Graphene
a new electronic material

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Overview / Roadmap

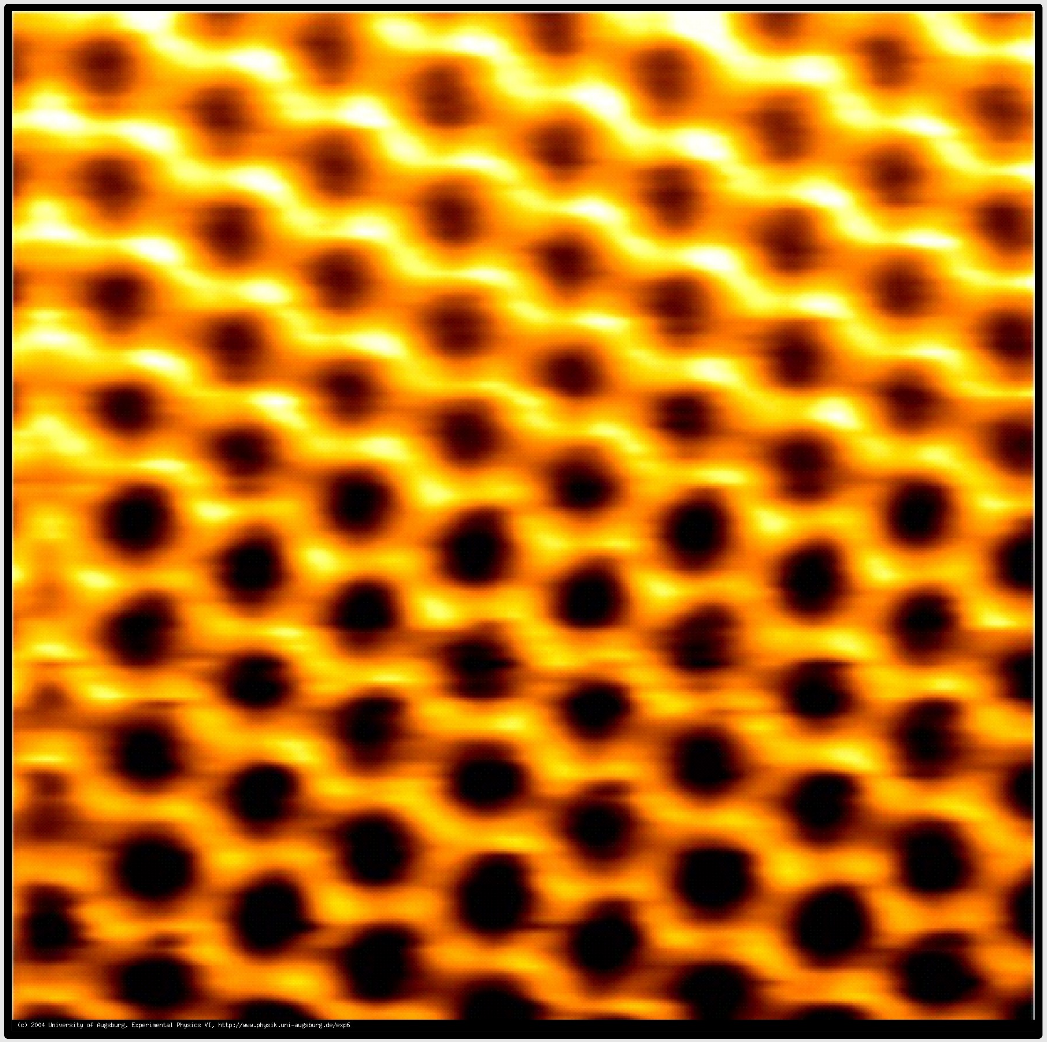
- Introduction
- Preparation of Graphene

- Atomic / Electronic Structure
- Description as Dirac Fermions

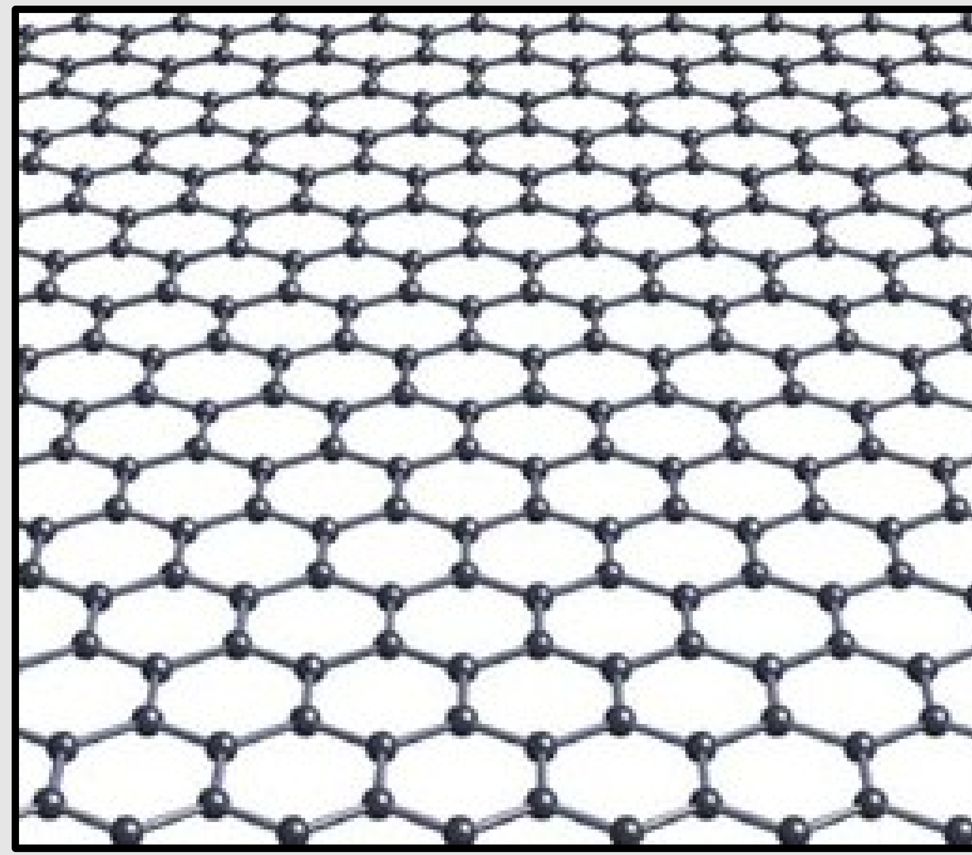
- Anomalous Quantum Hall Effect
- Tunneling of Chiral Particles

- Graphene Devices
- Conclusions

Graphene: a carbon modification



AFM image of graphite surface, 2x2 nm²
(Exp. Physics VI, Uni Augsburg)

