International Journal of High Speed Electronics and Systems, Vol. 10, No. 1 (2000) 111–117

FRONTIERS IN ELECTRONIC NOISE: FROM SUBMICRON TO NANO STRUCTURES

L. REGGIANI, C. PENETTA, GY. TREFÁN
Dipartimento di Ingegneria dell' Innovazione and INFM, Università di Lecce
Via Arnesano s/n, 73100 Lecce, Italy

J.C. VAISSIERE, L. VARANI
Centre d'Electronique et de Micro-optoelectronique de Montpellier
(CNRS UMR 5507) Université Montpellier II, 34095 Montpellier, France

V. GRUZHINSKIS, A. REKLAITIS, P. SHIKTOROV, E. STARIKOV
Semiconductor Physics Institute
Goshtauto 11, 2600 Vilnius, Lithuania

T. GONZALES, J. MATEOS, D. PARDO
Departamento de Física Aplicada, Universidad de Salamanca
Plaza de la Merced s/n, E-37008 Salamanca, Spain

and

O.M. BULASHENKO
Departament de Física Fondamental, Universitat de Barcelona
Av. Diagonal 647, E-08028 Barcelona, Spain

We survey recent results on electronic noise in nanostructured devices. Three kinds of excess noise referring to hot-carriers in submicron n^+nn^+ diodes, shot noise in mesoscopic structures, resistance fluctuations in thin film conductors, are considered. The influence of down-sizing on fluctuations is illustrated in each case.

1. Introduction

Noise is a key feature of any electronic device because it gives the intrinsic limit of the performance through the signal-to-noise ratio figure of merit. However, besides hindering the signal detection, noise is also a relevant probe of the microscopic phenomena at hand, thus providing information not otherwise available from the study of average quantities, like conductance. When moving toward nanostructures new phenomena were found to arise so that innovative concepts should be introduced. Here we summarize what we consider to be the three main issues which are addressed to date in research and development.

2. General definitions

To properly address the subject, we briefly introduce a general scheme in which electronic noise can be analyzed by providing a classification of different types of

noise. The basic quantity describing the noise of a two terminal device is the spectral density at frequency f of the fluctuating quantity α, $S_\alpha(f)$, where α can be conveniently chosen to be the current I, or the voltage V, or the resistance R. By considering current fluctuations, $S_I(f)$ can be conveniently decomposed into a thermal and an excess contribution. The thermal contribution is Nyquist noise which in its quantum form reads [1]

$$S_I^{thermal}(f) = 4KT\ Re[Y(f)]\ [\frac{x}{2} + \frac{x}{exp(x) - 1}]\quad ,\ x = \frac{hf}{KT} \tag{1}$$

where K is the Boltzmann constant, T the bath temperature, $Y(f)$ the small signal admittance and h the Planck constant. We remark that the Nyquist noise does not provide any new information that is otherwise available from the knowledge of the admittance, and its zero frequency value vanishes at $T = 0$. By contrast, the excess noise, which is detectable only in the presence of a net current, provides new information and differs from zero also at $T = 0$. The excess noise can be decomposed into the sum of three terms namely: hot-carrier, shot and resistance noise, whose expressions are reported below

$$S_I^{hot-carrier}(f) = \frac{4q^2}{L^2} D(E, f) \tag{2}$$

$$S_I^{shot}(f) = 2qI\gamma(f) \tag{3}$$

$$S_I^{resistance}(f) = I^2\ \frac{S_R(f)}{R^2} = \sum_i \frac{4B_i\tau_i}{1 + (2\pi f\tau_i)^2} + \frac{C}{f} \tag{4}$$

where q is the electron charge, L the length of the device, D the diffusion coefficient depending on the electric field E, γ the Fano factor, B_i the strength of the fluctuating quantity characterized by lifetime τ_i (e.g. number, mobility, defects, etc.), and C the strength of $1/f$ noise.

3. Diffusion noise in submicron n^+nn^+ structures

With reference to a simple n^+nn^+structure the problem we face is how to calculate diffusion noise when the length of the n region $L_n \simeq \ell_{in}$, ℓ_{in} being the inelastic mean free path. Indeed, the standard impedance field [2] (IF) based on velocity fluctuations gives for the voltage spectral density:

$$S_U(f) = \int_0^L dx \int_0^L dx' \nabla Z(x, f) \nabla Z^*(x', f) S_{jj}(x, x', f) \tag{5}$$

where ∇Z is the IF and, within a local approximation, the current correlator S_{jj} reads

$$S_{jj}(x, x', f) \simeq 4Aq^2 n(x) D(x, f) \delta(x - x'). \tag{6}$$

The drawbacks of the standard IF remain: (i) how to calculate $S_{jj}(x, x', f)$ beyond the local approximation, (ii) the lack of the dual property (no standard admittance field (AF) is defined). Fig. 1 illustrates the above drawbacks by reporting different

