Quantized conductance of a suspended graphene nanoconstriction

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One of the most promising characteristics of graphene¹ is the ability of charge carriers to travel through it ballistically over hundreds of nanometres. Recent developments in the preparation of high mobility graphene^{2–4} should make it possible to study the effects of quantum confinement in graphene nanostructures in the ballistic regime. Of particular interest are those effects that arise from edge states, such as spin polarization at zigzag edges⁵ of graphene nanoribbons^{6,7} and the use of graphene's valley-degeneracy for 'valleytronics'⁸. Here we present the observation of quantized conductance^{9,10} at integer multiples of $2e^2/h$ at zero magnetic field in a high mobility suspended graphene ballistic nanoconstriction. This quantization evolves into the typical quantum Hall effect for graphene at magnetic fields above 60 mT. Voltage bias spectroscopy reveals an energy spacing of 8 meV between the first two subbands. A pronounced feature at $0.6 \times 2e^2/h$ present at a magnetic field as low as ~ 0.2 T resembles the '0.7 anomaly' observed in quantum point contacts in a GaAs–AlGaAs two-dimensional electron gas, possibly caused by electron–electron interactions¹¹.

Conductance quantization in zero magnetic field in graphene ribbons is expected to strongly depend on the type of edge termination^{6,7,12–14}. In the case of ideal non-disordered armchair edges the valley degeneracy is lifted, leading to a quantization sequence 0 (for a semiconducting ribbon), 1, 2, 3, ... $\times G_0$, when the Fermi energy is raised or lowered from the charge neutrality point. Here $G_0 = 2e^2/h$, with e the electron charge, h the Planck constant and the factor two is due to the spin degeneracy. For zigzag edges on the other hand, theory predicts a quantization in odd multiples 1, 3, 5, ... $\times G_0$, reflecting the presence of both spin, as well as valley degeneracy. However, realistic devices have a finite (edge) disorder which will dominate the electronic transport in long and narrow ribbons, making the experimental observation of conductance quantization very challenging. Signatures of the formation of one-dimensional subbands because of quantum confinement have been reported for nanoribbons fabricated on a silicon oxide (SiO_2) substrate^{15,16}. However, those devices are not in the ballistic regime because they have the characteristics of a diffusive, disordered system and lack uniform doping owing to strong interaction with the substrate. In such a narrow and long ribbon an edge disorder of typically only a few per cent of missing carbon atoms will prevent the observation of quantum ballistic transport and conductance quantization^{17–19}.

A way to circumvent this problem is to prepare a constriction with a length comparable or shorter than the width, for which conductance quantization is theoretically possible for an edge disorder of 10% or even higher^{18–20}. To investigate quantum ballistic

Figure 1 | A typical suspended graphene device. a, Scanning electron microscopy picture of a typical suspended high-mobility graphene device showing the formation of graphene constrictions after the current annealing step in vacuum at 4.2 K (regions A and B). The scale bar is 2 μm . No current annealing was applied to region C. **b**, A schematic cross-section of the device. The graphene layer is suspended about 1 μm above the 500 nm thick SiO_2 and the electrodes are kept in place by pillars of LOR polymer. The n+ doped silicon substrate is used as a back gate electrode to control the charge-carrier density.

transport and conductance quantization in graphene it is therefore crucial to prepare a narrow, short and high-mobility constriction with uniform (gate-controllable) doping. This can be achieved by decoupling the graphene layer from the substrate and preparing a high mobility graphene layer suspended 0.2–1 μm above the SiO_2 surface. High-quality quantum Hall effect (QHE) and fractional quantum Hall effect (FQHE) were measured experimentally in such devices using a 2-probe geometry^{21,22}.

