Noise in nanoelectronic devices

Giuseppe Iannaccone
Dipartimento di Ingegneria dell'Informazione: Elettronica, Informatica, Telecomunicazioni,
Università di Pisa

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Giuseppe Iannaccone

Dipartimento di Ingegneria dell'Informazione
Università degli Studi di Pisa
Via Diotisalvi 2, I-56122 Pisa, Italy
g.iannaccone@iet.unipi.it

ABSTRACT. *In this paper we present a brief review of properties of noise in nanoelectronic devices, focusing on shot noise, that is particularly relevant in nanoscale devices and when few electrons determine device behaviour. We review cases in which shot noise is significantly altered with respect to full shot noise, i.e., that associated to a Poissonian process, in order to gain insights into the details of the transport mechanisms. We focus both on mesoscopic (ballistic) devices at very low temperature and on more conventional MOSFETs at the nanoscale, that are entering mass production and, due to their small scale, exhibit noise properties similar to those observed in more exotic mesoscopic devices.*

KEYWORDS: *noise, nanoelectronics, shot noise, mesoscopic devices, ballistic MOSFETs.*

1. Introduction

Noise in electronic devices, is extremely important from an engineer's and a physicist's point of view. From an engineer's point of view, performance limits of analog circuits and telecommunication systems are determined by noise properties of electron devices; therefore, designers always face a tradeoff between immunity to noise and power consumption. From a physicist's point of view, noise provides insights into the transport mechanism of electron devices that are not revealed by DC and AC characterization. In addition, in recent years, noise proved to be a uniquely sensitive probe of electron-electron interaction in nanoelectronic and microelectronic devices.

The main types of noise in electron devices are thermal, shot, generation-recombination, and $1/f$ noise. Here we will focus on shot noise, which is particularly meaningful for nanoelectronic devices.

Shot noise has been described for the first time by Schottky in the case of thermoionic diodes (Schottky, 1918). It is due to the granularity of charge, that is "quantized" in units of $q = 1.6 \times 10^{-19}$ C. Let us suppose that current can be considered a sum of independent pulses randomly distributed (obeying Poisson distribution) each corresponding to one transferred electron (transferred charge q). Following Landauer (Landauer, 1993), we can call dn/dt the rate of electron transfer, so that the average current is $I=\langle i \rangle = q\, dn/dt$. The mean squared current noise in a frequency range Δf is $\langle i^2 \rangle \Delta f = S\Delta f = 2q^2 dn/dt \Delta f$, which means that the power spectral density S is equal to $2qI$, the so called full shot noise.

S is white up to frequencies comparable to the duration of the pulse due to a single electron (*i.e.*, the electron transit time). Most importantly, shot noise in equilibrium reduces to thermal noise, as it must be. Let me stress the fact that *shot noise does not add up to thermal noise*, but thermal noise and shot noise are only particular cases of a more general noise formula, that reduces to shot noise far from equilibrium (when current is a unidirectional flux) and reduces to thermal noise in equilibrium. This point is very clearly stated in (Landauer, 1993).

As we already mentioned, noise is a very sensitive probe of electron-electron interaction. Indeed, if charge carriers do not interact with each other, the process of traversing the device is Poissonian, and we have full shot noise, $S = S_{full} = 2qI$. Interaction introduces "coordination" in the collective motion of electrons, making the process non Poissonian, *i.e.*, $S \neq 2qI$.

There are two main types of interaction, namely due to Pauli Exclusion, which limits the density of electrons in the phase space, and to Coulomb repulsion, which limits the density of electrons in the real space. In most cases, interaction make the collective motion of electrons more regular, and we end up with a sub-Poissonian process and reduced fluctuations, *i.e.*, $S < S_{full}$.

