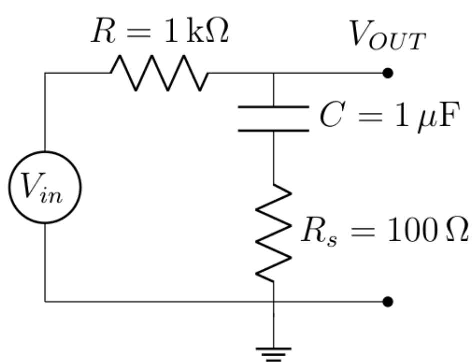
EE3113 Homework Assignment-1

Krishna Srikar Durbha

EE18BTECH11014

Note: Mathematical Explanations for some of the questions are at the end.

1 Spice Analysis



1.1 1a

When V_{in} is a DC Source, Capacitor charges exponentially and at infinite time Voltage across Capacitor is V_{in}. Solving using Kirchhoff's Law and by Assuming initial charge on Capacitor is Zero and $V_{in} = 2.5$ Volts.

$$I(t) = \frac{V_{in}}{R + R_s} e^{\frac{-t}{(R+R_s)C}} \tag{1}$$

$$V_{out} = V_{in} - \frac{V_{in}R}{R + R_s} e^{\frac{-t}{(R+R_s)C}} \tag{2}$$

SPICE Netlist:

```
Question-1a

* Circuit
Vin     Vin     0       DC      2.5
R       Vin     Vout    1k
C       Vout    1       1u
Rs      1       0       100

* Analysis
.op

* Results
.control
run
print all
.endc

.end
```

The results on Simulation are

$$V_{out} = 2.5 \text{ Volts} \tag{3}$$

1.2 1b

$V_{in} = \sin(\omega_0 t)$ where $\omega_0 = 2\pi \times 100$ rad/sec and $\omega_0 = 2\pi \times 1M$ rad/sec. V_{out} varies with ω_0.

$$\frac{V_{\text{out}}}{V_{\text{in}}} = \frac{R_S C j\omega_0 + 1}{C(R_s + R)j\omega_0 + 1} \tag{4}$$

$$V_{out} = \sqrt{\left(\frac{1 + (CR_s\omega_0)^2}{1 + (C\omega_0(R + R_s))^2}\right)} \sin\left(\omega_0 t + \tan^{-1}(R_s C\omega_0) - \tan^{-1}((R_s + R)C\omega_0)\right). \tag{5}$$

1.2.1 For $\omega_0 = 2\pi \times 100$ rad/sec

SPICE Netlist:

```
Question-1b_1

* Circuit
Vin     Vin     0       AC      1       SIN     0       1       100
R       Vin     Vout    1k
C       Vout    1       1u
Rs      1       0       100

* Analysis
.tran 1u 0.05

* Results
.control
run
plot Vin Vout
.endc

.end
```

Graph:

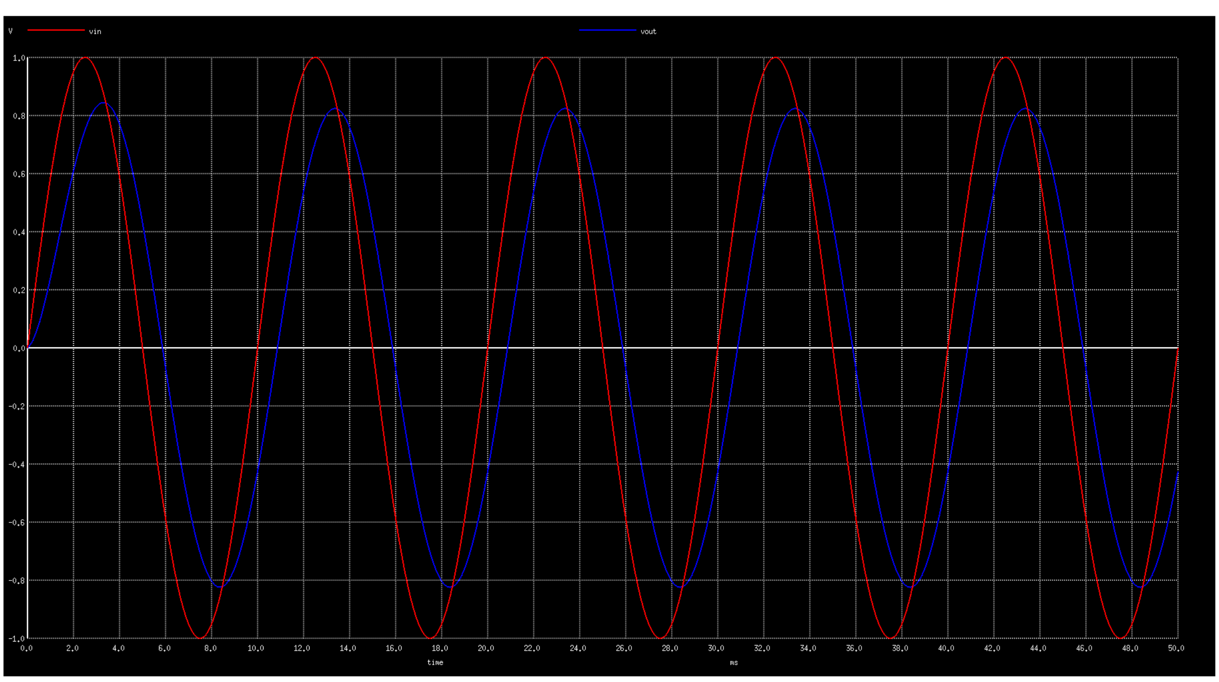


Figure 1: V_{out} and V_{in} for $\omega = 2\pi \times 100 rad/sec$

Phase Lag at $\omega = 200\pi \times rad/sec$ is $-31.05°$.

1.2.2 For $\omega_0 = 2\pi \times 1M$ rad/sec

```
Question-1b_2

* Circuit
Vin     Vin     0       AC      1       SIN     0       1       1MEG
R       Vin     Vout    1k
C       Vout    1       1u
Rs      1       0       100

* Analysis
.tran 0.01n 5u

* Results
.control
run
plot Vin Vout
.endc

.end
```

Graph:

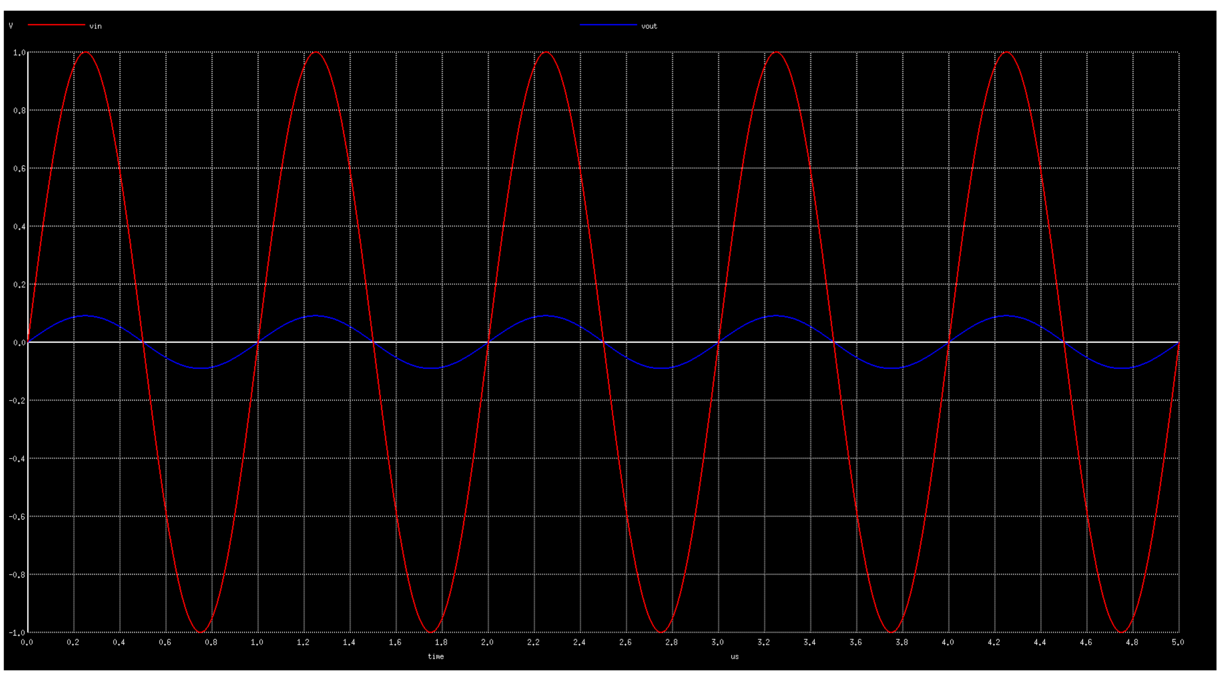


Figure 2: V_{out} and V_{in} for $\omega = 2\pi \times\ 1M$ rad/sec

Phase Lag at $\omega = 2\pi \times 10^6 rad/sec$ is $-0.9° \approx 0°$.

