Characterization, modeling and application of Gallium Nitride Power HEMT

Quanli Ren[1] and Lianqing Zheng[1]
[1]School of Electric Engineering
Chongqing University
Shapingba, Chongqing, China
{ 1853762537; 1146675738}@qq.com

Abstract:A model of Gallium Nitride(GaN) power HEMT based on PSpice is proposed in this paper, which is suitable for complex circuit simulations.The static and dynamic characteristics model is based on the theoretical analysis of nonlinear characteristics of source-drain current and interelectrode parasitic capacitances,which are the major influence factors of the device characteristics. The proposed model is verified by comparing the experimental tests with the simulation results.At last, the model of GaN HEMT is used in analysis of switching characteristics and snubber circuit design.

Keywords: Gallium Nitride,HEMT,static characteristic, dynamic characteristic,PSpice modeling

1.INTRODUCTION

Semiconductor material is the decisive force in promoting the development of power electronics.The applications of conventional silicon(Si) based power semiconductor are quite mature.However, it has been approaching the theoretical limit in many ways due to the limitations of the material feature itself.

In recently, Gallium Nitride(GaN) is attracting more attentions and considered as one of the most promising semiconductor materials,which maintains a relatively adequate performance in high-voltage, high-speed, high-efficiency and high-power-density applications [1-3].Due to the advantages of the material,the GaN high-electron-mobility transistor (HEMT) has been proved to be an outstanding candidate for future power electronics applications and has high breakdown voltage, low on-state resistance and splendid high-temperature operation capability [4-5].

It is of great significance to analyze the static and dynamic characteristics and establish a simple accurate device model for engineering applications.For the past few years,several GaN HEMT simulation models have been proposed,and most of which are based on the device physical characteristics[6-7].These models can reveal detailed characteristics of the device ,which also means it is quite complicated in parameter extraction and subsequent coding in circuit simulators.In this paper, on the contrary,we propose a new static and dynamic models of GaN HEMT based on the characteristics of the device itself and establish a PSpice simulation model taking EPC2027 for example[8]. Output and capacitance-voltage characteristics provided by the datasheet are used in parameter extraction.To this end,a test circuit is used to verify the accuracy of the GaN HEMT model,and we presents some model applications about switching effects analysis and snubber circuit.

2.MODELING OF THE GaN HEMT

A. Structure of Device

Figure.1 shows the structure of the newly developed GaN HEMT[4].It is similar to MOSFET in device structure as both of them have a conduction band channel.However,in GaN HEMT, it is the aluminium gallium nitride(AlGaN) to isolate the channel and the gate electrode instead of the oxide layer in MOSFET. Lattice matching of AlGaN layer and GaN layer forms a heterojunction. Buffer layer on a substrate is important and necessary for improving the nitride film quality which can only be obtained by heteroepitaxial methods currently,especially on a sapphire substrate.The switching process of enhancement mode GaN HEMT is:when applying a gate voltage higher than the threshold value, two-dimensional electron gas(2DEG) forms in the heterojunction and the device turns on because the electron in the AlGaN transfers to the potential well of GaN; Conversely ,when gate voltage is lower than the threshold value,the device turns off since the 2DEG is consumed.

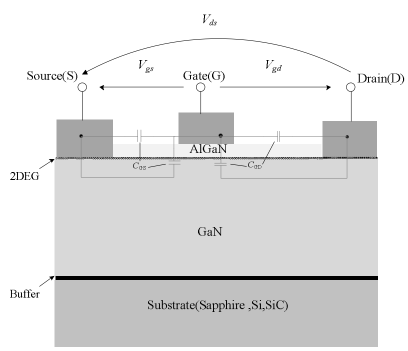


FIGURE.1 Structure of GaN power transistor

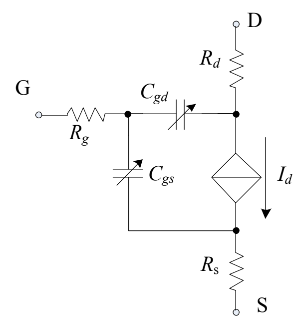


FIGURE.2 Simulation Model of GaN HEMT

B. Static Characteristics Modeling

The PSpice simulation model presented in this work by analyzing the structure of GaN HEMT is shown in figure.2.The voltage-dependent current source I_d is used to model static current-voltage (I-V)characteristics.When applying source-drain voltage to the device,source-drain current can be expressed by a nonlinear equations according to the current density equation as follows:

$$I_d = qWvn(x) = qW\mu\varepsilon(x)n(x) \tag{1}$$

Where W represents channel width,v represents electron velocity, μ represents electron mobility, $\varepsilon(x) = \frac{\mathrm{dV}(x)}{\mathrm{d}\,x}$ represents the channel electric field intensity of point x in the direction from source to drain , V(x) represents the electric potential, and $n(x)$ represents the density of 2DEG of point x.