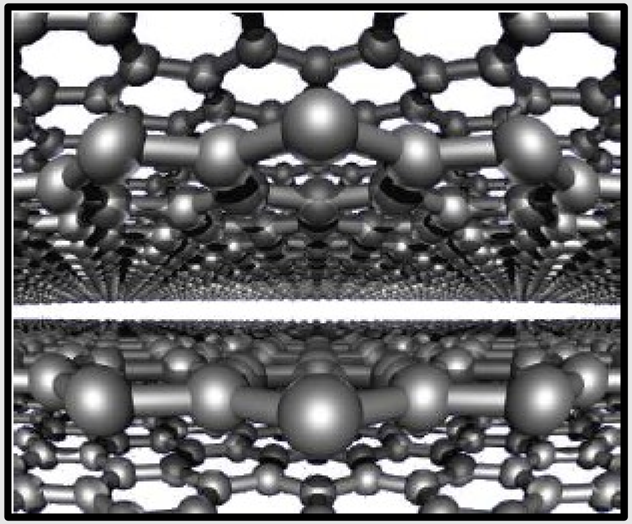
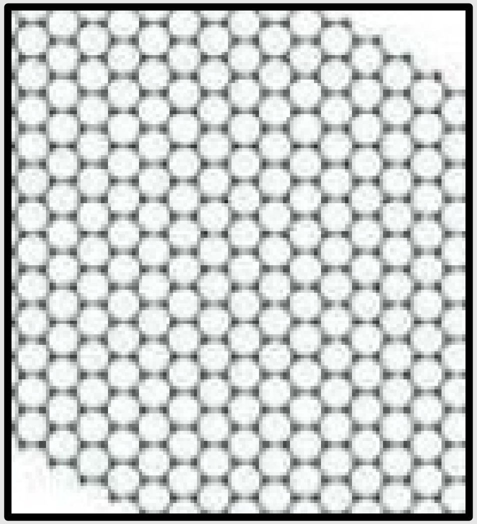
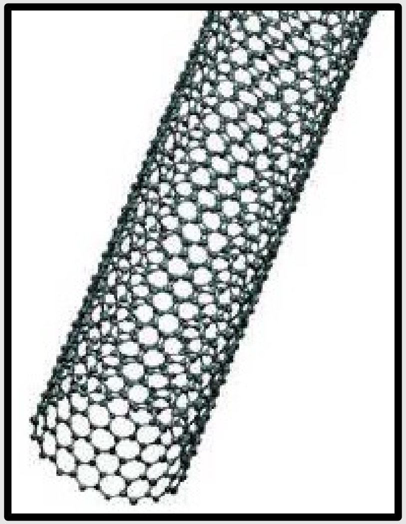
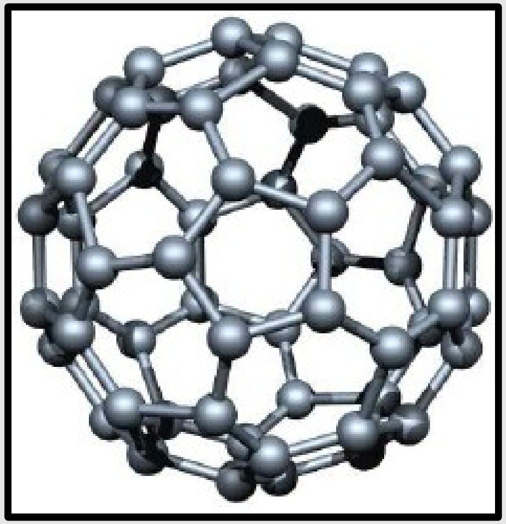


Planar, hexagonal structure of graphene

Introduction

Graphene in many dimensions:

- 3D in graphite crystals
- 2D in a single layer
- 1D in nanotubes
- 0D in fullerenes

Preparation of Graphene

Top – Down Approach:
Micromechanical cleavage

Bottom – Up Approach:
Growing Graphene on SiC

Top – Down Approach

(after Novoselov et al., Science 306, 666 (2004))

„Micromechanical cleavage“

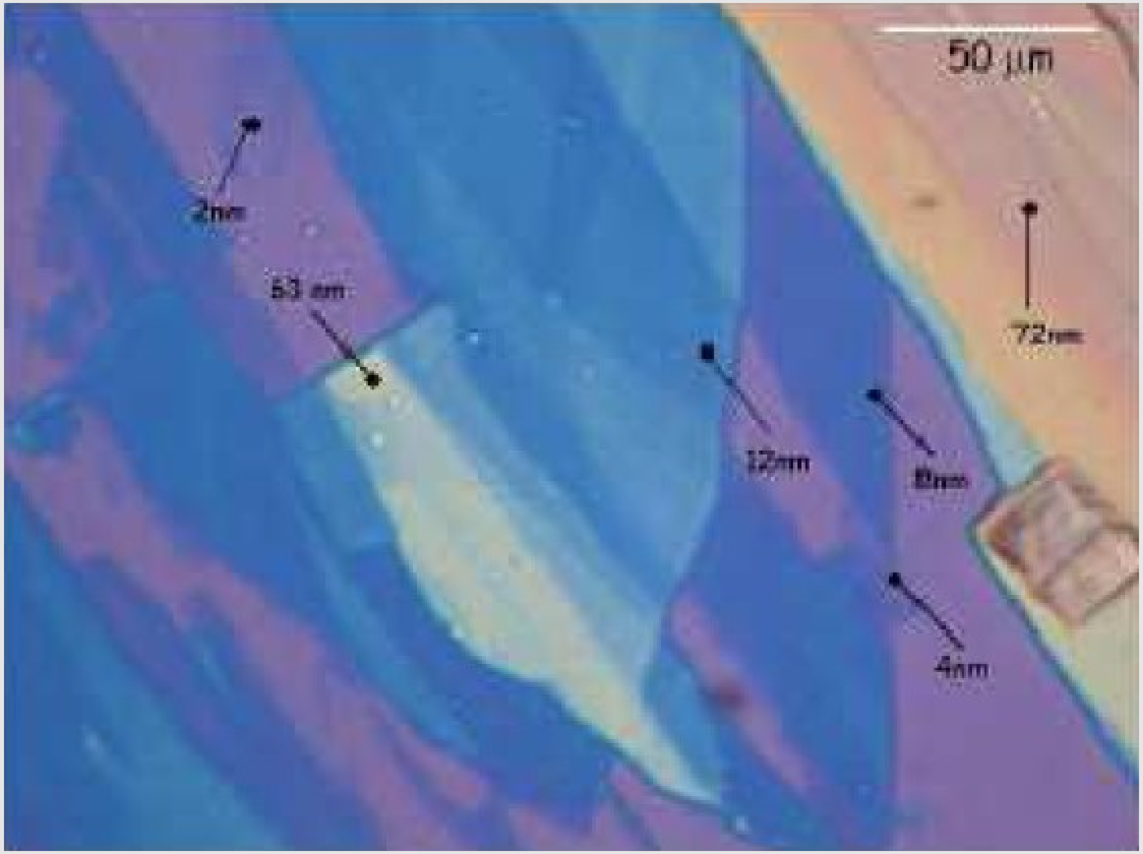
Recipe:

1. 1mm **highly-oriented pyrolytic graphite** (HOPG)
2. **dry etching:** 5µm
3. photoresist on glass surface, **baking** layer into it
4. **peel of** layers using scotch tape
5. **release** thin flake left on glass in acetone
6. **„wash“** flake on wafer
7. **ultrasound cleaning** in propanol: only thin flakes stick to SiO_2

Top – Down Approach

(after Novoselov et al., Science 306, 666 (2004))

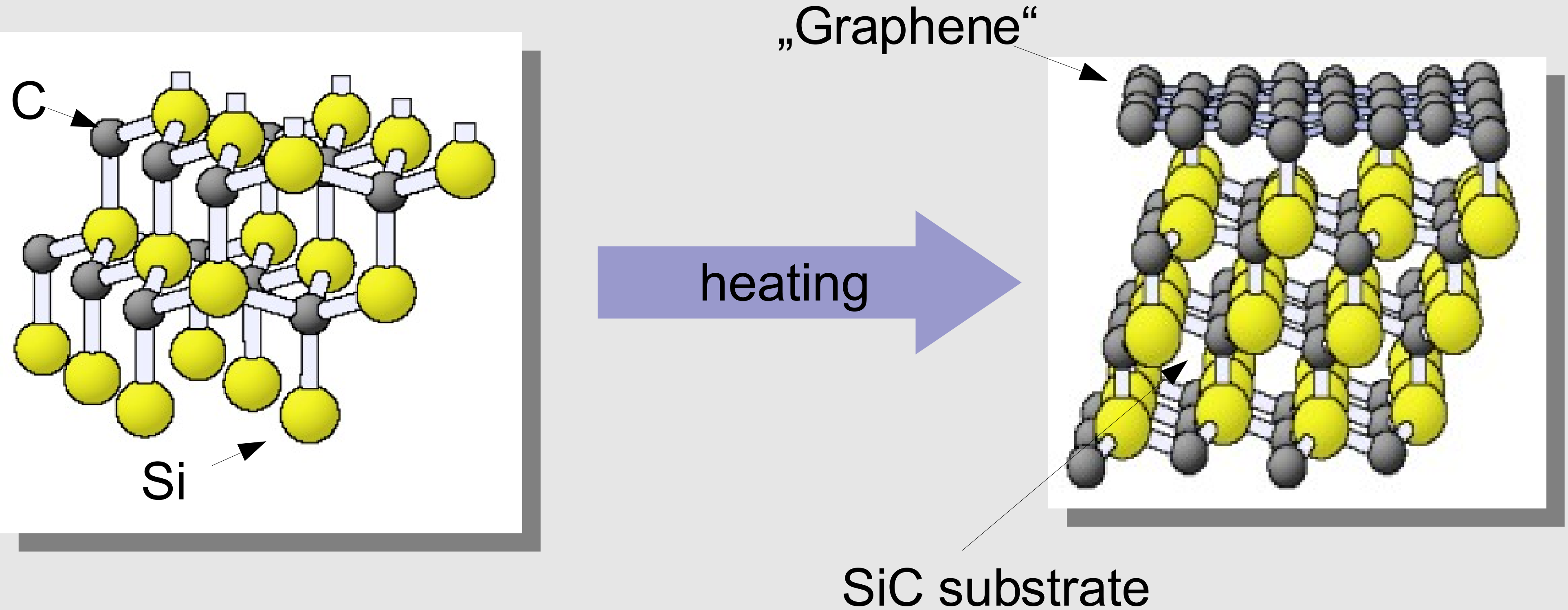
Final step: **selection process** finding thin layers using optical microscope, scanning electron micrographs, AFM



