Equivalent circuit model of millimeter-wave AlGaN/GaN HEMTs

Luo Xiaobin¹, Yu Weihua¹a), Lv Xin¹, Lv Yuanjie², Dun Shaobo², and Feng Zhihong²
¹ Laboratory of Millimeter-wave and Terahertz Technology, Beijing Institute of Technology, 100081, Beijing, China
² National Key Laboratory of Application Specific Integrated Circuit, Hebei Semiconductor Research Institute, 050051, Shijiazhuang, China
a) ywhbit@bit.edu.cn

Abstract: A 2×50 AlGaN/GaN High Electron Mobility Transistor (HEMT) is designed and fabricated with 0.1 µm gate-length and 2 µm source-drain distance in the paper. The maximum frequency of oscillation (fmax) may reach 177 GHz. The small signal equivalent circuit model is obtained by using the open-short test structure and reverse cut-off method. A novel large signal model is constructed based on the SDD form. The new I-V and C-V expressions are proposed to complete nonlinear fitting accurately by contrasting the measure results of the GaN HEMT. The convergence of the model is good during the harmonic balance simulation. So this modeling method can be applied to millimeter-wave GaN HEMTs.

Keywords: AlGaN/GaN, high electron mobility transistor, large signal model, millimeter-wave

Classification: Microwave and millimeter wave devices, circuits, and systems

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1 Introduction

AlGaN/GaN High Electron Mobility Transistors (HEMTs) are widely used in designing power amplifiers at microwave band for their special advantages such as
high 2DEG, high saturation drift velocity and high breakdown voltage. Along with rise of working frequency and diminishment of physical dimension of devices constantly, the HEMTs have been researched at millimeter-wave band [1]. The large signal equivalent circuit model of the HEMTs is very important during designing MMICs [2]. However, many classical nonlinear functions are based on GaAs HEMTs. So the nonlinear model which is fit for GaN characteristics needs to be obtained in order to satisfy device performance accurately.

In this paper, we realize a $2 \times 50$ AlGaN/GaN HEMT which can be used at millimeter-wave band through reduction of gate-length down to 0.1 µm and source-drain distance down to 2 µm. Then we complete extraction of small signal model parameters on the basis of the open-short test structure and reverse cut-off method. We propose a new method to construct the large signal model by using the SDD form and also give the I-V and C-V nonlinear fitting expressions which are fit for GaN HEMTs. This model shows excellent accuracy and convergence so that it can be used to design millimeter-wave GaN MMICs.

2 Design and fabrication

The cross-sectional structure of the $2 \times 50$ AlGaN/GaN HEMT is shown in Fig. 1. All the epitaxial layers are grown on a SiC substrate by MOCVD. The heterostructure is consisted of a GaN buffer layer which is 1.5 µm thick and a AlGaN with 24% Al content barrier layer which is 23 nm thick. In order to enhance 2DEG in the channel, the AlN layer is inserted between the barrier layer and buffer layer which is only 1 nm thick. The 2DEG mobility and sheet carrier concentration are 2000 cm$^2$/V·sec and $1 \times 10^{13}$ cm$^{-2}$ respectively.

![Fig. 1. Cross-sectional structure of the AlGaN/GaN HEMT](image)

The two T-gates are formed by using electron-beam lithography and Ni/Au is selected as the gate metal. The gate-length is 0.1 µm and the gate-cap-length is 0.35 µm. The SiN passivation layer has been considered to use because it can not only reduce surface defect but also make different electrodes isolated [3]. The single-finger gate-width is 50 µm in order to meet the principle that the phase difference is no more than $\pi/16$ at millimeter-wave band. The source-drain distance has been diminished to 2 µm and the lateral structure of the HEMT is symmetric [4]. So the channel series resistance can be cut down effectively and high frequency
characteristics of the device will be far more improved. Ti/Al/Ni/Au is evaporated to form source and drain electrodes by using rapid thermal anneal at 900°C for 35 seconds. The ohmic contact resistance is 0.4 Ω·mm through the method of transmission line matrix measure. After fabrication of the GaN HEMT, the photograph of the device is shown in Fig. 2.

