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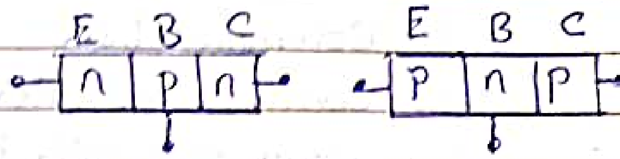
# Bipolar Junction Transistor

* BJT is a 3-terminal device.

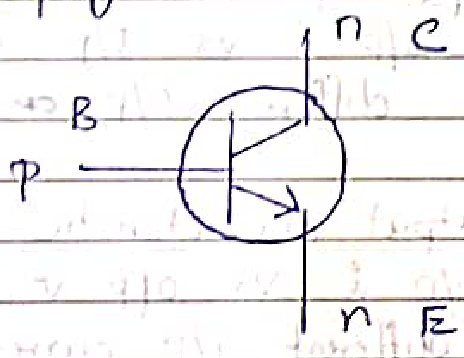


p-type is sandwiched b/w 2 ntypes

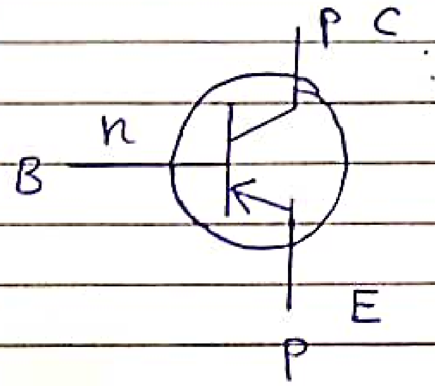
npn

n type is sandwiched b/w 2 p-types.

Width → C > E > B
Doping → E > C > B



n-p-n



p-n-p

Bipolar → holes, electrons
Junction → Two junctions
$E\text{-}B \leftarrow J_1$ & $J_2 \rightarrow C\text{-}B$
Transistor → Transfer resistance

BJT → amplifier
→ switching device

| E-B $J_1$ | C-B $J_2$ | Region of operation | Application |
|---|---|---|---|
| F.B | R.B | Active region | Amplifier |
| F.B | F.B | Saturation region | Digital ON |
| R.B | R.B | Cutoff region | Digital OFF |
| R.B | F.B | ~~Never used~~ Inverter | Never used |

BJT can be used in those configuration.

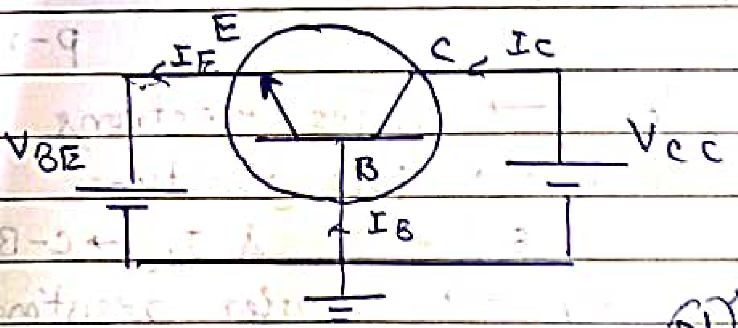
i) Common-base
ii) Common-emitter
iii) common-collector

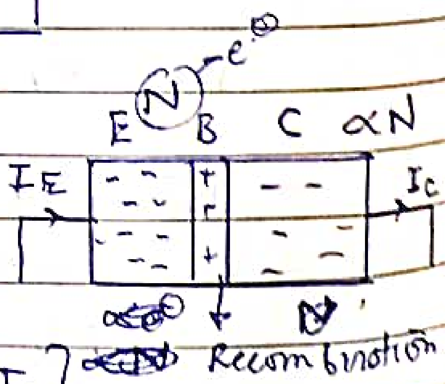
Transfer Characteristics

→ ~~input~~ input characteristics
I/P i vs I/P V for different O/P voltage

output characteristic
O/P i vs O/P V for different i/p current.

Common Base



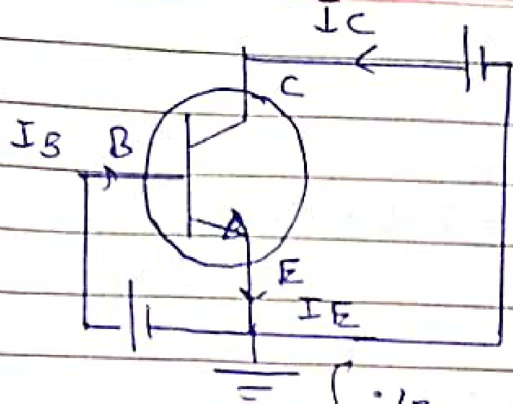

$$\left\{\begin{array}{l} I_E = I_C + I_B \\ I_C = \alpha I_E + I_{CBO} \end{array}\right\}$$

$$\therefore \{I_C = \alpha I_E\}$$

Reverse saturation current
Collector current which flow when emitter ckt is open. $I_{CBO}$

$$[I_C = \alpha I_E + I_{CBO}]$$

↳ negligible value

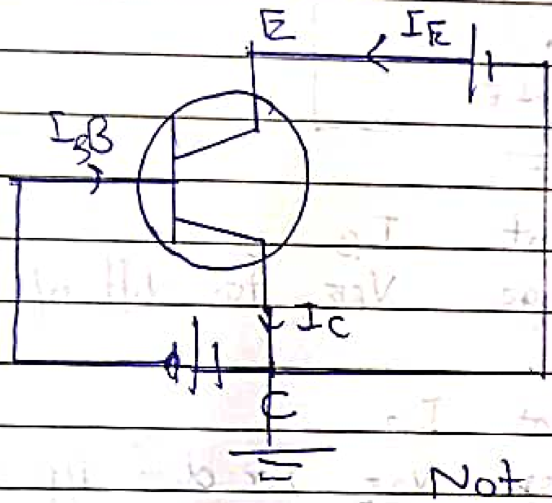



**Common Emitter**

used as amplifier

$$\left\{\begin{array}{ll} i/p & I_B \\ o/p & I_C \end{array}\right\}$$

$$\beta = \frac{I_C}{I_B} \qquad \beta = \{50 - 400\}$$

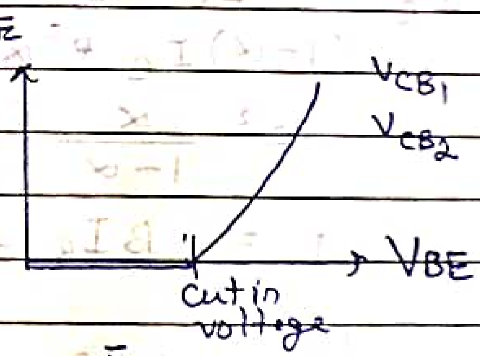


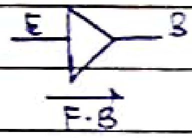

F.B → ~~rao~~ low resistance
R.B → high resistance

High input resistance
low output resistance
Not used for amplification purposes.

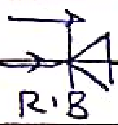
**C.B**

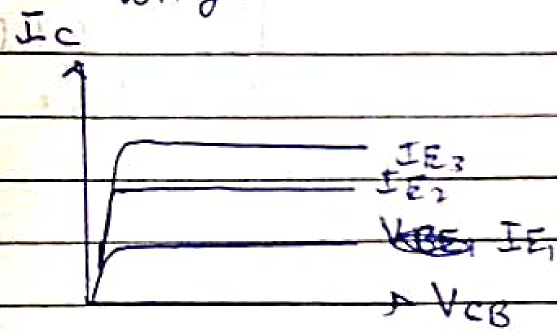
I/P characteristics




o/p characteristics



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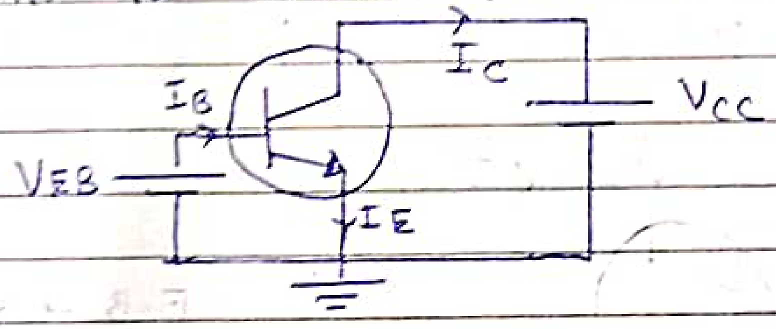
$I_E = I_C + I_B$

$I_C = \alpha I_E + I_{CBO}$

$\alpha = \dfrac{I_C}{I_E} \simeq 0.95$ to $0.98$

## Common Emitter Configuration

Emitter is common to base and collector




Input current $I_B$
Input voltage $V_{BE}$ for diff o/p voltage $V_{CE}$

Output current $I_C$
Output voltage $V_{CE}$ for diff i/p current $I_B$

$$I_C = \alpha (I_C + I_B) + I_{CBO}$$

$$(1-\alpha) I_C = \alpha I_B + I_{CBO}$$

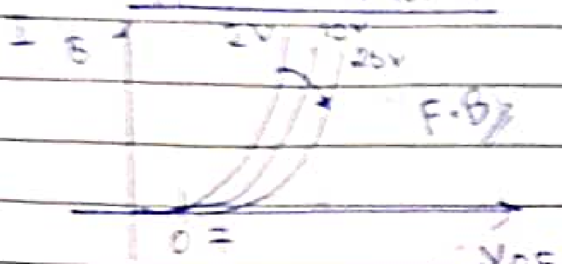
$$I_C = \frac{\alpha}{1-\alpha} I_B + \underbrace{\left(\frac{1}{1-\alpha} I_{CBO}\right)}_{I_{CEO}}$$

$$I_C = \beta I_B + (\beta+1) I_{CBO}$$

$$\left[ I_C = \beta (I_B + I_{CBO}) + I_{CBO} \right]$$

$$\left\{ \beta = \frac{I_C}{I_B} \right\}$$

i/p characteristics

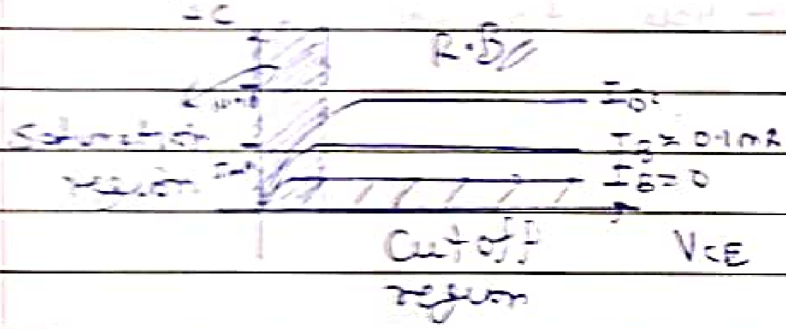



$V_{CE}\uparrow$ $W_{eff}\uparrow$ $I_B\downarrow$

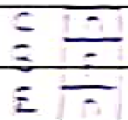
$\parallel$

$V_{CB}+V_{BE}$

o/p characteristics



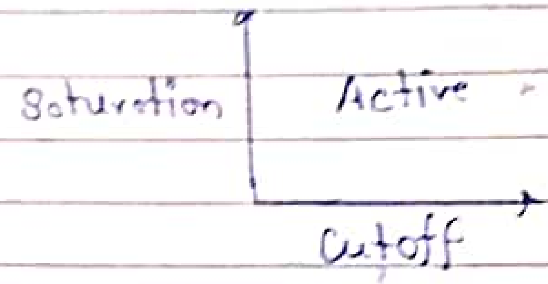

Early effect :




$$V_{CE}\uparrow = \underbrace{V_{BE}}_{\text{constant in forward bias}} + V_{CB}\uparrow$$

depletion width b/w collector & base increases so base current decreases

HW : In ~~CE~~ CB configuration i/p characteristic $I_E$ vs $V_{BE}$ which was F.B diode characteristic How will that i/p characteristic vary with output voltage $V_{CB}$ ? increase or decreases & why ?




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

$V_{BE}$ ↓ fixed (0.7V)

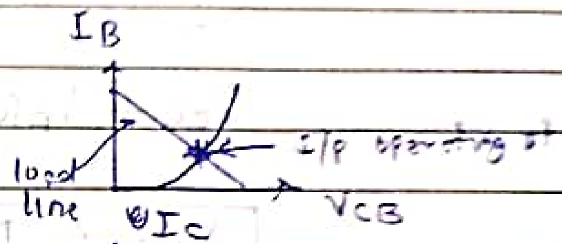
initially $V_{CE} < 0.7V$ at that pt. $V_{CB} < 0$

Collector - base forward bias.

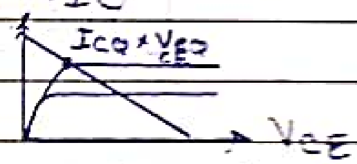
# DC Biasing of BJT

Biasing of the BJT is application of appropriate external DC voltage to establish an operating point of the circuit: when a ~~best~~ weak signal is applied to the BJT at this best operating point then we get an amplified signal at the output. Input operating point is the intersection of load line with the input characteristic of the BJT.

I/p operating pt

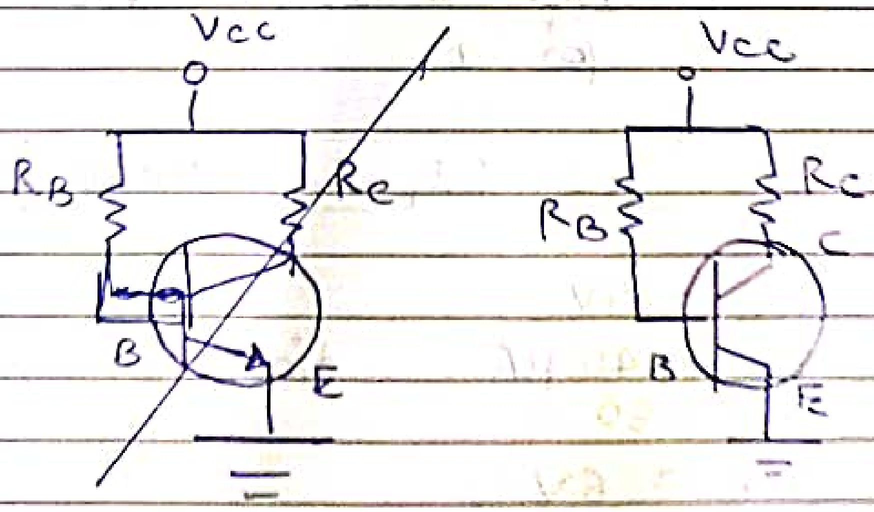



o/p operating pt.




* load lines keeps on changing as per $V_{CC}$
* operating pt in Active region so that we can amplify the week AC signal.

## Fixed Bias Configuration



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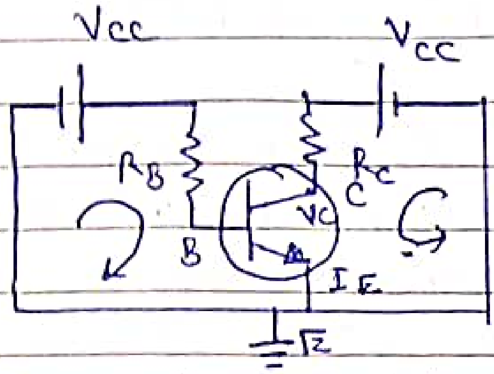


Base emitter $\longrightarrow$ i/p ckt
Collector emitter $\longrightarrow$ o/p ckt

KVL in i/p ckt

$$V_{CC} - i_B R_B - V_{BE} = 0$$

&

$$\boxed{V_{CC} = I_B R_B + V_{BE}}$$

(0.7V)

$$\left[ I_B = \frac{V_{CC} - V_{BE}}{R_B} \right]$$

$$V_{CC} - i_C R_C - V_{CE} = 0$$

$$V_{CC} - i_C R_C - \cancel{(V_{CB} + V_{BE})} = 0$$

$V_{CE}$

$$I_{CQ} = \beta \cdot I_B$$

$$\boxed{V_{CC} - \beta I_B \cdot R_C = V_{CEQ}}$$

let $V_{CC} = 14V$

$I_B = 40\ \mu A$

$\beta = 80$

$V_{CE} = 6V$

find $I_C$, $R_C$, $R_B$ & $V_C$

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

$I_C = 80 \times 40$

$= 3200\ \mu A$

$= 3.2\ mA$

$V_{CC} - I_B R_B - V_{BE} = 0$

$14 - (40\mu A)(R_B) - 0.7 = 0$

$R_B = \frac{13.3\ V}{40\ \mu A} = 0.3325 \times 10^6\ \Omega$

$= 332.5\ k\Omega$

$V_{CC} - I_C R_C - V_{CE} = 0$

$R_C = \frac{14 - 6\ V}{3.2\ mA}$

$= 2.5\ k\Omega$

$\boxed{V_{CE} = V_C}$

$V_{CE} = V_{BC}$ $\because \{V_E = 0\}$

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Reference Books :

- DC biasing is required to establish proper region of operation for ac amplification.

- Lower doping of base increases resistance by limiting number of "free" carriers.

- Bipolar $\rightleftarrows$ electrons / holes participate as charge carriers

- $I_C = I_{C_{majority}} + I_{CO}$ ← minority charge carrier current component
  $I_{CO}$ → leakage current

- $I_{CBO} / I_{CO}$ increases rapidly with temperature

C-B configuration  $I_E \rightarrow$ input  $I_C \rightarrow$ output

- At cutoff region $I_C = 0$
  At saturation region $V_{CB} = 0$

- $V_{BE} = 0.7V \rightarrow$ constant in active region.
- $\Delta V_{CB}$ has negligible effect on $I_C$

- $\alpha_{dc} = \frac{I_C}{I_E}$  $\alpha_{ac} = \left.\frac{\Delta I_C}{\Delta I_E}\right|_{V_{CB} = const}$

  $I_C = \alpha I_E + I_{CBO}$

  $\alpha_{ac}$ → common base, shortckt, amplification factor

- In an n-p-n transistor n-p is F.B & p-n is reverse biased. This means transistor has low input resistance and

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high output resistance. Thus voltage is amplified since $V = i \times R$ and $R_{output}$ is high.
(Transferring current from low R to high R)

<u>CE-configuration</u>: BE → FB, CE → RB; $I_B$ → input, $I_C$ → output

$$I_C \neq 0 \text{ when } I_B = 0$$

$$I_C = \frac{\alpha I_B}{1-\alpha} + \frac{I_{CBO}}{1-\alpha} \quad \text{when } I_B = 0$$

$$I_C = \frac{1}{1-\alpha} I_{CBO} = I_{CEO} \neq 0$$

→ distortion in signal

↓ {collector current delivered by $I_B = 0$}

For least distortion $I_C = I_{CEO}$

∴ $I_B < 0$ is avoided

cutoff $I_B = 0$ $I_C = I_{CEO}$

$$\beta_{dc} = I_C / I_B$$

$$\beta_{ac} = \left(\Delta I_C / \Delta I_B\right)\Big|_{V_{CE} = \text{constant}}$$

$$\alpha = \frac{\beta}{1+\beta} \quad \left\{ \beta \cong \frac{I_{CEO}}{I_{CBO}} \right\}$$

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

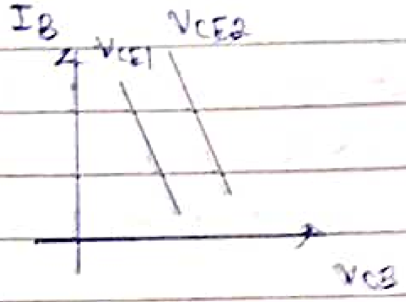
<u>Common collector</u> → input is same for CE & CC configuration

$\{V_C > V_B \ \& \ V_B > V_E\}$ Active region condition

$\{V_B > V_C > V_E\}$ saturation region

$\{V_B < V_C \ \& \ V_B < V_E\}$ cutoff region

BJT → current controlled device



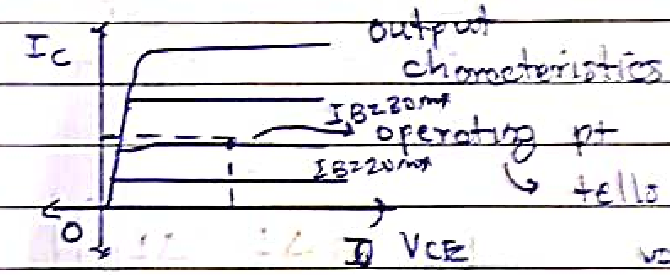

$\gamma = \frac{I_E}{I_B}$

$$\boxed{\gamma = \beta + 1}$$

$$\gamma = \beta + 1 = \frac{1}{1-\alpha}$$

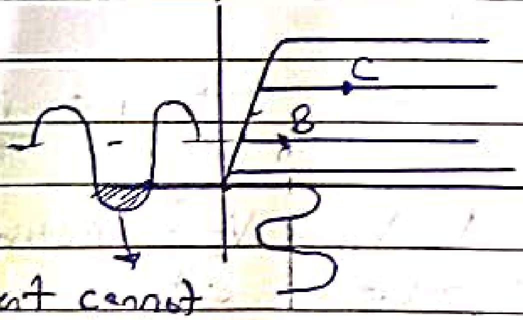
$$\boxed{\alpha \cdot \gamma = \beta}$$

<u>operating point / Q-point</u> ← a fixed point on o/p / i/p characteristics of transistor




tells us operating voltage & current of transistor

Q-point → inside active region for amplification.




At C gain is not best for amplification

current cannot go below OA so B point is not suitable

causes non-linear distortion in output waveform

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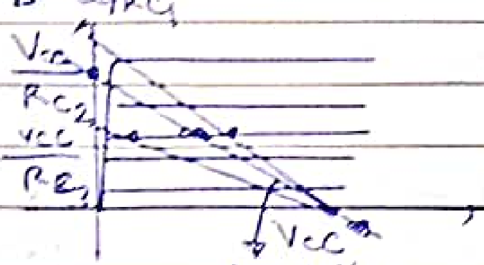
→ Temperature changes $\beta$, $I_{CEO}$

Stability factor (S) prevents change in operation of BJT




load line

$$\underset{\text{change in this causes}}{(I_B)} = \frac{V_{BB} - V_{BE}}{R_B} \quad \text{change in Q-point}$$

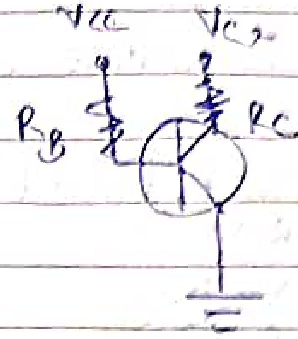
$R_{C3} > R_{C2} > R_{C1}$

As $V_{CC} \uparrow$ load line shifts towards left same for $R_C$

In fixed bias configuration even if base current is fixed external factor change the Q-point.

$V_{cc} = 12V$
$R_B = 240k\Omega$
$R_C = 2.2k\Omega$
$\beta = 50$

$I_{CQ}$ , $V_{CEQ}$




$V_{cc} - i_B R_B - 0.7 = 0$
$12 - i_B R_B - 0.7 = 0$
$i_B R_B = 11.3V$
$i_B = \frac{11.3}{240k} = 0.047\,mA$

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

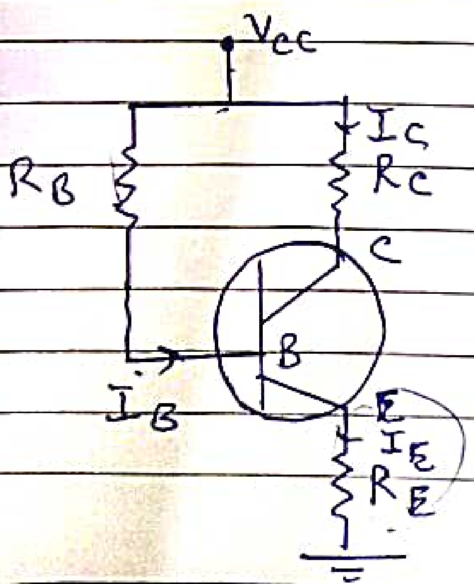
$\left[ i_{CQ} = 2.35mA \right]$

$V_{cc} - i_C R_C - V$
$12 - (2.35 \times 2$
$= V$
$[V_{CE}$

## Biasing Techniques

- → Fixed Bias
- → Emitter ~~follower~~ Feedback Bias
- → Collector feedback Bias
- → Voltage divider bias

## Emitter Feedback Bias Configuration



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$$V_{cc} - i_B R_B - V_{EB} - I_E R_E = 0$$

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

$$V_{cc} - I_B R_B - V_{BE} - (\beta+1) I_B \cdot R_E = 0$$

$$\boxed{I_B = \frac{V_{CC} - V_{BE}}{R_B + (\beta+1) R_E}}$$

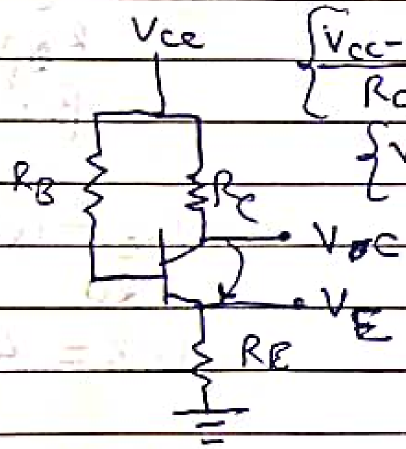
$$I_{CQ} = \beta \times I_B$$

$$V_{cc} - I_C R_C - V_{CE} - I_E R_E = 0$$

$$\cancel{V_{cc} - \beta I_B R_C -}$$

$$(I_C \simeq I_E)$$

$$\boxed{V_{CE} = V_{cc} - I_C (R_E + R_C)}$$



$$\left\{\frac{V_{cc} - V_c}{R_C} = i_C\right\}$$

$$\{V_{E0} = i_E R_E\}$$

$V_{cc} = 12V$

~~$\beta = 23$~~

for emitter bias configuration if $V_{cc}$ is $12V$ ; $I_C = 3mA$

$V_C = 7.6V$

$V_E = 2.4V$ $\quad \beta = \frac{I_C}{I_B}$

$\beta = 80$ $\quad I_B = 0.0375$

Find $R_C$, $R_B$, $R_E$ ? $\quad i_E = (\beta+1) i_B = 3.037$

$$V_{cc} - i_B R_B - 0.7 - i_E R_E = 0$$

$$12 - 0.0375\, R_B - 0.7 - 3.037\, R_E = 0$$

$$0.0375\, R_B + 3.037\, R_E = 11.3 \quad \text{--- (1)}$$

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$$V_{CC} - R_C i_C - V_{CE} - i_E R_E = 0$$
$$12 - 3R_C - 5.2 - 3.037 R_E = 0$$
$$6.8 = 3R_C + 3.037 R_E \quad \text{—} ②$$

$$V_E = i_E R_E$$
$$0.8 \qquad 800$$
$$R_E = k\Omega = \Omega$$

$$6.8 = 3R_C + 2.1259$$
$$R_C = 1.558\ k\Omega$$

$$\left[R_B = 237.6\ k\Omega\right]$$

φ) $V_{CC} = 20V$

$R_B = 430\ k\Omega$

$R_C = 2\ k\Omega$

$R_E = 1\ k\Omega$

$\beta = 50$


$$V_{CC} - i_B R_B - 0.7 - i_E R_E = 0$$
$$20$$
$$19.3 = 430 i_B + i_E \quad \text{—} ①$$

$$V_{CC} - i_C R_C - V_{CE} - i_E R_E = 0$$
$$20 - 2i_C - V_{CE} - i_E = 0 \quad \text{—} ②$$

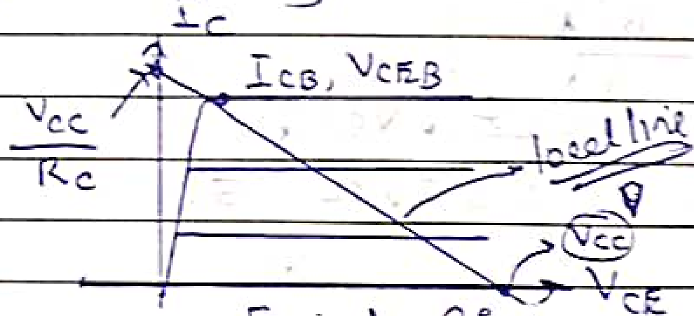
$$\beta \quad 50 i_B = i_C \quad \text{—} ③$$

$$i_E = 51 i_B \quad \text{—} ④$$

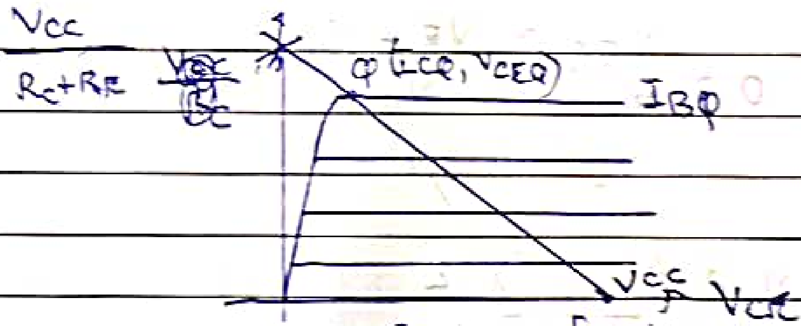
$19.3 = (430+51) i_B$

$$\left\{ \begin{aligned} i_B &= 0.04 \text{ mA} \\ i_C &= 2 \text{ mA} \\ i_E &= 2.04 \text{ mA} \end{aligned} \right\}$$

$V_{CEQ}$ $\boxed{V_{CE} = 13.96 \text{ V}}$




Fixed Bias




Emitter feedback

| | C-B | C-E |
|---|---|---|
| • Input impedance – | $\frac{\Delta V_{EB}}{\Delta I_E}$, $V_{CB}$ is constant | $\frac{\Delta V_{EB}}{\Delta I_B}$, $V_{CE}$ |
| • Output admittance – | $\frac{\Delta I_C}{\Delta V_{CB}}$, $I_E$ is constant | $\frac{\Delta I_C}{\Delta V_{CE}}$, $I_B$ |
| • Forward current gain | $= \frac{\Delta I_C}{\Delta I_E}$, $V_{CB}$ is constant | $\frac{\Delta I_E}{\Delta I_B}$ |
| • Reverse voltage gain | $= \frac{\Delta V_{EB}}{\Delta V_{CB}}$, $I_E$ is constant | $\frac{\Delta V_{BE}}{\Delta V_{CE}}$ |

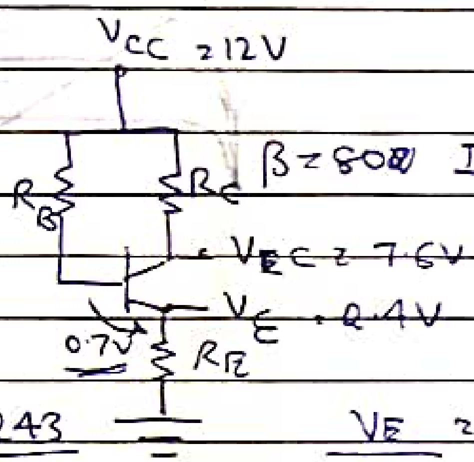
- $\alpha = \Delta I_C / \Delta I_E$
- $\beta = \Delta I_C / \Delta I_B$
- $\gamma = \Delta I_E / \Delta I_B$

$$\boxed{\gamma = \frac{1}{1-\alpha} = \beta + 1}$$

- $A_V = \frac{V_L}{V_i}$

- $I'_{CBO} = I_{CBO}\, 2^{(T_2-T_1)/10}$

Q)




$\beta = 80$ $I_C = 3mA$

$I_C = \beta I_B$

$3 = 80\, I_B$

$I_B = 3/80$ mA

$I_E = (\beta+1) I_B$

$I_E = \frac{81 \times 3}{80} = \frac{243}{80}$ mA

$\frac{V_E}{I_E} = R_E$

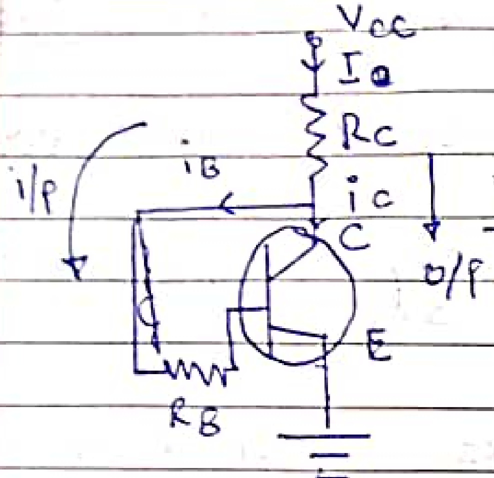
$\frac{V_{CC} - V_C}{R_C} = R_C$

$V_{CC} - 0.7$
$-2.4$

$i_B$

$= R_B$

## Collector Bias or Self Bias




KVL in input ckt,

$$V_{CC} - i_Q R_C - i_B R_B - V_{BE} = 0$$

$$V_{CC} - (i_C + i_B) R_C - i_B R_B = 0$$

$$V_{CC} - \beta i_B R_C - i_B (R_B + R_C) = V$$

$$i_B = \frac{V_{CC} - }{R_B + R_C}$$

$V_{CC} - i_C R_C -$

KVL in output ckt

$$V_{CC} - i R_C - V_{CE} = 0$$

$$V_{CC} - i_B R_C - i_C R_C - V_{CE} = 0$$

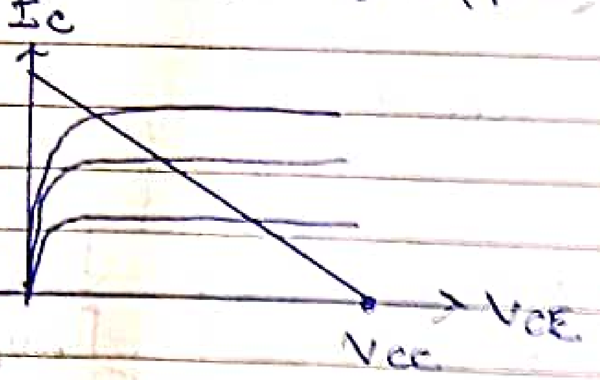
$$V_{CC} - i_B R_C - \beta i_B R_C - V_{CE} = 0$$

$$\boxed{\forall\, i_B = \frac{V_{CC} - V_{CE}}{(\beta+1) R_C}}$$

$$i_C = \beta \left[\frac{V_{CC} - V_{BE}}{R_B + R_C(\beta+1)}\right]$$

$$V_{CE} = V_{CC} - i_B R_C (\beta+1)$$

$\beta$



HW for collector bias with emitter resistance

$V_{CC} = 20V$

$R_C = 1k\Omega$

$R_B = 100k\Omega$

$\beta = 100$

$R_E = 1k\Omega$

$$V_{CC} - iR_C - i_B R_B - 0.7 = 0$$

$$20 - B(\beta i_B + i_B)R_C - i_B R_B - 0.7 = 0$$

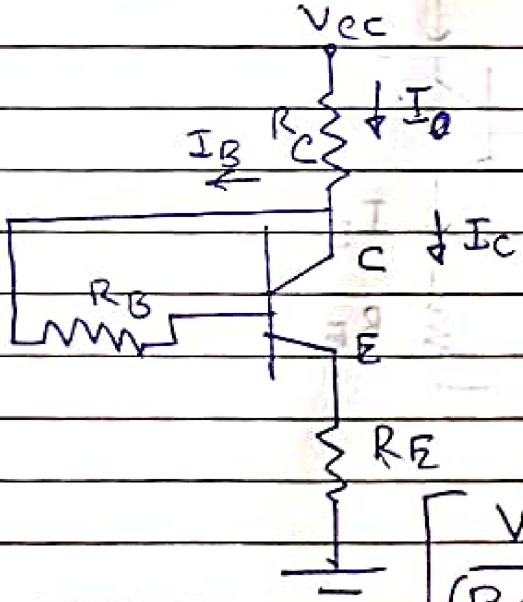
$$19.3 = (100 i_B + i_B)1 + 100 i_B$$

$$\cancel{B = \frac{119.3}{20} mA}$$

$i_B = 0.096$ mA

$i_C = 9.6$ mA

Collector bias with emitter resistance




$$V_{CC} - (i_C + i_B)R_C - i_B R_B - V_{BE} - i_E R_E = 0$$

$$V_{CC} - \beta i_B R_C - i_B R_C - i_B R_B - V_{BE} - (\beta+1) i_B R_E = 0$$

$$\left[\frac{V_{CC} - V_{BE}}{(\beta+1)R_C + R_B + (\beta+1)R_E} = i_B\right]$$

$$\left[i_B = \frac{V_{CC} - V_{BE}}{(\beta+1)[R_C + R_E] + R_B}\right]$$

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$$V_{CC} - (i_C + i_B) R_C - V_{CE} - i_E R_E = 0$$

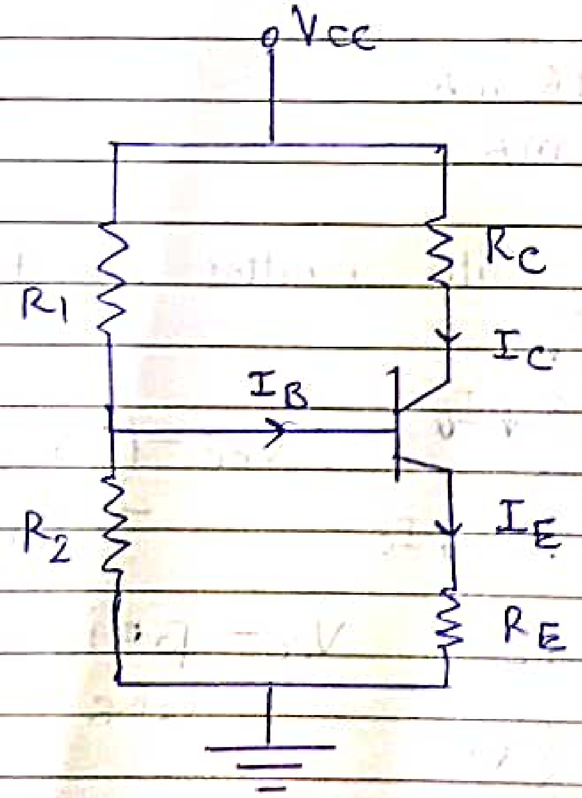
$$V_{CC} - (\beta i_B + i_B) R_C - (\beta+1) i_B R_E = V_{CE}$$

$$V_{CC} - i_B (\beta+1) R_C - (\beta+1) i_B R_E = V_{CE}$$

$$\boxed{V_{CC} - i_B (\beta+1)(R_C + R_E) = V_{CE}}$$

$V_{CC}$

## Voltage divider Bias ckt

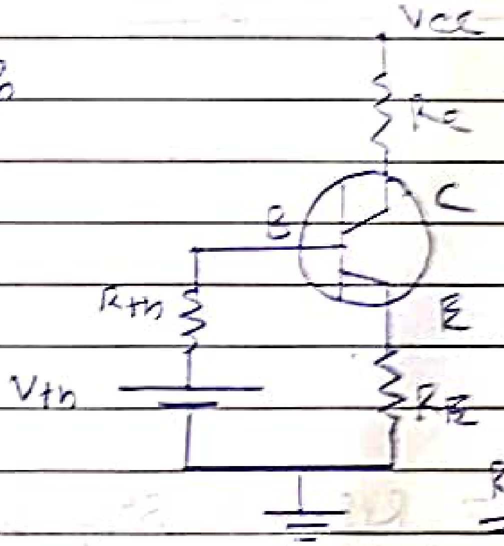


# Thevenin equivalent ckt

Thevenin equivalent ckt can be found out for a linear ~~bi dir~~ ~~directional~~ bidirectional 2-terminal network by replacing with an equivalent thevenin ckt consisting ~~of~~ an equivalent voltage source $V_{th}$ connected in series with an equivalent resistance $R_{th}$
where $V_{th}$ → open ckt voltage across the terminals

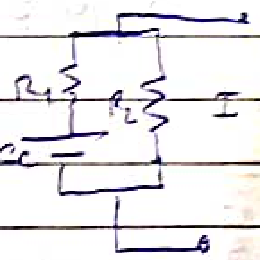
$R_{th}$ → equivalent resistance when voltage sources are turned off.