These values can be verified by Phase - Transfer Characteristic in next sub-section.

1.3 1c

For $V_{in} = \sin(\omega_0 t)$,

$$\frac{V_{\text{out}}}{V_{\text{in}}} = \frac{R_S C j\omega_0 + 1}{C(R_s + R)j\omega_0 + 1} \tag{6}$$

$$||\frac{V_{\text{out}}}{V_{\text{in}}}|| = \sqrt{\left(\frac{1 + (CR_s\omega_0)^2}{1 + (C\omega_0(R + R_s))^2}\right)} \tag{7}$$

$$\angle\frac{V_{out}}{V_{in}} = \tan^{-1}(R_s C\omega_0) - \tan^{-1}((R_s + R)C\omega_0) \tag{8}$$

At 3dB point, $\frac{V_{out}}{V_{in}} = \frac{1}{\sqrt{2}}$. Frequency at 3dB point is $145.89Hz$ and corresponding Phase is $-40°$.

SPICE Netlist:

```
Question-1c

* Circuit
Vin     Vin     0       AC      1       SIN     0       1       1000
R       Vin     Vout    1k
C       Vout    1       1u
Rs      1       0       100

* Analysis
.AC     DEC     10      1       1MEG

* Results
.control
run
plot  db(Vout/Vin)
plot  180*(phase(Vout) - phase(Vin))/PI
.endc

.end
```

Graph of Magnitude:

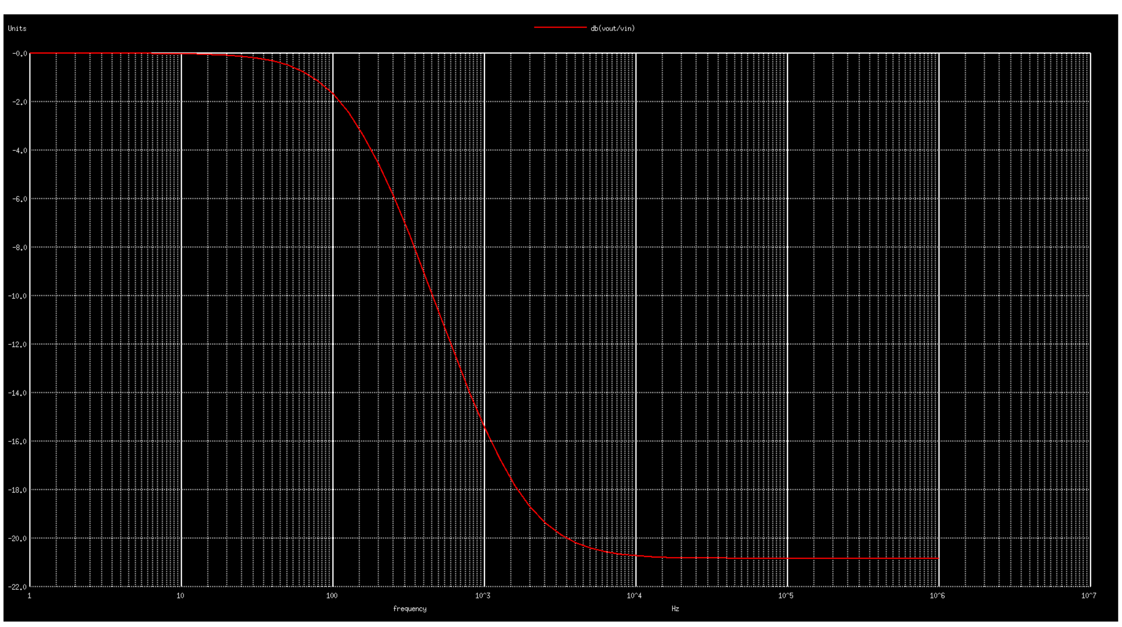


Figure 3: $||\frac{V_{\text{out}}}{V_{\text{in}}}||$

Graph of Phase:

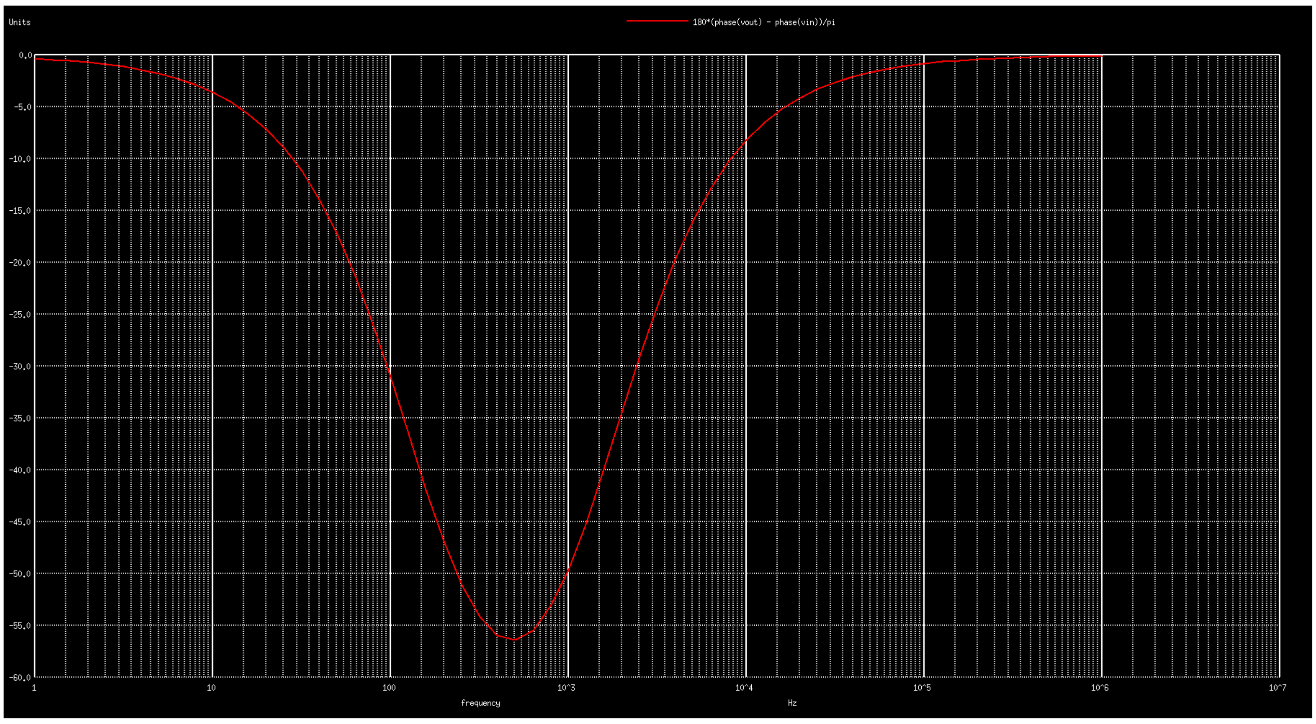


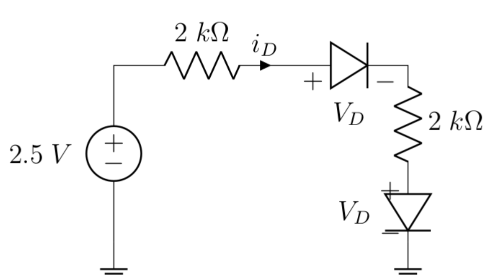
Figure 4: $\angle \frac{V_{out}}{V_{in}}$

2 Analytic calculations vs SPICE simulations

$I_s = 10^{-14} Amps$ and $T = 300K$ are standard conditions for a Ideal Diode. If we consider that $V_{Don} = 0.7V$ for both Diodes, Current i_D would be,

$$2.5 - 4 \times 10^3 i_D = 0.7 \times 2 \tag{9}$$

$$i_D = \frac{1.1}{4000} = 2.75 \times 10^{-4} Amps \tag{10}$$



2.1 2c

SPICE Netlist:

```
Question-2c

* Circuit
V       Vin     0       DC      2.5
R1      Vin     1       2k
D1      1       Vout    CustomDiode
R2      Vout    2       2k
D2      2       0       CustomDiode

```

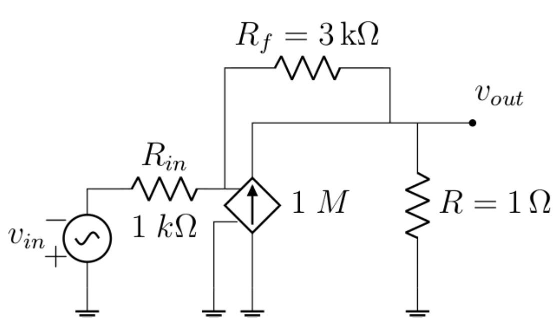
```
* Model
.model CustomDiode D

* Analysis
.op

* Results
.control
let ID = -Vin#branch
run
print all
.endc

.end
```

