EE236: Experiment 5

NMOS I/V Characteristics and Applications

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1 Overview of the experiment

This report contains my approach to the experiment, the circuit's design with the relevant simulation code and output plots.

1.1 Aim of the experiment

- To plot and understand I_D/V_{DS} characteristics of NMOS at different V_{GS} and calculate r_{DS} (resistance linear region), r_0 (resistance saturation region) and V_A (early voltage) considering channel length modulation.
- To plot and understand I_D/V_{GS} characteristics of NMOS in different regions and obtain the parameters V_T, g_m and K (in mA/V^2)
- To plot and understand the effect of Body Bias on I_D/V_{GS} characteristics of NMOS and calculate γ (body effect coefficient)
- To plot and understand voltage transfer characteristics and transient characteristics of CMOS inverter

1.2 Methods

1.2.1 NMOS

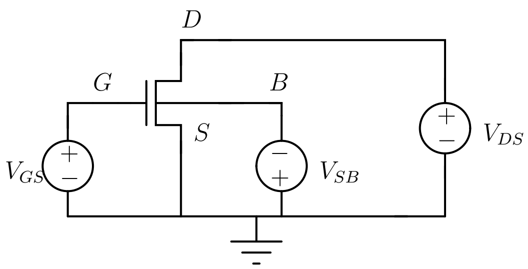
First, I_D/V_{DS} characteristics of NMOS at different V_{GS} was plotted and the parameters were calculated & compared.
Then, I_D/V_{GS} characteristics of NMOS at was plotted in different regions by changing V_{DS} and the parameters were calculated.
Lastly, I_D/V_{GS} characteristics of NMOS at was plotted for different body voltage and behaviour of V_T verses V_{SB} was observed which was used to calculate body effect coefficient.
All figures & parameters were calculated using Python by exporting the NGSPICE vectors.

1.2.2 CMOS Inverter

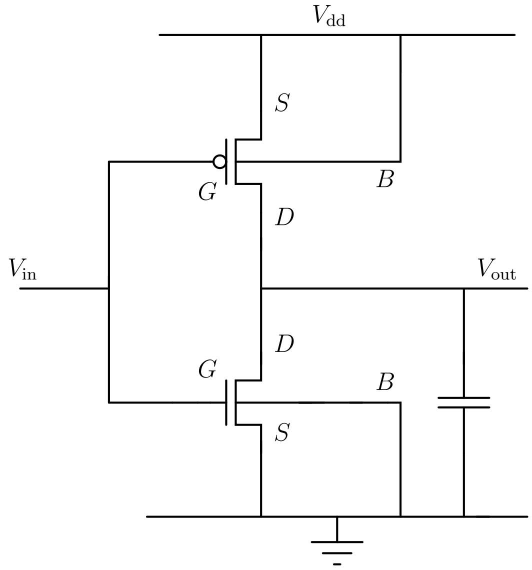
First, Voltage Transfer Characteristics (V_{out} vs V_{in}) was plotted for $W_p/W_n = 60um/30um, 60um/60um, 30um/60um$ and switching threshold was calculated respectively.
Then, Voltage Transfer Characteristics (V_{out} vs V_{in}) was plotted for various $V_{\text{dd}} = 1.5V, 2V, 2.5V, 3V, 3.3V$ and the VTC curves were observed.
All figures & parameters were calculated using Python by exporting the NGSPICE vectors.
Then, Rise (t_r), Fall (t_f), Propagation (t_p) delays were calculated using Transient Characteristics for $W_p/W_n = 60um/30um, 60um/60um, 30um/60um$.
Lastly, Propagation (t_p) delays were calculated using Transient Characteristics for various $V_{\text{dd}} = 2V, 2.3V, 2.6V, 3V, 3.3V$.
All parameters were calculated using NGSPICE and figures using Python.

2 Design

The common circuits designed for all parts are shown below



(a) Circuit for I/V measurement of NMOS



(b) Circuit for characteristics of CMOS inverter

2.1 I_D/V_{DS} Characteristics of NMOS

For the first part the Voltage V_{GS} was varied from $2.5V$ to $4V$ in steps of $0.5V$.
For each V_{GS}, V_{DS} was varied from 0 to $5V$
As in linear region slope I_D/V_{DS} is maximum $\rightarrow r_{DS} = \frac{1}{\text{maximum slope}}$
Similarly in saturation region slope I_D/V_{DS} is minimum $\rightarrow r_0 = \frac{1}{\text{minimum slope}}$
Early voltage can be calculated by taking the mean of the $x-$intercepts of the extrapolated lines from saturation regions.

$$x - \text{intercept} = \frac{-(y - \text{intercept})}{slope}$$

and slope, $y-$intercepts were calculated using Python's `Scipy` package This graph is a straight line in some range of I, V. Also, $I_L = 0$ for Dark characteristics.
We can calculate its slope to get η and y-intercept by interpolating that straight line.

2.2 I_D/V_{GS} characteristics of NMOS for different V_{DS}

Again, the above circuit was used (Figure 1a), V_{GS} was varied from 0 to $5V$

$$I_D = \frac{1}{2}K(2(V_{GS} - V_T)V_{DS} - (V_{DS})^2)$$

In linear region, $(V_{DS})^2$ can be ignored (as $V_{DS} = 200mV$) to give

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

So $V_T = -(\underbrace{y-\text{intercept}}_{-K\cdot V_T\cdot V_{DS}})/\underbrace{\text{slope}}_{K\cdot V_{DS}}$ and $g_m = \frac{\partial I_D}{\partial V_{GS}} = \frac{I_D}{V_{GS}}$(as the plot is linear)
In saturation region, as $V_{DS} = 5V \leq (V_{GS} - V_T)$, I_D depends only on $(V_{GS} - V_T)$ (ideally)

$$I_D = \frac{1}{2}K(V_{GS} - V_T)^2$$

$$\sqrt{I_D} = \frac{1}{\sqrt{2}}\sqrt{K}(V_{GS} - V_T)$$

So from the $\sqrt{I_D}/V_{GS}$ characteristics, $K = 2 \cdot \text{slope}^2$ (in A/V^2) $= 1000 \cdot 2 \cdot \text{slope}^2$ (in mA/V^2)
$V_T = -(\underbrace{y-\text{intercept}}_{-\frac{1}{\sqrt{2}}\sqrt{K}\cdot V_T})/\underbrace{\text{slope}}_{\frac{1}{\sqrt{2}}\sqrt{K}}$
and $g_m = \frac{\partial I_D}{\partial V_{GS}}$ will be different for different V_{GS} (as the plot is quadratic)
Say, $V_{GS} = 3V$, then at that point, $g_m = \frac{I_D}{V_{GS}}\mho$

2.3 I_D/V_{GS} characteristics of NMOS for different V_{SB}

Again, the same circuit ((Figure 1a)) was used.
With V_{SB} varying from 0 to $4V$ in steps of $1V$. $V_{DS} = 200mV$
To calculate V_T, again we extrapolate the lines and get the $x-$intercept.
Then γ was calculated for each V_T and V_{SB} as shown below (average of all γ was taken)

$$V_T = V_{T0} + \gamma(\sqrt{\varphi_s + V_{SB}} - \sqrt{\varphi_s}) \quad (\text{where } \varphi_s = 0.8V)$$

2.4 CMOS Inverter Voltage Transfer Characteristics

The circuit used is shown in (Figure 1b) with MOSFETs instantiated using the given templates
$V_{\text{dd}} = 3.3V$ and Load capacitance was taken as $0.05pF$
V_{in} was varied from 0 to $3.3V$ to obtain Voltage Transfer Characteristics (V_{out} vs V_{in})
The switching threshold was calculated in 2 ways, First, when in the simulation V_{out} and V_{in} were closest.
Second, when the slope of V_{out} vs V_{in} was maximum.
Average of both V_{out} and V_{in} at such point was taken as the answer.
Note that both approach yielded same answers.
As ideally at such point $V_{\text{out}} = V_{\text{in}}$ and slope is infinity (due to symmetry).

