Understanding graphene phase-space structure from high-frequency current fluctuations

S. M. Yaro and X.Oriols
Departament d'Enginyeria Electrònica, Universitat Autònoma de Barcelona, Bellaterra, Spain
E-mail:xavier.oriols@uab.es

INTRODUCTION

Graphene has many revolutionary properties for fundamental and applied physics. In this conference, we show how graphene (with almost all electrons traveling at the same velocity) provides an unprecedented opportunity to deduce information on the (wave packet) nature of (quasi-free) electrons.

THE SIZE OF ELECTRONS

The maximum number of electrons, whose positions x, z and wave vectors k_x, k_z fit inside a (2D) phase-space region S, is $N = S/(2\pi)^2$ with $S = \Delta x \Delta K_x \Delta z \Delta K_z$. We neglect spin and valley degeneracies. This last result implies that each electron requires a phase space region for itself equal to $\Delta x \Delta K_x = 2\pi$. Born-von Karman boundary condition suggests that each electron is an eigenstate with $\Delta x = L_x$ and wave vector $\Delta K_x = 2\pi/L_x$. However, a (time dependent) wave packet needs several momentum eigenstates. Many-particle exchange interactions on (quasi-free) electrons [1] shows that a larger $\Delta K_x'$ and shorter $\Delta x'$ (or vicerversa) are also compatible with the phase-space density $\Delta x' \Delta K_x{}' = 2\pi$. See Figs. 1 and 2. Then, *which is the size Δx of (wave packets) electrons in graphene ?* In this conference we show how to answer this question from, the experimentally accesible, high-frequency current fluctuations.

PHASE-SPACE DENSITY OF INJECTED ELECTRONS

By measuring the electrical current, we can access directly to the phase-space density of injected electrons. In the 2D material, all electrons in the phase-space region S move to another x-region during the time interval $T = \Delta x/v_x$ [1], [2]. See Fig. 2. Therefore, the time between two consecutive injections of electrons is:

$$t_o = T/N = 2\pi/(\Delta K_x \, v_x) \qquad (1)$$

being $v_x = v_g k_x/\sqrt{k_x^2 + k_z^2}$ the x-velocity for graphene electrons with $v_g = 3 \times 10^6 \ m/s$ and $v_x = \hbar k_x/m$ for parabolic (Silicon) band-structure materials with $m = 0.9 \ m_o$. Linear and parabolic phase space density of injected electrons, defined as $N/T = (t_o)^{-1} \propto v_x$, are plotted in Fig. 3. Almost all graphene electrons move at the maximum velocity v_g, while a much larger velocity dispersion appears in Silicon [2]. See also Fig. 4.

TIME CORRELATION BETWEEN ELECTRONS

As we have shown, for all intervals ΔK_x between 0 and the maximum wave vector, (almost) all electrons move at the same velocity and they *enter* into the active region at multiples of t_o. Therefore, there is a large temporal correlation between the total (particle plus displacement) current generated by two consecutive electrons (this is not true for Silicon where a large variations of the velocity implies a large variation of t_o). In Fig. 5, the power spectral density of the current fluctuations $S(f)$ with the quantum BITLLES simulator [3] shows a bump at f_o=1.5 THz, which corresponds to our selection of $\Delta x \approx 2um$ [2]. The smaller Δx, the higher f_o.

CONCLUSION

We have shown through numerical computations that the measurement of current noise $S(f)$ at THz frequencies [4] (for ideally ballistic graphene two-terminal structures) allows us to determine t_o, which can be related to the fundamental *size*, Δx, of the wave packet associated to (quasi-free) electrons through (1). Additionally, the present study implies that the (classical or quantum) electron injection models [5], [6] for linear dispersions are radically different from parabolic ones, which has important implications in the intrinsic behavior of AC and noise graphene performances (Figs. 4 and 5).

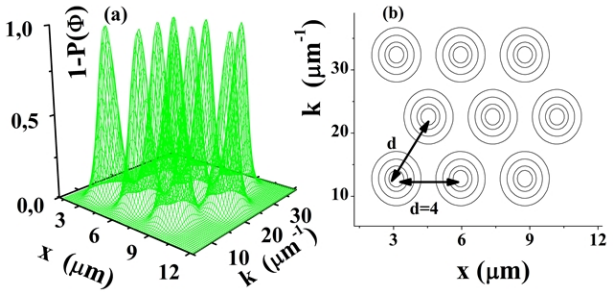

Fig. 1. (a) The presence of N=9 electrons in a region of the 1D phase-space implies that the probability $P(\Phi)$ of N=10 electrons inside the same region is almost zero. (b) Contour plot of the right figure where each electron is separated a normalized distance d from the rest [1]. Each electrons requires a phase space region equal to 2π.

