Comparing third-generation wide bandgap semiconductor devices SiC MOSFET and GaN HEMT

Keyi Peng *
School of engineering and Computing, University of Central Lancashire, Guizhou, 550081, China
* Corresponding author: K-Peng@uclan.ac.uk

Abstract. Third-generation wide-bandgap semiconductor materials feature a wide bandgap, excellent breakdown electric field strength, high temperature resistance, and great radiation resistance. They can compensate for the drawbacks of conventional semiconductors and allow equipment to function normally even under severely demanding circumstances. Wide bandgap semiconductor materials therefore have a significant impact on the microelectronics industry. SiC MOSFET and GaN HEMT are examples of third-generation wide-bandgap semiconductor materials. The SiC MOSFET and GaN HEMT properties and uses are the focus of this essay. First, the internal structure, iv curve, threshold voltage, transconductance, and device characteristics of the respective SiC MOSFET and GaN HEMT are introduced. Then the two were compared for their electrical properties. Finally, by contrasting the application situations according to various features, it is possible to determine the various benefits and drawbacks of SiC MOSFET and GaN HEMT. The issues with materials and processes involved in creating wide bandgap semiconductor devices will be gradually resolved over time. In the future application field, it is crucial to select the appropriate device according to different advantages.

Keywords: SiC MOSFET, GaN HEMT, Characteristic, Application.

1. Introduction

The third-generation wide-bandgap semiconductor materials generally refer to materials such as gallium nitride (GaN), silicon carbide (SiC), aluminum nitride (AlN), and diamond. These materials feature a wide band gap, high temperature resistance, excellent radiation resistance, and good breakdown electric field strength. Third-generation wide-bandgap semiconductor materials are crucial in the area of microelectronics because they may mitigate the drawbacks of conventional semiconductors and allow devices to function normally even in highly challenging environments. The fundamental components of solid-state light sources, power electronics, and microwave radio frequency devices are wide bandgap semiconductor semiconductors. They have several potential applications in consumer electronics, high-speed rail transportation, next-generation mobile communications, smart grids, semiconductor lighting, and new energy vehicles. It is anticipated that it will play a significant role in the advancement of the national defense, energy, transportation, and information industries [1].

The SiC MOSFET and GaN HEMT properties and uses are the focus of this essay. First, the internal structure, iv curve, threshold voltage, transconductance, and device characteristics of the respective SiC MOSFET and GaN HEMT are introduced. Then the electrical characteristics of the two were compared. Through comparison, it is discovered that SiC devices have low on-resistance, quick switching times, straightforward driving, low switching losses, and high permitted operating temperatures, which may increase power density and lower the working temperature of power electronic devices. Make miniaturization simpler, reduce energy loss during the conversion of electric energy, and be more resistant to high temperatures and high pressure. GaN devices can significantly reduce system manufacturing and production costs by effectively reducing the size and weight of power electronic devices. These devices also have very low on-resistance, higher power density output, and higher energy conversion efficiency. Finally, the study analyzes the application scenarios based on several properties after describing the SiC MOSFET and GaN HEMT application scenarios. The difference between the two is mostly due to heat conductivity and electron mobility, it is decided.

SiC has more advantages in high-power applications when it comes to thermal conductivity, whereas GaN offers greater advantages when it comes to electron mobility.

2. Principle Analysis of SiC MOSFET and GaN HEMT

2.1. Theoretical Study of SiC MOSFET Devices

2.1.1. Internal Structure of SiC MOSFET

SiC MOSFETs are mainly divided into two states: off and on. The majority of the surface layers in the P-type area underneath the source are holes when the voltage GSV=0. No inversion layer appears at this time. Electrons from the source cannot go across the channel to the drain. The carriers in the P-type region won't migrate and there won't be any conduction between the drain and source terminals when a forward voltage is put between them. It is in the off condition and there is no current flow. The surface layer of the P-type area underneath the gate terminal is in a depletion condition when an applied forward voltage is made between the gate and the source. It is still in the off state and there isn't an inversion. An inversion layer will develop on the surface of the P-type area below the gate terminal when the gate-source voltage exceeds the threshold voltage. There is no longer a PN junction. Thus, source and drain are linked. At this point, applying a forward voltage will cause a current to be produced between the drain and the source, entering the conduction state [2]. The SiC MOSFET Internal Structure is shown in figure 1. Figure 1 (a) is a planar SiC MOSFET. Figure 1 (b) is a grooved SiC MOSFET.

