MOSFET measurements with the 4155 parameter analyzer

First, a bit of review. There are two important parameters for MOSFETs:

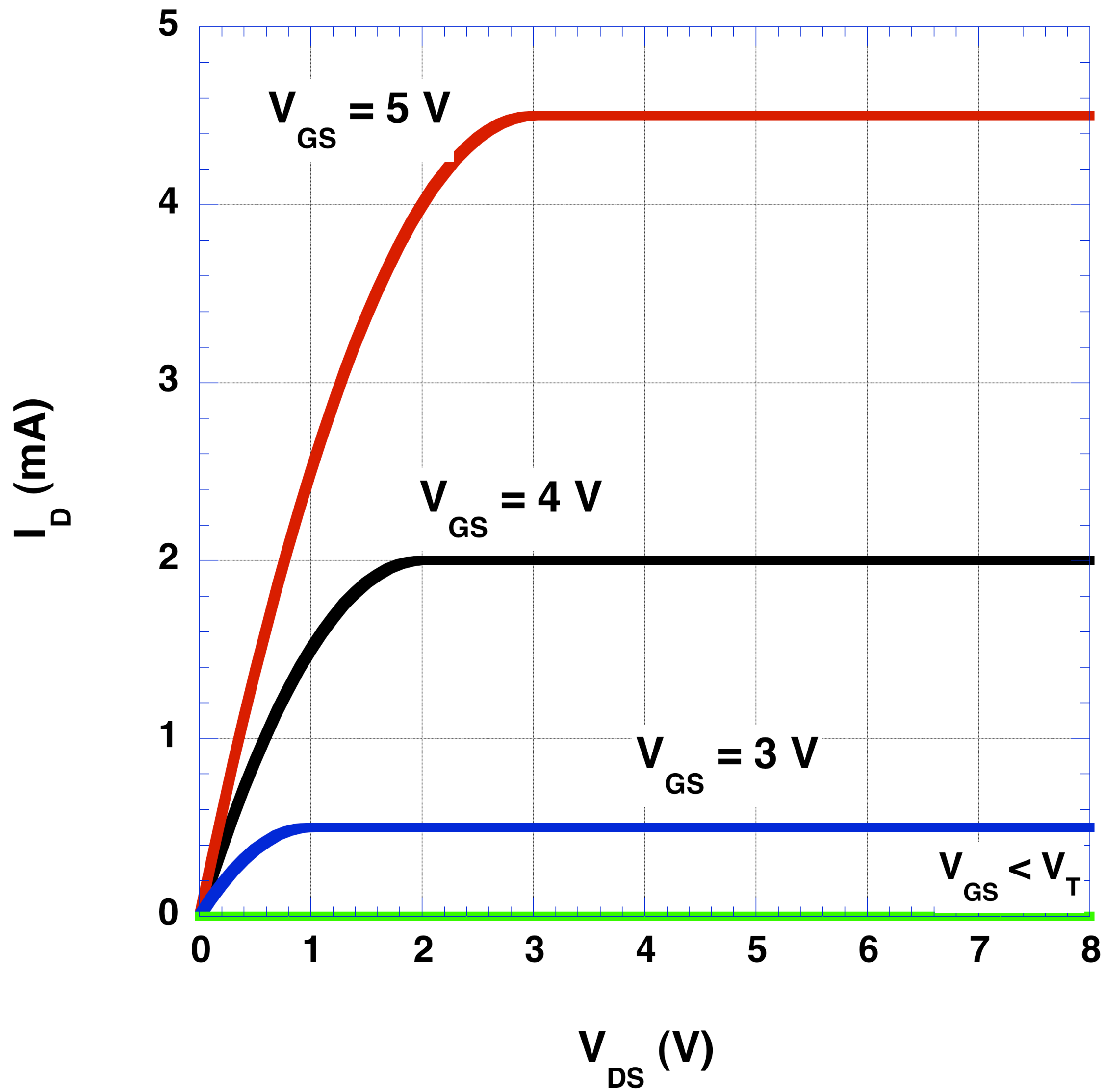
- Threshold voltage — V_T,
- "current parameter" — $K = \frac{1}{2}\mu C_{ox}\frac{W}{L}$.

