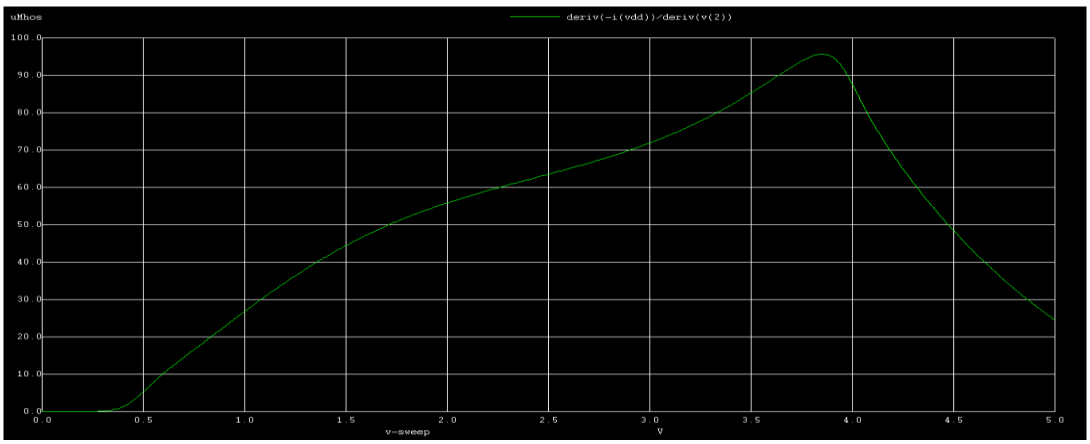
1.

a),b)

```

.include NMOS.txt
M1 3 2 0 0 CMOSN W=1u
R1 2 1 470
VDD 3 0 DC 5v
VIN 1 0 DC 0v
.dc VIN 0 5 0.01
.control
run
plot -i(VDD)
plot deriv(-i(VDD))/deriv(v(2))
.endc
.end
```

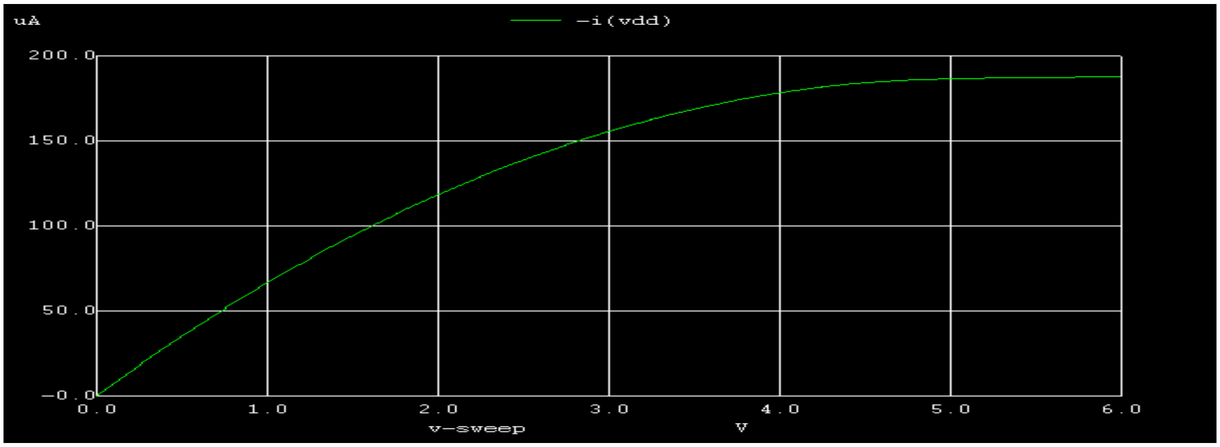


The peak transconductance (g_m) for the MOSFET at V_{DS} = 5 V was found to be 95.66 μS and corresponding Vgs was 3.85V.

c)

