# Analytical Calculation of the Quantum 1/f Coherence Parameter for HFETs

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## ABSTRACT

The ratio s of the coherent magnetic energy term and the incoherent mechanical kinetic energy terms of the drift motion in the hamiltonian of a current carrying system is calculated for the special cases of a HFET or FET. This ratio defines the resulting quantum 1/f noise from the coherent and conventional quantum 1/f effects.

In this case of FETs and HFETs of much larger width $w \gg L_{DS} > t$, the kinetic energy $E_k$ of average motion with drift velocity $v_d$ per unit length in the direction of the drain-source distance $L_{DS}$ in the channel of thickness t, 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 $E_m = \pi[\ln(w/2L_{DS})]L_{DS}[nevS/c]^2/w$. Here S=wt is the cross section though which current flows this indicates field-decoherence along the large 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 appear. For non-uniform current distribution across t, and for piezoelectric coupling, improved forms are derived for s. Specifically, the coherence parameter, called s' for the piezo case, is given by $s' = (gN'\hbar/m^*v_s)(v_s/u)^3F(u/v_s)t/12w$, where $F(u/v_s) = (2/3)(u/v_s)$ for small drift velocity $u$, much smaller than the sound velocity $v_s$ in the semiconductor. Here $N'=nwt$.

Keywords: Quantum 1/f noise, Quantum 1/f Effect, HFET, FET, MODFET, HEMT, Coherence

## 1. INTRODUCTION

There are as many types of quantum 1/f noise [1]-[6], as there are systems of massless infraquanta with infrared-divergent coupling [7], [8] to the current carriers. Each of these types has a conventional and coherent part, corresponding to terms in the hamiltonian that are proportional with the first and second power of the number of carriers defining the current, respectively. In piezoelectric materials, particularly those also showing ferroelectric spontaneous polarization, transversal phonons are the massless quanta leading to piezoelectric, or lattice-dynamic, quantum 1/f effects, again both conventional and coherent. As in the usual QED case, the observable 1/f noise is approximated by a weighted sum of the conventional and coherent quantum 1/f effects. The sum involves the coherence parameter, this time denoted by s', in the weight factors. The parameter s' is also estimated from first principles. The general formula involving s' is applied to bulk GaN and AlGaN and thin sheets, and includes a dependence on geometry.

The best known form of quantum 1/f noise [1]-[2], [4] is certainly the electromagnetic, or QED form, that has been used to improve semiconductor devices other than the MOSFET and many other high-tech devices, sensors, and systems since the 1980s. Both the coherent and conventional QED-type Quantum 1/f Effect (Q1/fE) contribute to quantum 1/f noise, and are caused by the infrared divergent coupling between charged particles and soft photons. In final analysis, this new aspect of quantum mechanics is therefore due to the non-linearity of the system of particle and field, where the field reacts on the particles that generated the field in the first place.

The conventional Q1/fE is a new property of the "physical cross sections and process rates" introduced by one of us in order to allow quantum mechanics to explain fundamental 1/f noise in materials, devices and systems, including phase noise. It does not depend on the presence of other similar charged particles drifting in the electrical field. The coherent Q1/fE, on the other hand, is a basic property of any particle. It is caused by the uncertainty of its rest mass, due to the same infrared divergent coupling and due to the coherent state in which the photon states happen to be. This coherent state of the field is simply due to the presence of all the particles and to their motion.

The energy of coherent states is uncertain, as is known since Schrödinger introduced them in the 1920s. This uncertainty, derived from Heisenberg's uncertainty principle, causes the state of any particle to be non-stationary and beset by the fundamental coherent quantum 1/f noise $2\alpha/\pi f$, where $\alpha=e^2/\hbar c=1/137$ is Sommerfeld's fine structure constant. It is remarkable that the power spectral density of fractional fluctuations $2\alpha/\pi f$ in current, votage, mobility, diffusion constant, recombination speed, quartz resonator dissipation rate and frequency, etc., etc, contains Planck's constant in the denominator.

