ANALYSIS OF ALGAN/GAN BASED HEMT DEVICE FOR MMIC DESIGN

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Abstract: In this paper AlGaN/GaN heterostructure device analysis carried out which are capable for high power and frequency with performances far superior to those offered by the mainstream silicon technology and other advanced semiconductor technologies. AlGaN/GaN HEMT primarily driven by microwave wireless communication applications need. The last few years have witnessed major effort in the development of AlGaN/GaN HEMTs. This paper analysis the latest progresses in this technology, including alternative approaches and HEMT device characteristics. AlGaN/GaN HEMTs promise for high power, temperature and frequency than their AlGaAs/GaAs. To accomplish this goal, we present a comparative analysis of different modeling techniques and show that the differences reflect the physical and technology differences of the tested microwave transistors. Many successful techniques have been described, those are developed in the last decades for extracting the small signal equivalent circuit for GaAs & GaN HEMT from scattering parameter measurements, small signal modeling is still object of intense research.

Keywords: HEMT, MMIC, Thermal Analysis, AlGaN/GaN, High Power Devices.

1. INTRODUCTION

Advances in integrated circuits technology are the key to opening and fully exploiting new consumer electronics market opportunities. This is exemplified recently by the massive expansion of the mobile communications which is fundamentally underpinned by advances in semiconductor manufacturing technologies. FET (Field Effect Transistor) at microwave frequency using the III-V compound Gallium Arsenide (GaAs) has been most exciting device to emerge from solid state microwave community over past three decades [1]. FET with new materials (GaN, InP, SiC) has now become an established item in microwave systems of today for high power, temperature and frequency applications. A Monolithic Microwave Integrated Circuit (MMIC) is a microwave circuit in which the active and passive components are fabricated on the same semiconductor substrate. The frequency of operation can range from 1 GHz to 1 THz, and a number of different device technologies and circuit approaches can be used.

With increasing demand of high power level and operating frequency of RF and microwave circuits in modern wireless systems, today’s high frequency power devices mostly based on Gallium Arsenide (GaAs) will soon come to their power limits. To still satisfy the requirements of future wireless systems, numbers of research activities in the field of wide-bandgap semiconductor materials are initiated. The different microwave materials of interest are Indium phosphide (InP), Silicon carbide (SiC) and Gallium Nitride (GaN) of this category with a great potential for high power, temperature and frequency applications. Due to high power densities of GaN and SiC (about 10 times as high as GaAs’s), these semiconductor materials are outstanding for power devices [2].

At a comparable power level and the frequency range of mobile communication applications, the material cost of SiC is much higher than GaN’s. GaN based transistors are capable of operating in wide frequency and power ranges. Their outstanding electrical and thermal properties have been demonstrated and reported in the literature [3]. Beside a high power density, the thermal conductivity of GaN is much higher than GaAs’s, so that operations at higher temperature and power levels are possible with less cooling requirements. High power MMICs with GaN based High Electron Mobility Transistors (HEMT) can be processed on low cost substrate materials e.g. Al₂O₃ or Silicon. Another substrate material for GaN based transistors is SiC which should be used only for
extremely high temperature and high power applications due to its high cost. Thus, although GaAs based transistors are currently the dominating devices for high frequency applications, it is expected that they will be soon replaced by GaN based HEMTs which will establish to be the key devices for future wireless communication systems and other high frequency, temperature and power applications.

2. **ALGAN/GAN HEMT STRUCTURE**

The device structure for AlGaN/GaN HEMT is shown in Figure 1.a and its conduction band diagram and electron distribution is shown in Figure 1.b. Because of the strong spontaneous and piezoelectric polarization of GaN and its ternary, a high density two dimensional electron gas (2DEG) is induced at the heterojunction interface and confined in the triangular potential well due to the large band discontinuity. The high electron velocity, which is estimated above 107 cm/s, bodes well for high frequency operation, and the large breakdown voltage allows for high power applications to be exploited. Figure 1.a The Schematic of AlGaN/GaN HEMT Structure Figure 1.b Conduction Band Diagram and Electron Distribution of AlGaN/GaN HEMT

![Figure 1](image)
microwave HEMTs from measured S-parameters. However, due to the high contact resistances in the source and drain region, the standard parameter extraction method for HEMTs cannot be performed directly for GaN-based HEMTs [5].

