Quantum anomalous Hall octet driven by orbital magnetism in bilayer graphene

Talk by **Björn Sinz**

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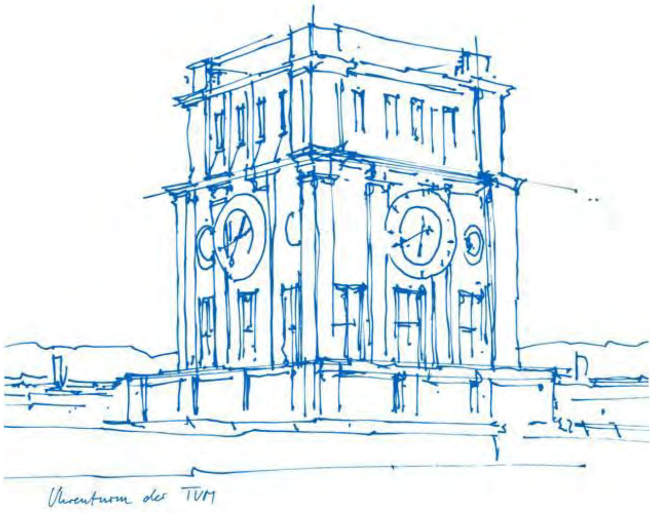


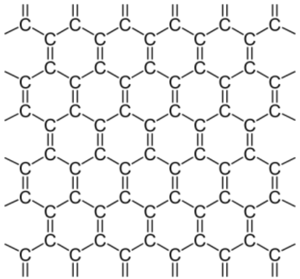
31st May 2022

Advisor: **Matthias Opel**

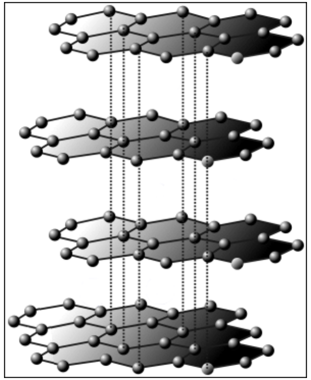
Outline

Graphene

- 2-dimensional (single layer) modification of graphite
- Graphite is carbon in a hexagonal structure
- Graphite is a Van-der-Waals-Material, which means…
  - it is built by the strong bounded 2D-layers graphene
  - the 2D-layers are weakly bounded by the Van-der-Waals-force
- As the valence band is touched by the conduction band, graphene is a **semimetal**
- In 2004, Konstantin Novoselov and Andre Geim discovered and investigated graphene and received the Nobel Price in 2010



Wikipedia, Graphen, Yikrazuul, Public domain



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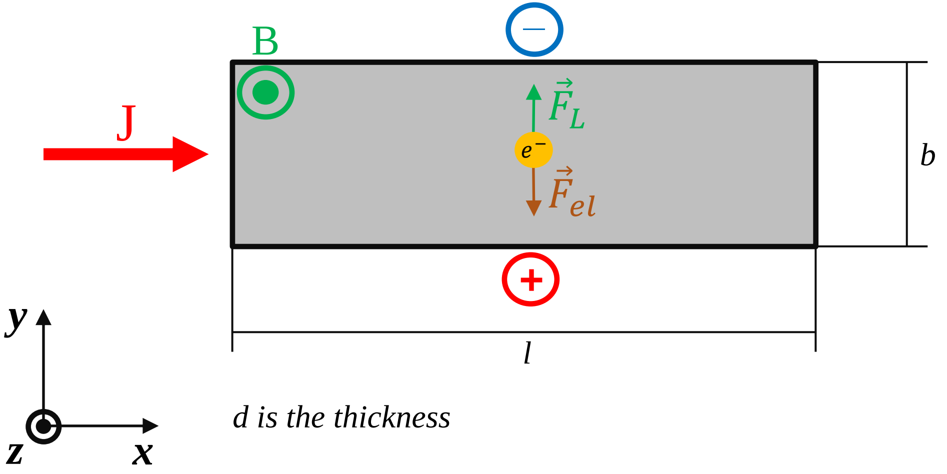
Ordinary Hall Effect

- Force on a charge carrier in an electric and magnetic field

$$\vec{F} = q \cdot (\vec{E} + \vec{v} \times \vec{B})$$

with $q \cdot (\vec{v} \times \vec{B}) = \vec{F}_L$ the Lorentz force

- In a system of equilibrium $\vec{F} = 0$, therefore $q \cdot (\vec{E} + \vec{v} \times \vec{B}) = 0$
- An electric field $\vec{E}$ emerges so that $\vec{F}_L$ gets compensated



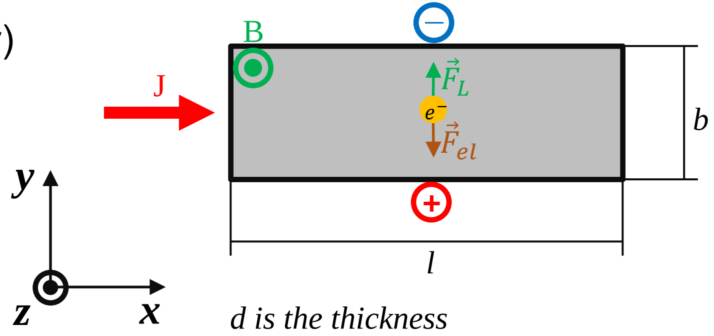
d is the thickness

Ordinary Hall Effect

- For simplicity, we can assume $E_y - v_x \cdot B_z = 0$ with $B_z = B$ and $\vec{j} = n \cdot q \cdot \vec{v}$
- With $v_x = \frac{1}{n \cdot q} j_x$ and $j_x = \frac{J}{b \cdot d}$, we obtain the **Hall voltage**

$$U_H = b \cdot E_y = b \cdot \frac{J \cdot B}{n \cdot q \cdot b \cdot d} = R_H \cdot \frac{J \cdot B}{d}$$