That makes this new aspect of quantum mechanics, or most important and fundamental form of quantum chaos, particularly interesting. It is the one that shapes our very existence, and causes us to like spontaneously, for instance, 1/f, or symphonic, music. Epistemologically, quantum 1/f noise is just a special case of the fundamental universal 1/f spectrum, caused by the simultaneous presence of nonlinearity and a special form of homogeneity in any system, e.g., traffic on the highways. This is described by Handel's "Sufficient Criterion" [1], that is satisfied also by QED at low frequencies. The drift motion of the current carriers, mentioned in the previous paragraph, causes a magnetic field and a magnetic form of kinetic energy, $LI^2/2$ where L is the inductance. In a thick copper wire, it is much larger than the mechanical form of the kinetic energy of the same drift motion of the current carriers. This magnetic energy of the drift motion of an electron is proportional to the number of other electrons, per unit length of the wire, that are drifting along with drift velocity v that is their average velocity. On the other extreme of a nanoscopically thin semiconductor, the mechanical form $mv^2/2$ dominates, as was pointed out already at the start of the theory of fundamental 1/f noise. Therefore we understand why the coherent Q1/fE is found to be dominant in a copper wire, while the conventional Q1/fE is found to be dominant in the very thin, poorly doped semiconductor whisker.

In Sec. 2 below we review the elementary relation between coherent and conventional Q1/fE [2] that is suggested by the relation between the magnetic and kinetic drift energies present in the Hamiltonian for the electromagnetic or quantum electrodynamical (QED) case, in which photons are the infraparticles. In Sec. 3 this relation is derived again for the special case of FETs or HFETs, that have a width exceeding their length and thickness by orders of magnitude. In Sec. 4 we extend this treatment to the case of piezoelectric quantum 1/f noise, in which soft (transversal) piezophonons are the infraparticles. This was also introduced as Quantum Lattice-Dynamical (QLD) quantum 1/f noise.

The application to QLD allows us for the first time to explain the giant quantum 1/f noise in large ferroelectric semiconductor samples of BaSrTiO3, GaN and AlGaN and its startling decrease for smaller sample thickness. The speed of sound replaces the speed of light in the denominator of $\alpha$, and the observed 1/f noise is $10^6$ times larger, as expected from the theory. But there are no low frequency piezophonons, even in the largest semiconductor samples. In Sec. 5 we calculate the s' parameter for piezoelectric Q1/f noise in FETs and HFETs for the first time.

## 2. ELEMENTARY DERIVATION OF THE s PARAMETER

We suggest that the relation of the coherent Q1/fE to the conventional Q1/fE is described in a first, rough, approximation through the parameter s defined here. The coherent state in a conductor or semiconductor sample is the result of the experimental efforts directed towards establishing a steady and constant current. It is, therefore, the state defined by the collective motion, i.e. by the drift of the current carriers. It is expressed in the hamiltonian by the magnetic energy $E_m$, per unit length of the current carried by the sample. In cylindrical samples or electronic devices, this coherent magnetic energy per unit length

$$E_m = \int(B^2/8\pi)d^3x = [nevS/c]^2[ln(R/r) +1/4] \qquad (2.1)$$

is much smaller than the total kinetic energy $E_k$ of the drift motion of the individual carriers per unit length

$$E_k = \Sigma mv^2/2 = nSmv^2/2 = E_m/s. \qquad (2.2)$$

Here we have introduced the magnetic field B, the carrier concentration n, the cross sectional area S and radius r of the cylindrical sample (e.g., a current carrying wire), the radius R>>r of the (e.g., circular) electric circuit, used as an upper cut-off for the integral in Eq. (2.1). One obtains the "coherence ratio"

$$s = E_m/E_k = 2ne^2S/mc^2[\ln (R/r)+1/4] \approx 2e^2N'/mc^2,= 2N'r_o. \qquad (2.3)$$

Here N' = nS is the number of carriers per unit length of the sample, $r_o = e^2/mc^2 = 2.8\cdot 10^{-13}$ cm is known as the classical radius of the electron, and the natural logarithm ln(R/r) has been approximated by one in the last form. We expect the total observed spectral density of the mobility fluctuations to be given by a relation of the form

$$(1/\mu^2)S_\mu(f) = [1/(1+s)][2\alpha A/fN] + [s/(1+s)][2\alpha/\pi fN] = [2\alpha/(1+s)fN][A+s/\pi], \qquad (2.4)$$

which can be interpreted as an expression of the effective Hooge constant if the number N of carriers in the (homogeneous) sample is brought to the numerator of the left hand side. In this equation $\alpha A = 2\alpha(\Delta\mathbf{v}/c)^2/3\pi$ is the usual nonrelativistic expression of the infrared exponent, present in the familiar form of the conventional quantum 1/f effect. This equation is limited to quantum 1/f mobility (or diffusion) fluctuations, and does not include the quantum 1/f noise in the surface and bulk recombination cross sections in the surface and bulk trapping centers, in tunneling and injection processes, in emission or in transitions between two solids.

