ENCM 467 Lab 1
Static Behaviour of N and P channel MOS transistors and a simple nMOS inverter

Andreas Smit

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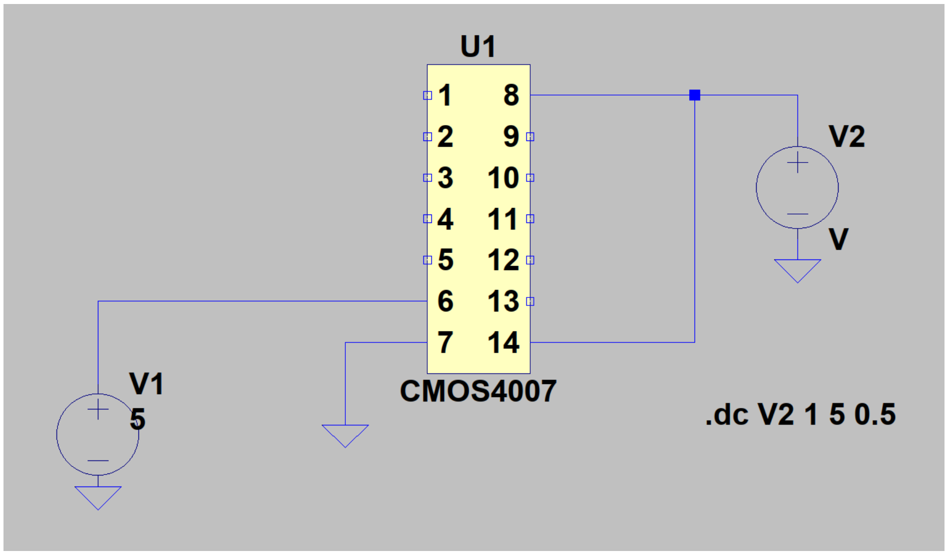

Figure 1: The NMOS circuit analyzed in LT Spice

1 LT Spice MOSFET Operation

1.1 Operation of a NMOS transistor in LT Spice

Figure 1 shows the NMOS circuit used to test. Figure 2 shows the NMOS IV characteristics.

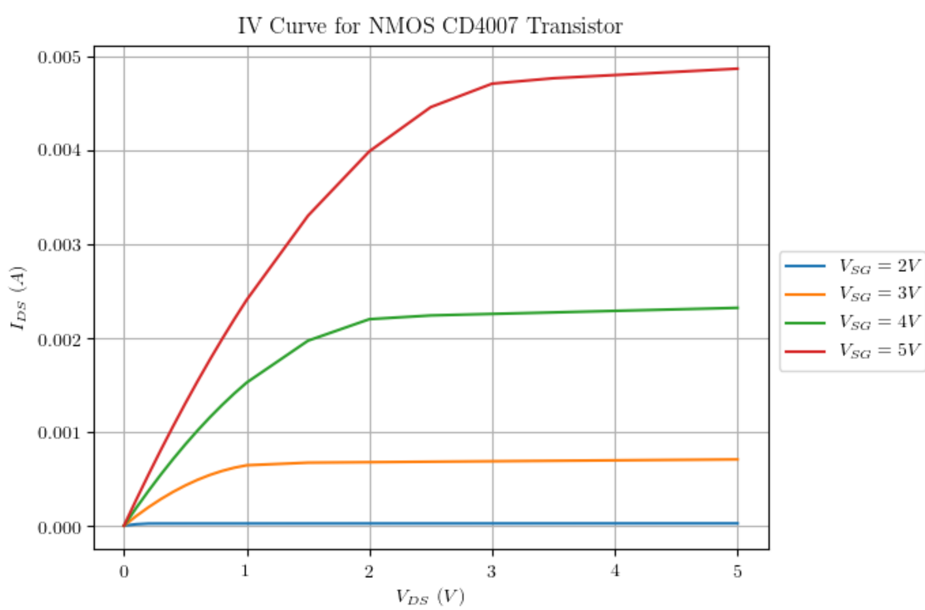

Figure 2: Operating characteristics of the NMOS transistor. The raw data is in appendix A

1.2 Operation of a PMOS transistor in LT Spice

Figure 3 shows the PMOS circuit used to test. Figure 4 shows the PMOS IV characteristics.

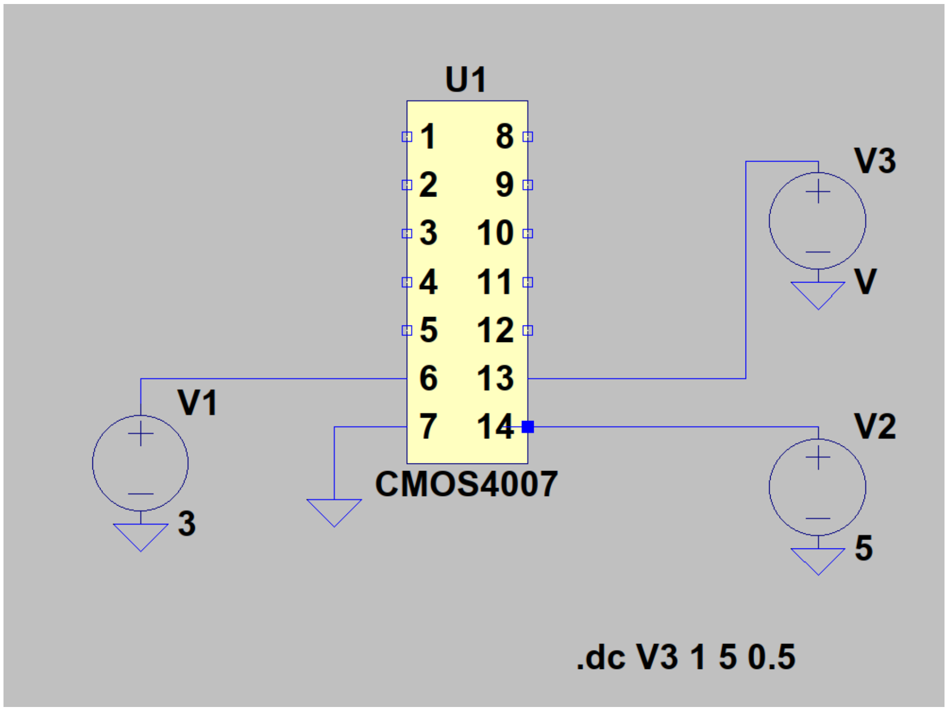

Figure 3: The PMOS circuit analysed in LT Spice

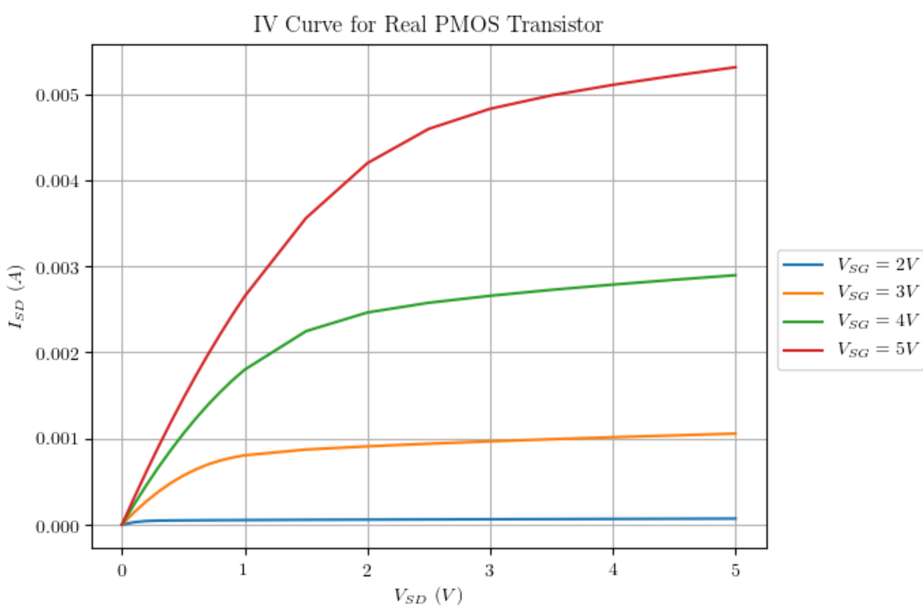

Figure 4: Operating characteristics of the PMOS transistor. The raw data is in appendix A

1.3 Analysis of the nMOS and pMOS circuits.

The complete solution for the nMOS circuit will be shown, however the same method is used for the pMOS circuit and is very similar.

