MOSFET & JFET Theory

MOSFET's

Another type of 3-terminal device is called a MOSFET. In essence,

- A transistor is a current-controlled current source.
- A MOSFET is a voltage controlled resistor.

The design of an n-channel MOSFET is as follows:

A p-type semiconductor is made. Two n-type regions are placed on the p-type substrate. A gate is created, slightly above the substrate.

- If the gate voltage is zero, there is a reverse biased-diode between the drain and source. This prevents current flow.
- If the gate voltage is positive, the + charges on the gate attract - charges to the surface of the substrate. This creates an n-type semiconductor near the surface. This in turn creates an n-channel between the drain and source.
- As you raise the gate voltage, the depth of this n-channel increases, decreasing the resistance from the drain to source.

The net result is a MOSFET behaves as a voltage-controlled resistor.

Up to a point.

If you try to push too much current through the MOSFET, you run out of charge carriers. You then get a current-limit, at which point the MOSFET behaves as a voltage-controlled current source.

Likewise a transistor had three operating modes:

- off (switch off)
- saturated (switch on)
- active (current controlled current source)

A MOSFET also has three operating modes:

- off (switch off)
- Ohmic (voltage controlled resistor)
- Triode (active) (voltage controlled current source).
Triode (Ohmic) Region

If you don’t try to push much current through a MOSFET, it behaves as a resistor. This is termed the Ohmic or Triode region. The condition for this is:

\[ V_{DS} < V_{GS} - V_{TN} \]

In this case, the VI relationship is

\[ I_{DS} = K_n \left( V_{GS} - V_{TN} - \frac{V_{DS}}{2} \right) V_{DS} \]

or

\[ \frac{1}{R_{DS}} = \frac{I_{DS}}{V_{DS}} = K_n \left( V_{GS} - V_{TN} - \frac{V_{DS}}{2} \right) \]

where

- \( V_{TN} \) is the turn on voltage. This is the voltage you need to just create the n-channel. As \( V_{GS} \) goes beyond this voltage, the channel gets thicker and the resistance drops.
- \( K_n \) is the transconductance parameter, which is a property of the MOSFET and is usually given the data sheets.
- \( V_{DS} \) also affects the resistance. As you apply more voltage, to the drain, the channel gets smaller near the drain. This pinches off the n-channel.

Note that if \( V_{DS} \) is a constant, the conductance of the MOSFET is linear with \( V_{GS} \).

Example: Plot the VI characteristic for a MOSFET with

- \( V_{TN} = 1 \text{V} \)
- \( V_{GS} = 4 \text{V} \)
- \( K_n = 25 \mu \text{A/V}^2 \)

Solution: In SciLab compute IDS for VGS varying between 0V and +5V. Clip the result so that \( I_{DS} > 0 \).

```matlab
VGS = 4;
VDS = [0:0.001:5]';
VTN = 1;
Kn = 25e-6;
// Ohmic
IDS1 = Kn*(VGS - VTN - VDS/2).*VDS;
plot(VDS, IDS1*1000)
xlabel('VDS (V)');
ylabel('IDS (mA)');
```
Note that the current increases as you increase $V_{DS}$, as you expect. Above 3V, however, where \[ V_{DS} < V_{GS} - V_{TN} \]
the MOSFET runs out of charge carriers. Likewise, the current saturates and remains constant. The equations for the Ohmic region predict that the current will drop as you increase VDS beyond 3V, which is nonsense. Likewise, the equation for the Ohmic region is only valid up to the maximum (3V).

Also note that for VDS small (near 0V), $I_{DS}$ is almost proportional to VDS. The MOSFET is behaving like a resistor with a resistance of \[
\frac{1}{R_{DS}} = \frac{I_{DS}}{V_{DS}} = K_n \left( V_{GS} - V_{TN} - \frac{V_{DS}}{2} \right) \]
\[ R_{DS} \approx \frac{1}{K_n(V_{GS}-V_{TN})} = 20k\Omega \]
If you vary $V_{GS}$, you'll vary the resistance.

