**LESSON 8 The Field Effect Transistor FET**

By the end of the lesson the learner should be able to:

(i) Explain the construction of FET
(ii) Describe the different configurations of FET
(iii) Describe output characteristics curve of FET
(iv) Describe the application of FET transistors

The Field Effect Transistor Family-tree

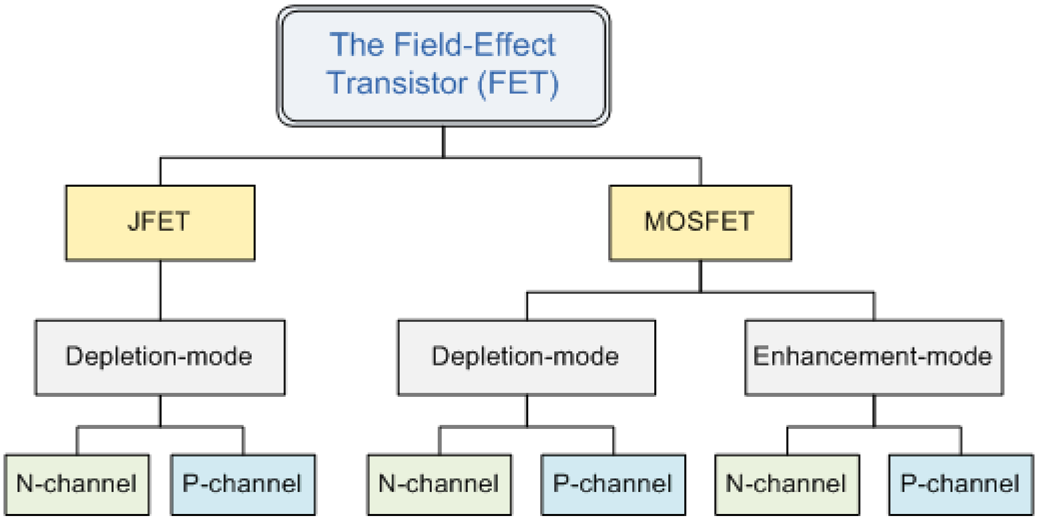


Fig 8.1 FET Transistor Family - tree

In the Bipolar Junction Transistor the output Collector current is determined by the amount of current flowing into the Base terminal of the device and thereby making the Bipolar Transistor a CURRENT operated device. The Field Effect Transistor, or simply FET however, use the voltage that is applied to their input terminal to control the output current, since their operation relies on the electric field (hence the name field effect) generated by the input voltage. This then makes the Field Effect Transistor a VOLTAGE operated device.

The Field Effect Transistor is a unipolar device that has very similar properties to those of the Bipolar Transistor ie, high efficiency, instant operation, robust and cheap, and they can be used in most circuit applications that use the equivalent Bipolar Junction Transistors, (BJT). They can be made much smaller than an equivalent BJT transistor and along with their low power consumption and dissipation make them ideal for use in integrated circuits such as the CMOS range of chips.

There are also two basic types of Field Effect Transistor, N-channel and P-channel. The Field Effect Transistor on the other hand is a "Unipolar" device that depends only on the conduction of Electrons (N-channel) or Holes (P-channel).

The Field Effect Transistor has one major advantage over its standard bipolar transistor cousins, in that their input impedance is very high, (Thousands of Ohms) making them very sensitive to input signals, but this high sensitivity also means that they can be easily damaged by static electricity. There are two main types of field effect transistor, the Junction Field Effect Transistor or JFET and the Insulated-gate Field Effect Transistor or IGFET), which is more commonly known as the standard Metal Oxide Semiconductor Field Effect Transistor or MOSFET for short.