2.5 CMOS Inverter Transient Characteristics

Here, again the same circuit (Figure 1b) was used. Transient Analysis was done and the parameters $t_r, t_f, t_{pr}, t_{pf}, t_p$ were calculated using definition given in handout.
For the first task, Wp/Wn was varied from $60um/30um, 60um/60um, 30um/60um$ and
For the second task V_{dd} was varied from $2V, 2.3V, 2.6V, 3V, 3.3V$

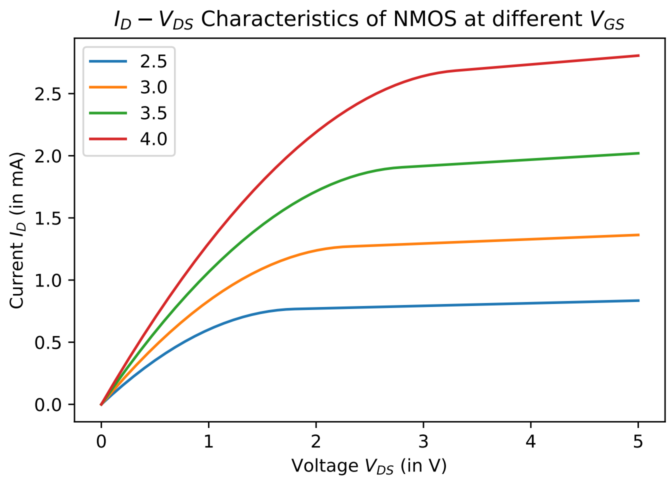
3 Simulation results

3.1 Plots

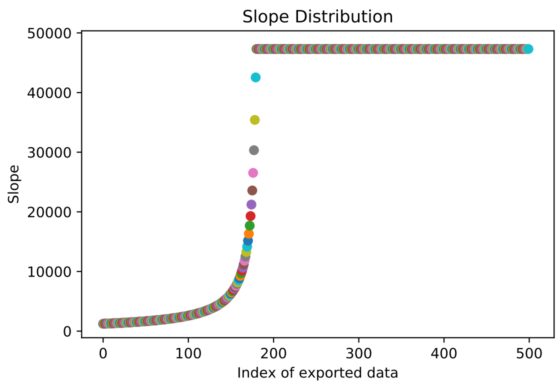
3.1.1 I_D/V_{DS} characteristics of NMOS for different V_{GS}

V_{GS} (in V)	R_{DS} (in Ω)	V_A (in V)	R_0 (in Ω)
2.5	1237.6478888513582	34.48275886	47301.45215462
3	968.0078253752603	34.48190104	28970.39225912
3.5	794.8400573159166	34.48198702	19547.66698594
4	674.2269987459377	34.48234203	14073.01077994

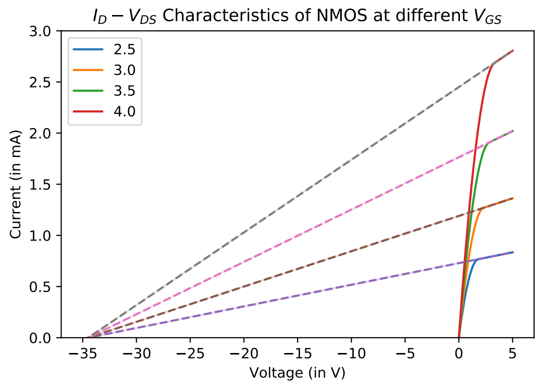
Table 1: Parameter Values obtained from the characteristics



(a) Different V_{GS}



(b) Slope Distribution



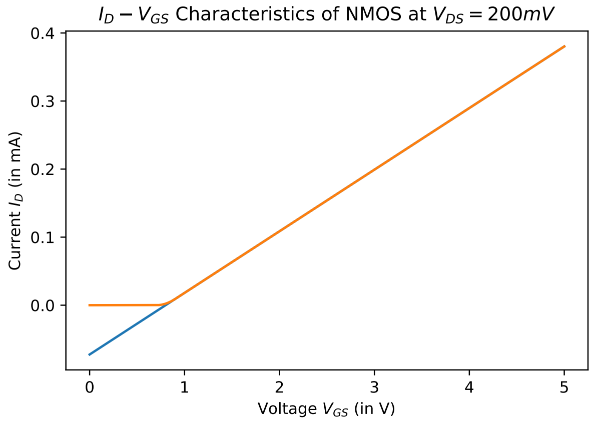
(c) Characteristics with the Extrapolated Lines

Figure 2: I_D/V_{DS} characteristics of NMOS

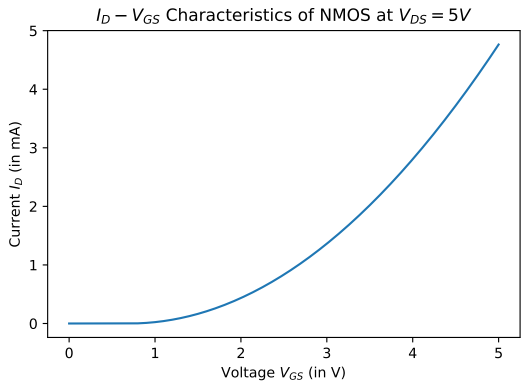
In Figure 2, as magnitude of V_{GS} increases, magnitude of I_D increases.

All extrapolated lines meet at $V_A = 34.48224723629818$
Also, both R_{DS} and R_0 decreases with the increase of V_{GS}.

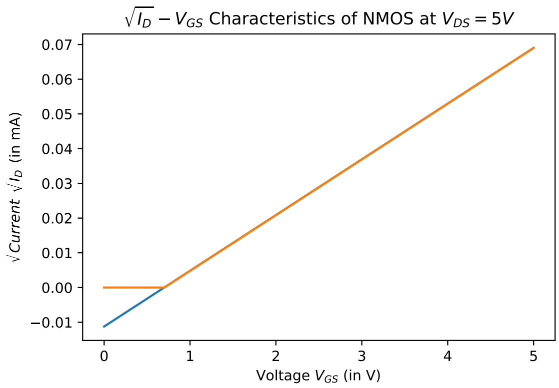
3.1.2 I_D/V_{GS} characteristics of NMOS for different V_{DS}



(a) $V_{DS} = 200mV$ with the Extrapolated Line



(b) $V_{DS} = 5mV$

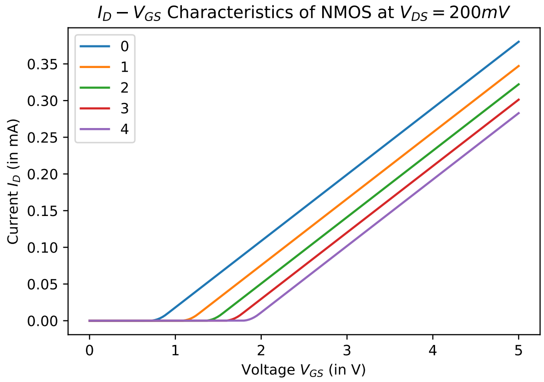


(c) $\sqrt{I_D}/V_{GS}$ characteristics when $V_{DS} = 5V$ with the Extrapolated Line

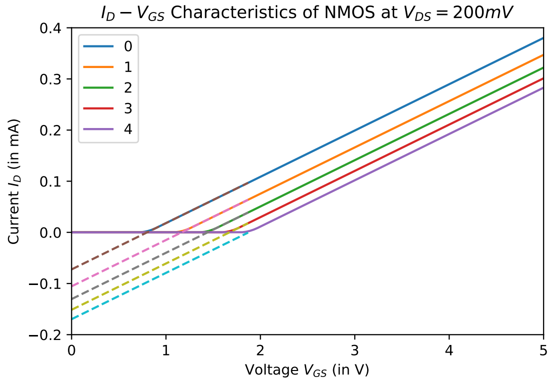
Figure 3: I_D/V_{GS} characteristics of NMOS

In Figure 3a), as magnitude of V_{GS} increases (neglecting the small V_{GS} values as NMOS is saturated), magnitude of I_D increases linearly giving
$V_T = 0.8V$ and $g_m = 0.090522m\mho$
In Figure 3b), as magnitude of V_{GS} increases (neglecting the small V_{GS} values as NMOS is not saturated), magnitude of I_D increases quadratically giving
$V_T = 0.7V$, $g_m = 1.187651m\mho$ (at $V_{GS} = 3V$) and $K = 0.5152501154659527mA/V^2$
V_T is different in both cases, because of approximations in the current (I_D) equation and neglection of channel length modulation.