1.3.1 Solution of parameters for nMOS circuit

We know that the current I_D for a nMOS transistor in triode is given by

$$I_D = \frac{k_n}{2}\left(2(V_{GS} - V_T)V_{DS} - V_{DS}^2\right)(1 + \lambda V_{DS}) \tag{1}$$

Equation (1) is cubic in terms of V_{DS} and can be written as a third degree polynomial,

$$I_D = -\frac{1}{2}k_n\lambda V_{DS}^3 + \left(k_n\lambda V_{sat} - \frac{k_n}{2}\right)V_{DS}^2 + k_n V_{sat} V_{DS} \tag{2}$$

where $V_{sat} = V_{GS} - V_T$. Fitting the data in for $V_{GS} = 5V$ in figure 2 for $V_{DS} \leq 3V$ to a cubic equation gets us the graph in figure 5 which has an equation of the form

$$I_D = AV_{DS}^3 + BV_{DS}^2 + CV_{DS} \tag{3}$$

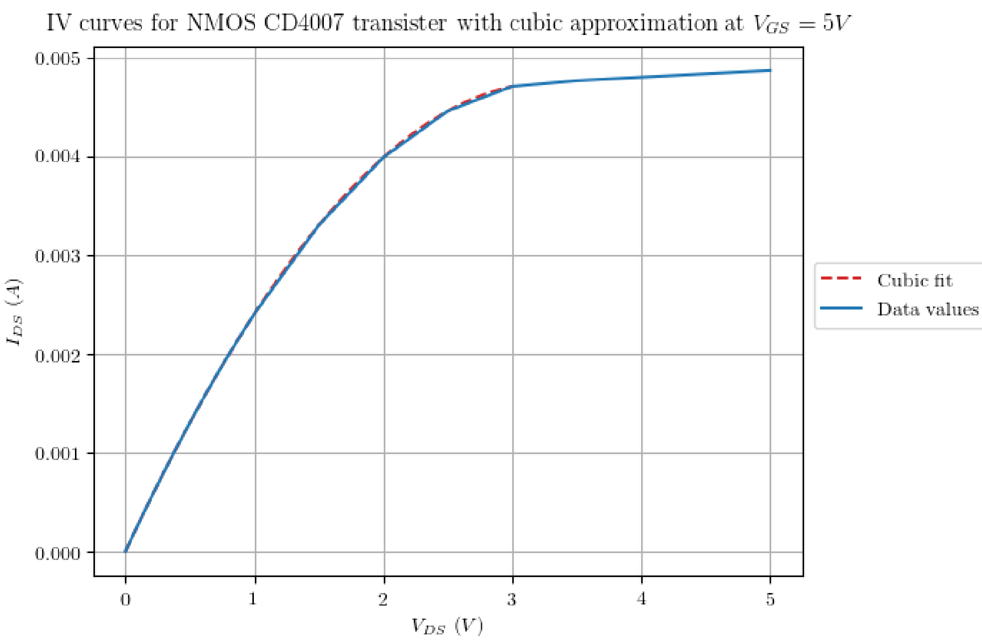

Figure 5: The IV curve for the nMOS transistor for $V_{GS} = 5V$. The cubic curve of best fit for $V_{DS} < 3V$ is plotted as well. Notice that they are a very good fit

The python code in appendix B is used to get the polynomial fit, and the constants A, B, and C. Relating the equations (2) and (3) the following system of non-linear equations is formed.

$$\begin{cases} A = -\frac{1}{2}k_n\lambda \\ B = k_n\lambda V_{sat} - \frac{k_n}{2} \\ C = k_n V_{sat} \end{cases} \tag{4}$$

To solve equation (4) for k_n, λ and V_{sat} we must start by substituting A and C into B.

$$\begin{aligned}
B &= k_n \lambda V_{sat} - \frac{k_n}{2} \\
&= \frac{-2}{-2} k_n \lambda \frac{k_n}{k_n} V_{sat} - \frac{k_n}{2} \\
&= -2 \left(-\frac{1}{2} k_n \lambda \right) \frac{1}{k_n} (k_n V_{sat}) - \frac{k_n}{2} \\
&= -\frac{2AC}{k_n} - \frac{k_n}{2} \\
0 &= \frac{k_n^2}{2} + B k_n + 2AC \\
k_n &= -B \pm \sqrt{B^2 - 4AC}
\end{aligned}$$

Using the value of k_n determined above and the formulas for A and C in equation (4) we can determine all of the constants.

The python script in appendix B gets values `A = -6.50707e-06`, `B = -3.91764e-04`, and `C = 2.80235e-03`, which can then be used to solve for the values of k_n, λ, and V_{sat} as shown below.

$$\begin{aligned}
k_n &= 867.6 \mu A / V^2 \\
\lambda &= 0.015 V^{-1} \\
V_T &= 1.77 V
\end{aligned}$$

1.3.2 Solution of parameters for a pMOS transistor

This will be done very similarly to the analysis shown in section 1.3.1. Using the same curve fitting approach the fit of the data onto a cubic polynomial is shown in figure 6

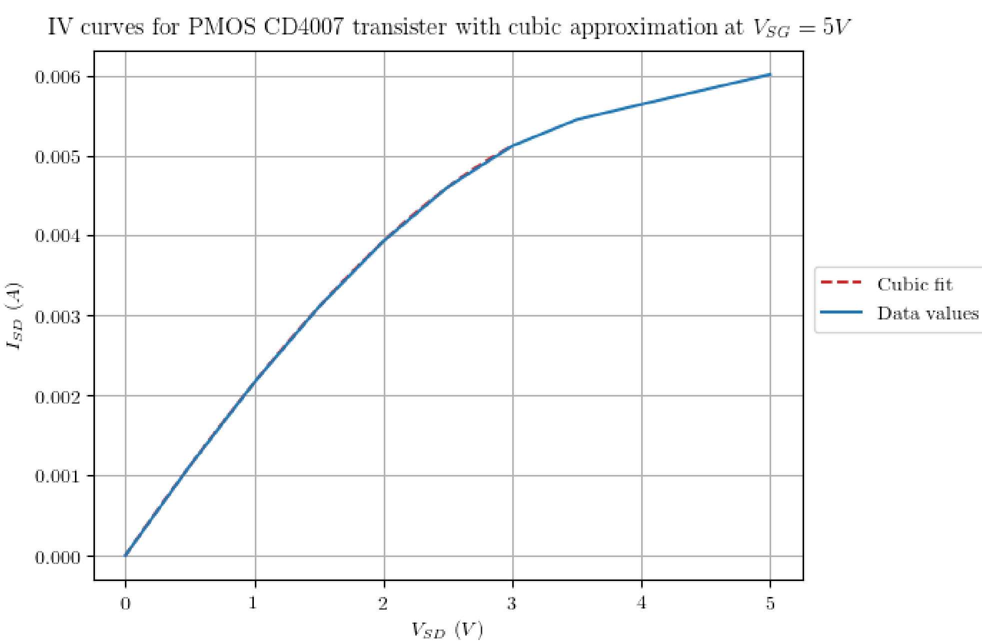

Figure 6: The IV curve for the pMOS transistor for $V_{SG} = 5V$ The cubic curve of best fit for $V_S D < 3V$ is plotted as well. Notice that they are a good fit.

