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PHYSICAL REVIEW LETTERS

Shot Noise in Ballistic Graphene

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We have investigated shot noise in graphene field effect devices in the temperature range of 4.2–30 K at low frequency ($f = 600$–850 MHz). We find that for our graphene samples with a large width over length ratio W/L, the Fano factor $\widetilde{\mathfrak{F}}$ reaches a maximum $\widetilde{\mathfrak{F}} \sim 1/3$ at the Dirac point and that it decreases strongly with increasing charge density. For smaller W/L, the Fano factor at Dirac point is significantly lower. Our results are in good agreement with the theory describing that transport at the Dirac point in clean graphene arises from evanescent electronic states.

Recently, graphene, a two-dimensional carbon crystal arranged in a honeycomb lattice, has attracted tremendous attention in the scientific community [1]. Its fundamental physical properties open up possibilities for realizing high-speed, ballistic field effect transistors [2] as well as for potential applications like spin control devices [3] or gas sensors [4]. Owing to its unique band structure, low energy conduction in graphene occurs via massless Dirac fermion quasiparticles leading to very rich and sometimes counter-intuitive behavior [1]. For example, despite the vanishing density of states at the Dirac point where the conduction and the valence band touch, the conductivity of graphene remains finite. Indeed, it has been proposed that transport at the Dirac point can be explained as propagation of charge carriers via evanescent waves [5]. Universal minimum conductivity of $\frac{4e^2}{\pi h}$ has been observed around the Dirac point for samples with a large width over length ratio (W/L) [2], yielding support to this evanescent-wave theory [5]. In addition to the minimum conductivity, current fluctuations are expected to exhibit nontrivial characteristics. A universal maximum value of 1/3 for the Fano factor $\widetilde{\mathfrak{F}}$, decreasing with increasing charge carrier density, is expected for large W/L in graphene. However, no experimental results have been reported yet [6]. In this Letter, we present a study of shot noise in short graphene strips at frequencies $f = 600$–850 MHz, which is well above the $1/f$ corner frequency, even at the large currents when working far away from the Dirac point [7]. Using a high resolution noise measurement setup [8], we measure shot noise of two-terminal graphene devices both as a function of the charge density as well as bias voltage. Our results indicate that ballistic transport occurs at the Dirac point via evanescent waves.

The role of disorder, interactions or carrier statistics in quantum transport can be probed by shot noise in mesoscopic devices [9]. Arising from the granular nature of electron charges, shot noise reveals information on fundamental conduction properties of low-dimensional systems in a complementary manner to conventional dc transport

measurements. Shot noise can be detected only when the drift time is shorter than electron-phonon energy relaxation time [10,11]. Naively, since electrical transport in graphene at submicron scale is believed to be ballistic, one would expect shot noise to be completely absent, i.e., the Fano factor $\widetilde{\mathfrak{F}} = \sum_{n=1}^{N} T_n(1 - T_n) / \sum_{n=1}^{N} T_n = 0$, where T_n are the transmission coefficients of the conducting channels in the scattering matrix formalism [9] (when $\widetilde{\mathfrak{F}} = 0$, all eigen values of the transmission matrix are equal to 1). However, Tworzydło *et al.* [5] have calculated that perfect graphene, contacted by highly doped graphene leads, should exhibit a Fano factor of 1/3 at the Dirac point for high W/L (note that Katsnelson reported similar sub-Poissonian shot noise in [12]). Similar calculations using metallic square lattice contact lead to the same conclusions [13]. In Ref. [5], the authors show that the transmission coefficients $T_n = \cosh^{-2}[\pi n \frac{L}{W}]$, i.e., they display the same distribution as in coherent disordered conductors. No clear-cut explanation for this intriguing coincidence between transmission eigenvalue distribution for the propagating modes in diffusive systems and evanescent states in graphene has been given [5].

