Novel Materials and Devices in Information Technology: Logic and Memories

Rainer Waser

Institut für Werkstoffe der Elektrotechnik, IWE 2, RWTH Aachen

& Peter Grünberg Institut, PGI-7, FZ Jülich

www.emrl.de

Additional lecturers: ***Dr. Felix Gunkel***
Dr. Dirk Wouters
Dr. Ulrich Böttger
Dr. Stephan Menzel

Tutorials: ***Dr. Felix Gunkel***
Dr. Stefan Wiefels

JARA | FIT
Fundamentals of Future Information Technology

Lecture schedule

Lecture: Wednesday 14:30-16:00; Tutorial: Wednesday 16:15-17:00

Room: 38 A 2 (5381|U103) (SB Chemie, Worringerweg)

<table>
<tr><th>Date</th><th>Lecturer</th><th>Topic</th></tr>
<tr><td>12.10</td><td rowspan="3">F. Gunkel</td><td rowspan="3">0. Overview
1. Mesoscopic electron transport
2. Nano-fabrication and nano-analysis
3. Interconnects</td></tr>
<tr><td>19.10</td></tr>
<tr><td>26.10</td></tr>
<tr><td>02.11</td><td>R. Waser</td><td>4. Processing of Information</td></tr>
<tr><td>09.11</td><td rowspan="6">R. Waser
D. Wouters
U. Böttger</td><td rowspan="6">5. Overview of memories
6. Flash & Charge-based memories
7. Magnetoresistive memories
8. ReRAM Overview
9. ECM
10. VCM</td></tr>
<tr><td>16.11</td></tr>
<tr><td>23.11</td></tr>
<tr><td>30.11</td></tr>
<tr><td>07.12</td></tr>
<tr><td>14.12</td></tr>
<tr><td>11.01.2023</td><td rowspan="4">D. Wouters</td><td rowspan="4">11. General Intro to Logic, von Neumann Architectures & Alternatives (PLA,FPGA)
12. Computing in Memory: logic gates, analog computing
13. General Intro Neuromorphic Computing + ML
14. Neuromorphic Computing mimicking brain functionality</td></tr>
<tr><td>18.01</td></tr>
<tr><td>25.01</td></tr>
<tr><td>01.02</td></tr>
</table>

Tutorial schedule

Tutorial: Wednesday 16:15-17:00

Room: 38 A 2 (5381|U103) (SB Chemie, Worringerweg)

Start: Tutorial + Introduction 19.10.

Lecturer: Dr. Felix Gunkel (FG), Dr. Stefan Wiefels (SW)

Date	Lecturer	Topic	Sub-topics
19.10	FG	Electronic transport & Mesoscopic effects	Mesoscopic effects, ballistic transport
26.10	FG		Coulomb-blockade, single electron transistor
02.11	FG		Interconnect arrays, delay times and scattering
09.11	FG	Overview	CMOS Scaling
16.11	SW	Memory	Memory overview, Write operation, Reading resistive memories
23.11	SW		DRAM read operation, DRAM scaling
30.11	SW		FeRAM operation principle, FeRAM read operation and scaling
07.12	SW		ECM operation principle, ECM switching kinetics
14.12	SW		VCM operation principle, VCM switching kinetics
11.01.2023	SW	Logic	Boolean Logic + Programmable logic arrays
18.01	SW		Compution-in-Memory: Memristive logic families
25.01	SW		Machine Learning
01.02	SW		Biological signal processing, neural networks, learning rules

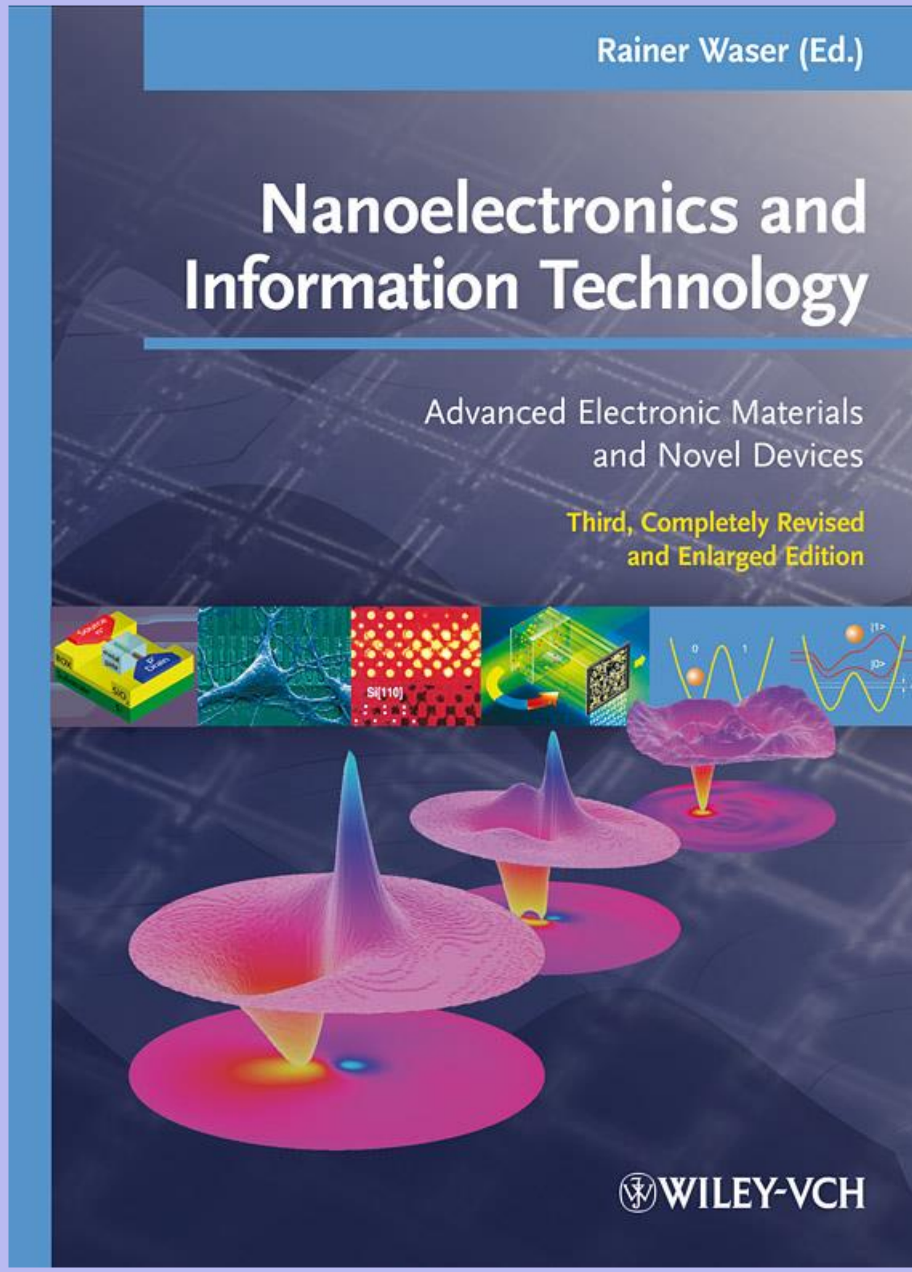
General information

Lecture and tutorial

- The lecture will be held in presence
- The lecture slides will be uploaded to Moodle during the morning of the lecture day
- The tutorial will be held in presence after the lecture.
- Before the tutorial, exercise and introduction will be uploaded to Moodle
- The tutorial solutions are additionally available online, after taking an e-Test in Moodle.

Exam

- Date of written exam: date will be announced
- Extra tutorial for the exam preparation:
  date will be announced
- 2nd date of exam: after the summer semester
- The exam will be in English. You can answer in English or German.
- Exam contains 3 problems, one for each topic: Overview/Logic; Mesoscopic effects, Memory
- Solving the problems requires calculations (about 50 %)
  and explanations in text form (about 50 %)



Main reference book of the lecture NMIT 1 & 2

- NMIT 1:
  Relevant chapters listed in Moodle
- Specific updates (introduced during the lecture)
- large number of copies in the *Lehrbuchsammlung*

Third, completely revised edition

April 2012

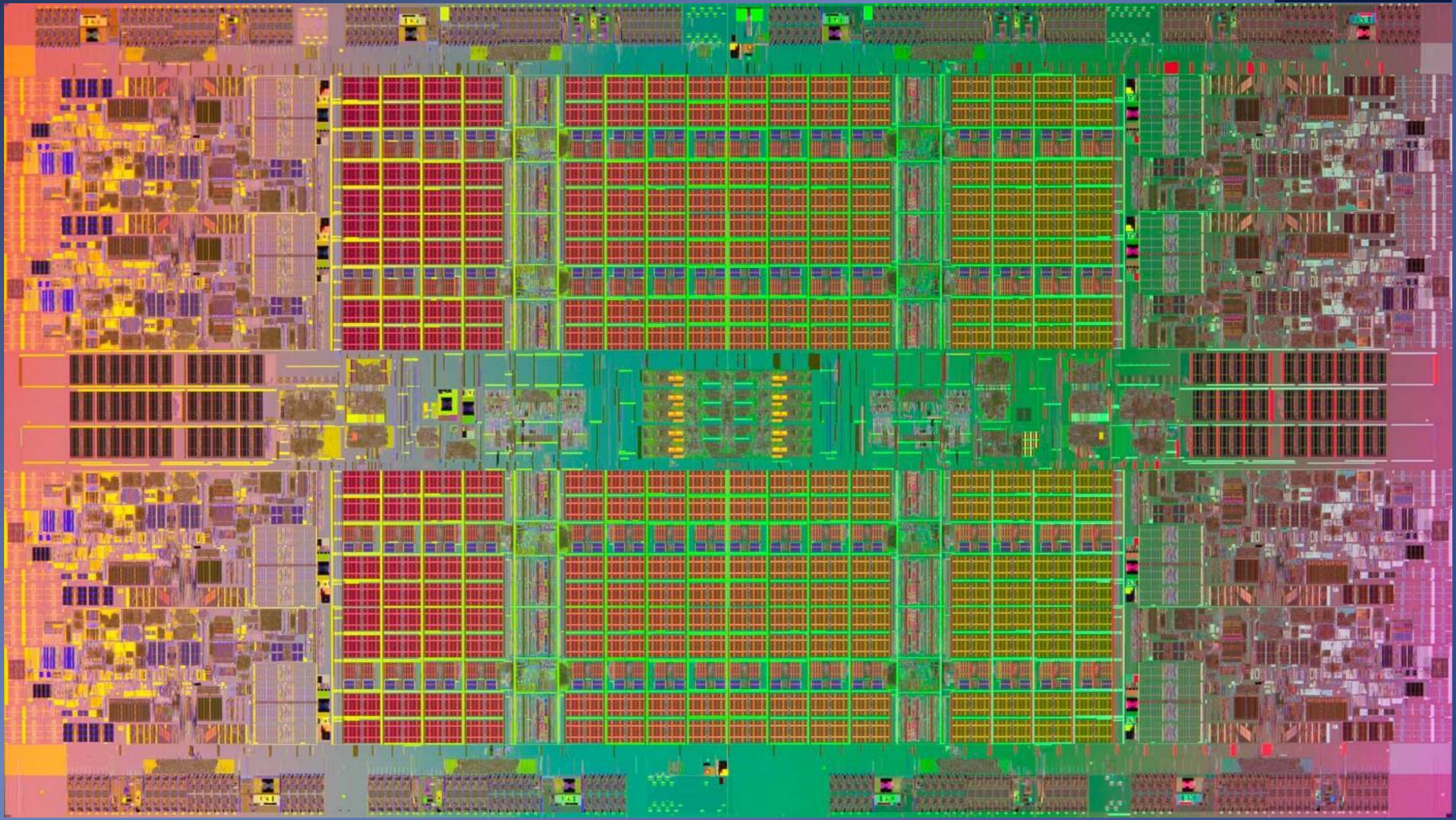
Student-friendly price (Euro 85,-)