The results on Simulation are

$$V_D = 0.6250153 \text{ Volts} \tag{11}$$

$$i_D = 3.12492 \times 10^{-4} \text{ Amps} \tag{12}$$

3 Controlled Sources



From the given properties,

$$V_{in} = 0.5\sin(2000\pi t) \tag{13}$$

And on solving using KCL and KVL and some valid approximations,

$$V_{out} = 3V_{in} \tag{14}$$

$$V_{out} = 1.5\sin(2000\pi t) \tag{15}$$

SPICE Netlist:

```
Question-3

* Circuit
Vin     0       1       AC      1       SIN     0       0.5     1k
Rin     1       2       1k
Rf      2       Vout    3k
R       Vout    0       1
G       Vout    0       2       0       1MEG

* Analysis
.tran 1u 0.005
```

```
*.AC   DEC    10     10     10MEG

* Results
.control
run
plot -V(1) V(Vout)
*plot -V(Vout)/V(1)
.endc

.end
```

Graph:

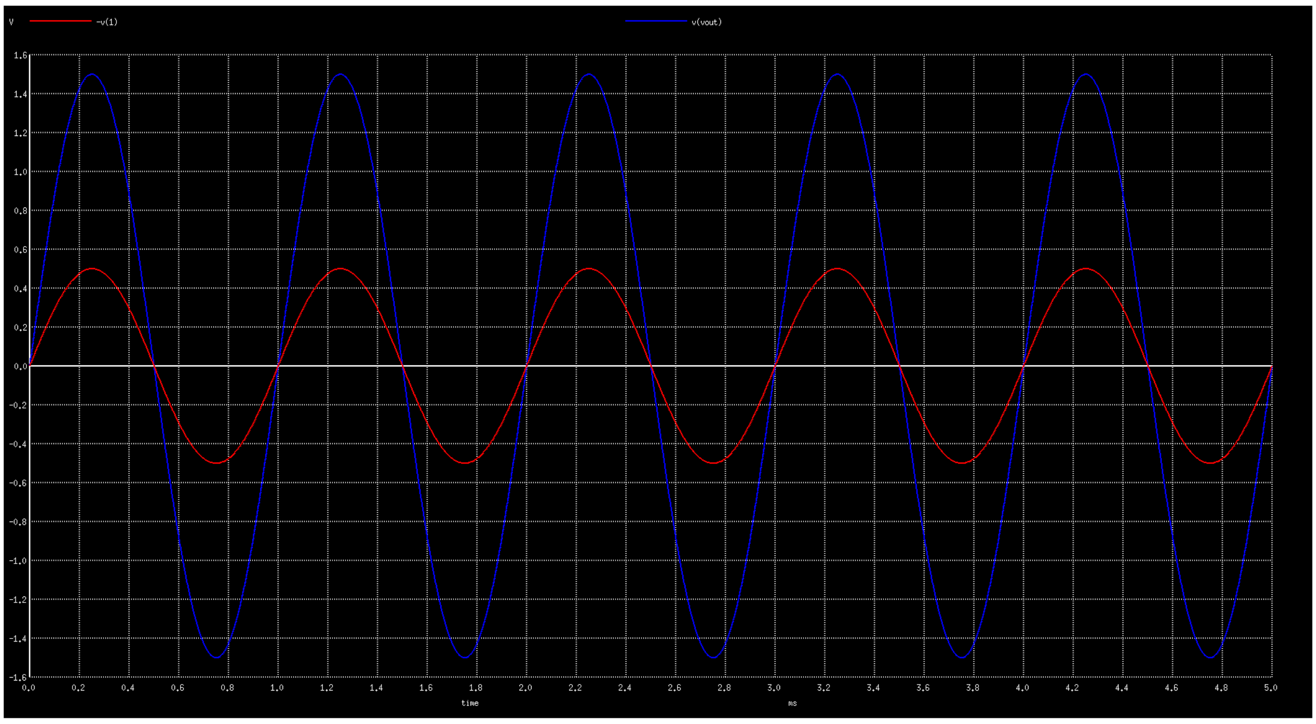


Figure 5: Plot of V_{out} and V_{in}

4 MOSFET Characteristics

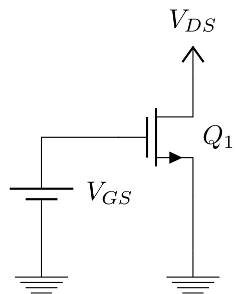
Long Channel MOSFET Parameters and Assumptions:

1. $\frac{W}{L} = 1.5$
2. L = 10μm
3. W = 15μm
4. V_{GS} and V_{DS} are supplied +ve.

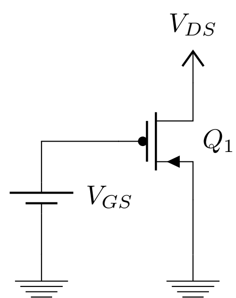
Short Channel MOSFET Parameters and Assumptions:

1. $\frac{W}{L} = 1.5$
2. L = 0.18μm
3. W = 0.27μm
4. V_{GS} and V_{DS} are supplied -ve.

N-MOS Circuit:



P-MOS Circuit:



4.1 4a

4.1.1 N-MOSFET

Long Channel SPICE Netlist:

```
Question-4anmosl
* Vgs value varies from 0.5,2 with a step of 0.5 *

* Circuit
M       td      tg      0       0       nch_tt W = 15u L = 10u
Vgs     tg      0       DC      0.5
Vds     td      0       DC      0.5

* Model
.include "TSMC180.lib"
.model nch_tt nmos

* Analysis
.dc Vds 0 1.8 1m

* Results
.control
run
let ID = -Vds#branch
wrdata ../Data/4a/nmosl1.dat       V(td)  ID
plot ID vs V(td)
.endc

.end
```

Short Channel SPICE Netlist:

```
Question-4anmoss
* Vgs value varies from 0.5,2 with a step of 0.5 *
```

```

* Circuit
M       td      tg      0       0       nch_tt W = 0.27u L = 0.18u
Vgs     tg      0       DC      0.5
Vds     td      0       DC      0.5

* Model
.include "TSMC180.lib"
.model nch_tt nmos

* Analysis
.dc Vds 0 1.8 1m

* Results
.control
run
let ID = -Vds#branch
wrdata ../Data/4a/nmoss1.dat V(td) ID
plot ID vs V(td)
.endc

.end
```

4.1.2 P-MOSFET

Long Channel SPICE Netlist:

```
Question-4apmosl
* Vgs value varies from -2,-0.5 with a step of 0.5 *

* Circuit
M       td      tg      0       0       pch_tt W = 15u L = 10u
Vgs     tg      0       DC      -0.5
Vds     td      0       DC      -0.5

* Model
.include "TSMC180.lib"
.model pch_tt pmos

* Analysis
.dc Vds -1.8 0 1m

* Results
.control
run
let ID = -Vds#branch
wrdata ../Data/4a/pmosl1.dat       V(td)  ID
plot ID vs V(td)
.endc

.end
```

Short Channel SPICE Netlist:

```
Question-4apmoss
* Vgs value varies from -2,-0.5 with a step of 0.5 *

* Circuit
M       td      tg      0       0       pch_tt W = 0.27u L = 0.18u
```

```
Vgs    tg     0      DC     -0.5
Vds    td     0      DC     -0.5

* Model
.include "TSMC180.lib"
.model pch_tt pmos

* Analysis
.dc Vds -1.8 0 1m

* Results
.control
run
let ID = -Vds#branch
wrdata ../Data/4a/pmoss1.dat       V(td)  ID
plot ID vs V(td)
.endc

.end
```

