Research Article

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Complex circuit simulation and nonlinear characteristics analysis of GaN power switching device

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Abstract: To overcome the problem of energy losses in the electrical circuits and to improve the energy conversion efficiency, it is necessary to increase the power switch frequency and reduce the open resistance of the power switch. Moreover, based on energy saving, failure protection, circuit design and other aspects of the research of enhanced devices are also essential, a new static and dynamic model of GaN power transistor is proposed, and the steady-state and dynamic characteristics of GaN power transistors are simulated and tested. The GaN power transistor used in the test has a constant voltage of 450 V and a current of 4 A. By changing the driving power U_g (take 2, 3, 4V) and the stray inductance L_s (take 2 μ H, 5 μ H), the switching characteristics of the simulation model were studied, and the simulation was carried out by changing the absorption capacitance C_c (select 1.5 μ F and 3.0 μ F). This proposed simulation model can be used to analyze the protection effect of the buffer circuit under various stray inductors and help to guide the design of the buffer circuit. The simulation results of the static and dynamic models of the new GaN power transistor agree well with the experimental results. With the increase of U_g , the opening speed is faster, but the turn-off delay is longer. With the increase of L_s , the peak of the turn-off voltage increases. After increasing the absorption capacitance, the peak voltage during the turnoff is limited to the rated voltage, and the buffer circuit plays a protective role and the greater the C_c , the better the protection. The simulation results are consistent with the theoretical analysis, which verifies the effectiveness of the model.

Keywords: Gallium nitride; power transistor; complex circuit simulation

1 Introduction

With the rapid development of the national economy, the demand for electric energy is increasing day by day. Power electronic devices and power converters including power electronic devices play a key role in the improvement of power energy control technology and utilization efficiency. In the ideal state, the resistance approaches zero when the switch is “on” and infinity when the switch is “off”, and the switching time between “on” and “off” approaches zero [1]. In the electrical circuits especially in heavy transmission lines, there is always a huge of energy due to the resistance. There is a need for a better circuit design which will increase the power switch frequency and reduce the open resistance. Now days, various transistors are used in wide range of applications like telecommunications, charger for electrical vehicles. They are basically high electron mobility transistors which are capable of minimizing the switch losses [2, 3]. Therefore, to improve the energy conversion efficiency and reduce energy loss, it is necessary to increase the power switch frequency (that is, the working speed) and reduce the open resistance of the power switch. In addition, based on energy saving, failure protection, circuit design and other aspects of the research of enhanced devices are also essential.

Since the beginning of the last century, the research on SI transistors has opened the prelude of the information industry revolution. In the past decades, the microelectronics industry has developed rapidly, and increasingly new technologies have sprung up like bamboo shoots after a spring rain, which has greatly driven the development of the world economy and the improvement of people’s living standards [4]. Thanks to this, the information exchange between people living all over the world is more efficient and convenient, and the cycle of knowledge update is also

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shorter, which puts forward higher requirements for the development of microelectronic devices, in semiconductor materials, silicon (Si), germanium (Ge) and other basic traditional semiconductors are generally regarded as the first generation of semiconductor materials, semiconductors such as GaAs and InP are considered second-generation semiconductor materials, the wide band gap semiconductor such as gallium nitride (GaN) and silicon carbide (SiC) is regarded as the third generation semiconductor materials [5]. To a large extent, the physical properties of the material determine the performance of the device.