about…

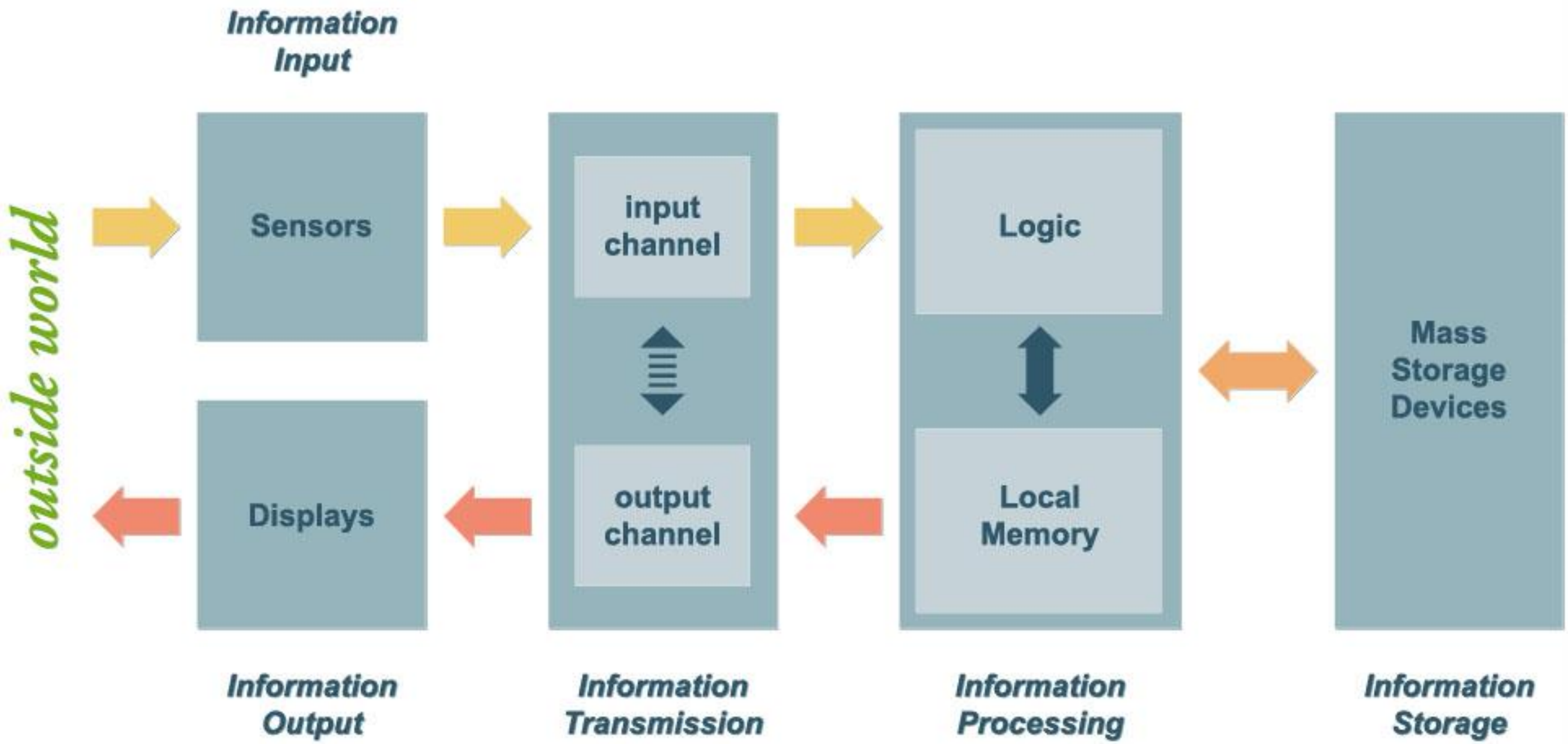
Felix Gunkel – Interface electronics & mesoscopic energy materials

2004 – 2009	**Diploma in Physics**, RWTH Aachen
semester abroad	Chalmers University of Technology, Sweden
2013	**PhD** PGI-7/RWTH Aachen
05/2013 – 09/2013	**Postdoc** at Stanford University (USA)
04/2013 – 12/2018	**Postdoc/Researcher** at PGI-7 & RWTH Aachen
12/2019 – 02/21	**Ørsted-Research-Fellow** at DTU Energy, Technical University of Denmark
since 2019	**Group leader & Senior researcher** at PGI-7, Forschungszentrum Jülich

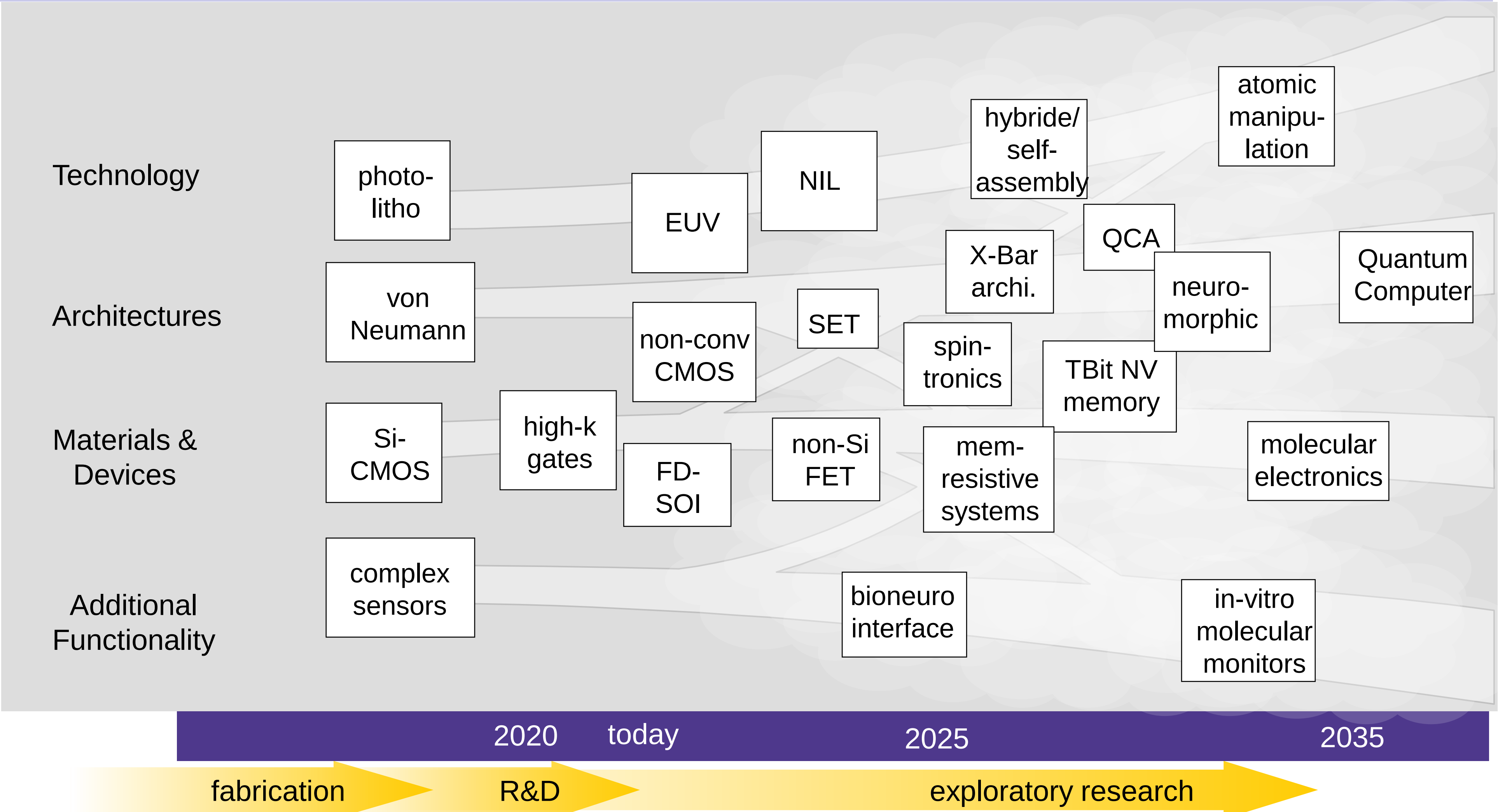
0 Overview – Novel Materials and Devices in Information Technology: Logic and Memories



