# A new small-signal model for asymmetrical AlGaN/GaN HEMTs

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**Abstract:** A new small-signal model for anisomerous AlGaN/GaN high electron mobility transistors (HEMTs) is proposed for accurate prediction of HEMT behavior up to 20 GHz. The parasitic elements are extracted from both cold-FET and pinch-off bias to obtain more precise results and the intrinsic part is directly extracted. All the parameters needed in this process are determined by the device structure rather than optimization methods. This guarantees consistency between the parameter values and the component's physical meaning.

**Key words:** small-signal model; GaN HEMT; parameter extraction; asymmetrical structure
**DOI:** 10.1088/1674-4926/31/6/064002 **EEACC:** 2570

## 1. Introduction

The great potential of GaN material in microwave high power applications has drawn unprecedented attention in industry. In many applications, such as GaN MMICs (monolithic microwave integrate circuits), LNAs (low noise amplifiers), and power amplifiers, a precise small-signal model will help us to understand the physical characteristics of devices, establish appropriate CAD models and provide feedback information for optimizing the fabrication process. A lot of small-signal models have been developed during the last 30 years[1−3]. However, few of them can be applied to the improved device structure which has a shorter gate-to-source distance (shown in Fig. 1). This structure can further increase the breakdown voltage of GaN devices and potentially raise the output power. The device sample used in this paper is fabricated on SiC substrate using MOCVD with a gate width of 100 $\mu$m.

The extraction method is another factor which can affect the precision of the small-signal model. The existing small-signal model extraction methods can be classified into three categories: whole optimization[4] (all parameters are determined by the optimization method), partial (extrinsic or intrinsic parameters) optimization[3], direct extraction[5]. Direct extraction methods have an apparent advantage over optimization-based methods when the parameter values are intended to be used in establishing a large-signal model. This is because the optimization strategies would make the parameter values unpredictable and may not reconcile the optimized values with their physical meaning.

In this paper, a new model is proposed to simulate the small-signal behavior of both symmetrical and asymmetrical structure GaN devices, and a new direct parameter extraction approach is developed to guarantee consistency between parameter values and their physical meanings. The new model and extraction method has four main merits:

(1) Using no optimization strategy, the extraction process will run faster, and the physical meanings of model components are guaranteed.

(2) It is compatible with different device structures.

(3) Most coefficients needed in the extraction are determined by the device structure which will ensure that the model reflects the true behavior of the device.

(4) The extraction method is performed on all measured frequency points rather than several selected points, and relatively (compared to Ref. [6]) good results are obtained.

## 2. The new model

The new 19 element small-signal model (shown in Fig. 2) takes the high frequency effect into consideration. $C_{\rm pg}$ and $C_{\rm pd}$ account for pad capacitance which cannot be ignored at high frequency and $C_{\rm gsi}$, $C_{\rm gdi}$ and $C_{\rm dsi}$ represent the inter-electrode and crossover capacitances.

## 3. Parameter extraction method

Two specific bias points are used to extract the extrinsic parameter value. The extraction process is implemented in 3 steps.

Step 1: In the cold pinch-off condition ($V_{\rm GS} < -V_{\rm p}$ and $V_{\rm DS}$ = 0 V), the equivalent voltage controlled current source in the intrinsic part is disabled. In the low frequency region, the whole circuit can be reduced to a capacitance network as shown in Fig. 3. The following equations imply the relationship between the imaginary part of the $Y$ parameter and extrinsic capacitances.

$$\mathrm{Im}(Y_{11}) = \mathrm{j}w(C_{\rm pg} + C_{\rm gsi} + C_{\rm gs0} + C_{\rm gd0} + C_{\rm gdi}),$$

$$\mathrm{Im}(Y_{12}) = \mathrm{j}w(C_{\rm gd0} + C_{\rm gdi}),$$

$$\mathrm{Im}(Y_{22}) = \mathrm{j}w(C_{\rm pd} + C_{\rm dsi} + C_{\rm ds0} + C_{\rm gd0} + C_{\rm gdi}).$$

Figure 4 shows the $Y$ parameter curves versus frequency at low frequency. It is clear that the $Y$ parameters have good linearity even at 5 GHz. So the capacities can be safely extracted from the low-frequency $Y$ parameters.

