Observation of Aharonov-Bohm conductance oscillations in a graphene ring

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We investigate experimentally transport through ring-shaped devices etched in graphene and observe clear Aharonov-Bohm conductance oscillations. The temperature dependence of the oscillation amplitude indicates that below 1 K, the phase coherence length is comparable to or larger than the size of the ring. An increase in the amplitude is observed at high magnetic field, when the cyclotron diameter becomes comparable to the width of the arms of the ring. By measuring the dependence on gate voltage, we find that the Aharonov-Bohm effect vanishes at the charge neutrality point, and we observe an unexpected linear dependence of the oscillation amplitude on the ring conductance.

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The investigation of transport phenomena originating from quantum interference of electronic waves has proven to be a very effective probe of the electronic properties of conducting materials. Recent work has shown that this is also the case for graphene, a novel material consisting of an individual layer of carbon atoms, in which the electron dynamics is governed by the Dirac equation.[1] The anomalous behavior of the weak-localization correction to the conductivity that is observed in the experiments,[2] for instance, is directly related to the presence of two independent valleys in the band structure of graphene[3,4] and can be used to extract the intervalley scattering time.[5] Another example is provided by the observation of a Josephson supercurrent in graphene superconducting junctions, which permits to conclude that transport through graphene is phase coherent even when the material is biased at the charge neutrality point (i.e., where nominally no charge carriers are present).[6]

Possibly, the phenomenon that most directly illustrates electronic interference in solid-state devices is the occurrence of periodic oscillations in the conductance of ring-shaped devices, measured as a function of magnetic field.[7] This phenomenon, which is a direct consequence of the Aharonov-Bohm (AB) effect, has been investigated extensively in the past in rings made with metallic films or with semiconducting heterostructures, and its study has contributed significantly to our understanding of mesoscopic physics. For example, the analysis of h/e and h/2e AB conductance oscillations has clarified the difference between sample-specific and ensemble-averaged phenomena.[7] The investigation of the temperature and magnetic field dependences of the oscillation amplitudes has been used to investigate processes leading to decoherence of electron waves, such as electron-electron interaction,[7,8] or the interaction with magnetic impurities.[9] In graphene, however, no experimental observation of AB conductance oscillations has been reported so far, although there is an emerging interest in the problem from the theoretical side.[10,11] In the course of recent experiments, we have observed AB conductance oscillations experimentally in several rings fabricated on few-layer graphene. In this paper, we report on systematic measurements that we have performed on a device made on single-layer graphene as a function of temperature, density of charge carriers, and magnetic field.

The devices used in our experiments were fabricated following a by now established procedure.[12] Thin graphite flakes were exfoliated from natural graphite using an adhesive tape and transferred onto a highly doped Si substrate (acting as a gate) covered by a 300 nm thick SiO_2 layer. The flakes were imaged under an optical microscope and their position was registered with respect to markers already present on the substrates. Single layer flakes were identified by looking at the shift of the light intensity in the green channel of the red-green-blue scale relative to the adjacent substrate.[13] In subsequent nanofabrication steps, the devices were patterned using electron-beam lithography to define pairs of metallic electrodes (Ti/Au) and to etch the rings in an argon plasma. The rings have inner and outer radii of 350 and 500 nm, respectively; the inset of Fig. 1(a) shows a scanning electron micrograph of a typical device.

Measurements were performed in a dilution refrigerator in the temperature range between 150 and 800 mK. The conductance of the ring was measured using a lock-in amplifier in a current-biased two-terminal configuration. For the different measurements, the excitation current was varied to ensure that resulting voltage was smaller than the temperature to prevent heating of the electrons and the occurrence of nonequilibrium effects.