2. Suppression and enhancement of shot noise in nanoelectronic devices

There are several examples of suppressed shot noise. Some of them are due to simple Coulomb repulsion, such as in charge-limited regime of a vacuum tube (Van der Ziel, 1986); others are due to Pauli exclusion, such as suppression of shot noise down to zero in quantum point contacts in correspondence with conductance plateaus (Lesovik 1989, Kumar *et al.*, 1996), the 1/3 suppression in elastic diffusive conductors (Beenakker 1992), and the ¼ suppression in chaotic cavities (Oberholzer *et al.* 2001, Oberholzer *et al.* 2002). In other cases shot noise is suppressed due to the combined effect of Pauli exclusion and Coulomb repulsion, such as in resonant tunnelling diodes in the positive differential resistance region, and in the stress-induced leakage currents in metal-oxide-semiconductor structrures (Iannaccone *et al.*, 2000).

There are also rarer cases of enhancement of shot noise due to interaction: in such cases we say that the process in super-Poissonian. Notable examples are the doubling of shot noise in normal metal-superconductor junctions (de Jong *et al.*, 1994, Jehl *et al.*, 2000) due to the pairing effect in superconductors; the strong enhancement up to 6.6. of shot noise in resonant tunnelling diodes in the negative differential resistance region (Iannaccone *et al.*, 1998) due to the interplay of Coulomb repulsion with the particular shape of the density of states in the quantum well; the enhancement of shot noise due to Coulomb repulsion in systems of coupled quantum dots (Gattobigio *et al.*, 2002); finally, known since a long time, the extreme enhancement of shot noise achievable in avalanche diodes and photodiodes.

A very useful parameter to investigate deviations from full shot noise is the so-called fano factor γ, defined as the ratio of the power spectral density of shot noise to S_{full}, *i.e.* $\gamma = S/S_{full}$. Of course we have suppressed shot noise if $\gamma<1$, enhanced if $\gamma>1$. There is also another intriguing interpretation of γ: we may say that *from the point of view of noise*, interacting particles behave as non-interacting quasi particle of charge γq, for which we have $S = 2(\gamma q)I$. This interpretation is straightforward in some cases: indeed the abovementioned doubling of shot noise in the case of metal-superconductor junctions is easily justified if we consider non-interacting quasi particles (the Cooper pairs) of charge $2q$. Analogoulsy, the Fano factor in the fractional quantum Hall regime has been experimentally measured to be 1/3 or 1/5, for quasi-particles of charge $1/3q$, and $1/5q$, respectively (dePicciotto *et al*, 1997). However, one should be careful to extend this interpretation to all cases.

3. Shot noise in ballistic devices at zero temperature

In such devices, interaction through Pauli exclusion takes place only in the reservoirs. Using Landauer-Büttiker formalism, and following (Lesovik 1989), current and power spectral density of the noise current can be written as:

$$I=\left(\frac{q^2}{h}\sum_i T_i\right)V\text{, and } S=\left[2q\frac{q^2}{h}\sum_i T_i(1-T_i)\right]|V| \quad [1]$$

where V is the applied voltage, h is Planck's constant, and T_i is the transmission eigenvalue of the i-th mode. In this case the Fano factor becomes

$$\gamma=\frac{S}{2qI}=\frac{\sum_i T_i(1-T_i)}{\sum_i T_i}, \quad [2]$$

i.e., depends only on the distribution of T_is. In quantum point contacts, when some modes are fully transmitted ($T_i = 1$) and others are fully reflected ($T_i = 0$), we can se that from (2) we have $\gamma = 0$, *i.e.*, complete suppression of shot noise. This is the case, for example, of quantum point contacts in correspondence of a conductance plateau.

On the other hand, when many poorly transmitted modes participate to conduction (all T_is << 1), we have $\gamma = 1$, i.e., full shot noise. In the case of elastic diffusive transport, when the device length is much larger than the elastic scattering length and much smaller than the inelastic scattering length, the distribution of transmission eigenvalues is bimodal, with two peaks around 0 and 1. General properties of such distribution, provided by Random Matrix Theory, allowed to determine that $\sum_i T_i(1-T_i)=1/3\sum_i T_i$, which means γ=1/3. Exactly the same result was obtained with a semiclassical model in which Pauli exclusion is introduced (Nagaev 1992). Such agreement is not a numerical coincidence, as was proposed (Landauer 1996), but is a result of the correspondence principle: since many modes need to be considered to obtain the result of Random Matrix Theory, quantum physics must provide results tending to those of classical physics. A detailed analysis of these results, using numerical simulations to investigate the behaviour of shot noise also in the case of very few propagating modes, can be found in (Macucci *et al.*, 2003).