**The Junction Field Effect Transistor**

The Field Effect Transistor has no junctions but instead has a narrow "Channel" of N-type or P-type silicon with electrical connections at either end commonly called the DRAIN and the SOURCE respectively. Both P-channel and N-channel FET's are available. Within this channel there is a third connection which is called the GATE and this can also be a P or N-type material forming a PN junction and these connections are compared below.

| Bipolar Transistor | Field Effect Transistor |
| --- | --- |
| Emitter - (E) | Source - (S) |
| Base - (B) | Gate - (G) |
| Collector - (C) | Drain - (D) |

The semiconductor "Channel" of the Junction Field Effect Transistor is a resistive path through which a voltage Vds causes a current Id to flow. A voltage gradient is thus formed down the length of the channel with this voltage becoming less positive as we go from the drain terminal to the source terminal. The PN junction therefore has a high reverse bias at the drain terminal and a lower reverse bias at the source terminal. This bias causes a "depletion layer" to be formed within the channel and whose width increases with the bias. FET's control the current flow through them between the drain and source terminals by controlling the voltage applied to the gate terminal. In an N-channel JFET this gate voltage is negative while for a P-channel JFET the gate voltage is positive.

Bias arrangement for an N-channel JFET and corresponding circuit symbols.

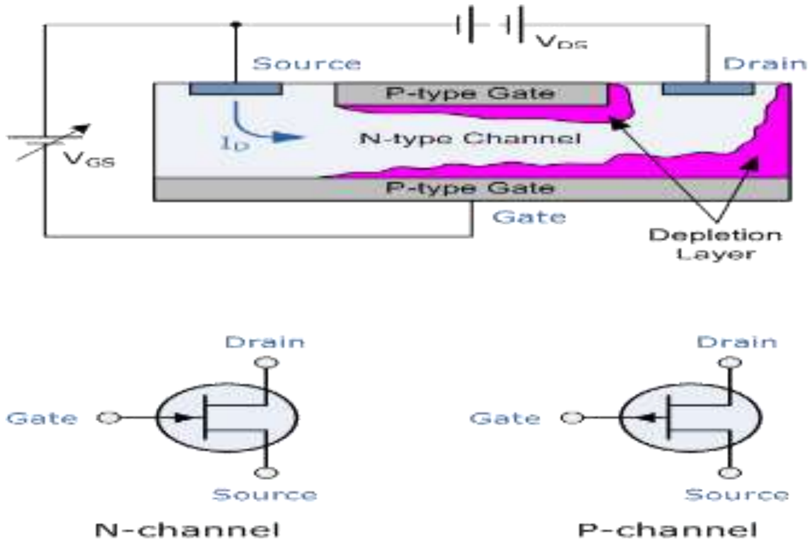


Fig 8.2 JFET Construction and Symbol

The cross sectional diagram above shows an N-type semiconductor channel with a P-type region called the gate diffused into the N-type channel forming a reverse biased PN junction and it's this junction which forms the depletion layer around the gate area. This depletion layer restricts the current flow through the channel by reducing its effective width and thus increasing the overall resistance of the channel.

When the gate voltage Vg is equal to 0V and a small external voltage (Vds) is applied between the drain and the source maximum current (Id) will flow through the channel slightly restricted by the small depletion layer. If a negative voltage (Vgs) is now applied to the gate the size of the depletion layer begins to increase reducing the overall effective area of the channel and thus reducing the current flowing through it, a sort of "squeezing" effect. As the gate voltage (Vgs) is made more negative, the width of the channel decreases until no more current flows between the drain and the source and the FET is said to be "pinched-off". In this pinch-off region the gate voltage, Vgs controls the channel current and Vds has little or no effect. The result is that the FET acts more like a voltage controlled resistor which has zero resistance when Vgs = 0 and maximum "ON" resistance (Rds) when the gate voltage is very negative.

Output characteristic voltage-current curves of a typical junction FET.