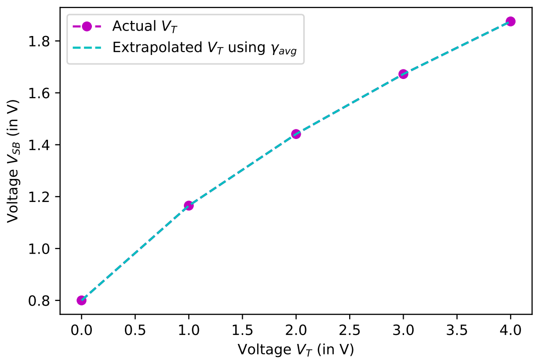
3.1.3 I_D/V_{GS} characteristics of NMOS for different V_{SB}



(a) Different V_{SB}



(b) Extrapolated Lines

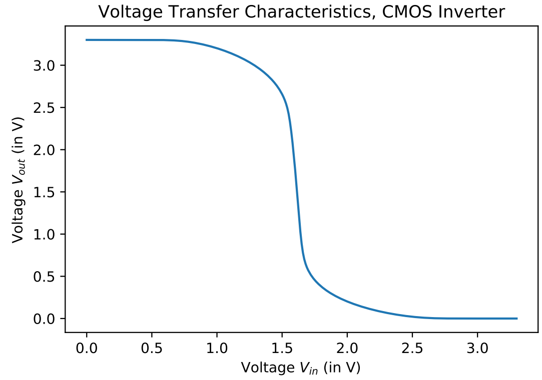


(c) V_T vs V_{SB}

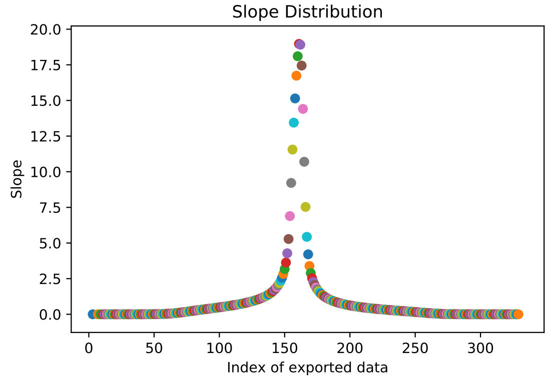
Figure 4: I_D/V_{GS} characteristics of NMOS

In Figure 4, as magnitude of V_{SB} increases, magnitude of I_D reduces giving $V_T = 0.8V, 1.16526333V, 1.44111701V, 1.67223466V, 1.87517436V$ for $V_{SB} = 0V, 1V, 2V, 3V, 4V$ respectively.
From these values, we get $\gamma = 0.85\sqrt{V}$ and it fits the original curve very well.
The dependence of V_T on V_{SB} is similar to a square root graph which increases very slowly. As magnitude of V_T increases, V_{SB}'s magnitude increases but the rate of increase decreases.

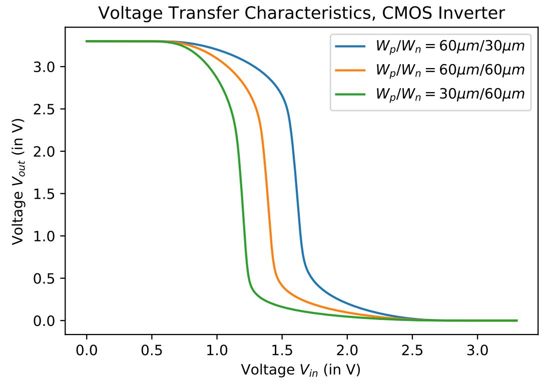
3.1.4 CMOS Inverter Voltage Transfer Characteristics



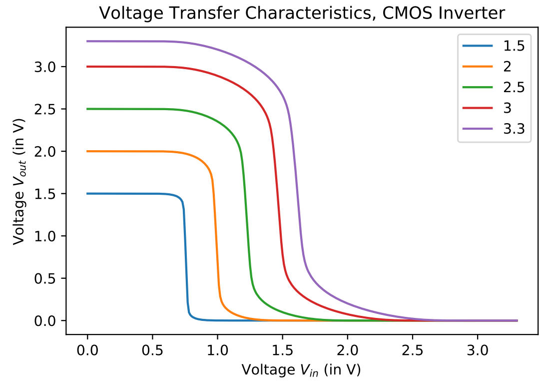
(a) VTC for $W_p/W_n = 60um/30um$



(b) Slope Distribution



(c) VTC dependence on W_p/W_n



(d) VTC dependence on V_{dd} (in V)

Figure 5: CMOS Inverter Voltage Transfer Characteristics

W_p/W_n (in um/um)	Switching Threshold (in V)
$60/30um$	1.596188005
$60um/60um$	1.417962135
$30um/60um$	1.244664655

Table 2: Parameter Values obtained from the characteristics

From the Figure 5,
As W_p/W_n decreases, the high slope (vertical) part of VTCs shift leftwards and the switching threshold decreases.
As V_{dd} increases, the high slope (vertical) part of VTCs shift rightwards and the maximum V_{out} value increases.

3.1.5 CMOS Inverter Transient Characteristics

W_p/W_n (in um/um)	t_r (in s)	t_f (in s)	t_{pr} (in s)	t_{pf} (in s)	t_p (in s)
60/30	4.665700e-11	3.676000e-11	3.407600e-11	3.523700e-11	3.465650e-11
60/60	5.675300e-11	2.373900e-11	4.213600e-11	2.368700e-11	3.291150e-11
30/60	8.996600e-11	1.992900e-11	6.511800e-11	1.933100e-11	4.222450e-11

Table 3: Delay parameter Values obtained from the characteristics

As W_p/W_n decreases, t_r, t_{pr} increases, t_f, t_{pf} decreases and t_p first increases then decreases. This shows that 'rise' delays increase and 'fall' delays decrease with decrease in W_p/W_n. Propagation delay t_p which is an average of 'rise' and 'fall' delay will increase/decrease depending on which factor got affected more.
Next, for $Wp/Wn = 60um/30um$, the variation of propogation delays with $V_{\rm dd}$ is shown

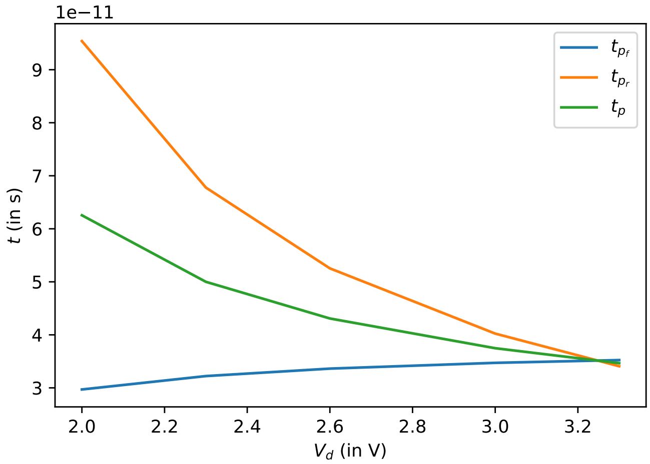


Figure 6: Variation of Propogation Delays with $V_{\rm dd}$
CMOS Inverter Transient Characteristics

As shown in Figure 6,
The rise propogation delay decreases with increase in $V_{\rm dd}$
The fall propogation delay increase with increase in $V_{\rm dd}$
The 'rise' delay factor got affected more than 'fall' delay factor.
Hence, propogation delay decreases with increase in $V_{\rm dd}$.

3.2 NGSPICE Netlists

3.2.1 I_D/V_{DS} characteristics of NMOS for different V_{GS}

3.2.1.1 $V_{GS} = 2.5V$

```
Param Rathour (190070049), I_D - V_DS Characteristics of NMOS at V_GS = 2.5V
.include ALD1105N.txt       ; Includes NMOS Model
M1 d g gnd gnd ALD1105N
VD mid gnd 0
Vdummy d mid 0
VG g gnd 2.5
.dc VD 0 5 0.01             ; DC Analysis
.control
run
let I_D = -I(Vdummy)
let V_DS = V(d)
plot I_D vs V_DS
wrdata 111.txt I_D vs V_DS
.endc
.end
```

3.2.1.2 $V_{GS} = 3V$

```
Param Rathour (190070049), I_D - V_DS Characteristics of NMOS at V_GS = 3V
.include ALD1105N.txt       ; Includes NMOS Model
M1 d g gnd gnd ALD1105N
VD mid gnd 0
Vdummy d mid 0
VG g gnd 3
.dc VD 0 5 0.01             ; DC Analysis
.control
run
let I_D = -I(Vdummy)
let V_DS = V(d)
plot I_D vs V_DS
wrdata 112.txt I_D vs V_DS
.endc
.end
```