They python script gets values of `A = -2.88000e-=5`, `B = -1.12640e-04` and `C = 2.30400e-03`, which can be used to find the constants,

$$k_p = 640.0\mu A/V^2$$
$$\lambda = 0.09V^{-1}$$
$$V_T = -1.4V$$

1.4 Alternative Measurement Method for the threshold voltage

Using the circuits in figure 7 with the left being an NMOS transistor and the right being a PMOS transistor we can find the curves shown in figures 8 and 9

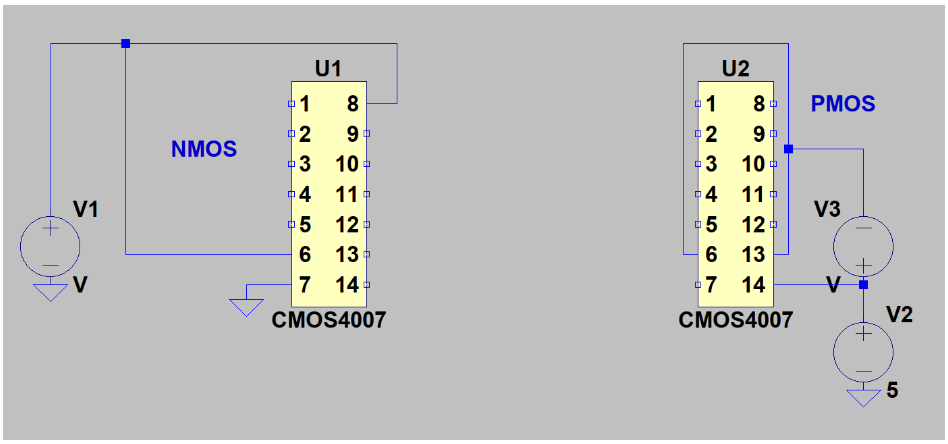

Figure 7: The NMOS and PMOS circuits used to measure the threshold voltage. Note that the circuit will enter saturation when it turns on.

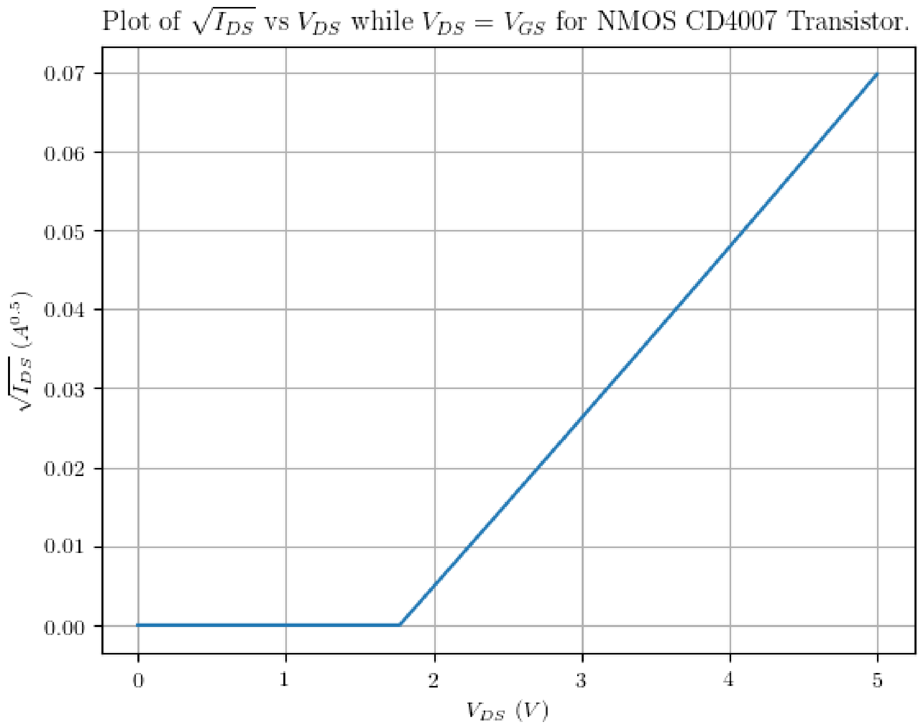

Figure 8: The graph of $\sqrt{I_{DS}}$ vs V_{DS} for the NMOS transistor. It can be seen from the graph that the cut-in voltage is the corner at $V_{DS} = 1.77V$.

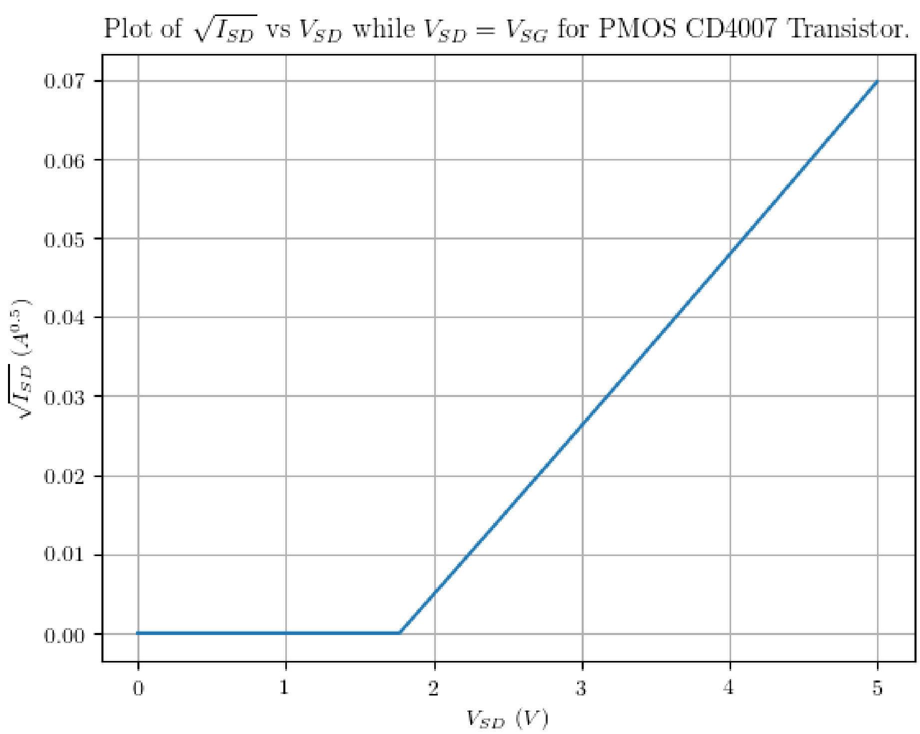

Figure 9: The graph of $\sqrt{I_{SD}}$ vs V_{SD} for the PMOS transistor. It can be seen from the graph that the cut-in voltage is the corner at $V_{SD} = 1.40V$ or $V_T = -1.40V$.

2 An NMOS inverter

The NMOS inverter circuit is shown below in figure 10.

