Update on NIST Graphene Research

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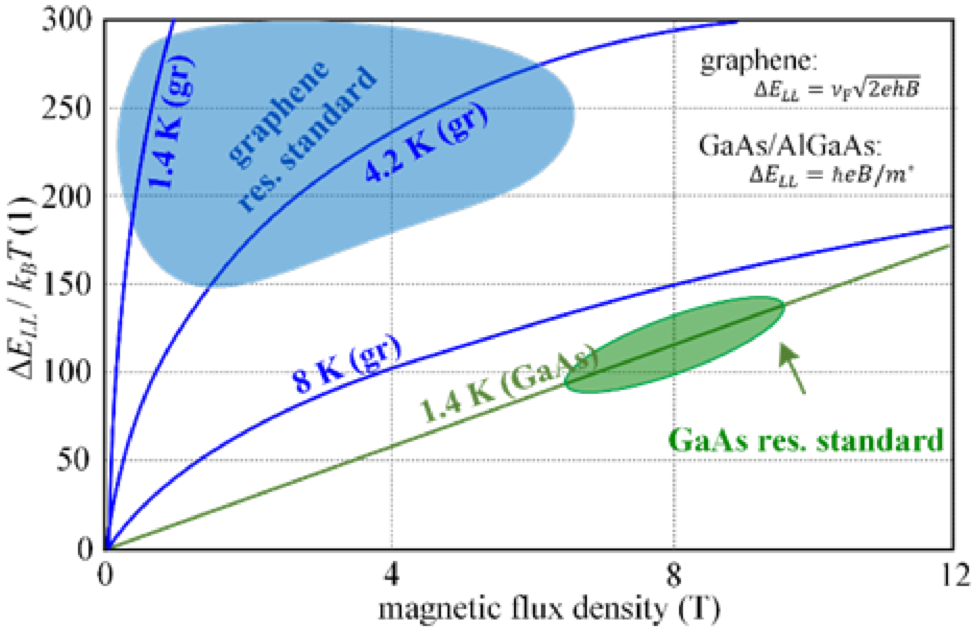
PML

