1/f Noise: A Window to HFET Stability

Peter H. Handel*[a], Taher Sherif[a], Cemil Kayis[b], Jacob Leach[b], Congyong Zhu[b], and Hadis Morkoç[b]
[a]Physics & Astronomy Dept. and Center for Nanoscience, Univ. of Missouri, St. Louis, MO 63121
[b]Virginia Commonwealth University, ECE Department, Richmond, VA 23284

ABSTRACT

A new stability criterion for heterojunction field effect transistors (HFETs) is introduced and discussed in terms of our own stress-induced degradation experiments on the GaN varieties. The new criterion explains how to choose the sheet conductance of the 2 DEG electron plasma in the channel and the temperature dependence of the spontaneous polarization in the gate insulation for maximal stability against stress-induced degradation. According to this criterion, for maximal stability against thermal breakdown, the sheet conductance is chosen to be in a well defined vicinity of the resonance of the optical phonons with the plasma frequency of the electrons in the channel. The first steps toward studying this concept experimentally have been taken by monitoring the 1/f noise of the HFETs both at baseband and through phase noise, i.e., with exponential modulation, and comparing to the extent possible at this point with the results of the quantum 1/f noise calculation. Our measurements of 1/f noise on pristine devices and on stressed devices, degraded by sustained high drain bias, show that even a small 8% decrease in the maximal drain current produces some 5-10 dB increase in the 1/f noise power. The latter is thus a much more sensitive indicator of damage. The quantum electrodynamic (QED)- and quantum lattice-dynamic (QLD) quantum 1/f noise formulas have been refined for the case of AlGaN/GaN HFETs through a better definition of the coherence parameters s and s'.

Keywords: HFET stability against thermal breakdown, QED and Piezoelectric Quantum 1/f noise, InAlN/AlN/GaN and AlGaN/GaN HFETs optimization and reliability, Noise in HFETs and MODFETs, 1/f noise-based FET/HFET reliability optimization and testing.

1. General Theory

FETs and HFETs have evolved in time, to some extent through trial and error, leading to better devices with larger transconductance, g_m, higher frequency cutoff, and lower noise figure, including lower *1/f* noise. This has been achieved by increasing the total gate width W of the device to hundreds of microns or millimeters in high power cases, and by reducing the length L to submicron magnitudes. Modern HFETs are thus very wide, narrow and thin, with a thickness $t<<L<<W$. The current flows along the short channel and perpendicular to the large width W. This geometry is inherently unstable against filamentation (taken to mean locally hot region) in the stationary high drain bias, high channel current, stress regime. The devices have a tendency to fail in some section of the large width W.

In our previous paper we investigated how this instability can be reduced by balancing the local conductance increase caused by a random fluctuation that raises the local temperature with an opposing effect.[1] Such an opposing effect is the reduction in spontaneous polarization of the specially designed AlGaN gate insulation layer, a reduction that would be triggered by the same random temperature increase. Indeed, if the polarization decreases, then the carrier density would decrease as well, and that would keep the random temperature fluctuation from generating a local hot spot that could initiate breakdown in a snowballing process. *The present paper includes experimental evidence of 1/f noise increase in damaged devices, and adds another opposing effect that can be used to stabilize the GaN HFET even better against the thermal runaway that is likely to occur under increased stress from large source to drain bias.* This second opposing effect is connected to the recently discovered resonance between the optical phonon frequency and the plasma resonance mode of the 2D channel. The resonance, if present, provides an up to 30 times faster decay of longitudinal optical phonons through interaction with plasmons, i.e., quanta of electrostatic waves in the plasma of current carriers, usually electrons. Since electrons strongly interact in GaN with longitudinal optical phonons, they are usually in thermal equilibrium with each other, perhaps at 600 K, when a strong drain bias is applied under stationary conditions close to breakdown. *We will consider this homogeneous, uniform, stationary pre-breakdown condition as the unperturbed initial state to which our stability investigation is applied.* Consider an HFET that is uniform in the direction of the large width of the device (e. g., width W=200 μm, with a submicron length L), with a uniform heat convection loss rate per unit width $r(T-T_o)$, where r is the heat exchange coefficient of the electrons and optical phonons with the rest of the lattice and the surroundings that are at a temperature T_o. The heat diffusion equation along the width coordinate z is

$$C\frac{\partial T}{\partial t}-\kappa\nabla^2 T=-r\left(T-T_o\right)+\sigma V^2+\sigma_G V_G^2 \tag{1.1}$$

where C is an effective heat capacity per unit width in the z direction, κ the heat conduction coefficient in the z direction, $\sigma\left(T,V_G\right)$ is the source to drain electrical conductance per unit width, V=V_{DS} the applied source to drain voltage, $\sigma_G\left(T\right)$the conductance per unit width of the gate insulation, and V_G =V_{GS} the gate to source voltage. The unperturbed stationary form of Eq. (1.1) is

$$r\left(T-T_o\right)=\sigma\left(T,V_G\right)V^2+\sigma_G\left(T\right)V_G^2 \tag{1.2}$$

