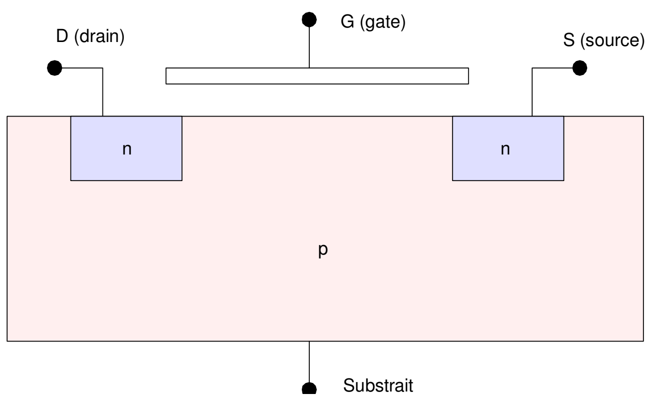
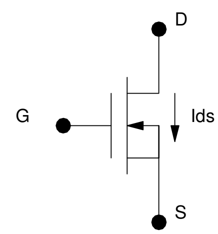
MOSFET Theory

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:

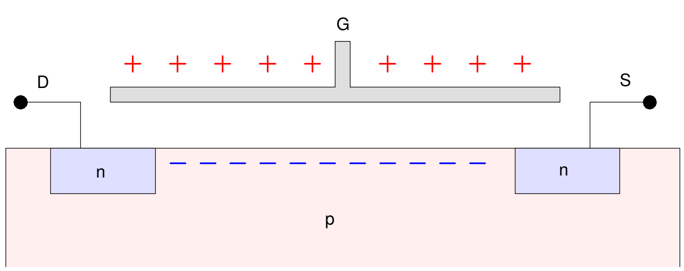




Symbol

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.



By applyting a positive voltage to the gate, negative charges are attractd to the surface,.
This crates an n-channel

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

- $V_{TN} = 1V$
- $V_{GS} = 4V$
- $K_n = 250\mu A/V^2$

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

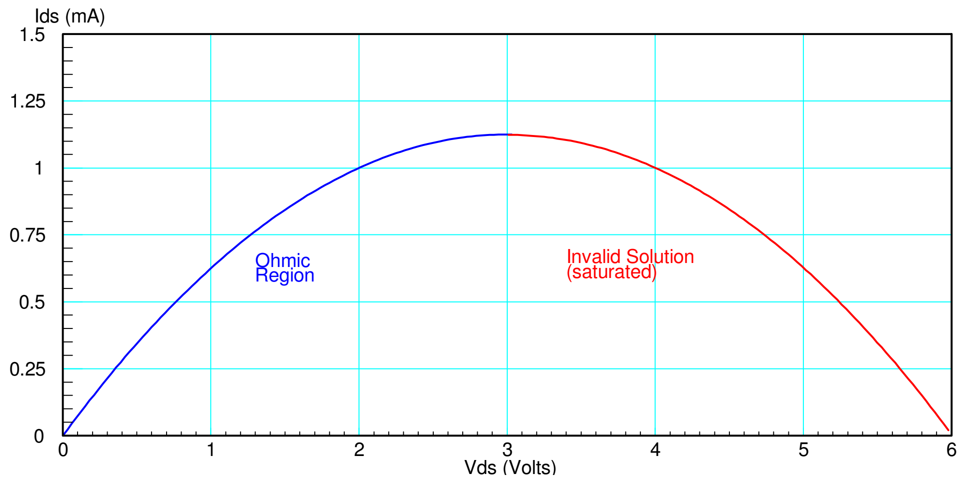
```
Vgs = 4;

Vds = [0:0.03:6]';
Vtn = 1;
Kn = 250e-6;

% Ohmic

Ids = Kn*(Vgs - Vtn - Vds/2).*Vds;

plot(VDS, IDS1*1000)
xlabel('VDS (V)');
ylabel('IDS (mA)')
```



Ide using the equation for the ohmic region.
The region past the peak is in valid (the MOSGET is no longer in teh ohmic region)

