EE236: Experiment No. 6
Study of NMOS and CMOS Characteristics

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March 16, 2022

1 Overview of the experiment

1.1 Aim of the experiment

Aim of this experiment is to analyze the I-V characteristics of NMOS in linear region and saturation region by varying V_{GS} and V_{DS}. To find the parameters of NMOS such as Threshold Voltage (V_T), Transconductance (g_m) and Body Effect Coefficient (γ).
To analyze the Voltage Transfer Characteristics and Transient Characteristics of CMOS Inverter.

1.2 Methods

Firstly, I read and understood the background material to understand the working and functionality of NMOS. Then, I wrote the ngspice netlist to plot the I_D vs V_{DS} characteristics of NMOS by varying V_{GS} from 2.5V to 4V in steps of 0.5V and V_{DS} from 0V to 5V.
After that, I modified the netlist to plot I_D vs V_{GS} characteristics of NMOS in linear and saturation region to find Threshold Voltage (V_T), Transconductance (g_m). Then, I modified the netlist again to analyze the Body Bias Effect on NMOS and calculated the Body Effect Coefficient (γ) by varying V_{SB}.
After that, I wrote the netlist for CMOS Inverter and plotted Voltage Transfer Characteristics to find the switching thresholds by varying V_{DD}, W_p/W_n.

Finally, I plotted the Transient Characteristics to find rise time, fall time and propagation delay of the Inverter.

2 Design

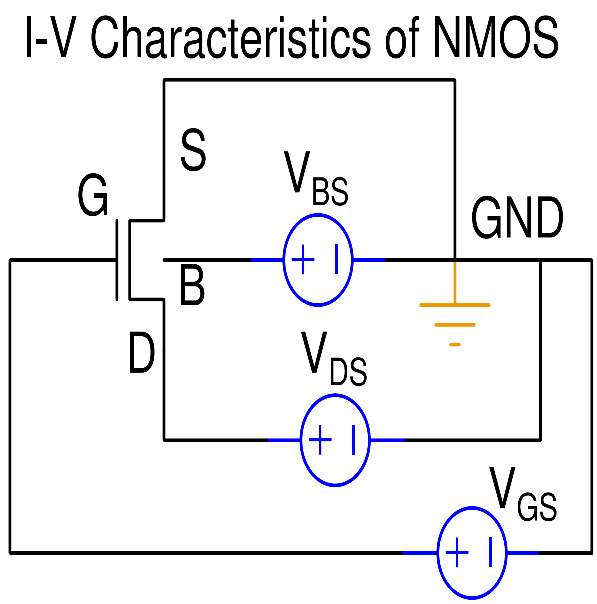


Fig. 1 : I-V Characteristics of PMOS

The circuit in Fig. 1 is for the I-V characteristics simulation of NMOS. I did DC analysis for V_{DS} varied from 0V to 5V. Also, I varied V_{GS} from 2.5V to 4V in steps of 0.5V.
Then, I calculated R_{DS} in the linear region by plotting the graph and took the rightmost value to get most accurate R_{DS} (in linear region).

$$R_{DS} = \frac{V_{DS}}{I_{DS}} \tag{1}$$

Then, I calculated the early voltage (V_A) using the x-intercept of straight line on the saturation region. And using it, I calculated R_O.

$$V_A = \frac{1}{\lambda} \tag{2}$$

$$R_O = \frac{1}{\lambda I_{D(sat)}} \tag{3}$$

After that, in the I_D vs V_{GS} characteristics in linear region and saturation region, I found Threshold Voltage (V_T) using the point of intersection of the straight line with the x-axis. And I calculated Transconductance (g_m) using the slope of the straight line.

$$g_m = \frac{\delta I_D}{\delta V_{GS}} \tag{4}$$

Then, I plotted I_D vs V_{GS} characteristics of NMOS by varying values of V_{SB} as 0V, 1V, 2V, 3V and 4V. Then, I calculated the value of Threshold Voltage (V_T) in all cases to plot V_T vs V_{SB} graph to find the value of Body Effect Coefficient (γ) using the given equation.

