Charge detection in gate-defined bilayer graphene quantum dots

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Abstract

We report on measurements of an electrostatically-defined quantum dot device in bilayer graphene with an integrated charge detector. The device is fabricated without any etching and features a graphite back gate, leading to high quality quantum dots. The charge detector is based on a second quantum dot separated from the first dot by depletion underneath a 150 nm wide gate. We show that Coulomb resonances in the sensing dot are sensitive to individual charging events on the nearby quantum dot. The potential change due to single electron charging causes a step-like change (up to 77%) in the current through the charge detector. Furthermore, the charging states of a quantum dot with tunable tunneling barriers and of coupled quantum dots can be detected.

Introduction

Graphene is a promising candidate for future nano-electronic devices including building blocks for quantum information processing. Reasons are the expected long spin lifetimes\[H\] and
high carrier mobilities. Experimentally these spin lifetimes have not been demonstrated yet. For progress in this direction a device is needed that allows to confine charges and simultaneously measure their dynamics in a time-resolved way. This is possible with a quantum point contact (QPC) as charge detector in close proximity to a graphene quantum dot (QD).

The gap-less electronic band structure and Klein tunneling through potential barriers make electrostatic confinement of charge carriers in monolayer graphene difficult. Therefore, in previous experiments, exfoliated graphene flakes have been etched to confine charge carriers in a quantum dot and to build charge detectors. A disadvantage of this fabrication method are charge carrier localizations at the rough sample edges.

In contrast, bilayer graphene offers the possibility to electrostatically define nanostructures by opening a band gap by applying a displacement field normal to the bilayer plane. With a suitable design of top and back gate electrodes, it allows for electrostatic confinement of charge carriers in high quality bilayer graphene devices. Recent experiments show the fabrication and measurement of high quality quantum dots and quantum point contacts using a graphite back gate. In GaAs based devices a combination of QDs and QPCs extended the possibilities to investigate QDs. For example, it allowed to detect spin-qubit states and molecular states in coupled QDs. Furthermore, charge detection can be used to investigate tunneling dynamics of charges in a time-resolved way and to obtain the full counting statistics of the charge current and the charge occupation. This makes coupling a QD to a charge detector interesting for advanced investigations of graphene QDs and a crucial ingredient to measure spin coherence times.

Here, we use bilayer graphene with its electrostatically induced band gap to fabricate a fully gate-defined device with quantum dots, which are also used as charge detectors. This allows to detect the charge carrier occupation of a graphene quantum dot. The quality of the bilayer graphene quantum dots and the amplitude of the detection signal matches what has been achieved in the traditional semiconductors Si and GaAs.
Figure 1: (a) False-color atomic force microscope (AFM) image of the electrostatically-defined device in bilayer graphene. By using the split gates SG (gray) in addition to the middle gate MG (gray) two conducting channels (channel 1 and channel 2, black) are created. The finger gates (blue and red) across the channels produce quantum dots and charge detectors in the bilayer graphene. (b) Schematic picture of the band structure at different lateral positions along the current direction (red and blue arrows in (a)) in the channel. The dashed line is the equilibrium electrochemical potential along the direction of current flow. (c) Measurement of Coulomb blockade diamonds of quantum dot 1 QD1, when the first three holes are charged into the dot.