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

$$V_{DS} > V_{GS} - V_{TN}$$

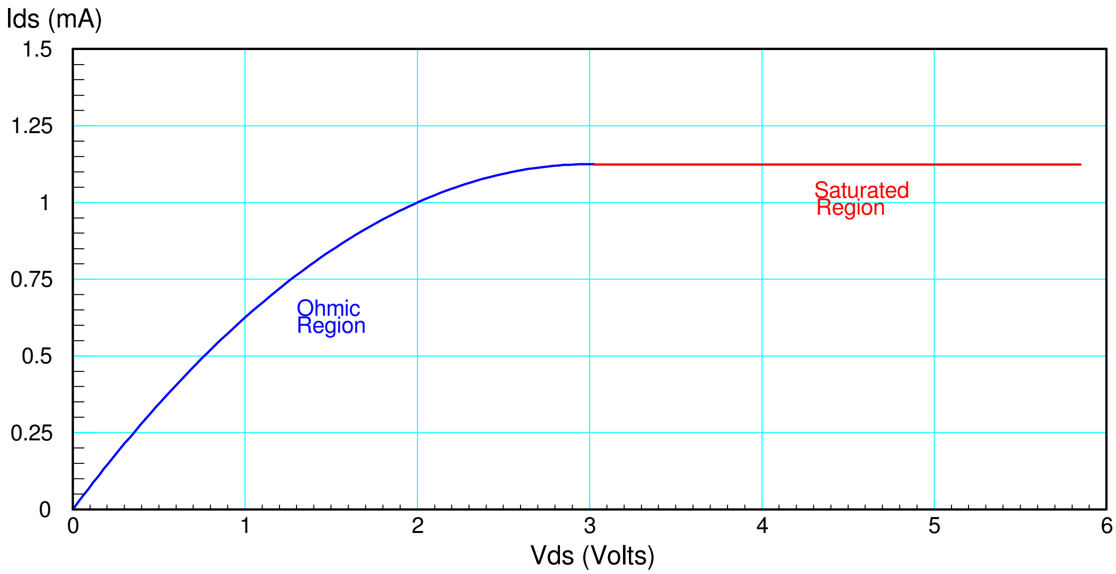
In this region, termed the Saturated or Pinch-Off region, I_{DS} is constant (not a function of V_{DS}):

$$I_{DS} = \frac{K_n}{2}(V_{GS} - V_{TN})^2$$

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:



Once you reach the peak (Vds > Vgs - Vth), the current remains constant

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 VDS 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.

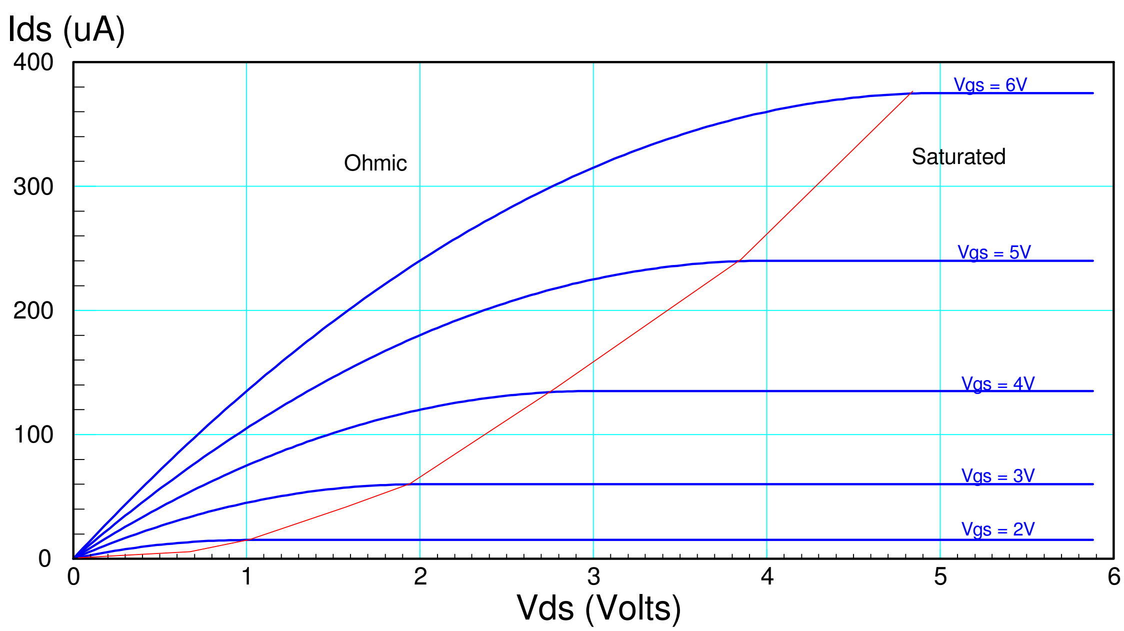
If you only plot the valid portion of each equation for various values of V_{DS}, you get the following:

Matlab Code

```
Vtn = 1;
Kn = 0.03;
Vds = [0:0.03:5.9]' + 1e-6;
DATA = [];

for i=1:5
   Vgs = Vtn + i;
% 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;
   DATA = [DATA, Ids];
   end
plot(Vds, DATA);
xlabel('Vds (V)');
```

ylabel('Ids (mA)')