$$V_T = V_{T0} + \gamma(\sqrt{\Phi_s + V_{BS}} - \sqrt{\Phi_s}) \tag{5}$$

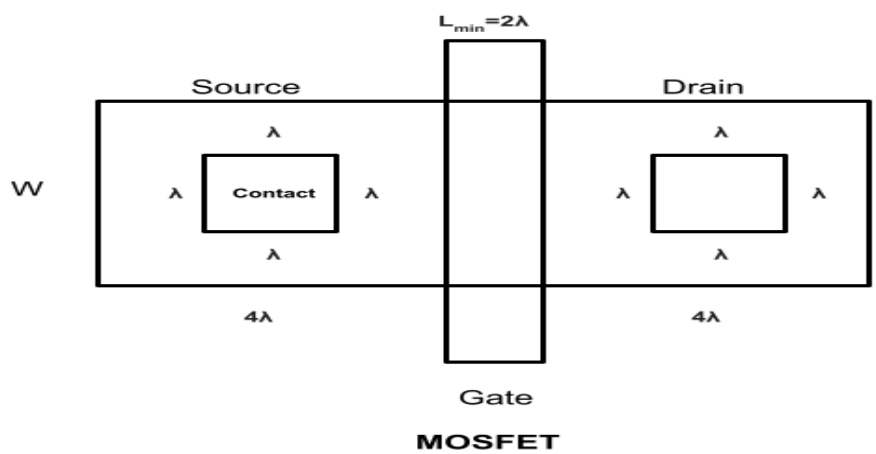


Fig. 2 : MOSFET Characteristics

Fig. 2 shows the structure of MOSFET. THe dimensions of it are given as L=0.4u W=Wn AS=2*Wn*L PS=2*Wn+4*L AD=2*Wn*L PD=2*Wn+4*L I plotted the Voltage Transfer Characteristics to find the Switching Thresholds by using combinations of W_p/W_n as 60um/30um, 60um/60um and 30um/60um. Also, I plotted the Voltage Transfer Characteristics for variations in V_{DD} as 1.5V and 3V.

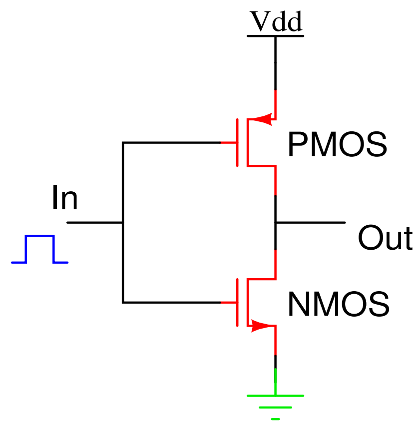


Fig. 3 : CMOS Inverter

Fig. 3 shows the CMOS Inverter circuit. Input is a square wave signal of frequency 125MHz with rise time and fall time of 20ps and CMOS inverter has load capacitance (C_L) 0.05pF. I calculated rise time, fall time and propagation delays for W_p/W_n = 60um/30um, 60um/60um, 30um/60um.

$$t_p = \frac{t_{pf} + t_{pr}}{2} \tag{6}$$

Then, I varied supply voltage V_{DD} between 2V to 3.3V for W_p/W_n = 60um/30um to plot propagation delay vs V_{DD}.