According to energy relation[9]:

$$qn(x) = C_1[V_{gs} - V_{th} - V(x)] \tag{2}$$

Where C_1 represents capacitance per unit area between the gate and the channel,V_{th} represents the threshold voltage. Substituting (2) in (1), and source-drain current is given by:

$$I_d = \mu W C_1 [V_{gs} - V_{th} - V(x)] \frac{\mathrm{dV}(x)}{\mathrm{d}x} \tag{3}$$

Calculate the integral of channel length L,and we can get this equation:

$$I_d = \alpha[2(V_{gs} - V_{th})V_{ds} - V_{ds}{}^2] \tag{4}$$

Where α represents the current parameter expressed as follows:

$$\alpha = \mu \frac{WC_1}{2L} \tag{5}$$

When V_{ds} up to $V_{dsat} = V_{gs} - V_{th}$, $qn(x)$=0 according to(2), in this case the channel pinch-off and the current reaches saturation, the channel current in the saturation region is given by:

$$I_{dsat} = \alpha(V_{gs} - V_{th})^2 \tag{6}$$

C. Dynamic Characteristics Modeling

1) *Parasitic Capacitances C_{gs} and C_{gd}*

The dynamic characteristics of GaN HEMT are mainly determined by the charge and discharge processes of the inter-electrode parasitic capacitances C_{gs} and C_{gd}. Due to the small parasitic parameters, GaN HEMT has faster switching speed and less switching power loss[10]. Thus, the parasitic capacitances C_{gs} and C_{gd} should be well expressed so as to reflect the advantages of GaN HEMT over Si based device.

In order to determine the parasitic capacitances C_{gs} and C_{gd}, the gate charge Q_g should be calculated first,which is given by:

$$Q_g = W\int_0^L (-qn)dx = -\frac{\mu W^2}{I_D}\int_0^{V_{ds}} (qn)^2 dV \tag{7}$$

From(2),(3),(7), the gate charge is given by:

$$Q_g = \frac{2}{3}\beta \frac{V_{gd}^{'3} - V_{gs}^{'3}}{V_{gs}^{'2} - V_{gd}^{'2}} \tag{8}$$

where $V_{gs}^{'} = V_{gs} - V_{th}$ and $V_{gd}^{'} = V_{gs}^{'} - V_{ds}$, β represents the capacitance parameter expressed as follows:

$$\beta = C_1 WL \tag{9}$$

Take a partial differential on Q_g ,C_{gs} and C_{gd} is given by:

$$C_{gs} = -\frac{\partial Q_g}{\partial V_{gs}^{'}} = \frac{2}{3}\beta[1 - \frac{(V_{gs}^{'} - V_{ds})^2}{(2V_{gs}^{'} - V_{ds})^2}] \tag{10}$$

$$C_{gd} = -\frac{\partial Q_g}{\partial V_{gd}^{'}} = \frac{2}{3}\beta[1 - \frac{V_{gs}^{'\,2}}{(2V_{gs}^{'} - V_{ds})^2}] \tag{11}$$

2) *Parasitic Resistances R_g,R_d and R_s*

The value of internal gate resistance R_g is important as it affects the time constant of the gate voltage and ultimately determines the switching speed limit of GaN HEMT. However,in this paper R_g is assumed to be zero because it is much smaller compared with the external gate resistance used to dampen oscillation during switching transients.R_d and R_s are related to both the static and dynamic characteristics.In this paper,$R_{ds(on)}$ is used to substitute for the R_d and R_s,and its value is provided in the datasheet.

So far , we have discussed the static and dynamic characteristics modeling of the GaN HEMT.The most important three factors: I_d,C_{gs} and C_{gd} are all voltage-dependent(V_{gs},V_{gd}),which means it's easy for us to complete the simulation model with a simple programming in PSpice.Two unknown parameters,current parameter α and capacitance parameter β can be extracted by fitting the curves of output and capacitance-voltage characteristics which are provided in the datasheet.

