Graphene nanoribbons will be essential components in future graphene nanoelectronics. However, in typical nanoribbons produced from lithographically patterned exfoliated graphene, the charge carriers travel only about ten nanometres between scattering events, resulting in minimum sheet resistances of about one kilohm per square\(^2\). Here we show that 40-nanometre-wide graphene nanoribbons epitaxially grown on silicon carbide are single-channel room-temperature ballistic conductors on a length scale greater than ten micrometres, which is similar to the performance of metallic carbon nanotubes. This is equivalent to sheet resistances below 1 ohm per square, surpassing theoretical predictions for perfect graphene by at least an order of magnitude. In neutral graphene ribbons, we show that transport is dominated by two modes. One is ballistic and temperature independent; the other is thermally activated. Transport is protected from back-scattering, possibly reflecting ground-state properties of neutral graphene. At room temperature, the resistance of both modes is found to increase abruptly at a particular length—the ballistic mode at 16 micrometres and the other at 160 nanometres. Our epitaxial graphene nanoribbons will be important not only in fundamental science, but also—because they can be readily produced in thousands—in advanced nanoelectronics, which can make use of their room-temperature ballistic transport properties.

The energy spectrum of a graphene ribbon with length \(L\) and width \(W\) is approximately given by

\[
E_{n,m} = \pm \hbar c \sqrt{\left(\frac{m\pi}{W}\right)^2 + \left(\frac{n\pi}{L}\right)^2}
\]

where \(c = 10^6\) m s\(^{-1}\) is the Fermi velocity and \(h\) is Planck’s constant divided by \(2\pi\). For reference, if \(W = 40\) nm and \(L = 1\) \(\mu\)m, then \(E_{0,0}/k_B = 600\) K and \(E_{n,m}/k_B = 23\) K, where \(k_B\) is Boltzmann’s constant. Following the Landauer equation, the conductance \(G\) of a long graphene ribbon, measured in a two-probe measurement, is

\[
G = 4G_0 \sum_{n} \rho_{n}
\]

where \(G_0 = 1/R_0 = e^2/h\) and \(0 \leq \rho_{n} \leq 1\) is the corresponding transmission coefficient (\(e\) is the electronic charge). At low temperatures for \(|E_{n,0}| \ll |E_{1,0}|\), \(\rho_{n} \approx (1 + L/\lambda_e)^{-1}\), where \(\lambda_e\) is the mean free path and \(E_{1,0}\) is the Fermi energy. For \(|E_{n,0}| > |E_{1,0}|\), \(\rho_{n} = 0\). The \(n = 0\) modes are special, and relate to edge states. They dominate transport when \(|E_{1,0}| < |E_{n,0}|\), that is, for charge-neutral ribbons with temperature \(T < 600\) K. By analogy with high-quality carbon nanotubes, charged graphenes with no defects were expected to be micrometre-scale ballistic conductors. However, in lithographically patterned exfoliated graphene ribbons, transport in the edge states is quenched due to disorder (Supplementary Fig. 2).

In contrast, well-aligned, single-crystal monolayer graphene sheets form spontaneously on silicon carbide (SiC) surfaces heated above 1,000 °C. In the structured growth method, graphene ribbons self-assemble on the sidewalls of steps that are etched into the (0001) surface of electronics-grade SiC wafers (see Figs 1a and 2), so that no graphene patterning is required to produce nanoribbons. More precisely, to prepare the ribbons shown below, 20-nm-deep trenches were etched along the SiC [100] direction. The samples in Fig. 2 were annealed at 1,600 °C for 15 min (ref. 7). The samples in Fig. 3 were heated at 1,300 °C in Ar (4 × 10\(^{-7}\) mbar), and then in ultrahigh vacuum (UHV) for 15 min at 1,100 °C (green dots, Fig. 3a) or at 1,150 °C (all others—see Supplementary Information). The natural-step ribbon'

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**Figure 1** Structure and characterization of nanoribbons and devices.

- **a**, Schematic diagram of a graphene ribbon (all black) on an annealed and faceted sidewall (yellow and black; see ref. 17).
- **b**, AFM image of an array of graphene ribbons on sidewalls of 20-nm-deep trenches. Bottom inset, three-dimensional view. Top inset, guided by an SEM, up to four individual probes are brought into contact with a selected graphene ribbon, and serve as current leads (I+, I−) and voltage probes (V+, V−). The sample can be transferred to and from an in situ heating stage for annealing up to 1,500 °C. Optical micrograph of sidewall ribbon (sample A) supplied with leads and gate consisting of wide graphene ribbons (1 μm apart) connected by a nominally 39-nm ribbon to form an H-shaped geometry, where the vertical, wide graphene ribbons serve as current leads (I+, I−) and voltage probes (V+, V−) for the 1.6-μm-long ribbon. White dashed lines indicate location of the graphene leads, while line indicates graphene ribbon. Green region locates the gate structure. Dark areas are the gold contacts. **d**, Electrostatic force image of a sidewall graphene nano-ring with 1.6-μm outer diameter attached to graphene leads. The ring is produced similarly to c and has graphene-covered sloping sidewalls.
Figure 2 | Scanning tunnelling analysis of ex situ produced sidewall ribbons similar to those used in fixed geometry transport measurements. Colour-coded line over the 27° slope indicates areas of the surface investigated: colours correspond to the frame colours of the images. Top row, green frame shows atomic resolution STM of graphene structure on the sloped sidewall, and corresponds to the typical graphene STS traces shown in the bottom row (green frame); red frame shows STM of upper terrace, blue frame shows STM of lower terrace. Middle row: blue frame shows STM of upper edge, and yellow frame STM of lower edge; both frames show helical edge structures. Bottom row: red and blue frames show STS of upper and lower terraces respectively, and show semiconducting gap.

(.Async

Figs 1c and 4) was connected at each end to two 200-nm-deep graphitized trenches 1 μm apart. These sidewall ribbons have been extensively characterized6,7,14–17 (Figs 1 and 2 and Supplementary Information) with scanning probe microscopies to determine ribbon widths and sidewall slopes. Angle-resolved photoemission spectroscopy (ARPES) performed at the Cassiopee beam line at the Soleil synchrotron shows a Dirac cone (Supplementary Fig. 1), demonstrating that the ribbons are well-aligned monolayers, and that the sidewall slope is uniform (that is, about 28°, consistent with the (2207) facet). Scanning tunnelling microscopy and scanning tunnelling spectroscopy (STM and STS) show that essentially charge-neutral graphene covers the sidewalls (Fig. 2). The top and bottom plates show the semiconducting properties of the ‘buffer layer’ (Fig. 2, red frames). Atomic-resolution images show zig-zag and chiral edges of the ribbons (Fig. 2).

Single-channel ballistic transport in epitaxial graphene ribbons was first reported10,15 on 40-nm-wide natural-step ribbons that were seamlessly connected to wide graphene leads (see Fig. 1c and Supplementary Information). These ribbons, used for the measurement presented in Fig. 4, were supplied with a top gate (20-nm Al2O3 coated with aluminium) so that Egs could be adjusted. Four wires were bonded to the graphene leads, facilitating four-point transport measurements.

Subsequently, we performed in situ variable-geometry transport measurements (at temperatures T from 30 to 300 K) on ~40-nm-wide ribbons (Fig. 1b), confirming single-channel ballistic transport as discussed below. Four nanoscopically sharp tungsten probes were positioned using a built-in scanning electron microscope and brought into ohmic electrical contact with a selected ribbon (Fig. 1b) in UHV (Omicron Nanoprobe UHV system). For two-probe (2p) measurements, a current I12 was passed between two probes, in contact with the ribbon, and the voltage V12 was measured so that R2p = V12/I12. For four-probe measurements, a current I34 was passed through outer probes and the potential difference V12 between the two inner probes (separated by a distance L) was measured: R2p = V12/I34. The resistance per unit length R increases from 0 to 6 kΩ μm−1 (Fig. 1b). The R values decrease after in situ heating (a process known to clean graphene), indicating that surface contamination increases scattering.