$C_{\rm gs0}$, $C_{\rm gd0}$ and $C_{\rm ds0}$ substitute the intrinsic part at the cold pinch-off condition. According to Ref. [8], we assume:

$$C_{\rm ds0} = 12C_{\rm pd}.$$

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Received 1 December 2009, revised manuscript received 6 February 2010

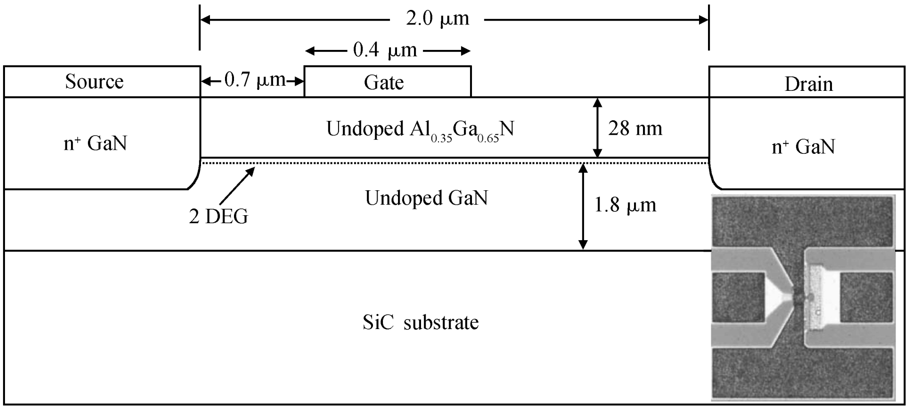


Fig. 1. Improved gate-close-to-source structure for a GaN HEMT.

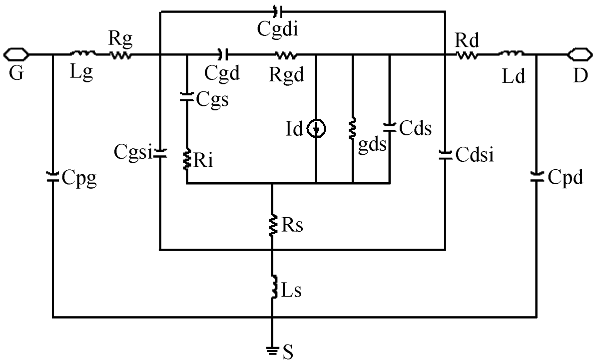


Fig. 2. New equivalent circuit for an anisomerous HEMT.

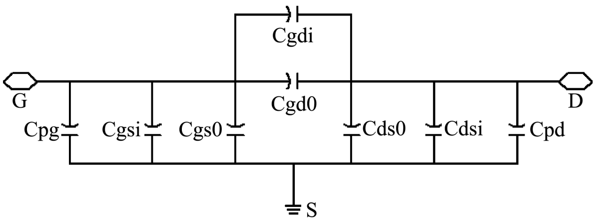


Fig. 3. Equivalent circuit of pinch-off device in the low frequency region.

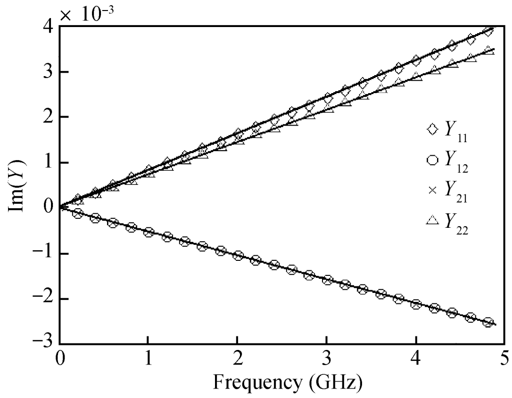


Fig. 4. Imaginary part of $Y$ parameters at low frequency.

