Electronic Noise in Nanoelectronic Building elements for NanoMEMS and BioMEMS

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ABSTRACT

One of the most widely known effects in nanoelectronics is the Coulomb—blockade effect which reduces the shot noise in a device. However, the effect of shrinking of the size is not always so beneficial, shot noise can even increase, because of other effects. Moreover, other types of noises and new effects can set strong limits for device performance. From classical knowledge on device noise, an increased 1/f noise and increased effective thermal noise voltage and quantum uncertainty noises are expected which imply performance limitations at the low frequency and high frequency ends, respectively. The result is a reduced long-term stability an increased frequency of false-bit-switching or false alarm events. These considerations can help us to understand why biology is using neural spikes.

From the research-and-development side, the origin and engineering of conductance noise (1/f noise) is often an unsolved problem. For example, in carbon nanotubes, the published experimental results are contradictory and it is not possible to draw a final conclusion about the nature and possible ways of engineering this crucial kind of noise source.

It is important to realize that more active noise sources do not always mean limitation of performance. In chemical sensing applications, the measurement of noise can be used to detect chemical agents and their composition with a great selectivity and sensitivity, because the chemical fragments dynamically interact with the current transport in the device. This is the situation when the noise in nano-sensors has a great advantage as compared to the noise in classical devices. The increased specific surface of nanostructures and the large number of possible structural combinations have a great potential for both gas and fluid sensing applications via noise analysis.

Keywords: Rice formula, false-bits, dissipation, thermal noise, quantum noise, ion channels, neural information, nanotubes, chemical sensors

1. INTRODUCTION

Approaching nanometer length scale with electronic device sizes has serious implications on performance and noise properties [1-5]. By shrinking to the mesoscopic size range, not only the parameters but also the governing physical phenomena can change. The changes relevant for nanoelectronics come in classical physical or quantum physical fashion, respectively [1]. In this paper, we devote our attention to the classical physical consequence, which is due to the shrinking of the characteristic capacitance of the device.

A well-known example of shrinking capacitance the Coulomb—blockade effect which is do to the high charging energy E_{ch} for each electrons [2-4].

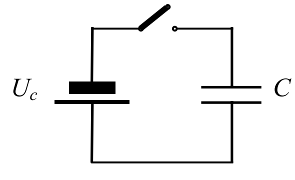

Figure 2. Simple model of the characteristic capacitance and the charging energy of the electrons. U_c voltage is needed to charge the capacitor by one electron and nU_c voltage is needed for n electrons.

The charging energy for the electron charge is obviously:

$$E_{ch} = \frac{1}{2}\frac{e^2}{C} \quad . \tag{1}$$

When $E_{ch} >> kT$, the probability of double or higher charging radically drops due to the Boltzmann factor $\exp(-E_{ch}/kT)$ characterizing the probability of higher-than-mean thermal energy excitations. This effect, the Coulomb-blockade, as it is well known, this effect leads to single electron devices and associated with a reduced shot noise. The classical shot noise, which is a Poissonian sequence of current spikes due to the transfer of electron charge, is a current noise with spectrum:

$$S_i(f) = 2Ie \quad , \tag{2}$$

where I is the mean dc current. Due to the single electron charging constrain, the electrons transfer through the device in an anti-correlated fashion. Figure 2 shows a simple illustration, from the Fourier-analysis side, of the implications of an anticorrelated electron transfer, which produces a more ordered current spike train than a Poissonian sequence. A totally periodic current spike train has no low-frequency noise spectrum. A partially periodic one, as caused by anticorrelated transfer, has a reduced low frequency noise compared to the pure Poissonian case.