Figure 1(a) shows the resistance of the ring measured at $T=150$ mK as a function of gate voltage. A clear peak, centered at approximately $V_G=+4$ V, is observed as it is typical for graphene. The large peak resistance value may be expected since the rings are made of fairly narrow ribbons (∼150 nm). It may originate either from the opening of a small gap due to lateral size quantization (as recently proposed[14]) or from the fact that, close to the charge neutrality point, disorder at the edges is not screened effectively, resulting in enhanced scattering with valley mixing and localization of electron states. To estimate the mobility μ of charge carriers, we use the value of the conductance per square measured at high gate voltage. With the density of charge carriers being determined from the known capacitance to the gate (i.e., $G_{\square}=ne\mu=\varepsilon_0\varepsilon_r e\mu V_G/d$), we obtain $\mu=6000\ \mathrm{cm}^2/\mathrm{V\,s}$, essentially independent of V_G for $V_G>10$ V and $V_G<-10$ V. The diffusion constant is estimated from the Einstein relation $\sigma=\nu e^2 D$, where σ is the

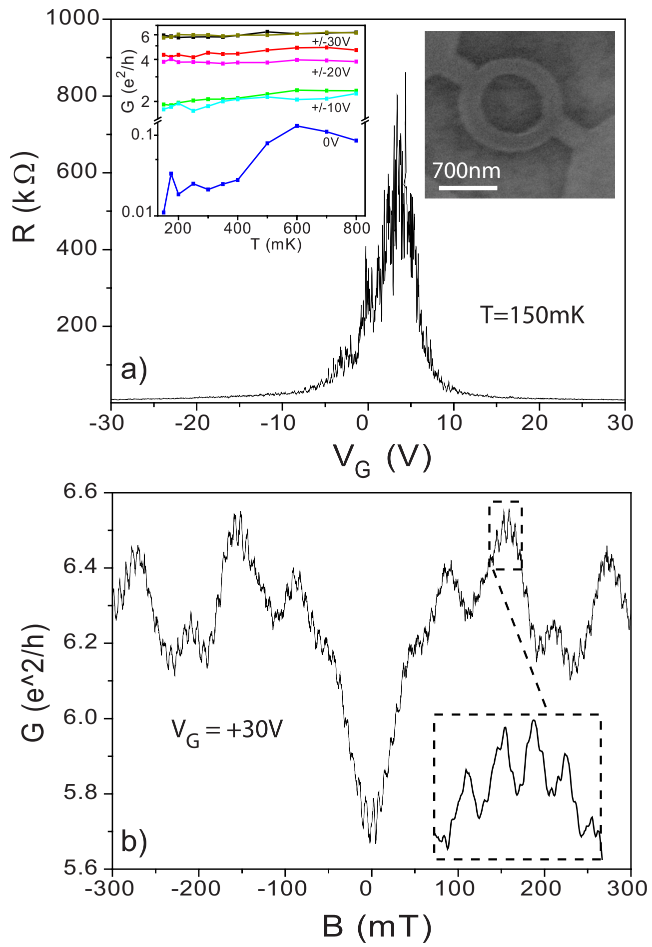

FIG. 1. (Color online) (a) The main panel shows the two-probe measurement of the ring resistance versus back gate voltage at $T=150$ mK. The charge neutrality point is at +4 V. Left inset: temperature dependence of the conductance measured for different values of gate voltage. Right inset: scanning electron microscopy image of a ring-shaped device etched in graphene similar to the one used in our measurements. (b) Magnetoconductance of the graphene ring measured at $T=150$ mK and $V_G=+30$ V. On top of the aperiodic conductance fluctuations, periodic oscillations are clearly visible as also highlighted in the inset.

