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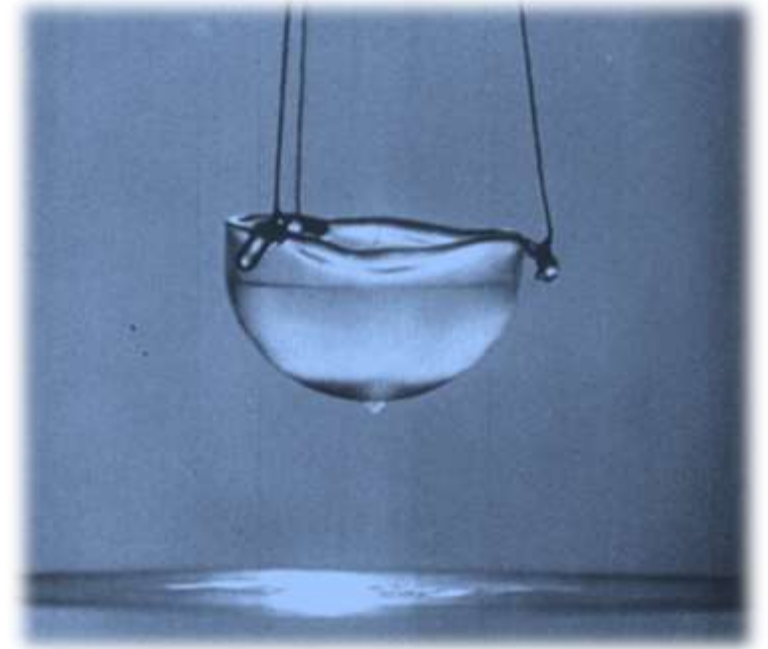
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Superconductivity and Low Temperature Physics II



**Lecture Notes
Summer Semester 2024**

**R. Gross
© Walther-Meißner-Institut**

Chapter 2

Quantum Transport in Nanostructures

Literature:

- 1. Introduction to Mesoscopic Physics**
Yoseph Imry
Oxford University Press, Oxford (1997)
- 2. Electronic Transport in Mesoscopic Systems**
Supriyoto Datta
Cambridge University Press, Cambridge (1995)
- 3. Mesoscopic Electronic in Solid State Nanostructures**
Thomas Heinzel
Wiley VCH, Weinheim (2003)
- 4. Quantum Transport**
Yuli V. Nazarov, Yaroslav M. Blanter
Cambridge University Press, Cambridge (2009)
- 5. Semiconductor Nanostructures**
Thomas Ihn
Oxford University Press (2010)



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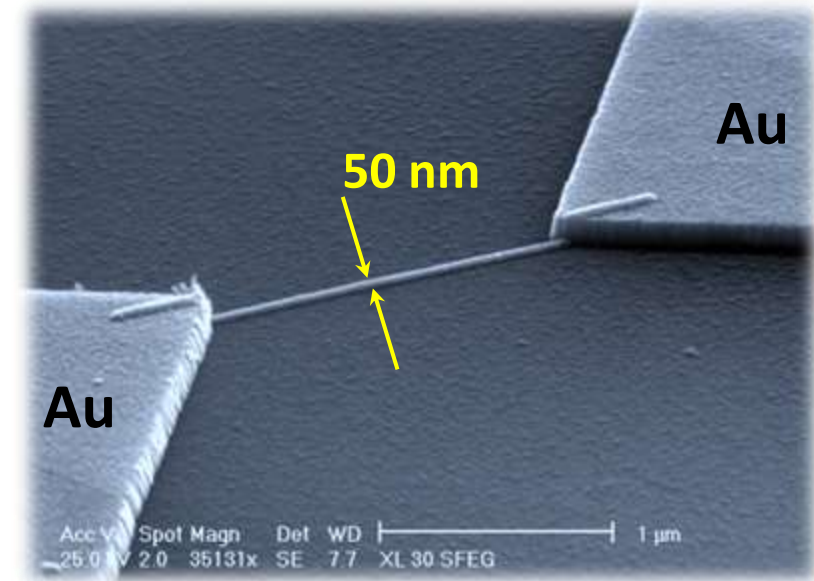
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Lecture No. 8