Eq. (2.1) agrees with the well-known solution

$$L = (2/c^2)\{\mu[\mathit{ln}(8R/r)-2] + \mu'/4\} \qquad (2.5)$$

for the inductance of a circular wire of radius R and thickness 2r in a medium of magnetic permeability μ, when the material of the wire has permeability μ'. The term μ'/4 reflects the magnetic energy inside the wire, often neglected.

Note that the coherence ratio s introduced here equals the unity for the critical value N' =N" = $2\cdot 10^{12}$/cm., e.g. for a cross section S = $2\cdot 10^{-4}$ cm$^2$ of the sample when n = $10^{16}$. For small samples with N'<<N" only the first term survives, while for N'>N" the second term in Eq. (2.4) is dominant. In practice, s is therefore twice the number of carriers in a salami slice perpendicular to the direction of the current, with a thickness given by the classical radius of the electron.

## 3. DERIVATION OF THE PARAMETER s FOR THE FET and HFET CASES

A large value of the coherence parameter s should be avoided in electronic devices, because it favors the coherent 1/f noise component, which is much larger than the conventional one, due to the absence of the small factor $(v/c)^2$. We show here that a special geometry allows for a coherence parameter s that remains practically unaffected when the channel width is increased by several orders of magnitude over the channel length.

Modern FETs and HFETs attempt to increase the denominator N in the quantum 1/f formulas without markedly increasing the coherence parameter s, by choosing an extreme case of a rectangular cross section for the portion between the source and drain, and even more extreme for the channel, which is the region under the gate. Indeed, the circular cross section expected for a wire is replaced in this case by a short rectangle of very small length $L_{DS}$, with a very large width *w* of several hundreds of microns and less than a micron in thickness, the channel being even thinner. The channel is reduced to a 2-dimensional quantum sheet, which is a quantum well of size (thickness) *t* in the 3rd dimension, towards the gate. Most important, the “length” $L_{DS}$ of the source-to-drain distance is only of the order of 1micron, while the gate length is just about a quarter micron or less. In this case the kinetic energy $E_k$ per unit length in the direction of $L_{DS}$ is still given by $mv^2/2$, where v is the drift velocity, 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

$$E_m = \pi[\ln(w/2L_{DS})]L_{DS}[nevS/c]^2/w. \qquad (3.1)$$

This indicates decoherence along the device width w. For $w >> L_{DS} > t$, this yields a coherence ratio

$$s \approx \pi n r_o t L_{DS} \ln(w/2L_{DS}) \qquad \text{for } w >> L_{DS} > t, \qquad (3.2)$$

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 and of the in this special case; larger widths are subject to de-coherence, i.e., their magnetic energy no longer increases proportional to $w^2$, or $N'^2$. This favors lower, mainly conventional, quantum 1/f noise in these devices, in spite of the large values of w, in agreement with the practical results, which anticipated the quantum 1/f result simply by trial and error, unaware of the subtleties of the transition from coherent to conventional Q1/f noise in this case, and in general. It also shows that fragmentation of the extremely large widths w does not reduce 1/f noise in this special case.

To derive the rough approximation given in Eq. (3.2), one writes the expression of the coherent ($\propto n^2$) contribution of the currents in the short, but very wide channel to the magnetic energy of the circuit in the form

$$E_m=\int[\mathbf{j}(\mathbf{x})\cdot\mathbf{j}(\mathbf{x'})/2c^2|\mathbf{x}-\mathbf{x'}|]d^3xd^3x'=e^2v_d^2\int[n(\mathbf{x})\cdot n(\mathbf{x'})/2c^2|\mathbf{x}-\mathbf{x'}|]d^3xd^3x'. \tag{3.3}$$

The integral coincides with the electrostatic energy of an equivalent constant charge density numerically equal to $e/c^2$ in CGS, or $e\mu_o/4\pi\varepsilon_0$ in SI, uniformly distributed over the volume $wtL_{DS}$ of the channel. This energy, in turn, is calculated as the corresponding volume integral over the squared equivalent electric field, using $L_{DS}$ as a lower cut-off. The equivalent electric field is $E=netw/cr(r^2+w^2/4)^{1/2}$ at a distance r in the median plane of a segment of length w oriented along (aligned with) the width w of the channel. In performing the equivalent integral over $E^2/8\pi$ over the whole space, we use this to approximate the field in space outside the length and along the width w of the channel, because w is very large. A more elaborate calculation does not simply approximate the field with its value in this median plane, but yields similar results in the end, as Eq. (3.1).

