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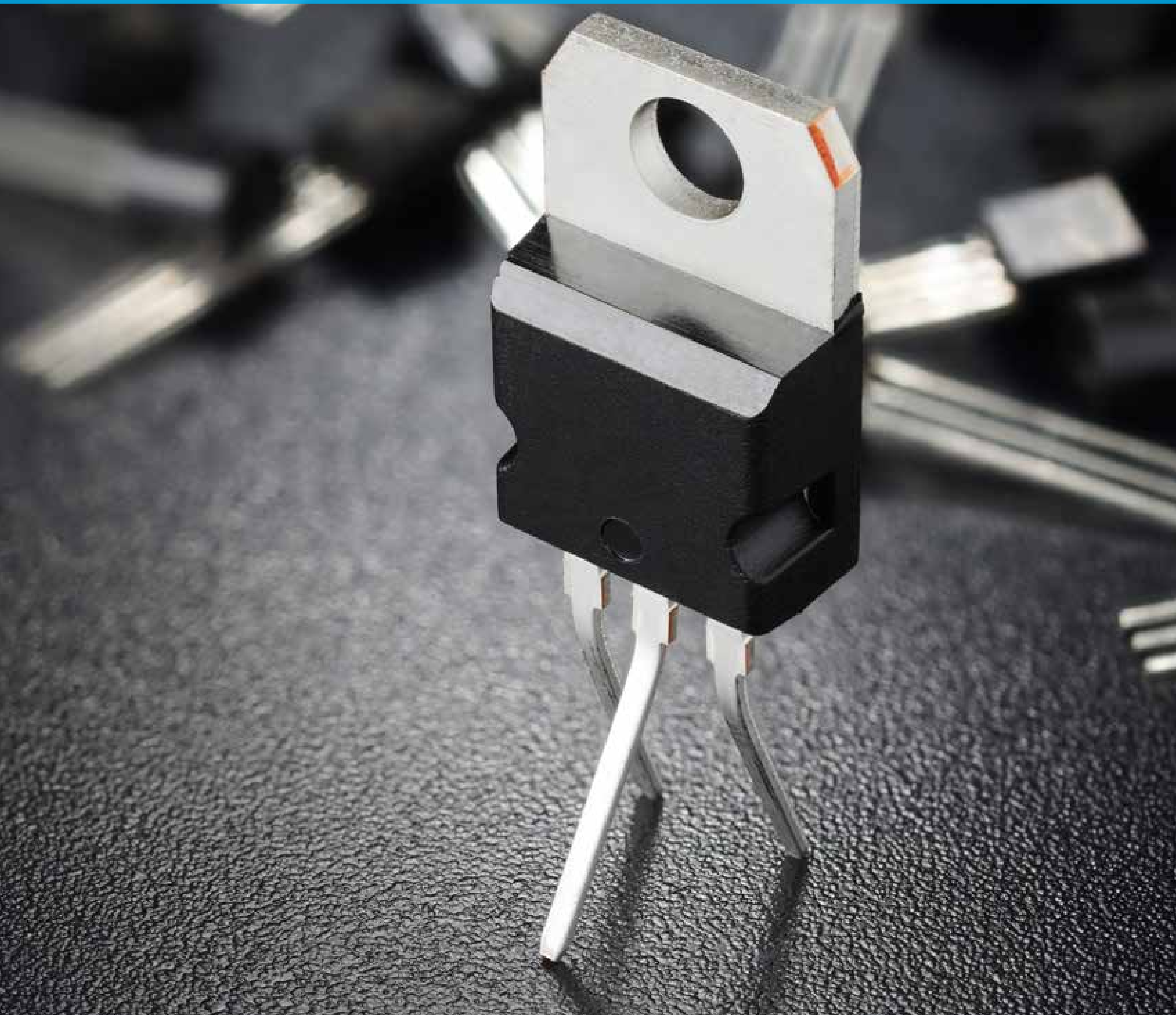
# Introduction to MOSFETs

## Background and Practical Applications



# Table of Contents



## References


- *TL074 Op Amp datasheet,* ST Microelectronics
- *Moore's Law Wikipedia*
- *IFX91041 Buck Converter datasheet,* Infineon
- *Microelectronic Circuits 6th Edition*. New York, Oxford University Press, 2010
- *MOSFET Wikipedia*
- *EE105 Spring 2008 Berkley Lecture*

# Introduction to MOSFETs

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A MOSFET is one of the most commonly used transistors in both digital and analog circuits. In this eBook, we will discuss how MOSFETs are constructed, their characteristics, examples of various practical applications, and more.

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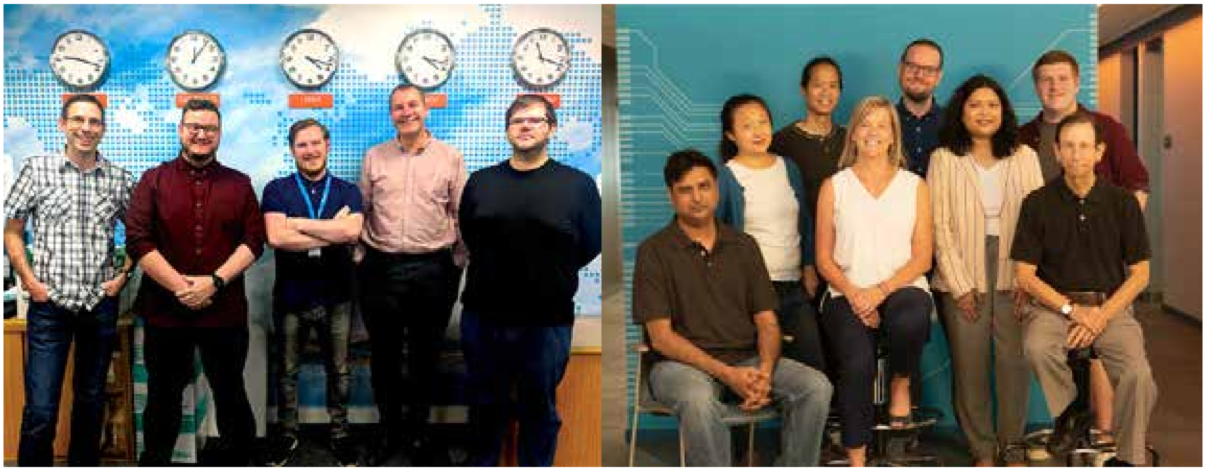