Consider now an arbitrarily small temperature perturbation. Without loss of generality, it can be considered as a superposition of Fourier components

$$T'==Ae^{i(kz-\omega t)}=Ae^{-i\omega t}e^{-ikz}Ae^{\gamma t}e^{-ikz} \text{ with } -i\omega=\gamma \tag{1.3}$$

with arbitrarily small $A_{k,\omega}$. Substituting the solution T+T' into Eq. (1.1) and subtracting Eq. (1.2) we obtain the linearized equation

$$\left(-i\omega C+\kappa k^2\right)=-rT'+\frac{\partial\sigma}{\partial T}T'V^2+\frac{\partial\sigma_G}{\partial T}T'V_G^2 \tag{1.4}$$

This yields the heat stability criterion (H-criterion)

$$\gamma C = i\omega C = -r - \kappa\left(\frac{\pi}{L}\right)^2 + pV^2 + qV_G^2 < 0. \qquad (1.5)$$

Here we have set $k = l\pi / L$ with l=1. The modes with higher n will then also be stable, having a negative time-dependent exponent, γt, which exponentially attenuates the initial perturbation. If the parameters r, κ, p and q, averaged over the length from source to drain, satisfy this inequality (1.5), the HFET or FET is expected to be stable against temperature fluctuations, which would otherwise lead to the filamentation instability, provided we neglect the self-constricting action [2] of the own magnetic field of the temperature and current fluctuation. This self-constriction is particularly large in the presence of a p-n junction or n-n+ junction with reverse bias, but less important in the FET and HFET case with low gate currents. Since $q>0$, this limits the applied gate voltage in general, for which stability can be achieved. It depends very much on $p=p_1+p_2$, which has two components of opposite signs. Indeed, since $s = s(T,n)$ we write

$$p=p_1+p_2, \text{ with } p_1 = \frac{d\sigma}{dT} = \frac{\partial\sigma}{\partial T} + \frac{\partial\sigma}{\partial n}\left(\frac{\partial n}{\partial T_{th\ activ}} + \frac{\partial n}{\partial T_{plasmon}}\right) = \frac{E_a\sigma}{T^2} > 0 \qquad (1.6)$$

where E_a is the relevant thermal activation energy for carriers in the (doped or unintentionally doped) channel. Here $\frac{\partial\sigma}{\partial n}\frac{\partial n}{\partial T_{plasmon}}$ is the derivative of the effective conductivity in the given high-bias stationary regime *w.r.t.* the temperature, modified by the plasmon resonance with the longitudinal optical phonon frequency. We also introduced the usually negative

$$p_2 = \frac{d\sigma}{dT_{polariz}} = \frac{\partial\sigma}{\partial P}\frac{\partial P}{\partial T} < 0 \qquad (1.7)$$

Indeed, the spontaneous polarization of AlGaN/GaN HFET gate insulation layers decreases with temperature, although to a lesser extent in this displacive type ferroelectric than in order-disorder types. The polarization of high-κ FET insulation layers also tends to decrease with temperature, in general. The carrier concentration in the channel is proportional to the spontaneous polarization of the AlGaN gate insulation in GaN HFETs, and therefore $p_2<0$. For stability, the absolute magnitude of p_2 should be chosen large enough to satisfy the inequality (1.5), which also implies $p<0$.

The effect of the plasmon resonance at the optical phonon frequency is displayed by differentiating the logarithm of the simple conductivity formula

$$\ln\sigma - 2\ln e - \ln\nu - \ln m + \ln n \qquad (1.8)$$

where $\nu = 1/\tau = \nu_{acoust} + \nu_{oph}$ is the total collision frequency. Neglecting the acoustic phonon scattering rate *w.r.t.* the optical, we obtain

$$\frac{\partial s}{\partial T} = s\left[\frac{1}{n} + \left(\frac{\partial t}{\partial n_{oph}}\right)\left(\frac{\partial n_{oph}}{\partial n}\right)/\tau\right]\left(\frac{\partial n}{\partial T}\right) = \sigma\left[1 + \left(\frac{\partial t}{\partial n_{oph}}\right)\left(\frac{\partial n_{oph}}{\partial n}\right)\frac{n}{\tau}\right]\left(\frac{E_a}{kT^2}\right) \qquad (1.9)$$

