Research on the advantages and development status of new material MOSFET

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Abstract. When using MOSFETs, in order to improve the operating speed, so that higher power density and lower functional consumption can be obtained in the process, researchers have explored in multiple dimensions. In this paper, three popular new material MOSFETs are mainly explained, including SiC MOSFET, GaN MOSFET and graphene MOSFET. This paper introduces their advantages and their development status, so as to compare the advantages of new materials. In conclusion, By adding materials, the electron mobility and stability of the FET can be increased in some situation. The research in this paper will undoubtedly promote the further development of MOSFET.

Keywords: MOSFET, SiC, GaN, graphene.

1. Introduction

Compared with traditional transistors, because the source and drain of the MOSFET are symmetrical with each other, even if the user wrongly connects them in the opposite direction, the command will cause the positive and negative of the gate voltage to change, which shows that the MOSFET is more flexible and convenient. Another point is that MOSFETs have the characteristics of being able to work under extremely small currents and extremely small voltages, so it can be easily fabricated on a single chip. In this context, MOSFETs are more and more widely used in large integrated circuits. With the increasingly high cost performance and technology requirements of FETs in the process, more and more new materials and new devices have brought new demands and challenges to the theoretical modeling of FET devices. In recent years, in order to achieve higher performance indicators, researchers have made improvements mainly from four aspects: process shrinkage, technological changes, process progress and material iteration. Among them, FETs due to process requirements require more power processing capabilities than computing. Therefore, the evolution of this level of process reduction has basically ended in more than 2000, but the evolution of the other three levels is still helping FETs continue to pursue higher power density and lower power consumption. This article starts from the last step of material iteration, and introduces the most popular three types of new material field effect transistors that can be mixed with SIC, GaN, and graphene. The structure and characteristics of the tube, which aspects are used, and the problems and challenges are introduced.

2. SiC MOSFET

2.1. Introduction of SiC MOSFET

SiC has excellent electromagnetic and physical properties, such as high critical breakdown electric field, large forbidden band width, and high thermal conductivity, making it suitable for special environments such as high temperature and high pressure [1].

2.1.1. Characteristics of MOSFETs after doped with SiC

SiC MOSFETs have many advantages. First, its loss is relatively low. The conduction loss of semiconductor components will decrease with the increase of its breakdown field strength. Therefore, when other values are the same, its conduction loss is smaller than that of traditional components, and semiconductor components will not affected by temperature. Second, it has faster switching speed, SiC thermal conductivity = 2.5*Si, SiC saturation electron drift rate = 2*Si, and SiC operating frequency is high. Third, it has a higher blocking voltage SiC breakdown field strength = 10*Si (or more), and the SiC blocking voltage is greater than the Si blocking voltage. Fourth, it can work normally at temperatures above 500ºC. As a stable compound of C and Si, SiC has a width of 2.2eV—3.3eV (equal to 2*Si or more), and the maximum high temperature of SiC is 600 ºC. [2].

