①

Obtaining of Transfer characteristic ($I_D - V_{GS}$) from Drain characteristic ($I_D - V_{DS}$) of FET

Let, us consider an example of FET with following specifications — (Fig-1.)

$I_{DSS} = 8\,mA$, $V_P = -4$ volt

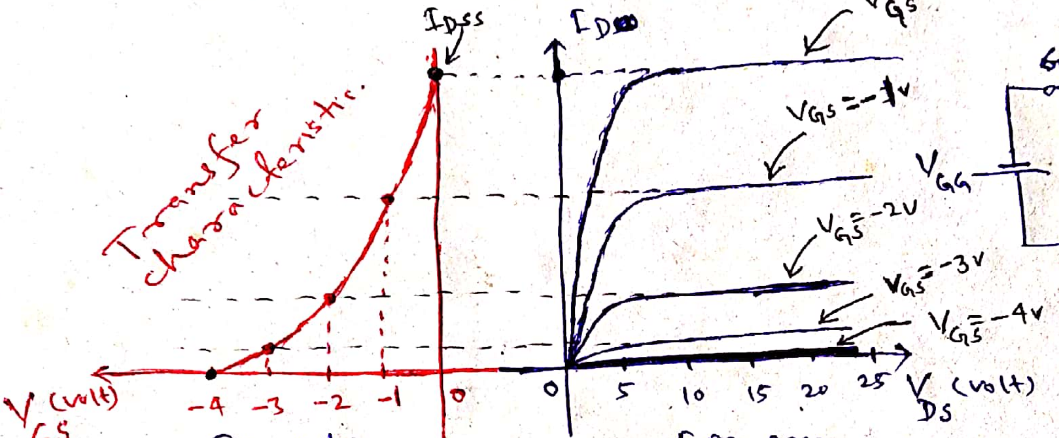


Fig-2(b)   Fig-2(a)

Fig-2

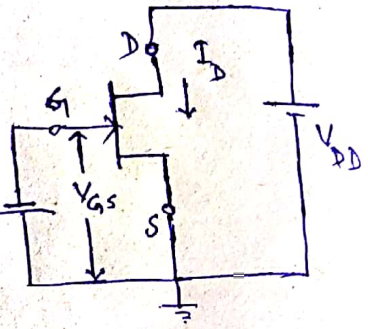


Fig-1.

From, ~~shock~~ shockley's eqⁿ — $I_D = I_{DSS}\left(1 - \frac{V_{GS}}{V_P}\right)^2$

When, $V_{GS} = 0v$; $I_D = I_{DSS}\left(1-\frac{0}{-4}\right)^2 = I_{DSS} \Rightarrow I_D = I_{DSS}\Big|_{V_{GS}=0} = 8\,mA$

When, $V_{GS} = -1v$, $I_D = 8\left(1-\frac{-1}{-4}\right)^2 = 8\times\left(\frac{3}{4}\right)^2 = 4.5\,mA \Rightarrow (V_{GS}, I_D) = (-1, 4.5)$

When, $V_{GS} = -2v$, $I_D = 8\left(1-\frac{-2}{-4}\right)^2 = 8\times\frac{1}{4} = 2\,mA \Rightarrow (V_{GS}, I_D) = (-2, 2)$

When, $V_{GS} = -3v$, $I_D = 8\left(1-\frac{-3}{4}\right)^2 = 8\times\frac{1}{16} = 0.5\,mA \Rightarrow (V_{GS}, I_D) = (-3, 0.5)$

When, $V_{GS} = -4v$, $I_D = 8\left(1-\frac{-4}{-4}\right) = 0\,mA \Rightarrow (V_{GS}, I_D) = (-4, 0)$

When, we plot I_D versus V_{GS}, we get a graph as shown in fig-2(b) which is called transfer characteristic of FET.

