac{1}{h_{oe}} = 40k\Omega$

الف) مقدار A_V , R_i , R'_o , A_i , $R_o = R_C \| R'_o$ را به طور دقیق بدست آورید. ب) با فرض h_{re} h_{oe} تقریباً صفر مقادیر قسمت الف را بدست آورید.

الف)

$$\rightarrow A_V = \frac{-h_{fe}(R_C \| \frac{1}{h_{oe}})}{h_{ie} - h_{re}h_{fe}R_C} = -44$$

$$R_i = R'_i = h_{ie} - h_{re}h_{fe}R_L = 1.09K \simeq 1.1K\Omega$$

$$A_i = -0.94 = \frac{-i_C}{i_b} \overset{\text{طبق فرض}}{\underset{R_C \gg R_L}{\simeq}} \frac{-i_C}{i_L}$$

$$y_o = h_{oe} - \frac{h_{fe}h_{re}}{h_{ie} + R_S \| R_b} = 11.4 \times 10^{-4} S \rightarrow R'_o = \frac{1}{y_o} \simeq 25K$$

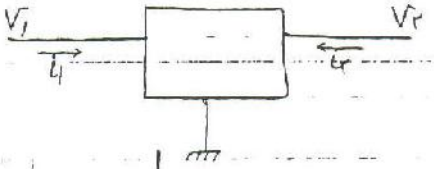
$$R_o = R_C \| R'_o \simeq 1k\Omega$$

$$\rightarrow R_i = R_b \| h_{ie} = 1.1K\Omega$$

$$R_o = R'_o \| R_C = \infty \| R_C = R_C = 1K\Omega$$

$$A_V = \frac{-h_{fe}R_C}{h_{ie}} = -45.5$$

$$A_i = \frac{-i_C}{i_b} = -h_{fe} = -50$$



$$\begin{cases} V_1 = h_{11} i_1 + h_{12} V_2 \\ i_2 = h_{21} i_1 + h_{22} V_2 \end{cases} \qquad \begin{matrix} h_i \\ h_r \\ h_f \\ h_o \end{matrix}$$

Common Collector

$$C.C \rightarrow \begin{cases} V_{bc} = h_{ic} i_b + h_{rc} V_{ec} \\ i_e = h_{fc} i_b + h_{oc} V_{ec} \end{cases}$$

$$h_{ic} = \frac{V_{bc}}{i_b}\Big|_{V_{ec}=0}$$ امپدانس ورودی

$$h_{rc} = \frac{V_{bc}}{V_{ec}}\Big|_{i_b=0}$$ بهره ولتاژ انتقالی معکوس

$$h_{fc} = \frac{i_e}{i_b}\Big|_{V_{ec}=0}$$ بهره جریان مستقیم

$$h_{oc} = \frac{i_e}{V_{ec}}\Big|_{i_b=0}$$ ادمیتانس خروجی

$$V_{bc} = V_{be} + V_{ec} = V_{be} = h_{ie} \times i_b$$

$$\rightarrow h_{ic} = \frac{V_{bc}}{i_b}\Big|_{V_{ec}=0} = \frac{h_{ie} \times i_b}{i_b} = h_{ie} \rightarrow \boxed{h_{ic} = h_{ie}}$$

$$h_{rc} = \frac{V_{be} + V_{ec}}{V_{ec}}\Big|_{i_b=0} = \frac{-h_{re} \cdot V_{ec} + V_{ec}}{V_{ec}} = 1 - h_{re}$$

$$\rightarrow \boxed{h_{rc} = 1 - h_{re}}$$

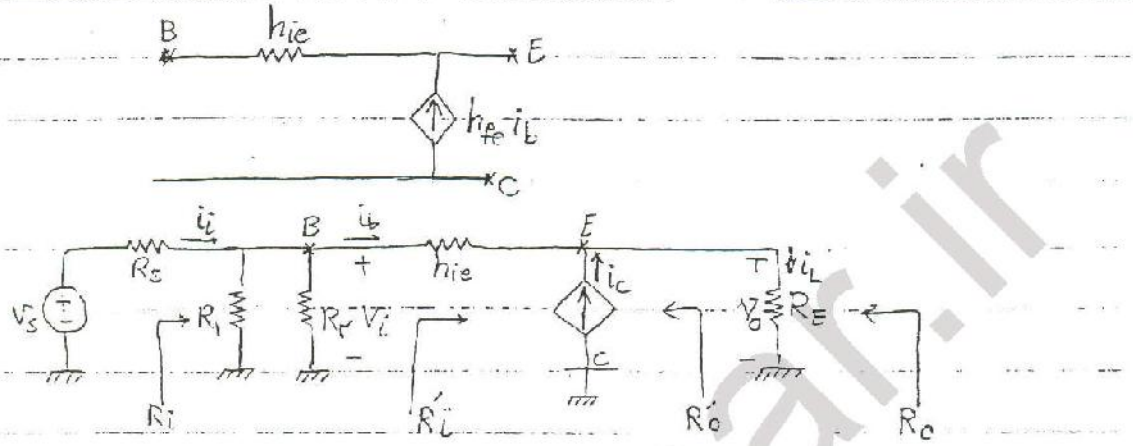
$$V_{be} = \cancel{h_{ie} i_b}^{\,0} + h_{re} V_{ce} = -h_{re} V_{ec} \quad (i_b = 0)$$

$$h_{fc} = \frac{i_e}{i_b}\Big|_{V_{ec}=0} \rightarrow h_{fc} = \frac{-(1+h_{fe}) i_b}{i_b}\Big|_{V_{ec}=0} = -(1+h_{fe})$$

$$V_{ec} = 0 \rightarrow i_e = h_{fe} i_b$$

$$\rightarrow \boxed{h_{fc} = -(1+h_{fe})}$$

$$h_{oc} = \left.\frac{i_e}{v_{ec}}\right|_{i_b=0} = \frac{-i_c}{-i_c \times \frac{1}{h_{oe}}} = h_{oe} \longrightarrow \boxed{h_{oc} = h_{oe}}$$



$$A_i = \frac{i_L}{i_i} = \frac{i_L}{i_b}\cdot\frac{i_b}{i_i} = \frac{i_b + h_{fe} i_b}{i_b}\cdot\frac{R_b}{R_b + R'_i}$$

$$A_v = \frac{V_o}{V_i} = \frac{(1+h_{fe})\, i_b \cdot R_E}{(1+h_{fe}) i_b \cdot R_E + h_{ie} \cdot i_b} = \frac{(1+h_{fe}) R_E}{h_{ie} + (1+h_{fe}) R_E} \simeq 1$$

$$\longrightarrow A_v = \frac{(1+h_{fe})\, R_E}{h_{ie} + (1+h_{fe})\, R_E}$$

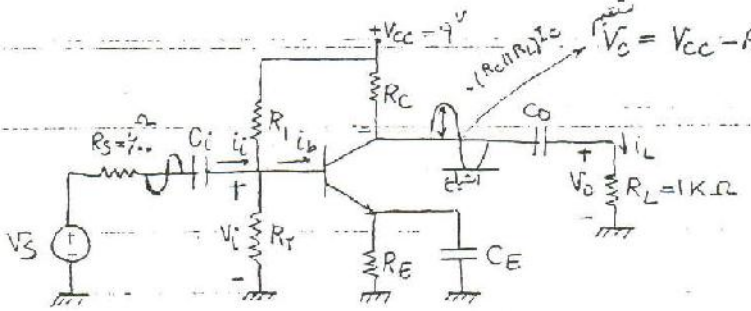
$$R_i = \frac{V_i}{i_i} = R_1 \| R_f \| R'_i$$

$$R'_i = \frac{V_i}{i_b} = \frac{(1+h_{fe}) i_b \cdot R_E + h_{ie} \cdot i_b}{i_b} = (1+h_{fe}) R_E + h_{ie}$$

$$R_o = \left.\frac{V_o}{i_o}\right|_{V_s = 0} = R'_o \| R_E$$

$$R'_o = \left.\frac{V_o}{i_e}\right|_{V_s=0} = \frac{-i_b \cdot h_{ie} - i_b \cdot R_1 \| R_f \| R_s}{-(1+h_{fe})\, i_b} = \frac{h_{ie} + R_1 \| R_f \| R_s}{(1+h_{fe})}$$

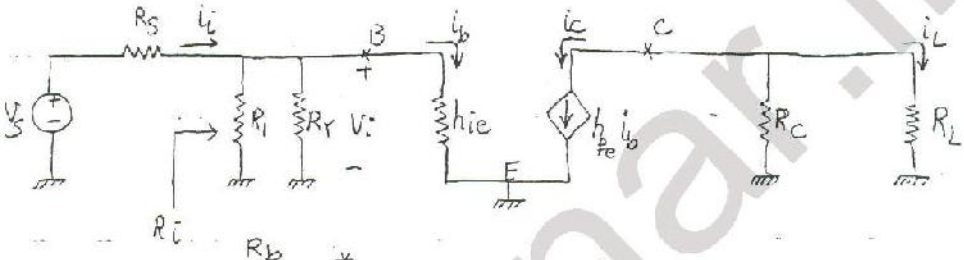
مدار مقابل را با داده های زیر طراحی کنید.



$-(R_C \| R_L) = -0.5$ ، نتیجه $V_C = V_{CC} - R_C I_C$

داده ها:

$$\beta = h_{fe} = 200 \quad , \quad \frac{i_L}{i_i} = A_i \geq 120 \quad , \quad R_i \geq 2\,K\Omega \quad , \quad V_{o_{pp}} \geq 2\,V$$



برای راحتی کار از تقریب مقابل استفاده می کنیم: $\frac{R_b}{R_1 \| R_b} \overset{*}{\gg} h_{ie}$

$$A_i \geq 120 \longrightarrow \frac{i_L}{i_i} = \frac{i_L}{i_b} = \frac{i_L}{i_C} \times \frac{i_C}{i_b} = \frac{-R_C}{R_C + R_L} \times h_{fE} \geq 120$$

$$\longrightarrow R_C \geq 1.0\,K\Omega$$

مقاومتهای استاندارد: 1.8 K، 2.2 K، 2.7 K

$$R_C = \boxed{2.7\ K}$$

$$R_i \overset{*}{\simeq} h_{ie} \geq 2\,K\Omega \quad , \quad h_{ie} = \frac{2V_T}{I_C}\beta \geq 2K\Omega \longrightarrow \boxed{I_C \leq 2.5\ mA} \quad (1)$$

$$(R_C \| R_L) I_C \geq 1\,V \longrightarrow \boxed{I_C \geq 1.3\ mA} \quad (2) \leftarrow V_{o_p}^{+}$$

چون $V_{CE_{sat}}$ را نداده آن را صفر می گیریم $V_{CC} = R_C I_C + V_{CE} + R_E I_C$

$$\longrightarrow V_{CE} = V_{CC} - I_C(R_C + R_E) \geq 1\,V \longrightarrow I_C \leq \frac{8}{R_C + R_E}$$

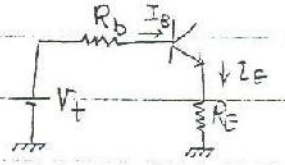
$$\text{if } R_E = 0 \longrightarrow \boxed{I_C \leq 2.99\ mA} \quad (3) \leftarrow V_{o_p}^{-}$$

$$(1), (2), (3) \longrightarrow I_C = 2\,mA$$

$$I_C \leq \frac{\Delta}{R_E + R_C} \xrightarrow{I_C = 2\,mA} \boxed{R_E = 1\,k\Omega}$$

$$R_b = \frac{\beta_{min} R_E}{10} = 20\,k\Omega$$

مدار DC:



$$\begin{cases} R_1 = R_b \dfrac{V_{CC}}{V_t} \\ R_2 = \dfrac{R_b}{1 - \frac{V_t}{V_{CC}}} \end{cases} , \quad V_t = R_b I_B + V_{BE} + R_E I_E = 2{,}9\,V$$

$$\longrightarrow R_1 = 47\,k\Omega \;,\; R_2 = 21{,}9\,k\Omega$$

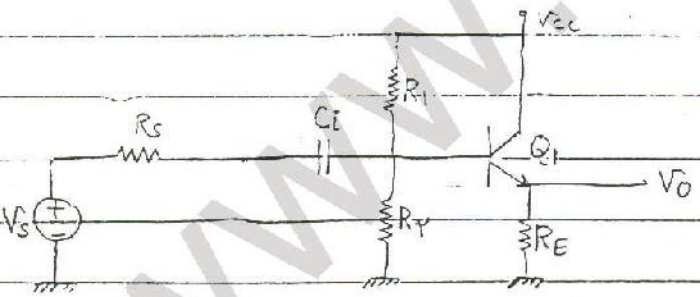
$R_1 = 47\,k$ استاندارد

$R_2 = 22\,k$ استاندارد

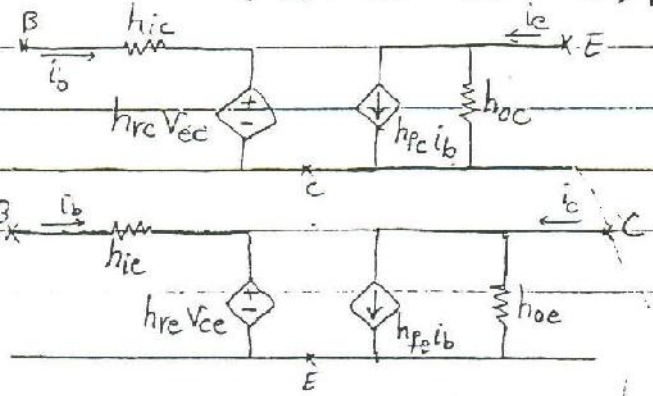
اگر اعداد بدست آمده را در مسئله قرار داده و یکبار دیگر تحلیل کنیم خواهیم دید که:

$$\longrightarrow R_i = R_1 \| R_2 \| h_{ie} = 2{,}9\,k\Omega \;,\; A_i = -12{,}2 \;,\; V_{CE} = 1{,}4\,V$$

تقویت کنندهٔ کلکتور مشترک:



با فرض اینکه پارامترهای هیبرید را در تقویت کنندهٔ امیتر مشترک داریم، پارامترهای هیبرید کلکتور مشترک را بدست می آوریم ($h_{oc}, h_{rc}, h_{fc}, h_{ic}$).



