1/f Noise in Nanowires by Quantum Mechanics

Thomas Prevenslik
QED Radiations, Discovery Bay, Hong Kong, CHINA
qedradiation@gmail.com

ABSTRACT

The 1/f noise commonly observed in power measurements of circuit elements - capacitors, resistors, and inductors - is perhaps one of the oldest puzzles of contemporary physics. Simulations of 1/f noise made by a summation of Lorentzians for step changes of power in time, or by a Markov chain of such steps in a stochastic stationary process do indeed produce 1/f noise in the frequency domain, but lack a physical basis. The dramatic increase in 1/f noise in nanoelectronic circuit elements, and nanowires in particular suggest a physical basis may be found in the size effect of QM and even extended to submicron regions of ordinary circuit elements. QM stands for quantum mechanics. In nanowires, QM precludes atoms from the heat capacity necessary to conserve Joule heat by an increase in temperature. Instead, conservation proceeds by the creation of charge that produces a step change of power in time, the Fourier transform of which gives the 1/f noise spectrum in the frequency domain.

1. Introduction

The 1/f noise is commonly observed in power measurements of electronic circuits comprising capacitors, resistors, and inductors. Other processes in the natural world also display this behavior including stock prices and music suggest [1] a generic origin might exist, but no generally recognized physical explanation of 1/f noise has been proposed. Indeed, the ubiquity of 1/f noise is one of the oldest puzzles of contemporary physics.

Of interest is the origin of the 1/f noise in nanoelectronics, say in nanowires of tin oxide [2] having submicron diameters of 10-50 nm and lengths greater than about 10 microns. In 1925, Johnson and Nyquist discovered [3,4] electronic noise or white noise in vacuum tubes. White noise has a constant power spectrum generated by the thermal agitation of charges inside a resistor by itself without any applied voltage. In contrast, 1/f noise sometimes called pink noise differs in that under applied voltage the frequency f of the power spectrum is not constant, but rather increases as f is lowered, i.e., having a slope of -1 on a log-log plot.

Over the past 80 years, explanations of 1/f noise have proved [1] elusive. Schottky [5] proposed a mathematical model of exponentially decaying current pulse I caused by the release of electrons from the cathode of a vacuum tube, i.e., $I = Io \cdot e^{-bt}$, where Io is the initial step, b is the relaxation rate and t is time. For a train of such pulses at an average rate, the power spectrum is of the Lorentzian form which is constant near f = 0 and for large f is proportional to $1/f^2$ with a narrow transition region where the power spectrum resembles that of 1/f noise. Later, Bernamont [6] pointed out only a superposition of such processes with a variety of relaxation rates yield 1/f noise for a reasonable range of frequencies.

Given that 1/f noise as a stochastic stationary process has a mean and variance that do not change over time, Erland et al. [1] showed observations of such processes may be modeled as a Markov chain in which one observation depends stochastically only on the immediately previous one.

To date, mathematical models [1,3-6] are presented that simulate 1/f noise,

But what is the physical basis that underlies the mathematical models of 1/f noise?

In this regard, Hooge [7,8] in an effort to systematically collect data on l/f noise from the literature proposed,

$$\frac{S_R}{R^2} = \left(\frac{S_I}{I^2}\right)_V = \frac{\alpha}{fN} \qquad (1)$$

where, S_R and S_I are the spectral power density of resistance R and current I, f is the frequency at which the noise is measured, N is the total number of free electrons, and α is an empirical dimensionless constant. Many years later, Vandamme and Hooge [9] concluded there is no theory behind (1). The relation normalizes [8] the relative noise to one electron. The only assumption is that whatever the electrons do, they do it independently.

Hooge [8] noted the difficulty of reconciling LFN with the residence time of the electron in the size of the sample. LFN stands for low frequency noise. If 1/f noise is a summation [1,5,6] of Lorentzians having long characteristic times t >> 1s, the electrons must stay in the sample much longer than a few seconds. However, in a sample with a length of 1 cm, an electron only stays about 0.1 s as its diffusion coefficient D is of order 0.001 m^2/s. For nanowires, the residence time of the electron is far shorter, yet LFN is still observed.

How can electrons that stay in the nanowire for such short times produce LFN at frequencies below 1 Hz?

