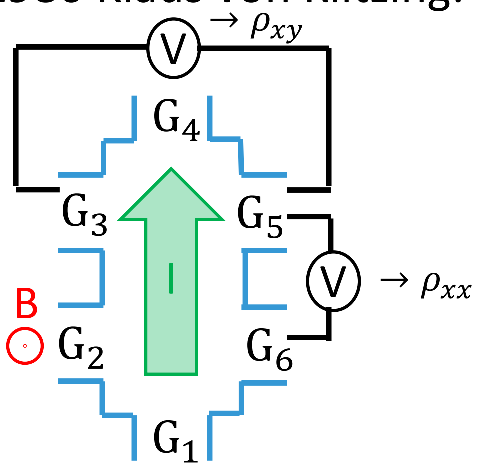
# Room-Temperature Quantum Hall Effect in Graphene

# Content

1. Integer Quantum Hall Effect (IQHE)
2. QHE in Graphene
3. Room Temperature QHE (K.S. Novoselov Science 315, 2007)
4. Conclusion

# Integer Quantum Hall Effect

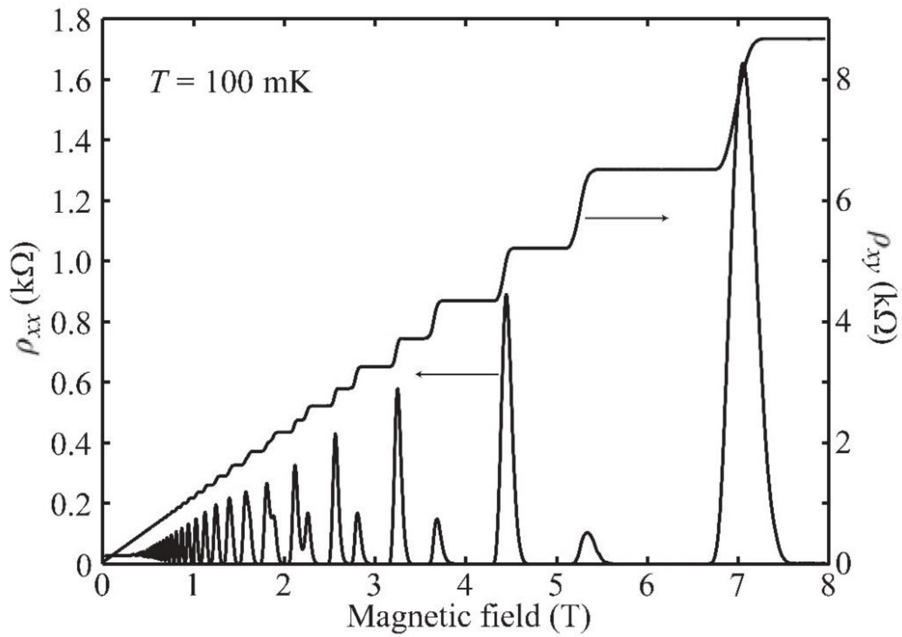
1980 Klaus von Klitzing: $\rightarrow$ resistance quantum $\frac{h}{e^2}$




Landau level (LL) quantization

low T: $\hbar\omega_c \gg kT$

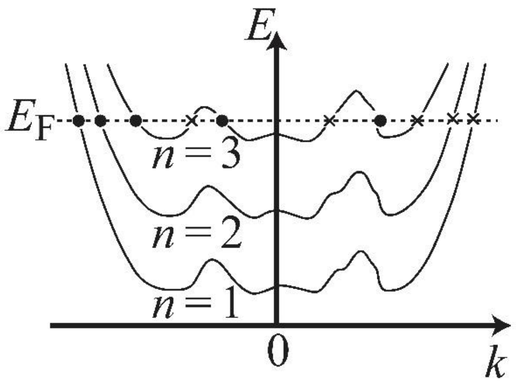
high B: $\omega_c \tau_q \gg 1$ with $\omega_c = \frac{eB}{m^*}$