# CHAPTER - 1 Introduction and a Brief Overview

The invention of the transistor has arguably had one of the most significant influences on society over the past century. It has allowed engineers to create electronics that have completely altered the way humans live, work, and play. Two major types of transistors exist: bipolar junction transistors (BJTs) and field-effect transistors (FETs). This tutorial will focus on FETs and, more specifically, metal oxide semiconductor field-effect transistors (MOSFETs). The information that will be covered in the tutorial includes:

- Theory of operation
- Important properties
- Applications of MOSFETs
- Additional Types of FETs

# CHAPTER - 2 The MOSFET and Theory of Operation

The MOSFET transistor is a fundamental active component in modern electronics. The device is constructed in a substrate and consists of a gate, drain, and source. There is also technically a 4th terminal, known as the body; this can be very important to be aware of in some applications, as connections to the body can have unwanted effects in the circuit. A variety of the different symbols found in schematics to represent MOSFETs can be seen in the image below:

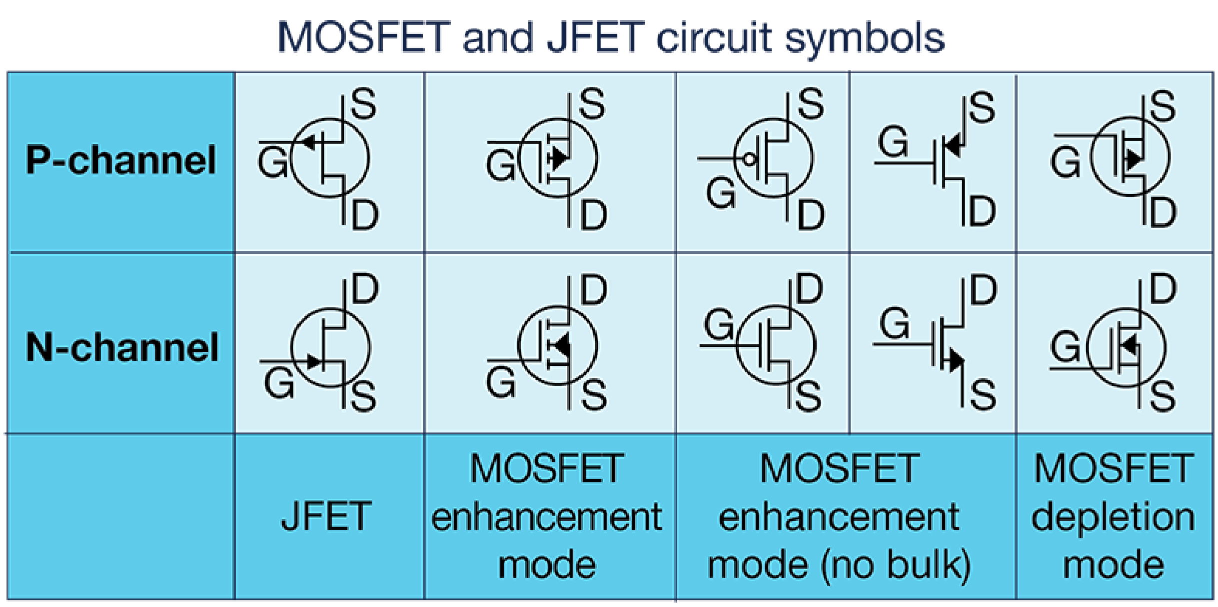



*Figure 1. Image showing the variety of MOSFET symbols commonly used. Image Source: MOSFET Wikipedia*

The body of a MOSFET is fabricated in a p-type substrate with two areas of heavily doped n-type material that make up the drain and source. A thin layer of silicon dioxide separates the gate from the body. This type of device is known as an NMOS device or an n-channel MOSFET. Alternatively, there exists a PMOS device that is constructed in an n-type substrate with heavily doped p-type material that makes up the drain and source.

A key difference between the two is that in NMOS devices, the flow of current happens through electrons, while in a PMOS device the flow of current happens through holes. Since positive charges move more slowly than negative charges, the PMOS transistor generally has slightly worse performance than its counterpart.

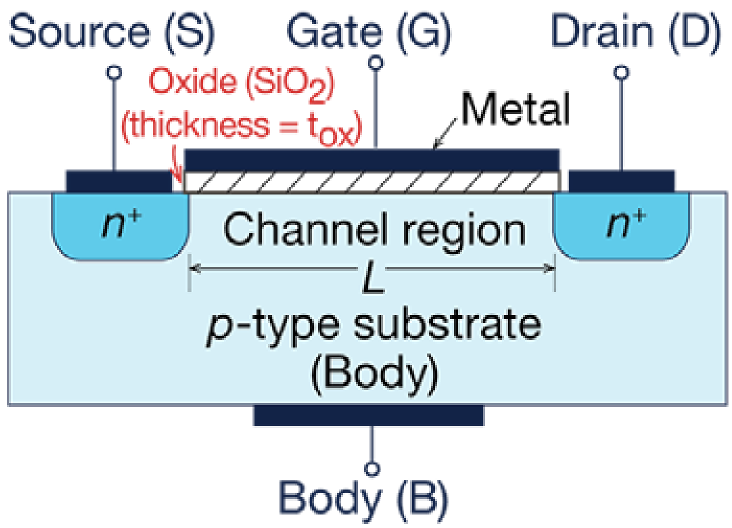



*Figure 2. Construction of a MOSFET. Image Source: Microelectronic Circuits 6th Edition by Sedra and Smith*

To understand the theory of how a MOSFET works, we must consider the situation in which the source and drain are grounded. When a positive voltage is applied to the gate, the holes (positive charges) are pushed away from the gate area in the body of the substrate. Consequently, negative charges are attracted to the gate area in the "channel" region. This action creates a channel underneath the gate that connects the drain and source. This is often referred to as the inversion layer, since it is inverting the charges in the substrate.

The gate-source voltage in which the channel can sufficiently conduct is known as the threshold voltage, and is generally somewhere between 0.2V and 1.0V. Thus, when the gate-to-source voltage is greater than the threshold voltage, the channel of a MOSFET is able to support current flow.

Also, note that the threshold voltage is defined by the construction and fabrication of the transistor; the user does not have much control over it.

