Energy gaps in graphene nano-constrictions with different aspect ratios

B. Terrés[1,2], J. Dauber[1], C. Volk[1,2], S. Trellenkamp[2], U. Wichmann[1], and C. Stampfer[1,2]
[1] *JARA-FIT and II. Institute of Physics B, RWTH Aachen University, 52074 Aachen, Germany, EU*
[2] *Institute of Bio and Nanosystems, Forschungszentrum Jülich, 52425 Jülich, Germany, EU*
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We present electron transport measurements on lithographically defined and etched graphene nano-constrictions with different aspect ratios, including different length (l) and width (w). A roughly length-independent effective energy gap can be observed around the charge neutrality point. This energy gap scales inversely with the width even in regimes where the length of the constriction is smaller than its width ($l < w$). In very short constrictions we observe in the gap region both, resonances due to localized states or charged islands and an elevated overall conductance level (0.1 - $1e^2/h$), which is strongly length-dependent. This makes very short graphene constrictions interesting for high transparent graphene tunneling barriers.

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Graphene nanoribbons and constrictions [1–11] are promising candidates for overcoming the gapless nature of graphene [12]. Graphene, a truly two-dimensional (2D) semi-metal with unique electronic properties, is becoming increasingly interesting for high mobility ultrafast nanoelectronics [13]. However, the missing band gap in graphene makes it difficult to implement graphene switches, transistors and logic devices in general. By tailoring graphene into narrow ribbons or constrictions the formation of an effective band gap has been shown. Graphene constrictions have been successfully demonstrated as tunneling barriers in single electron transistors [14], quantum dots [15, 16] and more recently in double quantum dots [18–20]. The nature of the observed energy gaps has been discussed in great detail. From a theoretical point of view different models have been proposed to described the observed energy gap including quasi-1D Anderson localization [21–26], percolation [27] or Coulomb blockade on a series of localized states [28]. Experimentally, the nanoribbon width, w, dependence of the energy gap has been studied by a number of groups. However, only recently the influence of the nanoribbon length, l, has been investigated systematically for nanoribbons with $w < 40$ nm [10, 11]. So far, the experimentally studied graphene nanostructures exhibited an aspect ratio of $l > w$, such that the width was the smallest and dominating length scale in all systems.

Here, we present a systematic study on transport through graphene constrictions with different aspect ratios, including both different width and length. In particular, we focus on graphene constrictions in the regime of $l \approx w$, or even $l < w$ [see Fig. 1(a)]. We show that in these regimes the effective energy gap in bias direction, E_g, i.e. the charging energy of the smallest island in the constriction [6, 7], is still predominantly given by the width. However, the overall conductance level is strongly influenced by the length of the constriction. Most interestingly we show that in very short constrictions Coulomb blockade diamonds with high transparency can be observed.

The samples have been fabricated from graphene, which has been mechanical exfoliated from natural bulk graphite and deposited onto 295 nm SiO_2 on a highly p-doped Si substrate. Raman spectroscopy is used to verify the single-layer character of the investigated graphene nanostructures [29]. Electron-beam (e-beam) lithography is used to pattern the etch mask (≈ 110 nm of e-beam resist) for the nanostructured graphene devices.

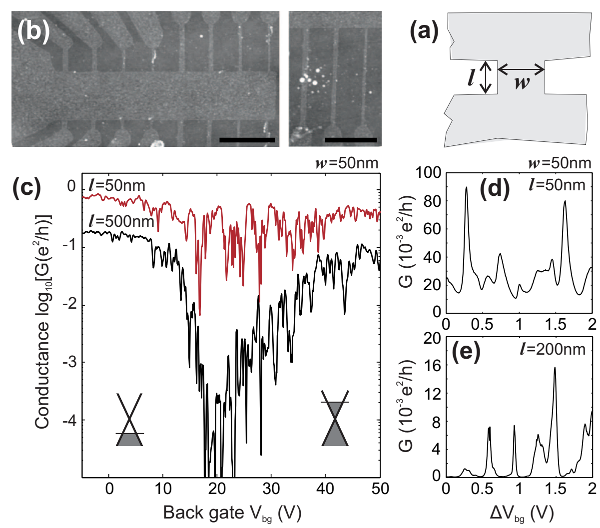

FIG. 1: (color online) (a) Schematic illustration of a constriction with length l and width w. (b) Scanning force microscope images of etched graphene constrictions with different aspect ratios. The length of the scale bars is 1 μm. (c) Back-gate characteristics at $V_b = 500$ μV for two graphene constrictions with width $w = 50$ nm and different length $l = 50$ nm (red curve) and $l = 500$ nm (black curve). (d,e) Conductance peaks in the transport gap region for two different constrictions, $w = l = 50$ nm (d) and $w = l/4 = 50$ nm (e) at $V_b = 100$ μV.

