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NOISE MODELING & NOISE FIGURE CALCULATION OF HEMT

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Abstract: ***Nowadays, there has been strong demand for low noise amplifiers operating in the µm-mm wave band. For the DBS applications and satellite communication for military applications, the minimum noise figure of the device is taken in account as a critical device parameter. The short gate length devices have the capability of achieving the ultra-low noise figures. This work will investigate several aspects of the noise performance of GaN HEMTs. Measurements of noise figure (NF) and low-frequency noise (LFN) are used to characterize devices. Modeling useful for calculations and circuit simulation are applied, with some introduced. Here we design an analytical noise model of an AlGaN/GaN modulation doped High Electron Mobility Transistor (HEMT). The developed model explains the influence of Noise in Ohmic region (Thermal Noise) and Low frequency Noise (Flicker Noise). 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 to validate our model.***

Keywords: AlGaN/GaN HEMT, thermal noise, flicker noise, Noise figure.

1. INTRODUCTION

For electronic applications, GaN high electron mobility transistors (HEMTs) provide some of the highest microwave power performance to be found from solid state devices. The GaN HEMTs are being con-sidered mainly for power amplifiers in microwave products such as base stations due to their expensive cost and reliability. Instead of a chip with just a power amplifier, it is preferred to have the amplifier, and complete transmit and receive paths, in a single chip called a front-end module (FEM). It may be possible that GaN monolithic microwave integrated circuits (MMICs) provide better performance in terms of power, radiation hardness, and operation temperature, leading to future products. An important metric of such circuits will be their noise performance. In particular, the noise figure (NF) is common figures of merit for characterizing noise.

To characterize, compare, and 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. A common approach is to add discrete noise sources to a small-signal model. Depending on the model, the sources may be correlated, adding complexity to the derivation and interpretation of the particular model. Noise sources of interest to noise figure (NF) are reviewed, as is a full small-signal model along with the noise parameters NF_{min}, Γ_{opt} and r_n. The two most common types of noise are Thermal Noise and Flicker Noise.

Noise in the channel is the internal generation of signals that cause degradation from the desired response. Fluctuations in signal phase, amplitude and spectral content are forms of noise.

Thermal noise originates because heat in the electrical device provides energy to the carriers causing random fluctuations in their movements. The thermal noise within the channel influence to rise of both drain channel noise and induced gate noise. If we increase the drain source voltage, the electric field within the channel increases. The increasing electric field causes more carriers to reach velocity saturation due to more carriers present at the time of velocity saturation, therefore amount of diffusion noise near the drain increases.

Modest cooling requirements, large instantaneous bandwidth, and very low noise of HEMT millimeter wave amplifiers have spurred interest in their use as broadband continuum radiation detectors, especially for cosmic microwave background radiation measurements. Lower corner frequencies for 1/f noise are desirable to avoid the difficulty of implementing very fast switching rates. HEMTs are also used in microwave and millimeter wave power amplifiers, mixers, oscillators, frequency converters, attenuators, and phase shifters. Their low frequency noise could be the limiting factor to applications involving signal mixing and local signal generation.

It has thus become common to examine the low frequency noise of any HEMT once it has been shown to have promising high frequency behavior.

Several theoretical models have been developed to study the noise properties of HEMT. These models could not explain the behavior and effect of noise by changing the noise parameters.

In this paper we propose 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, gate to source and source to drain capacitance 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. MODEL FORMULATION:

2.1 Drain Current Formulation:

The drain current can be written in general as [1, 2, and 3]:

$$I_d = g(V_x)\frac{dV_x}{dx} = q\mu W n_s(x)\frac{dV_x}{dx} \quad (1)$$

W is the device width (cm), ns(x) is the sheet charge of the 2DEG (cm^{-2}), and µis the mobility (cm^2/Vs). V_x is the potential difference at a distance x from the source, relative to the source. $g(V_x)$ is the channel conductivity per unit length at some point along the channel, which depends on V_x.

The effective capacitance can be defined [1,2,3] as:

$$C = \frac{Q}{V} = \frac{\varepsilon_B}{d+\Delta d} \quad (2)$$

With ε_B and d being the dielectric permittivity and thickness of the AlGaN layer respectively and Δd is the centroid of the electron wave functions in the quantum well.

