LTspice Advanced Simulation Examples

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MOSFET Characterization - DRAFT

For any new technology, we need to first characterize the devices to get an idea of the range of performance metrics that can be achieved in that technology. Characterization will also help in getting the initial values for a new design.

The basic $I_D - V_{GS}$ and $I_D - V_{DS}$ characteristics were already demonstrated in the LTspice Basic Exercises. However, they have been repeated here for completeness.

- Let us use the Predictive Technology Model (PTM) which can be downloaded from `http://ptm.asu.edu/`. Navigate to *Latest Models* and download the *180nm BSIM3 model card for bulk CMOS.* Save the file as *180nm_bulk.txt*
- The name of the default n-channel MOSFET model is *nmos*. The name of the model in the PTM file is also *nmos.* To avoid confusion, use a text editor to open *180nm_Bulk.txt* and change the name to *nmos*_180.

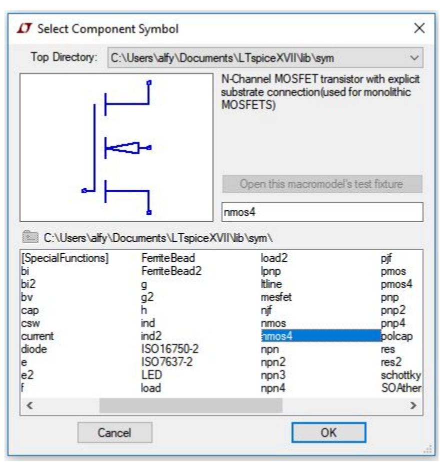
Change `.model nmos nmos level = 54` to `.model nmos-45n nmos level = 54`

Do the same for *pmos* and change it to *pmos_180.*

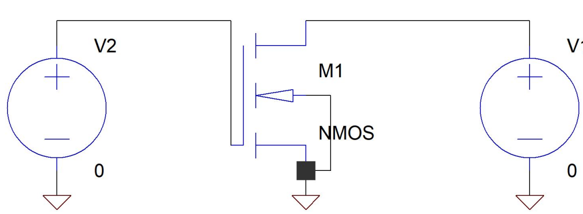
- Now to add the model file to this schematic, first save the model file in the same folder as the schematic. Use the spice directive *.include 180nm_bulk.txt* to add the file.

DC Characteristics

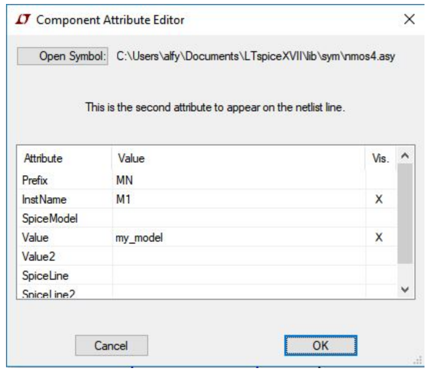
- Use the *Add Component* icon and search for *nmos4* to add an n-channel MOSFET.

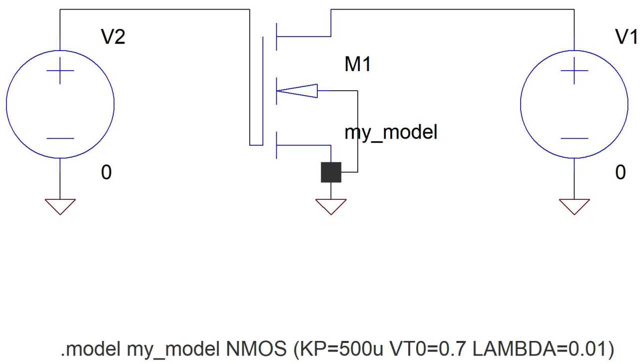


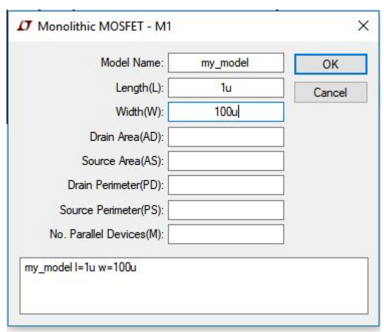
- Draw the following circuit.



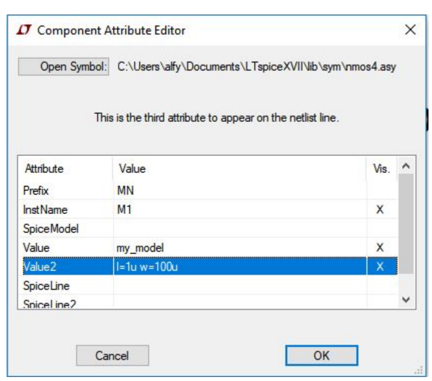
- Right-click the MOSFET in the schematic and change the model name to *nmos_180*. Change the width and length also.