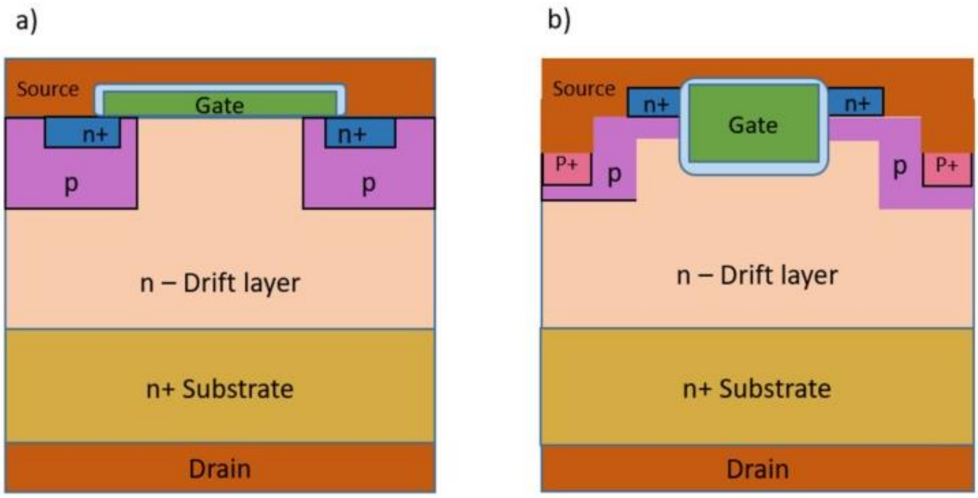

Figure 1. SiC MOSFET Internal Structure [2]

2.1.2. Threshold Voltage of SiC MOSFET

The input voltage at the gate terminal when the semiconductor side at the SiO2/semiconductor interface enters a critical inversion condition is referred to as the threshold voltage. Simple explanation of its calculating formula is provided in formula (1).

$$V_{th} = \left|Q_{dep(\max)}\right| / C_{ox} - Q_{SS} / C_{ox} + \phi_{ms} + 2\phi_{fp} \quad (1)$$

The characteristics of doping concentration, gate oxide thickness, and material have the most impacts on Vth. In practical circuit construction, it is frequently essential to supply a bias of double the threshold voltage to the gate terminal to guarantee that the device is fully switched on [3]. Interface traps have a major role in how MOSFET threshold voltage varies with temperature. The interface state density, interface trap charges, and threshold voltage all rise as the temperature drops [4].

2.1.3. IV Curve of SiC MOSFET

Formula (2) can be used to represent the drain current when the drain voltage Vds is low, indicating that the device is operating in the non-saturation area.

$$I_{ds} = \mu_n C_{ox} \frac{W}{L}\left[(V_{gs} - V_{th})V_{ds} - \frac{1}{2}{V_{ds}}^2 \right] \tag{2}$$

The device reaches the saturation area when the drain voltage Vds rises to the saturation drain voltage Vds, sat (Vds,sat=Vgs-Vth). Equation (3) can be used to express the drain current.

$$I_{ds} = \mu_n C_{ox} \frac{W}{L}(V_{gs} - V_{th})^2 \tag{3}$$

Power MOSFETs typically operate in the linear part of the spectrum. The on-resistance must be as low as feasible in order for the gadget to operate with a minimal static power consumption. The device's on-resistance is made up of the resistance of a number of components, and formula (4) is used to represent the overall on-resistance:

$$R_{on} = R_{CS} + R_{N+} + R_{CH} + R_A + R_{JFET} + R_D + R_{SUB} + R_{CD} \tag{4}$$

The channel resistance RCH, the JFET region resistance RJFET, and the drift region resistance RD are among these [5]. The SiC MOSFET IV curve is shown in figure 2, which shows the current characteristics of the device during forward conduction.

