Application Note

MOSFETs: Basic Structure, Operation & Ideal Applications

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Introduction

Similar to Bipolar Junction Transistors (BJTs), Field Effect Transistors (FETs) are three-terminal devices capable of current switching and signal amplification. Both consist of N-type and P-type doped silicon, with BJTs being NPN or PNP and FETs being N-channel or P-channel. A FET is either classified as a Junction FET (JFET), Metal-Semiconductor FET (MESFET), or Metal-Oxide Semiconductor FET (MOSFET) - the latter of which is the most widely used in integrated circuits. BJTs carry current through collector and emitter terminals while being controlled by the base terminal, and FETs conduct through drain-source terminals and are controlled by the gate terminal. Practically speaking, the difference between a BJT and FET is that while the current switching of BJTs is controlled by the current applied to the base (I_B), a FET is controlled by the voltage between the gate and source (V_{GS}).

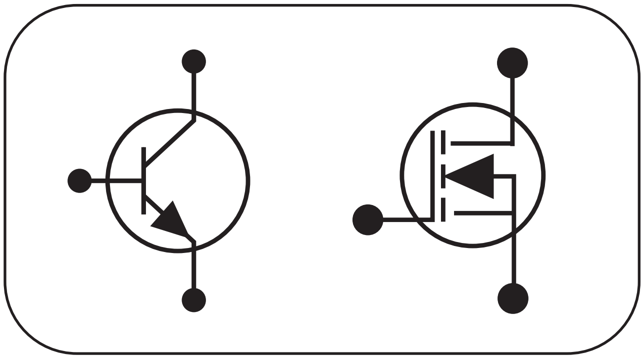


Figure 1:
Circuit symbols of NPN BJT (left) & N-Channel E-MOSFET (right)

BJTs and JFETs

To fully explain the structure of MOSFETs, it is useful to briefly discuss two other popular types of transistors (MESFETs are not as ubiquitous). The *bipolar* in bipolar junction transistor reflects both electrons and electron holes being used as charge carriers, while unipolar FETs use one or the other. BJTs and JFETs differ by the placement of the N- and P-type silicon in the device. In both, NPN/PNP (BJT) and N-channel/P-channel (FET) transistors are identical in performance, but with charge carriers reversed. In this section, only DC biasing will be considered.

Figure 2 below depicts a forward biased PNP BJT. In this configuration, the emitter-base junction is forward biased, while the base-collector junction is reverse biased. Majority carriers (holes for a PNP) easily cross the thin depletion region of the EB junction. For the depletion junction region of thicker reverse biased CB, minority carriers can cross from the N to P region. The minority carriers of the N-type are holes (majority carriers of the P-type), so the effect is a surge of holes (current) from emitter to collector. Collector and emitter currents (I_C and I_E) are approximately equal, and are proportional to the base current scaled by a constant, called either β or h_{fe} ($I_C = \beta I_B$).

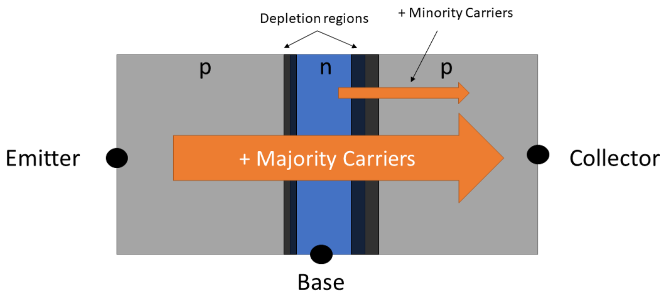
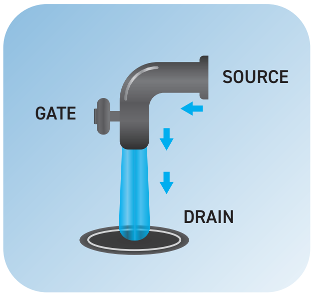


Figure 2:
Forward biased PNP BJT

Pictured in **Figure 3** is an N-channel JFET, appropriately named as N-type silicon forms a channel between the P-type materials connected to the gate. Relationships discussed pertain to the N-channel device, and their sign can be reversed in the case of a P-channel. The source-drain-gate nomenclature becomes easier to picture when imagining electric current as a current of water. The most important parameter of a JFET is its pinch-off voltage, called V_P or $V_{GS\,(off)}$. Drain-to-source current (I_D) is established by a positive drain-source potential (V_{DS}), and I_D increases nearly linearly (ohmic) with V_{DS} until $V_{DS} > V_P$, when I_D saturates at a fixed value. Maximum saturation current, called I_{DSS}, occurs when $V_{GS} = 0$ V. As V_{DS} grows, the depletion regions around the P-type material increase in size, reducing the channel width. At $V_{DS} = V_P$, the depletion regions nearly touch, or “pinch off” the channel, causing saturation. V_{GS} dipping below 0 V (for an N-channel) causes saturation at a lower V_{DS} value, but saturation current is lower in return. Once $V_{GS} > -V_P$, I_D drops to 0 A. This relationship is demonstrated on the right. In any case, I_D can be found by Shockley’s equation if I_{DSS} and V_P are known:



$$I_D = I_{DSS}(1 - \frac{V_{GS}}{V_p})^2$$

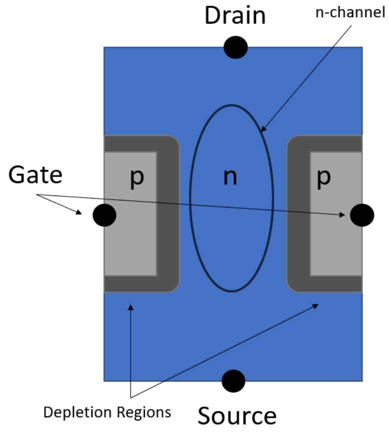


Figure 3:
N-Channel JFET

MOSFET DC Operation

MOSFETs are characterized by a thin dielectric layer (SiO_2 in all of Central Semiconductor’s MOSFETs) that isolates the gate terminal from the doped silicon. This results in a higher DC input resistance compared to a JFET (typically $10^{10}\Omega$ rather than $10^{8}\Omega$), and much higher than a BJT. Leakage current is further reduced and speeds are increased, as compared to a JFET. Because the current into the gate is nearly 0, power consumption is greatly reduced compared to other transistors. Unlike a JFET, MOSFETs may be shown with a fourth terminal, called either the substrate or the body. All of Central’s MOSFETs short the body to the source, as a potential between the two may reduce the drain current. Furthermore, MOSFETs are divided between enhancement and depletion modes (E-MOSFET/D-MOSFET), as pictured below. Both have heavily doped N-types at the drain and source, but D-MOSFETs are marked by a less doped N-type channel connecting the two. Currently, Central manufactures E-MOSFETs, but not D-MOSFETs.

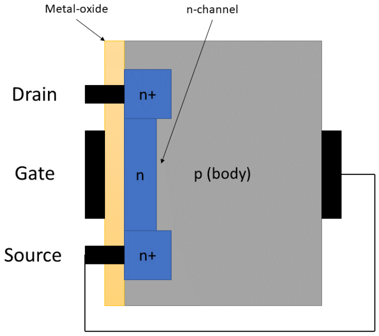


Figure 4:
N-Channel D-MOSFET

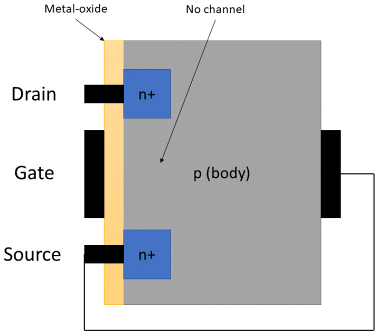


Figure 5:
N-Channel E-MOSFET

Shockley’s equation can be used for a D-MOSFET as it can for a JFET, and drain current is still defined as I_{DSS} when V_{GS} = 0V. Similarly, I_D = 0mA when at the pinch-off voltage. Unlike a JFET, I_D will continue to increase beyond I_{DSS} when V_{GS} > 0V. A positive potential at the gate causes a reverse leakage current at the PN junction, bringing more electrons over from the P-type substrate. The presence of more charge carriers is what allows drain current to exceed I_{DSS}. This isn’t without limit though, as each device is rated for a maximum drain current. Additionally, when V_{GS} is held constant, I_D behaves as it did in a JFET, eventually reaching saturation. Since it can conduct current without a gate voltage (positive V_{GS}), a D-MOSFET is referred to as *normally on*.

Alternatively, an E-MOSFET is *normally off*. While N-channel JFETs and D-MOSFETs conduct with a negative V_{GS}, n-channel E-MOSFETs require a positive V_{GS}, and do not follow Shockley's equation. At V_{GS} = 0V, I_D will approach 0mA, as opposed to I_{DSS}, due to the lack of an N-type channel for current to flow through. A positive potential at the gate attracts the minority carrier electrons and repels majority carrier holes in the P-type material. Once V_{GS} surpasses a level called threshold voltage (V_T or $V_{GS(Th)}$), this effect is significant enough to induce a channel resembling N-type silicon, allowing current to flow. If V_{GS} is held constant and V_{DS} is increased, there will eventually be a pinching-off at the drain end of this induced channel, resulting in a saturation. We can call the value of V_{DS} when I_D saturates $V_{DS(Sat)}$, and $V_{DS(Sat)} = V_{GS} - V_T$ for a given V_{GS}.