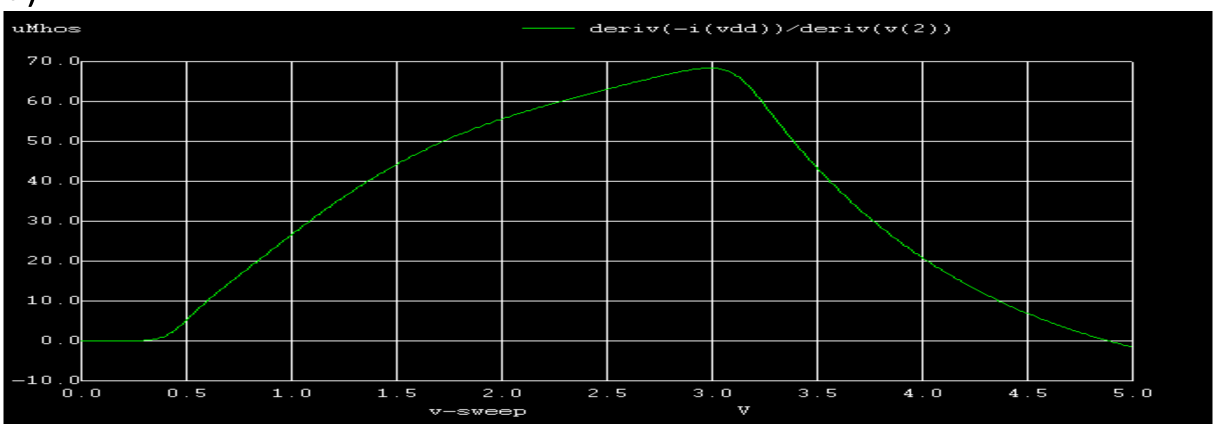
```

.include NMOS.txt
M1 3 2 0 0 CMOSN W=1u
VDD 3 0 DC 0v
VGS 2 0 DC 3.85v
.dc VDD 0 6 0.01
.control
run
plot -i(VDD)
.endc
.end
```

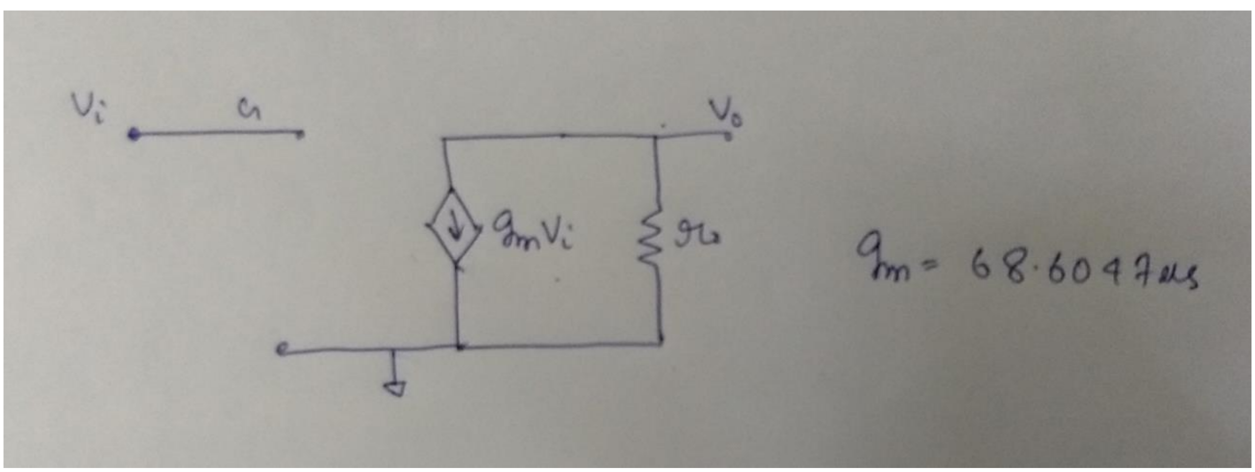


Output impedance is 0.2282 Mohm (reciprocal of slope from saturation region).

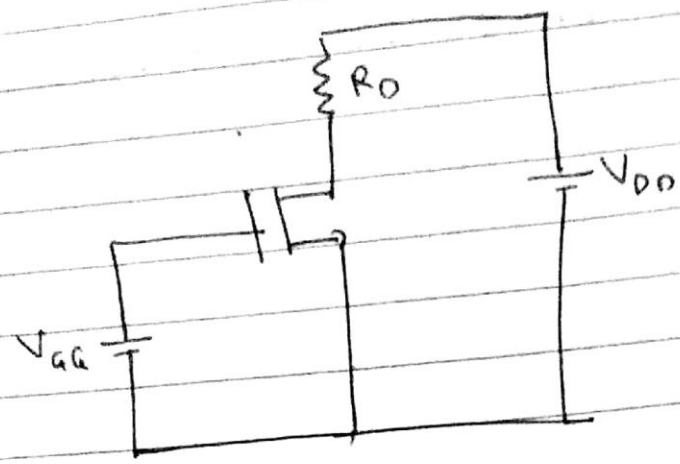
d)



