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Comparison Between Different Field-Effect Transistors

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Abstract:

Semiconductor devices are ubiquitous in modern life, essential to almost all electronic equipment. These devices, particularly diodes and transistors, are crucial for amplifying and controlling current and voltage in various components. Field-Effect Transistors (FETs), a type of transistor, control output current through input voltage and are categorized into Junction Field-Effect Transistors (JFETs) and Metal-Oxide-Semiconductor Field-Effect Transistors (MOSFETs). JFETs operate under reverse bias and function only with negative gate-source voltage, while MOSFETs are further classified into enhancement and depletion types, distinguished by positive and negative threshold voltages, respectively. Both JFET and MOSFET exhibit similar behavior as drain-source voltage increases, transitioning through ohmic and saturation regions, with current initially rising and then stabilizing. JFETs offer advantages in easy and low-cost processing, whereas MOSFETs provide superior stability and higher breakdown temperatures due to increased resistance between gate and source. This enhanced performance makes MOSFETs preferable in many applications, especially where high reliability and performance are required. The versatility and efficiency of these semiconductor devices continue to drive advancements in electronics, enabling the development of increasingly sophisticated and compact electronic systems that power this paper daily lives.

Keywords: Semiconductors; Transistors; JFET; MOSFET.

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1. Introduction

In this time and age, as the development of technology, electrical engineering is becoming more and more important. Many semiconductor devices such as diodes, transistors are commonly used to control the current and voltage. FET (Field effect transistor) is a semiconductor device that uses the electrical field effect of the input circuit (voltage) to control the current of the output circuit [1]. Only the majority carriers conduct electricity in FET so it is unipolar. BJT (Bipolar junction transistor) have both majority

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and minority carriers for conducting electricity. In this way, the movement of carriers in BJT is more complicated, involving disordered minority carrier and generating more noise. It has three terminals, gate, source and drain. Their character mainly depends on different operating regions, including cut-off, breakdown, ohmic and saturation region [2]. This paper will introduce the working principles and characteristics of different FETs, making comparison about their advantage and disadvantage. For making the study easy, all the comparison will be made based on N-channel, which means that it is the n-type semiconductor conducting electricity.

2. MOSFET

One type of FET is IGFET (insulated gate field effect transistor). Besides from gate, source and drain terminal that JFET has, it also has a base. As its name suggests, the gate is separated with source and drain by insulated material SiO2 (silicon dioxide). The gate is made up of aluminum metal so it is also known as MOSFET (metal-oxide-semiconductor field-effect transistor). For n-channel MOSFET, it has a P-type base (low doping), and the drain and source terminal is made up of highly doped N-type semiconductor. As the P and N type semiconductor contact with each other, a PN junction would form. MOSFET can be categorized into enhancement MOSFET and depletion MOSFET. Enhancement MOSFET has a zero current when Ugs is zero while there is a current when Ugs is zero for depletion MOSFET [3].

The working principle of enhancement MOSFET will be explained below. When a positive voltage is applied between g and s, it will push away the holes and attract the electrons to the region between the insulated material (SiO2) and the depletion region. These electrons can form a reverse layer. If the reverse layer can connect the two highly doped N-type region together, then the conductive channel can be formed. The voltage that just forms the conductive channel is called the threshold voltage Ugs(th). When Uds is applied then, the electrons in the conductive channel can move freely, forming Ids.

Assuming the Ugs is a constant value between greater than Ugs(th), then consider the effect of Uds. As Uds increases from 0, Id also increases linearly. Ugd=Ugs-Uds. When Uds is zero, Udg=Ugs>Ugs(th). Ugs is constant so it means the conductive channel between g and s will always remain. As Uds increases, Ugd would decrease. When Uds=Ugs-Ugs(th), then Ugd=Ugs(th), the conductive channel between d and s is just about to be cut-off. When Uds continues to increase, Ugd gets below Ugs(th) and the cut-off line is longer, making the resistance higher and reducing the current. It balanced the increase in current due to increase in voltage and the current became constant. Id no longer depends on Uds and one Ugs corresponds to one Id.

For the operating principle of (n-channeled) depletion MOSFET, it is quite similar to that of enhancement MOSFET. It also has a low doping P-type base with highly N-type doping drain and source. A reverse layer needs to be formed to conduct electricity. The only difference is that positive ions are added to the insulated SiO2. In this way, even when the Ugs is 0, the positive ions induced a reverse layer by attracting the electrons and repelling the holes. It can conduct when a suitable Uds is added and formed a current. Like JFET, a negative Ugs that is small enough (that balance the positive ion) should be applied to cut off the reverse layer [4].

Due to the different structures between enhancement and depletion MOSFET, they have different characteristics, leading to advantages and disadvantages. Enhancement MOSFET has a positive threshold voltage while depletion has a negative cut-off voltage. In this way, enhancement can only work when a voltage is applied while depletion can work when no voltage is applied between g and s, which is an advantage for depletion MOSFET. It means it’s easy to switch it on and doesn’t need external source to make it conductive. Therefore, it has a higher responding speed. Enhancement MOSFET, on the other hand, needs external source to make it conductive, making it more complicated to control and has a lower responding speed. However, just because it needs external source to be conductive, it means that it is flexible to control and can be switched off easily. There is no movement of electrons when closed (Ugs) and less power wasted. On the other hand, there is (a channel for) movement of electrons when closed for depletion MOSFET and power is being wasted.