Armed with this new knowledge, we can now think of adding an additional voltage to the MOSFET. Assume the gate-source voltage is greater than the threshold voltage. Next, envision applying a positive voltage across the drain-source terminals. This effectively creates current flow from the drain to the source. For a small drain-to-source voltage, the current increases with voltage in an approximately linear manner. This is often referred to as the linear region of operation. As the voltage across the drain-to-source further increases, the current begins to increase less and less, until it reaches a point where further increases in the drain-to-source voltage, in an ideal situation, no longer produce an increase in current. This is better illustrated in the curves shown in Figure 3.

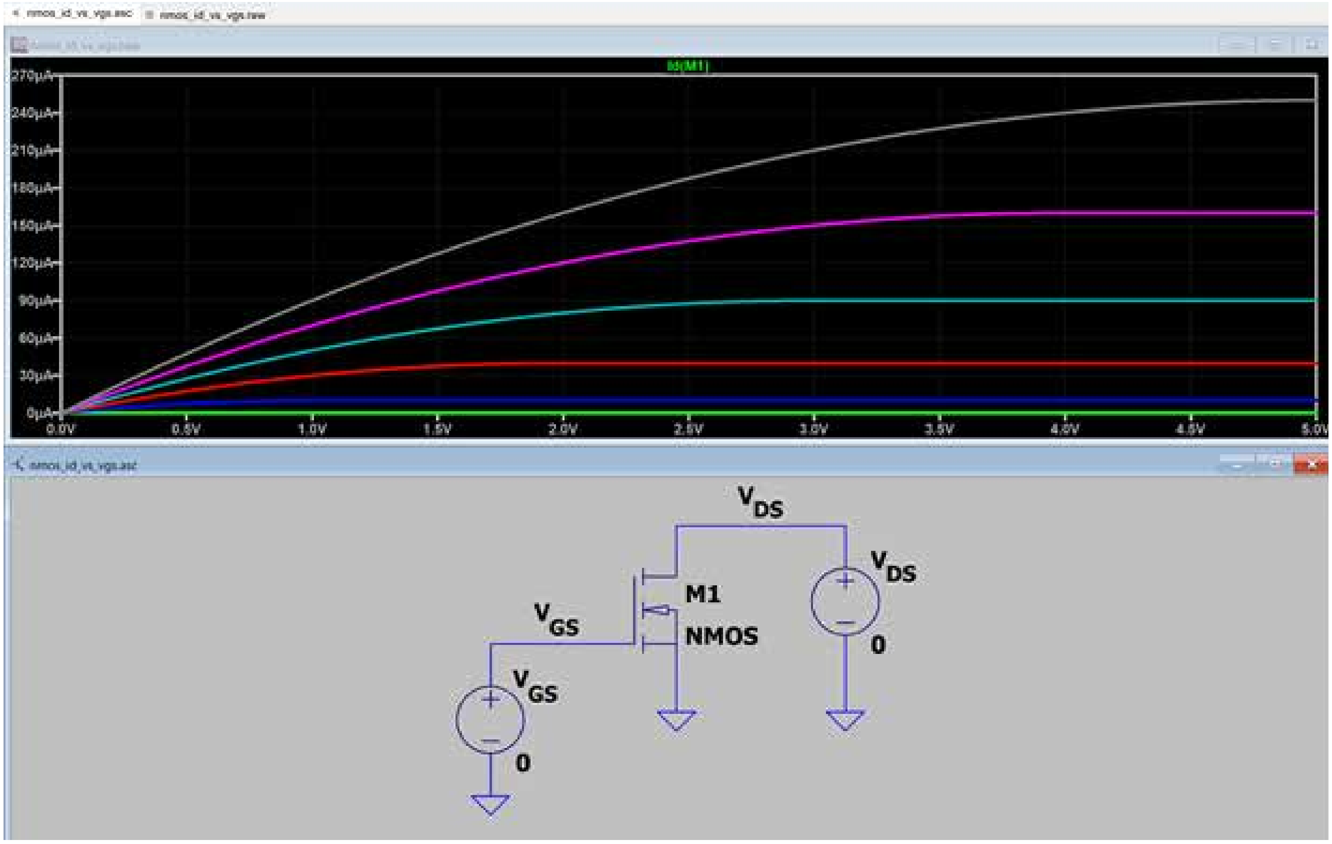



*Figure 3. LTSpice simulation of drain current vs. drain to source voltage*

The simulation in Figure 3 was run using LTSpice. The simulation shows how the drain current changes with an increasing drain-to-source voltage. The different traces correspond to different values of the gate to source voltages. Nonetheless, the way the current behaves for different values of drain to source voltage can be observed.

This leads to an important concept for understanding transistors. There exist three different regions of operation. For MOSFETs, these are:

1. Cutoff, when zero current flows in the channel
2. The linear or triode region, where the drain-to-source voltage is small and little current flows
3. The saturation region, when the transistor is fully conducting current and the drain-source voltage is large

The three regions can also be identified in the following $I_D$ vs. $V_{DS}$ plots (see following page figure 4).