مثال: تقویت‌کننده بیس مشترک بایپس شده:

$R_E = 1K$, $R_S = 10\Omega$

$h_{ib} = 21.4\Omega$, $R_L = 1K$, $h_{rb} = 2.5 \times 10^{-4}$, $h_{fb} = -0.98$

$h_{ob} = 0.49 \times 10^{-6} S$

$\rightarrow A_i = -h_{fb} = 0.98$

$A_V = \frac{-h_{fb} R_L'}{h_{ib}} = 480$, $R_L' = R_L \| R_C$

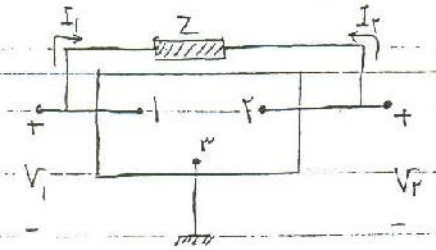
$R_O = \frac{1}{h_{ob}} \| R_C = R_C = 1K\Omega$

$R_i = h_{ib} \| R_E \simeq h_{ib} = 21.4$, $A_{VS} = \frac{V_o}{V_S} = \frac{V_o}{V_i} \cdot \frac{V_i}{V_S}$

$A_{VS} = A_V \cdot \frac{R_i}{R_i + R_S} = 31.2$

نوع تقویت‌کننده	A_i	A_V	R_i	R_O	
C.E با خازن بای‌پاس	h_{fe} بالا	$-\frac{h_{fe}}{h_{ie}} R_C \gg$ بالا	متوسط	بالا	با مقاومت‌های بایاس متوسط
C.E بدون خازن	متوسط	پائین	بالا	بالا	
C.C	متوسط	$\simeq 1$	بالا	پائین	مد
C.B با خازن بیس	$\simeq 1$	بالا	پائین	بالا	

قضیهٔ میلر:

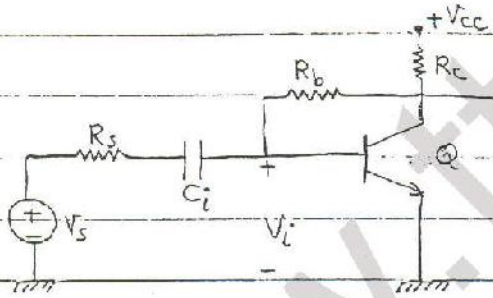


$$\begin{cases} \frac{V_2}{V_1} = K \\ I_1 = -I_2 = \frac{V_1 - V_2}{Z} \end{cases} \longrightarrow Z_1 = \frac{V_1}{I_1} \;,\; Z_2 = \frac{V_2}{I_2} = \frac{K V_1}{V_2}$$

$$\longrightarrow Z_1 = \frac{Z}{1-K}$$

$$Z_2 = \frac{Z}{1-\frac{1}{K}} = \frac{KZ}{K-1}$$

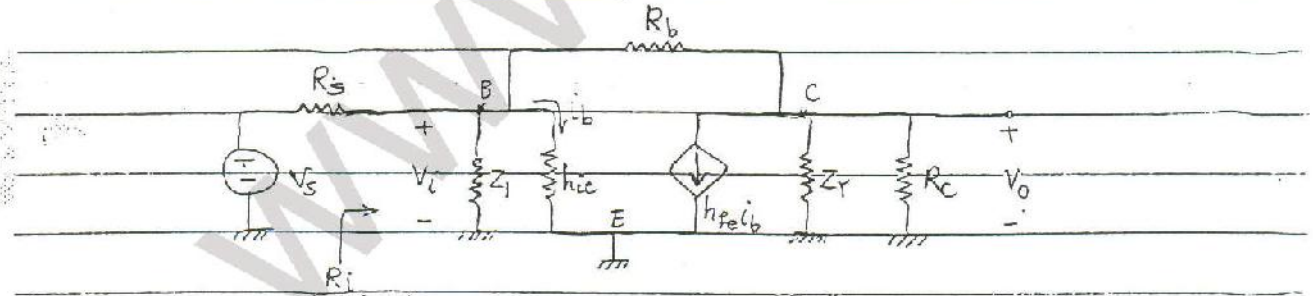
مثال:



$A_V = ?$

$A_{VS} = ?$

$R_i = ?$



$$Z_1 = \frac{Z}{1-K} \;,\; Z_2 = \frac{KZ}{K-1} \overset{\text{با فرض } |K| \gg 1}{\simeq} Z$$

$h_{ie} = 1\text{K}\Omega$

$h_{fe} = 100$

$(h_{oe})^{-1} = 40\text{K}$

$R_b = 200\text{K}$

$R_C = 10\text{K}$

$R_S = 10\text{K}$

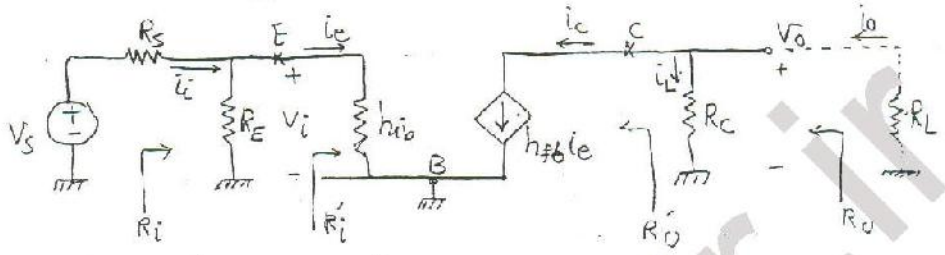
$$A_V = \frac{V_o}{V_i} = \frac{-h_{fe} i_b \left(\frac{1}{h_{oe}} \,\|\, Z_2 \,\|\, R_C\right)}{i_b h_{ie}} \simeq -312$$

$$R_i = Z_1 \,\|\, h_{ie} = 30.19\ \Omega$$

$$A_{VS} = \frac{V_o}{V_S} = \frac{V_o}{V_i} \cdot \frac{V_i}{V_S} = A_V \cdot \frac{R_i}{R_i + R_S} = -12.4\ \Omega$$

$$h_{ib} = \frac{v_{eb}}{i_e} = \frac{h_{ie}}{1+h_{fe}} \quad , \quad h_{rb} = \frac{v_{eb}}{v_{cb}} = \frac{h_{ie}h_{oe}}{1+h_{fe}} - h_{re}$$

$$h_{fb} = \frac{i_c}{i_e} = \frac{-h_{fe}}{1+h_{fe}} \quad , \quad h_{ob} = \frac{i_c}{v_{cb}} = \frac{h_{oe}}{1+h_{fe}}$$



$$A_i = \frac{i_L}{i_i} = \frac{i_L}{i_c} \cdot \frac{i_c}{i_e} \cdot \frac{i_e}{i_i} = -1 \times h_{fb} \times \frac{R_E}{R_E + h_{ib}}$$

$$\longrightarrow A_i = \frac{-h_{fb}R_E}{R_E + h_{ib}} \simeq -h_{fb}$$

$$R_i = \frac{V_i}{i_i} = R_E \,||\, R'_i$$

$$R'_i = \frac{V_i}{i_e} = \frac{i_e h_{ib}}{i_e} = h_{ib} \longrightarrow R'_i = h_{ib}$$

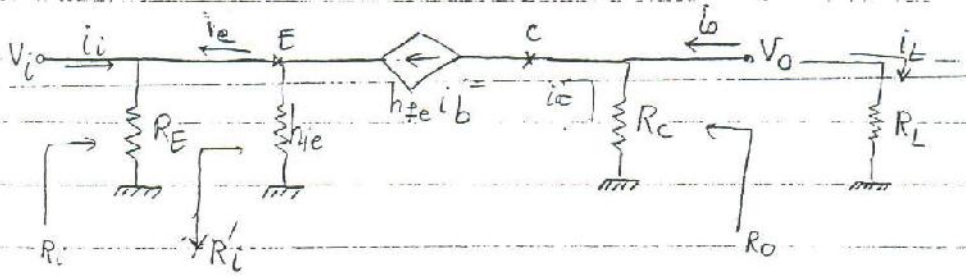
$$\longrightarrow R_i = R_E \,||\, h_{ib} \simeq h_{ib}$$

$$A_V = \frac{V_o}{V_i} = \frac{-R_C i_c}{h_{ib} i_e} = \frac{\overbrace{h_{fb}}^{\text{جریان منفی}}}{h_{ib}} R_C = -\frac{h_{fe}}{h_{ie}} R_C \longrightarrow A_V = -\frac{h_{fe}R_C}{h_{ie}}$$

$$A_V = A_i \frac{R_C}{R_i}$$ راه دیگر برای بدست آوردن A_V :

$$R_o = \left.\frac{V_o}{i_o}\right|_{V_S=0} = R_C \,||\, R'_o = R_C \longrightarrow R_o = R_C$$

$$R'_o = \left.\frac{V_o}{i_c}\right|_{V_S=0} = \infty \longrightarrow R'_o = \infty$$



$$A_i = \frac{i_c}{i_i} = \frac{i_c}{i_e} \cdot \frac{i_e}{i_i} = \frac{h_{fe} i_b}{(1+h_{fe}) i_b} \times \frac{-R_E}{R_E + R'_i} = \frac{-h_{fe}}{1+h_{fe}}$$

$$\longrightarrow A_i = -\frac{h_{fe}}{1+h_{fe}}$$

$$R_i = \frac{V_i}{i_i} = R_E \| R'_i = R_E \| \frac{V_i}{-i_e} = R_E \| \frac{h_{ie}}{1+h_{fe}} \simeq \frac{h_{ie}}{1+h_{fe}}$$

$$\longrightarrow R_i = R_E \| \frac{h_{ie}}{1+h_{fe}} \simeq \frac{h_{ie}}{1+h_{fe}}$$

$$R'_i = \frac{-i_b h_{ie}}{-(1+h_{fe}) i_b} = \frac{h_{ie}}{1+h_{fe}} \longrightarrow R'_i = \frac{h_{ie}}{1+h_{fe}}$$

$$A_V = \frac{V_o}{V_i} = \frac{-R_C i_c}{-i_b h_{ie}} = \frac{h_{fe}}{h_{ie}} R_C \longrightarrow A_V = \frac{h_{fe}}{h_{ie}} R_C$$

$$R_o = \frac{V_o}{i_o}\Big|_{V_s=0} = R_C \| R'_o = R_C \| \frac{V_o}{i_i} \simeq R_C \longrightarrow R_o \simeq R_C$$

اگر خازن C_b را از مدار برداریم آن گاه:

