Enhanced shot noise in carbon nanotube field-effect transistors

A. Betti,[a] G. Fiori, and G. Iannaccone
Dipartimento di Ingegneria dell'Informazione: Elettronica, Informatica, Telecomunicazioni, Università di Pisa, Via Caruso 16, I-56122 Pisa, Italy

(Received 6 October 2009; accepted 23 November 2009; published online 23 December 2009)

We predict shot noise enhancement in defect-free carbon nanotube field-effect transistors through a numerical investigation based on the self-consistent solution of the Poisson and Schrödinger equations within the nonequilibrium Green's functions formalism, and on a Monte Carlo approach to reproduce injection statistics. Noise enhancement is due to the correlation between trapping of holes from the drain into quasibound states in the channel and thermionic injection of electrons from the source, and can lead to an appreciable Fano factor of 1.22 at room temperature. © *2009 American Institute of Physics*. [doi:10.1063/1.3274128]

The progressive miniaturization of electron devices has led to a very limited number of carriers in the channel[1] down to few units. Signal-to-noise ratio can rapidly degrade, as noise power scales more slowly than signal power with size reduction, and can therefore be critical for nanoscale device operation.

In the past decade, efforts have been addressed toward the investigation of electrical noise in nanoscale devices, focusing on diffusive mesoscopic conductors,[2–6] nanoscale metal-oxide-semiconductor field-effect transistors (MOSFETs)[7–9] and on carbon-based electronic devices.[10–13]

When carriers are highly correlated, either sub- or super-Poissonian noise can be observed. In particular, noise enhancement has been observed in resonant tunneling diodes,[14,15] due to the positive correlation between electrons tunneling into the quantum well caused by the interplay between the density of states in the well and electrostatics. Here, we observe noise enhancement due to a different mechanism, i.e., the modulation of electron injection from the source due to the transfer of holes between the drain and the channel. We highlight this effect exploiting a recently developed methodology based on statistical simulations of carbon nanotube (CNT) field effect transistors (FETs) with states randomly injected from the contact.[12,13]

A p_z-orbital tight-binding Hamiltonian has been adopted, considering four transversal modes.[16] All simulations have been performed at room temperature, self-consistently solving the three-dimensional Poisson and Schrödinger equations within the nonequilibrium Green's functions formalism by means of our open-source simulator NANOTCAD VIDES (Ref. 17) and considering almost 1000 statistical configurations of incoming states of the many-particle system. In order to evaluate the zero-frequency noise power spectrum $S(0)$, we have exploited a statistical approach derived in Refs. 12 and 13, that extends Landauer–Buttiker's approach by including the effect of Coulomb interaction.[18]

Noise current power spectral density at zero frequency $S(0)$ can be expressed as $S(0)=S_{\mathrm{PN}}(0)+S_{\mathrm{IN}}(0)$, where S_{PN} and S_{IN} represent the partition and the injection noise contributions, respectively.[18]

A measure of correlation between charge carriers is the so-called Fano factor $F\equiv S(0)/(2qI)\equiv F_{\mathrm{PN}}+F_{\mathrm{IN}}$, where the term $2qI$ corresponds to the full shot noise spectrum, whereas $F_{\mathrm{PN}}\equiv S_{\mathrm{PN}}(0)/(2qI)$ and $F_{\mathrm{IN}}=S_{\mathrm{IN}}(0)/2qI$.

By neglecting the effect on noise of Coulomb interaction among electrons and, in particular, the dependence of the transmission and reflection matrices upon the actual occupation of injected states in the device,[12,13,18] $S(0)$ reduces to the result from Landauer[19] and Büttiker[20] $S_{\mathrm{LB}}(0)$, that only includes the correlation among charge carriers due to their fermionic nature (Pauli's exclusion principle). In a similar way, we introduce $F_{\mathrm{LB}}\equiv S_{\mathrm{LB}}(0)/(2qI)$.[18]

The considered device is a double gate CNT-FET; the nanotube is a 2 nm diameter zig-zag (25,0) CNT with a band gap $E_g=0.39$ eV. The oxide thickness is 1 nm, the channel is undoped and has a length L_C of 10 nm. Source (S) and Drain (D) extensions are 10 nm long and doped with a molar fraction $f=5\times10^{-3}$. For comparison purposes, we also consider a (13,0) CNT-FET ($E_g=0.75$ eV) with the same device geometry and doping profile.[12,13]

The Fano factors for a (25,0) and a (13,0) zig-zag CNT are plotted as a function of gate overdrive in Figs. 1(a) and 1(b). Noise enhancement occurs only in the case of the (25,0) CNT ($F>1$). If one neglects Coulomb interaction among carriers, the Fano factor (F_{LB}) is smaller than one. The whole shaded area in Fig. 1(a) indicates the shot noise enhancement due to the Coulomb interaction.