3. JFET

JFET (junction field effect transistor) is another type of FET. The structure of it is shown in figure1. It is made up by N-type semiconductor (uses as a conductive channel), with two small pieces of P-type semiconductor, one on the left and one on the right. They are connected by a wire, forming the gate terminal. When P and N combined together, a PN junction must be formed and there will be a depletion region. D and S represent drain and source respectively [3].

As its name suggests, a (P-N) junction needs to be formed. PN junction can only became significant when reversed biased. When forward biased, the depletion region (PN junction) would get smaller. In this way, JFET can only work when reverse biased and the g should have a lower potential comparing to s(Ugs<0). The following paragraph will explore the effect of Uds and Ugs to Id.

Considering Uds=0 V first, then d and s can be treated as a single point. When Ugs=0V, the PN junction (between g and s is not reversed biased), there would be very small depletion region and the conductive channel is very wide. As Ugs continues to decrease, Ugs is negative here, so its absolute value is actually increasing. In one way, the electrons would move faster due to higher potential difference (voltage) which increases the current Ids. However, the depletion region gets larger and conductive channel get smaller as the PN junction between g and s is more reversed biased. The small conductive channel brings larger resistance which blocks the electron from moving too fast and is actually restricting the current from being too large. When the Ugs reached a certain value, the conductive channel almost disappears and the resistance reached an infinite value. At this point, the current became constant, the Ugs here is called the cut-off voltage.

Considering Ugs is a fixed value in between Ugs(off) and 0. In this way, the depletion region g and s is also constant. When Uds is 0, as mentioned before, they can be treated as a single point with potential difference and therefore definitely no current. When Uds increases (it's s positive here), D and S can no longer be treated as a single point and D and S don't have the same potential difference. Ugd and Ugs aren't the same anymore. Ugd= Ugs- Uds. As Uds continues to increases, Ugd continues to decreases (Ugd is also negative as the PN junction between g and d is also reversed biased). The absolute value of Ugd increases, the higher voltage will drive the electrons to move faster which increases Ids. In this region, the current Ids are proportional to Ugd. However, the junction between g and d becomes more and more reversed biased which increases the depletion region and resistance between G and D. When Ugd reached the cut-off voltage Ugs(off), as shown on the graph, the depletion region on the two sides of the channel touch each other at a single point [5]. When Uds continues to increase, the depletion region increases more. The increase in Uds is all used to overcome the resistance when conducting. Then the current became a constant value. The current no longer depend on Uds and only depend on Ugs. One Ugs corresponds to one Ids.

4. Comparision

JFET and MOSFET have advantages and disadvantages comparing to each other. The resistance between gate and source for JFET can be very high, up to 10^7 ohms, but that's still not enough at certain circumstances. Besides, as the increase in temperature, the resistance between gate and source would decrease (All semiconductors behave this way). Then the (saturated) current through the reversed biased PN junction increase, which is not a desired situation. MOSFET won't have these problems. They have much higher resistance since the gate and source are separated by insulator. What's more, when JFET is forward biased, then the current between source and gate can be very huge and it may break the transistor. MOSFET wouldn't have this problem and it can work at both depletion and enhancement. However, MOSFET also has its disadvantages. The cost of producing one MOSFET is higher than that of JFET due to complex processing. The extra metal oxide layer increases its cost [3].

5. Conclusion

In conclusion, various types of Field-Effect Transistors (FETs) are widely utilized in modern electronics, each with distinct characteristics and applications. Junction Field-Effect Transistors (JFETs) operate under specific conditions, requiring a reverse bias (ugs(off)<ugs<0) and a positive Uds. As Uds increases, the drain current Id initially rises linearly in the ohmic region before reaching saturation, where it becomes solely dependent on Ugs. JFETs are advantageous due to their simple processing, resulting in lower production costs. However, they have limitations, such as only functioning under reverse bias conditions. When forward biased, the current can potentially damage the transistor. Additionally, in certain scenarios, the PN junction resistance may be insufficient, leading to undesirable reverse current.

Metal-Oxide-Semiconductor Field-Effect Transistors (MOSFETs) feature a silicon oxide layer separating the gate and source, offering improved performance in many aspects. Enhancement MOSFETs have a positive threshold voltage (Ugs), while depletion MOSFETs have a negative Ugs, owing to additional positive ions in the silicon oxide that simulate a voltage even when no Ugs is applied. Both types exhibit similar current-voltage characteristics: as Uds increases from zero, Id rises until saturation, after which it depends solely on Ugs.

A significant advantage of MOSFETs over JFETs is their higher gate-to-channel resistance due to the insulating oxide layer. This feature substantially reduces reverse current leakage, making MOSFETs more suitable for applications requiring precise current control and low power consumption. The insulation also allows for a wider range of operating voltages and improved thermal stability.

The choice between JFET and MOSFET, as well as between enhancement and depletion types, depends on specific application requirements, considering factors such as power efficiency, switching speed, ease of control, and

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manufacturing costs. Each type has its unique strengths, contributing to the diverse landscape of semiconductor devices in electrical engineering.

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