Actually, there dozens of possible parameters that can be used to describe MOS behavior, but these are the two most basic. Also, "current parameter", as defined here is not typically used in discussing MOSFETs. Genearally, the quantities μCox and W/L are treated as separate parameters. However, for our purposes in looking at individual transistors, it is easier to lump everything together into a single parameter.

In terms of I-V characteristics, NMOS and PMOS transistors are mirror-images of each other. The same parameters and equations describe the I-V behavior, but the current and voltages have opposite polarity. For an NMOS, the threshold voltage, V_{TN}, is positive and in order to form the inversion layer, the gate-to-source voltage must be more positive than the threshold voltage. The drain-to-source voltage. V_{DS}, is also positive and the current flows from drain to source. The PMOS is exactly opposite, with the threshold voltage, V_{TP} being negative, the drain-to-source being negative, and the current flows from source to drain.

		NMOS	PMOS
off	$I_D = 0$	$V_{GS} < V_{TN}$	$V_{GS} > V_{TP}$
liner (or ohmic)	$I_D = K\left[2\left(V_{GS} - V_T\right)V_{DS} - V_{DS}^2\right]$	$V_{GS} > V_{TN}$ $V_{DS} < V_{GS} - V_{TN}$	$V_{GS} < V_{TP}$ $V_{DS} > V_{GS} - V_{TP}$
saturation	$I_D = K\left[V_{GS} - V_T\right]^2$	$V_{GS} > V_{TN}$ $V_{DS} > V_{GS} - V_{TN}$	$V_{GS} > V_{TP}$ $V_{DS} < V_{GS} - V_{TN}$

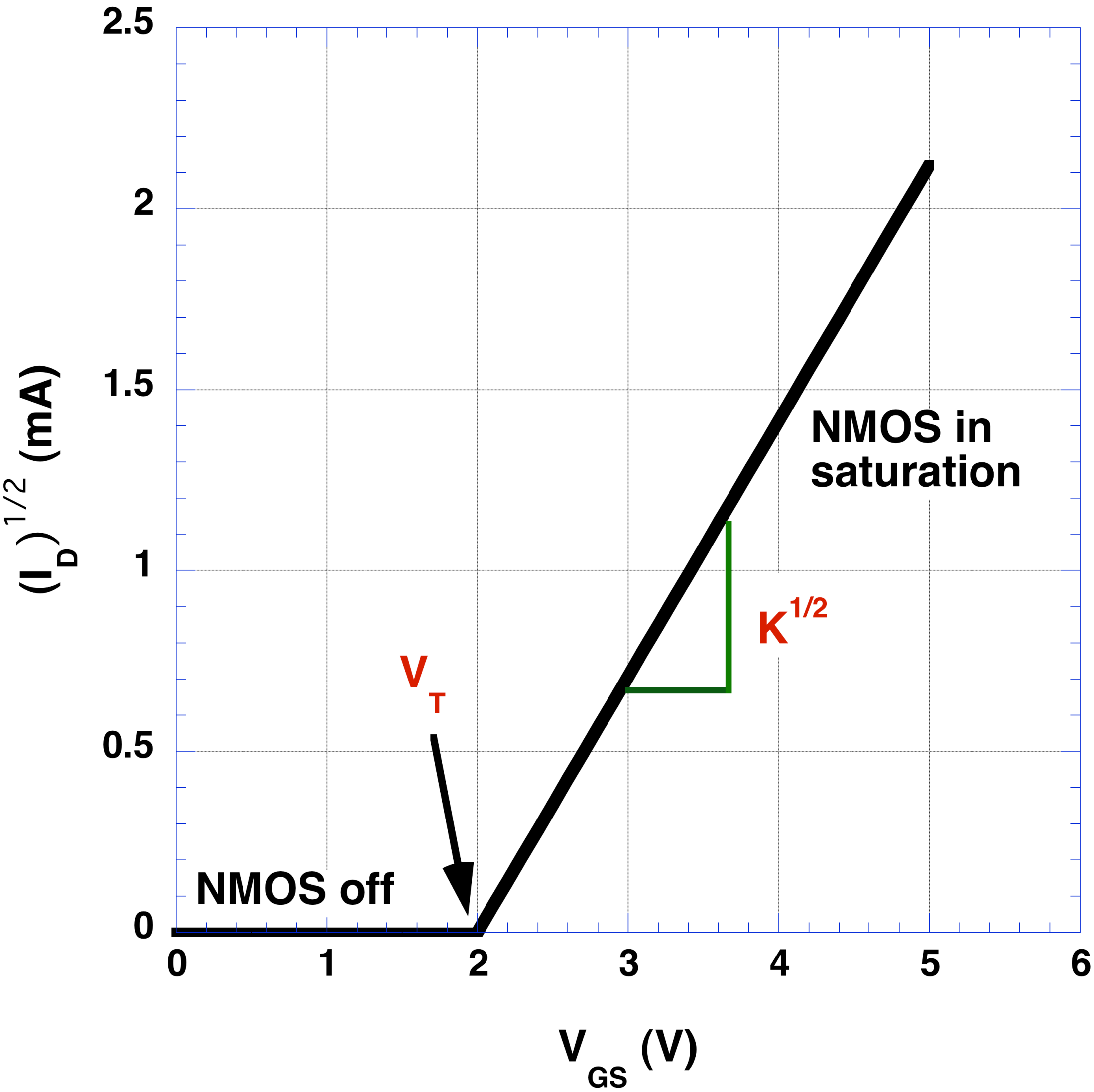
The usual way to view the MOSFET I-V characteristics is to look at I_D as function of V_{DS} for various values of V_{GS}. With VGS below threshold voltage, the MOSFET is off and the there will be no drain current. With VGS above the threshold voltage, the MOSFET is "on" and current can flow. There are two regions of operation: linear (ohmic) for low values of drain voltage in which the MOSFET is behaving somewhat like a resistor and the current increases with increasing drain voltage and saturation for larger values of drain voltage in which the current saturates and does not change with drain voltage. A typical set of I-V curves is shown below.