Therefore,

$$p_1 = \frac{ds}{dT} = \sigma\left[1+\left(\frac{\partial t}{\partial n_{oph}}\right)\left(\frac{\partial n_{oph}}{\partial n}\right)\frac{n}{\tau}\right]\left(\frac{E_a}{kT^2}\right) \tag{1.10}$$

One can easily deduce that lowering p_1 will increase stability in the context of reliable operation. This is possible if we choose the high drain bias operating point to have a channel carrier density right above the resonance density, at which the plasma frequency in the channel matches the optical phonon frequency. Then $(\partial n_{oph}/\partial n)$ is very large and positive, recovering after a sharp resonance minimum of the longitudinal optical phonon occupation numbers. The factor $(\partial n/\partial n_{oph})$ is always negative, since the lifetime of the carriers between collisions with optical phonons decreases when the phonon numbers increase, enhancing the electron-phonon collision frequency.

In the framework of the above analysis, we conclude that indeed, when a small local temperature increase fluctuation occurs in this case at some value of z, the carrier concentration increase is more likely to decay exponentially, because in Eq. (1.5) both terms in p can be negative. The first term p_1 is negative since we selected a sheet concentration that has the largest slope $(\partial n_{oph}/\partial n)$ slightly above the resonance concentration. The second term p_2 is negative because the spontaneous polarization in the AlGaN is decreasing with any increase in temperature.

Summarizing the general theory section, it can be stated that to optimize a HFET or FET against the H-instability, choose the sheet concentration of the channel slightly above the plasmonic resonance concentration where the slope $\partial n_{oph}/\partial n > 0$ is maximal, and we need to provide enough ferroelectric or high-κ gate dielectric with a sufficiently high negative temperature derivative of the polarization or of κ, in order to satisfy the criteria (1.5) or

$$p = p_1 + p_2 < 0 \quad and \quad pV^2 + qV_G^2 < 0 \tag{1.11}$$

at the chosen operational value of $V=V_{DS}$ and of the gate voltage V_G. For an HFET with spontaneously polarized gate insulation generating the current carriers in the channel, a sufficiently large negative temperature derivative of the magnitude of the spontaneous polarization is needed in order to satisfy conditions (1.5) and (1.11).

Present day HFETs do not satisfy our new stability criterion yet. Therefore, they are degraded prematurely under high bias conditions, as we see in the next section.

2. Experimental

The lattice matched InAlN/AlN/GaN HFET structures were grown on (0001) sapphire substrates in a low-pressure custom-designed Organo-Metallic Vapor Phase Epitaxy (OMVPE) system using trimethylgallium (TMGa), trimethylaluminum (TMAl), trimethylindium (TMIn), and ammonia as the Ga, Al, In, and N sources, respectively [3].The structure consisted of a 250 nm AlN initiation layer grown at ~1030ºC, 3 µm of undoped GaN deposited at ~1000ºC, a 1 nm AlN spacer layer grown at 1000ºC, a 20 nm $In_{0.15}Al_{0.85}N$ barrier layer grown at 800ºC, and a 2 nm GaN cap layer grown at 900ºC. HFET devices and a gated Hall bar were fabricated using Ti/Al/Ni/Au Ohmic contacts followed by etched mesa isolation in a SAMCO inductively coupled plasma (ICP) etcher in a Cl-based chemistry. Finally, the standard liftoff procedure was used to form gate electrodes of Pt/Au (thickness 30/50nm, length/width 2/90μm). The devices were not passivated. We subjected the HFET devices to high field stress (V_D=20V) in the dark at room temperature. We stressed the devices for periods of time up to 20 hours, and observed the maximum drain current, peak transconductance, and channel access resistances every hour or half hour in order to quantify the device degradation, details of which can be found elsewhere [4]. In that work we simultaneously, measured the gate leakage current during the stress and observed the level of degradation, at a fixed electron density, as a function of the total charge passed through the drain and the gate electrodes. The degradation was observed to have a minimum at the optimum sheet density corresponding to the Plasmon- LO phonon resonance where the LO phonon lifetime is minimum. In this work we are interested in finding out the low frequency signature of device degradation. In this vein, as-fabricated devices and those that underwent the above mentioned stress were characterized using an Agilent E5505 phase noise measurement system, following the single spur calibration method.