For these ribbons, both R2p and R3p extrapolate to R ≈ R0 = h/e2 at L = 0 (Fig. 3a). Moreover, the resistivity ratio RR = R3p/R2p = 0.95 ± 0.02. These results are characteristic of single-channel ballistic transport involving nearly perfectly invasive contacts10,18,19. Furthermore, because an invasive probe acts as a scattering centre, R2p is strongly modified if a third passive probe (with a very large resistance to ground) is placed between the contact probes17. Left-moving charges that enter the invasive probe acts as a scattering centre, but on leaving either left or right with equal probability. Hence the transmission probability is Tr increases (see Supplementary Information). When two passive probes are used, the overall resistance R2p increases to 3R0. From these considerations it follows that RR = 1 for perfectly invasive probes34. This property of invasive probes is explicitly demonstrated in Fig. 3b. When one probe is placed on a ribbon, the end-to-end resistance R2p increases from approximately R0 to 2R0; when two probes are used, it increases to 3R0. Note that placing probes on a diffusive wire has no effect on the resistance of the wire. As shown in Fig. 3c, the resistance of these single-channel ballistic ribbons does not significantly depend on temperature or on the bias voltage.

For 0.1 μm ≤ L ≤ 1 μm, R(L) is found to increase nonlinearly from 0.5R0 to 1R0, as shown for two ribbons (Fig. 3a, upper left inset). For L < L0, R ≈ R0/2, whereas for L > L0, R increases (see Fig. 3a upper left inset, and Supplementary Fig. 7).
Figure 3 | Multiprobe in situ transport measurements of sidewall ribbons. a, Resistance versus probe spacing L. Linear fits extrapolate to $R_0 = h/e^2$. Slopes correspond to $R' = 6.2, 1.6, 0.92, 0.44 \text{ kΩ} \mu\text{m}^{-1}$, corresponding to the mean free path $\lambda_0 = 4.2, 28, 16, 58 \mu\text{m}$ (following transmission $T_r = (1 + L/\lambda_0)^{-1}$). Line 5 is consistent with zero slope. Numbered traces are as follows: 1, UHV annealed at 1,100 °C for 15 min; 2, UHV annealed at 1,150 °C for 15 min; 3–5, re-annealed at 1,150 °C for 15 min. Middle inset, comparison of two-probe (2p) and four-probe (4p) measurements. Upper insets, nonlinear resistance increases observed at $L = 160 \mu\text{m}$ and at $L = 16 \mu\text{m}$ in two different ribbons measured at room temperature, presented as $G(L)$ in the lower inset. Fit is explained in main text. b, Effect of passive probes contacting sidewall ribbons. The nonlinear resistance is observed with one passive probe and triples with two passive probes. This property of ballistic conductors explains why four-probe and two-probe measurements yield essentially identical resistance values for ballistic wires. Ideal invasive probe ($P = 1$) and non-invasive probe ($P = 0$) limits are indicated. Theoretical10,11 values (for $R_R = 0.95$) indicated by asterisks. c, Resistance $R_{nm}$ of a typical ribbon for $L = 5 \mu\text{m}$ versus bias voltage $V_g$. d, Resistance versus temperature for the same ribbon, showing less than 10% variation from 30 K to 300 K.

$R(L)$ was measured at 300 K from 1 μm to the apparatus limit, $L = 25 \mu\text{m}$ (Fig. 3a upper right inset). A second nonlinear increase is observed for $L > L_{0+} = 16 \mu\text{m}$. These nonlinearities are consistent with an exponential conductance decrease given by $G = G_0 \exp(1 - L/L_{0+})$ for $L \geq L_{0+}$ as shown in Fig. 3a (dashed line in upper right inset). It is intriguing that $E_{0+}/k_B = \pi \alpha e^2/2L_{0+} = 150 \text{K}$, suggesting that longitudinal excitations may be involved (equation (1)).

We next discuss the transport properties of a fixed-geometry sample (such as shown in Fig. 1c). Further examples are given in Supplementary Information. Sample A is a top-gated 39-mm-wide 1.6-μm-long graphene sidewall ribbon. The ribbon is seamlessly connected to micro-scale graphene pads to the left and right. Each pad is bonded to two wires, facilitating four-point transport measurements. Resistances around 20 kΩ are measured with better than 0.1% precision (corresponding to $\delta G < 5 \times 10^{-6} G_0$) using standard low-frequency lock-in techniques (13 Hz, 100 nA < $I < 1 \mu$A). Temperatures are measured with 2 mK precision. The charge density $n(V_g)$ is adjusted by applying a gate voltage $V_g$; we find that $n(V_g) = -0.95 \times 10^{12} \text{cm}^{-2} \text{V}^{-1}$, as determined from a Hall bar on the same substrate, so that $E_F = -0.11 \text{eVV}^{-1/2}$.

Figure 4c shows the conductance $G(V_g)$ as function of gate voltage for several temperatures, and can be globally explained in the Landauer picture with $T_{\text{dr}}(E_F) = T_{\text{dr}}(\theta[E_F] - \theta[E_0])$ (θ is the step function). The minimum conductance $G = 0.95 G_0$ at $V_g = 0$ and $T = 4.2 \text{K}$ is consistent with a single ballistic channel in charge-neutral graphene with $\lambda_{0+} = 22 \mu\text{m}$ (from $T_{\text{dr}} \approx (1 + L/\lambda_{0+})^{-1}$). The conductance increase with increasing $V_g$ corresponds to the opening of the $|n| \geq 1$ subbands20, as diagrammatically shown in Fig. 4b. From the $G(V_g)$ slope we deduce that $T_{|n| \geq 1} = 0.0035$, so that $\lambda_{|n| \geq 1} = 60 \text{nm}$. We note that each of the curves can be displaced vertically to overlap the others. This is consistent with the Landauer picture and Fig. 3, if we assume that $T_{|n| \geq 1}$ are temperature independent and that only $T_{n=0}$ is dependent on temperature, as indicated in Fig. 4b. (This subband-dependent temperature effect is also seen in exfoliated graphene ribbons, see Supplementary Fig. 2.)

Note that the large asymmetry with respect to $V_g$ (Fig. 4a) is caused by the np/np junctions (see, for example, ref. 21). For $V_g < 0$, the ribbon is p doped while the leads are slightly n doped7,16. Because $\lambda_{|n| \geq 1} \approx 50 \text{nm}$ is larger than the junction width, the junctions represent a significant barrier for the gapped $n \neq 0$ subbands; however, the ungapped $n = 0$ subbands are not affected21.