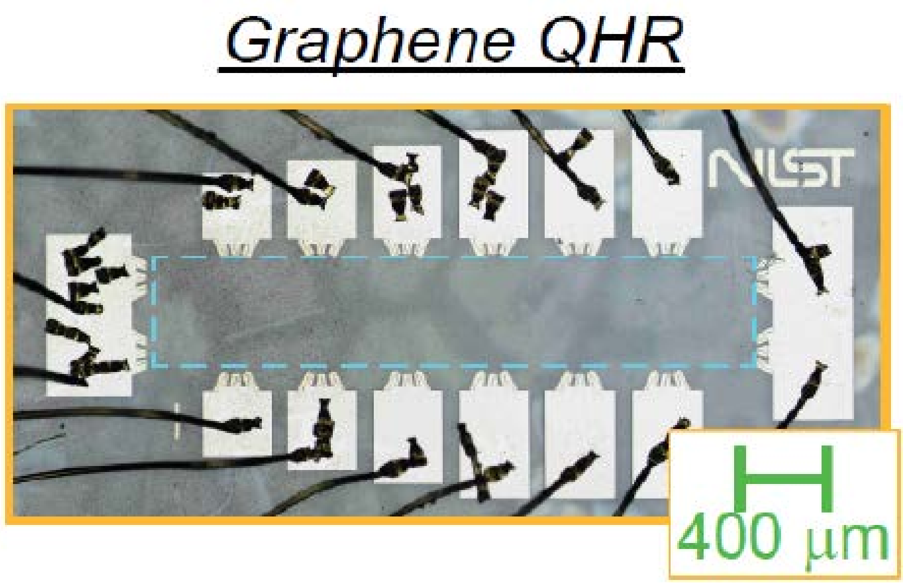
Graphene – Successor to GaAs

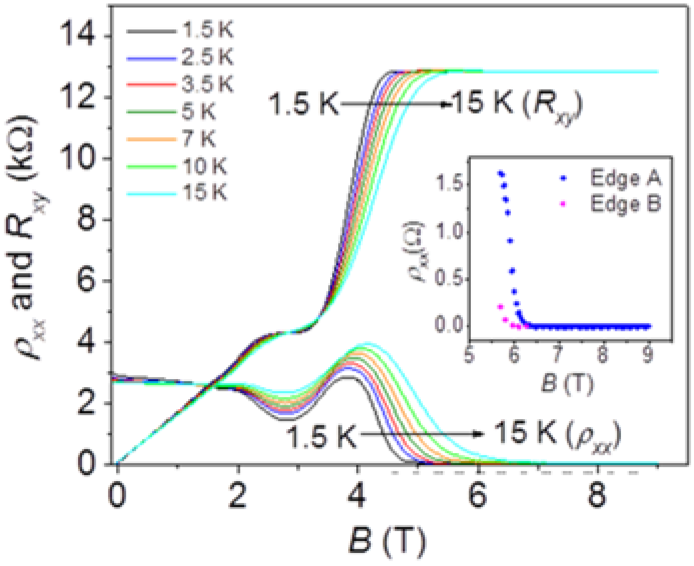
- Many present-day ohm standards are GaAs-based devices
- Less user-friendly than graphene
  - Limited current before breakdown (77 µA) – Important for equipment compatibility
  - Higher magnetic field requirement (> 8 T)
  - Some electrical properties not predictable while on shelf
  - Lower temperature requirement (He-3 needs)



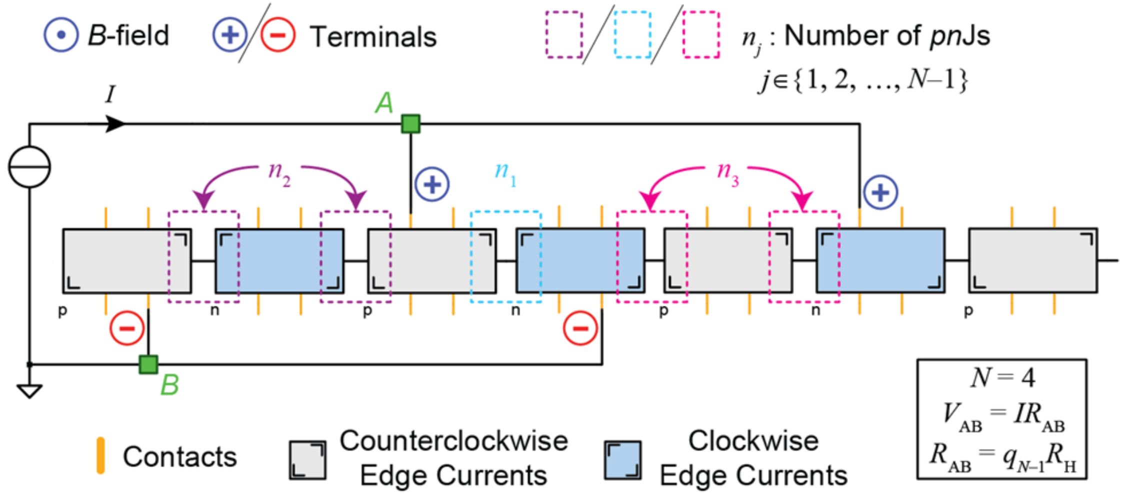
- Epitaxial graphene (EG) is more user friendly
  - Stable in air (after functionalization)
  - Goes beyond one value of resistance (via superconducting contacts and/or *p-n* junctions)

Graphene QHR Standard

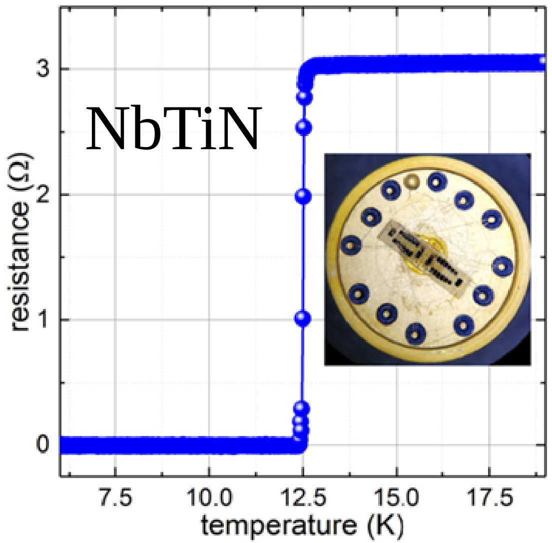




I. Millimeter-sized devices
II. Currents up to and beyond 1 mA
III. Compatible with commercial, room-temperature current comparator bridges
IV. Single QHR devices used in calibrations for at least 6 years
V. Going beyond single element
   A. Proof-of-concept of p-n junctions
   B. Using superconducting contacts for arrays