To draw in shorthand method, we can use —

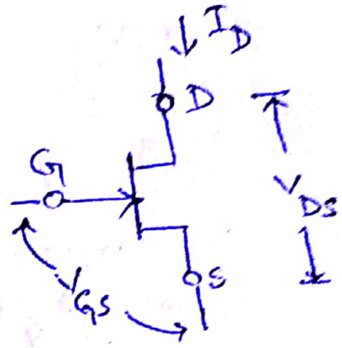
$V_{GS} = 0$,	$I_D = I_{DSS}$
$V_{GS} = 0.3V_P$	$I_D = I_{DSS}/2$
$V_{GS} = 0.5V_P$	$I_D = \frac{I_{DSS}}{4}$

$V_{GS} = V_P$, $I_D = 0$

FET Amplifier

②

Small signal Model. (OR AC equivalent ck)



We know that I_D is function of V_{DS} and V_{GS}

i.e

$$I_D = f(V_{GS}, V_{DS})$$

$$dI_D = \left(\frac{\partial f}{\partial V_{GS}}\right) dV_{GS} + \left(\frac{\partial f}{\partial V_{DS}}\right) dV_{DS}$$

or, $$\Delta I_D = \left(\frac{\Delta f}{\Delta V_{GS}}\right) V_{GS} + \left(\frac{\Delta f}{\Delta V_{DS}}\right) V_{DS}$$ [for small signal]

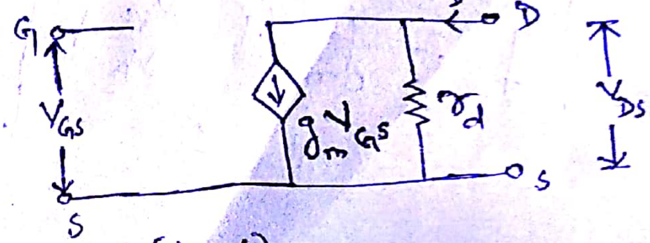
$$\Rightarrow \Delta I_D = \left(\frac{\Delta I_D}{\Delta V_{GS}}\right) V_{GS} + \left(\frac{\Delta I_D}{\Delta V_{DS}}\right) V_{DS}$$

$\because$ g_m = Transconductance = $\frac{\Delta I_D}{\Delta V_{GS}}$ and

r_d = Dynamic resistance = $\cancel{\frac{\Delta I_D}{\Delta V_{DS}}}$ $\frac{\Delta V_{DS}}{\Delta I_D} = r_d$

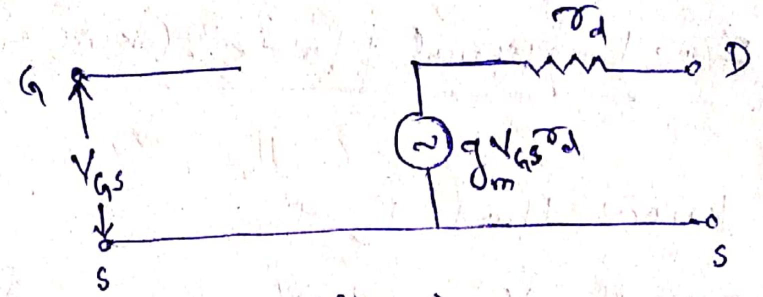
$$\therefore \boxed{\Delta I_D = g_m V_{GS} + \left(\frac{1}{r_d}\right) V_{DS}}$$

i.e Drain current or output current represents the sum of two currents as $g_m V_{GS}$ and $\frac{V_{DS}}{r_d}$. Hence a FET can be represents as a ckt model as below ——



(Fig-1)

(3) The ckt model as in fig-1 can be modeled as below —

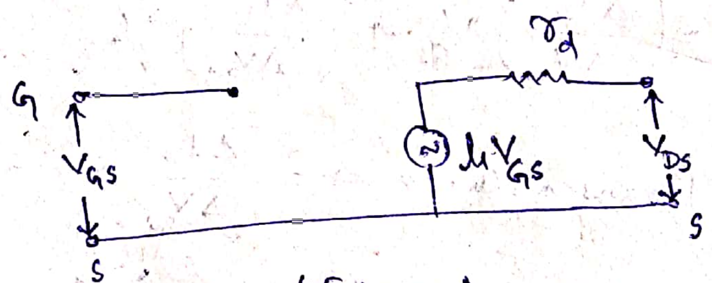


(Fig-2).

