Small-signal model parameter extraction for AlGaN/GaN HEMT

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Abstract: A new 22-element small signal equivalent circuit model for the AlGaN/GaN high electron mobility transistor (HEMT) is presented. Compared with the traditional equivalent circuit model, the gate forward and breakdown conductions (G_{gsf} and G_{gdf}) are introduced into the new model to characterize the gate leakage current. Additionally, for the new gate-connected field plate and the source-connected field plate of the device, an improved method for extracting the parasitic capacitances is proposed, which can be applied to the small-signal extraction for an asymmetric device. To verify the model, S-parameters are obtained from the modeling and measurements. The good agreement between the measured and the simulated results indicate that this model is accurate, stable and comparatively clear in physical significance.

Key words: AlGaN/GaN HEMT; small-signal; parameter extraction; modeling
DOI: 10.1088/1674-4926/37/3/034003 **PACS:** 85.30.Tv **EEACC:** 2520D; 2560S; 2570A

1. Introduction

The AlGaN/GaN high electron mobility transistor (HEMT) is a promising device for high power and high frequency applications in next generation information communication systems[1,2]. Today, GaN HEMT is becoming the most important device for the design of power amplifiers and GaN MMICs (monolithic microwave integrated circuits), which requires a reliable and accurate large-signal model (LSM). Nevertheless, the small-signal extraction for AlGaN/GaN HEMT under the condition of a certain bias is a key step in bottom-up large-signal AlGaN/GaN HEMT modeling. Therefore, to establish a precise and stable AlGaN/GaN HEMT small-signal model is of great importance in optimizing the fabrication process, analyzing the device characteristics and designing the MMIC power amplifier[3].

During the last decade, a large number of papers have presented different approaches for extracting the small-signal model (SSM) parameters of AlGaN/GaN HEMT. In Reference [4], an improved small-signal equivalent circuit model was proposed by considering the co-planar waveguide effect capacitances. In Reference [5], a method for extracting parasitic resistances and parasitic inductances was introduced by biasing the device with low DC forward gate current and by floating the drain. In Reference [6], a parasitic parameters extraction procedure was introduced, which uses only pinch-off S-parameters measurement for accurate extraction of the parasitic elements.

In this paper, an accurate small-signal modeling approach for the AlGaN/GaN HEMT will be presented. The principle of this method is first to generate reliable initial values for the model elements and then to tune these initial values by using an optimization algorithm[7]. The main advantage of this method is that it has a higher degree of reliability.

2. Device structure and fabrication

The structure of the investigated on-wafer AlGaN/GaN HEMT used in the model development is schematically shown in the cross section in Figure 1. The epitaxial layers were grown by MOCVD on a 3-inch semi-insulating SiC substrate. The source and drain ohmic contacts, with a source–drain spacing L_{sd} of 4 μm, were formed by using a Ti/Al/Ni/Au (= 200/1500/550/450 Å) metal stack, followed by rapid thermal annealing (RTA) at 870 ℃ for 50 s in N_2 ambient. The T-gate technology was e-beam defined with a gate length of 0.15 μm. A Ni/Au (400/5000 Å) metallization process was used to form gate Schottky contacts. The source-to-gate distance and gate-to-drain distance were 1.1 μm and 2.75 μm, respectively. As for the surface passivation layer, SiN film was deposited using PECVD. Via-holes were formed using plasma dry etching to

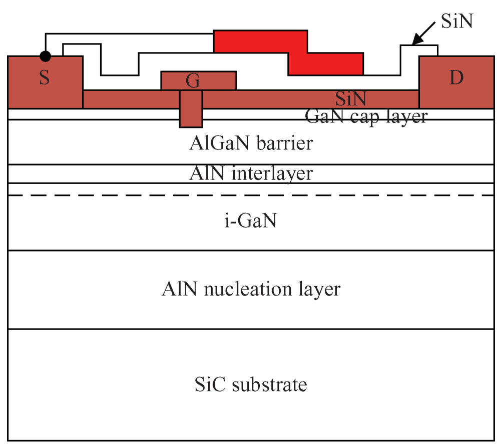

Figure 1. Schematic cross-section of the developed AlGaN/GaN HEMT.