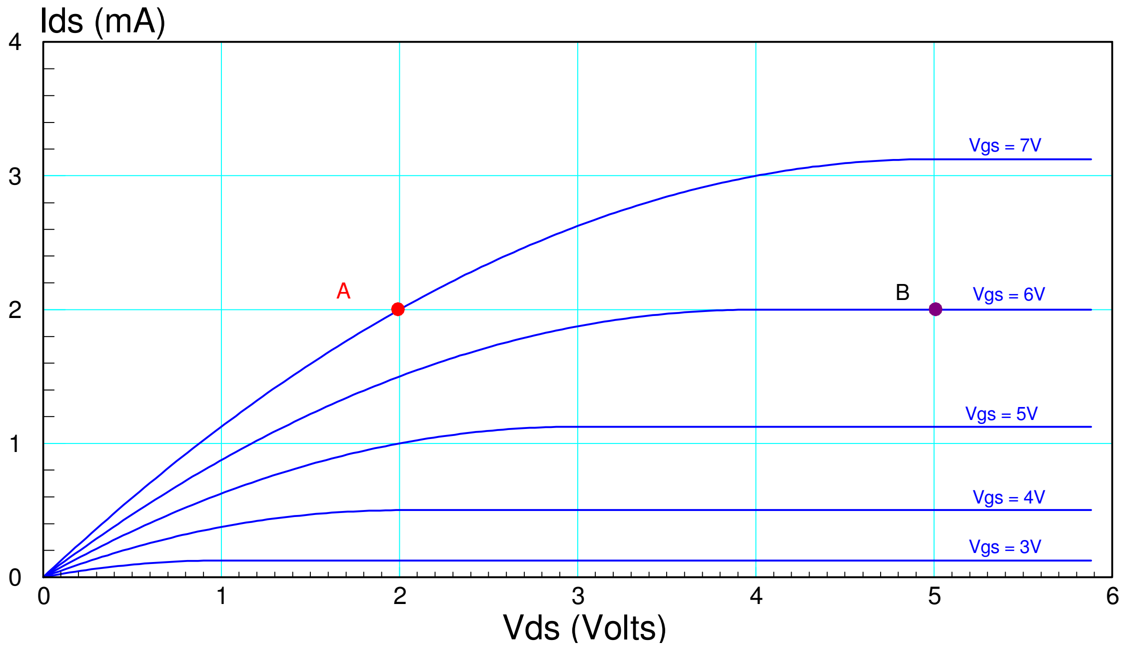


VI characteristic for a MOSFET where V_{GS} varies from 1.5V (bottom curve) to 5.0V (top curve) in 0.5V steps

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}.

MOSFET Example: Determine kn and Vth for the following n-channel MOSFET



Solution

Vtn = 2V

- Turns on at something less than 3V

k_n: Pick a point and plug in numbers.

For example, if you pick point A (Ohmic region)

$$I_{ds} = k_n\left(V_{gs} - V_{tn} - \frac{V_{ds}}{2}\right)V_{ds}$$

$$2mA = k_n\left(7V - 2V - \frac{2V}{2}\right)2V$$

$$k_n = 0.25mA/V^2$$

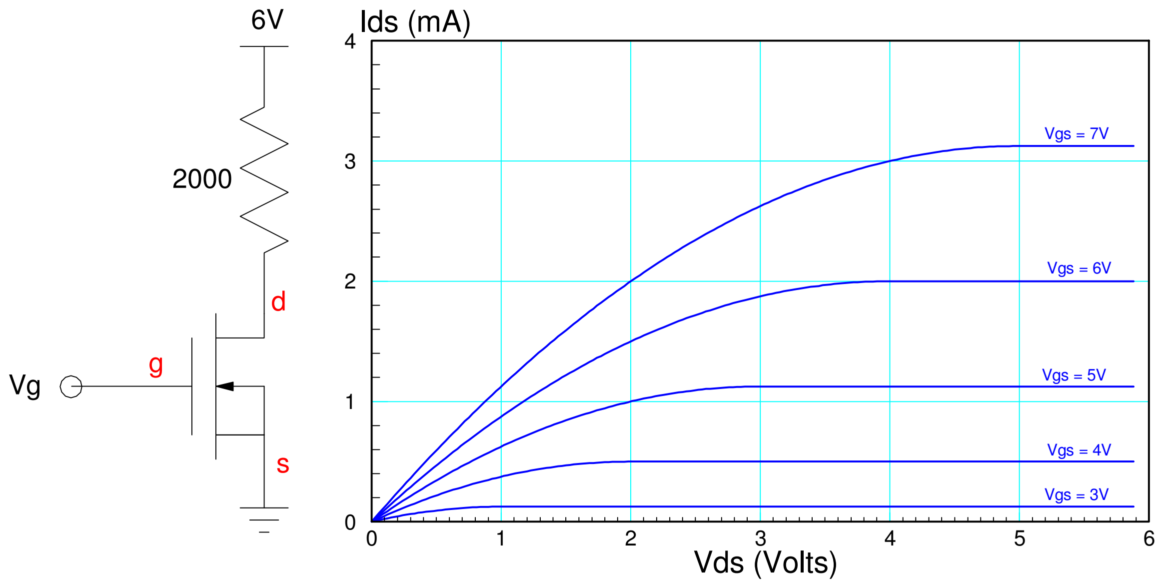
If you pick point B (saturated region) you get the same answer

$$I_{ds} = \frac{k_n}{2}(V_{gs} - V_{th})^2$$

$$2mA = \frac{k_n}{2}(6V - 2V)^2$$

$$k_n = 0.25mA/V^2$$

Example 2: Determine (Vds, Ids) for Vg = { 0V, 4V, 6V }



Solution: Draw the load line. The interesection of the Vgs lines and the load line is the solution.

Vg = 0V:

- Ids = 0mA, Vds = 6.0V

Vg = 4V

- Ide = 0.5mA,. Vds = 5.0V

Vg = 6V

- Ids = 1.75mA, Vds = 2.5V