GaN, as the representative of the third generation of semiconductor materials, has many excellent materials and physical properties and is likely to meet the requirements of power switching devices in the next generation of power electronic systems [6]. GaN has a unique crystal structure with a band gap of up to 3.4 eV, much higher than that of GaAs (1.4 eV) and Si (1.1 eV), and has the following characteristics: (1) The breakdown electric field is as high as 3.3×10^6 V/cm, about 10 times that of Si, and the voltage level is high. (2) After the growth of AlGaN layer on GaN layer, the concentration of two-dimensional electron gas formed by AlGaN/GaN heterojunction is higher, which can achieve the goal of high current density? (3) High electron saturation drift speed, the highest 2.5×10^7 cm/s, suitable for high frequency switching occasions. (4) The operating temperature is very high, and the theoretical junction temperature can reach 600° , so that the cooling system volume of the device can be reduced and thus greatly simplified. (5) Low thermal resistance, suitable for high temperature environment. (6) The ability to resist illumination is stronger than GaAs and Si. (7) Hardness higher than GaAs and Si, easy to implement high power integration of devices. Gallium nitride (GaN) is the third generation semiconductor material. GaN-based power switching devices have broad application prospects in high speed and high power fields [7].

Based on the characteristics of the device, a new static and dynamic model of GaN power transistor is proposed, and the steady-state and dynamic characteristics of GaN power transistor are simulated and tested.

Semiconductor technology is the decisive force to promote the development of power electronics industry. The applications of power devices based on silicon have been quite mature. GaN and SiC are an important research direction in the future high-efficiency power switching systems. To date, working transistor prototypes using these wide band gap materials have proven superior performance and show great potential [8]. Jia *et al.* proposed a field-path coupling model for parallel Schottky (MPS) silicon carbide (SiC) diodes. The physical model was established by using the lumped charge modeling method based on the MPS chip

structure, and the thermal model was established by using the finite element simulation software in accordance with the package structure and size of the SiC module. Based on the electrical model and thermal model of MPS-SiC diode, the field-circuit coupling model was established by using the PSPICE-COMSOL co-simulation platform [9].

Wide-band gap devices such as gallium nitride (GaN) have been widely used due to their low on-resistance and parasitic parameters [10]. Liang *et al.* introduced in detail the research results of the preparation of AlGaN/GaN HEMT epitaxial structure, power electronic materials on a 6-inch silicon substrate, and the preparation of Si-based GaN power MIS-HEMT on a 6-inch CMOS production line, as well as the research progress of normally close co-source co-gate GaN devices [11]. Wei *et al.* proposed a PSPICE based GaN power transistor model suitable for complex circuit simulation, the model is based on the theoretical analysis of the nonlinear characteristics of source-drain current and parasitic capacitance between poles, and the correctness of the proposed model is verified by the comparison of experimental and simulation results [12]. Wang *et al.* evaluated the switching performance of 1.2kV vertical GaN power field effect tube by using TCAD simulation of a mixed mode element circuit [13]. Frivaldsky *et al.* experimentally analyzed the switching performance of GaN (Galliuminn) power transistor selected and prospected its application in bidirectional Buck/Boost DC-DC converters. The switching performance of GaN system GS61008P transistor simulation model with high precision and verification was evaluated [14]. Wang *et al.* proposed a device model for finite element simulation to study the relationship between the frequency characteristics of the on-resistance and the internal current distribution of GaN devices [15]. Sarnago *et al.* proposed an improved gate drive circuit for GaN devices based on a constant current regulator (CCR). This circuit realizes a constant current without being affected by working conditions, and solves the influence of temperature, aging, and working conditions on the performance of the converter [16]. Zhang *et al.* proposed a multiphysical analysis model based on GaN high electron mobility transistor (HEMT). The electromagnetic – electro-thermal coupling model of GaN-HEMT is beneficial to simulate the influence of different stray parameters on the external characteristic waveform of the device [17]. On this basis, a simulation model suitable for the new GaN power transistor is proposed, and the application of the model in the analysis of switching effects and buffer circuit is briefly introduced, the theoretical basis and guidance are provided for the application of GaN power transistor in practical engineering [18]. The high electron mobility transistor offers a low operating resistance as well as high breakdown voltage. It

is suitable power semiconductor for next generation which can increase the efficiency and minimize the various kinds of power and energy equipment [19, 20].