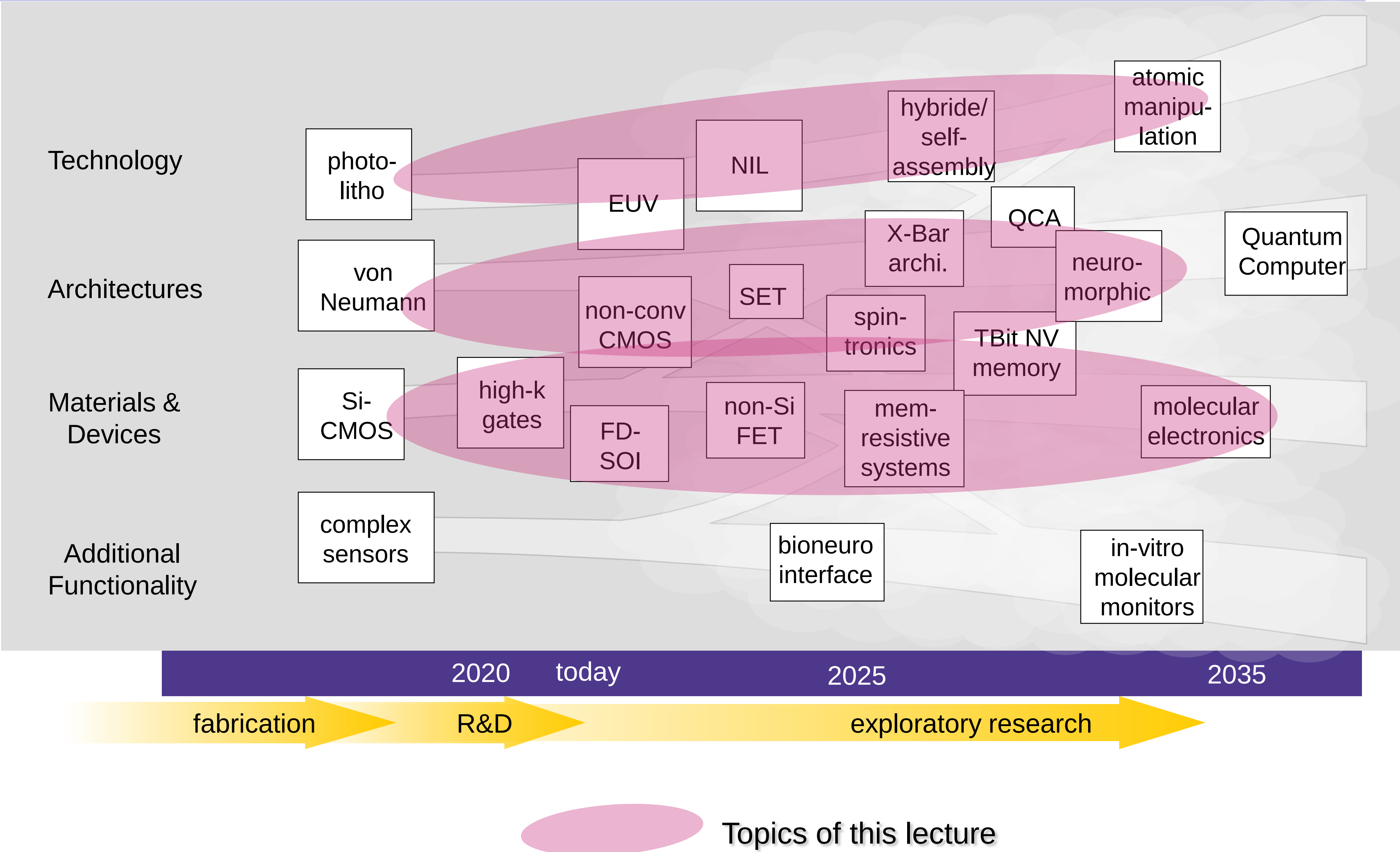
Areas in Information Technology



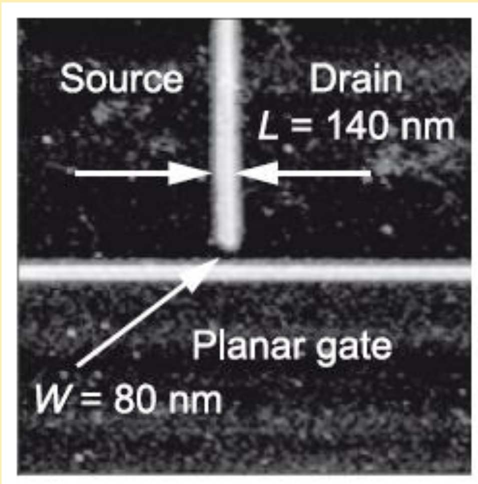
Emerging concepts
in Future Information Technology

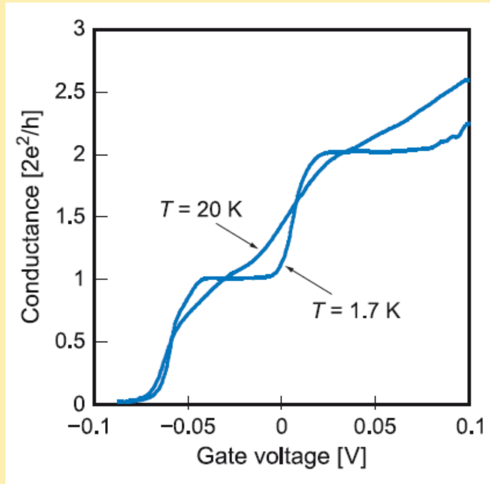


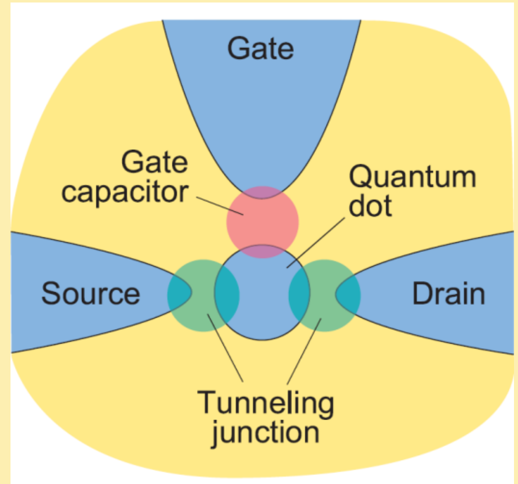
Emerging concepts in Future Information Technology



1 Mesoscopic electron transport







Transport in low dimensional structures

When is a system low dimensional?
When do we observe size effects?

Conductance quantization in ballistic 1D structures

Does the conductance diverge when there is no scattering?

Coulomb blockade in quantum dot structures

Transferring single electrons across a quantum dot

Outline

1.1 Mesoscopic regime: Transition from bulk to nanoscale

1.2 Review: Classical transport in 3 dimensions

1.3 Important time and length scales and quantized transport effects

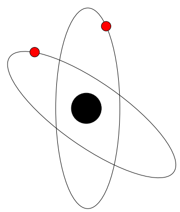
- Landauer quantization (ballistic transport in 1D)
- Electron interference (magnetic length scales)
- Coulomb blockade: single electron charging

1.1 Mesoscopic regime: Transition from bulk to nanoscale

Mesoscopic systems

mircoscopic < **mesoscopic** < macroscopic

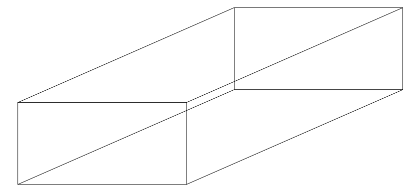
mircoscopic		mesoscopic		macroscopic
=		=		=
small		in between		large



atomic scale

too small
to be treated as bulk

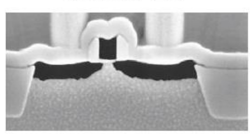
too large (complicated)
to be treated as single atoms



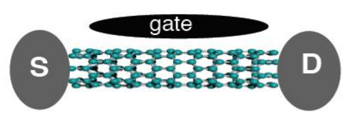
bulk

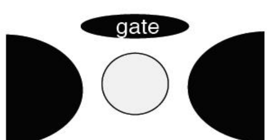
often "engineered" systems

MOSFET



CNT FET





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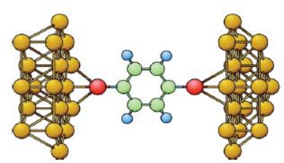
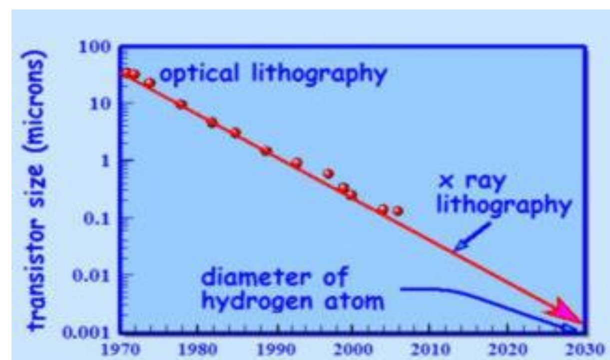
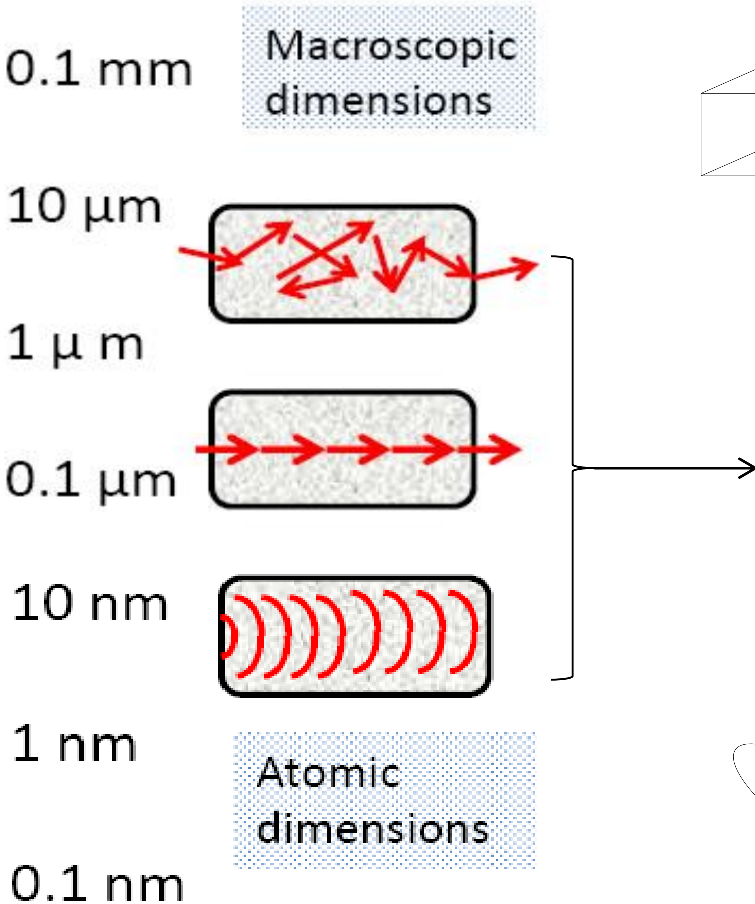


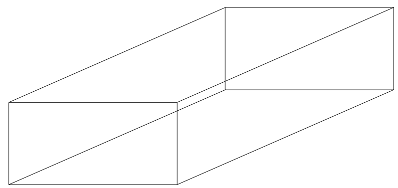
molecular electronics



Moore´s law

Mesoscopic systems: typical length scales

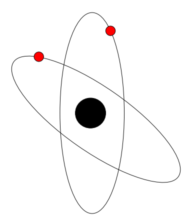




- Drude model
- Boltzmann model
- periodic potential

How can we describe electron transport in the mesoscopic regime?