The investigated bilayer graphene flake is encapsulated between two boron nitride flakes. The van-der-Waals heterostructure has been fabricated as described in Ref. The graphite back gate and two layers of patterned top gates (separated by an insulating Al₂O₃ layer) are used to tune the electric field perpendicular to the bilayer flake. The atomic force microscope image in Figure 1a shows the lateral layout of the two top gate layers with split gates (gray),
middle gate (gray), finger gates (blue and red) and the Ohmic contacts (yellow). Back
gate and top gates can be used to (i) open a band gap below the gates, and (ii) tune the
Fermi energy into the band gap, which renders these regions insulating. N-type channels
with a lithographic width of 100 nm are formed between the gates (see Figure 1b blue n-
doped regions) by applying a positive voltage to the graphite back gate ($V_{BG} = 3 \text{ V}$) and a
negative voltage to the split gates ($V_{SG} = -3.5 \text{ V}$). The MG is used to separate the channels,
where a gate width of 150 nm is needed to avoid leakage currents between them. Separate
source-drain bias voltages $V_{SD}$ can be applied to each channel using pairs of ohmic contacts
(Figure 1a). The finger gates (Figure 1a) are separated vertically from the split gates by a
30 nm thick layer of Al$_2$O$_3$. The wider finger gates have a width of 120 nm, the narrow one
is 20 nm wide. Their lateral separation is 90 nm. A quantum dot can be formed below each
of the finger gates (two quantum dots in channel 1 and three dots in channel 2). Using one
of the finger gates the Fermi-energy in the bilayer graphene region below the finger gate can
be tuned into the band gap (pinch-off) or into the p-region (Figure 1b red), where a QD
confining holes is formed. The band structure is sketched in Figure 1b (lower panel) with
source and drain contacts in the n-regions and the hole QD below the finger gate. Between
the n- and p-regions the Fermi-energy (at the edges of the finger gate, see Figure 1b) lies in
the band gap, hence natural tunnel barriers for the quantum dot are formed. Each quantum
dot with its sharp Coulomb resonances is also a sensitive detector for single charges in any
other QD nearby. All measurements presented here were performed in a dilution refrigerator
with an electronic base temperature of 60 mK in a two-terminal DC setup with a bias voltage
applied between source and drain, and the drain contact grounded.

Figure 1c shows a measurement of Coulomb blockade diamonds of QD1 formed under-
neath the red-colored finger gate in channel 1 (see Figure 1a). We measure the differential
current $\partial I_{QD1}/\partial V_{SD1}$ in channel 1 as a function of the finger gate voltage $V_{QD1}$ forming QD1
and the DC source-drain bias $V_{SD1}$. In the Coulomb blockade diamonds we see single holes
charging into the quantum dot at $V_{QD1} = -8.95 \text{ V}, -9.17 \text{ V}, -9.36 \text{ V}$ for $V_{SD} \approx 0 \text{ V}$. From
the Coulomb blockade diamonds a charging energy of about $E_{ch} = 5\, \text{meV}$ and a finger gate lever arm $\alpha = 0.02$ can be determined.

## Results and discussion

![Graph](image)

Figure 2: (a) Conductance $G_{QD2}$ of the signal dot (QD2) (upper panel) and conductance $G_{QD1}$ of the sensing dot (lower panel) as a function of the finger gate voltages $V_{QD2}$ and $V_{QD1}$ for a fixed back gate ($V_{BG} = 3\, \text{V}$) and split gate voltage ($V_{SG} \approx -3.5\, \text{V}$). Upper panel: Conductance $G_{QD2}$ of the signal dot (QD2) as a function of the finger gate voltages $V_{QD2}$ and $V_{QD2}$. The lines spaced with a periodicity of 0.09 V in $V_{QD2}$ are due to Coulomb blockade resonances. The lower panel shows the simultaneously-acquired measurement of the charge detector conductance $G_{QD1}$. We observe features aligned with the Coulomb resonances in the upper panel (highlighted with vertical dashed gray line) and tilted lines resulting from the cross capacitance between the sensing dot and $V_{QD2}$ (highlighted with diagonal dashed gray line). The dashed black lines in the upper and lower panel indicate the line cuts in b, respectively.

For the charge detection experiment shown in Figure 2, QD1 in channel 1 is used as sensing dot. A source-drain bias of 100 µV (optimized for the detection signal) is applied across the sensing dot and the finger gate voltage $V_{QD1}$ is chosen so that sequential tunneling through QD1 is possible and a current is measured. At this finger gate voltage the quantum dot is a sensitive detector for changes of the charge configuration in its environment. A small change in the electrostatic environment of the dot leads to a shift of the Coulomb resonance in energy (or equivalently, in finger gate voltage $V_{QD2}$) and therefore to a change...
in the conductance $G_{\text{QD1}}$ through channel 1.