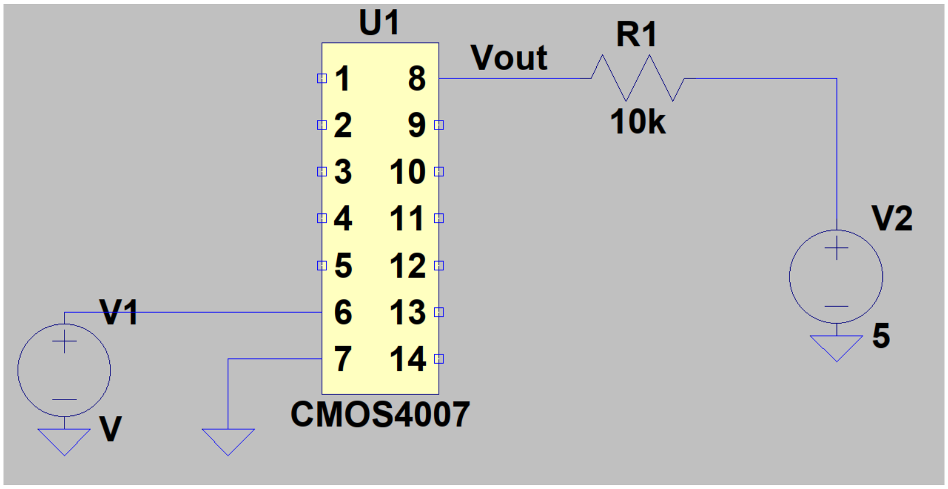

Figure 10: The inverter circuit designed in LT Spice

The graph of the voltage transfer characteristics for the above circuit is then shown in figure 11.

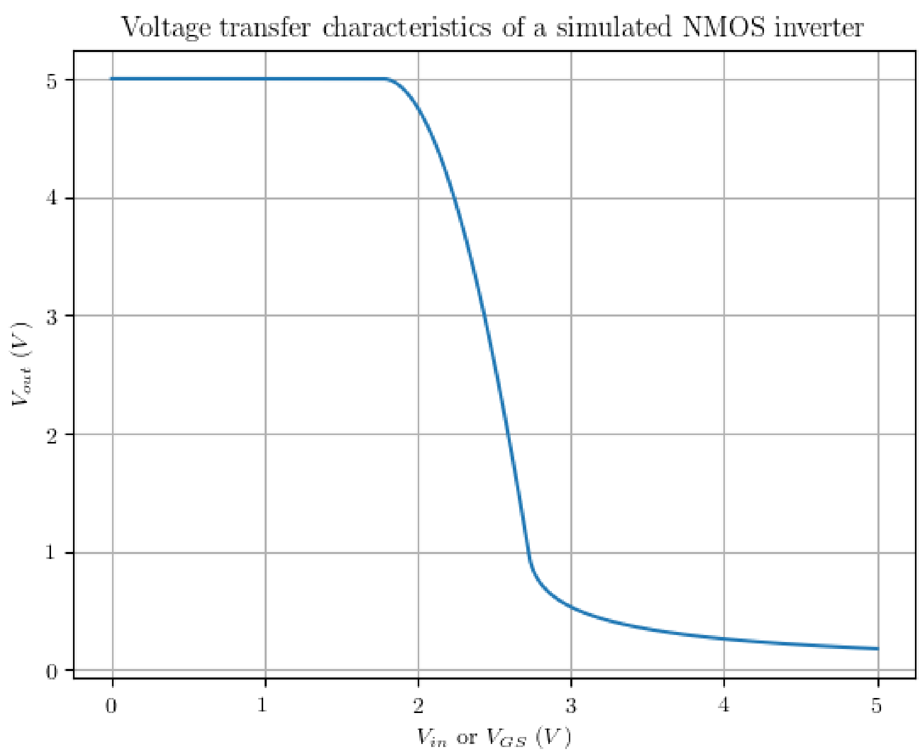

Figure 11: The graph of the voltage transfer characteristics of the NMOS inverter circuit.

3 Comparison of Data to Real Transistor Devices

The nMOS and pMOS iv curves of the real transistor are shown below in figures 12 and 13 respectively.

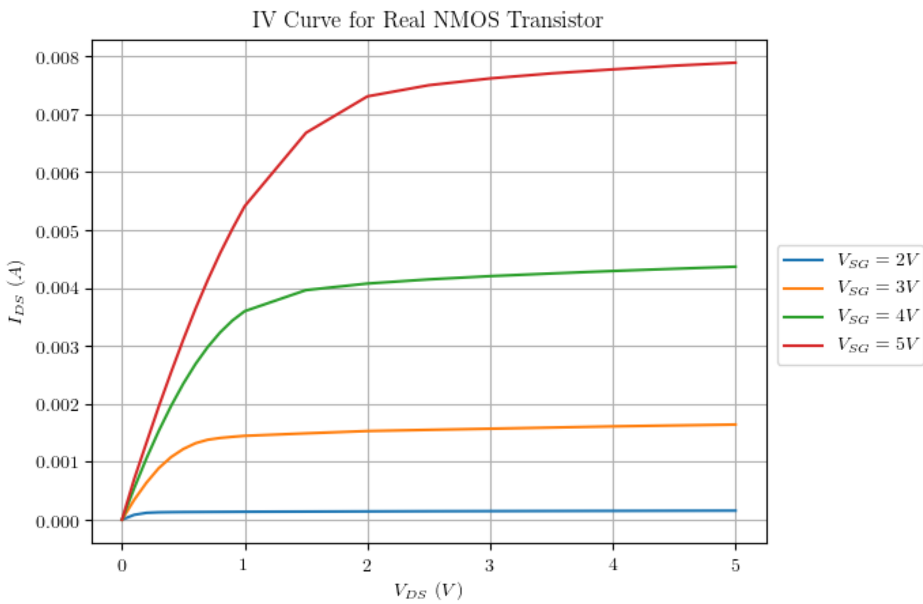

Figure 12: The graph of the iv characteristics for the real NMOS transistor.

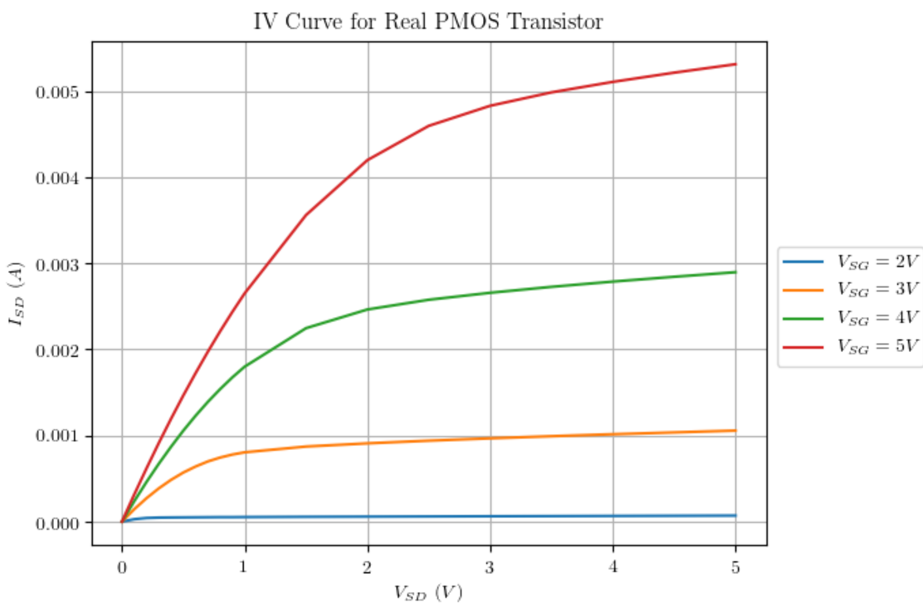

Figure 13: The graph of the iv characteristics for the real PMOS transistor.