In this work we prepared similar 2-probe devices using a newly developed polymer based method²³ (see Methods) resulting in suspended graphene at 1 μm distance above the SiO_2/Si substrate (Fig. 1a,b). The suspended graphene layer is contacted by 80 nm thick titanium/gold electrodes supported by 1 μm thick pillars of LOR-A polymer. The electrical characterization was performed using a standard lock-in technique with an applied current of

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Figure 2 | Quantized conductance in a graphene nanoconstriction at $T = 4.2$ K at zero external magnetic field. **a, Conductance G as function of the Fermi wavenumber k_F at zero external magnetic field for holes. A total of 80Ω contact resistance was subtracted. Clear quantization is observed at $1, 2, 3 \times 2e^2/h$ and plateau-like features are visible at 4 and $5 \times 2e^2/h$. The dashed line is a fit using the semi-classical relation $G = 4e^2/h * k_F W/\pi$ in the ballistic regime, which gives the width of the constriction $W \approx 200$ nm. **b**, For electrons we observe a similar sequence of quantization (a 80Ω contact resistance was subtracted). In this case we obtain $W \approx 275$ nm from the fit.**

2.5–10 nA. Application of a voltage to the Si substrate underneath the 500 nm thick SiO_2 allows us to tune the charge carrier density in the suspended graphene device. To obtain high mobility it is crucial to remove the polymer (and possibly other) contaminants present on the suspended graphene after fabrication. For this we anneal the graphene layer by sending a d.c. electrical current through it ($\sim 1 \text{ mA } \mu\text{m}^{-1}$) in vacuum at 4.2 K (refs 2,24), which leads to local Joule heating and to estimated temperatures in excess of 500°C (ref. 2). Mobilities as high as $600,000 \text{ cm}^2 \text{ Vs}^{-1}$ at a charge carrier density of $5 \times 10^9 \text{ cm}^{-2}$ at 77 K have been reported in such devices, indicating that the electron mean free path can be several hundred nanometres long²³. What makes the current annealing step special is that it not only can lead to a high-mobility sample, but it can also result in the formation of nanoconstrictions²⁵ (see Fig. 1a). Note however, that although we can systematically obtain high-mobility graphene devices with a typical yield of 20% (see Supplementary Information), the formation of these nanoconstrictions is still not well controlled.

We nevertheless succeeded in making electronic measurements on a high-mobility graphene nanoconstriction with uniform

Figure 3 | Quantized conductance in a graphene nanoconstriction in zero and finite magnetic field at $T = 4.2$ K. **a, Magnetic field dependence (in Tesla) of the two-probe quantum Hall effect in a graphene ballistic nanoconstriction as a function of the gate voltage V_g . A capacitance of $8 \text{ aF } \mu\text{m}^{-2}$ is extracted from the 2-probe quantum Hall measurements at a magnetic field of 500 mT. The quantized plateaux at $1, 3$ and $5 \times 2e^2/h$ are characteristic for graphene. A contact resistance of 80Ω was subtracted from the 2-probe measurements. **b**, Transition from the quantum Hall effect to quantized conductance at zero magnetic field. Note that at zero magnetic field we observe Fabry-Pérot like oscillations superimposed on the $2e^2/h$ plateau, possibly the result of reflection at the ends of the constriction. The feature at $0.6 \times 2e^2/h$ (e.g. at $V_g = -1.5$ V and 3 V for $B = 0.5$ T) is believed to be the result of electron-electron interactions, similar to the '0.7 anomaly' observed in a GaAs-AlGaAs heterostructures (see main text). **c**, The distance ΔV_N in gate voltage between the centre of the quantized plateau corresponding to the $N = 1$ subband and the charge neutrality point versus external magnetic field B applied perpendicular to the suspended graphene layer. Here, ΔV_N saturates at 0.5 V for fields below 60 mT, from which we extract the width of the constriction (300 nm). **d**, The same plot was made for the $N = 3$ subband and approximately the same width was obtained. Note that ΔV_N saturates below 150 mT in this case.**

Figure 4 | Voltage bias spectroscopy at $T = 4.2$ K. **a**, The differential conductance G versus DC bias voltage $V_{s,d}$ at zero external magnetic field measured with an excitation a.c. voltage of $V_{a.c.} = 150 \mu\text{V}$ in the gate voltage interval of $-6 \text{ V} < V_g < 0.8 \text{ V}$. Each line in this plot corresponds to a d.c. bias measurement at a different gate voltage, from $V_g = -6 \text{ V}$ (top) to 0.8 V (bottom) in steps of 50 mV . For $V_{s,d} = 0 \text{ V}$ we observe conductance quantization at $1, 2, 3$ and $4 \times 2e^2/h$. The energy spacing between the $N = 1$ and $N = 2$ subbands is approximately 8 meV , which is consistent with the energy spacing expected for a 240 nm wide constriction. **b**, Voltage bias spectroscopy at $B = 500 \text{ mT}$ and $-40 \text{ V} < V_g < 0.8 \text{ V}$. The regular $1, 3, 5$ and $7 \times 2e^2/h$ plateaux are obtained (after subtraction of 700Ω). The energy spacing between the $N = 5$ and $N = 7$ subbands is approximately 8 meV (see main text).