4.1.3 Results

Python Code for Plotting Characteristics from Saved Data

```
#Python Code to Plot Simulation from Data

import numpy as np
import matplotlib.pyplot as plt

def File2Numpy(Path):
       Content = []
       for i in open(Path).readlines():
              Content.append(i.strip().split())

       Content = np.array(Content).astype(float)
       x = Content[:,1]
       y = Content[:,3]
       return np.array([x,y]).T

# Data of Long Channel N-MOSFET
ln1 = File2Numpy("../Data/4a/nmosl1.dat")
ln2 = File2Numpy("../Data/4a/nmosl2.dat")
ln3 = File2Numpy("../Data/4a/nmosl3.dat")
ln4 = File2Numpy("../Data/4a/nmosl4.dat")

# Data of Long Channel P-MOSFET
lp1 = File2Numpy("../Data/4a/pmosl1.dat")
lp2 = File2Numpy("../Data/4a/pmosl2.dat")
lp3 = File2Numpy("../Data/4a/pmosl3.dat")
lp4 = File2Numpy("../Data/4a/pmosl4.dat")

# Data of Short Channel N-MOSFET
sn1 = File2Numpy("../Data/4a/nmoss1.dat")
sn2 = File2Numpy("../Data/4a/nmoss2.dat")
sn3 = File2Numpy("../Data/4a/nmoss3.dat")
sn4 = File2Numpy("../Data/4a/nmoss4.dat")

# Data of Short Channel P-MOSFET
```

```python
sp1 = File2Numpy("../Data/4a/pmoss1.dat")
sp2 = File2Numpy("../Data/4a/pmoss2.dat")
sp3 = File2Numpy("../Data/4a/pmoss3.dat")
sp4 = File2Numpy("../Data/4a/pmoss4.dat")


plt.figure(figsize=(20,20))

plt.subplot(2,2,1)
plt.plot(ln1[:,0],ln1[:,1],label=r"$V_{g}$ = 0.5")
plt.plot(ln2[:,0],ln2[:,1],label=r"$V_{g}$ = 1")
plt.plot(ln3[:,0],ln3[:,1],label=r"$V_{g}$ = 1.5")
plt.plot(ln4[:,0],ln4[:,1],label=r"$V_{g}$ = 2")
plt.title("Long Channel NMOS")
plt.grid()
plt.legend()
plt.xlabel(r"$V_{D}$")
plt.ylabel(r"$I_{D}$")

plt.subplot(2,2,2)
plt.plot(lp1[:,0],lp1[:,1],label=r"$V_{g}$ = -0.5")
plt.plot(lp2[:,0],lp2[:,1],label=r"$V_{g}$ = -1")
plt.plot(lp3[:,0],lp3[:,1],label=r"$V_{g}$ = -1.5")
plt.plot(lp4[:,0],lp4[:,1],label=r"$V_{g}$ = -2")
plt.title("Long Channel PMOS")
plt.grid()
plt.legend()
plt.xlabel(r"$V_{D}$")
plt.ylabel(r"$I_{D}$")

plt.subplot(2,2,3)
plt.plot(sn1[:,0],sn1[:,1],label=r"$V_{g}$ = 0.5")
plt.plot(sn2[:,0],sn2[:,1],label=r"$V_{g}$ = 1")
plt.plot(sn3[:,0],sn3[:,1],label=r"$V_{g}$ = 1.5")
plt.plot(sn4[:,0],sn4[:,1],label=r"$V_{g}$ = 2")
plt.title("Short Channel NMOS")
plt.grid()
plt.legend()
plt.xlabel(r"$V_{D}$")
plt.ylabel(r"$I_{D}$")

plt.subplot(2,2,4)
plt.plot(sp1[:,0],sp1[:,1],label=r"$V_{g}$ = -0.5")
plt.plot(sp2[:,0],sp2[:,1],label=r"$V_{g}$ = -1")
plt.plot(sp3[:,0],sp3[:,1],label=r"$V_{g}$ = -1.5")
plt.plot(sp4[:,0],sp4[:,1],label=r"$V_{g}$ = -2")
plt.title("Short Channel PMOS")
plt.grid()
plt.legend()
plt.xlabel(r"$V_{D}$")
plt.ylabel(r"$I_{D}$")

plt.savefig("4a.png")
plt.show()
```

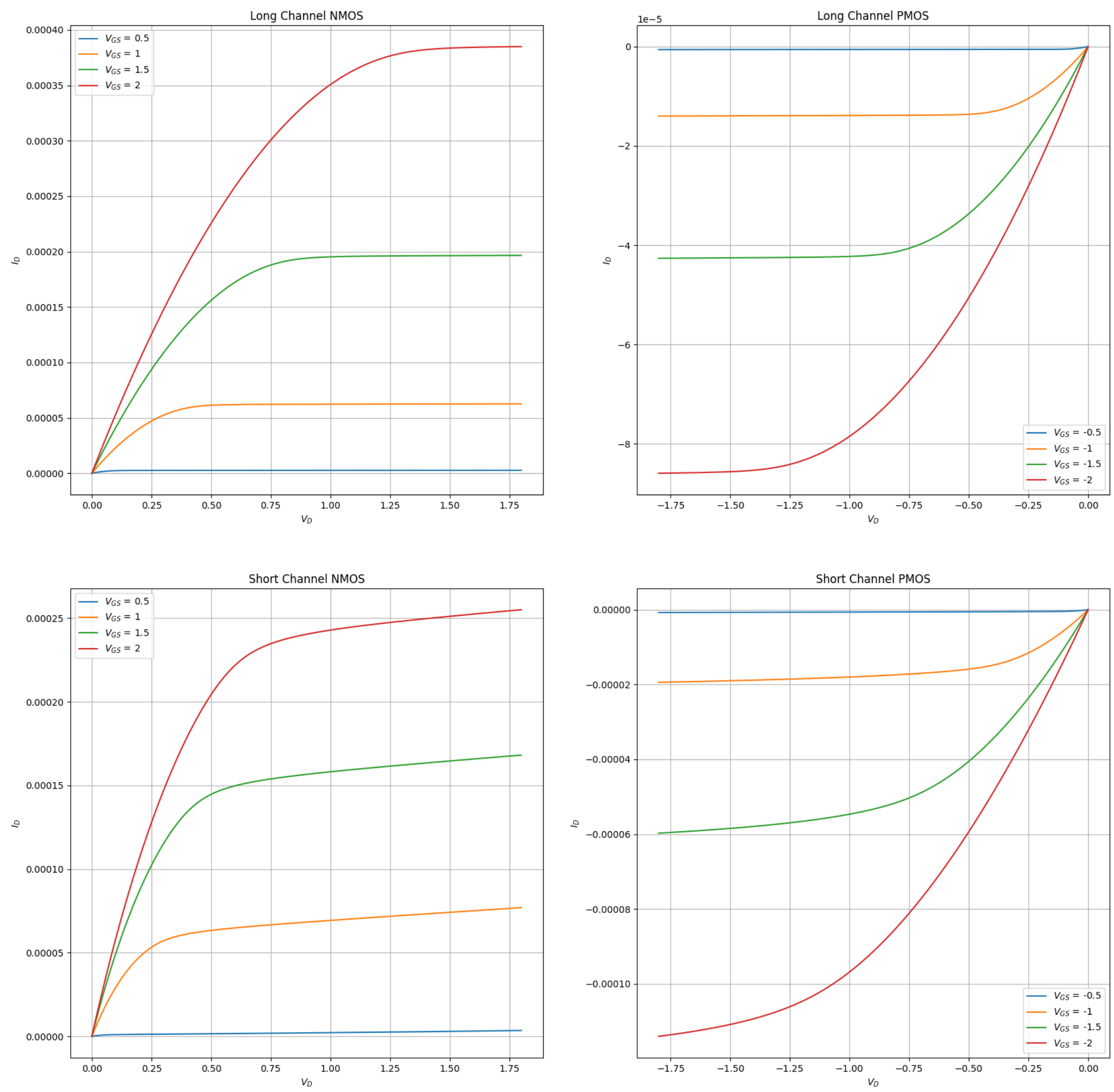


Figure 6: I_D vs V_D Characteristics of Long and Short Channel N-MOSFETs and P-MOSFETs

4.2 4b

4.2.1 N-MOSFET

Long Channel SPICE Netlist:

```
Question-4bnmosl

* Circuit
M       td      tg      0       0       nch_tt W = 15u L = 10u
Vgs     tg      0       DC      0.5
Vdd     td      0       DC      1.8

* Model
.include "TSMC180.lib"
.model nch_tt nmos

* Analysis
.dc Vgs 0 2 1m

```

```
* Results
.control
run
let ID = -Vdd#branch
wrdata ../Data/4b/nmosl.dat V(tg)-0.362   ID
plot ID vs V(tg)-0.362
.endc

.end
```

Short Channel SPICE Netlist:

```
Question-4bnmoss

* Circuit
M       td      tg      0       0       nch_tt W = 0.27u L = 0.18u
Vgs     tg      0       DC      0.5
Vdd     td      0       DC      1.8

* Model
.include "TSMC180.lib"
.model nch_tt nmos

* Analysis
.dc Vgs 0 2 1m

* Results
.control
run
let ID = -Vdd#branch
wrdata ../Data/4b/nmoss.dat V(tg)-0.362   ID
plot ID vs V(tg)-0.362
.endc

.end
```

4.2.2 P-MOSFET

Long Channel SPICE Netlist:

```
Question-4apmosl

* Circuit
M       td      tg      0       0       pch_tt W = 15u L = 10u
Vgs     tg      0       DC      -0.5
Vdd     td      0       DC      -1.8

* Model
.include "TSMC180.lib"
.model pch_tt pmos

* Analysis
.dc Vgs -2 0 1m

* Results
.control
run
let ID = -Vdd#branch
wrdata ../Data/4b/pmosl.dat V(tg)-0.388   ID
```

```
plot ID vs V(tg)-0.388
.endc

.end
```

