Edge Contribution to the Hall Potential Profiles in Graphene under Quantum Hall Conditions

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By using a scanning probe technique at a temperature of 1.4 Kelvin we extract Hall potential profiles in graphene flakes - exfoliated on a Si/SiO_2 substrate - under quantum Hall conditions, and compare them to former measurements on two-dimensional electron systems (2DESs) embedded in GaAs/(Al,Ga)As heterostructures [1]-[3]. We find for graphene flakes similar results as for the GaAs/(Al,Ga)As samples, i.e., electrostatic screening at the edges plays an important role: With varying the Landau level filling factor by the backgate voltage, incompressible strips evolve from both opposite edges towards the bulk, carrying the externally biased current as dissipationless Hall current through the flake. Remarkably, due to the evolution of the Hall potential profiles with varying the backgate voltage we can conclude that in the n-type regime a depletion of electrons towards the flake edges is observed whereas in the p-type regime an accumulation of holes is seen. Based on electrostatic simulations this indicates as the net effect the presence of fixed negative charges at the flake edges or on/in the uncovered SiO_2 layer next to the flake. We conclude that - due to the 'edge charges' - there is not a well defined charge neutrality point in such graphene flakes, i.e., while the bulk is still governed by electron surplus, holes dominate already at the edges.

The sample used here was prepared by exfoliation of highly oriented pyrolytic graphite (HOPG) onto a silicon/silicon-dioxide substrate. The highly n-doped silicon substrate worked later in the experiments as backgate, the 300 nm thick SiO_2 as insulator between the graphene flake and the backgate. The backgate allows the variation of the charge carrier concentration and for a transition from n- to p-type conduction. To electrically contact the flake, two metal electrodes were deposited, acting as source and drain contact, respectively. The sample was put into the scanning force microscope and pumped overnight without heating before it was cooled down to $1.4\,\mathrm{K}$. The inset in Fig. 1 shows a topographic scan of the flake which had a width of $3.5\,\mu$m and a length of $8.8\,\mu$m.

The Hall potential profiles obtained at a magnetic field of $3\,\mathrm{T}$ for different V_{BG}, i.e., different Landau level filling factor values ν, are shown in Fig. 1. The black dots represent the two-terminal resistance of the flake which was acquired simultaneously with the Hall potential measurements. The measured profiles clearly reflect the change of polarity in the Hall voltage with going from n-type conduction to p-type conduction by crossing the charge neutrality point (usually assumed to be at the position of maximum resistance) with lowering V_{BG}. Three striking features in the evolution of the Hall potential profiles can be identified in Fig. 1: (1) Different types of Hall potential profiles are observed at the lower and the upper tail of the resistance plateaus. For the lower V_{BG} side of the plateau the drop spreads over the bulk, whereas for the upper V_{BG} side pronounced drops appear close to both edges. The two positions of largest Hall potential drop move with negative going V_{BG} from the edges towards the bulk, leading to the u-shaped like features visible in the color-coded plot of Fig. 1. (2) An asymmetry across the charge neutrality point is found. The mentioned u-shape does not flip upside down by going from electron to hole conduction with decreasing V_{BG}. (3) At $V_{\mathrm{BG}} = 2.56\,\mathrm{V}$ - the value of maximum resistance which is usually assumed to be the charge neutrality point, the Hall potential drops with a finite slope over the center region of the flake. The V_{BG} value leading to zero Hall voltage drop in the flake center is at about $1.83\,\mathrm{V}$, i.e., below the V_{BG} value of maximum resistance.

A similar evolution of Hall potential profiles versus Landau level filling factor ν was found - more pronounced - in former measurements on GaAs/(Al,Ga)As samples [2]. There the evolution of Hall potential profiles - especially the u-shape feature - has been attributed to the shift of incompressible strips from the electrostatic depletion regions at the edges towards the bulk of the 2DES with increasing the magnetic field, which is equal to an increase of the Landau level degeneracy and therefore a decrease of the Landau level filling factor for a given electron density of the 2DES. The 2DES behaves locally incompressible wherever the Fermi level lies locally between two Landau levels, i.e., locally the filling factor is integer-valued. An electrostatic depletion of electrons towards the edges causes the following situation: Although the bulk is compressible, the electron concentration towards the edges reduces and therefore at certain positions the local electron density is equal to an integer multiple of the Landau level degeneracy n_{L} at the respective magnetic field value. It means incompressible strips are present along the edges of the 2DES. The innermost incompressible strip has filling factor $i = \mathrm{int}(\nu)$. The innermost incompressible strips at opposite edges move and broaden towards the bulk with lowering the bulk filling factor, they merge, and therefore the whole bulk becomes incompressible with $\nu_l = i$, interspered by compressible droplets due to the inhomogeneity of the 2DES. In this regime, the compressible/incompressible landscape and therefore the Hall potentail profile is very sensitive to magnetic field changes, however the Hall resistance value is quantized and insensitive. Increasing the magnetic field, i.e., the Landau level degeneracy

