EE334
MOSFETs

Transistors are one of the devices at the heart of modern electronics. You've probably heard of them, but don't know much else. This lecture aims to fix some of that. We'll cover a bit about the general nature of transistors and then focus specifically on one kind of transistor called the MOSFET.

Transistor Introduction and Background

Transistors exist to regulate current. As such, they have three operating modes. In the simplest mode the transistor is "off". That means that no current is flowing through the transistor. In the other two modes, the transistor is said to be "on". When "on" current flows through the transistor. In one of the "on" modes the transistor acts as an amplifier. That is, a small change to a currents or voltages external to the transistors causes a large, proportional, amount of current to flow in the transistor. In the other "on" mode, the transistor is *fully on* in the sense that the transistor is full of current (can't handle any more) and no changes to the currents or voltages external to the transistor affect the amount of current flowing in the transistor.

By way of analogy, a transistor acts like a valve hooked to a water faucet (but for current). When the valve is off, no water flows. When we turn the valve, we notice that small amounts of turning have a huge effect on the amount of water coming out of the faucet. This is the amplification aspect of the valve (transistor). Eventually, we'll reach a point at which turning the valve further doesn't change the flow of water. This is when the valve is fully open (transistor is fully on).

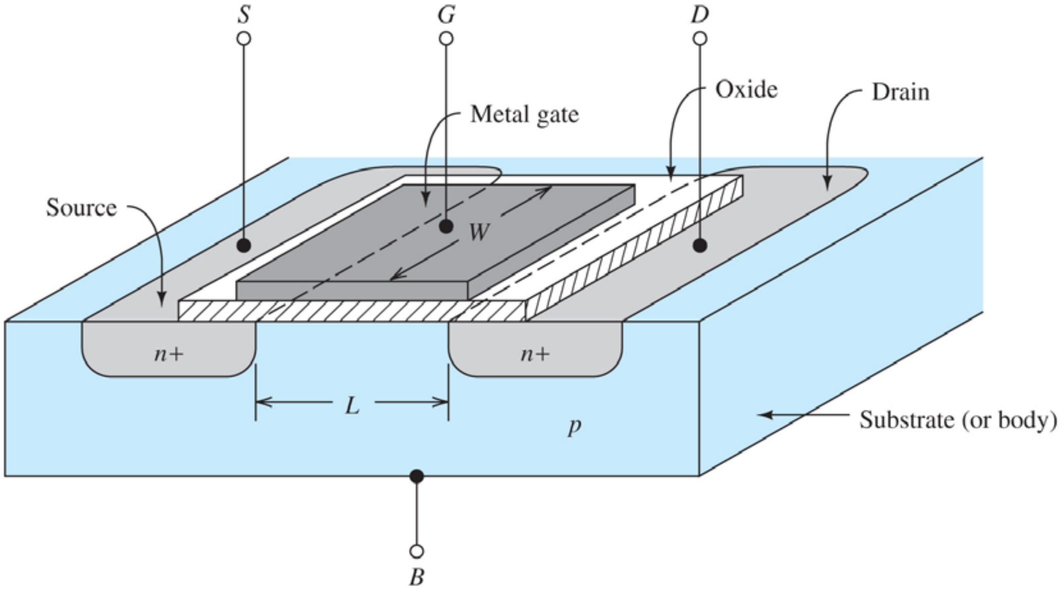
There are several types of transistors commonly in use in electronics. One kind is the bipolar junction transistor (BJT). The BJT was the most common transistor through the 1970s. This was due to its ease of manufacture (compared to other devices available at the time) and the fact that most electronic devices through that time were analog devices needing cheap and reliable amplifiers. Even today it's a very useful device, especially for circuits with high capacitances or where large amounts of current are needed (circuits where power levels are relatively high). However, it is not great for every situation.

The Field-effect transistor (FET) is another type of transistor. A particular type of FET is the metal-oxide-semiconductor field-effect transistor (MOSFET). MOSFETs are the primary transistor in digital electronics. MOSFETs are preferred over BJTs in digital circuits for several reasons. Generally speaking, compared to BJTs MOSFETs

- use less chip area,
- can be built using fewer processing steps (simpler usually equals cheaper),
- switch on and off more quickly,
- draw less current, and
- use less power.