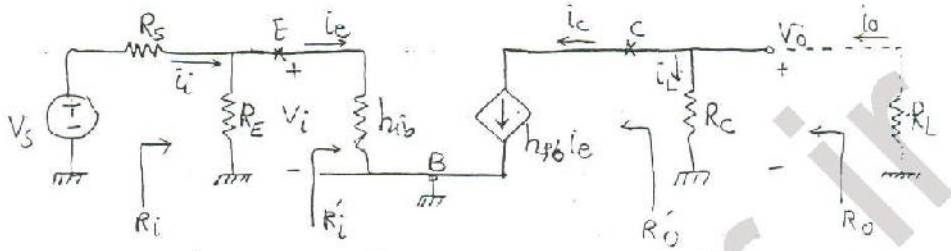
$$R_i = \frac{V_i}{i_i} = R_E \| R'_i = R_E \| \frac{V_i}{-i_e} = R_E \| \frac{h_{ie} + R_b}{1+h_{fe}} = \frac{h_{ic} + R_b}{1+h_{fe}}$$

$$R'_i = \frac{-i_b h_{ie} - i_b (R_b)}{-(1+h_{fe}) i_b} = \frac{h_{ic} + R_b}{1+h_{fe}}$$

$$A_V = \frac{V_o}{V_i} = \frac{-R_C i_c}{-i_b h_{ie} - i_b R_b} = \frac{h_{fe} R_C}{h_{ie} + R_b}$$

$$h_{ib} = \frac{v_{eb}}{i_e} = \frac{h_{ie}}{1+h_{fe}} \quad , \quad h_{rb} = \frac{v_{eb}}{v_{cb}} = \frac{h_{ie}h_{oe}}{1+h_{fe}} - h_{re}$$

$$h_{fb} = \frac{i_c}{i_e} = \frac{-h_{fe}}{1+h_{fe}} \quad , \quad h_{ob} = \frac{i_c}{v_{cb}} = \frac{h_{oe}}{1+h_{fe}}$$



$$A_i = \frac{i_L}{i_i} = \frac{i_L}{i_c} \cdot \frac{i_c}{i_e} \cdot \frac{i_e}{i_i} = -1 \times h_{fb} \times \frac{R_E}{R_E + h_{ib}}$$

$$\longrightarrow A_i = \frac{-h_{fb}R_E}{R_E + h_{ib}} \simeq -h_{fb}$$

$$R_i = \frac{V_i}{i_i} = R_E \,||\, R'_i$$

$$R'_i = \frac{V_i}{i_e} = \frac{i_e h_{ib}}{i_e} = h_{ib} \longrightarrow R'_i = h_{ib}$$

$$\longrightarrow R_i = R_E \,||\, h_{ib} \simeq h_{ib}$$

$$A_V = \frac{V_o}{V_i} = \frac{-R_C i_c}{h_{ib} i_e} = \frac{h_{fb}}{h_{ib}} R_C = -\frac{h_{fe}}{h_{ie}} R_C \longrightarrow A_V = \frac{-h_{fe}R_C}{h_{ie}}$$

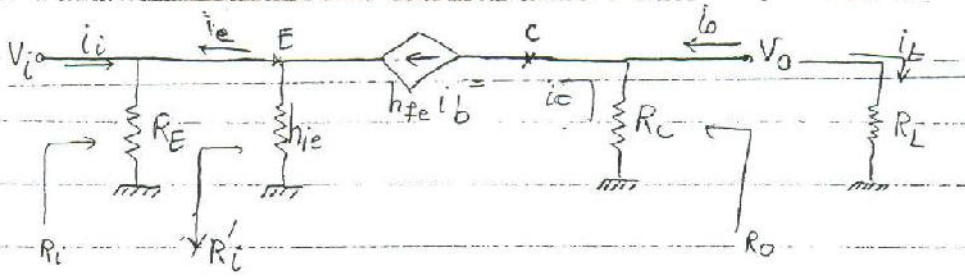
(عدد منفی)

$$A_V = A_i \frac{R_C}{R_i}$$

راه دیگر برای بدست آوردن A_V :

$$R_o = \left.\frac{V_o}{i_o}\right|_{V_S=0} = R_C \,||\, R'_o = R_C \longrightarrow R_o = R_C$$

$$R'_o = \left.\frac{V_o}{i_c}\right|_{V_S=0} = \infty \longrightarrow R'_o = \infty$$



$$A_i = \frac{i_c}{i_i} = \frac{i_c}{i_e} \cdot \frac{i_e}{i_i} = \frac{h_{fe} i_b}{(1+h_{fe}) i_b} \times \frac{-R_E}{R_E + R'_i} = \frac{-h_{fe}}{1+h_{fe}}$$

$$\longrightarrow A_i = -\frac{h_{fe}}{1+h_{fe}}$$

$$R_i = \frac{V_i}{i_i} = R_E \| R'_i = R_E \| \frac{V_i}{-i_e} = R_E \| \frac{h_{ie}}{1+h_{fe}} \simeq \frac{h_{ie}}{1+h_{fe}}$$

$$\longrightarrow R_i = R_E \| \frac{h_{ie}}{1+h_{fe}} \simeq \frac{h_{ie}}{1+h_{fe}}$$

$$R'_i = \frac{-i_b h_{ie}}{-(1+h_{fe}) i_b} = \frac{h_{ie}}{1+h_{fe}} \longrightarrow R'_i = \frac{h_{ie}}{1+h_{fe}}$$

$$A_V = \frac{V_o}{V_i} = \frac{-R_C i_c}{-i_b h_{ie}} = \frac{h_{fe}}{h_{ie}} R_C \longrightarrow A_V = \frac{h_{fe}}{h_{ie}} R_C$$

$$R_o = \frac{V_o}{i_o}\Big|_{V_s=0} = R_C \| R'_o = R_C \| \frac{V_o}{i_i} = R_C \longrightarrow R_o = R_C$$

اگر خازن C_b را از مدار برداریم آن گاه:

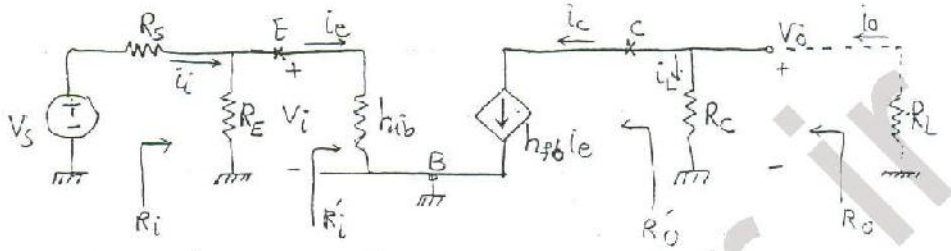
$$R_i = \frac{V_i}{i_i} = R_E \| R'_i = R_E \| \frac{V_i}{-i_e} = R_E \| \frac{h_{ie} + R_b}{1+h_{fe}} = \frac{h_{ie} + R_b}{1+h_{fe}}$$

$$R'_i = \frac{-i_b h_{ie} - i_b (R_b)}{-(1+h_{fe}) i_b} = \frac{h_{ie} + R_b}{1+h_{fe}}$$

$$A_V = \frac{V_o}{V_i} = \frac{-R_C i_c}{-i_b h_{ie} - i_b R_b} = \frac{h_{fe} R_C}{h_{ie} + R_b}$$

$$h_{ib} = \frac{v_{eb}}{i_e} = \frac{h_{ie}}{1+h_{fe}} \qquad h_{rb} = \frac{v_{eb}}{v_{cb}} = \frac{h_{ie}h_{oe}}{1+h_{fe}} - h_{re}$$

$$h_{fb} = \frac{i_c}{i_e} = \frac{-h_{fe}}{1+h_{fe}} \qquad h_{ob} = \frac{i_c}{v_{cb}} = \frac{h_{oe}}{1+h_{fe}}$$



$$A_i = \frac{i_L}{i_i} = \frac{i_L}{i_c}\cdot\frac{i_c}{i_e}\cdot\frac{i_e}{i_i} = -1 \times h_{fb} \times \frac{R_E}{R_E+h_{ib}}$$

$$\longrightarrow A_i = \frac{-h_{fb}R_E}{R_E+h_{ib}} \simeq -h_{fb}$$

$$R_i = \frac{V_i}{i_i} = R_E \,||\, R'_i$$

$$R'_i = \frac{V_i}{i_e} = \frac{i_e h_{ib}}{i_e} = h_{ib} \longrightarrow R'_i = h_{ib}$$

$$\longrightarrow R_i = R_E \,||\, h_{ib} \simeq h_{ib}$$

$$A_V = \frac{V_o}{V_i} = \frac{-R_C i_c}{h_{ib} i_e} = \frac{h_{fb}}{h_{ib}} R_C = -\frac{h_{fe}}{h_{ie}} R_C \longrightarrow A_V = \frac{-h_{fe}R_C}{h_{ie}}$$

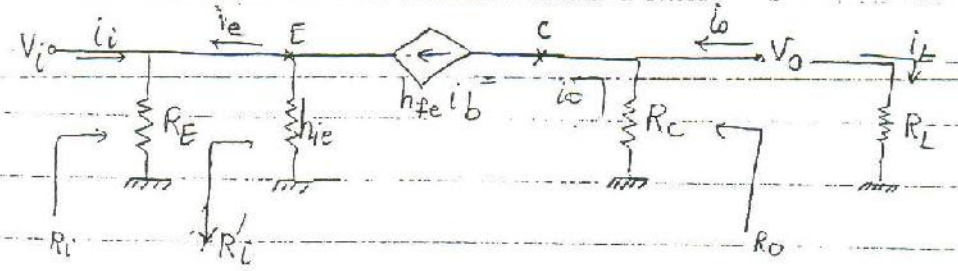
(مقاومت منفی)

$$A_V = A_i \frac{R_C}{R_i}$$

راه دیگر برای بدست آوردن A_V :

$$R_o = \left.\frac{V_o}{i_o}\right|_{V_S=0} = R_C \,||\, R'_o = R_C \longrightarrow R_o = R_C$$

$$R'_o = \left.\frac{V_o}{i_c}\right|_{V_S=0} = \infty \longrightarrow R'_o = \infty$$



$$A_i = \frac{i_c}{i_i} = \frac{i_c}{i_e} \cdot \frac{i_e}{i_i} = \frac{h_{fe} i_b}{(1+h_{fe}) i_b} \times \frac{-R_E}{R_E + R'_i} = \frac{-h_{fe}}{1+h_{fe}}$$

$$\longrightarrow A_i = -\frac{h_{fe}}{1+h_{fe}}$$

$$R_i = \frac{V_i}{i_i} = R_E \| R'_i = R_E \| \frac{V_i}{-i_e} = R_E \| \frac{h_{ie}}{1+h_{fe}} \simeq \frac{h_{ie}}{1+h_{fe}}$$

$$\longrightarrow R_i = R_E \| \frac{h_{ie}}{1+h_{fe}} \simeq \frac{h_{ie}}{1+h_{fe}}$$

$$R'_i = \frac{-i_b h_{ie}}{-(1+h_{fe}) i_b} = \frac{h_{ie}}{1+h_{fe}} \longrightarrow R'_i = \frac{h_{ie}}{1+h_{fe}}$$

$$A_V = \frac{V_o}{V_i} = \frac{-R_C i_c}{-i_b h_{ie}} = \frac{h_{fe}}{h_{ie}} R_C \longrightarrow A_V = \frac{h_{fe}}{h_{ie}} R_C$$

$$R_o = \frac{V_o}{i_o}\Big|_{V_s=0} = R_C \| R'_o = R_C \| \frac{V_o}{i_i} \simeq R_C \longrightarrow R_o \simeq R_C$$

اگر خازن C_b را از مدار برداریم آن گاه

$$R_i = \frac{V_i}{i_i} = R_E \| R'_i = R_E \| \frac{V_i}{-i_e} = R_E \| \frac{h_{ie} + R_b}{1+h_{fe}} = \frac{h_{ie} + R_b}{1+h_{fe}}$$

$$R'_i = \frac{-i_b h_{ie} - i_b (R_b)}{-(1+h_{fe}) i_b} = \frac{h_{ie} + R_b}{1+h_{fe}}$$

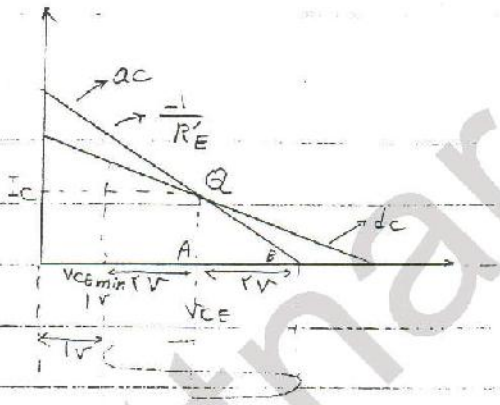
$$A_V = \frac{V_o}{V_i} = \frac{-R_C i_c}{-i_b h_{ie} - i_b R_b} = \frac{h_{fe} R_C}{h_{ie} + R_b}$$

$$A_V = \frac{(1+h_{fe})(R_E \| R_L)}{h_{ie} + (1+h_{fe})(R_E \| R_L)} > 0.98 \longrightarrow \frac{h_{fe}(R_E \| R_L)}{\frac{\eta V_T \beta}{I_C}_{h_{ie}} + h_{fe}(R_E \| R_L)} > 0.98$$

$$\longrightarrow 1 + \frac{1}{R_E} < 0.085 I_C$$

$$V_{CC} = R_E I_C + V_{CE} \longrightarrow I_C \underset{(*)}{=} \frac{9 - V_{CE}}{R_E}$$

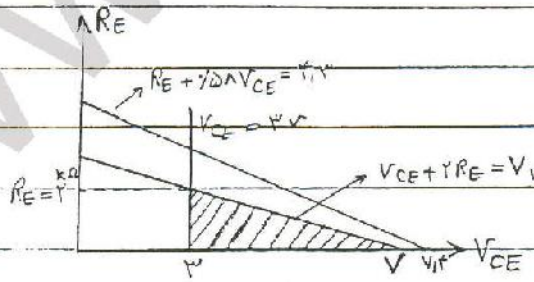
$$\longrightarrow R_E + 0.085 V_{CE} < 4.3 \ V \quad (1)$$



$$\longrightarrow \boxed{V_{CE} \geq 2\ V} \ (2) \qquad , \quad AB = I_C \cdot R'_E > 2\ V \qquad , \quad R'_E = \frac{R_E \cdot R_L}{R_E + R_L}$$

$$\longrightarrow I_C \cdot \frac{R_E}{1 + R_E} > 2\ V$$

$$(*) \longrightarrow \boxed{2R_E + V_{CE} < V_T} \ (3)$$



$$\longrightarrow R_E = 1.2\ k\Omega \text{ (مقاومت استاندارد)} \qquad , \quad V_{CE} = 4\ V \qquad , \quad I_C = \frac{V_{CC} - V_{CE}}{R_E} = 4.2\ mA$$