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II.1 Introduction

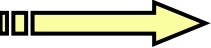
II.1.1 General Remarks

- *macroscopic solid-state systems*
 - usually consideration of thermodynamic limit $\rightarrow N \rightarrow \infty, \Omega \rightarrow \infty, N/\Omega = \text{const.}$
- *what happens if system size becomes small ?*
 - discrete spectrum of electronic levels
 - coherent motion of electrons
 - \rightarrow phase memory due to lack of inelastic scattering within system size: system size L smaller than *phase coherence length* L_ϕ
 - \rightarrow new *interference phenomena*
 - validity of Boltzmann theory of electronic transport and concept of resistivity ?
 - \rightarrow system size L smaller than *mean free path* ℓ : *ballistic transport*
 - discreteness of electric charge and magnetic flux becomes important
 - \rightarrow single electron and single flux effects
 - concept of impurity ensemble breaks down
 - \rightarrow sample properties show „fingerprint“ of detailed arrangement of impurities

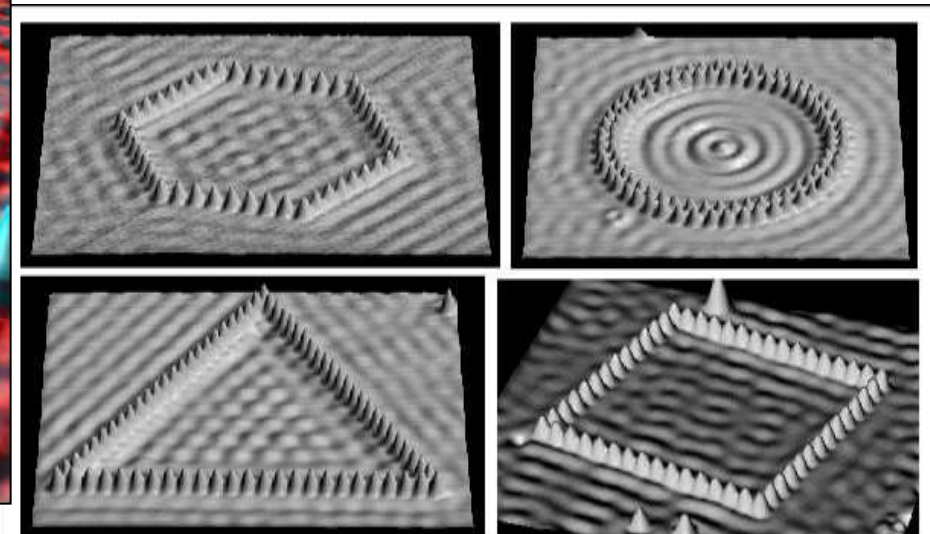
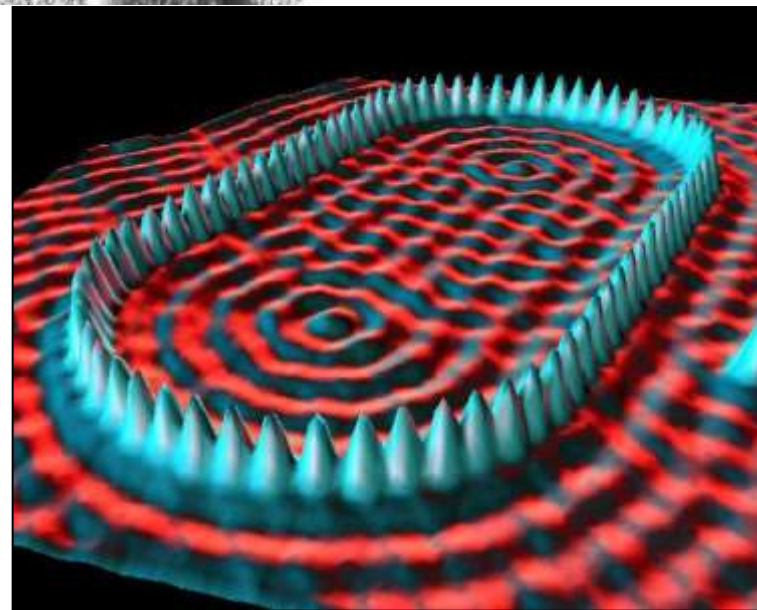
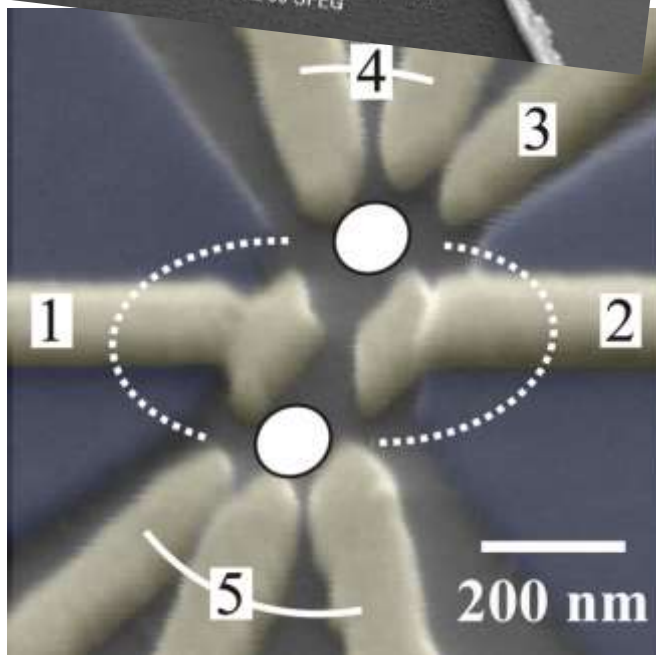
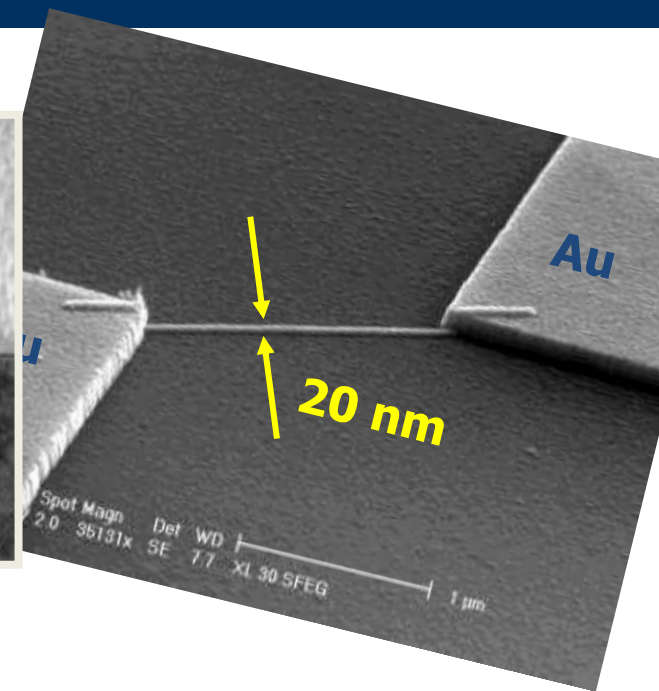
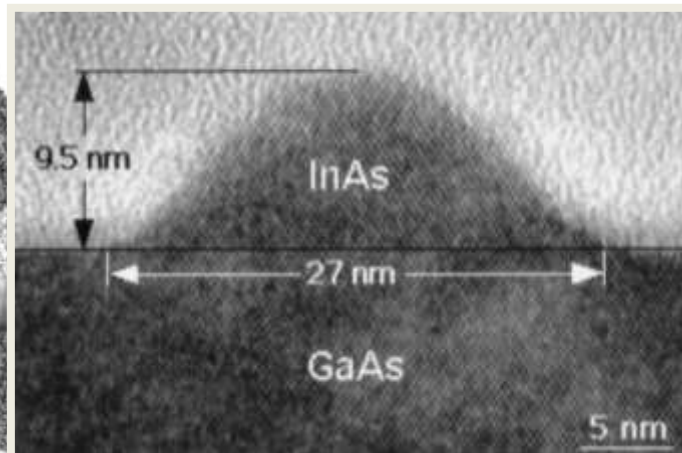
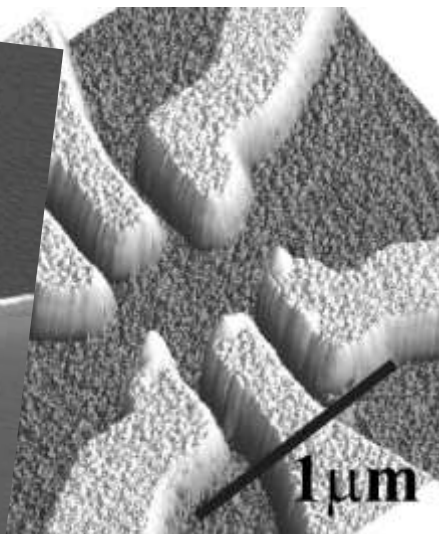
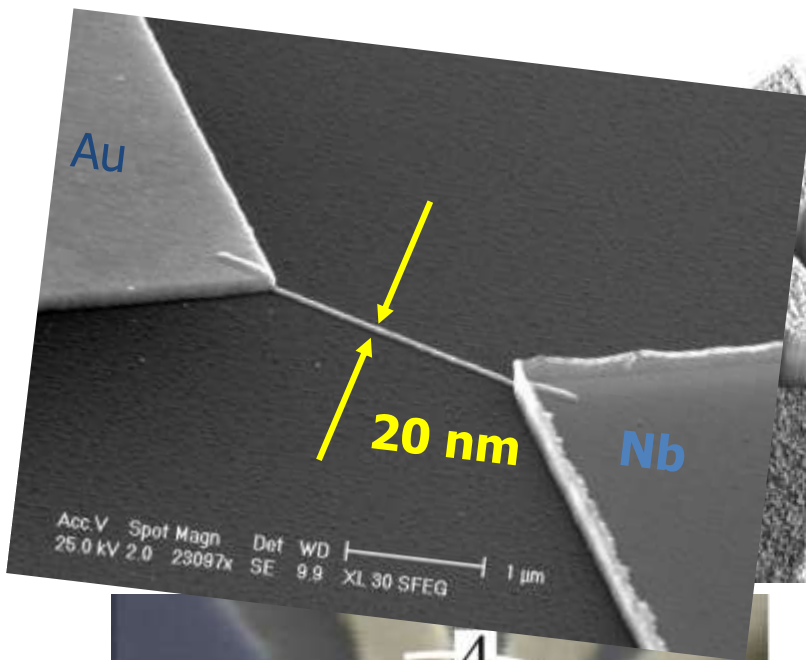
II.1.2 Mesoscopic Systems

