New factors affecting HFET stability, 1/f noise and reliability

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ABSTRACT

We have explored the practical applicability of our recently found stability criterion for HFETs with spontaneous polarization of the gate insulation, to determine in which conditions the criterion is satisfied. In essence, the criterion requires a faster decrease of the spontaneous gate polarization than of the resistivity when temperature increases locally. The instability will be stronger in certain temperature intervals, and will result in degradation and 1/f noise increase. The implications for engineering design for increased device reliability at large positive gate bias and high power dissipation are analyzed. Our criterion and optimization principle also includes the effect of the plasmon-optical phonon resonance effects in the channel, which could even reverse the channel resistance decrease when temperature is raised in the stationary regime.

Keywords: Quantum 1/f Noise, Piezoelectric Quantum 1/f noise, AlGaN/GaN HFETs optimization and reliability, Noise in HFETs and MODFETs, MISHFET, 1/f noise-based FET/HFET reliability optimization and testing.

1. INTRODUCTION

Our recently found stability criterion [i] provided stability against thermal breakdown in a section of the large width of HFETs whenever a local temperature increase leads to a faster decrease of the ferroelectric and piezoelectric AlGaN gate insulation polarization, faster than the local decrease in channel resistivity. It turns out, however, that the pyroelectric coefficients for AlGaN are relatively low, so most of the stabilization needs to be obtained by reducing and even reversing the channel resistance decrease, based on the influence of the plasmon-optical phonon resonance effects in the channel, in the stationary regime. Indeed, pyroelectric coefficients, describing the changes of the spontaneous polarization with temperature, are measured to be very small [ii], [iii]. Chang et al. [iv] showed that the effect of pyroelectric coefficients on the channel current at high temperature is negligible. The piezoelectric polarization can be determined from the elastic and the piezoelectric constants. It is found to be nonlinear in terms of the alloy composition. The temperature dependence of piezoelectric polarization is also expected to be very small, as in spontaneous polarization. Nevertheless, in certain temperature domains, it may turn out not to be so small, as we see from the general analysis in Sec. 2 below.

The temperature dependence of the channel conductivity, on the other hand, at least in stationary conditions, can show abnormal decrease when temperature rises, in certain conditions, as we show in Sec. 3. This can lead to the stability criterion being satisfied in carefully chosen stationary conditions, which is most beneficial for device stability and reliability under high bias and thermal stress.

2. TEMPERATURE DEPENDENCE OF THE FERROELECTRIC POLARIZATION IN THE ALGAN GATE INSULATION

Landau's expression for the free Energy F per unit volume in a very long sample, or in a large torus-shaped sample with an internal macroscopic field E and polarization P, is given by

$$F(P,T,E) = -EP + g_o + g_2P^2/2 + g_4P^4/4 + g_6P^6/6 + \ldots \qquad (2.1)$$

In AlGaN we have a finite energy difference when the critical temperature is reached and the sample suddenly looses its poarization. For first order ferroelectric transitions we have $g_4<0$; $g_6>0$. $g_2=\gamma(T-T_o)$, since g_2 must go through zero at some temperature T_o, if the sample is ferroelectric.

Considering E=0, we obtain the equilibrium spontaneous polarization Ps at the temperature T by setting

$$\partial F/\partial P=0 = \gamma(T-T_o)P_s - |g_4|P_s^3 + g_6P_s^5 \tag{2.2}$$

This yields either

1) $P_s = 0$;

or,

2) $\gamma(T-T_o) - |g_4|P_s^2 + g_6P_s^4 = 0$; Then $P_s^2 = |g_4|/2g_6 + [(|g_4|/2g_6)^2 + \gamma(T_o-T)/g_6]^{1/2}$

$$= |g_4|/2g_6 + [(\gamma/g_6)(T_c-T)]^{1/2}; \quad \text{Here we denoted } T_c = T_o + (g_6/\gamma)(g_4/2g_6)^2 > T_o. \tag{2.3}$$

