Tutorial Laboratory Experiment II: MOSFET Characterization

Appendix A. Report Template

Name:______________________________

Grading Rubric:

Data set completeness: ______

Error analysis thoroughness: ______

Procedure descriptions: ______

Accuracy: ______

Total Grade out of 20: ______

Grader comments:

Text in black indicates the answers to the basic tutorial lab questions.

Text in blue indicates the more detailed analysis in response to the Challenge questions.

Table 1. List of instruments and equipment used in experiment:

Instrument / Equipment	**Purpose**
Keithley Semiconductor parameter analyzer	Measure I-V characteristics of CD4007UBE NMOS FET

1. Describe the experimental procedure, including how the measurement was done and how the data way analyzed.

The Keithley SPA was used to measure the I_{DS}-V_{GS} and I_{DS}-V_{DS} characteristics of a CD4007UBE NMOS. NMOS #2 in the CD4007UBE package, connected to pins 3, 4 and 5 was used in the experiments. The setup information was recorded in the "Settings" tab of the Excel sheets that contained the exported measurement data. Pin 4 was used as the drain terminal, and connected to Source-Measure Unit #1 (SMU1) on the Keithley. Pin 3, the gate terminal, was connected to SMU2. Pin 5 was used as the source terminal, and connected to the Ground Unit (GNDU). Pin 7, the body pin for all three NMOS FETs in the package, was connected to the source terminal.

Two measurements were made. In the first, the drain voltage was kept at a constant V_{DS} = 50 mV, and the gate voltage was swept from 0 V to 5 V with 50 mV steps. This measurement's primary purpose is to determine the MOSFET's threshold voltage, V_{tn}. In the second measurement, the drain voltage was swept from 0 V to 5 V with 50 mV steps, for constant gate voltages from 0 V to 5 V stepped at 0.5 V intervals.

Matlab was used for data analysis, to determine the transistor's output resistance, r_o, from the I_{DS}-V_{DS} characteristics for V_{GS} = 2 V and V_{GS} = 3 V. First, the overdrive voltage for each gate voltage was calculated using the threshold voltage as determined from the I_{DS}-V_{GS} measurement, 0.6 V and 1.6 V respectively. Next, Matlab' *polyfit* command was used to determine the slope, m, and constant offset c between V_{DS} = 2 V to 5 V. The lower limit was chosen to ensure the MOSFET was operating in saturation mode for both measurements. The constant offset is the nominal drain current, I_{DS0} = c. The inverse of the slope is the transistor's output resistance at the given bias condition, $r_o = m^{-1}$.

2. Plot the I_{DS} vs. V_{GS} characteristic of your MOSFET as measured by the Keithley SPA. What is the threshold voltage estimated by the Keithley SPA? What was V_{DS} for your measurement?

$V_{t,n}$*:** ***1.4114 V ***V_{DS}*:** ***50 mV***

The Keithley SPA reported a threshold voltage of $V_{t.n}$ = 1.4114 V, with the drain voltage set to 50 mV. The threshold voltage estimate was in the Excel sheet's 'Data' tab, while the measurement conditions were recorded in the 'Settings' tab.

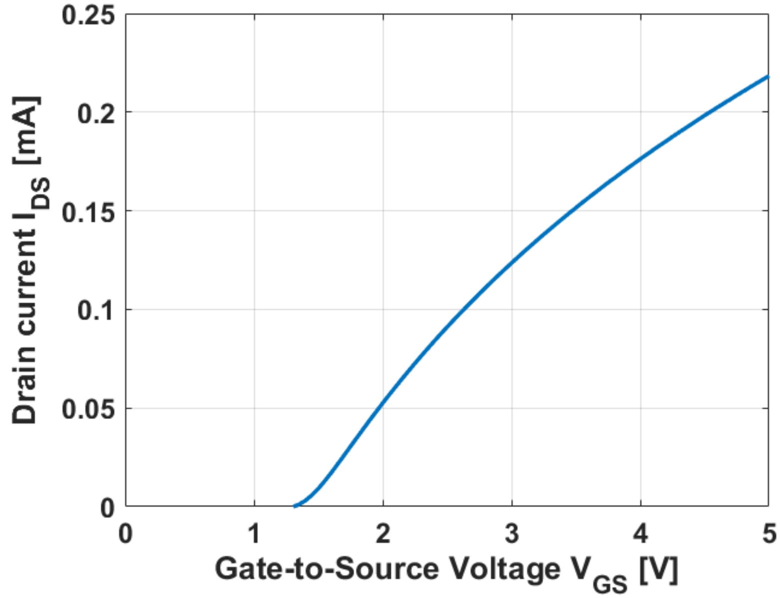

Figure 1. Plot of the MOSFET's I_{DS} vs. V_{GS} characteristic.