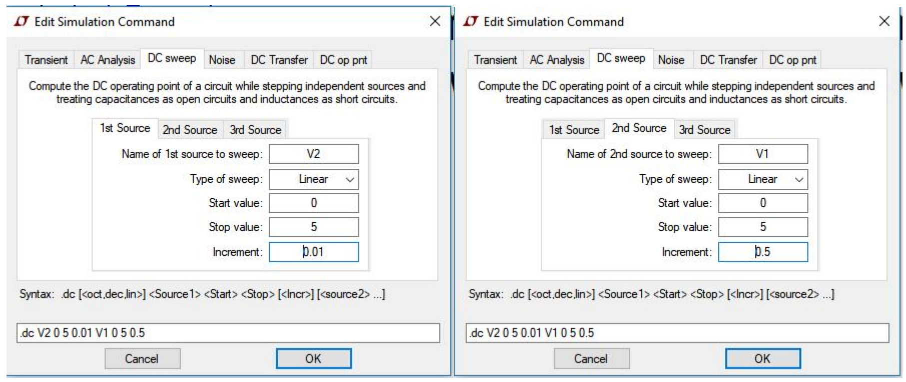


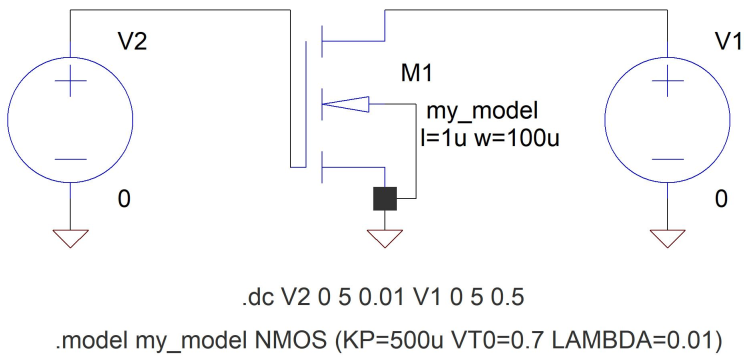


- We would like the width and length information to be visible on the schematic. Hold *Ctrl* and right-click the MOSFET. Double click under the column *Visible* to make *Value2* also visible.

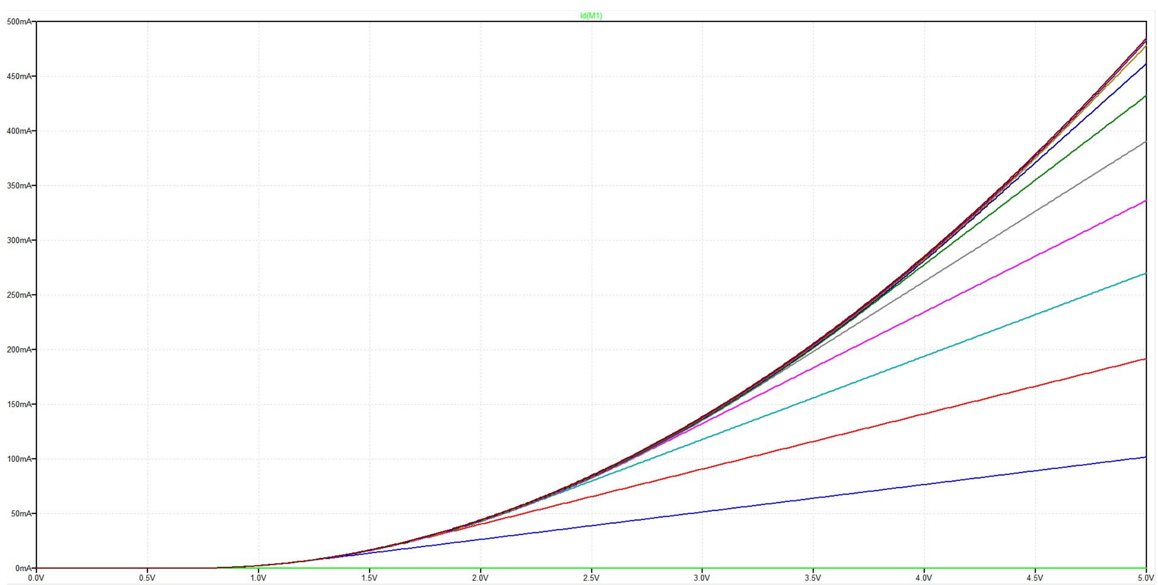


- To probe the $I_D - V_{GS}$ characteristics, we need to sweep both the voltage sources. Enter the following details in the simulation command window.





