The Effect of Gate Leakage on the Noise Figure of AlGaN/GaN HEMTs

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***Abstract*—The effect of gate leakage on the noise figure of AlGaN/GaN high electron mobility transistor (HEMTs) is explored. It is shown that these devices have a sizable amount of gate leakage that cannot be ignored when measuring their noise performance. Measurements across a single sample have more than 1 dB of variation in minimum noise figure. We will show this variation is because of gate leakage. A modified van der Ziel model is used to predict this large variation and allows easy noise figure prediction of HEMT and MESFET devices.**

***Index Terms*—AlGaN, GaN, gate leakage, high electron mobility transistor (HEMT), noise figure, van der Ziel.**

I. INTRODUCTION

GALLIUM nitride-based high electron mobility transistors (HEMTs) continue to push the boundaries of power performance [1] and to receive more attention. Power amplifiers (PAs) [2], [3] for cellular base-stations and a few, small, integrated circuits [4]–[7] have already appeared in the literature. A GaN monolithic-microwave integrated circuit (MMIC) transceiver would have advantages over other material systems. Not only would it provide more output power, it would have better efficiency. The receiver low-noise amplifier (LNA) might have lower noise and be more compact to implement in GaN because less input protection circuitry is needed.

To design LNAs, measurements of the device noise parameters (minimum noise figure ($\mathrm{NF}_{\mathrm{min}}$), optimum source reflection coefficient (Γ_{opt}), and noise resistance (r_n) are required. Characterization of GaN HEMTs, including different epitaxial structures, has already been performed [8], [9]. As new structures and devices appear, they need to be characterized for noise in addition to other electrical measurements. A problem with new or existing GaN HEMT devices is gate leakage [10]. The effect of gate leakage in GaAs HEMTs and MESFETs has been studied [11], [12], and some modeling of $\mathrm{NF}_{\mathrm{min}}$ that includes gate leakage for GaN HEMTs has been performed [13], but the significance of gate leakage in GaN HEMTs has not been emphasized nor has modeling been performed for noise parameters other than $\mathrm{NF}_{\mathrm{min}}$. This paper will show the importance of monitoring gate leakage of noise figure (NF) measurements and introduce a modified van der Ziel model [14] that is easy to use and predicts NF accurately.

II. DEVICE DETAILS

A. Structure and Processing

The devices were grown by metal–organic chemical vapor deposition (MOCVD) on a c-plane 4H-SiC substrate. The grown epitaxial structure, from first to last grown layer, are an AlN nucleation layer followed by semi-insulating Fe-doped AlN and GaN buffer layers, the GaN channel layer and finally a 29 nm $\mathrm{Al}_{0.27}\,\mathrm{Ga}_{0.73}\mathrm{N}$ layer. The electron mobility and sheet charge concentration from Hall measurements at room temperature are $1340\ \mathrm{cm}^2/\mathrm{V}\cdot\mathrm{s}$ and $1.18\times10^{13}\ \mathrm{cm}^{-2}$, respectively.

Source and drain ohmic contacts are Ti/Al/Ni/Au formed by electron beam evaporation and annealed at 870 °C for 30 s with a rapid thermal annealer. Devices are isolated by reactive ion etching (RIE) in Cl_2. Stepper photolithography Ni/Au/Ni gates are also deposited by electron beam evaporation with a gate length of 0.7 μm. $\mathrm{Si}_x\mathrm{N}_y$ passivation is performed with plasma-enhanced chemical vapor deposition (PECVD). Devices in this paper have a gate width of 150 μm, a gate–source spacing of 0.7 μm, and a gate–drain spacing of 2 μm. f_T and f_{max} of the devices are typically 22 and 48 GHz. Other than differences in gate leakage the devices presented are similar. The pads are a coplanar waveguide (CPW) layout.