Since Amplification factor, $\mu = \frac{V_o}{V_{GS}} = \frac{I_D r_d}{V_{gs}}$

or $\boxed{\mu = g_m r_d}$

fig-(2) can be written as —



(Fig-3)

Now,

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

or, $\frac{dI_D}{dV_{GS}} = -\frac{2I_{DSS}}{V_P}\left(1 - \frac{V_{GS}}{V_P}\right) \Rightarrow g_m = -\frac{2I_{DSS}}{V_P}\left(1 - \frac{V_{GS}}{V_P}\right)$

When, $V_{GS} = 0$, then —

$$g_{mo} = -\frac{2I_{DSS}}{V_P}$$

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

Common source FET amplifier in Fixed bias Configuration (AC analysis)

(4)

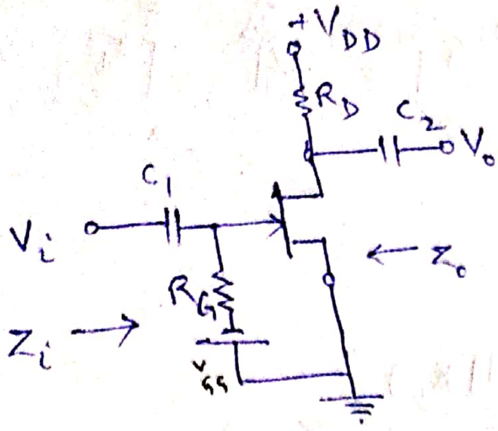


Fig-1.

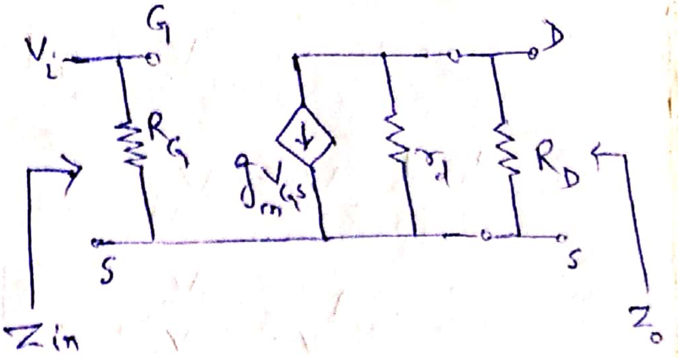


Fig-2

Above fig-1 represents common source FET amplifier. When, AC analysis is done, all capacitors as C_1, C_2 and various battery are assumed to be short circuited and the simplified equivalent ckt model is as shown in fig-2.

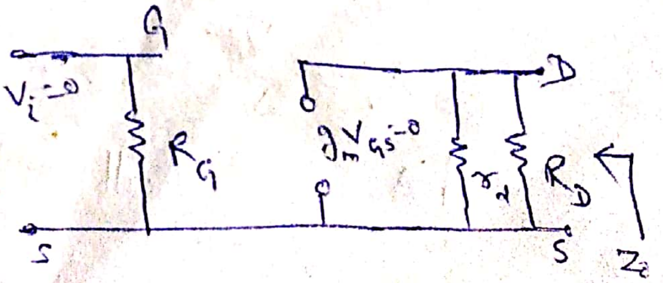
Input impedance (Z_i):- Since Gate to source is made in reverse bias, hence open-ckt equivalent impedance is given by —

$$\boxed{Z_{in} = R_G}$$

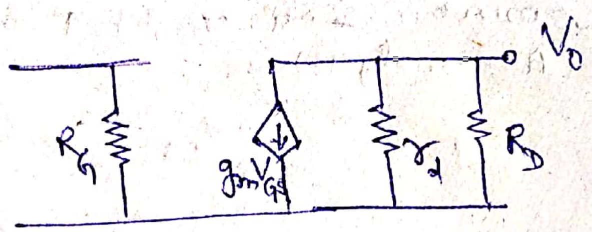
Output impedance (Z_o):- For calculating output impedance, we set, $V_i = 0$ which causes, $V_{GS} = 0$ and ckt is now as shown below —

$$\boxed{\therefore Z_o = R_D \| r_d}$$

If ~~R_d, R_D~~ $r_d \geq 10 R_D$ then $Z_o \simeq R_D$.