3.2.1.3 $V_{GS} = 3.5V$

```
Param Rathour (190070049), I_D - V_DS Characteristics of NMOS at V_GS = 3.5V
.include ALD1105N.txt       ; Includes NMOS Model
M1 d g gnd gnd ALD1105N
VD mid gnd 0
```

```
Vdummy d mid 0
VG g gnd 3.5
.dc VD 0 5 0.01             ; DC Analysis
.control
run
let I_D = -I(Vdummy)
let V_DS = V(d)
plot I_D vs V_DS
wrdata 113.txt I_D vs V_DS
.endc
.end
```

3.2.1.4 $V_{GS} = 4V$

```
Param Rathour (190070049), I_D - V_DS Characteristics of NMOS at V_GS = 4V
.include ALD1105N.txt       ; Includes NMOS Model
M1 d g gnd gnd ALD1105N
VD mid gnd 0
Vdummy d mid 0
VG g gnd 4
.dc VD 0 5 0.01             ; DC Analysis
.control
run
let I_D = -I(Vdummy)
let V_DS = V(d)
plot I_D vs V_DS
wrdata 114.txt I_D vs V_DS
.endc
.end
```

3.2.2 I_D/V_{GS} characteristics of NMOS for different V_{DS}

3.2.2.1 $V_{DS} = -200mV$

```
Param Rathour (190070049), I_D - V_GS Characteristics of NMOS at V_DS = 200mV
.include ALD1105N.txt       ; Includes NMOS Model
M1 d g gnd gnd ALD1105N
VD mid gnd 200m
Vdummy d mid 0
VG g gnd 0
.dc VG 0 5 0.01             ; DC Analysis
.control
run
let I_D = -I(Vdummy)
let V_GS = V(g)
plot I_D vs V_GS
```

```
wrdata 211.txt I_D vs V_GS
.endc
.end
```

3.2.2.2 $V_{DS} = -5V$

```
Param Rathour (190070049), I_D - V_GS Characteristics of NMOS at V_DS = 5V
.include ALD1105N.txt       ; Includes NMOS Model
M1 d g gnd gnd ALD1105N
VD mid gnd 5
Vdummy d mid 0
VG g gnd 0
.dc VG 0 5 0.01             ; DC Analysis
.control
run
let I_D = -I(Vdummy)
let V_GS = V(g)
plot I_D vs V_GS
wrdata 221.txt I_D vs V_GS
.endc
.end
```

3.2.3 I_D/V_{GS} characteristics of NMOS for different V_{SB}

3.2.3.1 $V_{SB} = 0$

```
Param Rathour (190070049), Effect of Body Bias
.include ALD1105N.txt       ; Includes NMOS Model
M1 d g gnd b ALD1105N
VD mid gnd 200m
Vdummy d mid 0
VG g gnd 0
VB b gnd 0
.dc VG 0 5 0.01             ; DC Analysis
.control
run
let I_D = -I(Vdummy)
let V_GS = V(g)
plot I_D vs V_GS
wrdata 311.txt I_D vs V_GS
.endc
.end
```

3.2.3.2 $V_{SB} = 1V$

```
Param Rathour (190070049), Effect of Body Bias
.include ALD1105N.txt       ; Includes NMOS Model
M1 d g gnd b ALD1105N
VD mid gnd 200m
Vdummy d mid 0
VG g gnd 0
VB b gnd -1
.dc VG 0 5 0.01             ; DC Analysis
.control
run
let I_D = -I(Vdummy)
let V_GS = V(g)
plot I_D vs V_GS
wrdata 312.txt I_D vs V_GS
.endc
.end
```

3.2.3.3 $V_{SB} = 2V$

```
Param Rathour (190070049), Effect of Body Bias
.include ALD1105N.txt       ; Includes NMOS Model
M1 d g gnd b ALD1105N
VD mid gnd 200m
Vdummy d mid 0
VG g gnd 0
VB b gnd -2
.dc VG 0 5 0.01             ; DC Analysis
.control
run
let I_D = -I(Vdummy)
let V_GS = V(g)
plot I_D vs V_GS
wrdata 313.txt I_D vs V_GS
.endc
.end
```

3.2.3.4 $V_{SB} = 3V$

```
Param Rathour (190070049), Effect of Body Bias
.include ALD1105N.txt       ; Includes NMOS Model
M1 d g gnd b ALD1105N
VD mid gnd 200m
Vdummy d mid 0
VG g gnd 0
```

```
VB b gnd -3
.dc VG 0 5 0.01             ; DC Analysis
.control
run
let I_D = -I(Vdummy)
let V_GS = V(g)
plot I_D vs V_GS
wrdata 314.txt I_D vs V_GS
.endc
.end
```

3.2.3.5 $V_{SB} = 4V$

```
Param Rathour (190070049), Effect of Body Bias
.include ALD1105N.txt       ; Includes NMOS Model
M1 d g gnd b ALD1105N
VD mid gnd 200m
Vdummy d mid 0
VG g gnd 0
VB b gnd -4
.dc VG 0 5 0.01             ; DC Analysis
.control
run
let I_D = -I(Vdummy)
let V_GS = V(g)
plot I_D vs V_GS
wrdata 315.txt I_D vs V_GS
.endc
.end
```

3.2.4 CMOS Inverter: Voltage Transfer Characteristics dependence on W_p, W_n

3.2.4.1 $W_p/W_n = 60um/30um$

```
Param Rathour (190070049), CMOS Inverter
.include CMOS.txt           ; Includes NMOS Model
.param Wn = {30u} Wp = {60u} Len = {0.4u}
* M drain gate source body cmos
Mn out in gnd gnd cmosn L=Len W=Wn AS={2*Wn*Len} PS={2*Wn+4*Len}
    AD={2*Wn*Len} PD={2*Wn+4*Len}
Mp out in Vdd Vdd cmosp L=Len W=Wp AS={2*Wp*Len} PS={2*Wp+4*Len}
    AD={2*Wp*Len} PD={2*Wp+4*Len}
C1 out gnd 0.05p
Vdd Vdd gnd 3.3
Vin in gnd 0
.dc Vin 0 3.3 0.01
```

```
.control
run
plot V(out) vs V(in)
wrdata 411.txt V(out) vs V(in)
.endc
.end
```

3.2.4.2 $W_p/W_n = 60um/60um$

```
Param Rathour (190070049), CMOS Inverter
.include CMOS.txt           ; Includes NMOS Model
.param Wn = {60u} Wp = {60u} Len = {0.4u}
* M drain gate source body cmos
Mn out in gnd gnd cmosn L=Len W=Wn AS={2*Wn*Len} PS={2*Wn+4*Len}
    AD={2*Wn*Len} PD={2*Wn+4*Len}
Mp out in Vdd Vdd cmosp L=Len W=Wp AS={2*Wp*Len} PS={2*Wp+4*Len}
    AD={2*Wp*Len} PD={2*Wp+4*Len}
C1 out gnd 0.05p
Vdd Vdd gnd 3.3
Vin in gnd 0
.dc Vin 0 3.3 0.01
.control
run
plot V(out) vs V(in)
wrdata 412.txt V(out) vs V(in)
.endc
.end
```

3.2.4.3 $W_p/W_n = 30um/60um$

```
Param Rathour (190070049), CMOS Inverter
.include CMOS.txt           ; Includes NMOS Model
.param Wn = {60u} Wp = {30u} Len = {0.4u}
* M drain gate source body cmos
Mn out in gnd gnd cmosn L=Len W=Wn AS={2*Wn*Len} PS={2*Wn+4*Len}
    AD={2*Wn*Len} PD={2*Wn+4*Len}
Mp out in Vdd Vdd cmosp L=Len W=Wp AS={2*Wp*Len} PS={2*Wp+4*Len}
    AD={2*Wp*Len} PD={2*Wp+4*Len}
C1 out gnd 0.05p
Vdd Vdd gnd 3.3
Vin in gnd 0
.dc Vin 0 3.3 0.01
.control
run
plot V(out) vs V(in)
```

```
wrdata 413.txt V(out) vs V(in)
.endc
.end
```