3. Plot the I_{DS} vs. V_{DS} characteristic of your MOSFET as measured by the Keithley SPA. What is the ratio of the currents measured at V_{GS} = 5V and V_{GS} = 0.5V, for V_{DS} = 5V? Essentially, this is the ratio of the current at large gate voltage to the sub-threshold current.

$$\frac{I(V_{GS}=5V)}{I(V_{GS}=0.5V)}: \underline{\;> 5.56x10^{8}\;}$$

The drain current at V_{GS} = 5 V and V_{DS} = 5 V is 5.56 mA. The current for V_{GS} = 0.5 V is on the order of 10 pA. However, the actual current appears to be below the SPA's measurement resolution, as the measured current is oscillating between positive and negative values as VDS increases from 0 V to 5 V. Thus, the sub-threshold 'OFF' current is very small compared to the 'ON' current.

FYI: For an ideal MOSFET, the I_{ON}/I_{OFF} ratio should be ∞. A MOSFET with a large gate L, such as the CD4007, will be very close to the ideal case. For this device, the 'OFF' current was below the SPA's measurement limit. The sub-threshold current can be significant for small gate length transistors. The latest generation of microprocessors have gate lengths of L = 13 nm. That is, only 26 Si atoms long! The 'OFF' current for these devices can be one-millionth, or large, of the 'ON' current.

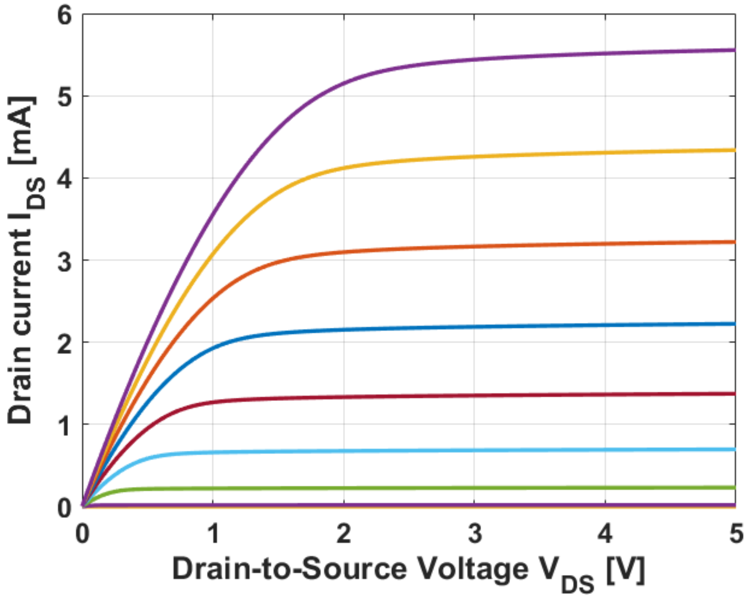

Figure 2. Plot of the MOSFET's I_{DS} vs. V_{DS} characteristic.

4. The transistor's output resistance, r_o, is defined in the saturation region. Calculate r_o for V_{GS} = 2V and V_{GS} = 3V.

$\boldsymbol{r_o|_{V_{GS}=2V} = 493\ k\Omega}$ $\qquad\qquad$ $\boldsymbol{r_o|_{V_{GS}=3V} = 77\ k\Omega}$

The procedure was described in part 1. The drain currents and the linear fits in the saturation region are plotted below.