However, I_D - V_{DS} curves are not convenient for trying to extract device parameters (V_T, K, etc.) Instead, looking at I_D as a function of V_{GS} (with V_{DS} set big enough so that the MOSFET is operating in saturation) is a more useful measurement. The saturation equation above describes the expected quadratic behavior. A slight change makes the equation and the measurement more useful. Taking the square-root of both sides of the saturation I-V equation gives

$$\sqrt{I_D} = \sqrt{K}\,(V_{GS} - V_T).$$

Plotting $\sqrt{I_D}$ vs V_{GS} gives two straight lines. For $V_{GS} < V_T$, the MOS is off and $I_D = 0$. As V_{GS} increases past V_T, the MOS turns on and the $\sqrt{I_D}$ increases linearly with increasing V_{GS}. The slope of this second part of the curve is $\sqrt{K}$, and the intercept with the horizontal axis is V_T. The plot is easy to generate and the parameters are easily extracted. (The parameters could also be extracted from the I_D vs. V_{GS} quadratic curve, but it much easier to measure slopes and intercepts than it is to measure curvature.)



Measurements with 4156 Parameter Analyzer

Measuring I-V curves is simply a matter of setting the various voltages and measuring the corresponding drain current. It can be done easily (and somewhat tediously), with a couple of power supplies and a multimeter. A *parameter analyzer* is an instruments that is set up to measure I-V characteristics and extract parameters for a variety of semiconductor devices.

To use a parameter analyzer, a simple program is set up to sweep through a range voltages, measure the corresponding currents, graph the results, and then extract parameter of interest. The analyzer is easily set up to measure either the ID-VDS or ID-VGS curves described for MOSFETs.

In the NSF lab, the Mac computer can communicate with the 4156 Parameter Analyzer to enter the measurement program and then transfer the data back to the Mac for easy plotting. There are two programs on the Mac for setting up the two MOSFET measurements.

The measured programs can also be entered directly into the parameter analyzer using the front panel of the instrument. Manual programming is described below.

In general, it is good to know how to program the parameter analyzer manually. As a device engineer, you might want to extract other parameters using measurement configurations that go beyond these simple setups. However, for EE 432/532 purposes, it is probably easier to use the canned Mac programs for the setups.

In fact, the Mac programs are probably essential, if you want to retrieve complete I-V data that can be plotted and included in a report. (The 4156 uses floppy disks to save data, and inasmuch as floppies are become somewhat rare, it is probably better to avoid using them to get data off the analyzer.)

However, the parameter analyzer is designed to take measurements and *extract parameters*. As such, it has nice tools that can extract slopes and intercepts from I-V plots. If your goal is get parameter information — and most of our measurements in EE 432/532 are done simply to get parameters — it is better to obtain those directly from the graphs on the analyzer rather than saving all of the I-V data to the computer and then spending a lot of time with Excel or Matlab to massage the data and extract the parameters. The latter approach is certainly possible, but you will obtain your results much more quickly if you use the tools directly on the analyzer.