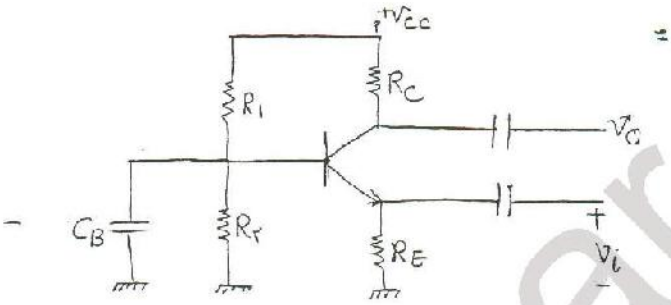
$$R_i = R'_i \| R_b = \left[h_{ie} + (1+h_{fe})(R_E \| R_L)\right] \| R_b > 1.5\ k$$

$$, \quad h_{ie\,min} = \frac{\eta V_T \beta_{min}}{I_C} = 1.44\ k\Omega \longrightarrow R_b > 18.1\ k\Omega$$

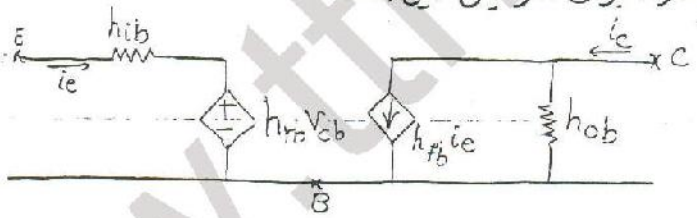
$$R_b = \frac{\beta_{min} \cdot R_E}{10} \simeq 18\,k\Omega \longrightarrow R_1 \| R_2 = 18\,k\Omega$$

با اغماض ← $R_1 = 30k$ (استاندارد: ۳۳k) ، $R_2 = 50k$ (استاندارد: ۵۶k)

تقویت کنندهٔ بیس مشترک :



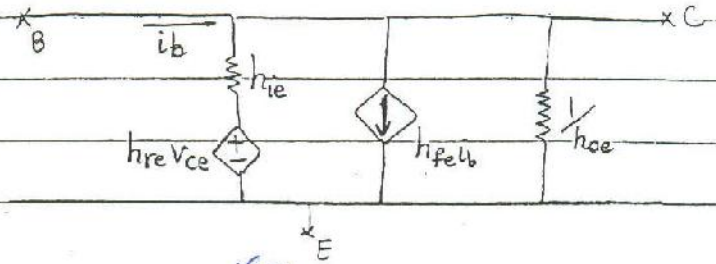
استفاده از خازن C_B صرفاً برای افزایش گین است.



$$\begin{cases} V_{eb} = h_{ib} \cdot i_e + h_{rb} V_{cb} \\ i_c = h_{fb} i_e + V_{cb} h_{ob} \end{cases}$$

$$h_{ib} = \left.\frac{V_{eb}}{i_e}\right|_{V_{cb}=0} \quad , \quad h_{rb} = \left.\frac{V_{eb}}{V_{cb}}\right|_{i_e=0}$$

$$h_{fb} = \left.\frac{i_c}{i_e}\right|_{V_{cb}=0} \quad , \quad h_{ob} = \left.\frac{i_e}{V_{cb}}\right|_{i_e=0}$$



تمرین: پارامترهای هیبرید را محاسبه کنید.

جواب:

$$h_{ib} = \frac{h_{ie}}{h_{ie}h_{oe} + (1+h_{fe})(1-h_{re})}$$

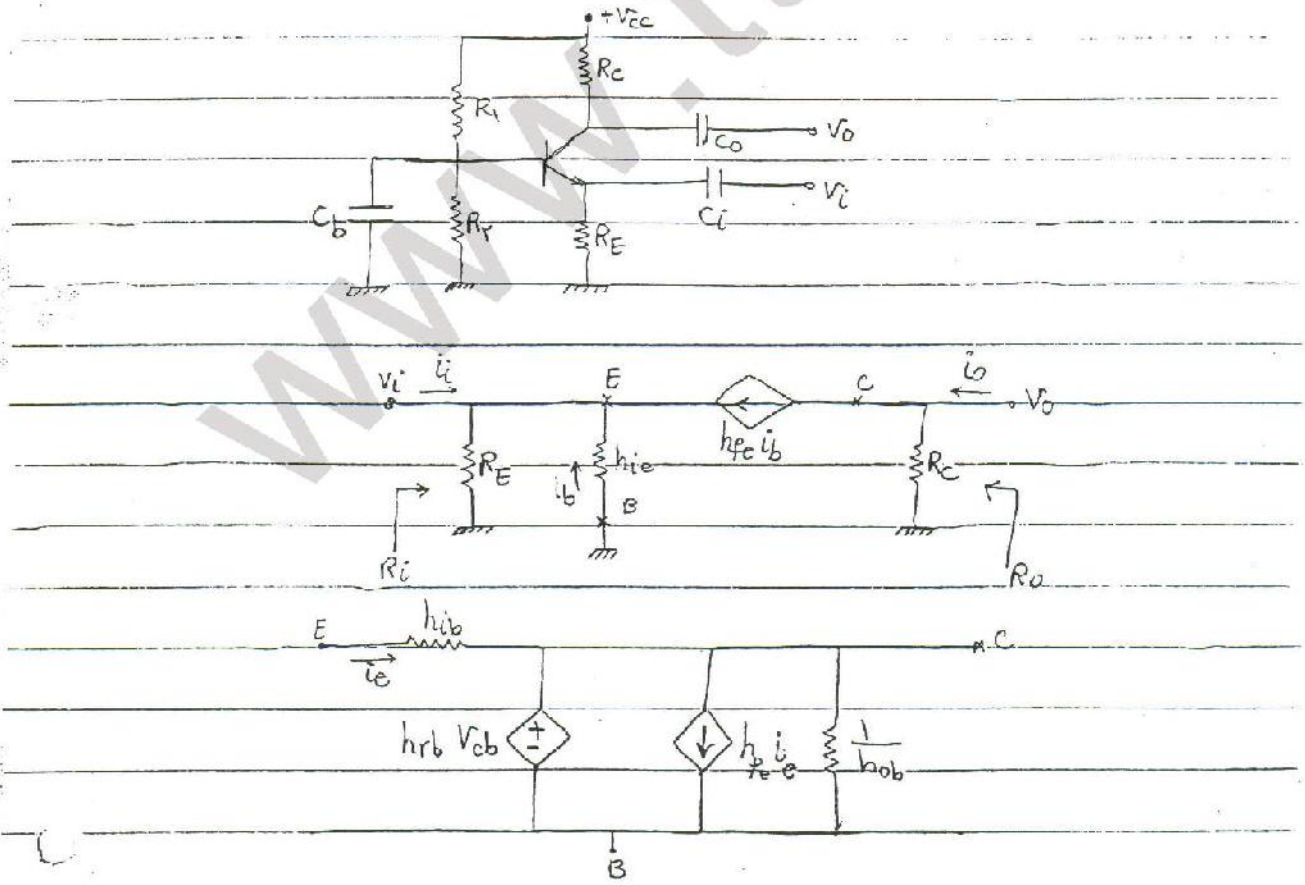
$$h_{fb} = \frac{-h_{fe}(1-h_{re}) - h_{oe}h_{ie}}{(1+h_{fe})(1-h_{re}) - h_{oe}h_{ie}} \quad , \quad h_{rb} = \frac{h_{ie}h_{oe}}{1+h_{fe}} - h_{re}$$

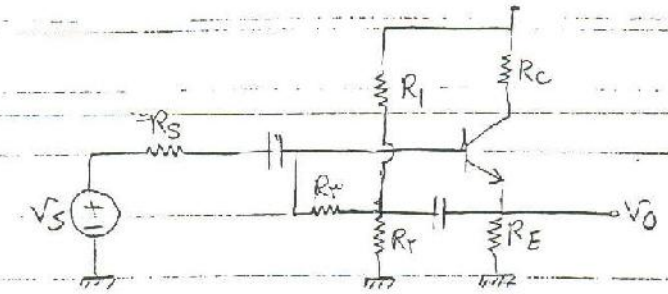
$$h_{ob} = \frac{h_{oe}}{h_{ie}h_{oe} + (1+h_{re})(1+h_{fe})}$$

می توان از تقریبهای $h_{ie}h_{oe} \ll h_{fe}$

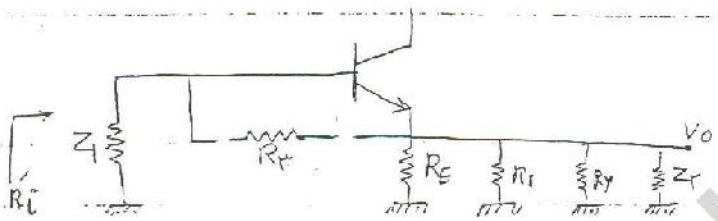
$$\rightarrow h_{ib} = \frac{h_{ie}}{1+h_{fe}} \quad , \quad h_{fb} = \frac{-h_{fe}}{1+h_{fe}} \quad , \quad h_{ob} = \frac{h_{oe}}{1+h_{fe}}$$

تقویت کنندهٔ بیس مشترک:





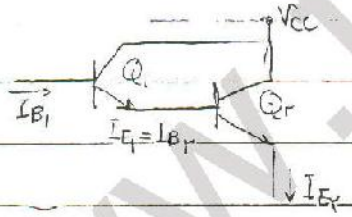
مدار معادل AC:



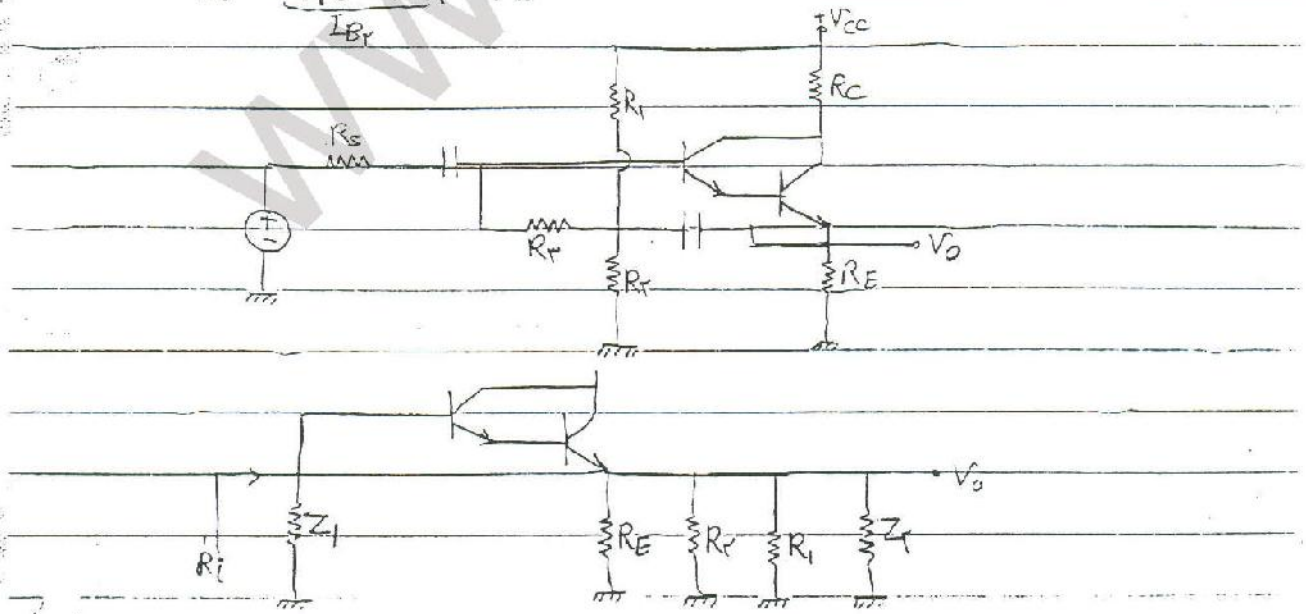
$$R_i' = R_{Z_1} \| \left[h_{fe} + (1+h_{oe})(R_E \| R_1 \| R_2 \| Z_2) \right]$$

$$Z_1 = \frac{R_2}{1-A_V} \quad , \quad Z_2 = \frac{R_2}{1-\frac{1}{A_V}}$$

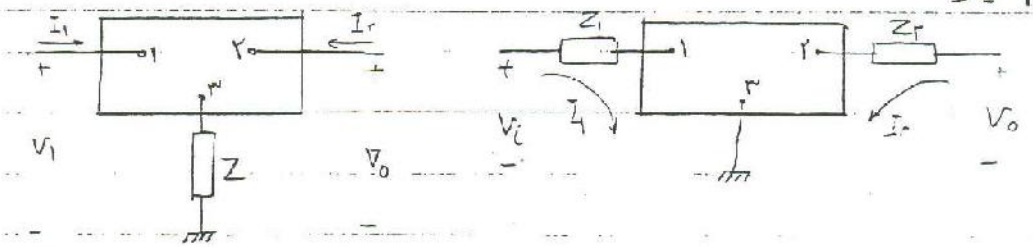
دارلینگتون:



$$I_{E_2} = \underbrace{I_{B_1}}_{I_{B_2}} (1+\beta_1)(1+\beta_2)$$



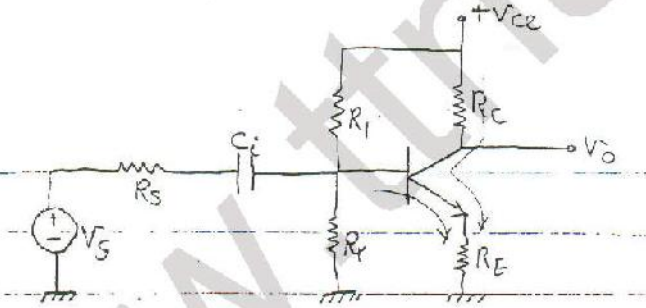
قضیهٔ دوم میلر:

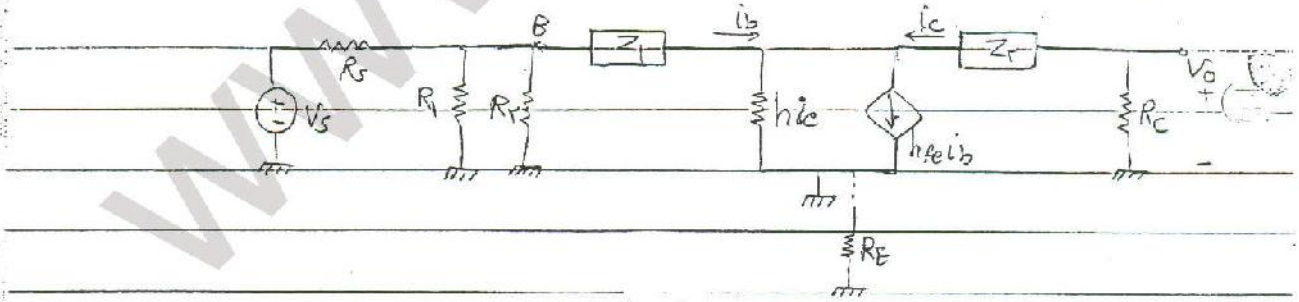


$$\frac{I_2}{I_1} = K \quad , \quad \begin{cases} V_i = V_{13} + Z(I_1 + I_2) \\ V_o = V_{23} + Z(I_1 + I_2) \end{cases} \quad , \quad \begin{cases} V_i = Z_1 I_1 + V_{13} \\ V_2 = Z_2 I_2 + V_{23} \end{cases}$$

$$\longrightarrow \begin{cases} Z_1 = Z(1+K) \\ Z_2 = \frac{K+1}{K} Z \end{cases}$$

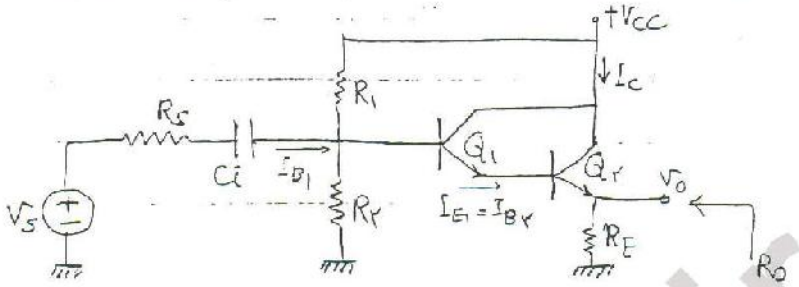
مثال:



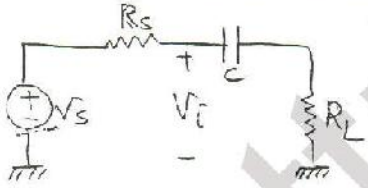


$$Z_1 = R_E(1+h_{fe}) \quad , \quad Z_2 = \frac{1+h_{fe}}{h_{fe}} R_E \simeq R_E \quad , \quad (h_{oe})^{-1} \gg (R_E + R_C)$$

$$R'_i = Z_1 \,||\, \left[h_{ie_1} + (1+h_{fe_1})\left[h_{ie_2} + (1+h_{fe_2})(R_E \,||\, R_1 \,||\, R_2 \,||\, Z_2)\right]\right]$$



$$R_0 = R_E \,||\, \frac{1}{1+h_{fe_2}}\left[h_{ie_2} + \frac{1}{1+h_{fe_1}}\left[h_{ie_1} + R_1 \,||\, R_2 \,||\, R_S\right]\right]$$



$(R_L+R_S)C = \tau$ ثابت زمانی

$f_{p_1} = \frac{1}{2\pi\tau}$ فرکانس قطع سیستم

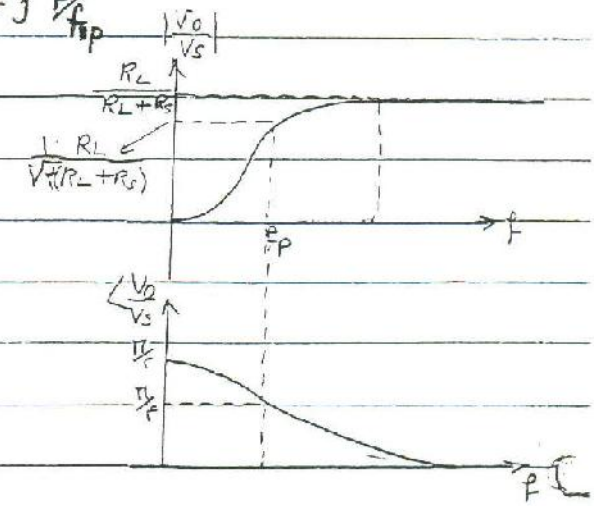
$$\frac{V_o}{V_s} = \frac{R_L}{R_L+R_S+\frac{1}{CS}} = \frac{R_L CS}{(R_L+R_S)CS+1} = \frac{R_L}{R_L+R_S}\cdot\frac{S}{S+p_1}$$

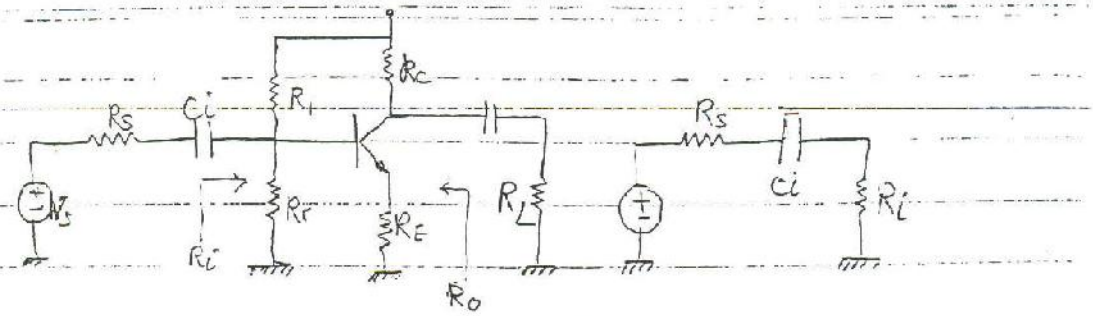
$$\frac{V_o(j\omega)}{V_s(j\omega)} = \frac{jR_L C\omega}{1+j(R_L+R_S)\omega_{p_1}C} \quad \text{if} \quad \omega_{p_1} = \frac{1}{(R_S+R_L)}$$

$$\Rightarrow \frac{V_o(j\omega)}{V_s(j\omega)} = \frac{jR_L C\omega}{1+j\frac{\omega}{\omega_{p_1}}} = \frac{j2\pi R_L C f}{1+j\frac{f}{f_{p_1}}}$$

$$\left|\frac{V_o}{V_s}\right| = \frac{2\pi R_L C f}{\sqrt{1+\left(\frac{f}{f_{p_1}}\right)^2}} = \frac{1}{\sqrt{2}}$$

$$\angle\frac{V_o}{V_s} = \frac{\pi}{2} - \text{Arctg}\frac{f}{f_{p_1}} = \frac{\pi}{4}$$





$$f_L = \frac{1}{2\pi(R_i + R_S)C_i}$$

$V_{GS}=0 \longrightarrow I_{DS}=I_{DSS}=12mA$

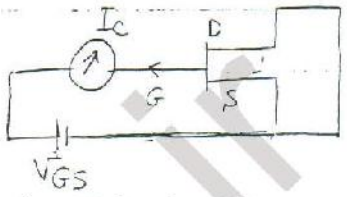
$V_{GS}=-1.2V \longrightarrow I_{DS}=12\left(1-\frac{-1.2}{-4}\right)^2=5.88\ mA$

$V_{GS}=2 \longrightarrow I_{DS}=$ ~~$4mA$~~

$I_{GG}=10nA$

$P_D=10\ W$

$T=-45t+30$



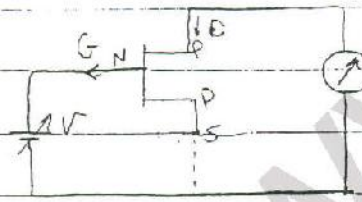
$I_{GSS}=0.01\ \mu A$

$V_{GS}=10V$

$T=100^\circ \longrightarrow I_{GSS}=1\ \mu A$

$V_{GS}=10V$

در حالتی که خطچین نیست

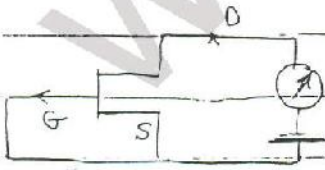


$BV_{DG_0}=-20V$

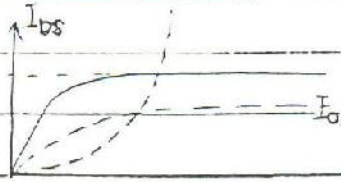
۲۸ ۳۸ ۸۲

$10\mu A$

در حالتی که خطچین وجود دارد: $BV_{DG_0}=-BV_{GSS}$



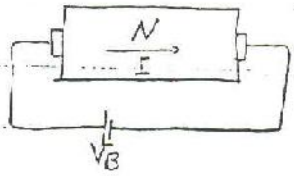
$V_{GS}=0 \longrightarrow I_{DSS}=I_{BS}$

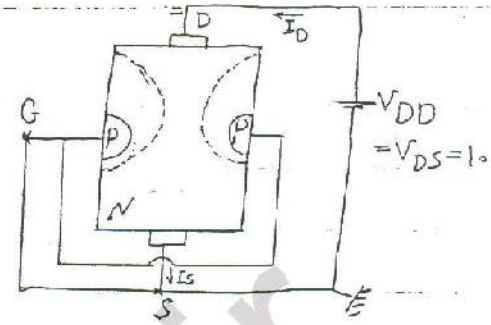


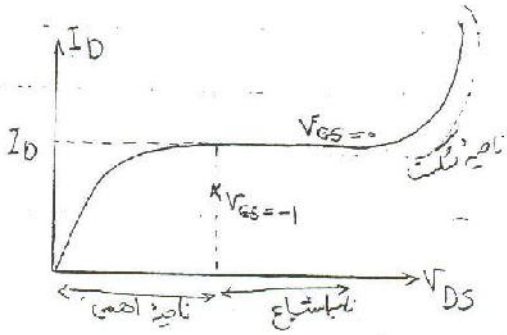
$V_{DS}=10V$

$V_{GS}=3.5V$

FET (ترانزیستور اثر میدانی) (field effect transistor)

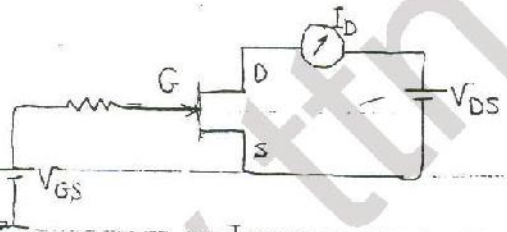


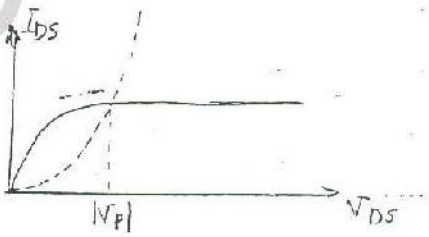




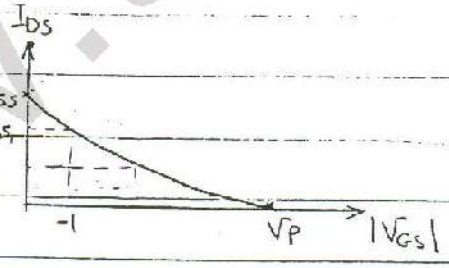
$I_{DSS} \longrightarrow V_{GS}=0$

$V_{GS}=V_P \longrightarrow I_D=0$ قطع





مشخصهٔ انتقال:



$V_{GS}=0 \longrightarrow I_{DS}=I_{DSS}$

$V_{GS}=V_P \longrightarrow I_{DS}=0$

$$I_{DS}=I_{DSS}\left(1-\left|\frac{V_{GS}}{V_P}\right|\right)^2$$

مثال عددی:

$V_P=-4\,V$, $I_{DSS}=12\,mA$ $\longrightarrow$

$V_{GS}=0$

$V_{GS}=-1.2$

$V_{GS}=-2\,V$

$$\longrightarrow \quad \frac{-V_{GS}}{R_S} = I_{DSS}\left(1-\frac{V_{GS}}{V_P}\right)^2 \longrightarrow V_{GS} = \begin{cases} -3{,}2 \checkmark \\ \boxed{-1{,}8} \end{cases}$$

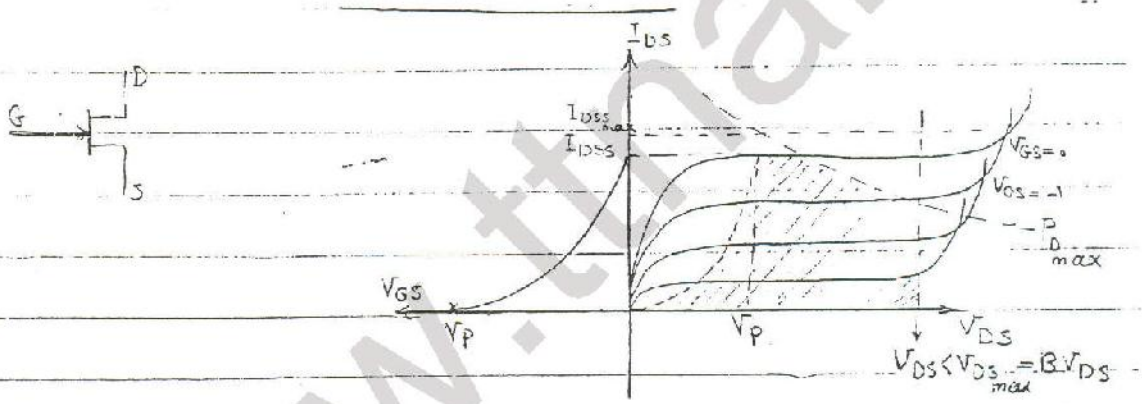
$$\begin{cases} I_{DS} < I_{DSS} & \text{شرایطی که باید حتماً در} \\ |V_{GS}| < |V_P| & \text{مدار برقرار چک شود.} \end{cases}$$

$$V_{DS} = V_D - V_S = V_{DD} - R_D I_{DS} = R_S \cdot I_{DS}$$

$$\longrightarrow V_{DS} = 5{,}4 \text{ V}$$

$$V_{DS} \geq V_{GS} - V_P \longrightarrow V_{DS} \geq -3{,}2 - (-5) = 1{,}8 \text{ V}$$

چک کردن برای ناحیه مجاز

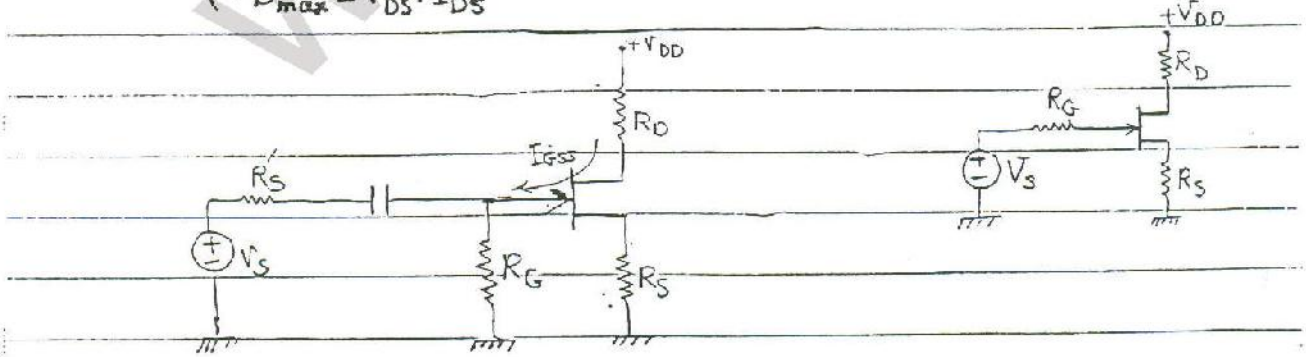


$$\begin{cases} V_{DS} \geq V_{GS} - V_P \\ B.V_{DS} \\ I_{DS_{max}} \\ P_{D_{max}} = V_{DS} \cdot I_{DS} \end{cases}$$

پارامترهای محدودکننده

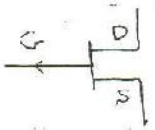
$$I_{DS} = I_{DSS}\left(1 - \left|\frac{V_{GS}}{V_P}\right|\right)^{2}$$

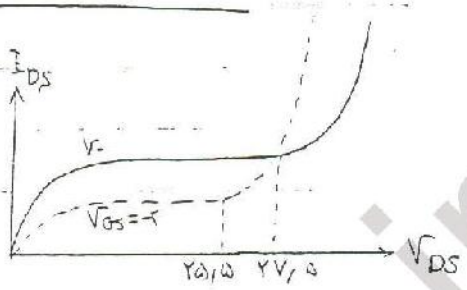
$$I_{DS} < I_{DSS}$$



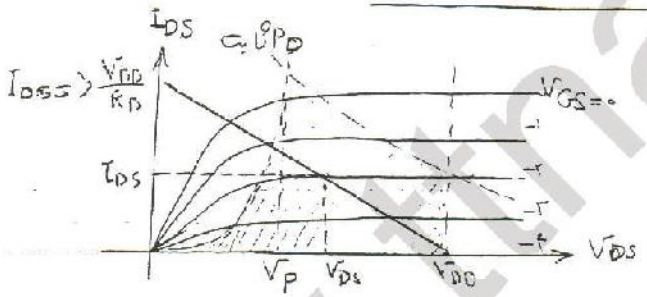
$I_{D_{off}} = 10\,nA$
$V_{DS} = 12\,V$ $\longrightarrow V_{GS} = -8\,V \simeq V_P$

BV_{DS}



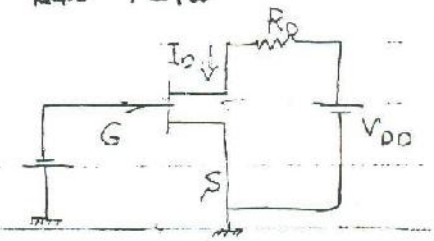


$BV_{DS_0} = -27/5$, $V_{DS} = V_{DG} + V_{GS}$



$P_D = I_{DS} V_{DS}$

$T = 25°$

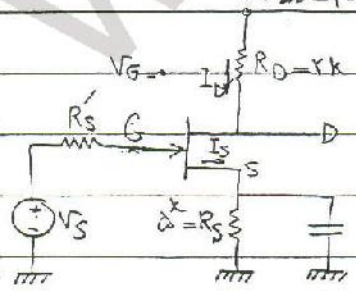


معادله خط بار $V_{DD} = R_D I_D + V_{DS}$

ناحیه اشباع $V_{GS} = 0$ ، $V_{DS} = |V_P|$

$\boxed{V_{DS} \geq V_{GS} - V_P}$

مثال: V_P، I_{DS}، V_{GS} را برای مدار نشان داده شده بدست آورید



$I_{DSS} = 8\,mA$, $V_P = -5\,V$

$$\begin{cases} V_{GS} = V_G - V_S = -V_S = -R_S I_{DS} \\ I_{DS} = I_{DSS}\left(1 - \frac{V_{GS}}{V_P}\right)^2 = I_{DSS}\left(1 + \frac{R_S I_{DS}}{V_P}\right)^2 \end{cases}$$

$\longrightarrow I_{DS}$

$$I_{DS} = \frac{-V_{GS}}{R_S} = 1.04$$

I_{GSS} ③ $I_{DS} - I_{GSS} = I_S$

① $V_G = I_{GSS} \times R_G = 10^{nA} \times 100^{M} = 1\ V$

$I_{GSS} = 10\ nA$

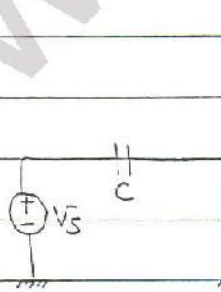
② $V_{GS} = V_G - V_S = V_G - R_S I_S$

$= 1 - 4 = -3$

R_G اگر کوچک باشد دیگر امپدانس ورودی آن خیلی بزرگ نخواهد بود و اگر خیلی بزرگ باشد با تغییرات دما که I_{GSS} تغییر می کند V_G تغییر خواهد کرد و احتمال این است که FET از ناحیه اشباع خارج شود. همچنین با توجه به اینکه در ورودی سیگنال های noise وجود دارند اگر R_G خیلی بزرگ باشد این سیگنال به خروجی منتقل می شود و در خروجی با توان بالایی تقویت و ظاهر می شود اما اگر R_G مناسب باشد noise توسط R_G به زمین منتقل می شود و در خروجی ظاهر نخواهد شد.

①، ②، ③ $\longrightarrow$ $V_{GS} = -R_S I_{DS} + (R_S + R_G) I_{GSS}$

مثال :



$25^\circ < T < 75^\circ$

$I_{GSS}(25^\circ) = 10\ nA$

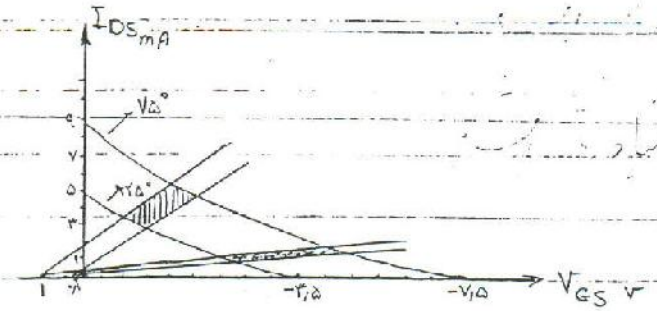
$\Delta T = 5^\circ C \longrightarrow I_{GSS} \times 10$

$I_{DS} = I_{DSS}\left(1 - \left|\frac{V_{GS}}{V_P}\right|\right)^2$

25° { $I_{DSS} = 5\ mA$, $V_P = -4.5\ V$ } 75° { $I_{DSS} = 9\ mA$, $V_P = -7.5\ V$ }

a) $R_S = 500\ \Omega$ b) $R_S = 5\ K\Omega$

مشخصه انتقالی را رسم کنید.



a) $R_S = 500\ \Omega$

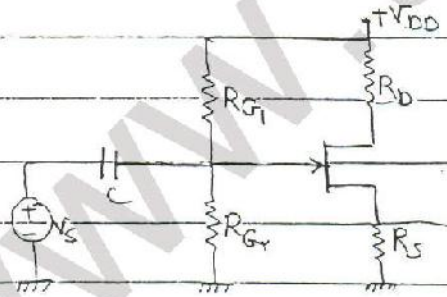
$25° \longrightarrow V_{GS} = -500 I_{DS} + 0.1$

$75° \longrightarrow V_{GS} \simeq -500 I_{DS} + 1$

b) $R_S = 5\ k\Omega$

$25° \longrightarrow V_{GS} = -5000 I_{DS} + 0.1$

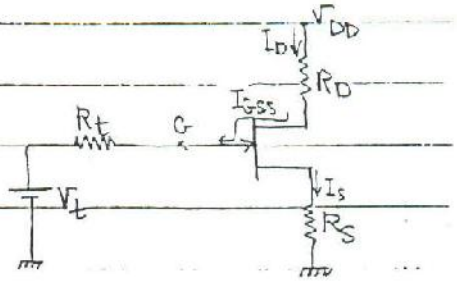
$75° \longrightarrow V_{GS} = -5000 I_D + 1$



$V_{GS} = V_G - V_S$

$$V_{GS} = V_{DD} \times \frac{R_{G2}}{R_{G1} + R_{G2}} - R_S I_S$$

$$\begin{cases} V_t = \dfrac{R_{G2}}{R_{G1}+R_{G2}} V_{DD} \\ R_t = R_{G1} \parallel R_{G2} \end{cases}$$

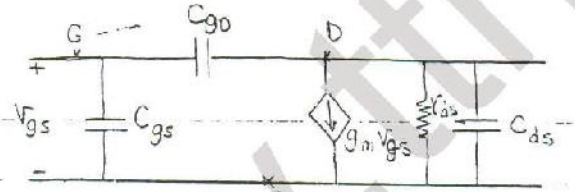


$$\begin{cases} I_D = I_S + I_{GSS} \\ V_G = R_t \times I_{GSS} + V_t \\ V_S = -R_S I_S \end{cases} \quad , \quad V_{GS} = V_G - V_S$$