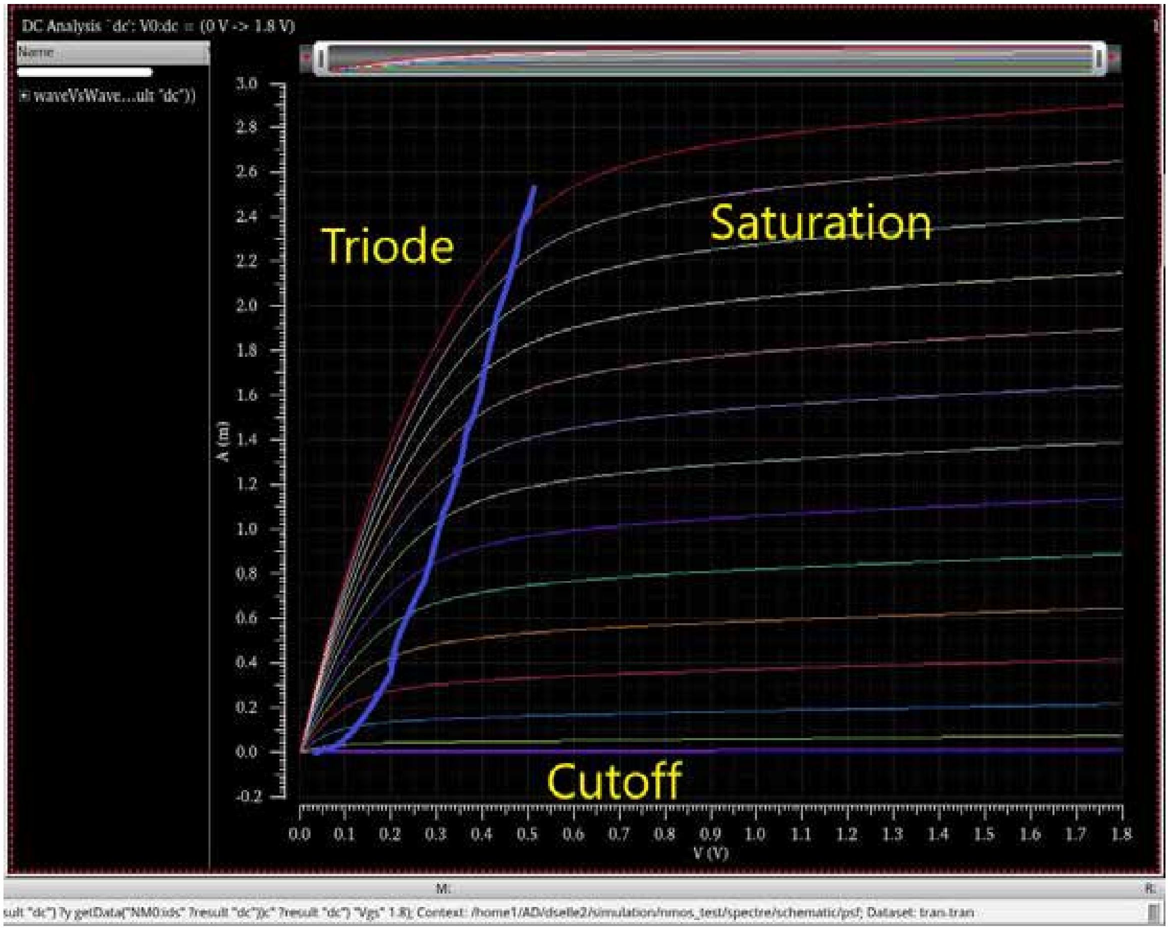



*Figure 4. Plot showing different areas of operation for a MOSFET*

Mathematically, it is important to understand the regions of operation as well. These are best described by the equations given below:

| Ids Current | Voltage Biasing | Operating Region |
|---|---|---|
| $0$ | $(V_{gs}-V_{th})<0$ | **Cutoff Region** |
| $\left(\frac{1}{2}\right)\cdot\mu\cdot C_{ox}\cdot\left(\frac{W}{L}\right)\cdot\left[2\cdot(V_{gs}-V_{th})\cdot V_{ds}-{V_{ds}}^2\right]$ | $0<(V_{gs}-V_{th})>V_{ds}$ | **Linear Region** |
| $\left(\frac{1}{2}\right)\cdot\mu\cdot C_{ox}\cdot\left(\frac{W}{L}\right)\cdot(V_{gs}-V_{th})^2$ | $0<(V_{gs}-V_{th})<V_{ds}$ | **Saturation Region** |

*Figure 5. Equations describing MOSFET region of operation*

In the equations shown in Figure 5, the first few terms are sometimes combined into a single variable, k. These are process parameters and are pre-determined when working with discrete devices. Mu (μ) is electron mobility, and C is oxide capacitance. Additionally, W and L are the width and length of the channel. In integrated circuit design, designers will have control over the width and length of the device as an extra degree of freedom.

# CHAPTER - 3 Important Properties and Parameters

One of the important parameters for MOSFET transistors is the drain-to-source resistance. When the drain-to-source voltage is kept small (linear region), the MOSFET can behave like a voltage-controlled resistor. The resistance of the drain-to-source is given by the equation in Figure 6.

$$r_{ds} = \frac{1}{(\mu \cdot C_{ox}) \cdot \left(\frac{W}{L}\right) \cdot V_{gs} - V_{th}}$$

*Figure 6. Equation for MOSFET drain-to-source resistance*

The resistance is potentially very important, depending upon the application. For switches, a designer would want the resistance to be as low as possible. Lower resistance will equate to less loss and better efficiency.

Another important parameter of MOSFETs often used in amplifier analysis is the transconductance. Transconductance is often described by the variable gm. Transconductance is the output current divided by the input voltage. The equation for transconductance is given in Figure 7.

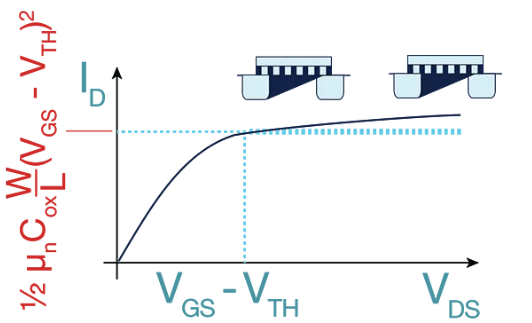
$$g_m = \mu \cdot C_{ox} \cdot \left(\frac{W}{L}\right) \cdot (V_{gs} - V_{th})$$

$$g_m = k_n \cdot (V_{gs} - V_{th})$$

*Figure 7. Equation for transconductance*

Note in Figure 7 that two equations are shown. Oftentimes, the first few variables are combined into a single variable to simplify the equation a bit. This is common when dealing with discrete devices where a designer will have no control over these parameters.

Another property to consider when working with MOSFETs is channel-length modulation. It was shown previously that, as the drain-to-source voltage passes a certain limit, drain current no longer increases. While this assumption is good for approximations, in reality, there is an effect the drain-source voltage continuously has on the drain current. This characteristic manifests itself, as shown in the plot below. Instead of the current being a flat line, it gradually increases with larger drain-source voltages.




$$I_D = \frac{1}{2} \mu_n C_{ox} \frac{W}{L} (V_{GS} - V_{TH})^2 (1 + \lambda V_{DS})$$

*Figure 8. Effect of channel length modulation on $I_D$ vs. $V_{DS}$ curve. Image source: EE105 Spring 2008 Berkley Lecture*

Also shown in Figure 8 is an additional equation to account for channel length modulation. This includes a new variable, lambda (λ). Lambda is another process-dependent variable that the designer will have no control over. When working with a discrete device, it can generally be found in the manufacturer's datasheet.