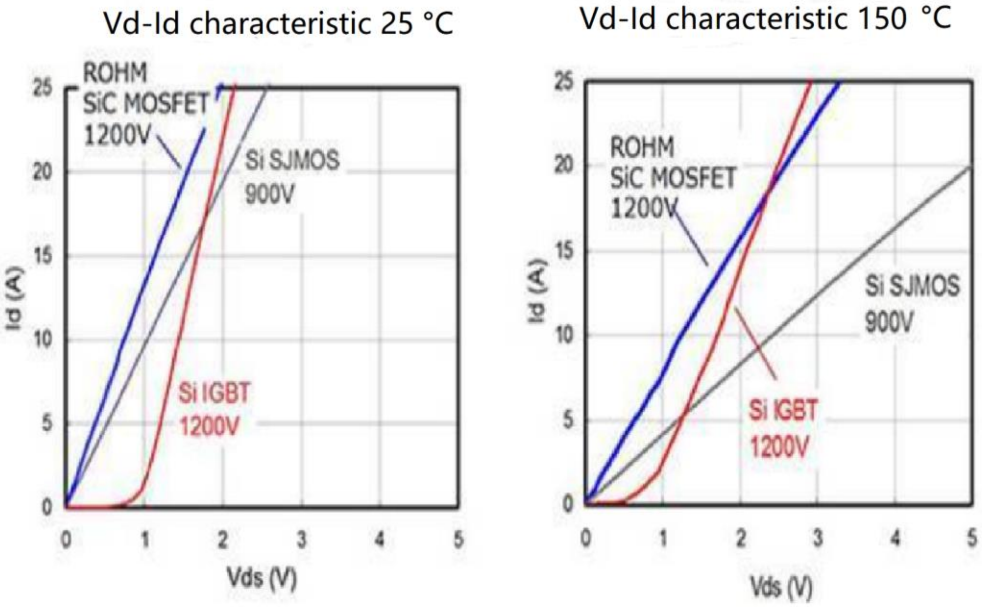

Figure 1. VI characteristic curves of Si C MOSFET,
Si MOSFET, and Si IGBT at different temperatures.

As a simple example, as shown in Figure 1, the VI curves of the three MOSFETs, SiC MOSFET, Si MOSFET, and Si IGBT, are compared respectively. Please see the left side at 25 degrees Celsius first. From the picture, we can see that the MOSFET tube does not need to increase the voltage, so it can maintain low on-resistance in a wider range.

Then we compare the left and right pictures at different temperatures, and we can find that the MOSFET tube of SIC material has a lower on-resistance, and the trend of change with the increase of temperature is also smaller [3].

2.1.2. SiC MOSFET structure description

The particle doping of the N source region and the P region of the SiC MOSFET is performed by ion implantation, and the annealing activation is performed at a temperature of 1700 °C. Another key process is the formation of SiC MOS gate oxide. Since both Si and C atoms exist in the silicon carbide material, a very special gate dielectric growth method is required. The advantages of its grooved star structure are shown in Figure 2:

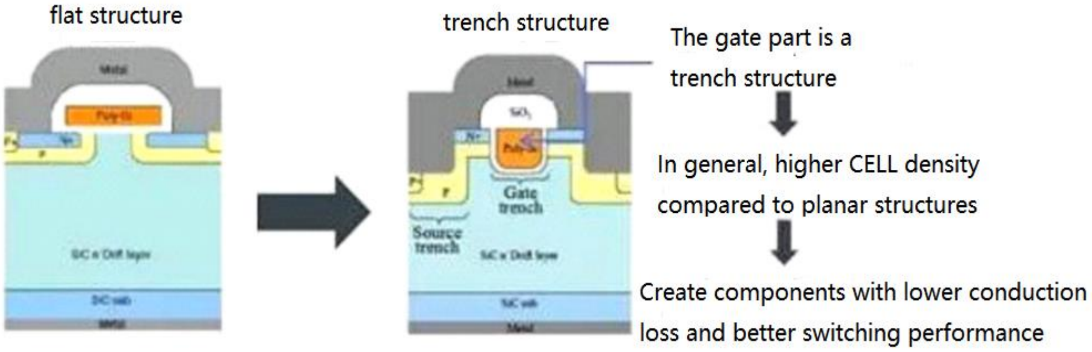

Figure 2. SiC MOSFET structure.

2.2. Application

SiC MOSFETs have advantages over conventional circuits when applied to drive circuits and interconnected with other circuits, as described below. (Comparing SiC MOSFET with traditional Si MOSFET) First, SiC MOSFETs have smaller circuit equivalent capacitance and are more easily affected by the equivalent parameters of the driving circuit; second, the driving voltage of SiC MOSFET is -5V~ +25V (recommended voltage -2V/+20V), Si MOSFET drive voltage -30V~+30V (recommended voltage 0/+15V); third, the saFETy threshold of SiC MOSFET is small; fourth, SiC MOSFET has a dedicated driver chip [4].

2.2.1. Practical applications

SiC MOSFET modules are used in medium and high-power power systems such as photovoltaics, wind power, electric vehicles, and rail transit because of their excellent physical and chemical properties. Breakthroughs in the performance of electric vehicle motor devices can be achieved by the high voltage, high frequency and high conversion efficiency characteristics of SiC MOSFETs. At present, how to use SiC MOSFETs to realize further innovation of electric vehicles has also become a research hotspot at home and abroad. For example, the new generation of electric vehicles developed by Toyota has been greatly reduced in size by using SiC MOSFET power control modules. It is expected that SiC MOSFET modules will be widely used in electric vehicles at home and abroad in the next few years. SiC MOSFETs can also be used in grid-connected inverters, dual active bridge bidirectional DC converters, three-phase motor drives, solid-state circuit breakers and other fields, which can greatly increase the operating frequency, reduce the volume of passive components, and reduce losses and the volume of the radiator increases the power density of the converter [5].

