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FAST TRACK COMMUNICATION

Regular conductance fluctuations indicative of quasi-ballistic transport in bilayer graphene

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Abstract
Quasi-periodic conductance fluctuations are observed in the low-temperature magneto-conductance of a bilayer graphene sample. The quasi-periodic nature of the fluctuations is confirmed by their Fourier power spectrum, which consists of just a small number of dominant frequency components. From an experimental study of these features, which are highly reminiscent of those reported previously for ballistic semiconductor quantum dots, we suggest that they are associated with the formation of an open quantum dot in the submicron graphene sample.

(Some figures in this article are in colour only in the electronic version)

Electrical transport in graphene is a subject of rapidly expanding interest, with the transport being strongly influenced by the linear energy spectrum and chirality of its charge carriers [1, 2]. Although most attention has focused thus far on issues of fundamental physics, including manifestations of quantum interference [3–11], this material may also have interesting applications in future electronics [12–18]. A critical issue for the development of graphene devices concerns the influence of the boundaries on transport, which are significantly more important, for example, than those in the buried two-dimensional electron gas (2DEG) in a semiconductor heterojunction. While techniques have been developed to optimize coupling to such systems, suppressing reflections at the 2DEG–metal interface, the nature of the contact is not obvious in graphene because of the generally complex interaction between organic materials and metals [19, 20]. Different behavior may also be expected for monolayer and bilayer graphene, due to the presence of a gap in the energy spectrum of the latter material.

In this communication, we report on the magneto-resistance of a submicron sized sample of bilayer graphene, and, on the basis of our results, highlight issues associated with the injection properties of its contacts, as well as the role of boundary scattering in the material itself. While this graphene device does not possess the one-dimensional quantum-point-contact leads that are used to source and sink carriers to open semiconductor-based quantum dots, our results nonetheless show many similarities with those reported for such nanostructures [21, 22]. Conductance fluctuations are observed that exhibit a *quasi-periodic* dependence on magnetic field, suggesting that the contacts may, in fact, be inhomogeneous [21]. The periodic nature of the fluctuations

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is confirmed by their Fourier spectrum, which consists of well-pronounced peaks at a few isolated frequencies. These observations are in marked contrast to those obtained in studies of disordered systems, in which highly *aperiodic* fluctuations yield a dense series of overlapping Fourier peaks [23]. By analogy with the behavior exhibited by open quantum dots [22], the regular nature of these fluctuations suggests the preferential injection of carriers into specific periodic orbits in the submicron sized graphene.

Our graphene device was fabricated by micromechanical cleavage [1, 2, 24], in which thin graphite flakes were exfoliated from highly-oriented pyrolytic graphite (HOPG, Structural Probe, Inc., Grade 2) using adhesive tape, after which they were transferred to a conducting p-type Si substrate with a 600 nm thick SiO_2 cap layer. An atomic-force microscope (AFM) image of the graphene flake selected for our study, obtained under ambient conditions prior to deposition of its contacts, is shown in figure 1. This flake was measured to be 0.9 nm thick, while, assuming an interlayer distance of 0.35 nm in graphite, the thickness of bilayer graphene is expected to be 0.7 nm. Although the measured thickness exceeds this value, it is insufficient to correspond to a trilayer sample. We suspect that these measurements can therefore be explained by considering that ambient molecules are absorbed onto the bilayer graphene. Indeed, further below we present an analysis of the quantum-Hall effect [25] in the device that is consistent with the presence of a bilayer. Electron beam lithography was used to form two metallic (Pt/Au: 3/30 nm thick) contacts to the graphene, as indicated schematically in figure 1. Magneto-resistance was then measured in a ^{3}He cryostat with a base temperature of 0.35 K, using lock-in detection ($<100\ \mu$V, 17 Hz) and while applying magnetic fields of up to ± 8 T.