B. Noise Measurements

Noise was measured with an HP 8970S noise figure meter and a Maury Microwave MT982A02 tuner as described in [9]. Error in the system is typically ±0.15 dB. Measurements at 10 GHz of $\mathrm{NF}_{\mathrm{min}}$ versus drain-source current appear in Fig. 1(a), while $\mathrm{NF}_{\mathrm{min}}$ against frequency for the same devices biased similarly ($I_{\mathrm{ds}} = 10$ mA, $V_{\mathrm{ds}} = 5$ V) appear in Fig. 1(b). The three devices are from the same sample and exhibit the following different values of gate leakage, I_{gs}, at a bias of $I_{\mathrm{ds}} = 10$ mA, $V_{\mathrm{ds}} = 5$ V: 22 μA (or 140 μA/mm); 73 μA (or 486 μA/mm); 141 μA (or 940 μA/mm). The gate leakage is from a three terminal measurement, and thus includes drain and source contributions. The devices are very similar in their other characteristics besides NF and gate leakage. In Fig. 1(a) and (b), we see that the $\mathrm{NF}_{\mathrm{min}}$ is larger for devices with higher gate leakage. The difference in NF for devices with low and high leakage can be more than 1 dB, which is significant. This large variation has made it difficult to compare NF of devices from the same sample or different samples if not carefully monitored. We will now present a simple but useful model for predicting the NF that takes into account the gate leakage.

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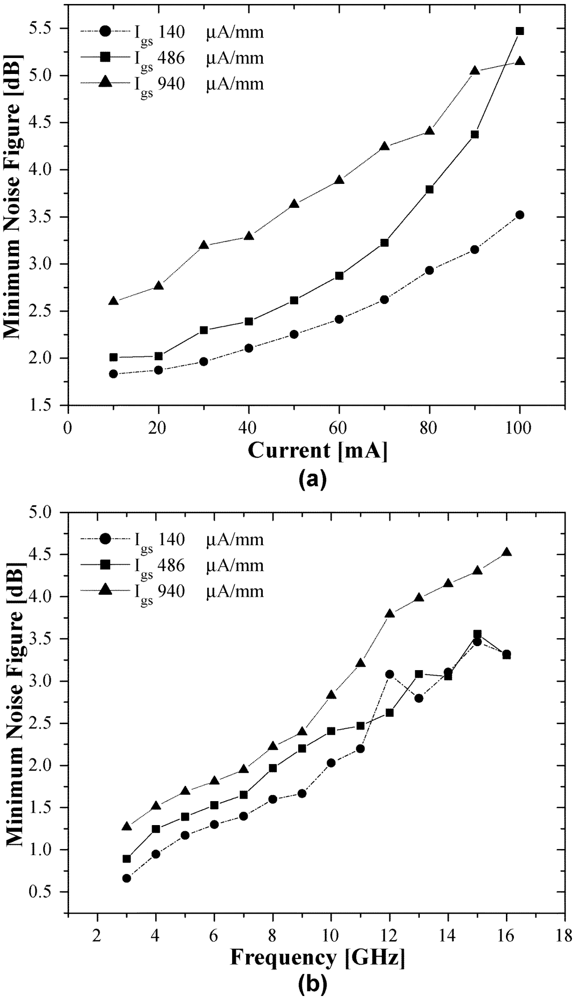

Fig. 1. Measured $\mathrm{NF}_{\min}$ for devices with different gate leakages: (a) noise versus drain-source current at 10 GHz with devices biased at $V_{\mathrm{ds}} = 5$ V and (b) noise versus frequency from 3 to 16 GHz with devices biased at $V_{\mathrm{ds}} = 5$ V and $I_{\mathrm{ds}} = 10$ mA.

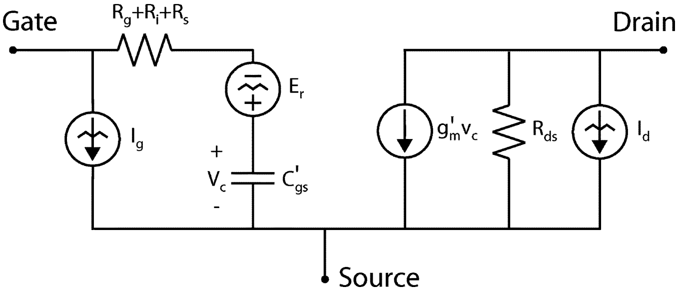

Fig. 2. Circuit used for noise modeling. C_{gs} and g_m are degenerate versions of the intrinsic elements. I_g and I_d are noise current sources and E_r is a noise voltage source.

