Noise in graphene and carbon nanotube devices

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I. INTRODUCTION

Carbon nano-materials, specifically carbon nanotubes and graphene, are genuine 1D and 2D systems benefitting from a wide tunability of carrier density by field effect doping. As such they constitute a unique platform for investigating electronic noise in conductors. In increasing sample current bias I, the current noise spectral density S_I, in reduced units given by the Fano factor $F = S_I/2eI$, is a faithful tracer of the transition form quantum to classic behavior. As depicted in Fig.1, the low bias regime is the realm of quantum scattering where shot noise is ruled by the nature of impurity scatterers; at intermediate bias electron-electron interactions set-in and show up by a hot electron noise characterized by a universal Fano-factor $F = \sqrt{3}/4$; at higher biases electron-phonon relaxation comes into play to cool the hot carriers with a scenario that is very generic in graphene.

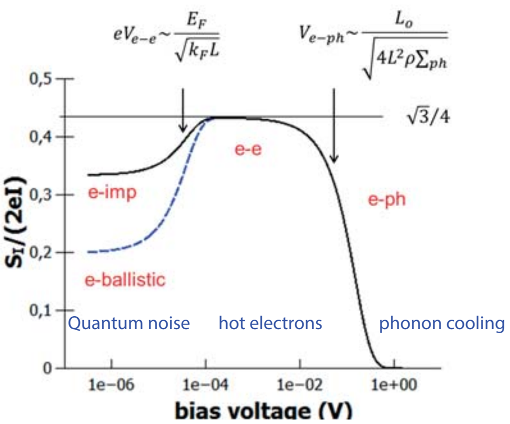

FIG. 1. Crossover from quantum to classical world illustrated by electronic noise.

Due to weak electron phonon coupling, the electronic temperature strongly decouples form phonon temperature in biased graphene (see fig.2). The first mechanism to come are the acoustic (AC) phonons coupling starting by cold-phonons in the Bloch-Grüneisen regime[1], the supercollision hot-phonon regime[2] and finally the ultimate non degenerate electron regime[3]. In the biasing process the electronic temperature strongly decouples from lattice temperature, reaching several hundreds of Kelvins. The good understanding of AC-phonon cooling and the recent availability of high mobility graphene, allow to investigate the more exotic case of optical (OP) phonon cooling which sets in above 1000 Kelvin in carbon nanomaterials[4,5]; few issues are yet unsolved like the role of substrate surface phonons, a very hot electromagnetic environment for electrons in nano-carbon materials.

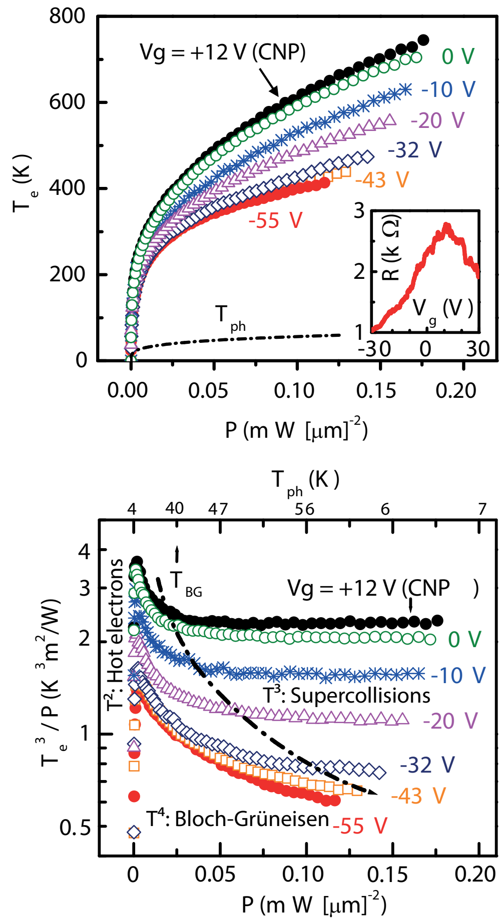

FIG. 2. a) Electronic temperature in graphene measured by high-frequency noise thermometry; b) three regimes of hot electrons in graphene (adapted from Ref.[2])

Hot electron thermometry requires high-resolution high-frequency noise measurements. These are needed to overcome the spurious contribution of $1/f$-noise that scales quadratically with current and invades gradually the thermal white noise spectrum (see Fig.3) which has a sublinear dependence on current (see Fig.3). The $1/f$-noise itself is a long-standing unsolved problems; it belongs to the family of flicker noises which may have different origins. Thanks to its wide tunability, graphene is a unique and versatile material to revisit the basics or $1/f$ resistance noise and eventually give new clues to the supposed universality of the Hooge constant $\alpha_H \sim 10^{-3}$.