3.1 Calculation of parameters of the real transistors

Using the same method from section 1.3.1, the following iv curves with the cubic approximation are obtained. Using the script from Appendix B we can obtain that for the nMOS

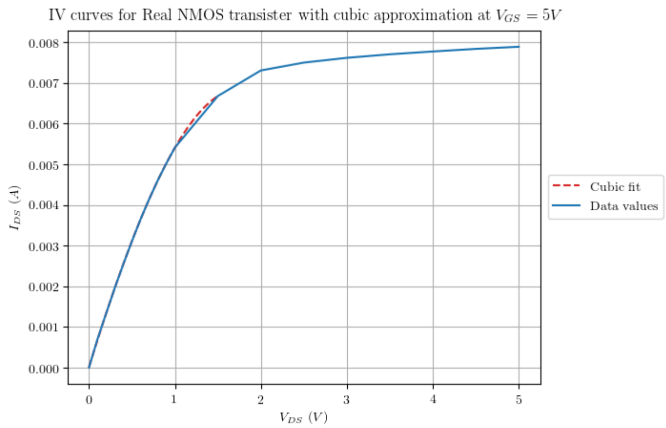

Figure 14: The nMOS cubic approximation with the iv curve at $V_{GS} = 5V$. The approximation is a very close fit to the line.

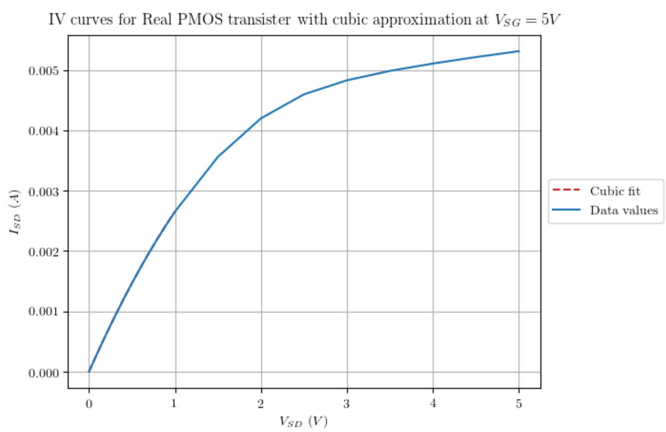

Figure 15: The pMOS cubic approximation with the iv curve at $V_{SG} = 5V$. The approximation is a very close fit to the line.

$$
\begin{aligned}
k_n &= 4.236mA/V^2 \\
\lambda &= 0.137V^{-1} \\
V_T &= 3.4V
\end{aligned}
$$

and for the pMOS

$$
\begin{aligned}
k_n &= 1.149mA/V^2 \\
\lambda &= 0.0064V^{-1} \\
V_T &= -2.2V
\end{aligned}
$$

Clearly these values are very different from the values obtained in part 1. The reason for these differences in values from the theoretical values determined in LT spice could be do to a number of reasons. The largest reasons for the differences will be that LT spice assumes an ideal system. The components in LT spice act according to the equations used to model them. However the actual components in the real world won't exactly follow the equations we have developed to model the devices. For example all wires in LT spice are assumed to be ideal conductors with no resistance, inductance or capacitance, where as in the real world all conductors will have all 3 of these properties that can effect the circuit operation. Another major consideration is temperature; LT spice will assume the temperature of the devices stays constant throughout operation however in the real world as a device is used and current flows through it power will be dissipated as heat. As the temperature of a semiconductor effects conductivity as the temperature changes the iv characteristics will change. All of the above discussed reasons could have lead to the discrepancies in values between the LT SPICE and real circuit data.

3.2 The alternative method for calculating Threshold Voltage

Similarly to with the LT spice simulation, the threshold voltages of the real nMOS and pMOS transistors was calculated by tying the $V_{GS} = V_{DS}$ and $V_{SG} = V_{SD}$ respectively. The graphs of these experiments are shown below.

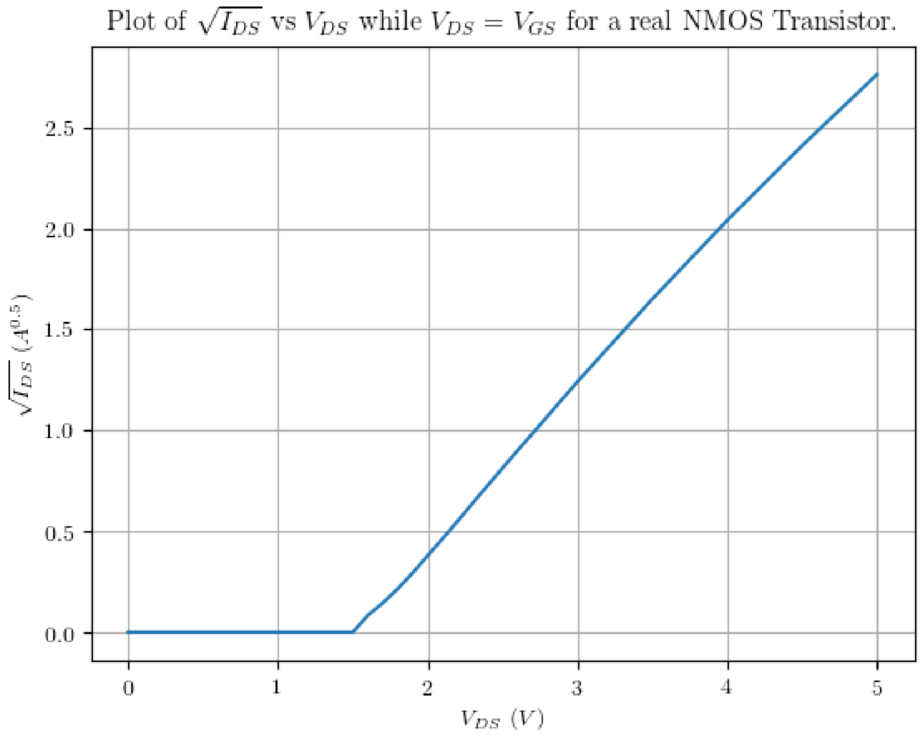

Figure 16: The graph of $\sqrt{I_{DS}}$ vs V_{DS} for the real nMOS transistor. From it we can see that $V_T \approx 1.6V$.

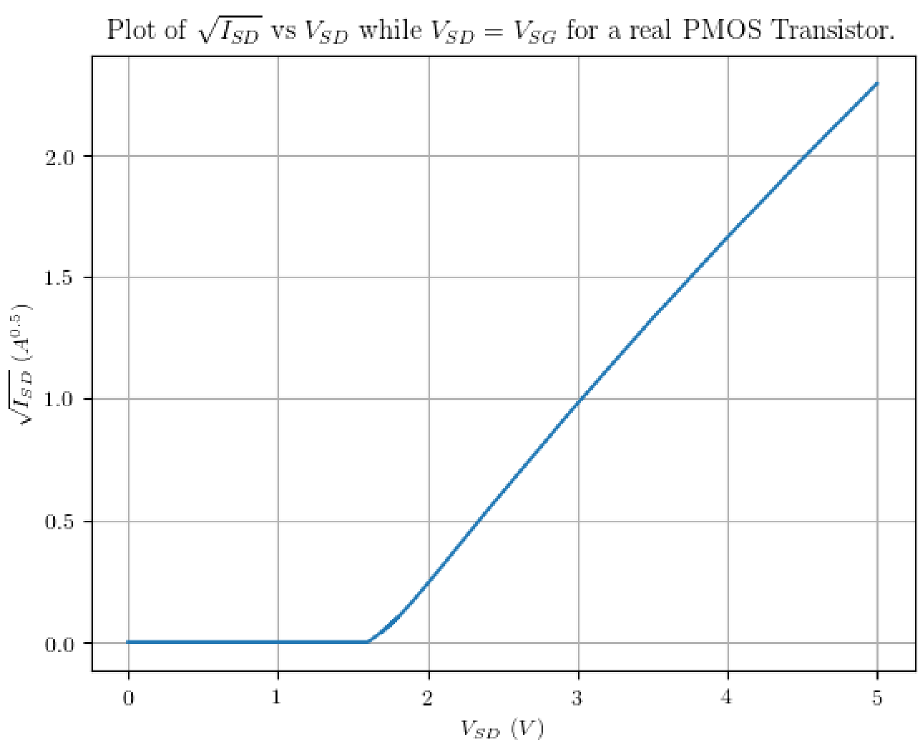

Figure 17: The graph of $\sqrt{I_{SD}}$ vs V_{SD} for the real pMOS transistor. From it we can see that $V_T \approx -1.7V$.

