MOSFETs

General Introduction

Transistors are devices that are used to drive output transducers. They deal with electrical power in response to electrical signals.

The above is a fairly concise description of what transistors do. By considering a systems approach to electronics, processes such as counters and logic circuits often need to drive larger output devices such as bulbs, motors and heaters etc. The devices used to perform the various processes are often small low power ICs that can only source or sink relatively small currents (several mA) and work at fairly low voltages. The output transducers may, on the other hand, require larger currents (several amps) and work at higher voltages. Something needs to allow the process devices to work with the output transducers and this is where transistors are used.

Transistors are devices that require only small input currents or voltages but can handle large output currents.

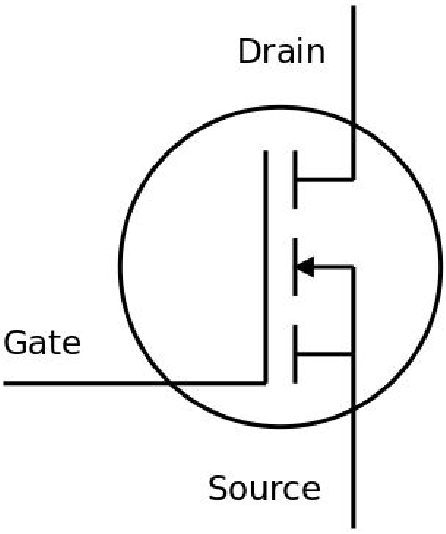
There are two distinct types of transistor, the bipolar transistor and the MOSFET, and for each type of transistor there are two varieties. Bipolar transistors can be either npn type or pnp type. Bipolar transistors are devices that are operated by current. MOSFETs are operated by voltages and can be either n-channel or p-channel MOSFETs. As transducer drivers, MOSFETs tend to be better at handling high currents than bipolar transistors but bipolar transistors are better suited to low voltage circuits.

Overview

An n-channel MOSFET is an active circuit component with three legs and usually made from silicon. The n-channel MOSFET is usually just referred to as a MOSFET. A MOSFET is just one example of a Field Effect Transistor (FET) and all these devices rely on the electric field due to a voltage. MOSFETs are voltage operated devices.

An n-channel MOSFET can be thought of as a simple electronic switch or transducer driver. As a transducer driver the MOSFET can be used to control powerful devices requiring large currents.

n-channel MOSFET basics

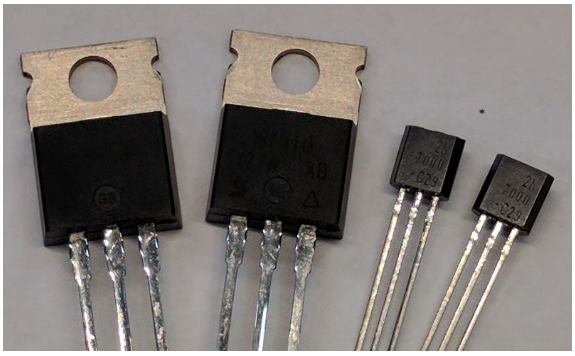


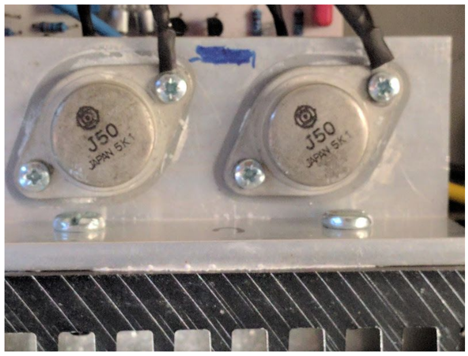
An n-channel MOSFET has three terminals or, in other words, three legs.

These legs are called the **Gate**, **Drain** and **Source**. The Source is identified by the arrow although this is not always shown.

Basic action: The minimum voltage between the Gate and the Source that allows the MOSFET to conduct is called the **threshold voltage**. When the Gate-Source voltage exceeds the threshold voltage of the MOSFET the Drain-Source resistance falls to a (very) low value and allows current to flow into the Drain and out of the Source. No current flows into the Gate as the Gate has a very high resistance.

Types of MOSFET

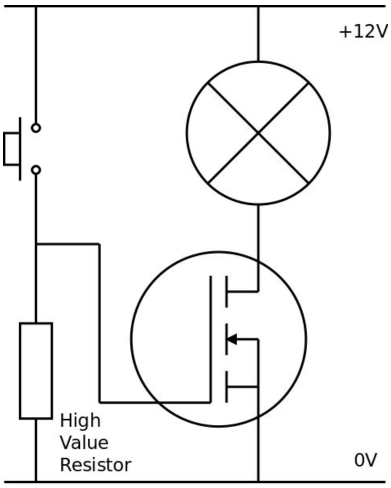




Small signal MOSFETs can be used to make amplifiers and other analogue circuits as well as making all types of digital circuits. The very high input (Gate) resistance of the MOSFET makes them ideal as input amplifiers to many devices. For example, a MOSFET is used as the input amplifier in a digital voltmeter (such as a multimeter) meaning the voltmeter has an almost infinite input resistance.