Hooge [8] argued that the 1/f noise is caused by lattice scattering of electrons, but this is unlikely because phonon frequencies are far higher than the low frequencies of 1/f noise. The number N of free electrons in (1) therefore has nothing to do with 1/f noise.

Nevertheless, 1/f noise theories based on electron scattering continued. Handel [10] proposed a quantum

1/f theory that claimed LFN is caused by low-frequency photons that are absorbed or emitted in each scattering event. However, the half-wavelength of LFN is far longer than the dimensions of the samples, and therefore QED at least, cannot be invoked as the mechanism by which the EM energy in scattering of electrons can produce 1/f noise. QED stands for quantum electrodynamics and EM for electromagnetic. The van Vliet [11] claim that the absence of an EM confinement mechanism to create the low frequency photons is not a serious problem must simply be rejected. It suffices to say the experimental results cited by Hooge [8] did not support the quantum 1/f theory.

2. Scope

In this paper, 1/f noise is hypothesized to be a consequence of the QM restriction that Joule heat cannot be conserved by an increase in temperature of the nanowires. Generally, the scope is nanoelectronics, although extensions may be made to submicron regions of ordinary electronic circuit elements. No attempt is made to provide a generic explanation of 1/f noise in areas such as stock prices and music [1] unless a connection can somehow be made to the dissipation of electrical current by Joule heat. .

3. Purpose

The purpose of this paper is to support the hypothesis that 1/f noise is a QM effect that occurs naturally upon passing current through a nanoelectronic circuit element, specifically a nanowire.

4. Methodology

QM in the 1/f noise of nanowires by the creationof charge finds similarity with nanoelectronics by Prevenslik [12] including memristors and the Ovshinsky Effect in PCRAM devices, the latter related to the creation of charge that locally reduces the resistance of the GST film to allow encoding of information based on difference in resistance. QM in combination with QED avoids the difficulties cited by Hooge [8] of producing LFN with long residence times in small samples, the methodology of which is described as follows.

1. QM precludes the atoms in nanostructures from having the heat capacity to conserve the Joule heat ($P = I^2R$) by an increase in temperature, and therefore QED is invoked to induce the conversion of Joule heat to photons within the nanowire.

2. The QED photons are created because of the EM confinement that is naturally provided by TIR under the high surface to volume ratio of the nanowire. TIR stands for total internal reflection. What this means is the Joule heat is almost totally absorbed in the surface of the nanowire that is the TIR mode of the QED photons, i.e., the QED photon provides its own EM confinement.

3. Charge is created in the nanowire by Einstein's photoelectric effect because the Planck energy of the QED photons created is beyond the ultraviolet. The charge in the form of excitons (holes and electrons) is created promptly as the current enters the nanowire.

4. The nanowire resistance drops abruptly that under a constant applied voltage causes the current to increase. The drop in resistance is caused by the increased conductance from the excitons in the nanowire. Power dissipated through the nanowire undergoes a steady step change. Repetitive Markov steps are not necessary.

5. The step change in power occurs abruptly because of the high mobility of the excitons and the short length of the nanowires. The shape of the steady power pulse may vary, but approximates the perfect step.

6. The Fourier transform (FT) of step change in power gives the 1/f slope in the frequency domain with variations thereof depending on the exact shape of the step. Hooge's [8] difficulty with long residence times in small samples is overcome because the FT naturally produces LFN from the step change in power.

5. Theory

5.1 QM Restrictions

The QM restrictions on the thermal energy of an atom in a nanowire depends on the EM confinement as given by the Einstein-Hopf [13] relation for the Planck energy E of the atom as a harmonic oscillator,

$$E = \frac{\frac{hc}{\lambda}}{\exp\left(\frac{hc}{\lambda kT}\right) - 1} \qquad (2)$$

where, h is Planck's constant, c the speed of light, k Boltzmann's constant and T absolute temperature. The Planck energy E with wavelength λ is shown in Fig. 1.