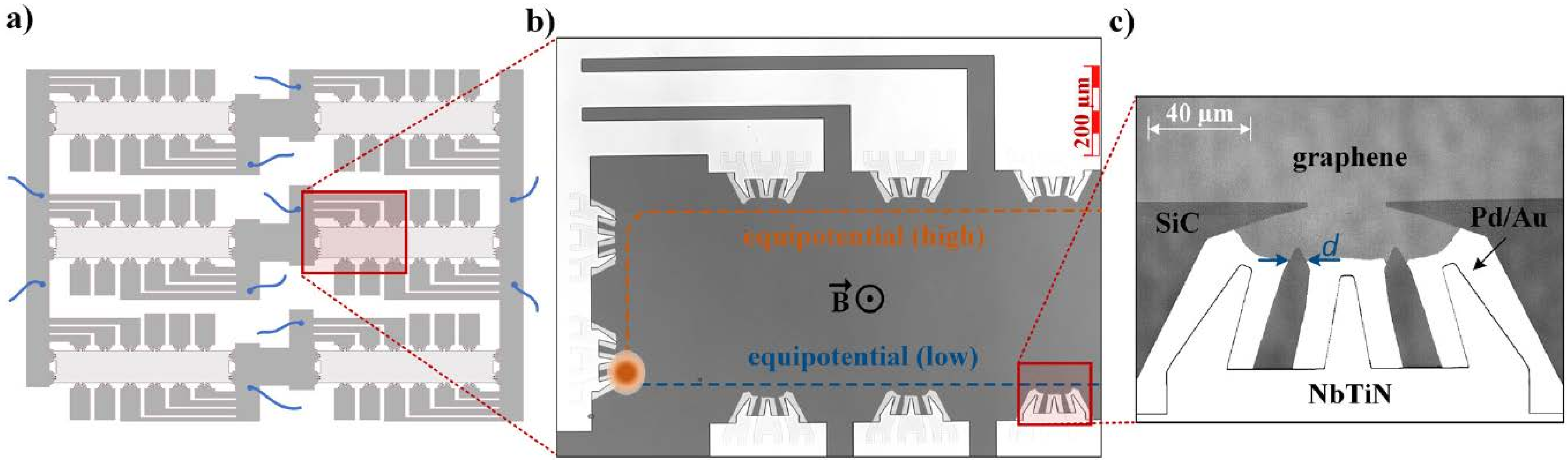
Use of Improved Contacts



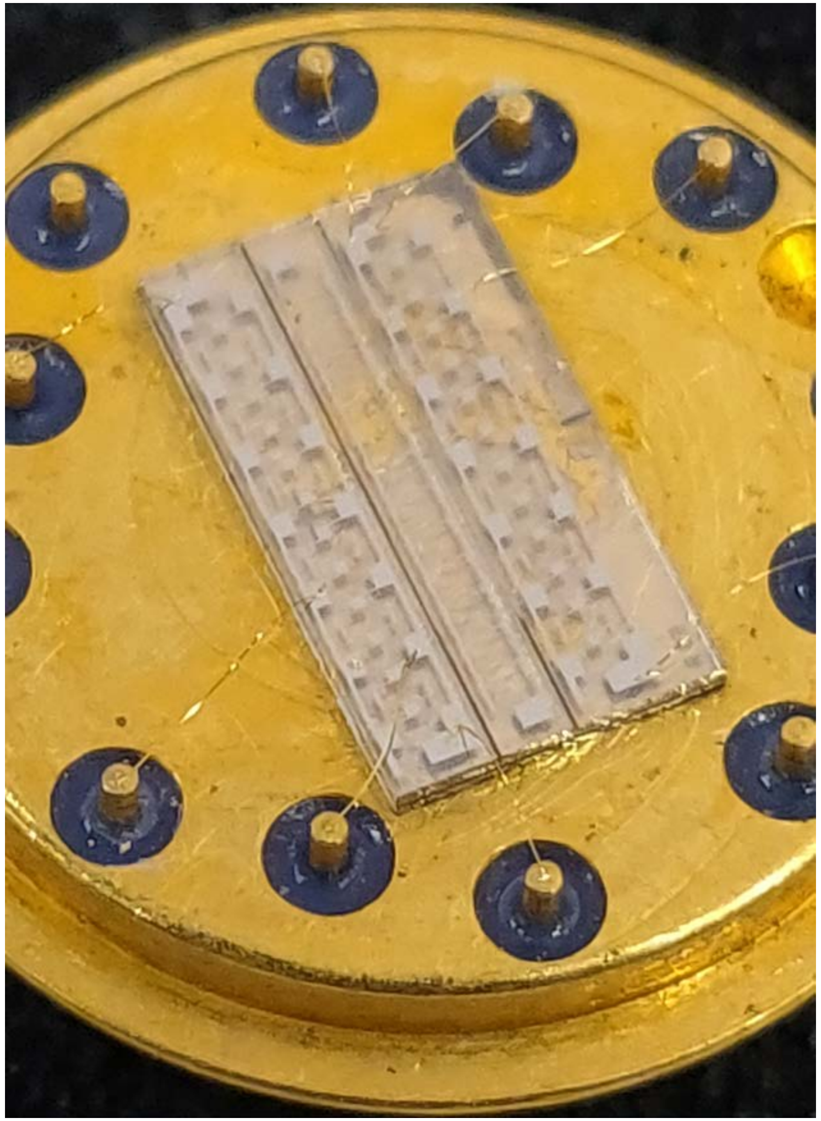
I. Two major improvements to electrical contacting
   A. Use of NbTiN, with superconducting transition near 12.5 K
   B. Use of multiple-series contacting (see (c) below)