Our spectral noise measurements on stressed and non-stressed HFETS show a change in 1/f noise, due in part to a form of the breakdown instability mentioned above in Sec. 1, and also due to structural modifications that affect both the QED-type and the Quantum Lattice Dynamical (QLD), i.e., piezoelectric, type of quantum 1/f noise present.

The increase in 1/f noise is what results when the effective width is reduced by about one order of magnitude, e.g., from 90μm to 1 μm. Indeed, since the quantum 1/f (coherence-) s-parameter only slowly increases with the width *W* when it gets to be larger than the length, we can consider the conventional quantum 1/f noise contribution to be dominant. The spectral density of the fractional quantum 1/f fluctuations is proportional to *1/W*, so when the instability develops in the linearized system of equations that describe small fluctuations, an exponential increase of the most unstable mode leads to the creation of a preferred current path from source to drain, of width *W'=W/a*, where *a* is introduced here as the current concentration ratio.

The width *W'* of the damage area in damaged devices is expected to be of the order of the longitudinal diffusion constant for electrons in the direction of the width of the devices, which is of the order of the effective longitudinal diffusion constant about *W'*=1μ for our InAlN/AlN/GaN HFETs. Therefore, the quantum 1/f noise spectral density *S'* will be increased in the stressed devices when compared with the unstressed devices, where it is denoted by *S*

$$S'(f) = \frac{W}{W'} S(f) \tag{1.12}$$

This inverse proportionality of the 1/f noise expected on the basis of the quantum theory of 1/f noise is displayed in the simplified expression of the quantum 1/f noise in FETs and HFETs, Eq. (3.8) below.

Changing gears a little to begin the discussion of the manifestation of defects in terms of their contribution to noise, we present the dependence of the LO phonon lifetime on the sheet density in Figure 1, as discussed in detail in [5]. Because LO phonons have hardly any group velocity, the thermal conductivity of the system is determined by the motion of the LA phonons (after the LO modes have decayed into the mobile LA modes). As such, long LO phonon lifetimes would imply reduced reliability, which also has been recently demonstrated experimentally [4]

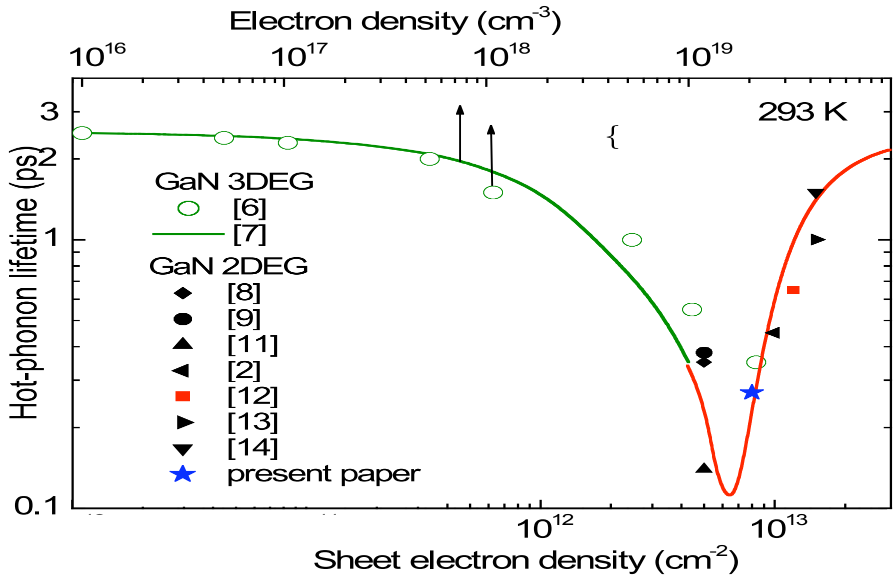

Fig. 1: Dependence of hot-phonon lifetime on electron density at zero electric field for GaN (open circles, top scale) and at low supplied power for GaN 2DEG channels (closed symbols, bottom scale). After references 4 and 5.

Indeed the reliability measurements, as judged by the reduction of the drain current after stressing at 20 V drain bias and under various gate biases in an attempt to control the channel density, indicate that the minimum degradation takes place when the sheet density is consistent with the shortest LO phonon lifetime [6], as shown in Fig. 2.

