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Shot noise suppression and hopping conduction in graphene nanoribbons

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We have investigated shot noise and conduction of graphene field-effect nanoribbon devices at low temperature. By analyzing the exponential I-V characteristics of our devices in the transport gap region, we found that transport follows variable range hopping laws at intermediate bias voltages $1 < V_{bias} < 12$ mV. In parallel, we observe a strong shot noise suppression leading to very low Fano factors. The strong suppression of shot noise is consistent with inelastic hopping, in crossover from one- to two-dimensional regime, indicating that the localization length $l_{loc} < W$ in our nanoribbons.

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Graphene, a two-dimensional crystal of carbon atoms, has attracted a tremendous interest of both scientific community and microelectronic industry.1 However, graphene is a zero-gap semiconductor with a minimum conductivity of $4e^2/h$ too large to be utilized as base material for high on-off ratio field-effect transistor. One way to circumvent this problem would be to open a gap in graphene’s band structure. It is possible in bilayer graphene by the means of doping or electrostatic 3 potential, or mechanical cleavage on natural graphite. The graphene sheets were deposited on a heavily doped substrate with 300 nm SiO$_2$ layer [see Fig. 1(a)]. The graphene sheet was first connected using standard e-beam lithography followed by a Ti(10 nm)/Au(40 nm) bilayer deposition with lift-off in acetone. A second lithography step allowed the patterning of the GNRs. The resist poly(methyl methacrylate) (PMMA) was used as mask in this step and GNRs were etched using an Ar plasma. We present the measurements on two GNRs: sample A with a length $L=100$ nm and a nominal width $W=90$ nm, and sample B with a length $L=200$ nm and a nominal width $W=70$ nm. After the experiments, the GNRs were observed using scanning electron microscope at 0.5 kV [see Fig. 1(b)].

The measurements were performed in a similar fashion as described in Ref. 14, from room temperature down to $T = 4.2$ K. The differential conductance $dI/dV$ was measured using standard low-frequency ac lock-in technique with an excitation amplitude from 0.38 mV up to 0.8 mV ($\sim 4$ to $\sim 8$ K) at $f = 63.5$ Hz. A tunnel junction was used for calibration of the shot noise.14,15

Figures 2(a) and 2(b) display the gate voltage $V_{gate}$ dependence of the zero-bias conductance $G$ for different temperatures $T$ of sample A and B, respectively. In both cases, we observe a drop of $G$ when $T$ is lowered and a high impedance region emerges as $T \rightarrow 4.2$ K. Clear conductance oscillations at zero bias are visible at the lowest temperatures. However, no periodicity is detectable in a Fourier analysis. Far away

FIG. 1. (Color online) (a) Schematics of an etched GNR. (b) False color scanning electron micrograph of sample A, highlighting the graphene and the GNR (in blue/dark gray) and the leads (in yellow/light gray).
from the charge neutrality point $G \sim 2e^2/h$, i.e., twice the conductance quantum $g_0$. Figures 2(c) and 2(d) show a color map of $\frac{dI}{dV}$ versus $V_{bias}$ and $V_{gate}$ at liquid helium temperature, for sample A and B, respectively. These measurements highlight the formation of a “large impedance region” or a “gap” as previously observed. This region can be viewed in different ways. In the Anderson picture, it arises due to localized states. This has recently been performed. An alternative way is to analyze $I$-$V$ curves at a temperature $T$. At high bias, below a certain $V_0$, the following equation can be used to describe VRH:

$$I(E,T) = G_0(T) \exp\left\{-\frac{V}{V_0}\right\} \left[\left(\frac{V}{V_0}\right)^{1/d+1}\right].$$

where $d$ is the dimensionality of hopping (for the effect of interactions, see below) and $G_0$ is the zero-bias conductance. Figure 3 displays $I$-$V$ curves for sample A and B measured in the gap region. Following Eq. (1), we see that the conduction follows variable range hopping law in the gap region. The data are plotted using $d=1$ which describes VRH for one-dimensional (1D) systems with or without interactions or two-dimensional (2D) systems with interactions. We obtain $V_0 \approx 8$ and $12$ mV for sample A and B, respectively. Here, $\frac{e}{h}V_0$ describes the bias needed to overcome the potential barrier of the localized state with radius $a$. The fact that we obtain a larger $V_0$ for sample B which has a width $20$ nm smaller (and is even shorter) than sample A indicates an enhanced influence of the rough edges on the conduction. Consequently, our results show that the appearance of the high impedance region in GNRs is also affected by defects such as localized states at the edges and, likewise, by the local doping due to contaminants. This is in agreement with the recent works on temperature dependence of GNR conductance.