In the tutorial that follows, it is assumed that you are measuring a garden-variety NMOS transistor with typical parameters. In the ID-VDS measurements, the drain voltage ranges from 0V to 10 V in small steps, and the gate voltage steps from 0 to 5 V in 0.5-V steps. For the ID-VGS measurements, the gate voltage ranges from 0V to 5-V in small steps with VDS held fixed at 8 V. It may necessary for you to adjust some of these measurement settings for your devices. Also, in measuring PMOS transistors, everything must be reversed — the voltages and currents will all be negative.

I_D vs. V_{DS} with VGS as a parameter

1. Go to the CHANNELS page using the CHAN button on the front panel. Push the soft key (MEM2 FET VDS-ID) that brings up the standard setup for a FET. This puts the 4155 into a configuration for measuring i_D vs. v_{DS} for FETs. Connect the drain, source, and gate of your MOSFET to the prescribed SMUs (SMU1 to source, SMU2 to drain, SMU3 to gate).

2. Next, go to the MEASURE page (user either the front panel "Meas" button or press the "NEXT PAGE" soft key *twice)*. to define the voltage and current ranges to be used. As a reasonable starting point, you might have the drain voltage range from 0 to 10V in 0.1V increments. The current compliance on the drain can be set to 25mA. Let the gate voltage step in 0.5V increment from 0 to 5V. The current compliance for the gate can be set to something small, like 1 μA.

   Note: The first push of the "NEXT PAGE" softkey takes you to a page where you can define your own functions for plotting. You don't need this for the i_D - V_{DS} measurement, but we will make use of a function in the second part.

   Note 2: In entering the measurement parameters for the VAR1 (VDS) you should specify the start voltage, the stop voltage and the size of the step. The 4155 will calculate the number of steps to be used in the sweep. For VAR2 (VGS) you should provide the start voltage, the step size, and the number of steps. The 4155 will determine the final voltage. It seems mildly crazy to have to specify VAR1 and VAR2 in different fashions, but that's the way it is.

   Jump over to the "Sweep" box and change the setting there to "CONTINUE AT ANY". This change is made by using the soft key in the upper right corner of the screen.

   The measurement page should look something like this:

• VARIABLE	VAR1	VAR2

UNIT	SMU2:HR	SMU1:HR
NAME	VDS	VG
SWEEP MODE	SINGLE	SINGLE
LIN/LOG	LINEAR	LINEAR
START	0.0000 V	0.0000 V
STOP	10.000 V	5.000 V
STEP	100.0mV	500.0mV
NO OF STEP	101	11
COMPLIANCE	25.00mA	1.000uA
POWER COMP	OFF	OFF

TIMING
HOLD TIME

0.0000 s

DELAY TIME

0.0000 s

• CONSTANT

UNIT NAME MODE SOURCE COMPLIANCE	- - - - - - - - - - - - - - - - - - - -	- - - - - - - - - - - - - - - - - - - -	- - - - - - - - - - - - - - - - - - - -

3. Now advance to the DISPLAY page. (Use either the "Display" front panel button or "NEXT PAGE" softkey). You can have the measured data displayed in the form of a graph or as list of measured values. The default is the graph -- leave it that way for now. Set up the graphics plot so that v_{DS} ranges from 0 to 10V and i_D ranges from 0 to 10 mA. (You may have to come back to this page to resize the graph later if needed.)

4. Advance to the GRAPH/LIST page. (Again, use either the front panel "Graph/List" button or the "NEXT PAGE" softkey.) This is the page where the measurements are done. To the right on the front panel is a button marked "SINGLE". Push this to have the 4155 to start sweeping through the voltages and measuring the currents. You should see lines sweeping across the graph. If everything is hooked up correctly, these should be the

familiar family of MOSFET curves. If all the lines are overlapping on what appears zero current, you might have to rescale the plot. Do this by hitting the "SCALE" soft key below the screen and then hitting the "AUTO SCALE" soft key that appears on the right side of the screen.