Voltage gain (A_v) :-



(5) $V_o = I_D Z_o = -g_m V_{GS} Z_o$

or, $V_o = -g_m V_{GS} (r_d || R_D)$

And, $V_{in} = V_{GS}$

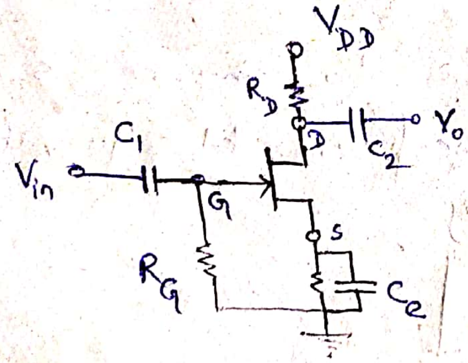
$$\therefore A_v = \frac{V_o}{V_{in}} = \frac{-g_m \cancel{V_{GS}} (r_d || R_D)}{\cancel{V_{GS}}}$$

$$\Rightarrow \boxed{A_v = -g_m (r_d || R_D)}$$

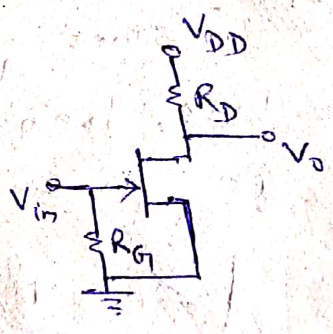
if $r_d \geq 10 R_D$

then, $\boxed{A_v = -g_m R_D}$

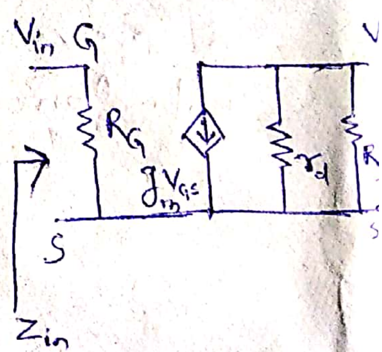
Common-source amplifier in self-bias configuration.



Self-bias conf.



A.c equivalent



$\boxed{Z_{in} = R_G}$

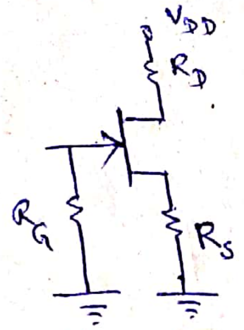
, $Z_o = r_d || R_D$

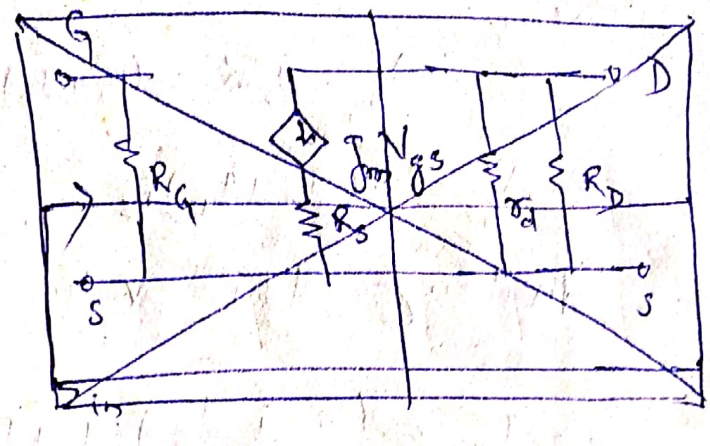
$$A_v = \frac{V_o}{V_{in}} = \frac{-g_m \cancel{V_{GS}} (r_d || R_D)}{\cancel{V_{GS}}} = -g_m (r_d || R_D)$$