In the proposed algorithm, GaN power transistor was used to solve complex circuit stimulation in electrical circuits. Static as well as dynamic models were tested at certain voltage and current value. It was observed that this model proved out to be energy conversion efficient and helped in controlling energy losses. Its application in the buffer circuit and switching effects was also discussed in detail.

2 Research methods

2.1 Static feature modeling

According to the device structure analysis, a GaN power transistor simulation model is proposed, as shown in Figure 1. Using voltage – controlled current source i_d simulator static characteristics.

Figure 1: Simulation model of GaN power transistor

When source-drain voltage is added to the device, source-drain current I_D can be expressed as, according to the current density equation:

$$I_D = qWvn(x) = qW\mu\epsilon(x)n(x) \quad (1)$$

In the formula:

q – electronic quantity;

W – Channel width;

v – Speed;

$n(x)$ – The concentration of 2DEG at x ;

μ – Electron mobility;

$\epsilon(x)$ – Channel electric field intensity at point x .

According to the energy relationship, it can be known that:

$$qn(x) = C_1 [U_{gs} - U_{th} - U(x)] \quad (2)$$

Type:

C_1 – Capacitance value per unit area between gate and channel;

U_{th} – Threshold voltage.

Substituting Eq. (2) into Eq. (1), the source leakage current can be expressed as

$$I_D = \mu WC_1 [U_{gs} - U_{th} - U(x)] \frac{dU(x)}{dx} \quad (3)$$

Integrating channel length, we can get:

$$I_D = \alpha [2(U_{gs} - U_{th})U_{ds} - U_{ds}^2] \quad (4)$$

$$\alpha = \mu \frac{WC_1}{2L} \quad (5)$$

Where:

α – current coefficient.

When U_{ds} increases to $U_{Dsat} = U_{gs} - U_{th}$, it can be known from Eq. (2) that, $qn(x) = 0$, at this time, the channel is clipped at the leak end, and the current reaches saturation; in the saturated region, channel current I_{Dsat} is

$$I_{Dsat} = \alpha (U_{gs} - U_{th})^2 \quad (6)$$

2.2 Dynamic characteristic modeling

1. Parasitic capacitors C_{gs} and C_{gd} . GaN dynamic characteristics of power transistors are mainly determined by the charge and discharge processes of parasitic capacitors C_{gs} , C_{gd} between electrodes [21]. Since the breakdown field strength and band gap width of GaN materials are much higher than those of Si materials, under the same pressure conditions, GaN power transistors have lower parasitic capacitance, resulting in lower switching losses and faster switching speeds, therefore, the parasitic capacitors C_{gs} , C_{gd} in the model must be set to more accurate and reasonable values.

To determine the parasitic capacitances C_{gs} and C_{gd} of the device, the total gate charge Q_g must first be calculated. This can be obtained from the integral of the gate to the source charge in the channel:

$$\begin{aligned} Q_g &= W \int_0^L (-qn) dx = -W \int_0^{U_{ds}} qn \frac{dx}{dU} dU \quad (7) \\ &= -W \int_0^{U_{ds}} \frac{qn}{\epsilon(x)} dU \end{aligned}$$

Substituting Eq. (1) in, we get:

$$Q_g = -\frac{\mu W^2}{I_0} \int_0^{U_{ds}} (qn)^2 dU \quad (8)$$

Substituting Eqs. (2) and (4) in, we get:

$$Q_g = \frac{2}{3} \beta \frac{U_{gd}'^3 - U_{gs}'^3}{U_{gs}'^2 - U_{gd}'^2} \quad (9)$$

Among them, $U_{gs}' = U_{gs} - U_{th}$, $U_{gd}' = U_{gs}' - U_{ds}$; Coefficient of capacitance $\beta = WC_1L$.