III. MODELING

The model was kept as simple as possible to explore the effect of gate leakage. A circuit of the model used to derive NF is in Fig. 2. It uses six small-signal parameters and three noise sources. S-parameter measurements were used to extract small-signal parameters for the devices using methods found in [15] and a complete small-signal model. Of these, only R_g, R_i, R_s, C_{gs} (intrinsic), and g_m (intrinsic) are used along with the measured gate leakage. R_{ds} was used in the derivation but cancels in the math. Ignoring the external reactive components will change the predicted Γ_{opt} slightly, but will not affect $\mathrm{NF}_{\min}$. A circuit technique, source degeneration [16], was used to simplify the derivation. This allows lumping the resistance and the thermal noise of R_s with R_i and R_g. It also modifies g_m and C_{gs}. Their standard small-signal model values are replaced with the following degenerate versions

$$C'_{\mathrm{gs}} = \frac{C_{\mathrm{gs}}}{1 + g_m R_s} \tag{1}$$

$$g'_m = \frac{g_m}{1 + g_m R_s}. \tag{2}$$

For simplicity in this discussion, the feedback capacitance, C_{gd}, was neglected. As will be seen, this did not affect our modeling, as has been shown to work in other noise modeling [17].

The noise sources in the model are E_r, I_g, and I_d. E_r is thermal noise of the parasitic resistances (R_g, R_i, and R_s). A shot noise term, I_g, has been added and accounts for the gate leakage. The drain current noise source, I_d, is the same as that given by van der Ziel, with a noise power spectrum of $4kT\Gamma g_m$ (with g_m replaced by g'_m in this model). The factor, Γ, is an electric field-dependent quantity. For FETs operating in the constant mobility region, which is typical when measuring NF of FETs, the factor becomes a constant of 2/3 [14]. To our knowledge, the addition of a shot noise source for the gate leakage, and assuming the noise sources are all uncorrelated, together are new for this model and derivation of NF. The minimum noise figure, $F_{\min}$ (where $\mathrm{NF}_{\min} = 10\log_{10}(F_{\min})$), with this model is found to be

$$\begin{aligned} F_{\min} = 1 &+ \frac{R_{\mathrm{in}}}{R_{\mathrm{opt}}} + b\frac{R_{\mathrm{opt}}^2 + X_{\mathrm{opt}}^2}{R_{\mathrm{opt}}} \\ &+ \frac{a}{R_{\mathrm{opt}}}\left| R_{\mathrm{in}} + R_{\mathrm{opt}} + j\left(X_{\mathrm{opt}} - \frac{1}{\omega C'_{\mathrm{gs}}}\right)\right|^2 \end{aligned} \tag{3}$$

with a, b, ω_τ, and R_{in} defined as

$$a = g'_m \Gamma \left(\frac{\omega}{\omega_\tau}\right)^2 \qquad b = \frac{qI_{\mathrm{gs}}}{2kT}$$

$$\omega_\tau = \frac{g'_m}{C'_{\mathrm{gs}}} \qquad R_{\mathrm{in}} = R_g + R_s + R_i$$

and ω being the angular frequency. R_{opt} and X_{opt} are the optimum source impedance ($Z_{\mathrm{opt}} = R_{\mathrm{opt}} + jX_{\mathrm{opt}}$, with $\Gamma_{\mathrm{opt}} = (Z_{\mathrm{opt}} - 50\Omega)/(Z_{\mathrm{opt}} + 50\Omega)$), and are found to be

$$R_{\mathrm{opt}}^2 = \frac{R_{\mathrm{in}}}{a+b} + \frac{a}{a+b}R_{\mathrm{in}}^2 + \frac{ab}{\left((a+b)\omega C'_{\mathrm{gs}}\right)^2} \tag{4}$$

$$X_{\mathrm{opt}} = \frac{1}{\omega C'_{\mathrm{gs}}}\frac{a}{a+b} \tag{5}$$

These equations were entered into Matlab and used for the simulations that follow in this paper. Using this model, one can examine the relative contribution of various noise sources to NF.

