Noise Figure of Indium Nitride-based HEMT Design

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1. Introduction
Nowadays, the high electron mobility transistors (HEMT, also called 2DEGFET, MODFET, HFET, ...) employing modulation-doped AlInN/GaN heterostructures has demonstrated excellent performance in the field of microwave amplifiers \cite{1}, \cite{2}. The new technology brings development not only in optoelectronic applications but also in microwave high-power devices there is a great acquire of effort for investigating Nitrate-based HEMT structures. Noise performance is vital of important in the low noise amplifier, and complete transmit and receive paths circuit. In particular, the noise figure (NF) is common figures of merit for characterizing noise. To improve the noise performance of devices, a theoretical framework is needed that identifies the noise sources, how these sources contribute to the overall noise, and how the noise changes with other parameters, such as bias and matching conditions. They are also excellent candidates for the design of low noise amplifier in the perspective of low noise amplifier-power amplifier (LNA-PA). Recently, low noise amplifier based on AlGaN/GaN HEMTs. Also, LNA design in millimeter wave frequency band will become a

Abstract: High electron mobility transistors, HEMTs, have been shown to be high performance millimetre wave devices due to their high power gain and low noise figures. The HEMT noise behaviour is presented from theoretical points of view. This work design an analytical noise model of an AlInN/GaN modulation doped High Electron Mobility Transistor (HEMT). The general method used in the high-frequency noise analysis is described and the different approximations commonly used in the derivation of the noise parameter expressions are discussed. The developed noise model explains the performance of noise in both thermal noise and flicker noise. The measurement techniques providing the noise figure and the other noise parameters are then described and compared. Small signal parameters are obtained and used to calculate the Noise Figure of the device. All the results have been compared with the experimental data.

Keywords: Flicker noise, Thermal noise, Indium Nitride, High Electron Mobility Transistor, Noise figure.
focus issue in the age of 5G communication [5]. To design LNAs, measurements of the device noise parameters minimum noise figure (NF), optimum source reflection coefficient, and noise resistance are required. This work will show the importance of monitoring noise figure (NF) measurements and introduce a modified Fukui model that is easy to use and predicts NF accurately.

In this work, High-frequency noise parameters NF\textsubscript{min} and g\textsubscript{m} of AlInN/GaN HEMT were measured in 50GHz frequency band. And then, it proposes an analytical model that accurately explains the calculations of noise parameters and noise characteristics of AlGaN/GaN HEMT. The effects of important parameters like aluminum concentration, gate length, barrier thickness and doping of the AlGaN layer on device and noise characteristics have been described in detail. The expressions of device transconductance (g\textsubscript{m}), gate to source and gate to drain capacitance (C\textsubscript{gs}, C\textsubscript{gd}) has been developed which are used for calculating the important noise parameters. The results of the proposed model have been verified with the published simulated or experimental data and near to agreement.

2. High-Frequency Noise Model Theory in HEMT's

Noise (a spontaneous fluctuation in current or in voltage) is generated in all semiconductor devices. The most important sources of noise are thermal noise, shot noise, generation-recombination noise, 1/f noise (flicker noise), 1/f\textsuperscript{2} noise, burst noise or random telegraph signal (RTS) noise, and avalanche noise. The types of noise model are van der Ziel, Pucel, Fukui, and Pospieszalski. In terms of noise modeling, Fukui’s theory has been applied in this work.

2.1 Derivation of Drain current and Transconductance

There is analyse the performance of an Al\textsubscript{0.83}In\textsubscript{0.17} N/GaN HEMT device as shown in Figure 1, having a gate length of 6 nm and 100 nm gate width. The physical properties of the narrow bandgap GaN and the wide bandgap Al\textsubscript{0.83}In\textsubscript{0.17} N/GaN HEMT are listed in Table 1.

![Figure 1 Al\textsubscript{0.83}In\textsubscript{0.17} N/GaN HEMT Structure](image)

The noise sources in parallel with the intrinsic part of the model are used to characterize the shot noise and thermal noise induced by the channel in GaN channel layer.