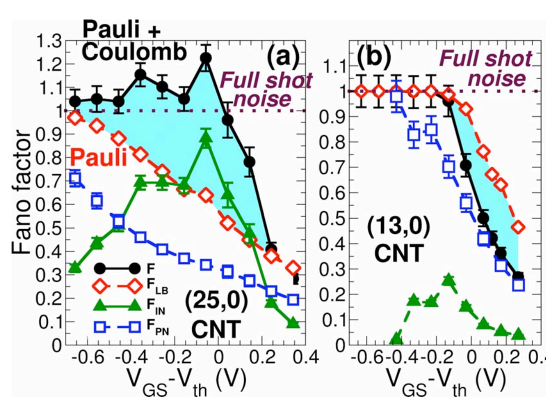

FIG. 1. (Color online) Fano factor as a function of the gate overdrive for (a) (25,0) and (b) (13,0) CNT-FETs for $V_{\mathrm{DS}}=0.5$ V. The different contributions F_{LB}, F_{IN}, F_{PN}, and the total Fano factor F are shown. The threshold voltage V_{th} is 0.43 V for the (13,0) CNT-FET, and 0.36 V for the (25,0) CNT-FET.

[a]Electronic mail: alessandro.betti@iet.unipi.it.

0003-6951/2009/95(25)/252108/3/$25.00

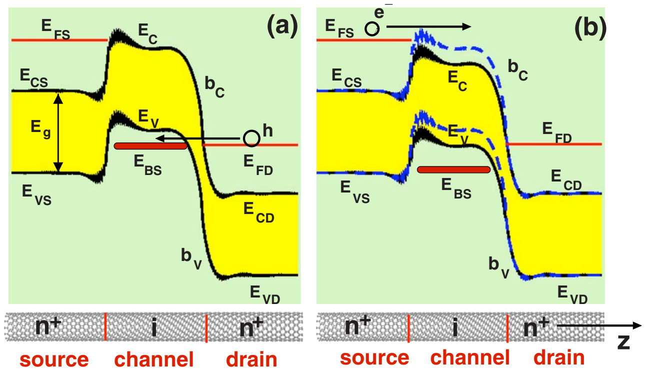

FIG. 2. (Color online) If an excess hole tunnels from the drain into a bound state in the intrinsic channel (a), the conduction band b_C and valence band b_V edge profiles are shifted downwards and more thermionic electrons can be injected in the channel, enhancing current fluctuations (b).

For (13,0) CNTs, instead, Coulomb interaction suppresses noise below the value predicted by only including Pauli's exclusion, as already observed in Refs. 12 and 13. The different behavior is strictly associated to the different amplitude of the injection noise (F_{IN} in Fig. 1), that is much larger for (25,0) CNTs. For both CNTs, in the deep subthreshold regime, full shot noise is obtained, since carriers are so scarce in the channel that correlations are irrelevant.

Shot noise enhancement in the (25,0) CNT-FET can be explained with the help of Fig. 2. E_C and E_V are the conduction and valence band edge profiles in the channel, respectively, whereas E_{CS} (E_{CD}) is the conduction band edge at the source (drain), and E_{BS} is the energy level of the quasibound state in the valence band. When the drain Fermi level E_{FD} roughly aligns with E_{BS}, holes in the conduction band in correspondence of the drain can tunnel into the bound state shifting downwards E_C in the channel by $-q^2/(C_T L_C)$, where C_T is the total geometrical capacitance of the channel per unit length. As a result, thermionic electrons injected from the source can more easily overcome the barrier. Instead, when a hole leaves the bound state, the barrier increases by the same amount, reducing thermionic injection. The noise enhancement is fully due to current modulation due to trapping/detrapping of holes in the bound state.

Since (13,0) CNTs have a much wider gap (E_g $=0.75$ eV), E_V in the channel is always below E_{CD} in the drain, and hole injection is completely inhibited, as well as noise enhancement.

The effect just illustrated resembles generation-recombination noise in semiconductors,[21] since bound states in the valence band act like traps. Three remarkable differences can however be found as follows: (i) the channel in this case is defect-free, and the traplike behavior depends on the particular bias condition; (ii) the generation-recombination process in this case is associated to a spatial movement of charge (drain-channel) and is therefore similar to what observed in Refs. 8 and 9 for metal oxide semiconductor capacitors; and (iii) in classical generation-recombination noise current fluctuations are due to fluctuations of the number of charge carriers, whereas here transport is elastic and current fluctuations are due to fluctuations in the occupation of injected states for electrons and holes and to the induced fluctuations of the potential barrier.