2.2.2. Requirements for SiC MOSFET application

For safety reasons, it is necessary to model the SiC MOSFET. In the actual engineering design in life, the engineer will analyze the switching characteristics, static characteristics and power loss of the SiC MOSFET to generate an effective assessment.

Compared with traditional MOSFET, SiC MOSFETs have smaller equivalent capacitance, so the driving circuit of SiC MOSFET has the following requirements. First,to meet the needs of high-speed switching of SiC MOSFETs , a driver chip with strong driving capability is used. Second, to reduce the influence of parasitic inductance of drive circuit, an appropriate amount of absorbing capacitance is added during the layout. Third, in order to avoid a series of interference factors such as Gaussian white noise, the switching and operation of the operating circuit of the SiC MOSFET are infected, and the negative pressure is used to turn off.

2.3. Problems and challenges

Even in the best-performing 4H-SiC MOSFETs, there is a problem with defects and extremely high density at the SiC-SiO2 interface, as shown in Figure 3.

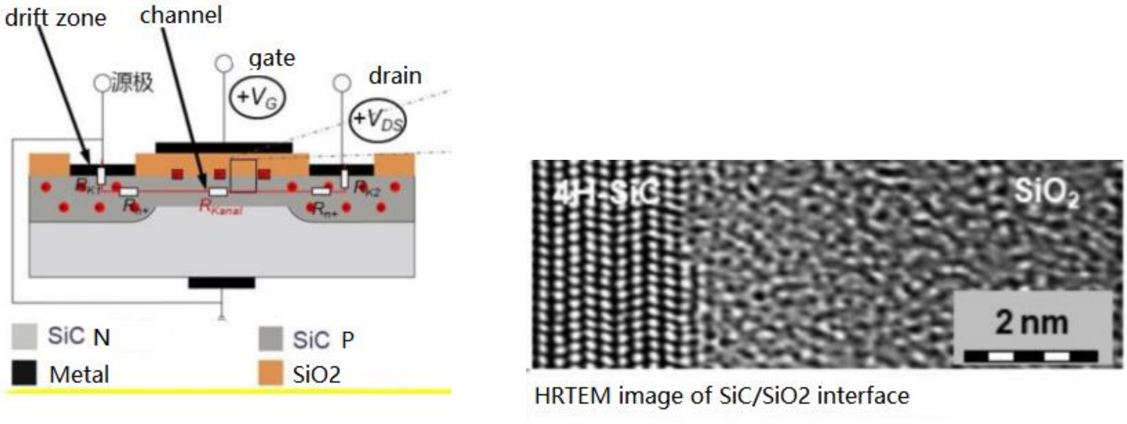

Figure 3. HRTEM image of SiC/SiO2 interface.

As a result, the electrons in the MOSFET channel are scattered, which reduces the electron mobility of the channel and degrades the performance: the channel resistance increases, the power loss increases, and the channel current decreases.

Our solution to the problem is to add a strong electric field at the oxide to turn on - either by increasing the gate-source voltage or by reducing the thickness of the oxide; but these actions greatly reduce the reliability of the gate, which leads to this The new problem, the solution to the new problem is to increase the trench MOS device, so that in the forward mode, the oxide can be stressed, thereby avoiding the use of high electric fields; in the reverse (blocking) mode: use design means Lower the electric field.

3. GaN MOSFET

3.1. Introduction to GaN MOSFETs

Like SiC, GaN materials have larger band gaps and higher critical field strengths than traditional materials, so MOSFET components based on GaN materials can have smaller resistances in the same area of circuits. Smaller equivalent voltage, thereby reducing the loss of the circuit; at the same time, the stability of the components, high temperature resistance, and pressure resistance have also been improved. Based on these, the operation and conversion rate of the circuit and the output of power per unit time (which can be understood as efficiency) will be greatly improved. Therefore, GaN is used in the field of switching power supplies.Figure 4 below is a comparison of the key properties of SiC, GaN, and Si materials, from which some characteristics of GaN materials can be seen [1].