- $R_H = \frac{1}{n \cdot q}$ is the **Hall coefficient** (n is the charge carrier density)
- The **specific Hall resistance** is $\rho_{xy} = \frac{E_y}{J} = \frac{U_y}{J \cdot b}$
- The **Hall conductivity** is given by $\sigma_{xy} = (\rho^{-1})_{xy}$



Filling Factor

- Degree of degeneracy in a magnetic field:

$$p = \hbar\, \omega_c\, D_{2D} = \cdots = \frac{\phi}{\tilde{\phi}_0} = N_\phi$$

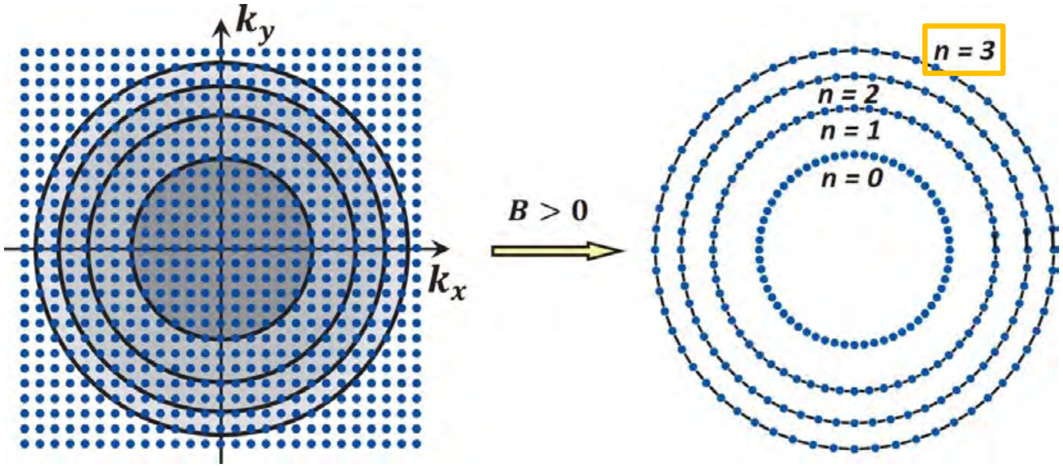
with $\tilde{\phi}_0 = \frac{h}{e}$ the flux quantum, ω_c the cyclotron frequency and D_{2D} the 2-dimensional density of states

- For $N_e = n \cdot p$ the total amount of electrons, we obtain $n = \frac{N_e}{N_\phi}$ for the n^{th} –Landau level
- If the chemical potential μ is located between the Landau levels, it holds that $v = n = \frac{N_e}{N_\phi}$

  with v the **filling factor**

Filling Factor

- In this case, the filling factor can be understood as the highest occupied Landau level



R. Gross & A. Marx, Festkörperphysik, 3rd edition (2018)

Integer Quantum Hall Effect (IQH)

- For very high magnetic fields and low temperatures, a quantisation of the Hall conductivity on surfaces and in 2D-materials can be observed

- The resistance is quantized by the resistance quantum $\frac{h}{e^2}$, so the quantum Hall conductivity is $(v = 1{,}2, \ldots)$

$$\sigma_{xy} = \frac{e^2}{h} \cdot v$$

- Filling factor is quantum number of the Hall conductivity

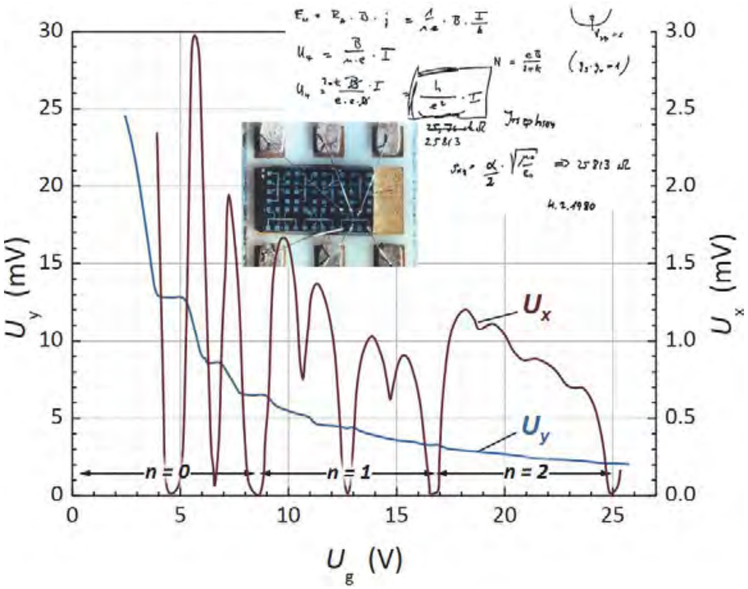
Integer Quantum Hall Effect (IQH)

<u>In the experiment:</u>

- Gate voltage U_g affects the electron density
- Current J_x and magnetic field B were fix
- For U_g, where $U_x = 0$, U_y has plateaus
- These plateaus can be understood as conductivity states

- **General reason:**

  Impurities and defects cause localised and delocalised electron states, which can explain the Hall-plateaus



R. Gross & A. Marx, Festkörperphysik, 3rd edition (2018)

Integer Quantum Hall Effect (IQH)