3 Simulation results

3.1 Code snippets

3.1.1 I_D-V_{DS} Characteristics of NMOS :

```
Mayur Ware | 19D070070
*EE236 | Lab 6
*I-V Characteristics of NMOS
.include ALD1105N.txt ;Including NMOS model file
*Netlist
M1 D G GND GND ALD1105N ;Defining the NMOS Model Drain, Gate, Source,
Body
Vd D GND dc 0
*Vg G GND dc 2.5
```

```
*Vg G GND dc 3
*Vg G GND dc 3.5
Vg G GND dc 4
*DC Analysis
.dc Vd 0 5 0.1
.control
run
set color0 = white
set color1 = black
set color2 = green
set xbrushwidth = 2
plot -I(Vd) vs V(D) ;Id vs Vds plot
plot abs((V(D))/(I(Vd))) ;R_DS plot
.endc
.end
```

3.1.2 I_D-V_{GS} Characteristics of NMOS :

```
Mayur Ware | 19D070070
*EE236 | Lab 6
*Id-Vgs Characteristics of NMOS
.include ALD1105N.txt ;Including NMOS model file
*Netlist
M1 D G GND GND ALD1105N ;Defining the NMOS Model Drain, Gate, Source,
Body
*Vd D GND dc 200m
Vd D GND dc 5
Vg G GND dc 0
*DC Analysis
.dc Vg 0 5 0.01
.control
run
set color0 = white
set color1 = black
set color2 = blue
set xbrushwidth = 2
plot -I(Vd) vs V(G) ;Id vs Vgs plot
plot sqrt(-I(Vd)) vs V(G) ;sqrt(Id) vs Vgs plot
.endc
.end
```

3.1.3 Effect of Body Bias on NMOS:

```
Mayur Ware | 19D070070
*EE236 | Lab 6
*Id-Vgs Characteristics of NMOS by varying Vsb
.include ALD1105N.txt ;Including NMOS model file
*Netlist
M1 D G GND B ALD1105N ;Defining the NMOS Model Drain, Gate, Source,
Body
Vd D GND dc 200m
Vg G GND dc 0
*Vb B GND dc 0
*Vb B GND dc -1
*Vb B GND dc -2
*Vb B GND dc -3
Vb B GND dc -4
*DC Analysis
.dc Vg 0 5 0.01
.control
run
set color0 = white
set color1 = black
set color2 = red
set xbrushwidth = 2
*plot I(Vd) vs V(G) ;Id vs Vgs plot
.endc
.end
```

3.1.4 CMOS Inverter Voltage Transfer Characteristics :

```
Mayur Ware | 19D070070
*EE236 | Lab 6
*CMOS Inverter
.include CMOS.txt ;Including CMOS model file
*Netlist
*M1 1 In Out 1 cmosp L=0.4u W=30u AS=24p PS=61.6u AD=24p PD=61.6u
M1 1 In Out 1 cmosp L=0.4u W=60u AS=48p PS=121.6u AD=48p PD=121.6u
*Defining the NMOS Model Drain, Gate, Source, Body
*M2 Out In GND GND cmosn L=0.4u W=60u AS=48p PS=121.6u AD=48p PD=121.6u
M2 Out In GND GND cmosn L=0.4u W=30u AS=24p PS=61.6u AD=24p PD=61.6u
*Defining the PMOS Model Drain, Gate, Source, Body
```

```
C1 Out GND 0.05p
Vdd 1 GND dc 3.3
Vin In GND dc 0
*DC Analysis
.dc Vin 0 5 0.01
.control
run
set color0 = white
set color1 = black
set color2 = violet
set xbrushwidth = 2
plot V(Out) vs V(In) ;Voltage Transfer Characteristics
.endc
.end
```

3.1.5 CMOS Inverter Transient Analysis :

```
Mayur Ware | 19D070070
*EE236 | Lab 6
*CMOS Inverter
.include CMOS.txt ;Including CMOS model file
*Netlist
M1 1 In Out 1 cmosp L=0.4u W=30u AS=24p PS=61.6u AD=24p PD=61.6u
*M1 1 In Out 1 cmosp L=0.4u W=60u AS=48p PS=121.6u AD=48p PD=121.6u
*Defining the NMOS Model Drain, Gate, Source, Body
M2 Out In GND GND cmosn L=0.4u W=60u AS=48p PS=121.6u AD=48p PD=121.6u
*M2 Out In GND GND cmosn L=0.4u W=30u AS=24p PS=61.6u AD=24p PD=61.6u
*Defining the PMOS Model Drain, Gate, Source, Body
C1 Out GND 0.05p
Vdd 1 GND dc 3.3
Vin In GND pulse(0 3.3 0 20p 20p 4n 8n)
*Transient Analysis
.tran 0.1n 10n
.control
run
set color0 = white
set color1 = black
set color2 = violet
set xbrushwidth = 2
plot V(Out) V(In) ;Vout and Vin plots
```

```
.endc
.end
```

