Low frequency noise in GaN/AlGaN heterostructure field effect transistors in non-ohmic region

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Experimental data on the low-frequency noise in GaN/AlGaN heterostructure field effect transistors show that the spectral noise density of the drain current fluctuations, $S_f$, close to the saturation voltage increases faster than the square of the drain voltage $V_d$. At drain voltages higher than the saturation voltage, $S_f$ decreases with a further increase in drain voltage. A model of noise behavior below saturation based on the tunneling mechanism of noise is in a good agreement with the data measured. © 2003 American Institute of Physics. [DOI: 10.1063/1.1574599]

I. INTRODUCTION

GaN/AlGaN heterostructure field effect transistors (HFETs) have demonstrated superior properties for high power and high frequency electronics. One of the most important parameters of microwave transistors is the level of low frequency noise (LFN), which determines the device’s suitablity for microwave applications. The LFN properties of GaN layers and of GaN-based devices have been studied intensively during the last several years. Both 1/f and generation-recombination (GR) noise were found in GaN/AlGaN HFETs, (for a review, see Ref. 5, and references therein). However, all noise measurements were performed at low drain bias that corresponded to the linear regime of transistor operation. For practical application, the noise level in the saturation regime is more important.5–9

In this article, we present experimental data on the low frequency noise in GaN/AlGaN HFETs for a wide range of drain biases from the linear regime to deep saturation. The experimental data obtained are shown to agree with a model based on the tunneling mechanism of noise.10–12

II. DEVELOPMENT OF THE MODEL

In HFETs, the electron concentration in the channel and dc current–voltage characteristic within the framework of the charge control model below the current saturation are given by

$$n_s(x) = \frac{\epsilon \epsilon_0 W}{q d} \left[ V_g - V_t - V(x) \right],$$

where $n_s(x)$ is the electron concentration at distance $x$ from the source, $q$ is the electronic charge, $V(x)$ is the channel potential, $\epsilon$ is the AlGaN dielectric constant, $\epsilon_0$ is the permittivity of vacuum, $d$ is the AlGaN barrier layer thickness, $\mu$ is the low-field mobility, and $W$ and $L$ are the gate width and length, respectively.

$$I_d = \frac{\epsilon \epsilon_0 \mu W}{L d} \left[ (V_g - V_t) V_d - \frac{1}{2} V_d^2 \right],$$

where $n_s(x)$ is the electron concentration at distance $x$ from the source, $q$ is the electronic charge, $V(x)$ is the channel potential, $\epsilon$ is the AlGaN dielectric constant, $\epsilon_0$ is the permittivity of vacuum, $d$ is the AlGaN barrier layer thickness, $\mu$ is the low-field mobility, and $W$ and $L$ are the gate width and length, respectively.

The resistance $\Delta R(x)$ of section $\Delta x$ of the transistor channel is given by

$$\Delta R = \frac{(\Delta x)^2}{q \mu \Delta N},$$

where $\Delta N$ is the number of electrons in a channel area of $\Delta x \times W$.

In Refs. 10 and 11 we showed that the gate voltage dependence of noise in the linear regime is consistent with the number of carrier fluctuations for the origin of 1/f noise in GaN/AlGaN HFETs. Therefore, in our model, we assume that the number of electron fluctuations is the main source of the 1/f noise in GaN/AlGaN HFETs.