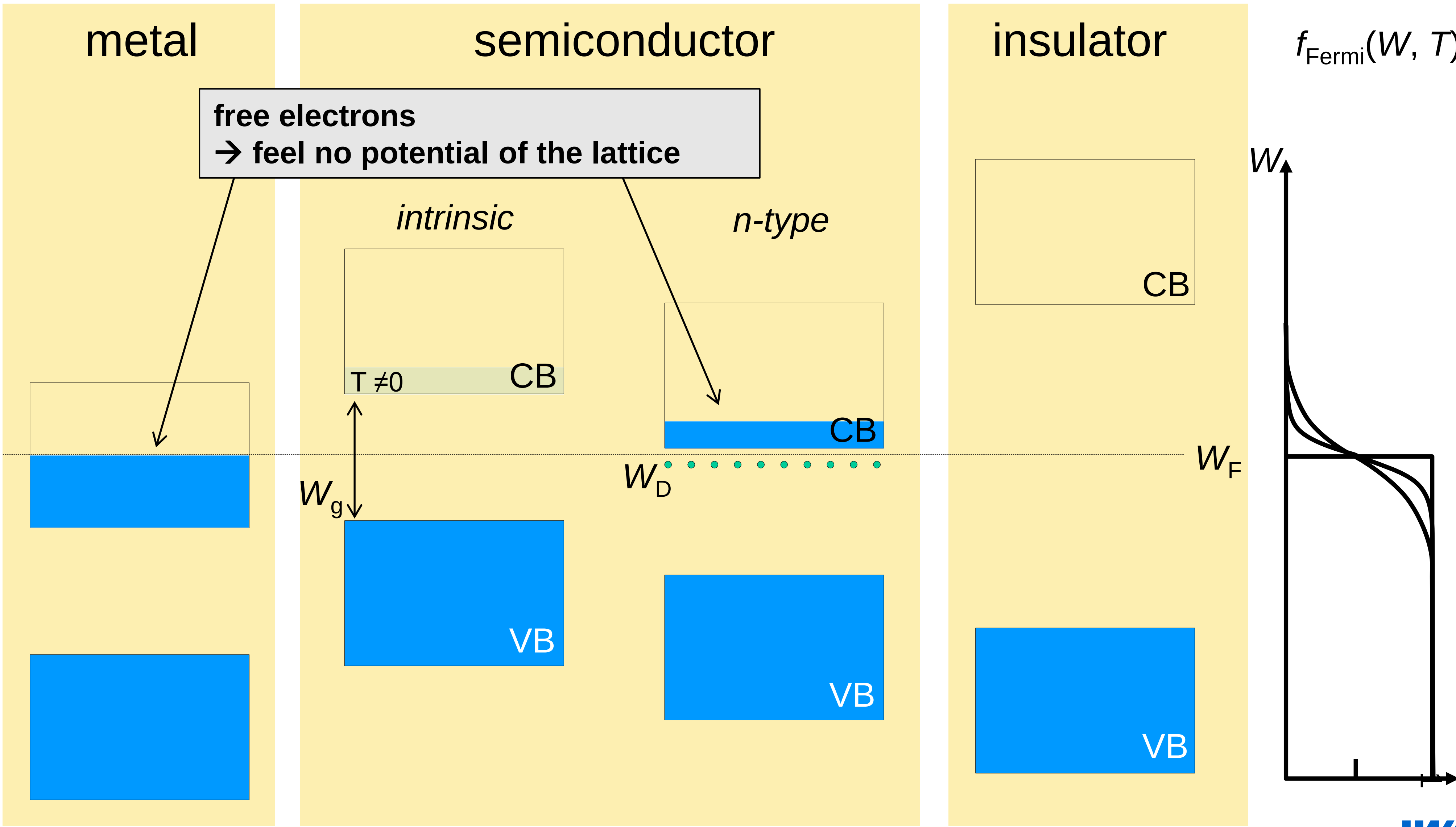
- size effects (quantization)
- interference effects
- Coulomb repulsion on the nanoscale



- Hydrogen atom
- atomic orbitals

1.2 Review: (Semi-)classical transport in 3 dimensions

Band structure of matter and Fermi distribution



Electronic conduction (Drude model)

Macroscopic model:

Current density (Ohm´s law)

$$j = \sigma E = -env_D$$

Electrons are accelerated as a result of an electric force

$$m^* \dot{v}_D = -eE$$

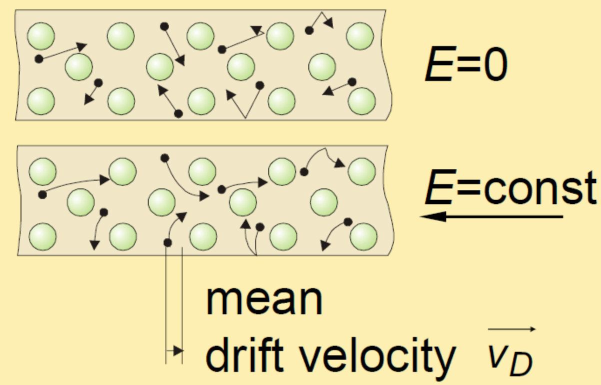
A friction force F_{fric} is introduced to avoid diverging v_D

$$m^* \dot{v}_D + \frac{m^*}{\tau} v_D = -eE$$

Stationary solution ($\dot{v}_D = 0$)

$$v_D = -\frac{e\tau}{m^*} E := -\mu E$$

drift velocity v_D
relaxation (or scattering) time τ
effective mass m^*



relaxation time τ

mean scattering time, i.e. averaged over many scattering events

electron mobility $\mu = \frac{e\tau}{m^*}$

IWE

Free electrons in infinite 3D potential well

Solution of Schrödinger equation:

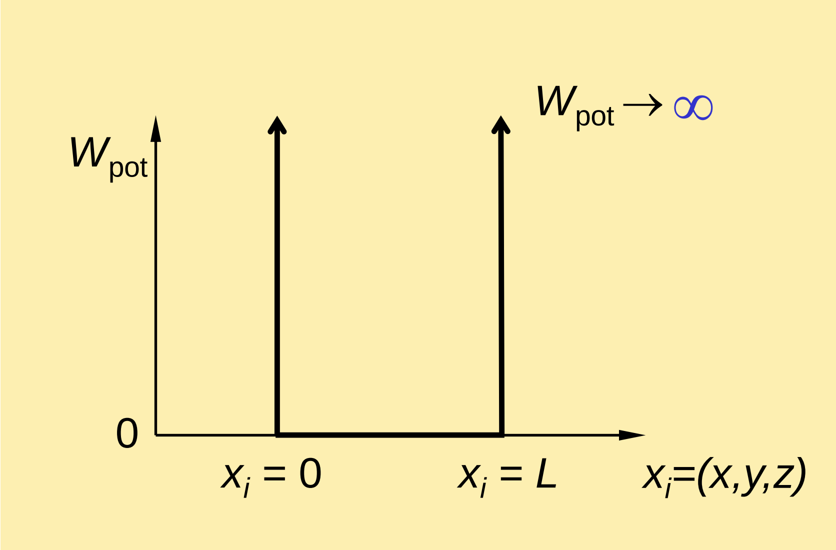
plane waves with discrete wave vectors (or Bloch waves for periodic potential)

$$W = \frac{\hbar^2}{2m^*}\underline{k}^2 = \frac{\hbar^2}{2m^*}\left(k_x^2 + k_y^2 + k_z^2\right)$$

$$k_i = \frac{2\pi}{L} n_i$$

L = size of potential well (bulk)

n_i = **integer**



$$W_F = \frac{\hbar^2}{2m^*}\underline{k}_F^2$$ Fermi energy

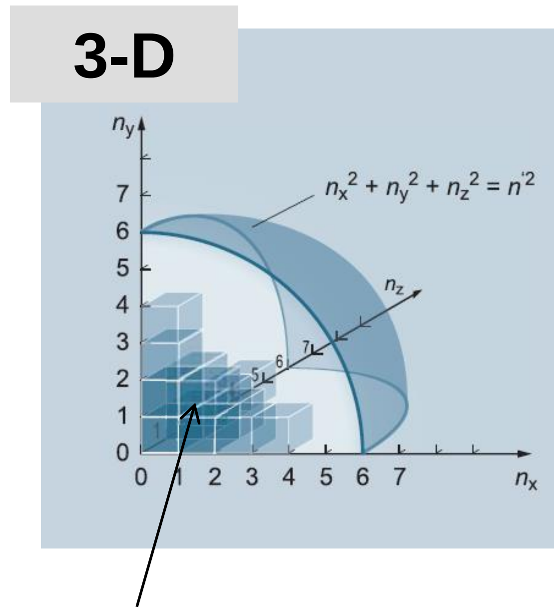
$$\lambda_F = \frac{2\pi}{k_F}$$ Fermi wavelength

$$m^* v_F = \hbar k_F$$ Fermi velocity

Free electrons in infinite 3D potential well

Density of states (per volume) in 3D

$$g_{3D}(k) = \frac{1}{(2\pi)^3}$$ in *k*-space, the density of states is constant (1/volume of a dice)



will be filled up until W(k)=W_F

n **= carrier density**

$$n_{3D} = 2 \cdot \frac{1}{(2\pi)^3} \int_{|k|<|k_F|} d^3k$$

$$= 2 \cdot \frac{1}{(2\pi)^3} \cdot \frac{4}{3}\pi k_F^3 = \frac{1}{3\pi^2} k_F^3$$

$$n_{3D}(W_F) \propto W_F^{3/2}$$

$$g_{3D}(W) = \frac{dn}{dW} = \frac{4\pi(2m^*)^{3/2}}{h^3}\sqrt{W}$$

Electronic conduction (Boltzmann model)