In conclusion, Eq. (3.1) just replaces the factor ln(R/r) of Eq. (2.1) according to the rule

$$\ln(R/r) \longrightarrow \pi[\ln(w/2L_{DS})]L_{DS}/w. \tag{3.4}$$

We now have all the ingredients for a discussion of the piezoelectric, i.e., Quantum Lattice-Dynamic (QLD) Quantum 1/f Effect (Q1/fE) case.

## 4. CONNECTION OF COHERENT AND CONVENTIONAL QLD-Q1/fE

The conventional, or incoherent, piezoelectric or quantum-lattice-dynamic quantum 1/*f* noise effect [3], is given by

$$\frac{S_\sigma(f)}{\langle\sigma\rangle^2} = \frac{2gA}{fN}, \tag{4.1}$$

and is dominant in small samples or devices, where $A = 2(\Delta v)^2/3\pi(v_s)^2$, $\Delta v$ is the change of electron velocity during scattering and $\sigma$ is any scattering cross section defined for carriers that exhibit piezoelectric coupling to ELF phonons. Here g is the dimensionless piezopolaron coupling constant, similar to the fine structure constant $\alpha$, but with the speed of transversal sound waves replacing the speed of light in the denominator. It also involves a geometrical factor of the order of unity, dependent on the lattice. In a first approximation, $\sigma$ can also be the mobility $\mu$, the conductivity, or the current *j*. In the *coherent case* [4] of large devices,

$$\frac{S_j(f)}{j^2} = \frac{4g}{\pi f}\frac{1}{\left[1-(\hbar k_s/m^* v_s)^2\right]}. \tag{4.2}$$

Here $(\hbar k_s/m^*)$= $|\mathbf{v}|$ = $u$ is the drift velocity of the carriers, m* their effective mass, and $v_s$ is the speed of sound for transversal acoustic phonons.

We now derive the connection between the coherent and conventional forms of Lattice-Dynamical (piezoelectric) Quantum 1/f Effect (LD-Q1/fE) similarly to the way this was done in 1985 for the usual QED-Q1/fE [3].

In QLD, the amplitude of the piezo-elastic transversal lattice mode with wave vector **q** is the Fourier component **q** of the displacement **B** caused by an electron in the lattice, expanded over a cubic box of volume V

$$B_{\vec{q}} = \frac{-iv_s(2\pi g/q^3V)^{1/2}}{v_s - \hbar\hat{q}\cdot\vec{k}/m} \tag{4.3}$$

This is similar to the well known expression of the magnetic field of a wire. The part corresponding to the motion is obtained by subtracting the static part (Eq. 5.3 for k=0) that applies for an electron at rest

$$B_{\vec{q}}^{mot} = -iv_s\left(\frac{2\pi g}{q^3V}\right)^{\frac{1}{2}}\left[\frac{1}{v_s-\hbar\hat{q}\cdot\vec{k}/m}-\frac{1}{v_s}\right] = -iv_s\left(\frac{2\pi g}{q^3V}\right)^{\frac{1}{2}}\frac{\hbar\hat{q}\cdot\vec{k}}{mv_s(v_s-\hbar\hat{q}\cdot\vec{k}/m)} \tag{4.4}$$

The corresponding motional energy $W^{mot}$ for an electron of wave vector k is thus

$$v_s^{-2} W_{\vec{k}}^{mot} = \sum_{\vec{q}} |B_{\vec{q}}^{mot}|^2 \hbar\omega_q = \frac{2\pi g}{V}\frac{\hbar^3}{m^2 v_s}\frac{V}{(2\pi)^3}\int d\Omega \int_0^{q_D} dq \frac{k^2\cos^2\theta}{(v_s - \hbar k\cos\theta/m)^2} \tag{4.5}$$

Here $q_D$ is the Debye wave vector. This is similar to the well known expression of the magnetic energy of a wire carrying an electric current $e\hbar\vec{k}/m$ per electron, but here the second term in the denominator was not neglected, since $v_s \ll c$. The integration yields

$$W_{\vec{k}}^{mot} = \frac{g\hbar^3}{2\pi m^2 v_s}\frac{V}{(2\pi)^3}\int_0^{q_D} dq \int_{-1}^{1}\frac{k^2 x^2 dx}{(1-\hbar kx/mv_s)^2} = \frac{g}{2\pi}\frac{mv_s^2 q_D}{k}F(\frac{v}{v_s}) \tag{4.6}$$