تحلیل ac و تقویت کننده ها:

C.S	G ورودی	D خروجی	$\|A_V\| > 1$
C.D	G ورودی	S خروجی	$A_V \simeq 1$
C.G	S ورودی	D خروجی	$A_V > 1$ ← کاربرد چندانی ندارد

مدار معادل:



$C_{gs}, C_{gd} \simeq PF$

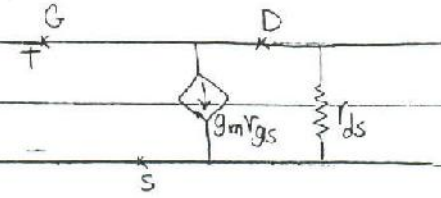
$C_{ds} \ll C_{gs}, C_{gd}$

مقادیری که در کاتالوگ FET داده می‌شوند:

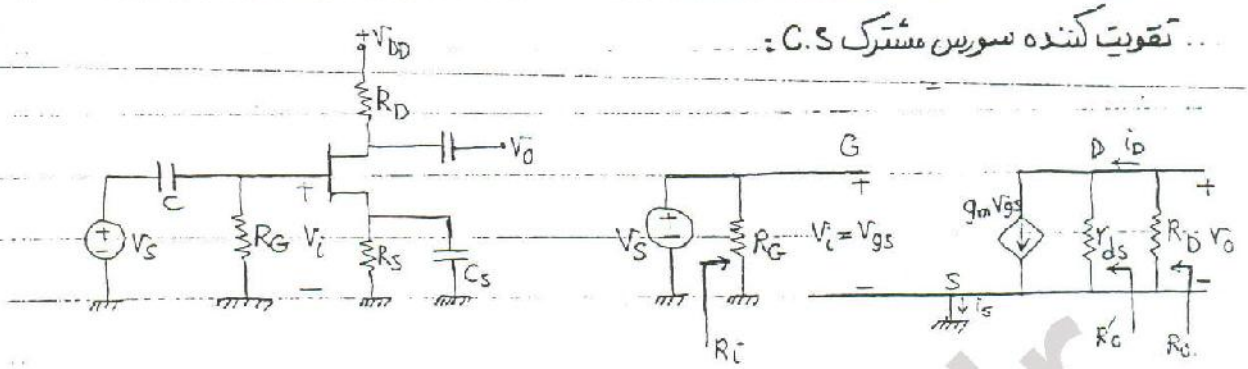
$C_{iss} = C_{gs} + C_{gd}$ ← خازن ورودی (وقتی خروجی اتصال کوتاه است)

$C_{rss} \simeq C_{gd}$ ← خازن خروجی (وقتی ورودی اتصال کوتاه است)

مدل سیگنال کوچک FET:



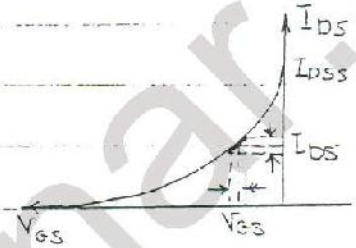
تقویت کننده سورس مشترک C.S :



$$A_V = \frac{V_o}{V_i} = \frac{-g_m V_{gs} (R_D \| R_{ds})}{V_{gs}} = -g_m (R_D \| R_{ds})$$

$$\begin{cases} g_m = \dfrac{\Delta I_{DS}}{\Delta V_{GS}} = g_{m_0}\left(1 - \dfrac{V_{GS}}{V_P}\right) \\ g_{m_0} = \dfrac{2 I_{DSS}}{|V_P|} \end{cases}$$

I_{DSS} : شیب مماس در نقطه



$$R_i = R_G$$

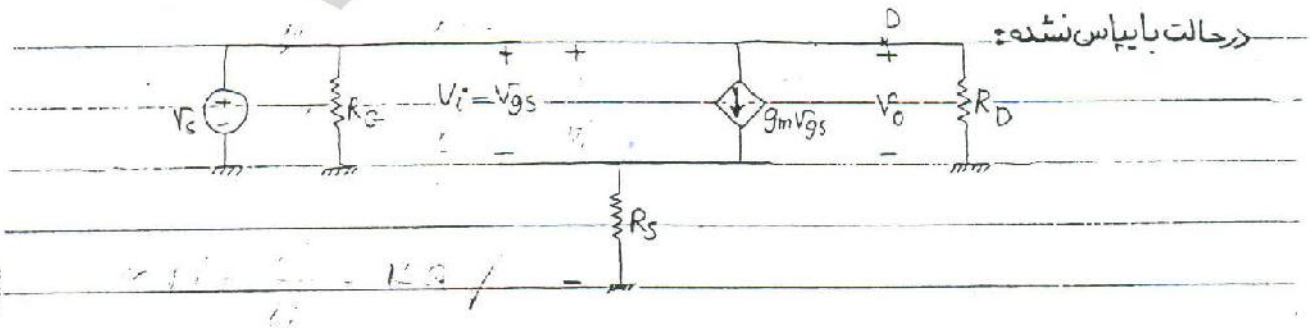
$$R_o = \left.\frac{V_o}{i_o}\right|_{V_s=0} \quad , \quad R_o = R_D \| R'_o$$

$$R'_o = \frac{V_o}{i_D} = r_{ds} \longrightarrow R_o = R_D \| r_{ds}$$

با توجه به اینکه V_s از نظر ac زمین است در نتیجه $V_i = V_{GS}$ لذا در این نوع تقویت کننده ها علاوه

بر پارامترهای بالا باید V_{ipp} را نیز محاسبه و محدود کنیم $V_{ipp} = \frac{V_{opp}}{A_V}$

در حالت بای پاس نشده:

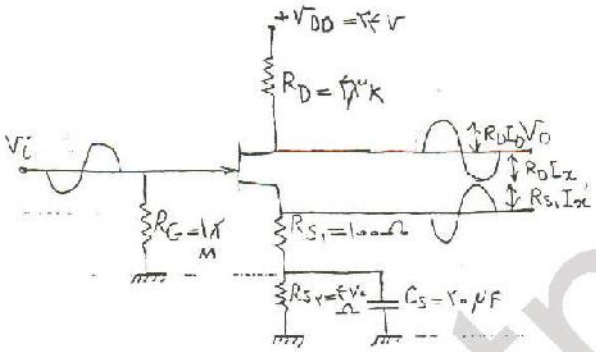


$$A_V = \frac{V_o}{V_i} = \frac{-g_m V_{gs} R_D}{V_{gs} + V_{gs} g_m R_S} = \frac{-g_m R_D}{1 + g_m R_S}$$

$$\longrightarrow A_V = \frac{-g_m R_D}{1 + g_m R_S}$$

$$R_i = R_G \qquad , \qquad R_o = R_D$$

مثال :



$I_{DSS} = 4\ mA$

$V_P = -4\ V$

$R_i , R_o , A_V , V_{opp} , \beta_L = ?$

$$\begin{cases} I_{DS} = I_{DSS}\left(1 - \left|\frac{V_{GS}}{V_P}\right|\right)^2 \\ V_{GS} = V_G - V_S = 0 - I_{DS}(R_{S1} + R_{S2}) = -1.5\,V\,I_{DS} \end{cases} \longrightarrow \begin{array}{l} I_{DS} = 2{,}98\ mA \\ \longrightarrow V_{GS} = -1{,}49\ V \end{array}$$

$$g_m = \frac{2 I_{DSS}}{|V_P|}\left(1 - \frac{V_{GS}}{V_P}\right) = 1{,}492\ mS$$

$g_{m_0} = 2\ mS$

$$A_V = \frac{-g_m R_D}{1 + g_m R_{S1}} = -0{,}72 \qquad , \qquad R_i = R_G = 1{,}2\ M\Omega$$

$$R_o = R_D = 4{,}2\ M\Omega \qquad , \qquad V_D = V_{DD} - R_D I_D$$

$$V_{op}^{+} = R_D I_D \longrightarrow V_{op}^{+} = 12{,}8\ V$$

(dc) $V_S = R_{S1} I_{DS} + R_{S2} I_{DS}$

(ac) $V_S = R_{S1} I_D$

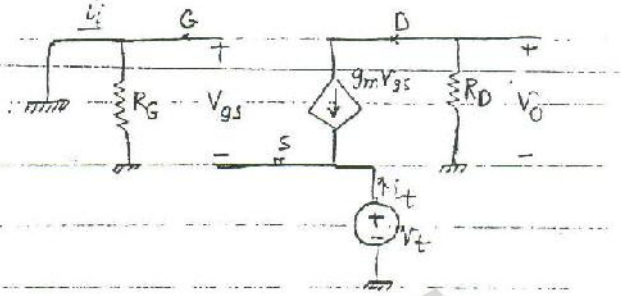
$$V_{op}^{-} = V_{DS} \times \frac{R_D}{R_{S1} + R_D} \longrightarrow V_{op}^{-} = 9{,}44\ V$$

(dc) $V_{DS} = V_D - V_S = V_{DD} - R_D I_D - I_D(R_{S1} + R_{S2}) = 9{,}05\ V$

$$\longrightarrow V_{opp} = 2 \times 9{,}44 = 18{,}88\ V$$

مقاومت سورس کارشین

$$R_{CS} = R_{S_2} \parallel (R_{S_1} + r_s)$$



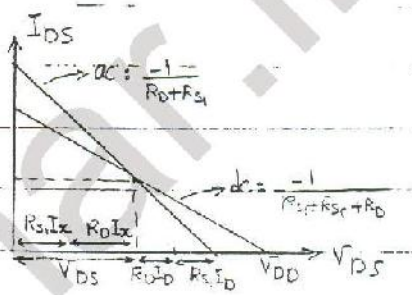
$$i_t = -g_m V_{gs}$$

$$V_t = -V_{gs} \longrightarrow \boxed{r_s = \frac{V_t}{i_t} = \frac{1}{g_m}}$$

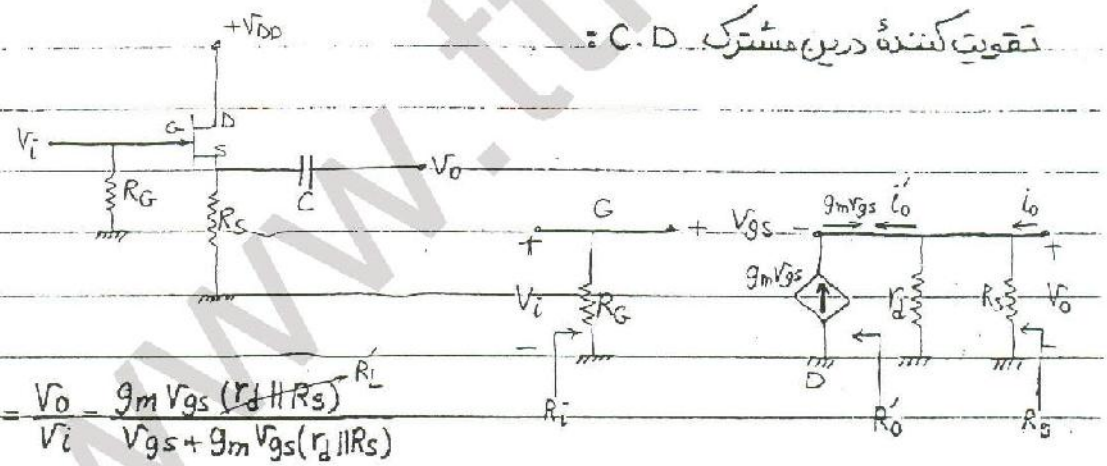
$$\longrightarrow R_{CS} = 4V_0 \parallel (100 + V_{18}) \simeq 3\,k\Omega$$

$$\longrightarrow f_L = \frac{1}{2\pi R_{CS} \cdot C_{as}} = 24.1\ \Omega\ Hz$$

روش دیگر یافتن V_{opp} از روی خط بار ac و dc ⟵



تقویت کننده‌ٔ درین مشترک C.D :



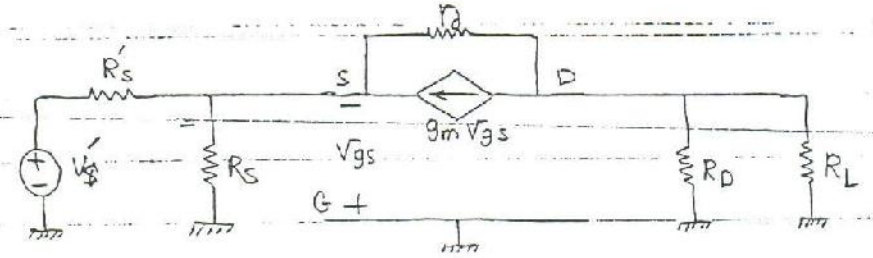
$$A_V = \frac{V_o}{V_i} = \frac{g_m V_{gs} (r_d \parallel R_S \parallel R'_L)}{V_{gs} + g_m V_{gs} (r_d \parallel R_S \parallel R'_L)}$$