- *mesoscopic systems* (coined by Van Kampen in 1981): **mesos (Greek): between**
 - *system size is between microscopic (e.g. atom, molecule) and macroscopic system (e.g. bulk solid)*
 - *system size L is smaller than phase coherence length L_ϕ (typically in nm - μm regime)*
 - phenomena related to phase coherence become important
 - statistical concepts no longer applicable due to smallness of system size
 - still coupling to environment/reservoir present (in contrast to microscopic objects such as atoms)

- *properties of mesoscopic systems are usually studied at low temperatures*
 - *phase coherence length L_ϕ decreases rapidly with increasing T*
 - $L < L_\phi$ can usually be satisfied only at low T
 - *observation of level quantization effects require $k_B T < \Delta E \simeq 1/L^2$*

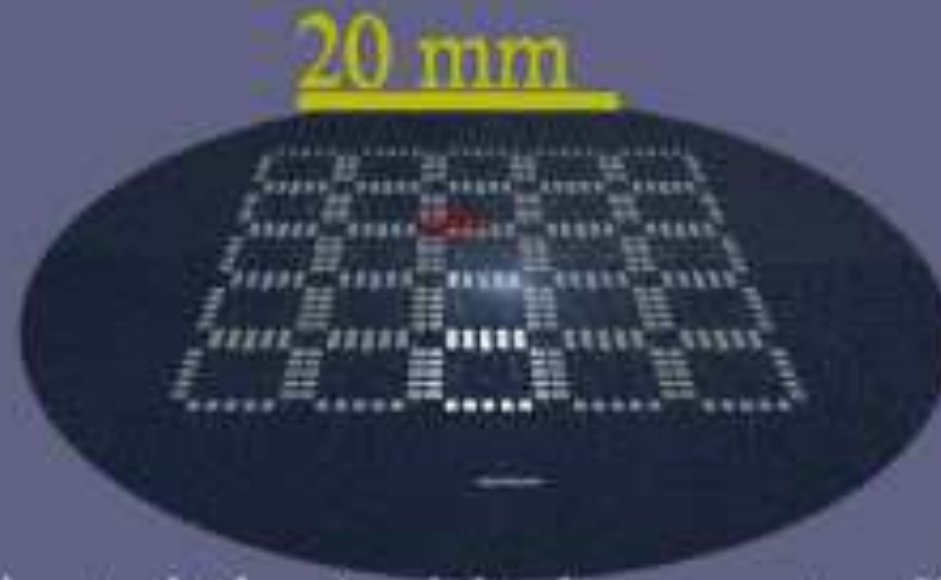
 ***study of nanostructures at low temperature***

II.1.2 Mesoscopic Systems



II.1.2 Mesoscopic Systems

Die folgende graphische Animation zeigt den Anflug auf eine Einzelelektronen-Schaltung.