Peak transconductance (g_m) for the MOSFET at V_{DS} = 3 V is 68.6047 µS (Vgs=3V)



e)

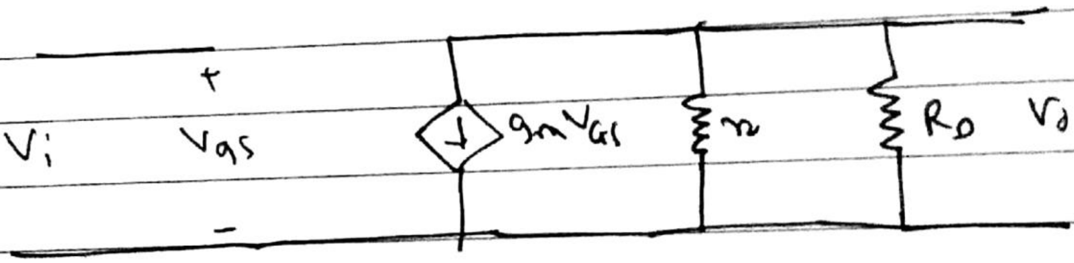


From spice simulation

$g_m = 95.66\ \mu\Omega^{-1}$ $I_D = 0.186\ mA$

$r_o = 0.22826 M\Omega$ $V_{gs} = 3.85V$

Small signal equivalen ckt



Designed gain = $A_V = 2$

$$g_m (r_o \| R_D) = 2$$

$$95.66 M\Omega^{-1} (r_o \| R_D) M\Omega = 2$$

$$(r_o \| R_D) = 0.021$$

$$r_o R_D = 0.021 r_o + 0.021 R_D$$

$$(r_o - 0.021) R_D = 0.021 r_o$$

$$R_D = \frac{0.021 r_o}{r_o - 0.021}$$

$R_D = 0.0231\ M\Omega$

Output impedance

with $R_D = (r_o \| R_D) = 0.021 M\Omega$

without $R_D = r_o = 0.22826 M\Omega$

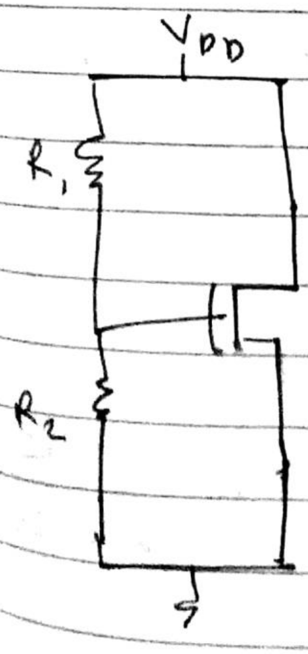
$V_{gg} = V_{gs} = 3.85V$

$V_{DD} = V_{DS} + I_D R_D$

$= 5 + 0.186\ mA \times 0.0231\ M\Omega$

$V_{DD} = 5.8V$

2)



For gain = 2 $V_{DS} = V_{DD} = 5V$

$V_{gs} = 3.85$

$$\frac{R_2}{R_1 + R_2} \times \overset{5}{\cancel{V_{gs}}} = 3.85$$

let $R_2 = 10K$ R1=2.987K

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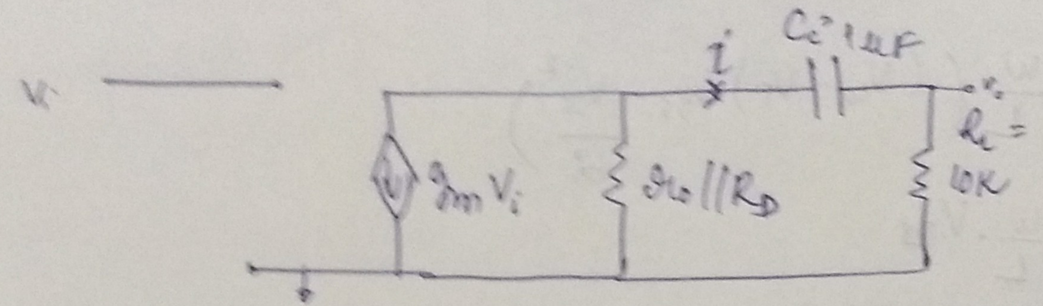
9)