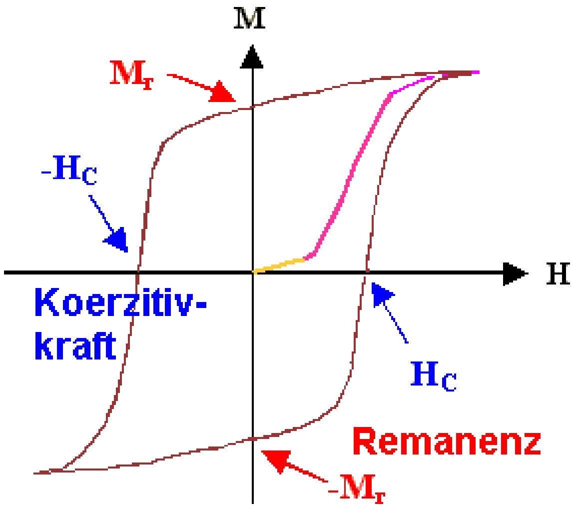
Very simplified explanation for the quantum Hall plateaus:

- **Assumption:** chemical potential μ between two Landau levels
- As μ is located in between two levels, one band is fully occupied, whereas the next level is empty

  $\rightarrow$ insulator
- Also no thermal excitation $k_B T \ll \hbar\omega_C$, therefore $\sigma_{xx} = \sigma_{yy} \rightarrow 0$

Anomalous Hall Effect

- Many contributions to the anomalous Hall effect (AH)
- Key ingredients are:
  - Intrinsic contribution
  - Skew-scattering contribution
  - Side-jump contribution

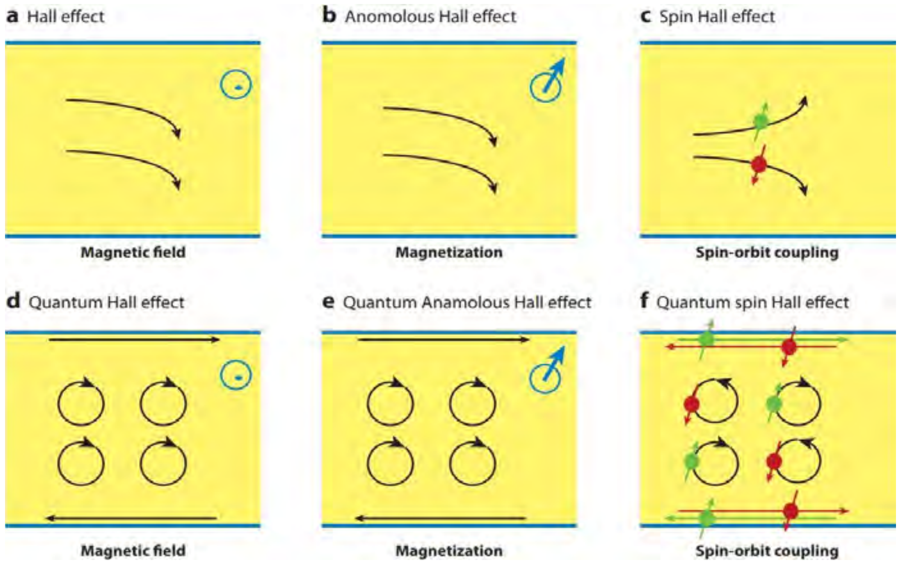


Uni Kiel, https://www.tf.uni-kiel.de/matwis/amat/mw_for_et/kap_7/backbone/r7_2_1.html

- Internal magnetisation creates a flux density, according to $\vec{B} = \mu_0 \cdot (\vec{H} + \vec{M})$
- Even for $H = 0$, the material has still a magnetisation $M \neq 0$ due to remanence
- Hence, the material has an internal flux density $\vec{B} = \mu_0 \cdot \vec{M}$, in our case **bilayer graphene**

Quantum Anomalous Hall Effect

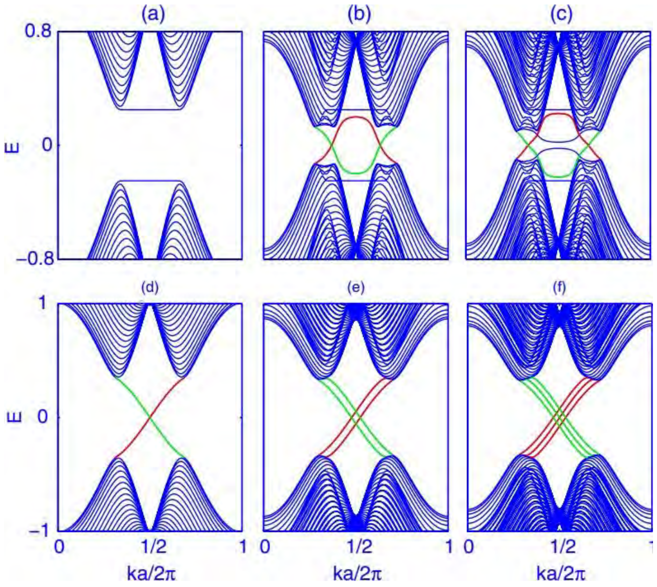
- Quantized version of the anomalous Hall effect
- **Quantized Hall resistance at zero external magnetic field**
- Hall conductivity is proportional to multiples of the **conductance quantum** $\frac{e^2}{h}$
- Observed in various two-dimensional material with periodic structure



C.-X. Liu et al., Annu. Rev. Condens. Matter Phys. **7**, 301(2016)

