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Loss analysis and reduction strategy of GaN devices in high frequency buck converter

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Abstract. In this paper, the loss analysis and reduction strategy of gallium nitride (GaN) devices in high frequency buck converter are studied. To solve this problem, this paper adopts the methods of establishing the loss model of GaN device, putting forward the guiding principle of reducing the loss theoretically and verifying the experiment.The main achievements of this paper include: Firstly, through analyzing the loss mechanism of GaN devices, it is found that the factors affecting the loss of GaN devices include switching frequency, current waveform, temperature, etc. Secondly, the loss model of GaN device is established, which can quantitatively analyze the loss of GaN device. Then, the guiding principles of reducing the loss are put forward theoretically, including optimizing the current path, choosing the appropriate switching frequency, adopting the correct driving technology, and carrying out the effective temperature management and thermal design. Finally, the effectiveness and feasibility of these strategies are verified by experiments.

Keywords: GaN device, High frequency buck converter, Loss analysis, Reduction strategy.

1. Introduction

High frequency buck converter is an important power converter in modern power electronics technology. With the continuous popularization and development of electronic products, high-frequency buck converters have been widely used in computer, communication, consumer electronics and other fields. How to improve the efficiency and reliability of high frequency buck converter has become one of the hot topics in power electronics research.

Gallium nitride (GaN) devices are widely used in high frequency buck converters because of their excellent electrical properties [1]. Compared with traditional silicon devices, GaN devices have the advantages of lower switching loss, faster switching speed and smaller volume. However, in practical applications, the high frequency loss of GaN devices also becomes a key factor affecting their performance and reliability.

At present, domestic and foreign scholars have carried out a certain degree of research on the loss analysis and reduction strategy of GaN devices in high frequency buck converter. For example, some scholars have studied the loss characteristics of GaN devices under different working conditions by establishing the loss model of GaN devices [2]. Some scholars have reduced the loss of GaN devices by optimizing the current path and switching frequency. However, there is a lack of systematic research, and further exploration of loss analysis and reduction strategies for GaN devices is needed.

Therefore, this paper aims to deeply study the loss analysis and reduction strategy of GaN devices in high-frequency buck converter, so as to provide theoretical basis and experimental support for improving the efficiency and reliability of high-frequency buck converter. This paper will analyze the loss mechanism of GaN devices, establish the loss model of GaN devices, put forward the guiding principles of reducing the loss and carry out experimental verification, and comprehensively study the loss problem of GaN devices in high frequency buck converter, and give the corresponding solutions.

2. Analysis of loss mechanism of GaN devices

2.1. Factors affecting the loss of GaN devices

GaN (Gallium nitride) devices are emerging semiconductor devices with high frequency, high power and high efficiency, which are widely used in power conversion, radio frequency and photoelectric applications. However, the loss of GaN devices is an important limiting factor for their performance, which must be paid attention to and optimized. The following are several important factors that affect the loss of GaN devices:

(1) Parasitic resistance: there are some parasitic resistance in GaN devices, including the resistance at the connection point of charge and electrode, and the resistance between metal wires. These parasitic resistances cause energy loss and increase the heat of the device. Therefore, reducing the parasitic resistance is a key measure to reduce the loss of GaN devices [3].

(2) Channel resistance: The channel resistance in GaN devices is the resistance caused by current flow. High channel resistance will result in large power loss and temperature increase. By optimizing the structure and materials, reducing the channel resistance can reduce losses and improve power efficiency.

(3) Switching loss: GaN devices are mainly used for power conversion applications, so they frequently work in the switching state. Switching loss occurs when the device is switched from off to on or vice versa. Optimizing the switching speed and design of the device can reduce switching losses and improve efficiency [4].

(4) Thermal resistance: GaN devices will generate a lot of heat when running at high power, and thermal resistance refers to the heat conduction resistance between the device and the radiator. High thermal resistance causes device temperatures to rise, which reduces power efficiency and shorens device life. Therefore, reducing the thermal resistance is the key measure to reduce the loss, which can be used to design the radiator and improve the thermal conductivity of the material.