The last additional property that will be considered here is the small-signal model for MOSFETs. These prove extremely useful when doing AC circuit analysis or designing amplifiers. The FET behaves as a voltage-controlled current source. Basically, a voltage at the input ($V_{GS}$) controls a current at the drain ($I_D$), which is equivalent to $g_m$*$V_{GS}$. Two small-signal models for the MOSFET are shown in Figures 9 and 10, known as the hybrid pi model of the transistor.

Figure 9 shows the basic small-signal model. This model can go a long way when doing circuit analysis and produce rather accurate results.

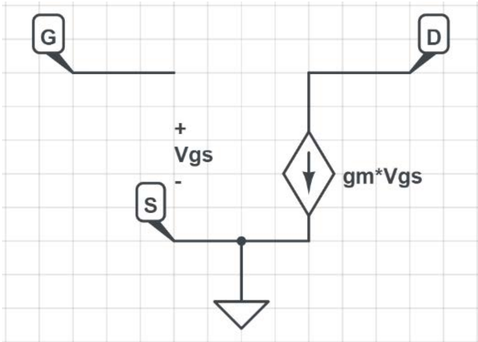



*Figure 9. MOSFET small-signal model*

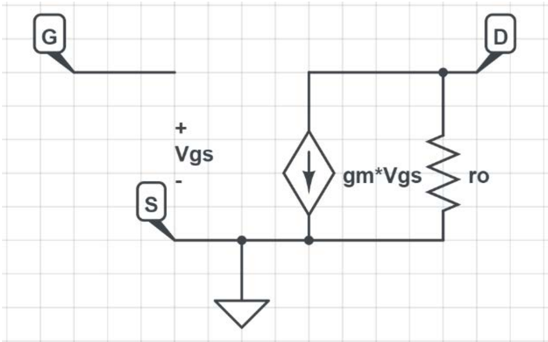



*Figure 10. MOSFET small-signal model with the output resistance*

When more precision is needed, or when the output resistance of the MOSFET needs to be taken into account, the second model (Figure 10) is more suitable, because it has the additional variable 'ro' included. ro is the output resistance and is a direct consequence of the aforementioned channel length modulation.

Determining which model is needed when doing circuit analysis for a particular application comes with experience and will become more intuitive over time.

# CHAPTER - 4 Applications of MOSFETs

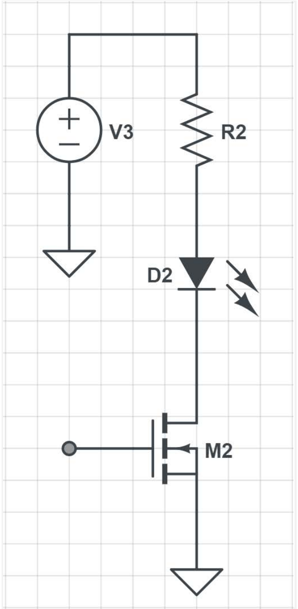



*Figure 11. MOSFET as a load switch*

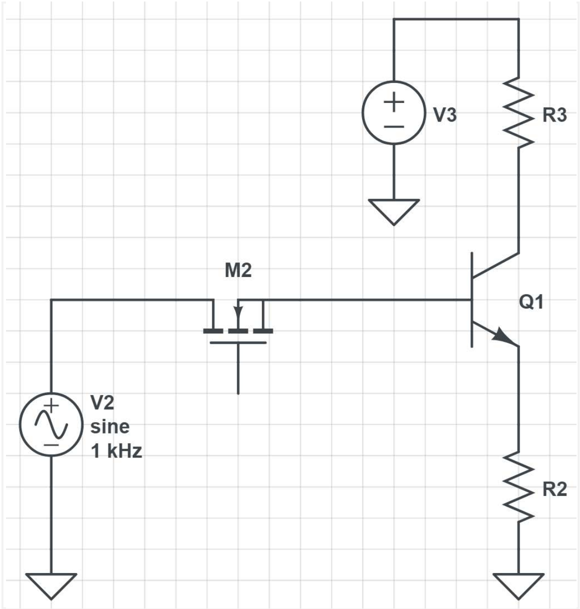



*Figure 12. MOSFET as a switch for signal flow*

The following section includes applications and examples where MOSFETs are commonly used. In addition, it should provide some examples for use cases in which the MOSFET is the ideal choice.

**Switches**: MOSFETs are used in many applications where a switch is needed. This includes analog and digital applications. MOSFETs can act as a switch to turn a load on or off, or they can be used as a switch to control the flow of a signal through a circuit. Both of these applications are shown in the schematics below.

In Figure 11, the MOSFET acts as a switch to control the flow of current through the LED. When the gate is pulled high, current will flow and the LED will turn on. On the other hand, when the gate is pulled low, the switch will open and no current will flow through the LED. This type of configuration is used in many applications. It allows a voltage signal with low current drive capabilities to control a circuit with a larger current draw. Additional applications can include controlling relays, motor controllers, and lighting applications.

In Figure 12, the MOSFET acts as a switch to control the AC signal flow to the amplifier. This is useful when multiple paths exist for a signal in a given circuit. Generally, when a switch like this is used for signal flow, there is also an additional MOSFET on the base of the transistor to pull it down (turn it off) when the amplifier is not being used. This type of application is common in integrated circuit design.

**Digital Logic Gates:** With a few exceptions, most digital logic circuits are made up of MOSFET transistors. Digital logic gates find use in many integrated circuits found in all types of applications today. Logic gates make up larger digital circuitry, such as shift registers, counters or dividers, and processors. Furthermore, FPGAs, which offer designers very complex digital signal processing capabilities, are made up almost completely of logic gates. Figures 13 and 14 show a couple of examples of logic gates made from MOSFET transistors.