The gate electrode is closer to the source than to the drain in our device structure. According to the ratio of the distance between gate and drain (0.9 $\mu$m) to that between gate and source (0.7 $\mu$m) as shown in Fig. 1, the relationship can be expressed as:

$$C_{\rm gs0} = 1.3C_{\rm gd0}.$$

When the device under test is symmetrical, these two capacitances are equal.

Because the size and shape of the drain pad is almost similar to that of the gate pad, it is reasonable to take their capacitances as being equal:

$$C_{\rm pg} = C_{\rm pd}.$$

According to the device structure, $C_{\rm dsi}$ is expected to be much bigger than $C_{\rm pd}$, and according to Ref. [3], the relationship between $C_{\rm dsi}$ and $C_{\rm pd}$ is :

$$C_{\rm dsi} = 3C_{\rm pd}.$$

$C_{\rm gdi}$ is essential in this structure. When the capacitance between gate and drain is big enough, $C_{\rm gd0}$ may be bigger than $C_{\rm gs0}$ which contradicts the physical expectation. So $C_{\rm gdi}$ is needed to reduce the $C_{\rm gd0}$. Here we make the following assumption:

$$C_{\rm gd0} = 0.7C_{\rm gdi}.$$

Step 2: The parasitic resistances and inductances can be extracted from the cold-FET $S$ parameter. After de-embedding $C_{\rm pg}$ and $C_{\rm pd}$ from the $Y$ parameter, the equivalent circuit is reduced to the structure in Fig. 5 in the high frequency region. In our model, $C_{\rm gsi}$, $C_{\rm gdi}$ and $C_{\rm dsi}$ are on the inside of parasitic resistance. Because no approximation is needed, the precision of the model is promoted.

Transforming $Y$ parameters to $Z$ parameters, we can extract $R_{\rm g}$, $R_{\rm d}$ and $R_{\rm s}$ from the real part of the $Z$ parameter and obtain the values of $L_{\rm g}$, $L_{\rm d}$ and $L_{\rm s}$ from the imaginary part of the $Z$ parameter.

$$Z_{11} = R_{\rm s} + R_{\rm g} + \frac{1}{1+c}R_{\rm ch} + {\rm j}w(L_{\rm s}+L_{\rm g}) + \frac{1}{{\rm j}wC_{\rm g}} + \frac{1}{{\rm j}wC_{\rm s}},$$

$$Z_{12} = R_{\rm s} + \frac{1}{1+c}R_{\rm ch} + {\rm j}wL_{\rm s} + \frac{1}{{\rm j}wC_{\rm s}},$$

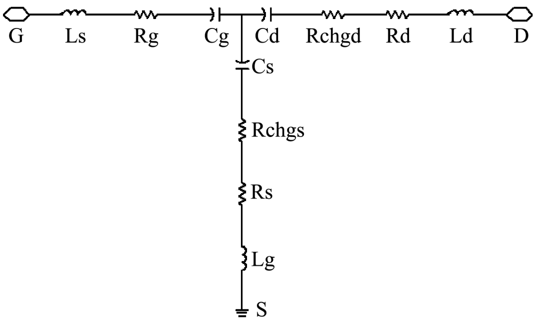


Fig. 5. Cold-FET equivalent circuit at high frequency.

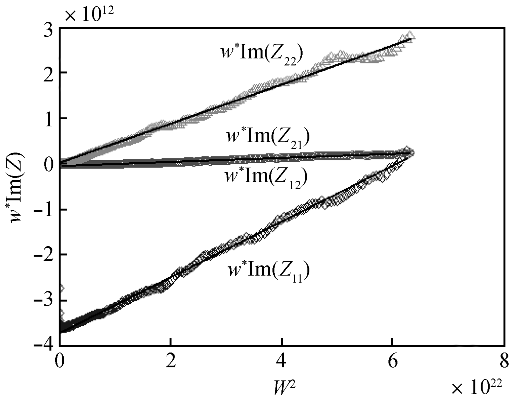


Fig. 6. Curve of $\mathrm{Im}(wZ_{ij})$ versus $\omega^2$.

$$Z_{22} = R_s + R_d + R_{ch} + jw(L_s + L_d) + \frac{1}{jwC_d} + \frac{1}{jwC_s}.$$

The parameter $c$ determines the ratio of channel resistance between gate and drain to that between gate and source. The following equations also express their relationship:

$$R_{chgd} = cR_{chgs},$$

$$R_{chgd} + R_{chgs} = R_{ch},$$

$$R_{chgd} = R_{ch}/(1+c).$$

According to the device structure, we set $c = 2$. As for symmetrical devices, $c = 1$.