10 Han et al.\(^{10}\) have shown that for various GNR geometries $l \approx W$ indicating 1D VRH transport in the high impedance region of GNRs; the origin of the transport gap would then be due to localized states. This has recently been confirmed by magnetotransport measurements.\(^{10}\) Our value for $V_0 \approx 10$ meV is close to the value $k_BT/e$ = 6 meV given in Ref. 10.
In order to gain more information on the hopping in GNRs, we have studied shot noise. Shot noise denotes current fluctuations arising from the granular nature of the charge carriers (see Ref. 20 for a review). It provides a powerful tool to probe mesoscopic systems and it is usually regarded as a complementary technique to conductance measurements. The Fano factor $F$, given by the ratio of shot noise and mean current, is commonly employed to quantify shot noise. The noise power spectrum then reads $S(I) = F \times 2eI$. In the case of phase-coherent transport in GNRs, shot noise strongly depends on the boundary conditions, i.e., whether the edges are zigzag or armchair. However, phase-coherent length in etched GNRs have been estimated to be at most 175 nm (Ref. 10) and it is clearly less in our experiment due to higher temperature and a finite bias that enhances energy relaxation. While in the case of phase-coherent transport, shot noise can be described simply by the scattering matrix theory, it can be treated using semiclassical means in the incoherent regime. When inelastic processes dominate (inelastic length $l_{in} < L$), shot noise starts to decrease and it becomes dependent on the details of the relaxation processes that govern the ensuing nonequilibrium state. In inelastic hopping conduction with short hopping length ($l_{hop} \ll L$), strong suppression of shot noise takes place as observed in 2D systems.

Assuming strongly inelastic behavior, classical addition of uncorrelated noise sources can be employed and networks of resistors with shunting current noise generators become an appealing choice for noise modeling in GNRs. Within this classical limit, the internal topology of the ribbon becomes relevant. If hopping is 2D in GNRs, then part of the noise current of individual noise generators is shunted via the conduction paths inside the ribbon and the noise coupled to an outside load becomes reduced. Consequently, we expect that the Fano factor is reduced a bit further down from the 1D classical limit given by $l_{hop}/L$.

We have performed our shot noise measurements at frequency around 800 MHz. This frequency is high enough so that all noise due to slow fluctuations of resistance (transmission coefficients) can be neglected. On the other hand, the frequency is low compared with internal charge relaxation-time scales and high-frequency effects can be neglected. Figure 4(a) displays the current noise per unit bandwidth $S_n$ versus current $I$ in the high impedance region for samples A and B, respectively. Both curves are fitted using the formula defined by Khlus with $F$ as the only fitting parameter. We find a rather low Fano factor for both GNRs $F \sim 0.1$ at low bias (the results involve a correction due to nonlinear $I$-$V$ curves as discussed in Ref. 14). Figures 4(b) and 4(c) show a zoom of the noise curves in the low-bias region, i.e., in the VRH regime (up to $I \sim 0.05 \mu A$ corresponding to $V \sim 10$ mV) for sample A and B, respectively. Despite some asymmetry in the shot noise, $F$ undergoes very little variation in the gap region. With increasing bias, we find a further reduction in the Fano factor, which signals a strong role of inelastic processes as the localized states become delocalized.