The fluctuations $\delta \Delta (N)$ lead to resistance fluctuations $\delta (\Delta R)$ and to open voltage fluctuations across section $\Delta x$, $\delta (\Delta V)$:

$$\delta (\Delta R) = \frac{(\Delta x)^2}{q \mu (\Delta N)^2} \delta (\Delta N),$$

$$\delta (\Delta V) = I_d \delta (\Delta R).$$

Fluctuations $\delta (\Delta V)$ result in drain voltage fluctuations $\delta (\Delta V_d)$:

$$\delta (\Delta V_d) = \frac{[V_g - V_t - V(x)]}{[V_g - V_t - V_d]} \delta (\Delta V).$$
Combining Eqs. (4)-(6) we obtain fluctuations of the drain voltage of the following form:

\[
\delta (\Delta V_d) = \frac{I_d (\Delta x)^2}{q \mu (\Delta N)^2} \frac{[V_g - V_t - V(x)]}{[V_g - V_t - V_d]} \delta (\Delta N).
\]

(7)

As the first step, let us consider GR noise from a single trap. In this case, the \(\delta (\Delta N)\) fluctuation exponentially decays with a single time constant, \(T\), and the autocorrelation function of \(\delta (\Delta N)\) is given by \([\delta (\Delta N)]^2 e^{-t/T}\).

The variance \([\delta (\Delta N)]^2\) can be determined as\[15,16]

\[
[\delta (\Delta V)]^2 = n_{eff} \Delta x W f(t) (1 - f_t),
\]

(8)

where \(n_{eff}\) is the effective sheet density of traps that contribute to noise in GaN and/or AlGaN layers adjoining the channel and \(f_t\) is the occupancy function. Equation (8) is valid when the electron sheet density \(n_s\) is larger than \(n_{eff}\). Generally speaking, \(f_t\) is a function of the voltage applied and hence is a function of the space coordinate. However, to first order, we assume that the traps are distributed homogeneously in space and energy, and the main contribution to LFN comes from traps with energy close to the Fermi level for all channel regions. In other words, we take the occupancy function as \(f_t \approx 0.5\) in the entire channel.

Using Eq. (5) rewritten as \([\delta (\Delta V)]^2 = I_d^2 [\delta (\Delta R)]^2\), along with Eqs. (4), (7), and (8), we obtain

\[
[\delta (\Delta V)]^2 = \frac{n_{eff} d^2 q^2}{\mu W^2 (e_c e_r)^2} \left[ \frac{V_g - V_t - V(x)}{V_g - V_t - V_d} \right]^2 \times f(t) (1 - f_t) dV.
\]

(9)

Integrating Eq. (9) with respect to \(V\), and taking the standard Fourier transform, we find

\[
S_V = \frac{2 \pi \mu n_{eff} d^2 q^2}{W^2 \mu (e_c e_r)^2 (V_g - V_t - V_d)^2} \left( \frac{V_g - V_t}{V_g - V_t - V_d} \right)^2 \left( \frac{\tau f(t) (1 - f_t)}{(1 + \omega^2 \tau^2)} \right).
\]

(10)

Since our analysis is limited to long channel devices, we assume that mobility does not depend on the drain voltage.

The relative spectral noise density of the short circuit current fluctuations can be written as

\[
\frac{S_f}{I_d^2} = \frac{S_V}{I_d^2 R_{ch}} = 4n_{eff}^2 \mu d \frac{\left( \frac{V_g - V_t}{V_g - V_t - V_d} \right)^2 \left( \frac{\tau f(t) (1 - f_t)}{(1 + \omega^2 \tau^2)} \right)}{I_d (e_c e_r) L^2}.
\]

(11a)

As can be seen, noise diverges at the saturation point where \(V_d = V_g - V_t\).

In the linear regime, \(V_d \ll (V_g - V_t)\), and \(\ln (V_g - V_t) / (V_g - V_t - V_d) = V_h (V_g - V_t)\). Then taking into account that \(n_s = e_c e_r (V_g - V_t) / q d\) and channel resistance \(R = (1/q n_s) L / W\), we reduce Eq. (11a) to the conventional formula for GR noise:

\[
\frac{S_f}{I_d^2} = \frac{4n_{eff}^2 \mu d (V_g - V_t)}{n_s^2 W L} \left( \frac{\tau f(t) (1 - f_t)}{(1 + \omega^2 \tau^2)} \right).
\]

(11b)