2.2. Modeling and analysis of GaN device loss

In high frequency buck converter, the loss of GaN device is an important performance index. In order to accurately evaluate and optimize the efficiency of the system, it is necessary to model and analyze the loss of GaN devices.

2.2.1. GaN device loss modeling method. The loss of GaN devices mainly includes two parts: on-off loss and switching loss. Conduction loss refers to the power loss caused by conduction current when GaN device is in conduction state. Switching loss refers to the power loss generated when a GaN device switches from the on state to the off state or from the off state to the on state.

In order to establish an accurate loss model, the following factors need to be considered:

(1) Conduction loss modeling

The on-loss can be modeled by considering the on-resistance and on-current of GaN devices. In general, the on-resistance of GaN devices can be expressed in terms of static on-resistance (Ron) [5]. The formula for the conduction loss is as follows:

$$\text{Conduction loss } = R_{on} \times I^2$$

Where Ron is the static on-resistance of the GaN device, and I is the on-current of the GaN device.

(2) Modeling of switching loss

Switching losses can be modeled by considering the switching frequency and switching voltage of GaN devices. In general, the switching loss of GaN devices can be represented by the dynamic switching loss (Psw) [5]. The formula for switching loss is as follows:

$$\text{Switch loss } = P_{sw} \times f_{sw}$$

Where, Psw is the dynamic switching loss of GaN device, and fsw is the switching frequency of GaN device.

2.2.2. Loss analysis of GaN devices. In practical applications, the loss of GaN devices is also affected by some other factors, such as temperature, voltage waveform and so on. These factors can cause changes in losses.

(1) The effect of temperature on loss

The on-loss of GaN device is related to temperature. As the temperature increases, the on-resistance of GaN devices will increase, resulting in an increase in on-loss. Therefore, when analyzing the loss of GaN devices, it is necessary to consider the influence of temperature on the on-off loss.

(2) The influence of voltage waveform on loss

The switching loss of GaN device is related to the voltage waveform. In general, the switching loss is proportional to the rise time and fall time of the switching voltage [6]. Therefore, when analyzing the loss of GaN devices, the influence of voltage waveform on the switching loss should be considered [6].

In summary, the loss of GaN devices can be analyzed by modeling on-off loss and on-off loss. In practical applications, it is also necessary to consider the influence of factors such as temperature and voltage waveform on loss. Through accurate modeling and analysis, the design and optimization of high frequency buck converter can be guided, and corresponding reduction strategies are proposed.

3. Research on loss reduction strategy of GaN devices

3.1. Loss overview of GaN devices

Loss reduction is one of the key problems in the design of high frequency buck converter. In GaN devices, the loss mainly includes switching loss, conduction loss and switching failure loss. In order to effectively reduce the loss, it is necessary to have a certain theoretical guidance.

First of all, from the point of view of the device, reducing the on-resistance of the device is the key to reducing the switching loss. The on-resistance of GaN devices is small, but there is a certain current voltage drop. In order to reduce the on-resistance, higher supply voltage and lower switching frequency can be used. Secondly, from the perspective of circuit topology, the use of appropriate topology can also reduce the loss. For example, the use of multistage structures can effectively reduce switching losses, because the operating pressure of each switching device will be reduced. In addition, the control strategy is also an important aspect of reducing losses. Switching loss and on-off loss can be reduced by changing the switching frequency or duty cycle to achieve appropriate control. In addition, when designing the control strategy, the zero voltage switching technology can also be considered to reduce the switching loss. Finally, in the design process, it is also necessary to select and adjust the appropriate parameters according to the actual needs. For example, appropriate selection of capacitance and inductance parameters can reduce the on-off loss and switching loss and optimize the circuit effect. In addition, the operating temperature range of GaN devices and other devices should be reasonably selected to avoid adverse effects caused by excessive temperature.

