Quantum interference noise near the Dirac point in graphene

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Effects of disorder on the electronic transport properties of graphene are strongly affected by the Dirac nature of the charge carriers in graphene. This is particularly pronounced near the Dirac point, where relativistic charge carriers cannot efficiently screen the impurity potential. We have studied time-dependent quantum conductance fluctuations in graphene in the close vicinity of the Dirac point at low temperatures. We show that the low-frequency noise arises from the quantum interference effects due to scattering on slowly fluctuating impurities. An unusually large reduction of the noise power in magnetic field suggests that an additional symmetry plays an important role in this regime.

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I. INTRODUCTION

Low-frequency noise is a ubiquitous phenomenon that plagues electronic devices, and graphene devices are not an exception [1–4]. There are many physical mechanisms that cause $1/f$ noise, but it is often difficult to determine which one contributes the most. There is, however, one particular mechanism that is easy to distinguish by its dependence on temperature and magnetic field: quantum interference noise (QIN). Expected to be observed only at very low temperatures when other mechanisms are mostly frozen out, QIN reflects time-dependent quantum conductance fluctuations. These fluctuations occur due to quantum interference between different paths taken by the electron upon scattering on impurities that fluctuate slowly over time [5–7]. QIN has been observed in disordered metals [8–11] but has not been reported in graphene. Vastly underutilized as a tool to study properties of disordered systems, QIN depends strongly on the underlying symmetries and offers disorder-averaged information that is complementary to conductance and tunneling measurements. This could be particularly useful in the case of graphene and other Dirac materials, where quantum conductance fluctuations can be nonuniversal [12] and nonergodic [13]. In this work, we report an observation of QIN in disordered graphene, focusing specifically on the low-carrier density regime near the Dirac point. We find that $1/f$ noise is reduced in magnetic field, with a characteristic field and temperature dependence that points firmly to quantum interference as the origin of the noise. The observed noise reduction in magnetic field is twice as large as what one would expect in conventional systems, most likely due to breaking of the symmetry between valley degrees of freedom in graphene. Our results demonstrate how QIN can be used as a unique probe of the relevant symmetry classes and unconventional degrees of freedom in novel materials.

II. EXPERIMENTAL METHODS

A scanning electron microscope image of a typical top-gated device (SL1) is shown in Fig. 1(a) [14]. Raman spectroscopy was used to confirm that all samples were made of single-layer graphene, with typical results shown in Fig. 1(b). All electrical measurements were done in a four-probe geometry, using external voltage probes [15], as shown on the schematic in Fig. 1(c). The typical resistance as a function of top-gate voltage V_{Tg} with zero back-gate voltage V_{Bg} is shown in Fig. 1(d). The peak in the resistance occurs at the Dirac point, at a value of top-gate voltage of −0.3 V, at which the carrier density in graphene reaches the minimum.

Low-frequency noise measurements were done at temperatures of 250 mK using the ac noise measurement technique [16]. The measured noise power S_V showed $1/f^\alpha$ dependence for either gate (top or back) voltage with values of α close to 1 [Fig. 2(a)]. We found that the noise data were highly reproducible over time at any temperature (all measurements were done below 2.5 K) and did not depend on the direction or scan step of the gate voltage. The normalized noise power density ($=f S_V/V^2$ or $f S_I/I^2$) was found to be independent of the bias current or voltage [14], ruling out any issues due to heating by the bias current.

III. RESULTS AND DISCUSSION

The normalized noise power as a function of the top-gate voltage in the vicinity of the Dirac point is shown in Fig. 2(b). We find that the noise decreases upon approaching the Dirac point from both directions, reaching a minimum close to the Dirac point.

When a magnetic field is applied perpendicular to the substrate, the noise power decreases rapidly, as shown in Fig. 2(c). After reaching some characteristic value of the field, the relative noise power saturates at the value that is smaller than the zero-field value by a factor of 4. As discussed below, the fact that the noise is reduced at this particular value of the magnetic field indicates that the $1/f$ noise is dominated by quantum interference effects and not by the classical fluctuations in the electrostatic environment (classical fluctuations become increasingly frozen out with decreasing temperature, as the thermal energy becomes lower than the characteristic activation energies for fluctuating impurities).