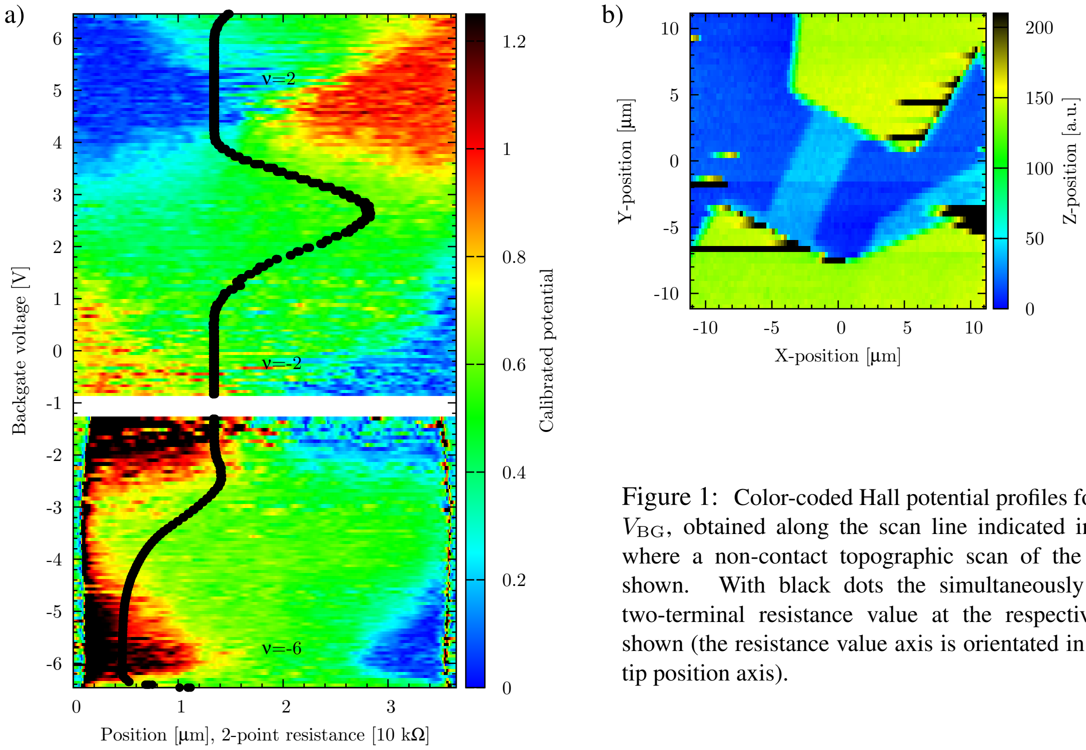

Figure 1: Color-coded Hall potential profiles for different V_{BG}, obtained along the scan line indicated in the inset where a non-contact topographic scan of the sample is shown. With black dots the simultaneously measured two-terminal resistance value at the respective V_{BG} is shown (the resistance value axis is orientated in parallel to tip position axis).

and spacing further, the bulk becomes compressible again, incompressible strips move and broaden again from the edges towards the bulk - but now with local filling factor $\nu_l = i - 1$. A Hall voltage drop over these incompressible strips allows for a dissipationless current flow. To prevent scattering of electrons from the outer compressible edge towards the compressible bulk (or vice versa) which limits the possible Hall voltage drop over the incompressible strip in between, the incompressible strip has to be wide enough to suppress such scattering. If the externally biased current is flowing completely within incompressible strips or the incompressible bulk of filling factor i, i.e., the Hall voltage drops only over such incompressible regions, a quantized Hall resistance value $h/(i\,e^2)$ is measured.

By finding the u-shaped feature in the evolution of Hall potential profiles versus filling factor (here tuned by the backgate voltage) also in n-type graphene, a similar electrostatic depletion of electrons at the edges of graphene seems to be present, with a depletion width of about a micron. To make this conclusion clear, in Fig. 2a the electron concentration profile for n-doped graphene in high magnetic field is sketched assuming depletion towards the edges. By reducing the overall electron density - which is obtained by lowering the backgate voltage from positive values towards the charge neutrality point - the positions of incompressible strips move towards the bulk center (see evolution sketched in Fig. 2a), i.e., pronounced Hall potential drops appear first close to both edges, then moving towards the bulk with lowering the backgate voltage. The u-shape-like evolution of Hall potential drops versus backgate voltage visible in Fig. 1 for n-type graphene is reconstructed.

