QUANTUM 1/f NOISE IN GaN/AlGAN HFETs AND OTHER NANODEVICES

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1/f Noise is calculated in the channel of AaAlGaN heterojunction field effect transistors, based on the quantum 1/f noise theory. The results are compared with measurements in the literature as a function of gate voltage, and with our own 1/f noise measurements on HFETs fabricated on three substrates: HVPE GaN, sapphire, and SiC.

1. Introduction

AlGaN/GaN HFETs have remarkable initial performance, but degrade appreciably over time, mainly due to a drop in 2-D electron gas mobility. Moreover, the output characteristic compression at high frequencies hinders power and power-added efficiencies. This is a case in point demonstrating the pitfalls of neglecting materials defects on the way to production of devices. Another related observation is that the Hall mobility in the best bulk GaN is well below 1,000 cm^2/Vs whereas in modulation doped structures it approaches 2,000 cm^2/Vs at room temperature. What is also vitally important is the high resistivity or semi-insulating material, which is used for buffer layers where the 2DEG layer is actually formed. The quality of this layer along with the AlGaN layer determines the performance, stability and reliability of a modulation doped HFET. A question is what is the best route towards semi-insulating materials?

At this stage of development, the major device problems are truly materials and design problems, and these are precisely the issues that we are studying with the quantum 1/f approach.

The present paper applies the quantum theory of 1/f noise to predict the 1/f amplitude and phase fluctuations measured on GaN doped channel HFETs, to compare the measured values of the effective Hooge parameter with the theoretical value, and to do the device optimization.

To apply the theory, the HFET channel is first considered here to be similar to a parallelepipedic sample of typical dimensions of 50μm gate width, 500Å channel depth and 1 μm gate length. In second approximation, the reduction in channel conductivity from source to drain is also taken into account, in order to find the effective quantum 1/f parameter that is to be compared with the measured Hooge parameter. In the uniform channel approximation we expect from the 2 10^{17} cm^{-3} doping level a number of electrons per unit channel length of

$$N' = 50\mu m \times 0.05\mu m \times 2\ 10^{17} cm^{-3} = 5\ 10^{9} cm^{-1} \qquad (1)$$

at flatband. This allows us to find the "s"-parameter present in the general quantum 1/f formula. *This "coherence parameter" is the number of charge carriers in a thin salami-*

slice-like section of the sample. “Thin” means twice the classical radius $r_o=e^2/mc^2 = 2.84\ 10^{-13}$ cm of the electron. In our case, the parameter is

$$s = 2 \times 5\ 10^9\ cm^{-1} \times 2.84\ 10^{-13}\ cm = 2.84\ 10^{-3}. \qquad (2)$$

Knowledge of the coherence parameter $s = N'r_o$ allows for the calculation of the quantum 1/f noise parameter in the general nonuniform channel case, with $N=N'(y)$:

$$\alpha_H = [s\alpha_{coh}+\alpha_{conv}]/(1+s) = [2/137\pi(1+s)]\{s + (2/3)(\Delta\mathbf{v}/c)^2\}. \qquad (3)$$

The terms in curly brackets correspond to the coherent and conventional quantum 1/f effect contributions respectively. The effective velocity change $\Delta\mathbf{v}$ of the current carriers is present in the conventional term, and the fine structure constant $\alpha=e^2/\hbar c=1/137$ in both terms, as required by the well known quantum 1/f formulas [2].

2. Theory

The element of resistance dR along the current can be written,

$$dR = dy/(q\mu_n N'), \qquad (4)$$

where μ_n is the electron mobility. The quantum 1/f noise in the element of resistance dR is given by the basic quantum 1/f formula for mobility fluctuations [2]

$$\frac{\langle(\delta dR)^2\rangle_f}{(dR)^2} = \frac{\alpha_H}{f dN}, \qquad (5)$$

where $dN=N'dy$ is the number of carriers in the element of length dy along the channel. Using Eq. (4) for dR, we obtain

$$f\langle(\delta dR)^2\rangle_f = [dR dy/q\mu_n N'] \frac{\alpha_H}{dN} \qquad (6)$$