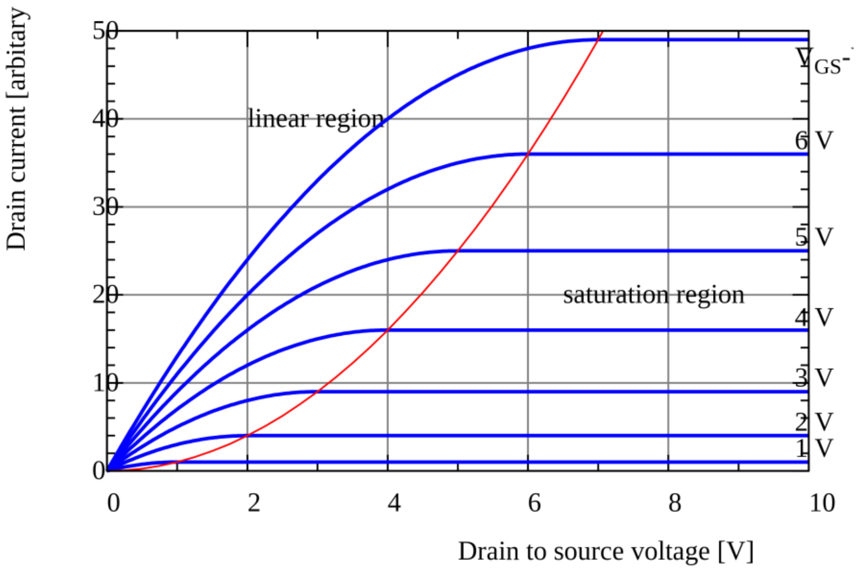

Figure 2. SiC MOSFET IV Curve [5]

2.1.4. Transconductance of SiC MOSFET

When VDS is fixed, transconductance is the rate at which IDS changes with VGS. By calculating the drain current with regard to the gate voltage, the transconductance's size may be determined. It might be derived using the current MOSFET formula. Transconductance is a crucial characteristic to assess a device's capacity for gate control. The absolute magnitude of the drain current generated at the same gate voltage increases with value, and the related device's conduction time decreases, improving sensitivity. Due to the impact of ambient temperature, gm will also wander. According to studies, the transconductance peaks about 200 K and subsequently tends to decline [3].

2.1.5. Switching Characteristics

SiC MOSFETs are generally used as switches in circuits and are often used in inductive load circuits. The dual-pulse switching circuit is based on the most common half-bridge inverter circuit topology in SiC MOSFET application environments [6]. The nonlinear parasitic capacitance is mostly responsible for the switching characteristics. The efficiency of the gate drive circuit also has a significant impact on how well the MOSFET switches. Power MOSFETs have a variety of parasitic capacitances, including those connected to the MOSFET structure, such as the gate-source capacitance CGS and the gate-drain capacitance CGD. The capacitance connected to the PN junction is known as the drain-source capacitance, or CDS. These capacitors significantly affect the power MOSFET switching action's transient process [7].

2.2. Theoretical study of GaN HEMT devices

2.2.1. Internal Structure of GaN HEMT

Devices made of GaN HEMT operate in depletion mode. The heterojunction's conduction channel is made up of a two-dimensional electron gas (2-DEG) that forms at the intersection of the buffer and barrier layers due to the different lattice structures of the two materials there. Additionally, potential wells are created to limit the device's carrier movement to a narrow two-dimensional plane. The conventional physical design of a GaN HEMT device is shown in Figure 3.