Reactive ion etching based on an Ar/O_2 plasma is introduced to remove unprotected graphene. Scanning force microscope images of etched graphene nanostructures after removing the residual resist are shown in Fig. 1(b). Finally, the graphene devices are contacted

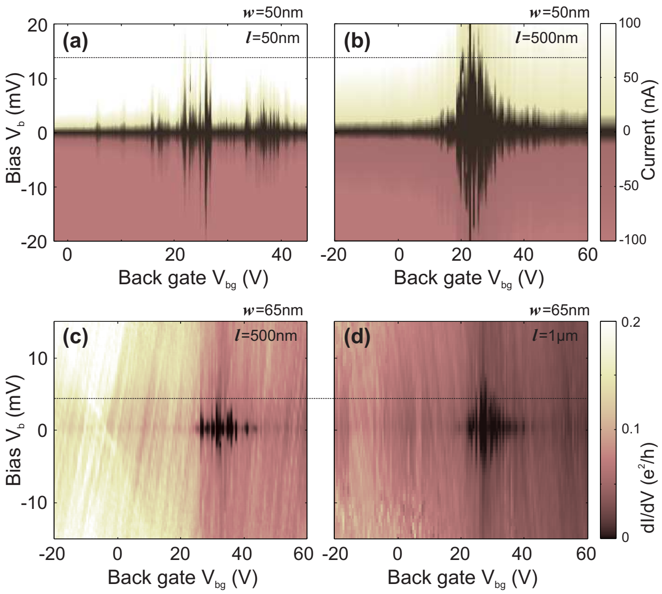

FIG. 2: (color online) (a,b) Color plot of the source-drain current as a function of applied back gate and bias voltage for two graphene constrictions with $w = 50$ nm and length $l = 50$ nm (a) and $l = 500$ nm (b). (c,d) Differential conductance as a function of back gate and bias voltage for graphene constrictions with $w = 65$ nm and length $l = 500$ nm (c) and $l = 1$ μm (d).

by e-beam patterned 5 nm Cr and 50 nm Au electrodes (not shown).

The measurements have been performed in a pumped ^{4}He system at $T \approx 1.3$ K. We have measured the current through the two-terminal constrictions by applying a small symmetric DC bias voltage V_b. The differential conductance has been measured directly by low-frequency lock-in techniques by adding an AC bias of 100 μV.

In Fig. 1(c) we show the conductance G as function of back gate (BG) voltage V_{bg} for two 50 nm wide constrictions with different length $l = 50$ nm and $l = 500$ nm (V_b = 500 μV). The transport gap, i.e. the V_{bg} region of suppressed conductance (roughly between 17 and 30 V) separates hole from electron transport as indicated by the two lower inserts in Fig. 1(c) [30]. Whereas for the 500 nm constriction the conductance is strongly suppressed in this regime (down to $10^{-5}e^2/h$) we observe for the shorter constriction a significantly elevated conductance. A number of pronounced resonances reaching lower conductance values, nevertheless mark the gap region in rather well agreement with the measurement on the longer constriction [compare also Fig. 2(a) and 2(b)]. A close-up of such resonances are shown in Fig. 1(d). These reproducible resonances have been taken at $V_b = 100$ μV within the BG range of minimum conductance. We observe neither complete pinch-off nor strong Coulomb blockade behavior, as it is found for longer constrictions with the same width. In Fig. 1(e), we show for example data recorded on a 200 nm long ($w = 50$ nm) constriction. The overall conductance level differs significantly, however the typical V_{bg} spacing between the resonances is comparable.

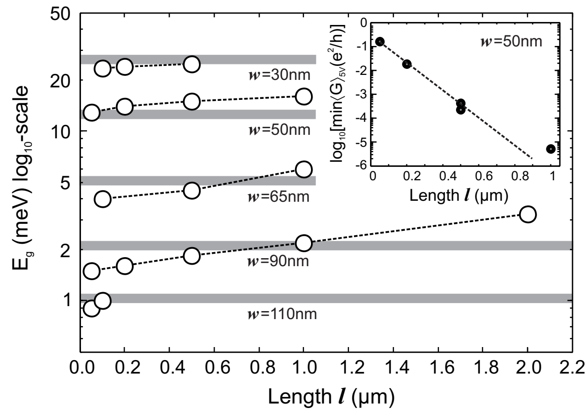

FIG. 3: Energy gap, E_g, as function of length l for a number of different graphene constrictions with different width w (see labels and data points connected by dashed lines). The horizontal gray lines are given by $E_g = a/we^{-bw}$, where $a = 2$ eV and $b = 0.026$ nm^{-1} taken from ref. [9]. The inset shows the minimum value of the running averaged conductance G over 5 V on back gate voltage.