- Probe the current through the drain.



- Interchange the order in which the voltage sources are swept to get the $I_D - V_{DS}$ characteristics. (Notice the change in the *.dc* directive)

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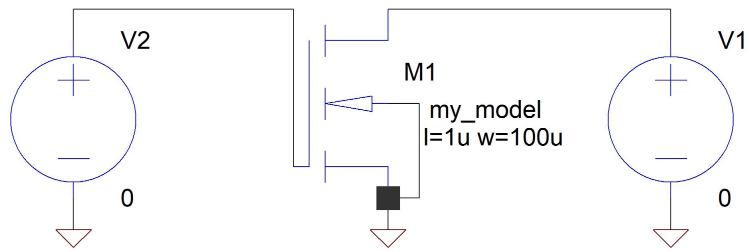
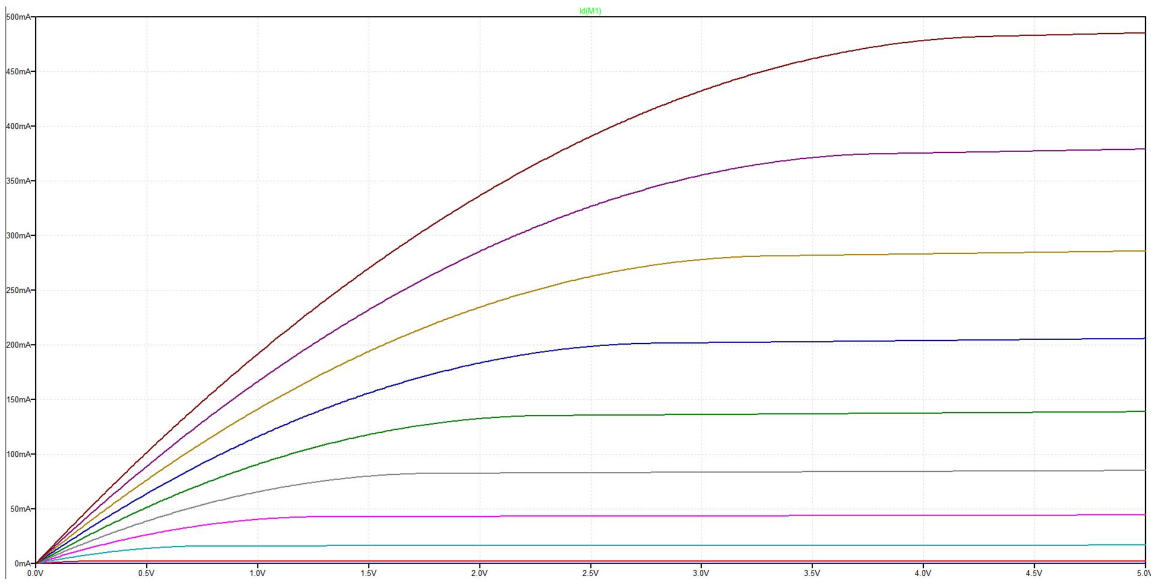


.dc V1 0 5 0.01 V2 0 5 0.5

.model my_model NMOS (KP=500u VT0=0.7 LAMBDA=0.01)



We get the expected curves of a long channel MOSFET

Small Signal Parameters (DC Operating Point)

- Draw the following circuit and run an operating point simulation.
- Click View -> Spice Error Log to see the calculated operating point and small signal parameters of the mosfet.
- For any circuit, running a DC operating point simulation will give you the small signal parameters for all the mosfets in the circuit. However, as of writing this document, there is no direct way to sweep a parameter and view how a given small signal parameter changes with the swept value. Hence, we will have to develop clever testbenches to get the required graphs.

Transconductance (DC Sweep)

- Transconductance is defined as $\frac{\delta I_D}{\delta V_{GS}}$. Hence one way to simulate transconductance is to plot $I_D - V_{GS}$ curves and then take the derivative of it. This is illustrated in the following circuit.
- Plot the drain current and then right-click the waveform name to edit it. Type *d(I(M1))* to find the derivative of *I(M1)* with respect to the current x axis.
- Note that the transconductance found is very close to the DC operating point value.
- However, one limitation of this method is that we always have to sweep the gate voltage as we need to find the derivative with respect to the gate voltage. For example, we cannot get transconductance as a function of V_{DS} using this testbench.

