Development and fabrication of graphene Hall probes

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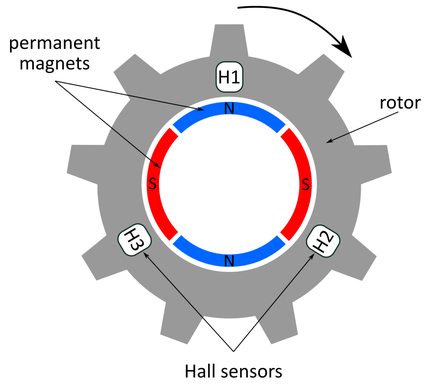
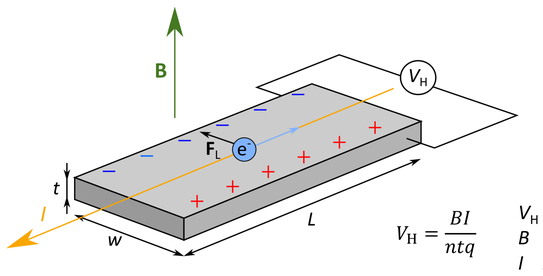
Hall probes & thesis goals

Hall probe applications:
- static & dynamic magnetic field detectors
- current sensing
- speed & directional sensors
- proximity sensors
- …



Hall effect



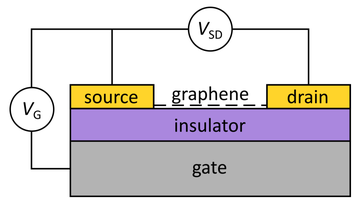
$$V_H = \frac{BI}{ntq}$$

V_H … *Hall voltage* n … *charge carrier density*
B … *magnetic field* t … *material thickness*
I … *current* q … *charge*

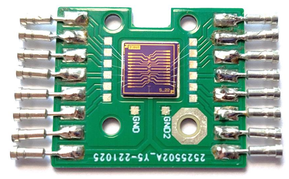
Goals of this work:
- ➢ fabrication of graphene Hall probes based on field effect transistors
- ➢ testing in varying magnetic fields from room temperature to 200 °C with applied gate voltage

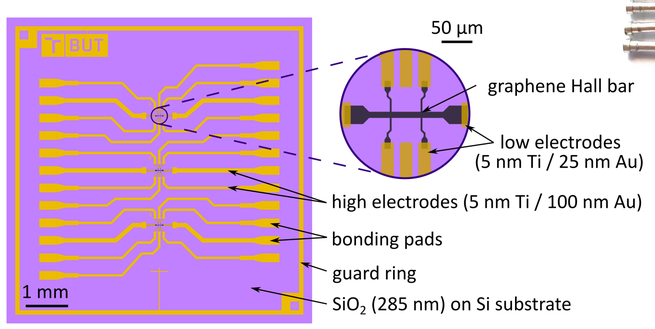
Graphene Hall probe design

- ➢ **field effect transistor** arrangement
  - enables control of charge carriers in graphene by applying gate voltage
  - silicon substrate as a global back gate with 285 nm SiO_2 insulation later



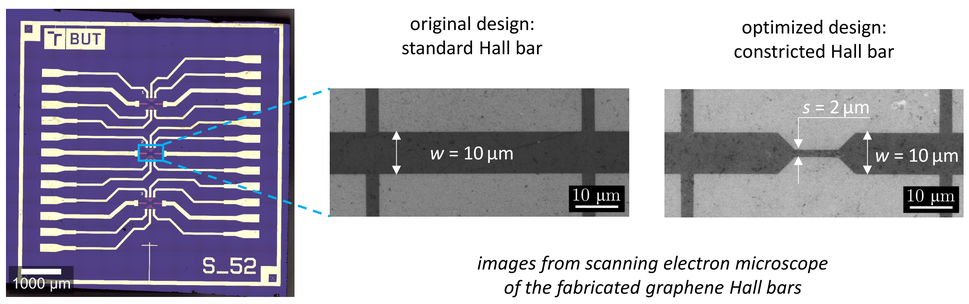
- ➢ chip glued and wire bonded on a **PCB expander** for electronic measurements