Wafer with graphene flakes, optical microscope

Bottom-Up Approach

Growing Graphene on SiC



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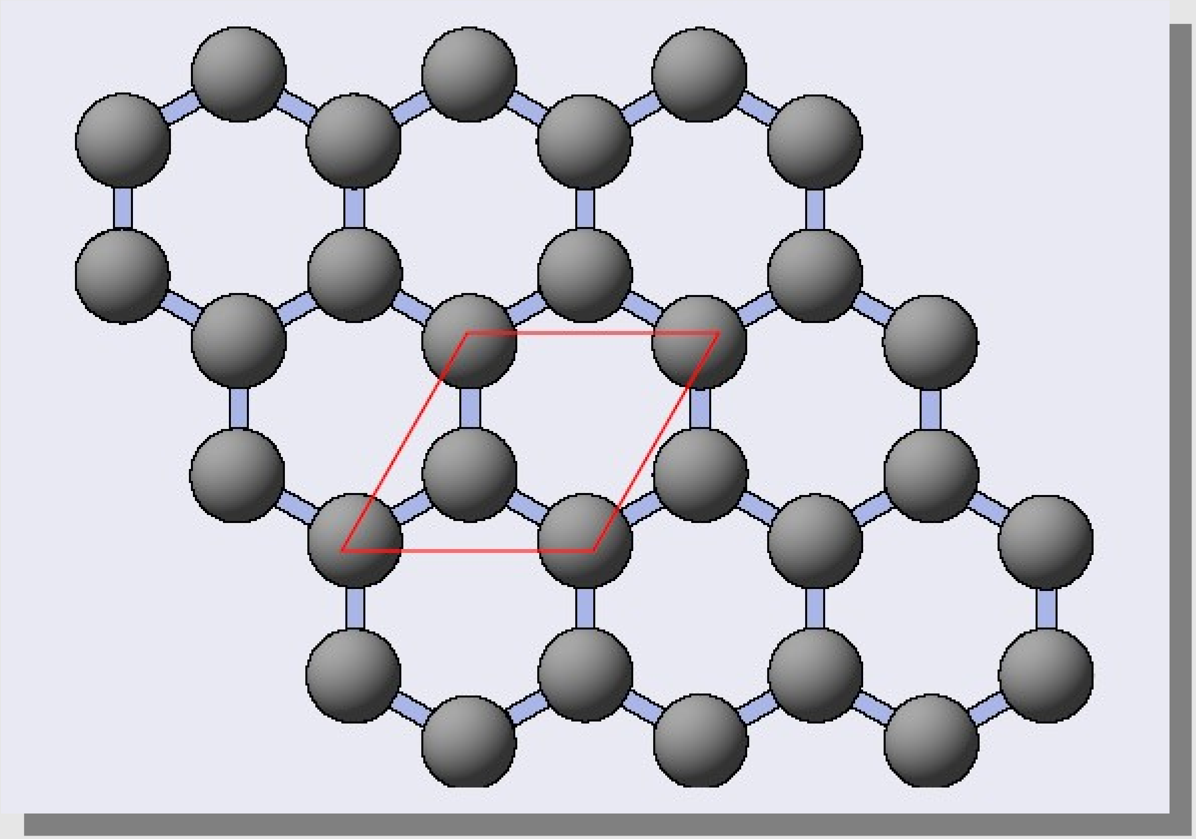
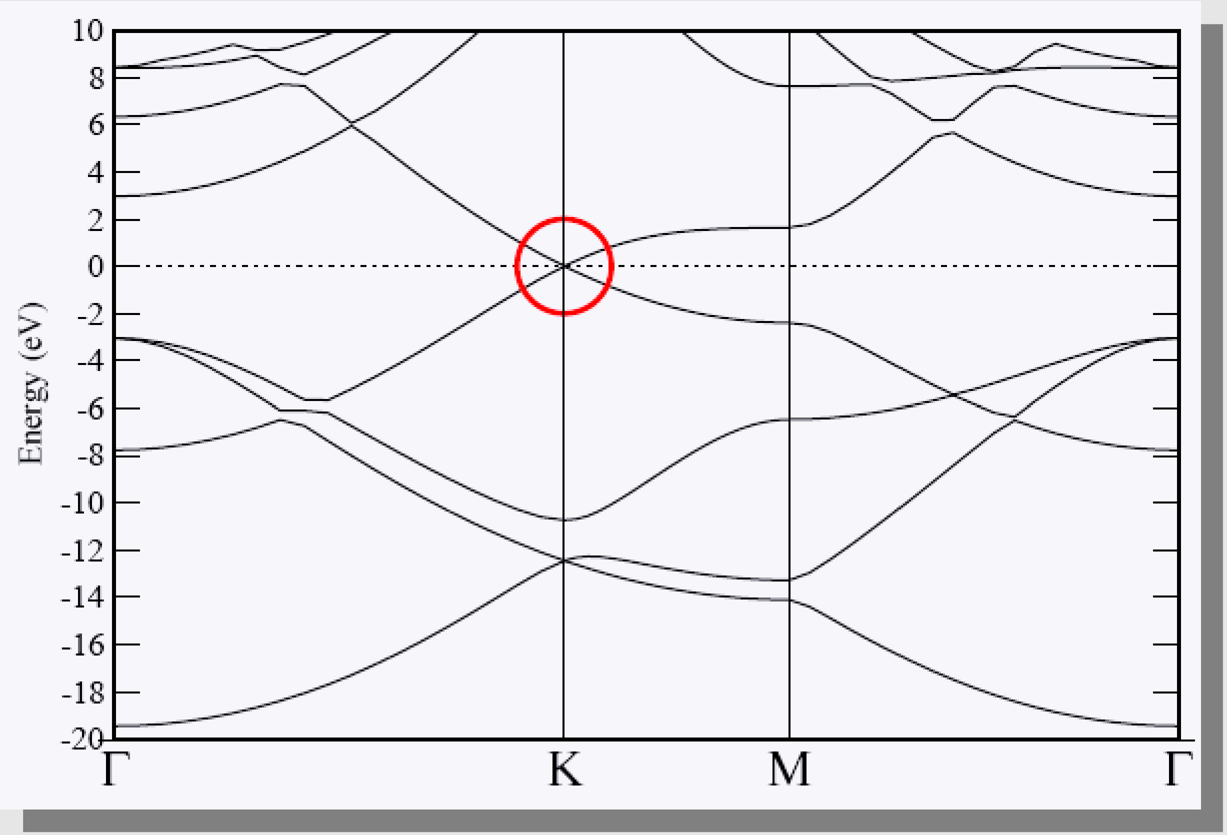
Atomic Structure