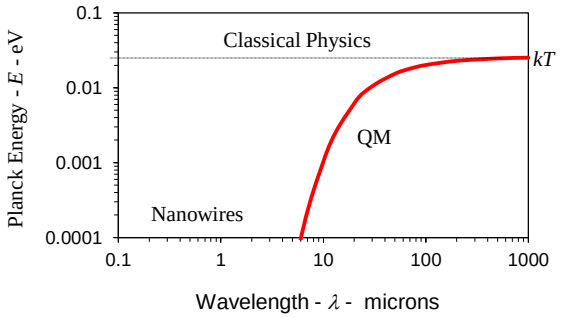

Fig. 1 Atom as a Harmonic Oscillator at 300 K

Classical physics allows the atom to have heat capacity at the nanoscale. QM differs by allowing the atom to only have heat capacity for $\lambda > 50$ microns. Unlike classical physics, QM precludes the atom from conserving absorbed EM energy at the nanoscale by an increase in temperature.

5.2 TIR Confinement

Nanowires lack of heat capacity by QM precludes conservation of Joule heat by an increase in temperature. However, the absorbed heat must still be conserved, and therefore conservation is proposed to proceed during TIR confinement by creating QED induced radiation *inside* the nanowire.

TIR has a long history beginning with Tyndall in 1870 who observed if the refractive index of a body is greater than that of the surroundings, absorbed light is trapped at its surface. However, TIR in nanostructures has an important significance and need not be limited to light absorption. Unlike the macro world, nanostructures have high surface to volume ratios, and therefore heat from any EM source (lasers, molecular collisions, Joule heat, etc.) is absorbed almost totally in the nanostructure surface. Since the nanostructure surface corresponds to the TIR wave function of the absorbed EM energy, QED induces the absorbed heat to undergo the spontaneous creation of photons *inside* the nanostructure. TIR confinement is not permanent, but rather sustains itself only during the absorption of EM energy, i.e., absent EM energy absorption, there is no TIR confinement and QED radiation is not created.

Similar to creating QED photons of wavelength λ by supplying EM energy to a QM box with sides separated by $\lambda/2$, the absorbed EM energy is frequency up-converted to the characteristic dimension D_C of the nanostructure. The QED photon energy E and frequency f are

$$E = hf,\ \ f = \frac{c}{\lambda},\ \ \lambda = 2nD_c \tag{3}$$

where, n the refractive index. For a nanowire, D_C is the diameter d.

5.3 QED Photons and Rate

Classical heat transfer conserves absorbed heat by an increase in temperature, but is not applicable to nanowires because of QM restrictions on heat capacity. Instead, the power P of the Joule heat pulse is conserved by creating number N_P of QED photons *inside* the nanowire. The rate of QED photon creation is,

$$\frac{dN_P}{dt} = \frac{\eta P}{E} = \frac{\eta I^2 R}{E} \tag{4}$$

where, t is time. Only a fraction η of the power P creates excitons, the remainder (1-η) is lost to the surroundings. By the photoelectric effect, the rate dN_{ex}/dt of excitons created, each comprising an electron and hole is,

$$\frac{dN_{ex}}{dt} = Y\frac{dN_P}{dt} = \frac{\eta YP}{E} \tag{5}$$

where, Y is the exciton yield. Unlike the probabilistic creation of excitons from an external source of radiation having Y<< 1, photons are created by the QED conservation of EM energy in the nanowire at Y = 1.

5.4 QED Photons, Excitons, and Charge

The creation of charge carriers in the nanowire requires QED photons having Planck energy greater than the energy Eg of the band gap, E > Eg. The excitons comprising electron-hole pairs form as the QED photons produce an electron charge Q_E and positive charged hole Q_H that separate under the field F.

The nanowire resistance R depends on the conductivity σ and resistivity ρ given by the number density of electrons Q_E and holes Q_H,

$$\sigma = \frac{1}{\rho} = e\left(Q_E\mu_E + Q_H\mu_H\right) \tag{6}$$

where, μ_E and μ_H are the electron and hole mobility.

5.5 QM Charging

Excitons form in proportion to the fraction ηP of QED photons absorbed and the yield Y. The Q_H and Q_E are the number of created positive charged holes and negative charged electrons. Under the high electric field F, the charge carriers separate to form independent charges that rapidly move to opposite polarity terminals.