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Received 2 July 2015, revised manuscript received 16 September 2015

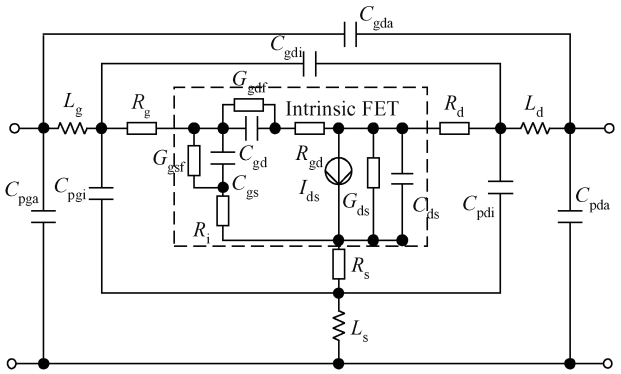

Figure 2. 22-element small signal model of AlGaN/GaN HEMT.

reduce source inductance. The backside of the die was thinned to 90 μm by mechanical polishing to reduce thermal resistance. Then a standard Au-plated air bridge process was used to complete the fabrication of the multifinger components.

3. Extraction procedure

Figure 2 shows the adopted 22-element small-signal equivalent circuit model for an AlGaN/GaN HEMT[8]. The equivalent circuit contains both intrinsic and extrinsic elements. The part outside the dashed box is the extrinsic part, in which the parameters are independent of bias conditions, including L_g, L_d, L_s, R_g, R_d, R_s, C_{pga}, C_{pda}, C_{gda}, C_{pgi}, C_{pdi}, and C_{gdi}. The intrinsic part in the dashed box includes C_{gd}, C_{gs}, C_{ds}, g_m, τ, R_i, G_{ds}, G_{gsf}, G_{gdf}, and R_{gd}, in which the parameters are dependent on bias conditions. All small-signal model parameters of AlGaN/GaN HEMTs are verified to be independent of frequency.

In this model, L_g, L_d, and L_s represent the electrode inductances. C_{pga}, C_{pda}, and C_{gda} account for parasitic pad capacitances due to the pad connections and inter-electrode of the gate and drain, respectively; while C_{pgi}, C_{pdi}, and C_{gdi} represent the inter-electrode capacitances. R_g, R_d, and R_s represent parasitic resistances of the gate, drain and source, respectively. C_{gs}, C_{ds}, and C_{gd} represent the intrinsic capacitances between gate–source, drain–source and gate–drain, respectively. The gate forward and breakdown conductions are represented by G_{gsf} and G_{gdf}, respectively. G_m and G_{ds} are the intrinsic and output transconductance, respectively. R_i represent the intrinsic channel resistance, while R_{gd} is the charging resistance. The transit time which the electrons take for the depletion region to respond to the gate signal is described by τ.

A complete extraction procedure of small-signal equivalent circuit elements of AlGaN/GaN HEMT is presented in this paper. During the extraction process, the parasitic parameters are extracted in the first place. Then a de-embedding process was performed to the measured S-parameters in order to determine the intrinsic parameters. Thus, the accuracy of the extracted parasitic parameters will directly affect the extraction of the intrinsic parameters. Namely, the extrinsic extraction is of particular importance.