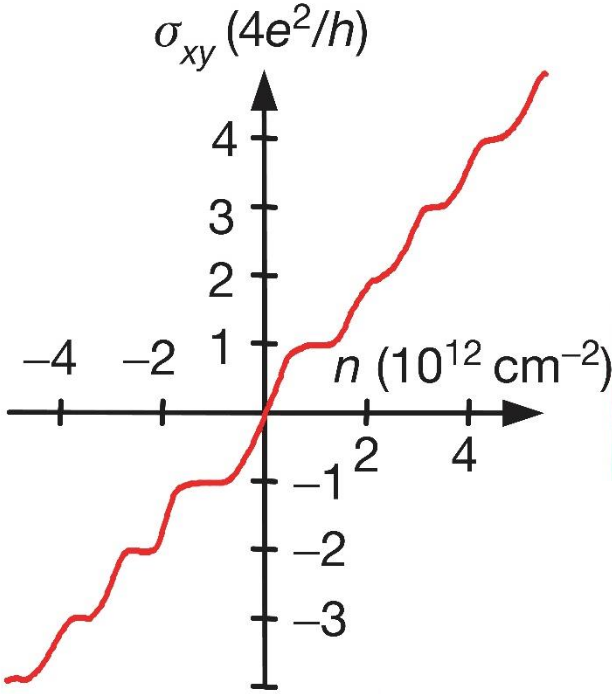



*Thomas Ihn: Semiconductor Nanostructures*

# Integer Quantum Hall Effect

- Fermi energy between LL:
  - $\rho_{xy} = const.$ and $\rho_{xx} = 0$
- Fermi energy close to LL:
  - $\rho_{xy}$- jump and $\rho_{xx}$- peak (SdHO)

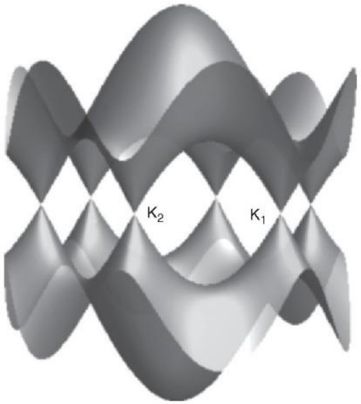



*K. S. Novoselov et al Nature 438 (2005)*

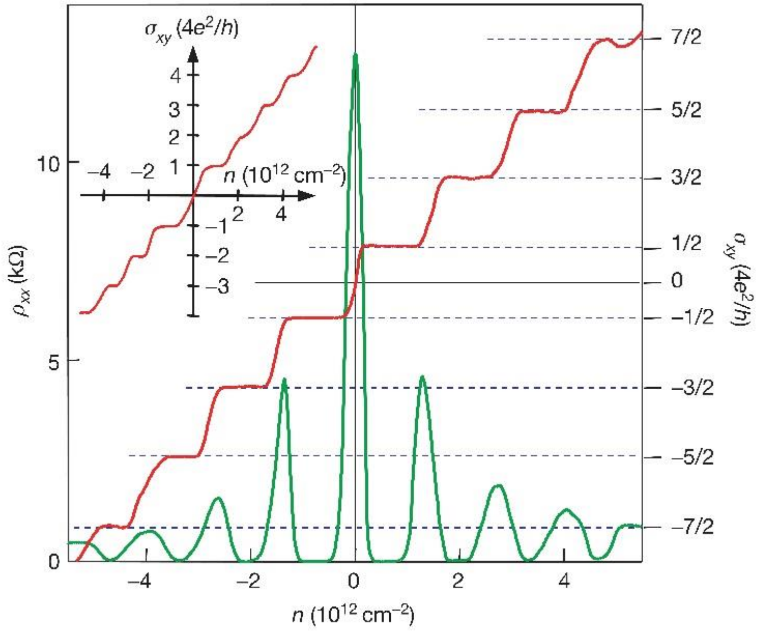
# QHE in Graphene

- First LL at half-integer
- Degeneracy of 4 (valley and spin):
  - 2 C-atoms in unit cell $\rightarrow 2 \cdot \frac{2e^2}{h} = \frac{4e^2}{h}$




*Mikhail I. Katsnelson: Graphene*

$B = 14\mathrm{T}, T = 4\mathrm{K}$



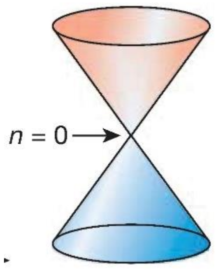

*K. S. Novoselov et al Nature 438 (2005)*

# QHE in Graphene

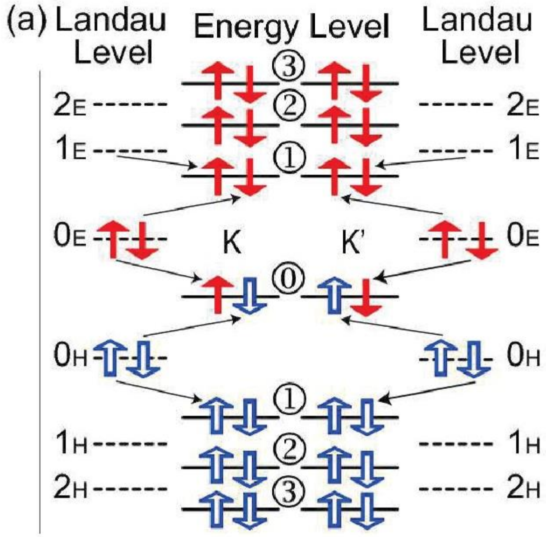
- Linear dispersion relation: Massless Dirac fermions