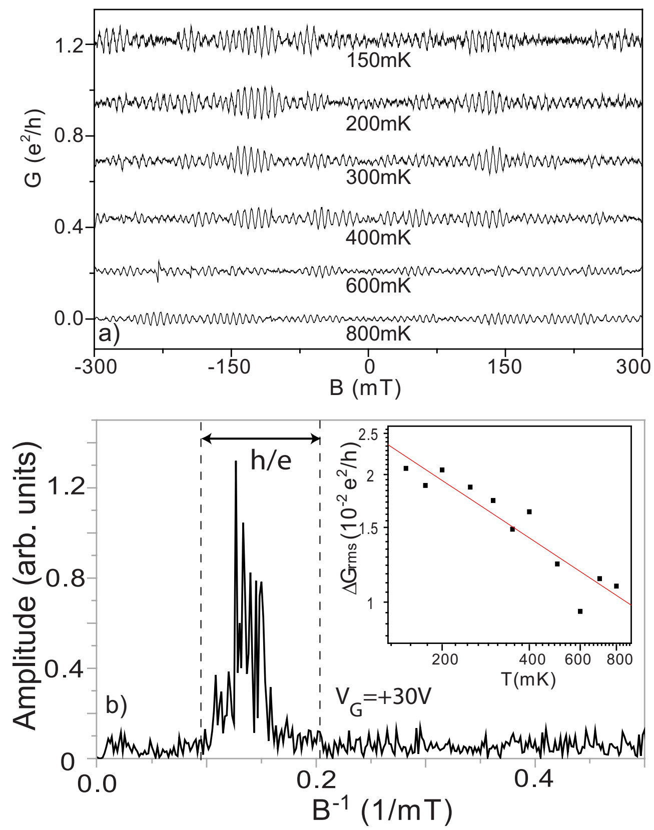

FIG. 2. (Color online) (a) Aharonov-Bohm conductance oscillations measured at $V_G=+30$ V for different temperatures (curves are offset for clarity). (b) Fourier spectrum of the oscillations measured at $T=150$ mK shown in panel (a). The vertical dashed lines indicate the expected position of the h/e peak, as determined from the inner and outer radii of the ring. In the inset: temperature dependence of the root mean squared amplitude of the AB conductance oscillations, obtained from the measurements shown in panel (a).

measured conductivity and ν the density of states at the Fermi level, which for graphene is given by $\nu(\varepsilon_F)=g_\nu g_s 2\pi|\varepsilon_F|/(h^2 v_F^2)$.[15] Here, $g_\nu=2$ and $g_s=2$ account for the valley and spin degeneracies, $v_F=10^6$ m/s is the Fermi velocity, and the value of ε_F is determined by equating the expression for the charge density $n(\varepsilon_F)=g_\nu g_s \pi\varepsilon_F^2/(h^2 v_F^2)$ to the value determined by the gate voltage. We obtain $D=0.06$ m^2/s, not far from the value of diffusion constant that is estimated assuming diffusive scattering at the ribbon edges ($D=W\,v_F=0.15$ m^2/s, with W the width of the ribbon). With this value of the diffusion constant, we obtain a Thouless energy for the ring of $E_{\mathrm{Th}}=\hbar D/L^2=10$ μeV (L is the ring circumference), which is slightly smaller than the lowest temperature ($T=150$ mK) at which the measurements have been performed.

The low-field magnetoresistance measured at $V_G=30$ V and $T=150$ mK is shown in Fig. 1(b). The presence of periodic oscillations is clearly visible. The period in field is approximately $\Delta B=7$ mT and the corresponding Fourier spectrum is shown in Fig. 2(b). In the spectrum, a peak is present, whose position and width correspond well to what is expected for h/e oscillations given the values of the inner and outer radii in our device. Figure 2(a) shows the evolution of the AB conductance oscillations (with the background removed by subtracting the magnetoresistance averaged over one period of the oscillations) measured at different temperatures. It is apparent that their amplitude decreases with increasing temperature. This decrease is quantified in the inset of Fig. 2(b), where we plot the root mean squared value of the amplitude as a function of T in a double logarithmic scale. We find that the oscillation amplitude is proportional to $T^{-1/2}$. This dependence, which is commonly observed in metal rings, is due to thermal averaging of the h/e oscillations $[\delta G_{\mathrm{AB}}\alpha(E_{\mathrm{Th}}/k_B T)^{1/2}\exp(-\pi r/L_\phi(T))$, where r is the radius of the ring].[7] It is expected for temperature values larger than the Thouless energy (which is the case here), if the phase coherence $L_\varphi=(D\tau_\varphi)^{1/2}$ length is longer than the arms of the ring. Indeed, with the value of diffusion constant given above and taking for the phase coherence time values

