

Metal Oxide Semiconductor Field Effect Transistors - MOSFETS

The MOSFET is one of a large number of transistor types. The MOSFET is the most widely used semiconductor device. To the first order, the MOSFET is a simple electronic switch that connects two of its terminals when a control voltage on a third terminal is high enough. The MOSFET's name is derived from the key principle of its operation. That is, current through the device is controlled by an electric field. This is in contrast to other transistors (such as BJT's) who control the flow of current through them via a electrical current.

The MOSFET can also act as a variable resistor, behaving more like a dimmer switch than an on-off switch. The control method is much the same but with a more continuous current variation. Depending on the electric field at one terminal, a variable amount of current is allowed to flow between the two other terminals.

While actually having four terminals, for most applications, two of them are usually connected together. In this discussion, of the MOSFET, we will concern ourselves with only three terminals; the *gate*, *drain*, and *source*. The gate is the control terminal where the electric field is applied. The drain and source are the terminals which carry the current we control.

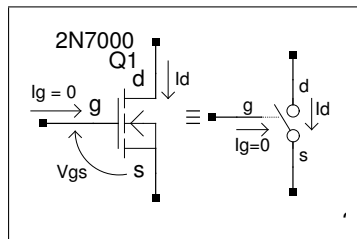


Figure 1: MOSFET Schematic Symbol and its Switch Model

The source terminal is common to both the voltage applied at the gate and to the current flowing from the drain to the source. When acting as a switch, the MOSFET connects the drain to the source terminals with a low resistance when the voltage between the gate and source (V_{gs}), is greater than the *threshold voltage* V_t . If V_{gs} is less than the threshold voltage, the resistance between the drain and source is very high. For the N-channel MOSFET we are discussing, the current always flows from drain to source.

Several schematic symbols for a MOSFET are shown below. The symbols on the left give the most clear indication as to the operational characteristics of the device. On device Q1, the gate is not connected either electrically or symbolically to the body of the part but is separated by an insulating barrier. The top and bottom terminals, drain and source respectively, form a conditionally conductive channel as shown by a segmented path from drain to source. The body connection is the one with the arrow and is usually tied to the source terminal as we will soon see. The symbols in the center column are commonly used analog representations of the MOSFET where the fourth terminal may have an independent connection.

The symbols on the top row are N-Channel devices. The devices on the bottom row are P-Channel devices. These names come from the type of conductive channel that is formed when the control voltage is placed on the gate.

The right column of MOSFETS, Q5 and Q6, are primarily used in the digital realm. Q5 is an N-Channel device and is *turned on* by having its gate at a logic one potential. Q6 however is a P-Channel device and is *turned on* with a logic zero potential. Digital logic gate schematic symbols regularly use the *bubble* to signify a input or output that is activated by a logic low potential.

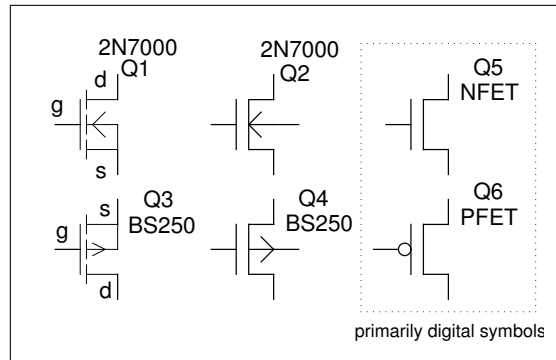


Figure 2: Common MOSFET Schematic Symbols

MOSFET Physical Structure and Operation

In figure 3 we see the physical structure of an N-Channel Enhancement mode MOSFET. While the structural implementation of modern MOSFETs differs considerably from our the discussion here, the fundamental concepts and operation of the device is very similiar.

The *substrate* or *body* of the transistor is made of p-type silicon formed from a single crystal. The p-type silicon is created by physically injecting boron or gallium atoms into the silicon crystal. This process is called *doping*. Boron and gallium have only three outer electrons compared to silicon's four. Embedded within the silicon lattice structure, the doping atoms create *holes* where free electrons are attracted, leaving a defecit of electrons, thus the p-type name.

Two highly conductive n+ regions forming the source and drain, are created in the substrate by bombarding the silicon with phosphorus or arsenic which supply extra electrons to the surrounding silicon atoms in the crystal lattice structure. This leaves the n+ region with plenty of free electrons to form a highly conductive region.

A very thin later of silicon dioxide, SiO_2 is grown on top of the substrate between the source and drain regions. The thickness of the oxide is about 1.5 nanometers. Given that the diameter of a Si atom is 0.25nm, this layer is roughly 6 Si atoms thick!

A metal gate area is deposited on top of the insulating oxide layer. The first gates were metal but are now polychrystalline silicon. Additional metal contacts are made to the source and drain

regions as well as to the back side of the substrate.