Why such a low shot noise? The observed conductance modulation in the high impedance regime suggests that a series/array of dots is formed in GNRs. Quantum dots often show super-Poissonian noise instead of low noise level (see, for example, the work done on carbon nanotubes and as theoretically expected for a series of quantum dots. However, a series of $N$ quantum dots without inelastic effects should lead to a Fano factor of $\frac{1}{N}$. We note that shot noise suppression could be seen in asymmetric, open quantum cavity, but the resistance of one or two open quantum cavities (regions at the ends of the ribbon) is too small to account for our results. There will, however, be a small contribution by the end reservoirs on the shot noise. The main contribution to the shot noise suppression can only come from hopping conduction via so small localized states that the nature of hopping conduction is likely to be almost 2D. $F$ for a series of $N$ sites with inelastic hopping is approximately $1/N \sim l_{hop}/L$ and this remains as a good approximation also in the 2D situation, where $N$ then denotes the number of hops along the voltage bias. In order to explain the observed suppression, the hopping length has to be in the range of $l_{hop} \sim 20–60$ nm; as the localization length $l_{loc} \sim l_{hop}$ is less than the width of the GNR, we conclude that the hopping conduction in our ribbons is not 1D in nature but rather it falls in the crossover regime between 1D and 2D (or quasi-1D). Our shot noise results thus indicate even a slightly smaller $l_{hop}$ than was found previously.

The shot noise crossover from VRH region to high-bias regime without localized states in Fig. 4 points to strong relaxation of electrons: otherwise an increase in the Fano factor would be expected across the crossover as the number of hops decreases and $l_{loc}$ increases. Indeed, even in the VRH regime, the apparent Fano factor could be formed by other means, for example, by noise from the graphene islands at the ends, and that the actual shot noise from the GNR nearly vanishes. This would be reminiscent to carbon nanotubes where very small $F$ have been observed in various configurations. Nearly total suppression of shot noise indicates very effective energy relaxation at finite bias which
could be realized by disorder-enhanced electron-phonon coupling or by relaxation via new degrees of freedom provided by the edges of the GNR.

To conclude, we have measured shot noise and conductance in GNRs. While the dc transport shows characteristic behavior of GNRs, we clearly observe a strong shot noise suppression. We were able to fit the I-V curves with VRH laws in the high impedance region. We have shown that shot noise suppression could be explained by inelastic hopping conduction in the quasi-1D limit. Our results are consistent with the strong effect of rough edges and local contaminants in the conduction and shot noise of GNRs.

