Quantum 1/f Phase Noise in GaN/AlGaN HFET Based Oscillators

P.H. Handel[1], A.G. Tournier[1], H.L. Hartnagel[2],* U.K. Mishra[3], and R. York[3]

[1]Dept. of Physics and Astronomy, Univ. of Missouri, St. Louis, MO 63121, USA
[2]Inst for High Frequency Technology, Technical Univ. of Darmstadt, Germany
[3]Department of Electrical Engineering, Univ. of California Santa Barbara

1 Quantum 1/f noise sources in GaN HFETs

1.1 Gate Noise

The gate leakage current results in relatively large noise, and can contribute considerably to the noise figure calculated in [1], and to the resulting phase noise. This large contribution is caused by the piezoelectric quantum 1/f effect affecting currents present in sufficiently large samples of spontaneously polarized ferroelectric material, with a 10^6 times larger quantum 1/f noise coefficient introduced by the speed of sound replacing the speed of light in Sommerfeld's fine structure constant. It is enhanced also because gate potential fluctuations appear amplified in the channel current. Our theory [2-4] yields a power spectrum of gate resistance fluctuations

$$S_{\delta R_G/R_G} = \alpha_G/N_G f; \qquad \alpha_G \approx 0.2 = \text{piezo Q1/f coefficient.} \tag{1}$$

Here $N_G = I_G\tau$, where I_G is the gate current and τ is the life time of the carriers in the AlGaN gate insulation.

To understand the large value of α, we mention that the piezoelectric Q1/f coefficient is also found [2-4] by combining the conventional and coherent parts in a weighted sum:

$$\boxed{\begin{aligned}\alpha_H = fNS_{\delta j/j}(f) &= [1/(1+s')](4g/3\pi)(\Delta\mathbf{k}/k_S)^2\\ &+ [s'/(1+s')]\{2g/\pi[1-(\langle\mathbf{k}\rangle/k_S)^2]\}\end{aligned}} \tag{2}$$

where v_S is the speed of sound, $\langle\mathbf{k}\rangle = m^*\langle\mathbf{v}\rangle/\hbar$, $|\langle\mathbf{v}\rangle| = u$ is the drift velocity of the carriers, $\Delta\mathbf{k}/k_S = \Delta\mathbf{v}/v_S$, and

$$\boxed{k_S = m^* v_S/\hbar; \quad s' = (gN'\hbar/\pi m^* v_S)(v_S/u)^3 F(u/v_S).} \tag{3}$$

Here N' is the number of carriers per unit length of the sample in the direction of current flow, and

$$F(u/v_s) = 2(u/v_s)\{1 + 1/[1-(u/v_s)^2]\} + \ln[1-(u/v_s)]^2 - \ln[1+(u/v_s)]^2. \tag{4}$$

For $u/v_s \ll 1$, $\quad F(u/v_s) = (2/3)(u/v_s)^3$. Then $s' = (2gN'\hbar/3\pi m^* v_s) \approx N'.10^{-7}$ cm. (5)

For $1-(u/v_s) \ll 1$, $F(u/v_s) = 1/[1-(u/v_s)]$. (6)

Due to the small number of carriers, their drift velocity is close to the sound velocity in the AlGaN gate, and the condition $1-(u/v_s) \ll 1$ is satisfied. Then we obtain

$$s' = (gN'\hbar/\pi m^* v_s)(v_s/u)^2\{1/[1-(u/v_s)]\}, \tag{7}$$

which can be larger than 1. In conclusion, due to the large value of s', the first term in Eq. (2) is negligible, and the coefficient s'/(1+s') of the second term is 1. From the graph in Fig. 4.1 on p. 48 of the Thesis of Sia Eng Kee [5], we find that g is about 3 and therefore a≈0.2, as mentioned above, for AlGaN which is stiffer.

1.2 Channel Noise

The noise present in the GaN/AlGaN HFET's channel was derived and discussed earlier [6].

In terms of the HFETs channel resistance R_{Ch} and of the current I_{Ch} through it, we obtain

$$fS_R = fS_{RS} + fS_{RD} + fS_{Rch} = R_S^3 e\mu_S\alpha_S/L_S^2 + R_D^3 e\mu_D\alpha_D/L_D^2 + \tag{8}$$

$$+\frac{1}{\mu I_{Ch}}\left\{\frac{\alpha_H^{coh}}{qZ^2D_{eff}^2V_{th}} + \frac{\alpha_H^{conv}qv_s^2R_{Ch}}{I_{ch}}\left(1-\frac{V_G^*}{R_{Ch}I_{Ch}}+\frac{V_{th}}{R_{Ch}I_{Ch}}\right)\Theta()\right\}$$

$$\Theta() = \Theta\left(1-\frac{V_G^*}{R_{Ch}I_{Ch}}+\frac{V_{th}}{R_{Ch}I_{Ch}}\right) = Step-function$$

Here the source, channel and drain resistances form the total resistance: $R_S+R_{Ch}+R_D=1/G_m$; where Gm is the total HFET conductance.