![Photograph of the 2 x 50 GaN HEMT layout](image)

Fig. 2. Photograph of the 2 x 50 GaN HEMT layout

The DC I-V curves are measured from −6 V to 0 V Vgs with 0.05 V step interval at Vds = 10 V. The transconductance can be calculated at each point and the curve is shown in Fig. 3. It is seen that the threshold voltage of the HEMT is −5 V. The maximum transconductance is obtained at Vgs = −3.8 V and this value may reach 33.8 mS. The static operation point is determined at Vgs = −3.8 V so that the best high frequency power gain characteristics can be reflected at the greatest extent under this bias condition.

![Transconductance characteristics at Vds = 10 V](image)

Fig. 3. Transconductance characteristics at Vds = 10 V

The S-parameters of the HEMT have been measured from 0.1 GHz to 50 GHz at Vgs = −3.8 V and Vds = 10 V by using the vector network analyzer. The maximum available power gain (MAG) is calculated based on the S-parameters according to principle of input and output matching, shown in Fig. 4. The MAG can reach 13 dB at 30 GHz and 11 dB at 50 GHz. The maximum frequency of oscillation (fmax) is extrapolated to 177 GHz according to −20 dB/dec. So this GaN HEMT can be applied to millimeter-wave band.
3 Small signal model

The small signal equivalent circuit model of the HEMT is shown in Fig. 5. The Cgs, Cgd and Cds are parasitic capacitances of the PADs. They can be determined by using the open test structure like Fig. 6. The Lg, Ld and Ls are parasitic lead inductances. They are obtained by using the short test structure after removing the PAD capacitances like Fig. 7. The Rg, Rd and Rs are parasitic resistances of the HEMT. The Cgsi, Cgdi and Cdsi are coupling capacitances between electrodes. We can take advantage of the reverse cut-off method to extract these parameters after removing the parasitic capacitances and inductances [5]. First the resistances and coupling capacitances can be ignored when the frequency is lower than 5 GHz at $V_{gs} = -8$ V and $V_{ds} = 0$ V. So the equivalent circuit is composed of intrinsic capacitances Cgsp, Cgdp and Cdsp. Then the resistances and coupling capacitances are obtained when the frequency is 50 GHz. The low and high frequency equivalent models are shown in Fig. 8. After removing all the parasitic parameters, the intrinsic parameters Cgs, Cgd, Cds, Ri, Rds, Gm and t can be determined according to the Y-parameters.
4 Large signal model

The equivalent circuit model can be implemented nonlinear characteristics by using the 7 port SDD form, shown in Fig. 9. This method relies on the port voltages, currents and their derivatives. The large signal characteristics is reflected when the intrinsic parameters change with the gate and drain voltages. The Rds may affect the DC I-V fitting effect so that the DC block is needed to add in series to prevent the current. The Rleak is used to express the leak current between the source and drain which is not controlled by the gate voltage. Every port of the SDD model should be defined by means of equations.
For the SDD model, the port parameters are described as follows:

\[
\begin{align*}
I[1, 0] &= 1e^{-15} \cdot (\_V5) \cdot Cgd + 1e^{-15} \cdot (\_V6) \cdot Cgs \\
I[2, 0] &= 1e^{-15} \cdot (\_V7) \cdot Cds - 1e^{-15} \cdot (\_V5) \cdot Cgd \\
I[2, 2] &= \text{Ids} \\
H[2] &= \exp(-2 \cdot j \cdot \pi \cdot \text{freq} \cdot t \cdot 1e^{-12}) \\
I[3, 0] &= (\_V4 - \_V3)/\text{Ri} - 1e^{-15} \cdot (\_V7) \cdot Cds \\
I[3, 2] &= -\text{Ids} \\
F[4, 0] &= 1e^{-15} \cdot (\_V6) \cdot Cgs - (\_V4 - \_V3)/\text{Ri} \\
F[5, 1] &= \_V1 - \_V2 \\
F[5, 0] &= -\_V5 \\
F[6, 1] &= \_V1 - \_V4 \\
F[6, 0] &= -\_V6 \\
F[7, 1] &= \_V2 - \_V3 \\
F[7, 0] &= -\_V7 \\
\end{align*}
\]

The Ids expresses DC I-V characteristics which is shown with the change of the gate and drain voltages. We define a new formula combining the feature of GaN HEMTs as follows:

If \( Vgs > Vt \), then

\[
\text{Ids} = A \cdot B \cdot C \\
A = a1 \cdot \tanh(a2 \cdot (Vgs - Vt)^{a3}) \\
B = 1 + b \cdot \tanh(Vgs) \cdot Vds \\
C = \tanh(c1 \cdot \tanh(c2 \cdot (Vgs - Vt)) \cdot Vds)
\]

Else

\[
\text{Ids} = d \cdot Vds/\text{Rleak}
\]

Here, the \( Vt \) stands for the threshold voltage of the device. The \( a1 \sim a3, b, c1, c2 \) and \( d \) are fitting coefficients.

For the Ids nonlinear formula, the \( A, B \) and \( C \) sections are used to describe transconductance characteristics, self-heating effect and knee voltage feature of...
GaN HEMTs respectively. We have selected the 0.1 V Vds step interval and optimized the fitting parameters for many times both in the knee voltage region and saturation region. The fitting I-V curves are shown in Fig. 10.

![Fitting curves of DC I-V characteristics](image)

**Fig. 10.** Fitting curves of DC I-V characteristics

Meanwhile, the model can realize excellent S-parameter fitting effect, shown in Fig. 11. This result also proves that the small signal modeling method above is feasible during the parasitic and intrinsic parameter extraction.

![S-parameter fitting curves at Vgs = -3.8 V and Vds = 10 V](image)

**Fig. 11.** S-parameter fitting curves at Vgs = −3.8 V and Vds = 10 V

We can extract different intrinsic parameters by using this method at different Vgs. The change of Cgs and Cgd will generate great influence to the model so that we need to define the fitting expressions of them. Meanwhile, we can take the average values of the other intrinsic parameters because they have little impact at different Vgs. The C-V fitting expressions are shown as follows:

\[
C_{gs} = e_1 + e_2 \cdot \tanh(V_{gs} + (V_{gs} + e_3)^2)
\]

\[
C_{gd} = f_1 + f_2 \cdot \tanh(V_{gs} + (V_{gs} + f_3)^2)
\]
Here, the $e_1 \sim e_3$ and $f_1 \sim f_3$ are fitting coefficients.

The output characteristics of the GaN HEMT are obtained based on this large signal model through the harmonic balance simulation at 35 GHz which is in the atmosphere window. Meanwhile we have completed the large signal measurement by using the nonlinear vector network analyzer (PNA-X N5245A, Agilent) on wafer. The large signal S-parameters at 35 GHz are extracted from 0 dBm to 18 dBm Pin at $V_{gs} = -3.8$ V and $V_{ds} = 10$ V. Then we can obtain the Pout (output power) according to the matching condition of maximum power transfer though these S-parameters at each Pin. We have also tested the dynamic output current from the ammeter so that the PAE (Power Added Efficiency) can be calculated. The comparison results between the model and measurement are shown in Fig. 12.

![Fig. 12. Large signal characteristics at $V_{gs} = -3.8$ V and $V_{ds} = 10$ V](image)

It can be seen that the Pout, Gain and PAE measure curves are accord with the simulation ones based on the large signal model. The measurement shows that the Pout is 21.7 dBm and the Gain is compressed to 6.7 dB when the PAE reaches the peak value which is 36%. The relative errors of the Pout and PAE may be caused by some uncertain factors in the intrinsic region of the GaN HEMT or measure errors at large signal state. During the whole simulation, the model has exhibited excellent calculation convergence so that it can be applied to design circuits at millimeter-wave band.

5 Conclusions

We have completed fabrication of a $2 \times 50$ AlGaN/GaN HEMT with 0.1 µm gate-length and 2 µm source-drain distance in the paper. The $f_{max}$ of the HEMT can be extrapolated to 177 GHz through measuring the S-parameters from 0.1 GHz to 50 GHz. Based on the HEMT, we have proposed a new method to establish the equivalent circuit model including the small and large signal modeling. This method has well reflected nonlinear characteristics of the GaN HEMT. We have also obtained large signal output results by using the harmonic balance simulation.
On the basis of above research, the multi-finger GaN HEMTs will be designed and fabricated so that the high power gain and high output power millimeter-wave GaN MMICs can be realized through applying this modeling method in the future.

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