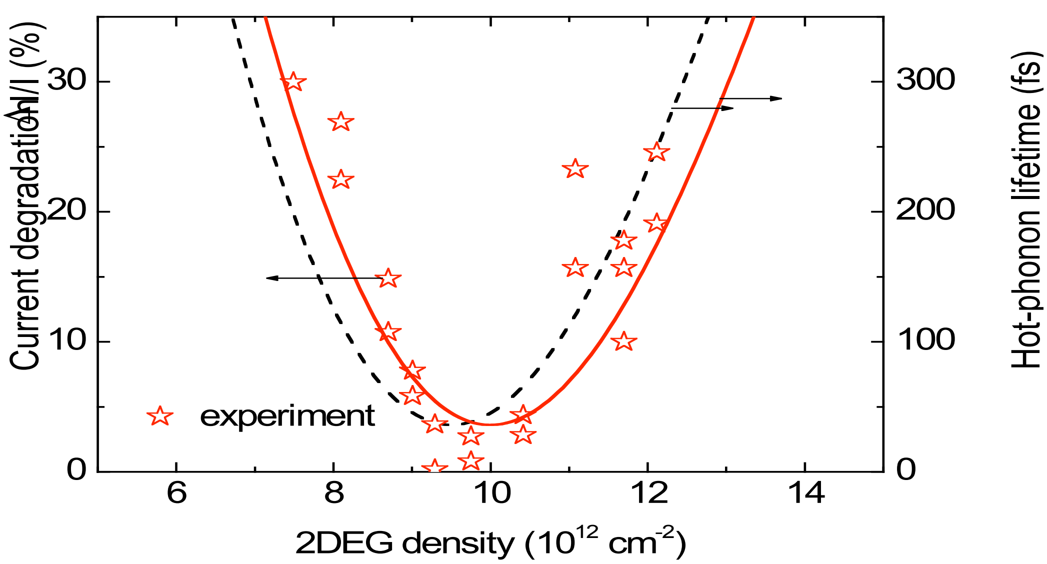

Figure 2. Density dependence of drain current degradation under drain voltage of 20 V for $In_{0.15}Al_{0.85}N/AlN/GaN$ HFETs (reference **Error! Bookmark not defined.**). Curves represent

calculations for resonance 2DEG densities: 9.5×10^{12} cm^{-2} (dashed curve) and 1×10^{13} cm^{-2} (solid curve).

What has been a proverbial problem and ironically of prime interest is to find the genesis of the degradation. One would naturally assume that the local heating due to heat retention by the inability of LO phonons to decay to LA phonons efficiently together with a complicated polarization field which is inherently inhomogenous, being caused by inhomogenities in the crystal, would cause defects which could be detected in the generation recombination noise, not to mention its manifestation as 1/f noise. At the moment it is a daunting task to make a clear correlation. However, if we ever hope to do that clear correlation, the process which at the beginning will be less than ideal must start. In this spirit, we have undertaken low frequency measurements utilizing the phase noise route in AlInN barrier GaN HFET that have undergone various stages of degradation. As shown in Figure 4, the group of devices that have undergone DC stressing which resulted in a change in the maximum drain current of >20% exhibits more low frequency noise, as compared to the group which has undergone DC stressing resulting in a change of the maximum drain current of <10%. The spikes in the spectrum are spurious contributions and should be neglected. The figure also indicates that the noise floor of the instrument with all the cabling, etc., is much lower than the low frequency noise component associated with the devices. Check if we have >20% or >30% degraded? More importantly, the effect of stress on the 1/f noise for a device that has undergone stress for 10 hrs at a drain bias of 20V is shown in Figure 5. The fact that the device only suffered ~8% decrease in the maximum drain current after stress, yet showed a 5-10dB increase in the 1/f noise demonstrates that *the 1/f noise measurement is more sensitive to device degradation than typical IV characteristic based techniques*.