We can compare Eq. (11a) with the Van der Ziel expression for short circuit current fluctuations in junction FETs (JFETs) based on the assumption that \([\delta (\Delta N)]^2 = \gamma \Delta N^{17}\)

\[
S_f = \frac{4 q \mu \gamma}{L^2} I_d (1 + \omega^2 \tau^2).
\]

(12)

Later, the above approach is used to calculate the noise dependence on the drain voltage in the velocity saturation regime for metal–semiconductor FETs (MESFETs) (Ref. 8) and for GaAs-based HFETs.\[9\]

The transition from GR to 1/f noise can be obtained by integrating over a fairly wide range of values of \(\tau\). Following Ref. 12, we obtain from Eq. (11a) for the tunneling mechanism of noise in HFETs

\[
\frac{S_f}{I_d^2} = \frac{8 n_{eff}^2 \mu d}{3 \pi n_s f} \left( \frac{\tau}{\omega^2} \right)^{1/2},
\]

(13)

where \(J\) (defined in Ref. 12) is of the order of unity and only weakly depends on the frequency. In the linear regime, \(V_d \ll (V_g - V_t)\), and Eq. (13) can be written in the form of the Hooge formula.\[18\] Taking \(f_t = 0.5\) and \(J = 1\) we obtain from Eq. (13)

\[
\frac{S_f}{I_d^2} = \frac{8 n_{eff}^2 \mu d}{3 \pi n_s f} \left( \frac{\tau}{\omega^2} \right)^{1/2}.
\]

(14)

where \(\alpha = n_{eff} / 3 \pi n_s \) is the Hooge parameter and \(N\) is the total number of electrons in the device channel. Note that \(\alpha\) decreases as \(\alpha \approx 1/n_s\) as was experimentally observed in Refs. 10 and 11.

Equations (12) and (13) predict qualitatively different \(S_f (V_d)\) dependencies in the non-ohmic regime. Equation (12) predicts a sharp increase of the noise level close to the threshold value \(V_d = V_g - V_t\). In contrast, Eq. (13) leads to a much slower increase of \(S_f\) with \(V_d\) close to the saturation point (%I\(_d\)const). Equations (12) and (13) describe only the spectral noise density of current fluctuations that originate from the channel, i.e., the relative spectral noise density of the channel resistance fluctuations \(S_{Rch}\):

\[
\frac{S_{Rch}}{S_f} = \frac{S_f}{I_d^2}.
\]

(15)

In real transistor structures, the contribution to noise from contact resistance and from the un gated source–gate and gate–drain regions should be taken into account. The effect of contact resistance, \(R_c\), and of the resistance of the source–gate and drain–gate regions, \(R_s\) and \(R_d\), on the noise properties of field effect transistors has been investigated in several papers (see, for example, Refs. 19 and 20). The expression for the relative spectral noise density of drain current fluctuations that accounts for these resistances is given by\[20\]

\[
\frac{S_f}{I_d^2} = \frac{S_{Rch} R_{ch}^2}{[1 + g_m (R_s + (R_s + R_d)/R_{ch}^2)]^2},
\]

(16)
where $S_{RS}$ and $S_{RD}$ are spectral noise densities of resistance $R_S = R_c + R_t$ and $R_D = R_c + R_d$ fluctuations, respectively, and $g_{mi}$ is the intrinsic transconductance.

III. EXPERIMENTAL DETAILS

The GaN/AlGaN HFETs were grown by metalorganic chemical vapor deposition (MOCVD) on a semi-insulating 4H-SiC substrate. They consisted of a 50-nm-thick AlN buffer layer, 0.4-μm-thick undoped GaN layer, followed by an Al$_{0.2}$Ga$_{0.8}$N barrier layer. As in all our devices, we added traces of indium and carbon to improve the materials quality. The transistors had source–drain spacing of 4–5 μm, gate length, $L$, of 1–1.5 μm, and gate width, $W$, in the range of 50–150 μm. LFN in the special test transistors with very long gates (100 μm) was measured as well.