The conductance $G(T)$ increases monotonically with increasing temperature, as shown in Fig. 4e. In these experiments samples were cooled from 120 K to 4 K over 10 h, and two measurements were performed per second. The conductance is described to remarkable precision by

$$G(T) = \frac{\alpha}{\hbar} \left[ 1 + 0.5 \exp \left\{ -\frac{T}{T_{\text{eff}}} \right\} \right]$$

where $T_{\text{eff}} = \text{the effective electronic temperature (in this case, it is equal to the sample temperature), } \alpha = 0.312, \text{ and the measured } T^* = T_{\text{m}} = 29 \text{K; for } L = 1.06 \mu\text{m, the calculated } T^* = 1.47 \text{K. Equation (2) applies to samples B, C and D (see Supplementary Information) as well. Specifically, for sample B (Supplementary Fig. 4), } \alpha = 0.31 \text{ and the measured } T^* = T_{\text{m}} = 29 \text{K; for } L = 1.06 \mu\text{m, the calculated } T^* = 1.47 \text{K. For the ring structure (Fig. 1d), } T_{\text{m}} = 6 \pm 1 \text{K, and the measured contact-to-contact distance is } 5 \mu\text{m (following half a turn.}
Consequently activated longitudinal modes of the graphene ribbon. The dependence of the order of (but larger than) the ballistic transit time through the disordered conductors ballistically hop from one scattering centre to conductance. Moreover, we define $G_\text{e}(V_g)$ for all the curves onto a single curve. The increase of conductance with increasing bias voltage is due to the $T^*$ dependence of $G_\text{e}(V_g)$, from which decomposition of $G_\text{e}(V_g) = G_{0\text{in}} + G_{0\text{out}}(T) + G_\text{dir}(V_g)$. The $|n| \geq 1$ bands $(E_F \neq 0)$ show no temperature dependence (apart from weak oscillations), as seen by the collapse of all the curves onto a single curve. Four-point $G$ versus $T$ (red curve) of the circle), from which $T^* = 6.7$ K. This establishes the inverse $L$ dependence of $T^*$ in these samples ($x$ and $T^*$ appear to be unrelated), and implies that $T^*$ is related to $E_{0\text{in}}$ (see equations (1) and (2)).

The increase of conductance with increasing bias voltage $V_g$ (Fig. 4f) is attributed to electronic heating. Using the conductance (equation (2)) as a thermometer allows us to determine $T_{\text{el}}(V_g)$ from the conductance. Moreover, we define $T_{\text{el}} = eV_g/k_B$, to enable us to plot $T_{\text{el}}$ versus $T_{\text{vb}}$, as shown in Fig. 4g. The $T_{\text{el}}$ are fitted with:

$$T_{\text{el}} = \sqrt{T^2 + (TV_{\text{vb}}/\nu)^2}$$

Figure 4g shows a good fit for all temperatures with the coefficient $\nu = 5$ for $T_{\text{el}} < 15$ K and $\nu = 12$ for $T_{\text{el}} > 15$ K. This behaviour is observed in samples B, C and D, and also in carbon nanotubes (Supplementary Figs 3, 4, 5, 6, 8).

Equation (2) resembles Mott’s expression for one-dimensional variable range hopping. It is therefore reasonable to expect a related mechanism. Following Mott’s heuristic argument, charge carriers in disordered conductors ballistically hop from one scattering centre to the next, separated by a hopping distance $L^*$, following the path of least resistance, that is, one with the largest transmission coefficient. This transmission coefficient involves the product $Z$ of two competing terms. One is the Boltzmann factor of the lowest longitudinal mode between the hopping endpoints, with activation energy $E_{0\text{in}} = \pi\hbar c^*/L^*$, and the other is determined by the lifetime of the charge carrier $\tau$. Consequently $Z = \exp(-E_{0\text{in}}/k_BT)\exp(-\pi\hbar c^*/L^*k_BT)\exp(-L^*/c^*)$, with $\tau$ the carrier transit time over the distance $L^*$. We note that $Z$ is a maximum for $L^* = \sqrt{(\pi\hbar c^*/T_k)T}$, so that $Z = \exp(-L^*/c^*)$, where $T^* = 4\pi\hbar c^*/k_BT$. From equation (2) and the inverse relation between $T^*$ and $L^*$, we conclude that $\tau = 2.8L^*/c^*$, that is, of the order of (but larger than) the ballistic transit time through the ribbon. This rough estimate suggests that transport involves thermally activated longitudinal modes of the graphene ribbon. The dependence on bias voltage indicates that impinging electrons produce hot charge carriers that overcome the activation barrier. The factor $\nu$ relates to the efficiency of this heating process.

The transport properties reported in Fig. 3 agree with those reported in Fig. 4, both showing two-component behaviour, each component contributing at most $1G_0$ to the conductance. The mean free path of the first component typically exceeds tens of micrometres and its resistance increases nonlinearly above 16 μm. The second component is unusual. Transport is ballistic between scattering centres on the length scale $L^*$, which can be larger than the ribbon length $L$. Transport appears to be thermally activated with an activation barrier determined by the lowest longitudinal mode between the scattering centres (that is, $E_{0\text{in}}$). This channel exhibits a positive linear magnetoconductance (discussed in Supplementary Information) that typically saturates at $B = 2$ T.

Room-temperature single-channel ballistic conduction in the $n = 0 +$ mode was first observed two years ago in epitaxial graphene sidewall ribbons. Single-channel ballistic transport in the $n = 0 +$ channel is supported by the robust value of the quantum ‘contact resistance’ (at $L = 0$); the independence of the resistance with respect to length, temperature and bias voltage; the equivalence of two- and four-probe resistance measurements; and resistance doubling and tripling due to passive probes. Its insensitivity to gate voltages implies that this component is derived from a metallic subband. Conduction in the $n = 0 -$ mode appears to involve thermally activated transport (equation (2)) that is ballistic between widely spaced scattering centres. The separation of scattering centres can exceed the ribbon length in fixed geometry samples, where the ribbon is seamlessly connected to graphene leads. The activation barrier is found to be inversely proportional to the ribbon length. In addition, an energy gap equivalent to $T_{\text{el}} = 2.2$ K appears to be involved. The conductance bias voltage dependence is explained in terms of electronic heating. Its insensitivity to gate voltages implies that it too is derived from a metallic subband. The $n = 0 -$ mode also exhibits linear positive magnetoconductance. If the conductance increase is

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Figure 4 | Gated ribbon transport (see Fig. 1c). a, Schematic band structure. b, Conductance increase with increasing $V_g$ is due to opening of subbands; for $|E_F| < E_i$, only the $n = 0 \pm$ subbands contribute; the conductance increase with increasing temperature is due to the 0- subband. c, Conductances $G_{\text{e}}(V_g)$ for various temperatures. Minimum conductance at $V_g = 0$ corresponds to charge-neutral ribbons ($E_i = 0$). d, Decomposition of $G_\text{e}(V_g) = G_{0\text{in}} + G_{0\text{out}}(T) + G_\text{dir}(V_g)$. The $|n| \geq 1$ bands ($E_F \neq 0$) show no temperature dependence (apart from weak oscillations), as seen by the collapse of all the curves onto a single curve.
properties of these two modes are so different is not expected and points presents an excited state derived from the much shorter mean free paths than the typically patterned ribbons, the inverse is true: the other subbands (160 nm for the 0 mode) and the 0 subbands have a conductance of 1 with those observed by others in two-dimensional graphene samples subbands (60 nm) are much larger than those observed in exfoliated other subbands (102 nm) and voltage probes.

All ribbons were characterized with AFM, conducting AFM, SEM, and electrostatic force microscopy, to determine ribbon widths and sidewall slopes (see ref. 7 for details, and also refs 6,15). The Solen synthesis facility (Cassiopeia ARPS beam line) was used for graphene band structure measurements (Supplementary Fig. 1), to determine the number of graphene layers and the sidewall slopes7,24.

Low-temperature (T = 77 K) STM-STS measurements (Fig. 2) were performed (in Nancy) in a UHV chamber coupled to a preparation chamber. For STM, bias voltages are relative to the grounded tip. STS spectra were acquired with a Pd tip (Vbias = 70 mV, 1,100 Hz) and a lock-in current detection, in open feedback loop conditions.

The multi-probe measurements in Fig. 3 were performed in an Omicron Nano-probe UHV system (in Hannover), from 30 K to 300 K, using W tips positioned using a built-in SEM. The STS set point (Fig. 1d) was 2 V/0.1 nA. The resistance between neighbouring ribbons was >490 MΩ (Supplementary Fig. 11).