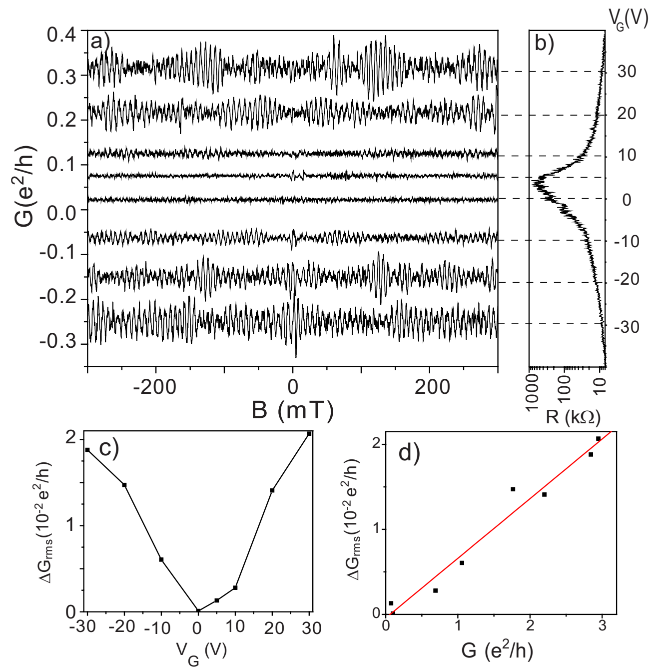

FIG. 3. (Color online) (a) AB conductance oscillations measured at $T=150$ mK for different values of the back gate voltage, as indicated by the dashed lines on panel (b). Panel (b) shows the dependence of the ring resistance (in logarithmic scale) on gate voltage, measured at $T=150$ mK. (c) rms amplitude of the AB conductance oscillations as a function of gate voltage. In panel (d), the same data are plotted as a function of the ring conductance. The red line is a guide to the eye.

estimated in the literature (away from the charge neutrality region $\tau_\phi \sim 0.1$ ns at $T=1$ K, increasing roughly linearly with decreasing T),[16] we find that in our ring also this condition is satisfied. A similar $T^{-1/2}$ dependence was observed for all gate voltages at which the AB oscillation amplitude was sufficiently large to be accurately measured.

The detailed dependence of the amplitude of the AB conductance oscillations on gate voltage is particularly interesting. It is apparent from Figs. 3(a) and 3(b) that at the charge neutrality point, essentially no AB oscillations are observed and that the amplitude of the oscillations becomes larger as the charge density in the sample is increased. This finding is summarized in Fig. 3(c), in which the dependence of rms amplitude on V_G is shown to anticorrelate with the gate-voltage dependence of the total sample resistance. Indeed, if we plot the amplitude of the AB oscillations as a function of the device conductance [Fig. 3(d)], we observe that a linear relation is surprisingly well obeyed. Such a relation is predicted theoretically for rings containing tunnel barriers[17] and it has not been observed previously in metallic rings. It is also not usually observed in rings formed in semiconducting heterostructures. Only recently, a similar dependence has been observed in experiments performed on rings fabricated using GaAs-based heterostructures in which the carrier density was changing by controlled illumination of the devices.[18] Both in these GaAs-based devices and in our graphene rings, the origin of this relation between conductance and AB oscillation amplitude is unknown.