$r_o \| R_D = 0.0231\,M\Omega \,\|\, 0.22826\,M\Omega$
$= 0.020977\,M\Omega$

$$i = -g_m V_i \frac{r_o \| R_D}{r_o \| R_D + \frac{1}{C_L s} + R_L}$$

$$= -\frac{g_m V_i (r_o \| R_D) C_L s}{1 + (r_o \| R_D + R_L) C_L s}$$

$V_o = i R_L$

$$A_v = -\frac{g_m R_L (r_o \| R_D) C_L s}{1 + (r_o \| R_D + R_L) C_L s}$$

$$= -\frac{95.66 \times 10^{-6} \times 0.020977 \times 10^{6} \times 10^{-6} s \times 10K}{1 + (30.977 \times 10^{3}) 10^{-6} s}$$

$$= -\frac{2.067 \times 10^{-2} s}{1 + 0.030977 s}$$

A_v @ 1MHz,

$$|A_v| = \frac{2.067 \times 10^{-2} \times 2\pi \times 10^{6}}{\sqrt{1 + (0.030977 \times 10^{6} \times 2\pi)^2}}$$

$$\simeq \frac{2.067 \times 10^{-2}}{3.0977 \times 10^{-2}}$$

$$\simeq 0.667269$$

A_v @ $1\,mHz$

$$|A_v| = \frac{2.067 \times 10^{-2} \times 2\pi \times 10^{-3}}{\sqrt{1 + (0.030977 \times 10^{-3} \times 2\pi)^2}}$$

$$\simeq 1.2987 \times 10^{-4}$$

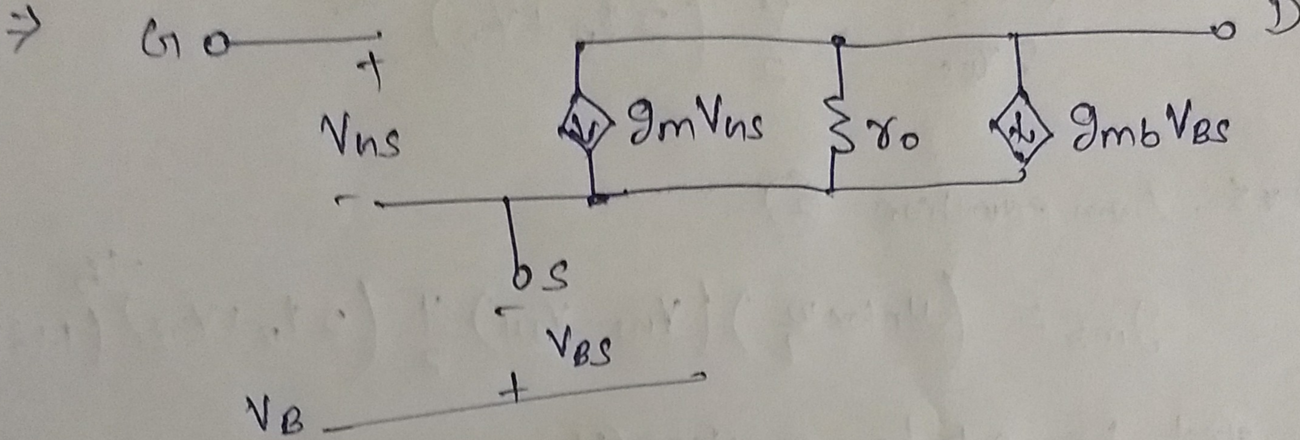
Q. No. 2

Ans when $V_{BS} \neq 0$ then

Small signal equivalent circuit is given below on current

$$I_{DS} = \frac{1}{2} \mu_n C_{ox} \frac{W}{L} (V_{GS} - V_{TH})^2 (1 + \lambda V_{DS}) \quad \text{--- (1)}$$

⇒



$$\Rightarrow \text{where } r_o = \left(\frac{\partial I_D}{\partial V_{DS}}\right)^{-1} = \frac{1}{\frac{1}{2} \mu_n C_{ox} \frac{W}{L} (V_{GS} - V_{TH})^2 \lambda}$$

$$\boxed{r_o \simeq \frac{1}{\lambda I_D}}$$

and $$g_m = \left.\frac{\partial I_D}{\partial V_{GS}}\right|_{V_{DS} = \text{constant}}$$

(trans conductance) $$\boxed{g_m = \mu_n C_{ox} \frac{W}{L} (V_{GS} - V_{TH})(1 + \lambda V_{DS})}$$ (from equation (1))

and $$g_{mb} = \frac{\partial I_D}{\partial V_{BS}} = \mu_n C_{ox} \frac{W}{L} (V_{GS} - V_{TH}) \left(-\frac{\partial V_{TH}}{\partial V_{BS}}\right)(1 + \lambda V_{DS}) \quad \text{--- (2)}$$