3.2 Simulation results

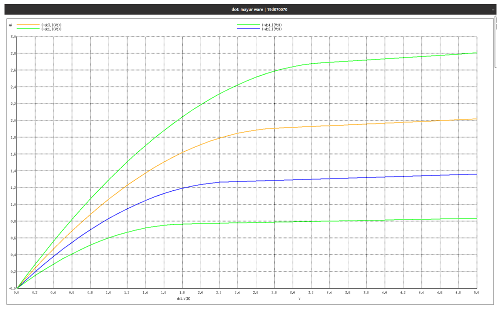
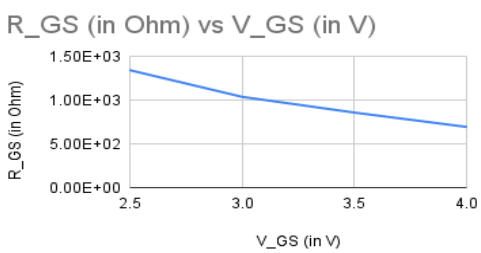
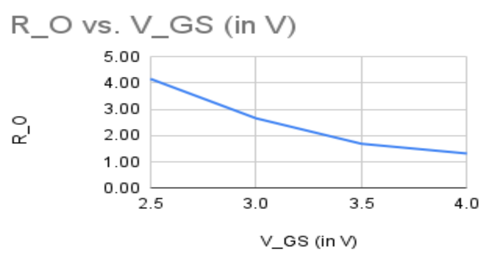


Fig. 4 : Id-Vds Characteristics of NMOS

For lower values of V_{DS}, PMOS is in the linear mode. Whereas, after a certain value, NMOS is going into the saturation region. Red, Blue, Yellow and Green curves are for V_{DS} values 2.5V, 3V, 3.5V and 4V respectively.

V_{GS} (in V)	R_{GS} (in kΩ)	Early Voltage (V_A)	$I_{D(sat)}$	R_O (in kΩ)
2.5	1.35	-34.56	0.831mA	41.6
3	1.04	-36.06	1.36mA	26.6
3.5	0.860	-34.00	2.02mA	16.9
4	0.696	-36.91	2.80mA	13.2





Id-Vds Characteristics of NMOS

Fig. 5 : R_{GS} vs V_{GS}

Fig. 6 : R_O vs V_{GS}

It can be seen in Fig. 5 and Fig. 6 that both R_{GS} and R_O decrease with increase in V_{GS}.

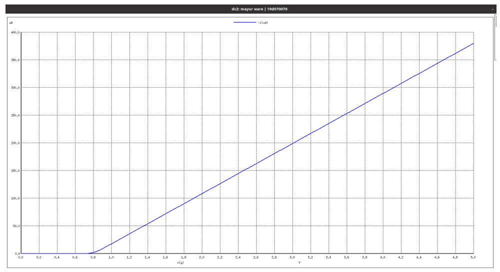
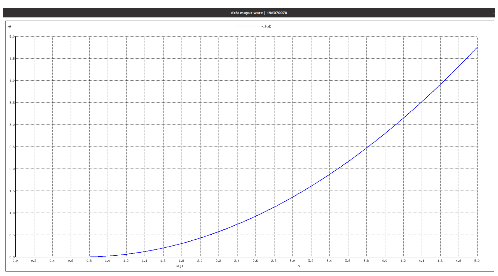
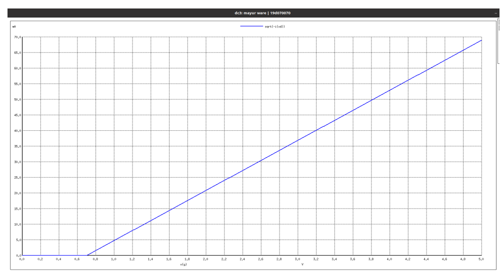