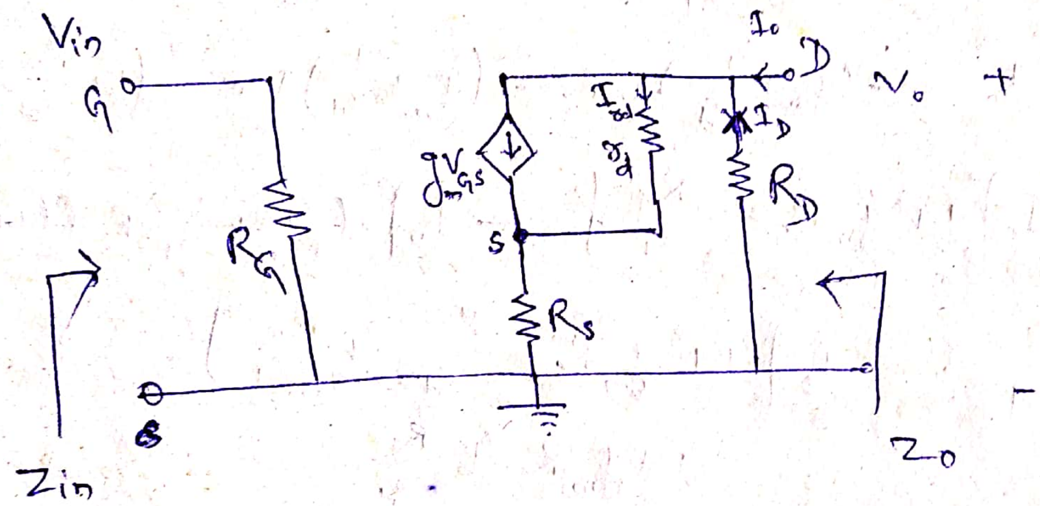
$\boxed{A_v = -g_m (r_d || R_D)}$, $\boxed{A_v = -g_m R_D}$, if $r_d \geq 10 R_D$

When, By-pass capacitor is removed —

(6)







Output impedance (Z_o)

$$Z_o = \frac{V_o}{I_o} = \frac{-I_D R_D}{I_o} \quad \text{———} \quad (1)$$

from output side —

$$I_o + I_D = g_m V_{GS} + I_{rd} \Rightarrow I_o = g_m V_{GS} + I_{rd} - I_D$$

or, $$I_o = g_m V_{GS} + \frac{V_o - V_{SG}}{r_d} - I_D \qquad [\because V_G \approx 0]$$

$$I_o = g_m V_{GS} + \frac{V_o + V_{GS}}{r_d} - I_D = g_m V_{GS} + \frac{V_o}{r_d} + \frac{V_{GS}}{r_d} - I_D$$

$$I_o = \left(g_m + 1/r_d\right) V_{GS} + \frac{V_o}{r_d} - I_D = \left(g_m + \frac{1}{r_d}\right) V_{GS} + \frac{-I_D R_D}{r_d} - I_D$$

or, $$I_o = \left(g_m + \frac{1}{r_d}\right) V_{GS} - \left(\frac{R_D}{r_d} + 1\right) I_D$$

7

or $I_o = \left(g_m + \frac{1}{r_d}\right) V_{GS} - \left(\frac{R_D}{r_d} + 1\right) I_D$ — (11)

Now,

$\because V_{SG} = I_S R_S = (I_o + I_D) R_S$

$\Rightarrow V_{GS} = -(I_o + I_D) R_S$

Putting this value in eq^n (11)

$\therefore I_o = -\left(g_m + \frac{1}{r_d}\right)(I_o + I_D) R_S - \left(\frac{R_D}{r_d} + 1\right) I_D$

or, $I_o = -\left(g_m + \frac{1}{r_d}\right) I_o R_S - \left(g_m + \frac{1}{r_d}\right) I_D R_S - \left(1 + \frac{R_D}{r_d}\right) I_D$

or, $I_o \left[1 + g_m R_S + \frac{R_S}{r_d}\right] = - I_D \left[\left(g_m + \frac{1}{r_d}\right) R_S + \left(1 + \frac{R_D}{r_d}\right)\right]$

or, $I_o = \dfrac{- I_D \left[1 + g_m R_S + \frac{R_S}{r_d} + \frac{R_D}{r_d}\right]}{1 + g_m R_S + \frac{R_S}{r_d}}$

$\therefore Z_o = -\dfrac{I_D R_D}{I_o} = \dfrac{-\cancel{I_D} R_D}{\dfrac{-\cancel{I_D}\left[1 + g_m R_S + \frac{R_S}{r_d} + \frac{R_D}{r_d}\right]}{1 + g_m R_S + \frac{R_S}{r_d}}}$

$$\boxed{Z_o = \left(\frac{1 + g_m R_S + \frac{R_S}{r_d}}{1 + g_m R_S + \frac{R_S}{r_d} + \frac{R_D}{r_d}}\right) R_D}$$

if $\left(1 + g_m R_S + \frac{R_S}{r_d}\right) >> \frac{R_D}{r_d}$ then

$Z_o = \dfrac{\cancel{\left(1 + g_m R_S + \frac{R_S}{r_d}\right)}}{\cancel{\left(1 + g_m R_S + \frac{R_S}{r_d}\right)}} \cdot R_D \approx R_D$