Valley Hall Effect

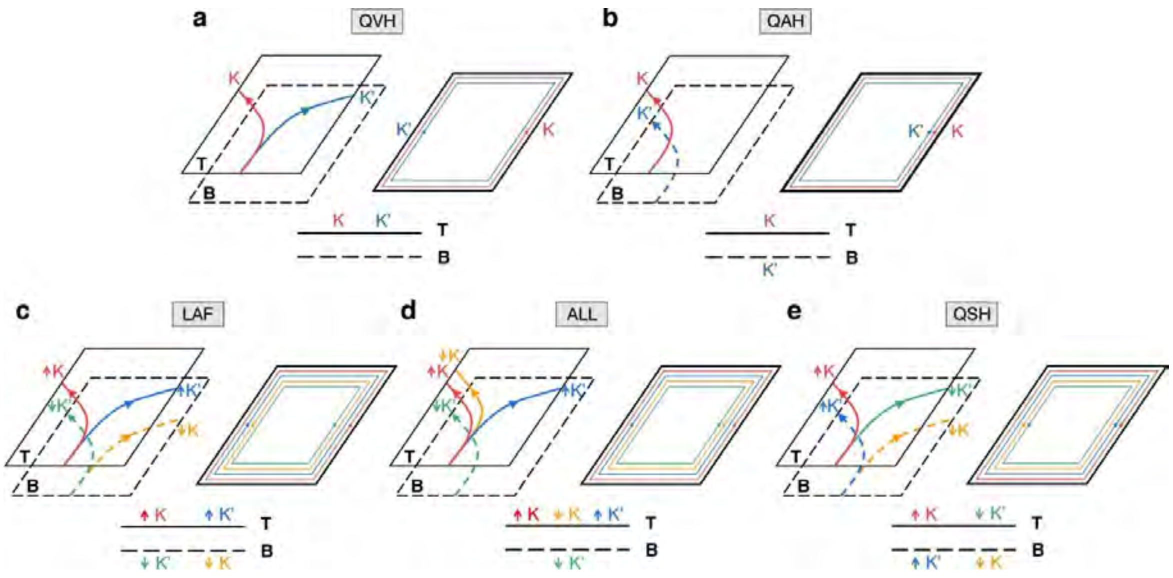
- The band structure of a certain material in the first Brillouin zone can have multiple valleys
- Valleys are at different wave vectors $\vec{k}$ & $\overrightarrow{k'}$
- In **bilayer graphene**, we obtain **8 possible electron states** (spin up/down, two valleys, top/bottom graphene layer)



F. Zhang et al., Phys.Rev.Let. **106**, 156801-3 (2011)

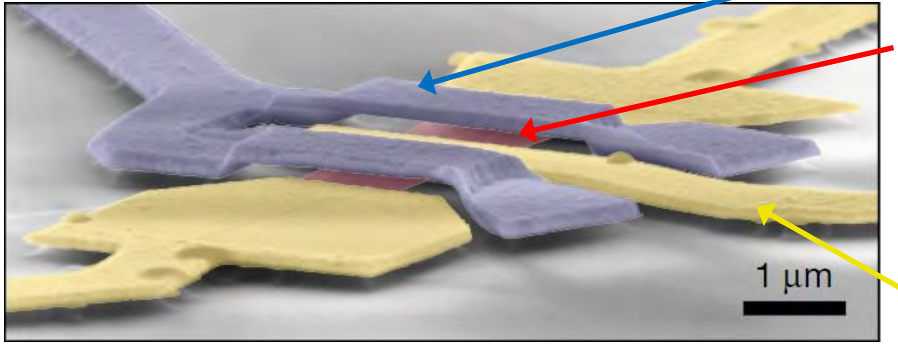
Valley Hall Effect

- There also exists a quantum valley Hall effect (QVH)
- Layer antiferromagnetic effect (LAF) is layer dependend
- **ALL phase:** all different Hall effects unify to one
- One spin species is in one of the QVH phases, whereas the other spin species is in one of the QAH phases