Results in Fig. 4 were obtained (in Atlanta) in a Janis variable temperature cryostat (4–300 K) with a 9-T magnet, using standard low-frequency lock-in techniques (13 Hz, 100 nA < J < 1 μA). For G(T), samples were cooled from 120 K to 4 K over 10 h, with a rate of two measurements per second.

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Author Contributions J.B. and F.E. produced samples and performed the in situ transport experiments in Hannover relating to Fig. 3. C.T. performed and supervised the transport experiments in Fig. 3, discussed the data and commented on the paper. M.R. produced the samples and performed transport experiments shown in Fig. 4 and Supplementary Figs 3–6. E.H.C., A.T. and A.T.-I. performed ARPES experiments, and A.T. and M.S. the STM and STS experiments. Z.J. performed confirming spin transport measurements and contributed to C-AFM results shown in Supplementary Fig. 6b. A.-P.L. performed earlier SPM measurements. W.A.d.H. conceived and supervised the experiment and interpreted the data, C.B. supervised and performed the Atlanta based experiments. W.A.d.H. and C.B. wrote the paper.

Author Information Reprints and permissions information is available at www.nature.com/reprints. The authors declare no competing financial interests. Readers are welcome to comment on the online version of the paper. Correspondence and requests for materials should be addressed to W.A.d.H. (walt.deheer@physics.gatech.edu).
This section is in three parts. The first part presents Angular Resolved Photoemission Spectroscopy and STM experiments on arrays of epitaxial graphene sidewall ribbons and a comparison of ARPES data with other exfoliated graphene. The second part describes details of the transport analysis presented in the main text, which is brought into context with other graphene ribbon work. We also present details of three samples (B through D) showing that the effects presented in the paper are general. We also provide additional measurements on Sample A, presented in Fig. 4, main text.

The second part describes the preparation and in situ growth and characterization of the graphene nanoribbons in Fig. 3 (main text). It also provides all the data for 50 resistance measurements on various ribbons at 3 different lengths.

A. **Surface characterization: ARPES and STM**

B. **Transport analysis**

1. Comparison with exfoliated and other graphene ribbons.
2. Graphene Ribbon Sample A
3. Graphene ribbon Sample B
4. Graphene ribbon Sample C
5. Graphene ribbon Sample D
6. Length dependence
7. Comparison with carbon nanotubes
8. Explanation of the resistance doubling and tripling effect
9. FAQs

C. **Preparation and characterization of epitaxially-grown graphene nanoribbons by local in-situ transport measurements**

1. Growth of GNRs for in-situ resistance measurements and their -situ characterization
2. Characterization by 4-tip STM SEM
3. Additional 4-probe in-situ resistance measurement of GNR
A. Surface characterization: ARPES and STM

**Figure S1.** Comparison of epitaxial graphene (blue frame) and exfoliated graphene (red frame) from a surface science perspective. STM topographical images of exfoliated graphene on SiO$_2$ (Bottom left); and epitaxial graphene (bottom middle) and a sidewall ribbon (bottom right from Fig. 2). The deposited exfoliated material is topologically rough with 0.6 nm fluctuations obscuring the structure of the carbon layer. The epitaxial graphene (both on the 2D, C-face and the sidewall ribbon) clearly shows the honeycomb structure and no substrate induced roughness. The 2D material, in addition shows a faint moiré pattern, which is not seen in the sidewall ribbon. *Top:* Angle resolved photoelectron spectra (ARPES); the horizontal and vertical scales are the same for all spectra. *Top left:* Exfoliated graphene on SiO$_2$ shows a broad unresolved peak, $\delta k \approx 0.5$ Å$^{-1}$, that corresponds to a correlation length $L_c = 2\pi/\delta k = 1$ nm. (The x's result from a fit to the graphene band structure.); (Center left): ARPES of suspended graphene$^4$ ($\delta k \approx 0.5$ Å$^{-1}$) corresponding to a correlation length of 3 nm (after accounting for broadening due to corrugations). (Center right): ARPES of 2 dimensional epitaxial graphene on the C-face, the peak width corresponds to the instrument resolution ($\delta k \approx 0.01$ Å$^{-1}$), corresponding to $L_c > 50$ nm. (Left): ARPES of an array of a thousand of 24 nm wide sidewall ribbons; peak widths correspond to the instrument resolution corresponding to $L_c > 50$ nm parallel to the ribbon axis. Note that disorder in exfoliated graphene severely distorts the band structure near close to the Dirac point whereas epitaxial graphene has a well defined Dirac point.
B. Transport analysis

1. Comparison with exfoliated and other graphene ribbons

Figure S2. Comparison of the conductances of 6 gated ribbon samples measured at several temperatures from the literature, demonstrating temperature independence of the \( n \neq 0 \) subbands and temperature dependence of the \( n = 0 \) subband. (a) 30 nm X 1.7 \( \mu \)m patterned exfoliated graphene ribbon\(^5\); (b) 36 nm X 0.5 \( \mu \)m patterned exfoliated graphene ribbon\(^6\); (c) 16 nm X 0.086 \( \mu \)m unzipped nanotube \(^7\); (d) 35 nm X 0.060 \( \mu \)m gate defined exfoliated graphene constriction\(^8\); (e) 39 nm X 1.6 \( \mu \)m epitaxial sidewall graphene ribbon (Sample A); (f) 35 nm X 1.6 \( \mu \)m epitaxial sidewall graphene ribbon (Sample B); (g) Data from (b) after \( G_0(T) \) subtraction; (h) Data from (d) after \( G_0(T) \) subtraction; (i) Data from (f) after \( G_0(T) \) subtraction. Also note that the mean free paths measured in transport agree well with the correlation lengths that are measured in ARPES (Fig. S1). The relatively poor transport properties of exfoliated graphene ribbons are due to the strong interactions with the disordered substrate and disorder at the interface with the graphene layer. These cause the mobility gap at \( n = 0 \) in exfoliated graphene ribbons. In contrast, epitaxial graphene sidewall ribbons are ordered and do not have a mobility gap.
Figure S2 shows 6 graphene ribbon samples including 4 samples produced by patterning exfoliated graphene deposited on oxidized silicon wafers (Fig. S2a-d). The data were extracted from published work, representing transport properties as a function of temperature and back gate voltages. Samples A and B (Fig. S2e-f) were produced and measured by us. The main point here is the observation that the temperature dependence of the conductivity for $V_g \neq 0$ is represented by a conductivity shift that depends on $T$ only (and not on $V_g$). In the Landauer picture, this shift is consistent with the contribution of the $n=0$ subbands (i.e. the transmission $T_{0} \rightarrow 0$ for $T \rightarrow 0$) while the transmission coefficients of the $n \neq 0$ subbands, $T_{n \neq 0}$, are insensitive to temperature.

- In Fig. S2a a shift of 0.028 $G_0$ causes the $T=100$ K data to overlap with the $T=33$ K data.
- In Fig. S2b shifts are applied to produce Fig. S2g.
- Figure S2c is for an opened carbon nanotube ribbon where the $n \neq 0$ subbands are reasonably parallel to each other.
- Fig. S2d shows a very short ribbon (a gate-produced constriction). This ribbon is not defined by lithographic patterning of the graphene itself, so that graphene is not damaged and the effective ribbon edges are smooth. Excellent overlap of the data is found by applying uniform $G(T)$ shifts (see Fig. S2h) resulting in a trend that is consistent with Eq. 2, of the main text. The residual conductance is very close to $1 G_0$ and is clearly related to our observations.

An analysis of the scattering lengths shows the following. The back-gate induced charge density is assumed to be equivalent to that of an infinite sheet, yielding an upper limit for the effective scattering lengths along the ribbon. These scattering lengths $\lambda_{bulk}$ are estimated from the measured subband conductivity $\Delta G=G(E_F)-G(E_{F}=0)$ in units of $G_0$, where, for bulk back gated graphene, $E_F$ (meV)≈31.2 $V_g^{1/2}$ (V)$^{1/2}$, so that $\lambda_{bulk} \approx 10.5 \Delta G V_g^{1/2}L/W$ where $L$ is the length and $W$ is the width of the ribbon. The scattering lengths determined by this procedure are noted in the figures.