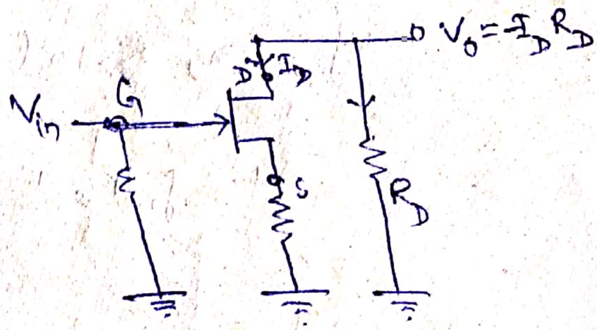
$\boxed{Z_o = R_D}$

Voltage gain (A_v)

8

$$A_v = \frac{V_o}{V_{in}} = \frac{-I_D R_D}{V_{in}} \quad \text{——— (111)}$$

$V_{in} = V_{GS} + V_{R_S} \Rightarrow V_{GS} = V_{in} - V_{R_S}$



from small signal model —

$$I_D = g_m V_{GS} + \left(\frac{1}{r_d}\right) V_{DS}$$

or, $I_D = g_m V_{GS} + \frac{1}{r_d}(V_o - V_{R_S}) = g_m V_{GS} + \frac{-I_D R_D - I_D R_S}{r_d}$

Putting $V_{GS} = V_{in} - V_{R_S}$, we get —

$$I_D = g_m(V_{in} - V_{R_S}) - \frac{I_D R_D + I_D R_S}{r_d}$$

$$= g_m V_{in} - g_m I_D R_S - \frac{I_D(R_D + R_S)}{r_d}$$

$$= g_m V_{in} - I_D\left(g_m R_S + \frac{R_D + R_S}{r_d}\right)$$

or, $I_D\left(1 + g_m R_S + \frac{R_D + R_S}{r_d}\right) = g_m V_{in}$

or, $I_D = \dfrac{g_m V_{in}}{1 + g_m R_S + \frac{R_D + R_S}{r_d}}$

Putting the value of I_D into eqn (111)

$$A_v = -\frac{R_D}{\cancel{V_{in}}} \cdot \frac{g_m \cancel{V_{in}}}{1 + g_m R_S + \frac{R_D + R_S}{r_d}} = -\frac{g_m R_D}{1 + g_m R_S + \frac{R_D + R_S}{r_d}}$$

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⑨ $\therefore A_v = -\dfrac{g_m R_D}{1 + g_m R_S + \dfrac{R_D + R_S}{r_d}}$

if $r_d \gg 10(R_D + R_S)$ then

$$1 + g_m R_S + \frac{R_D + R_S}{r_d} \approx 1 + g_m R_S$$

$$\therefore \boxed{A_v = -\frac{g_m R_D}{1 + g_m R_S}}$$

Common-source amplifier in voltage-divider biased.

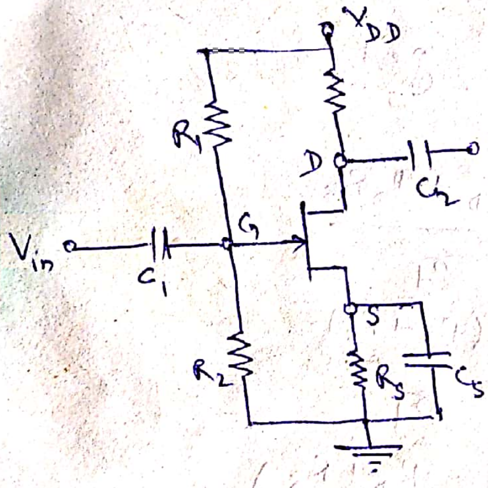


Fig-1.

