AC measurements of the quantum Hall effect in epitaxial graphene

C.-C. Kalmbach¹, J. Schurr¹, F. J. Ahlers¹, A. Müller¹, M. Kruskopf¹, K. Pierz¹, S. Novikov², N. Lebedeva², and A. Satrapinski³

¹PTB, ²Aalto, ³MIKES
• Motivation:
  Why graphene for QHE, and why at ac?

• Reminder:
  ac measurement of the QHE

• Results:
  ac-QHE in SiC-graphene

• Summary, Outlook
Why graphene for resistance metrology?

• Energy gap between lowest Landau levels is much larger than in GaAs:
  \[ \rightarrow \text{operation at lower } B \text{ and higher } T \]

• Hall plateau \( \nu = 2 \) is wider and breakdown current is higher than in GaAs:

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Why QHE for impedance metrology?

Tracing a capacitance to $h/e^2$ typically requires a step-up sequence involving a cryogenic current comparator, a calculable resistor, a 10:1 ratio bridge, and a quadrature bridge for the $R$ to $C$ transition.

Using the QHR-device at ac would simplify the chain considerably. Also just one cryo-magnet could be used for ac and for dc work.

B. Kibble et al., Metrologia, 45, L25 (2008)
J. Schurr et al., Metrologia, 48, 47 (2011)
• In this first ac-QHR study no quadrature bridge was used.
• The graphene QHR device was compared to a well-characterized reference resistor with a four-terminal-pair ratio bridge.
• For the quantized Hall resistor the triple-series connection was used.

Combined type-A/type-B uncertainty: \(< 1 \times 10^{-8}\)
\[ Z_H = \frac{U_{Hi}}{I_{Lo}} = R_H [1 + \omega R_H C(j + \tan \delta)] \]

Parallel capacitance, currents do not contribute to the Hall voltage, but to \( I_{Lo} \)

\( \rightarrow \) negative frequency dependence

In the measurement, only lossy (\( \tan \delta \neq 0 \)) capacitive currents matter. They lead to a linear frequency dependence, if \( C \tan \delta \neq f(\omega) \). This behavior is observed in GaAs devices.

Series capacitance: currents contribute to the Hall voltage, but not to \( I_{Lo} \)

\( \rightarrow \) positive frequency dependence
The shielding can never be perfect. An **optimum bare device** should have a frequency dependence which is
- not too high (the smaller the better)
- does not depend on $B$ too much

**All following measurements refer to unshielded devices in order to assess the 'bare' device performance.**

All were taken in a $^3$He cryomagnet with 0.3 K base temperature.
Graphene grown on Si-face of 4H-SiC (5 min, 1650°C, 1 atm argon)
- 800 µm x 200 µm Hall bars and contacts by laser lithography
- Contacting by a two-step Ti/Au (5/50 nm) metallization process
- 6.3 x 10^{11} cm^{-2} charge-carriers by photochemical gating, mobility 1730 cm²/Vs
ac-QHR plateaus of unshielded devices

**f-dependence for**

GaAs:
- linear
- positive
- $B$-dependent

Graphene:
- linear
- negative
- negligible $B$-dependence

![Graphene and GaAs f-dependence plots](image)
ac-QHE plateaus: GaAs vs. Graphene

Plotted in dependence on filling factor and with common y-axis, graphene’s potential advantages over GaAs become obvious.
Frequency dependence

• is negative, because for this device negative contributions dominate
  + part decreases with smaller size
  - part increases with smaller size

• is linear,
  \[ C \tan \delta \] is independent of frequency

\[
\begin{array}{c|c|c|c|c|c|c|c}
 f (\text{kHz}) & 0 & 1 & 2 & 3 & 4 & 5 & 6 & 7 \\
 \Delta r (10^{-6}) & -0.8 & -0.6 & -0.4 & -0.2 & 0.0 & & & \\
\end{array}
\]
Caution (I): avoid long bond wires

Driven mechanical resonance of current carrying bond wires in strong magnetic field create an apparent impedance:

\[
\Delta r (10^{-6}) = \text{fitted oscillator function + offset linear in } f
\]
Caution (II): avoid close-by conductors

Different device with „trench“-isolated Hall bar

Conductive areas close to Hall bar:
→ more stray capacitance
→ larger $f$-dependence
→ $B$-dependence

The $f$-dependence is still linear:
Next steps

- Explicitly determine the \((C \tan \delta)\) term as was done in GaAs:

- Determine contributions from the substrate and from the photo-chemical gate

- Optimize device geometry to minimize the frequency dependence

J. Schurr et al., *Metrologia, 51, 235(2014)*
• ac-QHE measurements demonstrated the excellent prospects of graphene as an impedance standard

• *Same ac-specific challenges* for graphene as for GaAs: tuning of device layout and understanding of parasitic capacitances is required

• *Additional ac-specific advantage* of graphene over GaAs: smaller devices can be used due to increased tolerance against breakdown
  → easier tuning of frequency dependence
Thank you!

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