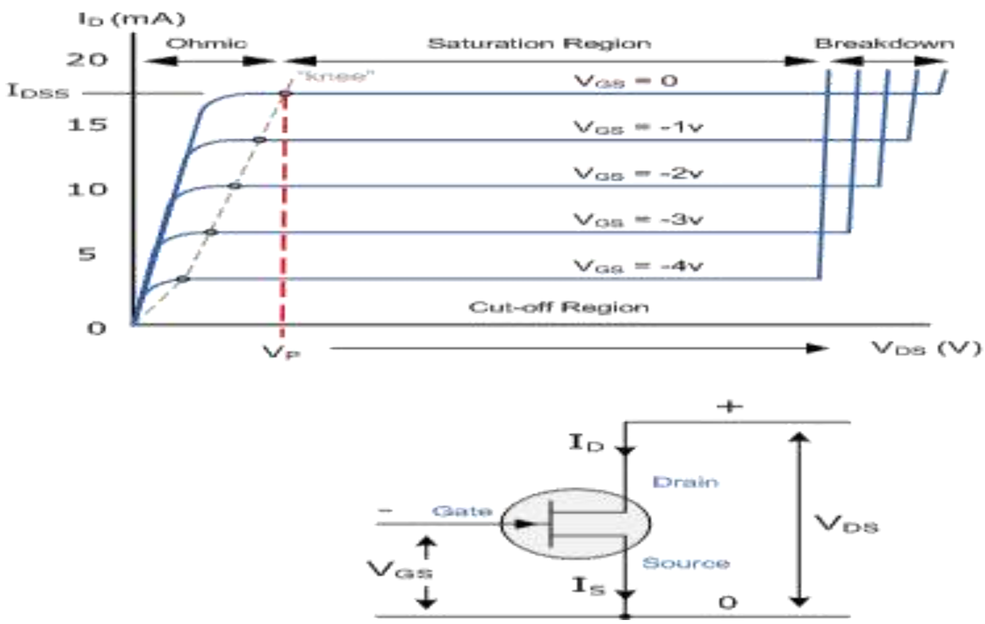


Fig 8.3 JFET Output Characteristic V-I Curves and Symbol

The voltage Vgs applied to the gate controls the current flowing between the drain and the source terminals. Vgs refers to the voltage applied between the gate and the source while Vds refers to the voltage applied between the drain and the source. Because a Field Effect Transistor is a VOLTAGE controlled device, "NO current flows into the gate!" then the source current (Is) flowing out of the device equals the drain current flowing into it and therefore (Id = Is).

The characteristics curves example shown above, shows the four different regions of operation for a JFET and these are given as:

- Ohmic Region - The depletion layer of the channel is very small and the JFET acts like a variable resistor.
- Cut-off Region - The gate voltage is sufficient to cause the JFET to act as an open circuit as the channel resistance is at maximum.
- Saturation or Active Region - The JFET becomes a good conductor and is controlled by the gate-source voltage, (Vgs) while the drain-source voltage, (Vds) has little or no effect.
- Breakdown Region - The voltage between the drain and source, (Vds) is high enough to causes the JFET's resistive channel to break down and pass current.

The control of the drain current by a negative gate potential makes the Junction Field Effect Transistor useful as a switch and it is essential that the gate voltage is never positive for an N-channel JFET as the channel current will flow to the gate and not the drain resulting in damage to the JFET. The principals of operation for a P-channel JFET are the same as for the N-channel JFET, except that the polarity of the voltages need to be reversed

The MOSFET

As well as the Junction Field Effect Transistor, there is another type of Field Effect Transistor available whose Gate input is electrically insulated from the main current carrying channel and is therefore called an Insulated Gate Field Effect Transistor. The most common type of insulated gate FET or IGFET as it is sometimes called, is the Metal Oxide Semiconductor Field Effect Transistor or MOSFET for short.

The MOSFET type of field effect transistor has a "Metal Oxide" gate (usually silicon dioxide commonly known as glass), which is electrically insulated from the main semiconductor N-channel or P-channel. This isolation of the controlling gate makes the input resistance of the MOSFET extremely high in the Mega-ohms region and almost infinite. As the gate terminal is isolated from the main current carrying channel ""NO current flows into the gate"" and like the JFET, the MOSFET also acts like a voltage controlled resistor. Also like the JFET, this very high input resistance can easily accumulate large static charges resulting in the MOSFET becoming easily damaged unless carefully handled or protected.