Short Channel SPICE Netlist:

```
Question-4apmoss

* Circuit
M       td      tg      0       0       pch_tt W = 0.27u L = 0.18u
Vgs     tg      0       DC      -0.5
Vdd     td      0       DC      -1.8

* Model
.include "TSMC180.lib"
.model pch_tt pmos

* Analysis
.dc Vgs -2 0 1m

* Results
.control
run
let ID = -Vdd#branch
wrdata ../Data/4b/pmoss.dat V(tg)-0.388   ID
plot ID vs V(tg)-0.388
.endc

.end
```

4.2.3 Results

Python Code for Plotting Characteristics from Saved Data

```python
#Python Code to Plot Simulation from Data

import numpy as np
import matplotlib.pyplot as plt

def File2Numpy(Path):
        Content = []
        for i in open(Path).readlines():
                Content.append(i.strip().split())

        Content = np.array(Content).astype(float)
        x = Content[:,1]
        y = Content[:,3]
        return np.array([x,y]).T

# Data of Long Channel N-MOSFET
ln1 = File2Numpy("../Data/4a/nmosl1.dat")
ln2 = File2Numpy("../Data/4a/nmosl2.dat")
ln3 = File2Numpy("../Data/4a/nmosl3.dat")
ln4 = File2Numpy("../Data/4a/nmosl4.dat")

# Data of Long Channel P-MOSFET
lp1 = File2Numpy("../Data/4a/pmosl1.dat")
lp2 = File2Numpy("../Data/4a/pmosl2.dat")
```

```python
lp3 = File2Numpy("../Data/4a/pmosl3.dat")
lp4 = File2Numpy("../Data/4a/pmosl4.dat")

# Data of Short Channel N-MOSFET
sn1 = File2Numpy("../Data/4a/nmoss1.dat")
sn2 = File2Numpy("../Data/4a/nmoss2.dat")
sn3 = File2Numpy("../Data/4a/nmoss3.dat")
sn4 = File2Numpy("../Data/4a/nmoss4.dat")

# Data of Short Channel P-MOSFET
sp1 = File2Numpy("../Data/4a/pmoss1.dat")
sp2 = File2Numpy("../Data/4a/pmoss2.dat")
sp3 = File2Numpy("../Data/4a/pmoss3.dat")
sp4 = File2Numpy("../Data/4a/pmoss4.dat")

# Transition
a = File2Numpy("../Data/4b/nmosl.dat")
b = File2Numpy("../Data/4b/pmosl.dat")
c = File2Numpy("../Data/4b/nmoss.dat")
d = File2Numpy("../Data/4b/pmoss.dat")

plt.figure(figsize=(20,20))

plt.subplot(2,2,1)
plt.plot(ln1[:,0],ln1[:,1],label=r"$V_{g}$ = 0.5")
plt.plot(ln2[:,0],ln2[:,1],label=r"$V_{g}$ = 1")
plt.plot(ln3[:,0],ln3[:,1],label=r"$V_{g}$ = 1.5")
plt.plot(ln4[:,0],ln4[:,1],label=r"$V_{g}$ = 2")
plt.plot(a[:,0],a[:,1],label=r"Transition")
plt.title("Long Channel NMOS")
plt.grid()
plt.legend()
plt.xlabel(r"$V_{D}$")
plt.ylabel(r"$I_{D}$")

plt.subplot(2,2,2)
plt.plot(lp1[:,0],lp1[:,1],label=r"$V_{g}$ = -0.5")
plt.plot(lp2[:,0],lp2[:,1],label=r"$V_{g}$ = -1")
plt.plot(lp3[:,0],lp3[:,1],label=r"$V_{g}$ = -1.5")
plt.plot(lp4[:,0],lp4[:,1],label=r"$V_{g}$ = -2")
plt.plot(b[:,0],b[:,1],label=r"Transition")
plt.title("Long Channel PMOS")
plt.grid()
plt.legend()
plt.xlabel(r"$V_{D}$")
plt.ylabel(r"$I_{D}$")

plt.subplot(2,2,3)
plt.plot(sn1[:,0],sn1[:,1],label=r"$V_{g}$ = 0.5")
plt.plot(sn2[:,0],sn2[:,1],label=r"$V_{g}$ = 1")
plt.plot(sn3[:,0],sn3[:,1],label=r"$V_{g}$ = 1.5")
plt.plot(sn4[:,0],sn4[:,1],label=r"$V_{g}$ = 2")
plt.plot(c[:,0],c[:,1],label=r"Transition")
plt.title("Short Channel NMOS")
plt.grid()
plt.legend()
plt.xlabel(r"$V_{D}$")
```

```
plt.ylabel(r"$I_{D}$")

plt.subplot(2,2,4)
plt.plot(sp1[:,0],sp1[:,1],label=r"$V_{g}$ = -0.5")
plt.plot(sp2[:,0],sp2[:,1],label=r"$V_{g}$ = -1")
plt.plot(sp3[:,0],sp3[:,1],label=r"$V_{g}$ = -1.5")
plt.plot(sp4[:,0],sp4[:,1],label=r"$V_{g}$ = -2")
plt.plot(d[:,0],d[:,1],label=r"Transition")
plt.title("Short Channel PMOS")
plt.grid()
plt.legend()
plt.xlabel(r"$V_{D}$")
plt.ylabel(r"$I_{D}$")

plt.savefig("4b.png")
plt.show()
```

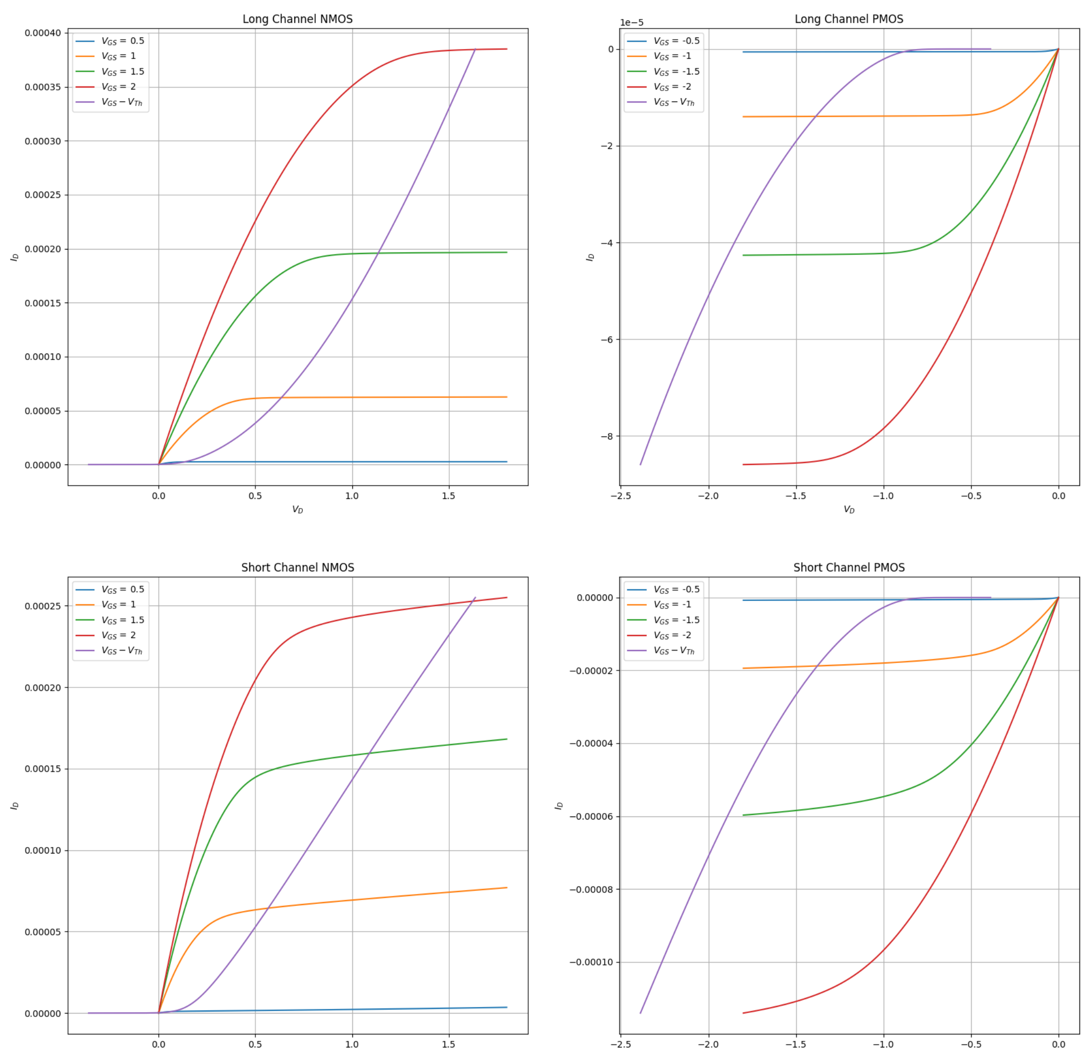


Figure 7: I_D vs V_D Characteristics of Long and Short Channel N-MOSFETs and P-MOSFETs with Regions

The Graph of I_D vs $V_{GS} - V_{Th}$ separates Linear Region from Saturation Region. The side of Parabolic Curve where I_D vs V_D varies Linearly is the Linear Region and the other one is Saturation Region.