⇒ Also given $V_{TH} = V_{TO} + \gamma\left(\sqrt{2\phi_B + V_{SB}} - \sqrt{2\phi_B}\right)$

then $\frac{\partial V_{TH}}{\partial V_{SB}} = \frac{\gamma}{2}\left(2\phi_B + V_{SB}\right)^{-1/2}$

we can write $\frac{\partial V_{TH}}{\partial V_{SB}} = -\frac{\partial V_{TH}}{\partial V_{BS}}$

Hence $\frac{\partial V_{TH}}{\partial V_{BS}} = -\frac{\gamma}{2}\left(2\phi_B + V_{SB}\right)^{-1/2}$

thus, from equation (2)

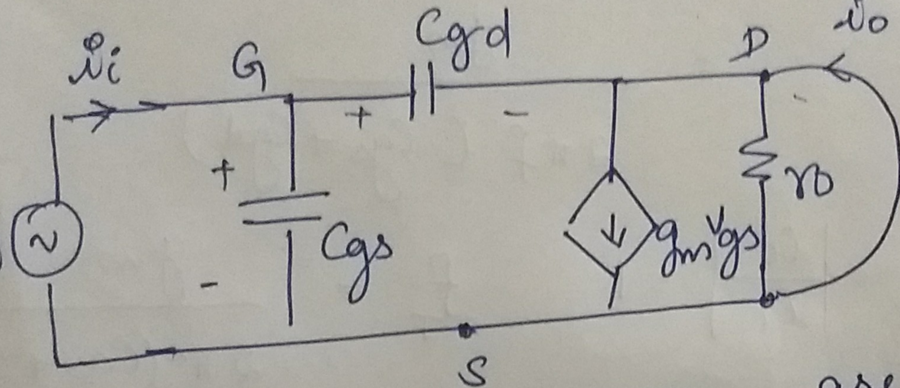
$$g_{mb} = \left(\mu_n C_{ox}\frac{W}{L}\right)\left(V_{GS} - V_{TH}\right)\frac{\gamma}{2}\left(2\phi_B + V_{SB}\right)^{-1/2}\left(1+\lambda V_{DS}\right)$$

~~and fror put from equation (1)~~

and from equation of $g_m = \mu_n C_{ox}\frac{W}{L}\left(V_{GS} - V_{TH}\right)\left(1+\lambda V_{DS}\right)$

Hence $\boxed{g_{mb} = \frac{g_m \cdot \gamma}{2\sqrt{2\phi_B + V_{SB}}}}$

3. The small signal equivalent model of MOSFET when o/p terminal is shorted to ground is shown below



Since drain and source are shorted

$$v_{gd} = v_{gs} = v_i$$

∴ The input current

$$i_i = j\omega(C_{gs} + C_{gd})\, v_{gs}$$

The ouput current

$$i_o = g_m v_{gs} - j\omega C_{gd} v_{gs}.$$

The short circuit current gain

$$\frac{i_o}{i_i} = \frac{g_m - j\omega C_{gd}}{j\omega(C_{gs} + C_{gd})}$$

~~Since C_{gd} is very small~~ $\approx \dfrac{g_m}{j\omega(C_{gs} + C_{gd})}.$

$$\left|\frac{i_o}{i_i}\right| = \frac{g_m}{\omega\,(C_{gs} + C_{gd})}$$

$$= \frac{g_m}{2\pi f\,(C_{gs} + C_{gd})}$$

when $\left|\frac{i_o}{i_i}\right| = 1$ $\quad f_T = \frac{g_m}{2\pi\,(C_{gs} + C_{gd})}$.

when $C_{gs} = 1nF$ & $C_{gd} = 0$

$$f_{T1} = \frac{g_m}{2\pi\,C_{gs}} = \frac{g_m}{2\pi} \times GHz$$

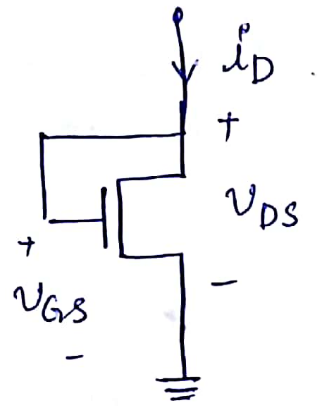
$$= 15.2247\ KHz$$

when $C_{gs} = 1nF$ & $C_{gd} = 0.2nF$

$$f_{T2} = \frac{g_m}{2\pi\,(C_{gs} + C_{gd})} = \frac{g_m}{2.4\pi}\ GHz$$

$$= 12.6873\ KHz$$

Q.4) When the MOSFET has the gate connected to the drain, it acts like a diode with characteristics similar to a pn junction diode



$V_{GS} = V_{DS}$, MOSFET is in saturation.