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1A. H. Castro Neto et al., Rev. Mod. Phys. 81, 109 (2009); N. M. R. Peres, ibid. 82, 2673 (2010); S. Das Sarma, S. Adam, E. Hwang, and E. Rossi, arXiv:1003.4731 (unpublished).
2T. Ohta et al., Science 313, 951 (2006).
3J. B. Oostinga et al., Nature Mater. 7, 151 (2008).
4K. Nakada, M. Fujita, G. Dresselhaus, and M. S. Dresselhaus, Phys. Rev. B 54, 17954 (1996).
5Z. Chen et al., Physica E 40, 228 (2007).
6M. Y. Han, B. Özüyilmaz, Y. Zhang, and P. Kim, Phys. Rev. Lett. 98, 206805 (2007).
7X. Li et al., Science 319, 1229 (2008); X. Wang, Y. Ouyang, X. Li, H. Wang, J. Guo, and H. Dai, Phys. Rev. Lett. 100, 206803 (2008); J. M. Pounirol, A. Cresti, S. Roche, W. Escoffier, M. Goiran, X. Wang, X. Li, H. Dai, and B. Raquet, Phys. Rev. B 82, 041413(R) (2010).
8B. Özüyilmaz et al., Appl. Phys. Lett. 91, 192107 (2007); K. Todd et al., Nano Lett. 9, 416 (2009); C. Stampfer, J. Guettiger, S. Hellmüller, F. Molitor, K. Ensslin, and T. Ihn, Phys. Rev. Lett. 102, 056403 (2009); F. Molitor, A. Jacobsen, C. Stampfer, J. Guettiger, T. Ihn, and K. Ensslin, Phys. Rev. B 79, 075426 (2009); X. Liu, J. B. Oostinga, A. F. Morpurgo, and L. M. K. Vandersypen, Phys. Rev. B 80, 121407(R) (2009); P. Gallagher, K. Todd, and D. Goldhaber-Gordon, Phys. Rev. B 81, 115409 (2010).
9M. Y. Han, J. C. Brant, and P. Kim, Phys. Rev. Lett. 104, 056801 (2010).
10J. B. Oostinga, B. Sacépé, M. F. Craciun, and A. F. Morpurgo, Phys. Rev. B 81, 193408 (2010).
11Y.-W. Son, M. L. Cohen, and S. G. Louie, Phys. Rev. Lett. 97, 216803 (2006); D. Gunlycke, D. A. Areshkin, and C. T. White, Appl. Phys. Lett. 90, 142104 (2007); F. Solis, F. Guinea, and A. H. Castro Neto, Phys. Rev. Lett. 99, 166803 (2007); A. Lherbier, B. Biel, Y.-M. Niquet, and S. Roche, ibid. 100, 036803 (2008); D. Querlioz et al., Appl. Phys. Lett. 92, 042108 (2008); S. Adam, S. Cho, M. S. Fuhrer, and S. Das Sarma, Phys. Rev. Lett. 101, 046404 (2008); M. Evaldsson, I. V. Zozoulenko, H. Xu, and T. Heinzel, Phys. Rev. B 78, 161407(R) (2008); I. Martin and Y. M. Blanter, ibid. 79, 235132 (2009).
12B. I. Shklovskii and A. L. Efros, Electronic Properties of Doped Semiconductors (Springer-Verlag, Berlin, 1984).
13M. F. Craciun et al., Nat. Nanotechnol. 4, 383 (2009).
14R. Danneau, F. Wu, M. F. Craciun, S. Russo, M. Y. Tomi, J. Salmilehto, A. F. Morpurgo, and P. J. Hakonen, Phys. Rev. Lett. 100, 196802 (2008); J. Low Temp. Phys. 153, 374 (2008); Solid State Commun. 149, 1050 (2009).
15E. Wu et al., in Low Temperature Physics, AIP Conf. Proc. No. 850 (AIP, New York, 2006), p. 1482.
16B. I. Shklovskii, Sov. Phys. Semicond. 6, 1964 (1973).
17M. Pollak and I. Riess, J. Phys. C 9, 2339 (1976).
18A. A. Kinkhabwala, V. A. Sverdlov, and K. K. Likharev, J. Phys.: Condens. Matter 18, 2013 (2006).
19A. S. Rodin and M. M. Fogler, Phys. Rev. B 80, 155435 (2009).
20Ya. Blanter and M. Böttiker, Phys. Rep. 336, 1 (2000).
21A. Cresti, G. Grosso, and G. P. Parravicini, Phys. Rev. B 76, 205433 (2007); E. R. Mucciolo, A. H. Castro Neto, and C. H. Lewenkopf, ibid. 79, 075407 (2009); R. L. Dragomirowa, D. A. Redkin, and B. K. Nikolic, ibid. 79, 214401(R) (2009).
22V. V. Kuznetsov, E. E. Mendez, X. Zhuo, G. L. Snider, and E. T. Croke, Phys. Rev. Lett. 85, 397 (2000); S. H. Roshko et al., Physica E 12, 861 (2002); F. E. Camino, V. V. Kuznetsov, E. E. Mendez, M. E. Gershenson, D. Reuter, P. Schafmeister, and A. D. Wieck, Phys. Rev. B 68, 073313 (2003); A. K. Savchenko et al., Phys. Status Solidi B 241, 26 (2004).
23V. A. Khlus, Zh. Eksp. Teor. Fiz. 93, 2179 (1987) [Sov. Phys. JETP 66, 1243 (1987)].
24It is important to note that even stronger asymmetries in the noise power spectra curves have been measured in 2D systems in the VRH regime, see Ref. 22.
25E. Onac, F. Balestro, B. Trauzettel, C. F. J. Lodewijk, and L. P. Kouwenhoven, Phys. Rev. Lett. 96, 026803 (2006).
26E. Wu, T. Tsuneta, R. Tarkiainen, D. Gunnarsson, T.-H. Wang, and P. J. Hakonen, Phys. Rev. B 75, 125419 (2007).
27J. Aghassi et al., Appl. Phys. Lett. 89, 052101 (2006).
28See, D. S. Golubev and A. D. Zaikin, Phys. Rev. B 70, 165423 (2004).
29P. E. Roche et al., Eur. Phys. J. B 28, 217 (2002).
30P. Tsuneta et al., EPL, 85, 37004 (2009).
31A. Sergeev and V. Mitin, Phys. Rev. B 61, 6041 (2000).