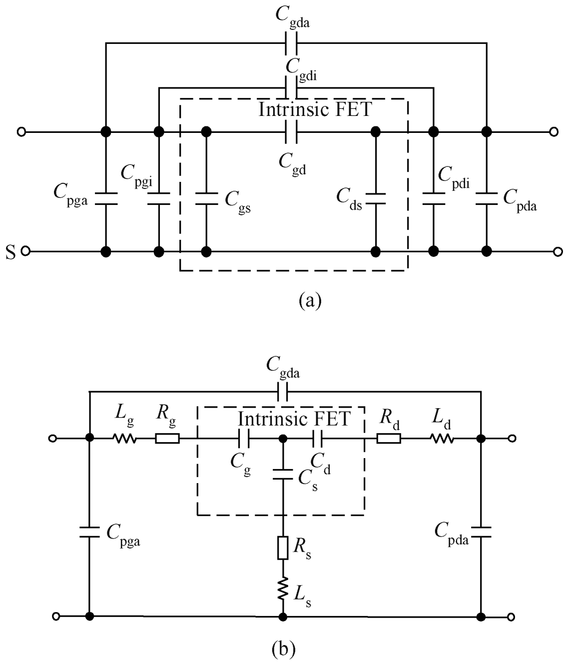

Figure 3. (a) Cold pinch-off equivalent circuit for the AlGaN/GaN HEMT at low frequency. (b) Cold pinch-off equivalent circuit at high frequency.

3.1. Extrinsic parameter extraction

Parasitic pad capacitances of GaN HEMT are generally extracted from the conventional cold-FET method. When $V_{ds} = 0$ and $V_{gs} < -V_p$ (pinch-off voltage), the channel conductivity is negligible and the now passive device exhibits a purely capacitive behavior under low frequency[9]. For our self-developed AlGaN/GaN HEMT, under the pinch-off bias of $V_{gs} = -6.0$ V, the device can be described by the capacitive network shown in Figure 3(a). For frequency up to a few gigahertz (below 5 GHz), the resistances and inductances have no influence on the imaginary part of the Y-parameters, which can be written as

$$\mathrm{Im}(Y_{11}) = \omega(C_{gso} + C_{gdo}), \tag{1}$$

$$\mathrm{Im}(Y_{22}) = \omega(C_{dso} + C_{gdo}), \tag{2}$$

$$\mathrm{Im}(Y_{12}) = \mathrm{Im}(Y_{21}) = -\omega C_{gdo}, \tag{3}$$

where

$$C_{gdo} = C_{gd} + C_{gdi} + C_{gda}, \tag{4}$$

$$C_{gso} = C_{gs} + C_{pgi} + C_{pga}, \tag{5}$$

$$C_{dso} = C_{ds} + C_{pdi} + C_{pda}. \tag{6}$$

Therefore, the total gate–source, gate–drain and drain–source capacitances can be calculated from the slope of the curves for the imaginary part of the Y-parameters as shown in Figure 4. Then the proposed algorithm for generating the starting values depends on searching for the optimal distribution of the total capacitances[6]. During the searching process, some assumptions are made to simplify the algorithm. According to our device structure, the distance between the gate and the drain is not equal to that between the gate and the source, so the intrinsic capacitances C_{gs} and C_{gd} are unequal:

$$C_{gs} \neq C_{gd}.$$

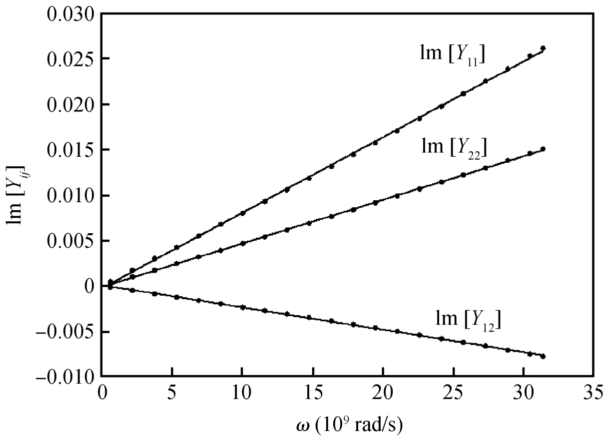

Figure 4. Imaginary parts of measured Y-parameters of an 8×100 μm AlGaN/GaN HEMT under cold pinch-off bias condition.