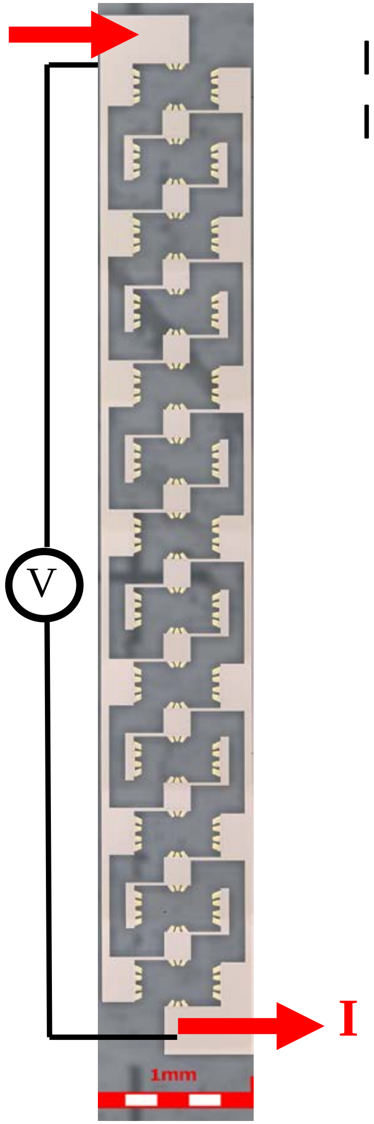
II. Advances allow many single Hall elements to be connected – outputs new values of quantized resistances ("QHARS" devices)