3.VERIFICATION OF PROPOSED MODEL

Simulations and experimental tests are both carried out to verify the validity and accuracy of the static and dynamic characteristics of the model.The type of GaN HEMT used in the experiment is EPC2027(450V,4A).

A. Static Characteristics Verification

Figure.3 shows the comparison of output characteristics between experimental and simulation results of GaN HEMT.The gate-source voltage V_{gs}=2,3,4,5V. The comparison result proves that the proposed GaN HEMT model has high accuracy on the static characteristics simulation.

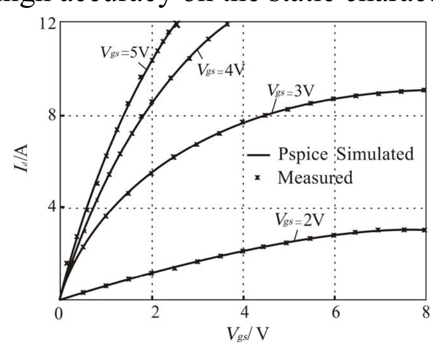


FIGURE.3 Simulation and experimental results of the output characteristic of GaN HEMT

B. Dynamic Characteristics Verification

In order to verify the dynamic characteristics of the proposed GaN HEMT model,simulations and experimental tests are both carried out based on an inductive load switching circuit, which is shown in figure.4.

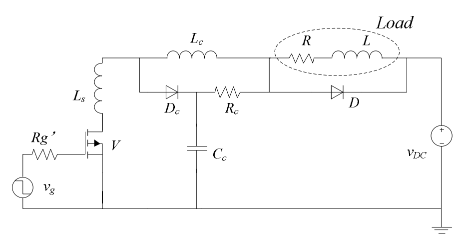
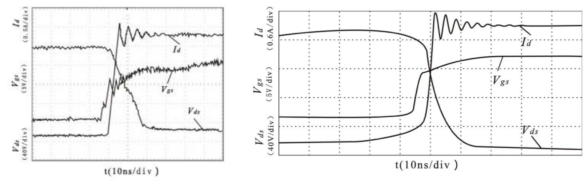
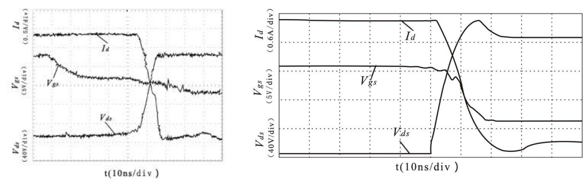


FIGURE. 4 Topology of GaN HEMT testing circuit

The dc source voltage V_{DC} is 200V, di/dt snubber circuit consists of inductance L_c(0.5μH),resistance R_c(2Ω),diode D_c and capacitance C_c(0.5μF), stray inductance L_s is 1μH calculated by the method from paper[11].Simulations and experimental waveforms of source-drain voltage V_{ds},source-drain current I_d and gate voltage V_{gs} during turn-on and turn-off transients are shown in figure 5. The comparison indicates that the simulations match well with the experiment waveforms in rising and falling slopes as well as turn-on and turn-off times.



(a)



(b)

FIGURE.5 GaN HEMT switching waveforms of experiment(left) and simulation(right).
(a)turn-on ;(b)turn-off

TABLE.1 Switching losses comparison

	Experiment	Simulation	Error rate
Turn-on loss	3.5μJ	3.8μJ	8.6%
Turn-off loss	1.2μJ	1.1μJ	8.3%

With the switching waveforms,the switching losses can be calculated[12].Turn-on loss E_{on} is defeined as the integral of the instantaneous product of V_{ds} and I_d from t_1(the moment when I_d starts to increase) to t_2(the moment when I_d up to steady state within 10% error band).Turn-off loss E_{off} is calculated as the same method.The switching losses measured by experiment and simulation waveforms are shown in table 1.The results of the simulation switching losses also match well with the experiment.