Fig. 7 :Id vs Vgs Characteristics in linear mode of NMOS

Graph is a straight line with positive slope and Id is increasing with increase in V_{GS}.
Threshold Voltage (V_T) = 0.78V and Transconductance (g_m) = 8.94E-05.





Saturation mode of NMOS

Fig. 8 : I_D vs V_{GS} Fig. 9 : $\sqrt{I_D}$ vs V_{GS}

I_D vs V_{GS} curve is parabolic. Whereas, $\sqrt{I_D}$ vs $V_G S$ curve is a straight line with positive slope. Both increase with increase in V_{GS}.
Threshold Voltage (V_T) = 0.7V and and K = 0.000487 mV/A^2

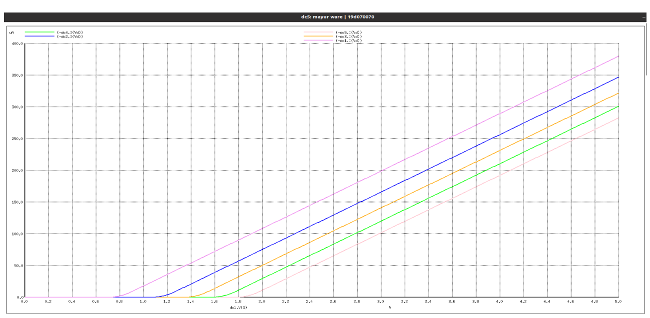


Fig. 10 :I_D vs V_{GS} Characteristics of NMOS varying V_{SB}

I_D vs V_{GS} Characteristics of NMOS varying V_{SB} are straight lines with positive slopes. Curves shift to right with increase in V_{SB}.

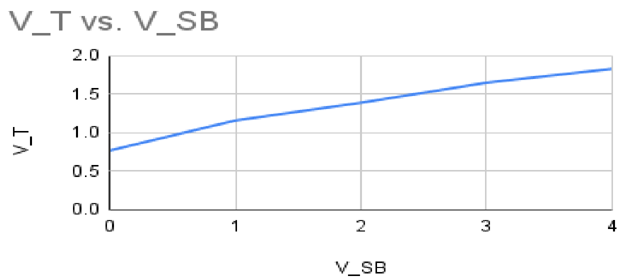


Fig. 11 :V_T vs V_{SB}

V_T increases with increase in V_{SB}. Using this graph and given equation (5), the value of Body Effect Coefficient (γ) comes out to be 0.914.

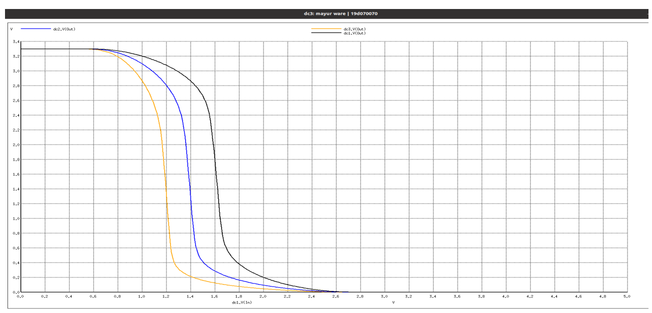


Fig. 12 : Voltage Transfer Characteristics of CMOS Inverter

Green curve is for W_p/W_n = 60um/60um, Blue curve is for W_p/W_n = 60um/30um and black curve is for W_p/W_n = 30um/60um. Switching thresholds for these values for V_{DD} = 3.3V are given in the table below.