III. Reduction of contact resistances from about 1 Ω down 3-4 orders of magnitude

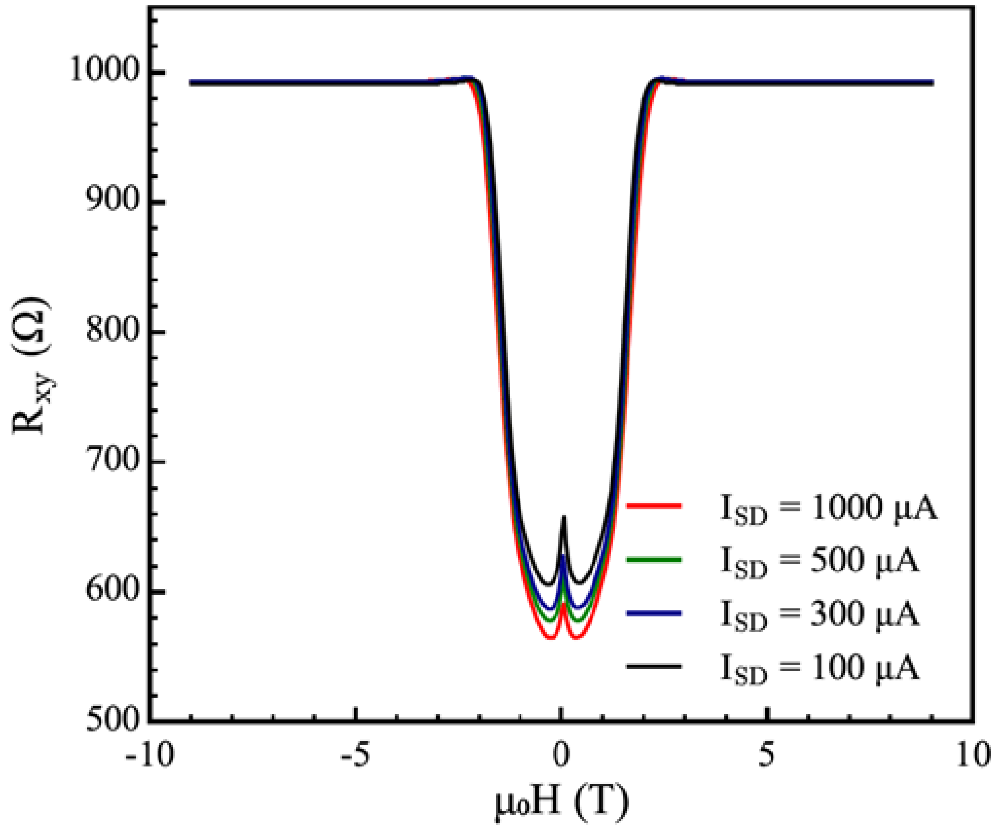


NIST QHARS Devices at 1 kΩ





I. 13 parallel devices yields 992.8 Ω
II. This resistance value is more versatile and compatible with bridges



Graphene Arrays for Kibble Balances

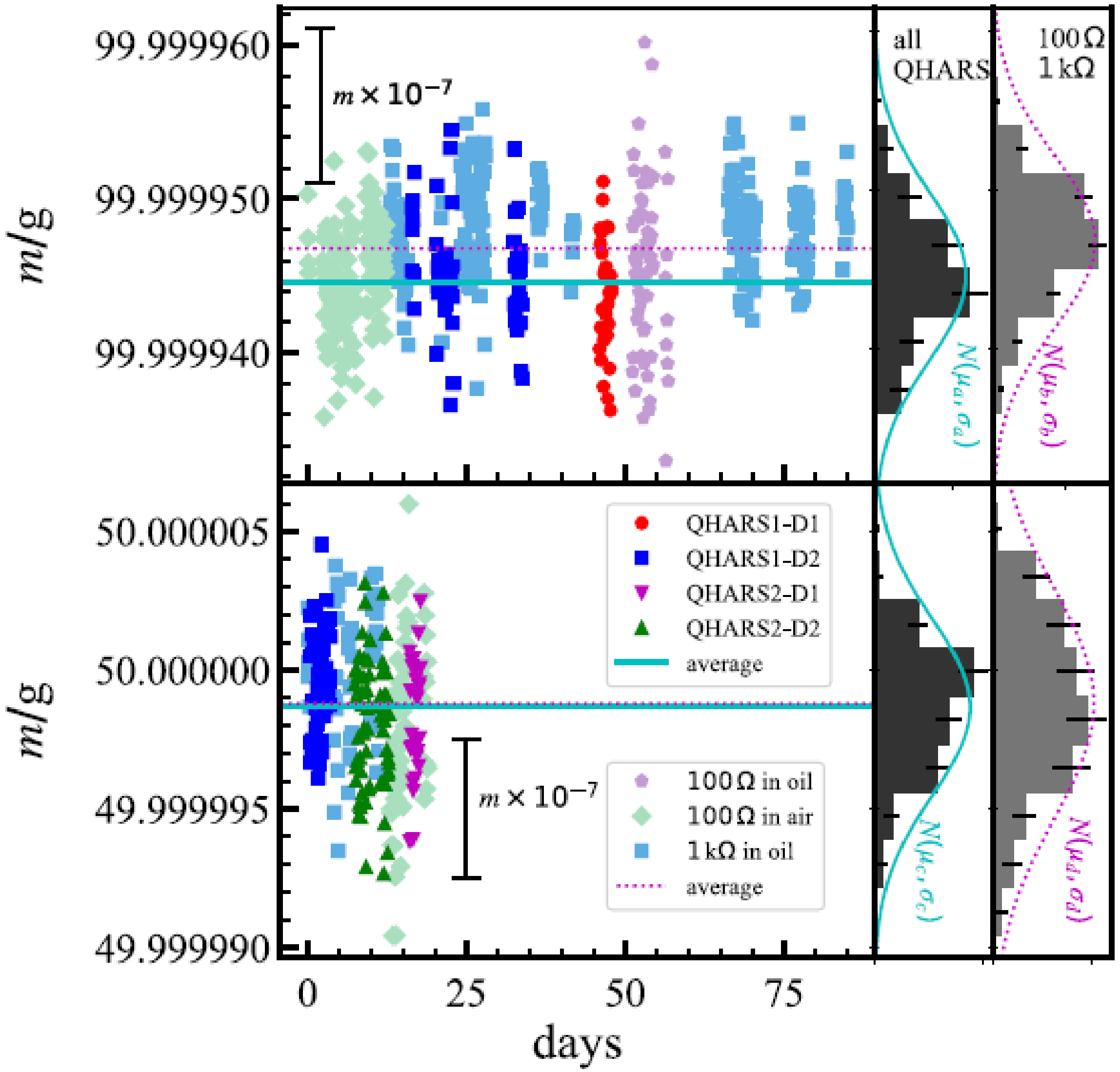
I. Kibble balance mass determination with 992.8 Ω array