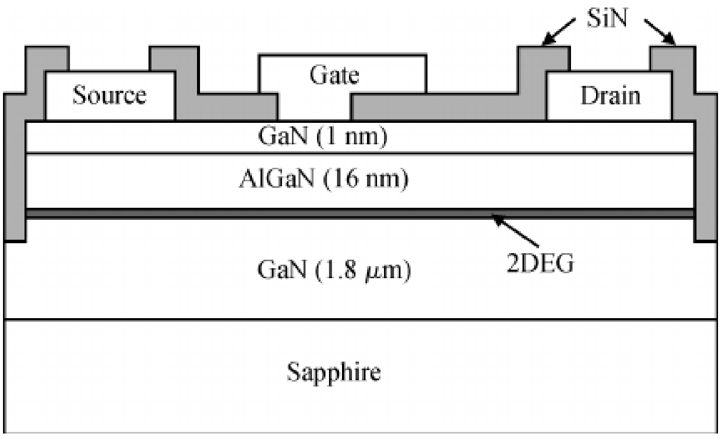

Figure 3. GaN HEMT Internal Structure [8]

The input and output terminals of the component linked to the peripheral circuit are represented by the three electrodes (source, drain, and gate). The major purpose of the SiN passivation layer is to restrict the device's ability to capture electrons through a certain method. A conductive channel forms between the AlGaN barrier layer and the GaN buffer layer as a result of the doping method and material variations between the two layers. To lessen trapping effects within the device, the AlN nucleation layer and AlN insertion layer are processed through the device material. Through the doping procedure, the SiC substrate supplies the device with electrons, and the heterojunction will result in self-heating and trap effects. This is the main physical property of GaN HEMT devices [8].

2.2.2. Threshold Voltage of GaN HEMT

When the two-dimensional electron plasma inside the device runs out, the bias voltage that is delivered outside is represented by the threshold voltage. Since GaN HEMTs are depletion-type devices, their values are typically negative, and as the voltage rises, less two-dimensional electron gas will be present in the device's conductive channel. The device's physical characteristics and the threshold voltage's approximate connection the sentence is:

$$V_{th} = \psi_b - \Delta E_c - \frac{qN_d d_d^2}{2E_0 E_b} - \frac{qN_d d_i^2}{E_0 E_b} - \frac{\delta_p d}{E_0 E_b} \tag{5}$$

From formula (5), it is clear that the device's material and structural characteristics, as well as its polarization charge density (2DEG), material properties, shape of the conduction band, discontinuity of the conduction band, and heterogeneity, all influence the threshold voltage value. Band continuity at the connection and Schottky barrier layer thickness, for example, have a direct correlation [8].

2.2.3. IV Curve of GaN HEMT

Factors such as surface potential voltage, two-dimensional electron gas (2-DEG), resistance between source and drain, electron mobility, channel length, barrier width access region resistance, and parasitic parameters all affect the volt-ampere characteristics of GaN devices. When transconductance gm, DC characteristics, and other factors that impact the performance of the device are combined, the volt-ampere characteristic (I-V) of the internal conductive channel of the device serves as a performance reflection. The drain-source current Ids is connected to the device's internal and external characteristics, and equations (6) and (7) provide its short formulations.

The connection between the drain-source current (Ids) and the drain-source voltage (Vds) can be roughly linear when the voltage between the drain and source (Vds) is minimal.

$$I_{ds} = \mu_0 C_0 \frac{W}{L}(V_{gs} + \phi_{ms} - V_{th})V_{ds} \tag{6}$$

Formula (7) illustrates how the two relate when the drain voltage (Vds) is reasonably high and the drain-source current (Ids) is saturated [8].

$$I_{ds} = \mu_0 C_0 \frac{W}{L_g}(V_{gs} + \phi_{ms} - V_{th})^2 \tag{7}$$

The GaN HEMT iv curve is shown in figure 4.