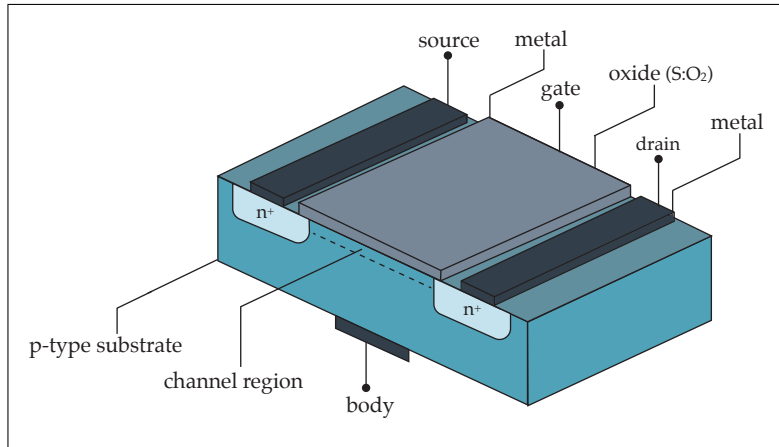


Figure 3: MOSFET Physical Structure

In figure 4 we see the side view of the MOSFET. It is helpful to see that the structure of the MOSFET closely resembles a MOS capacitor. The gate forms an upper plate that is insulated from the body by the thin oxide film. The p-type capacitor body and the highly conductive n+ region on the left provide the other terminal for the capacitor.

If a positive charging potential is applied to the gate and a negative to the body/n+ terminal, free electrons are drawn from the n+ area and fill the region under the gate. The numerous free electrons extending from the n+ region create the bottom plate of the capacitor. The abundance of electrons beneath the gate oxide essentially form the bottom conductor of the MOS capacitor.

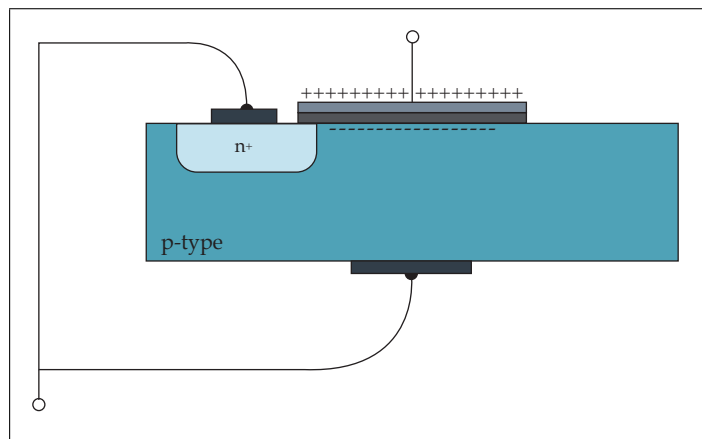


Figure 4: MOS Capacitor

However, consider what could happen if another highly conductive n+ region is placed on the right side of the gate. If the gate potential is made sufficiently positive as before, the conductive

channel underneath the gate would extend from the left n+ region to the right n+ region, forming connection between the two n+ regions.

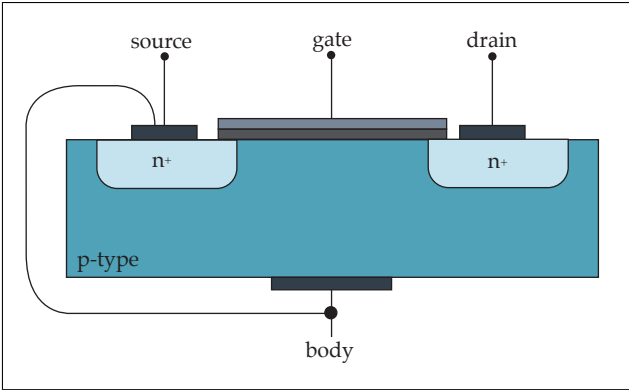


Figure 5: MOSFET Formed by Adding Source and Drain Terminals

Now, let's look at the MOSFET when it is in its *on* state.

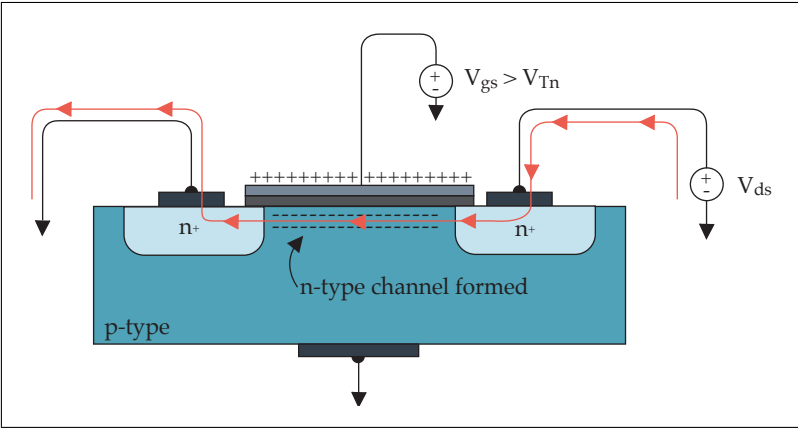


Figure 6: MOSFET Conduction Channel Formed by Positive Gate

When the gate potential is made sufficiently positive with respect to the body/n+ region, free electrons will be attracted to the area directly under the insulator creating a conductive channel. Essentially, we create a bridge of n+ material within the p-type material. This is the MOSFET in its *on* state. The point at which the conductive channel begins to form is when $V_{gs} > V_t$. The voltage v_t is known as the threshold voltage.

If, as shown, the source is at the lower potential, electrons drawn from it flow through the channel and are drained to the higher potential of the power supply V_{ds} . Of course, we are speaking of electron flow here and not current flow. Conventional current flow is depicted in figure 6. If the positive potential is removed from the gate, the conductive channel disappears, and current can no longer flow between drain and source.