The Primary Difference between the Graphs in Long Channel and Short Channel MOSFETs is value of Channel Modulation Parameter λ. $\lambda \approx 0$ for Long Channel Devices and λ is considerably large for Small Channel Devices. The considerable increase in λ is one of the Short Channel Effects which happens due to shortening of length of the inverted channel region with increase in drain bias for large drain biases. For $\lambda = 0$, I_D vs V_{DS} graph saturates at the end whereas for considerable λ I_D vs V_{DS} graph doesn't saturate.

4.3 4c

The Small Signal Output Resistance r_0 parameter of the MOSFET doesn't depend on Small Signal Input Voltage. It also depends on Channel Modulation Parameter λ. It is independent on whether it is N-MOS or P-MOS.

$$g_o = \left.\frac{\partial i_D}{\partial v_{DS}}\right|_Q = \mu_n C_{ox}\left(\frac{W}{2L}\right)(V_{GS} - V_{Tn})^2 \lambda_n \cong \lambda I_D \tag{16}$$

$$r_o = \frac{1}{g_o} = \frac{1}{\lambda I_D} \tag{17}$$

4.3.1 Calculations

Calculations are done for Graphs in Question-4a or for Section-4a in this document for $V_{GS} = 1.5$ Volts.

$$r_0 = \frac{1}{(\frac{dI_D}{dV_{DS}})} \tag{18}$$

$$r_0 = \frac{dV_{DS}}{dI_D} \tag{19}$$

N-MOSFET

Long Channel Calculations:

$$\frac{dI_D}{dV_{DS}} = 0 \tag{20}$$

$$r_0 \approx \infty \tag{21}$$

Short Channel Calculations:

$$\frac{dI_D}{dV_{DS}} = 1.17647 \times 10^{-5}\ \Omega^{-1} \tag{22}$$

$$r_0 = 85000\ \Omega \tag{23}$$

P-MOSFET

Long Channel Calculations:

$$\frac{dI_D}{dV_{DS}} = 2.117 \times 10^{-8}\ \Omega^{-1} \tag{24}$$

$$r_0 = 4.722 \times 10^{7}\ \Omega \tag{25}$$

Short Channel Calculations:

$$\frac{dI_D}{dV_{DS}} = 1.468 \times 10^{-7}\ \Omega^{-1} \tag{26}$$

$$r_0 = 6.8102 \times 10^{6}\ \Omega \tag{27}$$

4.4 4d

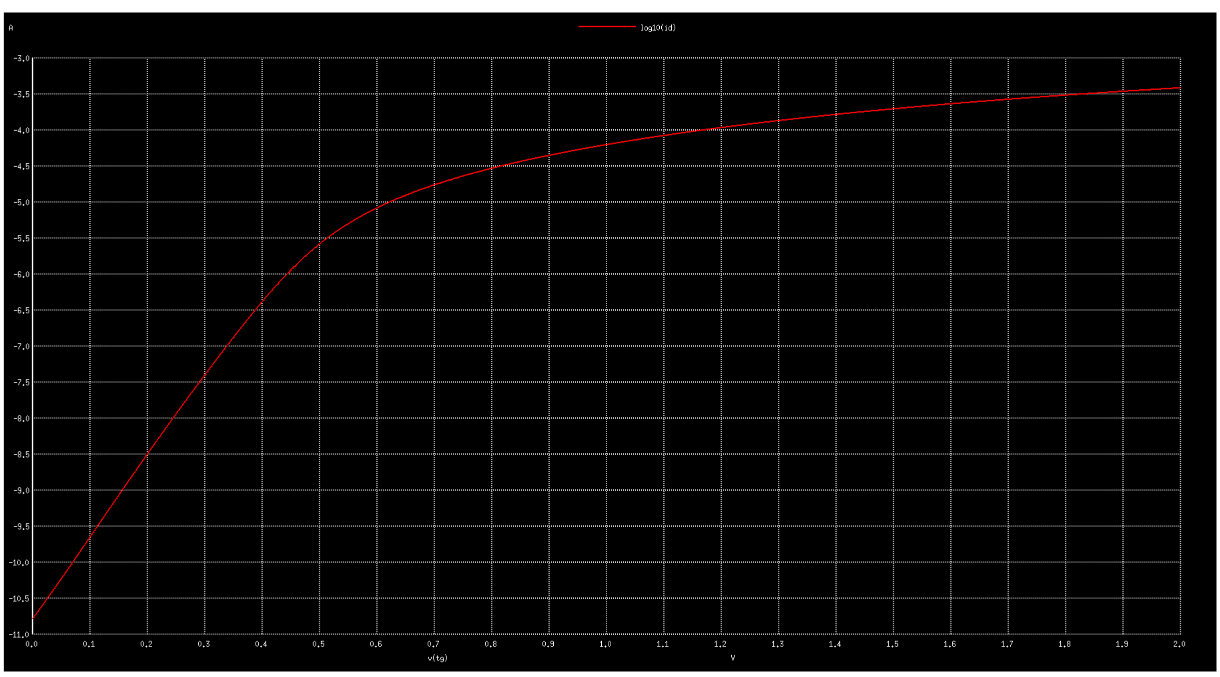
4.4.1 N-MOSFET

Long Channel

SPICE Netlist:

```
Question-4dnmosl

* Circuit
M       td      tg      0       0       nch_tt W = 15u L = 10u
Vgs     tg      0       DC      0.5
Vdd     td      0       DC      1.8

* Model
.include "TSMC180.lib"
.model nch_tt nmos

* Analysis
.dc Vgs 0 2 0.1m

* Results
.control
run
let ID = -Vdd#branch
wrdata ../Data/4d/nmosl.dat V(tg)  log10(ID)
plot log10(ID) vs V(tg)
.endc

.end
```

Plot:



Calculations:

$$S = 0.0921821 \text{ V/dec} \tag{28}$$

$$S = \eta \frac{KT}{q} ln(10) \tag{29}$$

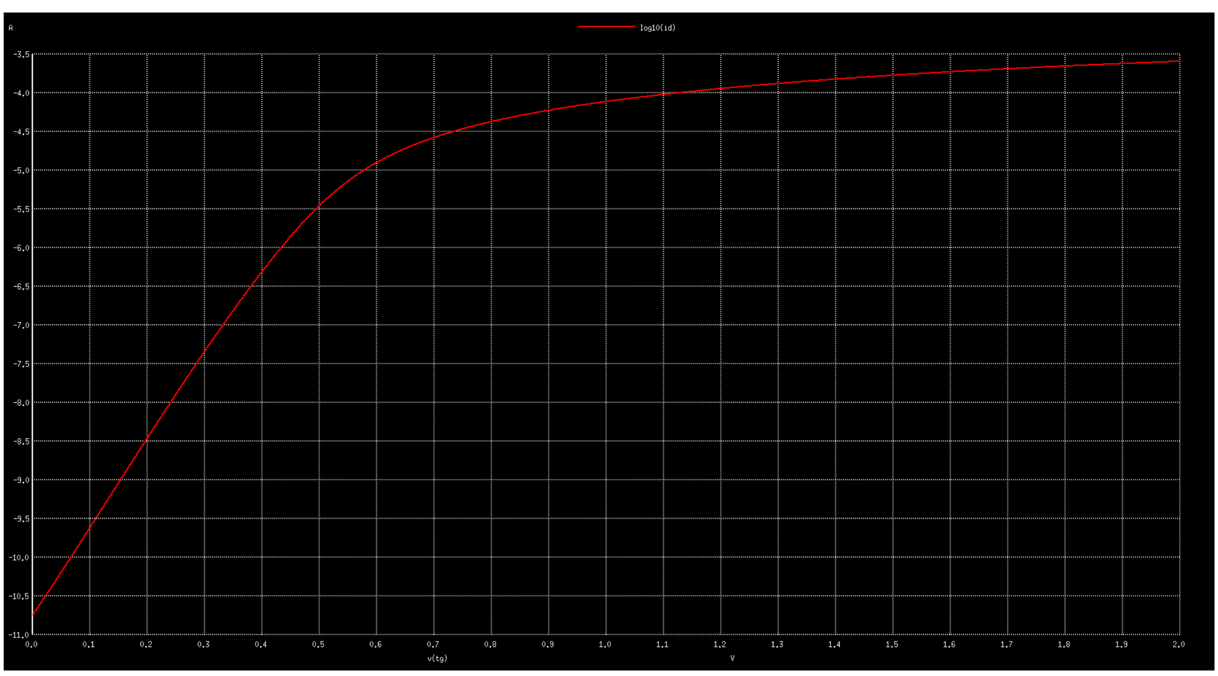
$$\eta = 1.5514 \tag{30}$$

Short Channel

SPICE Netlist:

```
Question-4dnmoss

* Circuit
M       td      tg      0       0       nch_tt W = 0.27u L = 0.18u
Vgs     tg      0       DC      0.5
Vdd     td      0       DC      1.8

* Model
.include "TSMC180.lib"
.model nch_tt nmos

* Analysis
.dc Vgs 0 2 1m

* Results
.control
run
let ID = -Vdd#branch
wrdata ../Data/4d/nmoss.dat V(tg)  log10(ID)
plot log10(ID) vs V(tg)
.endc

.end
```