In Figs. 2(a), 2(b) we show 2D-plots of current as function of bias and back gate voltage for the two 50 nm wide constrictions with $l = 50$ nm (a) and 500 nm (b). In good agreement with earlier studies [2, 5–11] we find a non-linear I-V characteristic inside the transport gap region, which can be best seen for the longer constriction [see e.g. dark area in Fig. 2(b)]. The maximum extend in bias direction marks the effective energy gap E_g, which has been shown to agree with the charging energy of the smallest island in the constriction [6, 7]. Interestingly, this energy scale does only weakly depend on the constrictions length. By comparing Figs. 2(a) and 2(b) we observe also in the 50 nm long constriction an effective energy gap of $E_g \approx 14$ meV, allowing the conclusion that the smallest island or localized state is predominantly a function of the width, w. The main difference can be found in the back gate coverage of the observed gaps. The shorter the constriction the fewer islands [or localized (edge) states] are in the constriction leading to fewer charging events. Consequently, the current is suppressed in smaller and fewer gate voltage regimes. However, the smallest island is found to be roughly length-independent (this is also true for $l < w$). The definition of the transport gap in BG voltage [5, 9], used as figure of merit in earlier work, is hard to define for very short constrictions since it is considered to strongly depend on the disorder potential [6, 7, 10], which due to missing averaging becomes very sample dependent.

Similar behavior can also be seen for a 65 nm wide, 500 nm and 1 μm long constriction as shown in Figs. 2(c) and 2(d), respectively. Here we plot the diff. conductance as function of V_b and V_{bg}. In both measurements an effective energy gap of roughly 4-6 meV can be observed. In total we studied roughly 20 graphene constrictions on 3

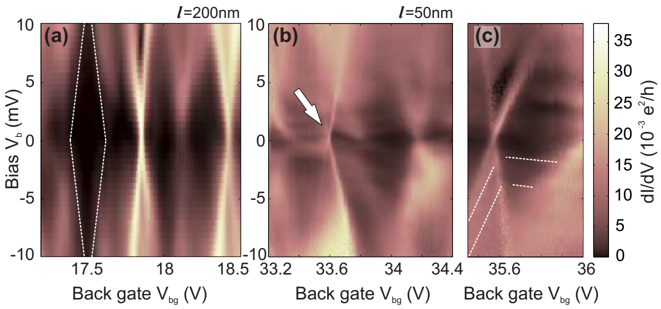

FIG. 4: (color online) Differential conductance versus back gate voltage and source-drain bias voltage of (a) 200 nm and (b,c) 50 nm long graphene constriction with a width of 50 nm. (a) Clear distinct diamonds of fully suppressed conductance can be observed (see white dashed line). (b,c) Similar data taken on a 50 nm long constriction. Diamonds at an elevated conductance level can be observed. Very sharp resonances [white arrow in panel (b)] and inelastic co-tunneling features [dashed lines in panel (c)] can be observed.

different samples. In Fig. 3 we summarize the extracted effective energy gaps E_g as function of the length for 5 different widths. It can be seen that E_g strongly depends on the width and we find good agreement with earlier experiments and theoretical models [11, 28]. In particular, we compare our results with the model from Sols et al., [28] where the energy gap is approximated by $E_g = a/we^{-bw}$, (see gray bars in Fig. 3), in agreement with earlier work [2, 9, 28]. In contrast to the weak E_g-length dependence we observe a rather strong length dependence of the minimum conductivity as shown by the inset in Fig. 3. The minimum value of the running averaged conductance decreases exponentially with increasing constriction length. This fits well with the scenario, where localizations or tunneling processes are dominating the transport through the constrictions. Moreover it shows that by making graphene constrictions very short we can access a conductance level close to e^2/h. More insights on the transparency of the shorter constrictions is gained by focusing on a smaller BG voltage range as shown in Fig. 4. These are high-resolution differential conductance dI/dV_b plots for different constrictions length with constant width (w=50 nm). Measurements on a 200 nm long constriction [Fig. 4(a)] show well distinguishable diamonds of suppressed conductance in good agreement with earlier studies. In shorter constrictions [w=50 nm; Figs. 4(b),4(c)] we observe diamonds where the conductance is not fully suppressed, most likely due to strong coupling to localized states or isolated charged islands. Moreover, we observe inelastic co-tunneling lines inside the diamond, which are well aligned with excited state features outside the diamond [see dashed lines in Fig. 4(c)]. According to recent experiments by Han et al. [11] the average hoping length L_c is found in the range of $w \lesssim L_c < 2w$. Consequently it will be likely that for very short constrictions L_c exceeds l ($l < w \lesssim L_c$) such that transport through short constrictions is no longer effectively 1D. Thus we may have parallel channels in the constrictions, which (i) may explain the strong increase in conductance and (ii) may open the door for interference or Fano resonances leading to very sharp features in the conductance [see e.g. white arrow in Fig. 4(b)].

In summary, we presented transport measurements on graphene nano-constrictions with different aspect ratios. We showed that the strongly width-dependent effective energy gap is roughly length-independent, whereas the overall conductance level depends strongly on the length. In the gap region of very short graphene constrictions a conductance level close to 0.1e^2/h can be reached, making these structures potential candidates for exploring Fano resonances and Kondo physics in graphene nanostructures.

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