Take the partial differential of Q_g , and we can get:

$$C_{gs} = -\frac{\partial Q_g}{\partial U_{gs}'} = \frac{2}{3} \beta \left[1 - \frac{(U_{gs}' - U_{ds})^2}{(2U_{gs}' - U_{ds})^2} \right] \quad (10)$$

$$C_{gd} = -\frac{\partial Q_g}{\partial U_{gd}'} = \frac{2}{3} \beta \left[1 - \frac{U_{gs}^2}{(2U_{gs}' - U_{ds})^2} \right] \quad (11)$$

2. Parasitic resistance R_g , R_d and R_s . The internal gate resistance R_g affects the time constant of the gate voltage, the switching speed limit of the device is determined, but the resistance value is negligible compared to the external gate resistance used to suppress switching oscillations [22]. Both drain resistance R_d and source resistance R_s are related to the static and dynamic characteristics of the device. Replace the values of R_d and R_s with $R_{ds}(on)$, the values of $R_{ds}(on)$ can be looked up in the data sheet.

3 Results analysis and discussion

The steady state and dynamic characteristics of GaN power transistor are simulated and tested. The GaN power transistor used in the test is EPC2027. The device has a quota voltage of 450 V and a current of 4 A.

3.1 Steady state characteristics

When the grid driving voltage is $U_{gs} = 2, 3, 4, 5$ V, the simulation and test results of GaN power transistor output characteristics are shown in Figure 2.

At low driving voltage, there is steady increment in the output value, but as the grid driving voltage increase and reach to 5V, there is a gradual increase in output in the value as clear from the above curve. It can be seen from Figure 2 that the steady-state characteristics of GaN power transistors described by the proposed model are in good agreement with the experimental results.

Figure 2: Simulation and test results of GaN power transistor output characteristics

3.2 Dynamic characteristics

The test circuit topology of GaN power transistor is shown in Figure 3. Where, U_{DC} is the DC bus voltage, R and L are the inductive load, and VD is the continuation diode. Inductance L_c , resistance R_c , diode VDC , capacitor C_c to form di/dt buffer circuit; L_s is the equivalent stray inductance of loop.

Figure 3: GaN power transistor test circuit topology

Under the test condition $U_{DC} = 200$ V, the stray inductance of the test circuit is calculated to be approximately $L_s = 1 \mu\text{H}$, buffer circuit parameters $L_c = 0.5 \mu\text{H}$, resistance $R_c = 2 \Omega$, capacitance $C_c = 0.5 \mu\text{F}$, this is shown in Table 1. The on-off and off waveform of GaN power transistor test and simulation is shown in Figure 4. As can be seen from

Table 1: Circuit parameter values in the case of $U_{DC} = 200$ V

The test conditions	Circuit features
$U_{DC} = 200$ V	$L_s = 1 \mu\text{H}$
	$L_c = 0.5 \mu\text{H}$
	$R_c = 2 \Omega$
	$C_c = 0.5 \mu\text{F}$

Figure 4, the simulation results are very consistent with the test results.

Figure 4: GaN power transistor test and simulation on and off waveform

3.3 Analysis of switching characteristics of the model

The simulation model can be used to analyze the influence of driving power supply U_g , gate external resistance R_g , stray inductance L_s and the recovery characteristics of continuation diode on the switching characteristics of GaN power transistor. Here, U_g and L_s are taken as examples for analysis and explanation [23, 24]. The analysis methods of other factors are similar. The circuit in Figure 3 is still used, and the working conditions remain unchanged. Except for the selected analysis factors, other parameters remain unchanged.

1. Influence of driving power U_g . The size of the driving power supply will affect the switching speed of the device. Keep $L_s = 1 \mu\text{H}$, let U_g be 2, 3, 4 V respectively, and just to make it easier to see, so let us take -5 V for the low level of U_g . The simulation curve of gate voltage U_{gs} under different U_g is shown in Figure 5. As can be seen from Figure 5, with the increase of U_g , the opening speed is accelerated, but the turn-off delay is also longer. Therefore, the appropriate driving power value should be selected when designing the circuit.