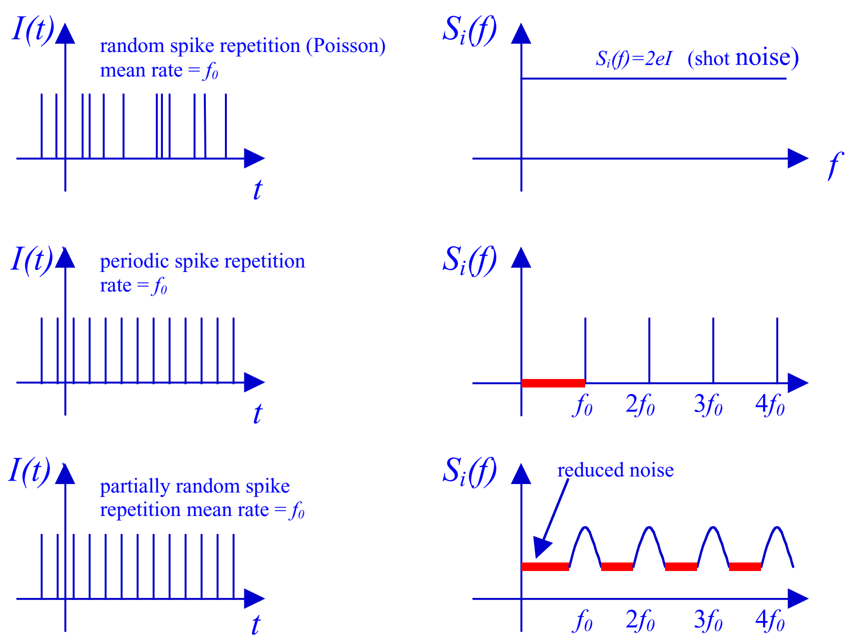

Figure 2. Simple illustration of the reason for reduced shot noise. A totally periodic spike (charge) train has no low-frequency noise spectrum. A partially periodic one has reduced low frequency noise compared to the pure Poissonian case. Increased shot noise (not shown in the figure) needs positive correlations between the jumps of electrons (super-Poissonian spike train) which results in a seemingly increased effective charge in Eq.1.

The effect described above is basically a (semi)classical physical effect, though, quantum physical refinements can obviously be made. It is interesting to note that quantum phenomena at nano sizes, e.g. resonant tunneling, can result in even the opposite effect [5]. Increased shot noise is due to positive correlations between the jumps of electrons (super-Poissonian spike train) which can result in a seemingly increased effective charge in Eq.2.

The purpose of the introduction above is only to illustrate the new nature of noise processes at nano sizes by well established example. However, though in the dominant part of nanoelectronic literature the focus is mostly shot noise related phenomena, we believe that shot noise processes shall not play a major role in determining the performance limits of nanoelectronics. Here we show that *thermal noise* and *quantum uncertainty noise*, due to the small device size, have much stronger implications for the perspectives of technology. The generation of false bits due to these noise processes imply firm fundamental limits on speed, dissipation and information transfer rate. The main implications are lower limits set to the battery voltage and speed or miniaturization of the nanoelectronic devices or the density of integration them into an integrated circuit.

Other noise phenomena, such as conductance noise (1/f noise, diffuion noise, etc.) in nanotubes and quantum dots are not of fundamental nature, however represent serious practical problems at practical applications. On the other hand, this kind of noises have important technical applications for chemical sensing and, for nanoelectronic sensors, that implies single molecule detection and identification abilities.

2. TRADE BETWEEN SHRINKING SIZE, NOISE AND DISSIPATION

The literature of noise in nanoelectronic devices is focusing on different versions of charge quantization noises, such as shot noise, partition noise, ballistic transport noise, resonant tunneling noise. These noises are important aspects, however their impact on the evolution of the nanoelectronics related technology is not strong. The ultimate impact will be given by thermal noise, quantum uncertainty noise and excess (conductance) noise. The reasons for this conclusion are the following arguments.