The temperature derivative of the equilibrium polarization can get very large:

$$\partial P_s/\partial T = -(\gamma/4g_6)\{(T_c-T)(|g_4|/2g_6 + [(\gamma/g_6)(T_c-T)]^{1/2})\}^{-1/2}$$

$$\partial P_s/\partial T = -\infty \quad \text{for } T = T_c \qquad (T < T_c) \tag{2.4}$$

We conclude that the temperature derivative is negative, as we have expected, and can have considerable magnitude in the vicinity of the critical temperature. Here is the qualitative behavior of the free energy F as a function of spontaneous polarization at various temperatures (Fig. 1). The polarization is displayed qualitatively as a function of temperature in Fig. 2.

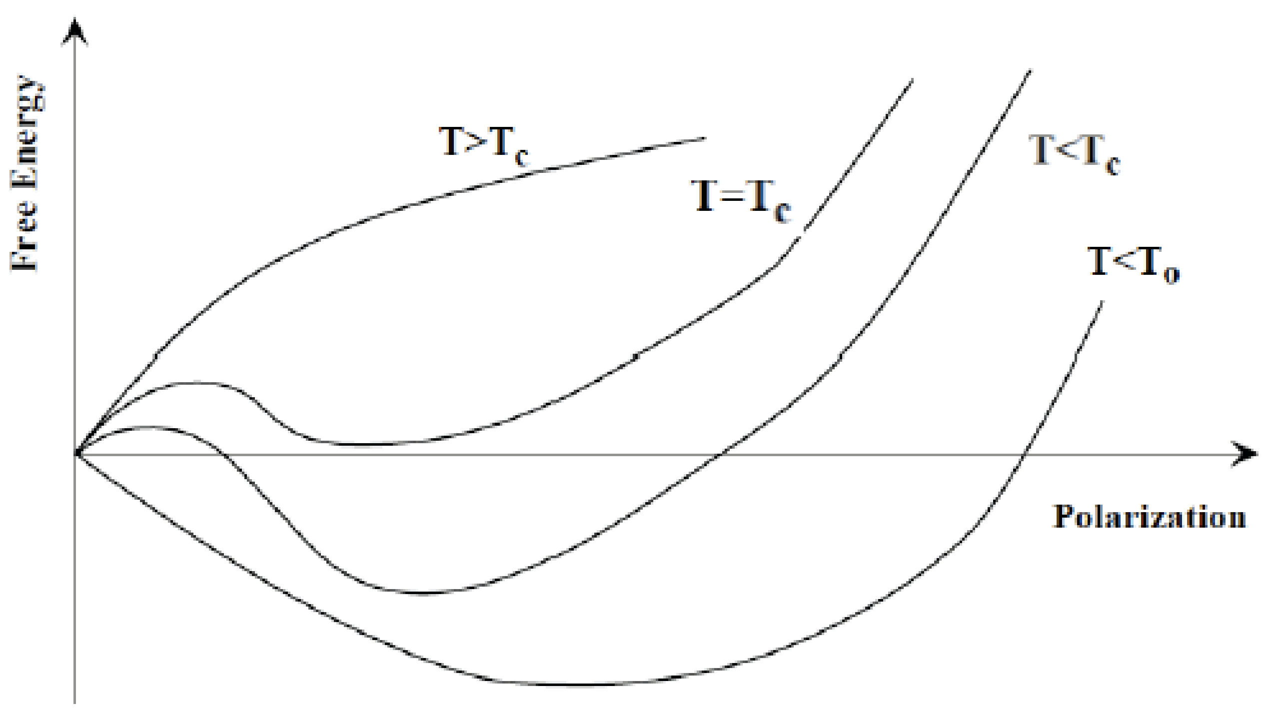

Fig. 1: Polarization dependence of the free energy.