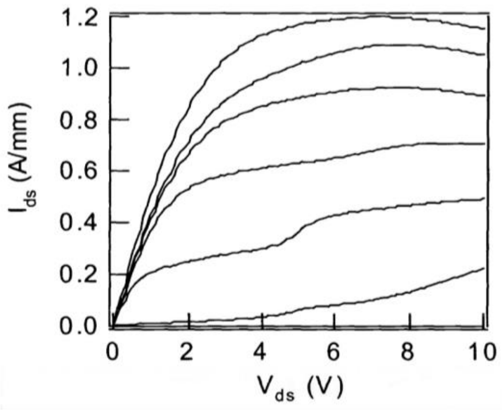

Figure 4. GaN HEMT IV Curve (Photo/Picture credit: Original)

2.2.4. Transconductance of GaN HEMT

The transconductance is constant at a given bias, and the greater the transconductance value, the more impact the drain voltage (Vds) of the device has on the drain current (Ids). To some extent, the GaN device's noise figure value may also be characterised by the magnitude of the transconductance value. The transconductance value of the device often suggests that the GaN device's noise performance is greater and that its coefficient is less [8].

$$g_m = \frac{\partial I_{ds}}{\partial V_{gs}} | V_{ds} = cons\tan t \tag{8}$$

2.2.5. Self-Heating Effect

The self-heating effect is that when GaN devices work under high power conditions, the internal junction temperature of the device continues to rise. Temperature has an impact on a number of physical properties of GaN materials, including thermal conductivity, electron concentration, band gap, electron drift rate, and electron mobility. GaN HEMT device performance is impacted by many physical characteristics that vary as the device junction temperature rises. lower output current and output power as a result. The GaN HEMT device can operate above 700°C because to its high thermal conductivity and other inherent characteristics, however as the temperature rises, so does the output performance of the device. GaN HEMT devices have longer operating times in nonlinear microwave circuit design. The temperature of the device's heterojunction gradually increases as a result of the device's restricted thermal conductivity, which prevents the heat from dissipating over time. Electron mobility and field velocity of the device, for example, start to decline with physical parameters. As a result, the performance and reliability of the GaN HEMT device are decreased, along with its current and power [8].

2.2.6. Trap Effect

GaN HEMT's process maturity is low because it lacks a uniform process standard. GaN materials have complicated structural features and significant processing instability. As a result, there are more defects and impurities in the active region of the GaN device. This adds several levels of trapping to the system. Traps are various defects that are introduced throughout the device fabrication process for process-related causes, such as lattice vacancies and dislocations. In the course of electron transit, these flaws might create traps. A trap is an impurity level that can gather carriers from an energy level standpoint. The free electrons passing through these trap positions have a chance of being captured by the covalent bonds due to the unsaturation of the covalent bonds at these trap positions. Eventually, the free electrons enter the conduction band directly from the valence band as a result. Extension of time [9].

2.3. Characteristic Parameter Comparison

As a representation of materials for third-generation semiconductors. The following are the primary benefits of SiC technology: Its broad bandgap effect enhances silicon carbide device stability. It has good high temperature resistance, high pressure resistance and radiation resistance, and significantly improves the power density of the device, thereby facilitating system heat dissipation and terminal miniaturization and portability. Its advanced electric field strength characteristics help to improve the power range of silicon carbide devices, reduce the on-resistance, and make them have high-voltage resistance, which is conducive to device thinning and improves system driving force. Due to its high saturation electron drift rate, which results in reduced resistance and a large reduction in energy loss, peripheral devices are made simpler, switching frequency is dramatically increased, and overall efficiency is increased [10].

The way that GaN technology operates is by giving transistors extremely high breakdown voltages. GaN transistors are able to function at high supply voltages as a result, producing outstanding output power densities. GaN technology is generally utilized for high power production, although additional applications are driven by the high-power handling capacity, inherent high linearity, and low noise of GaN HEMT devices. GaN LNAs have good linearity and can handle very high input power levels [11].