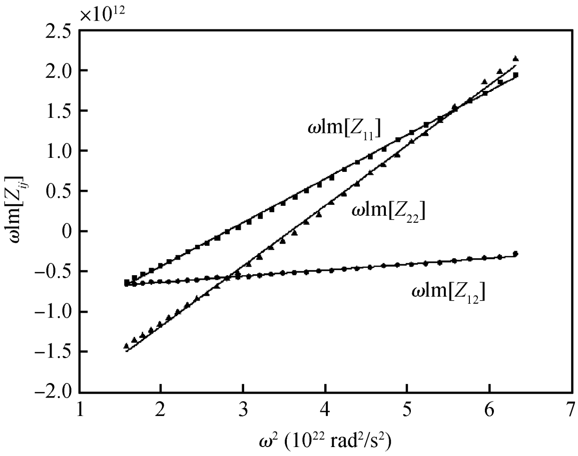

Figure 5. Parasitic inductances estimation from pinch-off Z-parameters of an 8 × 100 μm AlGaN/GaN HEMT on SiC substrate.

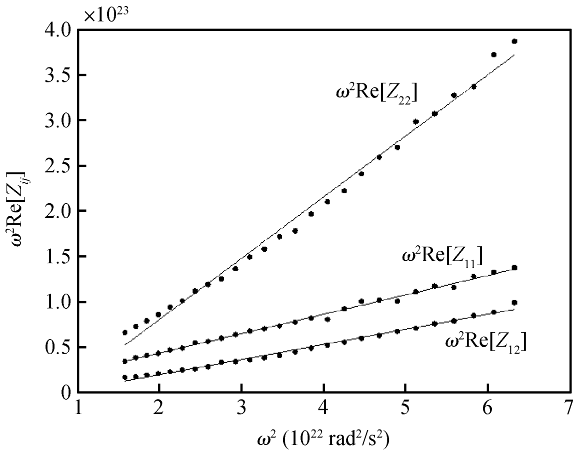

Figure 6. Parasitic resistances estimation from cold forward Z-parameters of an 8 × 100 μm AlGaN/GaN HEMT on SiC substrate.

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

Because the size and shape of the gate pad is similar to that of the drain pad, C_{pga} is assumed to be equal to C_{pda}:

$$C_{\mathrm{pga}} = C_{\mathrm{pda}}.$$

Moreover, we found that it can obtain satisfactory results by assuming the drain–source inter-electrode capacitance C_{pdi} to be twice the parasitic pad capacitance C_{pda}:

$$C_{\mathrm{pdi}} = 2C_{\mathrm{pda}}.$$

After de-embedding parasitic pad capacitances, the parasitic inductances and resistances can be extracted under cold pinch-off conditions. At high frequencies, the influence of the parasitic resistances and inductances cannot be neglected, thus the device can be described by the equivalent circuit of Figure 3(b). The S-parameter measured under the cold pinch-off conditions is converted to a Y-parameter, after de-embedding the values of C_{pga}, C_{pda}, and C_{gda} from the Y-parameter, and then converting the stripped Y-parameter to a Z-parameter. Multiplying the Z-parameters by ω and then taking the imaginary parts of ωZ_{ij} gives

$$\mathrm{Im}(\omega Z_{11}) = (L_{\mathrm{s}} + L_{\mathrm{g}})\omega^2 - \left(\frac{1}{C_{\mathrm{s}}} + \frac{1}{C_{\mathrm{g}}}\right), \quad (7)$$

$$\mathrm{Im}(\omega Z_{22}) = (L_{\mathrm{s}} + L_{\mathrm{d}})\omega^2 - \left(\frac{1}{C_{\mathrm{s}}} + \frac{1}{C_{\mathrm{d}}}\right), \quad (8)$$

$$\mathrm{Im}(\omega Z_{12}) = L_{\mathrm{s}}\omega^2 - \frac{1}{C_{\mathrm{s}}}. \quad (9)$$

Thus, the values of L_{s}, L_{d}, and L_{g} can be obtained from the slope of the imaginary parts of ωZ_{ij} versus the ω^2 curve as given in Figure 5.