The rate ηYP/E of excitons created is balanced by the electron Q_E and hole Q_H charges lost in moving toward opposite polarity terminals by their respective μ_E and μ_H mobility in the electric field F.

$$\frac{dQ_E}{dt} = \frac{\eta YP}{E} - Q_E\frac{\mu_E F}{L} \tag{7}$$

$$\frac{dQ_H}{dt} = \frac{\eta YP}{E} - Q_H\frac{\mu_H F}{L} \tag{8}$$

Both exciton electron and hole equations are identical allowing the hole response to represent that of the electron for the same mobility. Taking F = Vo/d,

$$\frac{dQ_H}{dt} = \frac{\eta YP}{E} - \frac{\mu_H V_o}{L^2}Q_H \tag{9}$$

The hole Q_H solution is given by,

$$Q_H = \frac{L^2}{\mu_H V_o} * \tag{10}$$

$$* \left\{\frac{\eta YP}{E}\left[1 - e\left(-\frac{\mu_H V_o}{L^2}t\right)\right] + \frac{\mu_H V_o}{L^2}Q_{H0}e\left(-\frac{\mu_H V_o}{L^2}t\right)\right\}$$

On average, the holes and electrons are centered in the nanowire and need to move L/2 to reach the voltage terminals, the resistance R is,

$$R = \rho\frac{L}{2A} = \frac{L}{2A}\frac{1}{e(\mu_E Q_{EO} + \mu_H Q_{HO})/AL} \approx \frac{L^2}{4e\mu_H Q_H} \tag{11}$$

The resistivity ρ assumes $\mu_E = \mu_H$ with the same number Q_E of electrons as the Q_H holes. Note ρ requires units of per unit volume, where volume is AL and A is the nanowire area. The initial resistance R_o gives the initial number Q_{HO} of holes,

$$Q_{HO} = \frac{L^2}{4e\mu_H R_O} \tag{12}$$

The current I is,

$$I = \frac{V_o}{R} \tag{13}$$

6. Analysis

Comparisons of QED theory with experimental data [2] for 1/f noise are made for SnO_2 nanowires. The assumed mobility μ_H = 0.0172 m^2/V-s, is higher than the typical range of 0.004 to 0.01 m^2/V-s. Wire diameters d ranged between 10-50 nm with a length L > 10 microns. The initial resistance Ro = $25x10^6$ ohm was taken from (Fig. 1(a) of [2]) for Vo = 2.5 volts at a current I = 0.1 μA. The power P ranged from 1 to 3 μW.

The Planck energy E and rate dN_p/dt of QED photons created at power of 1 and 3μW shown in Fig. 2. The fraction η = 1 assumes there is no loss of QED radiation to the surroundings. The exciton velocity $\mu_H Vo/L$ and rise time of power pulse are shown in Fig. 3. The initial QH_O and final QH number of holes in the nanowire is given in Fig.4.