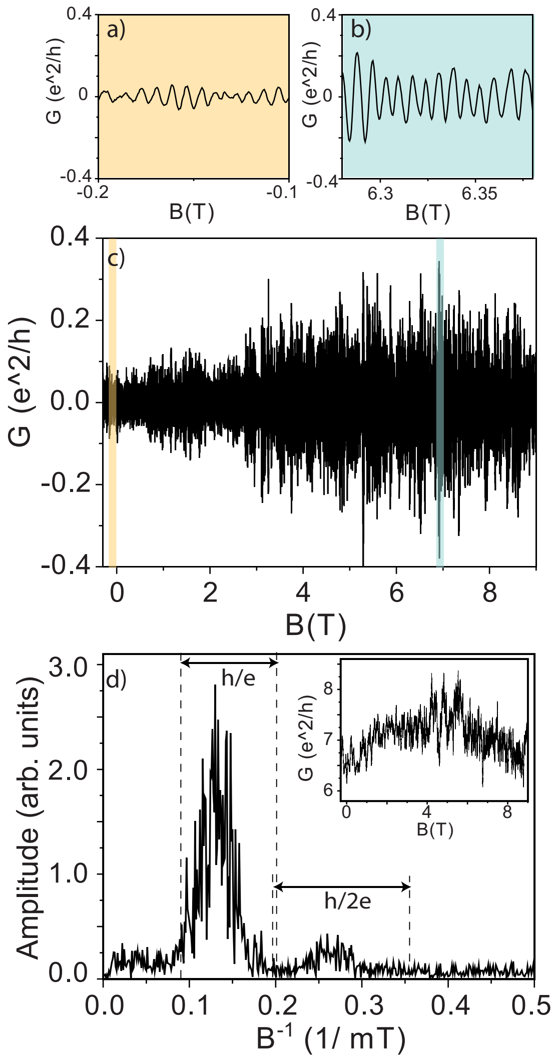

FIG. 4. (Color online) Panels (a)–(c) show the AB conductance oscillations measured at $V_G=+30$ V in different magnetic field ranges. For $B\sim 3$ T a clear increase of AB amplitude is observed. (d) Fourier spectrum of the AB oscillations measured between 4 and 5 T. The dashed lines indicate the position of the h/e and h/2e peaks expected from the device geometry. The inset shows the magnetoconductance of the ring. All measurements were taken at 150 mK.

All measurements discussed so far have been performed at magnetic fields smaller than 0.5 T, for which the maximum observed amplitude of the AB conductance oscillations is only $0.02e^2/h$. In Fig. 4(c), we now plot the AB conductance oscillations measured in a larger magnetic field range (up to 9 T): the data clearly show that the rms amplitude of the oscillations is significantly larger at higher fields than around $B=0$ T [see also Figs. 4(a) and 4(b)]. We have performed a quantitative analysis of the evolution of the h/e oscillations by determining their rms amplitude in a 350 mT interval (approximately 50 periods) as a function of magnetic field. Figure 5(a) shows that, irrespective of the temperature at which the measurement is performed, the oscillation amplitude increases and saturates starting from approximately 3 T. The relative increase is also comparable in magnitude (roughly four times) at the two different temperatures. Ow-

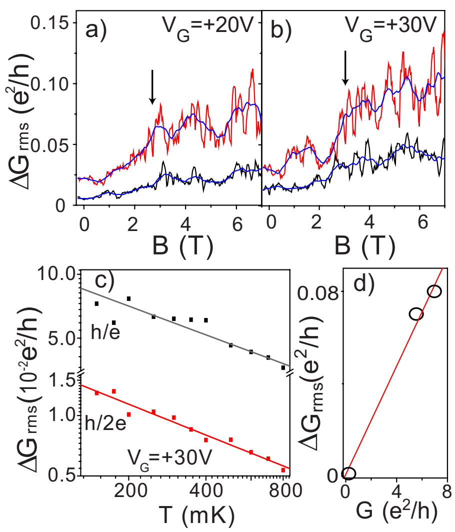

FIG. 5. (Color online) Panels (a) and (b) show the rms amplitude of the AB conductance oscillations determined on an interval of 50 periods as a function of magnetic field and for two different temperatures (T=150 mK, red line and 800 mK, black line), measured at V_G=+20 and +30 V. The blue curves are obtained by smoothing the corresponding data over 20 points. The arrows indicate the position in field where the oscillation amplitude starts to saturate, slightly higher at V_G=+30. Panel (c) shows the temperature dependence of the amplitude of the h/e and h/2e components of the AB conductance oscillations measured between 4 and 5 T. The continuous lines are linear fits with slopes -0.5 ± 0.07. Panel (d) shows that the rms values of the AB oscillations measured between 4 and 5 T (at V_G=+4, +20, and +30 V) scales linearly with the conductance of the device.

ing to the large amplitude, in the high field regime, the second harmonic in the Fourier spectrum of the AB oscillations becomes visible [see Fig. 4(d), obtained from the measurement of magnetoresistance between 4 and 5 T]. The temperature dependence of the amplitude of both the h/e and h/2e components measured at high field still scales linearly with $T^{-1/2}$, similar to what is seen in the low field regime.