The extraction of the extrinsic resistances is described as follows. Multiplying the de-embedded Z-parameters by ω^2 and taking the real part of this Z-parameter gives

$$\omega^2\mathrm{Re}\,[Z_{11}] = \omega^2(R_{\mathrm{s}} + R_{\mathrm{g}}), \quad (10)$$

$$\omega^2\mathrm{Re}\,[Z_{22}] = \omega^2(R_{\mathrm{s}} + R_{\mathrm{d}}), \quad (11)$$

$$\omega^2\mathrm{Re}\,[Z_{12}] = \omega^2 R_{\mathrm{s}}. \quad (12)$$

Hence, the values of $R_{\mathrm{s}} + R_{\mathrm{g}}$, $R_{\mathrm{s}} + R_{\mathrm{d}}$, and R_{s} can be obtained from the slope of $\omega^2\mathrm{Re}[Z_{ij}]$ versus ω^2 curves.

However, it finds that the extraction of the reliable extrinsic resistances is very difficult due to the unavoidable high measurement uncertainty for a cold pinch-off device[10]. So in this paper, we use cold gate-forward S-parameter measurements at a high gate voltage ($V_{\mathrm{gs}} = 2.5$ V), in order to achieve more reliable extrinsic resistances, as shown in Figure 6.

3.2. Intrinsic parameter extraction

After obtained all of the parasitic parameters, the S-parameters are measured under the normal working bias conditions ($V_{\mathrm{gs}} > V_{\mathrm{p}}$, $V_{\mathrm{ds}} > 0$). Then the bias-dependent intrinsic parameters can be extracted from the intrinsic Y-parameters after de-embedding the extracted extrinsic parasitic parameters from the measured S-parameters as Equation (13) shows. For the intrinsic parameter extraction, we used the proposed procedure given by Jarndal *et al.*[8]. The gate forward and breakdown conductions (G_{gsf} and G_{gdf}) are first estimated from Y_{11} and Y_{12} at low frequencies, since the capacitance terms tend to vanish at such low frequencies. Then separate the real part

Table 1. Optimized values for the model elements of an 8 × 100 μm AlGaN/GaN HEMT.

Extrinsic parameters		Intrinsic parameters	
R_g = 0.474 Ω	C_{pga} = 12.124 fF	C_{gs} = 1.450 pF	R_{gd} = 80.092 Ω
R_d = 5.074 Ω	C_{pda} = 11.558 fF	C_{gd} = 0.079 pF	R_{ds} = 184.201 Ω
R_s = 1.671 Ω	C_{gda} = 10.983 fF	C_{ds} = 0.255 pF	G_{gsf} = 0.156 mS
L_g = 0.052 pH	C_{pgi} = 346.019 fF	G_m = 294.5 mS	G_{gdf} = 0.00972 mS
L_d = 0.067 pH	C_{pdi} = 26.086 fF	τ = 0.945 ps	
L_s = 0.007 pH	C_{gdi} = 104.000 fF	R_i = 0.760 Ω	

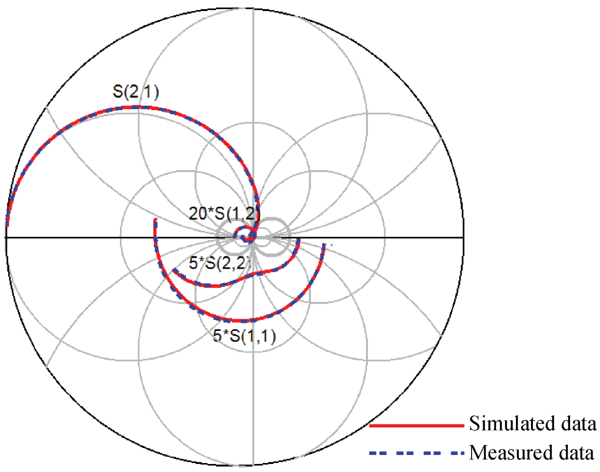

Figure 7. (Color online) Comparison of (short dash) measured and (solid lines) simulated S-parameters for an 8 × 100 μm AlGaN/GaN HEMT (V_{gs} = –2.5 V and V_{ds} = 30 V).