~~Rth~~



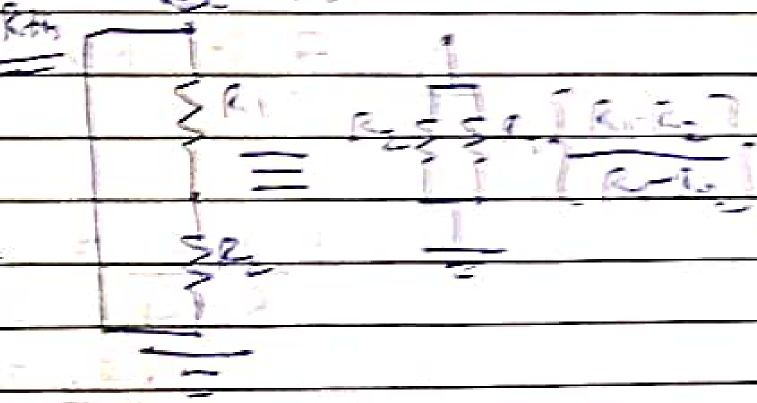

$$\left\{ R_{th} = R_1 \parallel R_2 \right\} = \frac{R_1 R_2}{R_1 + R_2}$$

$V_{th}$




$$I = \frac{V_{cc}}{R_1 + R_2}$$

$R_{th}$




$V_{Th}$ = Voltage drop across $R_2$

$$\boxed{V_{Th} = \left(\frac{V_{CC}}{R_1 + R_2}\right) R_2}$$

$$V_{th} - i_B R_{th} - V_{BE} - i_E R_E = 0$$

$$V_{th} - i_B R_{th} - V_{BE} - (\beta+1) i_B R_E = 0$$

$$\boxed{i_B = \frac{V_{th} - V_{BE}}{R_{th} + (\beta+1) R_E}}$$

$$V_{CC} - i_C R_C - V_{CE} - i_E R_E = 0$$

$$V_{CC} - \beta i_B R_C - (\beta+1) i_B R_E = V_{CE}$$

$$\boxed{V_{CE} = V_{CC} - \left[\beta R_C + (\beta+1) R_E\right] i_E}$$

Q) $V_{CC} = 22V$
$R_1 = 39k\Omega$
$R_2 = 39k\Omega$
$R_C = 10k\Omega$
$R_E = 1.5k\Omega$
$\beta = 140$

$V_{th}$ $i$ $\quad R_{th} = \frac{R_1 R_2}{R_1 + R_2} = 39/2\ k\Omega = 19.5\ k\Omega$

$$i = \frac{V_{CC}}{R_1 + R_2} = \frac{22}{39 \times 2} = \frac{11}{39}$$

$$V_{th} = i_C \times R_2 = \frac{11 \times 39}{39} = 11V$$

$$i_B = \frac{11 - 0.7}{19.5 + 141 \times 1.5} = 0.044\ mA$$

$i_C = 6.242\ mA \qquad i_E = \cancel{6.168}\ 6.286\ mA$

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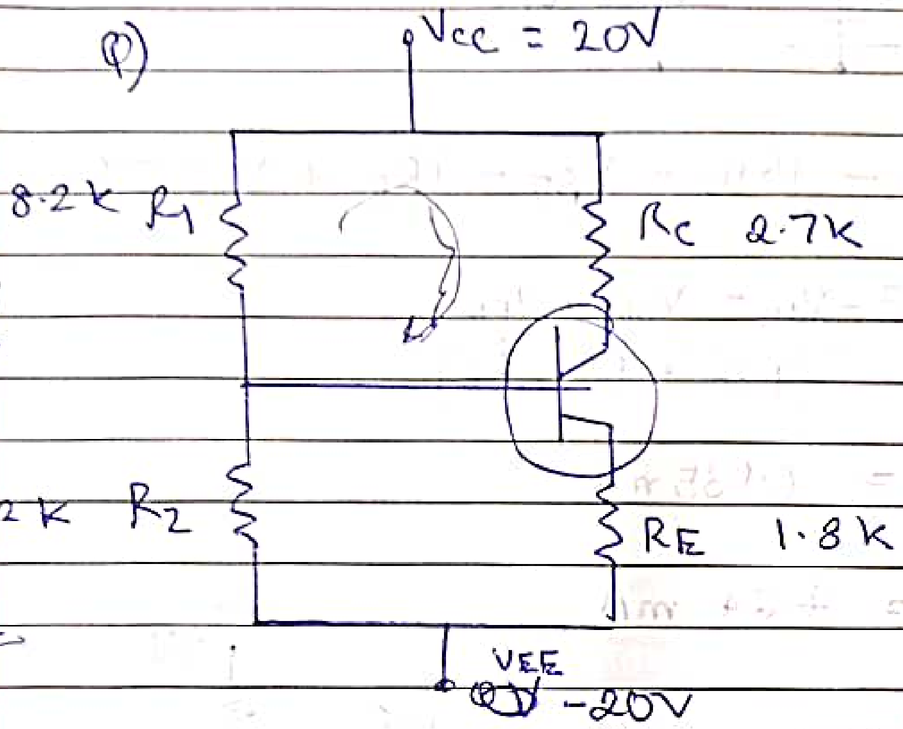
$V_{CE}$ = ~~3.454 V~~ ~~-48.906 V~~

$$\boxed{V_{CE} = 6.53\ V}$$

(P)




imp

$R_{th} = 1.73\ k\Omega$

~~$i_{th}$ @ $V_{th}$ = $\frac{V_{cc}}{R_1+R_2}$ = 1.92 mA~~

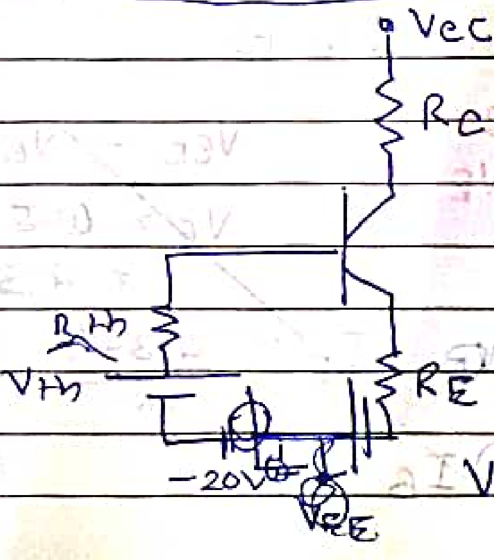
~~$V_{th} = i_{th} \times R_2$~~
~~= 4.23 V~~

$(V_{th} + iR_2)$

$V_{th} - iR_2 + V_{EE} = 0$

$\boxed{V_{th} = iR_2 - V_{EE}}$

{only magnitude}




$i_{th} = \frac{20+20}{8.2+2.2} = 3.84\ mA$

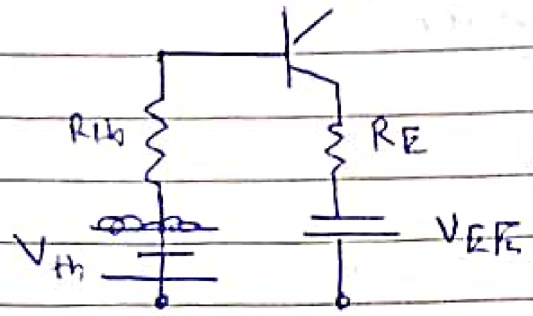
$V_{th} = 8.46\ V$

$V_{th} - i_B R_{th} - V_{BE} - i_E R_E = 0$
$+ V_{EE}$

$\frac{V_{th} - V_{BE} + V_{EE}}{(R_{th} + \beta R_E)} = i_B$

~~$V_{th} = iR_2 - V_{EE}$~~
~~$= 28.46\ V$~~

$V_{th} = iR_2 - V_{EE}$
$= -11.53\ V$




$$V_{th} - i_B R_{th} - V_{BE} - i_E R_E + V_{EE} = 0$$

$$i_B = \frac{-V_{th} - V_{BE} + V_{EE}}{(R_{th} + (\beta+1) R_E)}$$

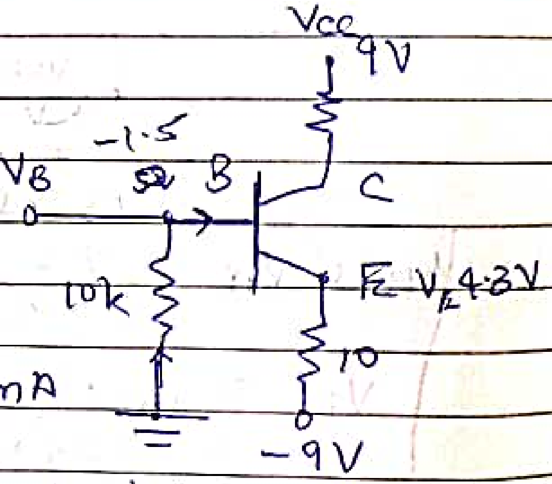
$$= 0.035 \text{ mA}$$

$$i_C = 4.24 \text{ mA}$$

Q) ~~Same diagram~~

IMP

-1.5V




$$i_B = \frac{1.5}{10} = 0.15 \text{ mA}$$

Calculate $\beta$

$$V_{EB} = V_B - V_{EB}$$

$$V_B + 0.7 = V_E$$

$$V_E =$$

$$V_{BE} = V_B - V_E$$

$$V_E = \ldots$$

$$= 4.3V - \ldots$$

$$I_E = \frac{4.3 + 9}{10} = \frac{13.3}{10}$$

$$= 1.33$$

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

$$\cancel{\begin{array}{l} V_{EB} = V_E - V_B \\ 0.7 = V_E + 1.5 \end{array}}$$

$$V_{BE} = V_B - V_E$$

$$0.7 = -1.5 - V_E$$

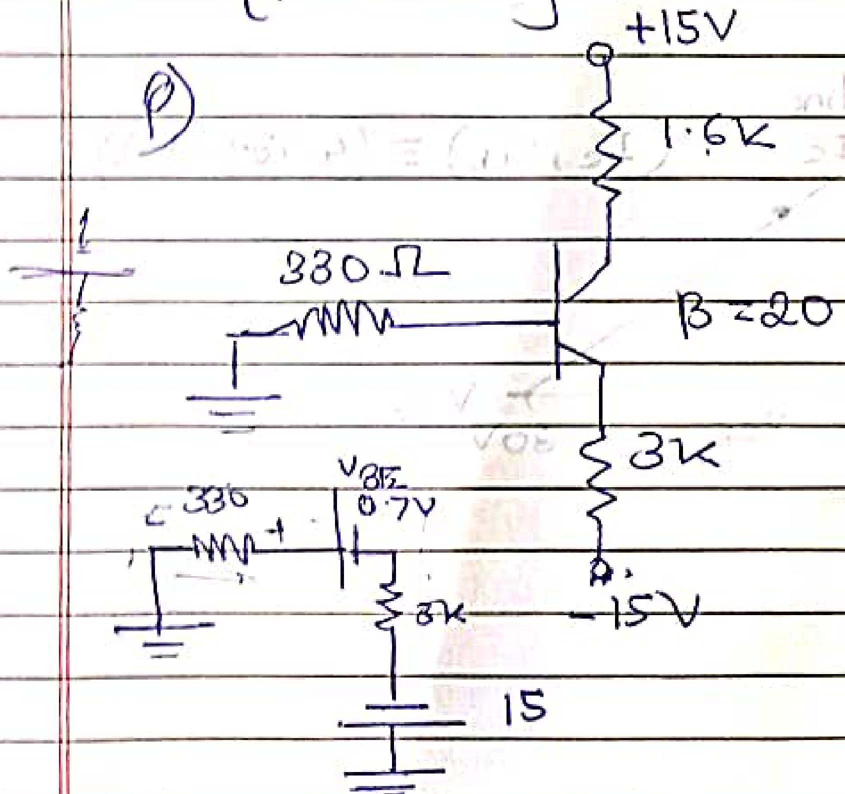
$$V_E = -2.2V$$

$$i_E = \frac{-2.2+9}{10} = 0.68 \text{ mA}$$

$$\cancel{\beta =} \ (\beta+1) = \frac{I_E}{I_B}$$

$$\boxed{\beta = 3.53}$$

β)




$$i_C = 4.739$$

$$i_E = 4.76 \text{ mA}$$

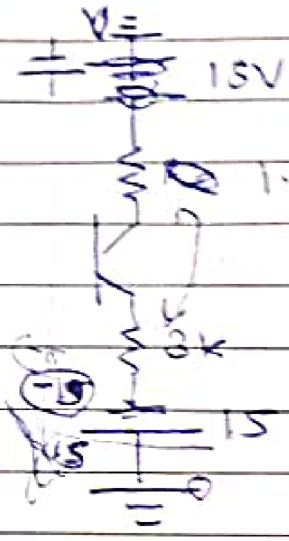
$$i_B = 2.155 \times 10^{-3} \times 10^{-2}$$
$$= 0.021 \text{ mA}$$

$$i_B = \frac{14.3}{3000 \times (\beta+1) + 330}$$

$$-i_B(330) - 0.7 - 3000(\beta+1)\, i_B + 15 = 0$$

$$\cancel{-3300 i_B - 0.7 - 3000\beta + 15 = 0}$$

$$\cancel{i_B = \frac{14.3 - 3000\beta}{3300\, i_B}}$$



$$15 - 1.6 \times i_C - 3 \times i_E + 15 = V_{CE}$$

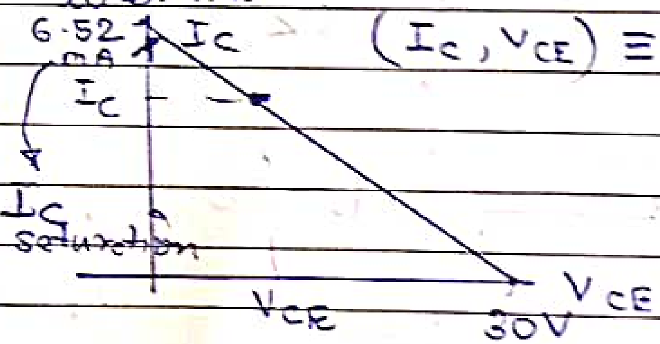
$$V_{CE} = 8.13\ V$$

load line

$i_C \simeq i_E$

$\therefore$ if $i_C = 0$

$i_E = 0$

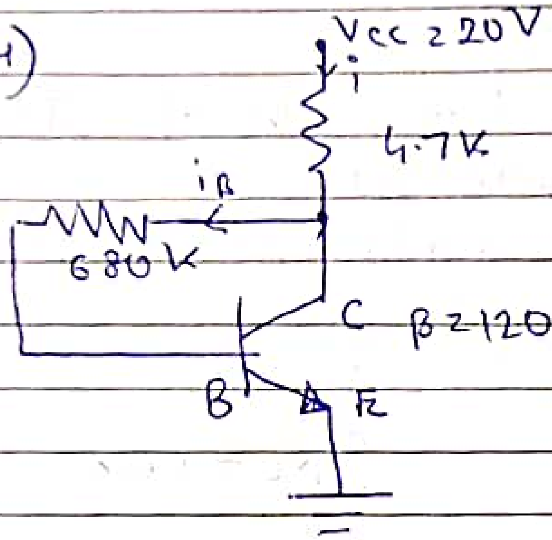



$(I_C, V_{CE}) \equiv (4.73, 8.13V)$

$$i_C = \frac{30}{4.6}$$

## Boyloested

eg 4.14)



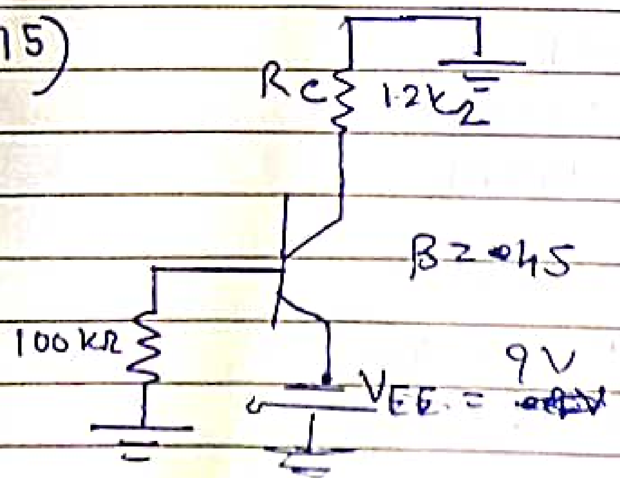

$$V_{cc} - i(4.7) - i_B(680) - V_{BE} = 0$$

$$V_{cc} - (i_B + \beta i_B)(4.7) - i_B(680) - 0.7 = 0$$

$$i_B = \frac{V_{cc} - 0.7}{4.7(1+\beta) + 680} = 0.015 \text{ mA}$$

$$i_C = 1.8 \text{ mA}$$

4.15)



$-100\, i_B + V_{BE} + 3 = 0$

$100\, i_B = 3.3$

$i_B = 0.0233$ mA

$i_C = 2.733$ mA

$i_E = 2.318$ mA

$-i_E R_E \quad -i_C R_C = V_{CE} + 3 = 0$

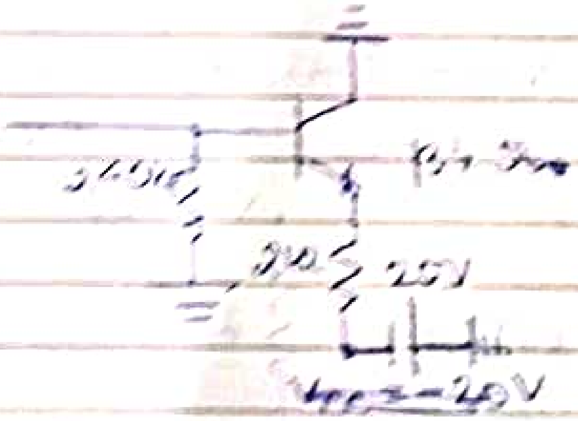
$9 - 2.733 \times 1.2 \cdot V_{CE} = 4.518\,V$

$V_C - V_E = 4.318$

$V_C + 3 = 4.318$

$V_C = -4.48\,V$

eg 4.15)




$-I_B(240) - V_{BE} - 2 I_E + 20 = 0$

$$i_E = \frac{20 - V_{BE}}{240 + (\beta+1)2} = 0.056 \text{ mA}$$

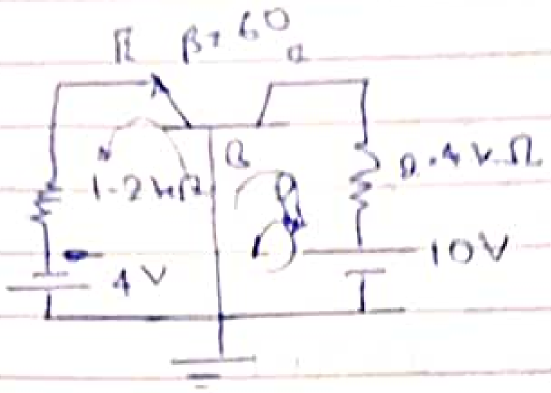
$I_E, \; i_E = 2.87$ mA

$i_C = 2.82$ mA

$-V_{CE} - 2 i_E + 20 = 0$

$V_{CE} = 14.22\,V$

eg) 4.17




$$V_{EB} - V_{BE} - 1.2 i_E + 4 = 0$$

$$\frac{3.3}{1.2} = i_E =$$

$$i_E = 2.75 \text{ mA}$$

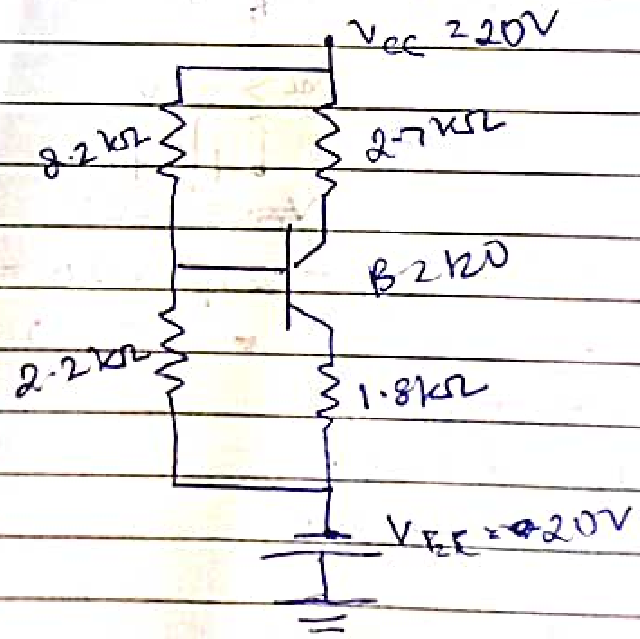
$$i_B = \frac{i_E}{(\beta+1)} = 0.045 \text{ mA}$$

$$i_C = 2.704 \text{ mA}$$

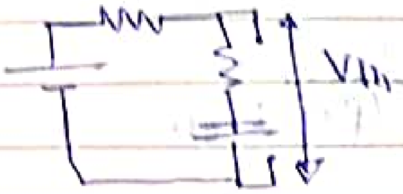
$$-V_{CB} - 2.4 i_C + 10 = 0$$

$$V_{CB} = 3.5V$$

eg 4.18



$R_{th} = 1.73\,\Omega$

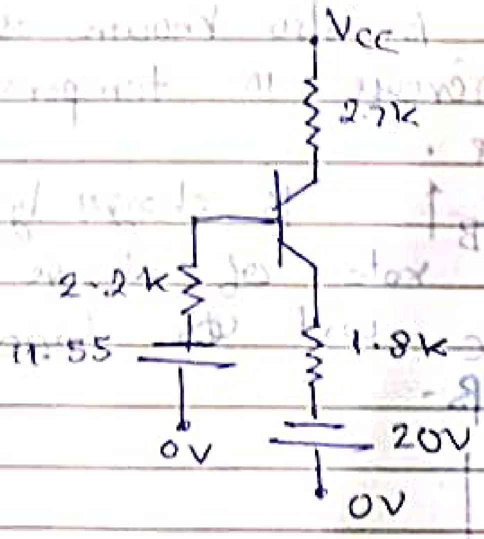



$V_{cc} - i(8.2 + 2.2) + 20 = 0$

$i = \dfrac{40}{8.2+2.2} = 3.84\ mA$

$V_{th} - i_R(2.2) + 20 = 0$

$V_{th} = -11.55\ V$




$-11.55 - 2.2 i_B - V_{BE} - 1.8 i_E + 20 = 0$

$\dfrac{20 - V_{BE} - 11.55}{2.2 + (\beta+1)1.8} = i_B$

$i_B = 0.035\ mA$

$i_C = 4.22\ mA$

$i_E = 4.26\ mA$

$V_{cc} - i_c(2.7) - V_{CE} - 1.8 i_E + 20 = 0$

$40 - i_c(2.7) - 1.8 i_E = V_{CE}$

$V_{CE} = 20.938V$

# Stabilization of DC biasing BJT ckt

$I_C$, $V_{CE}$

$(\cancel{I_C = \beta I_B + I_{CBO}})$

$$I_C = \beta I_B + (\beta+1) I_{CBO}$$

Flow of collector current $I_C$ produces heat and this will increase the temperature of the circuit. With the increase in temperature the reverse saturation current $I_{CBO}$ increases. This forms a chain reaction. The circuit becomes unstable. This is also known as thermal runaway. With increase in temperature $V_{BE}$ & $\beta$ also varies.

If $V_{BE}\uparrow$ varies $I_B\uparrow$ $\beta$ changes by Temp.

∴ Stability factor is rate of change of collector current $I_C$ wrt $I_{CBO}$ at constant $V_{BE}$ & $\beta$.

$$S = \frac{\partial I_C}{\partial I_{CBO}}$$

$V_{BE}, \beta \Rightarrow$ constants

$$S' = \frac{\partial I_C}{\partial V_{BE}}$$

$\beta, I_{CBO} \Rightarrow$ constant

$$S'' = \frac{\partial I_C}{\partial \beta}$$

$V_{BE}, I_{CBO} \Rightarrow$ constant

very complex
not in syllabus.

## Fixed bias

$$I_B = \frac{V_{CC}-V_{BE}}{R_B \cancel{+(\beta+1)R_E}}$$

$$\partial\ I_C = \beta\left(\frac{V_{CC}-V_{BE}}{R_B}\right) + (\beta+1) I_{CBO}$$

$$S = \frac{\partial I_C}{\partial I_{CBO}} = \beta+1$$

---

~~Voltage divider~~

## Emitter bias, Collector bias, ~~fixed bias~~

$$i_B = \frac{V_{CC}-V_{BE}}{R_B+(\beta+1)R_E} \qquad i_B = \frac{V_{CC}-V_{BE}}{R_B+(\beta+1)R_C}$$

$$S = \frac{\partial\left(\beta i_B + (\beta+1) i_{CBO}\right)}{\partial I_{CBO}} = \beta+1$$

$$S = \frac{\partial\left(\frac{\beta(V_{CC}-V_{BE})}{R_B+(\beta+1)R_C} + (\beta+1) I_{CBO}\right)}{\partial I_{CBO}} = \beta+1$$

## Voltage divider bias

$$i_B = \frac{V_{th}-V_{BE}}{R_{th}+(\beta+1)R_E}$$

$$S = \frac{\partial\left(\beta i_B + (\beta+1) i_{CBO}\right)}{\partial i_{CBO}}$$

$$= \beta+1$$

Fixed bias

$$S' = \frac{\partial I_c}{\partial V_{BE}} = -\beta/R_B$$

Emitter bias

$$S' = \frac{\partial I_c}{\partial V_{BE}} = \frac{-\beta}{R_B + (\beta+1)R_E} \quad \times$$

{can't directly use formula}

Collector bias

$$S' = \frac{\partial I_c}{\partial V_{BE}} = \frac{-\beta}{R_B + (\beta+1)R_c} \quad \times$$

Voltage divider bias

$$S' = \frac{\partial I_c}{\partial V_{BE}} = \frac{-\beta}{R_{th} + (\beta+1)R_E} \quad \times$$

---

Emitter bias

$$I_c = \beta I_B + (\beta+1) I_{CBO}$$

$$I_B = \frac{V_{cc} - V_{BE} - I_c R_E}{R_B + R_E} \qquad (I_c \simeq I_E)$$

$$I_c = \beta I_B + I_{CBO}(\beta+1)$$

$$\frac{\partial I_c}{\partial I_c} = \frac{\beta}{R_B+R_E} \frac{\partial}{\partial I_c}\left(V_{cc} - V_{BE} - I_c R_E\right) + (\beta+1)$$

$$1 = \frac{\beta}{R_B+R_E}(-R_E) + (\beta+1)\frac{1}{S}$$

$$S = \frac{\beta+1}{1+\frac{\beta R_E}{R_B+R_E}}$$

**Collector base**

$$V_{CC} - (i_B+i_C)R_C - i_B R_B - V_{BE} = 0$$

$$i_B = \frac{V_{CC} - V_{BE} - i_C R_C}{R_B + R_C}$$

$$i_C = \beta\frac{(V_{CC} - V_{BE} - i_C R_C)}{R_B+R_C} + (\beta+1) I_{CO}$$

$$1 = \frac{\partial i_C}{\partial i_C} = \frac{\beta}{R_B+R_C}(-R_C) + (\beta+1)\frac{1}{S}$$

$$S = \frac{\beta+1}{1+\frac{\beta R_C}{R_B+R_C}}$$

$$1 = \beta\left(0 - \frac{\partial V_{BE}}{\partial I_C} - R_E\right)\frac{1}{R_B+R_E} + 0$$

S' (for emitter bias)

$$i_C = \beta\frac{V_{CC} - V_{BE} - i_C R_E}{R_B + R_E} + (\beta+1) I_{CO}$$

$$S'' = \frac{-\beta}{R_B+\beta R_E}$$

$$1 = \frac{\beta}{R_B+R_E}(-R_E) + (\beta+1)\frac{1}{S}$$

$$\left\{ S' = \cancel{\frac{-\beta}{R_B + \beta R_E}} \right\}$$

$$1 = \frac{\beta}{R_B + R_E}\left(0 - \frac{1}{S'} - R_E\right) + 0$$

$$R_B + R_E = -\frac{\beta}{S'} - R_E\beta$$

$$R_E(\beta+1) + R_B = -\beta \, \frac{1}{S'}$$

$$\left\{ S' = \frac{-\beta}{R_E(\beta+1) + R_B} \right\}$$

~~Collector bias~~

~~$V_c$~~

Q) Why do we include emitter feedback resistance in our ckt?

→ Stability $S'$ with respect to $V_{BE}$ is equal to $-\beta / (R_E(\beta+1)+R_B)$. If we design the ckt such that emitter res $R_E$ is much greater than $R_B$. Then $S'$ can be approximated as $\frac{-\beta}{(\beta+1)R_E}$

Further approximation of $\beta+1 \simeq \beta$ make the stability $S' = 1/R_E$. Thus the ckt. becomes stable with respect to $V_{BE}$ with change in temperature.

---

Stability of system is measure of sensitivity of a network to variation in parameters.

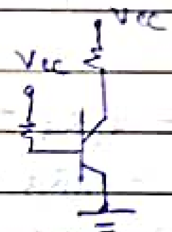
$\beta \uparrow \quad T\uparrow$

$V_{BE} \downarrow \quad T\uparrow$

$I_{CBO} \uparrow \quad T\uparrow$

Practice

Fixed Bias




$$V_{CC} - V_{BE} - i_B R_B = 0$$

$$i_B = \frac{V_{CC} - V_{BE}}{R_B}$$

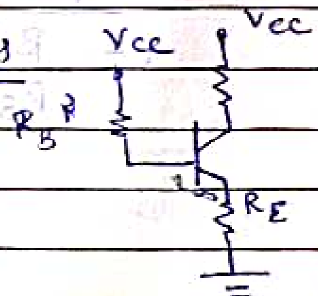
$$i_C = \beta i_B + (\beta+1) i_{CBO}$$

$$\frac{di_C}{di_C} = \beta \frac{i_B}{di_C} + (\beta+1)\frac{d\,i_{CBO}}{di_C}$$

$$1 = 0 + \frac{(\beta+1)}{S}$$

$$\{S = \beta + 1\}$$

Emitter bias




$R_B i_E = (\beta+1) i_B R_{BE}$

$i_C = \beta i_B R_E + i_B R_E$

$$V_{CC} - i_B R_B - V_{BE} - i_E R_E = 0$$

$$V_{CC} - V_{BE} = i_B R_B - \cancel{R_B} i_C R_E$$

$$\frac{1}{R_B}(V_{CC} - V_{BE} - i_C R_E) = i_B$$

$$i_C = \beta \frac{1}{R_B}(V_{CC} - V_{BE} - i_C R_E) + (\beta+1) i_{CBO}$$

$$1 = -\frac{\beta}{R_B}(R_E) + (\beta+1)\frac{1}{S}$$

$$R_B = -\beta R_E + \frac{R_B(\beta+1)}{S}$$

$$R_B - \beta R_E = \frac{R_B(\beta+1)}{S}$$

$$S = \frac{R_B(\beta+1)}{R_B - \beta R_E}$$

$$\cancel{X} = \frac{\beta+1}{1 - \frac{\beta R_E}{R_B}}$$

$$V_{CC} - V_{BE} - i_B R_B - (\beta+1) i_B R_E = 0$$

$$V_{CC} - V_{BE} - i_B R_B - i_B R_E - \beta i_C R_E = 0$$

$$i_B = \frac{1}{R_B + R_E}(V_{CC} - V_{BE} - i_C R_E)$$

$$i_C = \frac{\beta}{R_B + R_E}(V_{CC} - V_{BE} - i_C R_E) + i_{CBO}(\beta+1)$$

$$1 = \frac{\beta}{R_B + R_E}(-R_E) + \frac{\beta+1}{S}$$

$$1 + \frac{\beta R_E}{R_B + R_E} = \frac{\beta+1}{S}$$

$$\left\{ S = \frac{\beta+1}{1 + \frac{\beta R_E}{R_B + R_E}} \right\}$$

$$= \frac{\beta r^2}{1 + \frac{\beta (r_2/r_1)}{1 + \frac{r_2}{r_1}}}$$

$$= \frac{(\beta + 1)\left(1 + \frac{r_2}{r_1}\right)}{\left(\frac{r_2}{r_1} + 1 + \beta\right)}$$

$$= \frac{(\beta + 1)(1 + r_2/r_1)}{r_2/r_1} \approx \beta + 1$$

if $\frac{r_2}{r_1} \ll$

$S = 1$

lowest level

Most imp

| | $S = \frac{\partial I_C}{\partial I_{CBO}}$ | $S' = \frac{\partial I_C}{\partial V_{BE}}$ | $S'' = \frac{\partial I_C}{\partial \beta}$ |
|---|---|---|---|
| Fixed Bias | $\beta + 1$ | $-\beta / R_B$ | — |
| Emitter Bias | $\frac{(\beta+1)(R_B+R_E)}{R_B+(\beta+1)R_E}$ | $\frac{-\beta}{R_B+(\beta+1)R_E}$ | — |
| Collector Bias | $\frac{(\beta+1)(R_B+R_C)}{R_B+(\beta+1)R_C}$ | $\frac{-\beta}{R_B+(\beta+1)R_C}$ | — |
| Voltage Divider Bias | $\frac{(\beta+1)(R_{Th}+R_E)}{R_{Th}+(\beta+1)R_E}$ | $\frac{-\beta}{R_{Th}+(\beta+1)R_E}$ | — |

General form

$$I_C = (\beta+1) I_{CBO} + \beta I_B$$

$$\frac{\partial I_C}{\partial I_C} = \beta \frac{\partial I_B}{\partial I_C} + (\beta+1) \frac{\partial I_{CBO}}{\partial I_C}$$

$$1 = \beta \frac{\partial I_B}{\partial I_C} + (\beta+1) \frac{1}{S}$$

$$S = \frac{\beta+1}{1 - \beta \frac{\partial I_B}{\partial I_C}}$$

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Q) For an emitter feedback ckt if $V_{CC} = 10V$, $R_C = 1.5k$, $R_B = 270k$, $R_E = 1k$ and $\beta = 50$ Find the operating point and the stability factor ~~of~~ S of the ckt.

$$V_{CC} - i_B R_B - V_{BE} - R_E(\beta+1) i_B = 0$$

$$i_B = \frac{V_{CC} - V_{BE}}{R_B + (\beta+1)R_E} = 0.028 \text{ mA}$$

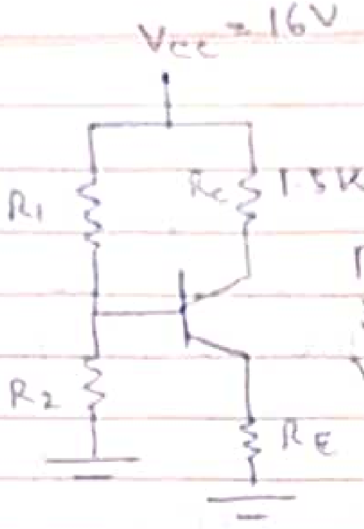
$$i_{CQ} = 1.448 \text{ mA}$$
$$i_E = 1.476 \text{ mA}$$

$$V_{CC} - i_C R_C - V_{CE} - i_E R_E = 0$$
$$V_{CEQ} = 6.352 V$$

$$Q \equiv (\cancel{1.448 \text{ mA}}, 6.352V, 1.448 \text{ mA})$$

$$S = \frac{(\beta+1)(R_B + R_E)}{R_B + (\beta+1)R_E}$$
$$= 43.05$$

Q) A voltage divider bias ckt is to be designed for stability $(S) = 12$ supply voltage is 15V ~~&~~ $R_C = 1.5k$, $\beta = 50$. The germanium transistor is to be used having $V_{BE} = 0.2V$. The ckt has an operating point $V_{CE} = 5V$ and $i_C = 4 \text{ mA}$. Design the ckt.