However, there are not enough equations to solve all parasitic resistance by using only cold-FET data. So the pinch-off $Z$ parameter is used to form another equation to determine the value of $R_{ch}$:

$$\mathrm{Re}(Z_{22\text{pinch-off}}) = R_s + R_d.$$

Then,

$$R_{ch} = \mathrm{Re}(Z_{22}) - \mathrm{Re}(Z_{22\text{pinch-off}}).$$

The values of other resistances are also obtained from the equations above.

By multiplying $\omega$ by the imaginary part, we can extract the values of $L_g$, $L_d$ and $L_s$from the slope of the $\mathrm{Im}(wZ_{ij})$ versus $\omega^2$ curve (shown in Fig. 6):

$$\mathrm{Im}(\omega Z_{11}) = \omega^2(L_s + L_g) - 1/C_g - 1/C_s,$$

$$\mathrm{Im}(\omega Z_{12}) = \omega^2 L_s - 1/C_s,$$

$$\mathrm{Im}(\omega Z_{22}) = \omega^2(L_s + L_d) - 1/C_d - 1/C_s.$$

Step 3: After de-embedding all parasitic components, the intrinsic $Y$ parameters are obtained[1]:

$$Y_{11\text{int}} = \frac{\omega^2 C_{gs}^2 R_{gs}}{D_{gs}} + \frac{\omega^2 C_{gd}^2 R_{gd}}{D_{gd}} + j\omega\left(\frac{C_{gs}}{D_{gs}} + \frac{C_{gd}}{D_{gd}}\right),$$

$$Y_{12\text{int}} = -\frac{\omega^2 C_{gd}^2 R_{gd}}{D_{gd}} - j\omega\frac{C_{gd}}{D_{gd}},$$

$$Y_{21\text{int}} = g_{me}^{-j\omega\tau} - \frac{\omega^2 C_{gd}^2 R_{gd}}{D_{gd}} - j\omega\frac{C_{gd}}{D_{gd}}$$

$$Y_{22\text{int}} = g_{ds} + j\omega C_{ds} + \frac{\omega^2 C_{gd}^2 R_{gd}}{D_{gd}} + j\omega\frac{C_{gd}}{D_{gd}}.$$

$D_{gd}$ and $D_{gs}$ are defined as:

$$D_{gs} = 1 + \omega^2 C_{gs}^2 R_{gs}^2,$$

$$D_{gd} = 1 + \omega^2 C_{gd}^2 R_{gd}^2.$$

So, the value of the intrinsic components can be derived from the equations above:

$$g_{ds} = \mathrm{Re}(Y_{22\text{int}} + Y_{12\text{int}}),$$

$$C_{ds} = \frac{\mathrm{Im}(Y_{22\text{int}} + Y_{12\text{int}})}{\omega},$$

$$C_{gd} = -(1+a^2)\frac{\mathrm{Im}(Y_{12\text{int}})}{\omega},$$

$$R_{gd} = -\frac{a}{(1+a^2)\mathrm{Im}(Y_{12\text{int}})},$$

$$C_{gs} = (1+b^2)\frac{\mathrm{Im}(Y_{11\text{int}} + Y_{12\text{int}})}{\omega},$$

$$R_{gs} = \frac{b}{1+b^2}\mathrm{Im}(Y_{11\text{int}} + Y_{12\text{int}}),$$

$$g_m = |Y_{21\text{int}} - Y_{12\text{int}}|,$$

$$\tau = -\arctan\left(\frac{\mathrm{Im}(Y_{21\text{int}} - Y_{12\text{int}})}{\mathrm{Re}(Y_{21\text{int}} - Y_{12\text{int}})}\right)/\omega.$$

Figure 7 illustrates different curves of extracted element values versus frequency. Because the element values are almost the same from 1 to 20 GHz, the extraction precision is assured.