3.2.5 CMOS Inverter: Voltage Transfer Characteristics dependence on $V_{\mathbf{dd}}$

3.2.5.1 $V_{\mathbf{dd}} = 1.5V$

```
Param Rathour (190070049), CMOS Inverter
.include CMOS.txt           ; Includes NMOS Model
.param Wn = {30u} Wp = {60u} Len = {0.4u}
* M drain gate source body cmos
Mn out in gnd gnd cmosn L=Len W=Wn AS={2*Wn*Len} PS={2*Wn+4*Len}
    AD={2*Wn*Len} PD={2*Wn+4*Len}
Mp out in Vdd Vdd cmosp L=Len W=Wp AS={2*Wp*Len} PS={2*Wp+4*Len}
    AD={2*Wp*Len} PD={2*Wp+4*Len}
C1 out gnd 0.05p
Vdd Vdd gnd 1.5
Vin in gnd 0
.dc Vin 0 3.3 0.01
.control
run
plot V(out) vs V(in)
wrdata 421.txt V(out) vs V(in)
.endc
.end
```

3.2.5.2 $V_{\mathbf{dd}} = 2V$

```
Param Rathour (190070049), CMOS Inverter
.include CMOS.txt           ; Includes NMOS Model
.param Wn = {30u} Wp = {60u} Len = {0.4u}
* M drain gate source body cmos
Mn out in gnd gnd cmosn L=Len W=Wn AS={2*Wn*Len} PS={2*Wn+4*Len}
    AD={2*Wn*Len} PD={2*Wn+4*Len}
Mp out in Vdd Vdd cmosp L=Len W=Wp AS={2*Wp*Len} PS={2*Wp+4*Len}
    AD={2*Wp*Len} PD={2*Wp+4*Len}
C1 out gnd 0.05p
Vdd Vdd gnd 2
Vin in gnd 0
.dc Vin 0 3.3 0.01
.control
run
plot V(out) vs V(in)
wrdata 422.txt V(out) vs V(in)
.endc
```

```
.end
```

3.2.5.3 $V_{\mathbf{dd}} = 2.5V$

```
Param Rathour (190070049), CMOS Inverter
.include CMOS.txt           ; Includes NMOS Model
.param Wn = {30u} Wp = {60u} Len = {0.4u}
* M drain gate source body cmos
Mn out in gnd gnd cmosn L=Len W=Wn AS={2*Wn*Len} PS={2*Wn+4*Len}
    AD={2*Wn*Len} PD={2*Wn+4*Len}
Mp out in Vdd Vdd cmosp L=Len W=Wp AS={2*Wp*Len} PS={2*Wp+4*Len}
    AD={2*Wp*Len} PD={2*Wp+4*Len}
C1 out gnd 0.05p
Vdd Vdd gnd 2.5
Vin in gnd 0
.dc Vin 0 3.3 0.01
.control
run
plot V(out) vs V(in)
wrdata 423.txt V(out) vs V(in)
.endc
.end
```

3.2.5.4 $V_{\mathbf{dd}} = 3V$

```
Param Rathour (190070049), CMOS Inverter
.include CMOS.txt           ; Includes NMOS Model
.param Wn = {30u} Wp = {60u} Len = {0.4u}
* M drain gate source body cmos
Mn out in gnd gnd cmosn L=Len W=Wn AS={2*Wn*Len} PS={2*Wn+4*Len}
    AD={2*Wn*Len} PD={2*Wn+4*Len}
Mp out in Vdd Vdd cmosp L=Len W=Wp AS={2*Wp*Len} PS={2*Wp+4*Len}
    AD={2*Wp*Len} PD={2*Wp+4*Len}
C1 out gnd 0.05p
Vdd Vdd gnd 3
Vin in gnd 0
.dc Vin 0 3.3 0.01
.control
run
plot V(out) vs V(in)
wrdata 424.txt V(out) vs V(in)
.endc
.end
```

3.2.5.5 $V_{\mathbf{dd}} = 3.3V$

```
Param Rathour (190070049), CMOS Inverter
.include CMOS.txt           ; Includes NMOS Model
.param Wn = {30u} Wp = {60u} Len = {0.4u}
* M drain gate source body cmos
Mn out in gnd gnd cmosn L=Len W=Wn AS={2*Wn*Len} PS={2*Wn+4*Len}
    AD={2*Wn*Len} PD={2*Wn+4*Len}
Mp out in Vdd Vdd cmosp L=Len W=Wp AS={2*Wp*Len} PS={2*Wp+4*Len}
    AD={2*Wp*Len} PD={2*Wp+4*Len}
C1 out gnd 0.05p
Vdd Vdd gnd 3.3
Vin in gnd 0
.dc Vin 0 3.3 0.01
.control
run
plot V(out) vs V(in)
wrdata 425.txt V(out) vs V(in)
.endc
.end
```

3.2.6 CMOS Inverter: Transient Characteristics dependence on W_p, W_n

3.2.6.1 $W_p/W_n = 60um/30um$

```
Param Rathour (190070049), CMOS Inverter
.include CMOS.txt           ; Includes NMOS Model
.param Wn = {30u} Wp = {60u} Len = {0.4u}
.param Vd = 3.3
* M drain gate source body cmos
Mn out in gnd gnd cmosn L=Len W=Wn AS={2*Wn*Len} PS={2*Wn+4*Len}
    AD={2*Wn*Len} PD={2*Wn+4*Len}
Mp out in Vdd Vdd cmosp L=Len W=Wp AS={2*Wp*Len} PS={2*Wp+4*Len}
    AD={2*Wp*Len} PD={2*Wp+4*Len}
C1 out gnd 0.05p
Vdd Vdd gnd Vd
Vin in gnd pulse(0 Vd 0 20p 20p 4n 8n)
* .dc Vin 0 Vd 0.01
.tran 1p 30n
.control
let Vddd = 3.3
run
let l = {Vddd*0.1}
let h = {Vddd*0.9}
let mid = {Vddd*0.5}
meas tran tr1 WHEN V(out) = l CROSS = 2
```

```
meas tran tr2 WHEN V(out) = h CROSS = 2
let tr = tr2-tr1
meas tran tf1 WHEN V(out) = l CROSS = 3
meas tran tf2 WHEN V(out) = h CROSS = 3
let tf = tf1-tf2
meas tran tpr1 WHEN V(in) = mid CROSS = 2
meas tran tpr2 WHEN V(out) = mid CROSS = 2
let tpr = tpr2-tpr1
meas tran tpf1 WHEN V(in) = mid CROSS = 3
meas tran tpf2 WHEN V(out) = mid CROSS = 3
let tpf = tpf2-tpf1
let tp = (tpr + tpf)/2
print tr tf tpr tpf tp
plot V(out) V(in)
wrdata 431.txt V(out)
.endc
.end
```

3.2.6.2 $W_p/W_n = 60um/60um$

```
Param Rathour (190070049), CMOS Inverter
.include CMOS.txt           ; Includes NMOS Model
.param Wn = {60u} Wp = {60u} Len = {0.4u}
.param Vd = 3.3
* M drain gate source body cmos
Mn out in gnd gnd cmosn L=Len W=Wn AS={2*Wn*Len} PS={2*Wn+4*Len}
    AD={2*Wn*Len} PD={2*Wn+4*Len}
Mp out in Vdd Vdd cmosp L=Len W=Wp AS={2*Wp*Len} PS={2*Wp+4*Len}
    AD={2*Wp*Len} PD={2*Wp+4*Len}
C1 out gnd 0.05p
Vdd Vdd gnd Vd
Vin in gnd pulse(0 Vd 0 20p 20p 4n 8n)
* .dc Vin 0 Vd 0.01
.tran 1p 30n
.control
let Vddd = 3.3
run
let l = {Vddd*0.1}
let h = {Vddd*0.9}
let mid = {Vddd*0.5}
meas tran tr1 WHEN V(out) = l CROSS = 2
meas tran tr2 WHEN V(out) = h CROSS = 2
let tr = tr2-tr1
meas tran tf1 WHEN V(out) = l CROSS = 3
meas tran tf2 WHEN V(out) = h CROSS = 3
let tf = tf1-tf2
```

```
meas tran tpr1 WHEN V(in) = mid CROSS = 2
meas tran tpr2 WHEN V(out) = mid CROSS = 2
let tpr = tpr2-tpr1
meas tran tpf1 WHEN V(in) = mid CROSS = 3
meas tran tpf2 WHEN V(out) = mid CROSS = 3
let tpf = tpf2-tpf1
let tp = (tpr + tpf)/2
print tr tf tpr tpf tp
plot V(out) V(in)
wrdata 432.txt V(out)
.endc
.end
```