Since we're about to begin looking at digital logic and circuits, we'll focus on the MOSFET in this packet of notes.

The figure below show an orthogonal view of a MOSFET as it would be implemented in a digital circuit.



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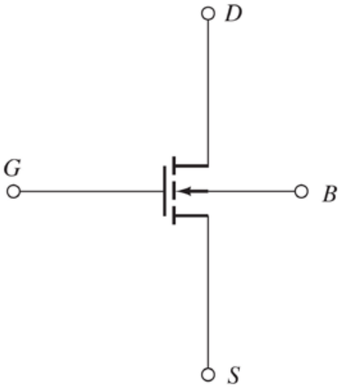
You'll notice that the MOSFET has three terminals: the **drain (D)**, **gate (G)**, **source (S)**, and **body (B)**. In many MOSFETs the body is nearly neutral (transmits very, very low currents) and is often tied to the source terminal to create a 3-terminal MOSFET (drain, gate, source). The oxide layer is a thin strip of very resistive (practically non-conducting) material that separates the gate from the substrate.

You'll notice that some of the substrate material is marked as n+ and p. Let's explain what that means as it will be important later. The substrate starts off as a single piece of silicon with a low set of charge carriers (free electrons). Silicon like this is said to be **semi-conductive**. That means that it's not a good conductor of electricity (like copper wire) nor is highly resistive (like rubber or glass).

One of the nice properties of silicon crystal is that it can be easily embedded with other atoms. For example, if you inject phosphorous atoms, which has excess electrons, into the silicon the substrate becomes negatively charged and is said to be **n-type** silicon. Since it has an excess of electrons, n-type silicon is a good conductor. Conversely, if you embed atoms with a lack of electrons into the silicon, such as boron, the silicon will become positively charged. This type of silicon is called **p-type**. Although we usually think of electron-heavy materials as being good conductors, p-type material can also conduct under certain situations. MOSFETs use the p-type material as an insulator that can be turned into a conductor by temporarily causing electrons to gather in the p-type material, thus creating a temporary highly conductive path.

The particular type of MOSFET shown above is called an **n-channel MOSFET** because when the MOSFET is "ON" an electron-heavy layer (an n-layer) will form in the p-type region under the gate and electrically connect the source and drain.

The picture above shows the circuit diagram for a MOSFET circuit. Like all other transistors, the MOSFET has three operating modes and allows for currents to flow only in certain directions into and out of certain terminals.



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1. Following your instructor's lead, mark the currents flowing into and out of the terminals on the MOSFET above.

2. Write an equation for the relationship of the drain current to source current.

Cutoff Mode

In cutoff, the following are true for a MOSFET

- $i_D = i_S = 0$ A
- $v_{GS} < V_{to}$

V_{to} is the threshold voltage. The MOSFET will stay in cutoff as long as v_{GS} stays below the threshold voltage. The threshold voltage ranges from a fraction of a volt to one volt.

Triode Mode

To be in the triode mode the following must be true for a MOSFET

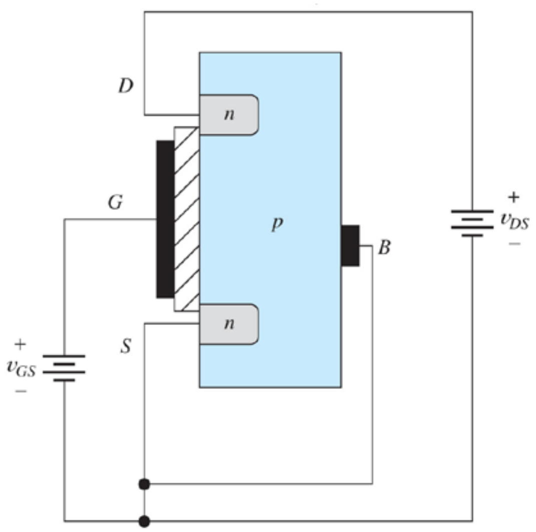
- $v_{DS} < v_{GS} - V_{to}$
- $v_{GS} \geq V_{to}$