Our experimental setup is illustrated in Fig. 1(a). In our work, we use the sensitive lock-in detection technique described in Refs. [8,14]. To enhance the sensitivity of noise detection, we use a low-frequency sine-wave modulation of the current, $I = I_{dc} + \delta I \sin(\omega t)$ where $I_{dc} \gg \delta I$. In order to avoid external spurious signals, the set-up is placed in a Faraday cage and the signal is band limited to the range of 600–850 MHz, thus avoiding EMI from mobile phone frequencies. We measure the shot noise of a tunnel junction ($\widetilde{\mathfrak{F}} = 1$) for calibration. A microwave switch is used to alternatively measure the noise from the graphene sample and the tunnel junction. Bias-tees are used to split dc bias and the bias-dependent high-frequency noise signal. The noise signal is first amplified by a low-noise amplifier (LNA) with a noise temperature of $T_n = 3.5$ K in matching conditions, thermalized at the same temperature as the sample, then by a series of room-
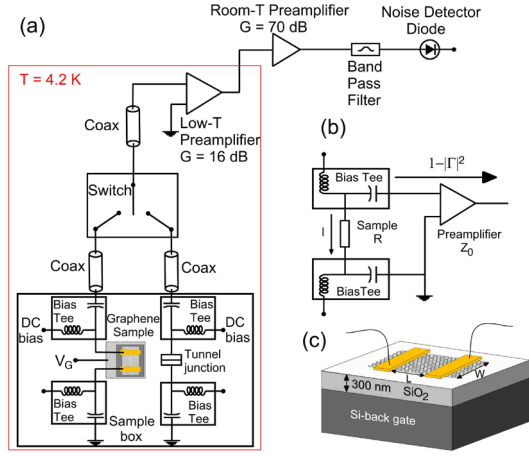
FIG. 1 (color online). (a) Experimental setup for detecting shot noise at $T = 4.2$–30 K. (b) Schematic of the principle of our measurements in terms of the noise power reflection $|\Gamma|^2$. (c) Illustration of a typical graphene sample fabricated for our shot noise study.

temperature amplifiers, and finally collected by a zero-bias Schottky diode with band-pass filtering of $f =$ 600–850 MHz. The noise power measured at the output of the LNA is a mixture of thermal noise of the LNA and shot noise from the sample. It can be defined in terms of the reflected signal $|\Gamma|$ [see Fig. 1(b)]. Here $\Gamma = \frac{R-Z_0}{R+Z_0}$ is the signal reflection coefficient when the noise generator, i.e., the measured sample with a resistance R, does not match to cold amplifier with the impedance $Z_0 = 50\ \Omega$. Then, the measured noise power reads: $P(I) = P_{noise}(1 - |\Gamma|^2) = \Im \times 2eI \times 4Z_0(\frac{R}{R+Z_0})^2$, where $P_{noise} = \Im 2eIR$ is the shot noise generated by the sample at $T = 0$. When $R \gg Z_0$, the coupling factor, $(\frac{R}{R+Z_0})^2$ can be taken as $= 1$. In our graphene samples, this is not fully true, and we employ the differential resistance measured at bias voltage V_{bias} for calculating the shot noise of the source from the measured noise power. The lock-in detection yields the noise derivative $P_d = \frac{dP}{dI}$, which can be integrated to yield the average Fano factor $F = \frac{1}{P_{cal}}(\int_0^I P_d dI)/(2eI)$, where P_{cal} denotes the separately determined calibration constant. Thus, in terms of current noise, our average Fano factor corresponds to $F = (S_I(I) - S_I(0))/(2eI)$ [14].