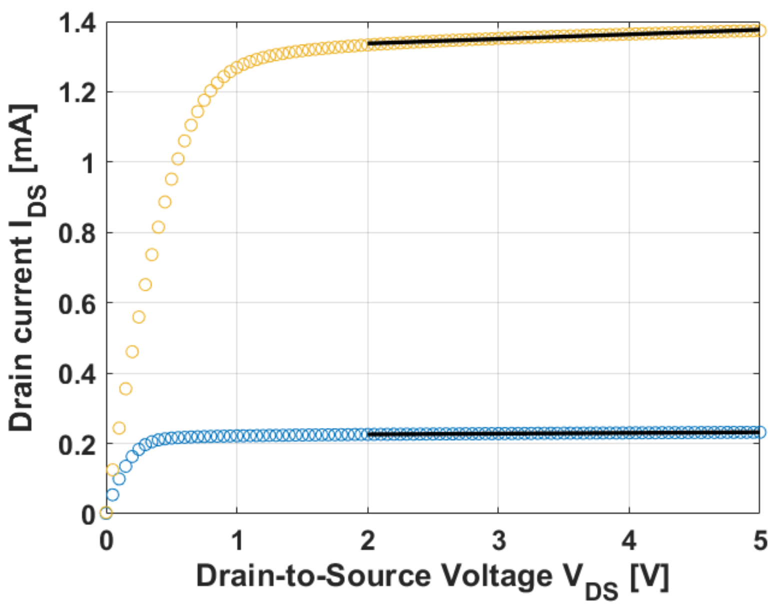

Figure 3. Plot of the MOSFET's I_{DS} vs. V_{DS} characteristic for V_{GS} = 2 V and V_{GS} = 3 V, and the linear fits (black lines) to the two curves in the saturation regions.

Challenge – simple answer:

The output resistance of the MOSFET is given by $r_o = \frac{1}{\lambda I_{DS0}}$ which means that the slope of the linear fit, m = λI_{DS0}. Also, the constant offset is equal to I_{DS0}. Hence, the channel-length modulation parameter can be calculated directly from:

$$\lambda = \frac{m}{I_{DS0}}$$

Using the fit values, the channel length modulation parameter was calculated to be $\lambda = 9.1 \times 10^{-3}$ V^{-1} for V_{GS} = 2 V, and $\lambda = 9.8 \times 10^{-3}$ V^{-1} for V_{GS} = 3 V. This values are pretty close to the UMaine.lib model, which has $\lambda = 0.01$ V^{-1}.

Challenge Questions:

A. Threshold voltage and transconductance extracted from the I_{DS}-V_{GS} measurement

The n-channel MOSFET I_{DS} equation for operation in the triode region is:

$$I_{DS} = \mu_n C_{ox} \frac{W}{L}\left[(V_{GS} - V_{tn})V_{DS} - \frac{1}{2}V_{DS}^2\right]$$

For $V_{DS} << V_{OV} = V_{GS} - V_{tn}$ the V_{DS}^2 term is much smaller than the V_{DS} term, and can be ignored:

$$I_{DS} = \mu_n C_{ox} \frac{W}{L}(V_{GS} - V_{tn})V_{DS} = \left(\mu_n C_{ox} \frac{W}{L} V_{DS}\right)V_{GS} - \mu_n C_{ox} \frac{W}{L} V_{DS} V_{tn}$$

From the second expression, it can be seen that the slope of a linear fit is $m = \mu_n C_{ox} \frac{W}{L} V_{DS}$ and the constant offset is $c = -\mu_n C_{ox} \frac{W}{L} V_{DS} V_{tn}$. Thus, the threshold voltage can be extracted using:

$$V_{tn} = -\frac{c}{m}$$

Additionally, the transistor's transconductance parameter k_n can be calculated using:

$$k_n = \mu_n C_{ox} \frac{W}{L} = \frac{m}{V_{DS}}$$

The drain-to-source voltage drop was chosen to be 50 mV for this experiment. A linear data fit can be attempted to the I_{DS}-V_{GS} data, as long as $V_{OV} >> ½V_{DS} = 25$ mV for the chosen data range.