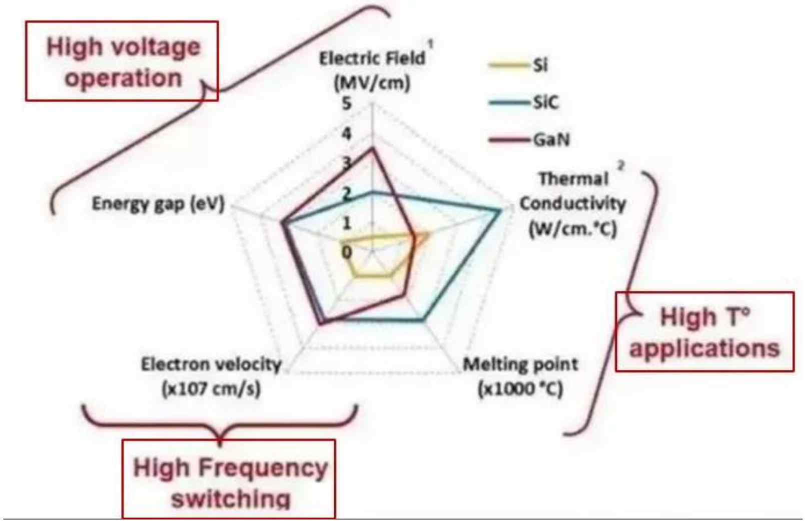

Figure 4. Comparison of key properties of SiC, GaN and Si materials.

Heterojunction field effect transistor is a typical GaN MOSFET, and its specific structure is shown in Figure 5.

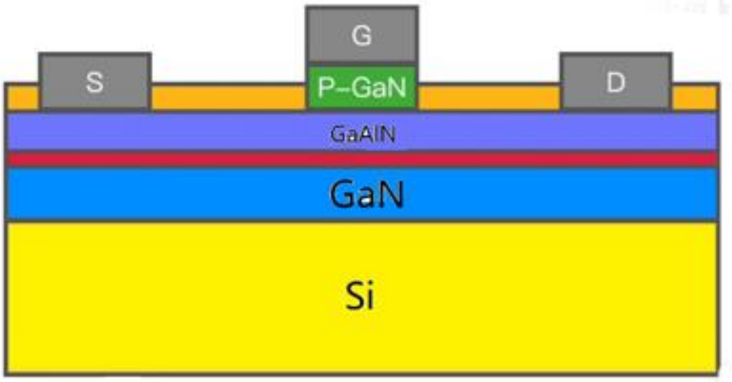

Figure 5. HFET model diagram.

Compared with the Si MOSFET, when the output charge is constant, a partial reverse recovery charge will be generated, which increases the output loss of the system. The HFET undergoes polarization reaction between the two substances, AlGaN/GaN, resulting in a higher concentration of bismuth. Dimensional electron gas, using this two-dimensional electron gas to work, can greatly reduce the reverse recovery charge, highlighting the characteristics of fast operation and small loss of the device. As shown in the figure 5 [6].

3.2. Application

Based on some studies, it can be found that in the field of industrial production, the operating speed and output efficiency of circuits are often more important. The improvement of these two parts can help companies win the market. Key examples include automotive electrification trends, high-frequency electronic communications, and more. GaN MOSFETs, through the advantages described in the above text, enable better integration, higher operating rates, and more efficient systems of output power. Therefore, GaN MOSFETs can be applied in the following aspects. First of all, it can help the Internet of Things infrastructure, because the cloud needs to consume a lot of power to keep interconnected, process and store energy, so a very efficient high-end power supply is required to reduce the power loss of industrial automation, data center telecommunications infrastructure. This is also the key advantage of GaN-on-silicon field effect transistors, which can improve power density and power conversion efficiency. Second, it can be used to electrify the powertrain. Any CO2 emitted by modern vehicles is critical, so vehicle electrification is the trend. In this field, the high operation rate and high power output of GaN-on-Si MOSFETs will play an important role, especially in electric vehicle charging piles, circuit data converters, etc. Finally, it also helps in the design of time-of-flight lidar systems, integrating GaN MOSFETs and drivers on a single chip, resulting in powerful, ultra-fast ICs, and reducing the size and cost of the system [7].