A second p-type quantum dot (signal dot QD2) is formed below the left blue gate in channel 2 (Figure 1a), by tuning the finger gate voltage $V_{\text{QD2}}$. The linear conductance $G_{\text{QD2}}$ through channel 2 is shown in Figure 2a upper panel, where the gate voltages $V_{\text{QD1}}$ and $V_{\text{QD2}}$ are changed and a source-drain voltage of $V_{\text{SD}} = 100 \mu V$ across the signal dot is applied. By changing $V_{\text{QD1}}$ we scan across one Coulomb resonance of QD1 (detector dot) and measure the conductance $G_{\text{QD1}}$ in channel 1 and $G_{\text{QD2}}$ channel 2 at the same time. The upper panel in Figure 2a shows regularly spaced Coulomb resonances in the conductance of the signal dot, which slightly shift by changing $V_{\text{QD1}}$.

These resonances are observed through charge detection in the lower panel of Figure 2a. A line-cut in $V_{\text{QD1}}$ direction shows a Coulomb resonance of the sensing dot (QD1), that shifts to more negative $V_{\text{QD1}}$, when $V_{\text{QD2}}$ is increased. The diagonal shift of the sensing dots resonance (marked by diagonal dashed line) is due to the cross capacitance between the sensing dot and the finger gate voltage defining the signal dot. From this shift a ratio between the lever arm of the blue gate (FG2) on the sensor dot and the red gate (FG1) on the sensor dot $\alpha_{\text{FG2-QD1}}/\alpha_{\text{FG1-QD1}} = 0.07$ is calculated.

We identify single charging events in the signal dot as abrupt shifts of the conductance resonance in the sensing dot (marked with vertical dashed line), when the signal dot gets charged with an additional charge carrier. These abrupt shifts are aligned with the Coulomb resonances of the signal dot (see vertical dashed lines).

Line cuts from Figure 2a at $V_{\text{QD1}} = 9.1$ V are shown in Figure 2b. Regularly spaced conductance resonances are observed in Figure 2b (upper panel), when sequential tunneling through the signal dot is possible.

The corresponding conductance $G_{\text{QD1}}$ measured simultaneously in the detector channel is shown in the lower panel in Figure 2b. We observe a broadened resonance with its maximum at $V_{\text{QD2}} = -7.75$ V and a width of 1 V with step-like features on top, when we take a line cut in the lower panel in Figure 2a. The resonance is broader in $V_{\text{QD2}}$ than in $V_{\text{QD1}}$, due to
the much smaller lever arm of the blue finger gate on the sensing dot as compared to the red finger gate. The conductance steps (marked with vertical dashed lines) are related to a shift $\Delta V_{\text{QD2}}$ in the resonance of the sensing dot with respect to the signal dot’s voltage $V_{\text{QD2}}$.

From an analysis of the charging events an average shift in $\Delta V_{\text{QD2}} = 61 \text{ mV}$ (see Figure 2a) is observed. The conductance in the detector channel $\Delta G_{\text{QD1}} = 0.2 e^2/h$ (see Figure 2a) changes by up to 77% for a single charging event. This change in conductance is comparable with observations in GaAs quantum dots.

Figure 3: (a) Conductance $G_{\text{QD1}}$ of the signal dot and (b) conductance $G_{\text{QD2}}$ of the sensing dot as a function of the finger gate voltage $V_{\text{QD1}}$ for a fixed back gate ($V_{\text{BG}} = 3 \text{ V}$) and split gate voltage ($V_{\text{SG}} = -3.5 \text{ V}$). (a) The first three Coulomb resonance of the signal dot are measured directly in the current through the dot and (b) in the charge detector. At $V_{\text{QD1}} = -8.9 \text{ V}$ the first Coulomb resonance and also the first step in the detector signal is measured, proofing the charging of the QD with the first hole.