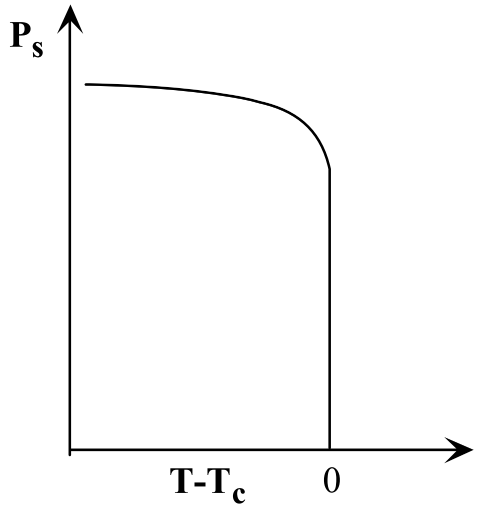

Fig.2. Temperature dependence of the spontaneous polarization P_S.

3. STABILITY CRITERION

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 [v]. 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 μ, 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

$$C\frac{\partial T}{\partial t} - \kappa\nabla^2 T = -r\left(T - T_o\right) + \sigma V^2 + \sigma_G V_G^2 \tag{3.1}$$

where C is an effective heat capacity per unit width in the z direction, κ the heat conduction coefficient in the z direction, $\sigma(T, V_G)$ is the source to drain electrical conductance per unit width, $V=V_{DS}$ the applied source to drain voltage, $\sigma_G(T)$ 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. (3.1) is

$$r(T-T_o)=\sigma(T,V_G)V^2+\sigma_G(T)V_G^2 \tag{3.2}$$

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

$$T' == Ae^{i(kz-\omega t)} = Ae^{-i\omega t}e^{-ikz}Ae^{\gamma t}e^{-ikz} \text{ with } -i\omega=\gamma \tag{3.3}$$

with arbitrarily small $A_{k,\omega}$. Substituting the solution $T+T'$ into Eq. (3.1) and subtracting Eq. (3.2) we obtain the linearized equation

$$\left(-i\omega C+\kappa k^2\right)=-rT'+\frac{\partial\sigma}{\partial T}T'V^2+\frac{\partial\sigma_G}{\partial T}T'V_G^2 \tag{3.4}$$

This yields the heat stability criterion (H-criterion)

$$\gamma C=i\omega C=-r-\kappa\left(\frac{\pi}{L}\right)^2+pV^2+qV_G^2<0 \tag{3.5}$$

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 (3.5), 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 [vi] 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

$$\sigma=\sigma(T,n),$$

w e write

$$p=p_1+p_2, \quad \text{with} \tag{3.6}$$

$$p_1=\frac{d\sigma}{dT}=\frac{\partial\sigma}{\partial T}+\frac{\partial\sigma}{\partial n}\left(\frac{\partial n}{\partial T_{th\ activ}}+\frac{\partial n}{\partial T_{plasmon}}\right)=\frac{E_a\sigma}{T^2}>0$$

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

$$p_2 = \frac{d\sigma}{dT_{polariz}} = \frac{\partial \sigma}{\partial P}\frac{\partial P}{\partial T} < 0 \qquad (3.7)$$

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 (3.5), 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

$$\ln\sigma = 2\ln e - \ln\nu - \ln m + \ln n \qquad (3.8)$$

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

$$\frac{\partial\sigma}{\partial T} = \sigma\left[\frac{1}{n} + \frac{1}{\tau}\left(\frac{\partial\tau}{\partial n_{oph}}\right)\frac{\partial n_{oph}}{\partial n}\right]\frac{\partial n}{\partial T} = \sigma\left[\frac{1}{n} + \frac{1}{\tau}\left(\frac{\partial\tau}{\partial n_{oph}}\right)\frac{\partial n_{oph}}{\partial n}\right]\frac{E_a}{kT^2} \qquad (3.9)$$

Therefore,

$$p_1 = \frac{d\sigma}{dT} = \sigma\left[1 + \left(\frac{\partial\tau}{\partial n_{oph}}\right)\left(\frac{\partial n_{oph}}{\partial n}\right)\frac{n}{\tau}\right]\left(\frac{E_a}{kT^2}\right) \qquad (3.10)$$

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. (3.5) 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 (3.5) or

$$p = p_1 + p_2 < 0 \qquad and \quad pV^2 + qV_G^2 < 0 \qquad (3.11)$$

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 (3.5) and (3.11).

