The development status and future of the field effect transistor

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Abstract

FET is short for Field Effect Transistor (FET). There are two main types: Junction FET-JFET and metal-oxide Semiconductor FETs (MOS-FETs). Conduction by the majority of carriers, also known as a monopolar transistor. It is part of voltage controlling semiconductor device. With the advantages of high input resistance (107 ~ 1015 Ω), low noise, low power consumption, extensive dynamic range, easy integration, no secondary breakdown phenomenon, and wide safe working area, it has become a strong competitor of bipolar transistors and power transistors.

Keywords: Field Effect Transistors; Working principle of FETs; Projection of future developments;

1. Introduction

Transistors, which are the foundation of modern electronic information technology, are normally composed of silicon - based CMOS Field Effect Transistors (FETs). Field effect transistor is a voltage control current source element, through the gate modulation, to control the current between the source and drain, so that it appears on and off state, thus defining logic 1 and logic 0. The core part of the FET is the channel part that is modulated by the gate, which controls the interaction among the internal structure of the FET. Take JFET as an example, it consists of two positive channels, one negative channel and two depletion regions between the p/n-channels. And the value of the current--ID flowing through the channel between the drain and the source is controlled by the reverse biased gate voltage formed by the PN junction between the gate and the channel. Except for the FET, MOSFET is also well implemented in the field of Electronic Engineering, such like Integrated circuits, Microprocessors, Amplifiers and so on. Such wide use of the MOSFET is mainly due to its working function that can work as the logic gates. Since M. M. (John) Atalla and Dawon Kahng at Bell Labs achieved the first successful insulated-gate field-effect transistor (FET) in 1959, there has been an increasing focus on innovation in the development of FET, which has seen rapid technological progress over the past 60 years [1]. However, after several decades' rapid development, the development of FET has also met with obstacles and difficulties, the size of transistors had been shrunk to the point which may influence the characteristic of the FETs. Short channel effect is one of the troubles, to deal with it, some FETs which apply new materials or structure are launched.

In the future, significant demand from the rapid development of electric vehicles is expected to drive the introduction of a number of new FETs.

2. FET classification, internal structure and working principle

2.1 *Definition and classification of FETs*

To begin with, The FET is an active device which has three 'legs' that are called terminals. Specific electric field is required in order to control the drifting electron flow. Moreover, it is its pattern of working and high internal resistance that make itself useful in many circuits. The merit of the voltage controlling semiconductor device--FET mainly gets benefit from the synthetic material of silicon (most of FET is made of silicon, while some of it uses GaN).

There are mainly two types: junction FET-JFET and metal oxide semiconductor FET (MOS-FET). It is also called unipolar transistor because most carriers participate in conduction. It belongs to a voltage controlling semiconductor device. It has the advantages of high input resistance (107-1015 Ω), low noise, low power consumption, large dynamic range, easy integration, no secondary breakdown, wide safe working area, etc., and has become a strong competitor of bipolar transistors and power transistors [2].

The diversity of FETs comes from their various working functions. And the working principle of the FET has a close relationship to its special structure. Take JFET as an instance, as for the outer characteristic of the JFET which is clearly exhibited in the fig.1, both p-channel JFET and n-channel JFET have the same three main parts which are the 'Gate', Drain' and 'Source'. Once mentioned that the JFET is a voltage controlling device while the 'Gate' plays the role of accepting voltage in order to control the current flow that drifts through the 'Drain' and 'Source'.

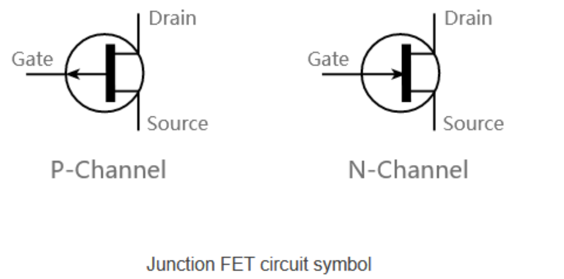

Figure 1 The structure sketch of the JFET

2.2 *The internal structure and working principle of JFET*

The operating principle of the JFET is, in a word, "the ID flowing through the channel between the drain and the source is controlled by the reverse biased gate voltage formed by the PN junction between the gate and the channel." In different cases of the value of V_{GS} (the voltage difference between 'Gate' and 'Source'), different curves of I_D (the current flow through the 'Drain') vs V_{DS} (the voltage difference between 'Drain' and 'Source') will emerge. As higher the V_{GS} goes, the scope of the Id that rises with the increase of V_{DS} turns out to be more intense to some extend. When the V_{DS} increases further, there exists a point where the drain current stops increasing, the drain-source voltage at which this occurs is called the pinch-off voltage, V_P, as shown in the Fig.2.