3.2.6.3 $W_p/W_n = 30um/60um$

```
Param Rathour (190070049), CMOS Inverter
.include CMOS.txt           ; Includes NMOS Model
.param Wn = {60u} Wp = {30u} Len = {0.4u}
.param Vd = 3.3
* M drain gate source body cmos
Mn out in gnd gnd cmosn L=Len W=Wn AS={2*Wn*Len} PS={2*Wn+4*Len}
    AD={2*Wn*Len} PD={2*Wn+4*Len}
Mp out in Vdd Vdd cmosp L=Len W=Wp AS={2*Wp*Len} PS={2*Wp+4*Len}
    AD={2*Wp*Len} PD={2*Wp+4*Len}
C1 out gnd 0.05p
Vdd Vdd gnd Vd
Vin in gnd pulse(0 Vd 0 20p 20p 4n 8n)
* .dc Vin 0 Vd 0.01
.tran 1p 30n
.control
let Vddd = 3.3
run
let l = {Vddd*0.1}
let h = {Vddd*0.9}
let mid = {Vddd*0.5}
meas tran tr1 WHEN V(out) = l CROSS = 2
meas tran tr2 WHEN V(out) = h CROSS = 2
let tr = tr2-tr1
meas tran tf1 WHEN V(out) = l CROSS = 3
meas tran tf2 WHEN V(out) = h CROSS = 3
let tf = tf1-tf2
meas tran tpr1 WHEN V(in) = mid CROSS = 2
meas tran tpr2 WHEN V(out) = mid CROSS = 2
let tpr = tpr2-tpr1
meas tran tpf1 WHEN V(in) = mid CROSS = 3
meas tran tpf2 WHEN V(out) = mid CROSS = 3
```

```
let tpf = tpf2-tpf1
let tp = (tpr + tpf)/2
print tr tf tpr tpf tp
plot V(out) V(in)
wrdata 433.txt V(out)
.endc
.end
```

3.2.7 CMOS Inverter: Transient Characteristics dependence on $V_{\mathbf{dd}}$

3.2.7.1 $V_{\mathbf{dd}} = 2V$

```
Param Rathour (190070049), CMOS Inverter
.include CMOS.txt           ; Includes NMOS Model
.param Wn = {30u} Wp = {60u} Len = {0.4u}
.param Vd = 2
* M drain gate source body cmos
Mn out in gnd gnd cmosn L=Len W=Wn AS={2*Wn*Len} PS={2*Wn+4*Len}
    AD={2*Wn*Len} PD={2*Wn+4*Len}
Mp out in Vdd Vdd cmosp L=Len W=Wp AS={2*Wp*Len} PS={2*Wp+4*Len}
    AD={2*Wp*Len} PD={2*Wp+4*Len}
C1 out gnd 0.05p
Vdd Vdd gnd Vd
Vin in gnd pulse(0 Vd 0 20p 20p 4n 8n)
* .dc Vin 0 Vd 0.01
.tran 1p 30n
.control
let Vddd = Vd
run
let mid = {Vddd*0.5}
meas tran tpr1 WHEN V(in) = mid CROSS = 2
meas tran tpr2 WHEN V(out) = mid CROSS = 2
let tpr = tpr2-tpr1
meas tran tpf1 WHEN V(in) = mid CROSS = 3
meas tran tpf2 WHEN V(out) = mid CROSS = 3
let tpf = tpf2-tpf1
let tp = (tpr + tpf)/2
print tpr tpf tp
plot V(out) V(in)
wrdata 441.txt V(out)
.endc
.end
```

3.2.7.2 $V_{\mathbf{dd}} = 2.3V$

```
Param Rathour (190070049), CMOS Inverter
.include CMOS.txt           ; Includes NMOS Model
.param Wn = {30u} Wp = {60u} Len = {0.4u}
.param Vd = 2.3
* M drain gate source body cmos
Mn out in gnd gnd cmosn L=Len W=Wn AS={2*Wn*Len} PS={2*Wn+4*Len}
    AD={2*Wn*Len} PD={2*Wn+4*Len}
Mp out in Vdd Vdd cmosp L=Len W=Wp AS={2*Wp*Len} PS={2*Wp+4*Len}
    AD={2*Wp*Len} PD={2*Wp+4*Len}
C1 out gnd 0.05p
Vdd Vdd gnd Vd
Vin in gnd pulse(0 Vd 0 20p 20p 4n 8n)
* .dc Vin 0 Vd 0.01
.tran 1p 30n
.control
let Vddd = Vd
run
let mid = {Vddd*0.5}
meas tran tpr1 WHEN V(in) = mid CROSS = 2
meas tran tpr2 WHEN V(out) = mid CROSS = 2
let tpr = tpr2-tpr1
meas tran tpf1 WHEN V(in) = mid CROSS = 3
meas tran tpf2 WHEN V(out) = mid CROSS = 3
let tpf = tpf2-tpf1
let tp = (tpr + tpf)/2
print tpr tpf tp
plot V(out) V(in)
wrdata 442.txt V(out)
.endc
.end
```

3.2.7.3 $V_{\mathbf{dd}} = 2.6V$

```
Param Rathour (190070049), CMOS Inverter
.include CMOS.txt           ; Includes NMOS Model
.param Wn = {30u} Wp = {60u} Len = {0.4u}
.param Vd = 2.6
* M drain gate source body cmos
Mn out in gnd gnd cmosn L=Len W=Wn AS={2*Wn*Len} PS={2*Wn+4*Len}
    AD={2*Wn*Len} PD={2*Wn+4*Len}
Mp out in Vdd Vdd cmosp L=Len W=Wp AS={2*Wp*Len} PS={2*Wp+4*Len}
    AD={2*Wp*Len} PD={2*Wp+4*Len}
C1 out gnd 0.05p
Vdd Vdd gnd Vd
Vin in gnd pulse(0 Vd 0 20p 20p 4n 8n)
```

```
* .dc Vin 0 Vd 0.01
.tran 1p 30n
.control
let Vddd = Vd
run
let mid = {Vddd*0.5}
meas tran tpr1 WHEN V(in) = mid CROSS = 2
meas tran tpr2 WHEN V(out) = mid CROSS = 2
let tpr = tpr2-tpr1
meas tran tpf1 WHEN V(in) = mid CROSS = 3
meas tran tpf2 WHEN V(out) = mid CROSS = 3
let tpf = tpf2-tpf1
let tp = (tpr + tpf)/2
print tpr tpf tp
plot V(out) V(in)
wrdata 443.txt V(out)
.endc
.end
```

3.2.7.4 $V_{\mathbf{dd}} = 3V$

```
Param Rathour (190070049), CMOS Inverter
.include CMOS.txt           ; Includes NMOS Model
.param Wn = {30u} Wp = {60u} Len = {0.4u}
.param Vd = 3
* M drain gate source body cmos
Mn out in gnd gnd cmosn L=Len W=Wn AS={2*Wn*Len} PS={2*Wn+4*Len}
    AD={2*Wn*Len} PD={2*Wn+4*Len}
Mp out in Vdd Vdd cmosp L=Len W=Wp AS={2*Wp*Len} PS={2*Wp+4*Len}
    AD={2*Wp*Len} PD={2*Wp+4*Len}
C1 out gnd 0.05p
Vdd Vdd gnd Vd
Vin in gnd pulse(0 Vd 0 20p 20p 4n 8n)
* .dc Vin 0 Vd 0.01
.tran 1p 30n
.control
let Vddd = Vd
run
let mid = {Vddd*0.5}
meas tran tpr1 WHEN V(in) = mid CROSS = 2
meas tran tpr2 WHEN V(out) = mid CROSS = 2
let tpr = tpr2-tpr1
meas tran tpf1 WHEN V(in) = mid CROSS = 3
meas tran tpf2 WHEN V(out) = mid CROSS = 3
let tpf = tpf2-tpf1
let tp = (tpr + tpf)/2
```

```
print tpr tpf tp
plot V(out) V(in)
wrdata 444.txt V(out)
.endc
.end
```