$$E_N = \hbar\omega_c^*\left(N + \frac{1}{2}\right) \quad \rightarrow \quad E_N = \hbar\omega_c\sqrt{N}$$

$\Longrightarrow \quad E = 0$ level (shared by electrons and holes)




*K. S. Novoselov et al Nature 438 (2005)*



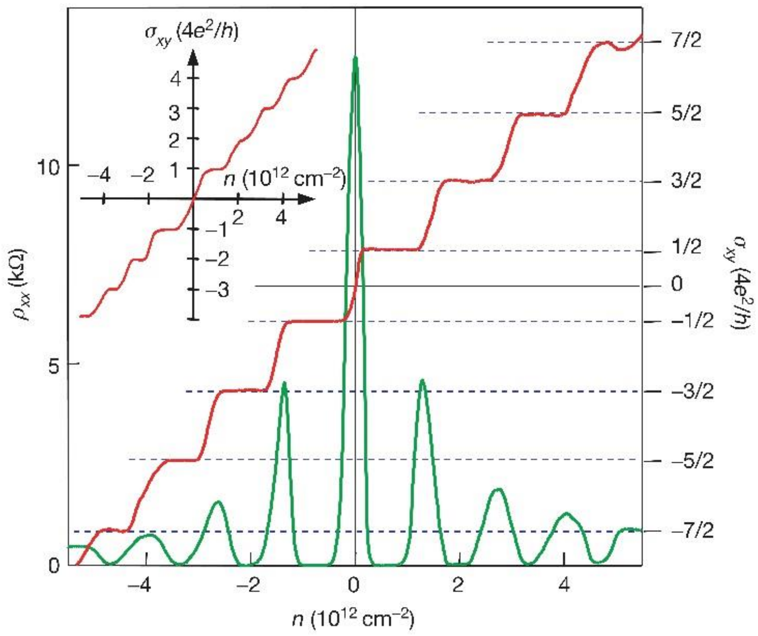

*M.Ezawa J. Phys. Soc. Jpn (2007)*

$$\Longrightarrow \quad \sigma = \frac{4e^2}{h}\left(N + \frac{1}{2}\right)$$

# QHE in Graphene

$$\sigma = \frac{4e^2}{h}\left(N + \frac{1}{2}\right)$$

$B = 14\mathrm{T}, T = 4\mathrm{K}$

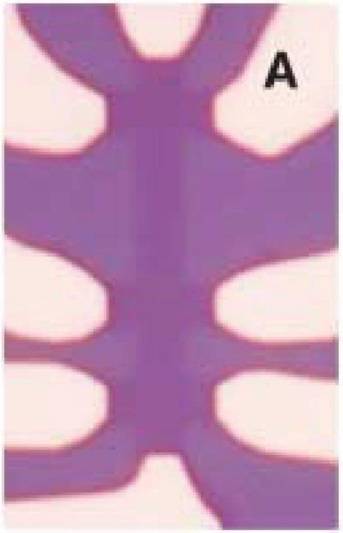



*K. S. Novoselov et al Nature 438 (2005)*

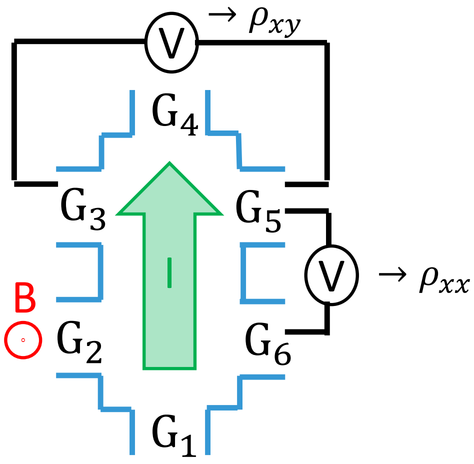
# Room Temperature QHE in Graphene

- Motivation:
  - Metrology: resistance standard
  - Investigation of finer features of the QHE

- Hall bar sample (2µm width)