The simulation results accord with the theoretical analysis.

Figure 5: Simulation curve of gate voltage U_{gs} under different U_g conditions

Table 2: Parameters to investigate the influence of driving power

Parameter	Value
L_s	$1 \mu\text{H}$
	2V
U_g	3V
	4V

2. The influence of stray inductance L_s . Stray inductance has a great influence on the device turn-off voltage. Keep $U_g = 3$ V, L_s . Take $2\mu\text{H}$ and $5\mu\text{H}$ respectively for simulation. The simulation curve of source-drain voltage U_{ds} under different L_s is shown in Figure 6. As can be seen from Figure 6, with the increase of L_s , the peak of the turn-off voltage increases significantly. The simulation results accord with the theoretical analysis. In practical circuit design, low inductive bus design, reasonable structure layout, and proper selection of inductive elements can be used to reduce the stray inductance.

Table 3: Parameters to study the influence of stray inductance

Parameter	Value
U_g	3V
L_s	2 μH
	5 μH

Figure 6: Source-drain voltage U_{ds} simulation curve under different L_s

capacitance C_c was selected as $1.5\mu\text{F}$ and $3.0\mu\text{F}$, respectively, for simulation [26]. The simulation curve of source-drain voltage U_{ds} under different C_c is shown in Figure 7. As can be seen from Figure 7, after increasing the absorption capacitance, the peak voltage during the turnoff is limited to the rated voltage, and the buffer circuit plays a protective role, and the bigger C_c is, the better the protection. Table 4 shows the parameters settings to study the effect of absorption capacitance.

Table 4: Parameters to study the effect of absorption capacitance

Parameter	Value
L_s	5 μH
C_c	1.5 μF
	3.0 μF

Figure 7: Simulation curve of source-drain voltage under different C_c

3.4 Buffer circuit design

The proposed simulation model can be used to analyze the protection effect of the buffer circuit under various stray inductors and guide the design of the buffer circuit. The simulation results in Figure 6 show that when the buffer circuit parameters are constant and L_s to $5\mu\text{H}$ is increased, the device's turn-off peak voltage exceeds the rated voltage [25]. Under the guidance of the simulation results, the buffer circuit parameters were redesigned, and the absorption ca-

4 Conclusions

Based on the characteristics of the device, a new static and dynamic model of GaN power transistor is proposed, and a simulation model based on PSPICE is established, the accuracy of the model is verified by the test circuit. The application of the model in the analysis of switching effects and buffer circuit is briefly introduced, the theoretical basis and guidance is provided for the application of GaN power transistor in practical engineering. A new static and

dynamic model of GaN power transistor is presented based on the device's features, and the steady-state and dynamic characteristics of GaN power transistor are simulated and tested. The GaN power transistor used in the test has a constant voltage of 450 V and a current of 4 A. By changing the values of driving power U_g (take 2, 3, 4V) and stray inductors L_s (take 2 μ H, 5 μ H), the switching characteristics of the simulation model were studied and the simulation was carried out by changing the absorption capacitance C_c (select 1.5 μ F and 3.0 μ F), the protection effect of buffer circuit is studied. The results show that (1) The simulation results of the static and dynamic models of the new GaN power transistor are in good agreement with the experimental results; (2) With the increase of the opening speed increases, but the turn-off delay also becomes longer; (3) With the increase of, the peak of the turn-off voltage increases clearly; (4) After increasing the absorption capacitance, the peak voltage during the turnoff is limited to the rated voltage, and the buffer circuit plays a protective role, and the bigger the C_c , the better the protection. On this basis, a simulation model for the new GaN power transistor is proposed, and the model's application in the analysis of switching effects and buffer circuit is briefly described. The theoretical foundation and guidance for the application of GaN power transistor in practical engineering are also provided. The simulation results are consistent with the theoretical analysis, which verifies the effectiveness of the model.

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