Low frequency noise in AlGaN/InGaN/GaN double heterostructure field effect transistors

N. Pala a,b,* S. Rumyantsev a,1 M. Shur a, R. Gaska b, X. Hu b, J. Yang c, G. Simin c, M.A. Khan c

a Department of Electrical, Computer, and Systems Engineering, and Center for Integrated Electronics and Electronics Manufacturing, CH 9017, Rensselaer Polytechnic Institute, Troy, NY 12180-3590, USA
b Sensor Electronic Technology Inc., 1195 Atlas Road, Columbia, SC 29209, USA
c Department of Electrical and Computer Engineering, University of South Carolina, Columbia, SC 29208, USA

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Abstract

Low-frequency noise in AlGaN/InGaN/GaN double heterostructure field effect transistors was measured at room and elevated temperatures as function of gate and drain voltages. Both 1/f noise and generation–recombination (g–r) noises were observed. The Hooge parameter, n, was estimated to be close to $1 \times 10^{-3}$. The activation energy for observed g–r noise was found to be $E_a \sim 1.6$ eV (the largest reported activation energy for GaN based devices). The measurements also confirmed that the double heterostructure provided superior carrier confinement in 2D channel even at high carrier concentrations.

Keywords: Low frequency noise; 1/f noise; Generation–recombination noise; Activation energy

1. Introduction

Group-III nitride heterostructure field effect transistors (HFETs) have demonstrated impressive results in high frequency and high power electronics. Recently novel AlGaN/InGaN/GaN double heterostructure field-effect transistors (DHFETs) have been reported for high power high frequency applications [1]. DHFETs particularly attracted attention since they showed no current collapse in either the pulsed $I-V$ or the RF output power characteristics.

Low frequency noise (LFN) is one of the major factors determining the phase noise characteristics, which are important for applications in microwave and optical communication systems. The LFN properties of GaN and AlGaN thin films and AlGaN/GaN HFETs have been studied in numerous papers [2–6].

In this article, we present experimental data on the LFN in double heterostructure field effect transistors (DHFETs) and compare the results with those of LFN studies for regular AlGaN/GaN HFETs.

2. Experimental details

The double heterostructure employed in this study was grown by low-pressure metal organic chemical vapor deposition (LP-MOCVD) at 76 Torr and consisted of a 1.4 μm undoped GaN buffer layer on i-SiC substrate,
followed by 50 Å In,Ga1-xN layer with x < 0.1 and capped by a 250 Å Al0.25Ga0.75N layer. Traces of indium were present through the structure and played an important role in improving the overall materials quality. The growth temperatures for the GaN buffer, InGaN channel, and AlGaN barrier layers were 1000, 760, and 1100 °C, respectively. Transistors with the gate length and width of 1.5 and 200 μm and source–drain separation of 5 μm and transmission line model (TLM) test structures were fabricated. Ti(200 Å)/Al(500 Å)/Ti(200 Å)/Au(1500 Å) metal layers were used for the ohmic source and drain contacts. Ohmic contacts were annealed at 800 °C for 60 s. Pt/Au Schottky contacts were deposited as gate metal. The room temperature Hall mobility and sheet carrier concentration for the deposited DHFET structures were measured to be 800 cm²/V s and 1 × 10¹³ cm⁻², respectively. This mobility value was lower than typical values of the mobilities for regular AlGaN HFETs (typically around 1000–1500 cm²/V s with the record value of 2000 cm²/V s [7]).

The LFN was measured in the frequency range from 1 Hz to 100 kHz in the temperature interval from 300 to 550 K in the common source configuration at small values of the source–drain bias, Vds (in the linear regime). The voltage fluctuations, Sv, from the 100 Ω resistor connected in series with the drain were analyzed by a SR770 Network Analyzer. The spectral noise density of the short circuit drain current fluctuations, Sd, was calculated using the well-known expression:

\[ S_d = \left( \frac{R + r_d}{R r_d} \right)^2 S_V \]

where R = 100 Ω is the load resistance, r_d is the differential resistance of the device under test. The temperature dependencies of noise were measured with the gate grounded and at a constant drain voltage. The probe station with 10-μm diameter tungsten probes and controlled pressure on the probes provided contacts to the sample pads.

### 3. Results and discussion

#### 3.1. The DC measurements

The capacitance–voltage measurements were performed at frequencies from 1 to 10 kHz on the test Schottky diodes with the area of 4 × 10⁻⁴ cm² in order to find thickness and doping level of the double heterostructure layers. For the entire range of the gate biases, Vgs, (from zero to the threshold voltage, Vt) the gate capacitance was practically constant, manifesting the linear dependence of the electron channel sheet concentration, ns, on the gate bias. The thickness of the double heterostructure barrier layers extracted from the capacitance measurements was 25 nm, in agreement with the estimated value from the growth parameters.