2. Oscillator Phase Noise

The oscillator can be modeled in a first approximation as an oscillant circuit (Fig. 1) described by a harmonic oscillator equation

$$d^2x/dt^2+2\gamma dx/dt+\omega_0^2 x = F_0\exp(i\omega t) \qquad (9)$$

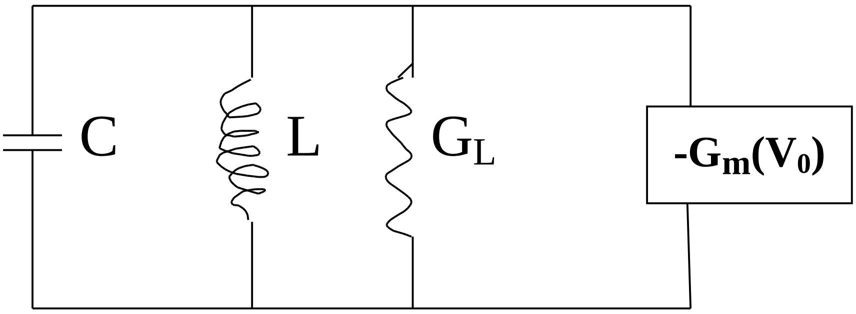

Fig. 1: *Equivalent circuit of an oscillator, with active element shown as a negative conductance.*

In Fig. (1) $-G_m(V_o)$ is a negative conductance that represents the active element, the force $F_0\exp(i\omega t)$, causing the oscillations. This force, or emf is assumed to be free of fluctuations. The fluctuations are present in the dissipative element that may be present in the active device and in the resonator. The solution for x, which can be the current or the voltage in the oscillant circuit, is

$$(x,I,V) = (x_0,I_0,V_0)\exp(i\omega t);\ \ |x_0|^2=|F_0|^2/[(\omega_0^2-\omega^2)^2+4\gamma 2\omega^2] \qquad (10)$$

The resonance condition $d|x_0|^2/d\omega=0$ yields

$$\omega_r^2=\omega_o^2-2\gamma^2. \qquad (11)$$

Conventional quantum 1/f noise is a fundamental quantum fluctuation present in quantum mechanical cross sections and process rates [4]. The latter determine the dissipation in quartz crystals and in general in resonant systems of any kind [7]. Considering therefore fluctuations of the dissipative constant γ, we obtain for the resulting frequency fluctuations of the arbitrary resonant system [7]

$$\omega_r\delta\omega_r=-2\gamma\delta\gamma;\quad \delta\omega_r/\omega_r=-2(\gamma/\omega_r)^2\delta\gamma/\gamma \qquad (12)$$

With $y\equiv\delta\omega_r/\omega_r$ and with $2\gamma/\omega$ being the quality factor Q, we obtain the frequency fluctuations power spectrum

$$S_y(f) = 4(\gamma/\omega_r)^4 S_{\delta\gamma/\gamma}=(1/4Q^4)S_{\delta\gamma/\gamma} \qquad (13)$$

This defines the phase noise that is to be expected in first approximation. However, there are also contributions from the source and drain series resistances, and from the gate leakage current. Together with the channel noise shown in Eq. (12), they define the total quantum 1/f frequency fluctuation noise $S_y^{Q1/f}$, and the corresponding phase noise $\mathcal{L}(f)$.

3. Total 1/f-type Phase Noise S_y^H

In terms of R and I_{ch}, with $R_S+R_{Ch}+R_D=R$, our goal is to find the total quantum 1/f frequency fluctuation noise $S_y^H=\mathrm{Const}/f = S_{\delta\omega/\omega}$. The quantum 1/f resistance fluctuations in the channel, source, drain and gate are independent, because they are fluctuations of different scattering cross sections and process rates. According to Eqs. (11), (13) and (14) of [1], we obtain, by including the fluctuations of the channel resistance induced by the gate resistance fluctuations,

$$S_R=S_{Rs}+S_{RD}+S_{Rch}+(4kT_o/g_nI_{Ch}^2)|R_{Ch}Y_{tr}|^2 \qquad (14)$$

$$=R_S^3 e\mu_S\alpha_S/fL_S+R_D^3 e\mu_D\alpha_D/fL_D+$$

$$+\frac{1}{\mu f I_{Ch}}\left[\frac{\alpha_H^{coh}}{qZ^2D_{eff}^2V_{th}}+\frac{\alpha_H^{conv}qv_s^2R_{Ch}}{I_{ch}}(\xi)\Theta(\xi)\right]+$$

