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Analysis on Noise Figure of Indium Nitride-based HEMT Design

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Abstract:- High electron mobility transistors (HEMTs) have been shown to be high performance millimeter wave devices due to their high-power gain and low noise figures. From theoretical points of view presented the noise behavior of HEMT. This work designs an analytical noise model of an AlInN/GaN modulation doped High Electron Mobility Transistor (HEMT). The method used in the noise of high-frequency analysis is designated 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 device's Noise Figure (NF) simulate by using MATLAB software.

Keywords:- *Flicker Noise., Thermal Noise, Indium Nitride, HEMT, Noise Figure.*

I. INTRODUCTION

Nowadays, HEMT, high electron mobility transistors (also called 2DEGFET, MODFET, HFET, ….) using modulation-doped AlInN/GaN heterostructures have demonstrated outstanding performance in the field of microwave amplifiers [l], [2]. The new technology brings development not only in optoelectronic applications but also in microwave high-power devices. So, there is a great acquire of effort for investigating Nitrate-based HEMT structures. Noise performance is also vital 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 to 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. They are also popular candidates for the design of low noise amplifier and power amplifier (LNA and PA). In the age of 5G communication, LNA design in millimeter wave frequency band will become a focus issue [5]. Measurements of the device noise parameters optimum source reflection coefficient, noise resistance and minimum noise figure (NF) are required to design LNAs [3]. The aim of this work is to get the excellent noise figure for low noise amplifier. So, this work will show the importance of Noise Figure (NF) measurements and make known to a modified Fukui model that is very easy to use and predicts NF precisely.

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

II. HIGH-FREQUENCY NOISE MODEL THEORY IN HEMT'S

A spontaneous variation in current or in voltage (Noise) is generated in all electronic devices. The most important types of noise are $1/f^2$ noise, avalanche noise, shot noise, generation-recombination noise, burst noise or random telegraph signal (RTS) noise, 1/f noise (flicker noise) and thermal noise. The types of noise model are van der Ziel, Pucel, Fukui, and Pospieszalski [2]. This work applied Fukui's theory for HEMT design.

A. Derivation of Transconductance and Drain current

The performance of an $Al_{0.83}In_{0.17}N/GaN$ HEMT device is analyses as shown in Figure 1, having a gate length of 6 nm and 100 nm gate width. The physical parameters of the narrow bandgap GaN and the wide bandgap $Al_{0.83}In_{0.17}N/GaN$ HEMT are listed in Table 1 [4]. The shot noise and thermal noise encouraged by the GaN channel layer.

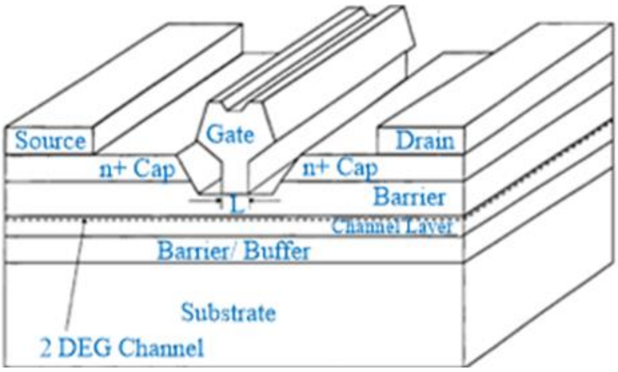

Fig 1:- Al$_{0.83}$In$_{0.17}$ N/GaN HEMT Structure [4]

Material	GaN	Al$_{0.83}$In$_{0.17}$ N
Eg (eV)	4.7	3.4
Lattice constant (Å)	3.190	3.186
ε_0	11.7	9.5
CBO(eV)	-	0.57
VBO(eV)	-	0.73
μ_e (cm^2/(V.s)	1540	940
μ_h (cm^2/(V.s)	82	22

Table 1:- Physical parameters of GaN and Al$_{0.83}$In$_{0.17}$ N

The drain current can be written in general as [7]:

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

Where,

I_d = Drain Current (A)
W = device width (cm)
$n_s(x)$ = sheet charge of the 2DEG (cm−2)
μ = mobility (cm^2/Vs)
V_x = potential difference at a distance x from the source

The charge of capacitance [2], $C = \frac{Q}{V} = \frac{\varepsilon_B}{d+\Delta d}$ is equal $qn_s(x)$, with a voltage along the channel of V_g - V_t - V_x . V_t is the threshold voltage. ε_B and d being the dielectric permittivity and thickness of the AlGaN layer respectively and Δd is the centroid of the electron movement functions in the quantum well. Combining all this together and rearranging [7],

$$n_s(x) = \frac{\varepsilon_B}{q(d+\Delta d)}\left(V_g - V_t - V_x\right) \quad (2)$$