$S_U(f)$ calculated [3] by using different nonlocal noise sources within the standard IF method for a $0.3-0.6-0.4\ \mu m$ GaAs n^+nn^+ structure with $n = 5\times10^{15}$ and $n^+ = 5\times10^{17}\ cm^{-3}$ at $T = 300\ K$ and $U = 0.6\ V$. To agree with exact MC calculations [3], a current correlator accounting only for nonlocal velocity fluctuations should be used, otherwise an unphysically large noise is obtained. The above drawbacks are overcome by introducing the generalized IF based on acceleration fluctuations [4], according to which Eq. 5. is reformulated as:

$$S_U(f) = \sum_{\alpha,\beta}\int_0^L dx\nabla Z_\alpha(x,f)\nabla Z^*_\beta(x,f)S_{\dot\alpha\dot\beta}(x) \tag{7}$$

where, within a hydrodynamic Langevin approach, α, β stand for the velocity v and energy ϵ entering the conservation equations, $\nabla Z_{\alpha,\beta}$ are the generalized IFs related to the small signal response to velocity or energy perturbations, and $S_{\dot\alpha\dot\beta}$ is the spectral density of the Langevin source. The advantages of the above generalization are: (i) the noise source $S_{\dot\alpha\dot\beta}(x)$ is white and spatially local, (ii) the dual representation is made possible by the AF $\nabla Y_\alpha(x,f)$ as:

$$S_I(f) = \sum_{\alpha,\beta}\int_0^L dx\nabla Y_\alpha(x,f)\nabla Y^*_\beta(x,f)S_{\dot\alpha\dot\beta}(x) \tag{8}$$

where $\nabla Y_\alpha(x,f) = \nabla Z_\alpha(x,f)/Z(f)$, $Z(f)$ being the small signal impedance of the device. Fig. 2 illustrates the advantage of the generalized IF by showing the excellent agreement with the MC calculations for the same structure of Fig. 1.

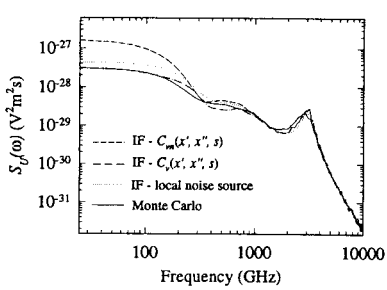

Fig. 1. Spectral density of voltage fluctuations of the n^+nn^+ GaAs structure described in the text calculated by using different techniques: MC simulation (—), IF method neglecting spatial correlations (·····), IF method including spatial correlations and considering a noise source related to number and velocity fluctuations (– – –) and only to velocity fluctuations (–·–).

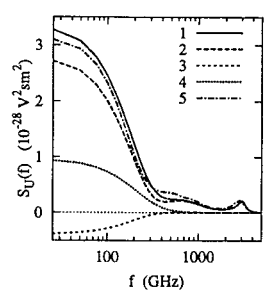

Fig. 2. Spectral density of voltage fluctuations and its three microscopic contributions corresponding to $S_{\dot v\dot v}$, $S_{\dot v\dot\epsilon}$, $S_{\dot\epsilon\dot\epsilon}$ (respectively curves 1 to 4) together with $S_U(f)$ obtained directly by MC simulations of the same structure in Fig. 1 at $U = 0.6\ V$ (curve 5).

4. Shot noise in nanostructures

Shot-noise comes from fluctuations due to the discreteness of electrical charge, and its expression was given in Eq. 3. The Fano factor γ probes the correlation between different current pulses. $\gamma = 1$ corresponds to full shot-noise (absence of correlations), $\gamma < 1$ to suppressed shot-noise (negative correlations), and $\gamma > 1$ to enhanced shot-noise (positive correlations). Here we focus on suppressed shot-noise, a well-known phenomenon since the times of vacuum tubes [5]. A breakthrough started when the suppression phenomenon was observed in resonant tunneling diodes [6]. Then, other devices exhibiting shot-noise suppression were found, e.g. mesoscopic conductors, non-resonant tunneling structures, etc. Physical mechanisms responsible for suppression are: long range Coulomb interaction (space charge), Pauli principle, tunneling processes, inelastic collisions, fractional charge, etc., as recently reviewed by some of the authors [8]. In the following we consider the case of mesoscopic structures for which the following inequality holds $\lambda_{deBroglie} \ll \ell_{el} \ll L \ll \ell_{in}$, ℓ_{el} being the elastic mean free path. An interesting suppression factor $\gamma = 1/3$ was found for the following different conditions. (i) coherent, degenerate transport. Here the transport is described by a transmission eigenvalue T_i of the i-th eigenmode and it is found [7]