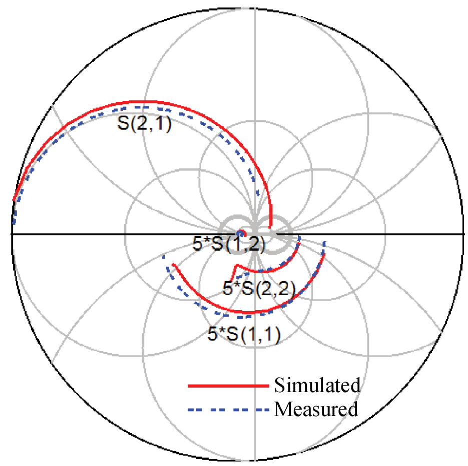

Figure 8. (Color online) Comparison of (short dash) measured and (solid lines) simulated S-parameters without G_{gsf} and G_{gdf} considered. Freq: 0.1 to 10.5 GHz.

and imaginary part in Equation (13) to determine the rest of the eight intrinsic parameters[11].

$$Y_{int} = \begin{bmatrix} \dfrac{1}{R_i + \dfrac{1}{G_{gsf} + j\omega C_{gs}}} + \dfrac{1}{R_{gd} + \dfrac{1}{G_{gdf} + j\omega C_{gd}}} & -\dfrac{1}{R_{gd} + \dfrac{1}{G_{gdf} + j\omega C_{gd}}} \\ \dfrac{g_m e^{-j\omega\tau_m}}{R_i G_{gsf} + j\omega C_{gs} R_i + 1} - \dfrac{1}{R_{gd} + \dfrac{1}{G_{gdf} + j\omega C_{gd}}} & G_{ds} + \dfrac{1}{R_{gd} + \dfrac{1}{G_{gdf} + j\omega C_{gd}}} + j\omega C_{ds} \end{bmatrix}. \quad (13)$$

4. Analysis and results

To verify the reliability of the extraction procedure, an 8 × 100 μm AlGaN/GaN HEMT device is investigated. The S-parameters were measured in the range 100 MHz–40 GHz. The whole extraction procedure is implemented as a Matlab program. Then the extracted initial values will be optimized by using an optimization algorithm. Model parameter optimization has been done by using the same previously implemented method for distributed small-signal model[7]. In general, the allowable range is within 10% of the initial value. The optimized values for the model elements of an 8 × 100 μm AlGaN/GaN HEMT are listed in Table 1.

Figure 7 shows the comparisons between the measured and the simulated S-parameter at the bias point V_{gs} = –2.5 V and V_{ds} = 30 V. As it can be seen, there is excellent agreement between the measured and simulated S-parameters. This accordingly validates the accuracy of the proposed model and the extraction method.

In order to demonstrate the importance of the two parameters G_{gsf} and G_{gdf} to AlGaN/GaN HEMT, a comparison is performed between the measured and simulated S-parameters based on the conventional circuit model without G_{gsf} and G_{gdf}. As is shown in Figure 8, the measured and modeled S-parameters do not fit well even in low frequencies. Neglecting the G_{gsf} and G_{gdf} may impart a profound effect onto R_{gd} and R_i at lower frequencies[11]. Therefore, in our point of view, G_{gdf} and G_{gsf} cannot be neglected for AlGaN/GaN HEMT because they are used in characterizing the current conduction of the gate diode applicable for not only large-signal analysis but also small-signal extraction.

5. Conclusion

In this study, a 22-element small-signal equivalent circuit model for AlGaN/GaN HEMT is proposed. Meanwhile, a highly accurate and robust small-signal model parameter extraction algorithm is also presented for an 8 × 100 μm Al-

GaN/GaN HEMT device. We find that the gate forward and breakdown conductions (G_{gsf} and G_{gdf}) must be included in the intrinsic part of the circuit to take into account the current conduction through the gate diode. The validity of all extracted elements is verified by the excellent agreement between the measured and modeled S-parameters up to 40 GHz.

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