And then by substitution equation 2 in equation 1, the final equation of I_d is

$$I_d = \frac{\mu\varepsilon_B W}{(d+\Delta d)}\left(V_g - V_t - V_x\right)\frac{dV_x}{dx} \quad (3)$$

Consideration over the device length, *L* as:

$$I_d = \frac{\mu\varepsilon_B W}{L(d+\Delta d)}\left[\left(V_g - V_t\right)V_d - \frac{V^2{}_d}{2}\right] \quad (4)$$

The device transconductance, g_m can be defined as the following equation [7],

$$g_m = \frac{\partial I_d}{\partial V_g} = \frac{\mu\varepsilon_B W}{L(d-\Delta d)}V_d \quad (5)$$

B. Thermal Noise

The thermal noise is sometimes called the Johnson noise. This noise is generated by the motion of electrons and holes due to the current excitation. These carriers motion creates a changing voltage each resistive element on the terminals. Although the power on its terminals is not zero, the average value of this voltage is zero. The Nyquist equation for internal noise current or voltage sources can be expressed by the following [3]:

$$V_n^2 = 4KTR\Delta f \quad (6)$$

$$i_n^2 = \frac{4KT\Delta f}{R} \quad (7)$$

According to work of van der Ziel to derive the channel noise, we assume that a thermal voltage noise source, vn, creates a drain noise current fluctuation, ΔId, along the distributed channel. Then the thermal noise current can be written as [7]

$$\left\langle i_d^2 \right\rangle = 4KTg_m\Gamma \quad (8)$$

$$\Gamma = \frac{1 - \frac{V_d}{\left(V_g - V_t\right)} + \frac{V_d^2}{3\left(V_g - V_t\right)^2}}{1 - \frac{1}{2}\frac{V_d}{\left(V_g - V_t\right)}} \quad (9)$$

Where,

$|\Gamma_{opt}|$ = The magnitude of the source reflection coefficient that provides the minimum noise figure, F_{min}.

$\angle\Gamma_{opt}$ = The angle of the source reflection coefficient that provides F_{min}.

C. Flicker Noise

Flicker noise (1/f noise) is produced in all semiconductor devices under biasing. In the low frequency range, the Flicker noise is the main noise. This noise is usually related with defectiveness of a fabrication process or with material failures. The results of other work determine that this noise exists even for very low frequencies (10^{-6} Hz). The spectral density function of flicker noise is directly proportional to 1/f. The Hooge bulk model is more suitable for low noise amplifier. In this noise model, this is uses in the carrier transport two scattering mechanisms of carries that are scattering on impurities and scattering on the silicon lattice. All imperfections of the crystal lattice lead to large 1/f noise. The Hooge model for the noise spectral density function is [3]:

$$S_{1/f} = \frac{\alpha_H I^2}{fN} \qquad (10)$$

Where,

$S_{1/f}$ = Spectral Intensity
α_H = 2 x 10^{-3} is the Hooge constant
N = number of carriers
I = average Current

D. Noise Figure Calculation

The noise figure is 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 gate-to-source capacitance, Cgs, transconductance, g_m, and source and gate resistances, Rs and Rg. In this work, the Fukui equation [7] can be expressed as:

$$F_{min} = 2\left(\frac{f}{f_t}\right)\sqrt{Pg_m\left(R_s - R_g\right)} \qquad (11)$$

Where,

f = operating frequency
g_m = transconductance
R_s , R_g = source and gate resistance
P = a fitting factor described by Fukui model

$$P = \frac{\left\langle i_d^2 \right\rangle}{4KTg_m\Delta f} \qquad (12)$$

$$f_t = \frac{1}{2\pi}\left(\frac{g_m}{C_{gs}}\right) \qquad (13)$$

The gate to source and drain to source capacitance, Source and Gate resistance can be defined as:

$$C_{gs} = C_{gd} = \varepsilon W_g \frac{d + d_i + \Delta d}{L_g} \qquad (14)$$

$$R_s = R_T + R_{Sheet}\frac{L_g}{W_g} \qquad (15)$$

$$R_g = \frac{R_{Sheet}\dfrac{L_g}{W_g}}{LN_{fingers}} \qquad (16)$$

III. RESULTS AND DISCUSSIONS

The device active with an AlInN/GaN HEMT simulated by MATLAB simulation in this work. 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, the drain voltage 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.