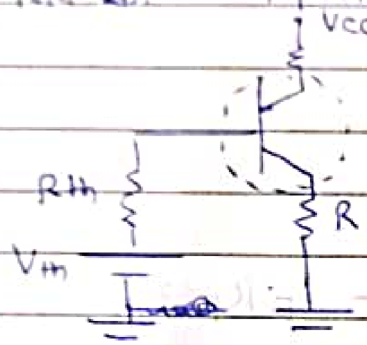



$\beta = 50$

$i_c = 4mA$

$V_{CE} = 8V$

$R_{th}$ ~~$V_{th}$~~ $= R_1 \| R_2$




$I_C = \beta I_B$

$I_B = 4/50$

$= 0.08\ mA = 80\mu$

$I_E = 0.08 + 4$

$= 4.08\ mA$

$V_{CC} - i_C R_C - V_{CE} - i_E R_E = 0$

~~16~~ ~~$V_{CE}$~~ $R_E = 0.49\ k\Omega$

$$S = \frac{(\beta+1)(R_{th} + R_E)}{R_{th} + (\beta+1) R_E}$$

$$12 = \frac{51(R_{th} + 0.49)}{R_{th} + 24.99}$$

$299.8 + 12 R_{th} = 51 R_{th} + 24.99$

$274.81 = 39 R_{th}$

$\{ R_{th} = 7.046\ \Omega \}$

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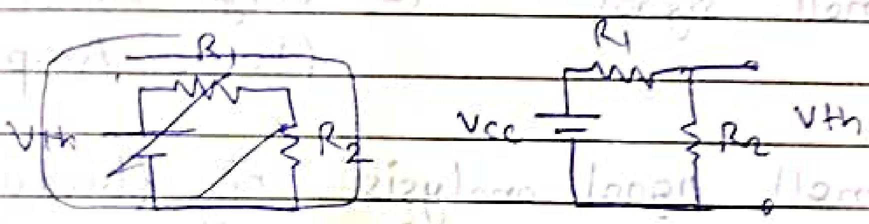
$$\frac{R_1 R_2}{R_1+R_2} = 7.046 \quad \text{—} \ (1)$$

$$1/R_1 + 1/R_2 = 1/7.046 \quad \text{—} \ (1)$$

$$V_{th} - i_B R_{th} - V_{BE} - i_E R_E = 0$$

$$V_{th} = 2.76 \, V$$




$$V_{th} = \left(\frac{V_{cc}}{R_1+R_2}\right) \cdot R_2$$

$$2.76 = \frac{16 R_2}{R_1+R_2}$$

$$2.76 R_1 + 2.76 R_2 = 16 R_2$$

$$13.24 R_2 = 2.76 R_1$$

$$R_1 = 4.79 R_2$$

$$\frac{(4.79) R_2^2}{(4.76+1)\cancel{R_2}} = 7.046$$

$$R_2 = \frac{7.046 \times 5.76}{4.79}$$

$$= 8.47 \ \Omega$$

$$R_1 = 40.58 \ \Omega$$

# Small Signal Analysis

In small signal analysis of BJT we find the AC response of the transistor using different two models.

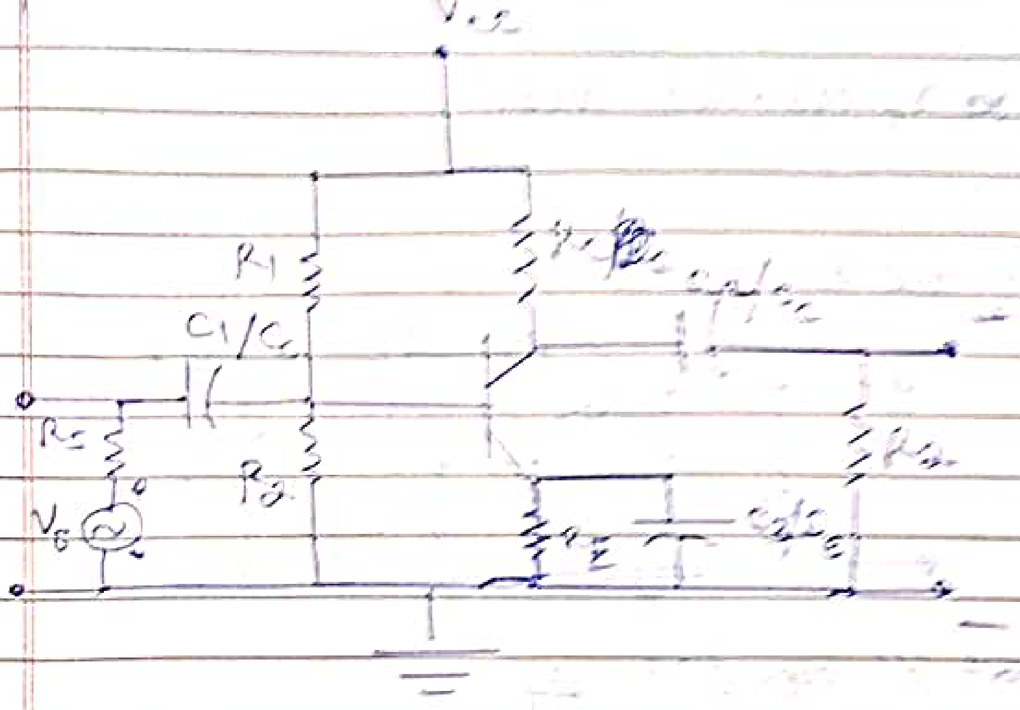
Hybrid Model    $r_e$ model

→ Two types of analysis are :

(1) Small signal    (2) Large signal (Power Amplifier)

→ In small signal analysis the fluctuation in source voltage $V_s$ is small so the base current will not change much and there won't be much change in collector current $I_c$. So operating point Q will not shift.

Small signal analysis means the AC signal is sufficiently small to keep the region of operation in active region of the transistor where the transistor behaves like an amplifier.




$C_1$, $C_2$ & $C_3$ capacitors are short circuit for AC signal and open ckt for dc signal

$$X_C = \frac{1}{2\pi f C}$$

in dc $f = 0$
so $X_C = \infty$
so open ckt

in ac $f$ = large value
so $X_C$ = v. small
so almost = short ckt

$C_1$ and $C_2$ are known as coupling capacitors while $C_3$ is known as emitter bypass capacitor

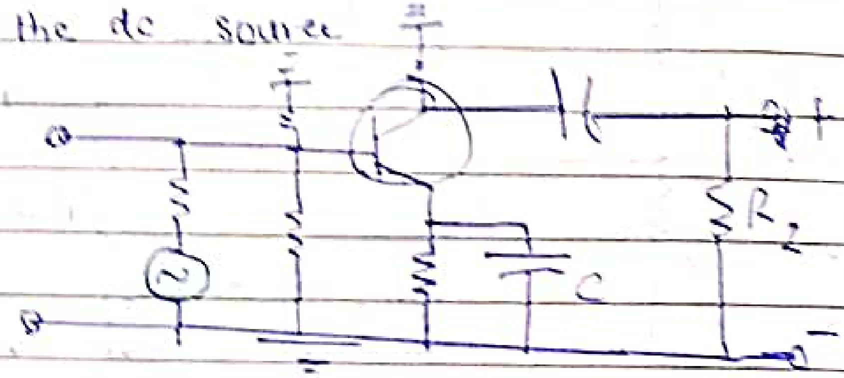
To find the AC response of the circuit:

Steps-

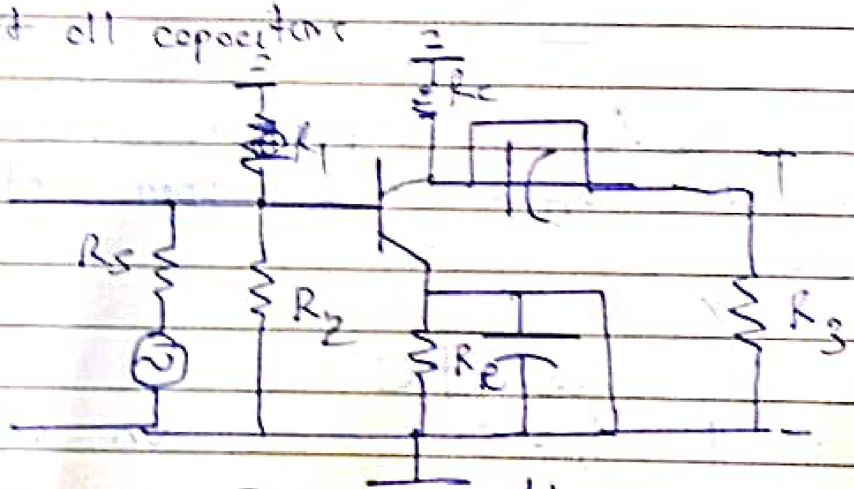
1) Draw the AC equivalent circuit by removing all DC sources
2) Short all the capacitors
3) Re-draw the circuit with elements arranged
(h-parameter)
4) a) Replace the transistor with hybrid equivalent model $\boxed{\text{OR}}$

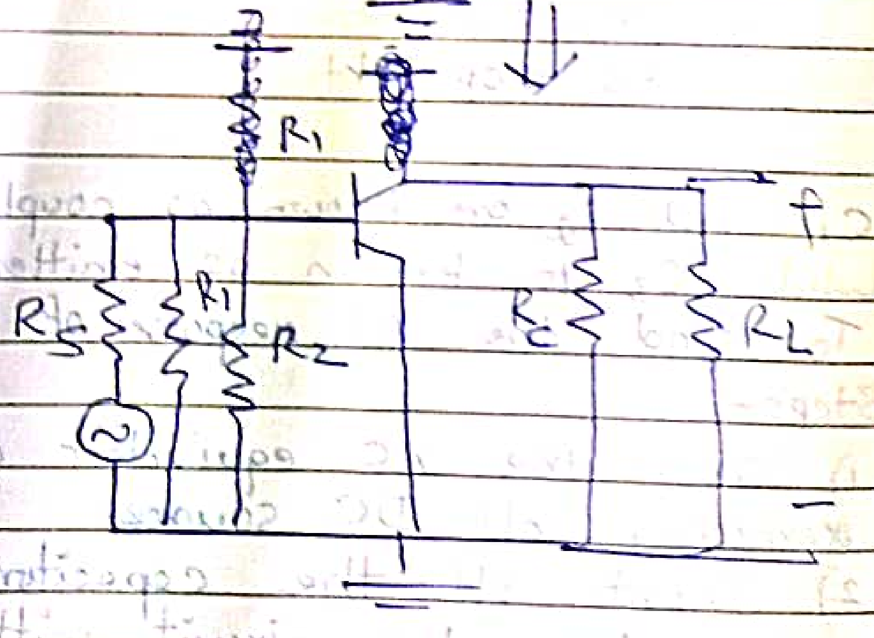
b) $r_e$ equivalent model

i) Remove the dc source

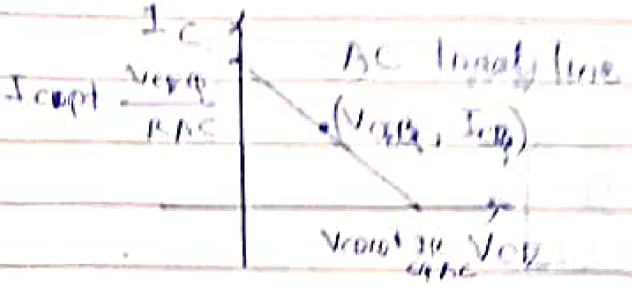


ii) Short all capacitors





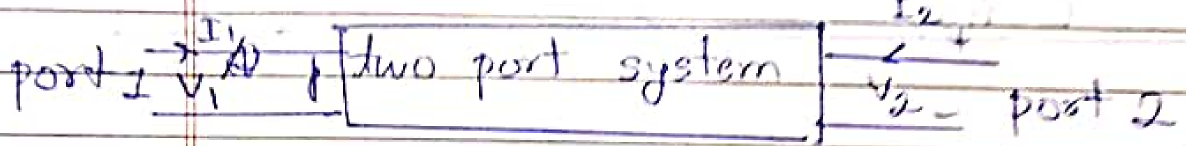
$R_{AC} = R_C \parallel R_L$




coordinates

## Hybrid Model

### Calculation of H-parameter




$V_1$ and $I_2$ are dependent parameters
$I_1$ and $V_2$ are independent parameters

$$I_2 = f_1(V_2, I_1)$$
$$V_1 = f_2(V_2, I_1)$$

The small change in $V_1$,

$$dV_1 = \frac{\partial V_1}{\partial I_1} \cdot \partial I_1 + \frac{\partial V_1}{\partial V_2} dV_2$$

$$\partial I_2 = \frac{\partial I_2}{\partial I_1} \cdot dI_1 + \frac{\partial I_2}{\partial V_2} dV_2$$

$$i_2(1+h_oR_L) = h_f i_1$$

$$\frac{i_2}{i_1} = \cancel{h_o R_L} \frac{h_f}{1+h_oR_L}$$

$$\boxed{A_i = \frac{-i_2}{i_1} = \frac{-h_f}{1+h_oR_L}}$$

$$\cancel{v_1 = h_i i_1 + h_r v_2}$$
$$\cancel{v_1 = h_i i_1 - h_r(i_2 R_L)}$$

$$Z_i = \frac{v_1}{i_1}$$

$$v_1 = h_i i_1 + h_r v_2$$
$$= h_i i_1 - h_r i_2 R_L$$

$$\frac{v_1}{i_1} = h_i - h_r R_L\left(\frac{i_2}{i_1}\right)$$

$$\boxed{Z_i = h_i + h_r R_L \times A_i}$$

$$\left\{ Z_i = h_i - \frac{h_r h_f}{h_o + 1/R_L} \right\}$$

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~~Voltage gain~~ Voltage Gain $A_V$

$$A_v = \frac{V_2}{V_1} = \frac{-i_2 R_L}{V_1} = -\frac{A_i \times i_1 \times R_L}{V_1}$$

$$= \frac{-h_f}{1+h_o R_L} \times \frac{R_L}{Z_i}$$

$$= \frac{-h_f}{1+h_o R_L} \times \frac{R_L}{h_i - \frac{h_f h_r}{h_o + 1/R_L}}$$

$$= \frac{-h_f}{\cancel{1+h_o R_L}} \times \frac{\cancel{h_o R_L + 1}}{h_i h_o + \frac{h_i}{R_L} - h_f h_r}$$

$$= \frac{-h_f}{h_i h_o + \frac{h_i}{R_L} - h_f h_r}$$

$$= \frac{-R_L h_f}{h_i h_o R_L + h_i - h_f h_r R_L} = \frac{-R_L h_f}{h_i + \Delta h R_L}$$

$$\begin{bmatrix} V_1 \\ i_2 \end{bmatrix} = \underbrace{\begin{bmatrix} h_i & h_r \\ h_f & h_o \end{bmatrix}}_{h} \begin{bmatrix} i_2 \\ V_2 \end{bmatrix}$$

Q) A common emitter amplifier has the following h parameters $h_{ie} = 1100\ \Omega$ $h_{re} = 2.5 \times 10^{-4}$

$h_{fe} = 50$ $h_{oe} = 25\ \mu\Omega$

$R_S = R_L = 1K\Omega$

find: $A_i$, $A_v$, $Z_i$

$$\cancel{A_i = \frac{-h_f}{1+h_oR_L} = \frac{-50}{1+25\times10^{-6}}}$$

$$\cancel{Z_i =}$$

$$A_i = \frac{-h_f}{1+h_oR_L} = -48.78$$

$$A_v = \frac{-R_L h_f}{h_i + R_L(h_ih_o - h_fh_r)} = -44.94$$

$$Z_i = h_i + h_R R_L A_i$$

$$\{ Z_i = 1087.805\ \Omega \}$$

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## Table

$$\left\{ \begin{array}{l} i)\ v_1 = h_i i_1 + h_r v_2 \\ ii)\ i_2 = h_f i_1 + h_o v_2 \end{array} \right\}$$

a) Current gain $A_i = \dfrac{-h_f}{1+h_oR_L}$

b) Voltage gain $A_v = \dfrac{-h_fR_L}{h_i+\Delta h R_L} = \dfrac{A_i \times R_L}{Z_i}$

c) Power gain $= A_i \times A_v$

$$= \frac{h_f^2 R_L}{(1+h_oR_L)(h_i+\Delta h R_L)}$$

d) Input impedance $= h_i - \dfrac{h_r h_f}{1+\dfrac{h_o}{R_L}} = h_i + h_r A_i R_L$

e) $\boxed{\cancel{A_v} = A_i \times \cancel{R}/Z_i}$

Output impedance $Z_o$

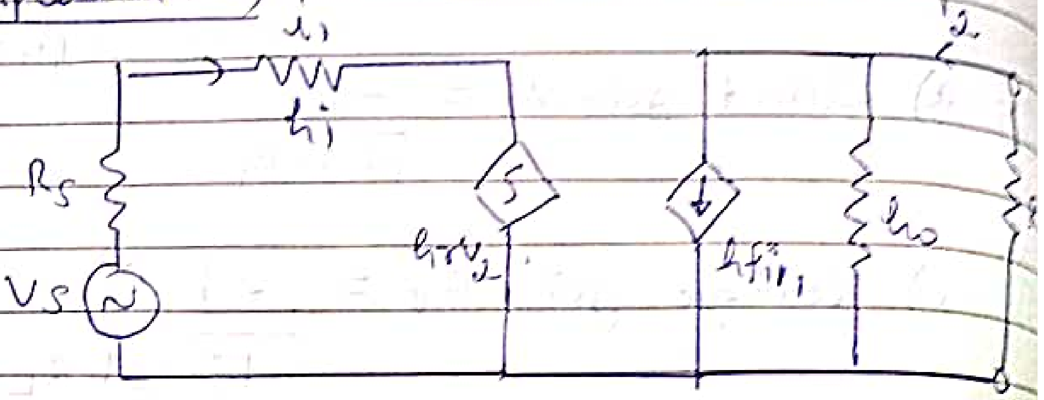
$$= \frac{R_s + h_i}{\Delta h + h_oR_s}$$

$$\left\{ \begin{array}{l} v_1/i_1 = h_i = \text{input impedance} \\ i_2/v_2 = h_o = \text{output impedance} \\ v_1/v_2 = h_r = \text{reverse voltage gain} \\ i_2/i_1 = h_f = \text{forward current gain} \end{array} \right.$$

f) Overall current gain $A_{is} = \dfrac{A_i \times R_s}{R_s + Z_i}$

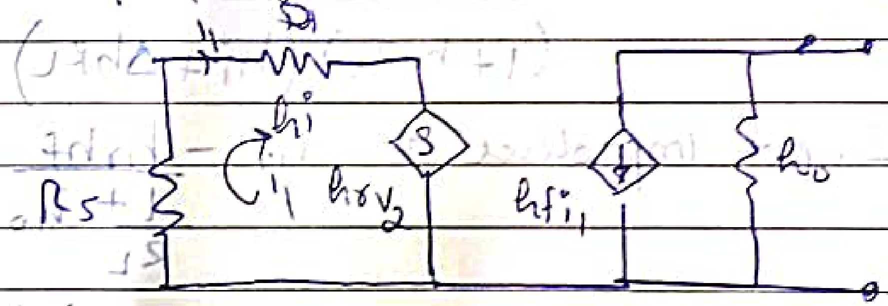
g) Overall voltage gain $A_{vs} = \dfrac{A_v \times Z_i}{Z_i + R_s}$

Output impedance ($Z_o$)




* Short ckt the voltage ($V_s = 0$)

* Open ckt load resistance $R_L$ ($R_L = \infty$)




$$Z_o = \frac{V_2}{h_f i_1 + h_o v_2}$$

$$-i R_s - i_1 h_i - h_r v_2 = 0$$

$$i_1 = \frac{-h_r v_2}{R_s + h_i}$$

$$= \frac{v_2}{h_f\left(\frac{-h_r v_2}{R_s + h_i}\right) + h_o v_2} = \frac{R_s + h_i}{h_o R_s + h_o h_i - h_f h_r}$$

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$$Z_0 = \frac{R_s + h_i}{h_o R_s + \Delta h}$$

Q) A common emitter amplifier ckt has following measurements when output is short circuited ie $V_{CE} = 0$, $i_b = 15\ \mu A$, $i_c = 1.5\ mA$
$V_{be} = 15\ mV$.
When input is open $V_{be} = 1\ mV$, $I_C = 90\ \mu A$, $V_{CE} = 1.5V$
Find out the h-factors?

$h_{ie}$, $h_{re}$, $h_{fe}$ & $h_{oe}$ = ?

$$h_{ie}\Big|_{V_2=0/V_{CE}=0} = \frac{V_1}{i_1} = \frac{V_{be}}{i_b} = \frac{15\ mV}{15\ \mu A} = 1000$$

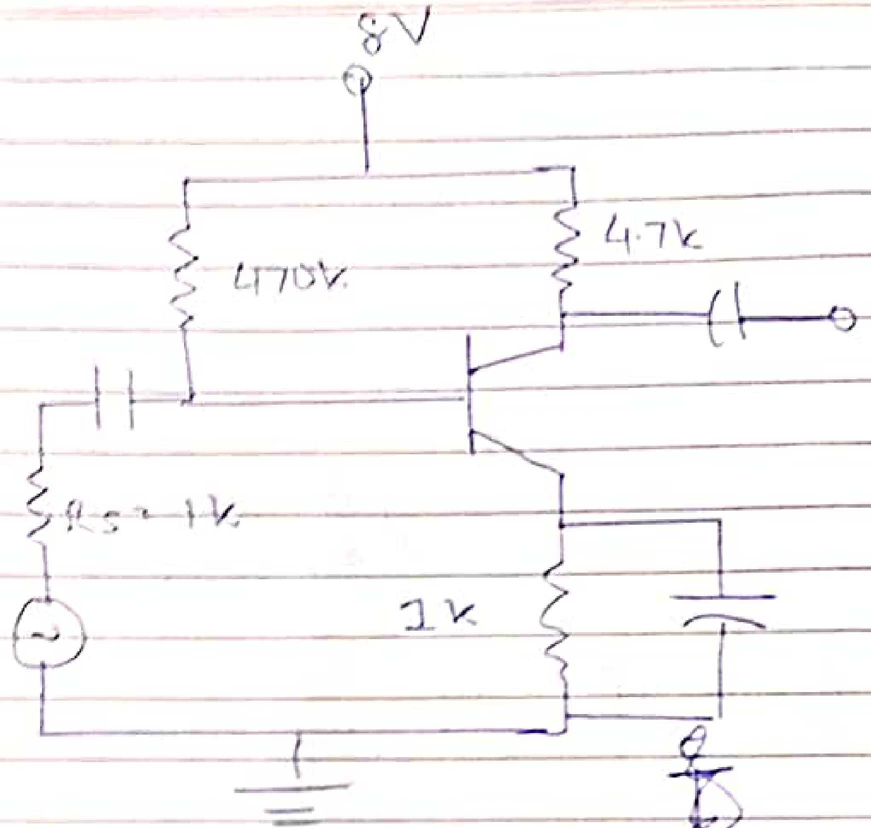
$$h_{fe} = \beta = i_C / i_B = \frac{1.5\ mA}{15\ \mu A} = 100$$

$$h_{re}\Big|_{i_b=0} = \frac{V_1}{V_2} = \frac{1\ mV}{1.5V} = \frac{2}{3} \times (1000)^{-1}$$

$$= 0.667 \times 10^{-3}$$

$$h_{oe} = i_2 / V_2 = \frac{90\ \mu A}{1.5} = 60 \times 10^{-6}\ mho$$

$$= 60\ \mu mho$$




Draw equivalent hybrid model and find out

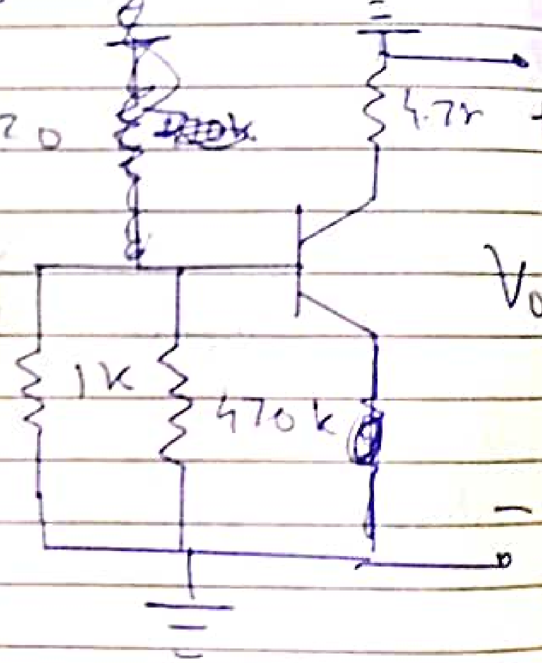
$h_{fe} = 110$

$h_{ie} = 1.6k$

$h_{oe} = 20 \mu A/V$

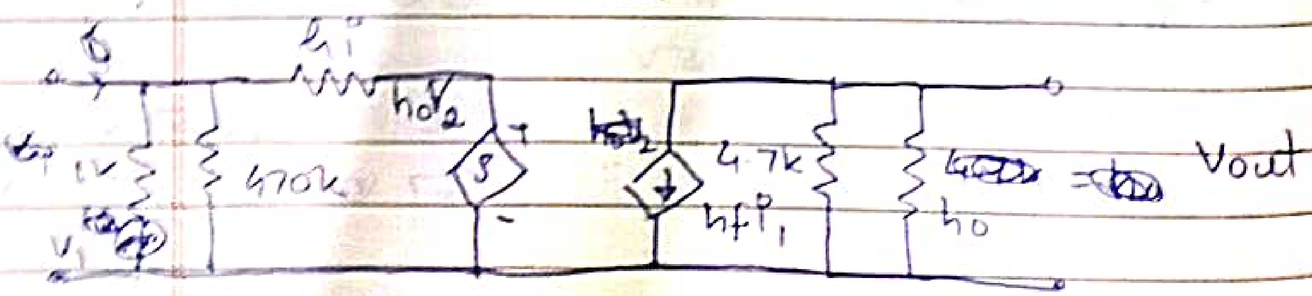
Find: $A_i$, $A_v$, $Z_i$, $Z_o$

$\rightarrow \cancel{A_i = \frac{-h_f}{1+h_o R_L}}$




Eq. ckt

$\Downarrow$



$$A_i = \frac{-h_f}{1 + h_o R_L}$$

$$= \frac{-110}{1 + 20 \times 4.7 \times 10^3 \times 10^{-6}}$$

$$= -100.58$$

$$A_v = \frac{-h_f R_L}{h_i + \Delta h R_L} = \frac{-110 \times 4.7 \times 10^3}{1.6 \times 10^3 + (h_i h_o - h_r h_f)(4.7 \times 10^3)}$$

$$= -313.9$$

$$Z_i \quad \frac{A_i \times R_L}{Z_i} = A_v$$

$$Z_i = 1505.97\ \Omega$$

$$Z_o = \frac{R_s + h_i}{\Delta h + h_o R_s} \qquad R_s = 2k \,||\, 470k \simeq 2k$$

$$= 86666.67\ \Omega$$

$$= 86.67\ k\Omega$$

<u>Note</u>: If $h_o$ near output is given as 50k then $h_o = 1/50k\ \Omega^{-1}$. If it is given as 20 $\mu$A/V take it $h_o = 20\ \Omega^{-1}$

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$$A_{v_s} = \frac{v_2}{v_s} = \frac{v_2}{v_s} \times \frac{v_1}{v_1} = \frac{v_2}{v_1} \times \frac{v_1}{v_s}$$

$$= A_v \times \frac{v_1}{v_s}$$

$$= \left\{ A_v \times \frac{Z_i}{R_s + Z_i} \right\}$$

$$\frac{v_1}{v_s} = \frac{Z_i}{Z_i + R_s}$$

<u>overall current gain</u>

$$A_{is} = i_2/i_s = \frac{i_2}{i_s} \times \frac{i_1}{i_1} = A_i \times \frac{i_1}{i_s}$$

$$A_{is} = A_i \times \frac{R_s}{R_s + Z_i}$$

$$i_1 = i_s \times \frac{R_s}{R_s + R_2}$$

$$\frac{i_1}{i_s} = \frac{R_s}{R_s + Z_i}$$

$$\boxed{\begin{aligned} A_{vs} &= \frac{A_v \times Z_i}{R_s + Z_i} \\ A_{is} &= \frac{A_i \times R_s}{R_s + Z_i} \end{aligned}}$$

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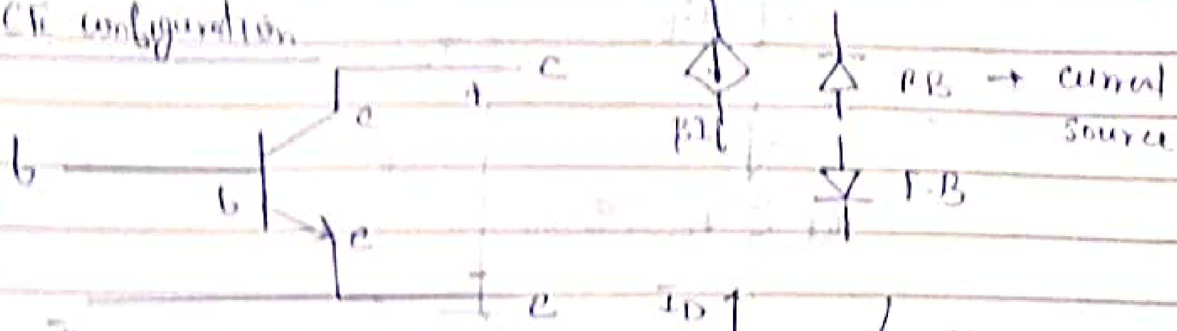
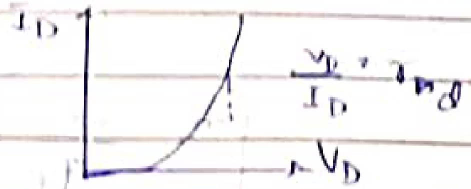
CE configuration




dynamic resistance $r_d$

$$I_D = I_s \left( e^{\frac{kV_D}{T_K}} - 1 \right)$$

$I_s$ → reverse saturation current

$T_K$ → Temperature in kelvin

$$\frac{dI_d}{dV_d} = I_s e^{\frac{kV_D}{T_K}} \cdot \frac{k}{T_K}$$

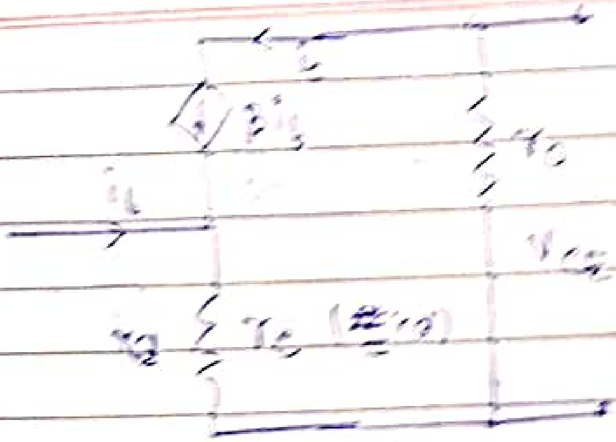
$$= \frac{k}{T_K} \left( e^{\frac{kV_D}{T_K}} \right) \cdot I_s$$

$$= \frac{k}{T_K} \left( \frac{I_D}{I_s} + 1 \right) \cdot I_s$$

$$= \frac{k}{T_K} \left( I_D + I_s \right)$$

$$\frac{1}{r_d} = G \simeq \frac{k}{T_K} I_D \qquad (I_D >> I_s)$$

$$\left\{ r_d \simeq \frac{26\,mV}{I_D} \right\}$$



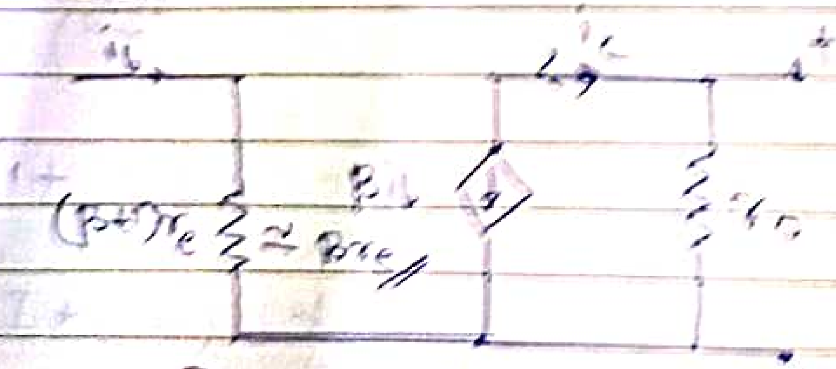
$\left[ r_e = \frac{26\,mV}{I_E} \right]$ & [ $r_o$ is ideally ∞, Practically $r_o$ is high value ]

voltage drop across $R_E$ = $i_e r_e$

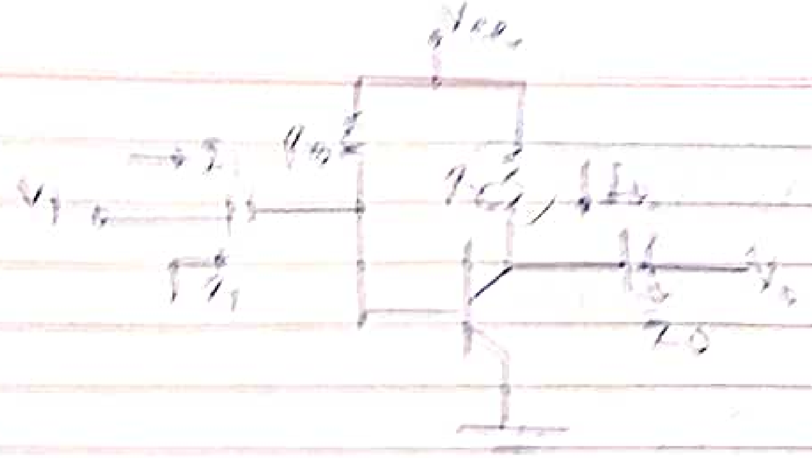
$= (\beta+1) i_b r_e$

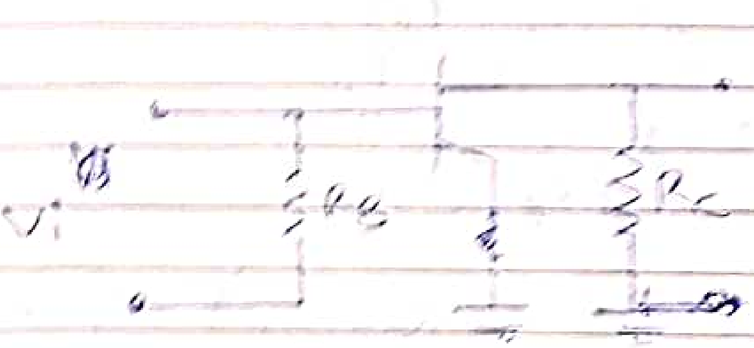
{ $r_e$ reflected towards base side has a value of $(\beta+1) r_e$ }

