The influence of lateral gates on the quantum capacitance of graphene nanoribbons

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Due to the low carrier density in the near vicinity of the charge neutrality point, graphene exhibits quantum capacitance effects [1, 2]. In advanced graphene nanodevices lateral side gates play an important role. For example, they are used to locally tune the potential in graphene nanoribbons (GNRs). Here we report on numerical calculations of the quantum capacitance of GNRs using the next**nano** software [3] where we solved the two-dimensional Poisson equation and calculated the density in graphene according to Ref. [2]. We investigated several device and potential configurations for nanoribbons with varying width, namely (i) nanoribbons without side gates, (ii) with lateral metal side gates with applied symmetric/antisymmetric potentials, and (iii) with lateral graphene side gates with applied symmetric/antisymmetric potentials. We found that the presence of lateral side gates has significant influence on the capacitance of a graphene nanoribbon.

For studying the electronic properties, and in particular different transport mechanisms in graphene, it is essential to tune the electrostatic potential globally and locally with gate electrodes. This allows, for example, to measure the conductance through a graphene sheet as a function of the Fermi level. Electrostatic coupling between several gate electrodes and graphene has to be calculated numerically. In order to optimally tune transport properties of graphene nanodevices by external parameters, an understanding of different device and gate configurations is necessary. The capacitance of a graphene sheet or a nanoribbon plays a significant role, since it reflects the coupling between the gate potential and the graphene. It also allows to draw a conclusion about the density of states in graphene, and the number of charge carriers which are involved in transport. Here we show numerical calculations of the quantum capacitance of nanoribbons with different gate configurations using the next**nano** software [3]. A simple model layout is shown in Fig. 1. It consists of an extended metal back gate (BG), a SiO_2 substrate acting as a dielectric material (ε_r = 3.9), a graphene nanoribbon of width *w* and lateral side gates separated by an air spacer of width *s*. The ideal classical parallel plate capacitance of a 300 nm thick silicon dioxide layer located between two metals is 11.5 nF/cm^2. Replacing one metal with a graphene layer leads to a slightly smaller capaci-

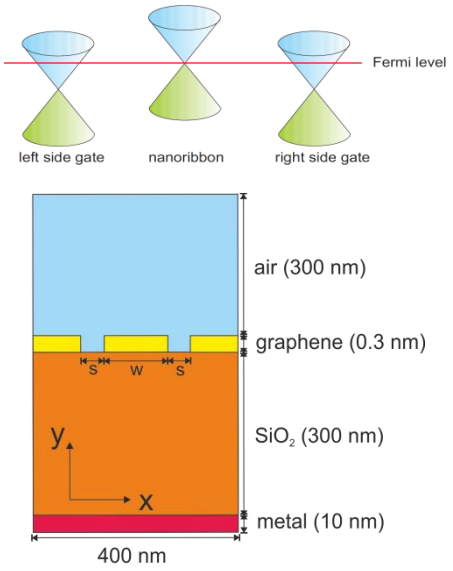

***Fig. 1**: 2D layout with side gates. The electrostatic potential in the graphene nanoribbon of width w (yellow) is tuned by a metal back gate (red) and by two lateral graphene side gates (yellow) that are separated from the nanoribbon by an air spacer of width s. The density in each graphene region can be tuned separately indicated by the schematic illustration of the three Dirac cones for the case of a symmetric side gate voltage.*

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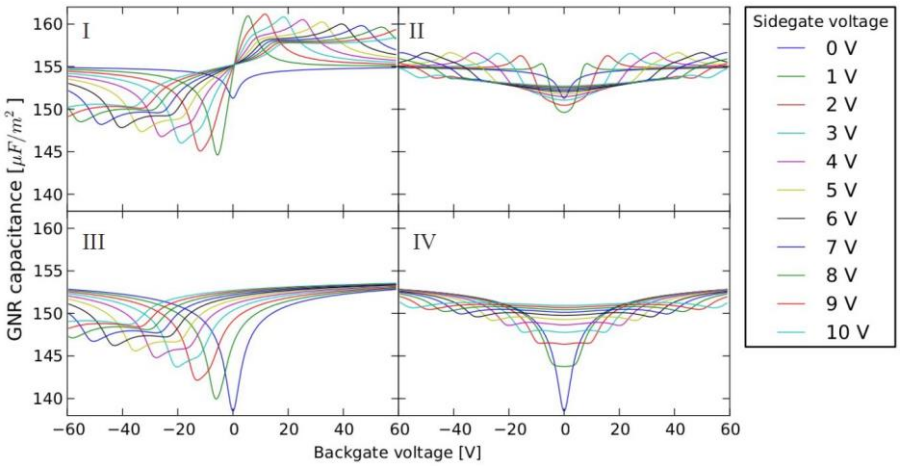

***Fig. 2**: Capacitance of a graphene nanoribbon (w = 80 nm, s = 30 nm, T = 300 K) with respect to the back gate voltage in the presence of graphene side gates with (I) symmetric and (II) antisymmetric ($V_{left} = -V_{right}$) voltage, and metallic side gates with (III) symmetric and (IV) antisymmetric side gate voltage. The bias of the graphene nanoribbon is at 0 V.*

tance with a dip around the Dirac point where for low back gate voltages the change of density as a function of voltage is smaller due to the low density of states, i.e. due to the quantum capacitance. Graphene nanoribbons (GNRs), however, show a larger capacitance than graphene. The capacitance of nanoribbons without side gates decreases with increasing ribbon width and approaches the limit of an infinite graphene sheet around $w > 300$ nm. For $w = 30$ nm values of about 80 nF/cm^2 are obtained. For very small GNR widths additional quantum confinement modifies the density of states which is not yet considered in our model but can easily be added [2]. Now we consider two cases: metallic side gates, and graphene side gates. Additionally, we compare a setup for which the same voltage is applied on both (the left and right) side gates (symmetric) with the one where antisymmetric potentials are applied (same absolute value but different in sign) (Fig. 2). We found that nanoribbons with side gates show a smaller capacitance than those without side gates because the side gates partially screen the electric field applied on the back gate. In all cases, the quantum capacitance dip gets broadened for larger side gate voltages. The location of this dip shows the back gate voltage where the Dirac point in the nanoribbon is reached. For symmetric, nonzero side gate potentials, the capacitance is not symmetric any more with respect to V_{BG} and the dip is shifted away from $V_{BG} = 0$ V. (I) is qualitatively very different from (III) because the graphene side gates exhibit additional quantum capacitance effects. Due to this, graphene side gates feature additional positive peaks (I, II). Furthermore, the dip splits into 2-3 local minima which can be explained by the different positions of the charge neutrality point in the side gates and the nanoribbon (see also the schematic illustration of the Fermi level and the dispersion relation for negative side gate voltages in Fig. 1).

In summary we have shown that the effect of quantum capacitance of a graphene nanoribbon can be differently tuned by either having metal or graphene side gates.

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