<table>
<thead>
<tr>
<th>Material</th>
<th>Al\textsubscript{0.83}In\textsubscript{0.17} N</th>
<th>GaN</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eg (eV)</td>
<td>3.4</td>
<td>4.7</td>
</tr>
<tr>
<td>CBO(eV)</td>
<td>0.57</td>
<td>-</td>
</tr>
<tr>
<td>VBO(eV)</td>
<td>0.73</td>
<td>-</td>
</tr>
<tr>
<td>(\varepsilon_0)</td>
<td>9.5</td>
<td>11.7</td>
</tr>
<tr>
<td>Lattice constant(Å)</td>
<td>3.186</td>
<td>3.190</td>
</tr>
<tr>
<td>(\mu_e) (cm\textsuperscript{2}/(V.s))</td>
<td>940</td>
<td>1540</td>
</tr>
<tr>
<td>(\mu_h) (cm\textsuperscript{2}/(V.s))</td>
<td>22</td>
<td>82</td>
</tr>
</tbody>
</table>

The drain current can be written in general as [2]:

\[
I_d = q\mu W n_s(x) \frac{dV_x}{dx}
\]  

(1)

Where,

- \(I_d\) = Drain Current (A)
- \(W\) = device width (cm)
- \(n_s(x)\) = sheet charge of the 2DEG (cm\textsuperscript{-2})
- \(\mu\) = mobility (cm\textsuperscript{2}/Vs)
- \(V_x\) = potential difference at a distance \(x\) from the source relative to the source

The charge of capacitance, \(C = \frac{Q}{V} = \frac{\varepsilon_0}{d+\Delta d}\) is equal \(qn_s(x)\), with a voltage along the channel of \(V_g - V_t - V_x\). \(V_t\) is the threshold voltage. \(\varepsilon_0\) and \(d\) being the dielectric permittivity and thickness of the AlGaN layer respectively and \(\Delta d\) is the centroid of the electron wave functions in the quantum well. Combining all this together and rearranging,

\[
n_s(x) = \frac{\varepsilon_0}{q(d+\Delta d)}(V_g - V_t - V_x)
\]  

(2)

And then by substitution equation 2 in equation 1, the final equation of \(I_d\) is
\[ I_d = \frac{uegW}{L(d+\Delta d)} \left( V_g - V_t - V_x \right) \frac{dV_x}{d\sigma} \quad (3) \]

Consideration over the device length, \( L \) as:
\[ I_d = \frac{uegW}{L(d+\Delta d)} \left[ \left( V_g - V_t \right) V_d - \frac{V_d^2}{2} \right] \quad (4) \]

The device transconductance \( (g_m) \) can be defined as the following equation,
\[ g_m = \frac{\partial I_d}{\partial V_g} = \frac{uegW}{L(d+\Delta d)} V_d \quad (5) \]

2.2 Thermal Noise

Thermal noise is created by random motion of charge carriers due to the thermal excitation. This noise is sometimes known as the Johnson noise. The thermal motion of carriers creates a fluctuating voltage on the terminals of each resistive element. The average value of this voltage is zero, but the power on its terminals is not zero. The internal noise voltage source or current source is described by the Nyquist equation.
\[ V_n^2 = 4kTR \Delta f \]
\[ i_n^2 = \frac{4kTR \Delta f}{R} \]  

According to work of van der Ziel to derive the channel noise, we assume that a thermal voltage noise source, \( v_n \), creates a drain noise current fluctuation, \( \Delta I_d \), along the distributed channel. Then the thermal noise current can be written as
\[ \langle i_n^2 \rangle = 4kT g_m \Gamma \]
\[ \Gamma = \frac{1}{1 - \frac{V_d}{V_t}} \]  

Where,
\[ \left| \Gamma_{\text{opt}} \right| = \text{The magnitude of the source reflection coefficient that provides the minimum noise figure, } F_{\text{min}}. \]
\[ < \Gamma_{\text{opt}} = \text{The angle of the source reflection coefficient that provides } F_{\text{min}}. \]

2.3 Flicker Noise

The Flicker noise \((1/f \text{ noise})\) is the dominant noise in the low frequency range and its spectral density function is proportional to \(1/f\). This noise is present in all semiconductor devices under biasing. This noise is usually associated with material failures or with imperfection of a fabrication process. Most of research results conclude that this noise exists even for very low frequencies up to \(10^{-6} \text{ Hz}\). The Hooge bulk model is more adequate. In this noise model, Hooge uses in the carrier transport two scattering mechanisms of carriers: scattering on the silicon lattice and scattering on impurities. All imperfections of the crystal lattice lead to large \(1/f\) noise. The noise spectral density function for the Hooge model is
\[ S_{1/f} = \frac{\sigma_H x f^2}{fN} \]  

Where,
\[ S_{1/f} \text{ = Spectral Intensity} \]
\[ \sigma_H = 2 \times 10^{-3} \text{ is the Hooge constant} \]
\[ N = \text{number of carriers} \]
\[ I = \text{average Current} \]

2.3 Noise Figure Calculation

The noise figure calculated with Fukui model equation. It is the most well established model for device and circuit optimization. In the Fukui model, the noise parameters are simple frequency dependent functions of the equivalent small-signal intrinsic circuit elements that are transconductance, \( g_m \), gate-source capacitance, \( C_{gs} \), source and gate resistances, \( R_s \) and \( R_g \).