In figure 2(a), we show the magneto-resistance of the bilayer graphene at 0.35 K, over the full range of applied magnetic field (B). Reproducible fluctuations are superimposed upon larger-field-scale features, and beyond ~ 3 T coexist with the quantum-Hall plateaus that are present due to the two-terminal nature of our measurement. The conductance fluctuations render the Hall plateaus less clear than those seen in studies of larger graphene flakes [1, 2]. In this regime of magnetic field, the fluctuations are likely related to the tunneling of electrons between edge states, since the width of our graphene flake is only 500 nm. In the inset to figure 2(b), the index of the quantum-Hall plateau is plotted as a function of inverse magnetic field ($1/B$) [1, 2, 24]. The curve, which can be extrapolated to the origin, indicates that our graphene is not a monolayer, but is consistent instead with our interpretation that the graphene is a bilayer [1, 2, 24]. From the slope of the straight-line plot, we determine a carrier density $n_s = 1.4 \times 10^{12}$ cm^{-2}. In all measurements reported here, the back substrate of the device was held at ground potential at all times. It is known, however, that surface impurities associated with ambient species [26], or the SiO_2 substrate [27, 28], can lead to unintentional doping of graphene, shifting the Fermi energy away from the Dirac point and so increasing the carrier density. In addition, our sample was not treated by annealing in an Ar/H_2 atmosphere, or by *in situ* heating in vacuum [16, 25], both of which are believed to improve graphene homogeneity.

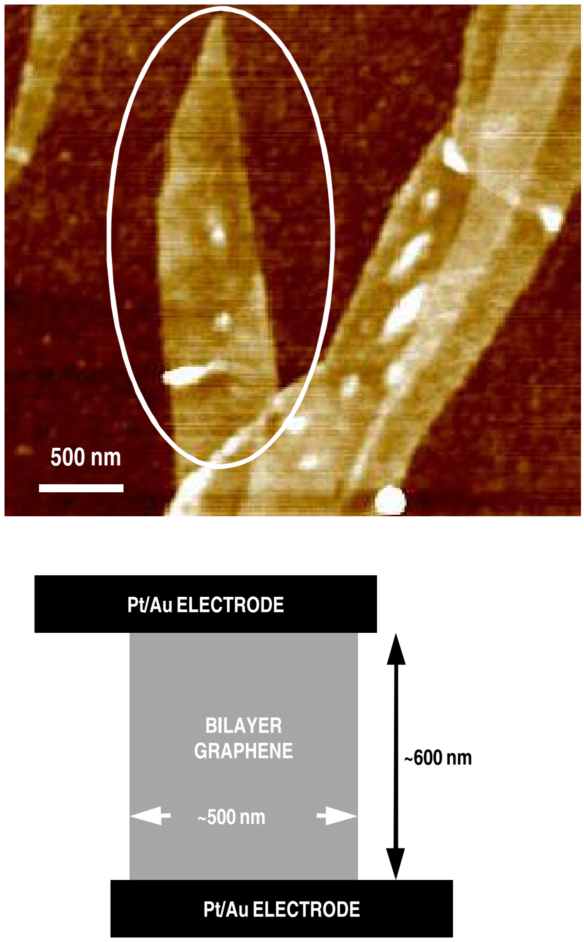

Figure 1. At top is an AFM micrograph of thin exfoliated graphite flakes. The circled area identifies the bilayer graphene flake studied in this experiment. The small white structures of sub-100 nm size in the image are of undetermined origin, may be particulates remaining after the mechanical exfoliation. The schematic at the bottom shows the two-terminal geometry of the sample fabricated from the flake.

Given such considerations, the value of the carrier density inferred from figure 2 appears reasonable. While we do not know whether the carriers are electrons or holes, the difference is not important to the results discussed here.

By subtracting the quantum-Hall background from the magneto-conductance, we obtain clear fluctuations, as shown in figure 3(a). The fluctuations are symmetric with respect to zero magnetic field, indicating their reproducible character. Conductance fluctuations have previously been widely observed in disordered systems [23], in which their important characteristic is a highly aperiodic nature. Our results instead reveal a quasi-periodic dependence of the fluctuations on magnetic field, which is shown in figure 3(b) by plotting their Fourier power spectrum. This consists of just a small number of dominant frequency components, behavior that is highly reminiscent of that reported previously for open, semiconductor-based, quantum dots [22].