## 4. Results and discussion

Complete component values of our small-signal model at a bias of $V_{gs} = -4$ V, $V_{ds} = 10$ V, are shown in Table 1.

Figure 8 shows a comparison between the measured $S$ parameter and the $S$ parameter from the proposed new model. High consistency is achieved by using our small-signal model and parameter extraction method. This demonstrates that our model is suitable for asymmetrical GaN HEMT simulation.

In order to better evaluate the exactitude of the model, we introduce the following error function[9]:

$$\varepsilon_S = \frac{1}{N}\sum_{n=1}^{N}\|\varepsilon(n)\|_1.$$

Table 1. Extracted component values of the new 19 element small-signal model.

| Extrinsic parameter | | Intrinsic parameter | |
|---|---|---|---|
| $C_{pg} = 1.5029$ fF | $R_d = 21.185\ \Omega$ | $C_{gs} = 182.08$ fF | $g_m = 42.059$ mS |
| $C_{pd} = 1.5029$ fF | $R_s = 5.5623\ \Omega$ | $C_{gd} = 42.863$ fF | $g_{ds} = 2.2113$ mS |
| $C_{gsi} = 0.665$ fF | $L_g = 59.279$ nH | $C_{ds} = 37.014$ fF | |
| $C_{dsi} = 4.7341$ fF | $L_d = 37.11$ nH | $R_{gd} = 95.163\ \Omega$ | |
| $C_{gdi} = 29.96$ fF | $L_s = 3.0154$ nH | $R_i = 5.5607\ \Omega$ | |
| $R_g = 4.1095\ \Omega$ | | $t = 1.958$ ns | |