In Fig. S2a, the staircase structure in the 33 K data are due to the opening of successive subbands (as explained by the authors), consistent with the Landauer picture (see main text). The subband indices are shown. Since the step heights $\Delta G_n/G_0 (=0.011, 0.011, 0.016, 0.022$ for $n=1-4$) correspond to $4T_{n}$, so for small $\lambda_{n}$ $\lambda_{n}=4.7, 4.7, 6.8, 9.3$ nm for $n=1-4$, which agrees with the value determined from the slope $dG/dV_g$. Moreover, the measured energy spacing $E_{n+1}-E_{n}=44, 42, 33$ meV, agreeing with the energy spacing for a 30 nm zigzag ribbon predicted to be $E_{n+1}-E_{n}=47$ meV (for small $n$).

For comparison, Fig. S2e is a reproduction of Fig. 4c of the main text for Sample A for which $\lambda_{bulk} \approx 60$ nm and $\lambda_{0} = 22 \mu$m. Fig. S2f shows a second epitaxial graphene sidewall ribbon, Sample B, (35 nm X 1.06 $\mu$m) for which $\lambda_{bulk} \approx 50$ nm and $\lambda_{0} = 0.8 \mu$m. As shown in Fig. S2i, the $G(V_g)$ all collapse together by applying a $V_g$-independent conductance shift for each temperature. Note that our data shows
reproducible fine structure from one temperature to the next, testifying to their high quality.

2. Graphene Ribbon Sample A

This sample was presented in Fig. 4 (main text). Here magnetic data are included. In addition in Fig. S3 we also show magneto-resistance data $G(B)$. These data are also presented after converting $G$ to $T_{el}(G)$, analogous to the bias voltage data (Fig. 4g). The magnetic field axis is converted to and equivalent temperature, $T_B = \mu_B B/k_B$. Hence plotted, the dimensionless slopes correspond to an effective magnetic moment $\mu$ (in units of $\mu_B$). This analysis presumes that the increasing conductance is caused by a magnetically induced increase in the chemical potential (and not due to weak localization). Note the essentially perfectly linear, V-shaped, about 4 Tesla wide, magneto-conductance dip. The dip corresponds to $T_{el} = T + \mu |B|$ where $\mu = 5\mu_B$ at low temperatures and increases to $\mu \approx 10\mu_B$ at high temperatures. For all ribbon samples at all temperatures the constant slope abruptly changes at $|B| \approx 2T$ (Figs. S3-S6).

![Graphene Ribbon Sample A](image)

**Figure S3.** Sample A is a 39 nm X 1.6 $\mu$m gated sidewall ribbon connected to wide graphene leads. The $T=4.2$ K conductance versus bias voltage (a) and versus magnetic field (c) show linearity at low bias voltage (magnetic field, resp); (b) and (d) are the same data as (a) and (c), resp, but plotted in units of electronic temperature $T_{el}$ derived from $G(T)$ and as a function $T_{el} = eV_b/k_B(T)$ and $T_B = \mu_B B/k_B$, resp. (e) Conductance versus magnetic field for $T$(in K) = 4.2, 7, 12, 20, 35, 55 and 80 (bottom to top). (f) Same data as (e) after converting $G$ to $T_{el}$ and $B$ to $T_B$ as in (d).
An extension to the detailed analysis already presented in the main text concerning sample A, highlighting the T=4.2 K data is presented here. The conductance G of this sample is given by $G(T) = \alpha G_0 (1 + 0.5 \exp(-\theta/2))$, where $\alpha = 0.922$, $\theta = T^*/(T - T_0)$ with measured $T_m^* = 21.5$ K, (compared with $T_p^* = 20.9$ K from $T_p^* = 1.4 \pi \hbar c^*/k_B L$ ($L=1.6 \mu m$) and $T_0 = 2.2$ K. This equation is algebraically inverted to determine the electronic temperature $T_{el}$ from the conductance: $T_{el}(G) = T^*(\ln(2G/\alpha G_0 - 2) + T_0)$. Likewise, the bias voltage is converted to $V_{vb} = eV_b/k_B$ and the magnetic field is converted to $B = \mu_B B/k_B$. In this way Figures S3b and S3d are generated (from S3a and S3c). The slopes in Fig. S2d correspond to the inverse electronic heat capacity $\nu$ in units of $k_B$ (as defined in the main text). Slopes in Fig. S3c correspond to magnetic moments (in units of $\mu_B$). Note the sharp V shaped dip in the magnetic data (with slopes corresponding to 5.6 $\mu_B$), which is typical for all low temperature, low field graphene ribbons. The lines $T_{el} = T + \mu |B|$ versus $B = \mu_B B/k_B$ corresponds $\mu = 5.6 \mu_B$ and $T = 4.2$ K is the sample temperature. The downturn at $B = \pm 2$ K, is seen in most graphene ribbon, 2D graphene and nanotube data. The hyperbolic fit to Fig. S3b, corresponds to Eq. 3: $T_{el} = \sqrt{(V_{vb}/\nu)^2 + T^2}$ with $\nu = 5$ and $T = 4.2$ K (i.e. the sample temperature) following Eq.3.

### 3. Graphene ribbon Sample B

Sample B is a graphene ribbon (1.06 $\mu m \times 35$ nm) sample similar to sample A in design. The main features observed in sample A are also observed here. The temperature dependent conductivity corresponds to $\alpha = 0.311$ and $T_m^* = 29$ K, following Eq. 2. Note that the predicted $T_p^*$ according to $T_p^* = 1.4 \pi \hbar c^*/k_B L$ is 31.6 K, in excellent agreement with the measured value (despite the significantly reduced value of $\alpha$).

The $G$ versus $V_g$ for several temperatures is similar to Sample A, Fig. 4c (main text). Note that all of the data collapse onto a common curve after subtraction of a gate voltage independent conductance (temperature dependent) as was seen in Sample A as well (Fig. 4c). The implications of this are discussed in the main text (see also discussion of Fig. S2).
Figure S4 Properties of Sample B (35 nm X 1.06 µm sidewall ribbon supplied with a top gate). (a) $G$ versus $V_g$ for various temperatures. (b) Collapse of the data in (a) by subtraction of a $V_{bias}$ constant $G(T)$ for each temperatures $T$. (c) Conductance as a function of magnetic field for $T=4.2$ K. (c) $T_e=|\mu|B$ versus $T_e=\mu_B B/k_B$ slopes (as for sample A) correspond to 4.3 $\mu_B$ (red) and 7.7 $\mu_B$ (green).
Figure S5. Graphene ribbon Sample C, \( L = 1 \mu m, W = 39 \) nm; \( T_m^* = 49 \) K, \( \alpha = 0.454 \). (a) Conductance versus magnetic field, measured at \( T \) (in K) = 4.2, 7, 12, 20, 35, 55 and 80 showing characteristic dip at \( B = 0 \). (b) Data from (a) after conversion (as for sample A) to \( T_{el} = T + \mu |B| \) versus \( T_B = \mu_B B/k_B \), showing linear response. Magnetic moments correspond to \( \mu (in \mu_B) = 14, 16, 16, 17, 20, 20, 27 \). (c) Bias voltage response for \( T \) (in K) = 4.2, 7, 12, 20, 35 and 55. (d) Data from (c) after conversion to \( T_{el} \) and \( T_{vb} \). Hyperbolic response agrees with Eq. 3 with \( \nu = 5, 6, 7, 9.5, 11, 12 \).
4. Graphene ribbon Sample C

The magnetic field and bias voltage dependence of graphene ribbon Sample C (measured from 4.2 K to 180 K) shows the characteristic features of graphene ribbons (Fig. S5). After converting $G(B)$ to $T_{el} = T + \mu |B|$ and $B$ to $B = \mu_B B/\kappa_B$ (like in the previous examples), the highly curved magnetic field response shows the typical behavior seen in previous samples. However, the magnetic moments obtained from the slopes range from 14 $\mu_B$ to 27 $\mu_B$; that are a factor of 2 greater than typically observed. The bias voltage dependence shows the hyperbolic response (Fig. S5d) as predicted in Eq. 3, with $\nu = 5$ at 4.2 K, typical for graphene ribbons. The (approximately factor of 2) slope change at $T_{el} \approx 15$ K is also typically seen, as reported in the main text.

