Physics Based Analysis of Gallium Nitride (GaN) High Electron Mobility Transistor (HEMT) for Radio Frequency (RF) Power and Gain Optimization

by Pankaj B. Shah and Joe X. Qiu
NOTICES

Disclaimers

The findings in this report are not to be construed as an official Department of the Army position unless so designated by other authorized documents.

Citation of manufacturer’s or trade names does not constitute an official endorsement or approval of the use thereof.

Destroy this report when it is no longer needed. Do not return it to the originator.
Physics Based Analysis of Gallium Nitride (GaN) High Electron Mobility Transistor (HEMT) for Radio Frequency (RF) Power and Gain Optimization

Pankaj B. Shah and Joe X. Qiu
Sensors and Electron Devices Directorate, ARL
## 4. TITLE AND SUBTITLE
Physics Based Analysis of Gallium Nitride (GaN) High Electron Mobility Transistor (HEMT) for Radio Frequency (RF) Power and Gain Optimization

## 6. AUTHOR(S)
Pankaj B. Shah and Joe X. Qiu

## 14. ABSTRACT
The power and gain characteristics of a power radio-frequency (RF) gallium nitride (GaN) high electron mobility transistor (HEMT) were investigated by using drift-diffusion model simulations that were self consistently solved with the current-voltage (I-V) characteristics of the external circuit elements. The results showed the expected drop in gain with frequency, as the corresponding output power increases, can be modeled with device physics considerations. This technique can be used to optimize device performance by determining which part of the device to modify for greatest impact.

## 15. SUBJECT TERMS
Power amplifier, distortion
## Contents

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>List of Figures</td>
<td>iv</td>
</tr>
<tr>
<td>1. Introduction</td>
<td>1</td>
</tr>
<tr>
<td>2. Procedure</td>
<td>1</td>
</tr>
<tr>
<td>3. Results</td>
<td>3</td>
</tr>
<tr>
<td>4. Conclusions</td>
<td>6</td>
</tr>
<tr>
<td>Distribution List</td>
<td>7</td>
</tr>
</tbody>
</table>
List of Figures

Figure 1. Simulated GaN HEMT ...................................................................................................2
Figure 2. Circuit simulated in Atlas mixed mode. ........................................................................3
Figure 3. I-V characteristics of the GaN HEMT. The curves from top to bottom are for \( V_g = 0, -1, -2, -3, -4, -5, \) and \(-6 \) V. ..................................................................................................4
Figure 4. Load current waveforms for input sinusoidal voltage (\( V_{in} \)) amplitudes of 1, 2, 3, 4, and 5 V. The input frequency is 100 MHz............................................................................4
Figure 5. Calculated power output and gain at 100 MHz. Blue curve is the power, red curve is the gain...................................................................................................................................5
Figure 6. Calculated power output and gain at 10 GHz. Blue curve is the power, red curve is the gain...................................................................................................................................5
1. Introduction

Gallium nitride (GaN) radio frequency (RF) devices have recently exhibited advances such as good reliability at low power and performance that allows them to enter the commercial market and compete with other devices as evidenced by the RF products available on such Web sites as Cree Inc., Triquint Semiconductor, and RFMD. Having reached this point in their development, researchers can now investigate more complex circuits and operational modes. To optimize the devices and push material and device designs to their limits, simulations are necessary. Embedding the device in a circuit for these simulations helps optimize the device performance for real applications.

Important issues for GaN high electron mobility transistors (HEMTs) in RF applications are power and linearity performance. The linearity of a GaN HEMT is tied to the internal gate-source capacitance ($C_{gs}$), gate-drain capacitance ($C_{gd}$), transconductance ($G_m$), and drain conductance ($G_d$). All of these are determined by the charge carrier flow and energy barriers they encounter; depletion regions; and internal electrostatic potential distributions in a semiconductor device. Power output is also tied to carrier transport behavior, device current, power gain, electric field distributions, etc. Understanding the relationship between these physical characteristics and RF performance will greatly speed the application of GaN devices in advanced RF systems. Towards this end, we have performed drift-diffusion-based simulations of a GaN HEMT operating as a class A amplifier.

2. Procedure

Simulations were performed using the drift-diffusion simulations software Atlas/Blaze provided by Silvaco Inc. to solve Poisson’s equation and the charge carrier continuity equations over a two dimensional cross section of the device. Mixed-mode simulations were also performed wherein external circuit elements are included along with the device and additionally the currents and voltages of the external elements are self consistently solved for and included in the solution process. The GaN HEMT structure is shown in figure 1.
The device consisted of a 19-nm aluminum gallium nitride (AlGaN) barrier layer containing 28% aluminum (Al) above a GaN layer. The HEMT gate length was 0.5 µm. GaN and AlGaN models used in the simulations included Shockley-Read-Hall recombination; concentration and field dependent mobility; and polarization charges at the interface. Also, a 1-eV Schottky barrier height was considered.