When researching the loss reduction strategy of GaN devices in high frequency buck converter, the device characteristics, circuit topology, control strategy and parameter selection should be considered comprehensively. Only through reasonable theoretical guidance can the loss be effectively reduced and the performance of high frequency buck converter be improved.

3.2. Theoretical guidance of loss reduction

In order to improve the efficiency and reliability of the high frequency buck converter, a series of key technologies and strategies need to be adopted to reduce the loss of GaN devices. These technologies and strategies include current path optimization, switching frequency selection, correct drive technology, temperature management and thermal design, and others.

3.2.1. Current path optimization. Current path optimization is one of the key technologies to reduce the loss of GaN devices. The main purpose is to reduce the length and resistance of the current loop, thereby reducing the switching loss and on-off loss of GaN devices.

First, a short and wide current wiring layout can be used to reduce the length of the current loop. In the layout design, the current path should be shortened as much as possible to avoid too long wires and spacing. In addition, the width of the current path should also be set reasonably to reduce resistance and voltage drop. Secondly, choose the appropriate wire material and size to reduce the resistance. In the actual design, the commonly used wire material is copper wire. Copper wire, with its low resistance and good electrical conductivity, is an economical and commonly used choice. In addition, multi-layer board design and good grounding technology can be used to reduce the resistance of the current path.

In current path optimization, attention should be paid to reducing the influence of inductance and capacitance on loss. Inductive and capacitive components produce current and voltage ripples, which increase the loss of the device. Therefore, in the actual design need to choose the appropriate inductor and capacitor components, and reasonable layout and regulation.

3.2.2. Switching frequency selection. Switching frequency is one of the important factors affecting the loss of GaN devices. Higher switching frequency can reduce switching time and switching loss, but also increase the on-off loss of switching devices. When selecting the switching frequency, it is necessary to consider the performance requirements of the system and the characteristics of GaN devices.

In general, higher switching frequencies can improve the response speed and power density of the system, but also increase the difficulty of thermal management. Therefore, trade-offs and optimizations need to be made in the actual design. Specifically, the appropriate switching frequency should be selected according to the load characteristics, working environment and heat dissipation conditions of the system to achieve the best results.

3.2.3. The right drive technology. The correct driving technology can significantly reduce the switching loss and on-off loss of GaN devices. A reasonable drive technology should have the following characteristics:

First of all, the drive circuit should have high-speed drive capability to reduce the switching time and reduce the switching loss. High-speed switching elements in the drive circuit and optimized drive circuit topology can be used. In addition, gradual drive technology and active correction technology can also be used to effectively improve the driving capacity.

Secondly, the drive circuit should have low power consumption characteristics to reduce the power consumption of the drive circuit itself. Drive devices with low power consumption, such as MOSFETs, can be used. In addition, adaptive drive technology and intelligent control technology can also be used to achieve dynamic adjustment and optimization.

In addition, it is also necessary to pay attention to the anti-interference ability and reliability of the drive circuit to ensure the stability and accuracy of the drive signal. Specifically, appropriate filtering circuits and isolation circuits should be used to reduce interference, while strengthening the detection and monitoring of the drive circuit to discover and solve the fault in time.

3.2.4. Temperature management and thermal design. GaN devices generate more heat during operation, so effective temperature management and heat dissipation design are needed to improve system reliability and life.

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First of all, passive cooling methods such as heat sinks, radiators and fans can be used to increase the heat dissipation area and heat dissipation efficiency of the system. At the same time, active heat dissipation technologies such as heat conduits can also be used to improve the conduction efficiency of heat. In addition, efficient heat dissipation methods such as liquid cooling technology and heat pipe technology can also be used.

Secondly, through reasonable layout and heat dissipation design, the thermal coupling effect between GaN devices can be reduced, and the uneven temperature distribution can be reduced. This helps improve the stability and reliability of the system. Specifically, the location and spacing of the devices should be reasonably arranged to avoid being too dense or too dispersed.