- sp^2 hybridization => planar, hexagonal lattice



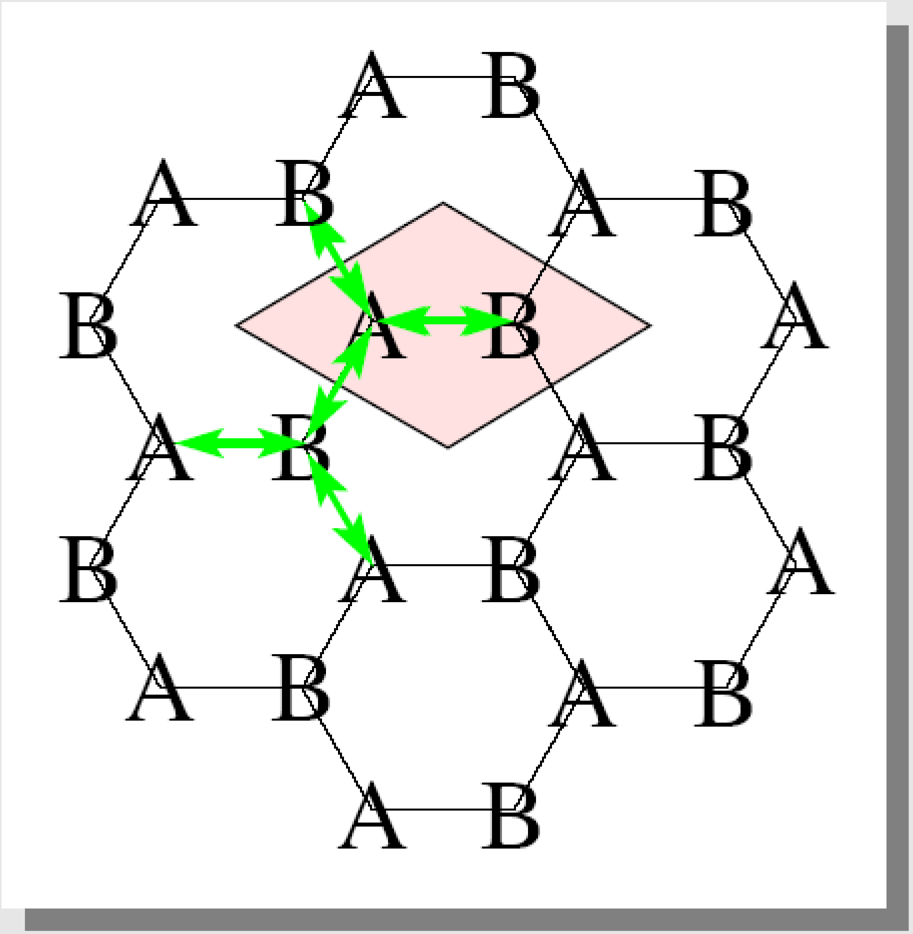
- a = 2.45 Å
- 2 carbon atoms per unit cell

Electronic Bandstructure

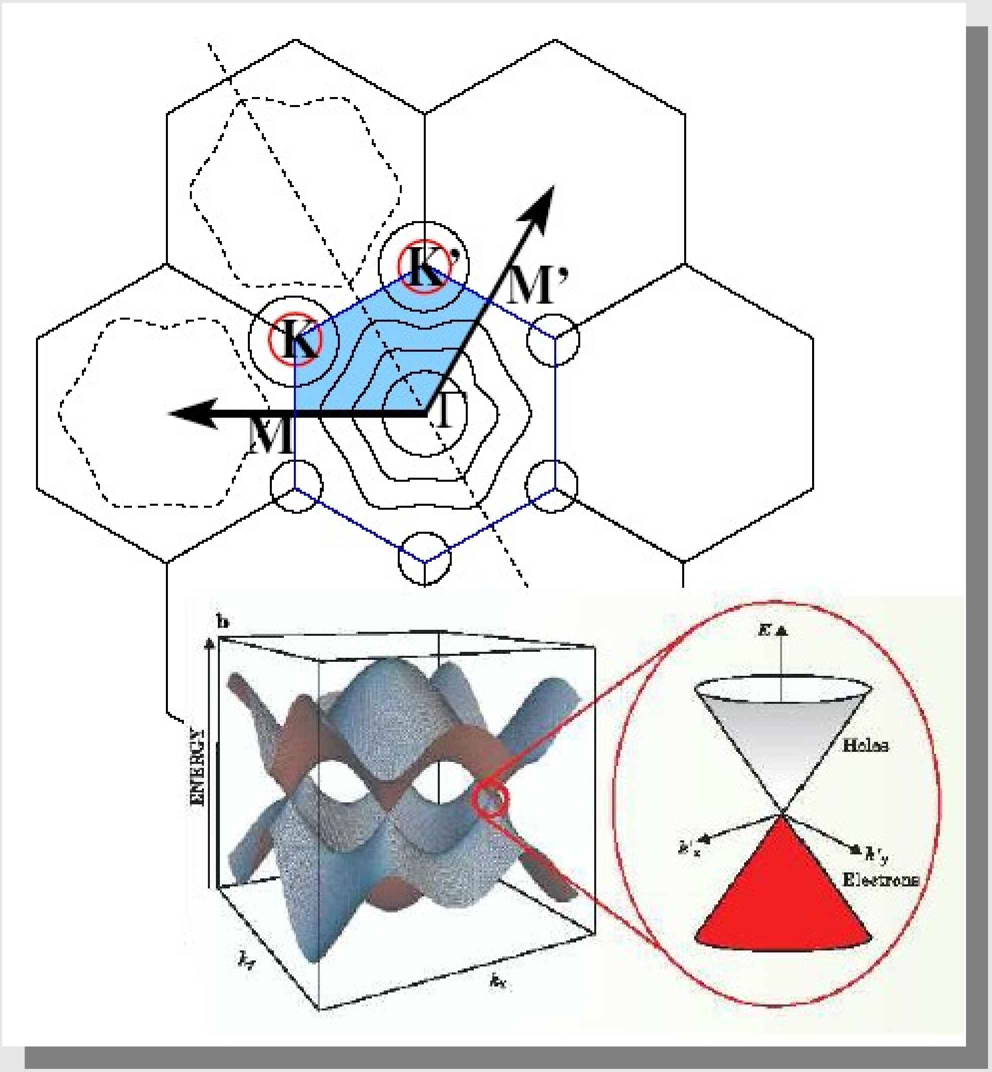


- gapless semiconductor <=> semi-metal
- linear dispersion relation at conic point

Bipartite lattice

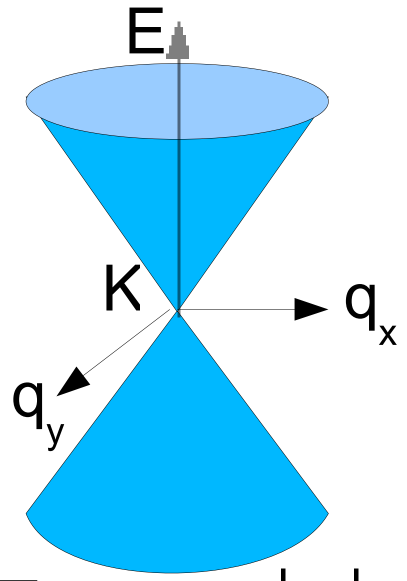


real space



momentum space

massless 2D Dirac Fermions



$$E = \pm v_F |q|$$

$$H_K = \begin{pmatrix} 0 & v_F(q_x - iq_y) \\ v_F(q_x + iq_y) & 0 \end{pmatrix}$$

- q = K - k
- 2x2 structure from 2 site unit cell => pseudo spin

„light cone" with $v_F = 10^6$ m/s

Pseudo spin

$$H_K = \begin{pmatrix} 0 & v_F\left(q_x - iq_y\right) \\ v_F\left(q_x + iq_y\right) & 0 \end{pmatrix} = v_F \begin{pmatrix} \sigma_x & \sigma_y \end{pmatrix} \begin{pmatrix} q_x \\ q_y \end{pmatrix}$$

- Pseudo spin comutes with H_K => is conserved
- Pseudo spin is projected on momentum
  - σ parallel q <=> electron
  - σ antiparallel q <=> hole

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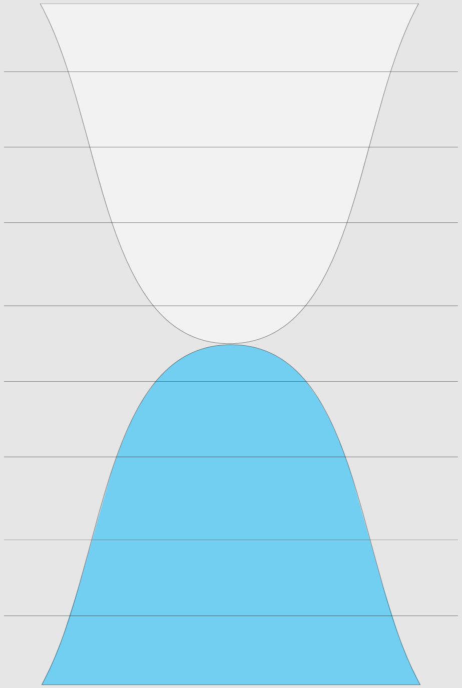
Anomalous QHE: setup