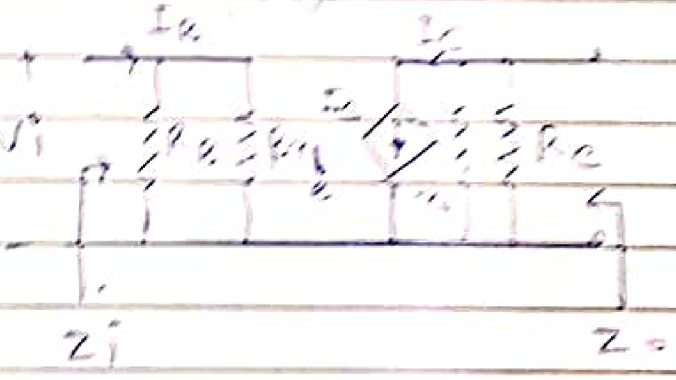
~~$v_{be}$~~ $= i_b (\beta+1) r_e$



Dynamic $r_e$ model of BJT




$Z_i = R_B \parallel \beta r_e$

$\cdot \quad R_B \geq 10 \times \beta r_e$

$$Z_i = \frac{R_B \cdot \beta r_e}{R_B + \beta r_e} \simeq \beta r_e$$

$$\boxed{Z_o = r_o \| r_L}$$

If $r_o \geq 10 R_C$

$$\boxed{Z_o = R_C}$$

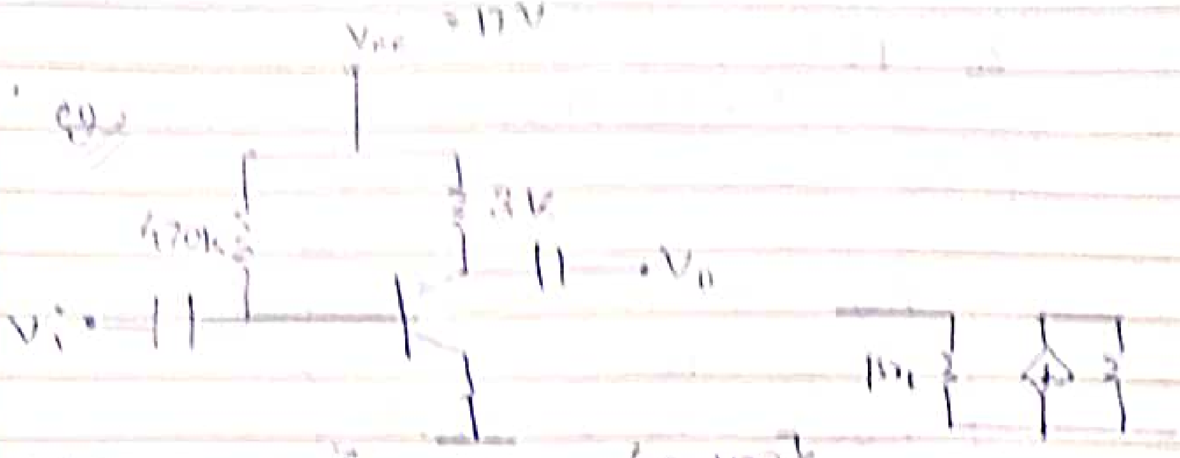
$$V_o = i_o \times (R_C \| r_o)$$

$$= -i_c \times (R_C \| r_o)$$

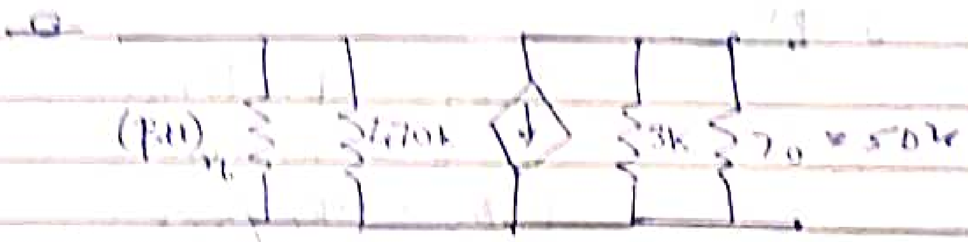
$$V_o = -\cancel{\beta} \frac{V_i}{\cancel{\beta} r_e} (R_C \| r_o) \quad \rightarrow i_B$$

$$A_V = \frac{V_o}{V_i} = -\frac{(R_C \| r_o)}{r_e} \simeq \boxed{-\frac{R_C}{r_e}}$$

Q)




Find $r_e$, $Z_i$, $Z_o$, $A_V$ $\{\beta = 100\}$




$r_e$

$V_{CC} - i_B R_B - V_{CE} = 0$

$i_B = \frac{12 - 0.7}{470k} = 0.024 \text{ mA}$

$i_C = 2.404 \text{ mA}$

$r_e$

$r_e = \frac{26 mV}{2.428 mA} = 10.71\ \Omega$

$Z_i = \beta r_e || 470k$

$= \cancel{1.0047}\ \cancel{10.709\ k\Omega}$

$= 10.68\ k\Omega \simeq \beta r_e$

$\boxed{Z_i = \beta r_e}$ $\{R_B > \beta r_e\}$

$Z_o = 15 r_o \| 3k$

$= 2.83\ k\Omega$ //

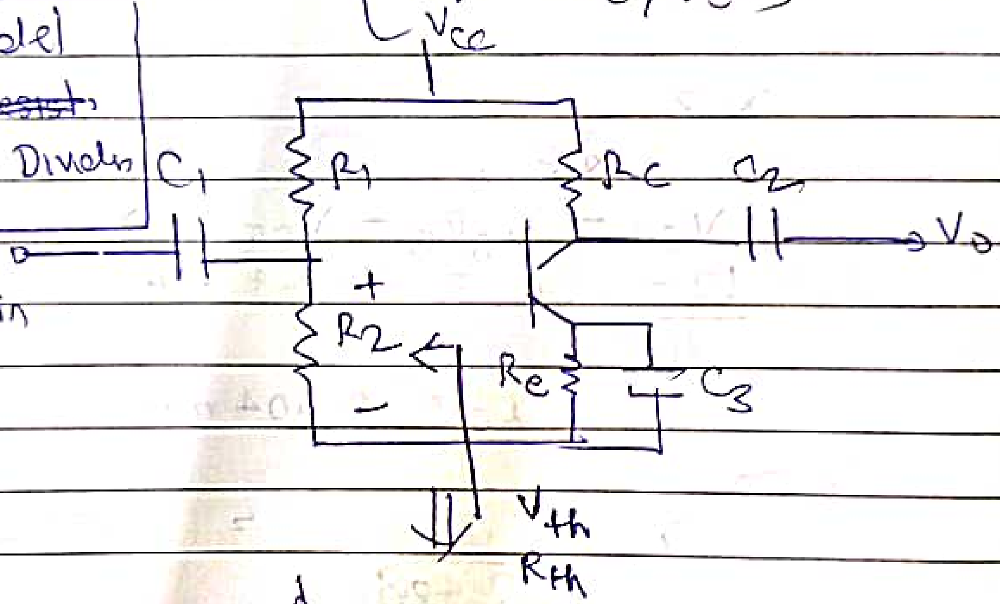
$\boxed{Z_o \simeq R_C}$

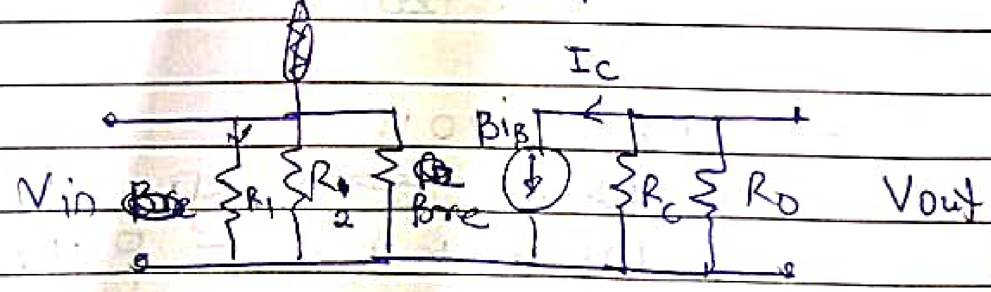
$$\left\{ \begin{array}{l} A_v = \dfrac{-R_C \| r_o}{r_e} = -264.24 \\ A_v = \dfrac{-R_C}{r_e} = -280.11 \end{array} \right\}$$

8 ~~AP~~ Summary

$$\left\{ \begin{array}{l} Z_i = \beta r_e \| r_B \\ Z_o = R_C \| r_e \\ A_v = -R_C / r_e \end{array} \right\}$$

RE Model for ~~Resist.~~ Voltage Divider Bias



$Z_i = \beta r_e = R_B \| \beta r_e$

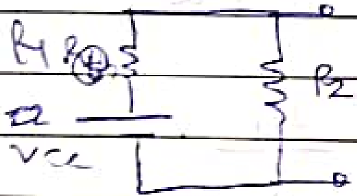
$Z_o = R_C = r_o \| R_C$

$A_v = -R_C/r_e = -\frac{R_C \| r_o}{r_e}$

$R_1 = 56k$ $\quad R_C = 6.8k$ $\quad R_E = \cancel{10}\ 1.5k$

$R_2 = 8.2k$ $\quad \beta = 90$ $\quad V_{CC} = 22V$

$R_{th} = 7.153\ k$



$V_{th} = \frac{R_2}{R_1+R_2} \times 22V$

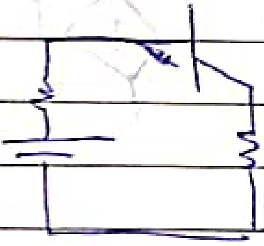
$= \frac{8.2}{56+8.2} \times 22$

$22 - i(\cancel{7.153}\ 56) - i(8.2) = 0$

$i = 1.43$

$V_{th} = \cancel{11.726}\ V$

$2.81$



$V_{th} - i_B R_{th} - V_{BE} - (\beta+1) i_B R_E = 0$

$i_B = \frac{V_{th} - V_{BE}}{R_{th} + (\beta+1) R_E}$

$i_B = \cancel{0.076}\ 0.014\ mA$

$i_C = \cancel{6.907}\ 1.321\ mA \quad 1.335$

$I_E = \cancel{6.8} \ \cancel{6.983}\ mA$

$r_e = \frac{26\ mV}{1.335\ \cancel{6.983}\ mA} = \cancel{3.53}\ 19.47\ \Omega$

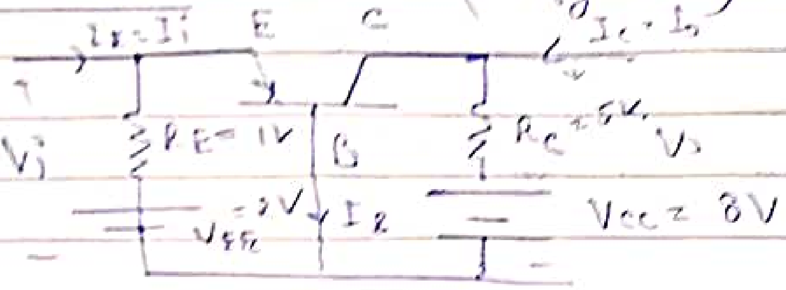
$Z_i = \beta r_e = \cancel{236.53}\ \Omega \qquad r_{th} = 7.15$

$1752.80 \| (r_B) = 1407.7\ \Omega$

$Z_o \cong R_C = 6.8\ k\Omega = (R_C \| r_o)\ 5.98\ k\Omega$

$A_v \cong -R_C/r_e = 349.25$

# Common Base (Configuration)

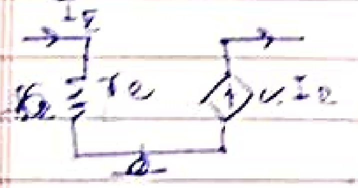


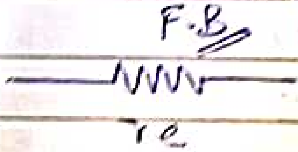

$$V_{EE} - (\beta+1) i_B R_E - V_{EB} = 0$$

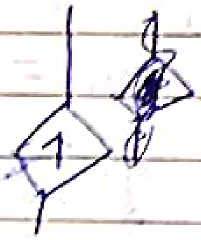
$$i_E = \frac{2-0.7}{(\cancel{\beta+1}) R_E} = \frac{1.3}{1k} = 1.3\,mA$$

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

$$r_e = \frac{26mV}{I_E} = 20\,\Omega$$




(current controlled source)

$$Z_i = R_E \| r_e$$
$$= 19.61\,\Omega$$
$$Z_o = 5k\,\Omega \;(R_C)$$
$$A_v = \frac{v_o}{v_i} = \frac{\alpha i_E R_C}{i_e \times R_E} = \frac{\alpha R_C}{r_e}$$
$$= 245$$

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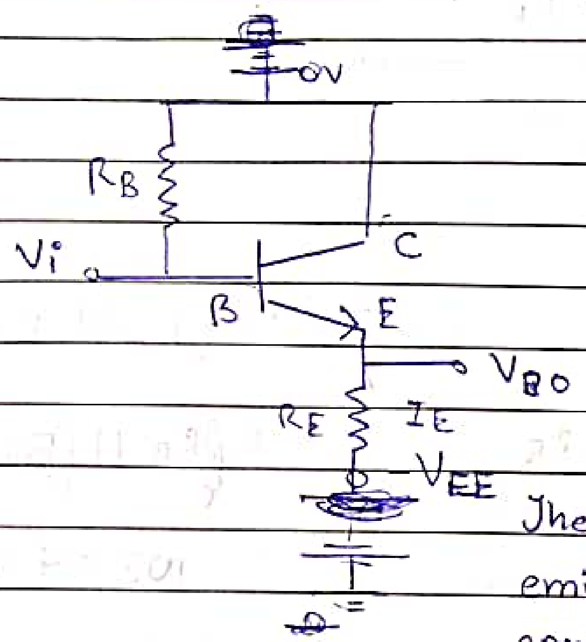
## Emitter ~~Forword~~ Follower
OR
## Common Collector




In emitter follower circuit the output is taken from the emitter terminal of the circuit

$$V_o = V_i - 0.7$$

The voltage gain of an emitter follower circuit is approximately equal to 1 because $V_{out} \approx (V_{in} - 0.7)V$

$$-i_B R_B - 0.7 - i_E R_E + V_{EE} = 0$$

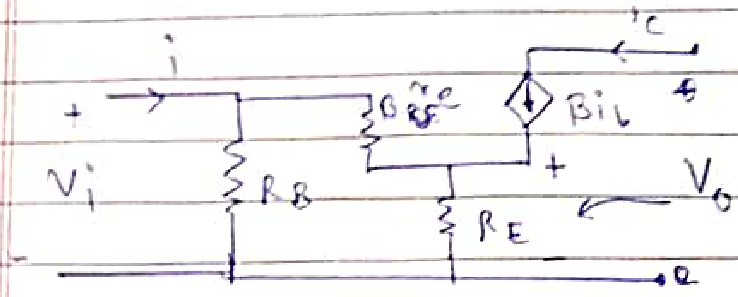
$$i_B = \frac{V_{EE} - \cancel{\beta}\, 0.7}{R_B + (\beta+1) R_E}$$

$$i_E = (\beta+1)\left[\frac{V_{EE} - 0.7}{R_B + (\beta+1) R_E}\right]$$

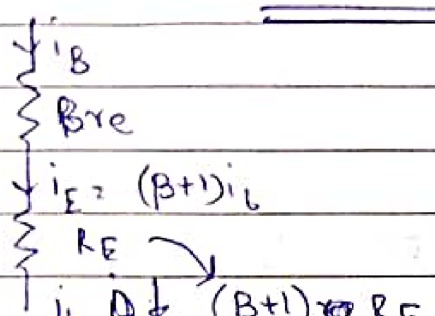
$R_B = 240K$, $R_E = 2K$, $V_{EE} = -20V$, $\beta = 90$

$i_B = 0.046\ mA$

$i_E = 4.162\ mA$




$r_e$ model




$$\therefore Z_i = \{R_B \| (\beta r_e + (\beta+1) R_E)\}$$

$$= \{R_B \| (\beta r_e + \beta R_E)\}$$

$$= 103.04\ k\Omega$$

Applying ~~KVL in input ckts~~

We short ckt the $V_i$

KVL in input ckt, $\boxed{i_b = \dfrac{V_i}{\beta(r_e + R_E)}}$

$$\boxed{i_E = \frac{V_i}{r_e + R_E}}$$

$$\boxed{Z_0 = R_E \| r_e} = 6.23\,\Omega$$

$$V_0 = i_E R_E$$

$$= \left(\frac{V_i}{r_e + R_E}\right) R_E$$

$$\boxed{\frac{V_o}{V_i} = \frac{R_E}{r_e + R_E}}$$

$$= \frac{2k}{6.25 + 2k} \simeq 1 \text{ (in phase)}$$

$$\therefore \boxed{A_v = 1}$$

In CE we get 180°
In CB, & CC ~~we get~~ output is in phase with input.

Input waveform → CE  $A_v$ [illegible] (out of phase) −[illegible]
CB  $A_v$ [illegible] in phase [illegible]
CC  $A_v$ [illegible] [illegible]
→ almost the same [illegible]

## Effect of $R_s$ and $R_L$

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

Once we add the load resistance $R_L$ in the circuit the equivalent output resistance changes from $r_o \parallel R_C$ to $r_o \parallel R_C \parallel R_L$

$$A_{v_s} = \left(\frac{Z_i}{Z_o + R_s}\right) A_{v_i}$$

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Q) A BJT amplifier has a voltage gain of 320. Source ~~input~~ voltage of 40 mV is given to a source resistance of 1.2 k. The amplifier is used in common emitter configuration, calculate the value of $V_i$, $Z_i$ and $I_i$ ~~V_0~~ ~~V_{oD}~~ $V_0 = -7.68V$

$$A_V = \frac{-V_0}{V_i}$$

~~$V_0 = 40 \times 320$~~

$$V_i = 0.024\ V = 24\ mV$$

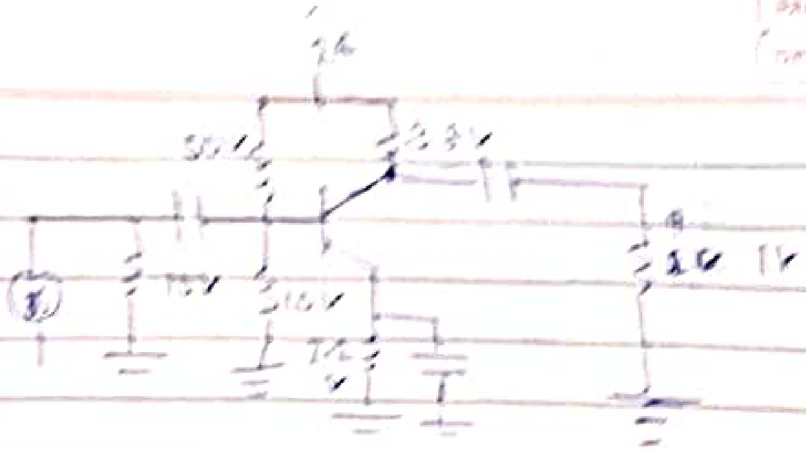
$$V_S - (1.2) i_i - 24 = 0$$

$$i_i = \frac{40-24}{1.2k} = 13.33\ \mu A$$

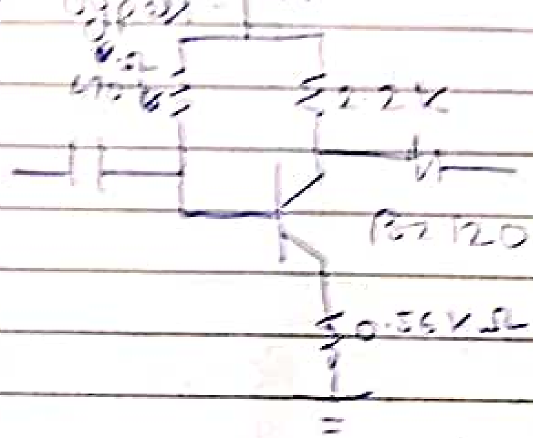
$$Z_i = \frac{V_i}{i_i} = \frac{24}{13.33} \times 10^3 = 1.8\ k$$

## Small Signal Analysis Miscellaneous questions

1) In an RC coupled amplifier shown below, the BJT has an $h_{fe} = 50$. All bypass's and capacitance capacitors are assumed to have zero ~~capacitance~~ reactance at signal frequency. Find quiescent condition and draw the small signal equivalence model. Find $Z_i$, $A_V$, $Z_0$



3) The following ckt is a CE configuration with emitter bypass.

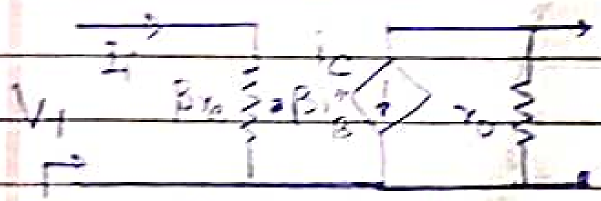


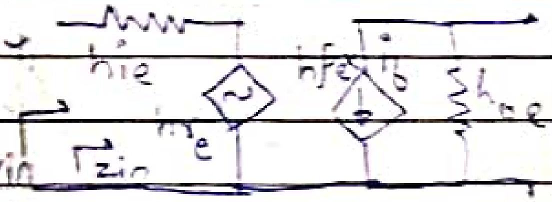

*Important* (2nd edition) Pg 297, 298, 299 (Boylestad)

Small Signal Analysis

$r_e$ model

Approximate Hybrid model




Emitter follower → Emitter

CE emitter bypass → collector

~~Rele~~ Replace $h_{re}V_o$ = short ckt.

$$h_{re} = \frac{V_i}{V_o}$$

= v. small

≈ 0

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$\beta r_e = h_{ie}$ {As there is zero voltage drop due to $h_{re} = 0$}

$\beta = h_{fe}$

$r_o = 1/h_{oe}$

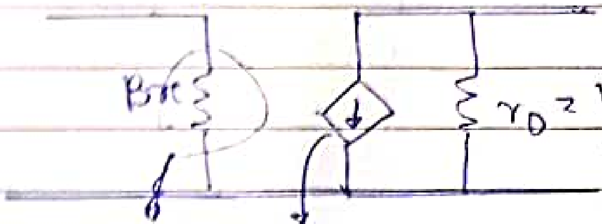
Q) $I_E = 2.5\,mA$

$h_{fe} = 140$

$h_{oe} = 20\,(\mu mho)$

Draw the $r_e$ and hybrid model.

re model



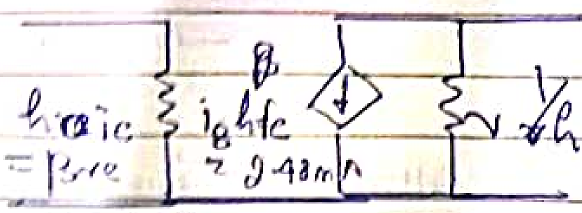
$r_o = 1/h_{oe} = 1/20 = 0.05\,\Omega$

$r_e = \frac{26\,mV}{I_E} = 10.4\,\Omega$

$\beta i_b = h_{fe}\left(\frac{I_E}{h_{fe}+1}\right) = 2.48\,mA$

$\beta r_e = 1456\,\Omega = 1.45\,k\Omega$

hybrid model

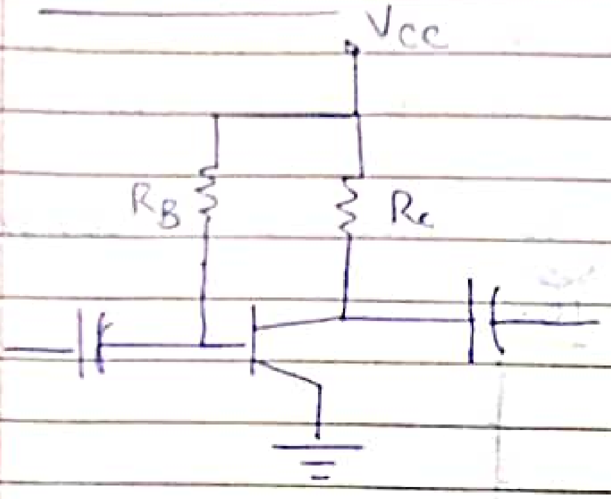


$h_{ie} = \beta r_e = 1.45\,k\Omega$

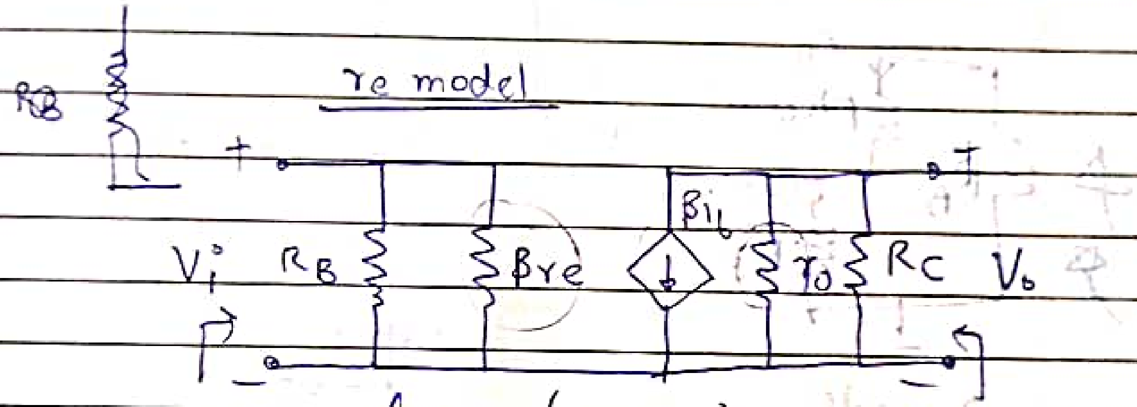
$i_B h_{fe} = 2.48\,mA$

$1/h_{oe} = 0.05\,\Omega$

## Fixed Bias



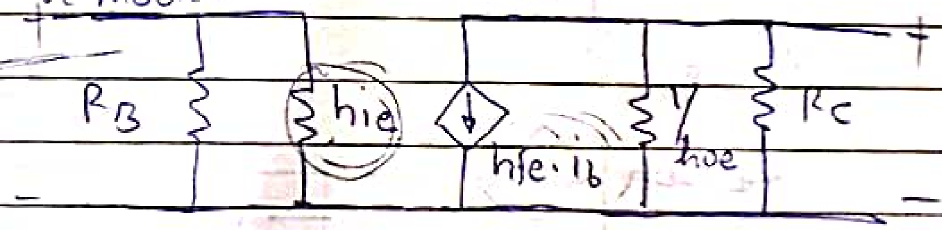

re model




For AC models
→ Short ckt cap.
→ DC Voltage source = 0

$$A_V = -\frac{(R_C \| r_o)}{r_e}$$

Approx. h-model




$$Z_i = R_B \| h_{ie}$$

$$\left\{ r_e = \frac{h_{ie}}{h_{fe}} \right\}$$

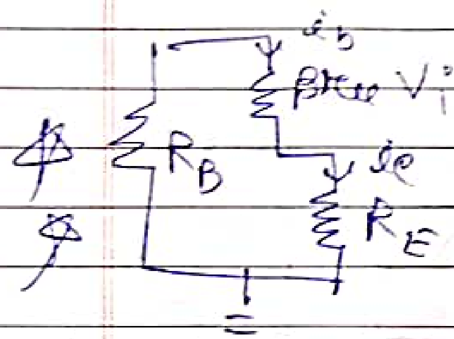
$$Z_o = \cancel{R}\left(\frac{1}{h_{oe}}\right) \| R_C$$

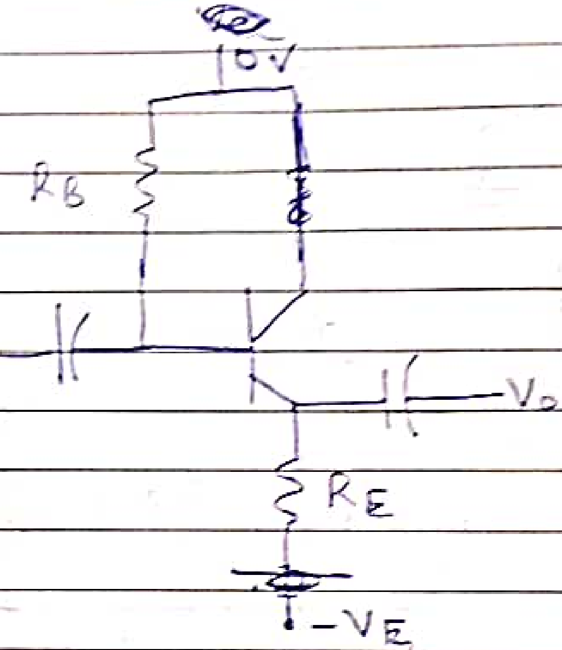
$$A_V = -\left(\frac{R_C \| \frac{1}{h_{oe}}}{h_{ie}}\right)$$

$$= -\left(\frac{R_C \| \frac{1}{h_{oe}}}{h_{ie}}\right) h_{fe}$$

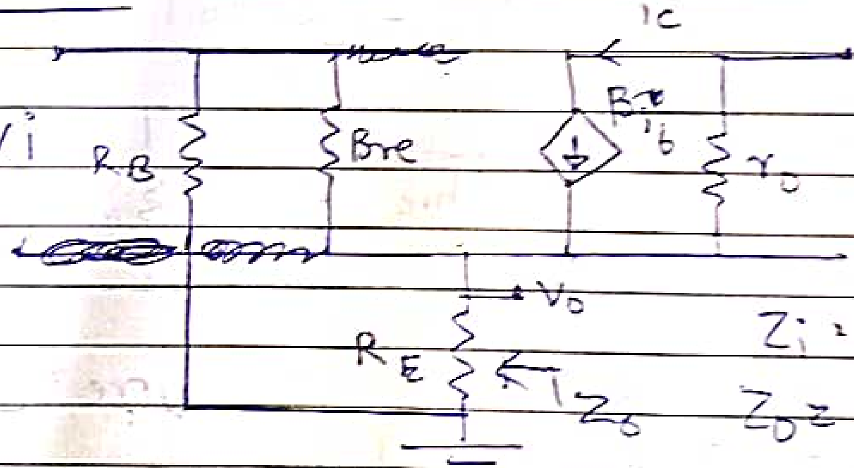
HW
For voltage divider ckt find expression of $Z_i$ and $A_v$ in terms of h-parameters.

{Emitter follower ckt is also called common collector}




re model

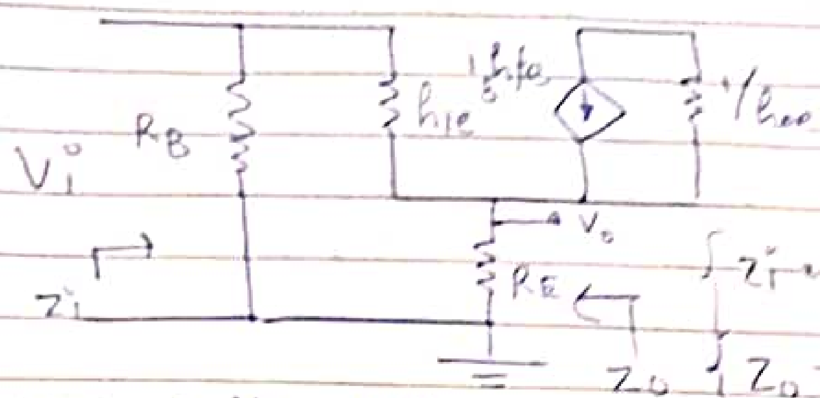



$Z_i = R_B \parallel \beta(r_e + R_E)$

$Z_o = R_E \parallel r_e$

$A_v \approx 1$

Approximate hybrid model




$\{A_V \simeq 1\}$

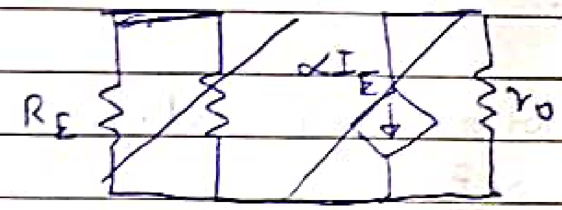
$\{Z_i = R_B \| (h_{ie} + h_{fe} R_E)\}$

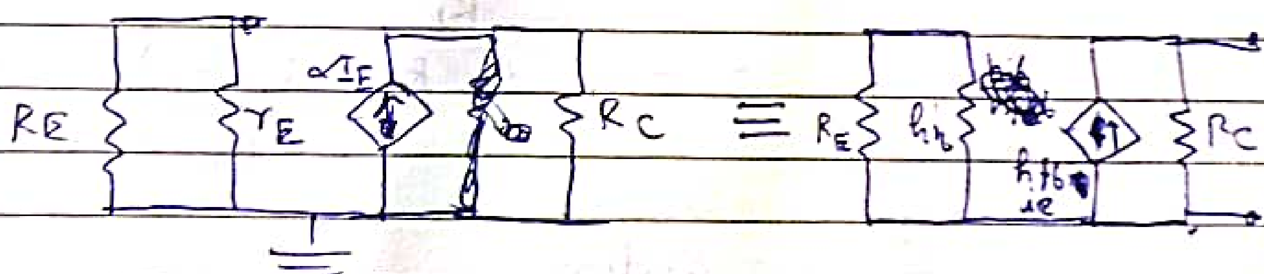
$\{Z_o = R_E \| (h_{ie}/h_{fe})\}$

HW: Emitter follower ckt $Z_i$, $Z_o$, $A_V$.

☆ { * Every ckt in small signal model, ~~~~ where we are taking input : $V_i$, $i_i$, $Z_i$ & output : $V_o$, $i_o$, $Z_o$ should be clearly marked }

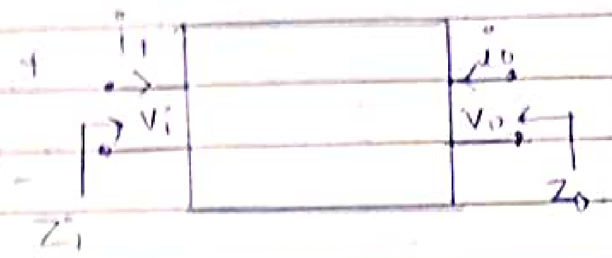
## Common base




$$\left\{\begin{array}{l} h_{ib} = r_e \\ h_{fb} = \alpha \end{array}\right\} \simeq 1$$

Coscode system of transistors




1) Effect of adding $R_L$

$$A_{VL} = \frac{R_L}{R_L + Z_o} \times A_{VNL}$$

2) Effect of adding $R_S$

$$A_{VS} = \frac{Z_i}{Z_i + R_S} \times A_{VNL}$$

3) Effect of both $R_S$ and $R_L$

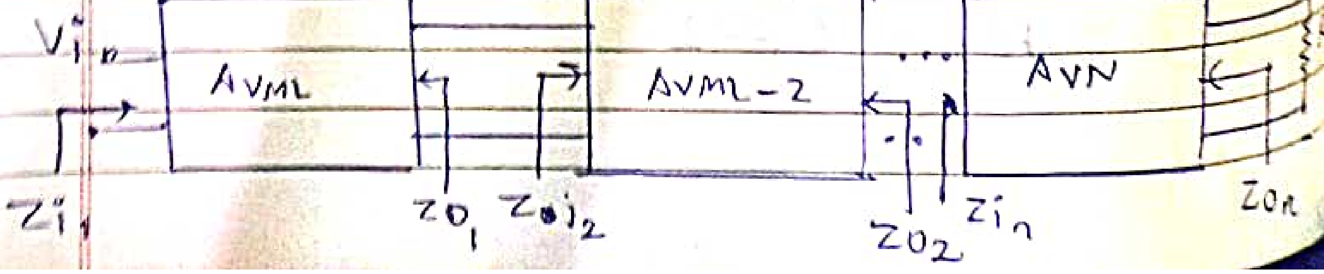
$$A_{VS} = \frac{Z_i}{Z_i + R_S} \times \frac{R_L}{R_L + Z_o} \times A_{VNL}$$

4) Current gain relation with voltage gain

$$A_{iL} = -A_{VL} \times \frac{Z_i}{R_L}$$

$$= -A_{VS} \times \cancel{R_{st}} \left( \frac{R_S + Z_i}{R_L} \right)$$

Coscode System



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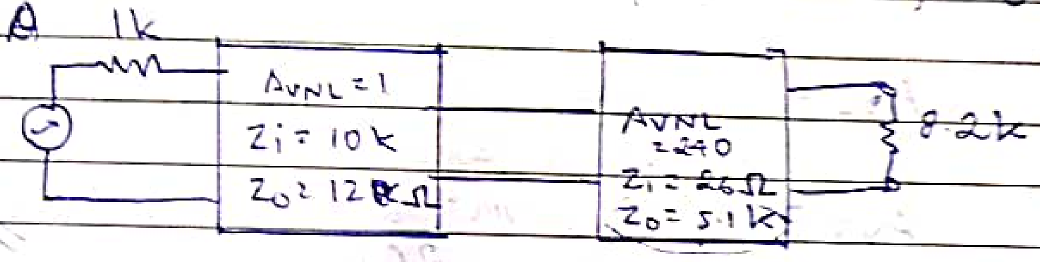
$$\left[ A_{VT} = A_{VL1} \times A_{VL2} \times A_{VL3} \times \cdots A_{VLn} \right]$$

Q) A two stage ~~amplifier~~ system ~~e...~~ employs an emitter follower followed by a common base configuration. No load voltage gain of ~~emitter~~ common base is 240. No load voltage gain of emitter follower is 1. The input impedance $Z_i$ of emitter follower is 10k. Zout = 12k on common base. $Z_i = 26\Omega$, $Z_0 = 5.1k$

$(A_v \simeq 1)$




Find :

1) localed gain of each stage
2) Total gain of overall system

Sol$^n$ →

1) $A_{VL} = \dfrac{R_L}{R_L + Z_0} \times A_{VNL}$

$R_L = Z_{i_2} = 26\Omega$

$= 0.684$

2) $A_{VL} = \dfrac{R_L}{R_L + Z_0} \times A_{VNL}$

$= \dfrac{240 \times 8.2}{8.2 + 5.1} = 147.97$

Total gain

$= A_{VL_1} \times A_{VL_2}$

$= 101.21$

$$A_{VS\,Total} = A_{VT} \times \frac{Z_i}{Z_i + R_S}$$

$$= 92$$

Q) If we remove the first stage of amplifier then find out what will be $A_{VL}$, $A_{VS}$=?

$$A_{VL} = \frac{R_L}{R_L + Z_0} \times A_{VNL}$$

$$A_{VS} = \frac{Z_i}{Z_i + R_S} \times A_{VM} = \frac{26}{26 + 1000} = 0.025$$

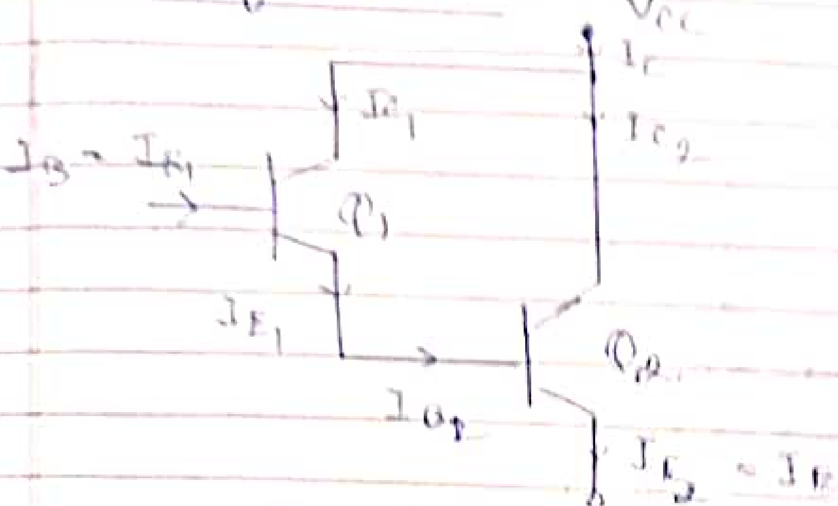
* Variation –

① Gain of amplifier can be given in dB
② in that case convert the gain to absolute value and then do the calculations.