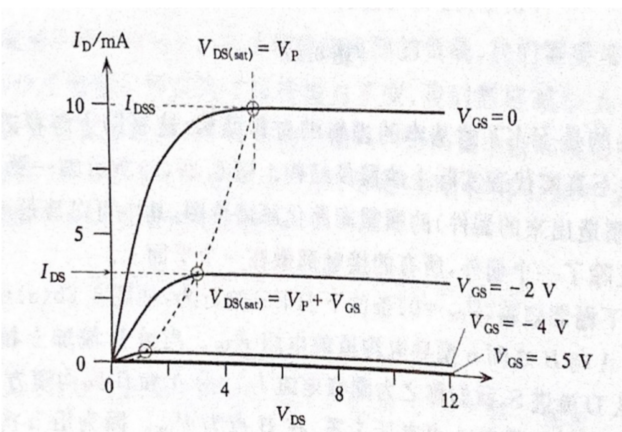

Figure 2 Curve of I_D versus V_{DS} [3].

About the internal structural features of the JFET, Fig.3 shows that JFET consists of two positive channels, one negative channel and two depletion regions between the p/n-channels.

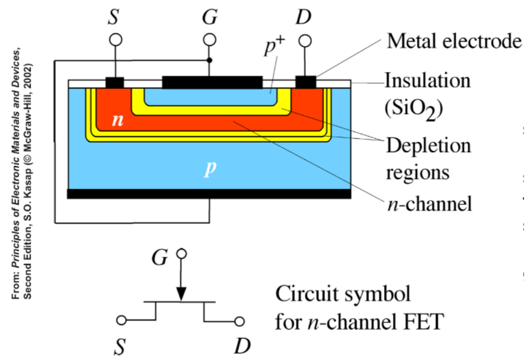

Figure 3 Interior structure of JFET [4].

According to Fig.4, when a PSU is connected to the JFET, the depletion region will act like the way it shows. The depletion is larger nearer to the drain, since there is a greater reverse bias at this end of the device. For a current passing through the junction, the voltage drop at the end of the channel is thus higher as it has a higher resistance owing to a narrower channel width.

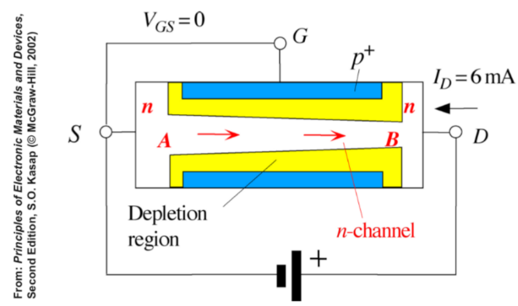

Figure 4 Internal working structure of JFET with a 6 mA I_D [4].

As V_{DS} increases, I_D does not increase linearly, since the resistance of the channel (Rab) increases with Vds as well. At an increased $V_{DS}(=V_P)$, the two depletion regions join and 'pinch-off' of the channel occurs. This happens when the reverse bias across the two p-n junctions is just enough to make the depletion regions touch, 'pinch-off' thus occurs according to Fig.5.

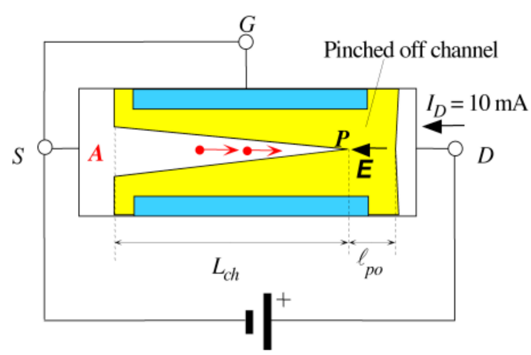

Figure 5 Internal working structure of JFET

with a 10 mA I_D . [4]

In this case, when $V_{DS} > V_P$, the current (I_D) does not increase substantially owing to the pinched-off channel: ℓ_{Po}. In this depletion region, there is a strong electric field in it and electrons in the n-channel drift towards P, and (from P) are swept across the depleted channel by the strong electric field.

As V_{DS} is increased, additional voltage is dropped across lpo, as this region is depleted of carriers and so has a high resistance. Point P moves by a small margin toward point A. Thus L_{ch} reduces slightly. while point P must remain at the same potential, and so the current is governed by R_{AP} , which slightly falls as Vds is increased; In practice, at Vgs = 0, Id can be assumed to saturate at a value of Idss which is the value when shorted gate to Source.

$$I_{DS} = \frac{V_P}{R_{AP}}$$

In a word the whole circuit can be regarded as a tube which has water flowing through it and a flow control gate limiting the water as shown in fig.6.

