Quantum Hall conductance of two-terminal graphene devices

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Measurement and theory of the two-terminal conductance of monolayer and bilayer graphene in the quantum Hall regime are compared. We examine features of conductance as a function of gate voltage that allow monolayer, bilayer, and gapped samples to be distinguished, including N-shaped distortions of quantum Hall plateaus and conductance peaks and dips at the charge neutrality point. Generally good agreement is found between measurement and theory. Possible origins of discrepancies are discussed.

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Outline

- Motivation
- Theory: Shape-dependent conductance of graphene and its bilayer samples
- Experiment: Two-terminal conductance of graphene devices in the QH regime
- Summary
Motivation

- After discovery of the quantized Hall effect (QHE) in graphene, this material has become an important part in the research on quantum transport.

- Mono-, bi- and gapped graphene-layers show interesting differences in their transport properties.

- Besides other techniques, two-terminal transport measurements in the QH regime show features which can be used for sample characterization.
Graphene

Electronic properties:

- Charge carriers are described by massless Dirac particles with Fermi velocity $v_f \simeq 1 \times 10^6 \text{m/s}$
- Linear dispersion relation for single layer graphene

Brillouin zone of graphene lattice with Dirac cones located at K and K’ points.

Energy spectrum close to a Dirac point

Shape-dependent conductance


Two-terminal measurement in the QHE regime often shows distorted conductance plateaus.

Macroscopic conductance for a square sample with ideal contacts:

\[ G_{L=W} = \sqrt{\sigma_{xx}^2 + \sigma_{xy}^2} \]

Levitov et al. showed that \( G_{L=W} \) is density-independent in the QHE regime near the charge neutrality point, where \( \sigma_{xx} \) and \( \sigma_{xy} \) have strong density dependence. Thus, the effect of sample geometry on conductance is important.

Is it possible to extend this result for a perfect square to other sample geometries?
Shape-dependent conductance

Longitudinal and Hall conductivity for rectangular shaped graphene monolayer and bilayer obtained from the semi-circle model (Levitov et al.)

\[ \nu_n = 4(n + \frac{1}{2})|B|/\Phi_0 \]
\[ n = 0, \pm 1, \pm 2, \]

a)

\[ \nu_n = 4n|B|/\Phi_0 \]
\[ n = \pm 1, \pm 2, \]

b)
Shape-dependent conductance

- Using conformal mapping techniques, the shape-dependent two-terminal conductance of rectangular graphene samples can be calculated.

- Conductance for arbitrary shape is characterized by a single parameter:
  \[ \xi = \frac{L}{W} \] effective device aspect ratio

- Finite longitudinal conductivity leads to N-shaped distortions of the plateaus with opposite signs for \( \xi < 1 \) and \( \xi > 1 \)
Shape-dependent conductance

Key features:

- Local extrema in the middle of each Landau level.
- Peak height at $\nu = 0$
- Spacing between the two extrema next to the charge neutrality point.
**Experiment**

- **Sample:**
  - Mechanically exfoliating pyrolytic graphite on highly n-doped Si wafer capped with 300nm of SiO$_2$.
  - 5/40nm of Ti/Au deposited by thermal evaporation form the source and drain contacts.

- **Identification:**
  - The aspect ratio $\zeta_s$ was measured using optical or scanning electron microscopy.

- **Measurement:**
  - $^3$He refrigerator, $T \sim 0.25 - 4K$
  - Differential conductance $g = dI/dV$ using current bias
  - Magnetic field $|B| < 8T$
Experiment: Single Layer

- Filling factors lines align with the local *maxima* of the conductance \( g \) for sample (a), where \( \xi > 1 \) and with the *minima* for (b) where \( \xi < 1 \).
- Extrema at \( \nu = 0 \) with opposite sign.
- Equal spacing between extrema in \( g \).
- But: for (b) the peaks increases for higher Landau levels.
Experiment: Bilayer

- Conductance maximum at the CNP is larger than those at higher LLs.
- Large spacing between the two minima next to the CNP.
Experiment: Arbitrary shape

Best fit value is consistent with the effective aspect ratio obtained from conformal mapping into a rectangle.
Summary

- Signatures provide the possibility to identify the number of layers:
  - Theoretically for $\xi_{fit} < 1$ ($\xi_{fit} > 1$) the two-terminal conductance shows a minimum (maximum) at filling factors where plateaus exists in multiterminal devices.
  - Behavior at the charge neutrality point.

- Measurements are well described by theory…

- …but there exist still some differences between best fit and measured aspect ratios.

- Further experiments have to be done for clarification of the physical mechanism.