4. PLASMON RESONANCE OF OPTICAL PHONONS

Consider the dependence of the LO phonon lifetime on the sheet density in Figure 3, caused by the resonance of optical phonons with plasmons, as discussed in Sec.3 and in detail in [vii]. 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.

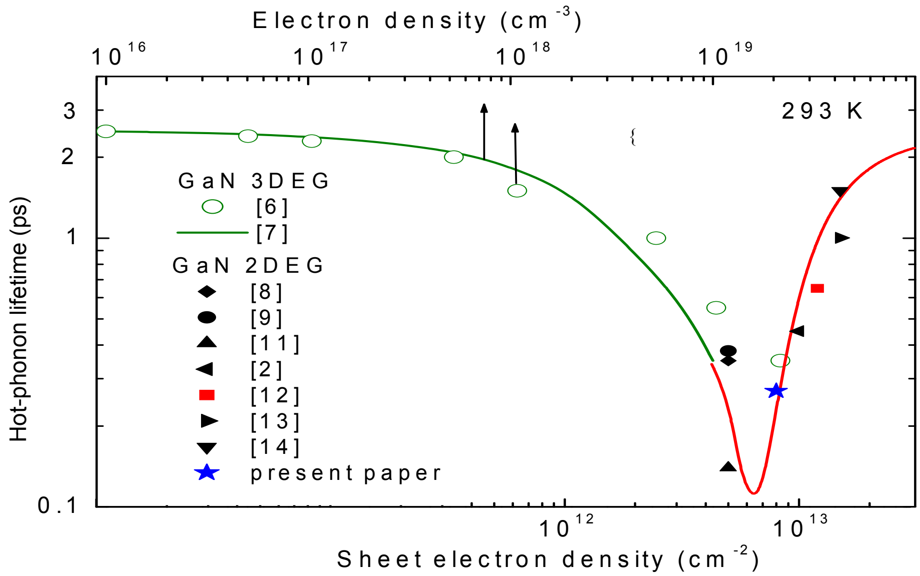

Fig. 3: Dependence of hot-phonon lifetime on electron density at zero electric field for GaN (open circles, top scale) and at low supplied power for GaN 2DEG channels (closed symbols, bottom scale). After reference [vii].

Indeed, our 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 [7], as shown in Fig. 4.

5. PLASMON RESONANCE -RELATED TERMS IN THE STABILITY CRITERION

We now consider the terms contained in the contribution p1 of the plasmon resonance to the stability criterion

$$p_1 = \frac{d\sigma}{dT} = \sigma\left[1 + \left(\frac{\partial \tau}{\partial n_{oph}}\right)\left(\frac{\partial n_{oph}}{\partial n}\right)\frac{n}{\tau}\right]\left(\frac{E_a}{kT^2}\right) \tag{5.1}$$

From Fig. 3 the life time of the optical phonons can be approximated as

$$\tau_{oph}=2.5\cdot10^{-12}\text{sec}[1-2.49\exp\text{-}10^{-24}(n-6.5.10^{12}\text{cm}^{-2})^2] \tag{5.2}$$