II. Strong agreement between quantum standard and artifact resistors

III. Deviation in mass value between QHARS devices and traditional resistors is:

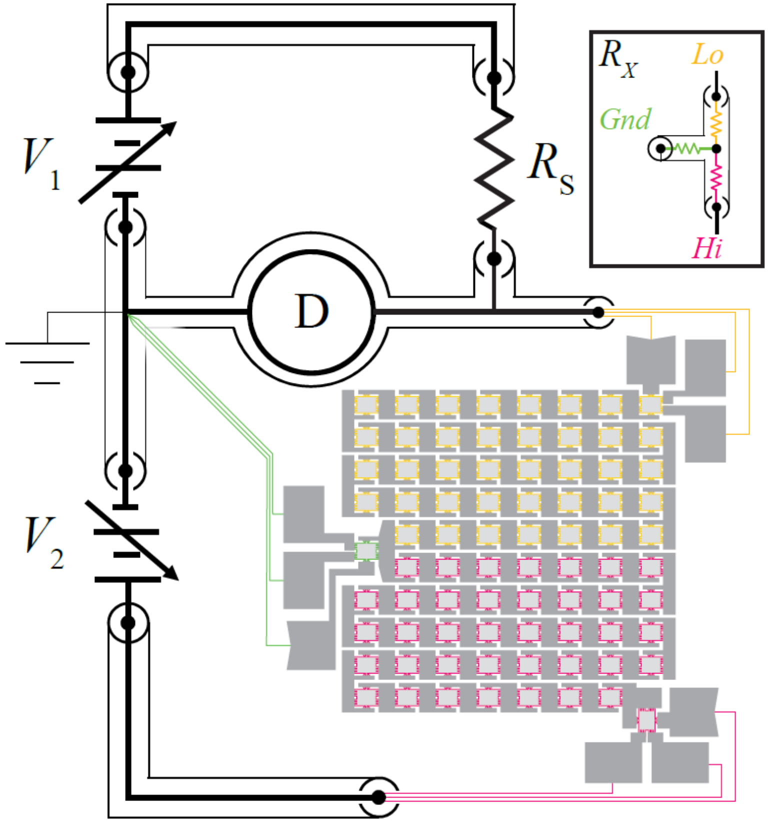
   A. $(-21.5 \pm 12.8) \times 10^{-9}$ for 100 g mass

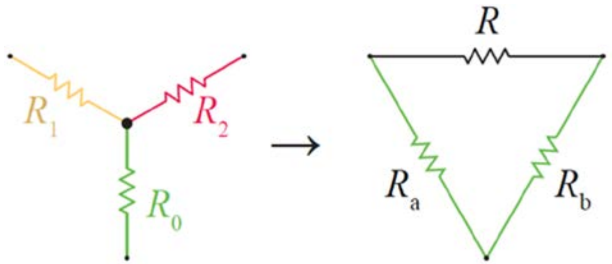
   B. $(-2.6 \pm 20) \times 10^{-9}$ for 50 g mass