$$+[4kT_o(r_s+R_G)+I_G^2S_{\_RG}]|R_{Ch}Y_{tr}/I_{Ch}|^2. \qquad (15)$$

Here we substituted for the noise resistance of the gate $r_n=R_G+I_G^2S_{\delta RG}/4kT=g_nR_G^2$, according to Eq. (8) of [1]. With $y\equiv\delta\omega/\omega$ these equations provide the quantum 1/f phase noise component $S_y^H(f)$, which is dominant close to the carrier,

arising from the GaN/AlGaN HFETs. To this result we have to add the well-known contribution of the sidebands arising from device nonlinearity (NSB-part). This part can be reduced by operating the HFET at

$$S_y^H=\frac{R^{-2}}{4fQ^4}\left\{\frac{1}{\mu I_{Ch}}\left[\frac{\alpha_H^{coh}}{qZ^2D_{eff}^2V_{th}}+\frac{\alpha_H^{conv}qv_s^2R_{Ch}}{I_{Ch}}\xi\Theta(\xi)\right]+\frac{\alpha_s}{fN_s}R_s^2+\frac{\alpha_D}{fN_D}R_D^2+\frac{4kT_0(r_s+r_n)}{I_{Ch}^2}|R_{Ch}Y_{tr}|^2\right\}$$

$$\xi\equiv 1-\frac{V_G^*}{R_{Ch}I_{Ch}}+\frac{V_{th}}{R_{Ch}I_{Ch}}; \qquad (32)$$

$$\Theta(\xi)\equiv(1+\mathrm{sign}\,\xi)/2$$

saturation, and restricting the dynamical range. Furthermore, partial compensation measures are possible for this classical part, as shown, e.g., by A. Hajimiri (HJM). Therefore,

$$S_y=S_y^{Q1/f}+S_y^{HJM}+S_y^{NSB} \, . \qquad (17)$$

The phase noise at a frequency $\Delta\nu=f$ from the carrier frequency is given most often not in terms of frequency fluctuations, but in dBc, i.e.,

$$\mathcal{L}(f)=\mathcal{L}(\Delta\nu)=10\log[(1/2)(\omega/2\pi f)^2 S_y(f)] \qquad (18)$$

This all can be applied to a practical example of GaN/AlGaN HFET –based oscillator.

4. Example: Robert York – X. Hu - BST-based oscillator

Consider now as a practical example the oscillator of R. York and X. Hu at UCSB, developed as part of our Ultra-low Phase Noise MURI Program. It uses a $BaSr(TiO_3)_2$ bypass capacitor, as seen in Fig. 2. Its frequency is ν_o=5 GHz; its unloaded quality factor is $Q_u\approx 23$ and the loaded quality factor is estimated to be about Q_l=10. From Table II we find for the HFET channel that provides the dissipation in the oscillator, approximately, $S_R/R^2\approx 10^{-10}/f$. Considering also negligible gate noise, $4kT_o(r_s+r_n)|Y_{tr}|^2\approx 0$, we obtain, from Q1/f theory,

$$S_y=(S_R/R^2)/4Q_l^4 f=10^{-10}/4\cdot 10^4 f=2.5\cdot 10^{-15}/f, \qquad (19)$$

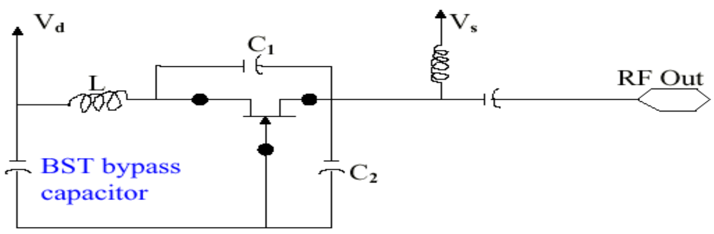

Fig. 2: *GaN/AlGaN HFET-based oscillator of R. York and X. Hu (UCSB)*

Therefore, in phase noise language,

$$\mathcal{L}(f)=\mathcal{L}(\Delta\nu)=10\log[(1/2)(\omega/2\pi f)^2 S_y(f)]=-45\text{dBc@1kHz}, \text{ or about } \underline{-105\text{dBc@100kHz}}. \qquad (20)$$

Note that Experimentally, $\mathcal{L}$(100KHz)= −105dBc was measured, in excellent agreement with our rough estimate. It is interesting to note that for Q=10^4, $\mathcal{L}(f)$= −165dBc@1kHz. Therefore, it would be advisable to use special high-frequency MEMS resonators.

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