The LFN was measured in the common source configuration in the frequency range from 1 Hz to 50 kHz.

IV. EXPERIMENTAL RESULTS AND DISCUSSION

The noise spectra of the drain current fluctuations had the form of $1/f$ noise with $\Gamma$ close to unity ($\Gamma = 1.0\sim 1.17$). Using the techniques described in detail in Ref. 22, we checked that neither the contact noise nor the noise from the gate leakage current contributed much to the total HFET noise output.

To find the relative contributions to overall noise from the channel and the ungated regions, i.e., spectral noise densities $S_{Rch}$, $S_{RS}$, and $S_{RD}$, we measured the gate voltage dependence of noise at a small drain voltage that corresponded to the linear regime. In Fig. 1, symbols show the experimental dependence of the relative spectral noise density of current fluctuations on the normalized gate voltage $U_{gn} = (V_g - V_s)/|V_s|$ for two transistors. The solid curve in Fig. 1 was calculated using Eq. (16). We assumed that $g_{mi} \ll R_{ch}^{-1}$ and $g_{mi} \ll R_S^{-1}$. These inequalities are satisfied quite well at small drain bias, $V_d$. We also assumed that the spectral noise densities in Eq. (16) comply with Eq. (14):

$$
\frac{S_{Rch}}{R_{ch}} = \frac{n_{eff}}{3\pi N \tilde{s} f}, \\
\frac{S_{RS}}{R_S} = \frac{n_{eff, DS}}{3\pi N_{GS} n_{DS} f}, \\
\frac{S_{RD}}{R_D} = \frac{n_{eff, DS}}{3\pi N_{GD} n_{DS} f}
$$

(17a)

(17b)

(17c)

where $n_{eff}$ is the effective sheet density of traps in the channel under the gate, $n_{eff, DS}$ is the effective sheet densities of traps in the ungated regions of the transistor, $n_{DS}$ is the electron sheet concentrations in the ungated regions of the transistor (at $V_s = 0$, $n_{DS} \approx n_s$), and $N_{GS}$ and $N_{GD}$ are the number of carriers in the ungated transistor regions.

In order to calculate the gate voltage dependence of noise, the resistances in Eq. (16) were found from the dc measurements of the transistors and TLM structures. The channel concentration’s dependence on the gate voltage was found from capacitance–voltage measurements. The only fitting parameters required for the calculation are $n_{eff}$ and $n_{eff, DS}$.

The values $n_{eff} = n_{eff, DS} = 3 \times 10^{11}$ cm$^{-2}$ give a good fit to the experimental data (see the solid line in Fig. 1). Note that this value of $n_{eff}$ is about two orders of magnitude smaller than the channel electron concentration. Since equal values of $n_{eff}$ and $n_{eff, DS}$ provide very good agreement with the experimental data, we conclude that the surface noise from the open surface of the ungated regions did not contribute much to the total noise, and that the noise properties of the gated and ungated regions of the transistor are close at $V_s = 0.24$.

Figure 2 shows the dependencies of the drain current $I_d$ and of the spectral noise density of short circuit drain current fluctuations $S_I$ at frequency $f = 1$ Hz on the drain voltage $V_d$ for two transistors at gate voltage $V_g = 0$. As is seen, $S_I \propto I_d^2$ for the linear part of the current–voltage characteristic. Close to the saturation voltage, the spectral noise density, $S_I$, increases faster than $\sim I_d^2$. Similar noise behavior at $V_d < V_s$ was reported in Ref. 25 for a GaAs-based HFET.
At drain voltages higher than saturation voltage $V_{ds}$, $S_I$ decreases with a further increase in drain voltage. We doubt that such a decrease has been observed for any type of transistor.