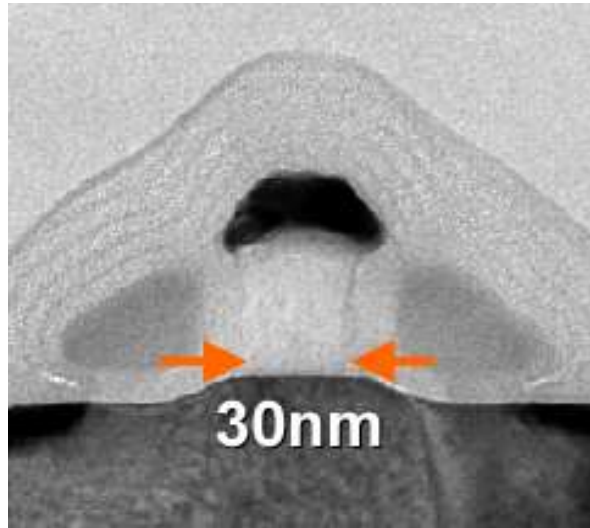


Sie beginnt mit der Ansicht des gesamten Wafers und endet mit der elektronenmikroskopischen Aufnahme einer realen Struktur.

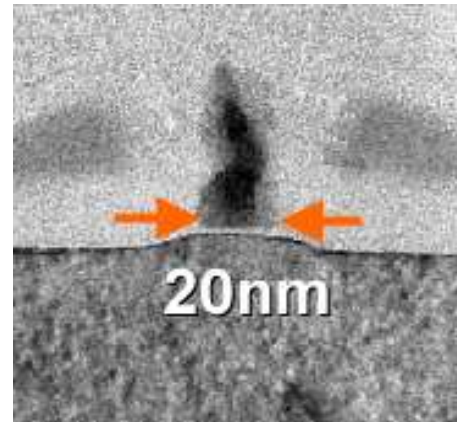
II.1.2 Mesoscopic Systems

- miniaturization of electronic devices

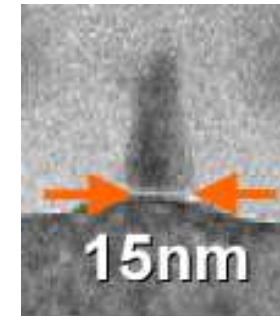
gate length of transistors



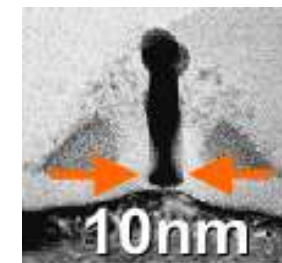
65 nm process
2005



45 nm process
2007



32 nm
2009

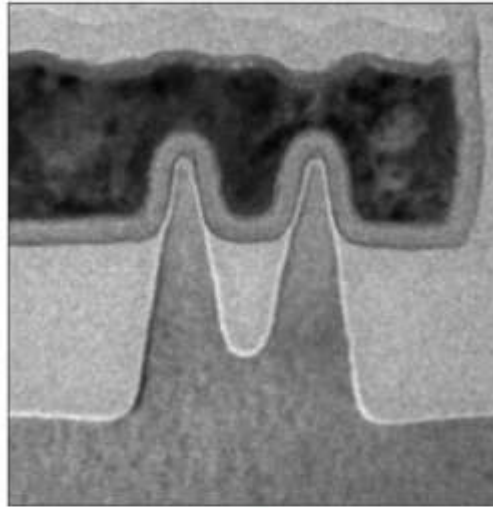


22 nm
2011

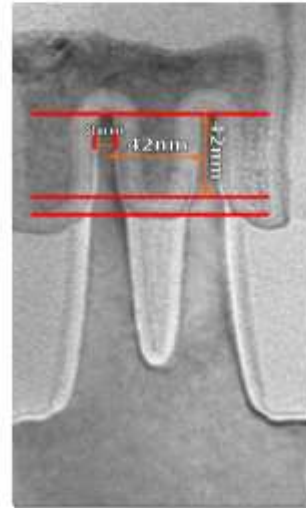
(Source: Intel Inc.)