Multiplying on both sides with the channel current

$$I_{ch} = -dV/dR \qquad (7)$$

and integrating, yields

$$fI_{ch}\langle(\delta R)^2\rangle_f = -\int_{V_s}^{V_d}[dV/q\mu_n N'^2] \qquad (8)$$

Introducing Fermi statistics, for a $GaN/Al_xGa_{1-x}N$ doped n-channel HFET the number of carriers per unit length N’ of the 2-dimensional channel is written in the form

$$N'(y) = ZD_{eff}V_{th}\log\{1 + \exp[(V_G^*-V(y))/V_{th}]\}. \qquad (9)$$

Here $D_{eff}=qm/\pi\hbar$ is q times the effective density of states per unit area. Multiplying Eq. (13) by I/f, this yields the spectral density of V_{DS} fluctuations in terms of device width Z, channel current I, and thermal voltage $V_{Th}=kT/q$

$$<(\delta V_{DS})^2>_f = (|I|/fZ^2 D_{eff} q V_{th}) \int_{X_0}^{X_1} (\alpha_H / \mu_n)[dX/(X-1)\ln^2 X]; \qquad (10)$$

$$X \equiv 1 + \exp\left(\frac{V_G^* - V}{V_{th}}\right). \qquad (11)$$

Here X_0 and X_1 are the values of X at the source (V=0) and at the drain ($V=V_{DS}$), while $\alpha_H=\alpha_H(y)$ is a y-dependent form of the quantum 1/f coefficient introduced in Eq. (3) above. For $(V_G^*-V)/V_{th}<<1$,

$$X-1=(V_G^*-V)/V_{th}, \qquad (12)$$

and the linear approximation of Eqs. (11)-(13) is regained for a 2D quantized channel.

In general, part of the channel may be sub-threshold, starting at $V(y) = V_{sat} = V_{G^*}$. In that case, the use of Fermi statistics becomes unavoidable, as is shown in Eq. (10). However, although Eq. (10) includes the field dependence of α and μ, it fails to reflect the physical situation correctly, because it neglects the impact ionization effect in the subthreshold section of the channel length.

Using the fact that the velocity of the carriers shows strong saturation in the subthreshold section, to include the impact ionization effect, we return to the variable V in Eq. (10), we split up the integral at $V(y) = V_{G^*}-V_{th}$, and write the second, subthreshold, part of the integral separately, with the number of carriers per unit channel length defined as $N' = I_{ch}/qv_s$, where v_s is the saturation velocity,

$$fI_{Ch} <(\delta R)^2>_f = \int_0^{V_{sat}} \frac{\alpha_{coh} dV}{q\mu N'^2} + \int_{V_{sat}}^{V_{DS}} \frac{\alpha_{conv} q v_s^2 dV}{q\mu I_{Ch}^2} \approx \frac{\sqrt{2}}{q\mu} \int_0^{V_{DS}} \frac{\alpha_H(N')dV}{I_{Ch}^2 / q^2 v_s^2 + Z^2 D_{eff}^2 V_{th} \ln\{1+\exp[(V_G^* - V)/V_{th})]\}} \qquad (13)$$

Here α was approximated by its coherent value, α_{coh} in the above-threshold term. We also can approximate the ratio v(E)/E by 3.5 μ_0, where μ_o is the low-field mobility and E is the electric field strength. The last form in Eq. (13) is an approximation in which the two denominators are added, allowing the larger one to prevail automatically, but keeping α in the general form given by Eq. (3). By multiplying both terms of the middle form of Eq. (13) with $I_{ch}/(V_{DS})^2$, one obtains for the spectral density of fractional fluctuations in V_{DS}

$$fV_{DS}^{-2} <(\delta V_{DS})^2>_f = (I_{Ch}/V_{DS}^2)\int_0^{V_{sat}} \frac{\alpha_{coh} dV}{q\mu N'^2} + \int_{V_{sat}}^{V_{DS}} \frac{\alpha_{conv} q v_s^2 dV}{V_{DS}^2 q\mu I_{Ch}} = \frac{1}{V_{DS}\mu}\left\{\frac{\alpha_H^{coh} I_{ch}}{qZ^2 D_{eff}^2 V_{th} V_{DS}} + \frac{\alpha_H^{conv} q v_s^2}{I_{ch}}\left(1 - \frac{V_G^*}{V_{DS}} + \frac{V_{th}}{V_{DS}}\right)\right\} \qquad (14)$$

