Flicker Noise in GaN/$Al_{0.15}Ga_{0.85}N$ Doped Channel Heterostructure Field Effect Transistors

A. Balandin, S. Cai, R. Li, K. L. Wang, V. Ramgopal Rao, and C. R. Viswanathan

***Abstract*—We have investigated noise characteristics of novel GaN/$Al_{0.15}Ga_{0.85}N$ doped channel heterostructure field effect transistors designed for high-power density applications. The measurements were carried out for various gate bias V_{GS} and the drain voltage V_{DS} varying from the linear to the saturation regions of operation $V_{DS} > 5$ V. Our results show that flicker, e.g., $1/f$ noise, is the dominant limiting noise of these devices; and the Hooge parameter is on the order of $10^{-5} - 10^{-4}$. The gate voltage dependence of $1/f$ noise was observed in the linear region for all examined V_{GS} and in the saturation region for $V_{GS} > 0$. These results indicating low values of the Hooge parameter are important for microwave applications.**

***Index Terms*— FET's, Gallium compounds, nitrogen compounds, noise measurement.**

300 A	n-$Al_xGa_{1-x}N$	2×10^{18} cm^{-3}
30 A	i-$Al_xGa_{1-x}N$	undoped
500 A	n-GaN	2×10^{17} cm^{-3}
1.2 μm	i-GaN	undoped
17 mils	Sapphire	

Fig. 1. Uncapped layer structure of the doped channel heterostructure field effect transistor with 15% of Al content.

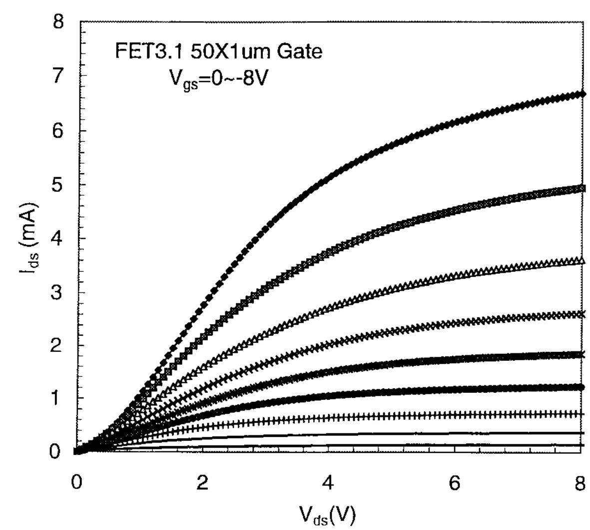

Fig. 2. DC current–voltage characteristics for GaN FET31.

I. Introduction

SOLID-STATE power sources have been significantly improved in recent decades. However, with the continuous demand for higher current and voltage handling capacity, higher frequency band, and increased packing density, the Si-based devices seem to be approaching their theoretical limits of performance. For high-frequency and high-power applications, devices based on GaAs or InP are also limited in their working temperature and life time. Recently, attention was directed to wide bandgap compound semiconductors as an attractive alternative. These materials offer several inherent advantages, such as higher breakdown voltage, higher thermal conductivity, comparable carrier mobility, and high saturation velocity. GaN is among those which show a great promise for high power microwave applications. According to a recently released report, GaN devices—which were nearly nonexistent three years ago—may comprise 20% of the total compound semiconductor market within the next ten years [1]. Recently, Rockwell reported a record power of 2.3 W at 10 GHz from a AlGaN heterostructure field effect transistor (HFET), a value exceeding any other high electron mobility transfer (HEMT) structures [2].

Development of high-performance microwave amplifiers and receivers requires knowledge of the noise behavior of their constituent devices. Particularly, it is important to know the value of flicker noise, e.g., $1/f$ noise, since this type of noise is the limiting figure for all kinds of HEMT's and MOSFET's. Especially, when these devices are used as oscillators or mixers, the flicker noise limits the phase noise characteristics and degenerates the performance of the electronic system. In the past, many researches focused on the flicker noise in Si CMOS, GaAs HEMT, and bipolar junction transistors (BJT's). To date, the noise characteristics of the GaN-based structures have not been investigated. These facts, together with the absence of a commonly accepted noise model for GaN devices, motivated our present study.