IV. DISCUSSION

The small-signal parameters used for these devices are similar to those used in [9] and are extracted at a bias of $I_{\mathrm{ds}} =$

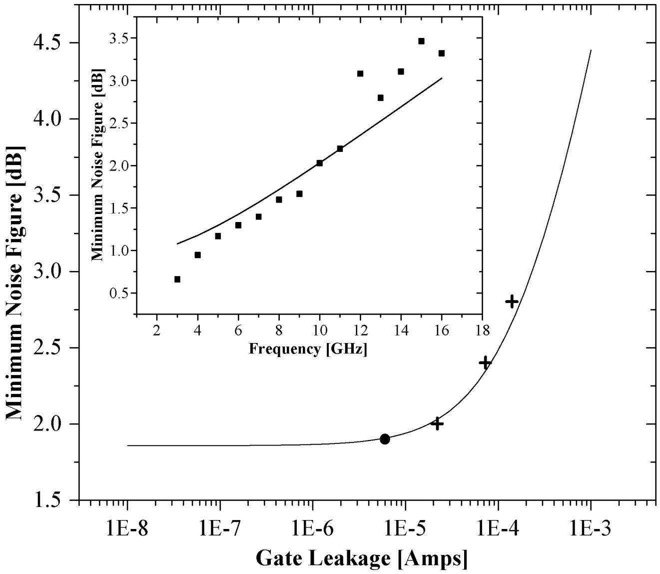

Fig. 3. Simulated effect of gate leakage (line) on $\mathrm{NF}_{\min}$ at 10 GHz for a device with a bias of $V_{\mathrm{ds}} = 5$ V and $I_{\mathrm{ds}} = 10$ mA. Data points (crosses) taken from the measurements in Fig. 1. The circle is from a different sample. Inset: Simulated (line) $\mathrm{NF}_{\min}$ versus frequency for a device biased at $V_{\mathrm{ds}} = 5$ V and $I_{\mathrm{ds}} = 10$ mA with a gate leakage of $I_{\mathrm{gs}} = 140\ \mu\mathrm{A/mm}$. The squares are data taken from Fig. 1.

10 mA and $V_{\mathrm{ds}} = 5$ V. The insert in Fig. 3 shows the measured data from Fig. 1(b) for the 140 $\mu\mathrm{A/mm}$ gate–leakage device along with a line predicted from simulation, validating this model. The model predicts $\mathrm{NF}_{\min}$ and Γ_{opt} well. To study the effect of gate leakage on NF, I_g was varied in the model (Fig. 3). The same small-signal parameters are used for this simulation as in the insert of Fig. 3, but now the leakage is varied from 10 nA to 1 mA. NF increases rapidly for I_g greater than 10 μA. This trend is similar to that observed in [11]. The cross points on the plot are measurements taken from Fig. 1. The solid data point is a device from another sample that had a leakage of 6 μA (40 $\mu\mathrm{A/mm}$) when biased the same as the other devices. The agreement of simulation and measurement is excellent. Increased gate leakage also changes the optimum source impedance, in particular $|\Gamma_{\mathrm{opt}}|$, and was observed in the simulations and measurements.

V. CONCLUSION

We have shown that gate leakage must be monitored while measuring NF of GaN HEMTs. A model was presented that only needs information from two measurements (de-embedded small-signal parameters from *S*-parameter measurements and gate leakage from a multimeter or other instrumentation) to predict $\mathrm{NF}_{\min}$ and Γ_{opt}. The model does not have correlation between noise sources, which can make other models difficult for prediction use. This model is simple, accurate, and can be quickly implemented in a software program, such as Matlab.

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