Shrinking of the characteristic size L implies the radical decrease of the characteristic capacitance $C(L)$ of the device, as $C(L) \propto L^2$. On the other hand, in the case of full speed (bandwidth), the thermal noise voltage U_{th} and quantum uncertainty noise voltage U_{qu} satisfy the following relations:

$$U_{th} = \sqrt{\frac{kT}{C(L)}} \propto \frac{1}{L} \qquad U_{qe} \cong \sqrt{\frac{hf_c}{C(L)}} \propto \frac{1}{L} \tag{1}$$

where f_c is the bandwidth. From our point of view, these two noise sources have similar implications and the only difference is that above ¯50 mK temperature, the thermal noise dominates and below that temperature the quantum uncertainty noise dominates. It is easy to show by the Rice formula for threshold crossings by noise that, in the 1GHz clock frequency range and above, the required potential barrier, that is the lower limit of bias voltage U_0, in the device to avoid false bit events in a one-year timescale, has to be at least 15 times greater than U_{th} and U_{qe} . Supposing fixed clock frequency, fixed thickness of the insulating layer between the device and the substrate, and that the device capacitance is due to the geometrical capacity to the substrate, this fact directly implies that the specific power dissipation P_S on a unit surface of the chip, scales with the size as:

$$P_S = \frac{P(L)}{L^2} \propto \frac{C(L)U_0^2(L)}{L^2} \propto \frac{L^2 / L^2}{L^2} = \frac{1}{L^2} \tag{2}$$

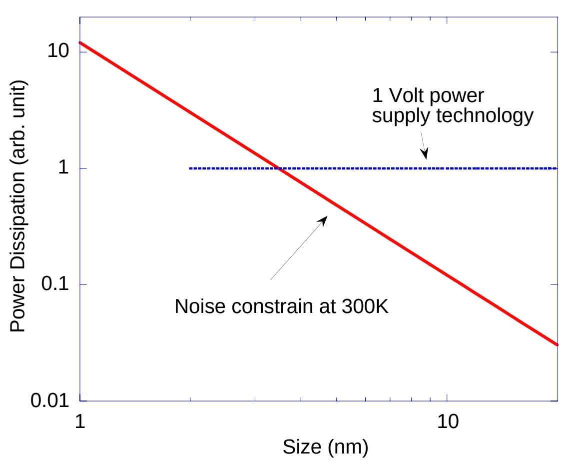

Figure 3. Estimation of power dissipation versus device size due to thermal noise constrain at room temperature. This constrain becomes dominant below 10 nm and prohibits more dense integration of digital circuits.

Relation (2) is very different from results valid for present microelectronics, where no similar lower limit on the bias voltage is forced by the Rice formula so fixed bias voltage and clock frequency imply a size-independent specific power dissipation:

$$P_S = \frac{P(L)}{L^2} \propto \text{constant} \qquad . \tag{3}$$

Practical examples are state-of-the-art microprocessors with ¯1 V bias voltage, where the low bias voltage is to reduce specific power dissipation. Supposing fixed, 1nm thick, insulating layer between the substrate and the device and supposing that the device capacitance is due to the geometrical capacity to the substrate, it is easy to show that using a microprocessor made of devices of 1 nm characteristic size would require about 3 V bias voltage, so it would produce about 10 times greater specific power dissipation for the same chip size as the 1V devices, which would prohibit using this technology or doing high integration density, see Figure 3.

3. NATURE'S BIOMEMS BUILDING ELEMENTS: HOW DO THEY DO SMART DEVICES?

After false-bit the considerations above, it is natural to ask, how does Nature do this? Characteristic sizes of ion channels are in the order of 1 nm and typical potential barriers are < 1 V, and similar calculations indicate that the frequency of the occurrence of false-bits is high in these devices. As ion channels are the building blocks of neurons, the false-bit events give natural explanation for the occurrence of spontaneous firing events of neurons: the neurons usually fire even in their "ground state" when no external excitation occurs.

From a more interesting angle of observation, we can realize that Nature actually gave noise a functional role. The information between neurons propagates by the modulation of this ground state noise. Detailed studies indicate [6-8] that these systems are optimized for maximal information transfer rate and dissipation.

Will nanoelectronics move in the same direction by using noise as a function? It is hard to judge. However, if that happens, it will imply a radically different microprocessor logic, architecture and language. Probably, such a microprocessor would be much slower and inaccurate for calculations, however much more smart/flexible than present techniques, similarly like brain.