In the following, we exchange the role of the two dots, to confirm that we are able to fully deplete the quantum dot and fill it with individual holes. The quantum dot in channel 2 (QD2) will be used as the sensing dot. The conductances of the signal dot in channel 1 (QD1) is shown in Figure 3a. For QD1, we can clearly see a first Coulomb resonance (marked by 1) in the conductance of the channel with the signal dot at $-8.9 \text{ V}$. The conductances $G_{\text{QD1}}$ and $G_{\text{QD2}}$ of both channels are shown in Figure 3a and b, while the gate voltage of the signal dot (QD1) is changed and a source-drain bias of $V_{\text{SD}} = 100 \mu\text{V}$ is applied to both channels. In the conductance of the detector $G_{\text{QD2}}$ a first step is also observed at about
Figure 4: (a) Differential conductance $\partial I_{QD1}/\partial V_{QD2}$ in the detection channel, when multi dots are formed in channel 2. The white dotted lines indicate the boundaries of four different regions. In region $\odot 1$, a single electron dot is formed between two barriers. In regions $\odot 2$ and $\odot 3$, an electron-hole double dot is formed between the gates and below one of the gates, respectively. In region $\odot 4$, a triple dot is measured. The three dots are formed below each of the gates and between them. (b) Schematic picture of the device showing the different dot configurations in (a). Red dots and blue dots show the QDs formed below the gates (hole dots) and between them (electron dots), respectively.

Furthermore, QDs with tunable tunneling barriers and multiple-dots can be formed in channel 2 using the two broader finger gates (blue in Figure 4b). Figure 4a shows the differential conductance of the charge detector $\partial I_{QD1}/\partial V_{QD2}$ (the conductance change through the signal dot is lower than our measurement resolution) as function of the gate voltages $V_{QD2}$ and $V_{QD3}$ that were applied to the two outer finger gates in channel 2. Three distinct sets of resonances are observed (vertical (marked with red arrows), horizontal (marked with blue arrows) and diagonal (marked with white arrows) resonances in Figure 4a). The measurement can be divided into four quadrants (1 to 4), separated by the white dashed lines. The corresponding sketch of the charge carrier distributions along channel 2 is shown in Figure 4b. In the first quadrant of Figure 4a we observe diagonal resonances only, that belong to a single electron dot formed between the two outer gates in channel 2 (dark blue in Figure 1a and Figure 4b). The two finger gates are tuned close to the charge neutrality point, thus creating tunneling barriers between the source and drain contacts (see Figure 4b).
Both gates have the same lever arm on the resonances of this dot, leading to diagonal resonances with a slope of about -1 in this measurement. The tunneling barriers of this dot are tunable, which allows for changing the tunneling rates through the dot.

By decreasing the voltages of the finger gates $V_{QD2}$ and $V_{QD3}$ further, we can form double- and triple-dots in channel 2 (sketches of the charge carrier density in the channel are shown in Figure 4 to 4) similar as demonstrated in Ref. Charge occupation of these multidots is also detected using QD1 as the charge detector. On the one hand, the gate voltage $V_{QD2}$ on the left outer finger gate in channel 2 is more negative and a hole dot forms below the gate. Hence, additional vertical resonances (marked with red arrows) are observed in region 2 at $V_{QD2} = -5.61 \text{ V}, -5.76 \text{ V}, -5.87 \text{ V} \text{ and } -5.97 \text{ V}$ (see schematic picture 2 in Figure 4b). For this situation of an electron-hole double-dot, we observe the typical honeycomb pattern using the charge detector.