MOSFETs designed to control large currents have a very low Drain-Source resistance when they are fully turned on so that, even when large currents flow, very little heat is generated through ohmic heating. A typical power MOSFET can take 30 A or more and still only get warm in use as a transducer driver. The metal tag or metal case is usually connected to the Source. Very high power applications, such as power amplifiers, use MOSFETs bolted to a heatsink (as shown in the picture).

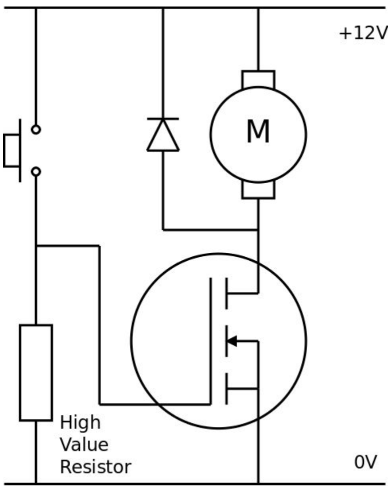
Used as a Transducer Driver



A MOSFET is very easy to use as a transducer driver because there are no other components needed and no calculations to perform. The electrical signal from a control circuit is used to control the MOSFET and the MOSFET controls the current through the output transducer. The only consideration is to make sure that the Gate-Source voltage is high enough to fully turn on the MOSFET.

The circuit shows an n-channel MOSFET being used to control a bulb. When the push button is pressed the Gate is connected to 12 V. This is well above the threshold voltage (the minimum voltage needed to "turn on" the MOSFET) and so the Drain-Source resistance reduces to almost zero and current flows through the bulb. The bulb is ON.

When the push button is released the high value resistor (nominally 10 kΩ but could be much higher if necessary) ensures the Gate is connected to 0 V. The Gate-Source voltage is less than the threshold voltage, the MOSFET is now "turned off" and the Drain-Source resistance rises to a very high value and no current flows through the bulb. The bulb is OFF.



If an inductive load, such as a motor or relay, is used then a protection diode is needed to protect the MOSFET from the back EMF produced when the transducer is turned off.

When the motor is turned off a large voltage can be generated between the 12 V rail and the Drain of the MOSFET. This large voltage can easily damage the MOSFET.

The diode restricts the maximum voltage at the Drain to a safe 12.7 V in the circuit shown.

Gate Resistance

One of the main advantages of a MOSFET is the very very high Gate resistance which can exceed 10 MΩ. This means that effectively no current flows into the Gate and MOSFETs have no effect on the circuit they are connected to.

The very high Gate resistance means that MOSFETs are sensitive to static electricity. Stray static can charge the Gate to very high voltages and damage the MOSFET and they must therefore be handled carefully. It is also important to ensure the Gate is connected to ground using a pull-down resistor if necessary otherwise the MOSFET can behave unexpectedly.

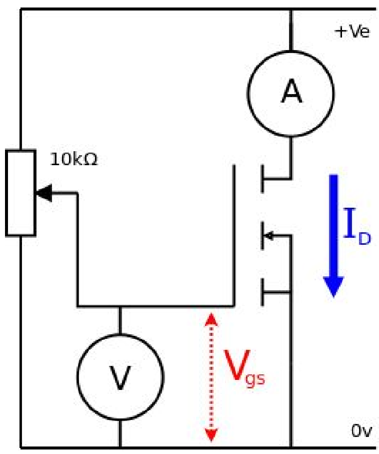
Gate-Source Voltage

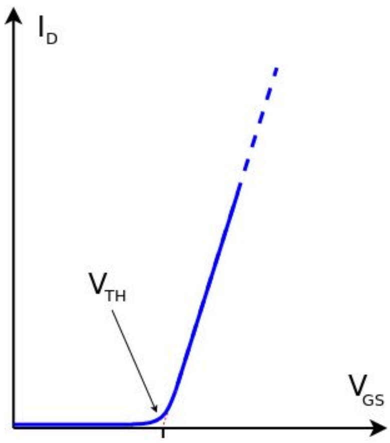
When the voltage between the Gate and the Source (called the Gate-Source voltage, V_{GS}) is less than the threshold voltage (V_{TH}) for a particular MOSFET then the Drain-Source resistance is very high and no current flows. When the Gate-Source voltage is much greater than the threshold voltage, the Drain-Source resistance falls to a few ohms or less and the MOSFET conducts.