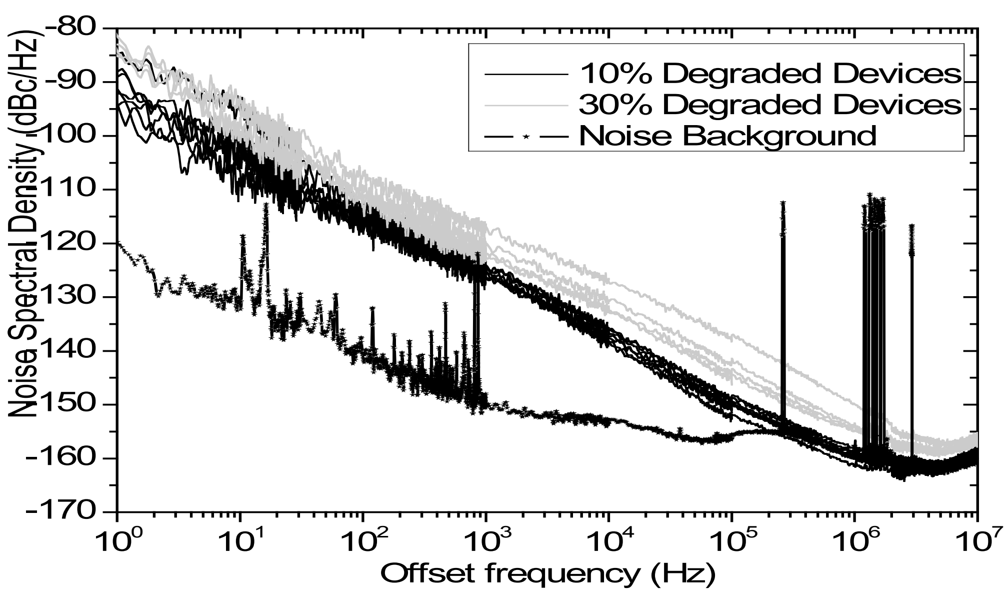

Figure 4. Low frequency noise spectrum for two groups of AlInN barrier GaN HFETs that have undergone stress resulting in >20% and <10% changes in maximum drain current along with the noise floor of the measurement setup including cabling, etc. The low frequency noise spectra have been obtained using a phase noise measurement apparatus calibrated using the single spur calibration method with the aid of a spectrum analyzer. Make figure 20%?

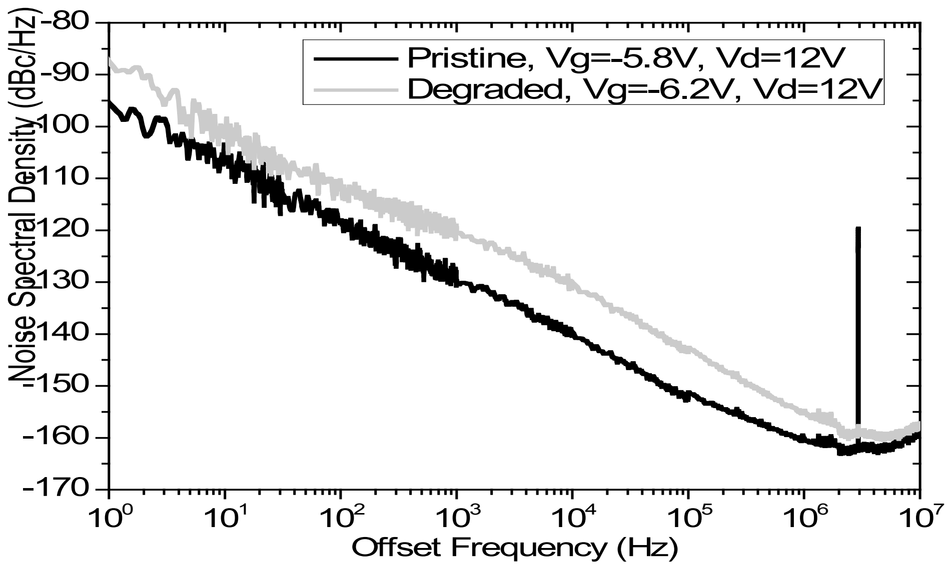

Figure 5. Low frequency noise-spectral-density for a pristine device (no stress applied before measurement) and for the same device but degraded under 10 hours of 20 V stress applied prior to measurement. Although stress resulted in 5-10 dB increase in the 1/f noise power of the device, the change in maximum drain current after stressing for 20hr was only 1.5%. Gate (V_g) and drain (V_d) bias conditions are given in the figure legend. These parameters are set to operate the HFET at the maximum power output to feed the detector of our noise measurement setup.

3. Quantum Theory of 1/f Noise in HFETs

The 1/f resistance fluctuations δR in a biased semiconductor yield voltage fluctuations. They are caused by conventional and coherent quantum 1/f effects (Q1/fE), given by the general quantum 1/f formula[78], shown below in Eq. (3). It contains the coherence parameter $s = 2N'r_0$ where N' is the number of current carriers per unit length in the direction of current flow, and $r_0 = e^2/mc^2 = 2.84.10^{-13}$ *cm* is the classical radius of the electron.