3.2.7.5 $V_{\mathbf{dd}} = 3.3V$

```
Param Rathour (190070049), CMOS Inverter
.include CMOS.txt           ; Includes NMOS Model
.param Wn = {30u} Wp = {60u} Len = {0.4u}
.param Vd = 3.3
* M drain gate source body cmos
Mn out in gnd gnd cmosn L=Len W=Wn AS={2*Wn*Len} PS={2*Wn+4*Len}
    AD={2*Wn*Len} PD={2*Wn+4*Len}
Mp out in Vdd Vdd cmosp L=Len W=Wp AS={2*Wp*Len} PS={2*Wp+4*Len}
    AD={2*Wp*Len} PD={2*Wp+4*Len}
C1 out gnd 0.05p
Vdd Vdd gnd Vd
Vin in gnd pulse(0 Vd 0 20p 20p 4n 8n)
* .dc Vin 0 Vd 0.01
.tran 1p 30n
.control
let Vddd = Vd
run
let mid = {Vddd*0.5}
meas tran tpr1 WHEN V(in) = mid CROSS = 2
meas tran tpr2 WHEN V(out) = mid CROSS = 2
let tpr = tpr2-tpr1
meas tran tpf1 WHEN V(in) = mid CROSS = 3
meas tran tpf2 WHEN V(out) = mid CROSS = 3
let tpf = tpf2-tpf1
let tp = (tpr + tpf)/2
print tpr tpf tp
plot V(out) V(in)
wrdata 445.txt V(out)
.endc
.end
```

3.3 Python Code for Plots and Calculations

```python
import numpy as np
import matplotlib.pyplot as plt
from scipy import stats
import math
```

```python
import pandas as pd
import bisect
```

3.3.1 I_D/V_{DS} characteristics of NMOS for different V_{GS}

```python
V_GS = np.arange(2.5, 4.5, 0.5)

V_DS = []
I_D = []

fig1, ax1 = plt.subplots()
ax1.set_xlabel('Voltage $V_{DS}$ (in V)')
ax1.set_ylabel('Current $I_D$ (in mA)')
ax1.set_title('$I_D-V_{DS}$ Characteristics of NMOS at different $V_{GS}$')

for i in range(len(V_GS)):
    data = pd.read_csv('E:\Program_Files\Spice64\EE236\Lab6\\11' + str(i+1)
                       + '.txt', header = None, skipinitialspace=True,
                       delim_whitespace=True)
    V_DS.append(data[0])
    I_D.append(data[1])
    ax1.plot(V_DS[i], 1000*I_D[i], '-o', markersize=0.01)
ax1.legend(V_GS)
fig1.set_dpi(150)
fig1.savefig('111.pdf')

slopes = []
for i in range(len(V_GS)):
    slope = []
    for j in range(len(V_DS[i])-1):
        slope.append((I_D[i][j+1]-I_D[i][j])/(V_DS[i][j+1]-V_DS[i][j]))
    slopes.append(slope)
# slopes[0]

slope_min = np.zeros(len(V_GS))
slope_max = np.zeros(len(V_GS))
for i in range(len(V_GS)):
    slope_min[i] = min(slopes[i])
    slope_max[i] = max(slopes[i])
print(slope_min)
print(slope_max)

r_DS = [1/i for i in slope_max]
print("r_DS", r_DS)
r_0= [1/i for i in slope_min]
print("r_0", r_0)
```

```
fig1, ax1 = plt.subplots()
ax1.set_xlabel('Index of exported data')
ax1.set_ylabel('Slope')
ax1.set_title('Slope Distribution')
for i in range(len(V_DS[0])-1):
    plt.scatter(i,(V_DS[0][i+1]-V_DS[0][i])/(I_D[0][i+1]-I_D[0][i]))
fig1.set_dpi(150)
fig1.savefig('121.pdf')

y_intercepts = np.zeros(len(V_GS))
slope_fit = np.zeros(len(V_GS))
for i in range(len(V_GS)):
    slope, intercept, r_value, p_value, std_err =
        stats.linregress(V_DS[i][-2:], I_D[i][-2:])
    y_intercepts[i] = intercept
    slope_fit[i] = slope
print(slope_fit)
print(y_intercepts)

V_A = np.zeros(len(V_GS))
R_0 = np.zeros(len(V_GS))
fig1, ax1 = plt.subplots()
ax1.set_xlabel('Voltage (in V)')
ax1.set_ylabel('Current (in mA)')
ax1.set_ylim([0,3])
ax1.set_title('$I_D-V_{DS}$ Characteristics of NMOS at different $V_{GS}$')
fig1.set_dpi(150)
intersect = -35
x = np.arange(intersect,5,0.01)
for i in range(len(V_GS)):
    ax1.plot(V_DS[i], 1000*I_D[i], '-o', markersize=0.01)
for i in range(len(V_GS)):
    ax1.plot(x, 1000*(slope_fit[i]*x+y_intercepts[i]), '--o', markersize=0.01)
    V_A[i] = -y_intercepts[i]/slope_fit[i]
    R_0[i] = 1/slope_fit[i]
print(V_A)
print(np.mean(V_A))
print(R_0)
ax1.legend(V_GS)
fig1.savefig('122.pdf')
```

3.3.2 I_D/V_{GS} characteristics of NMOS for different V_{DS}

```
data = pd.read_csv('E:\Program_Files\Spice64\EE236\Lab6\\211.txt',
                   header = None, skipinitialspace=True, delim_whitespace=True)
```

```
V_GS = data[0]
I_D = data[1]

fig1, ax1 = plt.subplots()
ax1.set_xlabel('Voltage $V_{GS}$ (in V)')
ax1.set_ylabel('Current $I_D$ (in mA)')
ax1.set_title('$I_D-V_{GS}$ Characteristics of NMOS at $V_{DS}=200mV$')
# ax1.legend(V_GS)
fig1.set_dpi(150)
slope, y_intercept, r_value, p_value, std_err =
    stats.linregress(V_GS[-2:], 1000*I_D[-2:])
ax1.plot(V_GS, slope*V_GS + y_intercept, '-o', markersize=0.01)
ax1.plot(V_GS, 1000*I_D, '-o', markersize=0.01)
print(y_intercept)
V_T = -y_intercept/slope
print("V_T =", V_T)
g_m = slope
print("g_m =", g_m)  # in m mhos
fig1.savefig('21.pdf')

data = pd.read_csv('E:\Program_Files\Spice64\EE236\Lab6\\221.txt',
                   header = None, skipinitialspace=True, delim_whitespace=True)
V_GS = data[0]
I_D = data[1]
I_D_sqrt = [math.sqrt(i) for i in I_D]
fig1, ax1 = plt.subplots()
ax1.set_xlabel('Voltage $V_{GS}$ (in V)')
ax1.set_ylabel('Current $I_D$ (in mA)')
ax1.set_title('$I_D-V_{GS}$ Characteristics of NMOS at $V_{DS}=5V$')
# ax1.legend(V_GS)
fig1.set_dpi(150)
ax1.plot(V_GS, 1000*I_D, '-o', markersize=0.01)

fig2, ax2 = plt.subplots()
ax2.set_xlabel('Voltage $V_{GS}$ (in V)')
ax2.set_ylabel('$\sqrt{{Current}}$ $\sqrt{I_D}$ (in mA)')
ax2.set_title('$\sqrt{I_D}-V_{GS}$ Characteristics of NMOS at $V_{DS}=5V$')
slope, y_intercept, r_value, p_value, std_err =
    stats.linregress(V_GS[-2:], (I_D_sqrt[-2:]))
ax2.plot(V_GS, slope*V_GS + y_intercept, '-o', markersize=0.01)
ax2.plot(V_GS, I_D_sqrt, '-o', markersize=0.01)
fig2.set_dpi(150)
V_T = -y_intercept/slope
print("V_T =", V_T)
K = 1000*2*slope**2
print("K =", K) # mA/V^2
# print(V_GS[300])
```

```
g_m = 1000*(I_D[301]-I_D[300]) / (V_GS[301]-V_GS[300])
print("g_m =", g_m)  # in m mhos
fig1.savefig('221.pdf')
fig2.savefig('222.pdf')
# fig2.legend(["Characteristics", "Extrapolation"])
```