Table 1. Characteristic parameter comparison

Main performance parameters	GaN HEMT	SiC MOSFET
Maximum drain voltage	650	650
Drain current	20	20
Threshold voltage	1.7	4.5
Gate-source voltage	-10/+7	-5/+23
Maximum on-resistance	50	142
Input capacitance	242	496
Output capacitance	65	75
Reverse transfer capacitance	1.5	7

3. Application and Comparison

3.1. Application field of SiC MOSFET

Devices made of silicon carbide are mostly employed in industries such as radio frequency, photovoltaics, charging heaps, and new energy vehicles. New energy vehicles will make up 52% of the silicon carbide market structure, while radio frequency, industry, and energy will make up the remaining 33% and 16%, respectively [10]. This chapter will introduce two ways of using SiC MOSFETs for photovoltaics and charging.

3.1.1. Photovoltaic Inverter

In photovoltaic power generation applications, silicon carbide-based devices are mainly used in photovoltaic inverters, which are the core devices for energy conversion. Devices made of silicon carbide provide advantages over silicon-based ones, including reduced system volume, increased power density, longer device life, and lower production costs [10]. Han Xu of Xihua University obtained a new series resonant soft switching circuit by using the resonant principle by connecting resonant inductors and resonant capacitors in series on the secondary side. The new circuit topology is a secondary side push-pull resonant circuit with quadruple voltage output. The new circuit topology can realize the soft switching of the front-stage SiC MOSFET switch tube and the rear-stage rectifier diode. And reducing the transformation ratio of the transformer can further improve the efficiency of the inverter and improve the quality of the output voltage. The new solar inverter has a 500 W rated output power, a switching tube frequency of 100 kHz, an output AC voltage frequency of 220 V, 50 Hz, and an efficiency of 93.4% [12].

3.1.2. Car Charger

The charging module can accomplish high power density, ultra-compact size, and quick charging all at once thanks to the usage of silicon carbide power devices. As a result, the charging module's high power and efficiency may be realized, which allows for increased charging speed and decreased charging costs [10]. For ultra-fast charging of electric cars, Orkhan Karimzada and the Research and Development Group at the Center for Technology Innovation have adopted a trench SiC MOSFET step-down DC-DC converter developed by Hitachi. By using SiC MOSFETs, switching losses can be reduced by 7% and conduction losses can be reduced by 38%. However, because the inductor loss does not directly depend on the kind of switch, it remains nearly constant. Converters may run at higher frequencies with greater thermal performance with enhanced drivers and cooling systems [13].

3.2. Application field of GaN HEMT

Due to its excellent performance, GaN devices can be used in: radio frequency and microwave applications, power amplification applications, communication systems, automotive applications, etc. This chapter describes how GaN hems are used in chargers and RF amplifiers.

3.2.1. Car Charger

Zhang Chi uses an interleaved parallel APFC-Boost converter as the front-stage AC/DC part, a GaN HEMT-based half-bridge LLC resonant converter as the rear-stage DC/DC part, and a DCM flyback converter as the system auxiliary power supply car charger solution. The efficiency of the converters is above 90%, and can achieve a maximum output power of 1kw. The maximum efficiency of the converter reaches more than 95% near 1kw [14].

3.2.2. RF amplifier

GaN HEMTs' outstanding output power density is a key benefit of high frequency PAs. Design of a 2.5 GHz Class E PA using an infinite DC feed in a shunt capacitor configuration and a finite DC feed using a shunt inductor. Dessy Oktani discussed the design and modeling work of a GaN HEMT operating at 2,4 GHz that uses a switching class-E topology to implement a high-efficiency RF amplifier for front-end module front-end signal transmission. Has a comparatively high PAE (Power Added Efficiency) of 64% and demonstrates high power RF amplifier performance at 43 dBm. On the other hand, switching GaN HEMT RF amplifiers show some nonlinearity. It is necessary to optimize [15].