To justify our assertion, let us focus on the local density of states (LDOS) computed for the (25,0) CNT. In Figs. 3(c) the LDOS averaged on each carbon ring is shown as a function of the coordinate along the transport direction z for a gate voltage in correspondence of the peaks in Fig. 1(a), i.e., $V_{GS}=0$ V, and a drain-to-source bias $V_{DS}=0.5$ V; two localized states appear in the valence band, due to the local confinement. Since the energy of the highest quasibound state is close to the drain Fermi energy, hole tunneling in and out of the channel can occur, with a zero net current flow. As shown in Fig. 1(a), shot noise enhancement ($F=1.22$) is observed whenever the applied gate voltage roughly aligns E_{BS} with E_{FD}, i.e., in the range -0.4 V$<V_{GS}-V_{th}<0.1$ V.

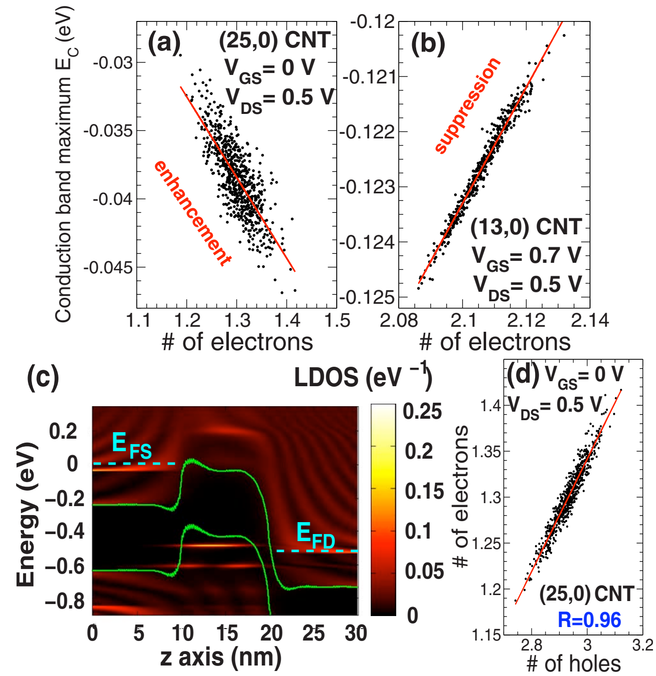

FIG. 3. (Color online) E_C as a function of the number of electrons in the channel for (a) (25,0) and (b) (13,0) CNT-FETs. (c) LDOS as a function of the longitudinal direction z for $V_{GS}=0$ V. (d) Scatter plot of electrons and holes in the channel.

In Figs. 3(a), 3(b), and 3(d), we show the scatter plots obtained from Monte Carlo simulations. In particular, Figs. 3(a) and 3(b) show E_C versus the number of injected thermionic electrons for $V_{DS}=0.5$ V and $V_{GS}=0.7$ V for (13,0) CNTs ($F=0.27$) and $V_{GS}=0$ V for (25,0) CNTs ($F=1.15$). As can be noted in Fig. 3(a), the net result of an electron entering the channel of the (25,0) CNT is a decrease in E_C in the channel, that is at first counterintuitive, and opposite to the trend observed in (13,0) CNTs (Refs. 12 and 13) [Fig. 3(b)]. However, it is fully consistent with the interpretation proposed above for the noise enhancement in (25,0) CNT. This is further confirmed by Fig. 3(d), which highlights a perfect correlation between statistical fluctuations of holes and electrons in the channel (correlation factor $R=0.96$).

To highlight the correlation between electrons and holes we can divide the states injected from the reservoirs in following four regions: regions I ($E>E_{CS}$) and II ($E\leq E_{CS}$) refer to source injected states, whereas regions III ($E>E_V$) and IV ($E\leq E_V$) to drain injected states. Regions II and III of course do not contribute neither to transport, nor to charge fluctuations. Instead turning on random injection of states only for region I or IV, the enhancement disappears [Fig. 4(a)], pointing out that the positive correlation between hole interband tunneling from the drain and thermionic electron

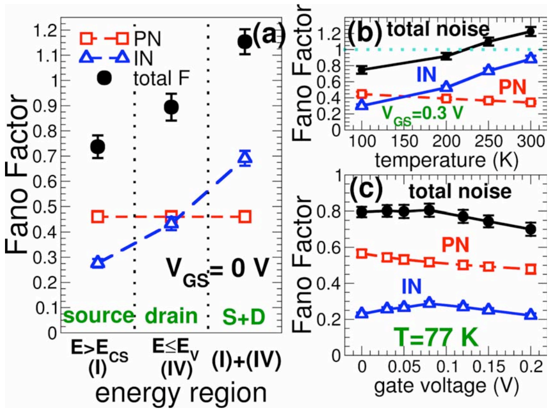

FIG. 4. (Color online) (a) F, F_{PN}, and F_{IN} when randomizing the occupancy at different energy regions and at different reservoirs [source (s): I and II; drain (d): III and IV] for $V_{GS}=0$ V. (b) F, F_{PN}, and F_{IN} at $V_{GS}=0.3$ V as a function of temperature and (c) as a function of V_{GS} for T=77 K.