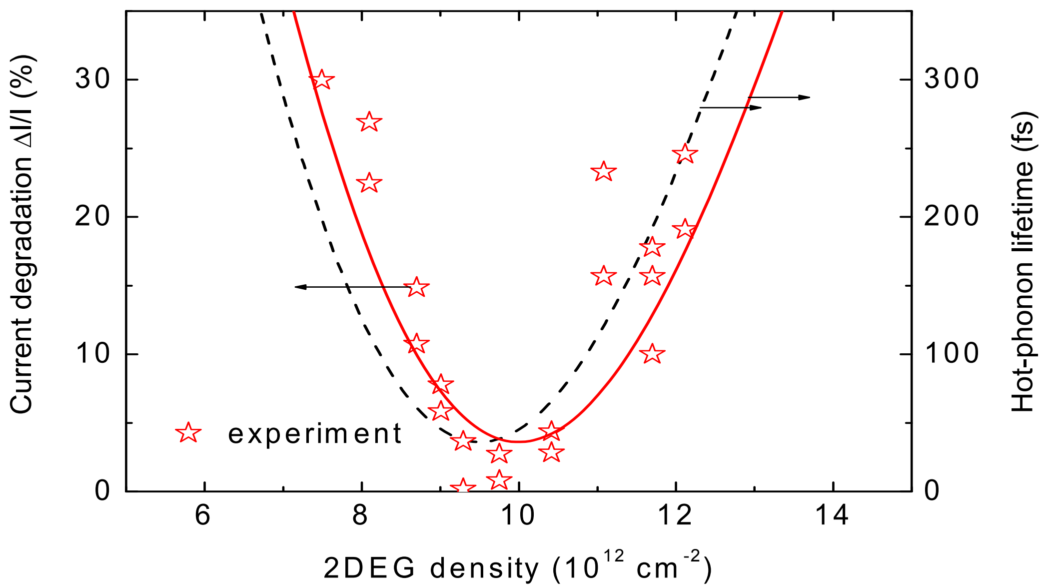

Figure 4. Density dependence of drain current degradation under drain voltage of 20 V for $In_{0.15}Al_{0.85}N/AlN/GaN$ HFETs

From Fig. 4, the percent measure of degradation is approximated by

$$100crtDegrad = 4 + 4\cdot10^{26}(n - 10^{13}\cdot cm^{-2})^2. \qquad (5.3)$$

Assuming a constant generation rate in stationary conditions, the number of optical phonons will be proportional to their lifetime:

$$n_{oph}=A(T)\tau_{oph}. \qquad (5.4)$$

Here we have introduced A(T) for the generation rate. This allows us to calculate the derivative of the optical phonon number with respect to the carrier concentration in the channel, in agreement with the data of Fig. 3:

$$\partial n_{oph}/\partial n=\partial n_{oph}/\partial\tau_{oph})(\partial\tau_{oph}/\partial n)=5\cdot10^{-12}sec[1-2.49\cdot10^{-24}(n-6.5.10^{12}cm^{-2})]A. \qquad (5.5)$$

Noticing that the collision frequency of the carriers (electrons) with optical phonons must be dominant and proportional to the concentration of optical phonons, we introduce the coefficient B and obtain

$$\nu=1/\tau =Bn_{oph};\ \partial\tau/n_{oph}=-(1/\nu^2)B \qquad (5.6)$$

Finally this yields

$$p_1=\sigma\{1 -(1/\nu^2)\ 5\cdot10^{-12}sec[1-2.49\cdot10^{-24}(n-6.5.10^{12}cm^{-2})]AB\}, \qquad (5.7)$$

which is the desired result. It relates the parameters entering our stability criterion to the measured parameters of the plasmon resonance.

6. CONCLUSIONS

As we have seen, stability against high stress degradation of the very wide HFETs can be achieved by working from both sides of our criterion. The actual decrease of the AlGaN ferroelectric and piezoelectric polarization components with temperature is limited in practice, even if we use a favorable operating point. *However, much can be obtained at the other end, as the numerical estimate in Sec. 5 shows.* This analysis can be repeated with other ternary and quaternary compounds similar to AlGaN.

We noticed experimentally a disproportionate large increase of 1/f noise even when the degradation visible in the I-V characteristics was small. 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 when a local instability leads to breakdown . 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 [[viii]] 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'*=1□ 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*

$$S'(f) = \frac{W}{W'} S(f) \tag{6.1}$$

This inverse proportionality of the 1/f noise is expected on the basis of the quantum theory of 1/f noise [8].

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