Nanoscience – quantum transport

Janine Splettstößer

Applied Quantum Physics, MC2, Chalmers University of Technology

CHALMERS
UNIVERSITY OF TECHNOLOGY

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Plan/Outline

4 Lectures

(1) Introduction to quantum transport

(2) Quantization effects in charge current and conductance

(3) Magnetic field effects

(4) Quantum transport in carbon-based nanoelectronics

Literature:

- "Electronic transport in mesoscopic systems", S. Datta, Cambridge Studies (2009).
- see also lectures and lecture material by Datta: https://nanohub.org/courses/FON1
- "Many-Body Quantum Theory in Condensed Matter Physics", H. Bruus and K. Flensberg, Oxford Graduate Texts (2004).
- "Quantum Transport", Yu. V. Nazarov and Ya. M. Blanter, Cambridge University Press (2009).
- "Scattering Matrix Approach to Non-Stationary Quantum Transport", M. V. Moskalets, Imperial College Presss (2012).

Contact: **janines@chalmers.se**, MC2 building, C519.

AN ELECTRON IS A

Particle!

Quantum transport

Nanoscience:

- Control and design of useful things at the atomic scale
- Goal/dream: build devices atom by atom
- Interdisciplinary: Physics, Chemistry, Biology, Materials Science, Engineering technology working on small spatial scales (”nano” $10^{-9} m$)

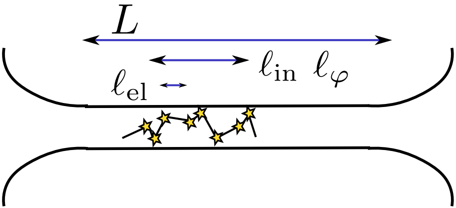
Quantum transport:

Properties and behavior of (charge) transport in nanostructures that

1) cannot be understood starting from classical (non-quantum) physics
2) do not depend on materials or atomic structure per se, rather, on a set of principles that holds in certain regimes

Mesoscopic physics

Example: wire with impurities (diffusive)



L	Length of the wire: Geometric length
ℓ_{el}	Elastic scattering length: typical length between two scattering events (without energy exchange).
ℓ_φ	Coherence length: length scale on which phase coherence is lost – phase has changed by about 2π.
ℓ_{in}	Inelastic scattering length: length scale on which energy of the order $k_B T$ has been exchanged.

Mesoscopic device: $\ell_{\mathrm{el}} \ll L \ll \ell_\varphi \leq \ell_{\mathrm{in}}$

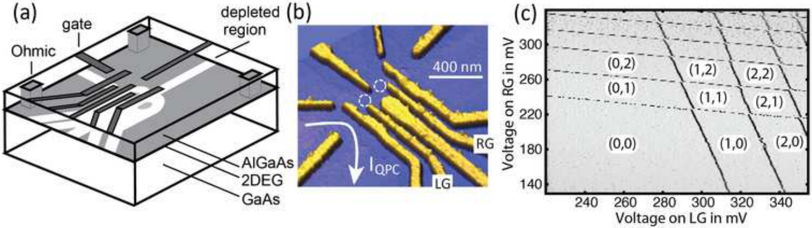
Energy scales

- Temperature $k_\text{B}T$,
  Boltzmann constant $k_\text{B} \simeq 0.087$ meV/K
- Bias voltage applied across the device $-eV$,
  with elementary charge $e = 1.6 \times 10^{-19}$C
- Level spacing δ in strongly confined structures, $\simeq \mu eV - meV$
- Charging energy $E_\text{ch} = e^2/C$,
  $\simeq 0.1$ meV (for $C = 10^{-15}$F)
- Fermi energy E_F or μ,
  several eV for 3D metals, ≈ 14 meV (GaAs 2DEG).

How to make a mesoscopic device?

- Typically a "small" device...
  - nanometer to micrometer range
  - Low-dimensional (two- or even one- or zero-dimensional devices)
- Low temperature (Kelvin to milli Kelvin regime)
- Clean-room conditions

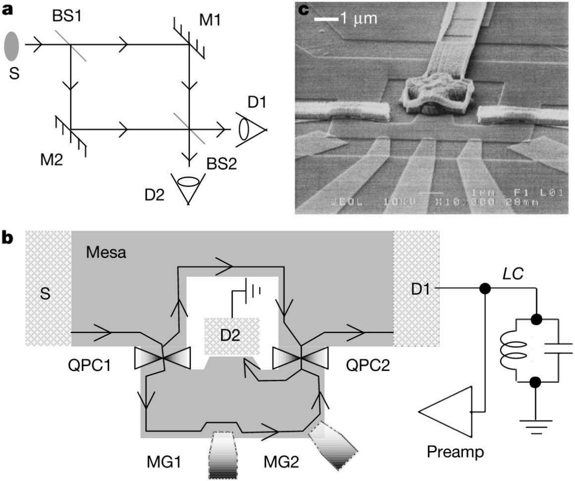
Examples – semiconductor heterostructures



homepage, Katja Nowack.