In disordered electronic systems, various types of quantum corrections to the conductance arise due to quantum interference between paths of electrons scattered on random impurities. In the absence of a magnetic field, the electron paths that traverse closed loops in a clockwise fashion interfere constructively with the counterclockwise paths through the same loops, resulting in a small change in the conductance.

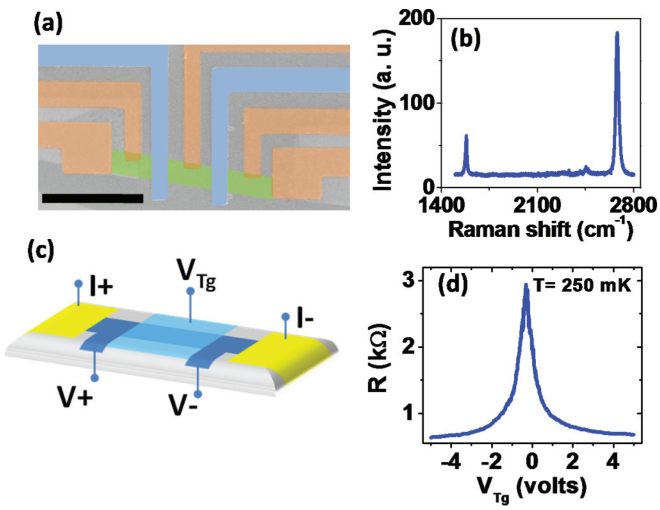

FIG. 1. (Color online) (a) False-color scanning electron microscope image of a typical single-layer device (SL1). The graphene flake is highlighted in green, and the top gates are shown in blue. The distance between the voltage leads is typically around 1 μm. The scale bar is 3 μm long. (b) Raman spectra of one of the samples. The observed peak structure is characteristic for single-layer graphene. (c) Schematic of the four-probe measurement setup with external voltage probes. (d) Resistance as a function of top-gate voltage for zero back-gate voltage for sample SL1. The Dirac point, or the charge neutrality point, is located at $V_{Tg} = -0.3$ V.

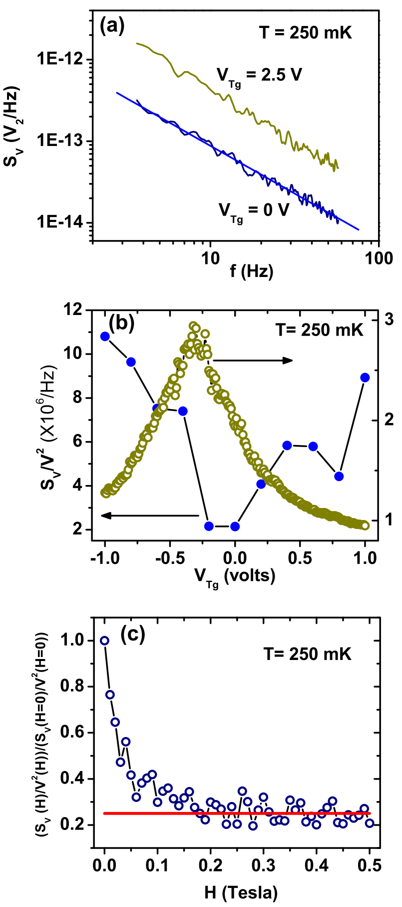

FIG. 2. (Color online) (a) Noise power as a function of frequency (plotted on a log-log scale) for two different values of the top-gate voltage. The straight line shows the $1/f$ dependence of the noise spectra. (b) Noise power (left) and resistance (right) as a function of top-gate voltage in the vicinity of the Dirac point. (c) Normalized noise power as a function of magnetic field for a single-layer graphene device. It is evident that the relative noise is reduced by a factor of 4 from its zero-magnetic-field value above a certain field. The straight line indicates the reduction of the zero-field value by a factor of 4.