A standard approach when analyzing the properties of conductance fluctuations is to define their correlation function $F(\Delta B) = \langle \delta g(B) \delta g(B + \Delta B) \rangle$ [29], where $\delta g(B) = g(B) - \langle g(B) \rangle$, $g(B)$ is the dimensionless conductance at

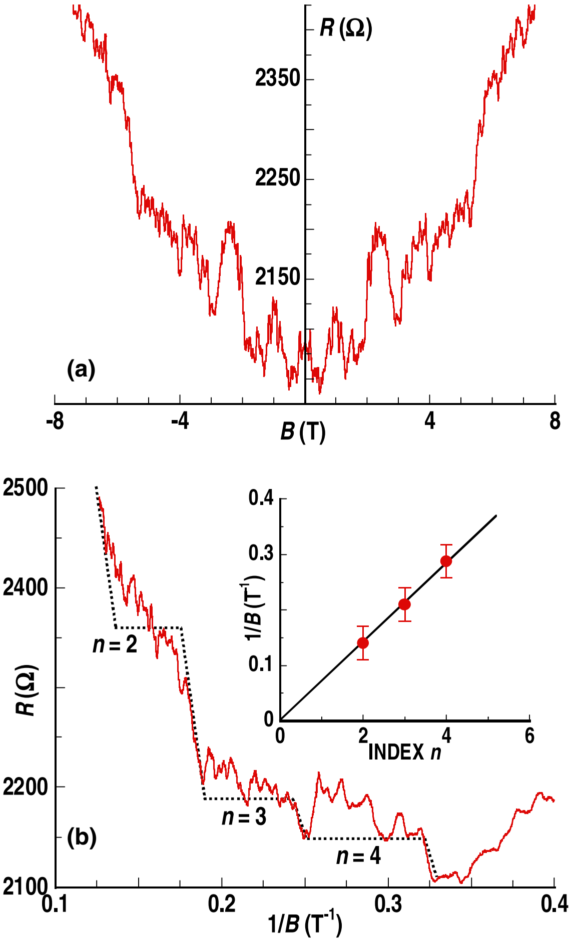

Figure 2. (a) Magneto-resistance of the graphene sample at 0.35 K. (b) High-field magneto-resistance as a function of inverse magnetic field. The broken line is a guide to the eye. The inset shows the result of a fan-diagram analysis of the data.

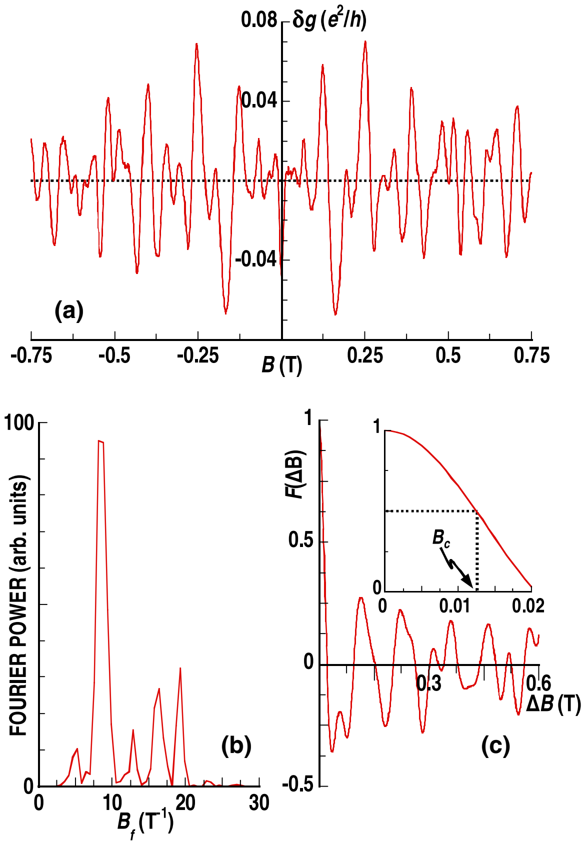

Figure 3. (a) Conductance fluctuations obtained by subtracting a slowly varying background, apparent in figure 2(a), from the original magneto-resistance. (b) Fourier power spectrum of the fluctuations from (a). (c) The main figure shows correlation function of the fluctuations of (a). The inset shows the initial decay of the correlation function, used to determine B_c.