Measurements of the current–voltage characteristics on the TLM structures with W = 200 μm width and distance, L, between the TLM pads ranging from 2 to 20 μm yielded the contact resistance of Rc = 3 Ω mm and the sheet resistance of Rs = 900 Ω/square.

The electron mobility, \( \mu_e \), in 2D gas can be extracted from the measured I–V characteristics:

\[ \mu_e = \frac{L_g}{q n_s W R_{ch}} \]

where \( R_{ch} = R_{tot} - R_{gs} - R_s - R_d \), Rtot is the measured drain–source resistance at low drain bias, Rs is the total series contact resistance, Rgs is the source–gate resistance, and Rg is the series resistance of source-to-gate and gate-to-drain regions, respectively. The values Rg, R_s, and R_d were found from the TLM measurements and known dimensions of the transistor. The sheet concentration, n_s, at the gate bias Vgs was found from capacitance–voltage measurements:

\[ n_s = \frac{1}{q} \int_{V_{gs}}^{V_{gs}} C dV_g \]

where C is the capacitance per unit area, Vgs is the gate voltage, which is taken to be well below the threshold voltage, Vt. Since at Vgs < Vt, the gate capacitance is very small, the chosen value of Vgs does not significantly affect the dependence \( n_s(V_{gs}) \) given by Eq. (3) [8].

Fig. 1 shows the dependence of the electron mobility, \( \mu_e \), in 2D gas on channel electron sheet concentration, n_s. The inset shows the same dependence for SiO₂/AlGaN/GaN MOSHFETs reported in Ref. [9]. As seen in the
figure, in both devices, $\mu_n$ first increases with $n_s$, reaches a maximum value, and then rapidly decreases with a further increase of $n_s$. However the concentration for the maximum mobility in DHFET is $n_s = 1.1 \times 10^{13}$ cm$^{-2}$ which is almost the twice of that reported for MOSHFET. The increase of $\mu_n$ with $n_s$ can be explained by increased screening of ionized impurities and dislocations in the 2D electron gas [10,11]. The subsequent decrease of $\mu_n$ can be attributed to the electron spillover from the 2D-channel to a parallel low electron-mobility "parasitic conduction channel" [12–14]. The higher concentration value corresponding to the maximum mobility in DHFETs is evidence of the superior carrier confinement in the channel of these devices.

### 3.2. Noise measurements

Fig. 2 shows the noise spectrum for a device with $W = 150$ µm at room temperature. As seen, $1/f$ noise is the dominant noise at the temperature of 300 K. The $1/f$ noise level in different semiconductor materials and structures is usually characterized by the dimensionless Hooge parameter, $\alpha$ [15]:

$$\alpha = \frac{S_i}{I^2/N}$$

where $N$ is the total number of the conduction electrons in the sample, $f$ is the frequency of the analysis, $S_i/I^2$ is the relative spectral density of noise. Using the value of $N$ extracted from capacitance–voltage measurements, we found $\alpha \approx 1 \times 10^{-3}$. This value of $\alpha$ is comparable with the values reported for regular AlGaN/GaN HFETs.

Contribution of the contact noise to the measured noise spectra can be determined by the noise measurements on the TLM structures [16].

Assuming that the noise sources are not correlated and located in the contacts and in the channel, the spectral noise density of the current fluctuations can be expressed as follows:

$$\frac{S_{id}}{I^2} = \frac{S_{RCHTLM}}{R_{CHTLM}^2} \left( \frac{R_{CHTLM}^2}{R_{CHTLM}^2 + R_C} \right)^2 + \frac{S_{Rc}}{R_C} \left( \frac{R_{CHTLM}^2}{R_{CHTLM}^2 + R_C} \right)^2$$

where $S_{RCHTLM}$ and $S_{Rc}$ are spectral densities of channel resistance $R_{CHTLM}$ between contact pads, and contact resistance $R_C$ fluctuations, respectively. When $R_{CHTLM} \gg R_C$, the spectral noise density, $S_i/I^2$, should be proportional to $1/L^2$ if the contact noise is dominant ($S_{Rc} \gg S_{RCHTLM}$) and to $1/L$ if the spectral noise density of the channel resistance fluctuations are dominant ($S_{Rc} \ll S_{RCHTLM}$).

Symbols in Fig. 3 show experimental dependence of noise measured at frequency $f = 100$ Hz as a function of the distance between contact pads in the TLM structure. Since this dependence is close to the $1/L$ law, we conclude that contacts do not contribute much to the overall noise.