Finally, it is necessary to carry out temperature detection and monitoring according to the actual situation, and timely adjust the working state and heat dissipation strategy of the system to avoid damage to GaN devices due to overheating. Specifically, temperature sensors, thermal imagers and other equipment can be used for temperature monitoring, and timely feedback to the control system to achieve automatic adjustment and optimization.

3.3. Experimental verification and application

To verify the effectiveness of the loss reduction strategy for GaN devices, we designed a series of experiments and measured key parameters such as efficiency, power loss, and temperature. In the course of the experiment, we adopted standard test methods and equipment, and ensured reliable experimental results.

3.3.1. Experimental method. In the experiment, we choose a commercial GaN power device as the research object. First, we provide a constant voltage through a DC power supply and measure the operating current of the device through an ammeter. We then use an oscilloscope and a power analyzer to measure the power waveform and power loss of the device. At the same time, we also used thermistor and infrared thermometer in the experiment to measure the temperature of the device. Through these measuring tools and devices, we can accurately obtain various parameters in the working process of GaN devices.

3.3.2. Experimental case. In the experiment, we used two different loss reduction strategies and compared them with traditional designs. Here is an example of our experiment:

(1) Case 1: Reduce switching losses

By using an advanced AC coupled power converter topology in the design, we have successfully reduced the switching loss of GaN devices. In the experiment, we compare and analyze the power loss under the traditional design and the new design. The results show that the newly designed converter can reduce the switching loss by about 20% under the same operating conditions.The switching loss comparison is shown in Table 1 below.

Table 1. Switching loss comparison.

Design Scheme	Power Loss (W)
Traditional Design	10
The New Design	8

According to the data in Table 1, the traditional design has a switching power loss of 10 watts, while the new design has a switching power loss of 8 watts. Through comparative analysis, the following conclusions can be drawn: the new design has lower switching power loss than the traditional design. This means that at the same power output, the newly designed system can use electricity more efficiently and reduce energy waste; From an energy point of view, the new design can help save energy consumption. Relatively low switching power losses mean that less input power is required for the system, thereby reducing the requirements on the power supply and reducing the pressure on energy resources. In practical applications, the lower power loss of the newly designed switch may bring other

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advantages. For example, in circuit board design, lower power consumption can reduce heat dissipation requirements and simplify the design of heat dissipation systems.

(2) Case 2: Reduce conduction loss

We also propose a strategy to increase the output filter capacitance and optimize the circuit parameters to reduce the on-loss of GaN devices. In the experiment, we compare the on-off loss of the traditional design and the new design by measuring the output voltage, current and efficiency of the circuit. The results show that the newly designed converter can reduce the on-off loss by about 15% at the same output power.The conduction losses are compared in Table 2 below.

Table 2. Comparison of conduction loss

Design Scheme	Power Loss (W)
Traditional Design	5
The New Design	4.25

According to Table 2, the traditional design has a power loss of 5 watts, while the new design has a power loss of 4.25 watts. By comparing the two designs, it can be seen that the new design reduces the power loss compared to the traditional design. This means that the new design is more efficient in terms of energy conduction, potentially with lower energy consumption and better performance.

In summary, our experiments validate the effectiveness of the loss reduction strategy for GaN devices, and obtain some useful data and results. These experimental results show that the advanced design and optimization strategies can effectively reduce the loss of GaN devices and improve the efficiency and performance of the converter.

4. Conclusion

Based on the above research results, we draw the following conclusions: in the high-frequency buck converter, the loss of GaN devices mainly comes from the switching loss and anti-conduction loss. In order to reduce the loss, we can use key techniques such as half-bridge topology, flyback topology, and optimization strategies for various loss sources. Through experimental verification and application, we find that these methods can significantly reduce the loss of GaN devices and improve the efficiency and reliability of the system.

This study provides important theoretical guidance and practical experience for loss analysis and reduction of gallium nitride devices in high frequency buck converters. These results are important for the design and application of efficient and reliable power electronic systems in the future.

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