Macroscopic model (considering Pauli principle)

Current density

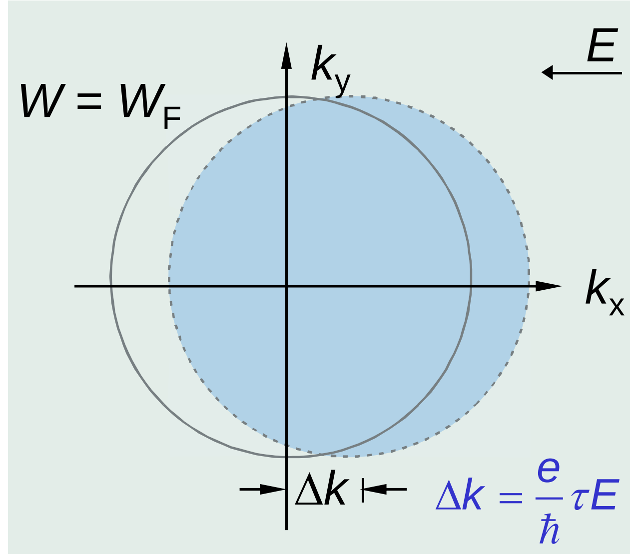
$$j_x = -e\int d^3k\ g(\mathrm{k})f(\mathrm{k})\mathrm{v}_x(\mathrm{k})$$

$$= -\frac{2e}{(2\pi)^3}\int d^3k\ f(\mathrm{k})\mathrm{v}_x(\mathrm{k})$$

f(W(k))
is **not Fermi-distribution,**
but a **non-equilibrium** distribution determined by *Boltzmann´s equation*

For metals it follows […]

$$j_x = -e\cdot\frac{k_F^3}{3\pi^2}\cdot\frac{e\tau(W_F)}{m^*}\cdot E = -en\mu E$$



relaxation time τ

Relaxation rate from non-equilibrium **distribution** *f* to equilibrium distribution f_{Fermi}

electron mobility $\mu = \frac{e\tau(W_F)}{m^*}$

1.3 Important time and length scales and quantized transport effects

How does a macroscopic system become mesoscopic?

1. Geometrical size *L* of the system becomes small

2. Magnetic fields become large

Preconditions for the Boltzmann model	Conditions defining the mesoscopic regime
$L \gg \ell_e$: diffusive	$L \leq \ell_e$: (quasi-)ballistic
$L \gg \ell_\phi$: incoherent	$L \leq \ell_\phi$: coherent
$L \gg \lambda_F$: no size quantization	$L \leq \lambda_F$: size quantization
$\ell_e \ll \ell_B$: no magnetic confinement	$\ell_e \geq \ell_B$: magnetic confinement
$e^2/C < k_B T$: no single electron charging	$e^2/C \geq k_B T$: single electron charging
$L \gg \ell_s$: no spin memory	$L \leq \ell_s$: spin memory effects

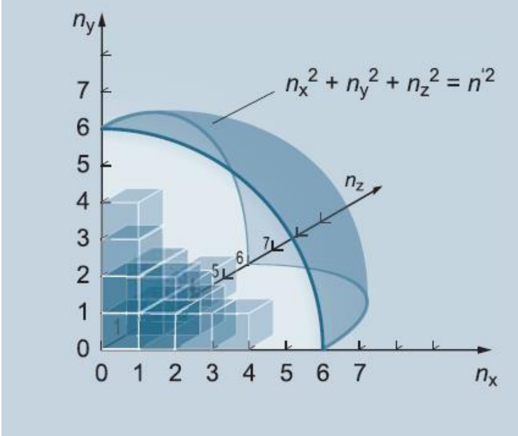
Table 1: The Boltzmann model is applicable if all the conditions in the left column hold. However, fulfillment of any of the conditions listed in the right column drives the system into the mesoscopic regime. Notations (as introduced below): L = characteristic sample size; ℓ_e = elastic mean free path; ℓ_ϕ = coherence length; ℓ_B = magnetic length; ℓ_s = spin relaxation length.

1.3.1 Size quantization

Size effects: When is a system low dimensional?

Characteristic density of states is obtained by continuous integration in k-space

3-D



This is only allowed if the spacing of *discrete* *k*-values is small against the size of the Fermi sphere

$$L \leq \lambda_F$$

λ_F is a measure of the length scale on which size quantization (i.e. the discreteness of the DOS) becomes important

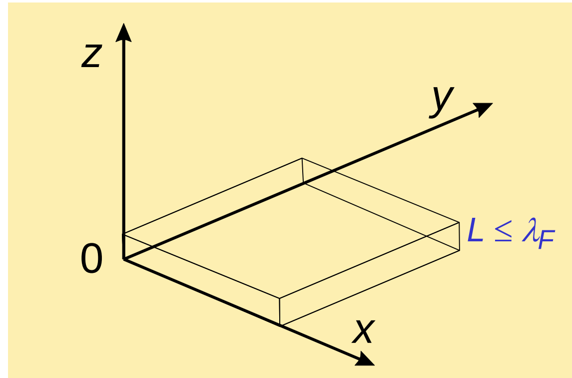
Typical values $\lambda_F = 2\left(\frac{\pi}{3n_{3D}}\right)^{1/3}$

metal	**semiconductor**
n~10^{23}cm^{-3}	n ~ 10^{15}-10^{17}cm^{-3}
λ_F~4x10^{-8} cm~ **4 Å**	λ_F ~ 10^{-5}- 10^{-6} cm~**10-100 nm**

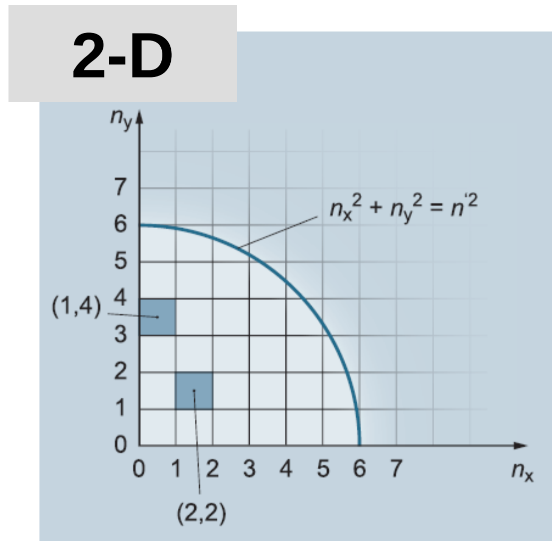
Density of states in 2 dimensions (2DEG)

Density of states (per volume) in *k*-space

2D



n = carrier density

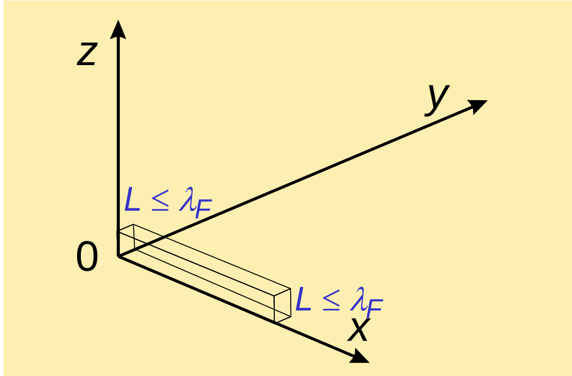


$$g_{2D}(W) = \frac{dn}{dW} = \frac{m^*}{\pi\hbar^2}$$ *(for each mode)*

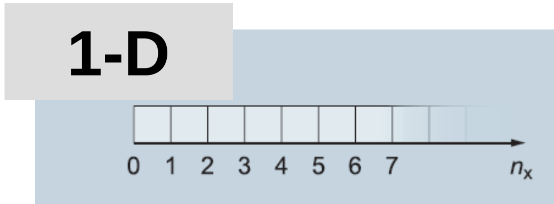
Density of states in 1 dimension (quantum wire)

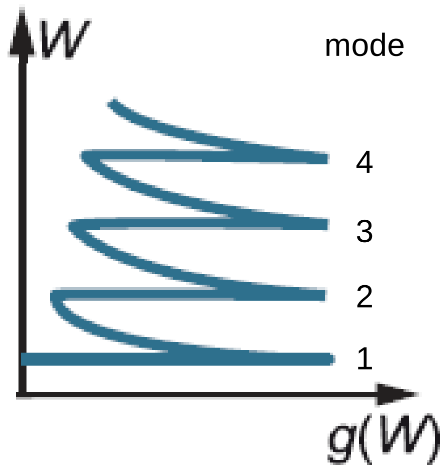
Density of states (per volume) in *k*-space

1D



n = carrier density





$$g_{1D}(W) = \sqrt{\frac{2m^*}{\pi^2\hbar^2}} \cdot (W - W_{n_x,n_y})^{-1/2}$$

(for each mode)

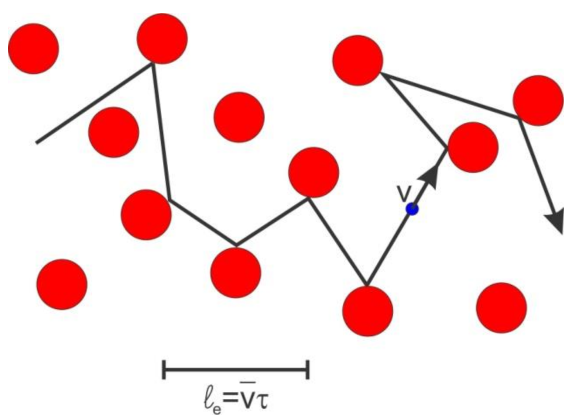
1.3.2 Ballistic transport – elastic scattering length