The schematic of a typical sample is shown in Fig. 1(c). Graphene sheets were mechanically exfoliated using the Scotch-tape technique [1] and transferred from the natural graphite crystals to the surface of SiO_2/Si substrate (300 nm thick thermally grown SiO_2 layer). The heavily doped Si substrate is used as a back-gate in the measurements. Single graphene layers were located using a 3CCD camera in an optical microscope on the basis of the RGB green component shift, in a similar manner as was recently done in Ref. [15]. After standard e-beam lithography, a bilayer of Ti(10 nm)/Au(40 nm) was evaporated, followed by lift off. Ti was chosen because it allows the formation of highly transparent contacts to graphene. In

fact, in previous work on graphene superconducting junctions with Al/Ti contacts [16], a very large probability for Andreev reflection was observed indicating an average transmission probability at the Ti-graphene interface ≥ 0.8. This is important because in our two lead configuration, we are sensitive to total transmission eigenvalues of both graphene and graphene-leads interface.

All the data were measured in a helium dewar, in which samples were in a He-gas atmosphere of 1 bar. The resistance of the samples was measured using standard low-frequency ac lock-in technique with an excitation amplitude of 0.3 mV (~ 3 K) at $\omega/2\pi = 63.5$ Hz, in the temperature range of 4.2–30 K. As shown in Fig. 2(a), the sample resistance as a function of the charge carrier density shows a maximum at the Dirac point for our large aspect ratio sample ($W/L = 24$ with $L \sim 200$ nm). Our graphene samples are nonintentionally p-doped, probably due to oxygen gas adsorption [4]. As a consequence, the Dirac point is shifted to a positive V_{gate} value. Nevertheless, from our measured conductivity values, it seems that adsorbed gas on a graphene sheet does not affect dramatically the transport properties of our samples. For our $W/L = 24$ sample, we obtain a minimum conductivity around $\frac{4e^2}{\pi h}$ which is the one calculated for large aspect ratio [5] and
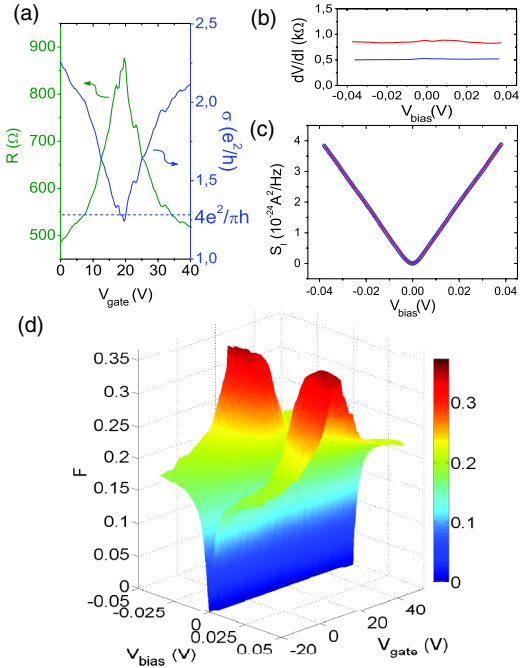

FIG. 2 (color online). Measurements on sample with $W/L = 24$: (a) Resistance R (left axis) and conductivity σ (right axis) as a function of V_{gate}. (b) Differential resistance dV/dI versus bias voltage V_{bias} at the Dirac point (red curve) and at high density (blue curve). (c) Current noise per unit bandwidth S_I as a function of bias at the Dirac point, at $T = 8.5$ K, fitted (red curve) using Khlus formula ($\Im = 0.318$). Note that the low bias data are perfectly fitted as well as the high bias (d) Mapping of the average Fano factor F as a function of gate voltage V_{gate} and bias voltage V_{bias} at $T = 8.5$ K.

measured in recent experiments [2]. Note that the resistance of graphene is nearly independent of the bias voltage V_{bias} [see Fig. 2(b)].