Solid curves 1 and 2 in Fig. 2 were calculated using Eq. (16) for two different dependencies of $S_{Rch}/R_{ch}^2$ on drain voltage $V_d$. For both curves the spectral noise densities $S_{Rch}$ and $S_{RD}$ were taken to be independent of the drain voltage. Curve 1 was calculated using the Van der Ziel model, which gives $S_{Rch}/R_{ch}^2 = R_{stat}$, where $R_{stat} = V_d/\lambda_d$ is the static channel resistance [see Eq. (12)]. Curve 2 was calculated by substituting Eqs. (15), (17b), and (17c) into Eq. (16) ($n_{eff} = n_{eff, DS} = 3 \times 10^{11}$ cm$^{-2}$, $f = 0.5$, and $J = 1$).

As can be seen, both approaches give results that are close to one another. Hence, one can conclude that in real transistors the $S_I$ vs $V_d$ dependencies at $V_d < V_s$ is determined mainly by the influence of $R_S$ and $R_D$ resistance.

In order to reveal the $S_{Rch}/R_{ch}^2$ vs $V_d$ dependence and eliminate the effect of series resistance on LFN, we studied LFN in special test transistors with very long gates (100 $\mu$m). The gate–source and drain–source spacing was 7 and 12 $\mu$m, respectively. In this transistor, the influence of drain $R_D$ and source $R_S$ resistance on the noise behavior was very small. To decrease the effect of $R_D$ and $R_S$ further we studied the drain voltage dependence of noise at negative gate voltages.

Figure 3 shows the dependence of the short circuit drain current fluctuation for the test transistor at $V_g = 0.5V_s$. As can be seen, the test transistor also demonstrates a faster than $1/f$ noise close to the saturation voltage. In the saturation regime, LFN decreases with an increase in drain voltage, similar to the LFN behavior in the transistor with gate length of $L_g = 1 \mu$m. Therefore, the effect of noise reduction at $V_d > V_s$ is determined by processes in the gated channel.

Curve 1 in Fig. 3 is calculated assuming $S_{Rch}/R_{ch}^2 = R_{stat}$ (Van der Ziel model). It is seen that the experimental dependence cannot be fit using this approach. Solid curve 2 is calculated using Eqs. (15) and (16). As is seen, the fast increase of the noise at $V_d \leq V_s$ can be successfully explained by the proposed model. Therefore the drain voltage dependence of noise in long channel devices can be explained by the dependence of the electron distribution in the channel on the drain bias. In long channel devices, the channel is nearly completely depleted on the drain side of the gate at saturation voltage and most of the drain voltage drops across this depleted region that becomes responsible for most of the overall noise. This explains faster than the square of the drain voltage $V_d$ rise in noise close to the saturation point. Hence, our model does not require any assumptions regarding the possible dependence of the capture cross sections or capture time constants on the electric field.

V. CONCLUSION

The low-frequency noise in GaN/AlGaN HFETs was investigated for a wide range of the drain voltages $V_d$ from the linear regime to deep saturation.

In the linear regime, the spectral noise density of the drain current fluctuations, $S_I$, is proportional to the square of the drain voltage, as expected. Close to saturation, $S_I$ increases faster than the square of the voltage. At drain voltages higher than the saturation voltage, $S_I$ decreases with a further increase in drain voltage. This behavior is manifested by the transistors with short gate length $L = 1 \mu$m as well as the special test transistors with $L = 100 \mu$m. For the transistor with $L = 100 \mu$m, the effect of drain and source series resistance on noise is very small, and the observed dependencies are definitely caused by processes under the gate.

A model that accounts for the tunneling mechanism of $1/f$ noise and nonuniform field distribution in the channel was proposed. This model describes the noise behavior below saturation well.

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15. Depending on the surface preparation, passivation, etc., the open surface might strongly contribute to LFN; see, for example, S. L. Rumyantsev, Y. Deng, S. Shur, M. E. Levinshtein, M. Asif Khan, G. Simin, J. Yang, X. Hu, and R. Gaska (unpublished).