Diffusive transport vs. ballistic transport

→ mean distance an electron travels between elastic scattering events is called **elastic scattering length ℓ_e (or mean free path)**

$$\ell_e = \bar{v} \cdot \tau$$

$\bar{v}$ mean velocity of electrons



transport in which electron undergo many elastic scattering events is called *diffusive*

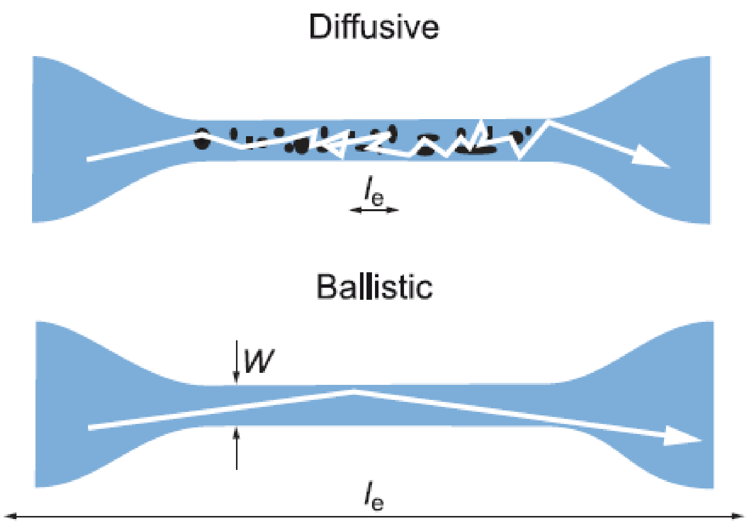
- described by Drude and Boltzmann
- mobility and relaxation time can be defined

Diffusive transport vs. ballistic transport

What happens if the geometrical size of the system becomes smaller than the elastic scattering length?

$\ell_e \geq L$

→ no backscattering event (*more precise*: only specular reflection) is expected while electrons travel through the system



Systems with geometrical size smaller than the elastic scattering length are called *ballistic*

- usually a wire or point contact
- μ, τ are meaningless in ballistic systems
- Drude and Boltzmann models break down

Temperature dependence of the mean free path

A long mean free path is required and, thus, a high mobility

$$\ell_e = \bar{v} \cdot \tau \sim \mu$$

ℓ_e, τ and μ depend on the particular scattering process

- phonon scattering time τ_p
- electron-electron scattering τ_e
- (ionized) defect scattering time τ_s
- boundary scattering τ_b

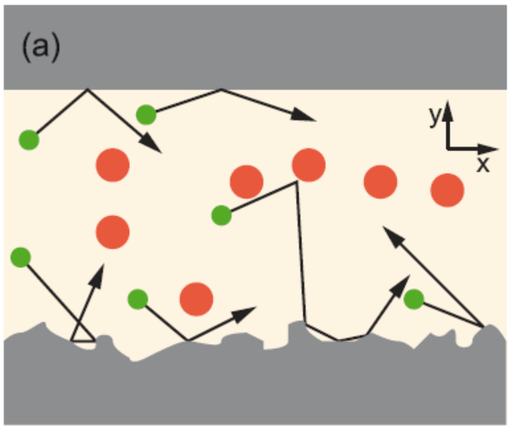
Matthiessen´s rule (strongest scattering process, i.e. lowest τ dominates)

$$\frac{1}{\tau} = \frac{1}{\tau_p} + \frac{1}{\tau_e} + \frac{1}{\tau_s} + \ldots$$

*Usually, the mean free path is maximum at **low temperatures** as phonons freeze out, defect scattering is the limiting effect!*

Boundary scattering

Are there other scattering processes to consider as the geometrical size of the system is reduced?



system becomes smaller
→ scattering at sample edges becomes important

- *specular* reflection on a smooth wall (top)
- *diffusive* reflection on a rough wall (bottom)

***specular* reflection does not affect momentum in propagation direction**

→ No momentum relaxation!

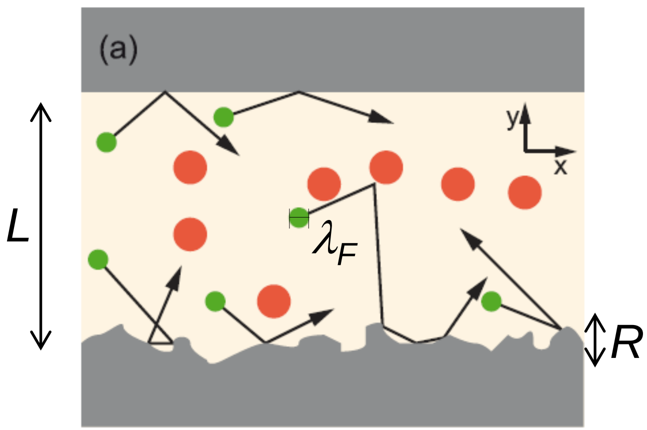
***diffusive* reflection does affect momentum in propagation direction**

→ Momentum relaxation!

Whether or not scattering at the boundary reduces ℓ_e depends on the roughness of the boundary!

Boundary scattering

When is a boundary rough or smooth?



spatial extension of electrons is ~ λ_F in a metal/deg. sc

rough means feature size *R* at boundary is of the order of or larger than Fermi wavelength

$$R \geq \lambda_F \longrightarrow \ell_e \leq L$$

For **metals** (λ_F<1nm) the boundaries are *rough* in most cases

For ***semiconductors*** (λ_F~10-100 nm) *smooth* boundaries can be obtained
→ ballistic samples may be available on the length scale of 50 nm

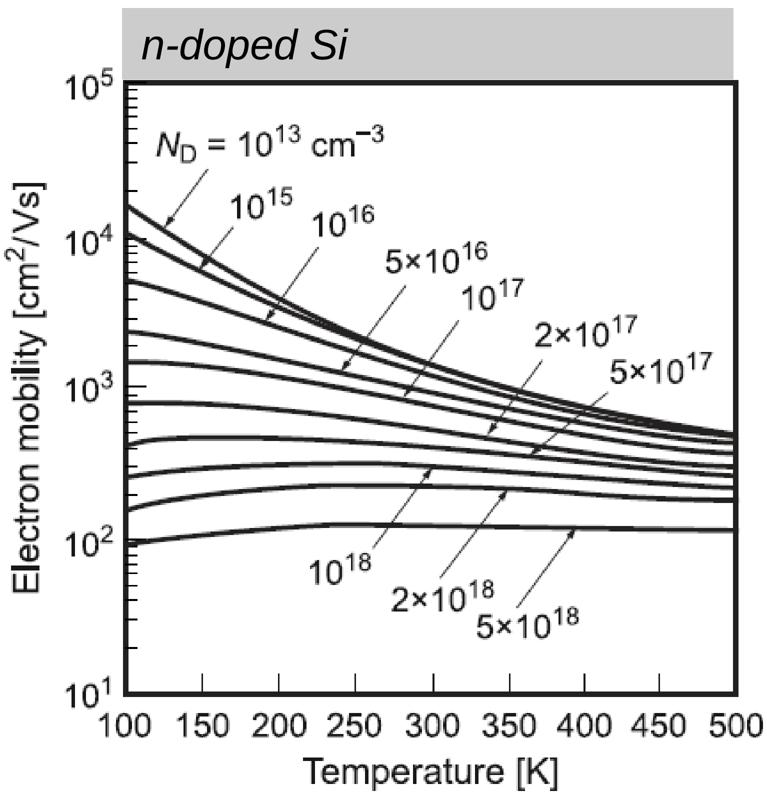
How to construct a ballistic sample?

How to get a ballistic sample from semiconductors?

Challenges in engineering ballistic systems from semiconductors

• *intrinsic* sc provide large ℓ_e, but they loose (all) carriers at low temperature

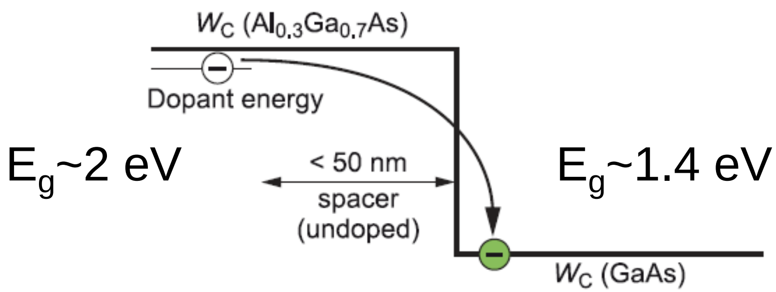
• *n-type* doped sc provide carriers, but the mobility drops



How to get a ballistic sample?

modulation doping – separate carriers and dopants

e.g. at AlGaAs/GaAs interface



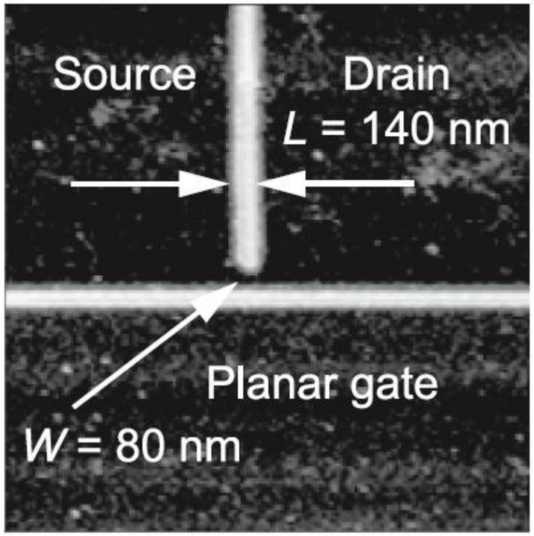
1. Engineer band gap by Ga-Al-ratio
2. Step in conduction band
3. Electrons diffuse to undoped GaAs
4. Emerging charge separation/electric field keeps electrons at the interface separated from positive ions(scatterers) forming 2D gas!