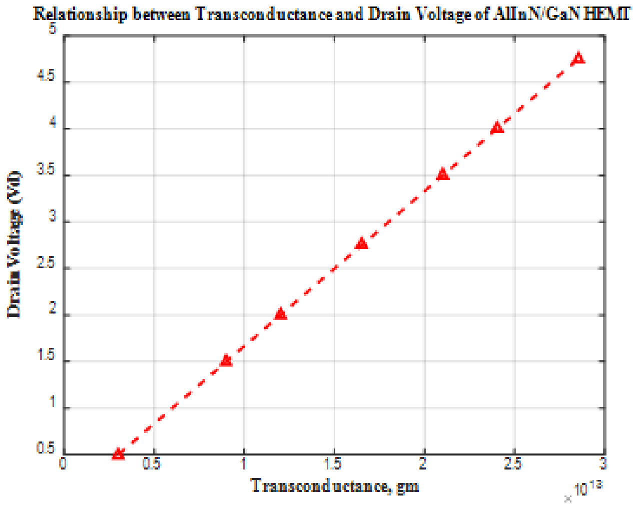

Fig 2:- Transconductance with Respect to Drain Voltage

Figure 2 present the relationship between transconductance and drain voltage for AlInN/GaN HEMT and the g_m value is directly proportional to the drain voltage. So, if the drain current is increased, the g_m is also improved as shown in Figure 2.

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 current. From Figure 3, it can be clearly seen that thermal noise increases with transconductance(g_m) as because thermal noise is directly proportional with g_m and g_m is also directly proportional with V_d.

Flicker Noise is called 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.

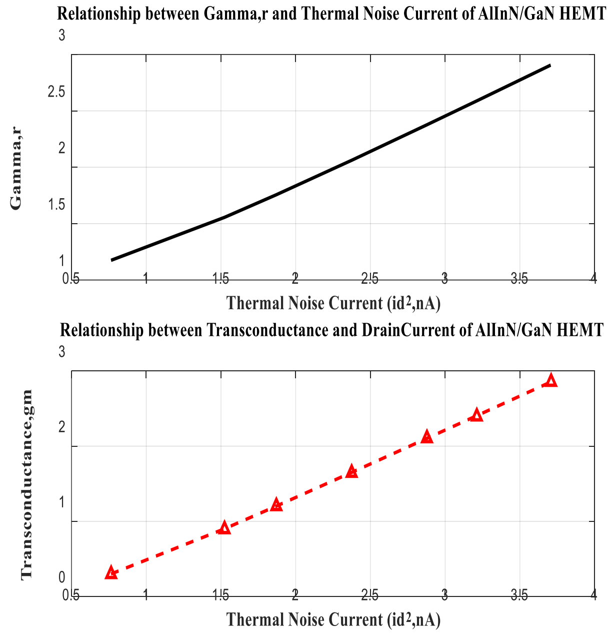

Fig 3:- Transconductance and Source Reflection Coefficient are Varies Based on Thermal Noise

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

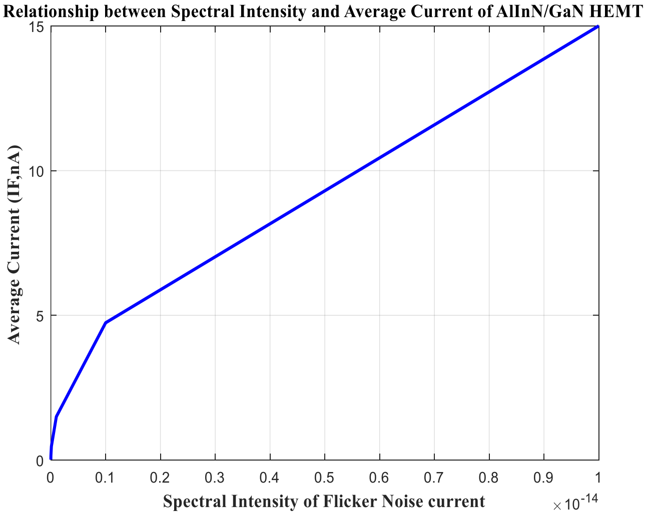

Fig 4:- Relationship between Spectral Intensity and Average Current of AlInN/GaN HEMT