The second term in curly brackets must be omitted when negative. Multiplying this expression with $L^2/Rq\mu$, one finds a theoretical expression

$$\alpha_{theor} = \frac{I_{ch} L^2}{qV_{DS}^2 \mu^2}\left\{\frac{\alpha_H^{coh} I_{ch}}{qZ^2 D_{eff}^2 V_{th} V_{DS}} + \frac{\alpha_H^{conv} q v_s^2}{I_{ch}}\left(1 - \frac{V_G^*}{V_{DS}} + \frac{V_{th}}{V_{DS}}\right)\Theta()\right\} \qquad (15)$$

for the experimental Hooge constant defined in the usual way by the simple uniform-channel expression $\alpha_{exp} \equiv [fS_V/V^2]\, L^2/Re\mu$. R is here the channel resistance and $V_{G^*} = V_{GS}-V_T$. Here Θ() represents the step function of the quantity in the preceding brackets, defined to be zero for negative argument, and 1 for positive values. The experimental values α_{exp} measured at V_{DS} =5V by Balandin et al. [1], are 4.9, 4.2, 11, 16 and 17, in units of 10^{-5} corresponding to V_{G*} values of 2, 3, 3.45, 4.25 and 5 volts respectively. Eq. (15) yields in the same conditions the values α_{theor} shown in Table I and Fig. 1 below. The agreement is good, with no fudge factors or adjustable parameters.

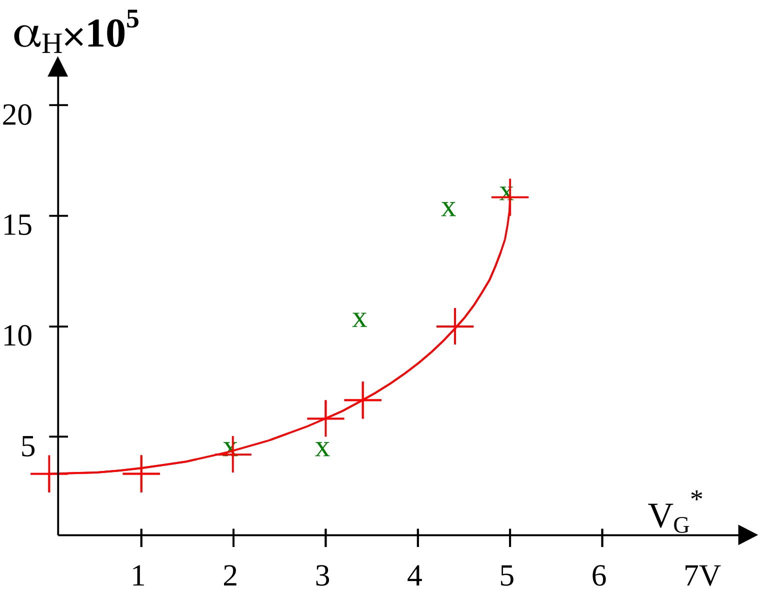

Fig. 1: Comparison of the quantum 1/f first-principles results + with the experimental results **x** of A. Balandin et al., on “Flicker Noise in GaN/AlGaN Doped Channel Heterostructure FETs”, IEEE-Electron Device Letters 19, 475-477 (1998).