Figure 2(c) displays the power spectral density of current noise as a function of the V_{bias} at $T = 8.5$ K for our $W/L = 24$ sample, at the Dirac point. The first way to extract the Fano factor $\mathfrak{F}$ is to use the formula originally introduced by Khlus [17] which describes the crossover from thermal to shot noise when $eV \sim k_B T$ [18], $S_I = \mathfrak{F} \frac{2e|V|R}{(R+Z_0)^2} \coth(\frac{e|V|}{2k_B T})$. Here Z_0 is the impedance of the cold LNA (50 Ω). Since the resistance of our graphene samples is bias independent, we may fit the Khlus formula to our data using only $\mathfrak{F}$ as a fitting parameter at fixed temperature T. From our nearly perfect fit, we extract that $\mathfrak{F} = 0.318$ at $T = 9$ K. To check the accuracy of our measurements, we also used the tunnel junction calibration technique to extract the average Fano factor F [8,14]. We found $F = 0.338$ at the Dirac point (at $V_{bias} = 40$ mV).

The values found for $\mathfrak{F}$ and F as well as for the minimum conductivity are very close to the expected theoretical value of $1/3$ and $\frac{4e^2}{\pi h}$ respectively at the Dirac point for perfect graphene strip with large W/L [5]. However, the Fano factor in this case is also the one expected for a diffusive mesoscopic system. In order to confirm that charge carriers in our sample do not undergo any scattering, we swept V_{gate} to move the Fermi level across the Dirac point to high carrier density. A diffusive system should not display any gate dependence (as measured by Dicarlo *et al.* in [6] and calculated for long range disorder in [19]). In Fig. 2(d), we can see a mapping of F, calculated by integrating the differential Fano factor as described in [14], as a function of the V_{bias} and V_{gate}. It shows a clear dependence of F on gate voltage [20] (i.e., the charge carrier density), with a clear drop (about a factor of 2) of the Fano factor at large carrier density confirming that our results are in good agreement with the evanescent state theory [5].

It is important to note that the Fano factor is barely affected by temperature indicating that both the length L and the width W are smaller than the electron-phonon inelastic scattering length $L_{e\text{-ph}}$: if this condition was not fulfilled, the Fano factor would decrease, approximatively as inversely proportional to $N = \frac{L_{e\text{-ph}}}{\max(W,L)}$, though the actual form would be model dependent [9]. Since our shot noise measurements do not depend on temperature (between 4 and 30 K) and with our contacts being highly transparent, the presence of inelastic scattering mechanism in the graphene sample and at its interfaces with the leads can be ruled out. Note that bad contacts can only increase the Fano factor toward the limit of two symmetrical tunneling barriers in series which gives a Fano factor of $1/2$. This is not the case of our samples in which the Fano factor has never been measured higher than $1/3$.

In Fig. 3, we have plotted the F as a function of $\delta V = V_{\text{gate}} - V_{\text{Dirac}}$ for three different samples with $W/L \geq 3$ (3,
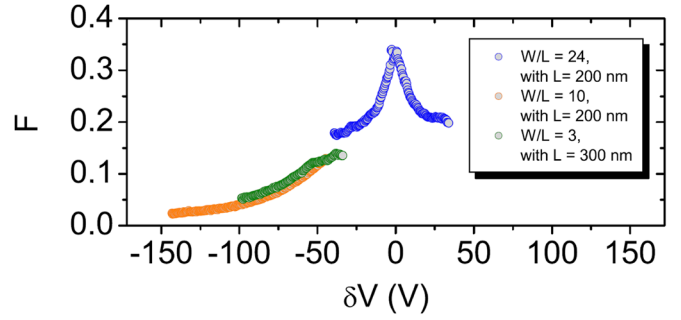

FIG. 3 (color online). F extracted at $V_{\text{bias}} = 40$ mV for three different samples, all having $W/L \geq 3$, as a function of $\delta V = V_{\text{gate}} - V_{\text{Dirac}}$. For the two unintentionally highly p-doped samples (orange and green dots), the Dirac point was estimated via extrapolation of the minimum conductivity at $\frac{4e^2}{\pi h}$.

10, and 24). All samples were p doped, the Dirac points being at positive V_{gate}, but only for one of these three samples we could reach the Dirac point (sample with $W/L = 24$). The gate voltages corresponding to the Dirac point for the two other samples were estimated from their conductivity curves. We observe that despite the high doping level of the samples, the Fano factor seems to behave universally and tends to zero at very high density, i.e., the value for a ballistic system.