Graphene Hall probe fabrication

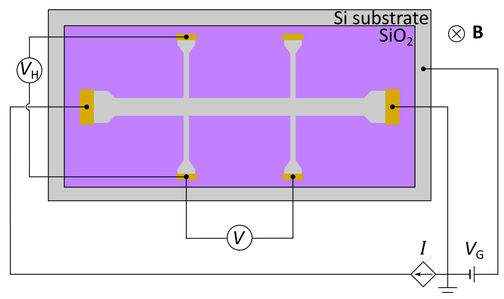
- ➢ **fabrication** by standard nano- & micro-fabrication processes
  1. patterning of **electrodes** by UV mask lithography & Ti/Au deposition
  2. graphene **transfer** onto pre-patterned chips
  3. patterning of **graphene Hall bars** by electron beam lithography & plasma etching
  4. wire bonding onto chip expanders
- ➢ **optimizatons:**
  - constricted Hall bar
  - SU-8 passivation layer
- ➢ **quality check** of graphene Hall bars after fabrication by Raman spectroscopy mapping

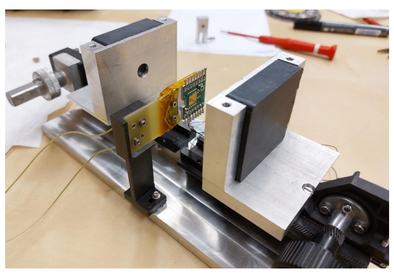


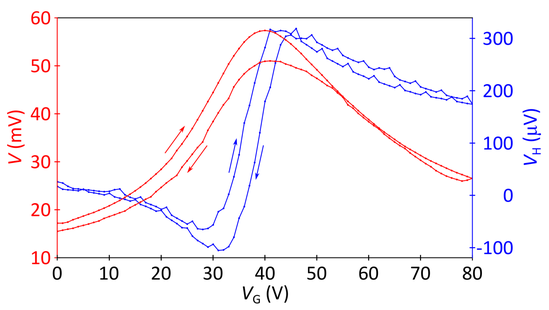
images from scanning electron microscope of the fabricated graphene Hall bars

Hall effect measurement

- ➢ **Experimental setup**
  - homogeneous magnetic field from a pair of ferrite magnets
  - magnitude & polarity of magnetic field determined by the distance & orientation of the magnets
  - simultaneous mesurement of the field effect (longitudinal voltage V) & the Hall effect (transverse voltage V_H) in response to applied gate voltage V_G

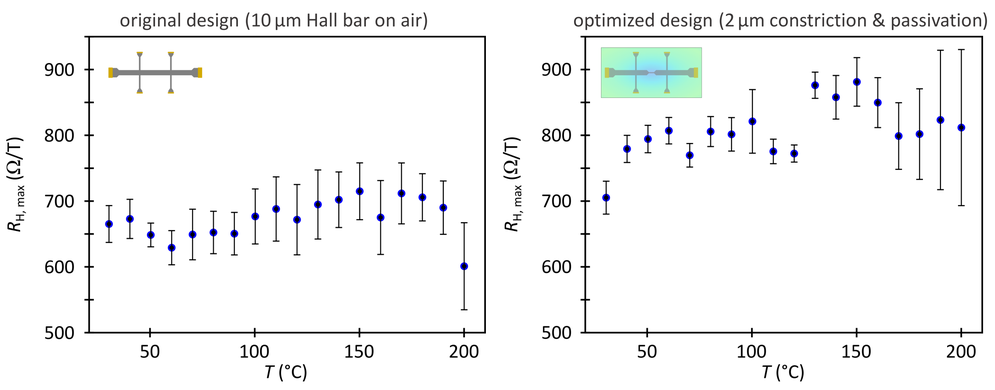






Sensitivity of the Hall probes

- ➢ Hall probe sensitivity expressed by the **Hall coefficient** $R_H = \frac{1}{I}\frac{\partial V_H}{\partial B}$
  - Hall elements based on silicon: $R_H \sim (100 - 400)\ \Omega/\mathrm{T}$ [1]
  - Hall elements based on graphene: $R_H \sim (1000 - 2000)\ \Omega/\mathrm{T}$
- ➢ Hall coefficient of our graphene Hall probes **consistent** across the whole temperature range
  - $R_H\ (200\ °\mathrm{C}) \approx 800\ \Omega/\mathrm{T}$ about **10x higher** compared to previous graphene Hall probes tested at 200 °C [2] due to the use of the incorporated field effect transistor



[1] Popovic. *Hall Effect Devices.* London, U.K. 2004.
[2] CIUK et al. *IEEE Transactions on Electron Devices*. 2019, **66**(7). DOI: 10.1109/TED.2019.2915632

Mobility of charge carriers in graphene Hall probes

- ➢ **mobility** characterizes how quickly can an electronic device react to electric field
  - mobility of silicon at room temperature: $\mu \sim 1000\ \mathrm{cm^2\ V^{-1}\ s^{-1}}$
- ➢ mobility of charge carriers in our graphene Hall probes calculated from the simultaneous field effect & Hall effect measurements