TABLE I

Markers						
V_G*/1V	1	2	3	3.45	4.25	5
I_{DS}/1mA		1.9	2.55	3.1	3.8	4.9
$\alpha_H^{theor}\cdot 10^5$ +	2.95	3.6	5.0	7.0	9.91	16 (Eq. 15)
$\alpha_H^{exp}\cdot 10^5$ **x**		4.9	4.2	11	16.0	17

$$\alpha_H^{theor} \equiv [fS_V/V^2]\, L^2/\mathrm{Re}\mu = \frac{I_{ch}L^2}{qV_{DS}^2\mu^2}\left\{\frac{\alpha_H^{coh} I_{ch}}{qZ^2 D_{eff}^2 V_{th} V_{DS}} + \frac{\alpha_H^{conv} q v_s^2}{I_{ch}}\left(1 - \frac{V_G^*}{V_{DS}} + \frac{V_{th}}{V_{DS}}\right)\right\}$$

$$\equiv \frac{L^2}{1\mu^2}\cdot\left(\frac{92.4\,cm^2/V\,s}{\mu_{eff}}\right)^2\cdot\left(\frac{5V}{V_{DS}}\right)^2\left\{2.4\ 10^{-5}\left(\frac{50\mu}{Z}\right)^2\frac{5V}{V_{DS}}\left(\frac{I}{1.9mA}\right)^2 + 1.95\ 10^{-5}\,\frac{\alpha_H^{conv}}{4.1\ 10^{-6}}\left(\frac{v}{10^7 cm/s}\right)^2\left(1 - \frac{V_G}{V_{DS}} + \frac{V_{th}}{V_{DS}}\right)\right\}$$

3. Experiment

We report investigation of low frequency noise through measurement of heterostructure field effect transistors (HFETs) grown on various substrates, SiC, Sappire, and HVPE. The experimental results are discussed and are compared with the quantum theory of 1/f noise.

Low frequency noise can be described in terms of resistance fluctuations, $\delta R/R$. If the current in a circuit is held constant, $\delta R/R$ equals the fractional voltage fluctuations $\delta V/V$ at the end of samples or device under study. We denoted the spectral density of fractional resistance fluctuations with $S_{\delta R/R}(f) = R^{-2}\langle(\delta R)^2\rangle_f$. The main experimental results are:

(1). At Vg = 0, the lowest $S_{\delta R/R}(f)$ was measured for a HFET on the SiC substrate with $S_{\delta R/R}(f) = 3.9 \cdot 10^{-13}$, followed by with $S_{\delta R/R}(f) = 2.0 \cdot 10^{-11}$ on Sapphire, and the noisiest, with $S_{\delta R/R}(f) = 7.8 \cdot 10^{-11}$ on HVPE.

(2). When Vg changes from 0 volt to –3.0 volts for HEFT on SiC, the $S_{\delta R/R}(f)$ increases from $1.24 \cdot 10^{-12}$ to $1.64 \cdot 10^{-10}$, about two orders of magnitude.

Agreement between the experimental values and the theory values is remarkable, as shown in Table II below. This research also indirectly proves that increasing the device channel width is very effective for decreasing the low frequency noise. This is very important for high power density microwave generation.

The apparatus is in Fig. 2 below, a typical spectrum and background in Fig. 3.

Table II

Substrate	R_{DS}/Ω	V_{DS}/V	$fS_{\delta R/R}$	α exp	αtheor
HVPE					
STD3	36	0.9	7.8E-11	9.99E-5	3.0E-5
Sapphire					
STD7	20.5	0.27	2.0E-11	2.06E-5	2.7E-5
SiC					
STD12	37.3	0.53	3.9E-13	2.69E-7	1.5E-7
STD4	40.4	2.1	1.24E-12	7.92E-7	3.3E-6

As shown in Fig. 2, the gate voltage V_G of the device under test is controlled with a Rheostat Rh. The devices were open, i.e., not capped. The agreement can be improved by including the 1/f noise of the series resistance present in the device.

In conclusion, the quantum 1/f theory yields a reliable description of 1/f noise in HFETs and can be used to optimize the devices based on a convenient figure of merit.