**Saturation (Pinch-Off) Region**

If you try to push too much current through a MOSFET, it saturates. This happens at the peak of the previous VI curve, or at \[ V_{DS} > V_{GS} - V_{TN} \]
In this region, termed the Saturated or Pinch-Off region, $I_{DS}$ is constant (not a function of $V_{DS}$): \[
I_{DS} = \frac{K_n}{2}(V_{GS} - V_{TN})^2
\]

For example, assume
- $V_{GS} = 4V$
- $V_{TN} = 1V$
- $K_n = 25\mu A/V^2$
If you compute and plot $I_{DS}$ vs. $V_{DS}$ for the Ohmic (blue) and Saturated (green) region, you get the following:

The Ohmic region (blue line) is valid up to the maximum. At this point, there are no more charge carriers in the n-channel and the current holds constant (the green line to the right of 3V). The equation for the Ohmic region predicts that the current drops as you raise $V_{DS}$, which is nonsense. Likewise, the Ohmic equations are not valid past the maximum of $I_{DS}$.

Similarly, the equations for the saturated region predict constant current flow (the green line). This makes sense past 3V - where the MOSFET saturates. It doesn't make sense for $V_{DS}$ small. For example, if $V_{DS} = 0V$, $I_{DS}$ must also be $0A$. The saturated equations (green line) is only valid to the right of $+3V$.

If you only plot the valid portion of each equation for various values of $V_{DS}$, you get the following:

SciLab Code:

```scilab
VGS = 4;
VDS = [0:0.001:5] + 1e-6;
VTN = 1;
Kn = 25e-6;

// Ohmic
IDS1 = Kn*(VGS - VTN - VDS/2).*VDS;
IDS1 = IDS1 .* (VGS - VTN > VDS);

// Saturated
IDS2 = Kn/2 * (VGS - VTN).^2;
IDS2 = IDS2 .* (VDS > VGS - VTN);
IDS = IDS1 + IDS2;
plot(VDS, IDS*1000)
xlabel('VDS (V)');
ylabel('IDS (mA)');
```

The Ohmic region (blue line) is valid up to the maximum. At this point, there are no more charge carriers in the n-channel and the current holds constant (the green line to the right of 3V). The equation for the Ohmic region predicts that the current drops as you raise $V_{DS}$, which is nonsense. Likewise, the Ohmic equations are not valid past the maximum of $I_{DS}$.

Similarly, the equations for the saturated region predict constant current flow (the green line). This makes sense past 3V - where the MOSFET saturates. It doesn't make sense for $V_{DS}$ small. For example, if $V_{DS} = 0V$, $I_{DS}$ must also be $0A$. The saturated equations (green line) is only valid to the right of $+3V$. 
VI characteristic for a MOSFET where $V_{GS}$ varies from 1.5V (bottom curve) to 5.0V (top curve) in 0.5V steps.

Note that
- on the left, you have a resistor where the slope determines the resistance.
- On the right you have a constant current determined by $V_{GS}$.
JFET Theory

A JFET (Junction Field Effect Transistor) behaves just like a MOSFET and has the same equations. It's built a little differently, however.

An p-channel JFET looks like the following:

![Diagram of p-channel JFET](image)

A p-channel JFET has a p-type semiconductor connecting the drain and source. If you apply a voltage to the gate, no current flows gate to source (or drain) since this is a reverse-biased diode. As you increases the voltage $V_{GS}$, the depletion region grows, restricting the current flow. If you go far enough, you pinch-off the p-channel and the JFET no longer conducts.

Just like a MOSFET, a JFET has three modes of operation (and the same equations)

- For $V_{DS}$ small, a JFET acts like a resistor. The resistance can be adjusted with $V_{GS}$.
- For $V_{DS}$ large, a JFET acts like a voltage controlled current source. You run out of charge carriers in the p-channel. Current, likewise, is limited by the number of charge carriers, not $V_{DS}$.
- For $V_{GS} > V_{TN}$, the p-channel disappears and the JFET no longer conducts.

Since the operation and equations for a JFET and MOSFET are identical, I won't repeat them.

As a sidelight, in lab you'll find BJT transistors. In industry, you'll find MOSFETs. The reason is:

- MOSFET's are sensitive to static. If you touch the gate, you'll arc across the insulator between the gate and substrate. This ruins the MOSFET.
- Transistors are not bothered by static too much. The base-emitter junction is just a diode, which conducts electricity like any other diode.

Likewise, here at NDSU we mostly have transistors. MOSFET's left in labs tend to be non-functional by the end of the week.

In industry, you'll find MOSFETs almost exclusively. It takes several micro-amps to bias a transistor in the active region. If your circuit has thousands of transistors, this can suck up a lot of current, draining your battery. MOSFETs, however, operate on voltage, not current. You can turn on and off a MOSFET with almost no current drain. This greatly reduces the current consumption of your device.