Transconductance (AC Analysis)

- For a simple mosfet model, the ratio of the small signal short circuit current flowing through the drain to the input small signal gate voltage is the transconductance.
- Hence, we can setup an AC analysis and give a AC gate voltage as stimulus and probe the drain current. Note that LTspice linearizes the circuit for AC analysis and hence, the magnitude of input does not matter. Therefore, we choose the AC gate voltage to be $1V$ so that the drain current is numerically equal to the transconductance. The following testbench illustrates this.
- Now, to see transconductance as a function of V_{DS}, we simply run the AC analysis at one very low frequency point and sweep V_{DS}

Output Resistance (DC Sweep)

- Output Resistance is defined as $1/\frac{\delta I_D}{\delta V_{DS}}$. Hence one way to simulate the output resistance is to plot $I_D - V_{DS}$ curves and then take the derivative of it. This is very similar to the transconductance.
- This method again has the same limitation as we cannot plot output resistance as a function of some other variable.

Output Resistance (AC Analysis)

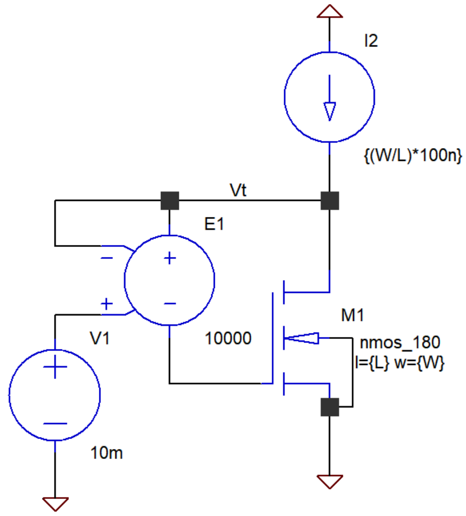
- For a simple mosfet model, the ratio of the small signal drain to source voltage to the small signal drain to source current is the output resistance.
- Hence, we can setup an AC analysis and give a AC drain voltage as stimulus and probe the drain current. We could also setup an AC current source with value $1A$ at the drain of the mosfet and measure the drain voltage. This way, the drain voltage is numerically equal to the output resistance. The following testbench illustrates this.
- Now, to see output resistance as a function of V_{GS}, we simply run the AC analysis at one very low frequency point and sweep V_{GS}

Intrinsic Gain (AC Analysis)

- The intrinsic gain can be found by finding the transconductance and output resistance in the same simulation (AC simulation) and then multiplying them using the waveform arithmetic option. This is illustrated below.
- Another way of directly getting the intrinsic gain is forcing the drain to be open circuited and finding the drain voltage in response to an AC voltage at the gate. Since we need a voltage source to set the drain bias voltage, we shall use a large inductor to create an open circuit.

Threshold Voltage (DC Analysis)

- The threshold voltage in the DC operating point simulation is calculated using various spice model and bias parameters, and hence, cannot be directly obtained from any simulation.
- Hence, we use other methods to obtain a close approximation to the threshold voltage. One commonly used method to define threshold voltage in the fabrication industry is the *constant current method*. Here, the threshold voltage is defined as that gate source voltage for which the drain current is $\frac{W}{L} \times 100nA$, where W and L are the width and length of the mosfet and, the drain-source voltage is kept at a low voltage.
- One way to simulate this is to keep the drain source voltage constant and sweep the gate voltage, and then find the gate voltage when the drain current is the value specified.
- However, this testbench cannot be easily used to get the threshold voltage as a function of other parameters. What we need is a single simulation (without any sweeps) that can give the threshold voltage. One way to accomplish this is to use negative feedback in the circuit to get the required parameter. The following circuit illustrates this.



- Now, to see the threshold voltage as a function of L, we simply run a DC operating point analysis and sweep L
- To get more accurate values, you can run one DC operating point simulation to get the threshold voltage for a certain W and L, and then tweak the above testbench ($100nA$ or $V_{DS} = 10mV$) to get the same value. Then used this modified testbench to get the threshold voltage for different parametric sweeps.

Transition Frequency (AC Analysis)

- All the metrics discussed so far characterize the DC/low frequency operation of the mosfet. One metric to characterize RF/high frequency operation is the transition frequency. This is the frequency at which the current gain (ratio of the short circuit drain current to the input gate current) of the mosfet is unity.
- The direct way to simulate this is to give an AC voltage/current source at the gate terminal, and measure the short circuit drain current. The AC input can be swept to find the frequency where the current gain is unity.