Specifically, the backscattered paths (the paths that return to their origin) lead to a correction to the average conductance of the system, known as weak localization (WL) [17–19]. Magnetic field adds a different phase factor to the paths that are identical but traversed in the opposite sense, removing the WL corrections, but one still observes the universal conductance fluctuations (UCF) as a function of magnetic field or chemical potential, which arise from adding the interference contributions from all possible paths [20,21]. The quantum interference contribution to the conductance also changes if the impurity *configuration* fluctuates in time, leading to time-dependent conductance fluctuations that cause QIN [5–7].

The corrections to the conductance can be calculated by considering all possible trajectories that an electron can take while scattering off of random impurities. Particularly important are the combinations of paths that connect two different points in a sample, as shown in Fig. 3(a). There are two contributions to the interference between paths from A to B and those from C to D: diffuson and cooperon contributions. The diffuson contribution includes interference between pairs of identical paths involving loops that are traversed in the same sense, while the cooperon contribution involves pairs of paths with loops that are traversed in the opposite sense. The diffuson contribution is insensitive to the magnetic field, as no relative phase is introduced between the two paths in each pair upon application of the magnetic field. On the contrary, the magnetic field removes the cooperon contribution since the magnetic field introduces a different phase to each path in a pair, destroying the interference. Therefore, applying a magnetic field reduces the number of conduction channels by a factor of 2, which results in a reduction of the relative noise by precisely a factor of 2 [7].

Such reduction of the conduction channels, and, consequently, reduction in the noise, would occur at the characteristic magnetic field which corresponds to threading one flux quantum through a phase-coherent area of the sample. Assuming this to be the case, we find the phase coherence length L_ϕ to be in the range between 200 and 300 nm for our samples. This is a reasonable range for L_ϕ in our relatively disordered samples (the mobilities are $\sim$3000 cm^2/V s, which is rather typical for graphene on SiO_2 substrates) and is consistent with values obtained by others near the Dirac point [22–24]. However, the noise reduction by a factor of 4, rather than 2, signals a breaking of an additional twofold symmetry.

Natural candidates for this additional twofold symmetry would be pseudospin and valley degrees of freedom, which are known to affect the quantum interference phenomena in graphene [25,26]. Conservation of pseudospin precludes

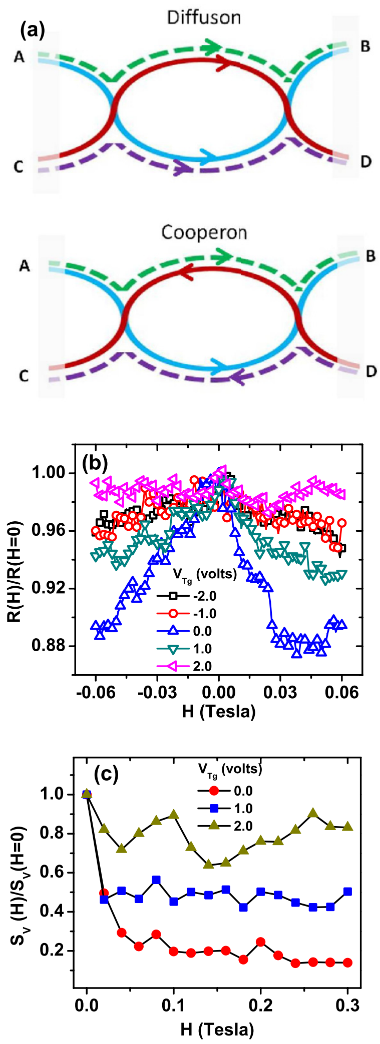

FIG. 3. (Color online) (a) Schematic of pairs of electron trajectories that form closed loops. The conductance fluctuations are caused by interference between paths from A to B and those from C to D that intersect somewhere in the interior of the sample. The diffuson contribution is shown in the upper panel: all the paths in the loop are traversed in the same sense, and the magnetic field does not introduce a relative phase factor. In the cooperon channel, shown in the bottom panel, the magnetic field introduces a relative phase when the loop is traversed in the opposite sense. In this case, contributions from various loops no longer add in a coherent way, and the quantum corrections to conductivity disappear. (b) Magnetoresistance as a function of magnetic field for various top-gate voltages with zero back-gate voltage (sample SL1). A negative magnetoresistance is observed in the vicinity of the Dirac point, with the maximum of magnetoresistance observed close to zero top gate. As the gate voltage is increased in both directions, the magnetoresistance decreases. (c) Relative noise power for different top-gate voltages as a function of a magnetic field (sample SL1). The reduction of the relative noise power by about a factor of 4 is observed at zero top-gate voltage, but this factor decreases for larger values of top-gate voltage.