The concentration dependence of noise in AlGaN/GaN HFETs and SiO$_2$/AlGaN/GaN MOSHFETs has been discussed in the past [8,17]. To assess the concentration dependence of noise, a more accurate procedure of the $\alpha$ extraction should take into account different noise properties of the channel and source-to-gate, gate-to-drain regions, as well as the effect of the series drain and source contact resistances. To account for this difference, we introduce two Hooge parameters: the Hooge parameter for the channel under the gate $\alpha_{Ch}$ and the Hooge parameter for the ungated regions $\alpha_0$. We estimated these parameters using the procedures developed in Ref. [17].

Assuming that the noise sources in gated and ungated parts of the transistor are not correlated the dependence of $\alpha_{Ch}$ on the channel concentration $n_s$ is given by

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Fig. 2. Noise spectra of relative drain current fluctuations of DHFET with $W = 150$ µm $L = 1$ µm.

Fig. 3. The dependence of the relative spectral noise density $S_i/I^2$ on the distance $L$ between the pads of TLM structures. $f = 100$ Hz.
where $R_{Ch}$ and $R_{sd} = (R_s + R_d)$ are resistances of the gated and ungated regions, respectively, $A_{sd}$ is the total area of the drain-to-gate, gate-to-source openings, $n_{sd}$ is the electron concentration in these regions, $n_i$ is the electron concentration in the channel given by the Eq. (3). At $V_g = 0$ the 2D concentrations under the gate and in ungated regions do not differ much. Therefore the value of $a_0$ can be estimated assuming that the value of the Hooge parameter is the same for the channel and ungated regions at zero gate voltage.

Fig. 4 shows the dependence of the Hooge parameter $a_{Ch}$ on the 2D sheet channel concentration, $n_s$, calculated for the DHFETs. At low channel concentrations, $a_{Ch}$ decreases with the increase of $n_s$ as $a_{Ch} \sim 1/n_s$, reaches a minimum and then increases with a further increase of $n_s$. The minimum of the Hooge parameter in Fig. 4 corresponds to nearly the same concentration $n_s$ as the maximum in the mobility curve shown in Fig. 1.

The dependence $a_{Ch} \sim 1/n_s$ is often observed in n-channel Si MOSFETs [18,19] as a result of tunneling of electrons from semiconductor to traps in the oxide. The same dependence was recently observed in AlGaN/GaN HFETs [8] and explained by the tunneling from the 2D gas into the traps in AlGaN or/and GaN layers. Since we observed the same behavior in AlGaN/InGaN/GaN (DHFETs), the measured noise also might be linked to the tunneling mechanism.

There might be several reasons for the increase of the $a_{Ch}$ at high concentration $n_s$. As discussed above, the decrease of the mobility at high concentrations, $n_s$, can be attributed to the electron spillover from the 2D-channel to a parallel low electron-mobility “parasitic conduction” channel. The noise level in such “parasitic channel” could be very large and corresponds to $x \sim (10^{-2} - 1)$ for the bulk GaN [20,21]. Another reasons for $a_{Ch}$ increase are contribution for noise from the forward gate current and from the ungated parts of the transistor which might become dominant when channel noise is very small.

Fig. 5a shows the temperature dependence of the noise spectral density $S/I^2$ in the frequency range from 100 to 3000 Hz. The temperature dependence of the measured noise spectral density has a wide and pronounced maximum at elevated temperatures. The temperature $T_{max}$ corresponding to the maximum noise increases with frequency that is typical for the generation–recombination noise caused by a local level [22–24]. Fig. 5b shows the dependence of $1/kT_{max}$ versus $\ln(f)$ (the Arrhenius plot). The slope of this dependence gives the activation energy $E_a = 1.6$ eV. This is the largest reported activation energy for GaN based devices.

4. Conclusions

LFN in AlGaN/InGaN/GaN (DHFETs was studied within the temperature range from 300 to 520 K. Both,
$1/f$ and generation recombination noise were found. The Hooge parameter, $x$, was estimated to be about 1 $\times 10^{-3}$. Noise measurements on TLM structures showed that contacts do not contribute much to the noise. The activation energy for observed $g$–$r$ noise was found to be $E_a \sim 1.6$ eV. This is the largest reported activation energy for GaN based devices. The concentration dependence of mobility showed that the double heterostructure provided superior carrier confinement in 2D channel at high carrier concentrations. This result might be linked to a smaller energy gap in the InGaN quantum well layer (see recent data on small energy gap of InN [25,26]). At low channel concentrations, $g_{ch}$ decreases with the increasing channel concentration following $1/n_i$ dependence. This dependence might be the evidence of noise generated by electron tunneling to AlGaN barrier layer or to GaN bulk layer.

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