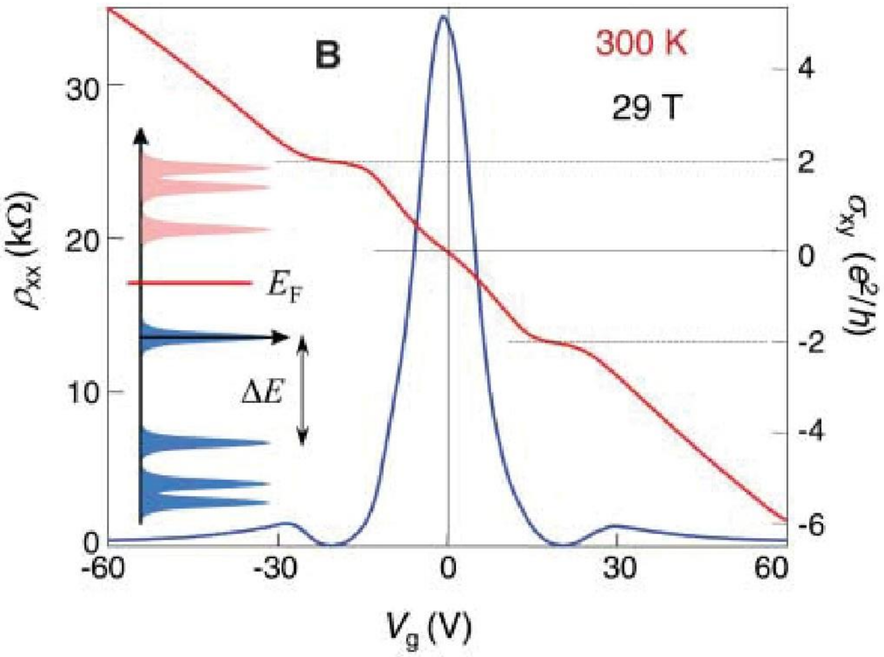



K. S. Novoselov et al Science 315 (2007)



# Room Temperature QHE in Graphene

- $\sigma_{xx}$-peaks very flat
  - SdHO is strongly T-dependent
- $\sigma_{xy}$-plateaus not sharp
  - LL smeared out due to high T
- QHE is still visible at 300K!!!




*K. S. Novoselov et al Science 315 (2007)*

# Room Temperature QHE in Graphene

- $E_N = v_F\sqrt{|2e\hbar BN|}$ with $v_F \approx 10^6 m/s$ and $B = 45\text{T}$
  $\rightarrow\ \Delta E_{0-1} \approx 2800K$
  $\rightarrow \hbar\omega_c \approx 10 \cdot k_B T$

*J.Guignard et al Physical Review (2012)*

| | |
|---|---|
| Graphene: | $36\sqrt{B}$ meV |
| GaAs: | $1.7B$ meV |

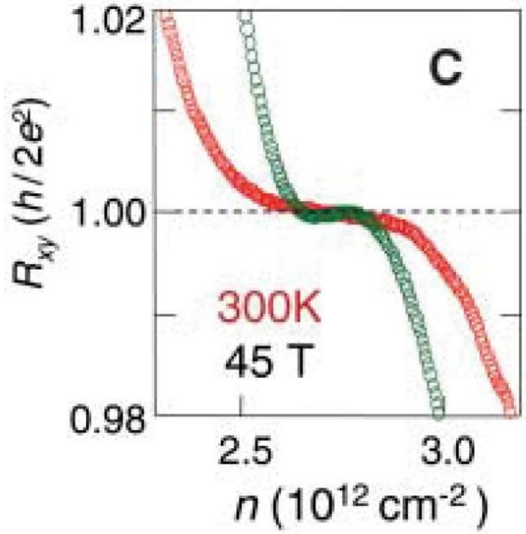
# Room Temperature QHE in Graphene

- Although a very high carrier concentration only one 2D subband is occupied, this is essential to fully populate the lowest LL.

➢ Other 2D systems do not exhibit this property what causes a reduction of the energy gap below $\hbar\omega_c$.

- Graphene's mobility is almost not affected by temperature rise (4-300K). $\rightarrow$ $\omega_c\,\tau = \mu B \gg 1$

# Room Temperature QHE in Graphene




*K. S. Novoselov et al Science 315 (2007)*

# 4 Conclusion

- large Landau level gap

- Very high carrier concentrations in only one subband
  -> lowest LL fully populated

- Mobility remains constant -> $\omega_c \tau = \mu B \gg 1$

# Thank you