Basic MOSFET Structure and Symbol

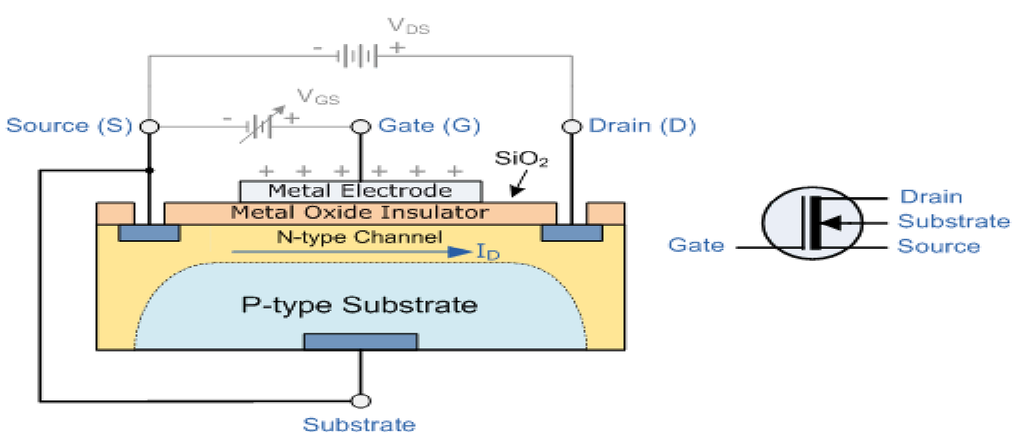


Fig 8.4 MOSFET Structure and Symbol

We also saw previously that the gate of a JFET must be biased in such a way as to reverse-bias the PN junction but in a MOSFET device no such limitations applies so it is possible to bias the gate in either polarity.

This makes MOSFET's specially valuable as electronic switches or to make logic gates because with no bias they are normally non-conducting and the high gate resistance means that very little control current is needed. Both the P-channel and the N-channel MOSFET is available in two basic forms, the Enhancement type and the Depletion type.

Depletion-mode MOSFET

The Depletion-mode MOSFET, which is less common than the enhancement types is normally switched "ON" without a gate bias voltage but requires a gate to source voltage (Vgs) to switch the device "OFF". Similar to the JFET types. For N-channel MOSFET's a "Positive" gate voltage widens the channel, increasing the flow of the drain current and decreasing the drain current as the gate voltage goes more negative. The opposite is also true for the P-channel types. The depletion mode MOSFET is equivalent to a "Normally Closed" switch.

Depletion-mode N-Channel MOSFET and circuit Symbols

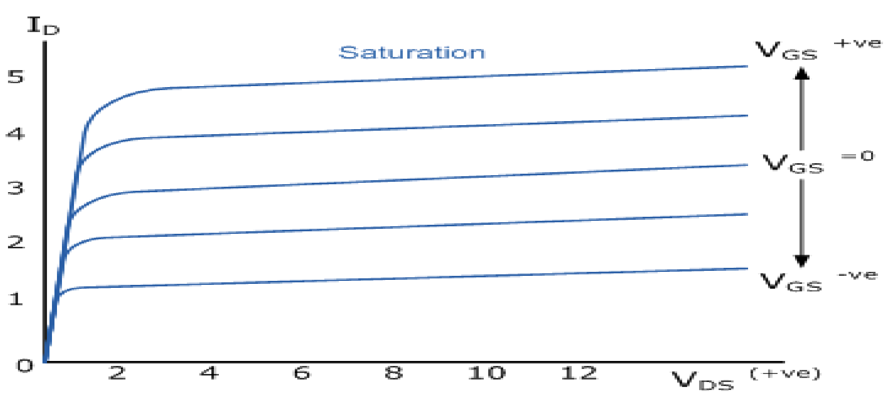


Fig 8.5 Depletion mode N-Channel MOSFET V-I output characteristics


8.6 Depletion mode N-Channel MOSFET Symbol

Depletion-mode MOSFET's are constructed similar to their JFET transistor counterparts where the drain-source channel is inherently conductive with electrons and holes already present within the N-type or P-type channel.