As noted, E-MOSFETs do not obey Shockley's equation. Instead, the drain current is found by the nonlinear relationship:

$$I_D = \frac{1}{2}\mu_n C_{ox}\left(\frac{W}{L}\right)(V_{GS} - V_T)^2 = k(V_{GS} - V_T)^2$$

Here, μ_n is the mobility of electrons in the N-type, C_{ox} is the gate oxide capacitance per unit area, W/L is the ratio of the channel width and length, V_T is the threshold voltage mentioned previously, and V_{GS} is found on its own. If desired, this equation can also be used to solve for drain current in D-MOSFETs. For a specific example, **Figure 6** and **Figure 7** indicate the characteristics for Central's 2N7002, an N-channel E-MOSFET. Each output characteristic can be seen saturating to I_{DSS} at a particular V_P for each V_{GS} value.

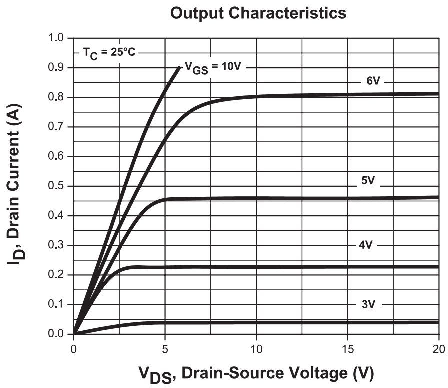


Figure 6:
2N7002 Output Characteristics

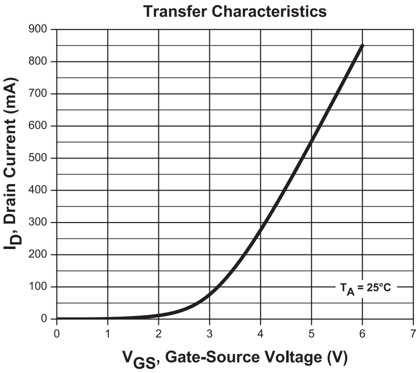


Figure 7:
2N7002 Transfer Characteristics

MOSFET Applications

MOSFETs have earned the status as the most popular electronic device ever thanks to integrated circuits (ICs), which have enabled the rapid growth of the computing industry. Unlike an IC, which may use billions of individual MOSFETs, the discrete devices manufactured by Central Semiconductor are mostly single transistors, with the exception of devices such as full-wave bridge rectifiers and Darlington pairs. Despite the "fame" of ICs, discrete MOSFETs are used in a wide range of applications, including in the power industry, consumer electronics, and radio frequency (RF) manipulation.

Someday, solar panels may be the vehicle by which the majority of power in the U.S. is produced, however, the battery of a solar panel typically releases energy as 12V DC, which is incompatible with devices meant to work on the 60Hz 120V AC in American wall outlets. To solve this dilemma, MOSFETs can be used as switches in solar inverters, which convert DC to AC. Central's power MOSFETs (rated for at least 600V), such as the CDM3-800 (3A, 800V) and CZDM8502 (2A, 850V), are ideal for these inverters. Power MOSFETs are connected to the DC source or battery. A microcontroller turns each on and off rapidly, producing a square wave. This is passed through capacitors, which filter out the harmonics of the square wave, producing something resembling a sine wave. Finally, this signal is passed through a step-up transformer, which increases the voltage to 120V. Though it may not be a perfect sine wave, it is more than suitable for most applications.