doping, showing conductance quantization at zero magnetic field^{9,10} for both electrons and holes. For this device we plot the conductance G at 4.2 K for holes versus the Fermi wavenumber k_F in Fig. 2a. The Fermi wavenumber $k_F = \sqrt{\pi n}$ is determined by the gate voltage applied to the Si substrate, which allows us to tune the density of charge carriers n in a continuous way from 0 to $\sim 3 \times 10^{11} \text{ cm}^{-2}$. The formation of quantized plateaux at $1, 2$ and $3 \times G_0$ is visible, and also the development of plateau-like features at 4 and (possibly) $5 \times G_0$. Note that the presence of quantization at both odd and even multiples of G_0 implies that the valley degeneracy is lifted. Although with slightly lower quality, similar plateaux are also observed for electrons (Fig. 2b). The initial width of this device before the current annealing step was about $2.5 \mu\text{m}$ and it is suspended over $1.5 \mu\text{m}$ distance between the gold electrodes (see Supplementary Information). An estimate of the actual width W of the constriction formed after the current annealing step can be obtained using the approximate semi-classical relation $G = 4e^2/h * k_F W / \pi$ for ballistic graphene constrictions. From this relation we extract $W \approx 200 \text{ nm}$ for holes and 275 nm for electrons. This difference in obtained widths is probably related to the uncertainty in the exact position of the Dirac point. This is caused by the presence of small non-uniform residual doping, which also results in different confinement potentials for electrons and holes and which can also account for the different quality of the quantized plateaux.

To confirm our conclusions we studied the transition to the QHE by applying a perpendicular magnetic field B at 4.2 K (Fig. 3a; ref. 26). The typical QHE behaviour for graphene, showing quantized plateaux at $1, 3, 5, \dots \times G_0$ is observed when the magnetic field is strong enough such that the electron (hole) cyclotron diameter is less than the width of the constriction. The situation changes when the field strength is reduced such that the cyclotron diameter $2l_c$ becomes equal to or greater than the width of the constriction. In this case the carriers begin to experience (quantum) confinement and a continuous crossover is expected from the QHE regime to quantized conduction at zero magnetic field^{26,27}. The edge channels, which carry the current in the quantum Hall regime, continuously transform into one dimensional subbands at zero field. This effect is clearly visible in Fig. 3b, where the G_0 plateau remains well developed down to 0 mT . The distance ΔV_N in gate

voltage between the centre of the quantized plateau corresponding to the first subband ($N = 1$) and the Dirac neutrality point versus magnetic field is shown in Fig. 3c. At magnetic fields above 60 mT we see the linear scaling of the plateau position in the gate voltage (or density) with magnetic field, characteristic of the QHE regime. However, at $B \approx 60 \text{ mT}$ we have a crossover below which we observe a saturation in the position of the plateau. Using the relation $l_c = \hbar k_F / eB$ and $2l_c = W$ (which holds at the crossover) at 60 mT for $N = 1$ and 150 mT for $N = 3$ (Fig. 3d), we extract $W \approx 300 \text{ nm}$. Although one must be careful when applying these semi-classical relations in the quantum regime, this width is consistent with the width extracted from the fit of G versus k_F in Fig. 2.

Surprisingly, in the magnetic field traces at $0.25, 0.5$ and 1 T (Fig. 3b) we observe a well developed feature at $\approx 0.6 \times G_0$ which strongly resembles the characteristic ‘ 0.7 anomaly’ observed at $\approx 0.7 \times G_0$ in quantum point contacts in GaAs–AlGaAs heterostructures¹¹. This feature cannot be the result of Zeeman splitting because at 200 mT this splitting is only $g\mu_B B \approx 25 \mu\text{eV}$ ($g \approx 2$) and an order of magnitude smaller than the thermal energy at 4.2 K . We attribute the observed effect to electron–electron interactions, similar to the case for the ‘ 0.7 anomaly’ in GaAs–AlGaAs (refs 11,28). This unique opportunity to study electron–electron interactions in a graphene nanoconstriction at a moderate field of a few hundred mT or lower is complementary to the high-magnetic field studies done recently in graphene^{21,22}. At fields above 2 T , other features develop that could be precursors of the fractional quantum Hall effect in a constriction (Fig. 3a). Note that the behaviour is different from that observed in GaAs–AlGaAs quantum point contacts, where the 0.7 anomaly continuously evolves into a $1/2G_0$ spin-resolved plateau when a magnetic field is applied¹¹.