The Coherent Q1/f E arises in a beam current of charged particles, from the definition of the electron as a bare particle plus a coherent state of the electromagnetic field. The expression for the power spectral density of fractional fluctuations given by the coherent quantum 1/f effect theory is

$$S^{coh}_{\frac{\delta R}{R}}(f) = \frac{2\alpha}{\pi f N} \qquad (3.1)$$

The Conventional Q1/f E is a fundamental quantum fluctuation of physical cross sections σ and process rates Γ. The Conventional Q1/f E is caused by the bremsstrahlung energy and momentum losses of charged particles, when they are scattered or accelerated in any way. The spectral density is given by

$$S^{conv}_{\frac{\delta R}{R}}(f) = \frac{4\alpha}{3\pi fN}\left(\frac{\Delta v}{c}\right)^2 \qquad (3.2)$$

Both components of quantum 1/f noise are combined in the general quantum 1/f formula

$$S_{\frac{\delta R}{R}} = \frac{1}{1+s}S^{conv}_{\frac{\delta R}{R}}(f) + \frac{s}{1+s}S^{coh}_{\frac{\delta R}{R}}(f) \qquad (3.3)$$

where the coherence parameter, $s = 2N'r_0$, indicates to what extent the energy of the drift motion of the electrons adds up coherently or conventionally over the cross section of the current, in the Hamiltonian. The spectral density fractional fluctuations aisre related to the fractional fluctuations spectral density in each region using the following relation

$$S_{\delta R} = R^2 \cdot S_{\frac{\delta R}{R}}(f) \qquad (3.4)$$

For V_{DS} constant, the spectral densitiesy of current and resistance fluctuations are related by

$$\frac{S_{\delta R}}{R^2} = \frac{S_{\delta I}}{I^2} \qquad (3.5)$$

The element of resistance *dR* along the current-carrying channel can be written $dR = dy/(q\mu_n N')$, where μ_n is the electron mobility. The quantum 1/f noise in the element of resistance dR is given from Eq. (3.3) by the basic quantum 1/f formula for mobility fluctuations, $(dR)^{-2}<(\delta dR)^2>_f = \alpha_H/fdN$, where $dN=N'dy=ntdy$ is the number of carriers in the element of length dy along the channel of thickness t and concentration n. The 1/N dependence of Eqs. (3.1)-(3.3) is used to define an effective Hooge parameter $\alpha_H = \alpha_{eff}$. Substituting, we obtain $f<(\delta dR)^2>_f = [dRdy/q\mu_n N']a_H/dN$. Multiplying on both sides with the channel current, $I_{ch} = -dV/dR$, and integrating, yields

$$fI_{ch}<\delta R)^2>_f = -\int_{V_s}^{V_d}[dV/q\mu_n N'^2] \qquad (3.6)$$

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 $N'(y) = WD_{eff}V_{th}\log\{1 + \exp[(V_G^*-V(y))/V_{th}]\}$, where $D_{eff} = qm/\pi\hbar$ is q times the effective density of states per unit area. Multiplying Eq. (3.6) by I/f, this yields the spectral density of V_{DS} fluctuations in terms of device width W, channel current I, and thermal voltage $V_{Th}=kT/q$, with $X=1+\exp[(V_G^*-V)/V_{th}]$

$$<(\delta V_{DS})^2>_f = \frac{|I|}{fW^2D_{eff}qV_{th}}\int_{X_0}^{X_1}(\alpha_H/\mu_n)[dX/(X-1)\ln^2 X] \qquad (3.7)$$

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 the y-dependent quantum 1/f coefficient.

In this case of FETs and HFETs of much larger width $W>>L_{DS}>t$, the kinetic energy E_k of average motion with drift velocity v_d per unit length in the direction of L_{DS} is still given by $Nmv_d^2/2$, but the magnetic energy E_m per unit length in the direction of L_{DS} is roughly proportional with the first power of *W* only, instead of W^2, and can be approximated by $E_m = \pi[\ln(W/2L_{DS})]L_{DS}[nevS/c]^2/W$. This indicates decoherence along the device width *W*. This yields a coherence ratio of $s \equiv E_m/E_k \approx$

$\pi n r_o t L_{DS} \ln(W/2L_{DS})$, which shows that only an effective width $W = W_{eff}$ about equal to L_{DS} should be used in the calculation of the coherence parameter s in this special case; larger widths are subject to de-coherence. This favors lower, mainly conventional, quantum 1/f noise in these devices, in spite of the large values of *W*. It also explains for the first time why the huge widths are possible with impunity, i.e., without causing the much larger coherent quantum 1/f noise to affect the device.

In general, part of the channel may be sub-threshold (the part closer to the drain), starting at $V(y) = V_{sat} = V_G^*$. The use of Fermi statistics becomes unavoidable, as is shown in Eq. (3.4). However, although Eq. (3.4) 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 sub-threshold section of the channel length. This effect is roughly included below in a first approximation, along with the variation of AlGaN polarization with y, by dividing the channel along its length into a coherent and conventional parts.