5. Graphene Ribbon Sample D

Sample D is a sidewall ribbon 36 nm X 0.37 $\mu$m. From $G(T)$, $\alpha = 0.628$ and $T_{m^*} = 87$ K. The value of $T_{p^*}$ determined from Eq. 2 is 93 K that agrees very well with the measured value. Conductance measurements were made on this graphene ribbon, as shown in Fig. S6a, using a conducting AFM tip at room temperature in ambient conditions. The left wide graphene pad was connected to ground. The contact resistance, measured by placing the tip on the left graphene pad was subtracted. The resulting conductance versus tip position is plotted in Fig. S6b, showing that the conductance decreases from about 2 $G_0$ to about 0.9 $G_0$ with increasing tip to pad distance $L$. The curve is identical to that in Fig. 3a where the exponential decrease is given by: $G = G_0 \exp(1-L/L^*)$ for $L>L^*$, where $L^* = 160$ nm as indicated by the theoretical curve (green line). While the correspondence is not nearly as good as in Fig. 3a, it is nevertheless consistent with the measurement.

The magnetic field and bias voltage dependence of this sample (simulated as for sample A) are typical for graphene ribbons, as in the examples above. Measurements were made for temperature ranging from 4.2 K to 180 K. The curved response of the raw data (Fig. S6c) converts to the typical V shape with a magnetic moment 5.4 $\mu_B$ at $T = 4.2$ K. The bias voltage response is also typical. The bias voltage dip converts to hyperbola given by Eq. 3; with $\nu = 7$ for $T = 4.2$ K (see the figure caption of Fig. S6 for the other values).
Figure S6. Transport properties of Sample D, a 36 nm x 0.37 µm sidewall ribbon. (a) Electrostatic force microscopy image. (b) Scanning probe conductance measurements using conducting AFM tip showing uniform conductance decrease from $G = 2G_0$ to $G = 0.8G_0$. Solid line corresponds to $G = G_0 \exp(1-L/L^*)$. (c) Magnetic field dependence for $T$ (in K) = 4.2, 7, 12, 20, 35, 55, 80, 120 and 180. Temperature dependence gives $\alpha = 0.628$ and measured $T_m^* = 87$ K from Eq. 2 (which agrees very well with the predicted $T_p^* = 93$ K). Fits are obtained like in the procedure described for sample A above. The magnetic moments correspond to $\mu$ (in $\mu_B$) = 5.4, 6.5, 6.4, 7.7, 9.2, 14, 15, 18 and 16 as typically found in graphene ribbons. (d) Same data as in (c) plotted in terms of $T_{el} = T + \mu |B|$ and $T_B = \mu B/k_B$ (e) Bias voltage dependence for $T$ (in K) = 4.2, 7, 12, 20, 35 and 55. (f) Data in (e) plotted in terms of $T_{el}$ and $T_{vb}$ using Eq. 3, for $\nu$ = 7.0, 7.0, 7.0, 7.5, 8.3 and 8.1, values that are typical for graphene ribbons.
6. Length dependence

The length dependence of the 0- subband for $T = 300$ K (for the samples presented in Fig. 3a, main text) is plotted on a logarithmic scale (Fig. S7), which brings out its exponential behavior more clearly for $L > L^* = h c^*/k_B T = 160$ nm. For both ribbons the conductance is approximately $G = G_0 \exp(1 - L/L^*)$ for $L > L^*$ and $G = G_0$ for $L < L^*$ as explained in the main text.

![Figure S7. Ln $G_0$ versus length for the two short ribbon segments in Fig. 3a (main text) measured at room temperature.](image)

7. Comparison with carbon nanotubes

As shown below the response of carbon nanotubes is remarkably similar to that of graphene ribbons. However the overall conductances are increased by a factor of 2. As was shown 15 years ago$^9$ carbon nanotubes are ballistic conductors at room temperature and the conductance is (nominally) $2e^2/h$, in contrast to the theoretical prediction of $4e^2/h$. In that respect, similar to the factor of 2 discrepancy observed in graphene ribbons. From thorough transport measurements on (multiwall) carbon nanotubes, Schönenberger et al.$^{10}$ concluded that (1) carbon nanotubes are quasi-ballistic with mean free paths on the order of 20 nm, (2) their magnetic response shows a conductance dip that can be modeled with a multi-parameter fit to standard weak localization theory, (3) their bias voltage response demonstrates Lüttinger liquid behavior, (4) the temperature response is complex and shows evidence of localization and no evidence for room temperature micron scale ballistic conductance.
In light of our measurements on graphene ribbons we reexamined the data from which these conclusions were drawn and found carbon nanotubes behaved essentially identically to graphene ribbons as shown in Fig. S8 in all details. Specifically, the temperature dependence is consistent with Eq. 2 with $T_m^* = 49.9$ K (corresponding to $L = 670$ nm, from $T_p^* = 1.4 \pi \hbar c^*/k_B L$, compared with the measured $L = 350$ nm) and $T_0 = 2.0$ K. However, the factor of $1/2$ in Eq. 2 is replaced by a factor of 3. The conductance $G(T)$ saturates at $G = 2\alpha(2e^2/h)$ at $T \approx 50$ K (Fig. S8b), a factor 2 higher that the short ribbons in Fig. 3a.

Like for graphene ribbons, the bias voltage dependence is found to follow Eq. 3, with $\nu = 5$ (see Fig. S8c) for small bias voltages and about twice that for large bias voltages. The magnetic field dependence shows the sharp characteristic dip at $B = 0$ that corresponds to $T_{el} = T + \mu|B|$ with $\mu = 5 \mu_B$. The V shape is interrupted for $|B| \geq 2$ T showing complex behavior at higher field, as seen in all graphene ribbon samples. Consequently, the transport properties carbon nanotubes, as well as underlying mechanisms are certainly similar to graphene ribbons. Nanotubes are certainly two component ballistic conductors as well.
Figure S8 Reexamination of transport properties of multiwall carbon nanotubes (a) Room temperature transport as measured by Frank et al\(^9\) showing \(2e^2/h\) ballistic transport indicating two channels. (b-f) Measurements by Schönenberger et al\(^{10}\). (b) Measured temperature dependence of the conductance, corresponding to \(\alpha = 0.90, T_m^* = 49.9\) K. Note the saturation at \(2\alpha\). (c) Measured bias voltage versus temperature with superimposed calculations following Eq. 2. The fits correspond to \(\nu = 4\), very close to \(\nu = 5\) observed in graphene ribbons. (d) Data of (c) converted to \(T_{el}\) and \(T_{vb}\) showing hyperbolic behavior consistent with Eq. 3. (e) Magnetic field dependence for \(T = 2.5\) K and \(T = 12\) K, showing typical dip at \(B = 0\); (f) Same data as in (e) plotted as a function of \(T_{el}\) and \(T_B\) with superimposed simulation according to \(T_{el} = T + \mu|B|\) and \(T_B = \mu_B B/k_B\) with \(\mu = 5\mu_B\), as for graphene ribbons. As for ribbons, the behavior becomes complex for \(|B| > 2T\).
8. Explanation of the resistance doubling and tripling effect

Figure S9. Ballistic wire connected to contacts (left and right) as in Fig S11a. (Top) Undisturbed wire. (Middle) wire with one thermalizing probe. (Right) wire with two thermalizing probe.