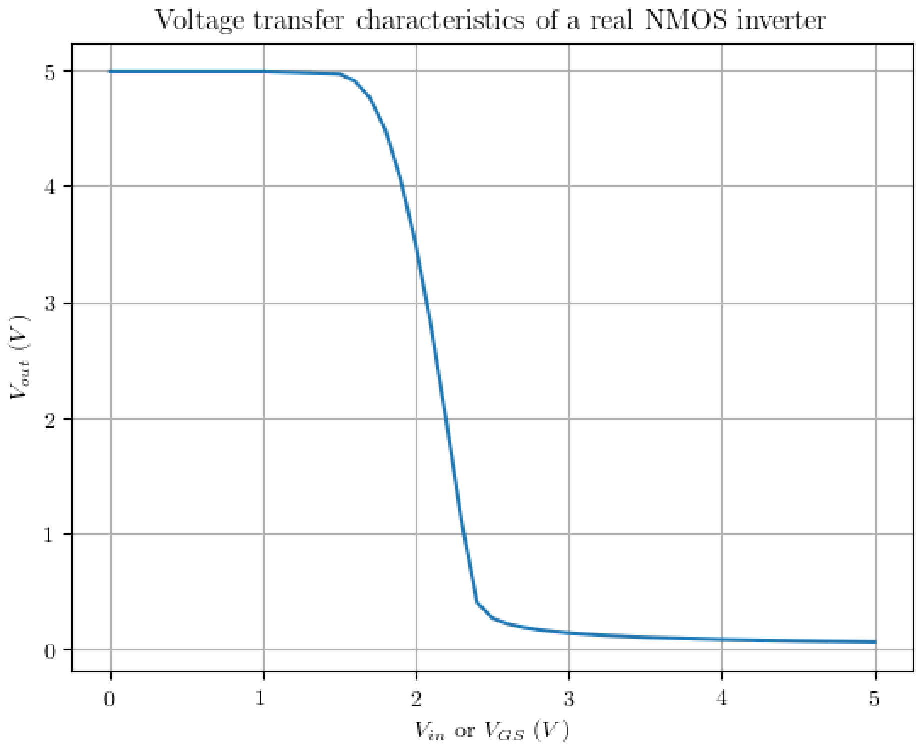

Figure 18: The voltage transfer characteristics of a real NMOS inverter circuit

Clearly there is discrepancy between the values calculated for the real transistors here as opposed to in section 3.1 and from part 1c however these values are much closer to the ones from the simulated transistors then the other real transistor data. As seen in sections 1.3 and 1.4 the two methods can produce very similar and accurate results. However the second method is computationally significantly easier and can even be done to some extent in experiment. Being able to do this for the actual transistor device is more useful then the simulated as the simulated transistor V_T is stated in the library file for LT spice, and the value could very slightly between real transistors purchased and the theoretical simulated values as seen in these experiments. For this reason, it would be best to use the second method with a real transistor to find the threshold voltage for when building a circuit.

3.3 NMOS inverter with a real transistor

The real transistor inverter voltage transfer curve is shown below. There is some minor discrepancies between the real inverter voltage curve and the simulated curve in figures 18 and 11 respectively. The major differences have to do with where some of the voltages occur between the two graphs. For example V_{IL} is greater than 2V for the simulated graph and less than 2V for the real curve. The reasons for this are in part due to the difference in threshold voltage between the two transistors; The real FET has a $V_T \approx 1.6V$ and the simulated FET is $V_T = 1.77V$. The lower threshold voltage of the real fet caused the inverter to trigger earlier then the simulated FET. The V_{OL} is also significantly closer to 0V for the real transistor then the simulated one. This and most of the other effects are probably due to similar reasons for the discrepancy in IV curves between the simulation and real data being that the simulation is a much more ideal situation then the actual data in the lab where non ideal components must be used.

4 Conclusion

Even with the differences in the LT Spice simulation software and the real data provided, the use of LT Spice is still extremely valuable in circuit analysis and design. It allows us to get see how a circuit will respond without having to either do the full calculations to solve the math, or buy the components and in some cases PCBs to properly test our circuit. This can save both time and money making it and other simulators like it a very useful tool for circuit design and analysis. As with all simulations the differences between the theoretical and real world must be taken into account but should normally not be too drastic to make large differences to the outcome.

Appendicies

A Raw Data for recorded in experiments

A.1 Part 1A

A.1.1 $V_{GS} = 2V$

```
v2      -I(V2)
0.000000000000000e+000  4.851912e-032
1.000000000000000e-001  1.564023e-005
2.000000000000000e-001  2.262527e-005
3.000000000000000e-001  2.305129e-005
4.000000000000000e-001  2.308571e-005
5.000000000000000e-001  2.312013e-005
6.000000000000000e-001  2.315455e-005
7.000000000000000e-001  2.318898e-005
7.999999999999999e-001  2.322340e-005
8.999999999999999e-001  2.325782e-005
1.000000000000000e+000  2.329224e-005
1.000000000000000e+000  2.329224e-005
1.500000000000000e+000  2.346436e-005
2.000000000000000e+000  2.363647e-005
2.500000000000000e+000  2.380858e-005
3.000000000000000e+000  2.398069e-005
3.500000000000000e+000  2.415280e-005
4.000000000000000e+000  2.432492e-005
4.500000000000000e+000  2.449703e-005
5.000000000000000e+000  2.466914e-005
```

A.1.2 $V_{GS} = 3V$

```
v2      -I(V2)
0.000000000000000e+000  4.851912e-032
1.000000000000000e-001  1.025304e-004
2.000000000000000e-001  1.966658e-004
3.000000000000000e-001  2.823674e-004
4.000000000000000e-001  3.595959e-004
5.000000000000000e-001  4.283124e-004
6.000000000000000e-001  4.884779e-004
7.000000000000000e-001  5.400532e-004
7.999999999999999e-001  5.829994e-004
8.999999999999999e-001  6.172775e-004
```

```
1.000000000000000e+000  6.428482e-004
1.000000000000000e+000  6.428482e-004
1.500000000000000e+000  6.710627e-004
2.000000000000000e+000  6.759849e-004
2.500000000000000e+000  6.809071e-004
3.000000000000000e+000  6.858294e-004
3.500000000000000e+000  6.907516e-004
4.000000000000000e+000  6.956738e-004
4.500000000000000e+000  7.005960e-004
5.000000000000000e+000  7.055182e-004
```

A.1.3 $V_{GS} = 4V$

```
v2      -I(V2)
0.000000000000000e+000  1.234231e-033
1.000000000000000e-001  1.894205e-004
2.000000000000000e-001  3.707064e-004
3.000000000000000e-001  5.438186e-004
4.000000000000000e-001  7.087181e-004
5.000000000000000e-001  8.653660e-004
6.000000000000000e-001  1.013723e-003
7.000000000000000e-001  1.153750e-003
7.999999999999999e-001  1.285408e-003
8.999999999999999e-001  1.408659e-003
1.000000000000000e+000  1.523462e-003
1.000000000000000e+000  1.523462e-003
1.500000000000000e+000  1.969409e-003
2.000000000000000e+000  2.198325e-003
2.500000000000000e+000  2.238141e-003
3.000000000000000e+000  2.254320e-003
3.500000000000000e+000  2.270499e-003
4.000000000000000e+000  2.286679e-003
4.500000000000000e+000  2.302858e-003
5.000000000000000e+000  2.319037e-003
```