The threshold voltage for many MOSFETs is around 3 V. MOSFETs cannot be used in devices where the supply voltage is relatively low. For example, a portable piece of equipment powered from an AA battery, such as the TV remote, is operating at 1.5 V and therefore standard MOSFETs cannot be reliably used without special circuitry to provide the necessary Gate-Source voltage.

The MOSFET Equation

The current that flows into the Drain (I_D) is related to the Gate-Source Voltage (V_{GS}), the threshold voltage (V_{TH}) and a property of the MOSFET, called the transconductance (g_M), that describes how well it conducts.





The circuit shown can be used to investigate the MOSFET equation. The potentiometer allows the V_{GS} to be varied and the ammeter measures the Drain current, I_D.

When the Gate-Source voltage is less than the threshold voltage the MOSFET does not conduct and the Drain current is zero.

When the Gate-Source voltage is above the threshold voltage, the Drain current increases linearly as the Gate-Source voltage increases.

The rate at which the Drain current increases is determined by the Transconductance (g_M) of the MOSFET. The Transconductance (from Transfer Conductance) is a property of the individual MOSFET and is measured in Siemens (S) or milliSiemens (mS). The Transconductance is given by the gradient of the linear section of the graph.

The MOSFET Equation, which is used to determine the Drain current when the MOSFET is conducting is:

$$I_D = g_M\ (V_{GS} - V_{TH})$$

Examples of the MOSFET Equation

Example 1: The threshold voltage of a MOSFET is 3.0 V and the Transconductance is 0.4 S (400 mS). What is the Drain current when the Gate-Source voltage is 4.5 V?

Solution: I_D = 0.4 × (4.5 − 3.0)

I_D = 0.4 × 1.5 = 0.6 A

If no other components are limiting the current, the Drain current flowing through the MOSFET will be 0.6 amps.

Example 2: If the threshold voltage of a MOSFET is 3.0 V and the Transconductance is 0.2 S (200 mS) what is the minimum Gate voltage if the MOSFET is used as a transducer driver controlling a device taking 1.6 amps?

Solution: I_D = 0.2 × (V_{GS} − 3.0)

1.6 = 0.2 × (V_{GS} − 3.0)

1.6 / 0.2 = 8.0 therefore 0.8 = V_{GS} − 3.0

V_{GS} = 8.0 + 3.0 = 11.0 V

A Gate-Source voltage of at least 11 V will ensure the MOSFET allows a current of 1.6 A to flow through the output device. Assuming that at 1.6 A the voltage drop across the output transducer is the full supply voltage then V_{DS} is close to zero and the MOSFET will dissipate very little power.

Example 3: A MOSFET with a threshold voltage of 3.5 V is controlled by the 5 V output from a logic gate. If the MOSFET is controlling an output load that requires a current of 200 mA, what is the minimum transconductance of the MOSFET?

Solution: I_D = g_M × (V_{GS} − 3.5) and 200 mA is 0.2 A

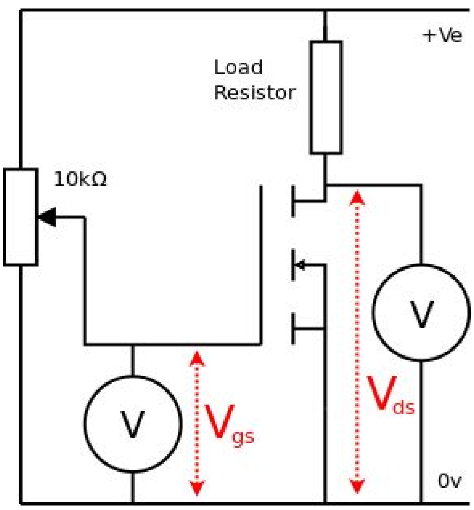
0.2 = g_M × (5.0 − 3.5)

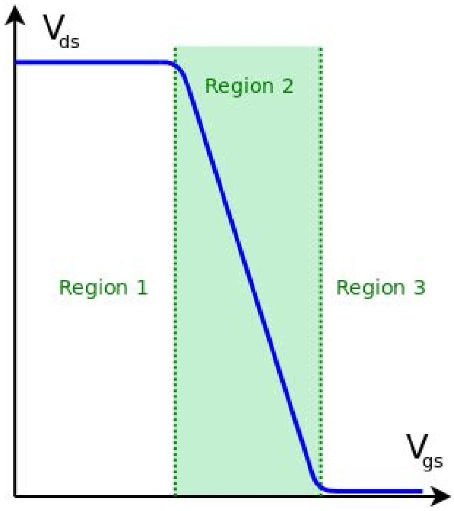
0.2 = g_M × 1.5

g_M = 0.2 / 1.5 = 0.13 S

To ensure that a Drain current of 200 mA flows through the MOSFET, the transconductance should be at least 130 mS.