When in the triode mode the drain and source currents are given by

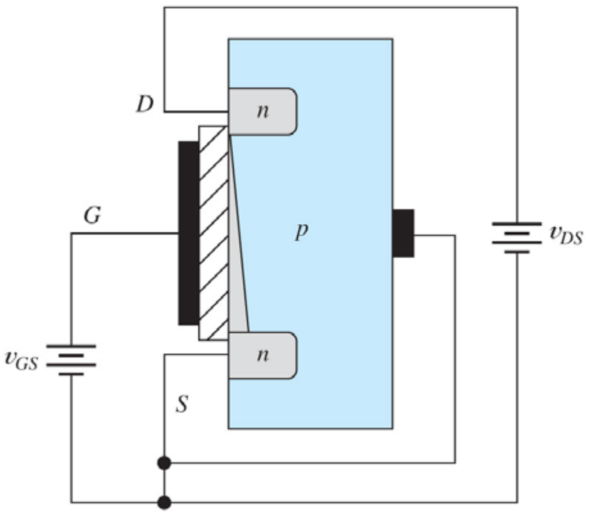
$$i_D = i_S = K\left[2(v_{GS} - V_{to})v_{DS} - v_{DS}^2\right]$$

$$K = \left(\frac{W}{L}\right)\frac{KP}{2}$$

where W is the width of the MOSFET channel and L is its length. Parameter KP is a device parameter that depends on the thickness of the oxide layer and certain properties of the channel material. A typical value for KP in n-channel MOSFETs is 50 $\mu A/V_2$.

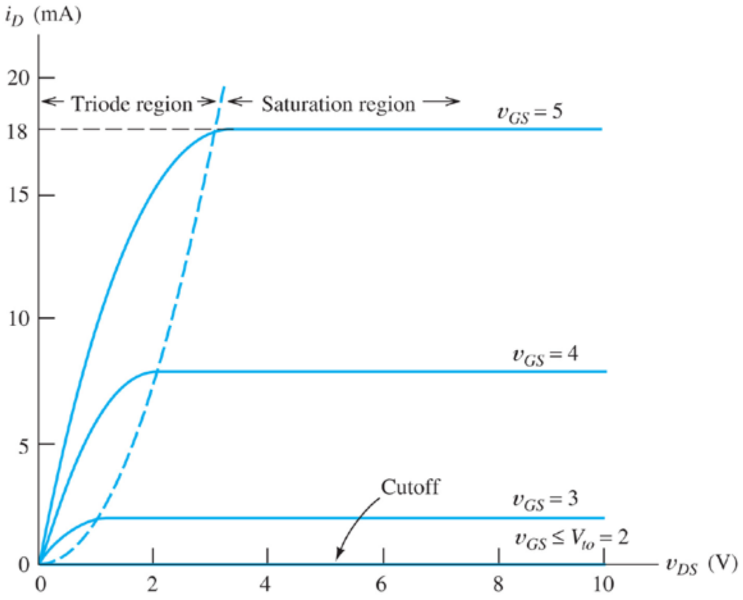


MOSFET in cutoff mode



MOSFET in triode region

The triode region is the transition mode of the MOSFET; the MOSFET is not completely “OFF” and not all the way “ON”. See how a temporary channel of n-type material is forming between the drain and source? The channel forms because the positively charged gate attracts electrons to it. Those electrons want to flow to the gate, but are blocked by the oxide layer. So, instead, the electrons collect underneath the oxide layer. Eventually the channel gets deep enough and long enough to connect the drain to the source. In the triode region, v_{DS} controls shape of the channel (makes it more resistive or less resistive). In the triode illustration above, v_{DS} is relatively low causing the channel to “pinch off” at the drain end. Thus this channel restricts the flow of electrons between the drain and source and will be heavily resistive. The higher v_{DS} becomes, the deeper the channel and the greater the current that can flow between drain and source. As show in the figure below, the triode region lies between the cutoff region (“OFF”) and the saturation region (“ON”).



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Another key thing about triode mode is that the drain and source currents depend mostly on v_{DS}. If v_{DS} can be made very small then the drain and source currents are proportional to the **excess gate-to-source voltage**, $v_{GS} - V_{to}$. Thus, if we can make both v_{DS} and v_{GS} very small then the MOSFET will be mostly "ON", but will have a very small drain current.

3. Consider the power equation P = IV. Why is desirable to have a MOSFET be "ON" with just a little current passing through it?