Fig. S9 shows how invasive probes affect a current flow. For a ballistic one-dimensional non-degenerate wire, the conductance $G = G_0 T_r$, where $T_r$ is the transmission. If the flow is undisturbed then $T_r = 1$ and $G = G_0 = e^2/h$. For a more complete discussion, see refs 11, 12.

However an invasive probe will alter the flow. $P$ is the probability that a charge carrier moving past the probe will enter it. After thermalization in the probe, it exits it with equal probability going either to the right or to the left. As indicated in Fig. S9 the total forward probability is $(1-P)+P/2$ (the reflected probability is $P/2$). Hence, $T_r = 1-P/2$ and $G = (1-P/2)G_0$. If $P = 1$ (every electron enters and exits the probe) then $G = G_0/2$ (the resistance is doubled: $R = 2R_0$). In fact this is what should be expected, since a perfectly invasive probe simply divides the ballistic wire into two ballistic wires.

If two invasive probes are inserted (Fig. S9 bottom) then the situation is slightly more complicated, since the backward scattered charges from probe 2 (for example) will scatter from probe 1 etc. This results in a geometric series that is easily summed to give $T_r = (1-P/2)/(1+P/2)$; Hence, for $P = 1$, $T_r = 1/3$ and $R \rightarrow 3R_0$. 
9. FAQs: Alternative explanations suggested by referees and others

The entire surface is graphitized with a diffusive conducting layer giving rise to high conductivities; the observed conductance quantization is simply fortuitous.

This proposed morphology is contradicted by numerous experiments, see for example Fig. 2, and extensive Raman and EFM characterization (see for instance refs 13-16).

Resistances between adjacent ribbons are more than 450 kΩ (and more than 30 MΩ for the low-temperature measurements), at least an order of magnitude greater than along a ribbon.

This cannot explain the dependence on the probe separation.
This cannot explain the resistance doubling and tripling effect.

The probability \( P \) that measured values fall within 20% of each other in more than 50 samples (assuming a random distribution with a dispersion of a factor of 2, which is very conservative) is \( P = 10^{-50} \). Hence it is impossible.

The graphene is multilayered making the conductivities large

ARPES measurements show a monolayer (Fig. S1) \(^17\). Moreover, it would require at least 100 highly doped layers to attain the observed resistivities \((dR/dL)\), which is physically impossible. Also, this cannot explain the consistent \( 1 \left( \frac{h}{e^2} \right) \) contact resistance or the length dependence (or any of the other observed effects).

The ribbons are diffusive and the resistance doubling and tripling effect is caused by multiple side-by-side ribbons that are broken when they are touched by the probe and reunite when the probe is removed.

It is inconceivable that ribbons break and reform when touched by a probe. In order for several ribbons to consist of three ribbons in parallel to produce this effect would require an impossible combination of parallel diffusive ribbons.

The magnetic field dependence and temperature dependence is due to weak localization.

The fit to Eq. 2 is exceptionally good and requires a minimal number of parameters, each of which are well defined and consistent from one ribbon to the next. Neither the temperature dependence nor the magnetic field dependence nor the length dependence can be reproduced over the same range with using standard weak localization theory with accepted expressions for \( L_f \) and \( L_m \) (see for instance Ref. 10, 18. For example, for carbon nanotubes, two different power laws are need for \( L_f \) for \( 2 \text{ K} \leq T \leq 10 \text{ K} \) and \( 10 \text{ K} < T < 50 \text{ K} \^{10} \)).
The bias voltage dependence is due to the well-known zero bias anomaly.

Attempts to fit the bias voltage dependence of conductivity with standard approaches (Luttinger liquid $G(V_b)$ power law dependence) failed to reproduce the observed bias voltage dependence over any reasonable range.

Properties measured on epitaxial graphene are not relevant because substrate interactions are large.

Properties within 1 meV from charge neutrality are reliably attributed to graphene as experimentally demonstrated (see main text). Substrate interactions and strain induced effects measured in ARPES, STM and in transport are very small (see Fig. S1) and much smaller than in deposited and suspended graphene as clear from the scientific literature (See also Figs. S1 and S2).

D. In-situ resistance measurements, growth and characterization

1. Growth of GNRs for the in-situ resistance measurements and their ex-situ characterization

The GNR structures for the in-situ resistance measurements were grown in Hannover selectively by sublimation epitaxy on MESA-structured 6H-SiC(0001) surfaces\textsuperscript{13}. Before, 1 µm wide line structures were generated by optical lithography (UV-light, 286 nm) and reactive ion etching (RIE, SF$_6$ and O$_2$ ratio 20:7) onto the 6H-SiC(0001) surface (nitrogen doped, $10^{18}$ cm$^{-3}$). The optical mask was aligned such that the trench structures run along the [1-100] direction, i.e. the zig-zag direction for graphene grown epitaxially on Si-terminated SiC(0001). The anisotropic etching and suitable etching rates of around 0.3 nm/sec allows us to fabricate defined terraces and trench MESA structures. By thermal annealing (DC-heating in an Ar atmosphere of $4\times10^{-5}$ mbar, sample clamped by graphite contacts) of this structure clean and well-ordered crystal facets are forming around 1420 K \textsuperscript{13, 19}. Further annealing to 1570 K results in growth of extended graphene nanoribbons on these facets\textsuperscript{13, 20} as sketched in Fig. S10. The formation of well orientated graphene nanoribbon structures has been proven recently by LEED and ARPES measurements\textsuperscript{17}.

In this study ribbons down to 40 nm in width were obtained by using MESA trench structures of 20 nm in depth. Electrical measurements on these nanostructures were performed with a 4-tip STM/SEM system (Fa.Omicron nanoprobe). Details are reported below. Before transfer of these structures into the 4-tip STM/SEM system for further processing and electrical characterization the overall quality of the
ribons has been checked by AFM and EFM (see Fig. S10d,e). The line scan of the AFM demonstrates nicely the accuracy of the etching process. The local change of the work function upon formation of graphene at the sidewalls has been monitored using electrostatic force microscopy (EFM) as shown in Fig. S10e. After deconvolution of the AFM tip radius the full widths of the EFM-peaks located at the facet sites represent almost the width of the GNRs.

2. Characterization by 4-tip STM SEM

The GNRs have been characterized in-situ by means of electrical transport measurements using a 4-tip STM/SEM system (Nanoprobe system, Fa. Omicron). The system operates at a base pressure of $10^{-8}$ Pa and by cooling with Liq-He, temperatures down to 30 K can be obtained. By means of the in-situ high-resolution SEM (<4 nm) the tungsten-tips can be navigated to desired positions above the nanostructures and approached individually to the surface via feedback control approach mechanisms. The transport measurements in this study were performed usually in the following way:

Prior to measurements on the GNRs, the W-tips (NaOH-etched) have been “calibrated” after installation. By means of sheet conductance in 2d-graphene on SiC we have ensured that the tips are mechanically stable with a geometrically small (20-40 nm radius) and metallic apex structures. As mentioned above with the help of SEM the tips have been navigated to individual ribbons and placed above the ribbon in a collinear arrangement with well-defined equal inter-probe spacings $d$
Each tip has been approached via a feedback controlled loop into a tunneling contact at its desired position (set point +2 V, 1 nA). At first hereafter, the feedback was switched off and the tips approached via calibrated piezo-elements pressing on top of the ribbons for the final transport measurements. After each measurement the ribbons have been carefully checked by SEM in order to exclude tip-induced changes to GNRs (and to tips).