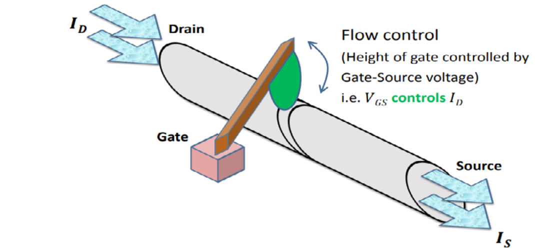

Figure 6 A 'pipe' that represents the relationship between I_D and V_{GS} [4].

When the Gate-Source voltage is at 0, there will be a large drain current going through the tube. Higher the Gate-Source voltage increases, lower the Drain current would be. While the V_{GS} is further bigger, there won't have any current go through the tube!

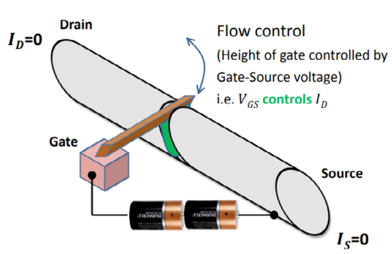

Figure 7 A 'pipe' that represents the relationship between I_D and V_{GS} [4].

The working principle of the JFET is stated as shown in figure 7. It is obvious that the JFET is quite reliable and easy to use. These advantages make Junction FETs being available for many years, and even though they do not offer the extremely high level of DC input resistance of MOSFETs.

This makes these electronic components ideal for many electronic circuit designs and can be easily used in a variety of electronic circuits from amplifiers to switching circuits.

2.3 The advantages of MOSFET and its application in IC

Except for JFET, MOSFET is also an electronic component that is important for students majored in EE during the years in university owing to the wide use of MOSFET in ICs.

Before introducing why MOSFET is essential to ICs, it is important to know what is ICs, in a specific manner. An integrated circuit is a minuscule chip made of semiconductor material. This chip is what makes the entire circuit. It is quite small in comparison to the basic circuit circuits made of different components and approximately the size of a human fingernail. At present, the most common integrated circuits used are the monolithic chips [5].

It would be a chip used in almost every electric equipment or appliance found in the present times. This includes computers, televisions, mobiles and even toys meant to be used by children.

These are IC chips that work only at a few levels that are specifically defined instead of working on all signal amplitude levels. The Digital Integrated circuits are specially designed using several digital logic flip flops, multiplexers, gates and other electrical elements of circuits. The logic gates must operate with digital input and binary input data like 0 and 1. And for electronic components, 0s and 1s are the language that they use to talk to each other.

As for MOSFETs (shown in figure 8 and table 1), these tiny transistors can be simply regarded as a switch, which can output 0s and 1s in reference to the input voltage. This function can also be regard as a AND gate for n-MOSFET and NAND gate for p-MOSFET. This property makes MOSFET fit for the integrated circuit and work as the most basic component in ICs (integrated circuits).

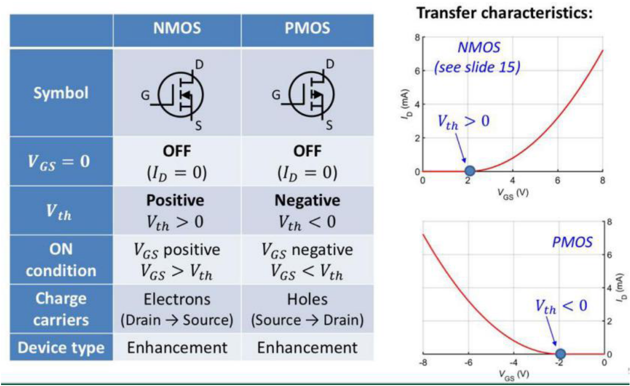

Figure 8 The operating condition of the MOSFET [6].