A.1.4 $V_{GS} = 5V$

```
v2      -I(V2)
0.000000000000000e+000  1.234231e-033
1.000000000000000e-001  2.763106e-004
2.000000000000000e-001  5.447469e-004
3.000000000000000e-001  8.052699e-004
4.000000000000000e-001  1.057840e-003
5.000000000000000e-001  1.302419e-003
6.000000000000000e-001  1.538968e-003
7.000000000000000e-001  1.767447e-003
7.999999999999999e-001  1.987817e-003
8.999999999999999e-001  2.200040e-003
1.000000000000000e+000  2.404076e-003
1.000000000000000e+000  2.404076e-003
1.500000000000000e+000  3.300090e-003
2.000000000000000e+000  3.985581e-003
2.500000000000000e+000  4.455668e-003
3.000000000000000e+000  4.705472e-003
3.500000000000000e+000  4.763396e-003
4.000000000000000e+000  4.797339e-003
4.500000000000000e+000  4.831283e-003
5.000000000000000e+000  4.865226e-003
```

A.2 Part 1B

A.2.1 $V_{SG} = 2V$

```
v3        -I(V2)
0.000000000000000e+000   1.670400e-004
1.000000000000000e-001   1.660032e-004
2.000000000000000e-001   1.649664e-004
3.000000000000000e-001   1.639296e-004
4.000000000000000e-001   1.628928e-004
5.000000000000000e-001   1.618560e-004
6.000000000000000e-001   1.608192e-004
7.000000000000000e-001   1.597824e-004
7.999999999999999e-001   1.587456e-004
8.999999999999999e-001   1.577088e-004
1.000000000000000e+000   1.566720e-004
1.000000000000000e+000   1.566720e-004
1.500000000000000e+000   1.514880e-004
2.000000000000000e+000   1.463040e-004
2.500000000000000e+000   1.411200e-004
3.000000000000000e+000   1.359360e-004
3.500000000000000e+000   1.307520e-004
4.000000000000000e+000   1.255680e-004
4.500000000000000e+000   1.170400e-004
5.000000000000000e+000   8.760414e-012
```

A.2.2 $V_{SG} = 3V$

```
v3        -I(V2)
0.000000000000000e+000   1.187840e-003
1.000000000000000e-001   1.180467e-003
2.000000000000000e-001   1.173094e-003
3.000000000000000e-001   1.165722e-003
4.000000000000000e-001   1.158349e-003
5.000000000000000e-001   1.150976e-003
6.000000000000000e-001   1.143603e-003
7.000000000000000e-001   1.136230e-003
7.999999999999999e-001   1.128858e-003
8.999999999999999e-001   1.121485e-003
1.000000000000000e+000   1.114112e-003
1.000000000000000e+000   1.114112e-003
1.500000000000000e+000   1.077248e-003
2.000000000000000e+000   1.040384e-003
2.500000000000000e+000   1.003520e-003
3.000000000000000e+000   9.666560e-004
3.500000000000000e+000   9.261600e-004
4.000000000000000e+000   7.673600e-004
4.500000000000000e+000   4.514400e-004
5.000000000000000e+000   8.760414e-012
```

A.2.3 $V_{SG} = 4V$

```
v3        -I(V2)
0.000000000000000e+000   3.136640e-003
1.000000000000000e-001   3.117171e-003
2.000000000000000e-001   3.097703e-003
3.000000000000000e-001   3.078234e-003
```

```
4.000000000000000e-001  3.058765e-003
5.000000000000000e-001  3.039296e-003
6.000000000000000e-001  3.019827e-003
7.000000000000000e-001  3.000358e-003
7.999999999999999e-001  2.980890e-003
8.999999999999999e-001  2.961421e-003
1.000000000000000e+000  2.941952e-003
1.000000000000000e+000  2.941952e-003
1.500000000000000e+000  2.844608e-003
2.000000000000000e+000  2.747264e-003
2.500000000000000e+000  2.646000e-003
3.000000000000000e+000  2.416640e-003
3.500000000000000e+000  2.015760e-003
4.000000000000000e+000  1.464960e-003
4.500000000000000e+000  7.858400e-004
5.000000000000000e+000  8.760413e-012
```

A.2.4 $V_{SG} = 5V$

```
v3      -I(V2)
0.000000000000000e+000  6.013440e-003
1.000000000000000e-001  5.976115e-003
2.000000000000000e-001  5.938790e-003
3.000000000000000e-001  5.901466e-003
4.000000000000000e-001  5.864141e-003
5.000000000000000e-001  5.826816e-003
6.000000000000000e-001  5.789491e-003
7.000000000000000e-001  5.752166e-003
7.999999999999999e-001  5.714842e-003
8.999999999999999e-001  5.677517e-003
1.000000000000000e+000  5.640192e-003
1.000000000000000e+000  5.640192e-003
1.500000000000000e+000  5.449360e-003
2.000000000000000e+000  5.120640e-003
2.500000000000000e+000  4.606000e-003
3.000000000000000e+000  3.927040e-003
3.500000000000000e+000  3.105360e-003
4.000000000000000e+000  2.162560e-003
4.500000000000000e+000  1.120240e-003
5.000000000000000e+000  8.760419e-012
```

B Python Script for Data Calculation and Graphing

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

plt.rcdefaults()
plt.figure(dpi=200)
plt.rc('text', usetex=True)
plt.rc('font', family='serif')


def read_data(path):
```

```python
    col1 = np.array([])
    col2 = np.array([])
    with open(path) as _file:
        _file.readline()
        for line in _file:
            if line == '\n':
                continue
            tmp = line.split('\t')
            col1 = np.append(col1, np.float(float(tmp[0])))
            col2 = np.append(col2, np.float(float(tmp[1])))
    return col1, col2


def get_values(voltage, current, cut_off, pmos=False):
    if pmos:
        v = voltage[voltage <= cut_off]
        i = current[current.size - v.size:]
    else:
        v = voltage[voltage <= cut_off]
        i = current[0:v.size]
    coef = np.polyfit(v,i,3)
    A = coef[0]
    B = coef[1]
    C = coef[2]

    v = np.arange(0, cut_off, 1E-4)

    i = A*v**3 + B*v**2 + C*v + coef[3]
    plt.plot(v, i, '--C3', label='Cubic fit')
    plt.legend()

    k = -B + np.sqrt(B**2 - 4*A*C)
    _lambda = -2 * A / k
    V_sat = C/k
    print(f'k_n: {k}')
    print(f'lambda: {_lambda}')
    print(f'V_sat: {V_sat}')
    print(A, B, C)

# part 1a

for i in range(2, 6):
    path = f'./part_1a/V_GS{i}.txt'
    voltage, current = read_data(path)

    plt.plot(voltage, current, label=f'$V_{{SG}} = {i}V$')
plt.legend(bbox_to_anchor=(1.01 , 0.6), loc='upper left', borderaxespad=0.2)
```

```python
plt.title('IV Curve for NMOS CD4007 Transistor')
plt.xlabel('$V_{DS}\ (V)$')
plt.ylabel('$I_{DS}\ (A)$')
plt.grid()
plt.savefig("./figures/part_1_nmos.png", bbox_inches='tight')


# part 1b

for i in range(2, 6):
    path = f'./part_1b/V_SG{i}.txt'
    voltage, current = read_data(path)
    v = 5 - voltage
    _i = current
    plt.plot(v, _i, label=f'$V_{{SG}} = {i}V$')
plt.title('IV Curve for PMOS CD4007 Transistor')
plt.legend(bbox_to_anchor=(1.01 , 0.6), loc='upper left', borderaxespad=0.2)
plt.xlabel('$V_{SD}\ (V)$')
plt.ylabel('$I_{SD}\ (A)$')
plt.grid()
plt.savefig("./figures/part_1_pmos.png", bbox_inches='tight')