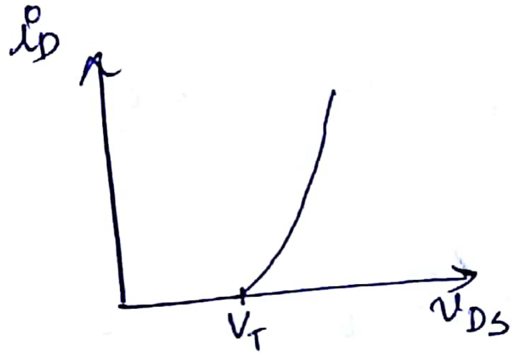
$$i_D = \frac{\mu_n C_{ox} W}{2L} (V_{GS} - V_T)^2$$

$$= \frac{\mu_n C_{ox} W}{2L} (V_{DS} - V_T)^2$$

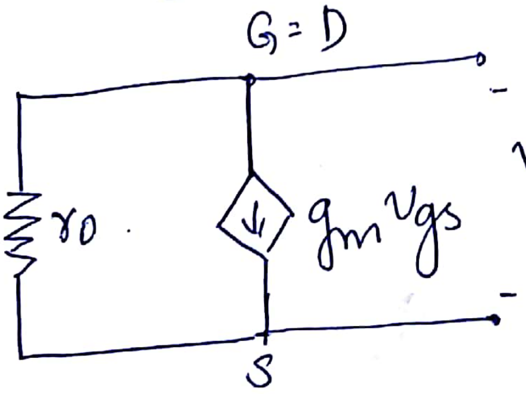
$$= \frac{\beta}{2} (V_{DS} - V_T)^2.$$

$$V_{DS} = V_{GS} = V_T + \sqrt{\frac{2 i_D}{\beta}}$$

where $\beta = \mu_n C_{ox} \frac{W}{L}$.



The small signal equivalent circuit model (excluding capacitor & bulk and source are at same potential)

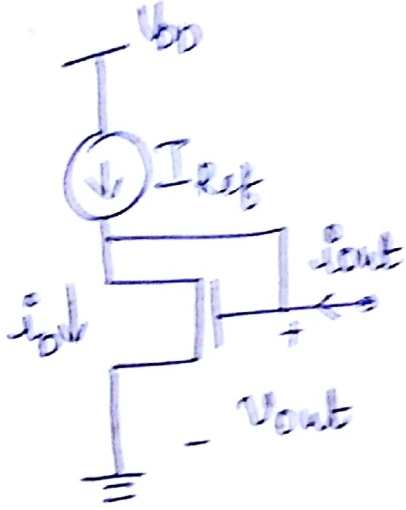


The output resistance $R_{out} = \frac{1}{g_m} \parallel r_o$

$$\approx \frac{1}{g_m}.$$

1. How to synthesize a voltage source with the

Assume a current source is available



$V_{GS} = V_{DS}$ take a value needed to sink the current.

$$i_D = i_{out} + I_{Ref} = \frac{\beta}{2}(V_{out} - V_T)^2$$

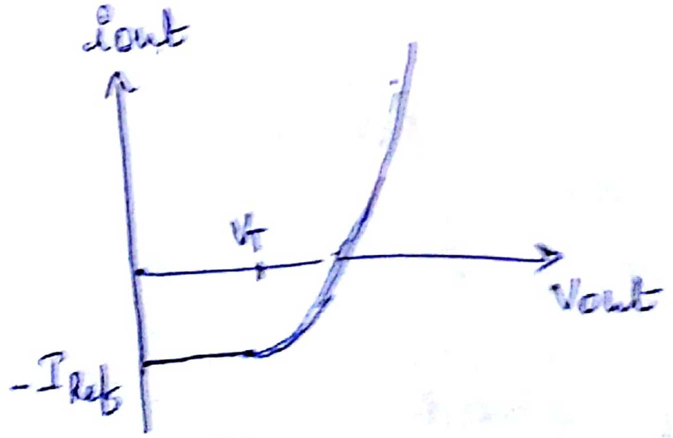
$$\therefore \quad V_{out} = V_T + \sqrt{\frac{I_{Ref} + i_{out}}{\beta/2}}.$$

where $\beta = \mu_n C_{ox} \frac{W}{L}$

V_{out} is a function of I_{Ref} & W/L.