3.3.3 I_D/V_{GS} characteristics of NMOS for different V_{SB}

```
V_SB = np.arange(0,5,1)

V_GS = []
I_D = []

fig1, ax1 = plt.subplots()
ax1.set_xlabel('Voltage $V_{GS}$ (in V)')
ax1.set_ylabel('Current $I_D$ (in mA)')
ax1.set_title('$I_D-V_{GS}$ Characteristics of NMOS at $V_{DS}=200mV$')

for i in range(len(V_SB)):
    data = pd.read_csv('E:\Program_Files\Spice64\EE236\Lab6\\31' + str(i+1)
                       + '.txt', header = None, skipinitialspace=True,
                       delim_whitespace=True)
    V_GS.append(data[0])
    I_D.append(data[1])
    ax1.plot(V_GS[i], 1000*I_D[i], '-o', markersize=0.01)
ax1.legend(V_SB)
fig1.set_dpi(150)
fig1.savefig('311.pdf')

y_intercepts = np.zeros(len(V_SB))
slope_fit = np.zeros(len(V_SB))
for i in range(len(V_SB)):
    slope, intercept, r_value, p_value, std_err =
        stats.linregress(V_GS[i][-2:], I_D[i][-2:])
    y_intercepts[i] = intercept
    slope_fit[i] = slope
print(slope_fit)
print(y_intercepts)

V_T = np.zeros(len(V_SB))
fig1, ax1 = plt.subplots()
ax1.set_xlabel('Voltage $V_{GS}$ (in V)')
ax1.set_xlim([0,5])
ax1.set_ylabel('Current $I_D$ (in mA)')
ax1.set_ylim([-0.2,0.4])
ax1.set_title('$I_D-V_{GS}$ Characteristics of NMOS at $V_{DS}=200mV$')
```

```
fig1.set_dpi(150)
intersect = -10
for i in range(len(V_SB)):
    x = np.arange(intersect,-y_intercepts[i]/slope_fit[i],0.01)
    ax1.plot(V_GS[i], 1000*I_D[i], '-o', markersize=0.01)
    V_T[i] = -y_intercepts[i]/slope_fit[i]
for i in range(len(V_SB)):
    ax1.plot(x, 1000*(slope_fit[i]*x+y_intercepts[i]), '--o', markersize=0.01)
print(V_T)
ax1.legend(V_SB)
fig1.savefig('312.pdf')

gamma = []
phi_s = 0.9
V_T0 = V_T[0]
for i in range(1,len(V_SB)):
    gamma.append((V_T[i] - V_T0)/(math.sqrt(phi_s+V_SB[i]) - math.sqrt(phi_s)))
gamma

gamma_avg = np.mean(gamma)
gamma_avg

V_Ta = np.zeros(len(V_SB))
for i in range(len(V_SB)):
    V_Ta[i] = V_T0 + gamma_avg*(math.sqrt(phi_s+V_SB[i]) - math.sqrt(phi_s))

fig1, ax1 = plt.subplots()
ax1.set_xlabel('Voltage $V_{T}$ (in V)')
ax1.set_ylabel('Voltage $V_{SB}$ (in V)')
ax1.plot(V_SB, V_T, '--om')
ax1.plot(V_SB, V_Ta, '--c')
fig1.set_dpi(150)
plt.legend(["Actual $V_T$", "Extrapolated $V_T$ using $\gamma_{avg}$"])
fig1.savefig('32.pdf')
```

3.4 CMOS Inverter Voltage Transfer Characteristics

```
data = pd.read_csv('E:\Program_Files\Spice64\EE236\Lab6\\411.txt',
                   header = None, skipinitialspace=True, delim_whitespace=True)
V_out = data[1]
V_in = data[0]

fig1, ax1 = plt.subplots()
ax1.set_xlabel('Voltage $V_{in}$ (in V)')
ax1.set_ylabel('Voltage $V_{out}$ (in V)')
ax1.set_title('Voltage Transfer Characteristics, CMOS Inverter')
```

```python
# ax1.legend(V_GS)
fig1.set_dpi(150)
ax1.plot(V_in, V_out, '-o', markersize=0.01)
fig1.savefig('411.pdf')

fig1, ax1 = plt.subplots()
ax1.set_xlabel('Index of exported data')
ax1.set_ylabel('Slope')
ax1.set_title('Slope Distribution')

maxi = 0
maxe = 0

for i in range(len(V_in)-1):
    if V_out[i+1] != V_out[i]:
        slope = abs((V_out[i+1]-V_out[i])/(V_in[i+1]-V_in[i]))
        if (maxe < slope):
            maxe = slope
            maxi = i
        plt.scatter(i,slope)
fig1.set_dpi(150)
fig1.savefig('412.pdf')
print(maxi)
print(V_in[maxi])

V_out = []
V_in = []

fig1, ax1 = plt.subplots()
ax1.set_xlabel('Voltage $V_{in}$ (in V)')
ax1.set_ylabel('Voltage $V_{out}$ (in V)')
ax1.set_title('Voltage Transfer Characteristics, CMOS Inverter')

for i in range(3):
    data = pd.read_csv('E:\Program_Files\Spice64\EE236\Lab6\\41' + str(i+1)
                        + '.txt', header = None, skipinitialspace=True,
                        delim_whitespace=True)
    V_out.append(data[1])
    V_in.append(data[0])
    ax1.plot(V_in[i], V_out[i], '-o', markersize=0.01)
ax1.legend(["$W_p/W_n = 60\mu m/30\mu m$", "$W_p/W_n = 60\mu m/60\mu m$",
            "$W_p/W_n = 30\mu m /60\mu m$"])
fig1.set_dpi(150)
fig1.savefig('421.pdf')

for i in range(3):
    maxi = 0
```

```
    maxe = 1e5
    for j in range(len(V_in[i])):
        diff = abs(V_out[i][j] - V_in[i][j])
        if maxe > diff:
            maxe = diff
            maxi = j
    print(V_in[i][maxi], (V_out[i][maxi]))
    print("Switching Threshold =", (V_in[i][maxi]+ (V_out[i][maxi]))/2)

for i in range(3):
    maxi = 0
    maxe = 0
    for j in range(len(V_in[i])-1):
        if V_out[i][j+1] != V_out[i][j]:
            slope = abs((V_out[i][j+1]-V_out[i][j])/(V_in[i][j+1]-V_in[i][j]))
            if (maxe < slope):
                maxe = slope
                maxi = j
    print(V_in[i][maxi], (V_out[i][maxi]))
    print("Switching Threshold =", (V_in[i][maxi]+ (V_out[i][maxi]))/2)

V_out = []
V_in = []
V_dd = [1.5, 3, 3.3]

fig1, ax1 = plt.subplots()
ax1.set_xlabel('Voltage $V_{in}$ (in V)')
ax1.set_ylabel('Voltage $V_{out}$ (in V)')
ax1.set_title('Voltage Transfer Characteristics, CMOS Inverter')

for i in range(3):
    data = pd.read_csv('E:\Program_Files\Spice64\EE236\Lab6\\42' +
                       str(i+1) + '.txt', header = None, skipinitialspace=True,
                       delim_whitespace=True)
    V_out.append(data[1])
    V_in.append(data[0])
    ax1.plot(V_in[i], V_out[i], '-o', markersize=0.01)
ax1.legend(V_dd)
fig1.set_dpi(150)
fig1.savefig('422.pdf')

V_out = []
V_in = []
V_dd = [1.5, 2, 2.5, 3, 3.3]

fig1, ax1 = plt.subplots()
ax1.set_xlabel('Voltage $V_{in}$ (in V)')
```

```
ax1.set_ylabel('Voltage $V_{out}$ (in V)')
ax1.set_title('Voltage Transfer Characteristics, CMOS Inverter')

for i in range(5):
    data = pd.read_csv('E:\Program_Files\Spice64\EE236\Lab6\\42' + str(i+1)
                       + '.txt', header = None, skipinitialspace=True,
                       delim_whitespace=True)
    V_out.append(data[1])
    V_in.append(data[0])
    ax1.plot(V_in[i], V_out[i], '-o', markersize=0.01)
ax1.legend(V_dd)
fig1.set_dpi(150)
fig1.savefig('422.pdf')
```

3.4.1 CMOS Inverter Transient Characteristics

```
V_d = [2, 2.3, 2.6, 3, 3.3]
t_p_f = [2.969600e-11, 3.222300e-11, 3.363000e-11, 3.471800e-11, 3.523700e-11]
t_p_r = [9.539800e-11, 6.777200e-11, 5.253800e-11, 4.023600e-11, 3.407600e-11]
t_p = [6.254700e-11, 4.999750e-11, 4.308400e-11, 3.747700e-11, 3.465650e-11]
fig1, ax1 = plt.subplots()
ax1.plot(V_d, t_p_f)
ax1.plot(V_d, t_p_r)
ax1.plot(V_d, t_p)
ax1.set_xlabel("$V_d$ (in V)")
ax1.set_ylabel("$t$ (in s)")
ax1.legend(["$t_{p_f}$", "$t_{p_r}$", "$t_p$"])
fig1.set_dpi(150)
fig1.savefig('43.pdf')
```

4 Experiment completion status

Completed everything in Lab successfully.

5 Questions for reflection

Please see my Design and Simulation Result sections for these comments.
Overall, the lab was good. Thanks!