Finally we perform voltage bias spectroscopy measurements to extract the subband energy spacing. In Fig. 4a, we present the measurement at $B = 0 \text{ T}$ and in Fig. 4b at $B = 500 \text{ mT}$. The results at $B = 500 \text{ mT}$ show a conductance quantization at $1, 3, 5$ and $7 \times G_0$ at zero or low voltage bias. The formation of a half-integer quantized plateau²⁹ in between the $N = 5$ and $N = 7$ plateaux in Fig. 4b is observed for a bias of approximately 8 meV . This is close to the expected value of 7.5 meV corresponding to the average energy spacing between $N = 5$ and $N = 7$ plus the average energy spacing

between $N = 7$ and $N = 9$ for subband energies $E_n = v_F \sqrt{2\hbar e B n}$ (where $n = 0, 1, 2, \dots$ indicates the orbital quantum number). After this control measurement we extract in a similar way the energy spacing (Fig. 4a) at $B = 0$ T. The results show quantization at 1, 2, 3 and $4 \times G_0$ at zero bias. Here we extract an energy spacing of 8 meV between the $N = 1$ and $N = 2$ subbands, which corresponds to an energy spacing $\Delta E = \hbar v_F \pi / W = 8$ meV when we assume a 240 nm wide constriction. These energy scales are consistent with the observed weak temperature dependence of the quantized conductance at 1.5, 4.2 and 12 K.

Although we have verified in three independent ways the formation of a constriction with a width of about 250 nm, we could not confirm the width after the measurement with, for example, scanning electron microscopy, because the constriction broke during warming up to room temperature. The brittleness of suspended graphene nanoconstrictions is a known problem, which might be solved by preparing high-mobility constrictions on a crystalline substrate such as boron nitride⁴.

Finally we note that we do not expect a particular edge structure to dominate in our nanoconstriction. We conjecture that the edges provide effective boundary conditions for the wave functions, which can lead to conductance quantization, provided that the constriction is sufficiently short. Future experiments in graphene nanoconstrictions can shed light on the detailed role of edges in the effective scattering of ballistic charge and spin carriers at zigzag or armchair edges and the effect of strain on quantized conductance³⁰.

Methods

Sample preparation. The preparation of our devices is done as in ref. 23. We use an acid-free method to fabricate a suspended graphene device. For this we spin coat a 1.150 μm thick LOR-A (MicroChem) resist layer on a highly n-doped (0.007 $\Omega\text{ cm}$) 4" Si wafer covered with 500 nm silicon oxide dielectric. The highly doped Si wafer is used as the back gate of our suspended graphene device. We deposit HOPG graphene on the LOR-A polymer using the Scotch tape technique and use standard electron beam lithography (EBL) to contact the graphene layer to metallic electrodes. We evaporate 5 nm of Ti as an adhesion layer and 75 nm of Au using an e-gun evaporator at a pressure of 5.0×10^{-7} mbar. After lift-off in hot (80 °C) xylene we perform a second EBL step to expose the LOR resist underneath the graphene layer. We develop in ethylacetate to remove the EBL-exposed LOR resist, rinse the sample in hexane and blow it dry gently with nitrogen. The current annealing technique used to improve the quality of our device is described in the Supplementary Information.

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Author contributions

N.T., A.V. and J.J. fabricated the devices, performed the electronic measurements and analysed the data. I.J.V.-M. developed the current annealing method for our devices and M.H.D.G. contributed to the DC bias spectroscopy measurements and analysis of data. N.T., H.T.J. and B.J.v.W. supervised the experiments and analysis of the results. N.T. wrote the paper with contributions from all authors.

Additional information

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