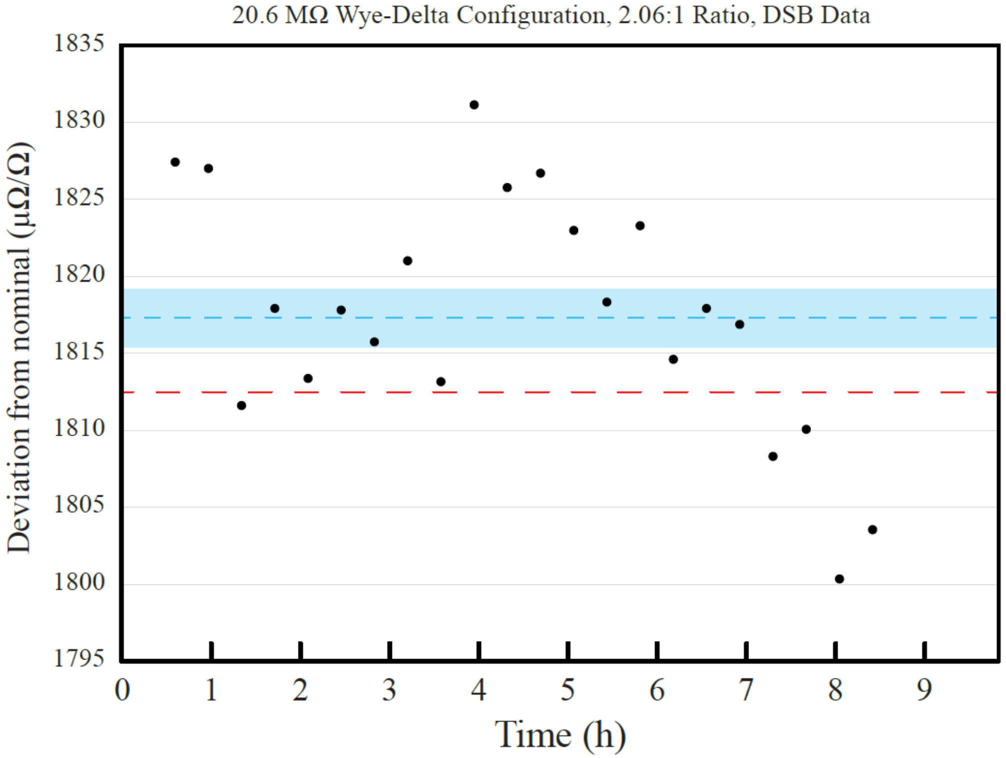
Wye-Delta Transformation

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

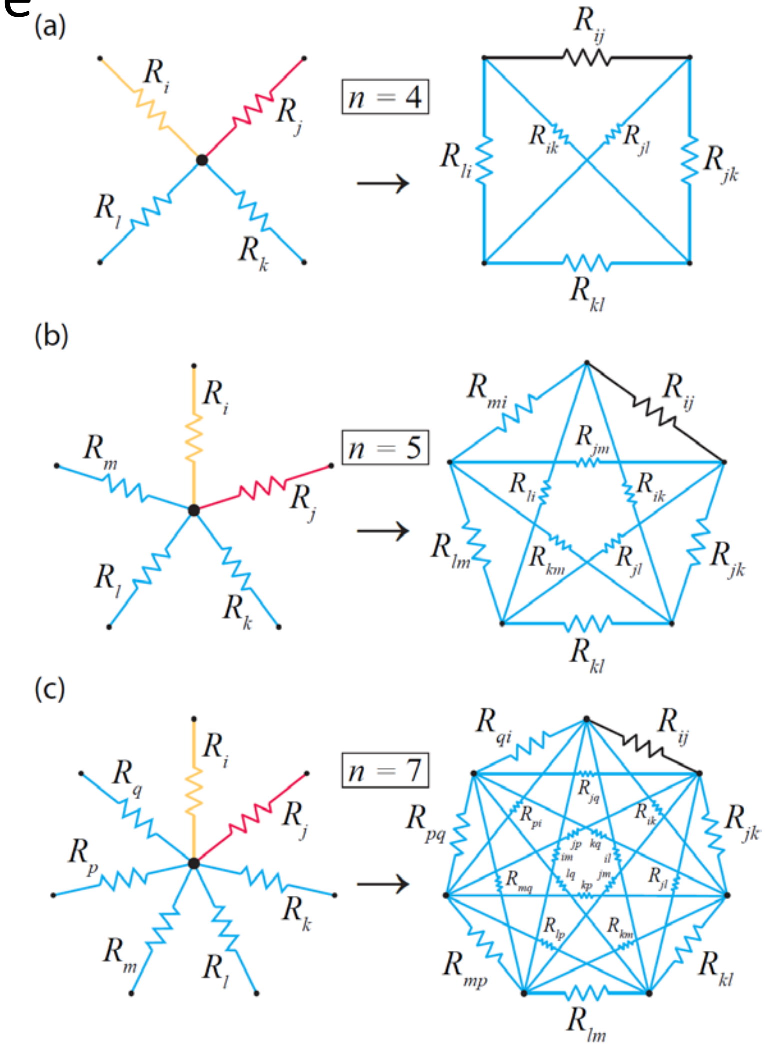
$$R_{ik} = R_i R_k \sum_{\alpha=1}^{n} \frac{1}{R_\alpha}$$

