

Comparative Analysis of Characteristics and Application Fields of SiC and GaN MOS Tube

Xiyao Liu

College of Logistics Engineering, Shanghai Maritime University, Shanghai, 201306, China

202110230021@stu.shmtu.edu.cn

Abstract. The characteristics and application fields of silicon carbide (SiC) Metal-Oxide-Semiconductor Field-Effect transistor (MOSEFT) and gallium nitride (GaN) MOSFET are compared and analyzed in this paper. SiC MOSFETs have advantages such as high melting point and thermal stability, high electron mobility, high breakdown field strength, low electron drift rate and high thermal conductivity. On the flip side, GaN MOSFETs are renowned for their lightning-fast switching speeds and efficient performance, making them suitable for a wide range of electronic systems. The investigation examined the structural differences between the two devices, looking at the selection of materials, manufacturing processes and electrical performance. Through detailed comparison, the unique advantages of each technology are highlighted. In addition, the paper explores the application of SiC MOSFETs and GaN MOSFETs in the electric vehicle and aerospace industries, providing case studies, experimental data, and trend analysis to illustrate their potential and promise. In conclusion, by comparing SiC MOSFETs and GaN MOSFETs, this paper offers valuable insight into their characteristics and applications. With the growing demand for more efficient and reliable electronic systems, these emerging semiconductor devices are predicted to play an increasing role in driving technological progress and industrial innovation.

Keywords: SiC MOSFET, GaN MOSFET, Electric vehicle, Aerospace industries.

1. Introduction

MOS tube, as a bright star in the field of semiconductor technology, its importance is self-evident. With the development of communication technology, automotive electronics and other industries, the functions of electronic products are becoming more and more abundant, and the required current and energy consumption are increasing. Reducing the supply voltage is an effective way to reduce power consumption. Therefore, high-efficiency low-voltage high-current switching power supply has become an important research topic. The loss of switching power supply or power converter mainly comes from the loss of high-frequency transformer, power switching tube and output rectifier tube. In traditional power converter, PN junction diode or Schottky diode is used to rectify the output end. The on-voltage drop of the diode is large, and the on-loss of the rectifier tube in the total power loss is larger when the current is large. In synchronous rectifier technology, power MOSFET with very low on-voltage drop is used to replace the power diode in power converter, which can effectively reduce the loss of this part, and is a better choice for the design of power converter [1]. With its unique electrical characteristics and excellent performance, this device has long penetrated into every corner of our daily life, from tiny electronic components to huge industrial systems.

In the global market, the sales of MOS tubes have maintained a steady growth trend over the past decade, and this growth is not accidental, but closely related to its wide range of application scenarios. Whether in the field of communication technology, high-speed data transmission and processing; In the field of electric vehicles, improving battery efficiency and drive performance; Or in the aerospace field, to ensure the stability and reliability of complex systems, MOS tubes play an indispensable role.

There are two new MOSFETs in MOSFTs that are particularly noteworthy, that is, SiC MOSFETs and GaN MOSFETs. They not only inherit the advantages of traditional MOS tubes, but also make up for the shortcomings of traditional MOS tubes in different aspects. For example, SiC MOSFETs show great potential in electric vehicles and aerospace due to their high temperature resistance, high frequency and low loss characteristics. GaN MOSFETs have ultra-high-speed switching capability and high efficiency, making them ideal for electronic systems.

In this paper, the structural characteristics of SiC MOSFETs and GaN MOSFETs are discussed, and the two MOS tubes are compared and analyzed in detail from the aspects of material characteristics, manufacturing process and electrical properties. At the same time, compare their different applications in the two fields of electric vehicles and aerospace. Through case studies, experimental data and trend analysis, the advantages and application prospects of SiC MOSFETs and GaN MOSFETs in these fields are demonstrated.

We believe that as technology continues to advance and market demand continues to grow, SiC MOSFETs and GaN MOSFETs will play an even more important role in the future. They will not only promote the innovation and development of semiconductor technology, but also inject new impetus into the scientific and technological progress and industrial upgrading of human society.

2. Classification and characteristic analysis of MOS tube

The Metal-Oxide-Semiconductor Field-Effect transistor (MOSEFT) is a three-terminal semiconductor device that utilizes electric field effects to control current. It has the advantages of small size, light weight, large power consumption, long life, high input impedance, low noise, good thermal stability, strong anti-radiation ability and so on. MOSFET is divided into P channel and N channel from the type of semiconductor conduction channel. It can be divided into depletion type and enhancement type according to the presence or absence of original conductive channel [2].