On the other hand, we decrease the voltage on finger gate 3 ($V_{QD3}$) such that a hole QD is formed below this gate. We observe horizontal resonances in region 3 in Figure 4a ($V_{QD3} = -6.26 \text{ V}, -6.38 \text{ V} \text{ and } -6.47 \text{ V}$, marked with blue arrows), which are not influenced by $V_{QD2}$. In region 4 in Figure 4a, three dots are formed- one p-type QD below each of the gates and an n-type dot between them. This leads to diagonal resonances for the tunneling through the electron dot in the middle, horizontal resonances for tunneling through QD3 and vertical line for tunneling through QD2.

The three dots measured in Figure 4a have different distances to the charge detector. Hence, charging the different dots leads to different energy shifts of the sensing dots resonance. The distance between the signal dot and the sensing dot changes from 260 nm (dot between the gates, blue in Figure 4b) to 315 nm (dot below left gate in Figure 4b). The energy shift of the detector resonance is evaluated from the detection signal using the shift in gate voltage and the relative lever arms $\alpha$, $\alpha_{FG1-QD1}/\alpha_{FG2-QD1}$ and $\alpha_{FG1-QD1}/\alpha_{FG3-QD1} = 0.01$. It decreases with the distance between sensing and signal dot from 50 $\mu$eV to 5 $\mu$eV in agreement with a Coulomb screening model. Our sample design allows for a minimal distance of
150 nm between the sensing dot and the signal dot, which leads to an energy shift of 6 meV which is of the same order as the charging energy of the sensing dot.

In conclusion, we presented an electrostatically-defined device that allows us to detect single charge carriers in bilayer graphene quantum dots. Using conductance resonances in the Coulomb-blockade regime of a second quantum dot as a sensitive detector, we reached a maximum relative conductance change of 77% for charge detection. Our measurements show that a width of 150 nm for the MG is sufficient to avoid leakage between the sensing and signal dot and to reach a high signal-to-noise ratio in the detector. Using this device, we were able to show complete depletion of one of the quantum dots. Furthermore, we were able to observe the changes in the charge state of a quantum dot with tunable tunneling barriers, and of a multi-dot system. In the multi-dot regime, the charge detection enables us to determine the number of charge carriers in each of the dots. Our experiments demonstrate a device that is needed as the starting point for time-resolved measurements in graphene quantum dots, which may allow us to investigate the spin-lifetime in graphene.

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References

(1) Trauzettel, B.; Bulaev, D. V.; Loss, D.; Burkard, G. Spin qubits in graphene quantum dots. *Nature Physics* **2007**, *3*, 192.
(2) Novoselov, K. S.; Geim, A. K.; Morozov, S.; Jiang, D.; Katsnelson, M.; Grigorieva, I.; Dubonos, S.; Firsov, A. Two-dimensional gas of massless Dirac fermions in graphene. Nature 2005, 438, 197.

(3) Zhang, Y.; Tan, Y.-W.; Stormer, H. L.; Kim, P. Experimental observation of the quantum Hall effect and Berry’s phase in graphene. Nature 2005, 438, 201.

(4) Banszerus, L.; Schmitz, M.; Engels, S.; Dauber, J.; Oellers, M.; Haupt, F.; Watanabe, K.; Taniguchi, T.; Beschoten, B.; Stampfer, C. Ultrahigh-mobility graphene devices from chemical vapor deposition on reusable copper. Science advances 2015, 1, e1500222.

(5) Elzerman, J.; Hanson, R.; Van Beveren, L. W.; Witkamp, B.; Vandersypen, L.; Kouwenhoven, L. P. Single-shot read-out of an individual electron spin in a quantum dot. Nature 2004, 430, 431.

(6) Katsnelson, M.; Novoselov, K.; Geim, A. Chiral tunnelling and the Klein paradox in graphene. Nature physics 2006, 2, 620.

(7) Ponomarenko, L.; Schedin, F.; Katsnelson, M.; Yang, R.; Hill, E.; Novoselov, K.; Geim, A. Chaotic Dirac billiard in graphene quantum dots. Science 2008, 320, 356–358.