Outline

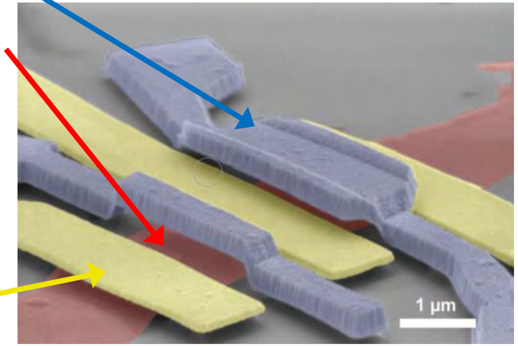
Bilayer Graphene Device



Top Gate

Bilayer Graphene

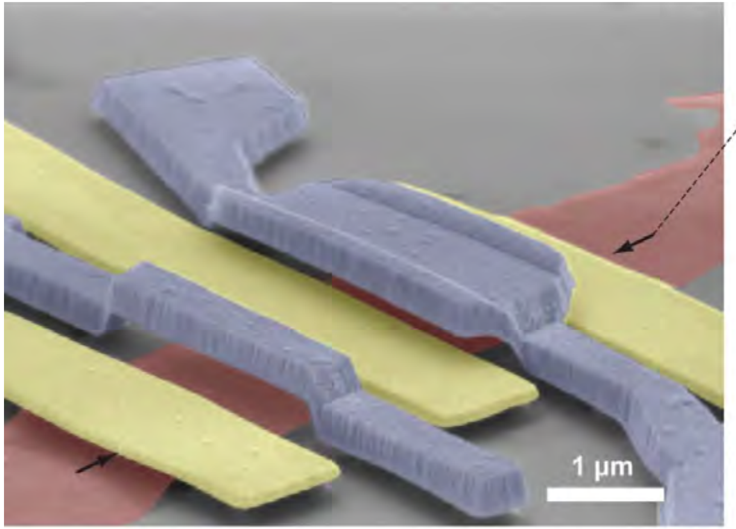
Gold Contacts



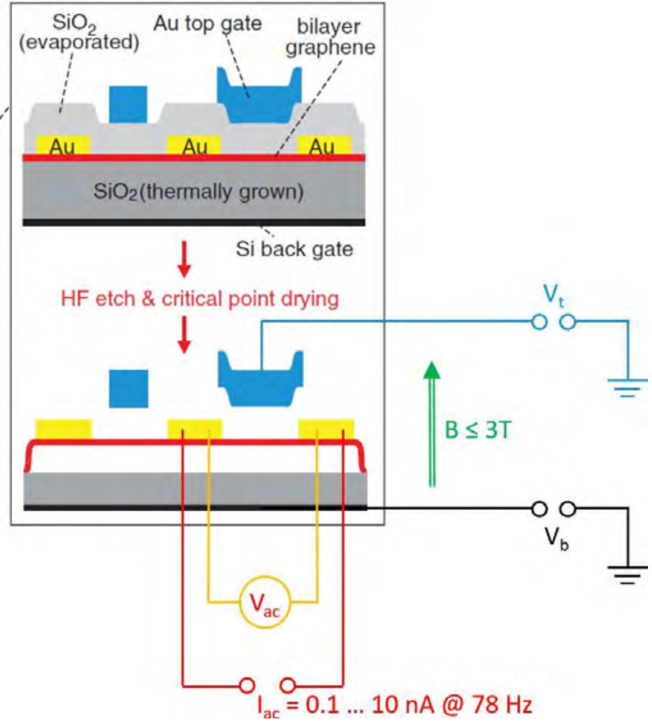
R.T. Weitz et al., Science **330**, 812 (2010)

Bottom Gate is the Si of the wafer

Bilayer Graphene Device

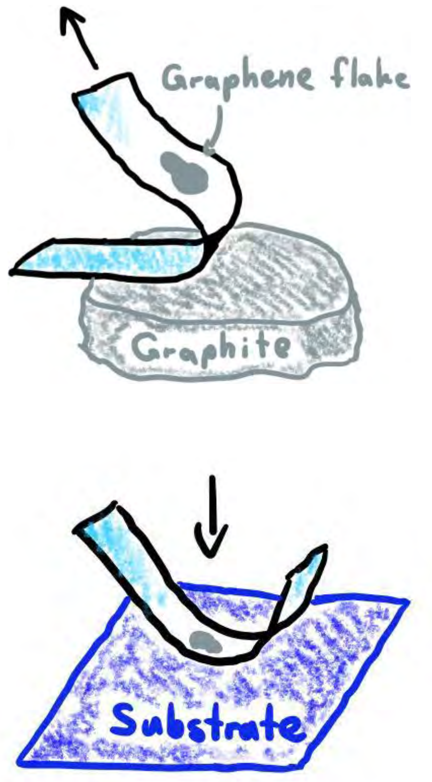


R.T. Weitz et al., Science **330**, 812 (2010); modified



Device Fabrication (Flake)

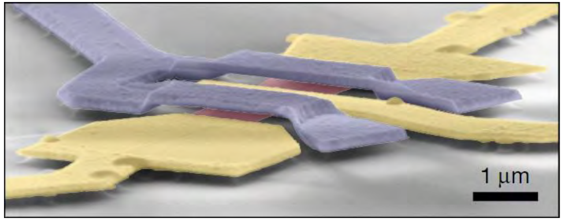
- Mechanical exfoliation is the most common way to achieve 2D-flakes
- Stick tape on crystal and just remove it
- Flakes on the tape-site are transferred onto a silicon/silicon dioxide (Si/SiO_2) substrate
- After the transfer, the flakes are examined under the microscope
- As different layer-thicknesses have different colours, bilayer flakes can be preselected just with the help of the optical contrast

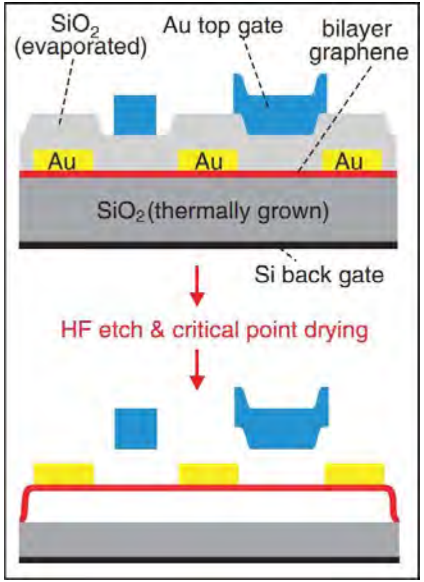


Device Fabrication (Chip)

- Standard lithography process with electron beam evaporation

- The electrodes, the top gate and spacer were fabricated by these standard lithography techniques
- Afterwards, the spacer (SiO_2) was etched with hydrofluoric acid





R.T. Weitz et al., Science **330**, 812 (2010)