injection from the source is key to enhancement. In addition, the total injection noise obtained by randomizing the statistics everywhere can be roughly expressed as the sum of the injection noise contributions obtained by separately randomizing the statistics in regions I and IV. Partition noise is instead not affected by the considered statistics [Fig. 4(a)], because it is fully taken into account by the shot noise formula.[12,13]

Significantly, lowering the temperature [Fig. 4(b)] suppresses shot noise enhancement by reducing the injection noise, due to the suppression of the hole trapping-detrapping process. Therefore, at T=77 K [Fig. 4(c)] noise enhancement disappears, although a maximum in the injection noise can still be observed when E_{BS} almost aligns with E_{FD}.

It is also interesting to evaluate the cutoff frequency f_H of shot noise enhancement, which in this case is limited by the process of charging and discharging channel with holes; it is therefore the cutoff frequency of an R-C circuit, where $C=5.5$ aF is the total capacitance of the channel, and R is the quasiequilibrium resistance between drain and channel, 21.3 KΩ.[18] The charging energy is comparable to the thermal energy but we can still consider $f_H=(2\pi RC)^{-1}=1.36$ THz.

In conclusion, we predict that shot noise enhancement can be observed in CNT-FETs biased in the weak subthreshold regime, due to the modulation of thermionic current caused by interband tunneling of holes between the drain and the channel. In (25,0) CNT-FETs, the enhancement is expected to be observable down to a temperature of 200 K and at frequencies well above those in which flicker noise is dominant.

This work was supported in part by the EC 7FP Programme under the NoE NANOSIL (Contract No. 216171), by the ESF EUROCORES Program FoNE, through funds from CNR and the EC 6FP Programme, under project DEWINT (Contract No. ERAS-CT-2003-980409).

[1]R. Landauer, Nature (London) **392**, 658 (1998).
[2]T. González, C. González, J. Mateos, D. Pardo, L. Reggiani, O. M. Bulashenko, and J. M. Rubi, Phys. Rev. Lett. **80**, 2901 (1998).
[3]E. V. Sukhorukov and D. Loss, Phys. Rev. Lett. **80**, 4959 (1998).
[4]Ya. M. Blanter and M. Büttiker, Phys. Rev. B **56**, 2127 (1997).
[5]A. H. Steinbach, J. M. Martinis, and M. H. Devoret, Phys. Rev. Lett. **76**, 3806 (1996).
[6]R. J. Schoelkopf, P. J. Burke, A. A. Kozhevnikov, D. E. Prober, and M. J. Rooks, Phys. Rev. Lett. **78**, 3370 (1997).
[7]G. Iannaccone, J. Comput. Electron. **3**, 199 (2004).
[8]G. Iannaccone, F. Crupi, and B. Neri, Appl. Phys. Lett. **77**, 2876 (2000).
[9]G. Iannaccone, F. Crupi, B. Neri, and S. Lombardo, IEEE Trans. Electron Devices **50**, 1363 (2003).
[10]L. DiCarlo, J. R. Williams, Y. Zhang, D. T. McClure, and C. M. Marcus, Phys. Rev. Lett. **100**, 156801 (2008).
[11]L. G. Herrmann, T. Delattre, P. Morfin, J.-M. Berroir, B. Placais, D. C. Glattli, and T. Kontos, Phys. Rev. Lett. **99**, 156804 (2007).
[12]A. Betti, G. Fiori, and G. Iannaccone, IEEE Trans. Electron Devices **56**, 2137 (2009).
[13]A. Betti, G. Fiori, and G. Iannaccone, http://arxiv.org/abs/0904.4274 (2009).
[14]G. Iannaccone, G. Lombardi, M. Macucci, and B. Pellegrini, Phys. Rev. Lett. **80**, 1054 (1998).
[15]G. Iannaccone, M. Macucci, and B. Pellegrini, Phys. Rev. B **55**, 4539 (1997).
[16]G. Fiori and G. Iannaccone, IEEE Trans. NanoTechnol. **6**, 475 (2007).
[17]Code and documentation can be found at http://www.nanohub.org/tools/vides.
[18]See EPAPS supplementary material at http://dx.doi.org/10.1063/1.3274128 for the noise formula $S(0)$ and the computation of the cutoff frequency f_H of noise enhancement.
[19]Th. Martin and R. Landauer, Phys. Rev. B **45**, 1742 (1992).
[20]M. Büttiker, Phys. Rev. B **46**, 12485 (1992).
[21]M. Rimini-Döring, A. Hangleiter, and N. Klötzer, Phys. Rev. B **45**, 1163 (1992).