The charge of this capacitance is = q $n_s(x)$, with a voltage along the channel of Vg−Vt−Vx. Vt is the threshold voltage.

Combining all this together and rearranging, we get [1, 2, and 3]:

$$n_s(x) = \frac{\varepsilon_B}{q(d+\Delta d)}(V_g - V_t - V_x) \quad (3)$$

And substituting in equation (1), we get:

$$I_d = \frac{\mu\varepsilon_B W}{d+\Delta d}(V_g - V_t - V_x)\frac{dV_x}{dx} \quad (4)$$

The DC current entering and leaving the device must be the same due to continuity and we will get I_d by integrating equation (4) over the length of the device, L as:

$$\int_0^L I_d\,dx = I_d L = \int_0^{V_d} g(V_x)\,dV_x \quad (5)$$

Where

$$g(V_x) = \frac{\mu\varepsilon_B W}{d+\Delta d}(V_g - V_t - V_x) \quad (6)$$

Now we get the final expression of I_d as:

$$I_d = \frac{\mu\varepsilon_B W}{L(d+\Delta d)}\left[(V_g - V_t)V_d - \frac{V_d^2}{2}\right] \quad (7)$$

From the above equation we will get the device transconductance as [1, 2,3]:

$$g_m = \frac{\partial I_d}{\partial V_g} = \frac{\mu\varepsilon_B W}{L(d+\Delta d)}V_d \quad (8)$$

2.2 Thermal Noise Formulation:

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, ΔId, along the distributed channel.

Then the thermal noise source can be written as [3]:

$$\langle v_n v_n^* \rangle = \frac{4kT}{g(V)} \quad (9)$$

Now, we can write an expression for the drain current fluctuations as [3]:

$$\Delta I_d = g(V)\frac{dV}{dx} + v_n g(V) \quad (10)$$

Separating the derivative and integrating over the length L gives as [3]:

$$\int_0^L \Delta I_d\,dx = \int_0^L g(V)\,dV + \int_0^L v_n g(V)\,dx \quad (11)$$

If we consider the drain AC shorted, the first term on the right of the equality in equation 11 will be zero. Continuing we have [3]:

$$\Delta I_d L = \int_0^L v_n g(V)\,dx \quad (12)$$

Taking the spectral density with the use of equation 10 we have [3]:

$$\langle \Delta I_d \Delta I_d^* \rangle = \frac{1}{L^2}\int_0^L \langle v_n v_n^* \rangle g^2(V)\,dx = \frac{4kT}{L^2}\int_0^L g(V)\,dx \quad (13)$$

The variable being integrated over x, can be changed to V through the use of equation 1. It is rearranged here as:

$$dx = \frac{g(V)}{I_d}dV \quad (14)$$

Substituting and changing the limits of integration we arrive at the following key equation:

$$\langle \Delta I_d \Delta I_d^* \rangle = \langle i_d^2 \rangle == \frac{4kT}{L^2 I_d}\int_0^{V_d} g^2(V_x)\,dV_x \quad (15)$$

Combining equations 6, 7 and 15 leads to an expression for the thermal noise as [3]:

$$\langle i_d^2 \rangle = 4kTg_m\Gamma \quad (16)$$

Where

$$\Gamma = \frac{1 - \frac{V_d}{V_g - V_t} + \frac{V_d^2}{3(V_g - V_t)^2}}{1 - \frac{1}{2}\frac{V_d}{(V_g - V_t)}} \quad (17)$$

2.1 Flicker Noise Formulation:

In general, the term 1/f noise is applied to any fluctuating quantity whose spectral density, $S_I(f)$, varies as $(1/f^{\beta})$ over many decades with 0.5<β<1.5. In the case of high electron mobility transistors (HEMTs), the varying quantity is current or voltage.

Based on measurements on a number of materials, Hooge (Hooge 1969, 1976, 1981) postulated the following empirical relationship [3]:

$$\frac{S_i(f)}{\bar{I}^2} = \frac{\alpha_H}{f\bar{N}} \qquad (18)$$

Where $S_i(f)$ is the spectral intensity of the l/f noise current, $\bar{I}$ is the average current, N is the average number of charge carriers, and α_H is the Hooges parameter. Hooge found α_H to be a constant equal to $2\text{x}10^{-3}$.