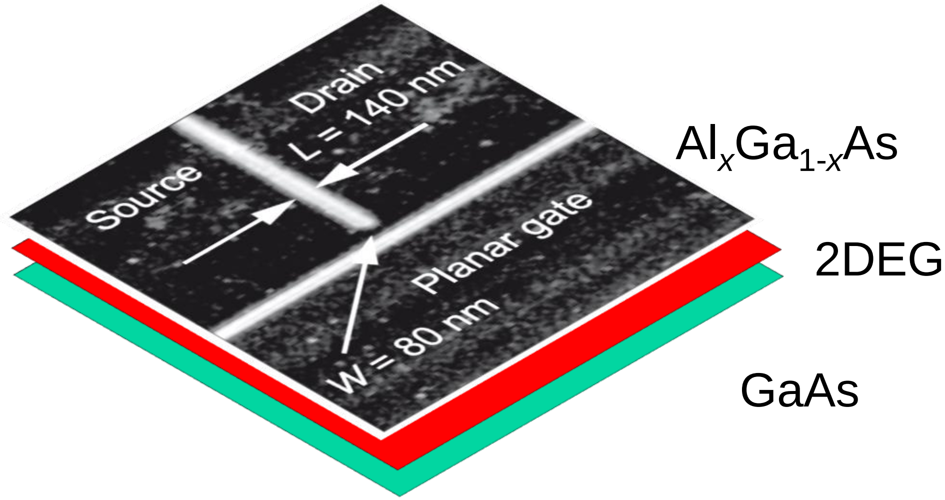
$$\ell_e = v_F \tau \approx 120\,\mu m$$

$$\mu \approx 1.4 \times 10^7 \frac{cm^2}{Vs}$$ at 4K

$$\tau \approx 400\,ps$$

Electrical transport in ballistic wires (point contacts)

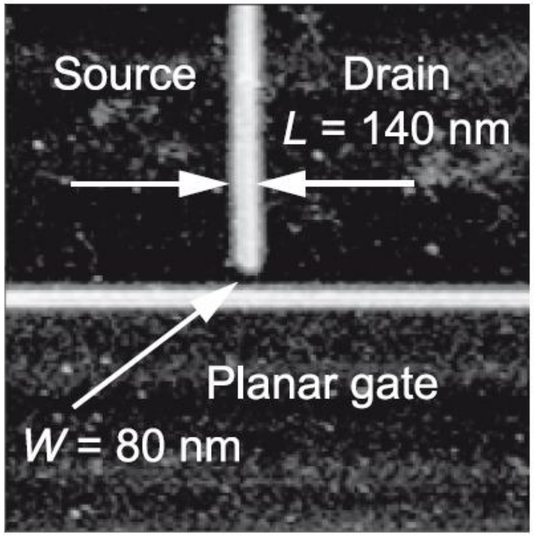


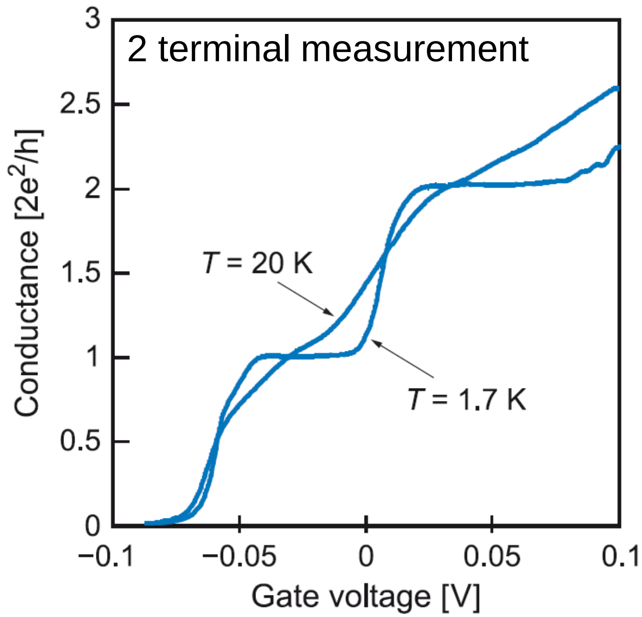


Ballistic channel
length ~ 140 nm << ℓ_e
width ~ 80 nm ~ λ_F

Such a wire is often called *(quantum) point contact (QPC)*

Electrical transport in ballistic wires (point contacts)





• at low temperatures the conductance of the quantum wire is a step-like function of gate voltage

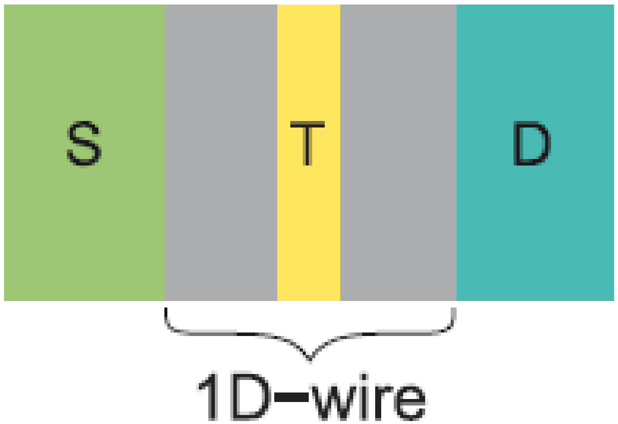
$$G_0 = \frac{2e^2}{h} = \left(12.9\ \mathrm{k}\Omega\right)^{-1}$$

conductance quantum

1.3.3 Conductance quantization in ballistic quantum wires

Electrical transport in ballistic wires (point contacts)

How can we understand this phenomenon?
Where does the resistance come from?



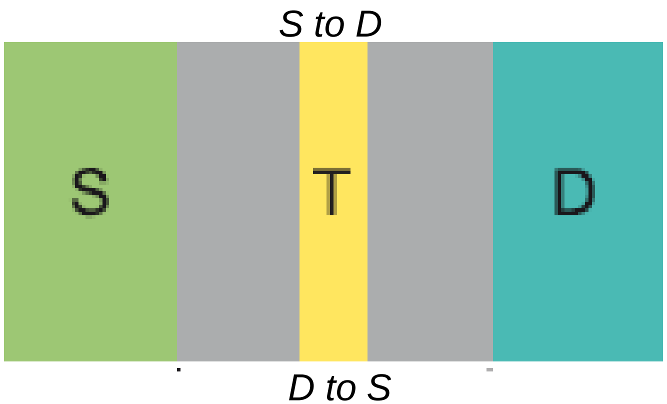
Simple but drastic model:

• source and drain are perfect metal reservoirs
• leads/transition region are ballistic, 1D quantum wires
• QPC is represented by barrier with transmission probability *T*

T=1 means the QPC is open

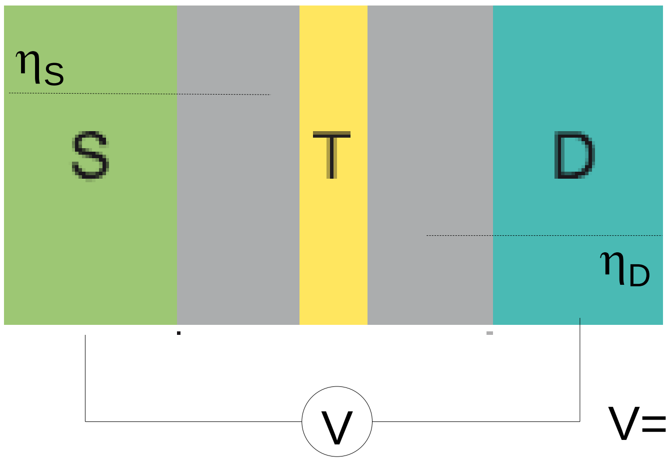
IWE

Electrical transport in ballistic wires (point contacts)



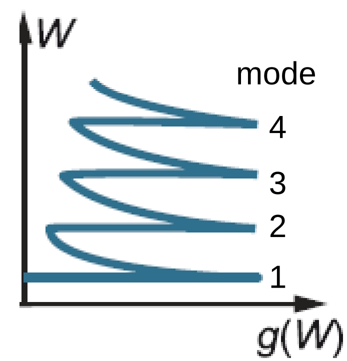
Current through QPC means electrons transverse barrier from left to right (S to D) or from right to left (D to S)

Electrical transport in ballistic wires (point contacts)

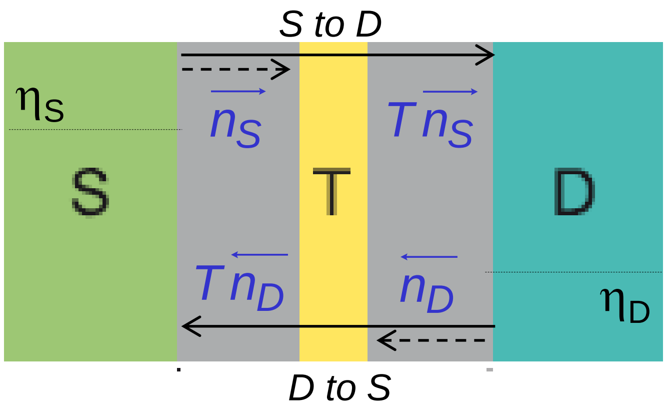


$V=(\eta_D-\eta_S)/e$

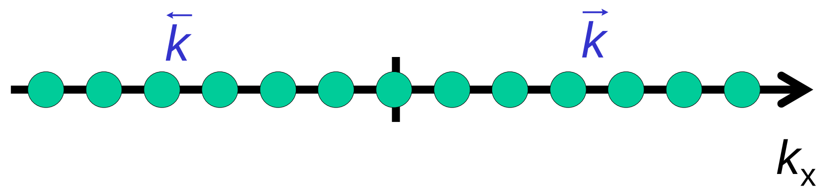
- reservoirs will fill up the 1D levels up to their chemical potential, η_S and η_D
- density of states in wires is 1D



Electrical transport in ballistic wires (point contacts)