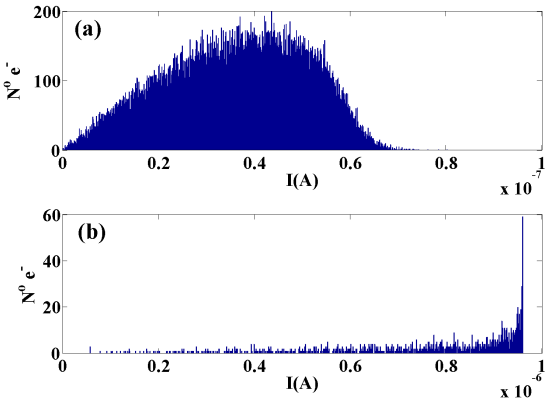

Fig. 4. Number of electrons as a function of instantaneous current I they take during a simulation time of 1 ps at 100 K, with Fermi energy $E_f = 0.1\ eV$ for (a) Silicon (b) Graphene. Almost all graphene electrons move at the same velocity and carry the same instantaneous current. This effect has important implications in the intrinsic behavior of AC and noise graphene performances [2], [4].

REFERENCES

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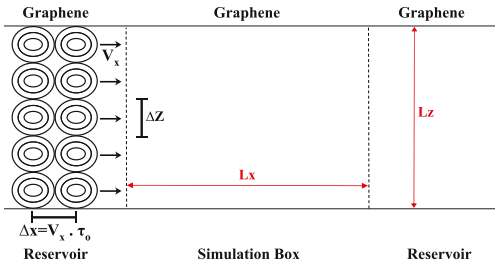

Fig. 2. Schematic representation of the (graphene) reservoir and (graphene) active region of length L_x where the injection of electrons (with constant rate) takes place.

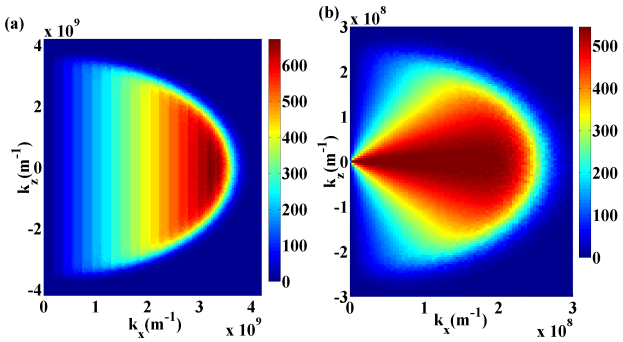

Fig. 3. Number of injected electrons computed from Eq. (1) as $N/T = (t_o)^{-1} \propto v_x$ for each point of the 2D wave vector space $\{k_x, k_z\}$ during a simulation time of 1 ps at 100 K, with Fermi energy $E_f = 0.1\ eV$. (a) Silicon where highest injection rate appears at highest energies, and v_x does only depend on $\{k_x\}$. (b) Garphene where the highest injection appears in almost all points $\{k_x, k_z\}$, except those with high k_z [2]. The velocity v_x does explicitly depend on $\{k_x, k_z\}$.

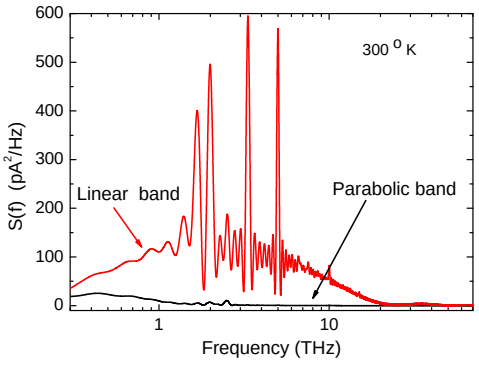

Fig. 5. Preliminary results with the quantum BITLLES simulator [3] for the power spectral density of the current fluctuations $S(f)$ as a function of frequency f for the ideally ballistic graphene two-terminal resistors of Fig. 1 with L_x=100 nm and L_z=1 um with a Fermi level $E_f = 0.05eV$. The graphene resistors (red) involves a higher cut-off frequency of $S(f)$ than Silicon one (black) because of a shorter current (particle and displacement) pulses. The presence of the graphene (red) bump at $f_o \approx 1.5\ THz$ (and other harmonics) is related to the time $t_o = 1/f_o$ in Eq. (1).