Recently, a number of papers have reported small-signal equivalent-circuit parameter-extraction methods for AlGaN/GaN HEMTs which can be classified into two categories:

1. Direct extraction method
2. Optimization-based methods.

In reported paper of Chigeava et.al., [8], a 14-element small-signal model for GaN HEMT was proposed, and the result showed that the elements of equivalent circuit model can be extracted from cold S-parameter measurement at high gate-forward voltages. However, the feedback inductance \( L_s \) obtained by this method is unreliable, and the resistance \( R_{gd} \) between the gate and the drain was not considered in this model. Jarndal [4] developed a 22-element distributed model for GaN HEMTs, which includes almost all the expected parasitical elements of the device, and an optimization-based procedure was employed. The results showed that the final accuracy is restricted by the precision of the measured cold S-parameters in a large frequency range, in addition, the results depend both on the starting point of the optimization calculation and the optimization strategy itself. Generally speaking, the consumption of the time and the resource in an optimization-based method is much more than a direct extraction method.

3. EQUIVALENT CIRCUIT'S PARAMETERS OF HEMT

The equivalent circuit of an HEMT device is an abstraction and simplification that yields a representation of the HEMT device. It must represent adequately all the important physical characteristics of the HEMT device. Exploiting the relationship between the equivalent circuit elements and device physics will be helpful to HEMT device modeling. Equivalent Circuit's Parameters of HEMT are as described below:

- Channel resistance, \( R_i \), is the resistance distributed along the channel under the gate, which is the ratio of the potential drop, \( E_{SLG} \), and the channel current, \( I_{CH} \).
- Transconductance, \( g_{m0} \), is the ratio of change of drain current and gate voltage. As a first order approximation, it is reasonable to use the channel current to replace the drain current while omitting the substrate current.
- Gate-channel space capacitance, \( C_{gc} \), is the capacitance of the gate. Gate-drain space capacitance, \( C_{gd} \), \( C_{gs} \) is associated with the electron inflow at the right edge of the space-charge layer.
- Gate series inductance, \( L_{gs} \) is the inductance determined by the strip's dimension of the gate length, \( L_G \), and the gate width.
- Gate resistance, \( R_g \).

3.1. Small Signal Equivalent Models for HEMT

Small signal equivalent circuits are empirical models where each lumped element represents a physical phenomenon inside the actual HEMT device. These models are simple, accurate and efficient therefore, today they are the most utilized models for CAD applications. A typical small signal equivalent circuit model for HEMT is composed of two subnetworks:

\( i \)  An intrinsic circuit, describing the electrical behaviour of the active part of the device and including bias dependent lumped elements;

\( ii \)  An extrinsic circuit, representing the electrical behaviour of the part of the device allowing the electrical connection between the external terminals and the active part of the device, such elements are usually assumed to be independent by the bias voltages. The topology of both parts is usually fixed a priori before the extraction, although it can be adjusted during the extraction if the measurements suggest it.

Small-signal characterization of HEMT is also used as part of large-signal modeling to extract the linear parts of the transistor model and to check the derivatives of the large signal model. Another field where small-signal models are of great interest is noise modeling. Noise models that are related to small-signal models can be physically meaningful and are easy to implement in CAD programs. HEMT's small-signal model has two major advantages over S-parameters:

1. It is a compact form for describing the HEMT's performance. This characteristic
becomes important when several HEMT’s bias conditions are of interest in a circuit design and not only because it saves disk space. S-parameter tables measured for multiple bias points often become too large for CAD programs to handle.