3.3. Problems and challenges

Due to the presence of 2-DEG, the insulating layer contains charged particles, so conventional HFET devices are all depletion-type (normally-on). When the device is working, the 2-DEG concentration and mobility are modulated by giving a bias voltage. Figure 6 shows the bias voltage when the AlGaN/GaN HFET is working. The bias voltage is inconsistent, and the device has an inconsistent working state. Essentially an HFET device is a field effect transistor. The gate-source bias voltage Vgs controls the turn-on and turn-off of the device, and the drain-source voltage Vds forms a lateral electric field, which makes 2-DEG transport along the channel to form a source-drain current Ids, and the source terminal is usually grounded.

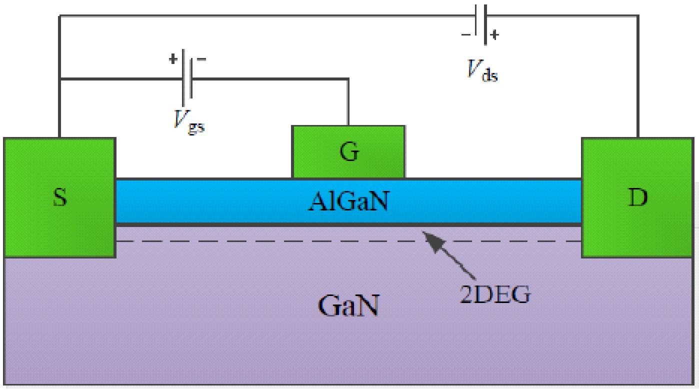

Figure 6. Bias voltage for AlGaN/GaN HFET operation.

When the gate-source voltage is less than the threshold voltage of the device, the FET is in the off state, and the source-drain current Ids of the device is static leakage (mainly composed of the leakage of the GaN buffer layer and the current generated by the Schottky barrier); when the gate-source voltage When it is greater than the cut-off voltage, if it is located at a position where the drain-source voltage is small, it will work in the linear region; if it is located in a position with a large drain-source voltage, it will work in the saturation region. However, HFET circuit modules and other circuit modules have different signal requirements, so they cannot produce good results in actual production. We currently have the following two solutions to solve the problem.

3.3.1 Cascode Technology

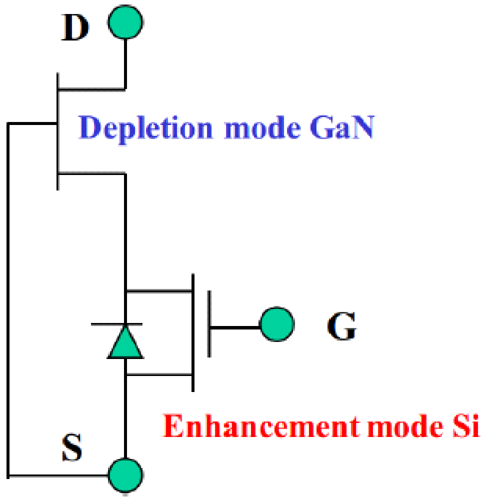

Figure 7. Connection diagram of enhancement mode Si-based MOSFET and depletion mode AlGaN/GaN HEFT.

The enhancement-mode Si-based MOSFET and the depletion-mode AlGaN/GaN HEFT are cascaded to form a whole device as shown in Figure 7, and the gate of the whole device is the MOSFET gate, the source is the MOSFET source and the drain is the HFET drain, and a high withstand voltage enhancement HFET is realized by controlling the enhancement MOSFET. The signal requirements of the HFET circuit module are basically the same as those of the Si MOSFET circuit module, so the above problems can be solved well, but a new problem is also introduced. The Si MOSFET will generate reverse recovery charges and increase the circuit output loss. Because of the cascade structure, the disturbance signal generated by external interference factors is more likely to affect the conduction and cut-off of the entire circuit by causing oscillation.

3.3.2. P-gate technology

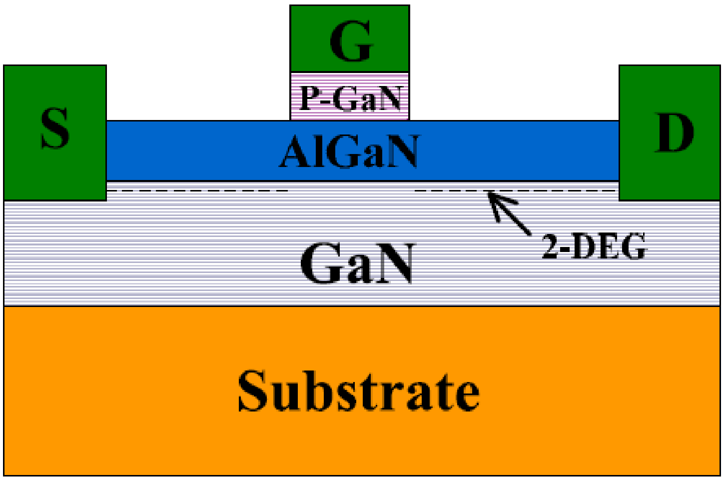

Figure 8. P-gate technology HFET device structure.