4. Noise in resonant tunnelling devices

In resonant tunnelling devices both Pauli exclusion and Coulomb repulsion introduce correlation among electrons. This leads, in the positive differential resistance region of the I-V characteristics, to a suppression of shot noise down to ½. In the negative differential resistance region, an enhancement of shot noise providing $\gamma = 6.6$ has been measured (Iannaccone *et al.*, 1998). Such effect, that has been called "Coulomb Breach", is due to Coulomb repulsion magnified by the particular shape of the density of states in the quantum well. The effect is sketched in Fig. 1: when the device is biased in the negative differential resistance region, the peak of the density of states in the well, corresponding to the energy of the ground state, is below the conduction band of the emitter. When an electron jumps in, it

raises both the conduction band and the peak of the density of states in the well, making more electron states available for tunnelling from the emitter into the well. Therefore, we could say that the presence of an electron in the well opens a "breach" through which other electrons can pass. Or, we could say that *electrons in the well attract other electrons*!

Results from experiments and from numerical simulations, confirming the interpretation described above, are shown in Figure 2.

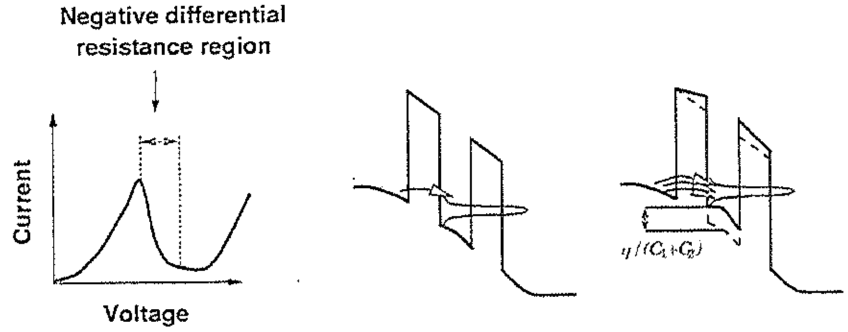

Figure 1. *Left: typical current-voltage characteristic of a resonant tunnelling diode. Center: band profile and density of states in the device biased in the negative differential resistance region. Right: illustration of the Coulomb Breach effect: As electrons tunnel into the well the conduction band in the well is raised and, since the peak of the density of states is also raised, more states are available from tunnelling from the emitter into the wel*

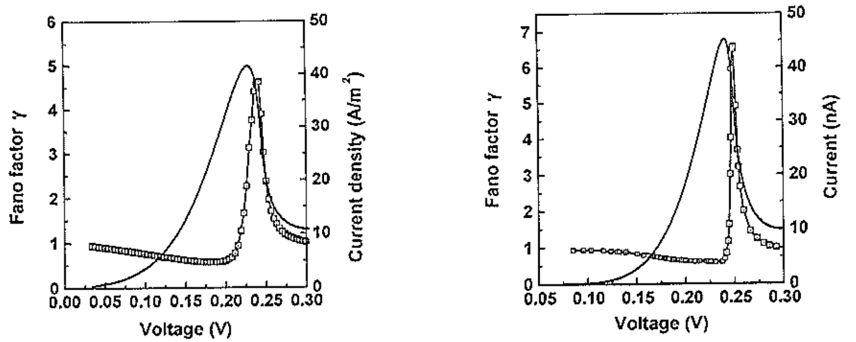

Figure 2. *Experimental (left) and simulated (right) current-voltage characteristics and Fano factor of a resonant tunnelling diode, from (Iannaccone et al. 1998)*

5. Noise in nanoscale MOSFETs

MOSFETs in commercial production have already reached channel lengths of only 70 nm, and will be downsized, according to the International Technology Roadmap for Semiconductors, to channel lengths of 30 nm by 2005 (65 nm technology node). Therefore they are nanoelectronic devices, and are expected to exhibit the rich noise behaviour typical of nanoelectronic and mesoscopic transport.