② $A_{VNL}(dB) = 10 \log_{10} A_{VNL}$ (convert to absolute value $A_{VT} = A_{V1} \times A_{V2}$ then convert back)

If gain is given in dB then the total gain of amplifier should also be given in dB.

Darlington Pair




Overall current gain / $\beta$ = ?

$$\beta = \frac{I_E}{I_B} = \frac{I_{E2}}{I_{B1}}$$

$$= \frac{(\beta_2+1) I_{B2}}{I_{B1}}$$

$$= \frac{(\beta_2+1)(\beta_1+1)\cancel{I_{B1}}}{\cancel{I_{B1}}}$$

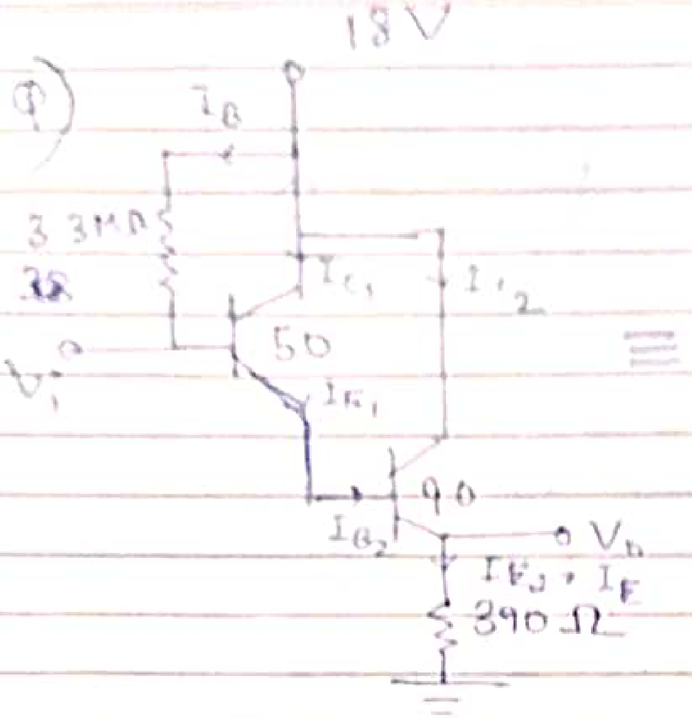
$$\boxed{\beta \simeq \beta_2 \cdot \beta_1}$$

~~$I_E$~~ $\Rightarrow$ ~~$\beta_2$~~ Super $\beta$ Transistor

$V_{BE} = V_{BE_1} + V_{BE_2}$

Voltage drop has increased

Q)

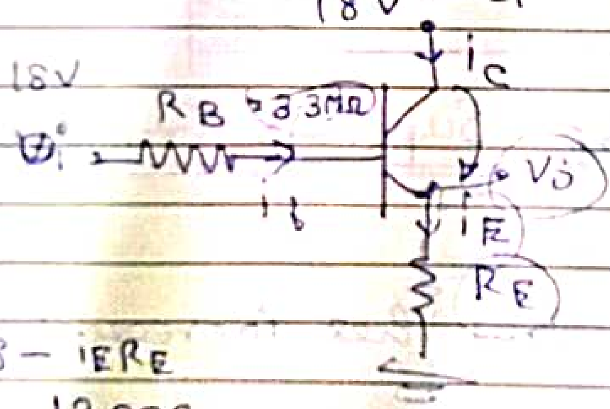



Calculate the value of $\beta_D$, $a_i$ $I_{b_1}$, $I_{C_2}$, $V_{E_2}$, $V_{CE_2}$

$\beta_D = 90 \times 50$
$= 4500$

$\frac{18 - 0.7}{R_B}$

$I_{C_2} \simeq I_{E_2}$
$I_{B_2} = I_{E_1}$
$I_{C_1} \simeq I_{E_1}$




$\frac{18 - 2V_{BE}}{(\beta+1)R_E + R_B} = 13$

$i_B = 3.28$ mA

$i_C = 14.77$ mA

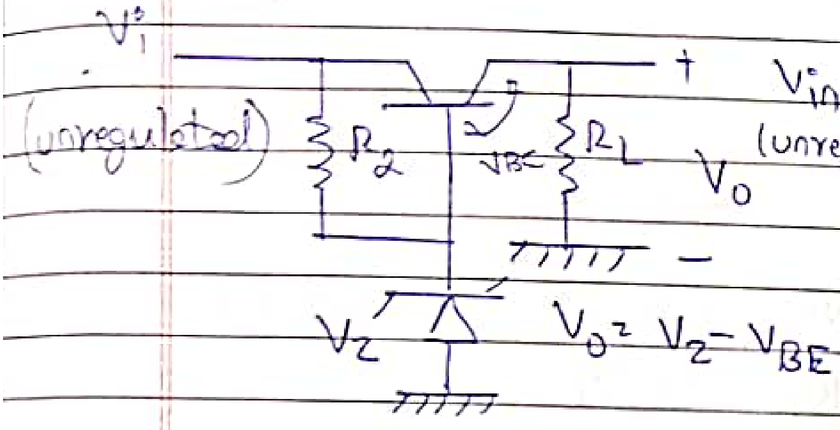
$i_E = 14.78$ A

$V_{CE_2} = 18 - i_E R_E$
$= 12.238$

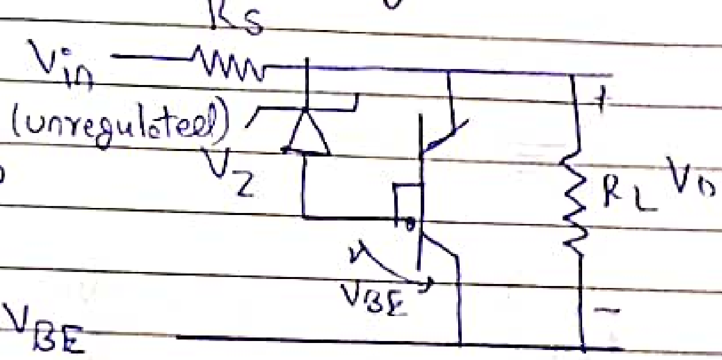
(ii) $V_o = i_{E_2} \times R_E$
$= 5.764$ kV

# Voltage Regulator

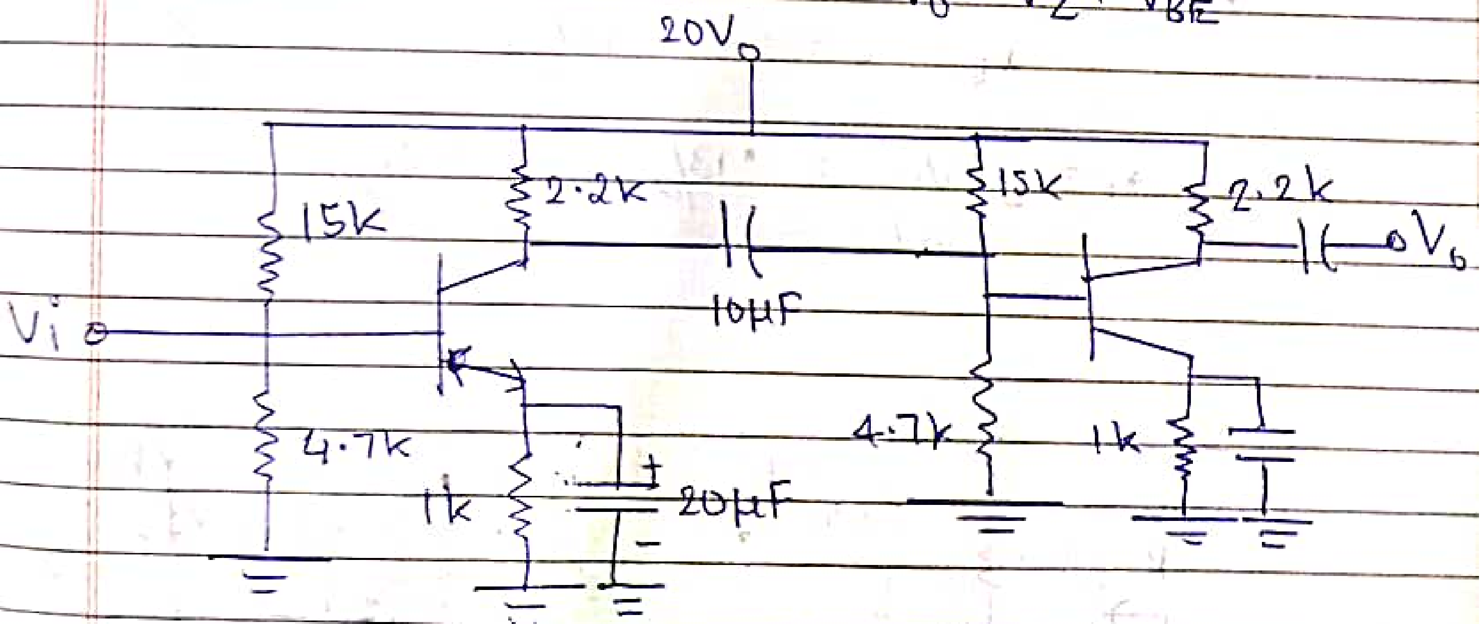
- Series Regulator
- Shunt Regulator




$V_0 = V_Z - V_{BE}$



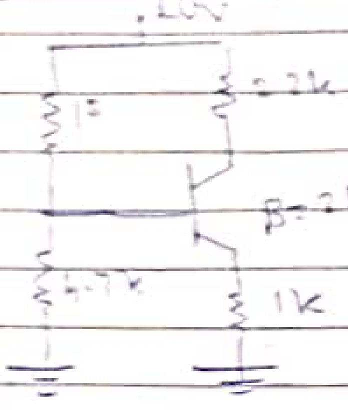

$V_0 = V_Z + V_{BE}$




RC coupled BJT

DC analysis capacitor becomes open
AC analysis capacitor is shorted.

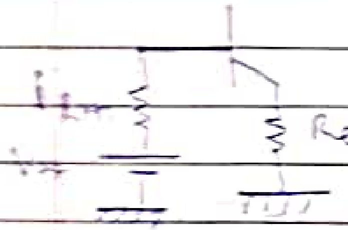
DC analysis to calculate $i_e$




$R_{th} = 3.578\ k\Omega$

$V_{th} = \frac{4.7}{4.7+15} \times V_{CC}$

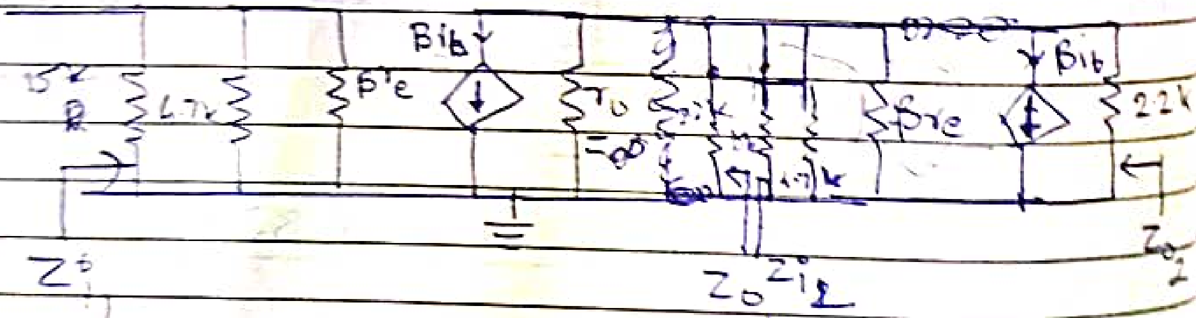
$= 4.771\ V$




$i_B = \frac{V_{th} - V_{BE}}{R_{th} + (\beta+1)R_E} = 0.0198\ mA$

$i_E = 3.999 \simeq 4\ mA$

$r_e = \frac{26\ mV}{4\ mA} = 13/2 = 6.5\ \Omega$




$Z_{i_1} = 15k \| 4.7k \| \beta r_e$

$Z_o = R_C = 2.2k$

$A_{v_1} = \frac{R_C \| R_L}{r_e}$

$A_{v_2} = R_C / r_e$

$\{ A_v = A_{v_1} \times A_{v_2} \}$

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without $\beta_{re}$

$A_{v1} = \frac{1.3624 \times 10^3}{6.5}$

$= -209.6$ (x)

$A_{v2} = -338.461$

$A_{ov} = 30$

For: $\beta_{re}$

$A_{v1} = \frac{0.665 \times 10^3}{6.5}$

$= -$ ~~[illegible]~~ $102.345$

$A_{v2} = -338.461$

$A_{ov} = 3.4 \times 10^4$

Revision :

max ↓ order of priority ↑ min

* DC biasing + stability → First, S.P, V.D, Emitter follower
* $r_e$ model (dynamic) — Common base
* approx. hybrid model
* Darlington Pair

{Revise all numericals done in class & tut}

→ can ask to draw ckts (DC, $r_e$ model, approx. hybrid)

{No AC analysis of Darlington} / Only DC Analysis

* Voltage shunt / series regulator (ckt. diagram) (2 or 3 mks)

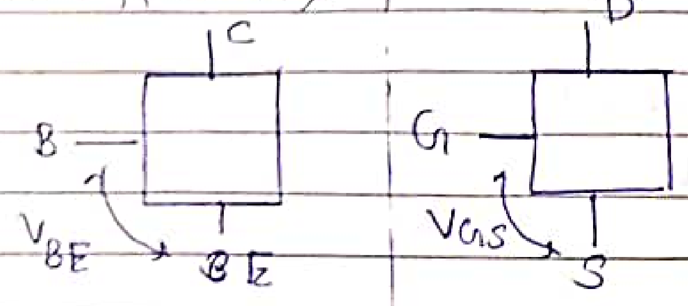
* Exact hybrid model . (Formula based)

# Field effect Transistor

Bipolar → BJT current controlled device

Unipolar → FET voltage controlled devices

(n channel, p-channel)




Base, Collector, Emitter | Gate, Drain, Source

FET

$\{V_{GS} \rightarrow I_D\}$

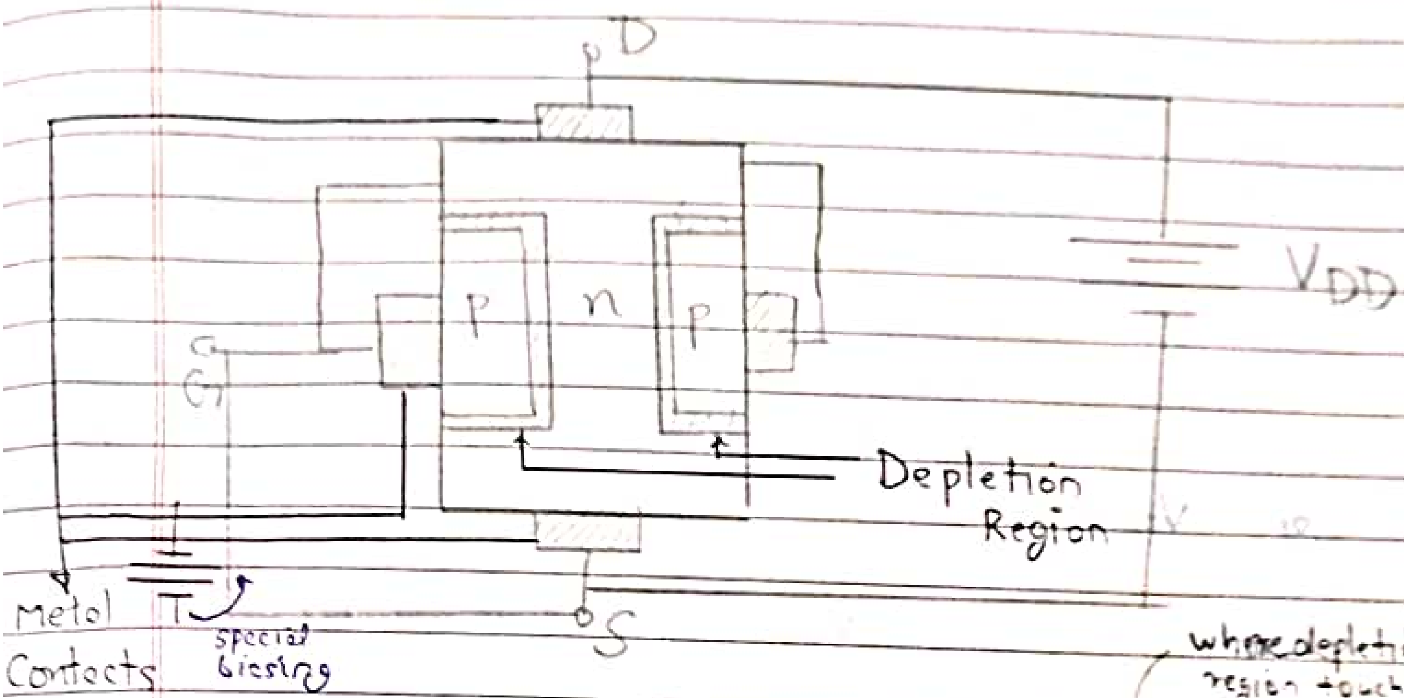
JFET
Junction
Field effect
Transistor

MOSFET
Metal-oxide ($SiO$)
Semiconductor
field effect
Transistor

JFET { n-channel, p-channel }

MOSFET:
→ enhancement type → n c... / p... / n ch...
→ Depletion type → n channel / p channel

# JFET




## n- channel JFET

[As $V_{DS} \uparrow$, $I_D \uparrow$ reaches saturation ~~& becomes~~ constant]

where depletion region touch that point is called pinchoff voltage

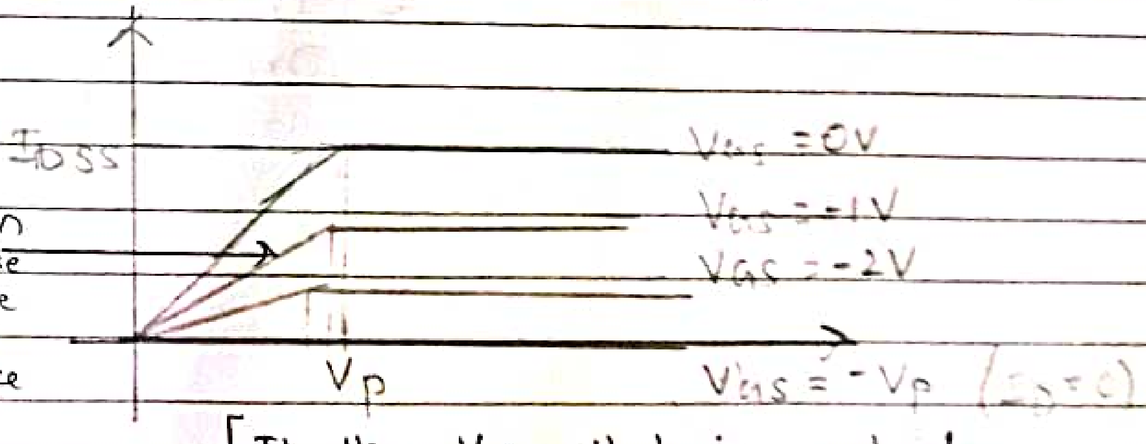
Cases :

① $V_{GS} = 0\ V$
$V_{DS} = V_{DD}$

{★ $I_G = 0$ (always) same as $V_{EE}$ in BJT}

★ {$I_D = I_S$}

## Drain Characteristics




This region acts like a voltage control resistance region

[It the $V_{GS}$ that is applied when $V_{GS} = 0\ V$] resulting in the drain current $I_D = I_{DSS}$]

Current
Drain to Source gate shorted

If a battery is applied between gate and ... then saturation occurs at a lower $I_D$ value.

The effect of applying '-ve' bias between gate and source is that we achieve the same depletion region as $V_{GS} = 0\,V$, but at a lower value of $V_{DS}$.

When we apply $V_{GS} = V_P$ drain current = 0.

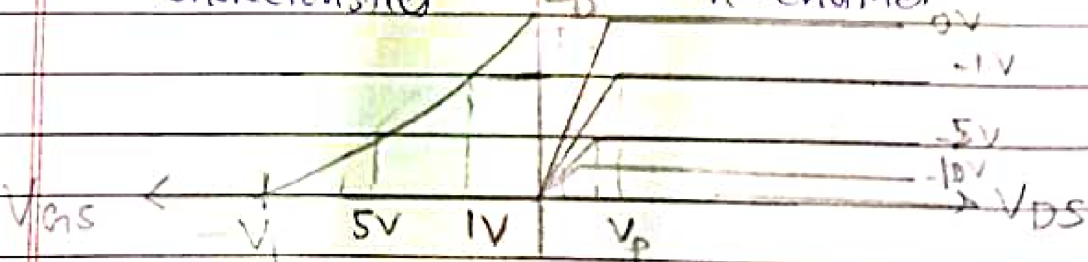
$$I_D = I_{DSS}\left(1 - \frac{V_{GS}}{V_P}\right)^2 \quad \text{(Standard Relation)}$$

$V_{GS} \Rightarrow$ gate to source voltage
$V_P \Rightarrow$ pinch off voltage
$I_{DD} \Rightarrow I_{DSS}$ (Drain to Source)

Drain characteristic & Transfer characteristic ⇒ Transfer characteristic Drain characteristic

Transfer Characteristics

Drain characteristic n-channel




for p-channel $V_{DS} = -ve$ & $V_{GS} = +ve$

$$V_{GS} = \left[1 - \sqrt{\frac{I_D}{I_{DSS}}}\right] V_P$$

Draw the transfer characteristic for a JFET having relation when $I_{DSS} = 12\,mA$ and $V_P = 6V$

A. $I_D = I_{DSS}\left(1 - \frac{V_{GS}}{V_P}\right)^2$

i) when $V_{GS} = 0$

$I_D = I_{DSS} = 12\,mA$

ii) when $V_{GS} = -V_P = -6V$

$I_D = 0$

~~iii) when $V_{GS} = -1V$~~

~~$I_D = 12\left(1 - \frac{1}{-6}\right)^2$~~

~~$= \frac{12}{3} \cdot \frac{25}{36} = 75/9$~~

~~iv)~~

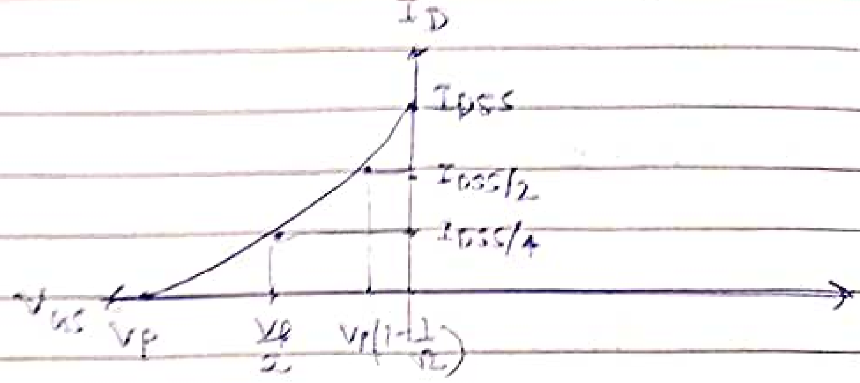
iii) when $V_{GS} = \frac{V_P}{2}$

$$I_D = I_{DSS}\left(1 - \frac{1}{2}\right)^2 = \frac{I_{DSS}}{4}$$

iv) when $I_{DS} = I_{DSS}/2$

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

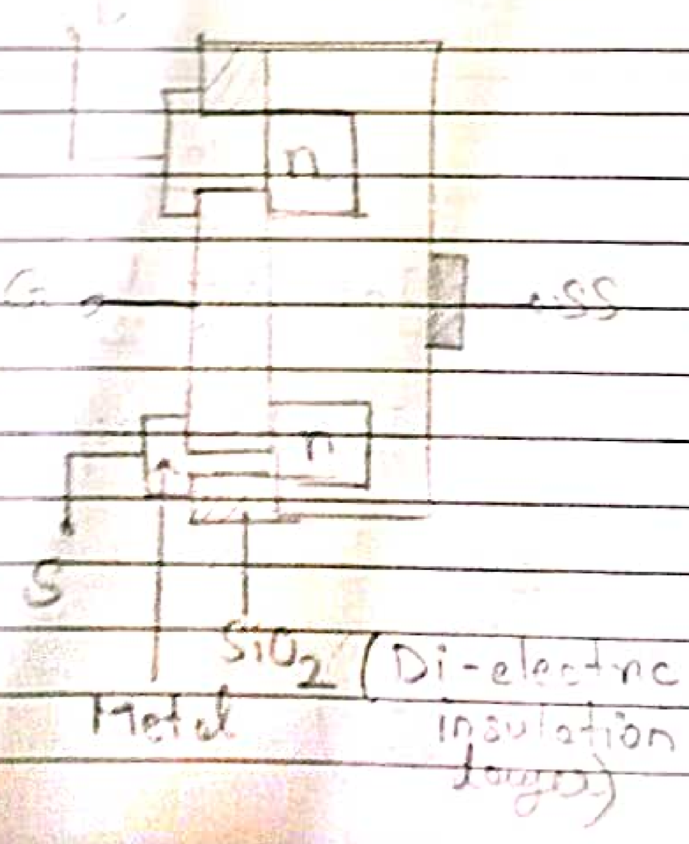
$$V_{GS} = V_P\left(1 - \frac{1}{\sqrt{2}}\right)$$

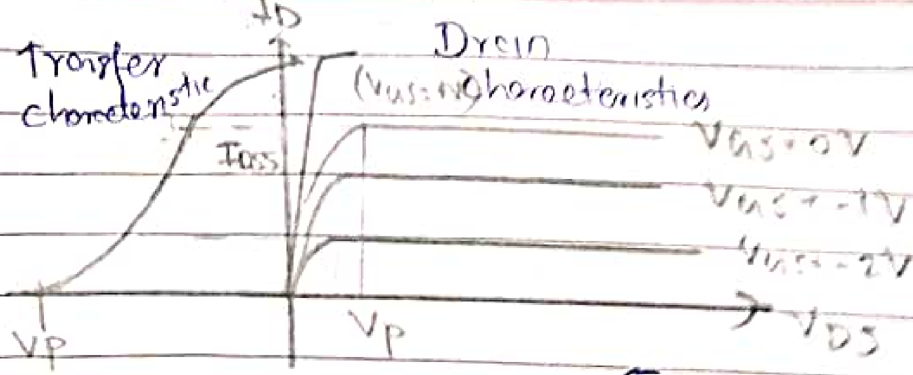



| $V_{GS}$ | $I_D$ |
|---|---|
| 0 | $I_{DD}$ |
| $V_P$ | 0 |
| $V_P/2$ | $I_{DSS}/4$ |
| $V_P\left(1-\frac{1}{\sqrt{2}}\right)$ | $I_{DSS}/2$ |

Generalized Table

## Depletion Type MOSFET






1) $V_{GS}=0$
$V_{DS}=+ve$

2) $V_{GS}\Rightarrow -ve$
$V_{DS}=+ve$

3) $V_{GS}=+ve$
$V_{DS}=+ve$

~~$V_{DS}\Rightarrow +ve$~~
~~$V_{GS}\Rightarrow -ve$~~

1) Free electrons in n-channel will establish a current just like J-FET.

2) The saturation is achieved at a lower voltage just like JFET.

3) When gate is made +ve, it will attract electrons from the p- substrate and the accelerating particle establishes new free electrons by collision.

Thus the drain current increases drastically. So we have to ensure that it does not exceeds the maximum power rating of the device.

In MOSFET the transfer characteristic has both depletion region & enhancement region.

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Draw the transfer characteristic for n-channel depletion MOSFET having $I_{DSS} = 10$ mA and $V_P = -4$ V

| $I_{DSS}$ | $V_{GS}$ | $I_D$ |
|---|---|---|
| 10 | 0 | $I_{DSS}$ |
| | $V_P$ | 0 |
| | $\frac{V_P}{2}$ | $I_{DSS}/4$ |
| | $V_P\left(1-\frac{1}{\sqrt{2}}\right)$ | $I_{DSS}/2$ |

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

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

$\frac{1}{\sqrt{2}} = 1 - \frac{V_{GS}}{V_P}$

| $V_{GS}$ | $I_D$ |
|---|---|
| 0 | $I_{DSS}$ |
| $V_P$ | 0 |
| $V_P/2$ | $I_{DSS}/4$ |
| $V_P(1-1/\sqrt{2})$ | $I_{DSS}/2$ |

$V_{GS} =$ +ve

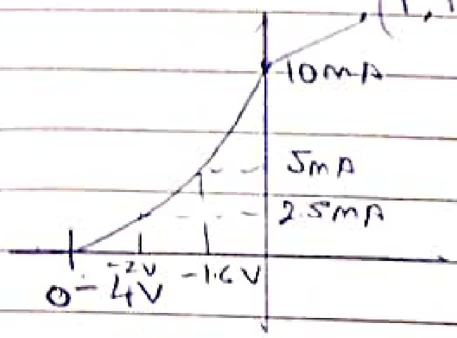
$I_D = I_{DSS}\left(1 - \frac{V_{GS}}{V_P}\right)^2$

$= 10\left(1+\frac{1}{4}\right)^2$

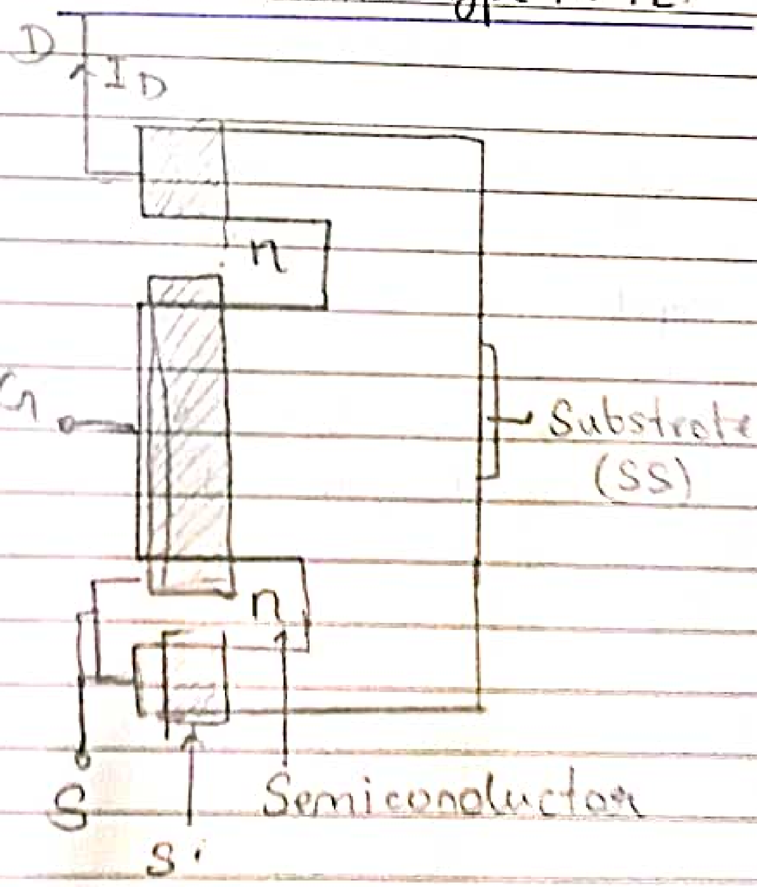
$= \frac{25}{16} \times 10 = 15.55$ mA

$16\overline{)25}$ 1.5

[All eqn of JFET are valid for depletion MOSFET]




## Enchancement Type MOSFET




1) Shockley eqn do not hold in Enhancement type MOSFET.

2)

$V_{GS} = 0V$

$V_{DS} = +Ve$

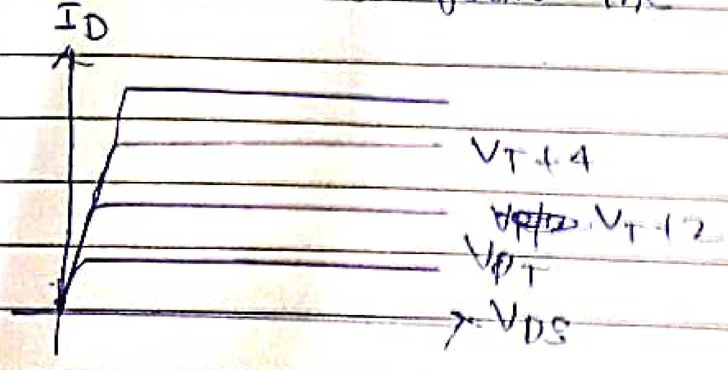
$$I_D = I_{DSS}\left(1 - \frac{V_{GS}}{V_P}\right)^2$$

When $V_{GS} = 0$ & $V_{DS} = +ve$ the absence of n channel between drain and source will not cause any electrons to flow.

2) $I_D = 0$ $\begin{matrix} V_{GS} = 0V \\ V_{DS} = +ve \end{matrix}$ (absence of n channel)

3) $V_{GS} = +ve$, $V_{DS} = +ve$ ($V_{Threshold}$ enhancement)

* When gate is made +ve with respect to source it attracts electrons from p substrate and repels the holes.
* When the $V_{GS}$ voltage is increased to a threshold value $V_P$ sufficient electrons accumulate and form the channel.




The current flow is enhanced by applying +ve $V_{GS}$. so ~~too~~ it is called as enhancement type ~~n~~ MOSFET.

iv) $V_{GS}$ = constant and $\geq V_T$
The behaviour is like JFET and depletion type ~~MOSFET~~ JFET and $V_{DS}$ = +ve.

The drain current equation is,

$$\boxed{I_D = k(V_{GS}-V_T)^2}$$

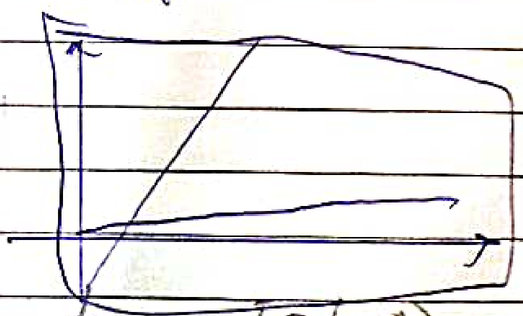
$$\boxed{V_{DS,sat} = V_{GS} - V_T}$$

Draw the transfer characteristic of an enhancement type MOSFET if $V_T = 2V$ and $V_{GS} = 8V$. $I_D = 10$ mA.