Table 1 How MOSFET works as gates.

type \ Input	NMOS	PMOS
0	0	1
1	1	0

3. History of the FET

In 1959, M. M. (John) Atalla and Dawon Kahng of Bell Labs succeeded in realizing the first insulated gate field effect transistor (FET) by overcoming the "surface states" that prevent electric fields from penetrating semiconductor materials (1926 Milestone) [7]. By studying the thermally growing silica layer, they found that at the interface of silicon and oxide in a sandwich consisting of metal (M-gate), oxide (O-insulation), and silicon (S-semiconductor)- hence the name MOSFET, often referred to as MOS. Since their devices were slow and could not meet the urgent needs of the telephone system, it was not pursued further. In a 1961 memo, however, Kang noted its potential " ease of fabrication and the possibility of application in integrated circuits." But Fairchild and RCA researchers did recognize this advantages. In 1960 Karl Zaininger and Charles Meuller built MOS transistors at RCA, while Fairchild's C.T. Sah manufactures MOS-controlled tetrode. Fred Heyman and Steven Hofstein followed in 1962 that developed an experimental 16-transistor integrated device at RCA. he conduction region of a MOS transistor is either p-type (making it a "p-channel" device) or an n-type ("n-channel" device) material. The latter is faster than the p-channel, but more difficult to make. MOS devices entered the commercial market in 1964. General Microelectronics (GME 1004) and Fairchild (FI 100) provide p-channel devices for logic and switching applications; RCA introduces an n-channel transistor (3N98) to amplify the signal. Owing to their less size, and lower power consumption than bipolar devices, MOS transistors are applied for producing more than 99 percent of the microchips. Achieving such popularity ubiquity took decades of effort (1964 milestone) [8].

4. The development status and facing trouble: short-channel effect

The above passage shows the rapid development of the field effect transistor, and here is a figure shows (figure 9) the changes of the number of transistors per square millimeter. During the 40 years (1970-2010), the quantity of transistors per square millimeter maintained a steep increase trend [9, 10].

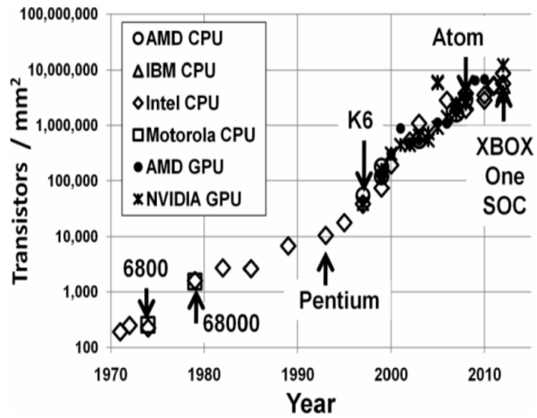

Figure 9 The development of transistors during the 40 years [11]

But in the current generation of transistors, the transistor size has been reduced to the point where the electrical characteristic of the device deteriorated significantly, making it unlikely to decrease the size of transistors.

One of the troubles at this point is the Short-channel effect. As the distance between the source and drain in MOSFETs becomes shorter and shorter, the gate's ability to control the channel is weakened. Think of it as a water pipe. If the pipe is long, only a small amount of pressure in the middle of the pipe is needed to keep the water from flowing out on the other side. However, if the pipe is short, the same pressure becomes too hard to stop the water flow. In reality, this situation will make the gate voltage become harder to pinch off the channel, therefore, the subthreshold leakage will be increased. Threshold voltage is the turning point where the output current changes sharply with the input voltage in characteristic curve.

5. Three innovative FETs

But the Short-channel effect is not an unsolvable problem, one of the ways to eliminate the effect is making the channel thinner, making it more susceptible to gate control. By this way, FETs could increase the immunity to the short-channel effect and reduce the performance influence which comes from the effect. The other is using multi-gate structure to counteract the short-channel effect. Employing the two methods, carbon nanotube transistors and mulitgate transistors are put forward, which will be discussed in after passage.

5.1 *carbon nanotube transistor*

Carbon nanotube transistor is an innovative field transistor that utilizes a single carbon nanotube or an array of carbon nanotube to take the traditional bulk silicon place as the channel material. The new application in channel material increases the immunity of Short-channel effect. The diameter of the carbon nanotube is only 1-3nm, it means that the channel of the transistor is more easily controlled by the gate, under this advantage, it has more potential than silicon transistor, especially in size reduction. In addition, carbon nanotube has higher carrier mobility and saturation rate at room temperature. According to the university of Maryland, Department of physics and center for superconductivity research estimated [9] that the intrinsic mobility in carbon nanotube is greater than 100000 cm^2/Vs and saturation rate is 4×10^7 cm/s, they are approximately 100 times and four times compared with silicon, respectively. Furthermore, carbon nanotubes are easily implemented as a channel for the ballistic transistor, which is an ideal model for the scatter-free transport of carriers in the channel and enables a significant increase in energy utilization. This gives carbon nanotube transistors a huge advantage in terms of low power consumption. Consequently, compared with traditional FET, carbon nanotube transistor has smaller channel diameter, higher intrinsic mobility, saturation rate and lower power consumption. It has a bright development prospect.