Using the fact that the velocity of the carriers shows strong saturation in the sub-threshold section, to include the impact ionization effect, we return to the variable V in Eq. (3.7), we split up the integral at $V(y) = V_G^* - V_{th}$, and write the second, sub-threshold, 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, Multiplying Eq. (3.7) by the (modulation) frequency f, and dividing by the channel current I_{Ch}, we obtain for $(f/I_{Ch})<(V_{DS})^2>_f$ the equivalent expression

$$
\begin{aligned}
fI_{Ch} < (\delta R)^2 >_f &= \int_0^{V_{sat}} \frac{\alpha_{eff} dV}{q\mu N'^2} + \int_{V_{sat}}^{V_{DS}} \frac{\alpha_{conv} q v_s^2 dV}{q\mu I_{Ch}^2} \\
&\approx \frac{V_{DS}}{\mu I_{Ch}} \{ \frac{\alpha_{eff} I_{ch}}{qZ^2 D_{eff}^2 V_{th} V_{DS}} + \frac{\alpha_{conv} q v_s^2}{I_{ch}} (1 - \frac{V_G^*}{V_{DS}} + \frac{V_{th}}{V_{DS}}) \}
\end{aligned}
\tag{3.8}
$$

This form of $(f/I_{Ch})<(V_{DS})^2>_f$ directly displays the quantum 1/f resistance fluctuations, which are the fundamental quantity, allowing the calculation of quantum 1/f fluctuations in both current or voltage, frequency or phase, depending on whether the channel is interrogated at baseband or at high frequency. However, this result displays only the QED form of quantum 1/f noise, and even this one only if we neglect the contribution of the series resistances from source to channel and from source to drain. More detailed formulas, including the noise from the series resistances, can be found in[9]. In ferroelectric materials we also find the quantum lattice-dynamic (QLD), or piezoelectric, form of 1/f noise, which strongly depends on the size and shape of the sample.

The quantum-electrodynamic (QED) quantum 1/f noise formulas have been recently refined for the case of AlGaN/GaN HFETs and FETs through a better definition of the coherence parameter, *s*, with much better agreement with the experiment. Indeed, for a FET/HFET width $W>>L>t$, where the parameters represent the gate width, the source-drain separation, and channel thickness or the gate to channel separation whichever applies, this yielded $s=\pi n r_0 t Log(W/2L)$ instead of the old formula, $s=2nr_0tW$, where *n* represents the carrier density, and $r_o=2.8\cdot 10^{-13}$ cm is the classical radius of the electron. Here we generalize this basic result for the first time to a finite piezoelectric case. In piezoelectric materials, particularly those also showing ferroelectric spontaneous polarization, transverse phonons are the massless quanta leading to large piezoelectric, or lattice-dynamic, quantum *1/f* effects, both conventional and coherent. As in the usual QED case, the parameter '*s*' yields the observed *1/f* noise as a weighted sum of conventional and coherent quantum *1/f* effects. The HFET piezo-coherence weighting parameter "*s*'", derived here is $\left(g_m N'\hbar / m^* v_s\right)\left(v_s / u\right)^3 F\left(v_s / u\right) t / 12W$, with $N' = nLt$, v_s the piezo-phonon speed, u the drift velocity, and $F(x)$ is a function defined as $\left(2/3\right)x^3$ for $x<<1$. Here $x=v_S/u$ and g_m is the transconductance. The parameter *s*' is $\sim t^2$, which is much smaller than its value in bulk GaN or AlGaN, and is important for reliability and device optimization, because it reduces the coherent piezoelectric quantum 1/f noise contribution. For HFET stability, when the temperature increases, a slower increase of thermally activated conductivity is found to be needed for stability along the large device width *W*. Indeed, that increase must be overcompensated by a decrease caused by two other heating induced effects: the decrease in the spontaneous polarization of the gate insulation and the approach of the plasmonic resonance of the optical phonons.

4. Conclusions

In summary, what could be construed as a first step has been taken to illuminate the manifestation of defects in HFETs that have undergone various protocols of DC stress as low frequency noise. It can be stated that the current degradation has been unquestionably linked to LO phonon lifetime and in this framework the electron concentration leading to the shortest LO phonon lifetime exhibiting the least current degradation. In terms of the low frequency noise, we demonstrated that the noise level is very sensitive to device degradation and very importantly even in cases when there is little current degradation due to stress, the noise level is seen to increase markedly. One can then conclude that the low frequency noise measurements are very sensitive to minute levels of degradation in devices. While there is considerable work that remains to be done to explain the observations in terms of their physical origin, we have begun the process along this important journey.

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