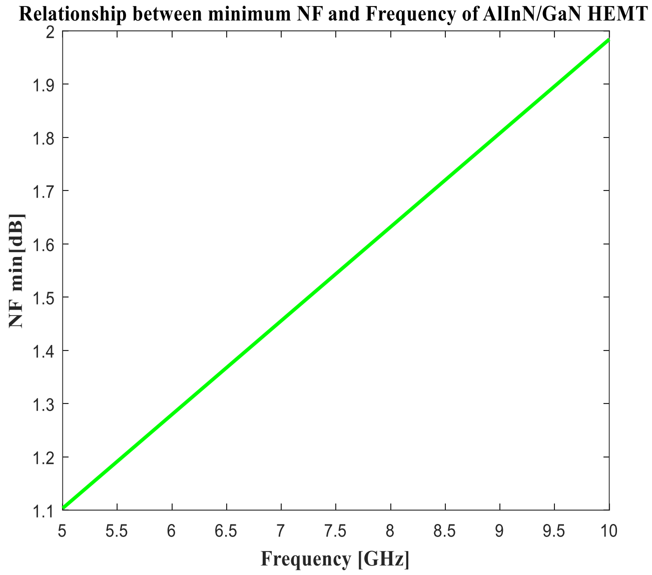

Fig 5:- Relationship between Minimum NF and Frequency of AlInN/GaN HEMT

According to the result of Figure 6, when the ambient temperature is increased, the minimum noise figure is also increased due to the values of parasitic resistances. At that time, the thermal noise is also induced by these effects.

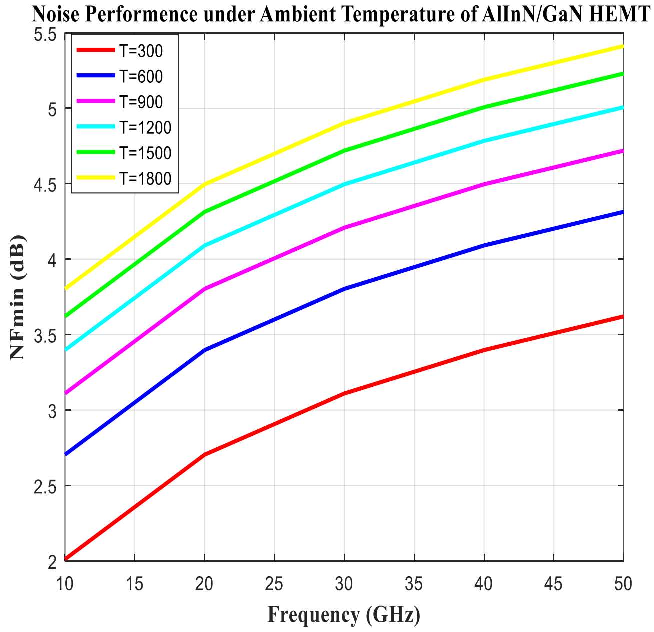

Fig 6:- Noise Performance under Ambient Temperature of AlInN/GaN HEMT

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 dB.

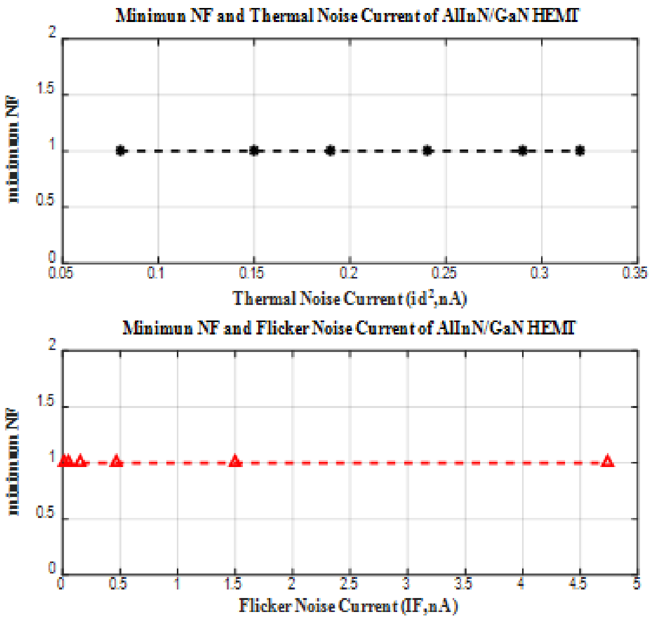

Fig 7

IV. CONCLUSION

Noise Figure close to 1(dB) is good for any device. So, this work observes that the model (AlInN/GaN) shows improved noise performance for the HEMT than other modelling approach designated in other works. The noise performance of AlInN/GaN HEMT has been presented based on temperature variation R_s, R_d and C_{gs}. Moreover, the variation of minimum noise figure based on frequency, transconductance, thermal and 1/f noise current are also discussed. All results are point out the temperature dependent physical appearance of them will have great effect on the NF_{min} and energy band. The results can give a reference for not only high frequency InN-based LNA-PA design but also the low frequency InN-based LNA design. Moreover, InN-based HEMT would be applied under changed ambient temperature and minimum noise figure calculation for different frequency.

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