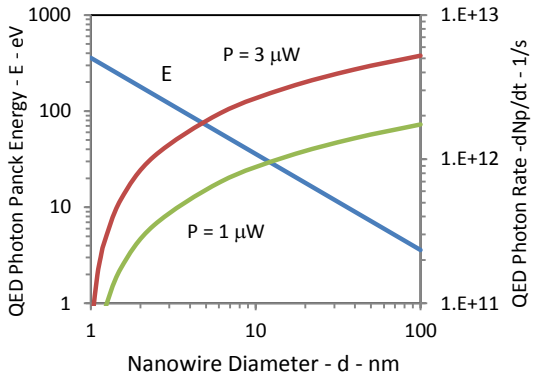

Fig. 2 QED Photon Energy and Rate

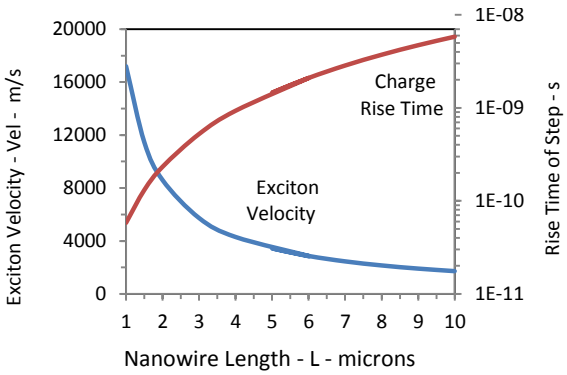

Fig. 3 Exciton Velocity and Rise time of Power Pulse

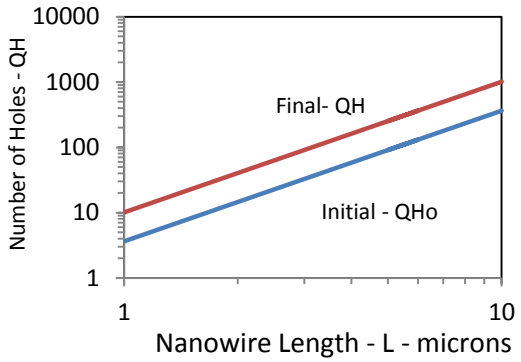

Fig. 4 Initial and Final Number of Holes

The charge creation as the current enters the nanowire is abrupt, i.e., the time constant from (10) is less than 6 ns at lengths L < 10 microns. Indeed, the time for the charge to traverse the full wire length is less than 10 ns for lengths L < 10 microns as shown in Fig. 3 What this means is the step in charge may be treated as a step function in power.

The FT of a unit step change of power in the time domain gives the 1/f spectrum in the frequency domain,

$$G(2\pi f) = \int_{-\tau/2}^{\tau/2} 1e^{-j\omega t}\, dt = \frac{\sin(\pi f \tau)}{\pi f} \qquad (14)$$

as illustrated to have the same -1 slope as 1/f and not $1/f^2$ in Fig. 5.

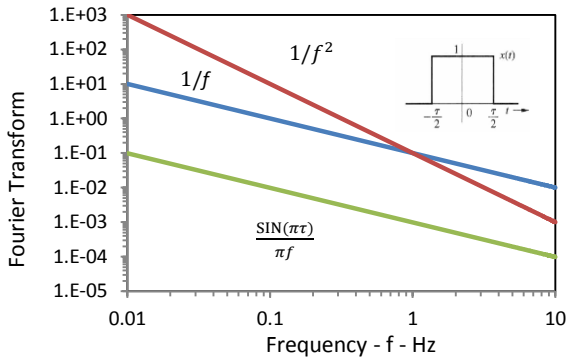

Fig. 5 FT - Step Change of Power in Frequency Domain

7. Discussion

7.1 Physical Markov Process

In nanowires, QED induces the Joule heat to produce a train of step changes in QED power each of which decay in the otherwise macroscopic circuit. In this way, a Markov process is formed with each step change in power effectively depending on the previous one.

However, stochastic Markov processes may not be necessary. Indeed, the 1/f spectrum may be considered deterministic and caused by the FT of a steady step change in power produced by simply passing current through the nanowire. .

7.2 Fourier Transforms

The FT of power [14] as an arbitrary step function t^a in time gives $f^{-(a+1)}$ in the frequency domain, where a is a rational number not necessarily an integer. For a = 0, the FT of a step is 1/f and as depicted in relation to the reference 1/f. Clearly, the FTs of t^a in [14] for a = +0.5 and -0.25 are not sufficient to bracket the 1/f noise. Numerical FTs of t^a for a = -1.1 and – 0.9 are required.

7.3 Crystal Damage

Hooge [8] notes damaging the crystal by mechanical stress or by irradiation strongly increases the l/f noise. The electron concentration and the mobility hardly change; but the noise increases by orders of magnitude. The first explanation is that the defects act as

generation recombination centers that in some unexplained way generate l/f noise. If correct, 1/f noise in damage is a fluctuation in the number of free carriers or number noise. However, the defects may act as scattering centers and generate l/f noise according to fluctuations in mobility. Generally, damaged crystals are thought to be number rather than mobility noise.

Perhaps the difficulty in explaining the dramatic increase in 1/f noise upon crystal damage is that electrons and their mobility have nothing to do with 1/f noise. The literature does not suggest that excitons are created by mechanical stress or irradiation, yet low levels of QED induced charge may be induced from local heating of submicron regions. Heat is produced in damaging the crystal by any means, and therefore likely excitons formed from QED photons created in conserving local heating of submicron regions. Subsequently, the local resistance was lowered thereby increasing the 1/f noise upon passing current through the damaged crystal.