APPLICABLE STAR-MESH TRANSFORMATIONS FOR FUTURE QHARS DEVICES

R_i (elements)	R_j (elements)	$R_k - R_n$ (single-elements in parallel)	Total (elements)	R (MΩ)
50	50	3	103	98.0887
44	44	4	92	101.083
44	43	6	93	99.9407
139	139	4	282	1 001.05
245	244	13	502	10 036.4

6.31 MΩ → 10.0 GΩ

Note: 502 elements required for 10 GΩ, rather than 7.75 × 10^5 elements if devices are in series



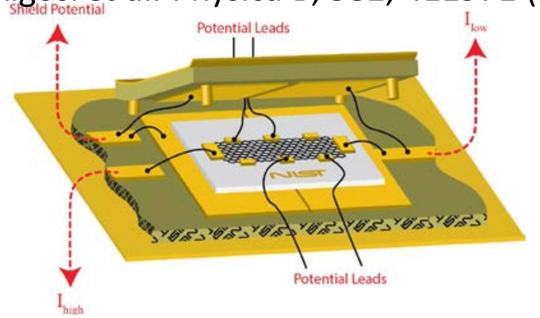
Future Outlook

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

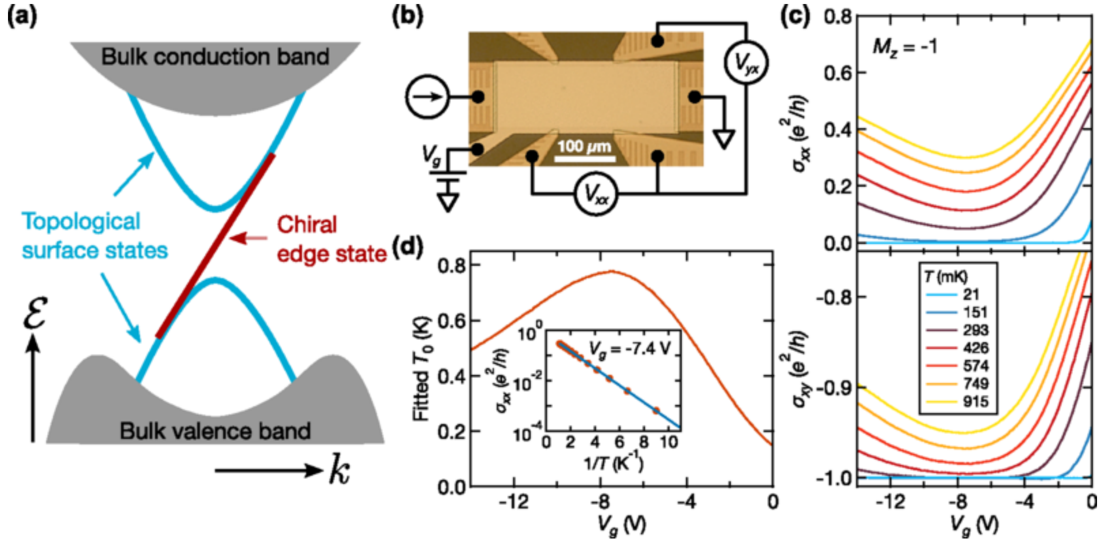
$$q_{N-1}(n_{N-1}) = \frac{q_{N-2}(n_{N-1}+1)}{n_{N-1} + \frac{q_{N-2}}{q_{N-1}^{(0)}}}$$

Rigosi *et al.* Physica B, 582, 411971 (2020)

- AC QHR exploration



- Simplifying the calibration chain
- Topological insulators with anomalous QHE
- *Is it time for guidelines for graphene resistance standards?*



E.J. Fox *et al.* "Part-per-million quantization and current-induced breakdown of the quantum anomalous Hall effect" Phys. Rev. B **98**, 075145 (2018).

Acknowledgements

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Thank you for your attention!