$$\gamma = \frac{\sum_{i=1}^{N} T_i(1-T_i)}{\sum_{i=1}^{N} T_i} = \frac{\int_0^1 P(T)T(1-T)dT}{\int_0^1 P(T)TdT} = \frac{1}{3} \tag{9}$$

where the sums run on all modes N with energies between the chemical potentials of the left and right electrodes. The origin of the 1/3 value stems from the bimodal shape of the probability distribution of transmission eigenvalues, $P(T)$, given by $P(T) \propto 1/[T\sqrt{(1-T)}]$. (ii) incoherent, degenerate transport. Here the transport is described by the Boltzmann-Langevin equation and it is found [9]

$$\gamma = \frac{1}{qV}[\frac{4}{3}KT + \frac{1}{3}qV\coth(\frac{qV}{2KT})]] \tag{10}$$

The origin of 1/3 under $qV \gg KT$ stems from Pauli principle. (iii) degenerate, sequential tunneling. Here the transport is described by the tunneling probability Γ and for a given number n of barriers it is found [11]

$$\gamma = \frac{1}{3}\{1 + \frac{n(1-\Gamma)^2(2+\Gamma) - \Gamma^3}{[\Gamma + n(1-\Gamma)]^3}\} \tag{11}$$

The origin of 1/3 under $n \to \infty$ stems from Pauli principle.
(iv) non-degenerate transport. Here Monte Carlo simulations [10] show:

$$\gamma = \frac{4}{3}\frac{KTG_0 < N >}{qI < N >_0} + \frac{1}{3}\coth(\frac{qV}{2KT}) \tag{12}$$

where G_0 is the low voltage conductance, and $< N >_0$, $< N >$ the number of carriers inside the device in the absence and presence of the applied voltage, respectively. The origin of 1/3 under $qV \gg KT$ stems from electrostatic interactions.

From the above it is argued that the 1/3 value of the suppression factor γ in diffusive conductors is an ubiquitous phenomenon. Experimental evidence of the reduced shot-noise level close to the predicted 1/3 value was given in diffusive mesoscopic conductors under degenerate conditions [12].

A second interesting case of shot-noise suppression is found from Monte Carlo simulations of single and multibarrier GaAs/ AlGaAs heterostructures [13,14], as reported in Fig. 3 for the case of four barriers. Here the Fano factor is found to

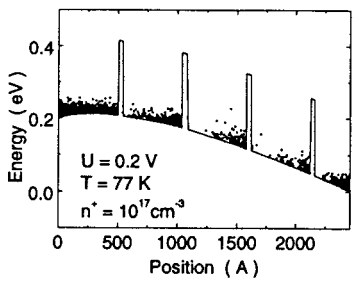

Fig. 3. Potential profile (solid line), and distribution of electron kinetic energy (points) for a voltage of 0.2 V applied to the four barrier diode studied here at $T = 77\ K$ and with a contact doping concentration of $10^{17}\ cm^{-3}$.

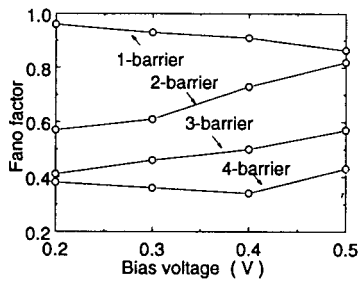

Fig. 4. Fano factor vs bias voltage for one, two, three and four barrier structures obtained from direct MC calculations.

be significantly below 1 for $U \geq 0.2\ V$, as shown in Fig. 4. In the single barrier diode shot noise at high voltages is suppressed more than predicted by the binomial distribution, while at the lowest voltages it recovers a nearly full shot-noise value. In the double barrier diodes shot noise is strongly suppressed to a minimum value of 0.5 at low voltages in reasonable agreement with the analogous degenerate case of resonant and nonresonant tunneling. By increasing the number of barriers shot noise is further suppressed, the maximum suppression value following a 1/(N+1) behaviour with N the number of barriers. The mechanism of suppression is based on the confinement of electrons in each well due to inelastic scattering through polar-optical phonon-emission.

5. Resistance fluctuations in thin film resistors

Resistance fluctuations in thin film resistors are modelled by a random resistor network, where the steady-state condition occurs via two competing mechanisms, a defect generation and a defect recovery, balancing each other[15]. Within a biased percolation model, [16] Monte Carlo simulations found that the resistance fluctuations increase with increasing current, see Fig. 5. The noise associated with these fluctuations becomes nonlinear when the current increases above a threshold value, see Fig. 6. Moreover, it increases up to a power 8 of the macroscopic resistance.