4.APPLICATION OF PROPOSED MODEL

A. Switch Characteristics Analysis

The simulation model proposed in this paper can be used to analyze the influence facts of GaN

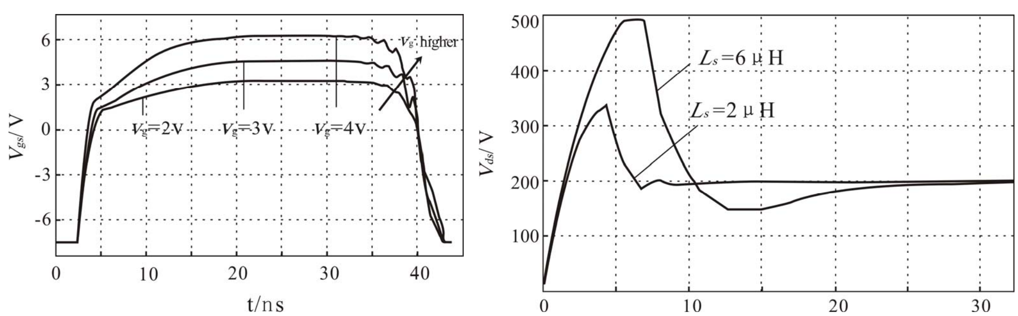
HEMT switching characteristics including driving source v_g,external gate resistance R_g',stray inductance L_s and freewheel diode.We choose v_g and L_s as analysis examples, similar analysis of the other factors. Still use the circuit of figure.4 and keep working conditions unchanged.

1) *Influence of driving source v_g*

The driving source voltage has something to do with the switching speed. Keep L_s=1μH,choose v_g as 2,3,4V,and in order to facilitate observation,the low level voltage of v_g is taken as -5V.The switching waveforms of gate voltage V_{gs} under different driving source voltages are shown in figure.6(a).The result indicates that with the driving source increasing ,the turn-on speed becomes faster,but the turn-off delay becomes longer too. The simulation result is consistent with the theoretical analysis[13].Therefore it is reasonable to select a appropriate driving source during designing.

2) *Influence of stray inductance L_s*

The stray inductance has something to do with the turn-off voltage peak. Keep v_g=3V,and increase L_s to 2μH,5μH artificially,Turn-off waveform of source-drain voltage V_{ds} is shown in figure.6(b). The result indicates that with the stray inductance increasing ,the peak of turn-off voltage increases apparently. The simulation result is consistent with the theoretical analysis.In the actual circuit design,it is necessary to reduce the circuit stray inductance by using lamination busbar design,reasonable structure and non-inductive components[13].



(a) Influence of driving source v_g (b) Influence of stray inductance L_s

FIGURE.6 Switching characteristics of the GaN HEMT model in different conditions

B. Snubber circuit design

The simulation model proposed in this paper can be used to analyze protection effects of snubber circuit under different stray inductances.Turn-off peak voltage of the device exceeds the rated voltage under the original snubber circuit if increasing the stray inductance to 5μH as shown in figure 7.Therefore,the parameters of snubber circuit need to be redesigned under the guidance of the simulation.Increase the subber capacitance C_c to 2μH and 5μH, Turn-off waveforms of source-drain voltage V_{ds} are shown in figure.7.

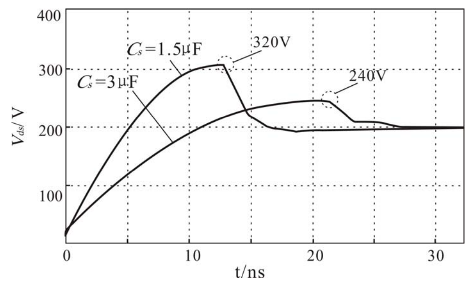


FIGURE. 7 Turn-off waveforms of anode voltage of simulation and experiment of of GaN HEMT using different snubber capacitor

The simulation result shows that the turn-off peak voltage is limited below the rated voltage by increasing the subber capacitance.In this case,the snubber circuit has played a protective role,and the protection is better with bigger subber capacitance.

5.CONCLUSION

A simple and accurate PSpice model of GaN HEMT is proposed in this paper,which takes both static and dynamic characteristics into consideration.The parameters of the model can be extracted easily from output characteristic and capacitance-voltage characteristic of the device. Experimental tests and Simulations based on the proposed model of an inductive load switching circuit have been conducted and the comparison results verify the high accuracy of the model in switching characteristics.

In addition,several applications of the proposed model have been carried out, including switch characteristics analysis and snubber circuit design,which shows the advantage of the GaN HEMT model in the applications of complex circuits.

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