4. A FEW WORDS ABOUT CONDUCTANCE NOISE IN NANOELECTRONIC DEVICES

Conductance noises cause problems when DC current is flowing through a device or contact because it induces a voltage or current noise. Experience acquired in homogeneous macroscopic systems would suggest that the normalized noise should scale with the inverse of the volume if the noise is generated in the bulk and it should scale inversely to the surface if it is a surface generated noise. This scheme has been confirmed down to the size of about one-micron.

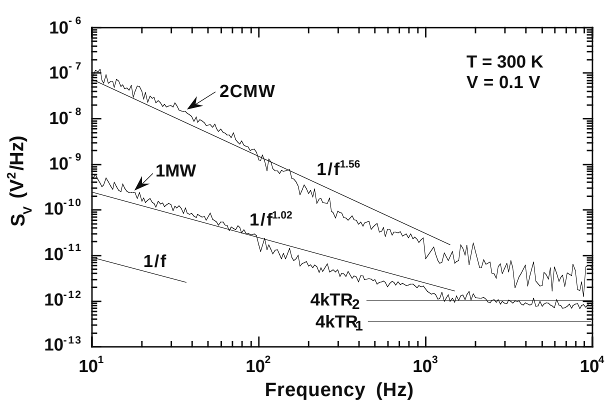

Figure 4. Conductance noise (-induced-voltage-noise) in multiple wall carbon nanotubes [9]. 1MW: a multiple wall nanotube; 2MW: two multiple wall nanotubes in series; $4kTR_1$ and $4kTR_2$ are the corresponding calculated thermal noise value.

Concerning the most important potential building elements of nanoelectronics, the carbon nanotubes, even this simple question about the scaling of the noise with size is an unsolved problem. One reason for that is the role of contacts and junctions in generating the noise, c.f. the change of the conductance noise versus thermal noise when two nanotubes are put in series, see Figure 4. Another difficult experimental problem is to fabricate several nanotubes of the same material property but with different diameter.

5. CHEMICAL SENSING BY NOISE

It is important to realize that more active noise sources do not always mean limitation of performance. In chemical sensing applications, the measurement of noise can be used to detect chemical agents and their composition with a great selectivity and sensitivity [10], because the chemical fragments dynamically interact with the current transport in the device. This is the situation when the noise in nano-sensors has a great advantage as compared to the noise in classical devices. The increased specific surface of nanostructures and the large number of possible structural combinations have a great potential for both gas and fluid sensing applications via noise analysis.

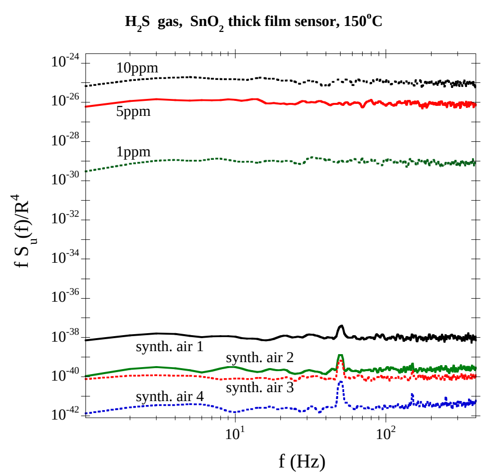

Figure 4. Sensing of H_2S gas by conductance noise. The normalized spectrum at 1ppm H_2S concentration is above the synthetic air level by 8 orders of magnitude. Data were measured on a macroscopic commercial gas sensor. Calculations indicate that nanometer size would provide single molecule sensitivity.

On Figure 4, results of gas sensing [11] of H_2S gas by conductance noise analysis are shown. The normalized spectrum at 1ppm H_2S concentration is above the synthetic air level by 8 orders of magnitude. Data were measured on a macroscopic commercial gas sensor. Calculations indicate that nanometer size would provide single molecule sensitivity.

5. CONCLUSION

The implication of the above considerations it that electronic noise will have an important role in nanoelectronics, a much more important role than in present microelectronics. Scientists and engineers, either they like or dislike noise problems, have to learn to live with its dominant appearance, obey its rules and try to use it for something useful, like sensing.

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