(8) Güttinger, J.; Molitor, F.; Stampfer, C.; Schnez, S.; Jacobsen, A.; Dröscher, S.; Ihn, T.; Ensslin, K. Transport through graphene quantum dots. Reports on Progress in Physics 2012, 75, 126502.

(9) Güttinger, J.; Stampfer, C.; Hellmüller, S.; Molitor, F.; Ihn, T.; Ensslin, K. Charge detection in graphene quantum dots. Applied Physics Letters 2008, 93, 212102.

(10) Bischoff, D.; Varlet, A.; Simonet, P.; Eich, M.; Overweg, H.; Ihn, T.; Ensslin, K. Localized charge carriers in graphene nanodevices. Applied Physics Reviews 2015, 2, 031301.
(11) McCann, E. Asymmetry gap in the electronic band structure of bilayer graphene. *Physical Review B* **2006**, *74*, 161403.

(12) Ohta, T.; Bostwick, A.; Seyller, T.; Horn, K.; Rotenberg, E. Controlling the electronic structure of bilayer graphene. *Science* **2006**, *313*, 951–954.

(13) Oostinga, J. B.; Heersche, H. B.; Liu, X.; Morpurgo, A. F.; Vandersypen, L. M. Gate-induced insulating state in bilayer graphene devices. *Nature materials* **2008**, *7*, 151.

(14) Eich, M.; Pisoni, R.; Overweg, H.; Kurzmann, A.; Lee, Y.; Rickhaus, P.; Ihn, T.; Ensslin, K.; Herman, F.; Sigrist, M. Spin and Valley States in Gate-Defined Bilayer Graphene Quantum Dots. *Physical Review X* **2018**, *8*, 031023.

(15) Banszerus, L.; Frohn, B.; Epping, A.; Neumaier, D.; Watanabe, K.; Taniguchi, T.; Stampfer, C. Gate-Defined Electron–Hole Double Dots in Bilayer Graphene. *Nano Letters* **2018**, *18*, 4785–4790.

(16) Eich, M.; Pisoni, R.; Pally, A.; Overweg, H.; Kurzmann, A.; Lee, Y.; Rickhaus, P.; Watanabe, K.; Taniguchi, T.; Ensslin, K.; Ihn, T. Coupled Quantum Dots in Bilayer Graphene. *Nano Letters* **2018**, *18*, 5042–5048.

(17) Petta, J. R.; Johnson, A. C.; Taylor, J. M.; Laird, E. A.; Yacoby, A.; Lukin, M. D.; Marcus, C. M.; Hanson, M. P.; Gossard, A. C. Coherent manipulation of coupled electron spins in semiconductor quantum dots. *Science* **2005**, *309*, 2180–2184.

(18) DiCarlo, L.; Lynch, H.; Johnson, A.; Childress, L.; Crockett, K.; Marcus, C.; Hanson, M.; Gossard, A. Differential charge sensing and charge delocalization in a tunable double quantum dot. *Physical review letters* **2004**, *92*, 226801.

(19) Gustavsson, S.; Leturcq, R.; Simović, B.; Schleser, R.; Ihn, T.; Studerus, P.; Ensslin, K.; Driscoll, D.; Gossard, A. Counting statistics of single electron transport in a quantum dot. *Physical review letters* **2006**, *96*, 076605.
(20) Vandersypen, L.; Elzerman, J.; Schouten, R.; Willems van Beveren, L.; Hanson, R.; Kouwenhoven, L. Real-time detection of single-electron tunneling using a quantum point contact. *Applied Physics Letters* **2004**, *85*, 4394–4396.

(21) Overweg, H.; Eggimann, H.; Chen, X.; Slizovskiy, S.; Eich, M.; Pisoni, R.; Lee, Y.; Rickhaus, P.; Watanabe, K.; Taniguchi, T.; Fal’ko, V.; Ihn, T.; Klaus, E. Electrostatically induced quantum point contacts in bilayer graphene. *Nano letters* **2017**, *18*, 553–559.