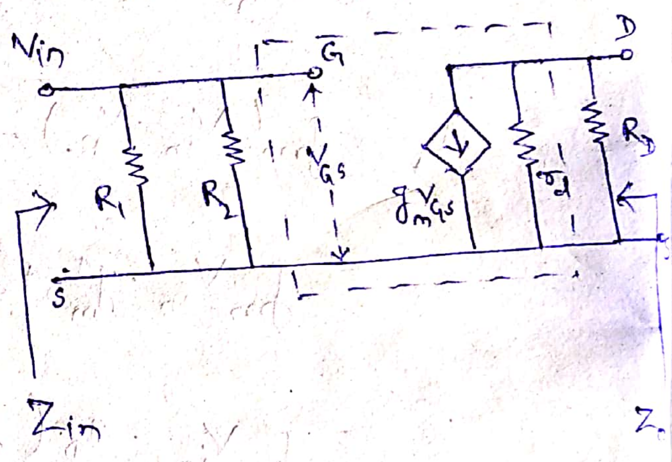


Fig-2

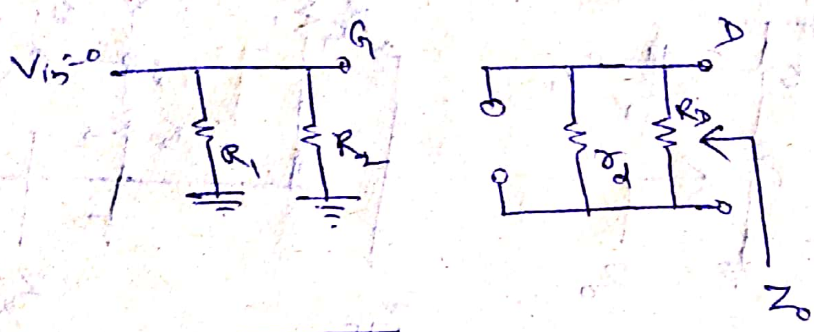
Fig-1. represents FET amplifier in voltage divider biasing configuration. Figure-② represent its equivalent a.c model by shorting all d.c components.

Input impedance (Z_{in})

$$\boxed{Z_{in} = R_1 \| R_2}$$

Output impedance (Z_o) :-

(10) For calculating output impedance, we set input as $V_{in} = 0$. that causes V_{GS} to 0. Thus, simplified ckt is ——



$$\boxed{Z_o = r_d \parallel R_D}$$

if $r_d >> 10 R_D$ then $\boxed{Z_o \approx R_D}$

Voltage gain (A_v) :-

$$A_v = \frac{V_o}{V_{in}} = \frac{-I_D Z_o}{V_{GS}}$$

or, $$A_v = \frac{-g_m \cancel{V_{GS}} (r_d \parallel R_D)}{\cancel{V_{GS}}} = -g_m (r_d \parallel R_D)$$

$$\therefore \boxed{A_v = -g_m (r_d \parallel R_D)}$$

if $r_d >> 10 R_D$ then —

$$\boxed{A_v = -g_m R_D}$$

Common-Drain (Source follower) amplifier.

(1)

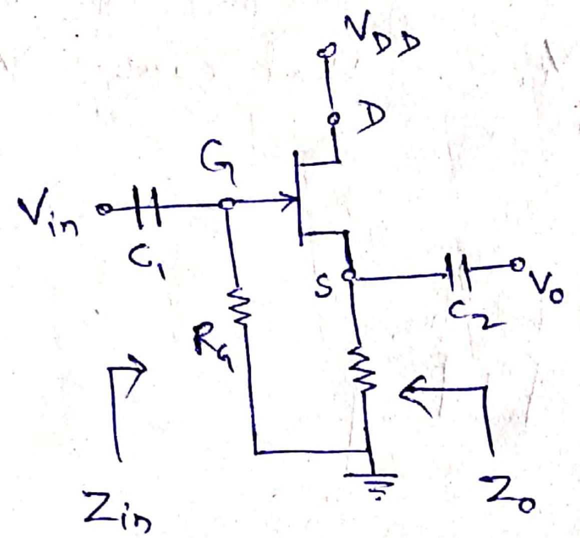


Fig – 1.

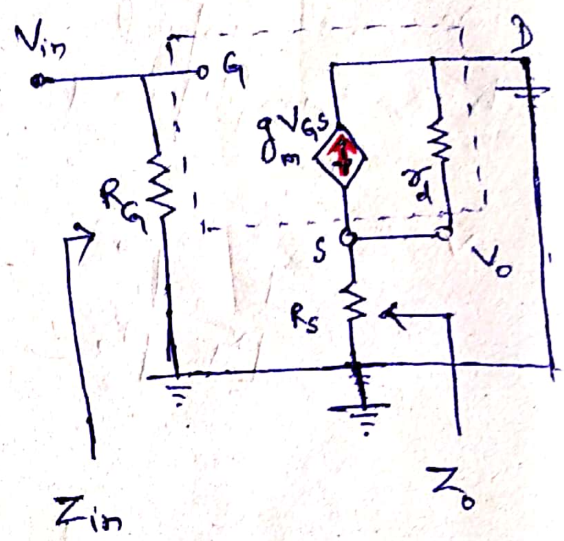


Fig-2. A.C equivalent model.