Plot:



Calculations:

$$S = 0.0906977 \text{ V/dec} \tag{31}$$

$$S = \eta \frac{KT}{q} ln(10) \tag{32}$$

$$\eta = 1.52645 \tag{33}$$

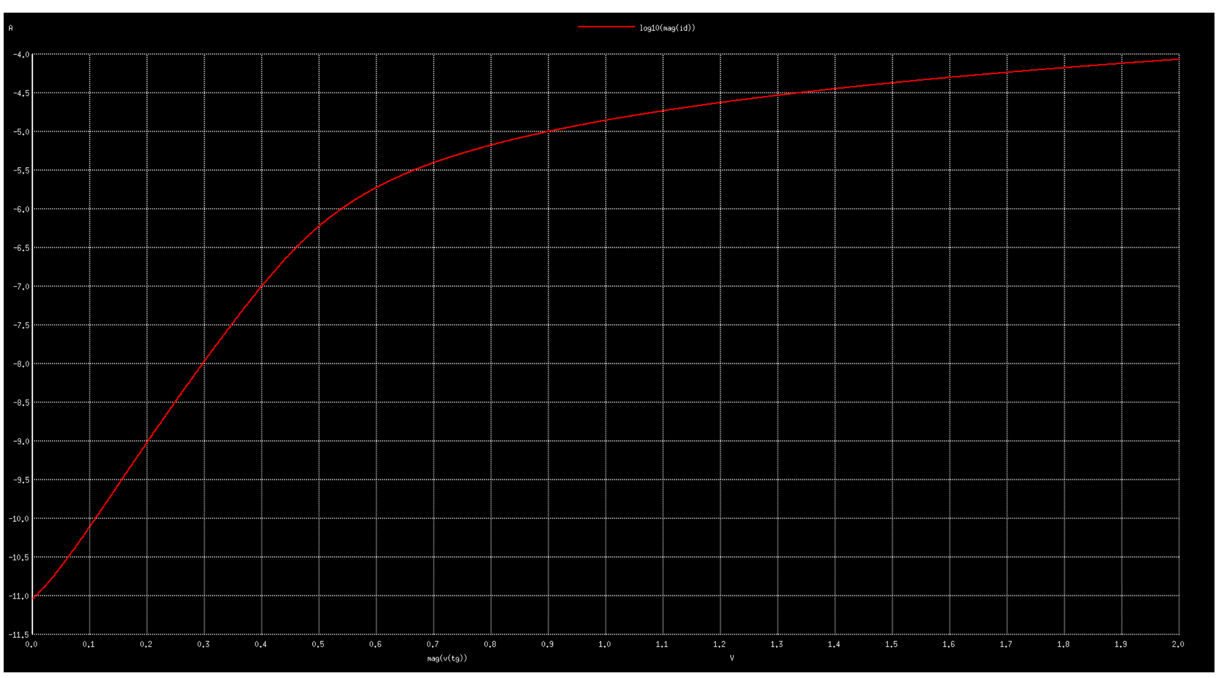
4.4.2 P-MOSFET

Long Channel

SPICE Netlist:

```
Question-4dpmosl

* Circuit
M       td      tg      0       0       pch_tt W = 15u L = 10u
Vgs     tg      0       DC      -0.5
Vdd     td      0       DC      -1.8

* Model
.include "TSMC180.lib"
.model pch_tt pmos

* Analysis
.dc Vgs -2 -0 1m

* Results
.control
run
let ID = -Vdd#branch
wrdata ../Data/4d/pmosl.dat V(mag(tg))    log10(mag(ID))
plot log10(mag(ID)) vs mag(V(tg))
.endc

.end
```

Plot:



Calculations:

$$S = 0.0930233 \text{ V/dec} \tag{34}$$

$$S = \eta \frac{KT}{q} ln(10) \tag{35}$$

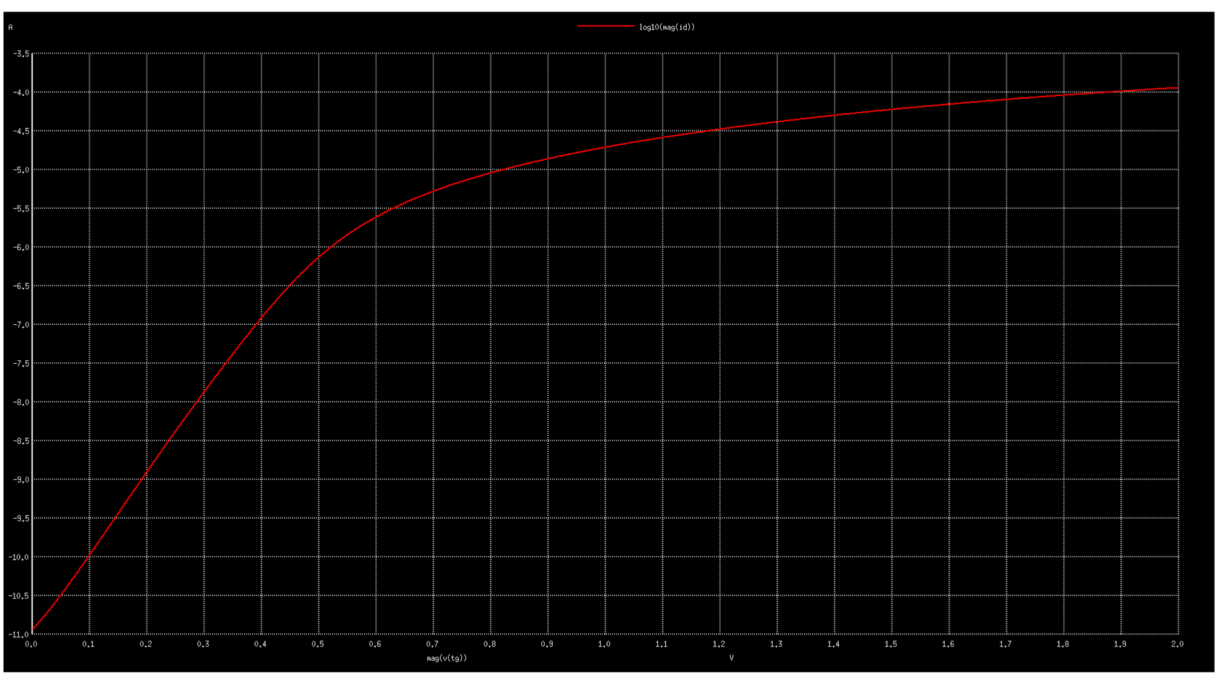
$$\eta = 1.56559 \tag{36}$$

Short Channel

SPICE Netlist:

```
Question-4dpmoss

* Circuit
M       td      tg      0       0       pch_tt W = 0.27u L = 0.18u
Vgs     tg      0       DC      -0.5
Vdd     td      0       DC      -1.8

* Model
.include "TSMC180.lib"
.model pch_tt pmos

* Analysis
.dc Vgs -2 0 1m

* Results
.control
run
let ID = -Vdd#branch
wrdata ../Data/4d/pmoss.dat mag(V(tg))    log10(mag(ID))
plot log10(mag(ID)) vs mag(V(tg))
.endc

.end
```

Plot:



Calculations:

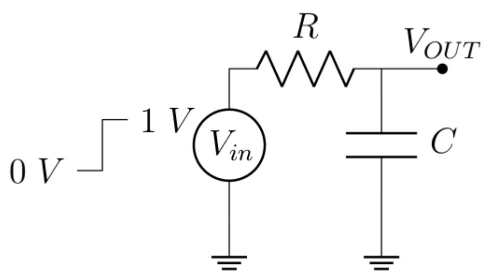
$$S = 0.0991792 \text{ V/dec} \tag{37}$$

$$S = \eta \frac{KT}{q} ln(10) \tag{38}$$

$$\eta = 1.66919 \tag{39}$$

5 Propagation Delay

Propagation Delay: Propagation Delay is the difference between time taken by the Output to have its magnitude half of its Final Value and time taken for the Input to have its magnitude half of its Final Value.
Rise Time: Rise Time is the amount of time taken for the Signal to have its magnitude change from 10% to 90% of Steady State Value.