The problem is Hooge [8] and others never considered the possibility that charge was created in the damaged crystal. Electrons cannot explain 1/f noise.

7.4 Number of Carriers

QED theory asserts only a small number of holes need be created to explain 1/f noise in SnO_2 nanowires. For carbon nanotubes (CNTs) having length 600 nm, 1/f noise is caused [15] by about 40 holes in the ON state that decrease in the OFF state. Fig. 4 shows a comparable number of holes for the final and initial conditions of the 1-micron long SnO_2 nanowire.

7.5 External Step Change

The hypothesis that 1/f noise is caused by a step change in power induced by QED charge may be easily verified by applying an external step change in voltage to a nanowire. Perhaps this has already been done.

8. Summary and Conclusions

1. Charge continuously created in nanowires by QM is consistent with a Markov chain of step changes in power in the manner of a stochastic stationary process.

However, a Markov chain may not be necessary as a step change in power occurs naturally upon passing current through nanowires.

2. The physical process that underlies the 1/f spectrum in nanowires begins with the QED induced conservation of Joule heat by non-thermal EM radiation instead of by an increase in temperature.

The EM radiation having the Planck energy necessary to create excitons by the photoelectric effect momentarily lowers the nanowire resistance causing an increase in the current to produce a step change in QED power.

In the manner of producing LFN by imposing a step change of current or voltage in an ordinary circuit element, the 1/f noise is produced as the step in QED power is sustained by current through the nanowire.

3. Damaged crystal show increased 1/f noise because heat is locally produced that by QED theory creates charge in the form of excitons that lower the resistance of the crystal, thereby increasing the 1/f noise.

4. 1/f noise in SnO2 nanowires and CNTs depends on the creation of a small number of holes.

5. Imposing a step change of voltage or current in a nanowire is expected to increase the 1/f noise, thereby verifying the hypothesis of QED theory that charge is produced upon passing current through a nanowire.

References

[1] S. Erland, P. E. Greenwood, L. M. Ward, "1/f noise" is equivalent to an eigenstructure power relation," EPL, 95 (2011) 60006.

[2] S. Ju, et al., "1/f noise of SnO2 nanowire transistors," Appl. Phys. Lett., Vol 92 (2008) 243120.

[3] J.B. Johnson, "The Schottky effect in low frequency circuits," Physical Review 26 (1925), 71–85.

[4] H. Nyquist, "Thermal agitation of electric charge in conductors", Phys. Rev., Vol. 32 (1928) 110-113.

[5] W. Schottky, "Small-shot effect and flicker effect," Physical Review 28 (1926), 74–103.

[6] J. Bernamont, "Fluctuations de potential aux bornes d'un conducteur metallique de faible volume parcouru par un courant," Ann. Physik (Leipzig) 7 (1937), 71.

[7] F. N. Hooge, "l/f noise is no surface effect," Phys. Lett**.,** 29 A (1969) 139.

[8] F. N. Hooge, "1/f Noise Sources," IEEE Trans. Elec. Dev., 41 (1994) 1926.

[9] L. K. J. Vandamme, F. N. Hooge, "What Do We Certainly Know About 1/*f* Noise in MOSTs?" ," IEEE Trans. Elec. Dev., 55 (2008) 3070.

[10] P. J. Handel, "1/ f noise-an infrared phenomenon," Phys. Rev. Lett., 34 (1975) 1492.

[11] C. M. van Vliet, "Further comments on Handel's theories of quantum l/f noise," Physica, A150 (1988) 244.

[12] T. Prevenslik, "Quantum Mechanics and Nanoelectronics," ICMON 2011 : International Conference on Microelectronics, Optoelectronics, and Nanoelectronics, Venice, November 28-30, 2011

[13] A. Einstein, L. Hopf, "Statistische Untersuchung der Bewegung eines Resonators in einem Strahlungsfeld," Ann. Physik, 33 (1910) 1105.

[14] S. Smith, "An Interesting Fourier Transform – 1/f Noise" http://www.dsprelated.com/showarticle/40.php

[15] Y. M. Lin, et al., "Low-Frequency Current Fluctuations in Individual Semiconducting Single-Wall Carbon Nanotubes," Nano Letters, 6 (2006) 930.