Here, we will address shot noise of the drain current, and shot noise of the gate current, that is significant, since the oxide thickness is only 1-2 nm. As far as the drain current is concerned, it has been the subject of a few recent theoretical papers (Naveh *et al.*, 1996, Bulashenko *et al.*, 2001, Bulashenko *et al.*, 2002, Gomila *et al.*, 2002). We will make the assumption of fully ballistic transport, which means that electrons with sufficient energy to overcome the barrier near the source reach the drain conserving energy and transversal momentum. This means that in the channel we have two separate populations of electrons: electrons originating from the source are in equilibrium with the source reservoir, and therefore obey Fermi Dirac statistics with source Fermi energy; electrons originating from the drain are in equilibrium with the drain reservoir. In typical devices transport occurs mainly in the first subband in the channel.

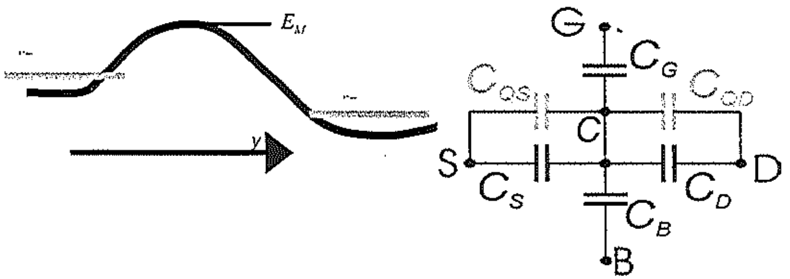

Figure 3. *Left: profile of the first subband in the channel; E_M represents the subband peak in the channel. Right: equivalent capacitance model of the ballistic MOSFET proposed*

The density of states in the first subband is

$$N_{2D}(E_y, E_z) = 2\frac{m_t}{h^2\sqrt{E_y E_z}}, E_y, E_z > 0, \quad [3]$$

where m_t is silicon transversal mass, E_y and E_z are the kinetic energies in the source-to-drain direction (y) and in the transversal direction (z). The electron density at the subband peak E_M (see Figure 3) is:

$$n_{2D} = 2\int_0^\infty dE_y \int_0^\infty dE_z N_{2D}\left[f_S(E_y + E_z + E_M) + f_D(E_y + E_z + E_M)\right], \quad [4]$$

where f_S and f_D are the Fermi Dirac occupation factors at the source and at the drain, respectively. The electron density fluctuates as a function of fluctuations of the occupation factors at the contacts and of subband maximum, *i.e.*:

$$\delta n_{2D} = 2\int_0^\infty dE_y \int_0^\infty dE_z N_{2D}\left[\delta f_S + \delta f_D\right] + 2\delta E_M \int_0^\infty dE_y \int_0^\infty dE_z N_{2D}\left(\frac{\partial f_S}{\partial E_M} + \frac{\partial f_D}{\partial E_M}\right). \quad [5]$$

The subband maximum depends on n_{2D} via electrostatics, therefore we can include all electrostatic effects in a single capacitance per unit area C_C, and write $\delta E_M = q^2 \delta n_{2D} / C_C$. If we define the quantum source (drain) capacitance C_{QS} (C_{QD}) as follows:

$$C_{QS} = -2q^2 \int_0^\infty dE_y \int_0^\infty dE_z N_{2D}\left(\frac{\partial f_S}{\partial E_M}\right), \; C_{QD} = -2q^2 \int_0^\infty dE_y \int_0^\infty dE_z N_{2D}\left(\frac{\partial f_D}{\partial E_M}\right), \quad [6]$$

we are able to define an equivalent non linear capacitive circuit of the nanoscale MOSFET, shown on the right of Figure 3. The potential of node C represents the subband maximum divided by the electron charge.