5.1 5a

When a Ideal Step Signal($t_{r,in} = 0$) is given as input to the given RC Circuit,

$$V_{out} = V_{in}(1 - e^{\frac{-t}{RC}}) \tag{40}$$

$$\text{Propagation Delay} = t_p = 0.69RC \tag{41}$$

$$\text{Rise Time} = t_r = 2.2RC \tag{42}$$

Assuming,

$$R = 1000\Omega \tag{43}$$

$$C = 1\mu F \tag{44}$$

$$t_p = 6.9 \times 10^{-4}s \tag{45}$$

$$t_r = 2.2 \times 10^{-3}s \tag{46}$$

SPICE Netlist:

```
*#destroy all

Vin    Vin    0      AC     1      PWL(0 0V   0 1V   1 1V)
R      Vin    Vout   1000
C      Vout   0      1u

* ANALYSIS
.tran 1u 0.008

* VIEW RESULTS
.control
run
plot Vin Vout
.endc

.end
```

Graph:

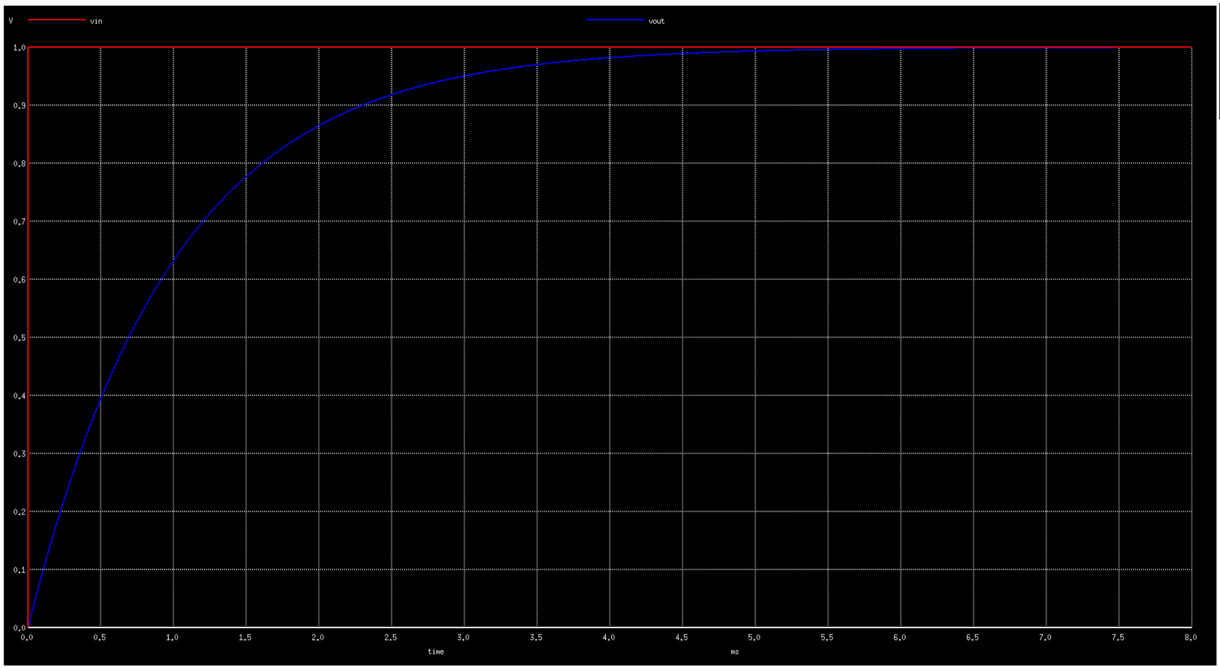


Figure 8: V_{out} and V_{in} for Ideal Step Signal as Input

5.2 5b

Parameters:

$$R = 10\Omega \tag{47}$$

$$C = 1nF \tag{48}$$

Readings: Table containing values of $\alpha = t_{r,in}/0.8$ and corresponding $t_{p,out}$.

α (in sec)	$t_{p,out}$ (in sec)
$10{\times}10^{-12}$	$6.9434{\times}10^{-9}$
$50{\times}10^{-12}$	$6.96226{\times}10^{-9}$
$100{\times}10^{-12}$	$7{\times}10^{-9}$
$200{\times}10^{-12}$	$7.02{\times}10^{-9}$
$300{\times}10^{-12}$	$7.1{\times}10^{-9}$
$400{\times}10^{-12}$	$7.137{\times}10^{-9}$
$500{\times}10^{-12}$	$7.185{\times}10^{-9}$
$600{\times}10^{-12}$	$7.23491{\times}10^{-9}$
$700{\times}10^{-12}$	$7.28977{\times}10^{-9}$
$800{\times}10^{-12}$	$7.34026{\times}10^{-9}$
$900{\times}10^{-12}$	$7.39123{\times}10^{-9}$
$1{\times}10^{-9}$	$7.44{\times}10^{-9}$
$2{\times}10^{-9}$	$7.9{\times}10^{-9}$
$3{\times}10^{-9}$	$8.47558{\times}10^{-9}$
$4{\times}10^{-9}$	$9.00455{\times}10^{-9}$
$5{\times}10^{-9}$	$9.54167{\times}10^{-9}$
$6{\times}10^{-9}$	$1.00883{\times}10^{-8}$
$7{\times}10^{-9}$	$1.06419{\times}10^{-8}$
$8{\times}10^{-9}$	$1.12035{\times}10^{-8}$
$9{\times}10^{-9}$	$1.17738{\times}10^{-8}$
$10{\times}10^{-9}$	$1.23509{\times}10^{-8}$

$$t_p = t_{p,out} - t_{p,in} \tag{49}$$

$$t_{p,in} = \alpha/2 \tag{50}$$

Python Code for Simulation:

```
import numpy as np
import matplotlib.pyplot as plt

alpha = np.array([10*1e-12, 50*1e-12, 100*1e-12, 200*1e-12, 300*1e-12, 400*1e-12,
                  500*1e-12, 600*1e-12, 700*1e-12, 800*1e-12, 900*1e-12, 1*1e-9,
                  2*1e-9, 3*1e-9, 4*1e-9, 5*1e-9, 6*1e-9, 7*1e-9, 8*1e-9, 9*1e-9, 10*1e-9])

tpout = np.array([6.9434*1e-9, 6.96226*1e-9, 7*1e-9, 7.02*1e-9, 7.1*1e-9, 7.137*1e-9,
          7.185*1e-9, 7.23491*1e-9, 7.28977*1e-9, 7.34026*1e-9, 7.39123*1e-9, 7.44*1e-9,
          7.9*1e-9, 8.47558*1e-9, 9.00455*1e-9, 9.54167*1e-9, 1.008833*1e-8, 1.06419*1e-8,
                  1.12035*1e-8, 1.17738*1e-8, 1.23509*1e-8])

tr = 0.8*alpha
tpin = alpha/2
tp = tpout - tpin

plt.figure(figsize=(9,9))
plt.plot(tr,tp)
plt.grid()
plt.scatter(tr,tp)
plt.title(r"$t_{p}$ vs $t_{r,in}$")
plt.xlabel(r"$t_{r,in}$")
plt.ylabel(r"$t_{p}$")
plt.savefig("5b.png")
plt.show()
```

Results:

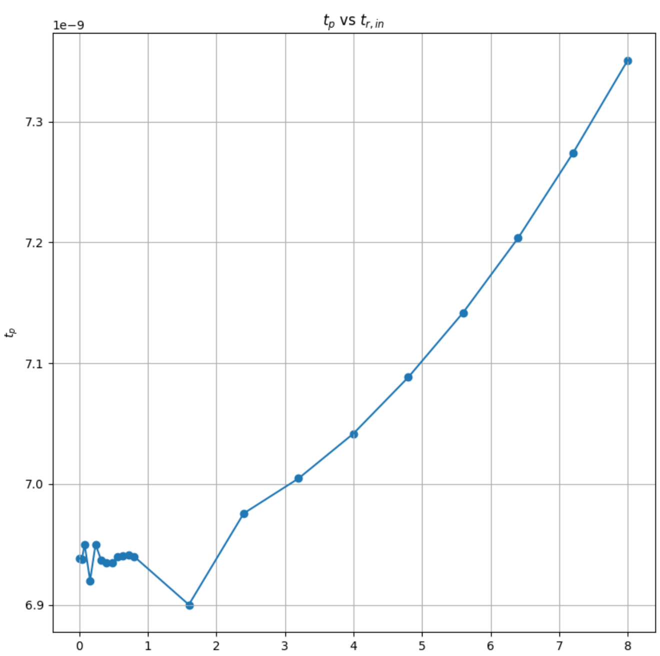


Figure 9: Plot t_p vs $t_{r,in}$