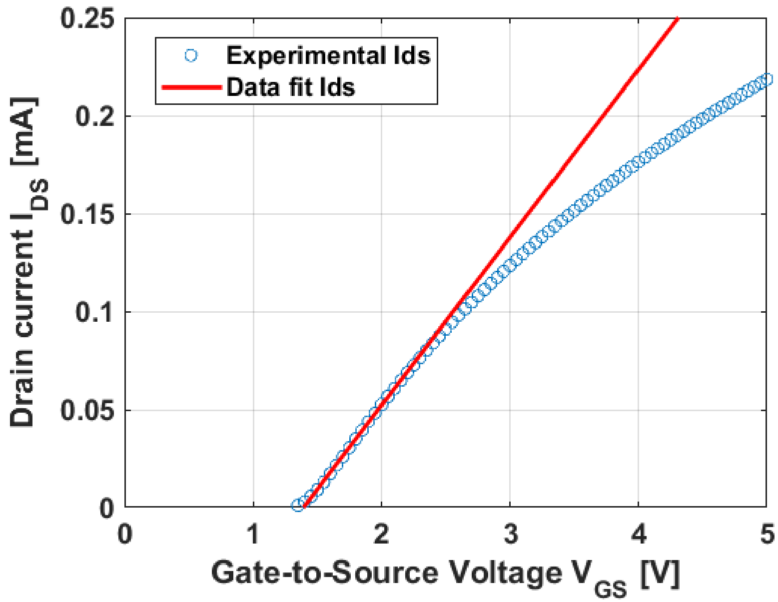

Figure 4. Plot of the MOSFET's I_{DS} vs. V_{GS} characteristic and the linear fit to I_{DS} for the range of V_{GS} from 1.7 V to 2.2 V.

Matlab' *polyfit* command was used for a linear fit to the I_{DS}-V_{GS} characteristic for the range of V_{GS} from 1.7 V to 2.2 V. The overdrive voltage is above 250 mV for these values, which means that the approximation made above is valid. The resulting slope and offset were:

m = 85.612 µA/V

c = -119.1 mA

Using these values, the threshold voltage and transconductance are found to be:

$$V_{tn} = -\frac{c}{m} = 1.391\ V$$
$$k_n = \frac{m}{V_{DS}} = 1.712\ {}^{mA}/_{V^2}$$

These values are significantly larger than the values in the CD4007UBE NMOS model in UMaine.lib. In the SPICE model, the zero-bias threshold voltage is V_{to} = 0.95 V and the transconductance is $k_n \cong 0.5$ mA/V^2. The script for the data fitting, *CD4007a.m*, is attached.

B. Channel length modulation parameter and transconductance extracted from the I_{DS}-V_{DS} measurements

The n-channel MOSFET I_{DS} equation for operation in the saturation region is:

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

The threshold voltage was extracted as V_{tn} = 1.391 V in part A. For 1.5 V ≤ V_{GS} ≤ 5.0 the overdrive voltage ranges from 109 mV to 3.609 V. The procedure for data fitting is similar to that described in #4 above. Two strategies can be pursued to choose the range for data fitting:

i) Simply choose the V_{DS} region from 4 V to 5 V, to ensure operation in saturation for all cases
ii) Chose a different V_{DS} range for each V_{GS}, such that $V_{DS,min} > V_{GS} - V_{t,n}$.

The first option was chosen for this data analysis. The second option would increase the reliability of the data for smaller gate-to-source voltages.

The script for the data fitting, *CD4007bSimple.m*, is attached. The calculated values for each data set is given in Table 1 below. The mean λ = 0.0076 V^{-1}, and the mean k_n = 988.5 µA/V^2. The k_n value for V_{GS} = 1.5 V was excluded from the mean calculation, as it is a significant outlier. This can be explained by the fact that V_{GS} is very close to V_{tn}, and the error in V_{tn} will cause a large error in calculating k_n.

Table 1. Fitted values of the channel length modulation and transconductance parameters, as a function of V_{GS}.

V_{GS} [V]	1.5	2	2.5	3	3.5	4	4.5	5
λ [10^{-3} V^{-1}]	8.3	7.7	7.4	7.3	7.3	7.2	7.3	7.6
k_n [mA/V]	2.756	1.183	1.088	1.027	0.974	0.926	0.882	0.841

Just as in Part A, the channel length parameter is close to the SPICE model in UMaine.lib, but the transconductance parameter is larger. This time, it is only twice as large as the SPICE model. A statistical analysis should be done on extracted parameters from more experiments. For example, 100 devices could be characterized, and the mean values obtained from these experiments would be used for the SPICE model.