Landau quantisation

- from Schrödinger's Eq. (non relativistic):

$$E_n = \pm \hbar \omega_c \left(n + \frac{1}{2}\right)$$

electron/hole
states



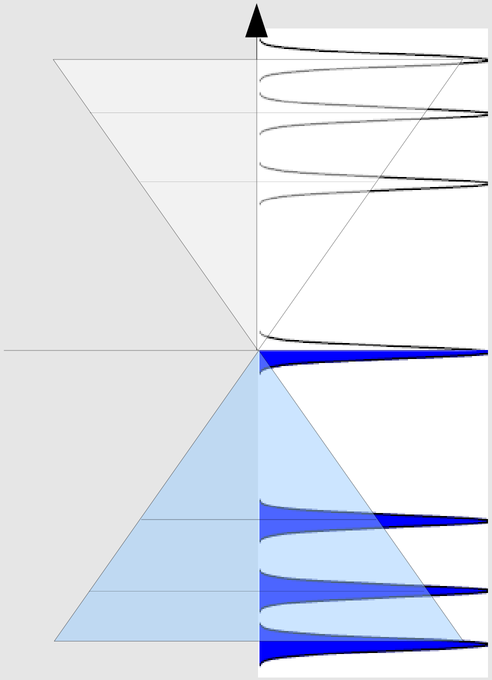
Landau quantisation (II)

- from Dirac Eq. (relativistic, massless):

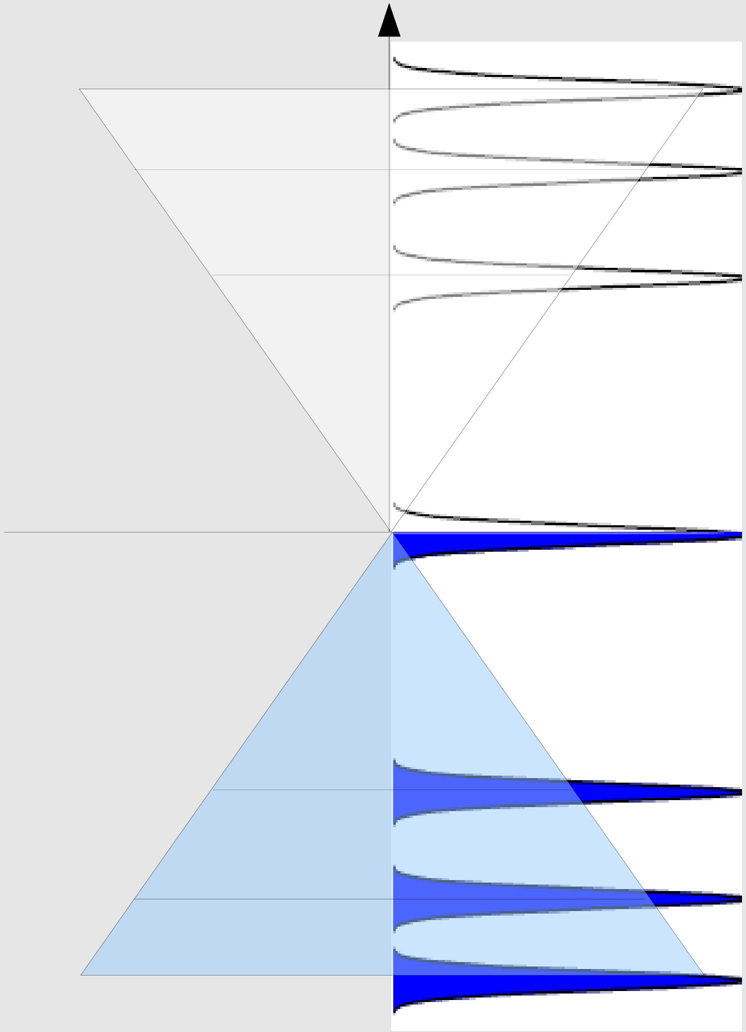
$$E_n = \pm \sqrt{2|e| B \hbar v_F^2 \left(n + \frac{1}{2} \pm \frac{1}{2}\right)}$$

electron/hole states

pseudo spin



Landau quantization (III)

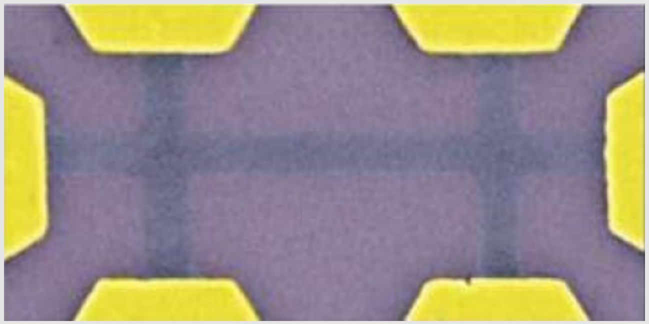


- There is an zero energy level! It doesn't move!
- Landau levels degeneracy:
  - E = 0 : 2x
  - E > 0 or < 0 : 4x

Understanding QHE: σ_{xx}

Understanding QHE: σ_{xy}

Anomalous QHE in graphene



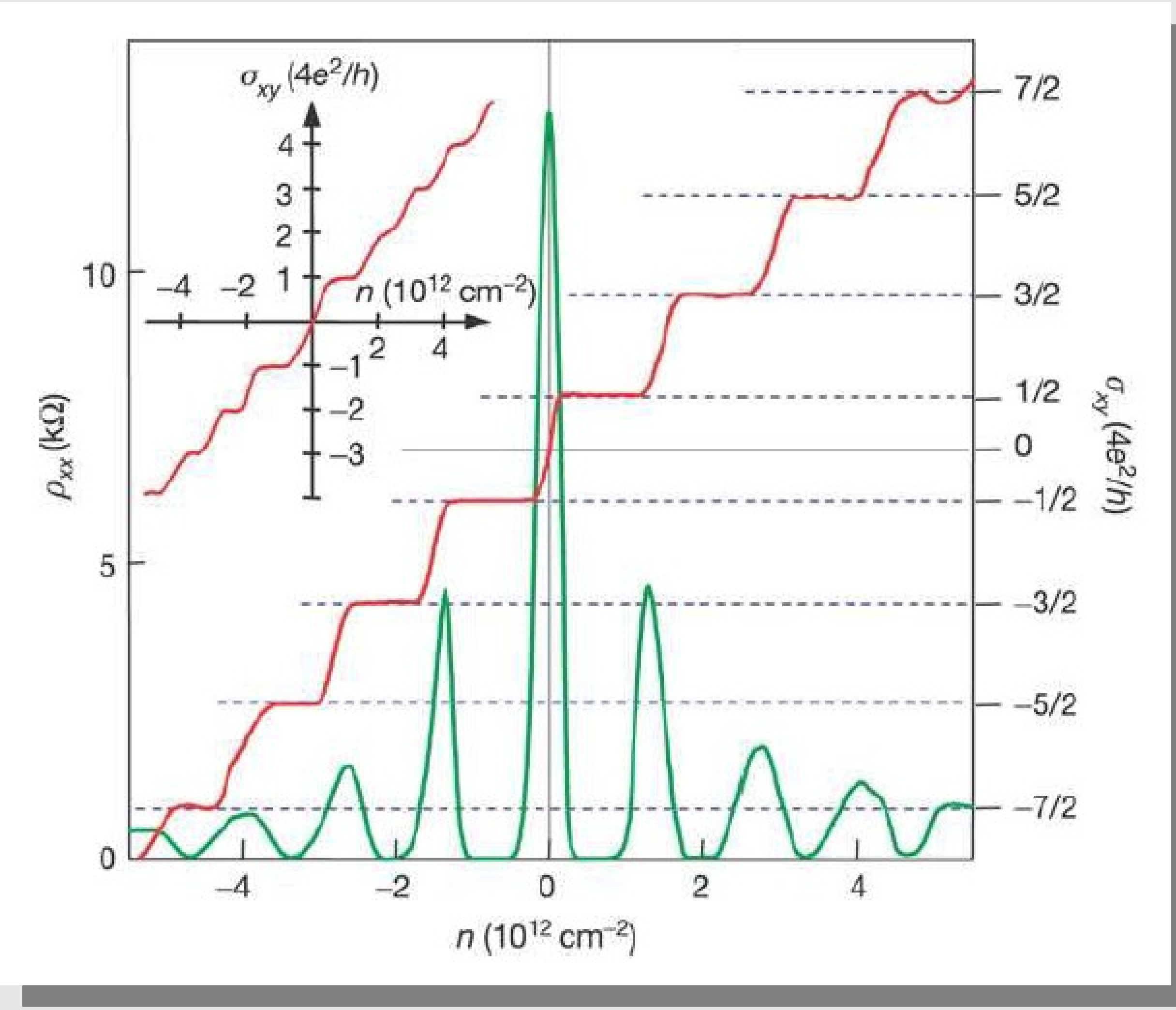
Hall bar, SEM false colors (L=200nm)