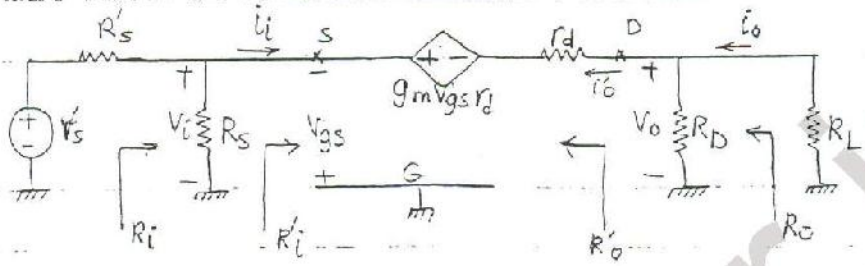
$$\longrightarrow A_V = \frac{g_m R'_L}{1 + g_m R'_L} < 1 \quad , \quad R_i = R_G$$

$$R_o = \frac{V_o}{i_o}\Big|_{V_i = 0} = R'_o \parallel (r_d \parallel R_S)$$

$$\longrightarrow R_o = \underbrace{R'_o}_{\frac{1}{g_m}} \parallel (r_d \parallel R_S) \simeq \frac{1}{g_m} \parallel R_S$$

$$R'_o = \frac{V_o}{i'_o} = \frac{-V_{gs}}{-g_m V_{gs}} = \frac{1}{g_m}$$





$$A_V = \frac{V_o}{V_i}$$

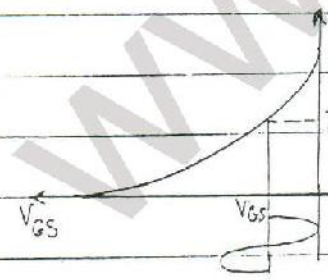
$V_o = (R_D \| R_L) i_i$, KVL: $+V_{gs} + g_m V_{gs} r_d + r_d i_i + (R_D \| R_L) i_i = 0$

$V_i = -V_{gs}$ (*)

$$\longrightarrow i_i \overset{*}{=} -V_{gs} \frac{1 + g_m r_d}{r_d + (R_D \| R_L)}$$

$$\longrightarrow A_V = \frac{V_o}{V_i} = \frac{(R_D \| R_L)\left[\frac{V_{gs}(1+g_m r_d)}{r_d + (R_D \| R_L)}\right]}{V_{gs}}$$

$$\longrightarrow A_V = \frac{(R_D \| R_L)(1 + g_m r_d)}{r_d + (R_D \| R_L)}$$



$V_D = V_{DD} - R_D I_D$

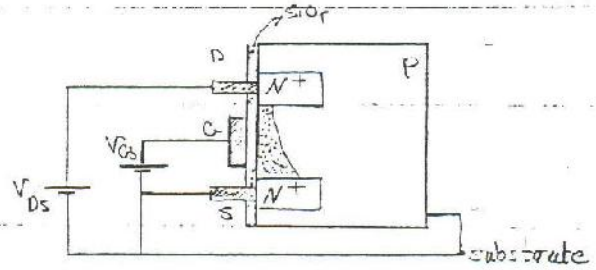
$V_i \downarrow \quad I_{DS} \uparrow \quad V_D \downarrow$

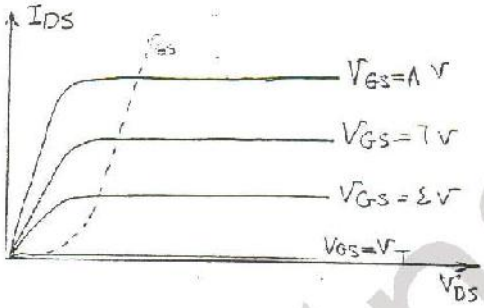
$$A_V \simeq \frac{(R_D \| R_L)(g_m r_d)}{r_d} \simeq g_m (R_D \| R_L) \longrightarrow A_V \simeq g_m (R_D \| R_L)$$

$$R_{in} = \frac{V_i}{i'_s} = R_S \| R'_i \qquad R'_i = \frac{V_i}{i_i} \overset{*}{=} \frac{-V_{gs}}{-V_{gs}\frac{1+g_m r_d}{r_d + (R_D \| R_L)}} \simeq \frac{1}{g_m}$$

$$\longrightarrow R'_i = \frac{r_d + (R_D \| R_L)}{1 + g_m r_d} \simeq \frac{1}{g_m}$$

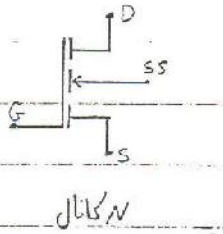
۲-نوع افزایشی :



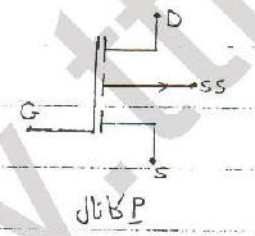


$V_T = V_{GD} \simeq ۱.۳$ ولت

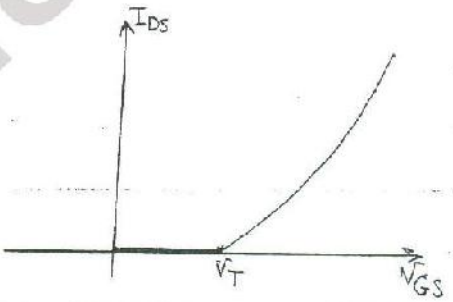
ولتاژ آستانه تشکیل کانال



کانال N



کانال P

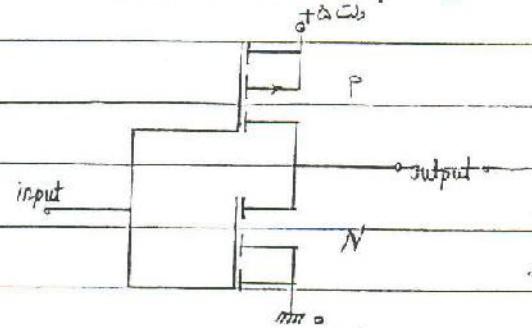


$$I_D = \frac{1}{2}\beta (V_{GS} - V_T)^2 \quad , \quad V_{GS} \gg V_T \quad , \quad \beta \simeq ۱۵ \times ۱۰^{-۳} \ A/V^2$$

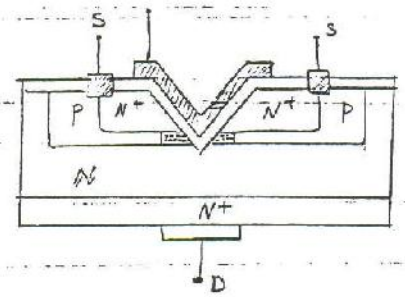
($\beta = K$)

$$V_{DS_{sat}} = V_{GS} - V_T$$

از ترکیب NMOS (کانال N MOSFET) و PMOS آلمانی به نام CMOS بوجود می‌آید



: VMOS



کاربرد VMOS در مدارهای سوئیچینگ با جریان بالا است چون مقاومت کمی دارد.

$$\longrightarrow R_i = R_s \parallel \left(\frac{r_d + (R_D \parallel R_L)}{1 + g_m r_d}\right) \simeq R_s \parallel \frac{1}{g_m}$$

$$R_o = \frac{V_o}{i_o}\Big|_{V_s=0} = R_D \parallel R'_o$$

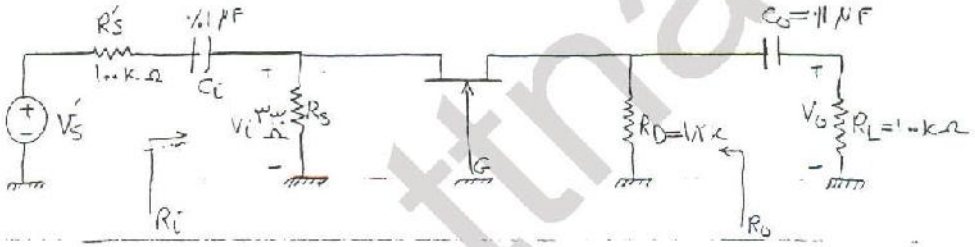
$$R'_o = \frac{V_o}{i'_o} = \frac{r_d i'_o + g_m (V_{gs}) r_d + i'_o (R_s \parallel R'_s)}{i'_o} = r_d + g_m r_d (R_s \parallel R'_s) + (R_s \parallel R'_s)$$

($-(R_s \parallel R'_s) i'_o$: V_{gs} 의 مقدار)

$\because r_d \longrightarrow R'_o = r_d \left(1 + g_m (R_s \parallel R'_s)\right)$

$$\longrightarrow R_o = R_D \parallel \left[r_d \left(1 + g_m (R_s \parallel R'_s)\right)\right] \simeq R_D$$

مثال :



$V_{GS} = -1.5\,V$, $g_m = 1.5\,mS$, $r_d = \infty$

R_i , R_o , A_v , f_L = ?

$$A_v = \frac{(1 + g_m r_d)}{r_d + R'_L} \times R'_L \simeq R'_L \left(\frac{1}{r_d} + g_m\right) \longrightarrow A_v = g_m R'_L = g_m (R_L \parallel R_D) = 7.2\,\Omega$$

$$R_i = R_s \parallel \frac{1}{g_m} = 1\,V\,\Omega \quad , \quad R_o = R_D = 1.2\,K$$

$$R_{Ci} = R_i + R'_s \simeq 100\,K\Omega \quad , \quad \tau_{Ci} = R_{Ci} \times C_i = 10\,ms$$

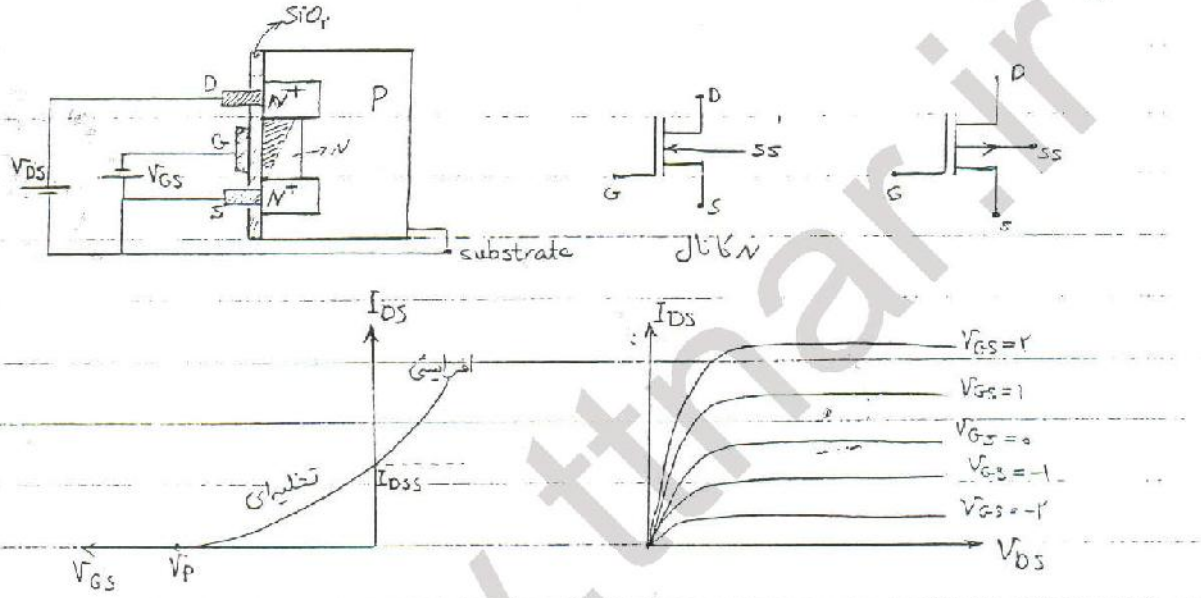
$$, \quad f_{Ci} = \frac{1}{2\pi \tau_{Ci}} = 16\,Hz$$

$$R_{Co} = R_D + R_L \simeq 100\,k\Omega \quad , \quad \tau_{Co} = R_{Co} \times C_o = 10\,ms$$

MOS FET : دونوع از این تقویت کننده داریم.

۱- تخلیه‌ای Depletion ۲- افزایشی Enhancement

نوع تخلیه‌ای:



$$I_{DS} = I_{DSS}\left(1 - \frac{V_{GS}}{V_P}\right)^2 \quad , \quad g_m = g_{m_0}\left(1 - \frac{V_{GS}}{V_{P_0}}\right)$$

$$g_{m_0} = \frac{2 I_{DSS}}{|V_P|}$$

مثال:

$I_{DSS} = ۱۸\ mA$ ، $V_P = -۵\ V$

الف- N کانال

$V_{GS} = -۳ \longrightarrow I_{DS} = ۱۸\left(1 - \frac{-۳}{-۵}\right)^2 = ۲,۸۸\ mA$

$V_{GS} = ۲,۵ \longrightarrow I_{DS} = ۱۸\left(1 - \frac{۲,۵}{-۵}\right)^2 = ۴۰,۵\ mA$

ب- P کانال $I_{DSS} = ۱۸\ mA$ ، $V_P = ۵\ V$

$V_{GS} = -۳ \longrightarrow I_{DS} = ۴۹,۰۸\ mA$

$V_{GS} = ۲,۵^V \longrightarrow I_{DS} = ۲۵\ mA$