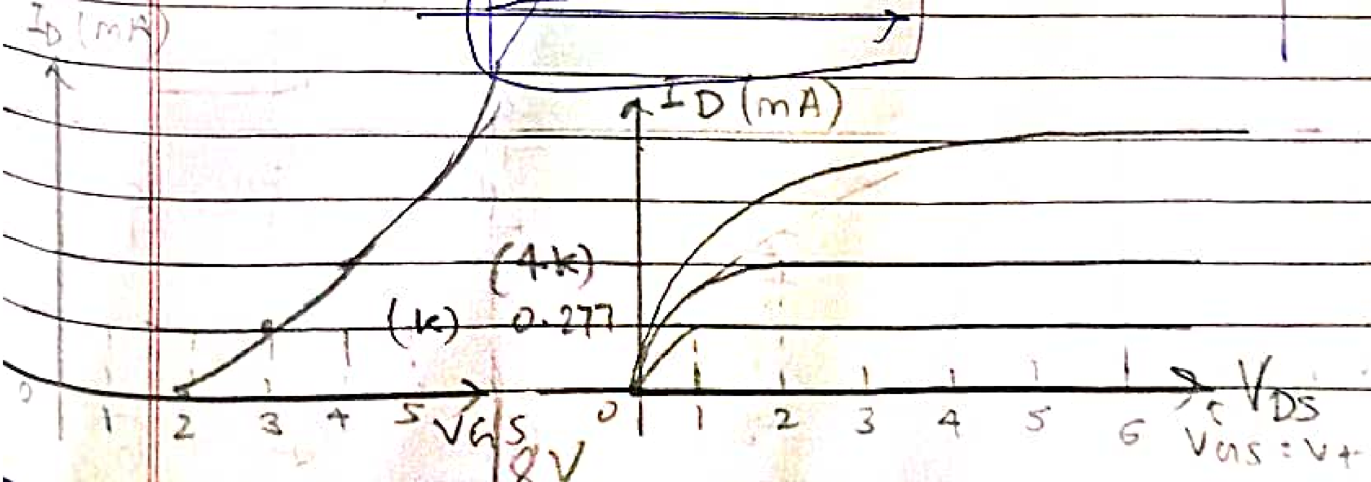
① $I_D = 0$
$V_{GS} = V_T$

② ~~$V_{GS} = V_T$~~ $I_D = 10$mA
$k = \frac{10}{6^2} = 5/18 = 0.277$ mA/V²

③ $I_D = \frac{V_{GS}-V_T}{2}$

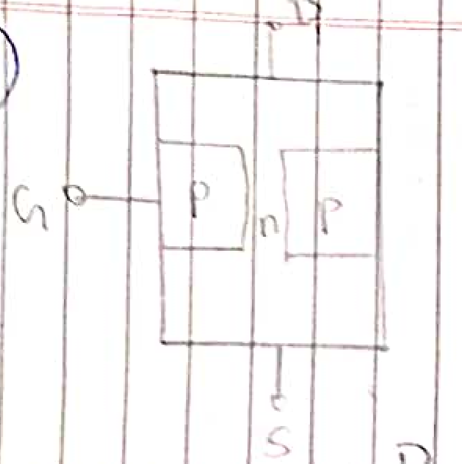


| | |
|---|---|
| $V_{GS} = 3V$ | $V_{GS} = 4V$ |
| $V_{sat} = 1V$ | $V_{sat} = 2V$ |
| $I_D = k$ mA | $I_D = 4k$ mA |

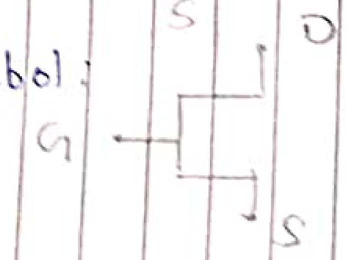


## n channel JFET

1)




2) Symbol:




3) $I_G = 0$

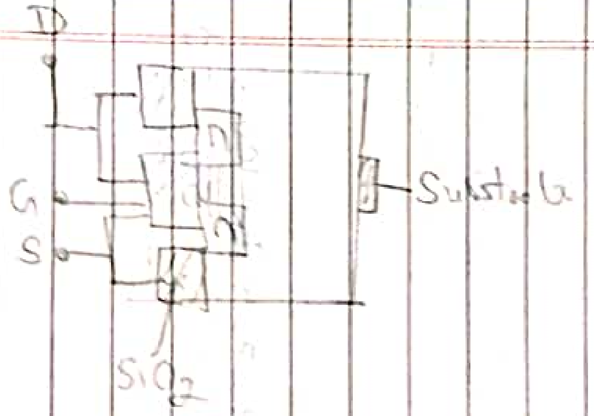
4) $I_D = I_S$

5) $I_D = I_{DSS}\left(1 - \frac{V_{GS}}{V_P}\right)^2$ [Shockley eqn] $\boxed{V_{GS} \leq 0}$

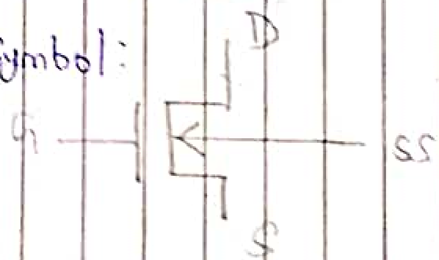
$\min(-V_{GS}) = V_P$

## n channel depletion MOSFET

1)




2) Symbol:




3) $I_G = 0$ {high input impedance}

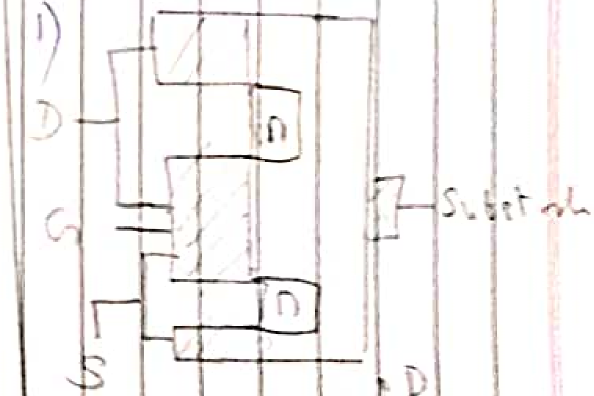
4) $I_D = I_S$

5) $I_D = I_{DSS}\left(1 - \frac{V_{GS}}{V_P}\right)^2$ [Shockley eqn] $V_{GS} \lessgtr 0$ [$V_{GS}$ can have +ve & -ve value]

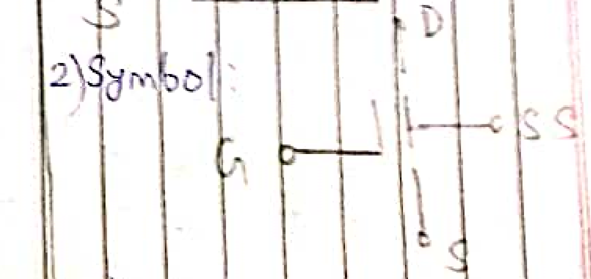
$\min(-V_{GS}) = V_P$

## n-channel enhancement MOSFET

1)




2) Symbol:




3) $I_G = 0$

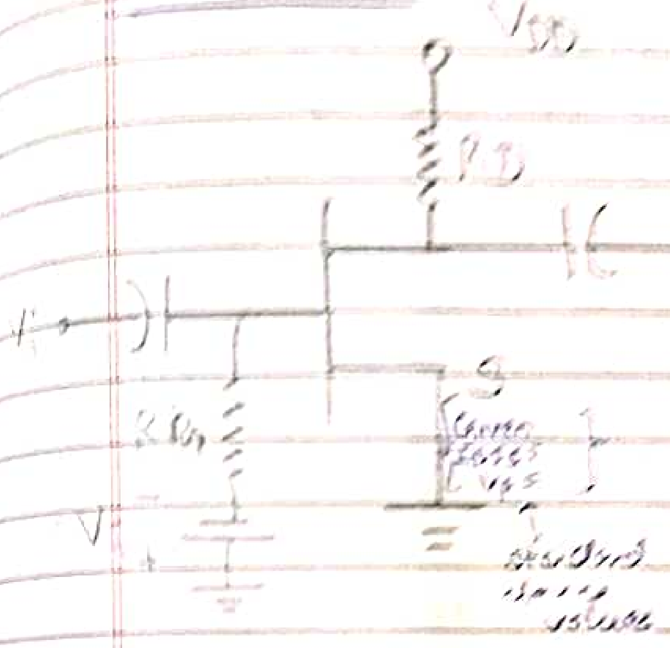
4) $I_D = I_S$

5) Shockley eqn does not hold

$I_D = K(V_{GS} - V_T)^2$

$V_{sat} / V_{DS} = V_{GS} - V_T$

## Fixed Bias




To find operating point find ($V_{GS}$, $I_D$)

$I_G = 0$

$I_S = I_D$

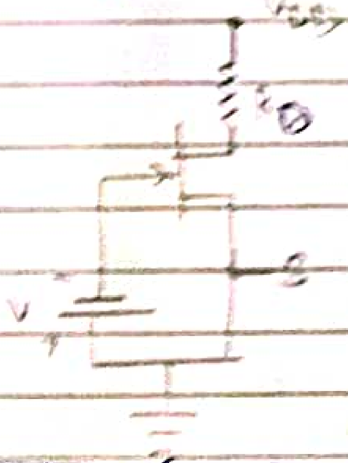
$I_D = I_{DSS}\left(1 - \frac{V_{GS}}{V_P}\right)^2$

Steps:

i> O C all capacitors

ii> $I_G = 0$

iii> $V_{R_G} = I_G \times R_G = 0$




$-V - V_{GS} = 0$

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

$\boxed{\cancel{V_{DD} - I_D R_D = 0} \quad \cancel{I_D = \frac{V_{DD}}{R_D}}}$

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

$= I_{DSS}\left(1 - \frac{V}{V_P}\right)^2$

For a fixed bias configuration, $V_D = 16V$, $R_D = 2k$, $V_{GG} = 2V$, $R_G = 1k\Omega$. Draw transfer characteristics & load line. $I_{DSS} = 10\ mA$ & $V_P = -8V$

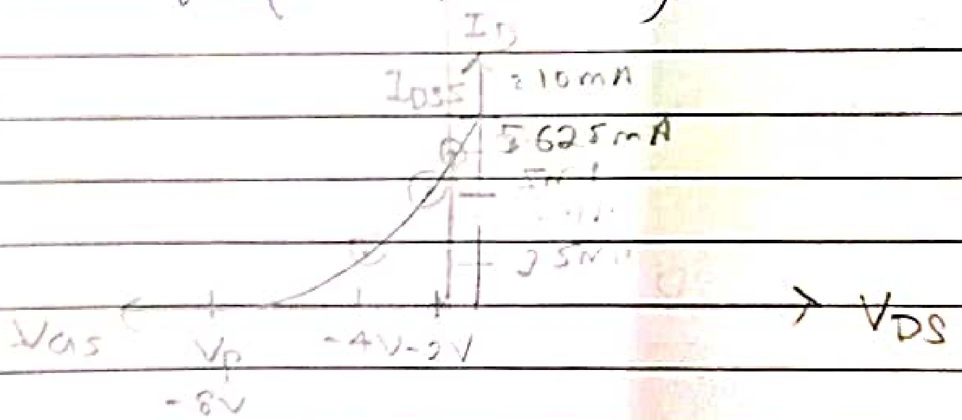
$$V_{GS} = -V_{GG}$$
$$= -2V$$

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

$$= 10\left(1 - \frac{\cancel{2}^{\,1}}{\cancel{8}_{\,4}}\right)^2 \quad 10 \times 9/16$$

$$= 10\left(3/4\right)^2 = 5.625\ mA$$

$$Q = (-2V, 5.625\ mA)$$



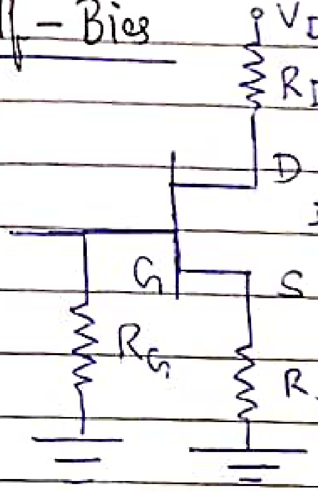

1 - 2

$$V_{R_D} = 2 \times 5.625$$
$$= 11.250\ mA$$

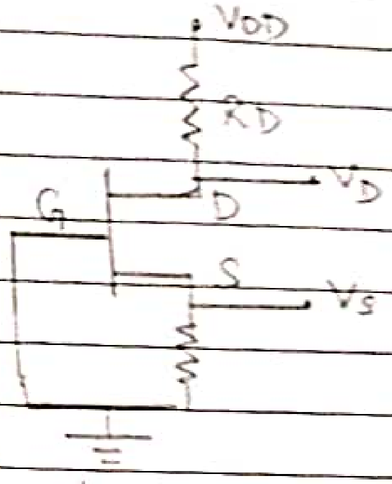
$$V_{DS} = 16 - 11.250$$
$$= 4.75\ V$$

$$V_D = 4.75V$$
$$V_S = 0\ V$$

## Self-Bias




$I_{DSS} = 8\,mA$
$V_P = -6V$




$I_G = 0\,mA$, $V_{R_G} = 0\,V$, $I_S = I_D$

$-V_{GS} - I_S R_S = 0$

$\{V_{GS} = -I_S R_S\}$ — (1)

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

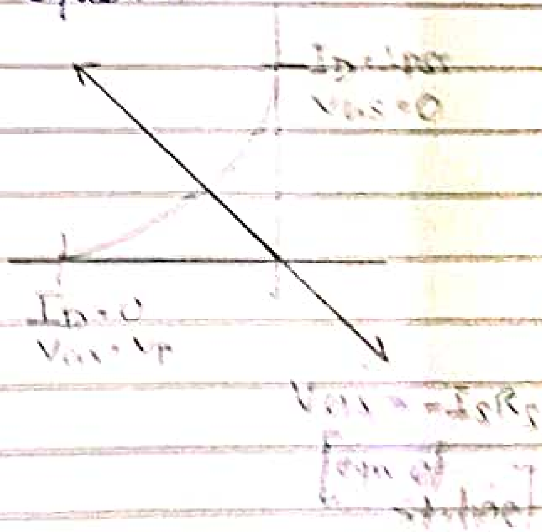
→ Analytical Method

→ Graphical Method

$I_D \Rightarrow$ Quadratic equation

$V_{DS} = V_{DD} - I_D R_D - I_D R_S$

$V_S = I_D R_S$




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

$= 8\left(1 + \frac{V_{GS}}{6}\right)^2$

$-\frac{V_{GS}}{R_S} = \frac{8(6 + V_{GS})^2}{36}$

$$\frac{-V_{GS}}{1} = 8/36\left(36 + V_{GS}^2 + 12V_{GS}\right)$$

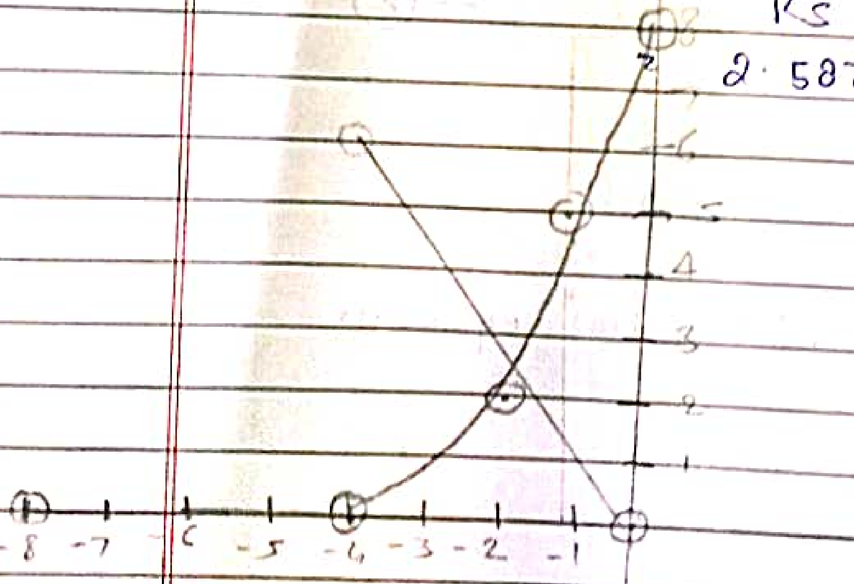
$$-\frac{36V_{GS}}{8} = 36 + V_{GS}^2 + 12V_{GS}$$

$$V_{GS}^2 + 16.5V_{GS} + 36 = 0$$

$$V_{GS} = -2.5876\ V$$
$$= -13.9123 \text{ // Not possible}$$

$$\therefore V_{GS} = -2.5876\ V$$

$$I_D = I_S = \frac{-V_{GS}}{R_S}$$
$$= 2.5876\ mA$$



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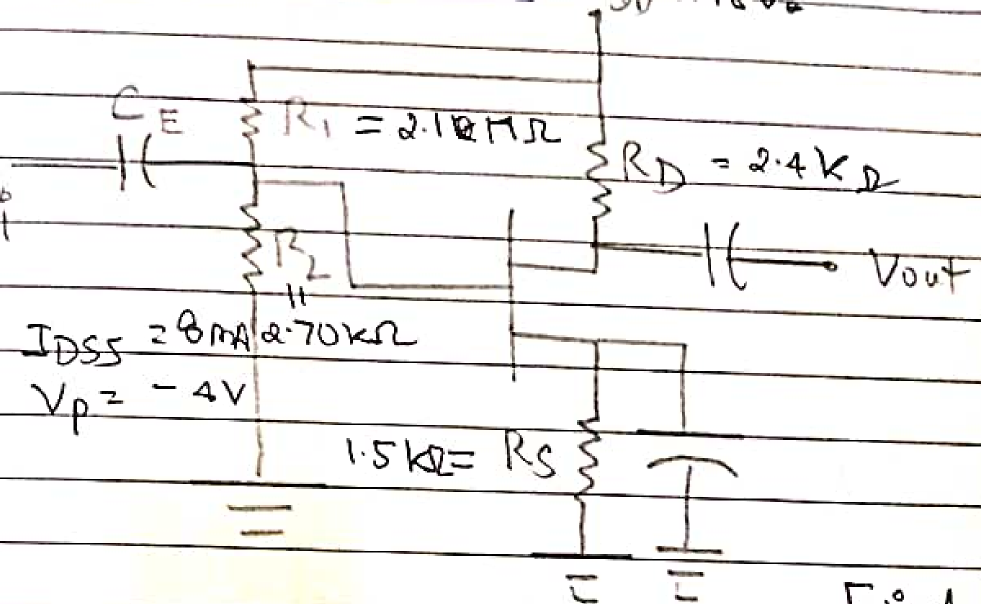
## Voltage Divider Bias




$I_{DSS} = 8mA$

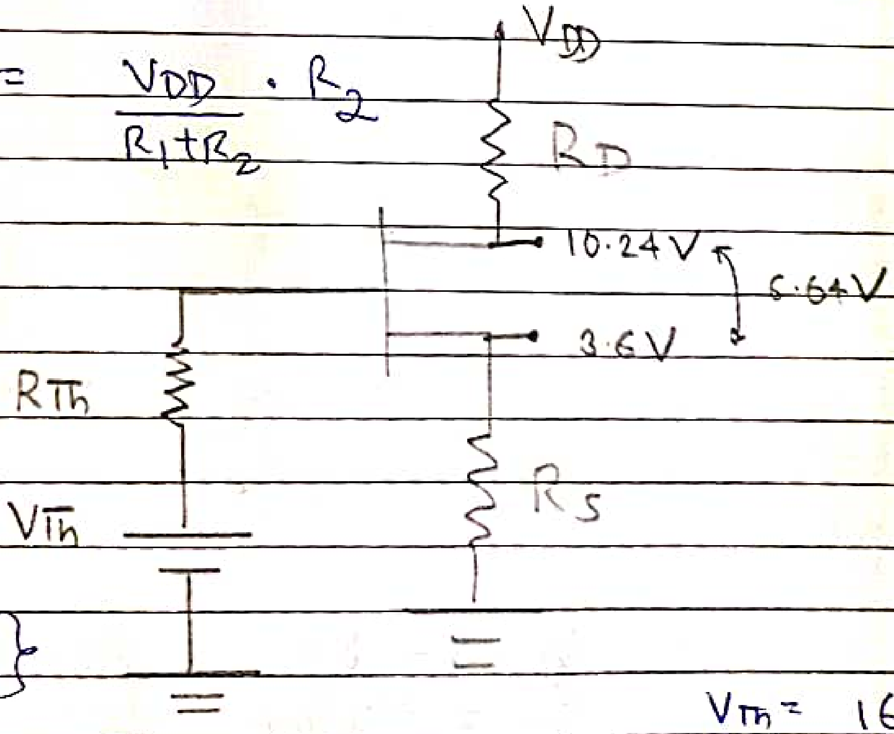
$V_p = -4V$

Find

$I_{DQ}, V_{GSQ}, V_D, V_S, \text{ \& } V_{DS}$

$$R_{Th} = R_p = \frac{R_1 R_2}{R_1 + R_2}$$

$$V_{Th} = \frac{V_{DD} \cdot R_2}{R_1 + R_2}$$




No voltage drop across $R_{Th}$. $\{I_G = 0\}$

$$V_{Th} = \frac{16 \times 270}{270 + 2100} = \cancel{0.025V} \; 1.82\Omega$$

$$V_{Th} - V_{GS} - I_D R_S = 0$$

$$V_{GS} = V_{Th} - I_D R_S$$

$$V_{GS} = 1.82 - I_D (1.5)$$

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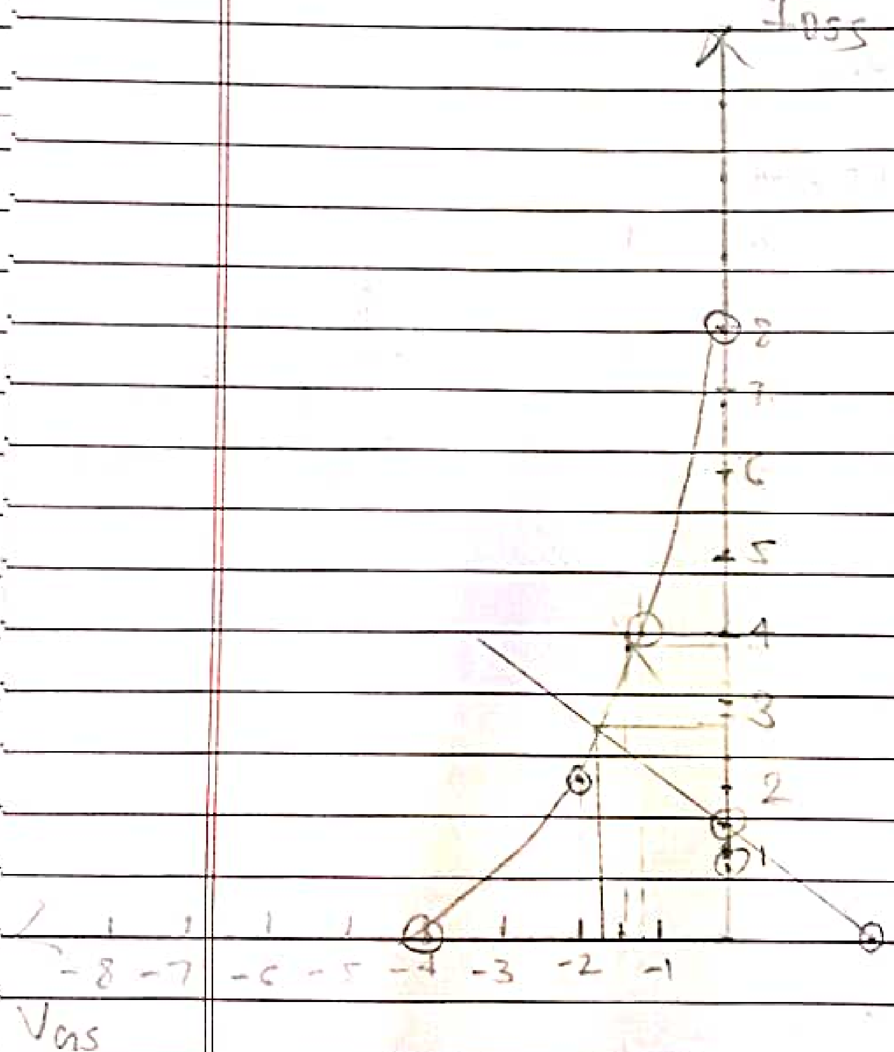
$$I_D = I_{DSS}\left(1 - \frac{V_{GS}}{V_P}\right)^2$$

$$= 8\left(1 - \frac{V_{GS}}{V_P}\right)^2$$



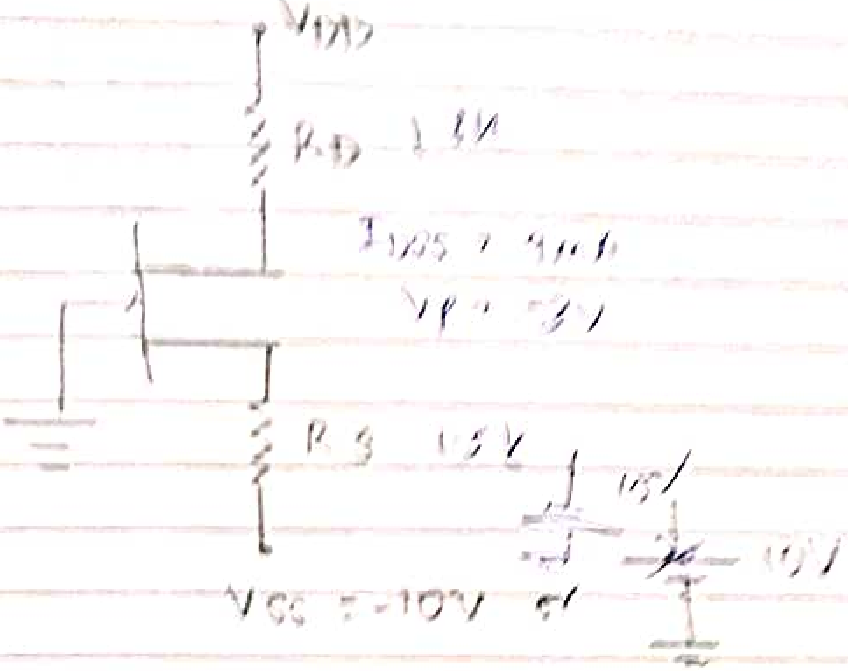

$V_{GS} = -1.8V$

$I_D = $ ~~[illegible]~~ mA

2.7

$2.25 I_D^2 + 20 I_D + 49 =$

(P)




Find $I_{DSQ}$, $V_{GSQ}$, $V_{DS}$, $V_D$, $V_S$

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

$$-V_{GS} - I_D R_S - 10 = 0$$

$$V_{GS} = -I_D R_S - 10$$

$$V_{GS} = -1.5 I_D - 10$$

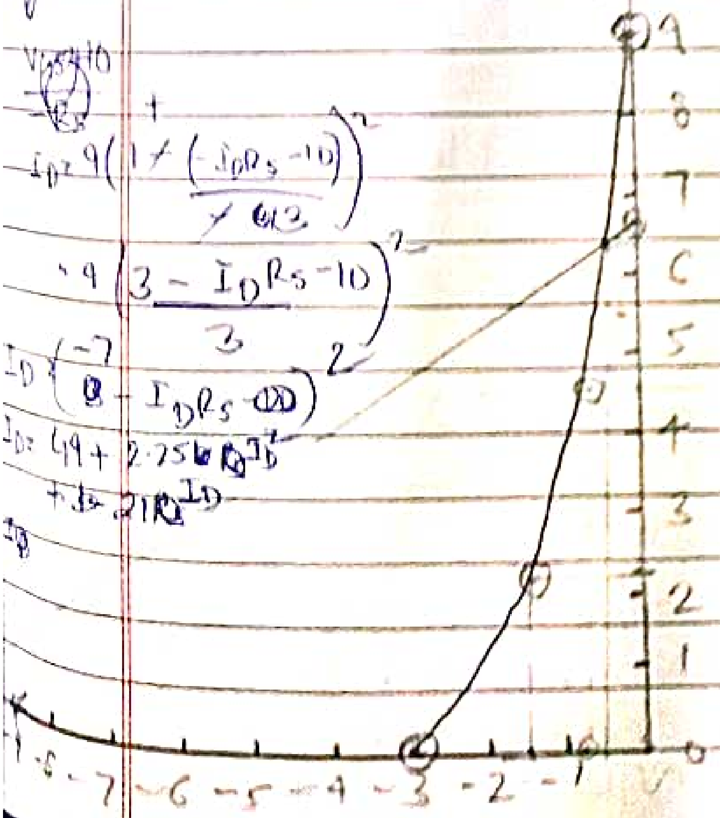
$V_{GS} = -I_D R_S - 10$

$$I_D = 9\left(1 + \frac{(-I_D R_S - 10)}{3}\right)^2$$

$$= 9\left(\frac{3 - I_D R_S - 10}{3}\right)^2$$

$$I_D = (-7 - I_D R_S)^2$$

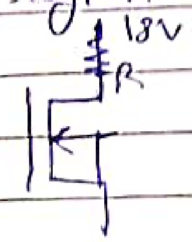
$I_D = 49 + 2.25 I_D^2 + 21 I_D$

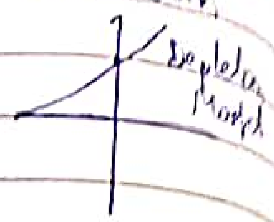



$V_{GS} = -0.35V$

$I_{DS} = 5.6 mA$

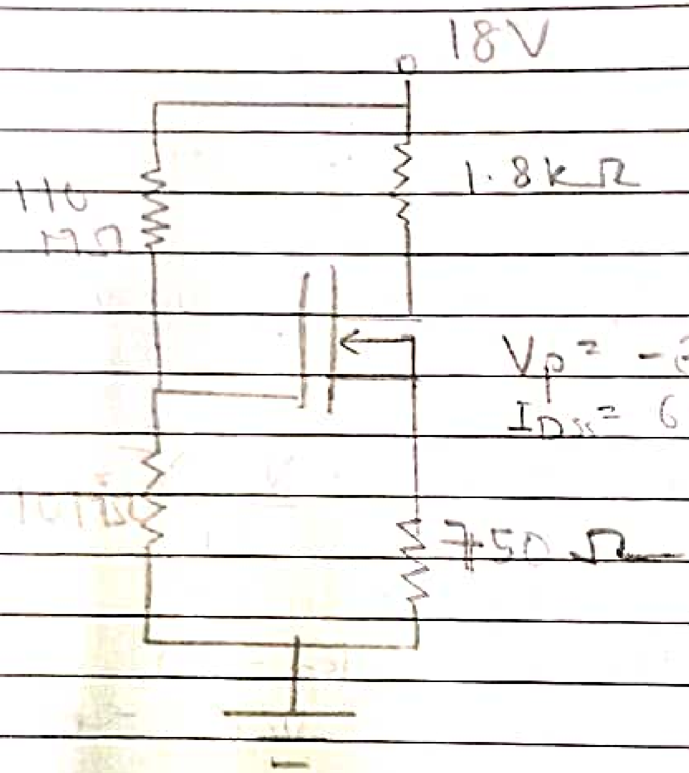
1) Depletion MOSFET is like JFET it has both enhancement & depletion region.




2) Symbol changes

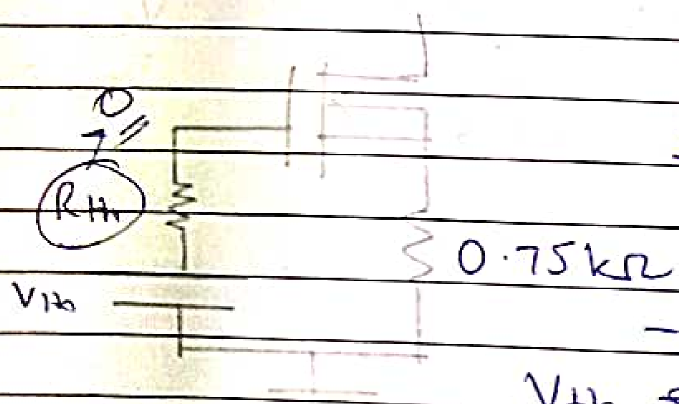
Q)




$V_p = -3V$
$I_{DSS} = 6mA$

Find operating point & load line.