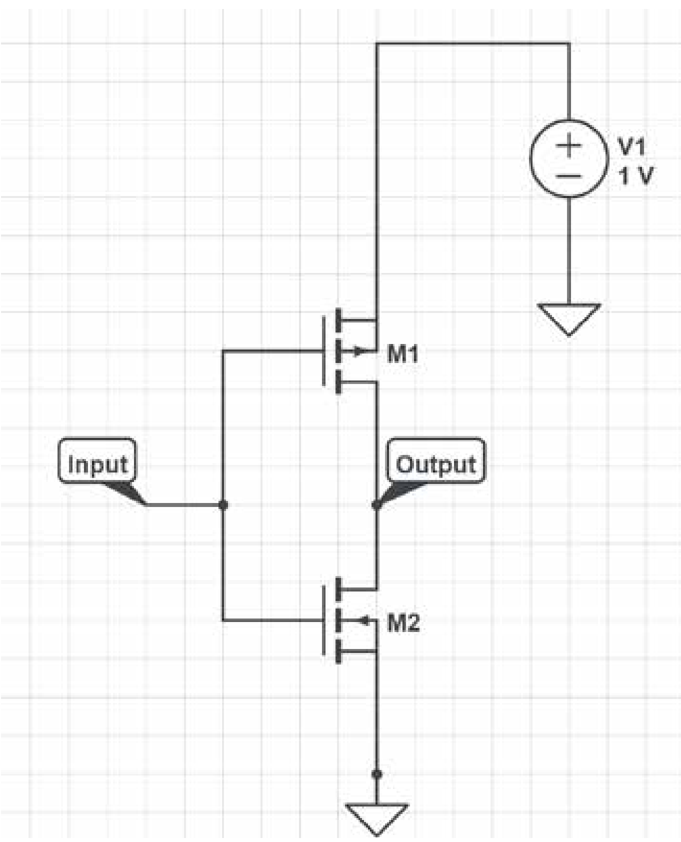



*Figure 13. Schematic of Inverter*

Figure 13 shows a digital inverter. The output is the opposite of what the input is. For example, if the input is a logic high, then the output is a logic low. Two inverters can be cascaded to make a logic buffer.

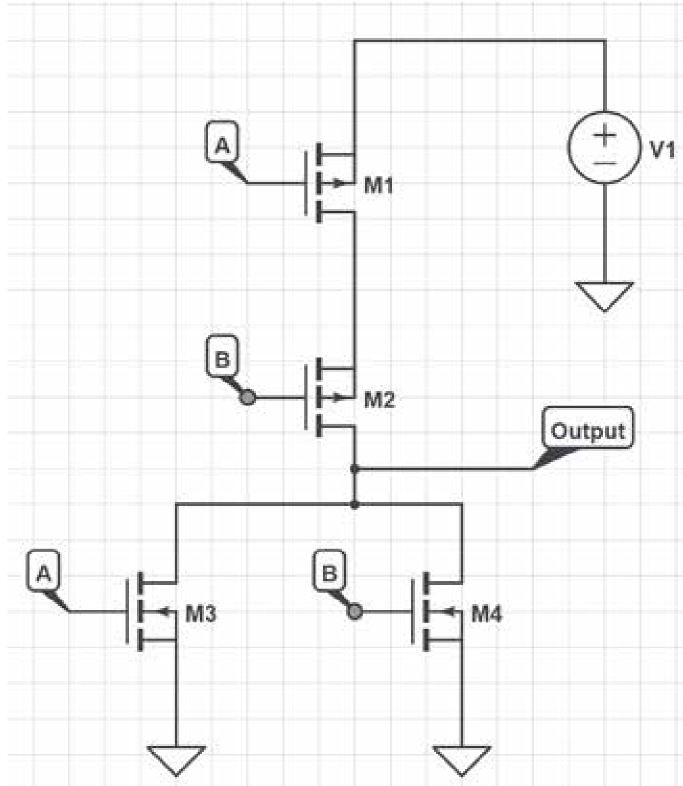



*Figure 14. MOSFET implementation of a NOR gate*

Figure 14 shows an implementation of a NOR gate. For a NOR gate, the output is only high if both inputs, A and B, are low. For all other combinations of inputs, the output is low. Note that by simply adding an inverter to the output of this circuit, we can create an OR gate.

**Variable Resistor:** For low drain-to-source voltages, the MOSFET can act as a linear resistor. It should be noted that it is only approximately linear. Nonetheless, this feature can be exploited. It is not often used at the discrete level, since variations in voltage and MOSFET construction can make the resistance desired hard to achieve consistently, however, it does find use in integrated circuit design.

**Amplifier Circuits:** MOSFETs have an important advantage over their bipolar counterparts in that they have an extremely high input impedance. This means that their input, the gate of the transistor, draws zero or close to zero current. This offers numerous advantages and, as a result, MOSFETs are found at the inputs of many amplifiers.

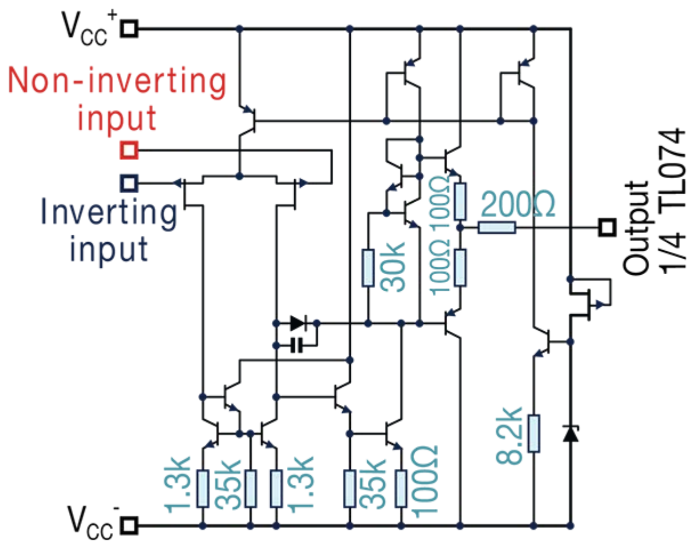



*Figure 15. Schematic of the TL074 op-amp.*
*Image Source: ST Microelectronics TL074 datasheet*