II.1.2 Mesoscopic Systems

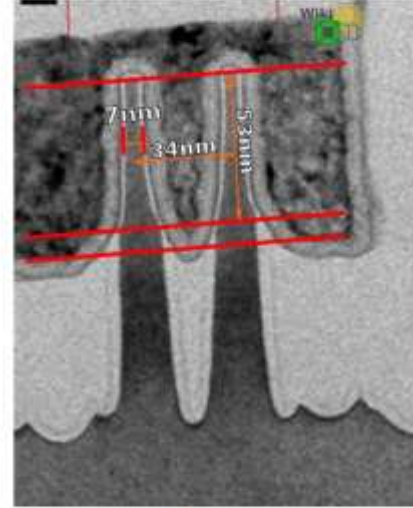
Transistor Fin Improvement



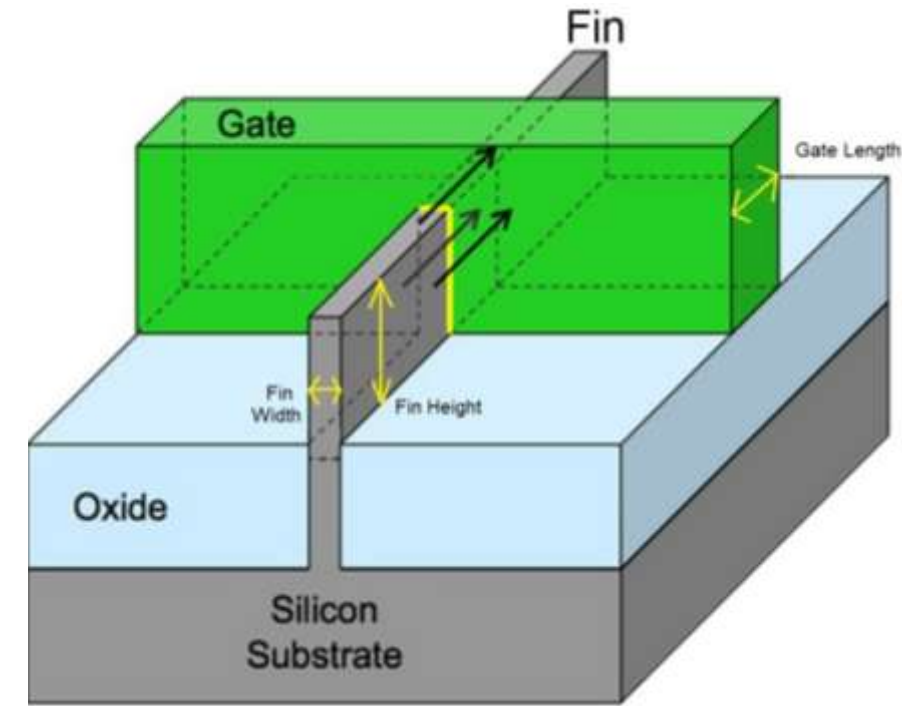
22 nm 1st Generation Tri-gate Transistor



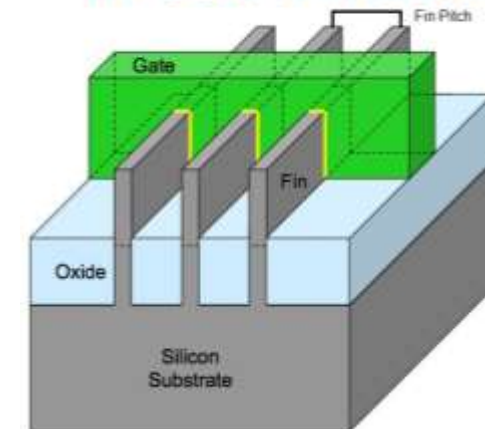
14 nm 2nd Generation Tri-gate Transistor



10 nm 3rd Generation Tri-gate Transistor



Tri-Gate Transistor



II.1.3 Characteristic Length Scales

- from microscopic to macroscopic systems

microscopic \leftrightarrow **mesoscopic** \leftrightarrow macroscopic

Fermi wave length: $\lambda_F < 1 \text{ nm}$ (for metals)