backscattering, suppressing WL and causing weak antilocalization (WAL) [27], while intervalley scattering restores the WL [28–30]. Additional effects, such as defects and corrugations, can completely suppress the quantum corrections [31]. Depending on the carrier density and the nature of the disorder, all three regimes (WL, WAL, and the suppression of quantum corrections) are observed experimentally [22,24,32–34]. UCF in graphene depend on the carrier density and the nature of the impurity scattering but can also depend on the details and the geometry of the sample [12,35,36]. In particular, strong intervalley scattering is found to suppress UCF [12,35], in contrast to its effect on WL, and *intravalley* scattering could reduce the amplitude of the fluctuations by a factor of 2 [35]. The additional degrees of freedom result in additional diffuson and cooperon terms [30,37], which might explain the relative reduction of QIN observed in our experiment. However, the majority of the theoretical work on quantum corrections has focused on the regime away from the Dirac point. In the close vicinity of the Dirac point (at low doping and low temperatures), the relativistic Dirac quasiparticles are unable to screen the long-range Coulomb interactions in the usual way, significantly altering electron-electron interactions [38]. These effects make the theoretical study of the Dirac regime more challenging.

In order to identify the appropriate regime in which to interpret the QIN results, we look at magnetoresistance for clues about the relevant degrees of freedom. In the same regime in which we observe the large reduction of QIN, we also find negative magnetoresistance as a function of magnetic field at different gate voltages, as shown in Fig. 3(b). Negative magnetoresistance certainly resembles WL [14], but we observe it only in the narrow range of gate voltages in the vicinity of the Dirac point: the negative magnetoresistance decreases as the gate voltage is tuned away from the Dirac point. The effect of magnetic field on the noise also depends on the gate voltage, as shown in Fig. 3(c). Away from the Dirac point, the noise becomes less sensitive to the magnetic field for both positive and negative gate voltages. The noise characteristics are found to be roughly symmetric with respect to magnetic field, and similar results were found for both back-gate and top-gate voltages. The fourfold reduction in the noise is not always observed precisely at the Dirac point, but it coincides with the gate voltage at which the maximum negative magnetoresistance is also observed (at small positive gate voltages relative to the Dirac point). Similar behavior is observed as a function of back-gate voltage [14]. The overall change in resistance is small compared to the change in the noise [14]. We also observe the standard universal conductance fluctuations as a function of magnetic field [14].

According to conventional wisdom, WL can be observed in graphene in the presence of strong intervalley scattering, which can arise due to atomically sharp potentials (such as edges or atomic defects). In the case of strong intervalley scattering, many aspects of quantum transport in graphene are expected to be identical to those in disordered metals [12,26,30,35]. In particular, the conductance fluctuations should exhibit universal properties, as they depend only on the symmetries of the random ensembles that describe the disordered system and not on their detailed configuration. The variance of the interference-induced conductance fluctuations in graphene may have a prefactor that depends on the interplay of inelastic and elastic scattering lengths and the shape of the sample [12,35], but graphene with broken valley symmetry should belong to the orthogonal Wigner-Dyson symmetry class in the