An increase in the amplitude of the AB conductance oscillations with increasing magnetic field is unusual. In metallic rings, a known mechanism causing such an increase is scattering off magnetic impurities.[7,9] At low field, the spin of these impurities can flip without any energy cost, causing dephasing of the electron waves. At higher field, the finite Zeeman energy prevents the spins to flip, leading to a decrease in dephasing and a corresponding increase in AB oscillation amplitude. Despite the fact that magnetic impurities have been predicted to form at defects in graphene or could be present at the edges,[19,20] in our device, the presence of magnetic impurities cannot account for the experimental observations. In fact, if the effect observed was due to spin, one should observe that the magnetic field required for the enhancement of the oscillation amplitude increases with temperature (since the Zeeman energy has to be larger than k_BT), which is not what we see. An indication as to the origin of the anomalous increase observed in our graphene ring comes from the estimate of the diameter of the cyclotron orbit. At V_G=30 V and 3 T—the field at which the amplitude starts saturating—the cyclotron diameter is approximately 140 nm, comparable to the width of the ribbons forming the AB ring. This suggests that the effect of the field is of orbital nature. Indeed, Fig. 5(b) shows the amplitude of the AB conductance oscillations as a function of field measured at V_G=20 V, where the increase occurs for a slightly smaller magnetic field, as it is expected since the cyclotron diameter ($hk_F/\pi eB$) is smaller at lower carrier density. The precise nature of the orbital mechanism leading to larger oscillation amplitude at higher magnetic field remains to be determined, but we suspect that the phenomenon originates from an asymmetry present in the arms of the ring caused by defects or inhomogeneity in graphene.[21]

Interestingly, the linear relation between the amplitude of AB oscillations and the device conductance persists also at high field. Although less data are available—we have only performed high field measurements at V_G=+4, +20, and +30 V—when plotted as a function of conductance, the points still fall on one single line [see Fig. 5(d)]. As mentioned above, such a linear relation is predicted theoretically for rings containing tunnel barriers in their arms.[17] This may indicate that, consistent with the scenario that we propose to explain the observed magnetic field dependence,[21] the graphene ring is rather strongly inhomogeneous and contains small, highly resistive regions acting as weak links or tunnel barriers. Whereas the presence of such highly resistive regions would not be surprising in the low density regime, it is less obvious that it should be expected when the density of charge carriers is of the order of $(2-5)\times10^{12}$ cm^{-2} (corresponding to the high V_G values in our experiments). A theoretical analysis of the relation between AB oscillation amplitude and ring conductance in graphene devices is called for, and it is likely that it will prove insightful to understand the nature of transport through narrow graphene ribbons.

In conclusion, we have reported the first observation and systematic study of Aharonov-Bohm conductance oscillations through a graphene ring. We find that in rings with a diameter of approximately 1 μm, the phase coherence length of electrons is comparable to or longer than the device size for temperatures below 1 K. As a result, the oscillation amplitude increases as $T^{-1/2}$ with decreasing temperature, owing to thermal averaging on an energy scale larger than the Thouless energy. We also observe an increase of the AB oscillation amplitude at high magnetic field, originating from an orbital effect of the magnetic field. Surprisingly, measurements as a function of gate voltage show that the amplitude of the conductance oscillations scales linearly with the total conductance of the device, a phenomenon whose microscopic origin remains to be understood in detail.

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[21] We envision the possibility that a defect—e.g., a constriction—is present in one of the arms of the ring. For such an asymmetric configuration, the AB oscillation amplitude is smaller than for a symmetric ring, which may explain why at low field $\delta G_{\mathrm{AB}} \sim 0.02e^2/h$ only. By squeezing the size of the cyclotron orbit, a large magnetic field can increase the transmission through the constriction and tends to equalize the transmission through the two arms. As a consequence, the oscillation amplitude increases. Note that one would then also expect an increase in conductance whose magnitude depends on the magnitude of the asymmetry between the two arms in the ring. Indeed, albeit small, an increase in the conductance is observed [see inset of Fig. 4(d)] to occur for the same fields that lead to the increase in the AB oscillation amplitude.