The structure of the enhancement mode AlGaN/GaN HFET device based on P-gate technology is shown in Figure 8. If we look closely, we can see that the technology is to add a layer of p-type GaN between the gate and AlGaN, through which the p-type GaN and the buffer layer can generate two-dimensional electron gas that can be consumed. This technology also has difficulties that P-type GaN is difficult to obtain, and it is difficult to achieve selective growth under the gate [8].

4. Graphene MOSFETs

4.1. Introduction to GaN MOSFETs

Graphene is a two-dimensional nanomaterial with a honeycomb hexagonal lattice structure composed of sp2-hybridized carbon atoms, which is the basis for carbon materials of other dimensions. The long-range Π-conjugated electrons of graphene make it have excellent performance in thermal, mechanical, electrical and optical aspects, and graphene has excellent electrical and thermal conductivity (high electron mobility, high temperature stability, high electrical conductivity). , low sheet resistance) is a possible material for it to be an improved MOSFET [9].

4.1.1. Characteristics of MOSFETs after doping with graphene

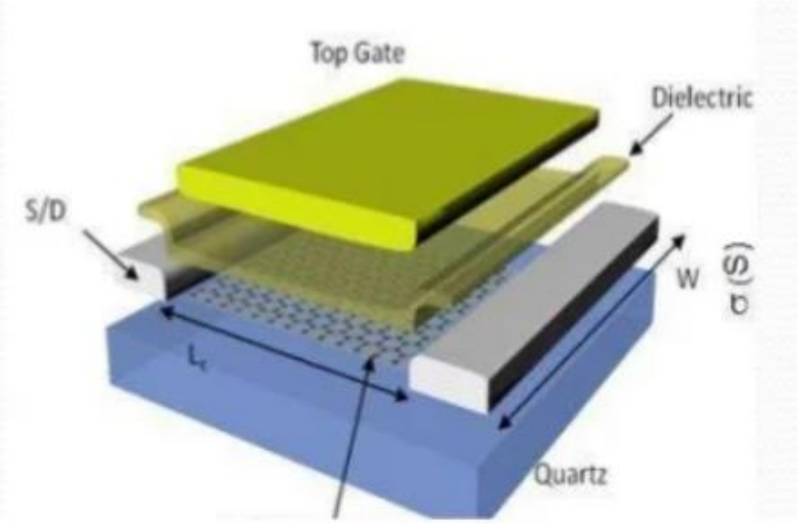

Figure 9. Graphene MOSFET block diagram.

The structure of graphene MOSFET is that ITO is the gate electrode, SiO2 is the gate insulating layer, graphene is the active layer, and Cr/Au double-layer metal is the source and drain electrodes.

By changing the shape of graphene, the particle gap of graphene is significantly increased, and a graphene MOSFET can be prepared, and a switching current ratio as high as 10^7 can be obtained, which is very suitable for use in digital integrated circuits. Different from the unipolar conduction characteristics of silicon-based MOSFETs, the conduction characteristics of graphene transistors reflect bipolar characteristics. Under high positive gate voltage, graphene is n-type electronic conduction; under low negative gate voltage, graphene is p-type. The holes are conductive, and the entire transfer characteristic curve is in a "V" shape, as shown in Figure 10.

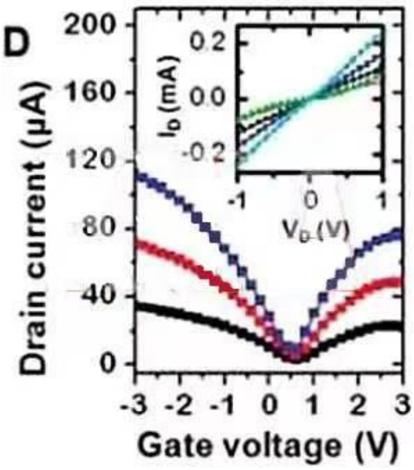

Figure 10. Graph of conduction characteristics of graphene transistors.