2. A HEMT model is superior for extrapolation to frequencies beyond the limits of the available vector network analyzer. Before a HEMT model is ready to be used in a simulation, the model parameters must be extracted. This extraction can be performed using a CAD program by minimizing the error function to fit measured and modeled S parameters [9].

The principal drawback to this approach is that it is very time consuming. Also, the resulting parameter values easily become nonphysical, which may lead to non scaleable models [10]. A better solution is to use a direct extraction method in which the model parameters then are extracted directly from the measured S-parameters data. The measurements are checked with both the gate-drain resistor model and the general model. This type of extraction has been developed in recent years for the HEMT [4, 11]. This work deals with the analysis of HEMTs by means of an equivalent circuit. The model used in the dynamic characterization is based on the analytic solution of the admittance parameters of the intrinsic FET to determined design parameters and frequency limits. The analytic solution leads to a direct computation of the equivalent circuit elements.

We describe here small signal equivalent circuits of GaAs HEMT and GaN HEMT.

3.2. Small Signal Equivalent Circuit of GaAs HEMT

A brief overview of small signal equivalent circuit for modeling an AlGaAs/GaAs HEMT have been developed to take into account the specific characteristics. Figure 2 shows the Small signal equivalent circuit for GaAs HEMT. In this the gate and drain pad capacitances \( C_{pg} \) and \( C_{pd} \) are extracted from \( \text{Im}(Y_{11}) \) at low frequencies under “pinch-off” condition. The other parasitic ECPs are extracted from the Z-parameters under “unbias” condition (i.e., \( V_{ds} = V_{gs} = 0 \) V) [12].

\[
Z_{11} = R_x + R_s + \frac{R_{th}}{2} + j\omega L_s + \frac{1}{\omega C_p}
\]

(1)

\[
Z_{21} = R_x + R_s + R_{ch} + j\omega L_d + L_s
\]

(2)

\[
Z_{22} = R_d + R_s + R_{ch} + j\omega L_d + L_s
\]

(3)

The approach based on forward bias of the gate junction, the “unbias” condition has the advantage of avoiding gate degradation due to large gate current. Finally, the intrinsic elements can be obtained straightforwardly from the intrinsic Y-parameters at each “hot” bias point.

Figure 2: Small Signal Equivalent Circuit for GaAs HEMT

3.3. Small Signal Equivalent Circuit of GaN HEMT:

Small Signal Equivalent Circuit of the AlGaN/GaN HEMT represents a significant improvement with respect to the conventional AlGaAs/GaAs HEMT. Figure 3 shows the Small Signal Equivalent Circuit of GaN HEMT. Since the large conduction band discontinuity of the AlGaN/GaN heterostructure, piezoelectric and spontaneous polarization effects lead to the formation of an extremely high density 2DEG, even without doping. Compared with the circuit topology used for the GaAs HEMT, the input and output RC parallel networks are added in series with \( C_{pg} \) and \( C_{pd} \) to model the parasitic conduction within the GaN buffer layer. This higher complexity necessitates the use of the combined method for extrinsic ECP determination, whereas only using the “cold” method was sufficient in case of the GaAs HEMT.

To model the parasitic conduction effect, an open structure present on the same wafer is characterized. The parasitic conduction reflects into not negligible real parts of the following equations:

\[
Y_{in} = Y_{11} + Y_{12}
\]

\[
Y_{out} = Y_{22} + Y_{12}
\]
The parameters $Y_{in}$ and $Y_{out}$ represent the coupling via the metal interconnections and the substrate between respectively gate source and drain source pads [13]. As a result, the elements $C_{pg}$, $R_{pgs}$, $C_{pgs}$, and $C_{pd}$, $R_{pds}$, $C_{pds}$ can be extracted from $Y_{in}$ and $Y_{out}$. By using frequencies sufficiently high to neglect the intrinsic resistances $R_y$ and $R_{ch}/2$ with respect to the impedances associated to the intrinsic capacitances $C_y$ and $2C_{ch}$, the $Z$-parameters can be simplified as follows:

Where, $R_g$, $R_s$, $R_d$ can be calculated by averaging $Re(Z_{ij})$ over the frequency, and $L_d$, $L_s$, $L_g$ can be evaluated from the slopes of straight lines interpolating the experimental data of $\omega Im(Z_{ij})$ vs $\omega^2$. Finally, the intrinsic elements can be obtained straightforwardly from the intrinsic $Y$-parameters at each "hot" bias point.