The structure characteristics of MOS tube: MOS tube is composed of three electrodes: drain, grid and source. Its internal structure is similar to that of the triode, but it is different. For example, NMOS is composed of two N-type semiconductors sandwiched between P-grade silicon semiconductors, while PMOS is the opposite. There is silicon insulation between the gate and the P-type semiconductor, so there is no current in the gate under normal operating conditions. Working principle of MOS tube: The working principle of MOS tube is based on electric field effect. When a voltage is applied to the gate, an inverse layer (N-type) is formed on the surface of the P-type semiconductor below the gate, which changes the conductivity between the drain and source. This change in conductivity can be controlled by changing the grid voltage.

Classification features is: N-channel MOS tube: When the gate voltage is positive, the inverse layer on the surface of the P-type semiconductor is N-type, forming an N-type conductive channel between the drain and the source. N-channel MOS tubes are divided into two types: enhanced and depleted. The grid source voltage of the enhanced MOS tube needs to reach a certain value to form a conductive channel, while the depletion MOS tube already has a conductive channel at zero or negative gate voltage. P-channel MOS tube: Compared with N-channel MOS tube, when the gate voltage is negative, the inverse layer on the surface of N-type semiconductor is P-type, forming a P-type conductive channel between the drain and the source. P-channel MOS tubes are also divided into enhanced and depleted types.

2.1. SiC - Structure, Features and Image

2.1.1 Structure

SiC is a binary compound semiconductor material formed by silicon (Si) and carbon (C) elements in a 1:1 ratio. The basic structural unit is the Si-C tetrahedron, in which the silicon and carbon atoms are joined together in the form of covalent bonds. The crystal structure of SiC can be divided into hexagonal crystal system and cubic crystal system. In the hexagonal system, the crystal structure of silicon carbide presents a hexagonal lattice structure, with each carbon atom connected to six surrounding silicon atoms.

2.1.2 Features

SiC materials have excellent properties such as high melting point and thermal stability, high electron mobility, high breakdown field strength, low electron drift rate and high thermal conductivity. The first feature is that SiC has a high melting point and good thermal stability. Due to the high

melting point of SiC (about 2700°C), it still has good stability even in high temperature environments. As a result, SiC devices can operate in high-temperature applications without additional cooling systems. The second feature is high electron mobility, which is the speed at which electrons move through the material. This enables SiC devices to operate in high-speed and high-frequency applications. In addition, SiC materials also have the characteristics of high breakdown electric field strength (breakdown electric field strength refers to the maximum electric field strength that the material can withstand), which makes SiC devices can work in high pressure applications. Second is the low electron drift rate. Although silicon carbide has a high electron mobility, its electron drift rate is very low. This means that electrons move more slowly when driven by an electric field, slowing down the flow of electricity. This is very useful for some specific applications, such as power supplies. The final characteristic is high thermal conductivity. SiC has a high thermal conductivity, which allows the SiC device to quickly conduct the generated heat away from the device to avoid overheating and not working.

2.1.3 Image

Modern electronic devices often have SiC MOSFETs, which are used to regulate the flow of current. My next step is to introduce the constituent structure of SiC MOSFETs. The first thing notices from left to right is the "source," which is an electrode in the MOSFET that provides current to the transistor. The source region is generally labeled "N+ pWell", which indicates that it is composed of two differentially doped semiconductor regions: the N+ region indicates that the region is doped with additional positive charge carriers (electrons), while the pWell region is a region with a higher concentration of holes.

The second layer is the "gate oxide layer", which is another important part of the MOSFET. It sits between the source and the drain and consists of a thin, transparent insulating layer, usually made of materials such as silicon glass or alumina. Below the gate layer is a metal layer called the gate electrode, which can be applied to control the flow of current in the transistor.

The 'Drain' electrode is an additional electrode in the MOSFET that gathers or discharges current. In this diagram, the drain region is labeled "n-Drift," which is a region of N-type semiconductors with a low doping concentration, allowing current to diffuse through it. Below the drain is the "n+ Substrate", a highly concentrated N-type doped region that provides a good current transport path for the transistor.

Finally, the entire structure is placed on a flat substrate, which is also referred to here as a "drain" (although "drain" has been used to describe a specific area in this description). The entire transistor is surrounded by a purple background to highlight its structure. The SiC image is shown in figure 1.