4. Conclusion

In this study, SiC MOSFET and GaN HEMT, two third-generation wide bandgap semiconductor devices, are primarily compared. The benefits and drawbacks of the gadget and various application conditions are determined by comparing its electrical properties. Small on-resistance, quick switching, easy driving, minimal switching loss, and a high working temperature are all characteristics of SiC devices. The power electronic device's power density and operating temperature can be raised. Make miniaturization simpler, reduce energy loss during the conversion of electric energy, and be more resistant to high temperatures and high pressure. The cost is also rather expensive, and the production process is challenging. Additionally, dependability needs to be increased. Currently, it is mostly utilized for high-temperature, high-frequency, high-power components. Large band gap, strong thermal conductivity, high temperature resistance, radiation resistance, acid and alkali resistance, high strength, and high hardness are all features of GaN devices. The GaN on-resistance is extremely low. It produces more power with a higher power density and converts energy more effectively. This can reduce the system's size and make it lighter. the size and weight of power electronic equipment are effectively reduced. therefore drastically cutting system production and fabrication costs. GaN's relatively poor thermal conductivity and reliability also need to be considered.

The heat conductivity of the two is one of the differences. SiC is superior in high power applications. GaN, however, has benefits over SiC in high-frequency applications because to its greater electron mobility and faster switching rate. GaN should ultimately prove to be the ideal device material for extremely high frequencies as a result of this. SiC devices with high thermal conductivity, broad bandgap, and high critical field provide certain benefits when high power is a goal.

Third-generation semiconductor materials are anticipated to see faster development, driven by new industry needs including 5G and new energy vehicles. The issues with materials and procedures used to create wide bandgap semiconductor devices will eventually be resolved as technology advances. However, due of the cost and attributes. GaN power electronic devices will be mostly employed in consumer electronics and computer/server power applications below 600 V, whereas SiC power electronic devices will be primarily used in high-voltage industrial applications over 600 V.

References

[1] Tang Linjiang, Wan Chengan, Zhang Minghua, et al. Research Status of Wide Bandgap Semiconductor Materials SiC and GaN. Dual-use technologies and products, 2020 (03): 20 - 28.

[2] Zhou Yangle. SiC MOSFET active driver chip design. Xi'an University of Technology, 2022.

[3] Liu Puyang. Research on high precision Spice model applied to high temperature integrated circuit SiC MOSFET. Xidian University, 2022.

[4] Tian Chenyu, Guo Wenyong, Zhao Chuang, et al. Low temperature characteristic test and comparative analysis of SiC MOSFET and GaN HEMT. Low temperature and superconductivity, 2022, 50 (07): 39 - 43+76.

[5] Hou Zijie. SiC MOSFET device design and threshold voltage stability research. University of Electronic Science and Technology, 2021.

[6] Zhang Lichuan. Research on structure design and characteristics of SiC MOSFET. North China Electric Power University (Beijing), 2022.

[7] Zhao Bin. SiC power device characteristics and its application in Buck converter. Nanjing University of Aeronautics and Astronautics, 2014.

[8] Li Chao. Physics-based modeling of GaN HEMT large-signal RF equivalent circuit. Southwest University of Science and Technology, 2021.

[9] Chang Chen. Research on GaN HEMT large signal model for power amplifier design. University of Science and Technology of China, 2021.

[10] Liu Yuhao. The performance of silicon carbide material is excellent, and its application ushers in a good opportunity for development. China IC, 2023, 32 (05): 16 - 21.

[11] Nikandish R. GaN Integrated Circuit Power Amplifiers: Developments and Prospects. IEEE Journal of Microwaves, 2022, 3 (1): 441 - 452.

[12] Han Xu. Research and design of photovoltaic inverter based on SiC MOSFET. Xihua University, 2019.

[13] Karimzada O, Uchida T, Masuda T, et al. Design of a DC-DC Converter using SiC Trench MOSFETs for EV Fast Chargers//2020 IEEE Workshop on Wide Bandgap Power Devices and Applications in Asia (WiPDA Asia). IEEE, 2020.

[14] Zhang Chi. Research and design of new energy electric vehicle on-board charger based on GaN HEMT devices. Shaanxi University of Science and Technology, 2021.

[15] Oktani D, Siregar L, Alam B R. Design and Analysis of 2.4 GHz GaN HEMT Class E Switching RF Power Amplifier//2019 International Symposium on Electronics and Smart Devices (ISESD).2019.