magnetic field B, and the angled brackets indicate a ensemble (i.e. magnetic field) average. The correlation function is shown in figure 3(c), which shows a region of significant negative excursion and quasi-periodic oscillation in the tail, consistent with interference that is dominated by a few discrete frequency components [22]. The characteristic coherent area for interference (S_φ, where $S_\varphi \times B_c = h/e$), and associated coherence length ($l_\varphi \equiv S_\varphi^{1/2}$), can be estimated from the correlation field (B_c), defined as the half width of the initial decay in the correlation function $F(B_c) = 1/2F(B = 0)$. From our data in figure 3(c), from which we obtain $B_c = 0.012$ T, we determine $S_\varphi = 0.33\ \mu\text{m}^2$ and $l_\varphi = 570$ nm. The expected value of l_φ can be independently estimated from the relation $l_\varphi = (D\tau_\varphi)^{1/2}$, where the diffusion coefficient (D) is found from the conductivity (σ) via $D = \sigma\pi h^2/2m^*e^2$, with $m^* = 0.033m_o$ the effective mass of carriers in bilayer graphene [10]. Using the resistance of the graphene sample at zero magnetic field (figure 2(a)), and its known dimensions, we then estimate $D = 0.01\ \text{m}^2\ \text{V}^{-1}\ \text{s}^{-1}$. Assuming a typical value of $\tau_\varphi \sim 0.1$ ns below 1 K [10], we then expect $l_\varphi \sim 1\ \mu$m, consistent with the value obtained from the correlation analysis. It is interesting that the value of S_φ is very close to the active area of the device (see the schematic in figure 1), which may indicate that decoherence is induced by the contacts themselves, a result well known in mesoscopic physics [30]. On the basis of these results, we therefore infer that electron coherence is preserved over reasonable distances in the graphene itself.

As mentioned already, aperiodic conductance fluctuations have been widely observed in disordered systems, yielding a dense series of overlapping peaks in their Fourier spectra [23]. Each unique frequency component can be related to a specific electron trajectory, and the density of the resulting spectra reflects the complicated motion of electrons through the disordered potential. The simple spectrum of figure 3(b), however, is reminiscent of the behavior exhibited by open quantum dots, and so suggests that the interference is dominated by a small number of discrete orbits. We can estimate the area (A) enclosed by a particular orbit from the Aharonov–Bohm criterion $A = B_F h/e$, in which B_F is the magnetic frequency associated with a specific Fourier peak. From the dominant component we observe at $B_F = 8.9\ \text{T}^{-1}$, we obtain $A = 0.037\ \mu\text{m}^2$, approximately an order of magnitude smaller than S_φ. This difference is actually well known from discussions of wavefunction scarring in open dots [21] which have shown that the area enclosed by individual orbits is a fraction of the active quantum dot area.

In previous studies of graphene dots contacted by Cr electrodes, the contact resistance was found to exceed the quantum resistance ($G_o^{-1} \equiv e^2/h$) at low temperatures, and Coulomb oscillations were observed due to the formation of tunnel barriers at the metal–graphene interfaces [15]. In our experiment, however, Pt electrodes are used and the device resistance is less than G_o^{-1} (see figure 2(a)). Nevertheless, due to the workfunction difference between the two materials, some form of injection barrier should still exist at the metal–graphene interface, and should allow injected carriers to be weakly confined in the submicron sized area of the graphene, thereby allowing it to function as an open dot. In semiconductor implementations of such dots, the transport through them has been found to be dominated by a small number of discrete orbits that are favored in transport due to the injection characteristics of the one-dimensional quantum-point-contact leads [21, 22]. The nature of injection from metallic electrodes into graphene is far less understood [19, 20]. Nonetheless, it is clear from the data in figure 3 that the more complex coupling in this case gives rise to behavior reminiscent of that exhibited by conventional dots. Our results therefore suggest that the actual contact between the metal and the graphene is probably not homogeneous, and also indicate the need to achieve a better understanding of the interfacial mechanisms that govern the injection of carriers from metal electrodes into graphene.

In conclusion, we have observed quasi-periodic conductance fluctuations in a submicron sized flake of bilayer graphene. The periodic nature of the fluctuations in this system was confirmed by the fact that their Fourier spectrum consists of just a small number of dominant frequencies, in contrast to the behavior expected for truly aperiodic oscillations. While the origins of the periodic fluctuations are not well understood at present, they suggest the open nature of the quantum dot formed by the metal–graphene–metal junction. Indeed, most-recent theoretical work, published during the review of this manuscript, has predicted precisely the regular fluctuations that we demonstrate here, connecting them to the transport contributions of specific ‘relativistic’ scars [31].

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