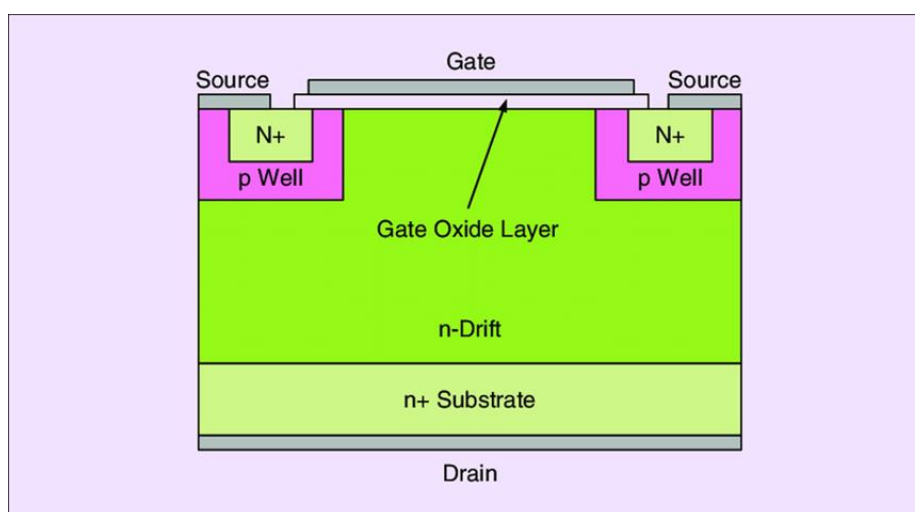


Figure 1. The structure chart of SiC MOSFET

2.2. GaN - Structure, characteristics, image

2.2.1 Structure

GaN, or gallium nitride, is an inorganic substance with the chemical formula GaN, which is a compound of nitrogen and gallium. Its structure is composed of a lattice of gallium and nitrogen atoms, in a cubic crystal system structure, where the cell contains an arrangement of atoms with a hexagonal close packing structure. This structure, called sphalerite structure or helical ene structure, consists of alternating covalent and ionic bonds of gallium and nitrogen atoms.

2.2.2 Features

The characteristics of gallium nitride mainly include the following aspects: chemical characteristics, electrical characteristics and physical characteristics.

First, here are chemical properties: At room temperature, gallium nitride is insoluble in water, acids and bases, but it dissolves more slowly in hot alkali solutions. It is unstable at high temperatures under HCL or H₂ gas, and is most stable under N₂ gas. NaOH, H₂SO₄, and H₃PO₄ can quickly corrode poor quality GaN, so they can be used to detect defects in these poor quality GaN crystals.

The second is the electrical characteristics: the electrical characteristics of gallium nitride is one of the main factors affecting the device. Undoped gallium nitride conducts N-type electricity in all cases, and the best sample has an electron concentration of about $4 \times 10^{16}/\text{cm}^3$. The doping concentration can be controlled in the range of $10^{11} \sim 10^{20}/\text{cm}^3$ by P-type doping process, low energy electron beam irradiation or thermal annealing of Mg. Due to its high electron mobility and saturation drift velocity, gallium nitride exhibits excellent performance in RF and microwave electronics.

Finally, there are physical properties: as a direct bandgap semiconductor, gallium nitride has a high hardness, and its melting point is about 1700°C. Each protocell contains four atoms, about half the size of the gallium arsenide atom. Gallium nitride has a higher dissociation degree (0.5 or 0.43) than mixtures of group III to V elements. In addition, it has excellent radiation resistance and excellent acid corrosion resistance (almost no acid erosion).

2.2.3 Image

GaN MOSFETs contain three key material layers that together form the core structure of the device. First, the top layer is the Oxide layer, also known as the silica layer. The main role of this layer is to act as a dielectric, which can isolate and protect the underlying layer of semiconductor material from the intrusion of external impurities and moisture, while also preventing the current from flowing through the unwanted path.

Next is the metallized layer (G), which is usually made of a well conductive metal such as gold or silver. The metallized layer plays an important role in the connection and conduction of semiconductor devices, which can effectively connect the external circuit with the internal semiconductor structure to achieve current transmission and control.