With $q_D=1/r'_0$, we obtain thus for cylindrical symmetry

$$W_{\vec{k}}^{mot} = \frac{g}{2\pi}\frac{mv_s^2}{kr'_o}F(\frac{v}{v_s}) \xrightarrow{Cylindrical-Symm} \frac{g}{2\pi}\frac{mv_s^2}{kr'_o}F(\frac{v}{v_s})N'[\ln\frac{R}{r'_0}+\frac{1}{4}] \tag{4.7}$$

*N*' is again the number of carriers per unit length of the sample in the direction of current flow, and *m** is the electron effective mass. The integration in Eq. (4.6) introduced the function

$$F(u/v_s) = 2(u/v_s)\{1 + 1/[1 - (u/v_s)^2]\} + \ln[1-(u/v_s)]^2 - \ln[1+(u/v_s)]^2. \tag{4.8}$$

We introduce the ratio of the coherent piezoelectric energy of the drift motion divided by the additional kinetic energy of the carriers introduced by the drift velocity u.

$$s' = \frac{\frac{g}{2\pi}\frac{mv_s^2}{kr'_o}F(\frac{u}{v_s})N'\ln\frac{R}{r'_0}}{N\copyright\, mu^2/2} = \frac{g}{\pi}\frac{v_s^2}{u^2 kr'_o}F(\frac{u}{v_s})[\ln\frac{R}{r'_0}+\frac{1}{4}] = (gN'\hbar/\pi m^* v_s)(v_s/u)^3 F(u/v_s)[\ln(R/r_o')+1/4]. \tag{4.9}$$

For an infinite piezoelectric medium, with a cylindrical current-carrying portion, this is the desired ratio s' of terms present in the hamiltonian, corresponding in QLD to the parameter s. If only the cylindrical sample is piezoelectric we drop the logarithm and keep only the term ¼, since this would correspond to having only the term with μ' in Eq. (2.5):

$$\boxed{s' = (gN'\hbar/\mathbf{4}\pi m^* v_s)(v_s/u)^3 F(u/v_s).} \tag{4.10}$$

As before, the coherent and conventional forms of QLD-Q1/fE are superposed with weights s/(1+s) and 1/(1+s). For the intermediate case, i.e., for sizes in between coherent and incoherent, we have $S_j(f)/j^2 = \alpha/Nf$, with α defined as

$$\alpha = \alpha_{incoh}\frac{1}{(1+s')} + \alpha_{coh}\frac{s'}{(1+s')} \tag{4.11}$$

Again, similar to s, the weight s' is the ratio between the piezoelectric or LD form of kinetic energy [associated with the electric current present in the sample or device, that is coherent], and the incoherent kinetic energy $m_{eff}u^2/2$ of individual particles, [caused by the drift velocity u].

The function F present in the definition of s' is given by Eq. (4.8). For $u/v_s \ll 1$, $F(u/v_s) = (2/3)(u/v_s)^3$; then *s*' can be simplified as $s' = 2gN'\hbar/3\pi m^* v_s$. This expression can be used for small drift velocity, much smaller than the sound velocity in the semiconductor. For $1-(u/v_s) \ll 1$, $F(u/v_s) = 1/[1-(u/v_s)]$, then *s*' can be approximated as $s' = (gN'\hbar/\pi m^* v_s)(v_s/u)^3\{1/[1-(u/v_s)]\}$, which is very large. This expression is used for drift velocities approaching the speed of sound.

## 5. THE PARAMETER s' FOR THE FET and HFET CASES

When the extreme geometry of very large width $w>>L_{DS}>t$ used for FETs and HFETs is considered, we realize that the mathematical equivalence of the magnetic and piezoelectric attractive interactions between current carriers tempts us to repeat the steps that led to Eq. (3.1) above. The vector potential $\mathbf{A_q}$ of the well known expression of the magnetic energy of a wire carrying an electric current $e\hbar\vec{k}/m$ per electron is just replaced by the displacement amplitude $\mathbf{B_q}^{mot}$ of Eq. (4.4). This would suggest, in analogy to Eq. (4.7), to try an expression of the type