In this work, the Fukui equation can be expressed as:
\[ F_{\text{min}} = 2 \left( f_t \right) \frac{P g_m \left( R_s - R_g \right)}{fN} \]  

Where,
\[ f = \text{operating frequency} \]
\[ g_m = \text{transconductance} \]
\[ R_s \text{ and } R_g = \text{source and gate resistance} \]
\[ P = \text{a fitting factor described by Fukui model} \]
\[ P = \frac{\langle i_n^2 \rangle}{4kT g_m \Delta f} \]  

\[ f_t = \frac{\left( g_m \right)}{2\pi C_{gs}} \]  

The gate to source and drain to source capacitance, Source and Gate resistance can be defined as:
\[ C_{gs} = C_{gd} = \frac{sW_g^d}{i_g} \]  
\[ R_s = R_T + R_{\text{Sheet}} \frac{i_g}{W_g} \]  
\[ R_g = \frac{\text{Sheet} \frac{i_g}{W_g}}{W_{\text{fingers}}} \]
3. Results and Discussions

The device employed in this work is an AlInN/GaN HEMT simulated by MATLAB simulation. AlInN/GaN HEMT which is grown on a gate width is 100 nm and gate length is 6 nm. At the heart of the model is the gate-source capacitance, $C_{gs}$, and the transconductance, $g_m$. The drain-source resistance, $R_{ds}$, is a measure of how effectively a signal can be extracted from the device. The value of $C_{gs}$ and $R_{ds}$ are 0.18 pF and 667 Ω respectively in this simulation.

![Transconductance and Drain Voltage of AlInN/GaN HEMT](image1)

Figure 2. Transconductance with respect to drain voltage.

In Figure 2, which present the relationship between transconductance and drain voltage for AlInN/GaN HEMT, the $g_m$ value is directly proportional to the drain voltage. Figure 3 point out the effect of transconductance and the source reflection coefficient that provides the minimum noise figure, $F_{min}$ based on thermal noise. So, if the drain current is increased, the $g_m$ is increased as shown in Figure 2. From Figure 3 it can be seen clearly that Thermal Noise increases with transconductance, $g_m$ as because Thermal Noise directly proportional with $g_m$ and $g_m$ is directly proportional with $V_d$.

![Transconductance and Drain Current of AlInN/GaN HEMT](image2)

Figure 3. Transconductance and source reflection coefficient are varies based on Thermal Noise.

Flicker Noise is called as 1/f noise and the result clearly shows that it varies based on spectral intensity as shown in Figure 4. This results present when the average current is increased, the spectral intensity of the noise current is also raised.

![Spectral Intensity and Average Current of AlInN/GaN HEMT](image3)

Figure 4. Relationship between Spectral Intensity and Average Current of AlInN/GaN HEMT.

The relationship between minimum NF and Frequency of AlInN/GaN HEMT is shown in Figure 5. When the frequency range is rised, minimum noise figure value is high under room temperature. Based on this result, the minimum noise figure variation under various temperature are analysed in Figure 6 continuously.

According to Figure 6 results, noise characteristics under ambient temperature have been investigated. NFmin increases with the addition of ambient temperature as the values of
parasitic resistances together with the channel resistance grow with the ambient temperature. The thermal noise induced by them will raise at the same time.

Figure 5 Relationship between minimum NF and Frequency of AlInN/GaN HEMT

Figure 6. Noise Performance under Ambient Temperature of AlInN/GaN HEMT

Finally, the results of Figure 7 are Minimum noise figure varies on Thermal Noise Current and Flicker Noise Current of AlInN/GaN HEMT. These two results are approached the minimum noise figure value up to 1.

4. Conclusion

Noise Figure close to 1 is good for any device. So, this work observes that the model (AlInN/GaN) shows better noise performance for the HEMT than other modeling approach described in other literature. In this work, the study of the effects brought by temperature dependent $R_s$, $R_d$ and $C_{gs}$ on noise performance of AlInN/GaN HEMT is presented. Moreover, the variation of minimum noise figure based on frequency, transconductence, thermal and 1/f noise current are also discussed. Results show that the temperature dependent characteristics of them will have great effect on the NFmin and $R_n$ especially in high frequency band while little effect on $\Gamma_{opt}$. The results of this work can give a reference to the low frequency InN LNA design and high frequency especially millimeter wave InN LNA-PA design which would be applied under different ambient temperature and minimum noise figure calculation for different frequency.

5. Acknowledgement

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6. References