$I_{Ref} \uparrow \Rightarrow V_{out} \uparrow$

$W/L \uparrow \Rightarrow V_{out} \downarrow$.



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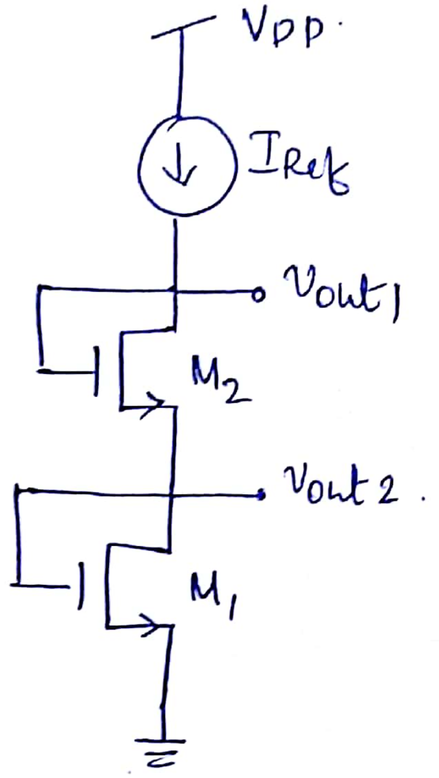
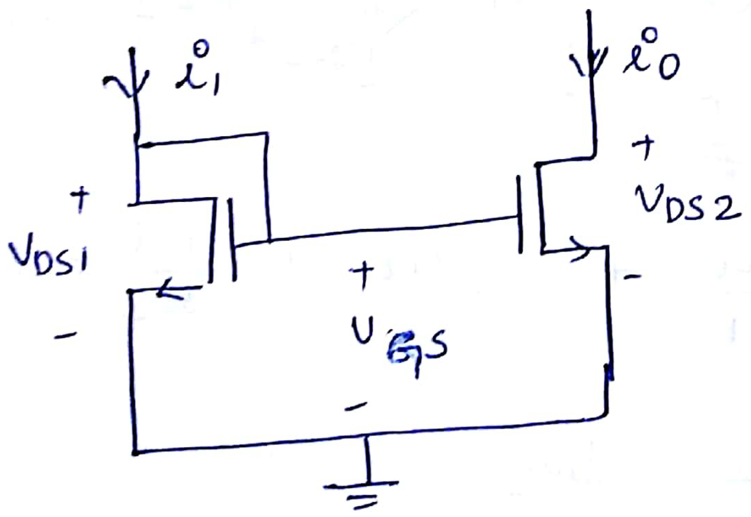
2. Voltage divider network using diode connected MOSFET (active resistor)

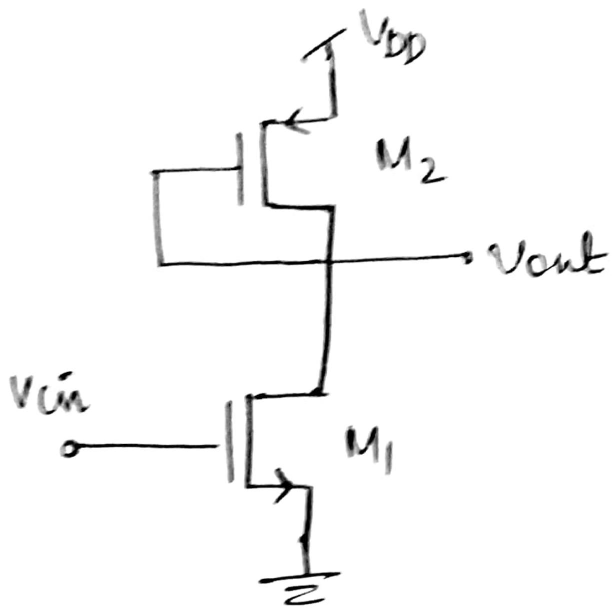


3. The MOS diode is used as a component of a current mirrors



$$\frac{i_0}{i_1} = \frac{\beta_2}{\beta_1} \frac{(V_{GS} - V_{T1})^2}{(V_{GS} - V_{T2})^2} \quad \frac{1 + \lambda V_{DS2}}{1 + \lambda V_{DS1}}$$