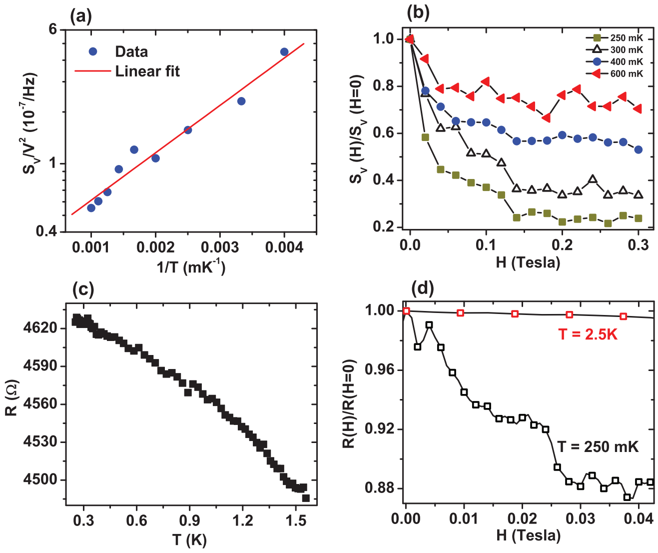

FIG. 4. (Color online) (a) Normalized noise power is shown as a function of inverse temperature on a log-linear scale. The line represents a linear fit, and the normalized noise power shows an $\exp(1/T)$ dependence on temperature. (b) Relative noise power is plotted as a function of magnetic field for different temperatures. The reduction of the relative noise power by a factor of 4 is observed at 250 mK, but the reduction is smaller at higher temperatures. (c) Resistance as a function of temperature is shown for $V_{Tg}, V_{Bg} = 0$, in the regime highlighted in Fig. 2(b). The slight increase of the resistance with decreasing temperature indicates insulating behavior. (d) Magnetoresistance as a function of magnetic field is shown for two different temperatures. It is evident that a much smaller magnetoresistance is observed at higher temperatures.

absence of a magnetic field [26]. Application of a magnetic field will put it in the unitary symmetry class, and a twofold reduction in the relative noise power will be expected on general symmetry grounds [39].

An additional twofold reduction in the relative noise power is expected when the Zeeman energy exceeds $hD/L_\phi{}^2$ [7]. The twofold reduction in the noise power has been observed in metals [8,9] and so was the additional twofold reduction at a larger magnetic field due to Zeeman splitting [10,11]. In our samples, the Zeeman splitting cannot explain the fourfold reduction, which is observed for small characteristic fields (50 mT), where the Zeeman splitting (0.006 meV) is smaller than both the thermal energy (0.02 meV) and $hD/L_\phi{}^2$ (0.08 meV).

The temperature dependence of the noise is also unusual in this regime. For normal metals in the phase-coherent regime, the noise due to fluctuating scatterers depends on temperature as T^{-1}, as observed in several systems [8,9]. We found that the noise decreases with increasing temperature and the normalized noise power shows an $\exp(1/T)$ dependence, as shown in Fig. 4(a) (a similar dependence was also found in other work [40]). As the temperature increases, the relative noise power is still reduced in magnetic field, but by a smaller factor, as shown in Fig. 4(b). The sample resistance increases slightly with decreasing temperature, as shown in Fig. 4(c), so the temperature dependence of the noise cannot be explained by the resistance change. The slowly increasing resistance with decreasing temperature is consistent with WL, as is the fact that the negative magnetoresistance also decreases with increasing temperature, as shown in Fig. 4(d).

It is well known that charge-inhomogeneous regions (puddles) tend to form in the vicinity of the Dirac point [41]. The presence of the top gate also locally dopes the graphene, forming *p-n* junctions at the edges. A random network of puddles or *p-n* junctions could be expected to show conductance fluctuations and magnetoresistance that reflect the fluctuations in the electrostatic environment [42,43]. However, one might expect such fluctuations to increase with temperature (as the thermal energy becomes larger than impurity activation energies). This would also lead to the increase of the noise power with increasing temperature, which is in contradiction to our observations. The temperature dependence of the resistance, magnetoresistance and the relative noise power reduction in magnetic field are all consistent with a decrease of the phase coherence length as the temperature is increased. In addition, the observation of the Aharonov-Bohm oscillations in similar samples confirms that both the electron and the hole transport are phase coherent across *p-n* junctions and electron-hole puddles in the vicinity of the Dirac point [44].

IV. CONCLUSIONS

The decrease of the QIN by a factor of 4 in magnetic field is not precisely understood but may offer insight into phenomena observed in other experiments, such as the fourfold decrease of mobility depending on the nature of impurity scattering [45] or the anomalous backscattering [46,47] observed in scanning tunneling measurements near the Dirac point. More generally, a detailed theoretical understanding of QIN in systems with unconventional degrees of freedom would allow QIN to serve as a unique probe of the underlying symmetries that determine the transport in novel topological materials.

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