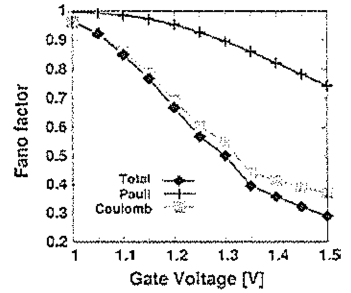

Figure 4. *Fano factor as a function of the gate voltage for the 25 nm well tempered MOSFET with applied drain-to-source voltage 0.5 V. Black diamonds: Fano factor computed including both the Pauli term and the Coulomb term in eq. (7). Red squares: only Coulomb term. Black crosses: only Pauli term*

Straightforward calculation, whose details can be found in (Iannaccone, 2003), allow us to obtain the Fano factor in far from equilibrium conditions as:

$$\gamma = \frac{S}{2qI} = \left\langle \left(1 - \frac{v_S C_{QS}}{C_C + C_{QS}} \frac{1}{v_y}\right)^2 (1 - f_S) \right\rangle \qquad [7]$$

where v_S is an average longitudinal velocity, and the angle brackets indicate a weighted average, where the weights are the contribution of each longitudinal energy to the total current. From (7) it is clear that the Fano factor is smaller than 1. The first term between brackets is the contribution of Coulomb interaction, while the second term is the contribution of Pauli exclusion. In subthreshold condition, where the channel is poorly populated, we have $f_S << 1$ and $C_{QS} << C_C$, which leads to a fano factor close to 1, *i.e.*, to full shot noise. In very strong inversion, we can have much larger f_S and both C_{QS} and have quasi zero shot noise. An example of the behaviour of the Fano factor in the case of the so-called well tempered MOSFET, with channel length of 25 nm, is provided in Figure 4. It is clearly seen that in that particular device the Coulomb interaction in mainly responsible for suppression of shot noise. No experimental results are available on the subject; it would be interesting to see whether such predictions will be confirmed.

As far as shot noise of the gate current is concerned, no deviation from full shot noise is observed in the gate oxide is "fresh", *i.e.*, has not been stressed with high electric field. Then, when Stress-Induced Leakage Currents (SILCs) appear, increase the total gate current by a few orders of magnitude, especially at low fields, and shot noise exhibits a suppression of the order or 25% with respect to the full shot value. To us, this was a demonstration that the main transport mechanism in SILCs is represented by trap-assisted-tunneling. Indeed, among other proposed transport mechanism, it was the only one introducing the correlation among tunnelling electrons that is required in order to obtain noise suppression.

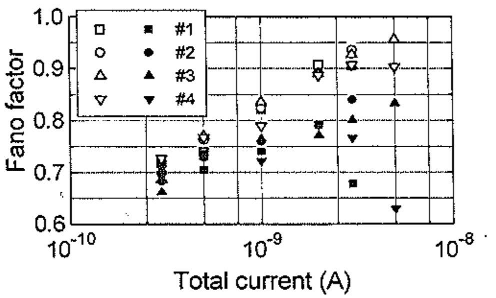

Figure 5. *Experimental Fano factor as a function of the total current through a 6 m oxide stressed with high electric field. White symbols indicate the Fano factor of the total current. Black symbols indicate the Fano factor of the SILC component [from (Iannaccone et al. 2000)]*

Considering only the SILC component, the Fano factor is suppressed down to 0.63. Details on the experiments and on the theoretical model can be found in (Iannaccone *et al.*, 2000).

6. Conclusion

Shot noise is the most relevant type of noise in nanoelectronic devices. We have shown several examples of altered shot noise with respect to that of a Poissonian process, as a consequence of interaction among electrons participating to conduction, due to Pauli exclusion and Coulomb repulsion. We have also shown that such deviations from full shot noise are relevant also for applied devices such as MOSFETs of the latest generations, and provide useful insights into the transport mechanisms.

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