QHE in graphene

$$\sigma_{xy} = 4\left(\frac{e^2}{\hbar}\right)\left(n \pm \frac{1}{2}\right)$$

normal QHE

$$\sigma_{xy} = \left(\frac{e^2}{\hbar}\right) n$$



(Novoselov et al., Nature 2005)

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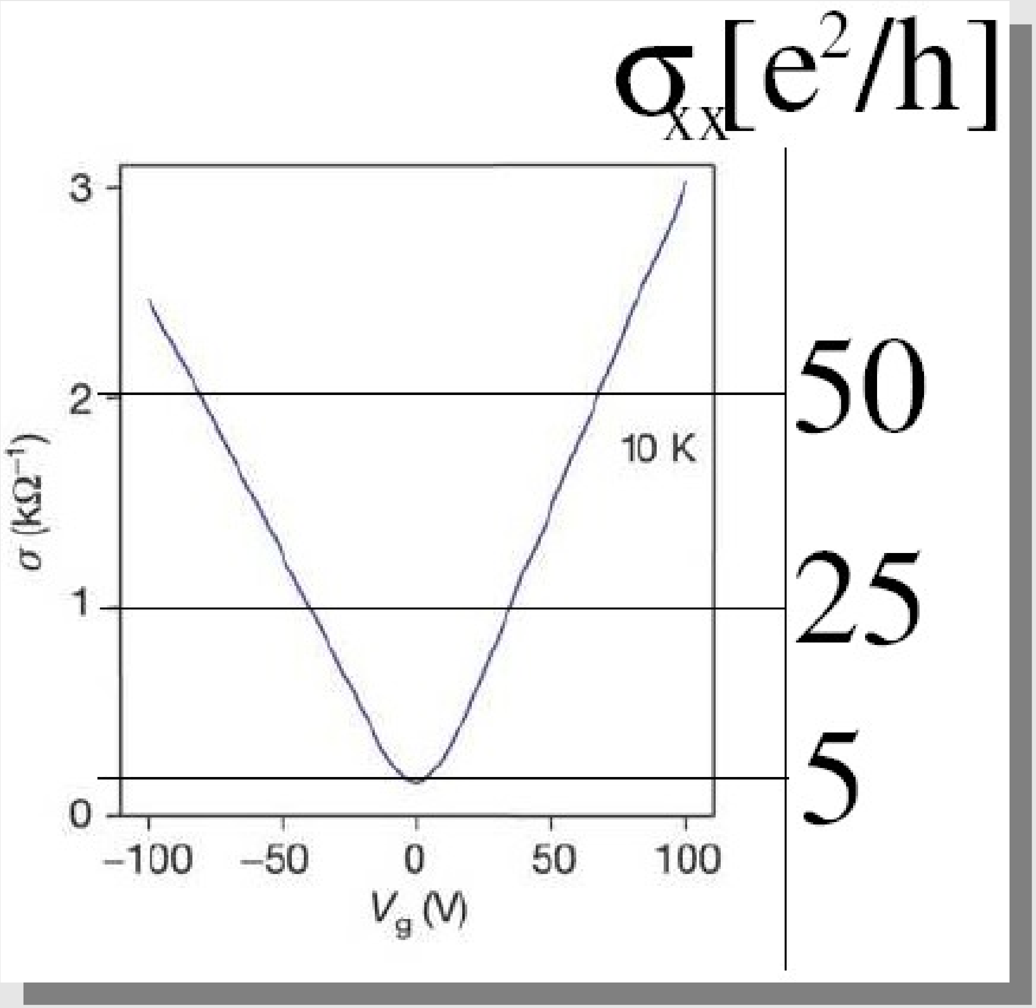
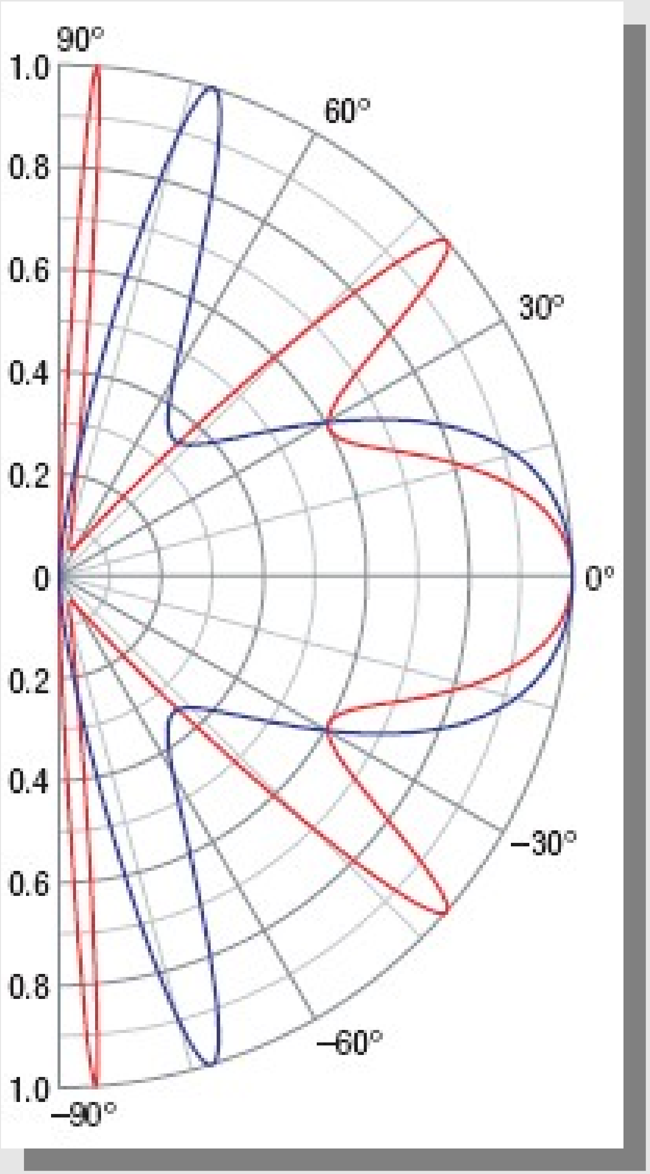
Tunneling of Chiral Particles

<u>Motivation:</u>
1D and 2D electron systems should crystalize at low temp.
=> the should be no conductivity