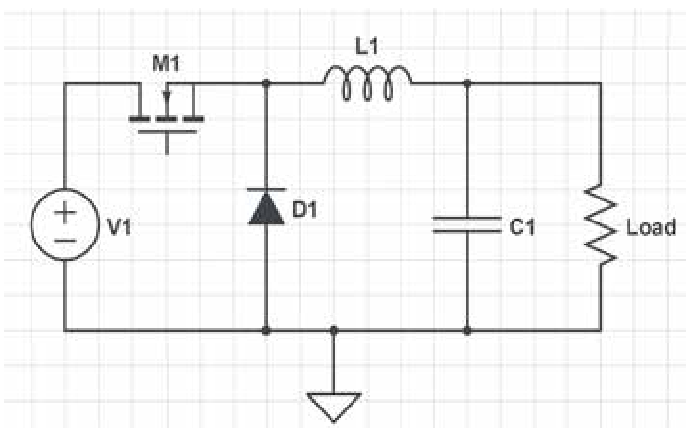



*Figure 16. Schematic of a Buck converter*

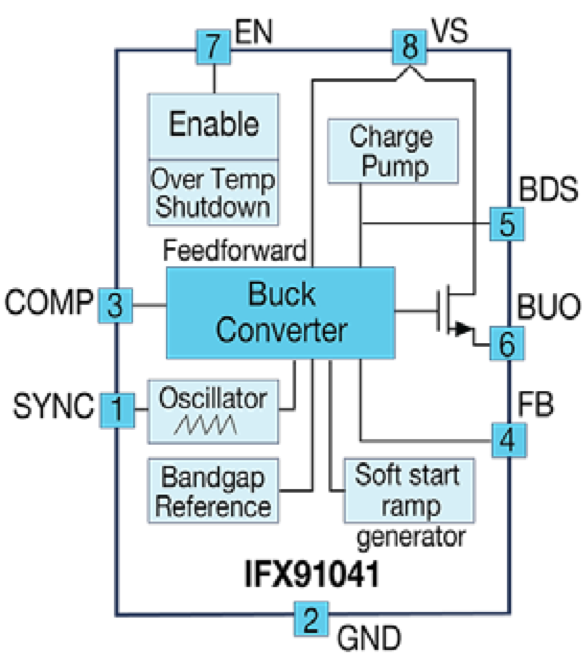



*Figure 17. Block diagram of IFX91041 buck converter*

Figure 15 illustrates the circuit of an op-amp offered by ST Microelectronics. As can be seen, the differential pair that makes up the input utilizes two FET devices. The rest of the op-amp is constructed using bipolar devices. Consequently, the device features characteristics that make it a great fit in applications such as filters, audio amplifiers, microphone preamplifiers, etc.

**Voltage Regulators:** MOSFETs are very useful in switching regulators. Figure 16 is the schematic of a Buck Converter.

All switching regulators include some sort of mechanism for switching the input voltage on and off. Depending on the circuit configuration, this allows the designer to step up or step down the voltage on the output. These designs are known as boost and buck converters. These circuits can be built discretely, similar to what is shown above. However, many integrated circuits exist that include the switching MOSFET on the inside of the IC. By doing so, these can optimize the performance and will generally achieve better performance than anything that can be achieved using discrete elements.

Figure 17 depicts a block diagram of a buck converter. The main MOSFET used for switching is shown at the right. Integrated circuit designs for switches can reach as high as 96% efficiencies.

**Replacement of Bipolar Transistors**: The MOSFET transistor is replacing bipolar transistors in many applications, due to its ease of manufacturing in integrated circuits. Indeed, many of the new integrated circuits being designed and manufactured use only FET devices, and are known as CMOS circuits. CMOS integrated circuits are being scaled continuously to include smaller and smaller devices. In doing so, we can not only achieve higher performance, but also we can fit more and more transistors onto a single substrate. This idea is generally known as Moore's Law, which states that the number of transistors in an integrated circuit will double every 2 years. Recent advances in MOSFET technology have allowed Moore's Law to continue.