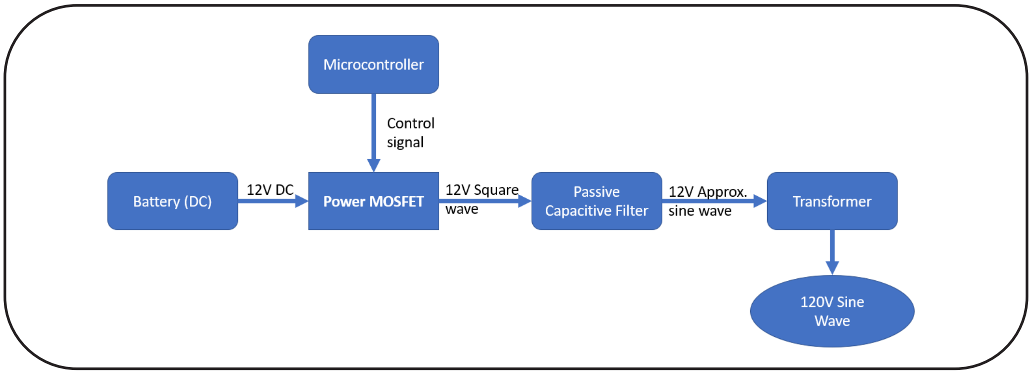


Figure 8:
DC-AC Inverter topology

On the flip side, discrete MOSFETs find use in active rectification, or the conversion of AC to DC. The classic rectifier uses a standard diode, which has an operating voltage of approximately 0.7V. Especially in low voltage applications, this could drastically reduce efficiency. Active rectification is built from an H-bridge of 4 MOSFETs, used as switches. A comparator detects the polarity of the AC source. Depending on the polarity, the comparator sends a control signal to the relevant MOSFETs such that the current flows in the specified direction. Reversing the direction in this way serves to make the negative cycle of the sinusoidal source positive. Then, the signal is passed to a similar capacitor-based passive filter as in the inverter. This acts to smooth out the humps, producing something close enough to DC to be useful in DC applications. The H-bridge is shown in operation in **Figure 9**, in addition to a block diagram of the signal at each step. It's very important that MOSFET switches are only activated in that particular pattern, as doing so otherwise would short the circuit.

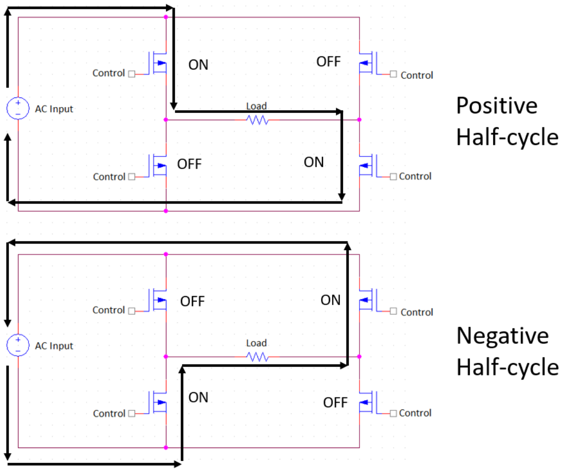


Figure 9:
H-Bridge Topology

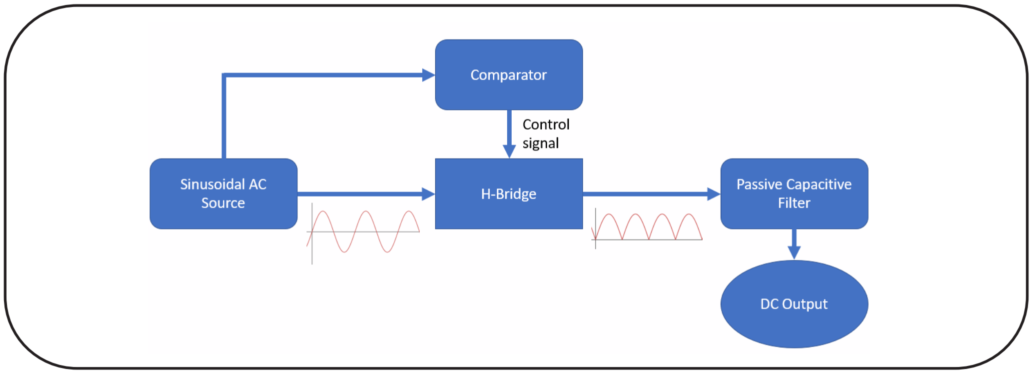
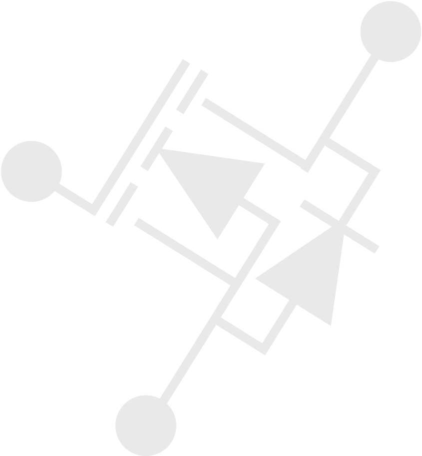


Figure 10:
Active rectifier topology

Conclusion

These applications previously mentioned are far from the only uses for discrete MOSFET semiconductors. Other applications include boost/buck converters, switch mode power supplies, radio frequency power amplifiers, and a wide variety of sensors. The ability of MOSFETs to rapidly switch current while consuming very little power makes these devices ideal for both analog and digital applications across a wide range of industries.



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