What about the evolution below the charge neutrality point, i.e., for the case of p-type conduction? To reconstruct the u-shape feature observed in this regime in Fig. 1, we have to assume an accumulation of holes towards the edges, as shown in Fig. 2b. Reducing the backgate voltage towards negative values, the overall hole density is increased, and the positions of incompressible strips moves from the edges towards the bulk (see evolution sketched in Fig. 2b). This leads to the same evolution of the Hall potential profile with lowering backgate voltage as for the n-type region, except that the Hall voltage polarity is switched. This is consist with our observation. To summarize, the pronounced Hall potential drops evolving from the edges towards the bulk with lowering backgate voltage reflect the moving position of the innermost incompressible strip along the respective edge. In reverse, such measurement allow to conclude on the electron density profile at the edges of the 2DES.

How to understand electron depletion in the n-regime and hole accumulation in the p-regime towards the edges in such graphene samples? The graphene flake and the backgate resemble a plate capacitor arrangement: For positive electrostatic potential on the backgate, electrons are accumlated in the graphene, whereas for negative electrostatic potential holes are accumulated, for zero potential, the charge neutrality point for graphene is reached. However at the edges of the flake, the electric field between backgate and flake is enhanced, leading to higher charge carrier concentrations at the edges in both cases - n-type and p-type. In case of electron enhancement towards the edges, the evolution of pronounced Hall potential drops versus backgate voltage should follow an inversed u-shape - which is in contradiction to our observation. Furthermore, in case of an enhancement (depletion) of holes in the p-type regime and electrons in the n-type regime towards the edges we should observe an upside-down flip of the u-shaped features with crossing the charge neutrality point. Also this is not observed. If we assume in addition fixed negative charges sitting close to the edges of the flake in this arrangement, electrons will be repelled from the flake edges and holes attracted - which is qualitatively consistent with our observation.

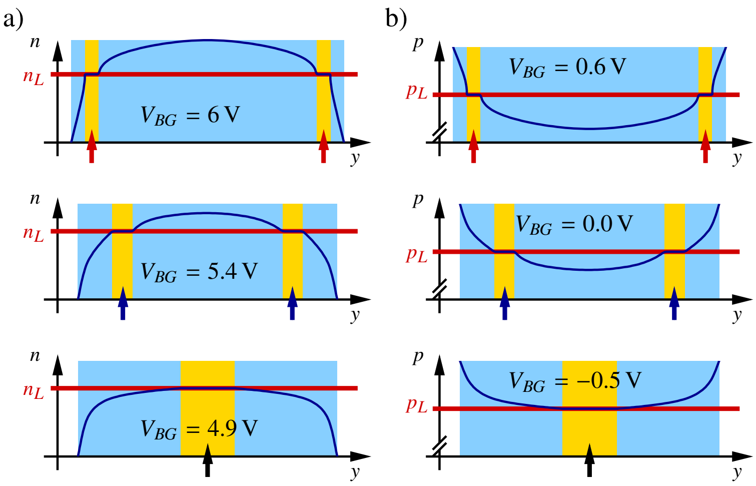

Figure 2: Sketches of the charge carrier profiles (black line) over the cross section of the graphene flake in case of n conduction (a) and p conduction (b) for various backgate voltages $V_{\rm BG}$. The $V_{\rm BG}$ values should help to link the sketched profile with the respective Hall potential profile presented in Fig. 1. Electrically incompressible regions are shaded in yellow, compressible ones in blue. The charge carrier density $2 \cdot n_{\rm L}$ leading to $\nu = \pm 2$ quantum Hall states at that given magnetic field is marked as red horizontal line.

To be more quantitative, we performed electrostatic simulations of charge carrier profiles at the flake edge and compare the results with the position of maximum Hall voltage drop in Fig. 1. From that comparison we could conclude that a surplus of localized negative charge is sitting on the silicon oxide surface close to the flake edges. It would require too many negative charges only located on the flake edges - for instance, due to defect or chemical adsorption - causing the strong electrostatic depletion we have observed in our flake.

As a consequence of this localized charge at the edges, moving from n to p-type conduction by negatively going backgate voltage, there is no backgate voltage value where no charge carriers are present over the whole flake. We find already holes towards the edges while still electrons are present in the flake center, with transition regions from n to p-type conduction in between. Having electron and hole currents in parallel, the Hall voltages of both type of currents (partly) compensate. However spatially resolved, the Hall potential profile should show positive and negative slopes depending on the locally dominant type of charge carrier. This clarifies the third feature we have identified in the data of Fig. 1: At maximum of resistance (at $V_{\rm BG} = 2.56$ V) which is usually identified as charge neutrality point, the bulk region of the flake shows a Hall potential drop indicating electron conductivity in the bulk of the flake. A flat Hall potential profile in the bulk is observed at $V_{\rm BG} = 1.83$ V, indicating the absence of current flow in the bulk - which is expected for charge neutrality as no charge carriers are present. We can conclude that maximum in resistance is not the right indicator for the charge neutrality point. The local scanning probe measurement performed here give a clear insight: The resistance value of the flake is not at maximum in case of charge neutrality in the bulk as already hole conduction is present along the edges.

References:

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