This doping of the channel produces a conducting path of low resistance between the drain and source with zero gate bias.

Enhancement-mode MOSFET

The more common Enhancement-mode MOSFET is the reverse of the depletion-mode type. Here the conducting channel is lightly doped or even undoped making it non-conductive. This results in the device being normally "OFF" when the gate bias voltage is equal to zero.

A drain current will only flow when a gate voltage (Vgs) is applied to the gate terminal. This positive voltage creates an electrical field within the channel attracting electrons towards the oxide layer and thereby reducing the overall resistance of the channel allowing current to flow. Increasing this positive gate voltage will cause an increase in the drain current, Id through the channel. Then, the Enhancement-mode device is equivalent to a "Normally Open" switch.

Enhancement-mode N-Channel MOSFET and circuit Symbols

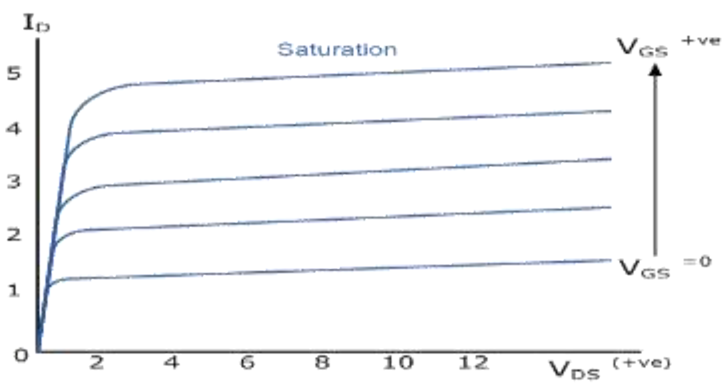


Fig 8.7 Enhanced mode N-Channel V-I output Characteristics

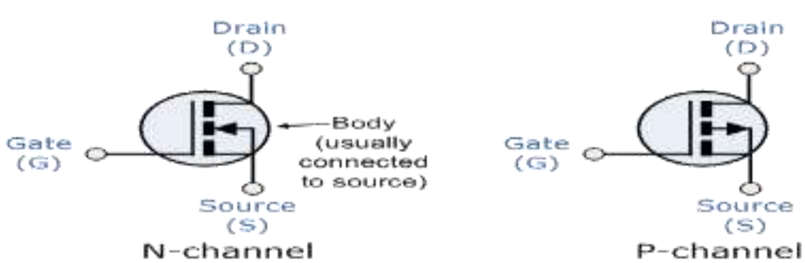


Fig 8-8 Enhanced mode N- Channel Symbol

Enhancement-mode MOSFET's make excellent electronics switches due to their low "ON" resistance and extremely high "OFF" resistance and extremely high gate resistance.

Enhancement-mode MOSFET's are used in integrated circuits to produce CMOS type Logic Gates and power switching circuits as they can be driven by digital logic levels.

**MOSFET Summary**

The MOSFET has an extremely high input gate resistance and as such are easily damaged by static electricity if not carefully protected. MOSFET's are ideal for use as electronic switches or common-source amplifiers as their power consumption is very small. Typical applications for MOSFET's are in Microprocessors, Memories, Calculators and Logic Gates etc. Also, notice that the broken lines within the symbol indicates a normally "OFF" Enhancement type showing that "NO" current can flow through the channel when zero gate voltage is applied and a continuous line within the symbol indicates a normally "ON" Depletion type showing that current "CAN" flow through the channel with zero gate voltage. For P-Channel types the symbols are exactly the same for both types except that the arrow points outwards.