Figure 3: Small Signal Equivalent Circuit of GaN HEMT

4. TEMPERATURE DEPENDENT ALGaN/GaN HEMT

Several papers have been reported for channel-temperature or thermal-resistance measurements, indicating how self-heating evaluation is critical for the AlGaN/GaN HEMTs. In particular, Micro-Raman Spectroscopy has proven to be a powerful technique [14] for measuring temperature profiles with high spatial resolution; variants were also demonstrated, which offer time-resolved measurements [15] and 3-D mapping [16], whereas a hybrid Raman/infrared (IR) approach [17] allows for the analysis of large multimaterial structures. Other studies involved liquid crystal thermography [21], photocurrent measurements [22], and scanning thermal microscopy [23].

These direct techniques have its own strengths and weaknesses; generally speaking, they offer the distinctive advantage of some degree of spatial resolution (allowing, for instance, resolution of temperature differences among different gate fingers) but often require costly equipment and time-consuming measurement sessions. Indirect electrical techniques cannot convey any space resolved information but are, on the other hand, simpler and cheaper than direct ones. One classical method for extracting TC and RTH is by comparing temperature-dependent fast pulsed measurements with dc measurements; examples of application to AlGaN/GaN HEMTs can be found in [18].

Pulsed techniques do not generally require simplifying assumptions and can provide some information on self-heating dynamics, but one must take care not to mistake electrical transients for thermal ones [18]; moreover, clean, nanosecond-scale, and temperature-dependent pulsed measurements are not easy to perform (particularly on high-power devices) and require adhoc setups and significant measurement effort.

DC electrical techniques are obviously the simplest and cheapest, since they are often relying only on standard I.V measurements at different ambient temperatures. The main drawback with respect to pulsed methods is the need to rely sometimes on drastic simplifying assumptions [19], including the independence of the thermal resistance with temperature and dissipated power. However, very few research works have been published in terms of simple dc electrical techniques for measuring $R_{TH}$. A variant of the method developed in [20] for LDMOSFETs is applied for the first time to extract the RTH of an AlGaN/GaN HEMT. The method assumes a linear dependence of the drain current ($I_D$) on the channel temperature once the linear dependence of $I_D$ on the ambient temperature ($T_A$) has been experimentally demonstrated. It therefore relies on the choice of suitably narrow intervals of $T_A$ and dissipated power ($PD$), wherein the drain.current temperature dependence can be linearized with good accuracy and $R_{TH}$ can be considered constant; apart from this, no other simplifying assumption is necessary. This RTH extraction procedure requires only dc I.V output curves measured at different ambient temperatures, which is a distinct advantage over classical pulse-based approaches.

4.1. Temperature Effect on HEMT

- The effects of temperature on HEMT performance include variations in transconductance, input capacitance, and device resistance.
• Transconductance variations are caused by an increase in electron mobility in the active channel as the temperature decreases.

• Variation of input capacitance is induced by an increase in the built-in Schottky voltage as temperature decreases.

• Resistance variation is caused by changes in the metallurgical nature of ohmic contacts in the source and drain areas at low temperature. Temperature changes have an impact on HEMT device equivalent circuit models and S-parameters, as well as noise-figure models.

• Using extensive S-parameter measurements at different temperatures, a modified HEMT model including the effects of temperature can be created. The modified GaN HEMT model should accurately predict the gain and noise figure at any temperature. Compact Software’s Version 4.0 of Supercompact™ PC microwave simulation software has the capability of temperature sensitivity simulation.