The second layer is the p-GaN layer, which contains doped gallium nitride. Gallium nitride is a material that is highly effective in semiconductor technology, and its doped form (P-type) means that additional trivalent impurity atoms are injected into this layer, forming the property of hole conduction. The specific electrical properties of the p-GaN layer can be controlled in semiconductor devices by using this doping method.

Below the p-GaN layer is the undoped gallium nitride layer (N-GaN). Despite not being explicitly stated in the figure, in semiconductor devices, this layer is frequently utilized to form the channel region and serves as the primary pathway for current flow.

The conductivity of the N+ GaN layer on the bottom has been greatly enhanced with the addition of nitrogen. The N+ GaN layer is often used as a source or drain in semiconductor devices to connect with external circuits to achieve current input and output.

Overall, the structural design of this semiconductor device makes full use of the electrical properties of different materials, and realizes effective control of current flow by precisely controlling

the connections and interactions between different layers. This design has wide application prospects in the field of electronics, especially in electronic devices requiring high performance and low power consumption. The GaN image is shown in figure 2.

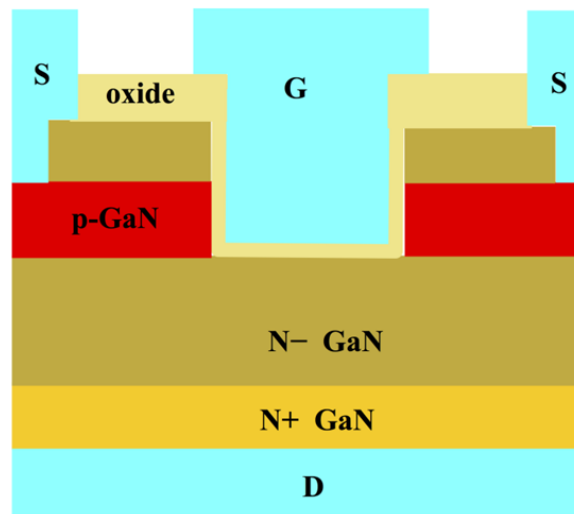


Figure 2. The structure chart of GaN MOSFET

3. Application of MOS tube in electric vehicles field

3.1. SiC MOS

In the rapid development of electric vehicles today, MOSFETs have also been widely used, and the two different MOSFETs, sic MOSFETs and gan MOSFETs, are used in different aspects due to their different characteristics. In the application of electric vehicles, the demand for motor controllers is high voltage, long life and high reliability. Therefore, the packaging design goals of automotive SiC power modules are: low parasitic inductance, low thermal resistance and high reliability. The potential of SiC technology can be maximized by optimizing the above packaging objectives individually or collaboratively [3]. In the past, Si materials were mainly used in electric vehicles, and with the emergence of SiC materials, the advantages of SiC compared with Si gradually reflected.

The first is the high temperature resistance of SiC materials, due to its highly stable crystal structure, its band width can reach 2.2-3.3eV, which is more than twice that of Si materials. Therefore, SiC materials can withstand higher temperatures, in general, SiC devices can achieve the highest operating temperature is 600°C, but limited by the packaging material, the currently available SiC MOSFETs can withstand up to 175°C (individual manufacturers of packaging technology up to 200°C), compared to the second generation of power semiconductors 150°C has a certain improvement.

Compared with Si materials, the breakdown field strength of SiC materials is more than 10 times that of Si materials, so the blocking voltage of SiC devices is much higher than that of Si devices. And then, just as importantly, low loss. The breakdown field strength of semiconductor devices is inversely proportional to their on-loss, as in most cases, so at the same power levels, SiC devices experience a much smaller on-loss than Si devices. In addition, temperature has a significant impact on the on-off loss of SiC devices, and it does not change much, which is also very different from traditional Si devices. Not only that, SiC switches faster. The thermal conductivity of SiC is approximately 2.5 times greater than that of Si materials, and the rate of absorbing electrons is twice as high as that of Si materials, so SiC devices can operate at higher frequencies.

From these four aspects, it can be seen that SiC devices have lower on-loss, higher operating frequency and higher operating voltage than Si devices. With the development of new energy vehicles, for electric drive systems, higher efficiency, higher operating voltage and higher power density

requirements mean that SiC MOSFET is one of the most important development directions for future electric drive systems [4].