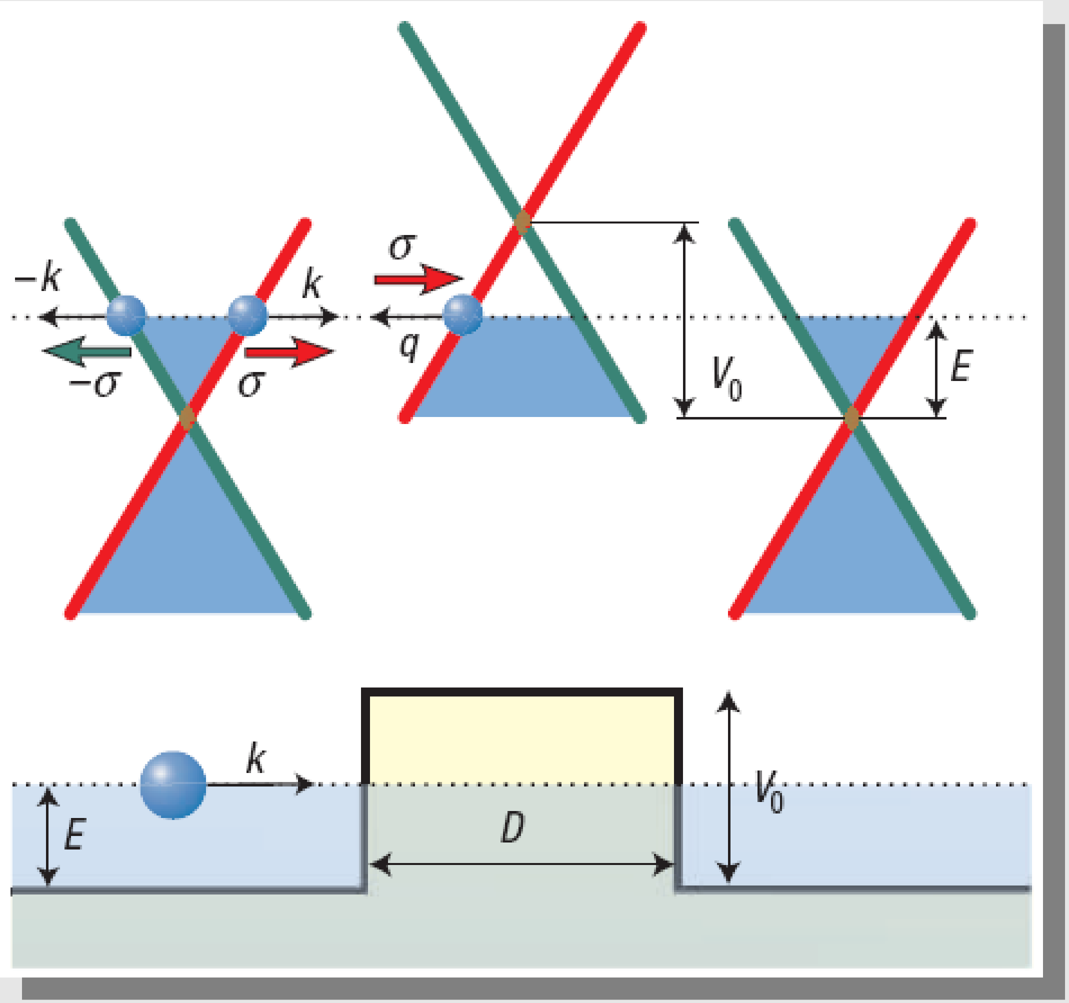
In graphene, this is not observed!!!



Forbidden Backscattering



Tunneling of Chiral Particles



electronic states outside the barrier
meet holelike states inside the barrier

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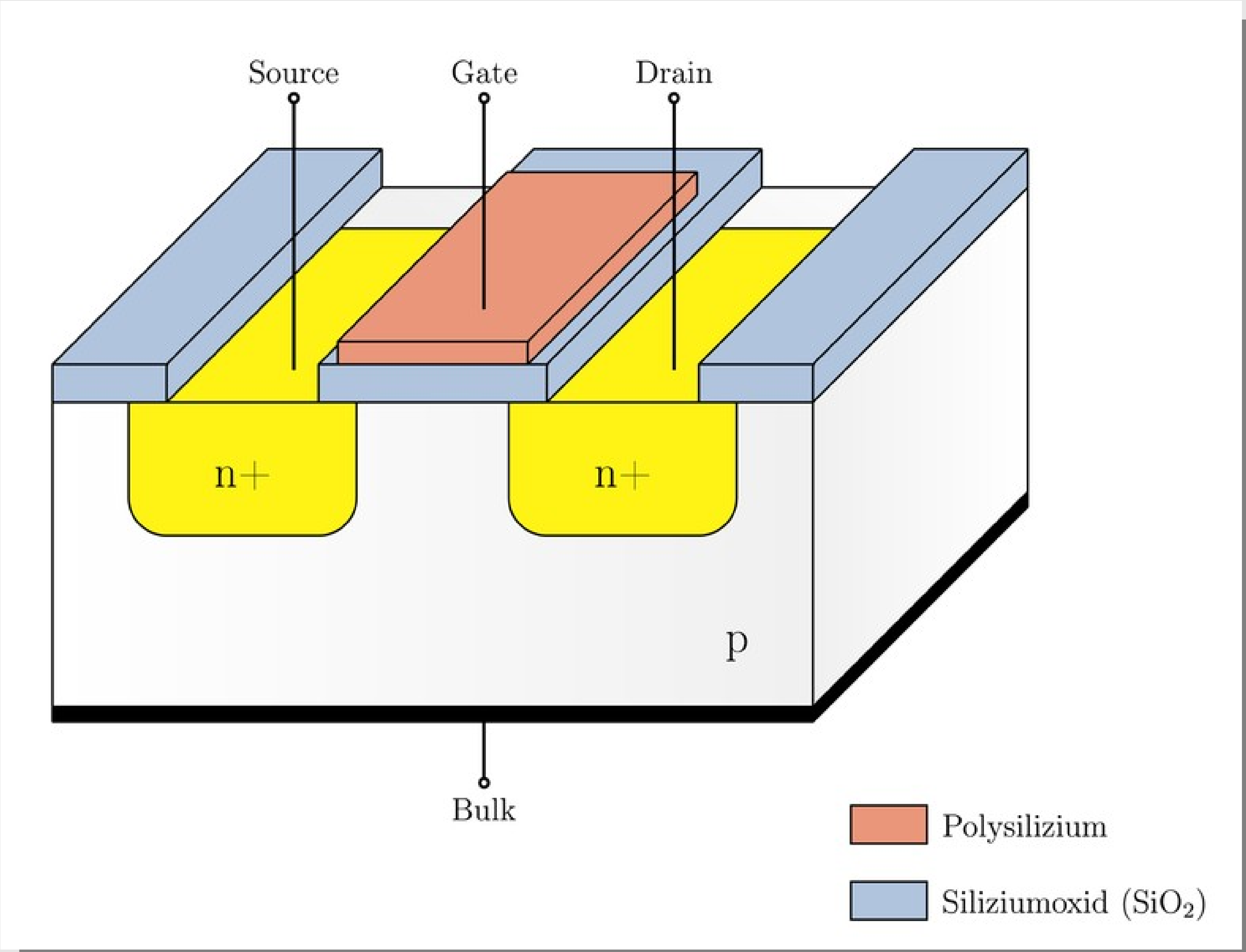
Graphene Devices: Electron mobility

- Graphene: 20.000 cm^2/Vs to 50.000 cm^2/Vs (only limited by defects, stable btw. 10 to 100K)