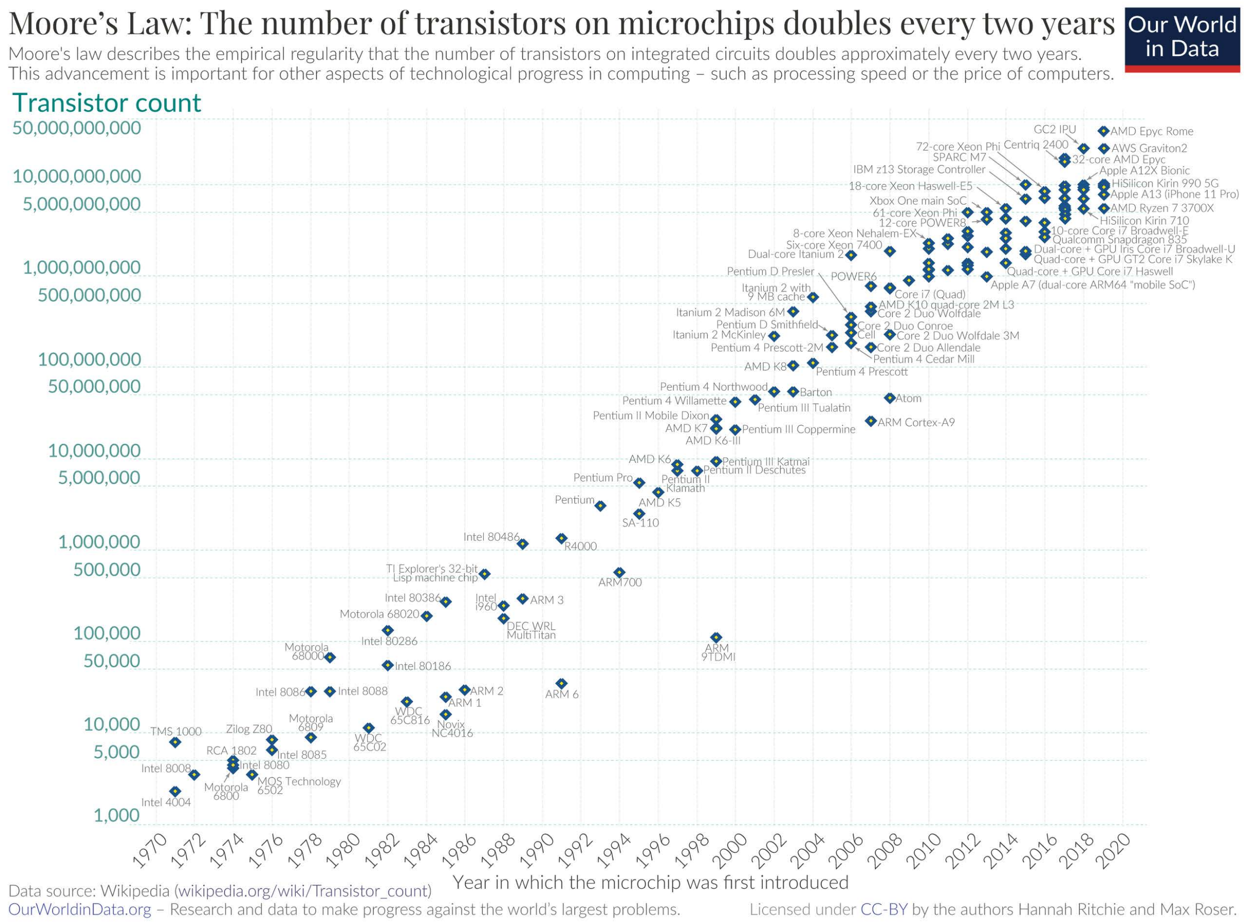



*Figure 18. Plot showing Moore's Law. Image Source: Moore's Law Wikipedia*

# CHAPTER - 5 Additional Types of FETs

Most of this article has focused on MOSFET devices. While these are arguably the most common FET devices encountered in electronics today, there do exist some additional devices that are better suited for specific applications. Some of these will be covered below.

**Junction Field Effect Transistors (JFETs)**

JFETs find much use in audio applications. They are very similar to MOSFET devices in their construction; however, they have an area under the gate known as a depletion layer. Consequently, the gate forms a semiconductor junction with the depletion layer that should not be forward biased. To operate a JFET, if a drain-to-source voltage is applied and 0V at the gate is applied, the device will operate in saturation mode, and a large amount of current will flow. On the other hand, to turn off the device, a negative gate-to-source voltage has to be applied. JFET devices generally have higher gain and lower noise than MOSFETs, making them ideal for low distortion amplification applications.

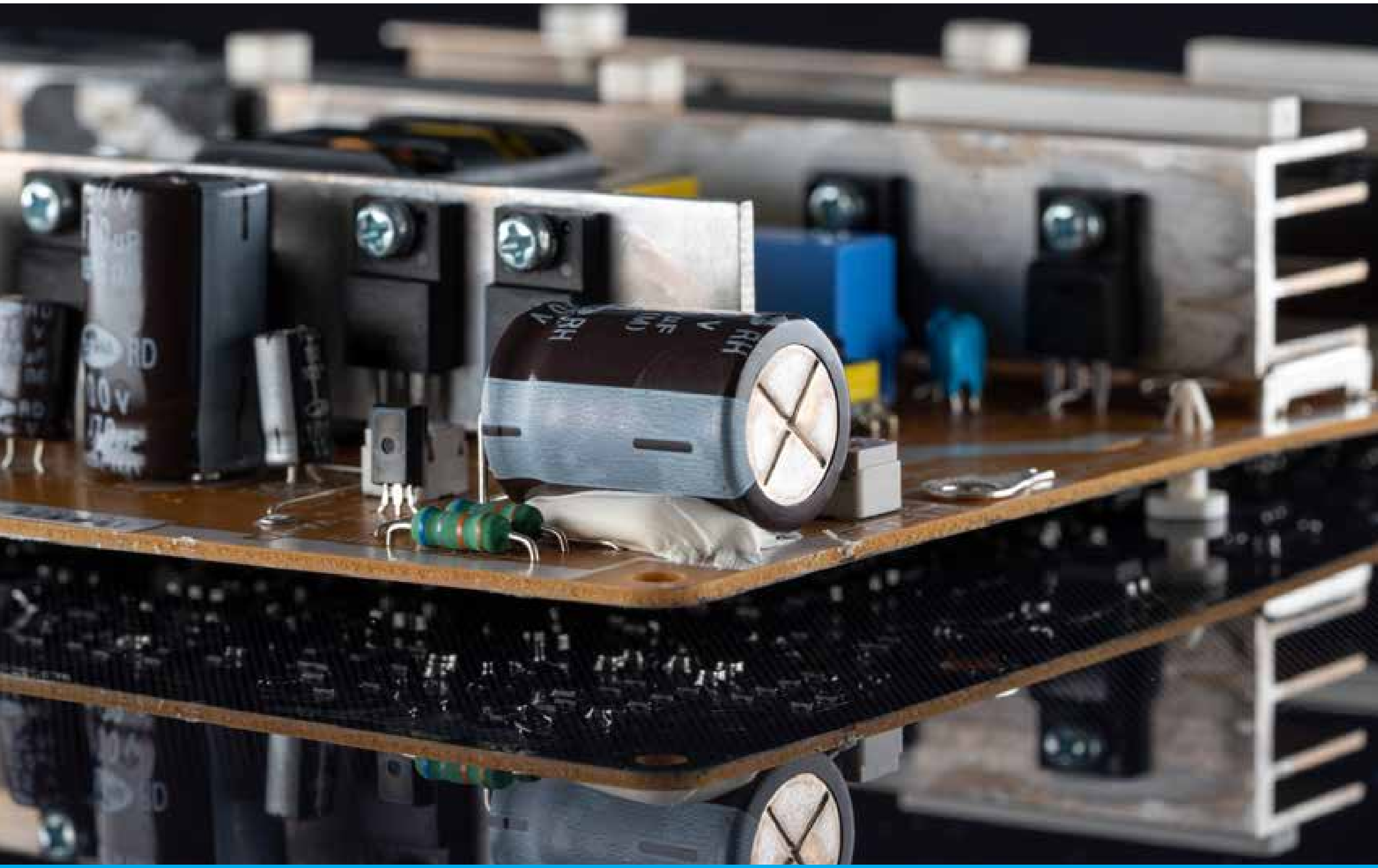
**Metal Semiconductor Field Effect Transistors (MESFETs)**

MESFET devices are made specifically for high-frequency applications. They are similar to a JFET in that there is no insulator under the gate. As a result, careful biasing must be chosen for proper operation and to keep junctions from conducting. MESFETs find use in many RF applications, such as low noise amplifiers used in the front end of receiving devices.

**Power MOSFETs**

There are MOSFET devices designed specifically for handling large voltages and large current levels. These are known as power MOSFETs. Their operation is the same as the previously covered MOSFETs. The main difference is in their construction and packaging to handle higher power. Power MOSFETs  are often found in power supplies, voltage regulators, and motor controllers.

Visit the Community for more information on MOSFETs and other electrical components.



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