5. You might want to save the data to disk before proceeding.

Step 2 - extracting V_T and K

Use the Chan front panel button to step back to the CHANNELS page. You do not need to change the connections to the MOSFET terminals or the names or the modes, but you do need to make changes to the SMU FCTNs. Make the following changes:

1. Change the function of SMU2 (VDS) to CONST.
2. Change the function of SMU3 (VG) to VAR1.

The CHANNELS page should now a table that looks something like the one below.

MEASURE					STBY
UNIT	VNAME	INAME	MODE	FCTN	
SMU1:HR	VS	IS	COMMON	CONST	
SMU2:HR	VDS	ID	V	CONST	
SMU3:HR	VG	IG	V	VAR1	
SMU4:HR	VSUB	ISUB	COMMON	CONST	
VSU1		- - - - - - - -			
VSU2		- - - - - - - -			
VMU1		- - - - - - - -		- - - - - - - -	
VMU2		- - - - - - - -		- - - - - - - -	

Use the "NEXT PAGE" soft key to step to the USER FUNCTION page. Here, you can enter your own function to to be measured. Of course, what we want is the square root of the drain current.

Enter a user function in the first row of the table. You can call it SQRTID (or some such thing - the name is irrelevant), skip the units (also irrelevant), and type in SQRT(ID) in the expression column.

Name	UNIT	DEFINITION
SQRTID		SQRT(ID)

Push the "NEXT PAGE" soft key to go on to the MEASURE page. Set up the page to look something like the table below.

• VARIABLE	VAR1	VAR2
UNIT	SMU2:HR	
NAME	VG	
SWEEP MODE	SINGLE	
LIN/LOG	LINEAR	
START	0.0000 V	
STOP	5.000 V	
STEP	50.0mV	
NO OF STEP	101	
COMPLIANCE	1.0000mA	
POWER COMP	OFF	

• TIMING

HOLD TIME	0.0000 s
DELAY TIME	0.0000 s

• CONSTANT

UNIT	SMU2:HR		
NAME	VDS		
MODE	V		
SOURCE	8.000 V	- - - - - - - - - -	- - - - - - - - - -
COMPLIANCE	10.000mA	- - - - - - - - - -	- - - - - - - - - -

You are programming the 4155 to sweep through a range of gate voltages while keeping the drain voltage constant. Using the numbers from the above table as an example, the gate voltage would sweep from 0 to 5V, while the drain voltage is held constant at 8V. Remember to set the compliances at reasonable values.

Important measurement note: The values used above are purely for illustration. The numbers you use in your measurement will depend on the particular device your are measuring. The gate must sweep through a range that includes the threshold voltage. For instance, if you were measuring an depletion-mode NMOS transistor, where the threshold voltage is negative, the gate voltage range would have to start at value more negative than the threshold. Or, if measuring a PMOS transistor, all the voltages would have to be negative. Also, in setting the constant drain voltage, you must make certain that the MOSFET will stay in saturation. You will be safe as long as you choose the constant drain voltage to be bigger than any applied gate voltage. After taking a measurement, you might find it necessary to return to this page to adjust the settings, and then measure again.

Move ahead to the DISPLAY page.

Set up the graph so that the gate voltage will be on the x-axis and your user-defined function, SQRTID (or whatever), will be on the Y1 axis. These are entered using the soft keys. To find your SQRTID function, you must push the "MORE 1/2" to go to the next menu of soft keys. SQRTID will show up there.

- GRAPHICS

	X axis	Y1 axis	Y2 axis
NAME	VG	SQRTID	
SCALE	LINEAR	LINEAR	
MIN	0.0000 V	0.0000	
MAX	5.000 V	1.0000	

• Extracting V_T and K

Once you have the graph in hand, determining the parameters is simply a matter of fitting a line to the sloping portion of the curve. Follow the procedure described above for creating a line and fitting it to a portion of the curve. The x-intercept and slope of the fitted line are given in the table at the bottom of the display.

At this point you might want to save a copy of your data.

Measurement note: For some MOSFETs the plot of the square-root of i_D is sublinear (meaning that it is not a straight line, but bends down at higher gate voltages). This is an indicator that the simple level 1 model for the MOSFET will probably not provide a very good description of the real MOSFET's behavior. When trying to find the threshold voltage for a MOSFET that displays this type of behavior, try to fit the straight line at lower gate voltages - just slightly above threshold. If you use higher gate voltages - in the region where the curve is bending - the extracted threshold voltage will be unreasonably low and perhaps even negative.