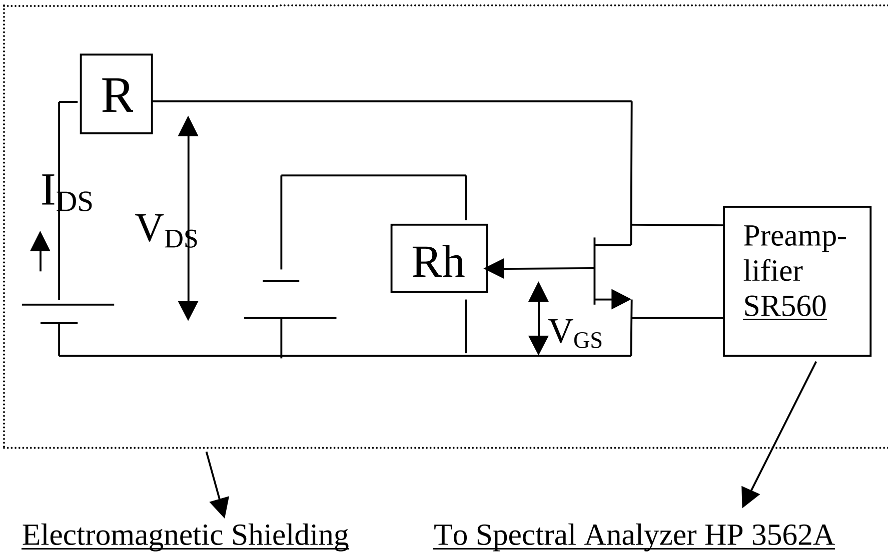

Fig. 2: Experimental Set-Up. As shown in Fig. 1, the gate voltage V_G of the device under test is controlled with a Rheostat Rh. The devices were open, i.e., not capped. They were never touched in any way.

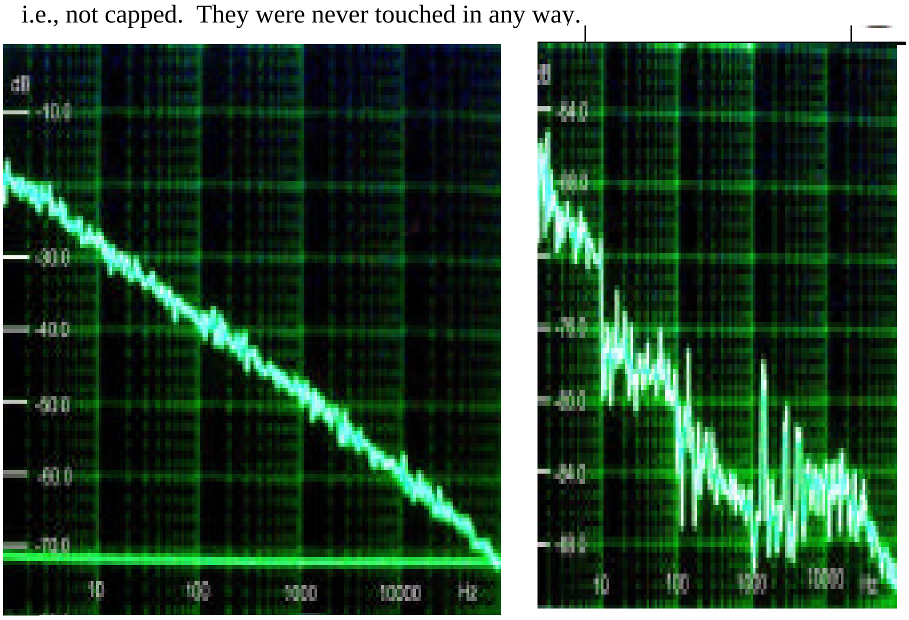

Fig. 3: Typical 1/f noise spectrum of the HFET channel, with the much lower background measured by us, on the right.

References

[1] A. Balandin, S. Cai, R. Li, K.L. Wang, V. Ramgopal Rao and C.R. Vishwanathan, Flicker Noise in GaN/$Al_{0.15}Ga_{0.85}N$ Doped Channel HFETs, IEE-ED Transactions 19, 475-477 (1998)

[2]. P.H. Handel, Noise, Low Frequency, Wiley Encyclopedia of Electrical and Electronics Engineering, vol. 14, pp. 428-449, John Wiley & Sons, 1999.