II. Device Structure and Measurements

Devices that were chosen for investigation of the flicker noise are GaN/$Al_{0.15}Ga_{0.85}N$ doped channel heterostructure field effect transistors (referred to as GaN FET's) fabricated in our group. The MBE grown layered structure used in

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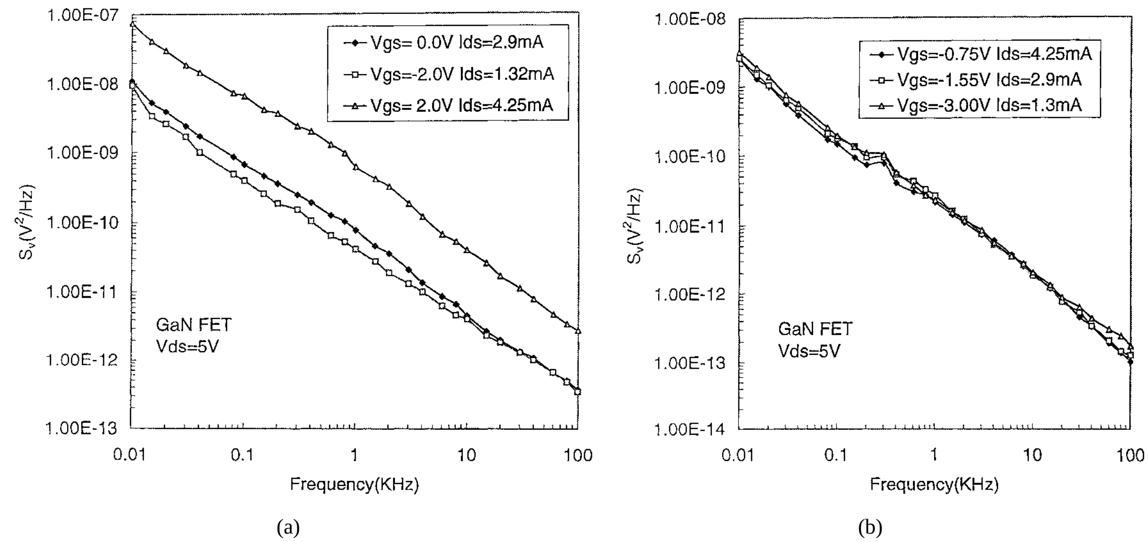

Fig. 3. (a) Input-referred noise spectra for GaN FET31 in the saturation region of operation for different gate bias and (b) input-referred noise spectra for negative values of the gate bias in the saturation region. The gate dimensions are 1 μm $\times$ 50 μm.

our investigation is shown in Fig. 1. We have examined a number of devices with the gate dimensions of 50 $\times$ 1 μm made from the same wafer in order to obtain experimental dependence of the input-referred noise power spectrum on frequency, gate, and drain voltages. The measurements were carried out for both the linear region of the device operation corresponding to low drain-source voltage, V_{DS}, and the saturation region of operation corresponding to $V_{DS} > 5$ V (see the current–voltage characteristics in Fig. 2). Description of the measurement setup and details of the measurements will be reported elsewhere.

Typical noise spectra of our devices for different gate bias V_{GS} at a fixed drain voltage $V_{DS} = 5$ V are shown in Fig. 3. This drain voltage corresponds to the onset of the saturation region of operation for the device. The threshold voltage in both figures is $V_T = -4.6$ V. As one can see, the slope ν of the $1/f^{\nu}$ dependence in all spectra is very close to one, thus we may conclude that the low-frequency noise is indeed dominated by flicker noise. One can also notice from Fig. 3(a) that for the positive gate bias, there is about an order of magnitude difference in noise figure for the spectra at $V_{GS} = 2$ V and at $V_{GS} = 0$ V. This difference becomes very small at negative V_{GS}. Fig. 3(b) shows that the noise spectra change very little as the gate bias voltage varies from 0 to -3 V. Considering the error of the measurement which was estimated to be 10%, we concluded that there is no gate bias dependence for $V_{GS} < 0$ in the saturation regime (high V_{DS}). Since $V_{DS} = 5$ V and is close to $-V_T$, we may assume that this change in the noise behavior is related to the pinch-off conditions, i.e., $V_{DS} = V_{GS} - V_T$.

In the linear regime of operation ($V_{DS} = 0.5$ V), we obtained a pronounced gate voltage dependence of the noise level for $-1.5 \text{ V} < V_{GS} < 1.5$ V. An example of such dependence is shown in Fig. 4 for several values of frequency of operation. We intentionally did not plot this dependence as a function of the effective gate voltage $V_G^* = V_{GS} - V_T$ since V_T itself was a function of V_{DS}. The inset in Fig. 4 shows the V_T versus V_{DS} dependence.