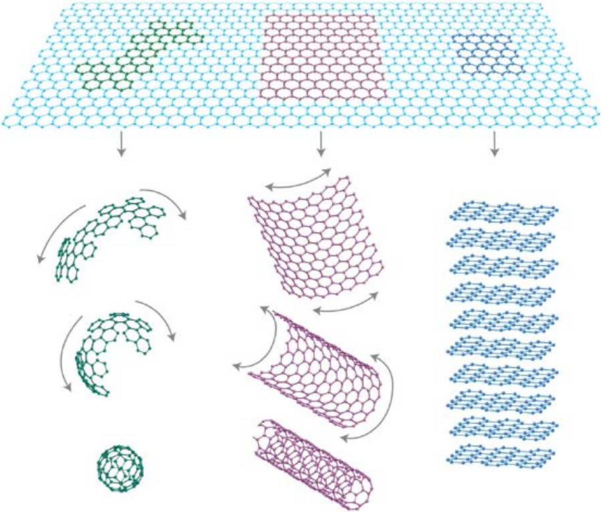
Examples

Hall samples – edge states can take the role of *"wave guides"*



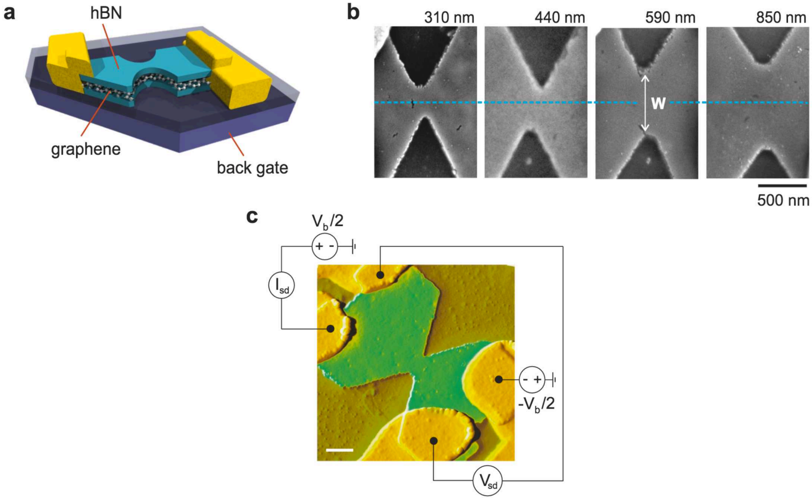
Y. Ji, Y. Chung, D. Sprinzak, M. Heiblum, D. Mahalu, and Hadas Shtrikman, Nature **422**, 415 (2003).

Examples – Carbon-based devices



Examples – Carbon-based devices

Clean, two-dimensional graphene devices

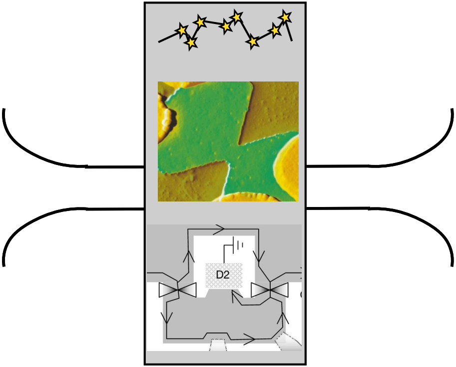


B. Terrés, L. A. Chizhova, F. Libisch, J. Peiro, D. Jörger, S. Engels, A. Girschik, K. Watanabe, T. Taniguchi, S. V. Rotkin, J. Burgdörfer, and C. Stampfer, Nature Communications **7**, 11528 (2016).

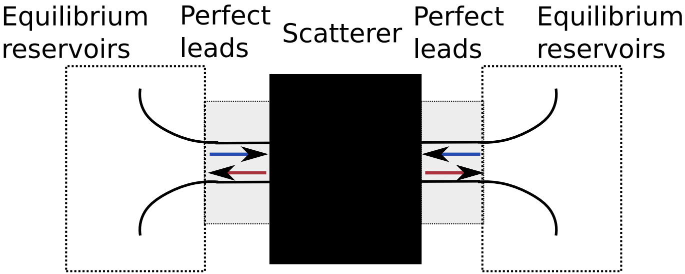
Scattering theory for electronic transport

Common features of mesoscopic devices:

- Possibly complex, phase-coherent device
- Coupled to electronic reservoirs
  - Transport between reservoirs, detection of currents
  - Each reservoir stays in equilibrium during device operation



Scattering theory for electronic transport



Scatterer	Characterized by a scattering matrix with transmission and reflection amplitudes.
Incoming scattering states	Occupied following the equilibrium occupation of the reservoir with μ_α, $k_{\mathrm{B}} T_\alpha$.
Outgoing scattering states	Nonequilibrium states