$R_{th} = 9.167\ M\Omega = 9167\ k\Omega$
$V_{th} = 1.5\ V$




$I_G = 0$

$V_{th} - V_{GS} - 0.75 I_D = 0$ ~~9.167~~

$9.5 = V_{th} = V_{GS} + 0.75 I_D$

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

$$I_D = 6\left(1 + \frac{V_{GS}}{3}\right)^2$$

$$I_D = 6\left(\frac{3 + 1.5 - 0.75 I_D}{3}\right)^2$$

$$I_D = \frac{2}{3}\left(4.5 - 0.75 I_D\right)^2$$

$$1.5 I_D = 20.25 + 0.5625 I_D^2 - 6.75 I_D$$

$$0.5625 I_D^2 - 8.25 I_D + 20.25 = 0$$

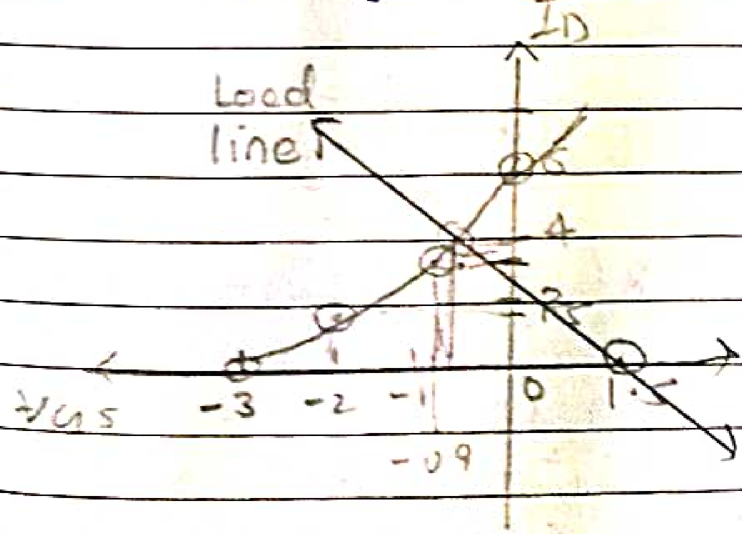
$$I_D = 11.549 \text{ or } \boxed{3.116\,mA}$$

&

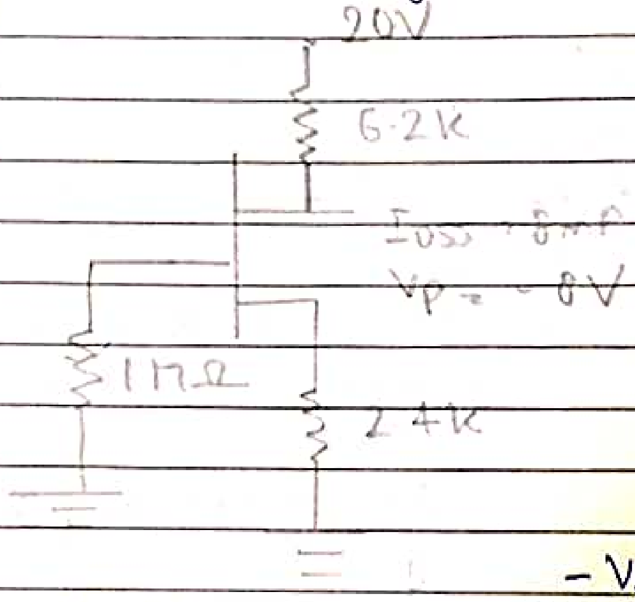
$$\underline{V_{GS} = -7.161\,V} \text{ or } \boxed{-0.837\,V}$$

Not possible

$$Q \equiv (-0.837\,V,\ 3.116\,mA)$$



Q) For a self bias ckt using depletion MOSFET find the operating point if $r_d = 6.2k$, $r_s = 2.4\ k$, $r_g = 1M\Omega$, $I_{DSS} = 8\ mA$, $V_{GP} = -8V$, supply $= 20V$.




$$-V_{GS} - I_D(2.4) = 0$$

$$V_{GS} = -I_D(2.4)$$

$I_G = 0$

$I_D = I_S$

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

$$= 8\left(1 + \frac{V_{GS}}{8}\right)^2$$

$$= 8\left(1 - \frac{\overset{0.3}{\cancel{2.4}} I_D}{\cancel{8}}\right)^2$$

$$I_D = 8\left(1 + 0.09 I_D^2 - 0.6 I_D\right)$$

$$0.125 I_D = 1 + 0.09 I_D^2 - 0.6 I_D$$

$$0.09 I_D^2 - 0.725 I_D + 1 = 0$$

Invalid

$I_{D1} = 6.288$ mA $\quad V_{GS} = -15.09$ (X)

$I_{D2} = 1.766$ mA $\quad V_{GS} = -4.238V$

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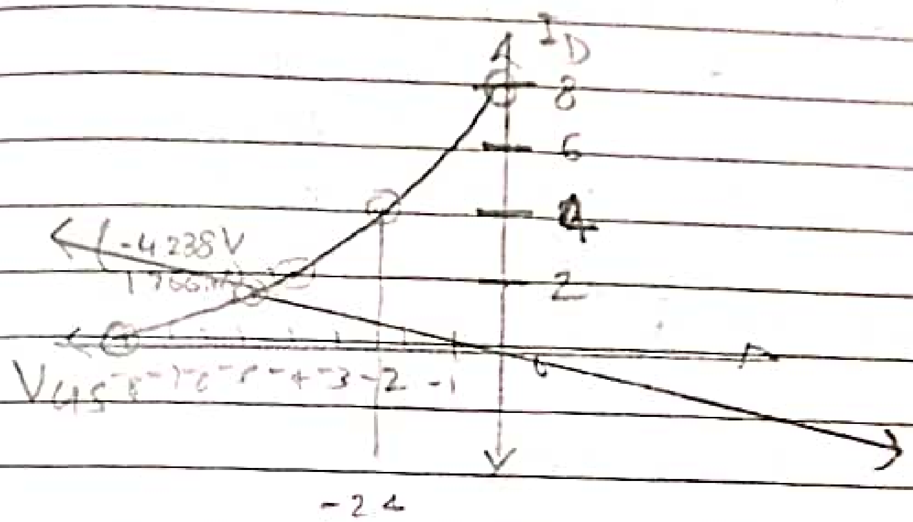
$Q \equiv (-4.238\,V,\ 1.756\,mA)$

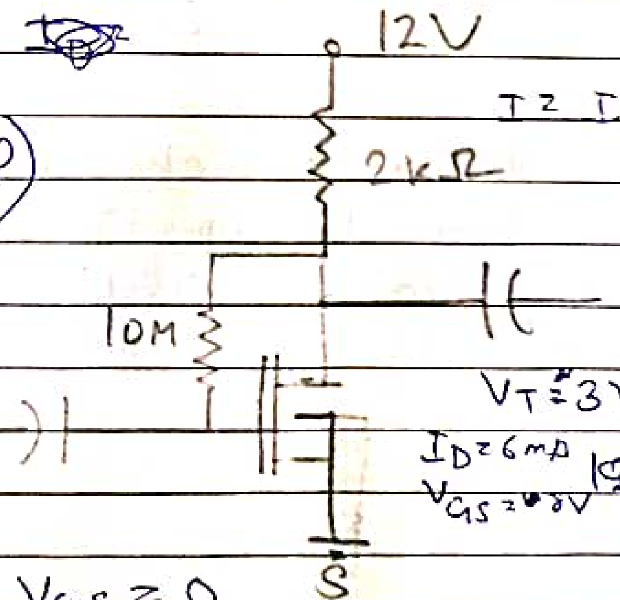



$V_S = 4.2\,V$

$\cancel{V_D = 20}$

$20 - V_D = 6.2 \times I_D$

$V_D = 9.0508\,V$




Q)

$I = I_D + \cancel{I_G}$

find Q pt

$V_D, V_S$

$V_T = 3V$

$I_D = 6mA$

$V_{GS} = 8V$

$2.4 \times 10^{-4}$

$12 - I_D(2) - V_{GS} = 0$

$V_{GS}$

$= 12 - 2I_D$

$I_D = k(V_{DS})^2$

$V_{DS} = (V_{GS} - V_T)$

$= -11\,V$

$k = \dfrac{I_D}{(V_{DS})^2}$

$I_D V = kV_{DS}^2$

$I_D = k(12 - 2I_D - 3)^2$

$= k(9 - 2I_D)^2$ 2000

$= 2.4 \times 10^{-4} (9 - 2I_D)^2$
4000

$4166.67 I_D = 81 + 4I_D^2 - 36 I_D$
36,000,000

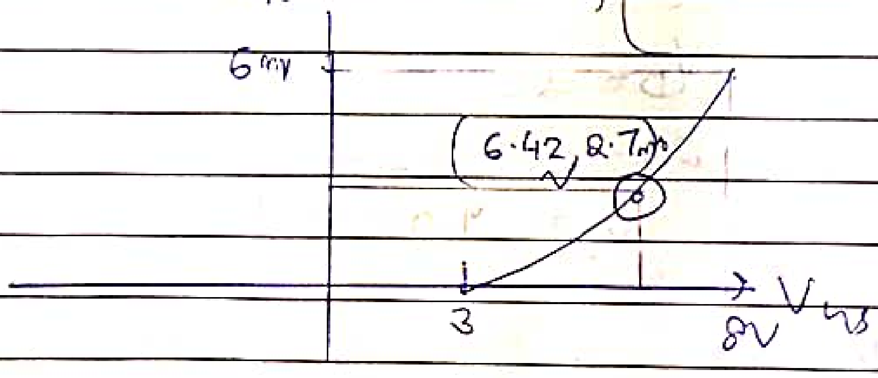
~~3600416.67~~

$4000 I_D^2 - \cancel{4000...67} I_D + 81 = 0$

~~$I_D = 1050.63$~~

$I_D = 7.247\ mA$ , $2.79\ mA$

$V_{GS} = -2.494V$ , $6.42V$




Q) For a voltage divider bias ckt. using enhancement type MOSFET find the operating point $V_{DS}$, $V_D$, $V_S$ & draw load line & transfer characteristic for the following parameters:

$V_{DD} = 40V$

$R_1 = 22M\Omega$

$R_2 = 18M\Omega$ $\qquad V_{GS(threshold)} = 5V$

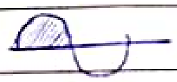
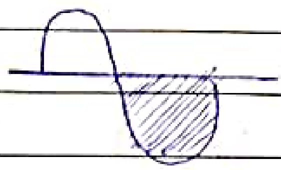
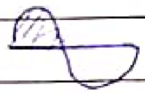
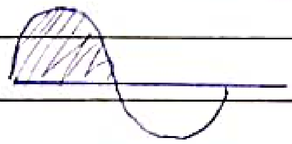
$R_D = 3k\Omega$

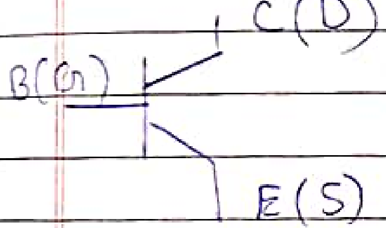
$R_S = 0.82\,k\Omega$

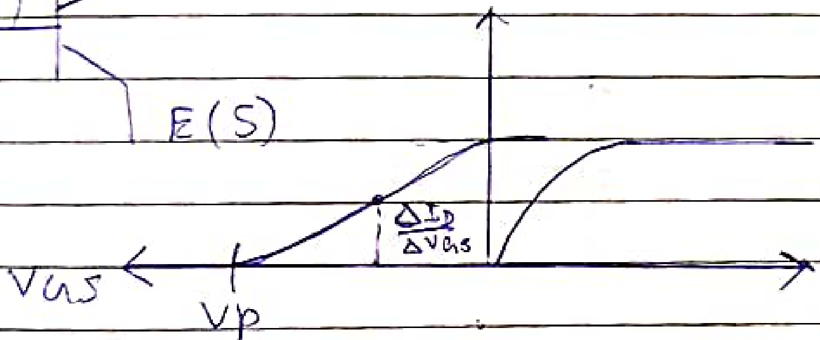
$I_{D(on)} = 3\,mA$

$V_{DGS(on)} = 10V$

Small Signal A.C analysis

| | BJT | FET | |
|---|---|---|---|
| | $I_C = f(I_B)$ | $I_D = f(V_{GS})$ | ~~commo~~ |
| CE |  |  | common soure |
| CC | (Emitter follower) Gain=1 | | Gain = 1 {Source follower} |
| CB |  |  | common gate |




$$g_m = \text{Transconductance}$$

$$= \frac{\Delta I_D}{\Delta V_{GS}} \quad \left(\begin{matrix}\text{Siemens} \\ S\end{matrix}\right)$$

Transconductance is the slope of point of operation in the transfer characteristics

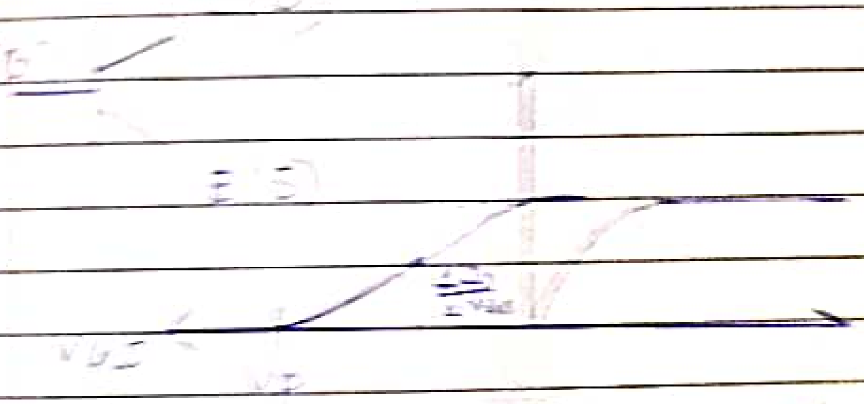
$$g_m = \frac{\partial I_D}{\partial V_{GS}} = \frac{\partial \left[ I_{DSS}\left(1 - \frac{V_{GS}}{V_P}\right)^2 \right]}{\partial V_{GS}}$$

$$0 - \cancel{\frac{I_{DSS}}{V_p}} = \left| -2 I_{DSS}\left(1 - \frac{V_{GS}}{V_P}\right)\left(\frac{1}{V_P}\right) \right|$$

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

[illegible]

[illegible]



$g_m$ = Transconductance

$= \frac{\Delta I_D}{\Delta V_{GS}}$ [illegible]

Transconductance is the slope of [illegible] in the transfer characteristics

$g_m = \frac{\partial I_D}{\partial V_{GS}}$ = [illegible]

[illegible]

Calculate the transconducotance value if

$I_{DSS} = 8\,mA$

$V_P = -4V$

$V_{GS} = -0.5\,V$

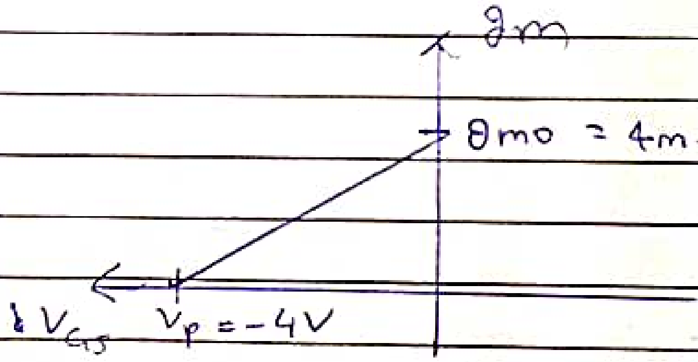
$$g_m = \left|\frac{2I_{DSS}}{V_P}\left(1-\frac{V_{GS}}{V_P}\right)\right|$$

$$= \frac{2\times 8\,2}{\cancel{4}}\left(1-\frac{1}{8}\right)$$

$$= \cancel{4}_{2}\left(\frac{7}{\cancel{8}}\right) = 3.5\,mS$$

Imp

$$g_{mo} = \frac{8\times 2}{|4|} = 4\,mS$$

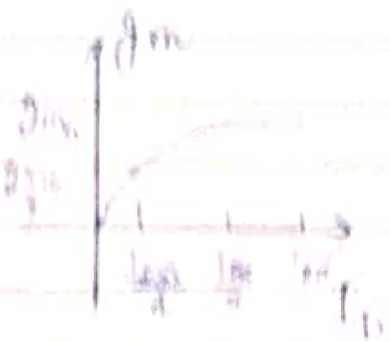



when $V_{GS} = 0$

$$g_m = \frac{2I_{DSS}}{|V_P|} = g_{mo}\Big|_{V_{GS}=0} \quad \{\text{fixed value}\}$$

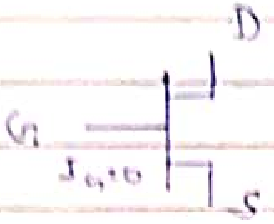
$$\therefore g_m = g_{mo}\left(1-\frac{V_{GS}}{V_P}\right)\Big|_{V_{GS}\neq 0}$$

$$g_m = g_{mo}\sqrt{\frac{I_D}{I_{DSS}}}$$



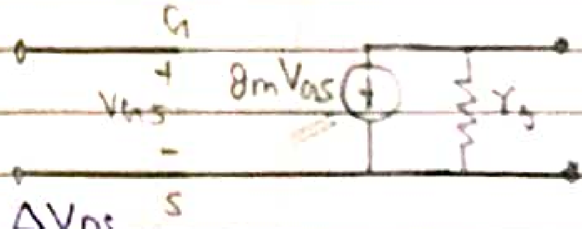
$\boxed{g_m = y_{fs}}$

In some specifications sheets the transconductance parameter $g_m$ is also denoted by $y_{fs}$ where fs stands for forward source.

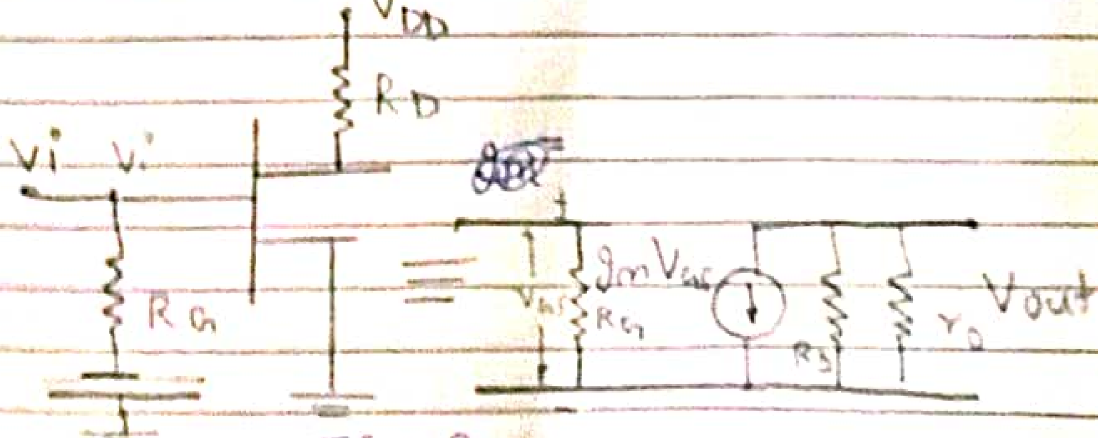


Gate current = 0
No current enters
Infinite resistance

$Z_i = \infty$
$Z_o = r_o$



$$r_o = \frac{1}{y_{os}} = \frac{\Delta V_{DS}}{\Delta I_D}$$



$Z_i = R_G$
$Z_o = R_D \| r_o$

Q) A fixed bias configuration has an operating point defined by $V_{GSQ} = -2V$ $I_{DQ} = 5.625V$ $I_{DSS} = 10 mA$ $V_P = -8V$. The value of $Y_{os} = 40 \mu S$.
Calculate $g_{m0}$, $g_m$, $r_0$.

$$g_{m0} = \frac{2 I_{DSS}}{|V_P|}$$

$$= \frac{\cancel{2} \times 10}{\cancel{8}\, 4} = 2.5 \text{ mS}$$

$$g_m = g_{m0}\left(1 - \frac{V_{GSQ}}{V_P}\right)$$

$$= 2.5\left(1 - \frac{\cancel{2}\,1}{\cancel{8}\,4}\right)$$

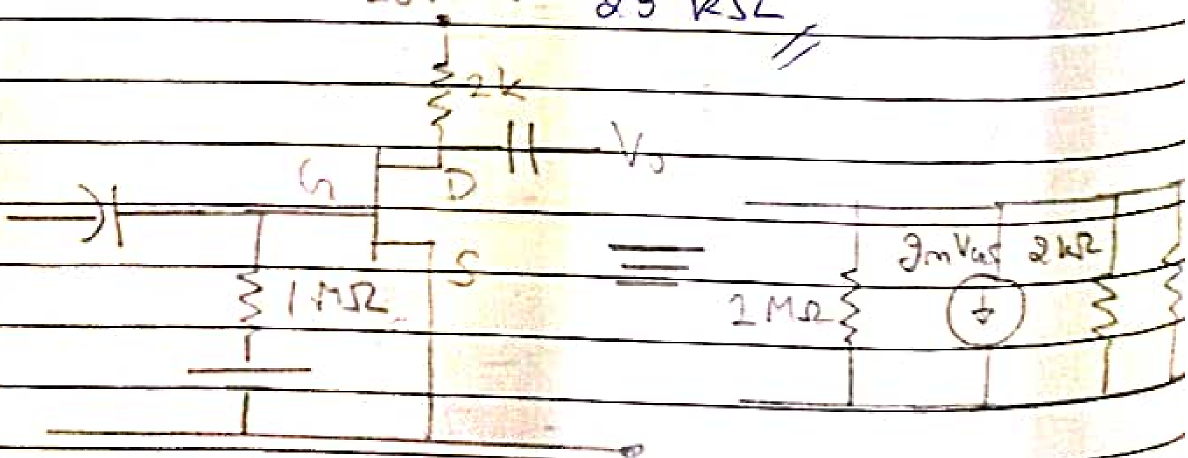
$$= 2.5 \times 3/4 = \frac{7.5}{4} = 1.875 \text{ mS}$$

$$r_0 = \frac{1}{Y_{os}} = \frac{1}{4\cancel{0}} \times 10\cancel{0} \times 10^4$$

$$= 2.5 \times 10^4 \, \Omega$$

$$= 25 \text{ k}\Omega$$

Q)

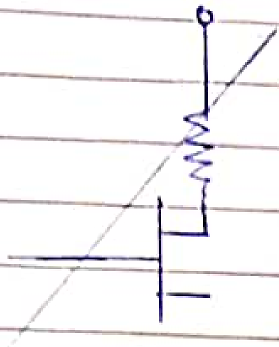



$Z_i = 1 M\Omega$

$$Z_o = \frac{25 \times 2}{27} = 50/27 \text{ k}\Omega$$

$$= 1.851 \text{ k}\Omega$$

Q)

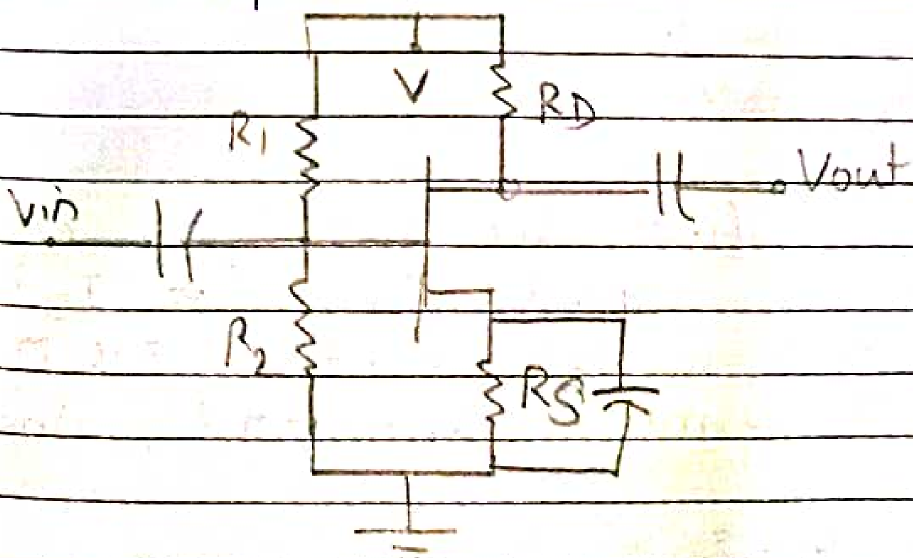


$$A_V = \frac{V_o}{V_i} = -\frac{g_m \cancel{V_{GS}}(r_d \,\|\, R_d)}{\cancel{V_{GS}}}$$

$$\boxed{A_V = g_m(r_d \,\|\, R_d)}$$

$$A_V = -1.875\,(r_o \,\|\, R_d)$$
$$= -3.471$$

* The output voltage is 180° out of phase with respect to input voltage.



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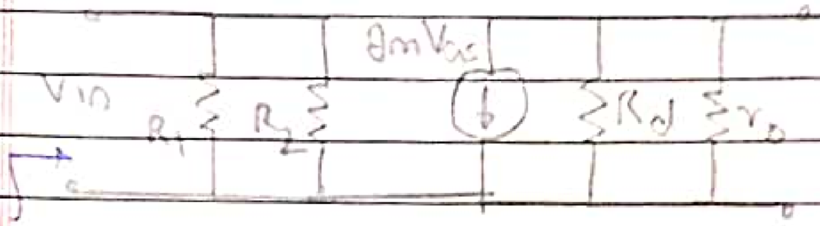


$Z_{in} = R_1 || R_2$

$Z_o = R_d || r_o$

$$A_v = -\frac{\cancel{g_m V_{gs}}(R_d || r_o)}{\cancel{V_{gs}}}$$

$$= -g_m(R_d || r_o)$$

Q) For a voltage divider bias ckt, $V_{DD} = 10V$, $R_D = 2k$

(H.W) $R_1 = 220\,k\Omega$

$R_2 = 1\,M\Omega$

$R_S = 22\,k\Omega$

$I_{DSS} = 10\,mA$

$V_p = -8\,V$

Q) Design a fixed bias ckt having a gain of 10 and operating point at $I_D = I_{DSS}$ if given gate resistance $= 10\,M\Omega$, $I_{DSS} = 10\,mA$, $V_p = -4V$, $Y_{OS} = 20\,\mu S$

$$Y_{OS} = \frac{1}{r_o}$$

$$r_o = 50\,k\Omega$$

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Av?

$$g_m = g_{m0}\left(1 - \frac{V_{GS}}{V_P}\right)$$

$$g_{m0} = \frac{2I_{DSS}}{|V_P|} = \frac{\cancel{2}\times 10}{\cancel{4}\,2} = 5\,mS$$

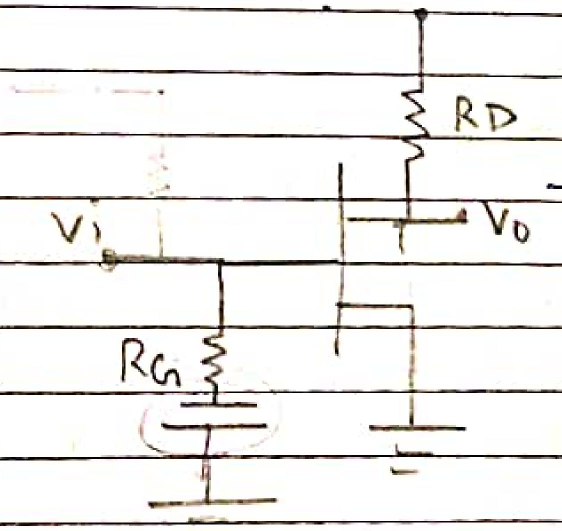
$$= 5\left(1 - 0\right) = 5\,mS \qquad \left\{\begin{matrix}\text{at } I_{DSS} \\ V_{GS} = 0\end{matrix}\right\}$$

$$A_v = g_m\left(R_D \,\|\, r_o\right)$$

$$10 = 5\times\cancel{10^{3}}\left(\frac{R_D \times 50\times\cancel{10^{3}}}{R_D + 50\times10^{3}}\right)$$

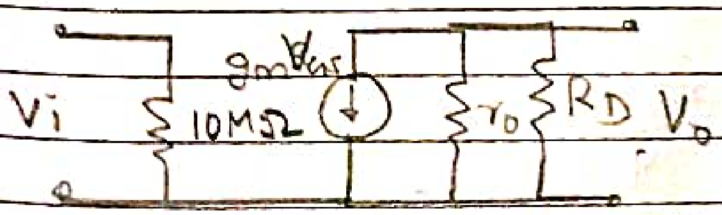
$$10R_D + 500\times10^{3} = 250R_D$$

$$R_D = \frac{50\cancel{0}\times10^{3}}{24\cancel{0}} = 2.083\ k\Omega$$




$$-V_{DD} - V_{GS} = 0$$

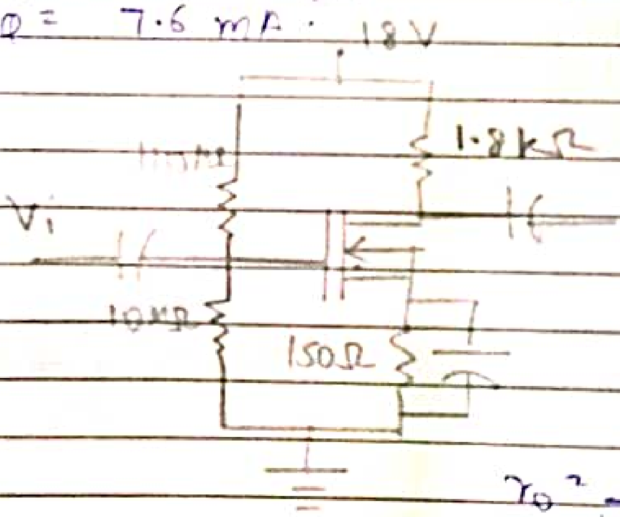
$$\boxed{V_{DD} = 0}$$



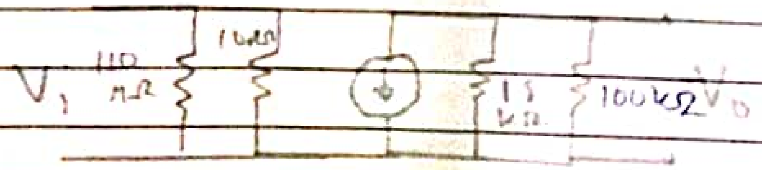
## Depletion Mosfet

In depletion type MOSFET the Schokley's equation of JFET is applicable here. So the $g_m$ model of JFET is valid here. The only difference is $V_{GS}$ can be +ve in depletion type MOSFET whereas it is not possible n channel n channel JFET.

Q) Draw a voltage divider bias ckt with depletion with $V_{DD} = 18\ V$, $R_D = 1.8\ k\Omega$, $R_1 = 110\ M\Omega$, $R_2 = 10\ M\Omega$, $R_S = 150\Omega$. $I_{DSS} = 6\ mA$, $V_P = -3V$, $y_{os} = 10\ \mu S$, $V_{GSQ} = 0.35V$, $I_{DQ} = 7.6\ mA$.




$$r_o = \frac{1}{y_{os}} = 10^5\ \Omega = 100\ k\Omega$$




$Z_i = 9.167\ M\Omega$

$Z_o = 1.768\ k\Omega$

$$g_{mo} = \frac{2 \times 6}{3} = 4\ mS$$

$$g_m = 4\left(1 + \frac{0.35}{3}\right)$$

$$g_m = 4.\overset{46}{\cancel{28}}\ mS$$

$$A_v = -\frac{g_m \cancel{V_{GS}}(1.768)}{\cancel{V_{GS}}} = -7.897$$

$\approx$ ea − ~~[illegible]~~

## Enhancement Type MOSFET

$$I_D = k(V_{GS} - V_{Th})^2$$

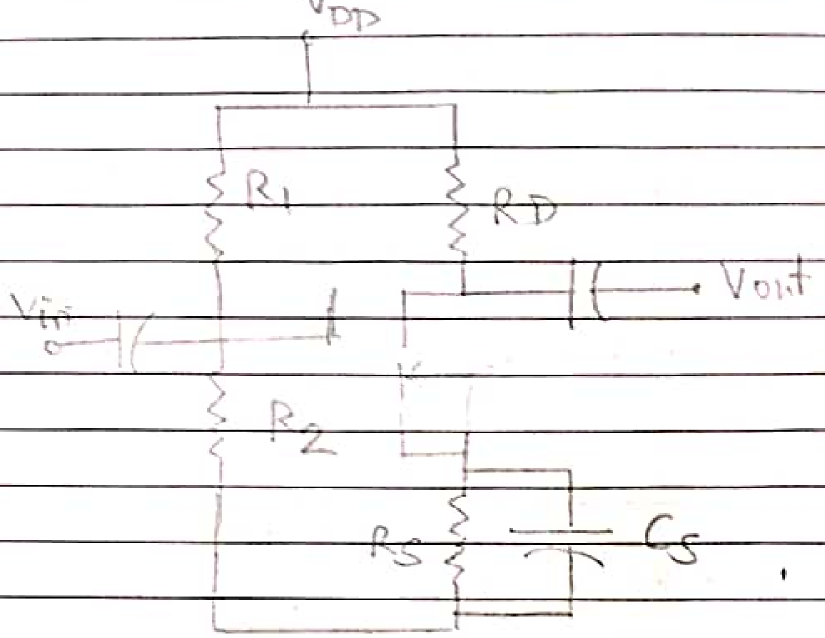
$$k = \frac{I_D}{(V_{GS(ON)} - V_{Th})^2}$$

$$g_m = \frac{dI_D}{dV_{GS}}$$

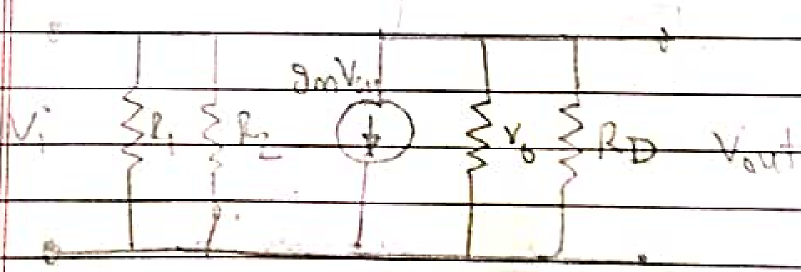
$$g_m = 2k(V_{GS} - V_{Th})$$

$$g_m = \frac{2 I_{D(ON)}}{V_{GS(ON)} - V_{Th}}$$

The small signal model of enhancement type MOSFET is same as depletion type MOSFET & JFET. Only the expression for $g_m$ is different in this case.




Draw the small signal model




$$Z_i = \frac{R_1 \cdot R_2}{R_1 + R_2}$$

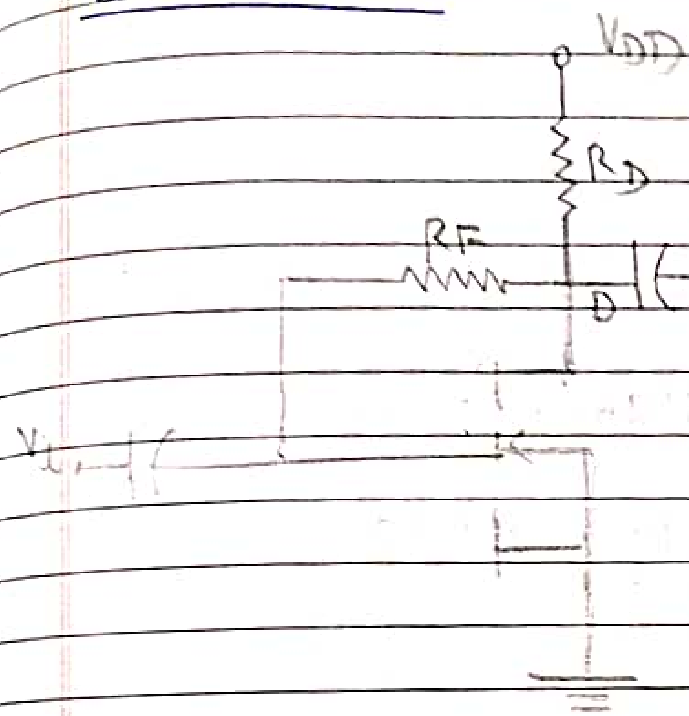
☆ {Output is 180° shift w.r.t. input}

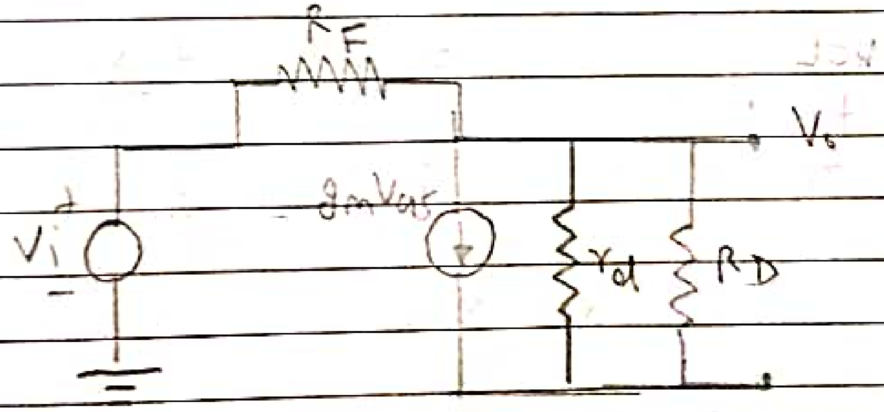
$$Z_o = \frac{r_D \cdot R_D}{r_D + R_D}$$

$$A_V = -\frac{g_m V_{gs} \cdot (R_D \| r_o)}{V_{gs}}$$

$$= -g_m (R_D \| r_o)$$

## Drain Feedback




$Z_i$ :- Applying KCL at node D

$$I_i = g_m V_{GS} + \frac{V_o}{r_d || R_D}$$

$$V_{GS} = V_Z$$

$$I_Z = g_m V_i + \frac{V_o}{r_d || R_D}$$

$$I_Z - g_m V_1 = \frac{V_o}{r_d || R_D}$$

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$$V_o = (r_d \| R_D)(I_i - g_m V_i)$$

$$I_i = \frac{V_i - V_o}{R_F}$$

$$I_i = V_i - (r_d \| R_D) I_i + (r_d \| R_D) g_m V_i$$

$$I_i \left( R_F + (r_d \| R_D) \right) = V_i \left( 1 + g_m (r_d \| R_D) \right)$$

$$Z_i = \frac{V_i}{I_i} = \frac{R_F + (r_d \| R_D)}{1 + g_m (r_d \| R_D)}$$

$A_V$ – voltage gain

KCL at node D

$$I_i = g_m V_{gs} + \frac{V_o}{r_d \| R_D}$$

$$I_i = \frac{V_i - V_o}{R_F}$$

$$V_{gs} = V_i$$

$$\frac{V_i - V_o}{R_F} = g_m V_D + \frac{V_o}{r_d \| R_D}$$

$$V_o \left[ \frac{1}{r_d \| R_D} + \frac{1}{R_F} \right] = V_i \left[ \frac{1}{R_F} - g_m \right]$$

$$A_V = \frac{V_o}{V_i} = \frac{\left[ 1/R_F - g_m \right]}{\left[ \frac{1}{r_d \| R_D} + \frac{1}{R_F} \right]}$$

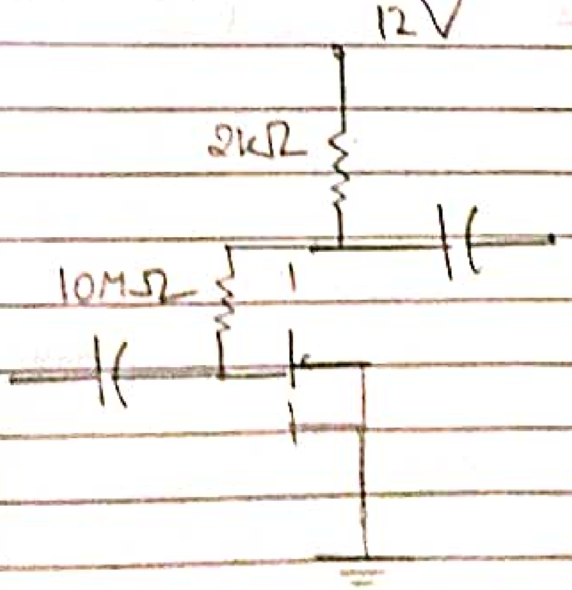
• $r_d \gg 10 r_d$
$R_F \gg r_d \| R_D$

$\therefore$ $\boxed{A_V = -g_m R_D}$ {Output is 180° out of phase w.r.t input}

A(2)

Q) An enhancement type MOSFET, was connected in drain feedback configuration. The parameters of the MOSFET are $k = 0.24 \times 10^{-3}\ A/V^2$, $V_{GS(Q)} = 6.4V$ & $I_{D(Q)} = 2.75\ mA$. Supply voltage = 12V, drain resistance is 2 kΩ, feedback resistance = 10 MΩ, $y_{os} = 20\ \mu S$. $V_{Th} = 3V$. Coupling capacitors are 1 μF

i) Draw ckt diagram
ii) Small signal model
iii) $Z_i$, $Z_o$, $A_V$




$r_o = 1/y_{os}$
$= \frac{1}{20} \times 10^6$
$= 50000\Omega$
$= 50k\Omega$

$I_D = K(V_{GS} - V_{TH})^2$

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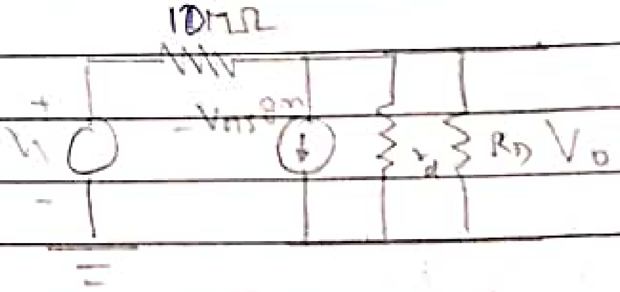



~~$Z_i = R_F +$~~

$$g_m = 2k(V_{GS} - V_{TH})$$
$$= 2 \times 0.24 \times 10^{-3} (6.4 - 3)$$
$$= 6.8 \times 0.24 \times 10^{-3}$$
$$= 1.632 \text{ mS}$$

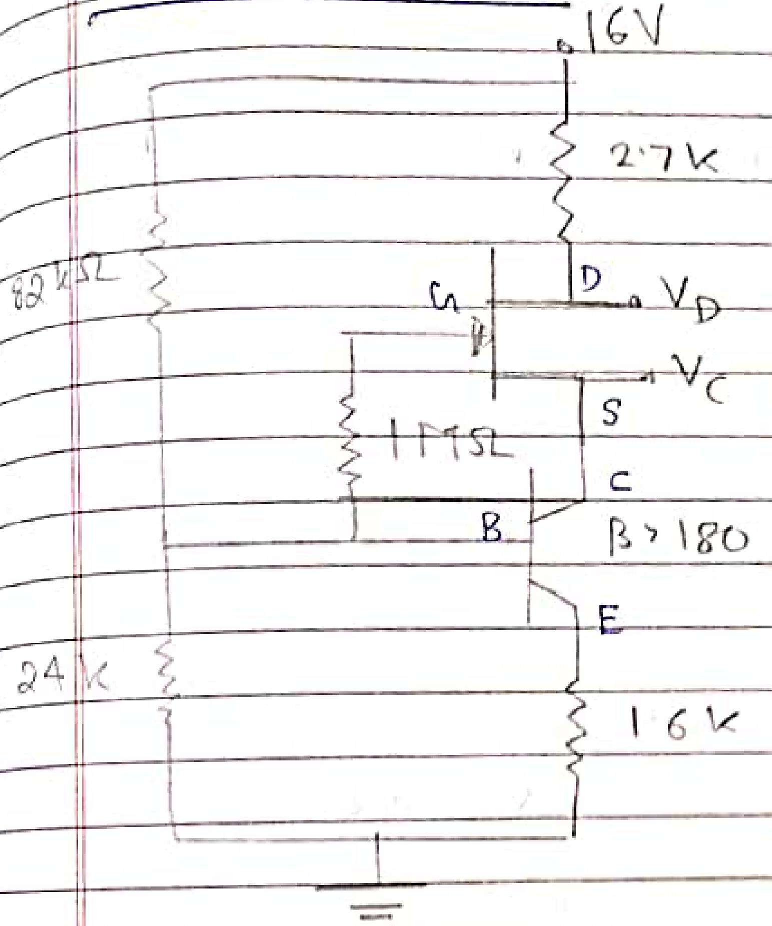
$$Z_i = \frac{V_i}{I_i} = \frac{R_F + \overset{1.922}{(r_d \| R_D)}}{1 + g_m (r_d \| R_D)}$$
$$= 24083.49.193$$
$$= 2.408 \text{ M}\Omega$$

$$Z_o \approx R_D = 2 \text{ k}\Omega$$

$$A_V = -g_m R_D$$
$$= -3.264$$

## Combinational Circuit

Determine $V_D$, $V_C$ for the network.