5.2 *Multigate transistor*

Traditional field effect transistors simply work with only one gate, but multigate transistors try incorporating more than one gate into a separate device. The gates are not similar to traditional FET's just a two-dimensional plane, they are expanded to three dimensions. Multiple gates wrapped around several sides of the channel area and controlled by only one gate electrode.

Table 2 Natural length for different gate architectures [9]

Gate architecture	Natural length
Single gate	$\lambda_1 = \sqrt{\frac{\varepsilon_{si}}{\varepsilon_{ox}} t_{si} t_{ox}}$
Double gate	$\lambda_2 = \sqrt{\frac{\varepsilon_{si}}{2\varepsilon_{ox}}(1+\frac{\varepsilon_{ox}}{4\varepsilon_{si}}\frac{t_{si}}{t_{ox}}) t_{si} t_{ox}}$
Triple gate, square section	$\lambda_3 = \sqrt{\frac{\varepsilon_{si}}{3\varepsilon_{ox}}(1+\frac{\varepsilon_{ox}}{4\varepsilon_{si}}\frac{t_{si}}{t_{ox}}) t_{si} t_{ox}}$
Quadruple gate, square section	$\lambda_4 = \sqrt{\frac{\varepsilon_{si}}{4\varepsilon_{ox}}(1+\frac{\varepsilon_{ox}}{4\varepsilon_{si}}\frac{t_{si}}{t_{ox}}) t_{si} t_{ox}}$
Cylindrical GAA	$\lambda_{GAA} = \sqrt{\frac{2\varepsilon_{si} R^2 \ln\left(1+\frac{t_{ox}}{R}\right) + \varepsilon_{ox} R^2}{4\varepsilon_{ox}}}$

As can be seen in table 2, λ (natural length for each gate architecture), R (semiconductor radius), tsi (semiconductor width and height), tox (gate oxide thickness). According to the analysis, it is clear that the more the number of the gates, the smaller λ. Therefore, the short-channel effects will be improved.

Nowadays, the gate length of the FETs with multigate architectures can already be shrunk to 5 and 3 nm [11-13].

5.3 *Ferroelectric field effect transistor (FEFET)*

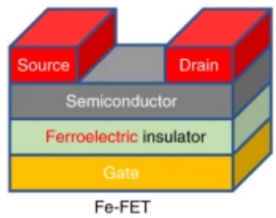

Figure 10 Structure of the Ferroelectric field effect transistor [14]

As can be seen in figure 10, unlike traditional transistor, ferroelectric field effect transistor could be applied in fresh aspect. It utilizes ferroelectric as the material of the gate insulators. Their polarization can be measured by the channel conductivity of the equipment, in a Fe-FET, binary data can be obtained by detecting the polarization state of the ferroelectric gate insulator. Because of this characteristic, it can be useful in the manufacture of single-transistor (1T) non-volatile memories [14].

6. The auto industry will affect future FETs

In the end, we will offer some forecasts about the FET's development. As we all know, the automotive industry is gradually moving towards new energy sources. The new direction requires more electrical components than traditional internal combustion vehicles.

Here are some events that show the FETs are receiving the impact of changes in the automotive industry.

In March 2021, Alpha and Omega (AOS) launched its AEC-Q101 approved 1200V SiC MOSFET in an optimized TO-247-4L package. Its main target users are electric vehicle manufacturers who are increasingly adopting 800V electrical systems, designed for on-board chargers for EVs, motor drive inverters and off-board charging [15].

In December 2021, STMicroelectronics published STPOWER silicon-carbide (SiC) MOSFETs. It is an automotive grade (AG) qualified device and it has an extended voltage range of 650 V to 2200 V. In addition, the SiC MOSFET product packages include HiP247, H2PAK-7, to -247 long pin, STPAK and HU3PAK and are designed to meet the requirements of automotive and industrial applications [16].

Combined with the above events, it is obvious that the relation between requirement in the automotive industry and FET's development. The rapid development of electric vehicles brings a bright FET market. Manufacturers are trying to release new FETs suitable for electric vehicles and it is expected that in the future, the development of the automotive industry will also lead to the development of FETs.

7. Conclusion

With the development of nearly 60 years, the FET has developed into a kind of device with advantages as reliable, flexible and also easy to use. These make the FET keep its high status in Electronic Engineering. But now, there are some physics challenges that limit the development of FETs. Even so, a number of emerging FETs are still driving the development of FETs. It is expected that FETs still have a promising future and will be influenced by the electric vehicle industry.

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Zhibo Yang and Jizhou Wu contributed equally to this work and should be considered co-first authors.

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