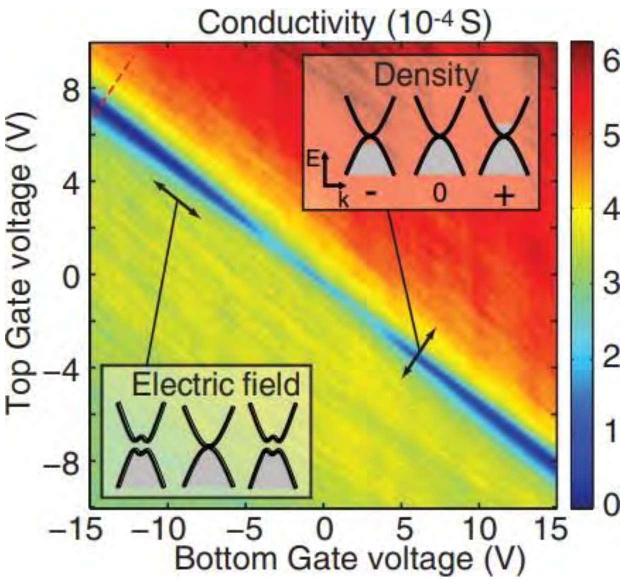
Electrical Transport Measurements

- Advantage of using a top and bottom gate is the **independent tunability** of the charge **carrier density $\boldsymbol{n}$** and the **perpendicular electric field $\boldsymbol{E_\perp}$**
- The electric field is given by

$$E_\perp = \frac{C_b}{2\varepsilon_0}(\alpha V_t - V_b)$$

with $\alpha = \frac{C_t}{C_b}$ the ratio between top and bottom capacity

- Changes by $\Delta V_t = \frac{\Delta V_b}{\alpha}$ will have no influence on $E_\perp$



Conductance map

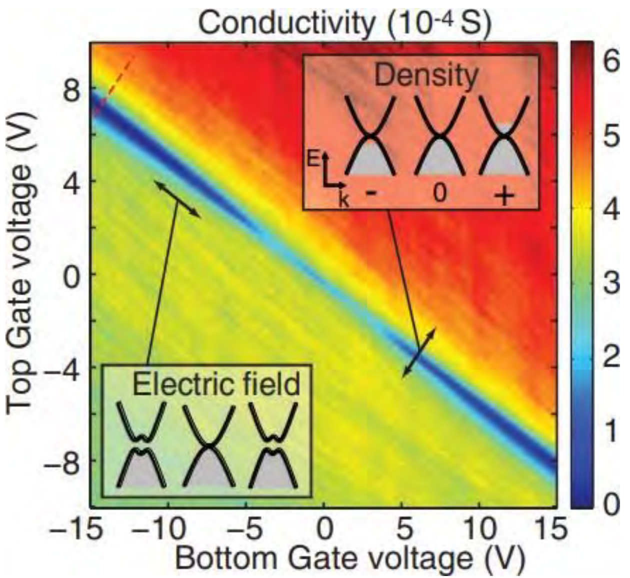
Electrical Transport Measurements

- Charge carrier density is given by

$$n = \frac{C_b}{e}(\alpha V_t + V_b)$$

- Changes by $\Delta V_t = -\frac{\Delta V_b}{\alpha}$ will have no influence on n

  - Shifting ΔV_t by $-\frac{\Delta V_b}{\alpha}$ → sweeps solely $E_\perp$
  - Shifting ΔV_t by $\frac{\Delta V_b}{\alpha}$ → sweeps solely n



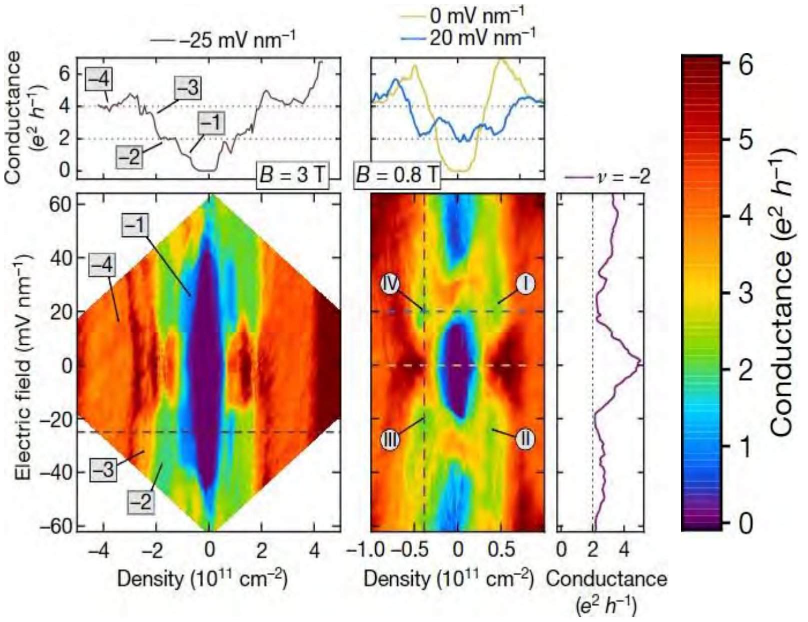
Conductance map

Outline

1. Introduction and Basics
   - Graphene
   - Ordinary Hall Effect
   - Filling Factor
   - Additional Hall Effects
2. Experimental Setup and Methods
3. Results
4. Summary

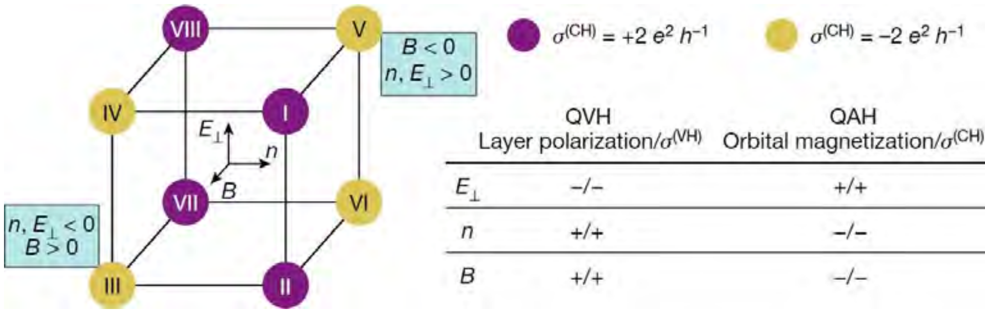
Orbital-Magnetism-driven QAH

- **Before:** Unclear ground state of bilayer graphene for $B = 0T$
- The filling factor ν is the quantum number of the conductance, given as $\sigma = \nu \cdot \frac{e^2}{h}$
- At different flux densities $B = 3T$ & $B = 0.8T$ the **ALL phases** $\boldsymbol{\nu = \pm 2}$ emerge
- States are only stable for a certain electric field $E_\perp$ and charge carrier density n