#part 1C NMOS
path = f'./part_1a/V_GS5.txt'
voltage, current = read_data(path)

get_values(voltage, current, 3)

plt.plot(voltage, current, label=f'Data values')

plt.title('IV curves for NMOS CD4007 transister with cubic approximation at $V_{GS} = 5V$')
plt.legend(bbox_to_anchor=(1.01 , 0.6), loc='upper left', borderaxespad=0.2)
plt.xlabel('$V_{DS}\ (V)$')
plt.ylabel('$I_{DS}\ (A)$')
plt.grid()
plt.savefig("./figures/part_1_ncube.png", bbox_inches='tight')


#part 1C pmos
path = f'./part_1b/V_SG5.txt'
voltage, current = read_data(path)
voltage = 5-voltage
get_values(voltage, current, 3, True)

plt.plot(voltage, current, label=f'Data values')
```

```
plt.title('IV curves for PMOS CD4007 transister with cubic approximation at $V_{SG} = 5V$')
plt.legend(bbox_to_anchor=(1.01 , 0.6), loc='upper left', borderaxespad=0.2)
plt.xlabel('$V_{SD}\ (V)$')
plt.ylabel('$I_{SD}\ (A)$')
plt.grid()
plt.savefig("./figures/part_1_pcube.png", bbox_inches='tight')


# part 1d NMOS


path = f'./part_1d_nmos.txt'
voltage, current = read_data(path)
plt.plot(voltage, np.sqrt(current), label=f'NMOS')
plt.legend(bbox_to_anchor=(1.01 , 0.6), loc='upper left', borderaxespad=0.2)
plt.xlabel('$V_{DS}\ (V)$')
plt.ylabel('$\sqrt{I_{DS}}\ (A^{0.5})$')
plt.grid()
plt.title('Plot of $\sqrt{I_{DS}}$ vs $V_{DS}$ while $V_{DS} = V_{GS}$ for NMOS CD4007 Transis
plt.savefig("./figures/part_1_nsqrt.png", bbox_inches='tight')


# part 1d PMOS


path = f'./part_1d_nmos.txt'
voltage, current = read_data(path)
plt.plot(voltage, np.sqrt(current), label=f'NMOS')
plt.legend(bbox_to_anchor=(1.01 , 0.6), loc='upper left', borderaxespad=0.2)
plt.xlabel('$V_{SD}\ (V)$')
plt.ylabel('$\sqrt{I_{SD}}\ (A^{0.5})$')
plt.grid()
plt.title('Plot of $\sqrt{I_{SD}}$ vs $V_{SD}$ while $V_{SD} = V_{SG}$ for PMOS CD4007 Transis
plt.savefig("./figures/part_1_psqrt.png", bbox_inches='tight')


# part 2

path = './part_2_Vout.txt'
v_in, v_out = read_data(path)
plt.plot(v_in, v_out, label=f'{i}MOS')
#plt.legend(bbox_to_anchor=(1.01 , 0.6), loc='upper left', borderaxespad=0.2)
plt.title('Voltage transfer characteristics of a simulated NMOS inverter')
plt.xlabel('$V_{in}$ or $V_{GS}\ (V)$')
plt.ylabel('$V_{out}\ (V)$')
plt.grid()
plt.savefig("./figures/part_2_invert.png", bbox_inches='tight')
```

```
# Part 3 1a

for i in range(2, 6):
    path = f'./part_3/part1a_VGS{i}.txt'
    voltage, current = read_data(path)

    plt.plot(voltage, current*1E-3, label=f'$V_{{SG}} = {i}V$')
plt.legend(bbox_to_anchor=(1.01 , 0.6), loc='upper left', borderaxespad=0.2)
plt.title('IV Curve for Real NMOS Transistor')
plt.xlabel('$V_{DS}\ (V)$')
plt.ylabel('$I_{DS}\ (A)$')
plt.grid()
plt.savefig("./figures/part_3_nmos.png", bbox_inches='tight')


# part 3 1b

for i in range(2, 6):
    path = f'./part_3/part1b_VSG{i}.txt'
    voltage, current = read_data(path)
    v = 5 - voltage
    _i = current * 1E-3
    plt.plot(v, _i, label=f'$V_{{SG}} = {i}V$')
plt.title('IV Curve for Real PMOS Transistor')
plt.legend(bbox_to_anchor=(1.01 , 0.6), loc='upper left', borderaxespad=0.2)
plt.xlabel('$V_{SD}\ (V)$')
plt.ylabel('$I_{SD}\ (A)$')
plt.grid()
plt.savefig("./figures/part_3_pmos.png", bbox_inches='tight')


#part 3 1C NMOS
path = f'./part_3/part1a_VGS5.txt'
voltage, current = read_data(path)
current = current *1E-3
get_values(voltage, current, 1.5)

plt.plot(voltage, current, label=f'Data values')

plt.title('IV curves for Real NMOS transister with cubic approximation at $V_{GS} = 5V$')
plt.legend(bbox_to_anchor=(1.01 , 0.6), loc='upper left', borderaxespad=0.2)
plt.xlabel('$V_{DS}\ (V)$')
plt.ylabel('$I_{DS}\ (A)$')
plt.grid()
plt.savefig("./figures/part_3_ncube.png", bbox_inches='tight')
```

```
#part 3 1C pmos
path = f'./part_3/part1b_VSG5.txt'
voltage, current = read_data(path)
voltage = 5-voltage
current = current *1E-3
get_values(voltage, current, 1, True)

plt.plot(voltage, current, label=f'Data values')

plt.title('IV curves for Real PMOS transister with cubic approximation at $V_{SG} = 5V$')
plt.legend(bbox_to_anchor=(1.01 , 0.6), loc='upper left', borderaxespad=0.2)
plt.xlabel('$V_{SD}\ (V)$')
plt.ylabel('$I_{SD}\ (A)$')
plt.grid()
plt.savefig("./figures/part_3_pcube.png", bbox_inches='tight')


# part 1d NMOS


path = f'./part_3/part1d_nmos.txt'
voltage, current = read_data(path)
plt.plot(voltage, np.sqrt(current), label=f'NMOS')
plt.legend(bbox_to_anchor=(1.01 , 0.6), loc='upper left', borderaxespad=0.2)
plt.xlabel('$V_{DS}\ (V)$')
plt.ylabel('$\sqrt{I_{DS}}\ (A^{0.5})$')
plt.grid()
plt.title('Plot of $\sqrt{I_{DS}}$ vs $V_{DS}$ while $V_{DS} = V_{GS}$ for a real NMOS Transis
plt.savefig("./figures/part_3_nsqrt.png", bbox_inches='tight')


# part 1d PMOS

path = f'./part_3/part1d_pmos.txt'
voltage, current = read_data(path)
plt.plot(5-voltage, np.sqrt(current), label=f'NMOS')
plt.legend(bbox_to_anchor=(1.01 , 0.6), loc='upper left', borderaxespad=0.2)
plt.xlabel('$V_{SD}\ (V)$')
plt.ylabel('$\sqrt{I_{SD}}\ (A^{0.5})$')
plt.grid()
plt.title('Plot of $\sqrt{I_{SD}}$ vs $V_{SD}$ while $V_{SD} = V_{SG}$ for a real PMOS Transis
plt.savefig("./figures/part_3_psqrt.png", bbox_inches='tight')


path = './part_3/nmos Inverter.txt'
```

```
v_in, v_out = read_data(path)
plt.plot(v_in, v_out, label=f'{i}MOS')
plt.title('Voltage transfer characteristics of a real NMOS inverter')
plt.xlabel('$V_{in}$ or $V_{GS}\ (V)$')
plt.ylabel('$V_{out}\ (V)$')
plt.grid()
plt.savefig("./figures/part_3_invert.png", bbox_inches='tight')
```