$$W_k^{mot}=(g/2\pi)(mv_s^2/kr_o')F(v/v_s)N'\pi[\ln(w/2L_{DS})]L_{DS}/w,$$

in which the logarithm was replaced as shown in (3.4). However, there is a major difference here, causing this expression to be wrong. The magnetic field extends over all of space, while the piezoelectric stress is present only in the sample. Therefore, the integral over the squared electric field that is equivalent to Eq. (3.3) in the expression of the magnetic energy $E_m$ must be limited to the space inside the sample in this case, in order to model the piezoelectric system. Applying the Gauss theorem with a constant concentration of carriers of charge e, n(x)=const, we obtain an electric field $4\pi net'Lw/Lw$, with t' integrated from (–t/2) to t/2, and an equivalent magnetic energy

$$\begin{aligned}E_m'&=(e^2v_d^2/2c^2)\int[n(\mathbf{x})n(\mathbf{x}')/|\mathbf{x}-\mathbf{x}'|]=(v_d^2/8\pi c^2)\int E^2d^3x\\&=(n^2e^2v_d^2/2c^2)4\pi Lw\int t'^2dt'=(n^2e^2v_d^2/2c^2)\pi Lwt^3/6=\pi(ev_dN'/c)^2Lt/12w.\end{aligned} \tag{5.1}$$

Here we have integrates assuming the current density to be constant over the thickness t of the channel. In conclusion, Eq. (5.1) just replaces the factor ln(R/r) of Eq. (2.1) according to the rule

$$\ln(R/r)\longrightarrow \pi t/12w. \tag{5.2}$$

This yields the final result

$$W_k^{mot}=(g/2\pi)(mv_s^2/kr_o')F(v/v_s)N'\pi t/12w = (gN'^2\hbar/\pi)(v_s^2/u)\,F(u/v_s)\,\pi t/12w. \tag{5.3}$$

Finally, we obtain this way the Quantum Lattice Dynamic coherence parameter s' in the form

$$\boxed{s' = (gN'\hbar/m^*v_s)(\,v_s/u)^3F(u/v_s)t/12w.} \tag{5.4}$$

This is the sought expression of the piezoelectric coherence parameter s' for the special case of FETs and HFETs with w>>LDS>t derived here for the first time. It can easily be generalized to the case of several sheets with different piezoelectric properties in the above integral over t. We notice that the coherent contribution is strongly reduced in modern HFETs and FETs, due to the extreme smallness of t, as compared to w.

To allow for a current density that is not constant over the thickness t of the channel, e.g., by writing $J(t')/J(t/2)=j(t')$, we integrate again over t' and obtain this time

$$E_m'=(e^2v_d^2/2c^2)\int[n(\mathbf{x})n(\mathbf{x}')/|\mathbf{x}-\mathbf{x}'|]=(v_d^2/8\pi c^2)\int E^2d^3x=(n^2e^2v_d^2/2c^2)4\pi Lw\int j(t')t'^2dt' \tag{5.5}$$

This would replace t by $(1/t^2)\int j(t')t'^2dt'$ in Eqs. (5.3) and (5.4). One likely choice for j(t') would correspond to the self-consistent diffusion potential at the surface.

## 6. CONCLUSIONS

The conventional and coherent Q1/fE are thus combined with the help of the coherence parameter s to yield an universal Q1/f formula for the QED case. The s parameter is given by a simple universal formula, applicable also in the transition region between the both regimes. For the case of FETs and HFETs, there is special formula for the s parameter, which takes into account the unusual geometry of these devices.

It is interesting to note that a similar situation exists in the QLD case of conductors or semiconductors with piezoelectric coupling of the current carriers to transversal acoustical phonons. The present paper introduces the corresponding s' parameters for the first time here both for the usual (wire-like) geometry and for the special geometry of FETs and HFETs.

Due to the six orders of magnitude larger piezoelectric coupling constant g, compared to QED's a, the presence of the small factor t in Eqs. (5.3) and (5.4) has played an important role. Historically, the first GaN devices had 1/f coefficients of the order of unity or larger, instead of $10^{-6}$ to $10^{-3}$. However when GaN was used in HFETs, surprisingly low 1/f coefficients were obtained when the 1/f noise was measured. We now understand that the huge initial values were caused by piezoelectric (QLD) Q1/fE, and that the very low values later realized in HFETs were caused by the special form of the s' parameter, proportional to t.

This reflects an essential difference between the QED and QLD cases. In the former, the electromagnetic field extends through space also outside the device, while in QLD the deformation field is defined only in the GaN and AlGaN materials. We are confident that the formulas derived in the present paper will help in the optimization of GaN-based HFETs and FETs for untra-low noise and phase noise applications. It is also important in the effort to extend microelectronics, miniaturization and Moore's law to ever smaller device sizes [9], while keeping the dissipated power in reasonable limits.

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