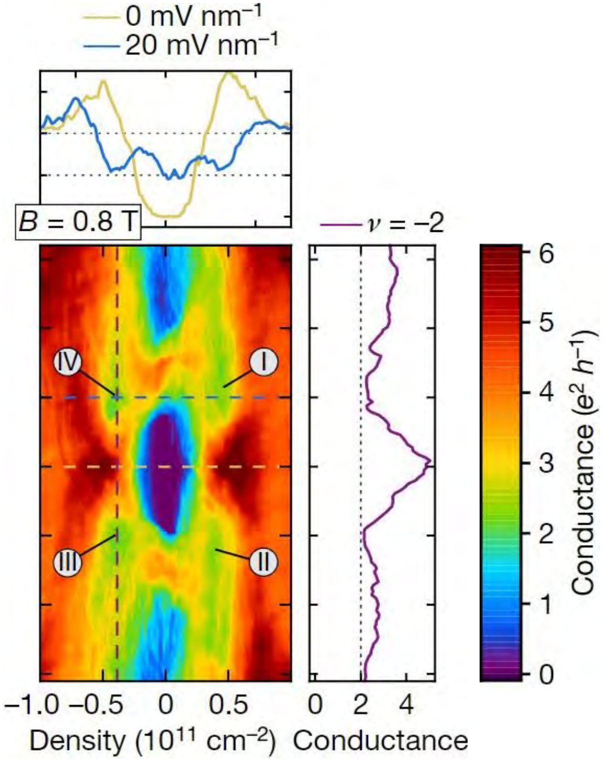


Octet of QAH Phases

- These four states additionally exist for $B < 0$
- Therefore, an **octet for the $\nu = \pm 2$ ALL states** exists

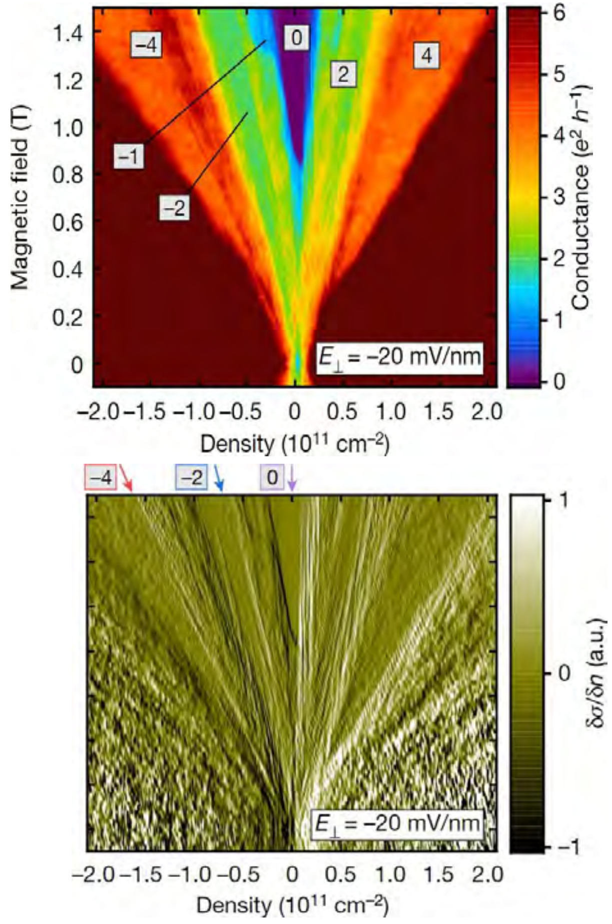


	QVH Layer polarization/$\sigma^{(VH)}$	QAH Orbital magnetization/$\sigma^{(CH)}$	Spin
$E_\perp$	−/−	+/+	+
n	+/+	−/−	+
B	+/+	−/−	−



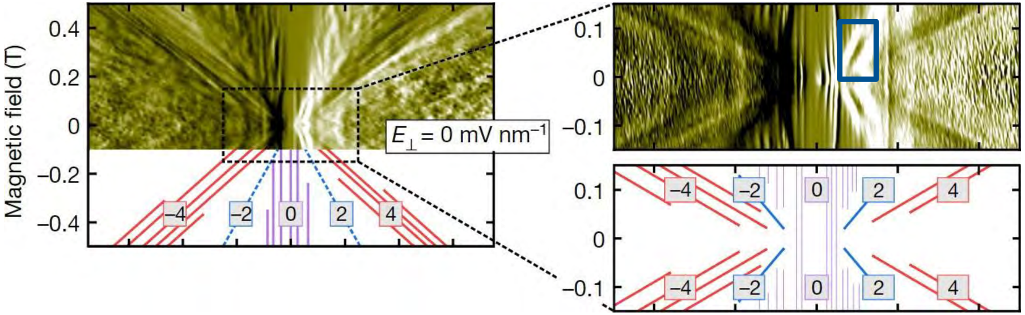
Tracing the $\nu = \pm 2$ States to $B = 0$