Saturation Mode

To be in the saturation mode the following conditions must hold:

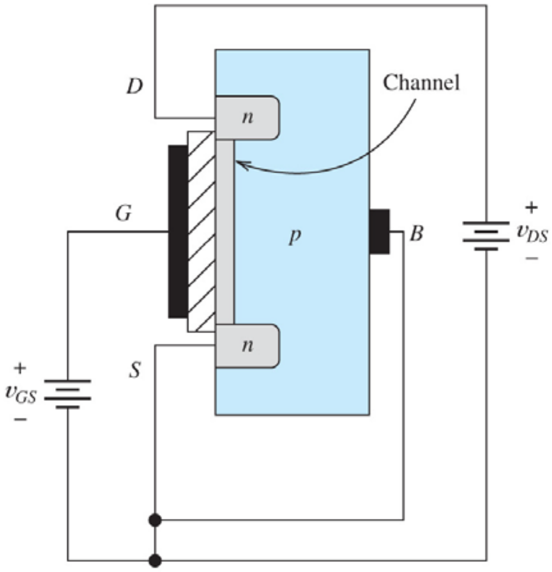
- $v_{GS} \geq V_{to}$
- $v_{DS} \geq v_{GS} - V_{to}$

When in saturation, the drain and source currents are given by

$$i_D = i_S = K(v_{GS} - V_{to})^2.$$

Note that the drain and source currents are proportional to the square of the excess gate-to-source voltage.

The figure below shows an n-channel MOSFET in the saturation mode. Note that the biasing of v_{DS} relative to v_{GS} causes the n-channel to pinch off (or at least narrow) at the drain end of the gate. The narrowness of the channel controls the amount of current that can flow from the drain to the source – the smaller the channel, the less the current. The channel's size can be controlled by altering v_{GS} which, in turn, regulates the current flow.



Saturation is the fully ON mode. The n-channel that forms between the drain and source is completely formed and changing v_{DS} has no effect on the drain current (as the equation above indicates). We can change the thickness of the n-channel by changing the term $v_{GS} - V_{to}$, so in sense amplification is still possible. However, this form of amplification doesn't result in the dramatic gains possible in the triode region by simply changing v_{DS}. Moreover, it's a lot simpler to worry about one value (v_{DS} in the triode region) rather than have to juggle two values for amplification (saturation region).

4. Complete the table below with the names of the MOSFET operating modes.

	MOSFET mode type		
Transistor type	OFF	ON	Transition
MOSFET			

MOSFETs in Logic Circuits

In logic circuits, MOSFETs are switched between their "ON" and "OFF" states. For this class, we're going to use cutoff ("OFF") and consider "ON" to be the absence of cutoff. Thus, OFF becomes the absence of drain current and ON is a non-zero (or at least significant amount of) drain current.

5. Real logic circuits made from MOSFET use cutoff and triode and try to avoid saturation. Why? Hint: Examine the relationship between cutoff, triode, and saturation in the graph at the bottom of page 4.

To make our lives easier, we're going to idealize (simplify considerably) MOSFET behavior and properties in order to quickly analyze MOSFET logic circuits.

Simplified MOSFET Model

- Given that $v_{DS} > 0$ V, figuring out that an n-channel MOSFET is "OFF" or "ON" is as simple as comparing the gate voltage to the drain voltage.
- When OFF, the drain and source have zero current and are not electrically connected. In other words, there's an open circuit between the drain and source. The drain and source can have different voltages.
- When ON, the drain and source are shorted and the voltage at the drain is the same as the voltage at the source.. Massive amounts of current can flow.

6. If $v_{GS} > 0$ V, then the MOSFET is “ON”. This means that current is _______________ from the drain to the source. Adopting an ideal model, the drain and source are ________________ (i.e., there is no _______________ between source and drain).
7. Otherwise, the MOSFET is “OFF” and current _____________________ from the drain to the source. The connection between source and drain is an _________________.

We’re going to make use of the two facts above to analyze actual MOSFET-based logic circuits. Using the facts above and some basic circuit analysis techniques, you’ll derive the logic function implemented by a MOSFET-based circuit. In a small lab, we’ll actually build the circuits using actual FETs.

INTERESTING FACT: The circuits you’ll analyze are of the kind actually used in digital devices. You can see more examples of actual basic logic circuits built from both n-channel and p-channel MOSFETs in Chapter 12.7 of your Hambley textbook.