CD4007a.m

```
% CD4007UBE NMOS Transistor characterization
%{
  Based on Nov. 2, 2018 data collection
  Nuri W. Emanetoglu
  Script used to calculate Vtn and Kn
  Vtn: Threshold voltage for VSB = 0, i.e. S&B connected together
  Kn = mobility x Cox x W / L
%}
clear;
close all;
% first, load the Vgs-Ids data
load cd4007VgsIds.mat
%{
  Variables are:
  Ids - drain current
  Vgs - gate-source voltage
%}
p = polyfit(Vgs(35:45),Ids(35:45),1);
% y = mx + c; p(1) is m and p(2) is c
% m = kn x Vds
% c = -kn x Vds x Vt
Vtn = -1*p(2)/p(1)
% Initial K fit: can use the linear region X2,Y2 to find K
% Vds was 0.05 V
Vds1 = 0.05;
Ka = p(1)/Vds1
Kb = -1*p(2)/(Vds1*Vtn)
if Ka == Kb
    kn = Ka;
end
Ix = polyval(p,Vgs);

figure;
handle1 = axes;
plot(Vgs,1000*Ids,'LineStyle','none','Marker','o','MarkerSize',6)
hold on
plot(Vgs,1000*Ix,'LineWidth',2,'Color','r','LineStyle','-');
xlabel('Gate-to-Source Voltage V_{GS}
[V]','FontName','Arial','FontSize',16,'FontWeight','Bold');
ylabel('Drain current I_{DS}
[mA]','FontName','Arial','FontSize',16,'FontWeight','Bold')
set(handle1,'FontName','Arial','FontSize',14,'FontWeight','Bold');
legend('Experimental Ids','Data fit Ids');
grid on
xlim([0 5]);
ylim([0 0.25]);

%save cd4007VgsIds.mat Vgs Ids kn Vtn
```

CD4007bSimple.m

```
% CD4007UBE NMOS Transistor characterization
%{
  Based on Nov. 2, 2018 data collection
  Nuri W. Emanetoglu
  Script used to calculate lambda and Kn
%}
clear;
warning off
% first, load the Vgs-Ids data
load cd4007VgsIds.mat
%{
  Variables are:
  Ids - drain current4;.
  Vgs - gate-source voltage
  Vtn - linear fit to Vgs-Ids
  kn - found using linear fit
%}

%%%%%%%%%%%%%%%%%%%%%555555
% Need to subtract Vov from Vds
% the linear fit will have m = p(1) = 1/ro = lambda*Ids0
% and c = p(2) = Ids0
% So can calculate lambda = m/c = p(1)/p(2)
% use Ids0 to calculate kn


% load the Vds-Ids data
load cd4007.mat
%{
  Vgs: Gate-source voltages for the test: array of 9 values, 0 to 5V
  Vds: Drain-source voltages, arroy of 101 values, 0 to 5V
  Ids: drain current, 101x9 matrix.
%}
NumberOfMeasurements = length(Vgs); % how many measurements were made

% Find the Threshold Voltage
% done automatically in SPA, also done manually
Vt0 = Vtn; % taking the SPA value

% Find Early Voltage
%{
Use polyfit (and polyval) for backward and basic Matlab compatibility
can use fit and cftool in Matlab 2011 and afterwards with UMaine
subscription
We will fit from 4V to 5V, and ensure that the transistor is in
saturation
%}

NumMeasUse = 8; % Not using all of the measurements
```

```
Ids0 = zeros(NumMeasUse,1);
x1 = Ids0;
for ind = 1:1:NumMeasUse
    Vov = Vgs(ind)-Vtn;
    p = polyfit(Vds(81:101)-Vov,Ids(81:101,ind),1);
    Ids0(ind) = p(2);
    x1(ind) = p(1); % x1 is lambda*Ids0
end

lambda = x1./Ids0
display('Mean lambda:');
mean(lambda)
Vov = Vgs-Vtn;
Vov2 = (Vov.*Vov)';
kn2 = 2*Ids0./Vov2
display('Mean kn:');
1000*mean(kn2(2:8))
% Threw out the first data set as Vgs was pretty close to Vtn:
% Vgs = 1.5V vs. Vtn = 1.4V
```