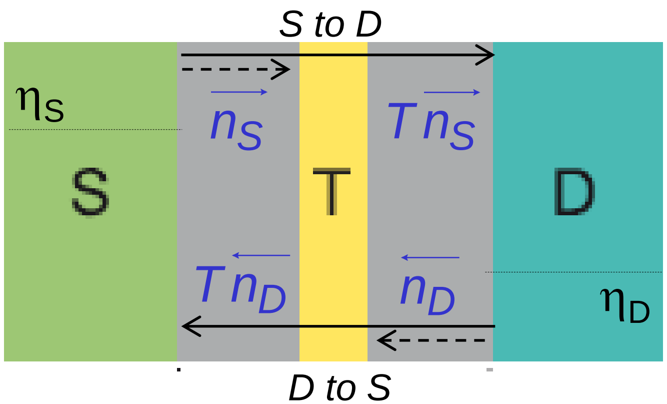


$$\overrightarrow{g_{1D}}(W) = \overleftarrow{g_{1D}}(W) = \tfrac{1}{2} g_{1D}(W)$$



$$\begin{aligned}
\overleftrightarrow{n_{S,D}}(W)\, v_{S,D} &= \tfrac{1}{2} g_{1D}(W) \cdot f_{Fermi}(W - \eta_{S,D}) \cdot v_{S,D} \\
&= \sum_j \frac{1}{2} \sqrt{\frac{2m^*}{\pi^2 \hbar^2}} \cdot (W - W_j)^{-1/2} \cdot \sqrt{\frac{2(W - W_j)}{m^*}} \cdot f_{Fermi}(W - \eta_{S,D}) \\
&= \sum_j \frac{1}{\pi \hbar} \cdot f_{Fermi}(W - \eta_{S,D})
\end{aligned}$$

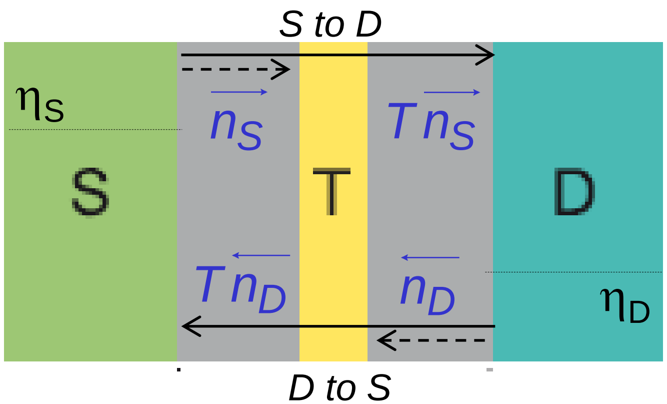
Electrical transport in ballistic wires (point contacts)

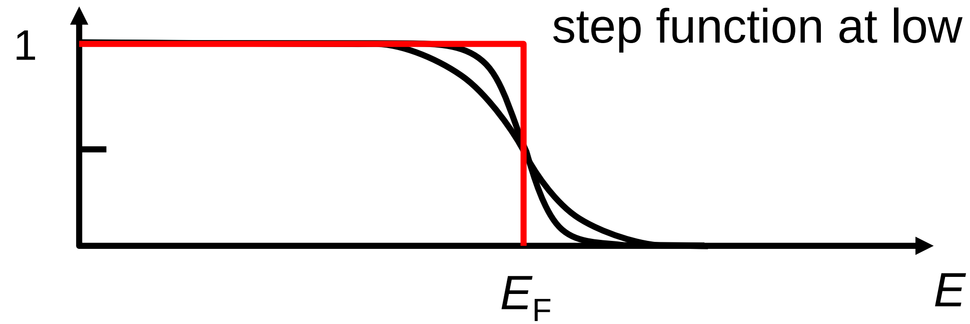


$$I(W) = \frac{2eT}{h}\sum_j f_{Fermi}(W-\eta_S) - f_{Fermi}(W-\eta_D)$$

$$= \frac{2eT}{h} M \cdot \left[f_{Fermi}(W-\eta_S) - f_{Fermi}(W-\eta_D)\right]$$

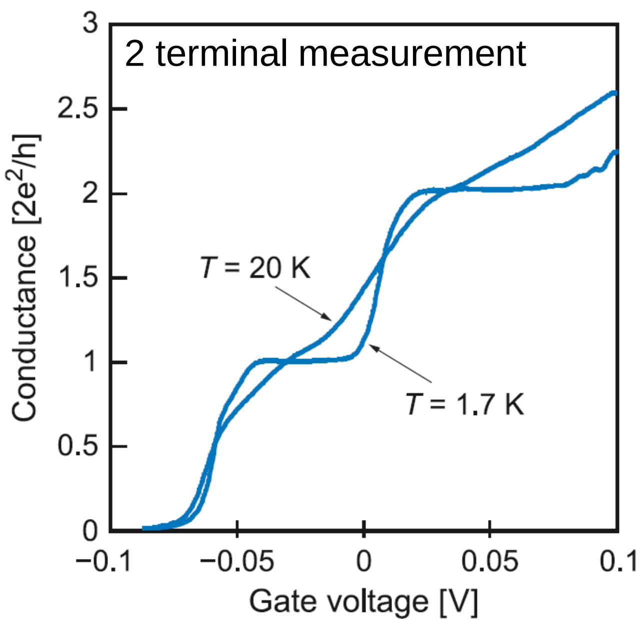
Electrical transport in ballistic wires (point contacts)





Fermi-function is a step function at low T

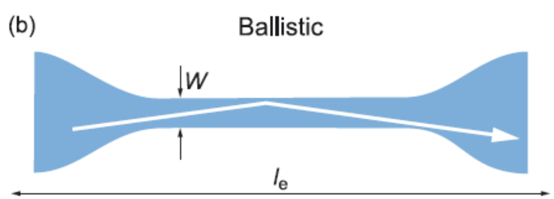
Electrical transport in ballistic wires (point contacts)



G is quantized because the energy dependence of the one-dimensional density of states and that of the electron velocity cancel out

- No of modes (M) can be tuned by gate voltage
→it controls how many 1D sub-bands are filled

- Increased temperature smears out step-like distribution function
→ Steps smear out

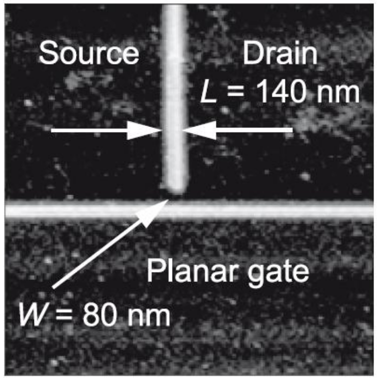


$$G = \frac{I}{V} = \frac{2e^2}{h} TM$$

Landauer Formula

no barrier means T→1
M is number of activated modes

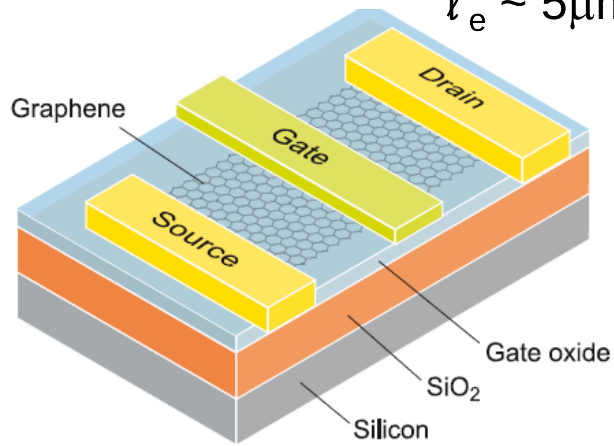
Other ballistic systems



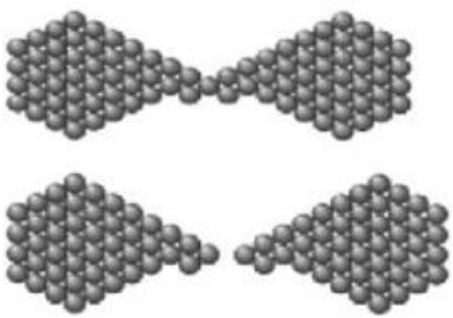
QPC in semiconductor devices

graphene

$\ell_e \sim 5\mu m$



Breaking metal contacts…

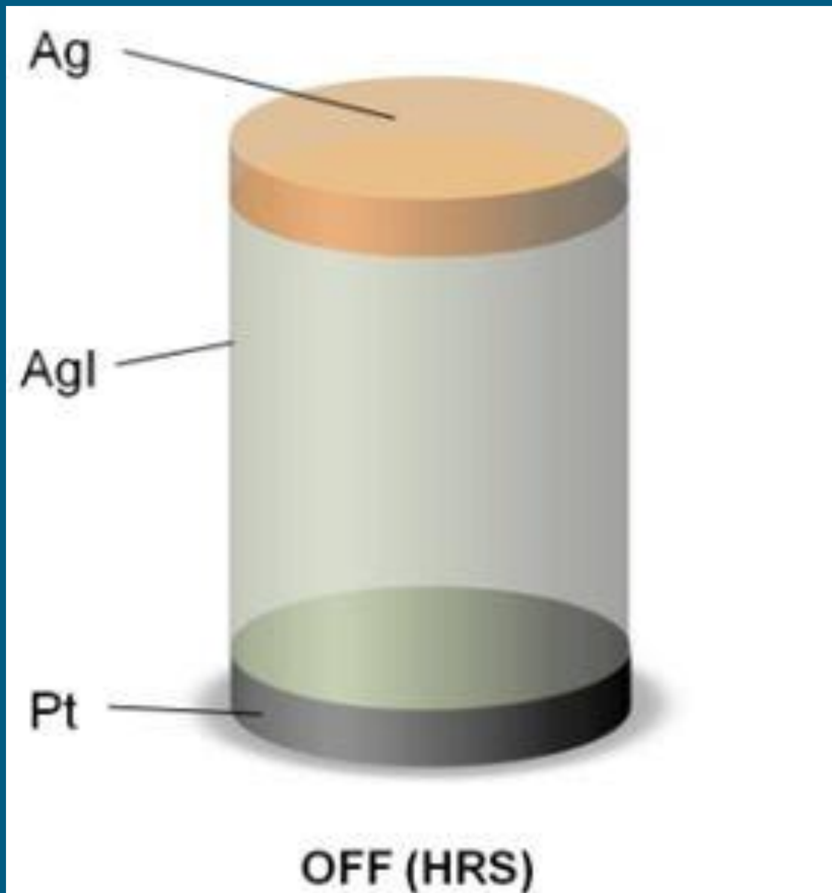


CNT FET

Carbon nanotubes

Atomic switch – a novel data memory device

„0“



…addressed/controlled by external voltage…