5. RESULTS AND DISCUSSIONS

5.1. Mobility and Sheet Carrier Density Variation with Temperature

The Figure 4 (a) shows the 2-D gas electron mobility from 100K to 500K. It can be seen from the result that as the temperature increased the mobility decreased due to the random movement and collision of carriers. The Figure 4 (b) shows the sheet carrier density ns within the same temperature range. ns is almost constant up to 400K, and a slight increase is observed and this was attributed to surface charge variation, e.g. trap ionisation.

5.2. Access Resistance & Schottky Barrier Variation with Temperature

The Figure 5 (a) shows the variation of the access resistance \( R_C \) between 290ºC to 520ºC. A steady increase was observed from 0.6 \( \Omega \)mm to 1.25 \( \Omega \)mm. C-V measurements were also shown for 100 \( \times \) 100 \( \mu \)m\(^2\) Schottky diodes to extract the barrier height as a function of temperature, Figure 5 (b). A non-expected increase of the barrier height was observed from 0.8eV to 1.25eV.
The high power RF device performance decreases as operation temperature increases (e.g. fall of electron mobility impacting the cut-off frequencies and degradation of device reliability) so it is very important to understand the thermal effect in the device.

5.3. Temperature Effects on $g_m$, $C_{gd}$, $C_{gs}$

Figure 6 shows the intrinsic transconductance ($g_{m,int}$) decreases with temperature from 338 mS/mm at RT to 236 mS/mm at 250ºC, likely related to a reduction in the effective electron velocity in the channel.

Whereas $C_{gs}$ can be considered constant at different temperatures, $C_{gd}$ suffers a clear decrease as devices are heated, which leads to a decrease in the HEMT global capacitance.

This result, together with the shift of $V_{th}$ to higher values as temperature increases,

Commercial substrates for GaN epilayers include sapphire, silicon, and silicon carbide have thermal conductivities between 40 and 400 W/mK. With thermal conductivity values ranging from 800 to 1800 W/mK, diamond provides GaN with a substrate that has far superior heat spreading properties compared to other commercially available substrate. Using GaN-on-diamond wafers, electronic systems can expect an increase in power handling capacity that would significantly reduce system-level cooling costs and packaging challenges.

GaN-on-diamond technology has two distinct advantages:

1. A more efficient thermal management due to the proximity of the heat spreader to the heat source;
2. A lower price per chip since both the diamond and the chip are smaller.

6. GAN-ON-DIAMOND SUBSTRATES

Currently, GaN devices are used for microwave power amplification at frequencies of up to 100 GHz. The very high thermal conductivity of diamond enables the increase in power and improvement in lifetime and reliability of the amplifiers by efficiently removing the heat from the active region of devices fabricated on GaN-on-diamond substrates. The primary significance of the GaN-on-diamond structure lies in its ability to efficiently remove the heat from the active regions, the state and quality of the bond between the GaN, the diamond, and any enabling adhesion layers are critical in the transmission of heat through the interface and the reliability of the completed devices.

In reported results, authors varied the total width of the chip as well as diamond thickness to observe the thermal resistance variation as a function of these two variables. 100µm is a good choice for the thickness of a diamond substrate for a typical GaN HEMT.

7. CONCLUSION

Small signal equivalent based analysis of HEMT has been carried out in this paper. The thermal management of structures such as HEMT Monolithic Microwave Integrated Circuits (MMICs) is important because of increased circuit packing.
densities and RF output powers. High temperature gradients are expected between gate metal and GaN channel. Semiconductor regions of the device heat up in nanoseconds up to a microsecond. In this paper thermal analysis for AlGaN/GaN HEMT device is carried out along with the latest progresses in GaN HEMT technology, including alternative approaches and HEMT device characteristics. AlGaN/GaN HEMTs promise for high power, temperature and frequency than their AlGaAs/GaAs. This paper presents analysis for AlGaN/GaN HEMT’s for wire less applications.

REFERENCES