Transfer Characteristics: How VDS depends on VGS





The circuit shown can be used to investigate the transfer characteristics of a MOSFET. The potentiometer allows the Gate-Source voltage to be varied. V_{GS} (sometimes called V_{in}) and V_{DS} (sometimes called V_{out}) are measured using voltmeters.

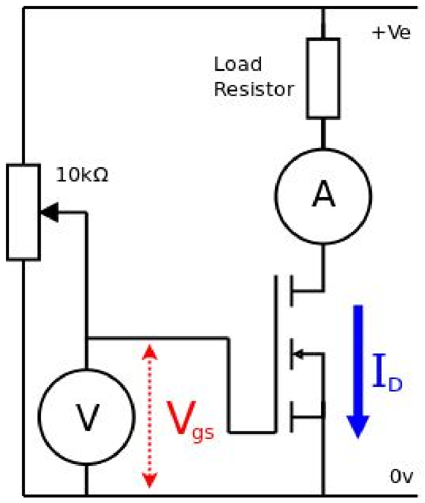
The transfer characteristics of a device describe how the output changes as the input changes. In this case the transfer characteristics of the MOSFET describe how the Drain-Source Voltage V_{DS} depends on the Gate-Source Voltage V_{GS}.

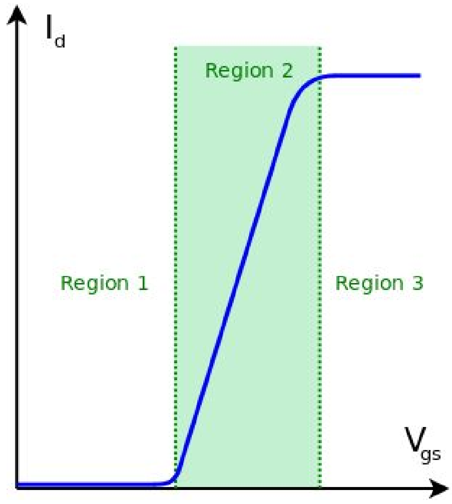
Region 1: When the Gate-Source voltage is less than the threshold voltage no current flows through the MOSFET. The potential difference across the load is zero (V = I x R and I = 0 therefore V = 0) and the Drain-Source voltage equals the supply voltage.

Region 2: When the Gate-Source voltage is above the threshold voltage, current flows through the load resistor. $V_{DS} = V_{supply} - V_{load}$. The Drain-Source voltage is not close to zero and the Drain current is not zero so the MOSFET dissipates power and may get hot or be damaged.

Region 3: When Gate-Source voltage is well above the threshold voltage the maximum current is limited by the load resistor. All of the supply voltage is dropped across the load resistor and the Drain-Source voltage is (almost) zero. When the MOSFET is used as a transducer driver, V_{GS} must be high enough (depending on load current and transconductance of the MOSFET) such that V_{DS} is close to zero.

Transfer Characteristics: How ID depends on VGS





The circuit shown can be used to investigate the transfer characteristics of a MOSFET and is very similar to the circuit used to investigate the MOSFET equation. A voltmeter measures V_{GS} and an ammeter in series with a load resistor measures I_D. The addition of the load resistor limits the maximum Drain current and means the MOSFET is acting as a transducer driver with the load resistor acting as the output transducer.

In this second case the transfer characteristics of the MOSFET describe how the Drain Current I_D depends on the Gate-Source voltage V_{GS}.

The linear section of the graph in region 2 is described by the MOSFET equation.

Region 1: V_{GS} is less than the threshold voltage, the MOSFET does not conduct and I_D is zero.

Region 2: $V_{GS} > V_{TH}$ and the MOSFET conducts. The Drain current depends on the transconductance of the MOSFET as described by the MOSFET equation and this part of the transfer characteristic is linear. The greater the transconductance, the steeper the line.

Region 3: V_{GS} is high enough to make I_D large enough to make the potential difference across the load resistor the same as the supply voltage. V_{DS} is zero and the Drain current cannot be any greater because it is limited by the load resistor.

End Note

The most basic application of a MOSFET is when it is configured as a transducer driver. Although it is acceptable to think of the MOSFET as a simple electronic switch in this case, there are many more complex applications where this simplistic approach is not appropriate.

Website

https://www.electronicsteaching.com/Electronics_Resources/DocumentIndex.html

July 2020