The switching table can be summarized as follows.

| MOSFET type | Vgs = +ve | Vgs = 0 | Vgs = -ve |
|---|---|---|---|
| N-Channel Depletion | ON | ON | OFF |
| N-Channel Enhancement | ON | OFF | OFF |
| P-Channel Depletion | OFF | ON | ON |
| P-Channel Enhancement | OFF | OFF | ON |

The MOSFET as a Switch

We saw previously, that the N-channel, Enhancement-mode MOSFET operates using a positive input voltage and has an extremely high input resistance (almost infinite) making it possible to interface with nearly any logic gate or driver capable of producing a positive output. Also, due to this very high input (Gate) resistance we can parallel together many different MOSFET's until we achieve the current handling limit required. While connecting together various MOSFET's may enable us to switch high current or high voltage loads, doing so becomes expensive and impractical in both components and circuit board space. To overcome this problem Power Field Effect Transistors or Power FET's where developed.

We now know that there are two main differences between FET's, Depletion-mode for JFET's and Enhancement-mode for MOSFET's and we will look at using the Enhancement-mode MOSFET as a Switch.

By applying a suitable drive voltage to the Gate of an FET the resistance of the Drain-Source channel can be varied from an "OFF-resistance" of many hundreds of kΩ's, effectively an open circuit, to an "ON-resistance" of less than 1Ω, effectively a short circuit. We can also drive the MOSFET to turn "ON" fast or slow, or to pass high currents or low currents. This ability to turn the power MOSFET "ON" and "OFF" allows the device to be used as a very efficient switch with switching speeds much faster than standard bipolar junction transistors.

Summary of Bipolar Junction Transistors

- The Bipolar Junction Transistor (BJT) is a three layer device constructed form two semiconductor diode junctions joined together, one forward biased and one reverse biased.
- There are two main types of bipolar junction transistors, the NPN and the PNP transistor.
- Transistors are "Current Operated Devices" where a much smaller Base current causes a larger Emitter to Collector current, which themselves are nearly equal, to flow.
- The most common transistor connection is the Common-emitter configuration.
- Requires a Biasing voltage for AC amplifier operation.
- The Collector or output characteristics curves can be used to find either Ib, Ic or β to which a load line can be constructed to determine a suitable operating point, Q with variations in base current determining the operating range.
- A transistor can also be used as an electronic switch to control devices such as lamps, motors and solenoids etc.
- Inductive loads such as DC motors, relays and solenoids require a reverse biased "Flywheel" diode placed across the load. This helps prevent any induced back emf's generated when the load is switched "OFF" from damaging the transistor.
- The NPN transistor requires the Base to be more positive than the Emitter while the PNP type requires that the Emitter is more positive than the Base.

Summary of Field Effect Transistors

- Field Effect Transistors, or FET's are "Voltage Operated Devices" and can be divided into two main types: Junction-gate devices called JFET's and Insulated-gate devices called IGFET´s or more commonly known as MOSFET's.

- Insulated-gate devices can also be sub-divided into Enhancement types and Depletion types. All forms are available in both N-channel and P-channel versions.
- FET's have very high input resistances so very little or no current (MOSFET types) flows into the input terminal making them ideal for use as electronic switches.
- The input impedance of the MOSFET is even higher than that of the JFET due to the insulating oxide layer and therefore static electricity can easily damage MOSFET devices so care needs to be taken when handling them.
- FET's have very large current gain compared to junction transistors.
- They can be used as ideal switches due to their very high channel "OFF" resistance, low "ON" resistance.

Field Effect Transistors can be used to replace normal Bipolar Junction Transistors in electronic circuits and a simple comparison between FET's and transistors stating both their advantages and their disadvantages is given below.

| | Field Effect Transistor (FET) | Bipolar Junction Transistor (BJT) |
|---|---|---|
| 1 | Low voltage gain | High voltage gain |
| 2 | High current gain | Low current gain |
| 3 | Very input impedance | Low input impedance |
| 4 | High output impedance | Low output impedance |
| 5 | Low noise generation | Medium noise generation |
| 6 | Fast switching time | Medium switching time |
| 7 | Easily damaged by static | Robust |
| 8 | Require an input to turn it "OFF" | Requires zero input to turn it "OFF" |
| 9 | Voltage controlled device | Current controlled device |
| 10 | Exhibits the properties of a Resistor | |
| 11 | More expensive than bipolar | Cheap |
| 12 | Difficult to bias | Easy to bias |

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