2.5 Noise Figure Formulation:

The Noise Figure Margin using Fukui equation can be expressed as[4]:

$$F_{\min} = 1 + 2\left(\frac{f}{f_t}\right)\sqrt{Pg_m\left(R_s + R_g\right)} \qquad (19)$$

Where f is the operating frequency, g_m is the transconductance, R_s and R_g are the source and gate resistance respectively, P is essentially a fitting factor which is described by Fukui as [4]:

$$P = \frac{\langle i_d^2 \rangle}{4kTg_m\Delta f} \quad \text{and} \quad f_t = \frac{1}{2\pi}\left(\frac{g_m}{C_{sg}}\right) \qquad (20)$$

The gate to sourse and drain to source capacitance can be written as [5] :

$$C_{gs} = C_{gd} \approx \varepsilon w_g \frac{d + d_i + \Delta d}{l_g} \qquad (21)$$

Source and Gate resistance can be defined as [5]:

$$R_s = R_T + R_{sheet}\frac{l_g}{w_g} \quad \text{and} \quad R_g = \frac{\left(R_{sheet}\right)\frac{l_g}{w_g}}{LN_{fingers}} \qquad (22)$$

3. RESULT ANALYSIS

The thermal noise is directly proportional to the temperature. So, if we increase the temperature then the thermal noise is increased as V_{ds} increased shown in fig 1.From fig 2 it can be seen clearly that Thermal Noise increases with W/L ratio as because Thermal Noise directly proportional with g_m and g_m is directly proportional with W/L ratio. Flicker Noise is proportional with $\bar{I}^2$ and $\bar{I}$ varies with V_{ds} So, Flicker Noise increases with increase in V_{ds} shown in Fig 3. In Fig 4 the variation of Flicker Noise with Frequency is shown. Flicker Noise is called as 1/f noise and the result clearly shows that it varies inversely with Frequency. Noise Figure close to 1 is good for any device. In fig 5 Noise Figure is plotted with V_{ds} and Noise Figure comes within the range of 1 to 1.01.

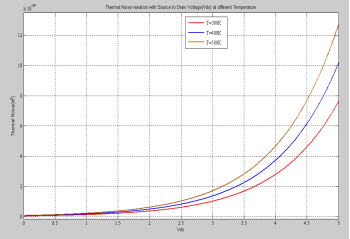

Figure 1 Variation of Thermal Noise with V_{ds} at different Temperature

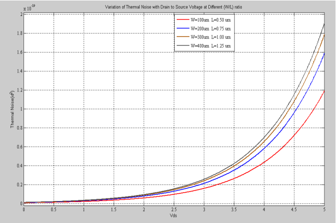

Figure 2 Variation of Thermal Noise with V_{ds} at different (W/L)

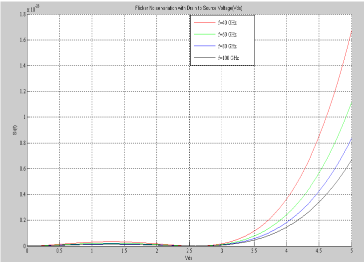

Figure 3 Variation of Flicker Noise with V_{ds} at different Frequency

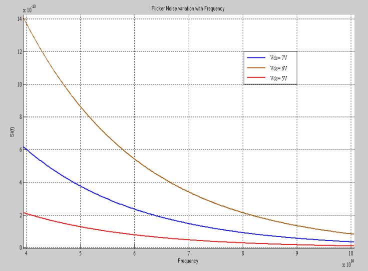

Figure 4 Variation of Flicker Noise with Frequency at V_{ds}

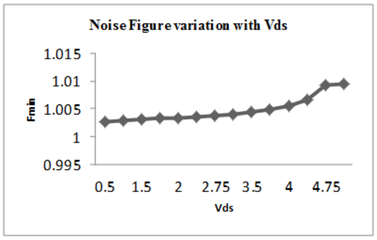

Figure 5 Variation of Noise Figure at V_{ds}

4. Conclusion

By our modeling we observe that our model (*AlGaN/GaN*) shows better noise performance for the HEMT than other modeling approach described in other literature. The compact model constitutes by the expressions for the thermal Noise, Flicker Noise can't only be used in hand calculations but also be incorporated in circuit simulation platform to predict the noise performance of HEMT. Thus this paper will show the way for compact modeling the noise including various noise resources, which will be very helpful for the low noise analog IC optimized design at low power supply voltage.

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