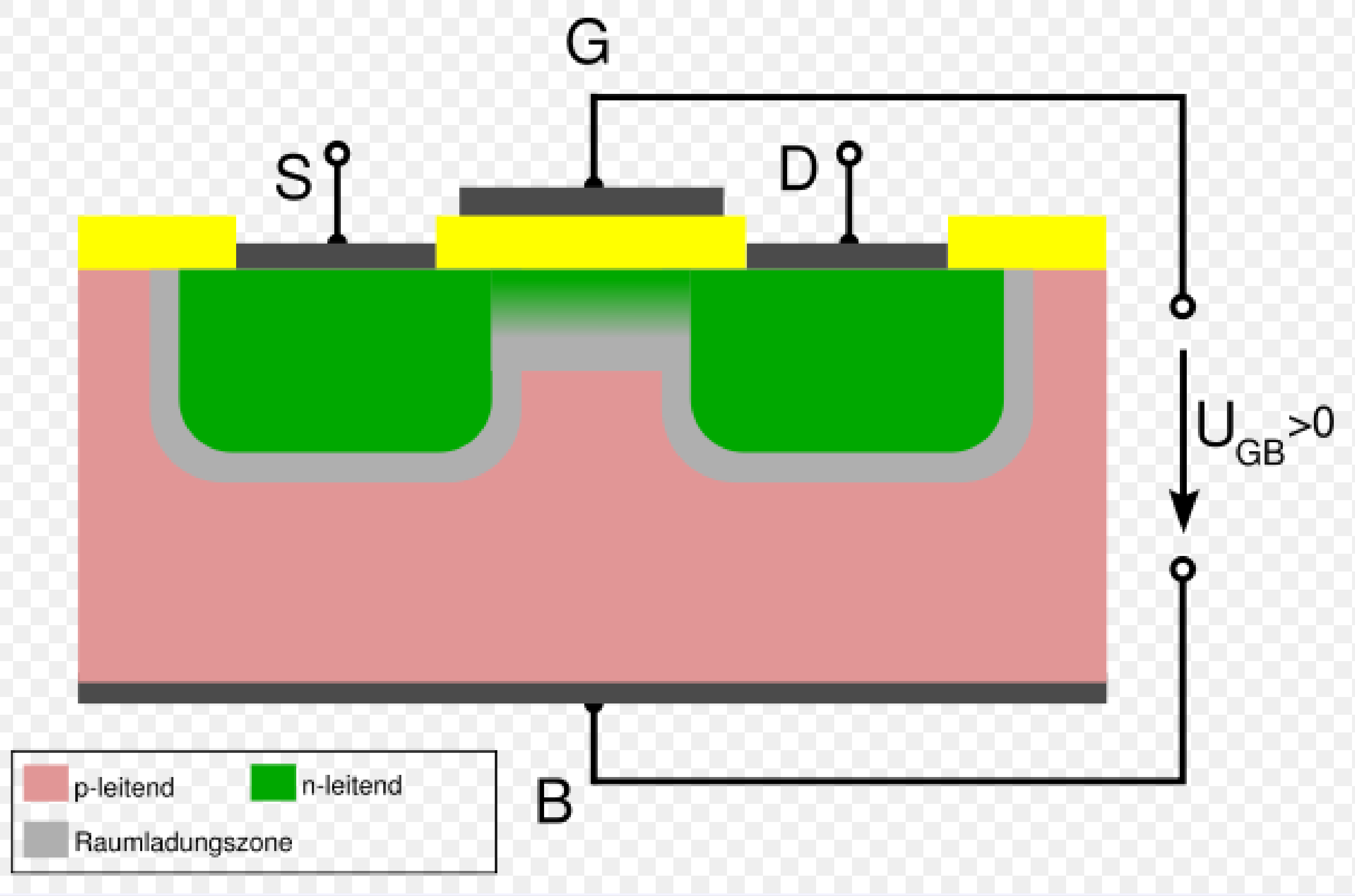
Current technologies:

- Silicon: 10.000 cm^2/Vs (max)
- InSb (indium antimonide): 30,000 cm^2/Vs at 295K (Intel, Qinetq, 2005)

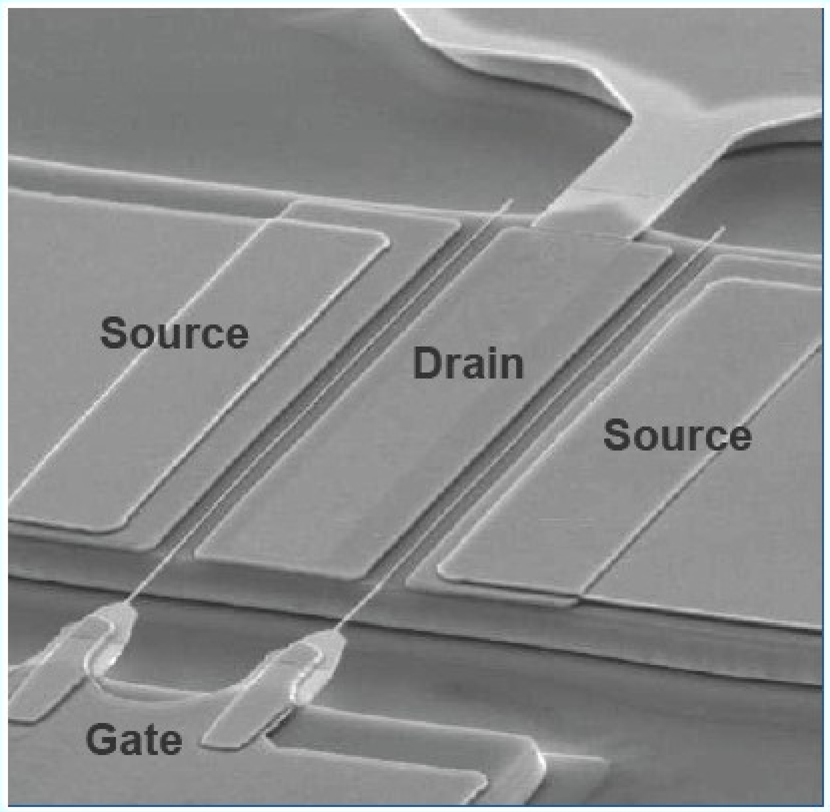
Classical FETs: n-MOSFET

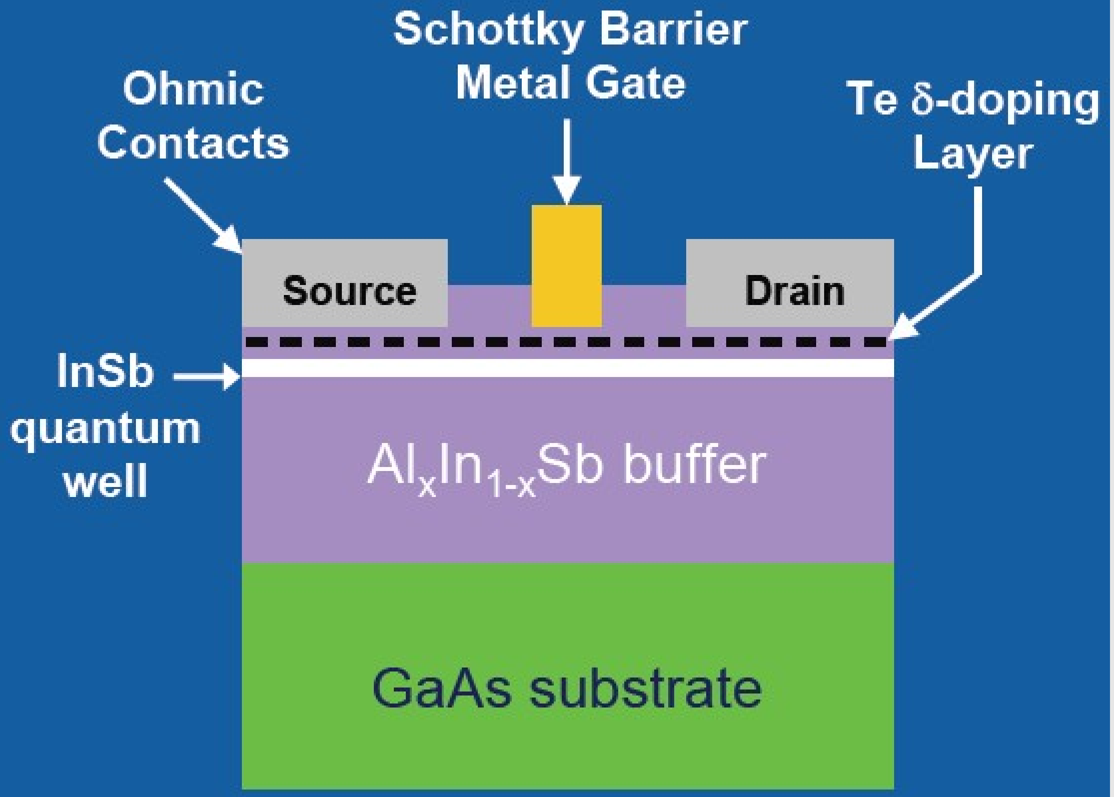


n-MOSFET with channel



InSb quantum well transistors





(Intel , 3rd Asian Academic Forum, Nov. 2006)

Graphene FETs: simple design

- direct application: Gas sensor

Conclusions & Outlook

- unexpected bridge btw. condensed matter & QFT
- possibility to study 2D massless Dirac fermions in a bench-top setup
- (anomalous QHE, absence of Anderson localisation)
- Carbon transistors, with ballistic transport
- even more possibilities with bilayer graphene!

any questions?

THE END

Thank you for your attention. Have a nice day.