- **So far:** stability of the $\nu = \pm 2$ states at small magnetic field
- At $E_\perp = -20\ \frac{mV}{nm}$, the $\nu = \pm 2$ & $\nu = \pm 4$ states emerge at unusually small magnetic fields
- One gets more insight by tracking fluctuations near incompressible quantum states
- Therefore, examining the derivative of the conductance
- Specific filling factors can appear even before the corresponding quantum Hall states emerge

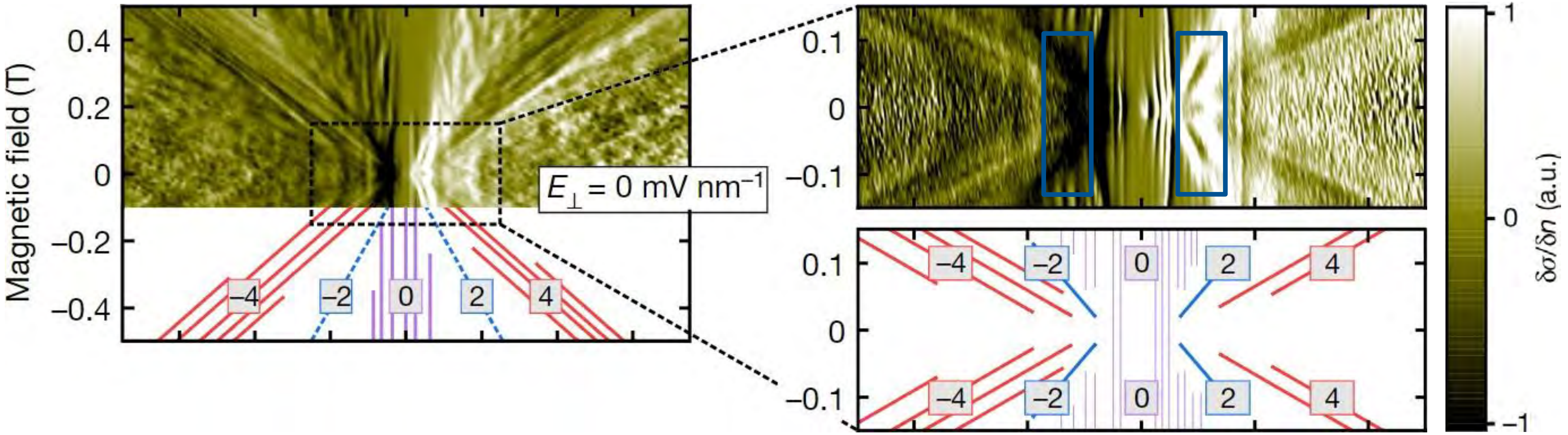


Tracing the $v = \pm 2$ States to $B = 0$

- Investigating the differential conductance at various electric fields shows that both states, $v = \pm 2$ & $v = \pm 4$, emerge at magnetic fields well below $B = 100\ mT$
- High resolution scan shows that the $v = \pm 2$ states are also present for $B < 20\ mT,$ which is by far further than the $v = \pm 4$ states
- **Provides strong evidence that the $\boldsymbol{v = \pm 2}$ states are potential ground states of bilayer graphene at $\boldsymbol{B = 0}$**

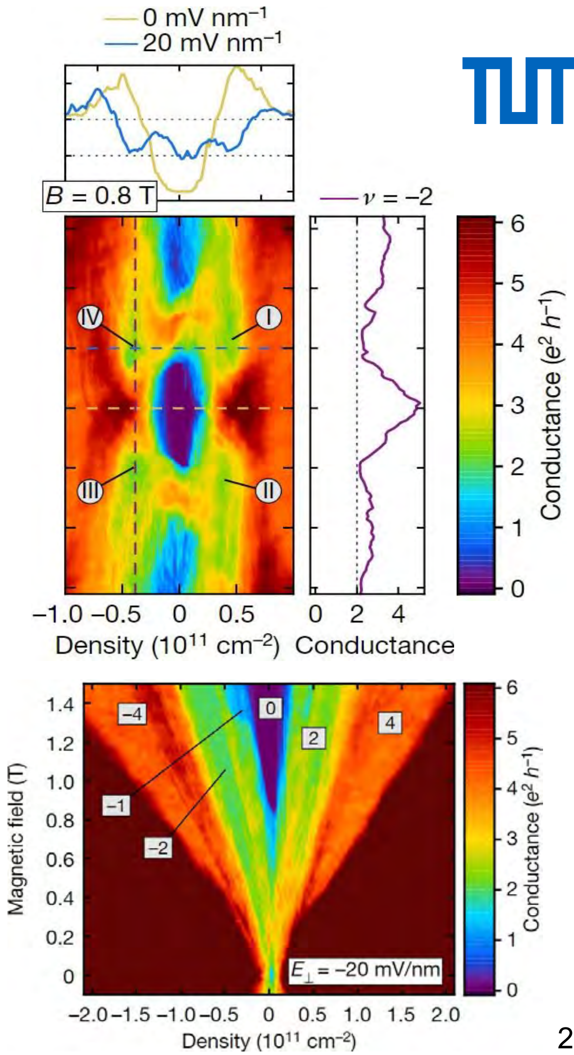


Tracing the $\nu = \pm 2$ States to $B = 0$



Summary

- **Before:** Unclear ground state of the conductivity of bilayer graphene for $B = 0$
- The anomalous Hall effect gives rise to $v = \pm 2$ states in bilayer graphene at very low magnetic field
- The 'ALL' phases form an octet for various $E_{\perp}, B, n$
- Strong evidence that $v = \pm 2$ states are ground states of bilayer graphene for $B = 0T$
- **Also a magnetic hysteresis was discovered, which supports this assumption**



Sources

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- Quantum anomalous Hall effect: https://en.wikipedia.org/wiki/Quantum_anomalous_Hall_effect