Mixed-mode simulations were performed in Atlas/Blaze, embedding the device in the circuit, as depicted in figure 2. The inductor L blocks the RF signal to the DC power supply and the capacitor C blocks the DC bias from the load resistor RL. Rd and Rs are the contact resistances of the HEMT. The contact resistances were set to 1.5 Ω-mm.

---

Following the mixed mode simulations, the RF output waveform was read into Mathcad, where it was first interpolated to uniformly space the discrete points of the output waveform. Then, a Fourier transform was taken followed by calculating the average RF power entering the HEMT and total power in the first harmonic at the output of the HEMT. This output power out is calculated from the product of the fundamental frequency component of the load current and load voltage.

3. Results

The current-voltage (I-V) characteristics obtained from a non-mixed-mode, drift-diffusion simulation of the device are plotted in figure 3. These I-V characteristics match typically fabricated GaN devices. A slight soft pinchoff is exhibited for the $V_g = -6$ V curve.
Figure 3. I-V characteristics of the GaN HEMT. The curves from top to bottom are for $V_g = 0, -1, -2, -3, -4, -5,$ and $-6$ V.

For the RF simulations $V_d$ was set to 20 V and $V_g$ was set to $-3$ V. The current in the load obtained for an input source at 100 MHz is shown in figure 4. There we see the waveform is compressed at negative values due to the current in the transistor reaching the knee of the I-V curves.

Figure 4. Load current waveforms for input sinusoidal voltage ($V_{in}$) amplitudes of 1, 2, 3, 4, and 5 V. The input frequency is 100 MHz.
The power output vs. power input is shown in figure 5 for a 100-MHz input RF source, and in figure 6, for a 10-GHz input RF source.

Figure 5. Calculated power output and gain at 100 MHz. Blue curve is the power, red curve is the gain.

Figure 6. Calculated power output and gain at 10 GHz. Blue curve is the power, red curve is the gain.

The results exhibit the expected lower gain at higher frequencies due to internal impedances of depletion regions, and charge carrier velocity limitations. Also, we observe the output power compression occurring as gain begins to drop rapidly.
4. Conclusions

The power and gain characteristics of a GaN HEMT were investigated by using drift-diffusion model simulations that were self consistently solved with the I-V characteristics of the external elements. The results showed the expected drop in gain with frequency, as the corresponding output power increases, can be modeled considering device physics. This technique can be used to optimize device performance by determining which part of the device to modify for greatest impact. This technique could also be expanded by using additional RF sources to analyze intermodulation distortion.
NO. OF COPIES | ORGANIZATION
--- | ---
1 | ADMNSTR
ELEC | DEFNS TECHL INFO CTR
ATTN | DTIC OCP
| 8725 JOHN J KINGMAN RD STE 0944
| FT BELVOIR VA 22060-6218

1 CD | OFC OF THE SECY OF DEFNS
ATTN | ODDRE (R&AT)
| THE PENTAGON
| WASHINGTON DC 20301-3080

1 | US ARMY INFO SYS ENGRG CMND
ATTN | AMSEL IE TD A RIVERA
| FT HUACHUCA AZ 85613-5300

1 | COMMANDER
US ARMY RDECOM
ATTN | AMSRD AMR W C MCCORKLE
| 5400 FOWLER RD
| REDSTONE ARSENAL AL 35898-5000

1 | CERDEC STCD SPACE SYSTEMS
ATTN | RDECOM CERDEC HERALD BELJOUR
| ABERDEEN PROVING GROUNDS,
| ABERDEEN MD 21001

11 | US ARMY RSRCH LAB
ATTN | IMNE ALC HRR MAIL & RECORDS MGMT
| RDRL CIO LL TECHL LIB
| RDRL CIO MT TECHL PUB
| RDRL SER E J QIU
| RDRL SER E P SHAH
| RDRL SER E T IVANOV
| RDRL SER E F CROWNE
| RDRL SER E E VIVEIROS
| RDRL SER E H A HUNG
| RDRL SEE M S RUDIN
| RDRL SER E R D DELROSARIO
| ADELPHI MD 20783-1197
INTENTIONALLY LEFT BLANK.