We found that the value for the Fano factor for high W/L is about $1/3$ to a good accuracy (± 5%), indicating that transport occurs via evanescent modes without any observable resonant scattering at the Dirac point. It has been theoretically demonstrated that the presence of disorder-induced scattering in graphene decreases the Fano factor while disorder, counterintuitively, enhances conductivity [21,22]. Such behavior may be understood as consequences of the absence of intervalley scattering [23] and the chirality conservation [24]. Recently, a model calculation near the Dirac point was performed [22] for conductivity and shot noise taking into account smooth disorder, namely, puddles [25,26] generated by charged impurities. According to this model, smooth disorder at length scales $\ll L$, W lowers the Fano factor at the Dirac point, down to 0.243 for one-dimensional disorder and to 0.295 for the two-dimensional case [22]. This value falls clearly below our experimental result $\mathfrak{F} = 0.33 \pm 0.02$ indicating that transport occurs via evanescent modes without any observable scattering at the Dirac point. Despite the probable presence of some disorder in our system, the transport regime can be considered as ballistic on our sample length scale. We note that weak disorder may induce anomalously large conductance fluctuations [27]. However, we do not observe any oscillations in the conductivity or in the Fano factor by increasing density.

We also measured one sample with a much smaller aspect ratio $W/L = 2$, having $L = 500$ nm. The data in Fig. 4(a) show that the minimum conductivity in this sample is $\sim 6\frac{e^2}{h} \gg \frac{4e^2}{\pi h}$. The resistance R of the sample can be considered as constant as a function of the bias

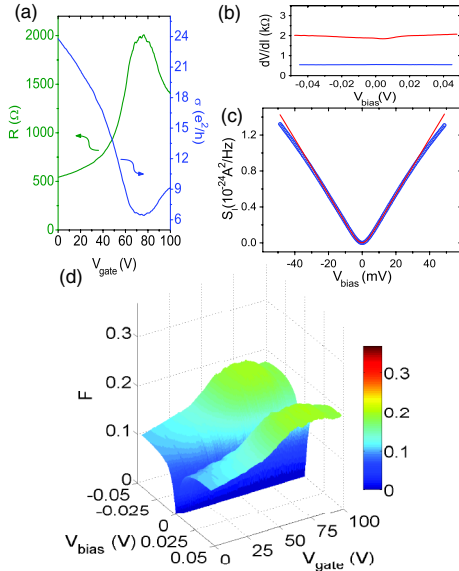FIG. 4 (color online). Measurements on sample with $W/L = 2$: (a) R (left axis) and σ (right axis) as a function of V_{gate}. (b) dV/dI versus V_{bias} at the Dirac point (red curve) and at high density (blue curve). (c) Current noise per unit bandwidth S_I as a function of V_{bias} at the Dirac point, at $T = 5$ K, fitted (red curve) using Khlus formula ($\widetilde{\mathfrak{F}} = 0.196$). (d) Mapping of the F as a function of V_{gate} and V_{bias} at $T = 5$ K.

[see Fig. 4(b)]. In Fig. 4(c), the integrated spectral density of current noise as a function of V_{bias} is fitted using Khlus formula. The fit is good at low bias, while deviations occur at large V_{bias}, indicating a decrease of the Fano factor, presumably due to electron-phonon coupling [9]. We find that the Fano factor is reduced and reaches $F = 0.19$ at the Dirac point, which is in agreement with the results of Ref. [5] calculated for the case of metallic armchair edge. F as a function of V_{bias} and V_{gate} is displayed in Fig. 4(d). Note that the determination of $\widetilde{\mathfrak{F}}$ in Fig. 4(c) yields almost the same result: $\widetilde{\mathfrak{F}} = F = 0.19$ at the Dirac point. We observe that F is lower than expected from the theory with disorder in Ref. [22], which strengthens the argument that transport at the Dirac point can occur without substantial scattering.