W_p/W_n	ViL	ViH	VoL	VoH
60um/30um	1.006	1.56872	0.317089	3.08958
30um/60um	1.25949	1.83408	0.34104	3.02687
60um/60um	0.810345	1.33367	0.271519	3.18247

Now, for W_p/W_n = 60um/30um I varied V_{DD} for the same.

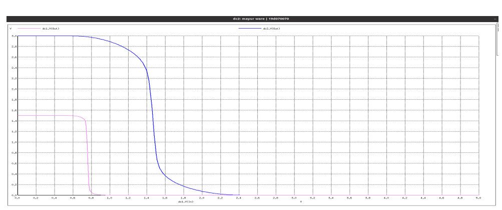
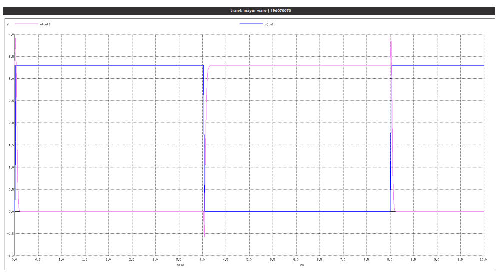
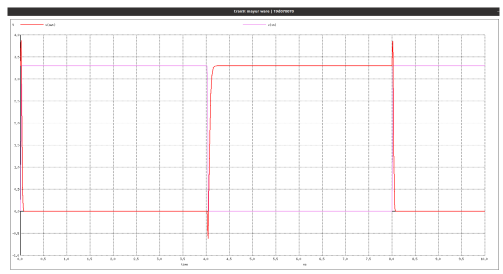


Fig. 13 : Voltage Transfer Characteristics of CMOS Inverter by varying V_{DD}

V_{DD}	ViL	ViH	VoL	VoH
1.5	0.707826	0.808592	0.0417722	1.44694
3	1.17439	1.70471	0.24023	2.7621

Finally, I did the transient analysis of CMOS Inverter. Rise time, Fall time and Propagation delay for W_p/W_n values 60um/30um, 30um/60um and 60um/60um for $V_{DD} = 3.3V$.





Transient Analysis of CMOS Inverter

Fig. 14 : W_p/W_n = 60um/30um Fig. 15 : W_p/W_n = 60um/60um

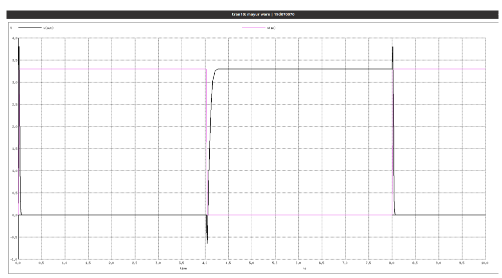


Fig. 16 : Transient Analysis of CMOS Inverter W_p/W_n = 30um/60um

W_p/W_n	Rise time (t_{rise})	Fall time (t_{fall})	Propagation Delay (t_p)
60um/30um	4.77E-11	3.76E-11	7.75E-12
30um/60um	9.12E-11	2.05E-11	4.52E-11
60um/60um	5.85E-11	2.45E-11	3.84E-11

Now, I varied the V_{DD} values form 2V to 3.3V in steps of 0.2V and calculated the propagation delay (t_p). I plotted the graph for t_p vs V_{DD}.

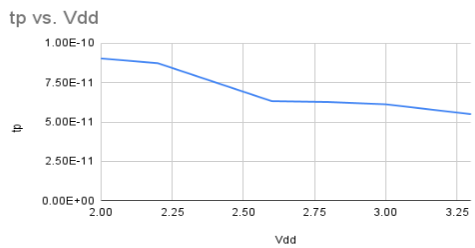


Fig. 17 : t_p vs V_{DD}

In Fig. 17, we can notice that propagation delay (t_p) decreases with increase in V_{DD}

4 Experimental results

This section is not applicable for this experiment.

5 Experiment completion status

I have completed all sections as well as exercises in this lab.

6 Questions for reflection

This section is not applicable for this experiment.

■