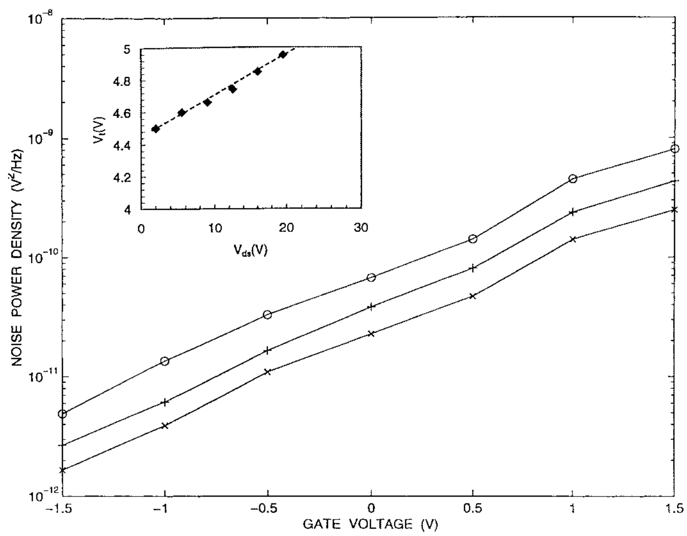

Fig. 4. Noise power spectral density as a function of the gate bias in the linear regime of operation. The results are shown for three frequencies $f = 0.1$, 0.3, and 0.6 kHz from the upper to lower curve, respectively. Inset shows the threshold voltage dependence on V_{DS}.

III. Results and Discussion

The obtained experimental data is not sufficient to determine the exact mechanism of the $1/f$ noise in our devices. In order to have quantitative characteristic of the overall noise figure, we apply the Hooge model which was successfully used for a number of similar devices [3]–[6]

$$\frac{S_V}{V^2} = \frac{\alpha_H}{Nf} \tag{1}$$

where S_V is the noise spectral density of the voltage V across the device terminals (in our case $V = V_{DS}$), f is the frequency, N is the total number of carriers, and α_H is Hooge parameter. From Ohm's law, the number of carriers can be expressed as $N = L^2/Re\mu$ for homogeneous samples. Here μ

is the mobility in the conducting channel, R is the resistance between two device terminals, and L is the distance across device terminals. Finally, the Hooge parameter can be written as

$$\alpha_H = \frac{S_V f}{V^2} \frac{L^2}{Re\mu}. \tag{2}$$

In our case, two quantities (R and μ) in (2) are determined experimentally. The resistance is found at a given V_{DS} during the noise measurements, while the mobility is determined for the layered structure using the Hall measurements. The gate leakage current for the devices was rather small (at least one order of magnitude lower than the drain current), and hence its impact on their noise performance was neglected. The value of α_H calculated using (2) is an approximate number since the conducting channel of the device is not a homogeneous one. Nevertheless, consistent use of (2) for devices similar in their design and with the utilization of the same type of mobility measurements for all devices can give a rather precise comparative characteristic of the device noise. We use the Hooge model and (2) in the linear regime up to $V_{DS} = 5$ V, which marks the onset on the saturation regime (see Fig. 2).

The mobility was determined at room temperature to be $\mu = 650$ cm^2/Vs for FET31A and $\mu = 320$ cm^2/Vs for FET31B. The values of the mobility extracted from the CV measurements were consistent with the Hall mobility measurement. Applying (2) to the noise power spectral density at different frequencies, we calculated the average values of the Hooge parameter at different values of effective gate voltage. The results for $V_{DS} = 5$ V are summarized in Table I. One can see that α_H depends on V_G^* and is smaller than the bulk value of 2×10^{-3} but still much higher than the predicted theoretical low limit $\alpha_H \approx 10^{-9}$ [7]. For comparison, the measured α_H for the commercial GaAs MESFET NEC NE244 device is about 2×10^{-4}, and it is not sensitive to the gate voltage [8]. In AlGaAs/GaAs MODFET's (1 μm $\times$ 300 μm), the Hooge parameter was about 7.2×10^{-5} as reported in [8]. These numbers indicate that the overall noise level in GaN FET's measured at high V_{DS} is comparable to that in conventional GaAs FET's. The noise characteristics of our devices are close to those of CMOS devices examined in [6] with the dominant noise mechanism identified as of mobility fluctuation type. So likely, the noise mechanism in GaN FET's is similar to the one presented in [6], although additional scattering processes (intervalley, defects, etc.) may contribute to the mobility fluctuations. Confinement of phonon modes [9] in a structure made from materials of different elastic properties (Ga and N) may also affect the scattering rates and, thus, noise performance [10], [11].

TABLE I
HOOGE PARAMETER VERSUS EFFECTIVE GATE VOLTAGE

V_G^*, (V)	α_H
2.00	4.9×10^{-5}
3.00	4.2×10^{-5}
3.45	1.1×10^{-4}
4.25	1.6×10^{-4}
5.00	1.7×10^{-4}

IV. CONCLUSIONS

We have investigated noise characteristics of novel GaN/$Al_{0.15}Ga_{0.85}$N FET's designed for high-power microwave applications. Our results indicate that the average value of the Hooge parameter of GaN FET's operating at high drain-source voltages is on the order of 10^{-5}–10^{-4}, which is comparable to the noise level in conventional GaAs FET's. The gate voltage dependence of $1/f$ noise was observed in the linear region for all examined V_{GS} and in the saturation region for $V_{GS} > 0$. These results indicating low values of the Hooge parameter for GaN devices are important for high-power microwave applications.

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