3.2. GaN MOS

In terms of on-board full-bridge DC-DC converter switching, compared with traditional Si MOSFETs, GaN power transistors have the characteristics of fast switching speed and small parasitic parameters, and have a more superior relationship in the combination of on-resistance and drain-source breakdown voltage. These advantages make the application of GaN transistor can effectively reduce the on-board full-bridge DC-DC converter switching loss and improve its power density [5].

In addition, gan MOSFETs are also more suitable than si and sic in DAB converters for electric vehicle chargers. Conduction and switching losses in V2G mode are more significant for the Si-based DAB converter. Wide bandgap switches are found to operate efficiently in all simulation studies., especially GaN based DAB converters which shows a minimal change of efficiency in G2V and V2G modes [6].

4. Application of MOS tube in aerospace field

4.1. SiC MOS

For high current and high voltage applications in aircraft applications, Si IGBT is currently the better option, but it suffers from high conduction losses, resulting in reduced efficiency. In contrast, wide-band gap (WBG) devices such as GaN and SiC MOSFETs have low on-state resistance, which reduces conduction losses. As for gallium nitride MOSFET, it is more suitable for application in low current situations because it is not limited to high current in the market [7].

The experimental study and efficiency test of the rear two-stage cascaded half-bridge inverter of the aircraft static converter show that the two-stage cascaded half-bridge inverter with Si C MOSFET can work stably and the highest efficiency can reach 97.3%, which proves the feasibility of Si C MOSFET applied to the inverter stage of the aircraft static converter [8].

4.2. GaN MOS

Space-rated power conversion applications that utilize MOSFET technology benefit from the superior performance of GaN MOSFETs, however the radiation hardening process severely restricts the performance of these technologies. Even though there are limited numbers of radiation-resistant GaN devices, the current optional space rating pool can still have a significant impact on efficiency [9].

Not only GaN MOSFETs, GaN HEMTs are also widely used in the aerospace sector, according to the advantages offered by GaN HEMTs, given their inherent radiation tolerance and small size, they will be able to replace traditional silicon transistors in aerospace applications, providing higher efficiency and smaller overall size at the system level [10].

5. Conclusion

SiC MOS and GaN MOS have their unique advantages in their respective characteristics and application fields. SiC MOS tubes play an important role in the field of high temperature electronics and power electronics because of their excellent high temperature and high frequency characteristics. GaN MOS tube is widely used in power conversion, radar system, electric vehicle and other fields by virtue of high temperature resistance, high pressure resistance, fast switching speed and low on-resistance.

But at the same time, cost issues, technical challenges and driver circuit design are some of the challenges encountered by SiC MOSFETs. First, due to their relatively high production costs, SiC MOSFETs are not widely used in some cost-sensitive applications. Second, SiC MOSFETs require higher reliability and stability in high temperature, high pressure and high frequency applications,

which cannot be achieved by current manufacturing processes. Finally, SiC MOSFETs require a high current gate drive to provide the full gate charge required, which increases the complexity of the drive circuit design. Therefore, it is crucial to reduce costs, improve performance and expand applications in the future. With the improvement of production technology, the cost of SiC MOSFETs is expected to be further reduced, thus making it more widely used in various fields. The performance of SiC MOSFETs in high temperature, high pressure and high frequency applications will also be further improved to meet the needs of more demanding operating conditions.

GaN MOSFET is faced with challenges such as materials preparation, reliability issues, and technology maturity. First of all, the manufacturing cost and popularity of GaN MOSFETs are impacted by the relatively complex and costly preparation of GaN materials. Secondly, further verification and improvement is required for GaN MOSFETs' reliability at high temperatures, high voltages, and high current densities. Finally, compared with Si based devices, the technical maturity of GaN MOSFETs still needs to be improved, including manufacturing process, packaging technology and test methods. With advances in material science, manufacturing processes and packaging technologies, the performance of GaN MOSFETs will be significantly improved, and the manufacturing cost will be able to be reduced. For the future development of GaN MOSFET, it can be more applied to efficient power conversion, high-frequency communication, radar systems and other fields to promote the development of related industries. Not only that, GaN MOSFETs can also be combined with other materials or technologies (such as SiC and Si) to form hybrid integrated circuits that compensate for their respective shortcomings, resulting in higher performance and lower costs.

In short, as emerging semiconductor devices, SiC MOSFETs and GaN MOSFETs have a wide range of application prospects in their respective fields. With the continuous progress of technology and the continuous reduction of costs, they will play a more important role in the future of electric vehicles, aerospace and other fields.

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