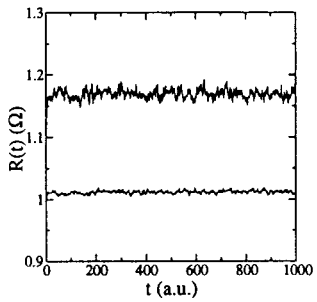

Fig. 5. Typical fluctuations of the resistance for the case in which recovery of defects allows for stationary conditions. Lower and upper signals refer to low and high current values, low 0.18 A, high 1.8 A.

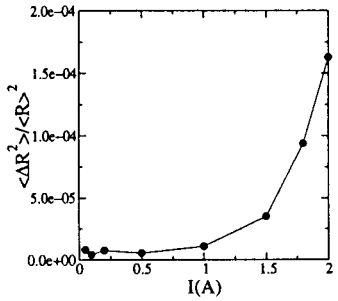

Fig. 6. Normalized variance of resistance fluctuations versus stress current I.

Interestingly, the model yields breakdown of the macroscopic resistance for high currents, which is preceded by non-gaussian behaviour of the fluctuations. Therefore, this kind of noise is a sensitive indicator of reliability and precursor of failure as found in electromigration experiments [17].

6. Conclusions

When scaling down the dimensions of devices towards the nanometric scale, excess noise is found to probe microscopic interactions, characterize devices, and monitor reliability features. New phenomena at the nanometric scale lengths are nonlocal effects of diffusion noise, suppressed shot-noise, fluctuations associated with defectiveness. Several theoretical approaches provide insight of the above phenomena with particular reference to: generalized impedance fields, Landauer-Buttiker formalism, Boltzmann-Langevin formalism, Monte Carlo simulations and percolation models. Overall the control of noise characteristics remains a mandatory issue in advancing the frontiers in electronics.

Acknowledgments

This work was performed within the Italian - Lithuanian Project "Research and development cooperation in submicron electronics" and supported by the Italian Ministery of Foreign Affairs. Partial support from the CNRS PECO/CEI Cooperation franco lituanienne Project 5380, Galileo Project 99055 and MURST through the Physics of Nanostructures project is gratefully acknowledged.

References

1. H.B. Callen and T.A. Welton, *Phys. Rev.* **83** (1951) 34.
2. W. Shockley, J.A. Copeland and R.P. James in:*Quantum theory of atoms molecules and the solid state*, Ed. P.O. Lodwin, Academic Press New York, 1966 p. 537.
3. P. Shiktorov, V. Gružinskis, E. Starikov, T. González, J. Mateos, D. Pardo, L. Reggiani and L. Varani, *Appl. Phys. Lett.* **71** (1997) 3093.
4. P. Shiktorov, E. Starikov, V. Gružinskis, L. Reggiani, T. González, J. Mateos, D. Pardo and L. Varani, *Phys. Rev.* **B57** (1998) 11866.
5. W. Schottky, *Ann. Phys* **57** (1918) 541.
6. Y.P. Li, A. Zaslavsky, D.C. Tsui, M. Santos and M. Shayegan, *Phys. Rev.* **B41** (1990) 8388.
7. C.W.J. Beenakker and M. Büttiker, *Phys. Rev.* **B 46** (1992) 1889.
8. L. Reggiani, A. Reklaitis, T. González, J. Mateos, D. Pardo and O.M. Bulashenko, *Austr. J. Phys.* to appear (1999).
9. M.J.M. de Jong and C. W. J. Beenakker, *Physica A* **230** (1996) 219.
10. T. González, O.M. Bulashenko, J. Mateos, D. Pardo, L. Reggiani and J.M. Rubi, *Phys. Rev. Lett.* **80** (1998) 2901.
11. K.E. Nagaev, *Phy. Lett. A*, **169** (1992) 103.
12. F. Liefrink, J.I. Dijkhuis, M.J.M. de Jong, L.W. Molenkamp and H. van Houten, *Phys. Rev.*, **49** (1994) 14066.
13. A. Reklaitis and L. Reggiani, *J. Appl. Phys.* **82** (1997) 3161.
14. L. Reggiani and A. Reklaitis, *Proc. 10-th International Symposium on Ultrafast Phenomena in Semiconductors (10- UFPS)*, Vol. 297-298 of Materials Science Forum, Eds. S. Asmontas and A. Dargys, (Trans. Tech. Publ. Inc., Uetichon-Zuerich, Switzerland), 1999, p. 129.
15. C. Pennetta, Gy. Trefán and L. Reggiani, *Proc. 2nd Int. Conf on Unsolved Problems of Noise*, Adelaide, 1999, (AIP, to be published).
16. C. Pennetta, Z. Gingl, L.B. Kiss and L. Reggiani *Semicond. Sci. Technol.* **12** (1997) 1057.
17. B. Neri, C. Ciofi, and V. Dattilo, *IEEE Trans. Electr.Dev.*, **44** (1997) 1454.