To conclude, we have measured a gate dependent shot noise in short graphene strips with large and small W/L. At the Dirac point, we observed that for large W/L both minimum conductivity and Fano factor reach universal values of $\frac{4e^2}{\pi h}$ and $1/3$ respectively. For W/L smaller than 3, the Fano factor is lowered and the minimum conductivity increases. These findings are well explained by the evanescent-wave theory describing transport at the Dirac point in perfect graphene.

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[1] A. K. Geim and K. S. Novoselov, Nat. Mater. **6**, 183 (2007).
[2] F. Miao *et al.*, Science **317**, 1530 (2007).
[3] N. Tombros *et al.*, Nature (London) **448**, 571 (2007).
[4] F. Schedin *et al.*, Nat. Mater. **6**, 652 (2007).
[5] J. Tworzydło *et al.*, Phys. Rev. Lett. **96**, 246802 (2006).
[6] When completing this manuscript, we became aware of a study of shot noise in diffusive graphene, L. Dicarlo *et al.*, Phys. Rev. Lett. **100**, 156801 (2008).
[7] Z. Chen *et al.*, Physica E (Amsterdam) **40**, 228 (2007).
[8] F. Wu *et al.*, AIP Conf. Proc. **850**, 1482 (2006).
[9] Ya. M. Blanter and M. Büttiker, Phys. Rep. **336**, 1 (2000).
[10] C. W. J. Beenakker and M. Büttiker, Phys. Rev. B **46**, 1889 (1992); K. Nagaev, Phys. Lett. A **169**, 103 (1992); A. Shimizu and M. Ueda, Phys. Rev. Lett. **69**, 1403 (1992).
[11] A. H. Steinbach, J. M. Martinis, and M. H. Devoret, Phys. Rev. Lett. **76**, 3806 (1996).
[12] M. I. Katsnelson, Eur. Phys. J. B **51**, 157 (2006).
[13] H. Schomerus, Phys. Rev. B **76**, 045433 (2007).
[14] F. Wu *et al.*, Phys. Rev. Lett. **99**, 156803 (2007).
[15] J. B. Oostinga *et al.*, Nat. Mater. **7**, 151 (2008).
[16] H. B. Heersche *et al.*, Nature (London) **446**, 56 (2007).
[17] V. A. Khlus, Zh. Eksp. Teor. Fiz. **93**, 2179 (1987) [Sov. Phys. JETP **66**, 1243 (1987)].
[18] Notice that when dealing with the integrated differential Fano factor, T_n drops out as an insignificant background offset: as a consequence, the coupling term $\frac{4k_BT_n}{Z_0}$ can be neglected from the Khlus formula [17].
[19] C. H. Lewenkopf, E. R. Mucciolo, and A. H. Castro Neto, Phys. Rev. B **77**, 081410(R) (2008).
[20] Note that we cannot obtain a quantitative agreement with the evanescent mode theory, probably because doping by the leads may cause variation of the gate coupling capacitance and because the presence of nonuniform doping, that, does not strongly scatter the charge carriers, also affects the electronic density of states. Nevertheless, the gate voltage scale is found to be larger than the one found in [5].
[21] M. Titov, Europhys. Lett. **79**, 17004 (2007).
[22] P. San-Jose, E. Prada, and D. S. Golubev, Phys. Rev. B **76**, 195445 (2007).
[23] A. F. Morpurgo and F. Guinea, Phys. Rev. Lett. **97**, 196804 (2006).
[24] M. I. Katsnelson, K. S. Novoselov, and A. K. Geim, Nature Phys. **2**, 620 (2006).
[25] E. H. Hwang, S. Adam, and S. Das Sarma, Phys. Rev. Lett. **98**, 186806 (2007).
[26] J. Martin *et al.*, Nature Phys. **4**, 144 (2008).
[27] A. Rycerz, J. Tworzydło, and C. W. J. Beenakker, Europhys. Lett. **79**, 57 003 (2007).