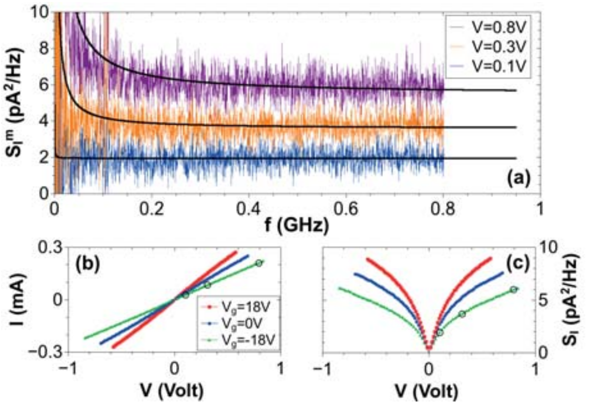

FIG. 3. Principles of hot-carrier noise thermometry (adapted from Ref.[1])

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A pillar of noise thermometry is the Johnson noise formula $S_I = 4G_n k_B T_e$ relating the current noise spectrum in a resistor to the electronic temperature via a so-called noise conductance G_n. It is common practice to identify G_n with the 2-terminal drain-source conductance G_{ds}. However, as pointed out by A. Van der Ziel back in 1962, the noise conductance may eventually deviate from the channel conductance in high-gain field effect transistors (FETs). This question was recently revisited using single carbon nanotube FETs as a ultimate single mode nano-transistor[7,8]. We could calculate the quantum correction in G_n which is proportional to the transconductance G_m, which is enhanced in CNT-FETs as measured by GHz noise thermometry in Ref.[8].

In conclusion graphene and carbon nanotubes have proved to be a valuable platform to put to test challenging issues in noise physics. This will probably continue to takkle more Unsolved Problems on Noise in the future.

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[1] Betz, A. C., Vialla, F., Brunel, D., Voisin, C., Picher, M., Cavanna, A., Madouri, A. Fève, G., Berroir, J.-M., Plaçais, B., Pallecchi, E. *Phys. Rev. Lett.* **109**, 056805 (2012). *Hot electron cooling by acousitic phonons in graphene*

[2] A.C. Betz, S.H. Jhang, E. Pallecchi, R. Ferreira, G. Fève, J.-M. Berroir, B. Plaçais, *Nature Physics* **9**, 109 (2013). *Supercollision cooling in undoped graphene*

[3] A. Laitinen, M. Oksanen, A. Fay, D. Cox, M. Tomi, P. Virtanen, and P. Hakonen, *Nano Lett.* 14, 3009 (2014). *supercollisions in suspended monolayer graphene*

[4] A. Laitinen, M. Kumar, M. Oksanen, B. Plaçais, P. Virtanen, and P. Hakonen, *Phys. Rev. B* 91, 121414(R) (2015) *Coupling between electrons and optical phonons in suspended bilayer graphene*

[5] D. Brunel, S. Berthou, R. Parret, F. Vialla, P. Morfin, Q. Wilmart, G. Fève, J.-M. Berroir, P. Roussignol, C. Voisin, B. Plaçais, *J. Phys. : Condens. Matter* **27**, 164208 (2015). *Onset of optical phonon cooling in multilayer graphene revealed by RF noise and black-body radiation thermometries*

[6] A. van der Ziel, *Proc. IRE* **50**, 1808 (1962) *Thermal noise in field effect transistors*

[7] J. Chaste, L. Lechner, P. Morfin, G. Fève, T. Kontos, J.-M. Berroir, D. C. Glattli, H. Happy, P. Hakonen, B. Plaais, *Nano Lett.* **8**, 525 (2008). *Single carbon nanotube transistor at GHz frequency*

[8] J. Chaste, E. Pallecchi, P. Morfin, G. Fève, T. Kontos, J.-M. Berroir, P. Hakonen, B. Plaçais, *Appl. Phys. Lett.* **96**, 192103 (2010). *Thermal shot noise in top-gated single carbon nanotube field effect transistors*