Graphene can form a good ohmic contact with the source-drain electrodes. At room temperature, the graphene MOSFET exhibits its unique bipolar characteristics, and the hole mobility is about 4,000cm2/(V s), the current switching ratio is about 6.2 [10].

4.2. Application

4.2.1. RF GNR MOSFET

MOS FET made of graphene material can solve the defects of traditional RF in operation speed and volume. On this basis, the main circuit switch can show stronger timeliness and faster response rate. For high-speed electronic Subsequent development of the device is also very beneficial [11].

4.2.2. GNR MOSFET IC

Such research is based on the fabrication of all-solid-state graphene MOSFET devices with high electrical performance consistency, and the realization of an unbiased common-source integrated amplifier circuit by secondary evaporation of metal wires. Compared with traditional silicon-based MOSFETs, G NR MOS FETs have the notable difference is that its gate voltage has a highly linear control of the drain saturation current. Since the gate control relationship of silicon-based MOSFETs is a quadratic function relationship, there is an inherent problem of positive and negative half-cycle distortion, while the highly linear characteristics of GNR MOS FETs have important positive effects on accurate analog amplification of weak signals. Significance. At the same time, there are also G NR MOS FET device tape-out and on-chip G NR MOS FET integrated circuits based on CMOS processing technology, and their frequency response characteristics do not change significantly compared with traditional silicon-based CMOS integrated circuits [12].

4.2.3. Novel Devices Based on GNR MOSFETs

The first is to use the gas molecules (such as NO2, NH3, etc.) adsorbed on the surface of graphene to have a more sensitive effect on the conductivity (or resistivity) of graphene, which makes MOSFETs have better performance in gas molecular sensors or detectors. Application prospects.

The second is that when a voltage is applied to the G NR MOS FET device combined with the ferroelectric gate dielectric, the ferroelectric gate dielectric will have a polarization response to the carrier concentration of the graphene channel, and the polarization response after the power is turned off. The effect remains the same, therefore, Fe-G NR MOS FET devices with memory properties can be fabricated using this feature.

4.2.4. Graphene MOSFETs can be used to make biosensors to detect biomolecules

The first is a nitrogen-doped graphene MOSFET biosensor for vegf detection and catecholamine detection

The second is a CVD graphene MOSFET biosensor developed to detect electrical signals from electricity-producing cells (cardiomyocytes)

4.3. Issues and challenges

The processing technology of graphene transistors is not yet mature and cannot be mass-produced for the time being, because mass-producing graphene is very difficult and expensive. Usually, small amounts of graphene sheets are obtained by mechanical exfoliation (this method was used for the first time in the discovery of graphene), however, this method cannot be applied to industrial large-scale production (due to quantitative reasons), and even if it is forcibly used, the finished product is produced The quality and quality of graphene will not be very high (because there are impurities in it). Graphene products on the market are generally expensive and are only used for laboratory research.

At present, there are only the following ways to prepare graphene, and there is no perfect method. The first is the mechanical lift-off method, which is easy to manufacture, and the physical and chemical properties of the finished product are perfect in all aspects, but due to technical reasons, the number of finished products obtained at one time is small; the second is the SiC epitaxial growth method, which is the same as the first one. This method can obtain more finished products, and its physical and chemical properties are better, but the production raw materials and production equipment are difficult to obtain, and the environment required for production is relatively harsh; the third is the reduction method of graphite oxide, This method can easily obtain finished products, but the physical and chemical properties of the finished products are poor; the fourth is chemical vapor deposition method, which can produce finished products on a large scale, and at the same time, the physical and chemical properties are good, but only polycrystalline products can be produced.

5. Conclusions

As a type of transistor, the FET is used in circuits to amplify power. However, with the development of electronic technology, the traditional FET is seriously affected by temperature due to its small amplification factor, and the electrical power loss is relatively small. High-level defects seriously hinder the operation of the circuit, thereby affecting the development of the device. The new FET mixed with new materials can better solve these problems. By adding materials such as SiC, GaN, and graphene, the electron mobility of the FET has been greatly increased, and the stability in some aspects has also been improved. Therefore, it can be better used in the field of electronics and electricity, but the development of graphene field effect transistors is restricted due to the difficulty in industrializing the synthesis of graphene materials.

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