Input impedance (Z_{in})

$$\boxed{Z_{in} = R_G}$$

Output impedance (Z_o) :-

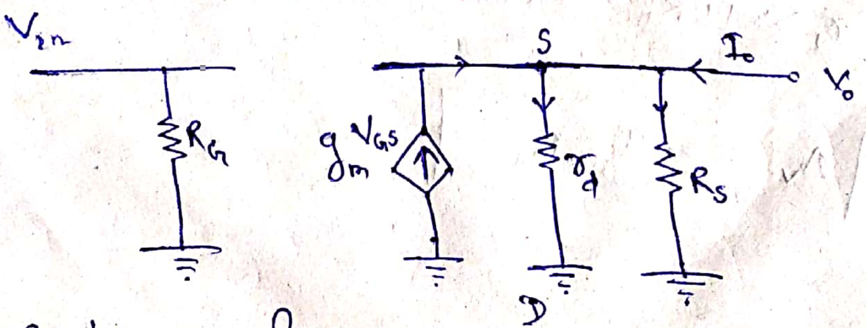
$$Z_o = \frac{V_o}{I_o}$$

Here $V_o = V_{R_s} = V_{SG} = -V_{GS}$

$\Rightarrow V_o = -V_{GS}$ —— (1)

[This is the fact due to which current source is reversed]

Now, ckt as in fig-(2) can be modeled as below–



Applying KCL at S —

$$I_o + g_m V_{GS} = I_{rd} + I_{R_s}$$

or, $I_o + g_m V_{GS} = \frac{V_o}{r_d} + \frac{V_o}{R_s}$

or, $I_o = V_o\left(\frac{1}{r_d} + \frac{1}{R_s}\right) - g_m V_{GS}$

Putting value of V_{GS} from eqn 1

$$I_o = V_o\left(\frac{1}{r_d} + \frac{1}{R_s}\right) - g_m(-V_o) = V_o\left[\frac{1}{r_d} + \frac{1}{R_s} + g_m\right]$$

$$\therefore \frac{V_o}{I_o} = \frac{\cancel{V_o}}{\cancel{V_o}\left(\frac{1}{r_d} + \frac{1}{R_s} + g_m\right)} = \frac{1}{\frac{1}{r_d} + g_m + \frac{1}{R_s}}$$

$$\Rightarrow \boxed{Z_o = \frac{1}{\frac{1}{r_d} + \frac{1}{(1/g_m)} + \frac{1}{R_s}}}$$

$$\Rightarrow \boxed{Z_o = r_d \| R_s \| 1/g_m}$$

if $r_d >> 10R_s$ then, $\boxed{Z_o = R_s \| 1/g_m}$

$$\boxed{Z_o = \frac{1}{g_m + 1/R_s}} = \frac{R_s}{1 + g_m R_s}$$

Voltage gain (A_V) :-

$V_{in} = V_{GS} + V_{R_s} \Rightarrow V_{in} = V_{GS} + V_o$

or, $V_o = V_{in} - V_{GS}$ —— ⊕ $\Rightarrow V_{GS} = V_{in} - V_o$

But, $V_o = (g_m V_{GS})(r_d \| R_s) = g_m(V_{in} - V_o)(r_d \| R_s)$

or, $V_o[1 + g_m(r_d \| R_s)] = g_m V_{in}(r_d \| R_s) \Rightarrow \frac{V_o}{V_{in}} = \frac{g_m(r_d \| R_s)}{1 + g_m(r_d \| R_s)}$

$$\Rightarrow \boxed{A_V = \frac{g_m(r_d \| R_s)}{1 + g_m(r_d \| R_s)}} \Rightarrow \boxed{A_V = \frac{g_m R_s}{1 + g_m R_s}} \text{ if } r_d >> 10R_s$$