The ex-situ processed GNR-samples have been annealed (600 °C) in-situ in order to remove organic contaminations adsorbed during transfer. Furthermore, high temperature annealing (>1300 °C) is possible in this system as well and has been used occasionally to improve further the quality, i.e. the mean free paths (the $\lambda_{0\nu}$ - see main text – Fig. 3), of the ribbons.

The selective growth of graphene nanoribbons (GNR) is demonstrated here by lateral four-probe measurements and local tunneling spectroscopy (STS). A typical tip assembly is shown in Fig.S11a). The resistances were calculated from $I(V)$ curves in a current range of +/- 1 μA (cf. Fig.S11b). Most noticeably, the resistance measured on the sidewall is around 26 kΩ and almost by a factor of 20 lower compared to collinear transport measurements on the terraces (dashed line in Fig. S10a) or valleys of the MESA-s. The resistances on these areas are finite, possibly due to the SiC doping, but can be well discriminated from the resistances measured at the side walls.
Local spectroscopy (STS), performed with the tip moved by the high resolution scanner in the system, has been used in addition to determine the chemical potential of the GNRs. As seen in Fig. S11c the GNR is slightly p-doped ($E_F = 150$ meV below $E_D$) in agreement with ARPES measurements on GNR array structures processed in a similar manner\textsuperscript{17}. The fact that the chemical potential coincides de-facto with the Dirac point (ED) ensures, that only low lying subbands are occupied with electrons (see discussion below).

The STS spectrum taken on the terrace structure shows in contrast a gap of more than 1 eV at $E_F$. This supports our conclusions that spatially extended graphene nanostructures are formed exclusively at the step edges of the MESA structures. The onset of the current seen in the STS spectrum in the negative bias regime, which probes the occupied surface states, correlates nicely with ARPES data taken solely on buffer layer structures\textsuperscript{21}. Please note, the STS spectra were taken by positing the tips with radii of 20-40 nm roughly above center of the GNR, thus the spectrum represents basically an average of the electronic states across the ribbon structure.

3. Additional 4-probe in-situ resistance measurement of GNR

The transport properties for various GNR structures have been systematically investigated in-situ with respect to the number of contact probes, contact separation and sample temperature. As outlined in the main text, the 0- channel start to localize for distances $\geq 150$ nm. Consequently, to probe both channels requires extremely small contact spacing ($< 100$ nm), which is experimentally very demanding. In contrast the 0+ channel that shows a $e^2/h$ behavior over long distance is easily measured using larger spacing. The robustness of the ballistic behavior over long distance of the 0+ channel has been verified for many different ribbons. In total 50 different GNRs have been probed for three contact spacing in the intermediate length regime ($L = 500$ nm, 1.5 $\mu$m, and 5 $\mu$m) and various temperatures (32 K, 78 K, 120 K, 298 K). All ribbons were located within an area of 100 x 100 $\mu$m$^2$. Their values (absolute and relative to $G_0 = e^2/h$) are listed in Table 1 below and visualized by the histogram in Fig. S12. Most ribbons show a $e^2/h$ conductance and the variance can be correlated with the probe spacing: Higher (lower) conductance values correspond to shorter (larger) probe spacing due to contributions of the 0. The variation within each spacing regime is attributed to slightly different mean free path for different ribbons.
Table 1: Conductance measured on different GNRs. The absolute values, the actual probe spacing L as well as the temperature are given.

| Number | Conductance ($\mu$S) | Conductance $(G_0)$ | Probe spacing ($\mu$m) | Temperature (K) |
|--------|-----------------------|---------------------|------------------------|------------------|
| 1      | 58.479                | 1.509               | 0.50                   | 298              |
| 2      | 36.101                | 0.931               | 5.00                   | 298              |
| 3      | 34.965                | 0.902               | 5.00                   | 298              |
| 4      | 49.751                | 1.284               | 1.50                   | 298              |
| 5      | 41.152                | 1.062               | 5.00                   | 298              |
| 6      | 45.871                | 1.184               | 1.50                   | 298              |
| 7      | 29.673                | 0.766               | 5.00                   | 298              |
| 8      | 34.722                | 0.896               | 5.00                   | 298              |
| 9      | 36.900                | 0.953               | 0.50                   | 298              |
| 10     | 40.012                | 1.032               | 1.50                   | 298              |
| 11     | 48.309                | 1.247               | 5.00                   | 298              |
| 12     | 50.021                | 1.291               | 1.50                   | 298              |
| 13     | 37.878                | 0.978               | 5.00                   | 298              |
| 14     | 38.610                | 0.997               | 5.00                   | 298              |
| 15     | 43.290                | 1.117               | 1.50                   | 298              |
| 16     | 44.444                | 1.147               | 5.00                   | 298              |
| 17     | 44.843                | 1.158               | 0.50                   | 298              |
| 18     | 48.780                | 1.259               | 5.00                   | 298              |
| 19     | 55.865                | 1.442               | 0.50                   | 298              |
| 20     | 62.111                | 1.603               | 0.50                   | 298              |
| 21     | 37.593                | 0.970               | 1.50                   | 120              |
| 22     | 35.460                | 0.915               | 5.00                   | 120              |
| 23     | 37.453                | 0.967               | 5.00                   | 120              |
| 24     | 41.667                | 1.076               | 1.50                   | 120              |
| 25     | 43.290                | 1.117               | 5.00                   | 120              |
| 26     | 42.735                | 1.103               | 1.50                   | 120              |
| 27     | 46.082                | 1.190               | 1.50                   | 120              |
| 28     | 56.179                | 1.450               | 0.50                   | 120              |
| 29     | 59.171                | 1.527               | 0.50                   | 120              |
| 30     | 54.644                | 1.411               | 1.50                   | 120              |
| 31     | 39.920                | 1.030               | 5.00                   | 120              |
| 32     | 39.904                | 1.030               | 1.50                   | 120              |
| 33     | 38.910                | 1.004               | 5.00                   | 120              |
| 34     | 45.248                | 1.168               | 0.50                   | 120              |
| 35     | 40.322                | 1.041               | 1.50                   | 120              |
| 36     | 40.512                | 1.046               | 1.50                   | 32               |
| 37     | 35.971                | 0.929               | 5.00                   | 32               |
| 38     | 31.152                | 0.804               | 5.00                   | 32               |
Figure S10. (a)-(c) Schematics of the MESA before (a) and after facet formation at 1420 K (b) and GNR formation at 1570 K(c). (d) AFM image of a MESA before annealing. The line scan demonstrates the successful fabrication of steep trench structures with well-defined etching depths of 20 nm. (e) EFM image taken after the final temperature step showing preferential growth of GNR at the step edges of the mesa. The dashed curve is obtained after de-convoluting of the AFM-tip shape.
Figure S11. Demonstration of the collinear 4-probe in-situ resistance measurements. (a) SEM image of the tip positioning on top of a GNR. A current (typically +/-1 µA) was passed to the nanostructure by using the outermost tips, while the voltage drop was measured with the inner two probes. The selective growth of GNR at the step edges is demonstrated with (b) 4-tip transport (1 µm tip distance), showing that the resistance on the terrace is 20 times higher than on the ribbon and (c) STS (set point 1 nA, 2 V, measured with lock-in technique). All measurements were done at room temperature. The color codes in the different graphs correspond to each other.
Figure S12. Histogram of the conductance values taken on 50 different GNRs and probe spacing ($L = 0.5 \mu m$, $1.5 \mu m$, $5 \mu m$) revealing clearly a peak at the conductance quantum $e^2/h$. There is a clear trend, that the smaller (larger) conductance values correspond to larger (smaller) probe spacing. The variation with temperature is extremely small (see table) and not shown here.

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