$V_P = -6V$

$I_{DSS} = 12mA$

$R_{Th} = 18.566$

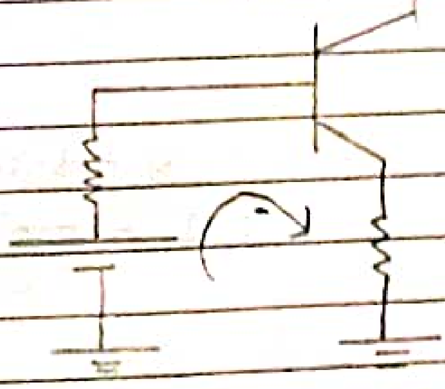
$I_D = I_S = I_C \simeq I_E$

$V_{Th} = 3.623\ V$

$V_D = 16 - I_D(2.7)$ — (1)

$V_B - V_{GS} -$

$\boxed{\cancel{I_D = I_{DSS}\left(1 - \frac{V_{GS}}{V_P}\right)^2}}$



$V_{Th} - I_B R_{Th} - V_{BE} - i_E R_E = 0$

$$\frac{V_{Th} - V_{BE}}{R_{Th} + (\beta+1)R_E} = i_B$$

$i_B = 9.485\ \mu A$

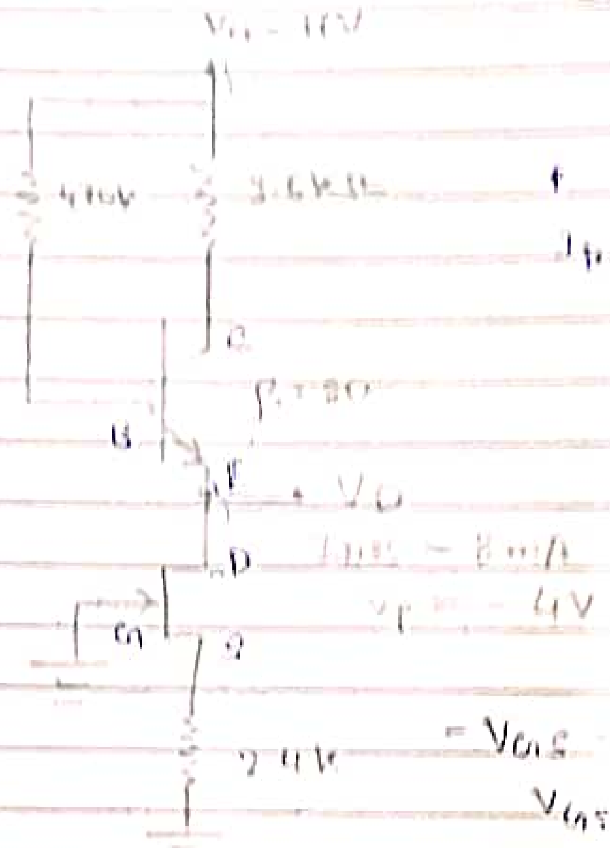
$i_C = \beta i_B = 1.707\ mA$

$I_D = i_C = 1.707\ mA$

$V_D = 16 - I_D R_D$

$= 11.3911\ V$

p)




$I_E = I_B + I_C \approx I_C$

$-V_{GS} - I_D(2.4) = 0$

$V_{GS} = -2.4 I_D$

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

$V_{CC} - 470 I_B$

$I_D = 8\left(\frac{1}{1} - \frac{2.4 I_D}{4}\right)^2$

$I_D = 8\left(\frac{16}{16} + \frac{5.76 I_D^2}{16} - \frac{19.2 I_D}{16}\right)$

$2 I_D = \frac{16}{4} + 5.76 I_D^2 - \frac{19.2}{4.8} I_D$

~~$5.76 I_D^2 - 6.8 I_D + 4 = 0$~~

~~$I_D = 1.23$ mA~~

~~$I_D = 0$ mA~~

$5.76 I_D^2 - 21.2 I_D + 16 = 0$

$I_D = 2.62$ mA × neglected

$I_D = 1.05$ mA $\qquad V_{GS} = -2.52V$

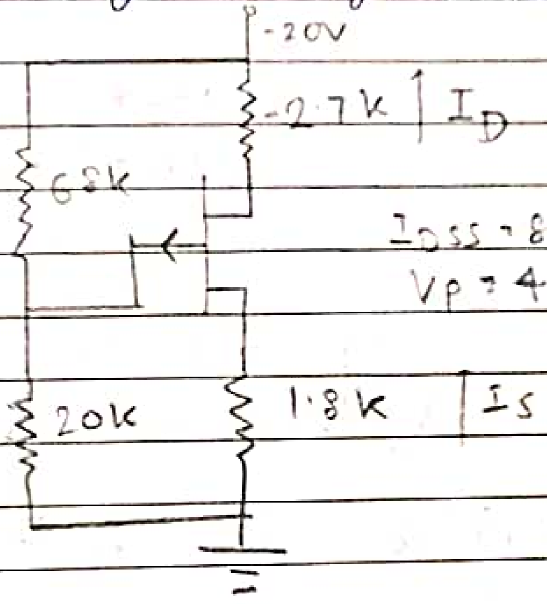
$I_B = \frac{1.05}{\beta} = 13.125\ \mu A$

$0.013125$ mA

$$V_{CC} - I_B(470) - V_{BR} = V_D$$

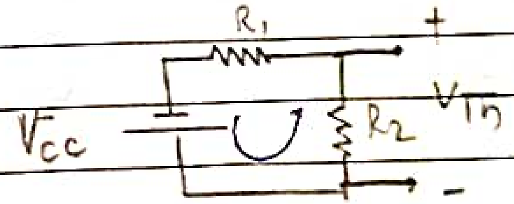
$$V_D = 9.0725 \text{ V}$$

Q) Determine the Q-point for a p-channel JFET which is used in the given voltage divider configuration.



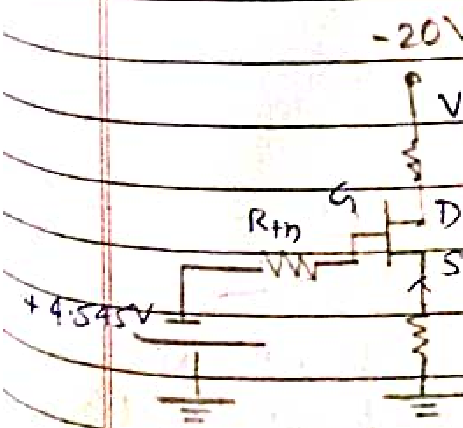

$I_{DSS} = 8mA$
$V_P = 4V$

$R_{Th} = 15.45 \text{ k}\Omega$




$\cancel{V_{cc} + iR_1 - iR_2 = 0}$

$R \quad \cancel{i =}$




$V_{cc} - i_1 R_2 - i_1 R_1$

$i_1 = \dfrac{V_{cc}}{R_1 + R_2}$

$$V_{Th} = -\frac{V_{cc} \cdot R_2}{R_1 + R_2}$$

$$= -4.545 \text{ V}$$

$$V_{Th} - V_{GS} + I_D R_S = 0$$

$$V_{GS} = V_{Th} + I_D R_S$$

$$= -4.545 + I_D(1.8)$$

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

$$= 8\left(1 - \frac{(4.545 + 1.3 I_D)}{4}\right)^2$$

$$I_D = \frac{8}{16}\left(4 + 4.545 - 1.8 I_D\right)^2$$

$$2I_D = \left(9.545 - 1.8 I_D\right)^2$$

$$2I_D = 3.24 I_D^2 + 91.107 + 34.362 I_D$$

$$3.24 I_D^2 - 32.362 I_D + 91.107 = 0$$

$$8\left(1 - (1.8 I_D - 4.54\right)$$

$$= 10^{-3} \times 8\left(1 - \left(\frac{1.8 \times 10^{3} I_D - 4.54}{4}\right)\right)^2$$

$$I_D = \frac{8 \times 10^{-3}}{16}\left[4 - 1.8 \times 10^{3} I_D + 4.54\right]^2$$

$$2 I_D \times 10^3 = \left(8.54 - 1.8 \times 10^{3} I_D\right)^2$$

$$=$$

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

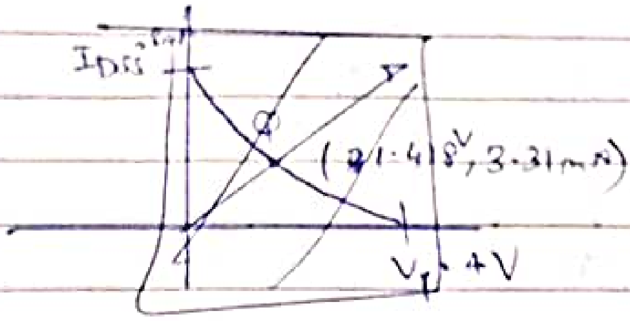
$$I_D = \frac{8}{16}\left(8.545 - 1.8 I_D\right)^2$$

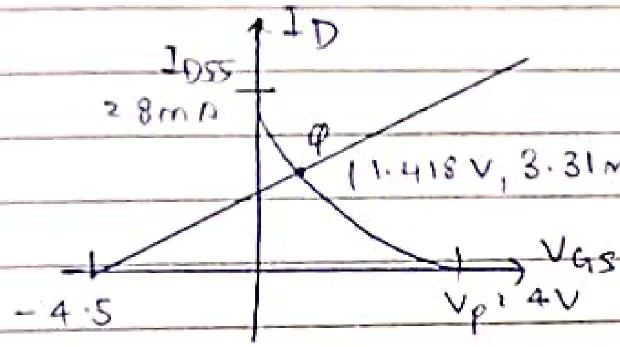
$$2 I_D = 3.24 I_D^2 + 73.017 - 30.762$$

$$3.24 I_D^2 - 32.762 I_D + 73.017 =$$

$I_D = 6.795$ mA (x)

$I_D = 3.31$ mA 1.418




## Frequency Response of BJT & FET

1) $A_P = \frac{P_2}{P_1}$ $\quad$ $Gain_P(dB) = 10 \log_{10} \frac{P_2}{P_1}$

2) $A_V = \frac{V_2}{V_1}$ $\quad$ $Gain_V(dB) = 20 \log_{10} \frac{V_2}{V_1}$

$A = A_{V_1} \times A_{V_2} \times A_{V_3} \times \dots$

$\underset{(dB)}{Gain} = \underset{(dB)}{G_1} + \underset{(dB)}{G_2} + \underset{(dB)}{G_3} \dots$

$P = V^2/R$

$P_2 = 10\ kW$ $\quad$ $V_o = \sqrt{PR}$

$V_2 = 1\ kV$ $\quad$ $= \sqrt{20 \times 500}$

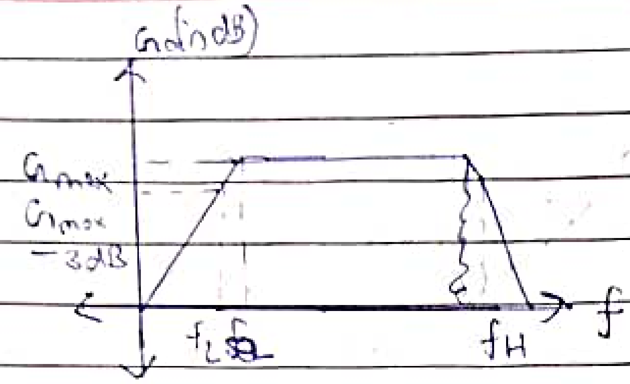
$P_o = 500W$ $\quad$ $= 100\ V$

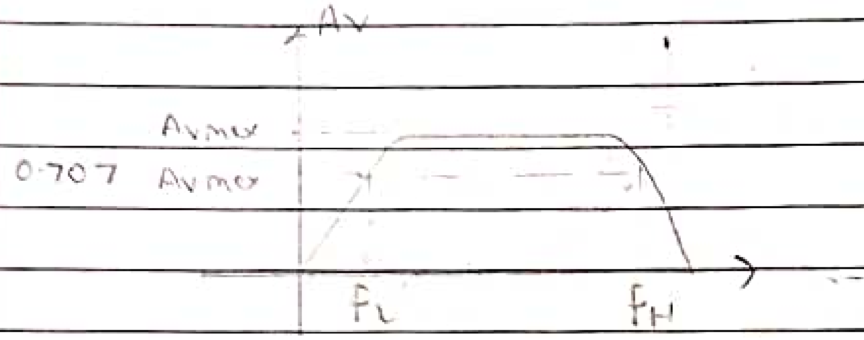
$Z_o = 20\ \Omega$

$G_P = 10 \log \left( \frac{1}{\frac{10 \times 10^3}{500}} \right) = 10 \log \left( \frac{1}{20} \right)$

$= -13\ dB$

$G_v = -20dB$



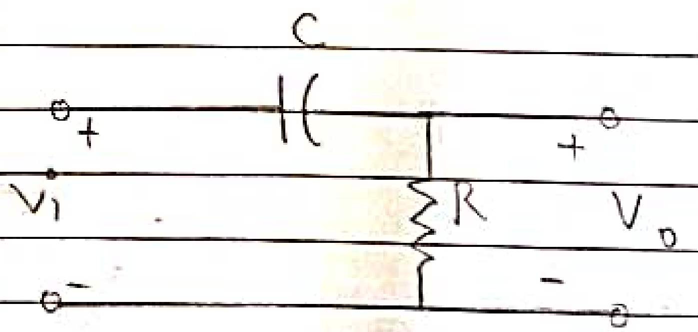

$$P_i = \frac{A_v \times V_i^2}{R}$$

$$P_{o,\,half} = \frac{P_i}{2}$$

$$\frac{1}{2} = \frac{V_o^2 \cancel{R}}{\cancel{R} \cdot V_i^2}$$

$$\frac{V_o}{V_i} = \frac{1}{\sqrt{2}}$$

$$A_v = \frac{1}{\sqrt{2}} = 0.707$$




$$X_C = \frac{1}{\omega C}$$

$\omega = 0 \qquad X_C = \infty$

$\omega = \infty \qquad X_C = 0$

$$V_0 = \left(\frac{R}{R - jX_C}\right) \cdot V_i$$

when $R = jX_C$

$$V_0 = \infty$$

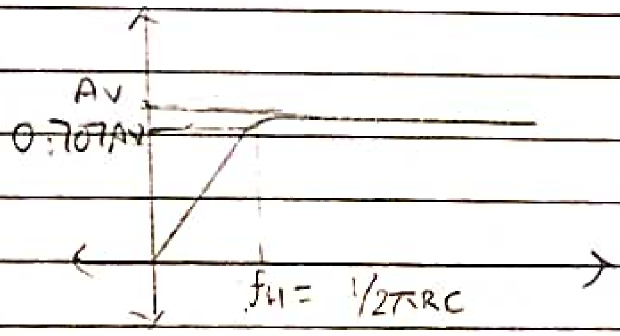
when $X_C = R$,

$$|V_0| = V_i \times \frac{R}{\sqrt{R^2 + X_C^2}}$$

$$|V_0| = \frac{V_i}{\sqrt{2}}$$

$$\boxed{|V_0| = 0.707 V_i}$$

$$f = \frac{1}{2\pi R_{eq} C_{eq}}$$




$$\frac{V_0}{V_i} = \frac{R}{R - jX_C}$$

$$V_0 = \frac{R}{\sqrt{R^2 + X_C^2}} \cancel{V_i} \qquad \boxed{\cancel{\frac{R}{\sqrt{R^2 + X}}}}$$

$$\cancel{\frac{R}{\sqrt{R^2 + \frac{1}{\omega^2 C^2}}}}$$

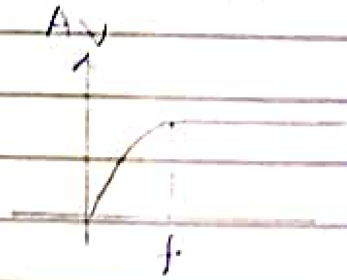
$$\frac{V_o}{V_i} = \frac{R}{R - jX_C}$$

$$= \frac{R}{R - j\frac{1}{2\pi f C}}$$

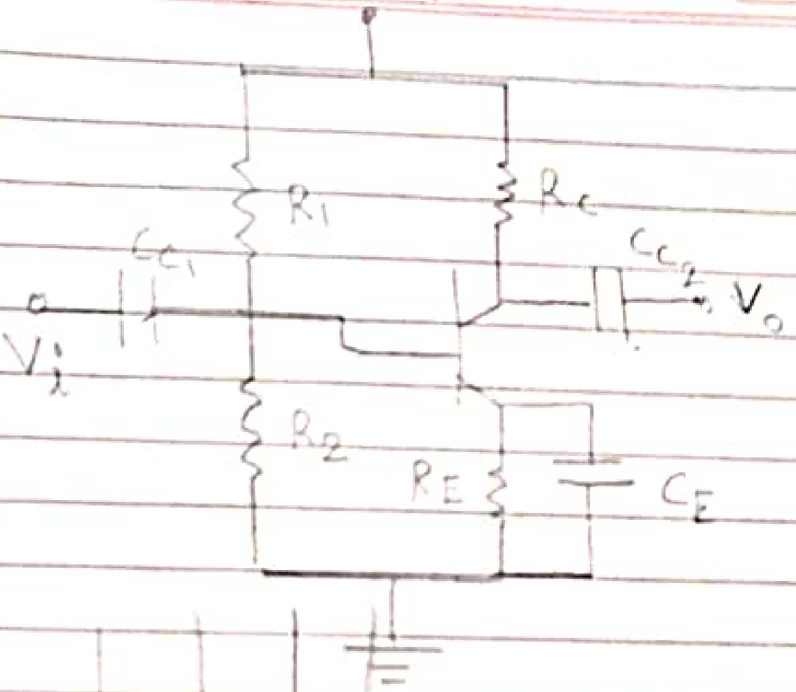
$$= \frac{1}{1 - \frac{j}{2\pi f C R}}$$

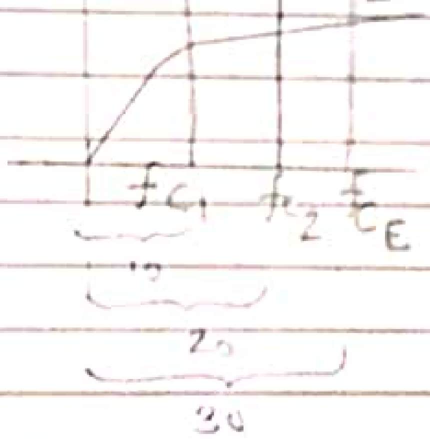
$$A_v = \frac{1}{1 - \frac{f_c j}{f}}$$

$$= \frac{1}{\sqrt{1 + f_c^2/f^2}} \angle \tan^{-1}\left(\frac{f_c}{f}\right)$$




In BJT, we have 3 capacitors i.e. $C_C$ i.e. coupling capacitor at input and output and ~~emitting~~ emitter bypass capacitor i.e. $C_E$. Corresponding to this we'll have 3 frequencies.




Assuming
$f_{c_1} < f_{c_2} < f_{c_E}$

$$f_c = \max(f_{c_1}, f_{c_2}, f_{c_E})$$

$C_S \Rightarrow f_{cs}$ $\qquad \max(f_{c_1}, f_{c_2}, f_{cs})$

$$f_{c_{C_1}} = \frac{1}{2\pi R_{eq} C_{C_1}}$$

$$f_{c_{C_2}} = \frac{1}{2\pi R_{eq} C_{C_2}}$$

$$f_{c_E} = \frac{1}{2\pi R_{eq} C_E}$$

Using $r_e$ equivalent model,

$$f_{C_{c_1}} = \frac{1}{2\pi(R_1 \| R_2 \| \beta r_e) C_{c_1}}$$

$$f_{C_{c_2}} = \frac{1}{2\pi(R_C \| r_o) C_{c_2}}$$

$$f_{C_E} = \frac{1}{2\pi(R_{eq}) C_E}$$

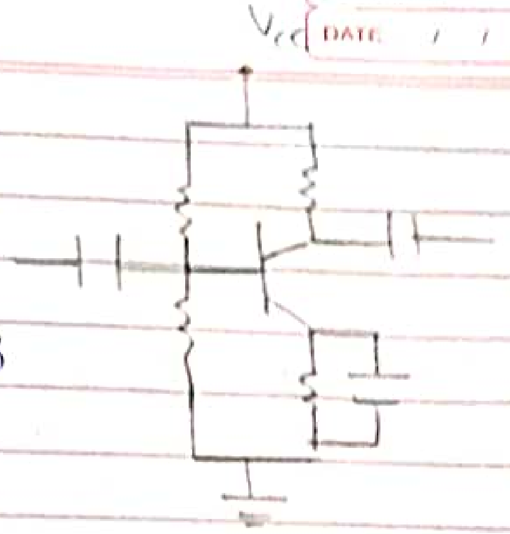
where $R_{eq} = R_E \| \left(\frac{R_S'}{\beta} + r_e\right)$

$R_S' = R_1 \| R_2$

Q) Find the lower cutoff frequency for a voltage divider network having

$C_{c_1} = 10\ \mu F$
$C_{c_2} = 1\ \mu F$
$C_E = 20\ \mu F$
$R_1 = 40K$
$R_2 = 10k$
$R_E = 2K$
$R_C = 4k$
$\beta = 100$
$V_{CC} = 20V$

$$r_e = \frac{26}{I_E}$$

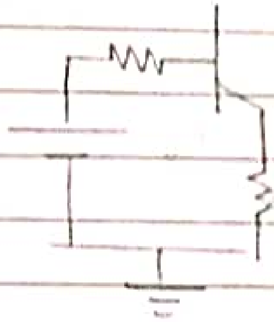



$f_{cc_1} \rightarrow$

$R_{Th} = 8\,k\Omega$

$V_{Th} = \frac{2\cancel{10}}{\cancel{50}} \times 20$

$= 4\,V$



$i_B = \frac{V_{Th} - V_{BE}}{R_{Th} + (\beta+1)R_E}$

$= 0.0157\ mA$

$i_E = 1.587\ mA$

$r_e = 16.38\ \Omega$

$f_{cc_1} = \frac{1}{2\pi(R_1 \| R_2 \| \beta r_e)C_{c_1}}$

$= \frac{1}{2\pi(1.35\,k\Omega)C_{c_1}}$

$= 11.789\ kHz$

$f_{cc_2} = \frac{1}{2\pi R_C \cdot C_{c_2}} = 39.788\ kHz$

$f_{CE} = \frac{1}{2\pi R_{eq} C_E}$

$R_{eq} = R_B \| (0.01638)\,k\Omega$

$= 0.065\ k\Omega$

$f_{CE} = 86.35$

$\underline{max}\ f_C = 86.35\ kHz$

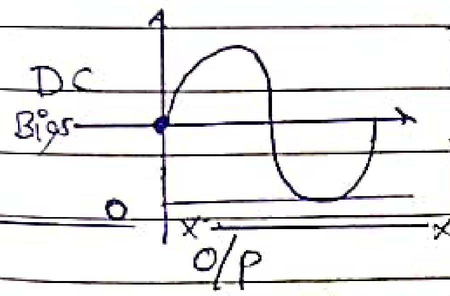
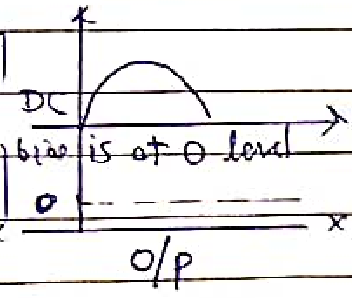
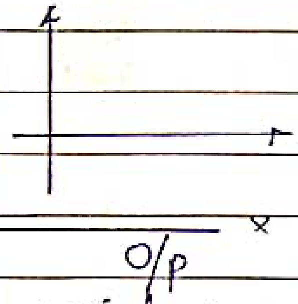
# Power Amplifiers / Large Signal Amplifiers

Power ~~amplifier~~ signals are used to provide power to an output load such as a speaker or a power device

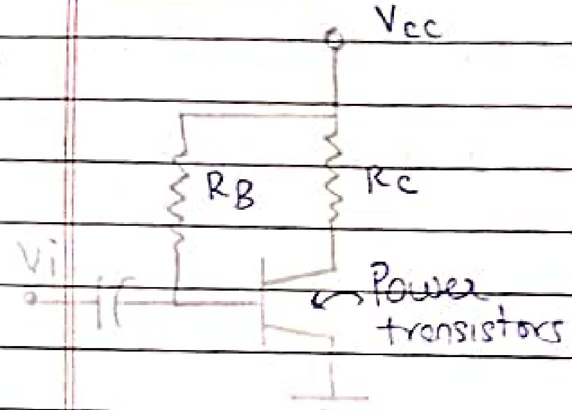
- Class A
- Class B
- Class AB

/ Class C & D Not in syllabus

Power amplifiers are categorized on the basis of the amount of output signal variation over 1 cycle of operation for a full cycle of input signal.

| | Class A | Class B | Class AB |
|---|---|---|---|
| |  |  |  |
| operating cycle | signal varies full 360° of the cycle | signal varies 180° of the cycle | signal varies 180° – 360° of the cycle |
| efficiency $\eta = \frac{P_o}{P_i}$ | 25% | 78.5% | 25% – 78.5% |

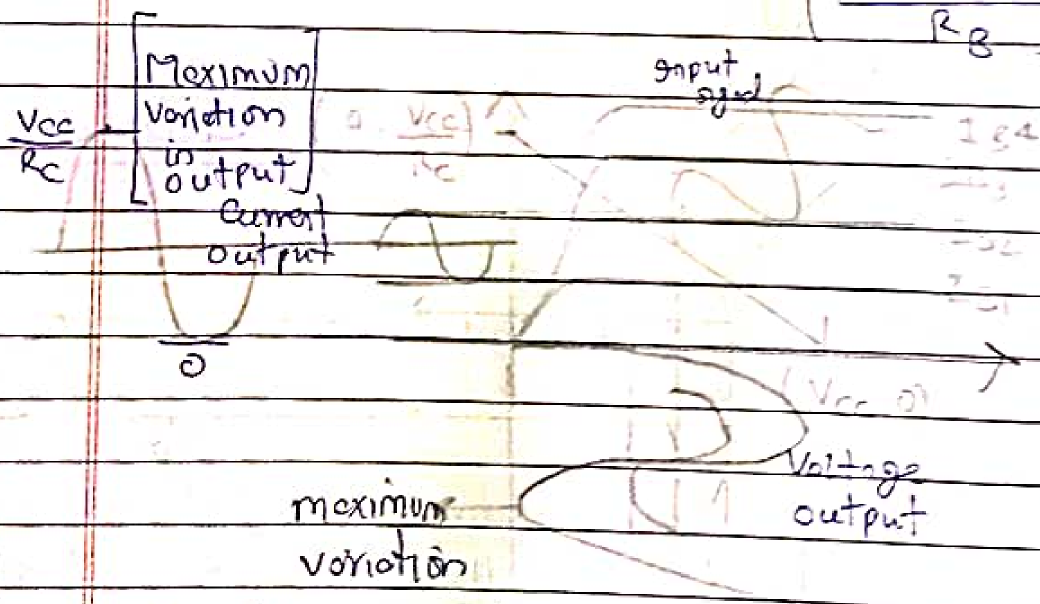
## Class A




$$I_B = \frac{V_{CC} - V_{BE}}{R_B}$$

$$I_{CQ} = \beta \cdot \left( \frac{V_{CC} - V_{BE}}{R_B} \right)$$

$$V_{CEQ} = V_{CC} - \beta \cdot R_C \left( \frac{V_{CC} - V_{BE}}{R_B} \right)$$




operating point is such that output conducts full cycle of the i/p.

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o/p current $\frac{V_{cc}}{R_C}$ to 0

o/p voltage $V_{cc}$ to 0.

$V_{cc} \times I_{cQ}$ = $P_{input}$ : $P_i$ (dc)

The output power ~~and~~ ~~th~~ is derived from the output voltage and current varying around the biased point.

$P_o = V_{rms} \times I_{rms}$

| Power output | RMS $V_{rms}$ | Peak $V_p$ | Peak to Peak $V_{pp}$ |
|---|---|---|---|
| $P_o$ (VI) | $V_{rms} I_{rms}$ | $\frac{V_p \cdot I_p}{2}$ | $\frac{V_{p-p} I_{p-p}}{8}$ |
| (I) | $I_{rms}^2 R_C$ | $\frac{I_p^2 R_C}{2}$ | $\frac{I_{p}^2 \times R_C}{8}$ |
| (V) | $\frac{V_{rms}^2}{R_C}$ | $\frac{V_p^2}{2R_C}$ | $\frac{V_{p-p}^2}{8R_C}$ |

<u>Maximum $\eta$</u> : Maximum $V_{CE}(p\text{-}p) = V_{cc}$

Maximum $I_c(p\text{-}p) = \frac{V_{cc}}{R_C}$

$P_o = V_{cc} \times \frac{V_{cc}}{R_C} \times \frac{1}{8}$

$$I_{cq} = \frac{V_{cc}}{R_c}$$

input power

Maximum efficiency : $P_i = V_{cc} \times \frac{V_{cc}}{2R_c}$

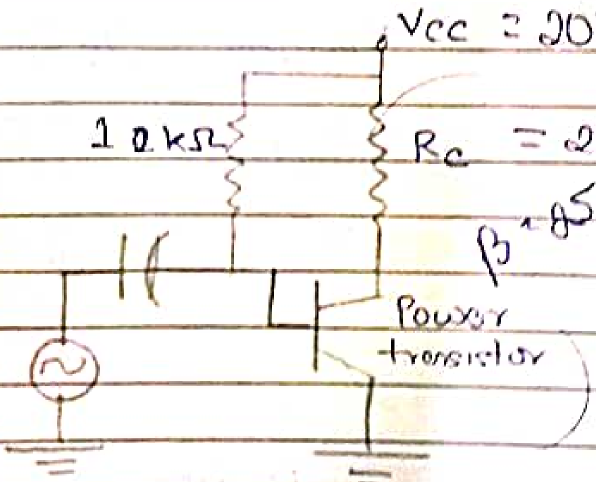
$$= \frac{V_{cc}^2}{2R}$$

$$\eta = \frac{P_o}{P_i}$$

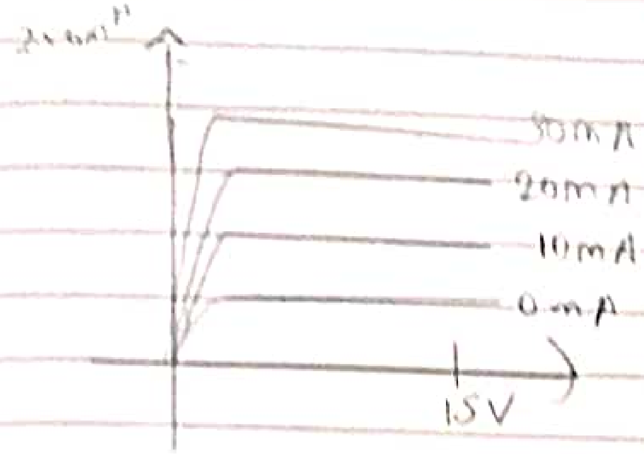
$$= \frac{\frac{V_{cc}^2}{8R_c}}{\frac{V_{cc}^2}{2R_c}} = \frac{1}{4} = 0.25$$

$$\boxed{\% \eta = 25\%}$$

<u>eg</u> :




Draw the DC load line and calculate the maximum efficiency. Calculate efficiency for a base current peak of 10 mA.

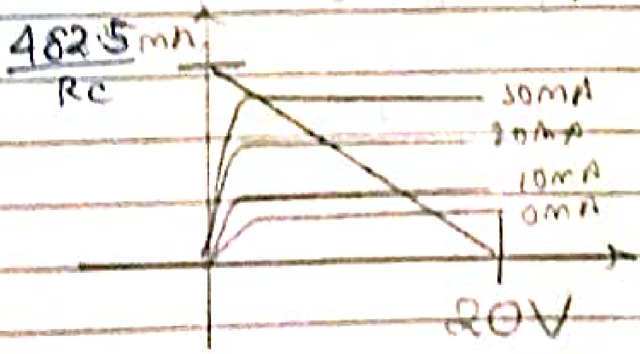



$I_C = \beta i_B$
$= 25 \times 10$
$= 250\,mA$
$V_{CEQ} = 15V$

$i_B = \dfrac{20 - 0.7}{1000 + 25 \times 20}$
$= \dfrac{19.3}{1000 + 500}$
$= \dfrac{19.3}{1500} = 0.0128\,mA$
$i_C = 0.321\,mA$
$V_{CE} = V_{CC} - i_C R_C$
$= 19.99$

$i_B = 0.0128\,mA$
$i_{CQ} = 0.321\,mA$
$V_{CEQ} = 19.$

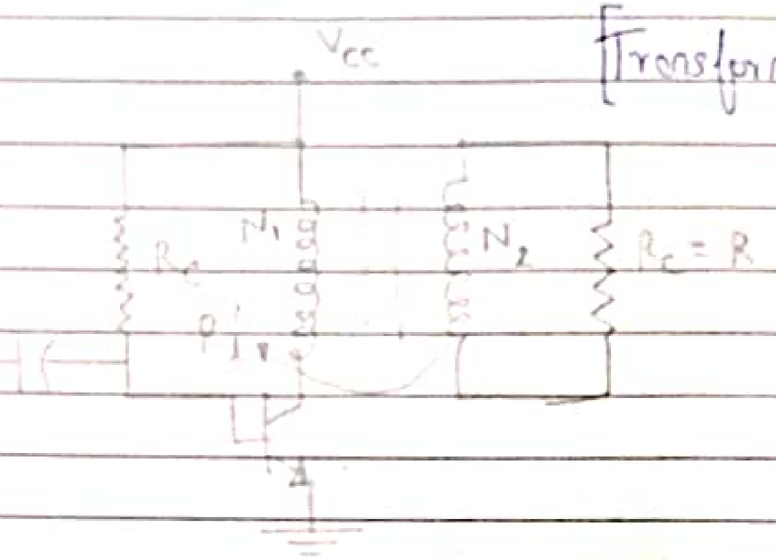
$i_B = 19.3\,mA$
$i_C = 482.5\,mA$
$V_{CEQ} = 10.35V$




$P_i = V_{CQ} \times I_{CQ}$
$= 9.6\,W$
$P_o = \dfrac{V_{p-p} \times I_{p-p}}{8} =$

eg.

[Transformer coupled class A amplifier]




$$\frac{V_1}{V_2} = \frac{I_2}{I_1} = \frac{N_1}{N_2}$$

$$R'_l = R_l \times \left(\frac{N_1}{N_2}\right)^2$$

eg. 15:1 Transformer. Calculate effective resistance seen from the primary side of a transformer (15:1) connected to a $8\,\Omega$ load.

$$R'_l = 8 \times (15)^2$$
$$= 1800\,\Omega$$
$$= 1.8\text{ K}$$