Update on NIST Graphene Research

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Graphene – Successor to GaAs

- Many present-day ohm standards are GaAs-based devices
- Less user-friendly than graphene
  - Limited current before breakdown (77 μA) – Important for equipment compatibility
  - Higher magnetic field requirement (> 8 T)
  - Some electrical properties not predictable while on shelf
  - Lower temperature requirement (He-3 needs)
- Epitaxial graphene (EG) is more user-friendly
  - Stable in air (after functionalization)
  - Goes beyond one value of resistance (via superconducting contacts and/or p-n junctions)
Graphene QHR Standard

I. Millimeter-sized devices
II. Currents up to and beyond 1 mA
III. Compatible with commercial, room-temperature current comparator bridges
IV. Single QHR devices used in calibrations for at least 6 years
V. Going beyond single element
   A. Proof-of-concept of p-n junctions
   B. Using superconducting contacts for arrays
I. Two major improvements to electrical contacting
   A. Use of NbTiN, with superconducting transition near 12.5 K
   B. Use of multiple-series contacting (see (c) below)

II. Advances allow many single Hall elements to be connected – outputs
    new values of quantized resistances ("QHARS" devices)

III. Reduction of contact resistances from about 1 Ω down 3-4 orders of magnitude
I. 13 parallel devices yields 992.8 Ω
II. This resistance value is more versatile and compatible with bridges.
Graphene Arrays for Kibble Balances

I. Kibble balance mass determination with 992.8 Ω array

II. Strong agreement between quantum standard and artifact resistors

III. Deviation in mass value between QHARS devices and traditional resistors is:
   A. \((-21.5 \pm 12.8) \times 10^{-9}\) for 100 g mass
   B. \((-2.6 \pm 20) \times 10^{-9}\) for 50 g mass
I. Using Wye-Delta Transformations for Higher Quantized Resistances
   A. Grounded terminal is always one QHR element
   B. Math transformation drastically reduces number of required elements for resistances > 1 MΩ

1.01 MΩ → 20.6 MΩ
Star-Mesh Transformations

- Using Star-Mesh Transformations for Higher Quantized Resistances
  - Formula suggests that even higher resistances accessible

\[ R_{ik} = R_i R_k \sum_{\alpha=1}^{n} \frac{1}{R_{\alpha}} \]

<table>
<thead>
<tr>
<th>( R_i ) (elements)</th>
<th>( R_k ) (elements)</th>
<th>( R_{ik} - R_{nk} ) (single-elements in parallel)</th>
<th>Total (elements)</th>
<th>( R ) (M( \Omega ))</th>
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<tr>
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6.31 M\( \Omega \) \( \rightarrow \) 10.0 G\( \Omega \)

Note: 502 elements required for 10 G\( \Omega \), rather than \( 7.75 \times 10^5 \) elements if devices are in series.
Future Outlook

- Use p-n junctions as a foundation for programmable quantized Hall resistance (PQHR) systems

$$q_{N-1}(n_{N-1}) = \frac{q_{N-2}(n_{N-1} + 1)}{n_{N-1} + \frac{q_{N-2}(0)}{q_{N-1}}}$$

- AC QHR exploration

- Simplifying the calibration chain
- Topological insulators with anomalous QHE

- *Is it time for guidelines for graphene resistance standards?*

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Thank you for your attention!