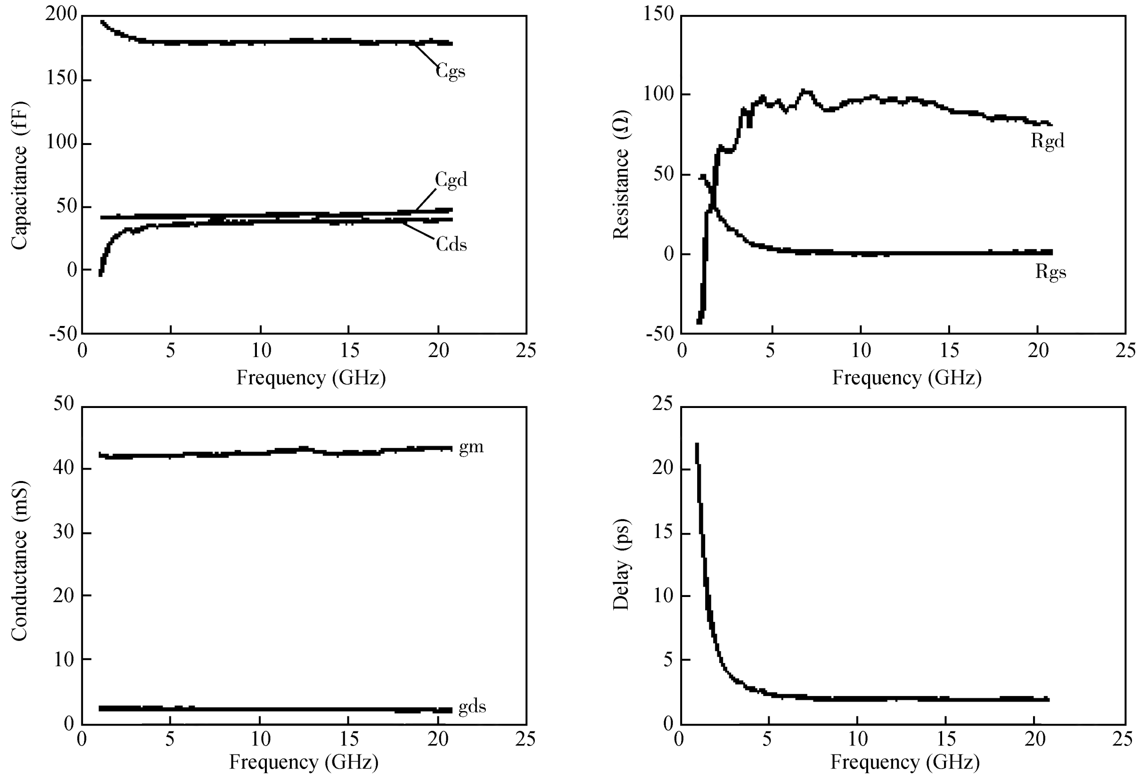


Fig. 7. Intrinsic component values versus frequency ($V_{gs}$ = –4 V, $V_{ds}$ = 10 V).

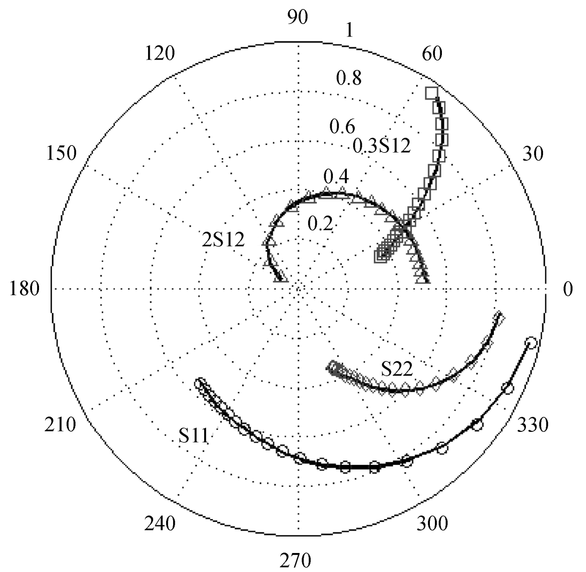


Fig. 8. Simulated and measured small-signal $S$ parameter when biased at $V_{gs}$ = –4 V, $V_{ds}$ = 10 V.

$\varepsilon(n)$ is the error function matrix of every frequency point. It is defined as:

$$\varepsilon(n) = \begin{bmatrix} \varepsilon_{11}(n) & \varepsilon_{12}(n) \\ \varepsilon_{21}(n) & \varepsilon_{22}(n) \end{bmatrix},$$

where

$$\varepsilon_{ij}(n) = \frac{\left|\mathrm{Re}(\delta S_{ij}(n))\right| + \left|\mathrm{Im}(\delta S_{ij}(n))\right|}{W_{ij}}, \quad i, j = 1, 2$$

$W$ is the weighting factor which can deemphasize the uncertainty brought by measurement[3].

$$W_{ij} = \max\left(\left|S_{ij}\right|\right), \quad i, j = 1, 2,$$

$$W_{ii} = 1 + |S_{ii}|, \quad i = 1, 2.$$

The calculated errors under different bias points are shown in Table 2.

## 5. Conclusion

A new small-signal model is proposed for not only symmetrical-structure but also asymmetrical-structure AlGaN/GaN HEMTs and a new extraction method is described

Table 2. Errors at different bias points.

| $V_{GS}$ (V) | $V_{DS}$ (V) | $\varepsilon_S$ (%) |
|---|---|---|
| 0 | 10 | 3.79 |
| −1 | 10 | 6.41 |
| −2 | 10 | 6.05 |
| −3 | 10 | 3.55 |
| −4 | 10 | 3.26 |
| −5 | 10 | 5.02 |
| −4 | 3 | 5.22 |
| −4 | 5 | 3.81 |
| −4 | 8 | 4.05 |

to determine the parameters' values. In this new method, all components can be directly extracted from different biased $S$ parameters. No optimizing algorithm is needed which ensures that the extracted values have a reliable physical meaning, as proposed. The results show good consistency between measured $S$ parameters and simulated $S$ parameters up to 20 GHz in various bias points.

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