5. nmos inverter with active pmos load



$$\frac{V_{out}}{V_{in}} \approx -\frac{g_{m1}}{g_{m2}}$$

$$R_{out} \approx \frac{1}{g_{m2}}.$$

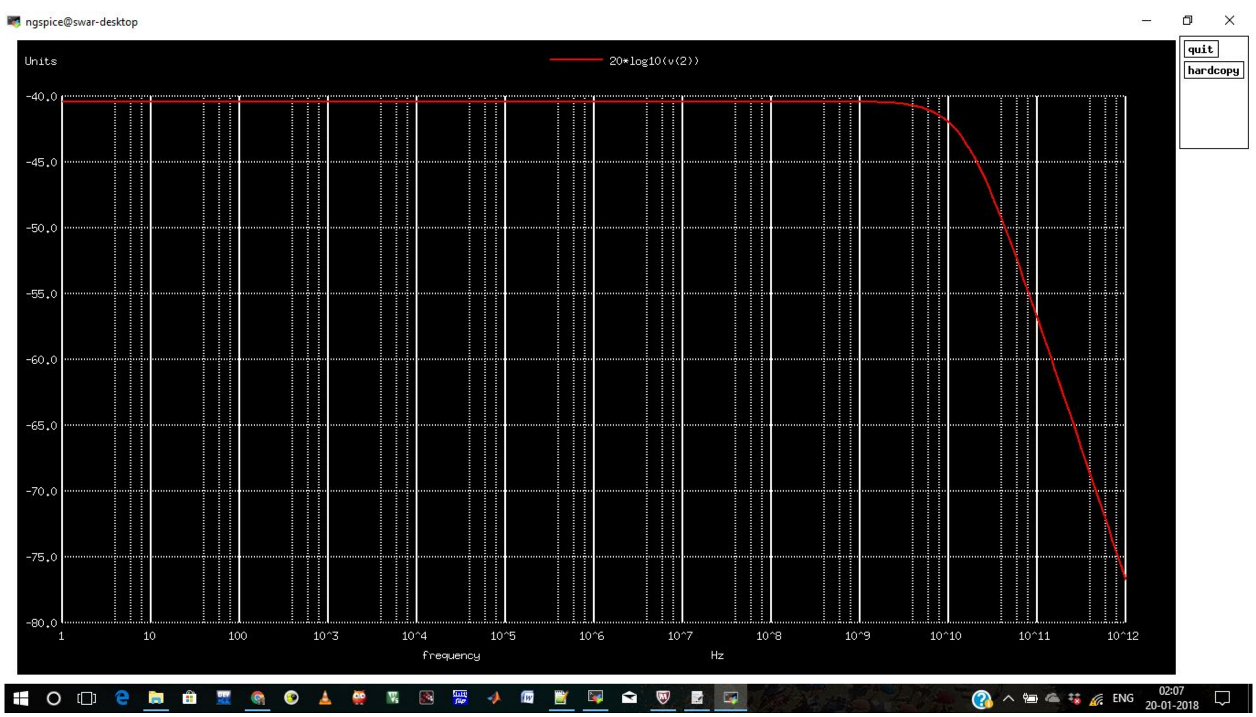
Q5.

For calculating Cgd..

Ngspice code:

```
*Compute unity current gain frequency
.include tsmc.txt
M1 2 1 0 0 CMOSN W=1u
RD 2 6 10k
VDD 6 5 DC 10v
VGG 1 0 DC 4.5V
V0 5 0 AC 0.01

*defining the run-time control functions
.AC DEC 20 1 1000Gig
.control
run
plot 20*log10(V(2))
.endc
.en
```



$$f_T = \frac{1}{2\pi C_{gd} * R_d}$$

Here, f_T corresponds to the point where amplitude is 3dB below the highest.
From Figure above $f_T = 15.7\ GHz$
Putting $R_D = 10k\Omega$ we get $C_{gd} =$ 0.001pF

For Calculating Cgs ..

```
*Compute unity current gain frequency
.include tsmc.txt
M1 2 1 0 0 CMOSN W=1u
RD 2 6 40k
VDD 6 0 DC 40v
VGG 1 3 DC 3.8V
*Vin 3 0 AC 0.01 sin(0 0.1 0.5Gig)
Vin 3 0 AC 0.01
C0 2 4 1
R0 4 5 0
V0 5 0 0

*defining the run-time control functions
.AC DEC 20 10Meg 1Gig
*.tran 0.005m 0.4m
.control

run
plot (log10(I(V0))-log10(I(Vin)))

.endc
.end
```

$$f_T = \frac{g_m}{2\pi(C_{gs}+C_{gd})}$$

Here, f_T corresponds to the point where current gain is unity.

From Figure above $f_T = 0.49\ GHz$

Putting $g_m = 95.66\ \mu S$ we get $C_{gs} = 0.031pF - C_{gd} = 0.030pF$