\rightarrow *"size" of charge carrier*

electron mean free path: $\ell \approx 10 - 100 \text{ nm}$

\rightarrow *distance between (elastic) scattering events*

phase coherence length: $L_\varphi \approx 1 \mu\text{m}$

\rightarrow *loss of phase memory*

sample size: $L, W \approx 0.01 - 1 \mu\text{m}$

mesoscopic regime: $L < L_\varphi(T)$

II.1.3 Characteristic Length Scales

1 mm

mean free path in the Quantum Hall regime

100 μm

mean free path / phase coherence length in high mobility semiconductors at $T < 4 \text{ K}$

10 μm

phase coherence length in clean metal films

1 μm

size of commercial semiconductor devices

100 nm

Fermi wave length in semiconductors

10 nm

mean free path in polycrystalline metal films

1 nm

Fermi wave length in metals

0.1 nm

distance between atoms

II.1.3 Characteristic Length Scales

- electron wavelength:** $\lambda_F = \frac{h}{\sqrt{2m^* \epsilon_F}} = \frac{2\pi}{(3\pi^2 n)^{1/3}}$ (Fermi wavelength)
 - mean free path:** $\ell = v_F \cdot \tau_m$ $\tau_m^{-1} = \tau_c^{-1} \cdot \alpha_m \leftarrow$ effectiveness of collision: $0 < \alpha_m < 1$

\uparrow
 collision time
 - phase relaxation length:** $L_\phi = v_F \tau_\phi$ $\tau_\phi^{-1} = \tau_c^{-1} \cdot \alpha_\phi \leftarrow$ effectiveness of collision in destroying phase coherence: $0 < \alpha_\phi < 1$

ballistic \downarrow
 $L_\phi = v_F \tau_\phi$
 diffusive \longrightarrow $L_\phi = \sqrt{D \tau_\phi} = \sqrt{\frac{1}{3} v_F^2 \tau_m \tau_\phi}$
- \rightarrow elastic impurity scattering: $\tau_\phi \rightarrow \infty$ or $\alpha_\phi \rightarrow 0$
 \rightarrow electron-phonon scattering: $\tau_\phi \approx \tau_{e-ph} ??$
 \rightarrow electron-electron scattering: $\tau_\phi \approx \tau_{e-e} ??$
 \rightarrow electron-impurity scattering (with internal degree of freedom, e.g. spin)

II.1.3 Characteristic Length Scales

- **question:** what is the effectiveness of an *inelastic scattering process* regarding destruction of phase coherence ?
 - *Altshuler, Aronov, Khmel'nitsky (1982):*

if $\hbar\omega$ is the characteristic energy of an *inelastic process* (e.g. phonon energy), then the mean-squared energy spread of electron after collisions is

$$\langle \Delta E \rangle^2 = (\hbar\omega)^2 \frac{\tau_\varphi}{\tau_c}$$

\uparrow
square of energy change

\leftarrow *number of scattering events*

τ_φ is time required to acquire a phase change of $\approx 2\pi$

$$\Delta\varphi \approx \frac{\Delta E}{\hbar} \tau_\varphi \approx 2\pi \Rightarrow \tau_\varphi \approx \left(\frac{\tau_c}{\omega^2} \right)^{1/3}$$

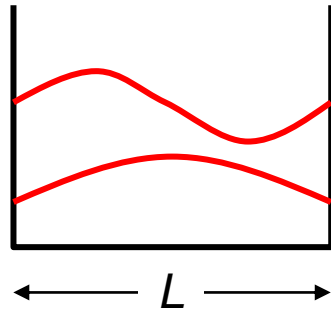
low-frequency excitations are less effective in destroying phase coherence !!

- at low T : e-e scattering is dominating

II.1.4 Characteristic Energy Scales

- size quantization

- electron in a box:



level spacing:

$$\Delta E = \frac{h^2}{2m^*} \left(\frac{1}{L}\right)^2$$

1 nm	↔	10.000 K	↔	800 meV
10 nm	↔	100 K	↔	8 meV
100 nm	↔	1 K	↔	0.08 meV

- Fermi wavelength:

$$\lambda_F = \frac{h}{\sqrt{2m^* \varepsilon_F}} = \frac{2\pi}{(3\pi^2 n)^{1/3}}$$

if $\lambda_F > L_x, L_y, L_z$

→ reduction of dimension by *size quantization*

3D → 2D → 1D → 0D

for metals:

$$n \approx 10^{22} - 10^{23} \text{ cm}^{-3} \rightarrow \lambda_F \approx 1 \text{ nm}$$

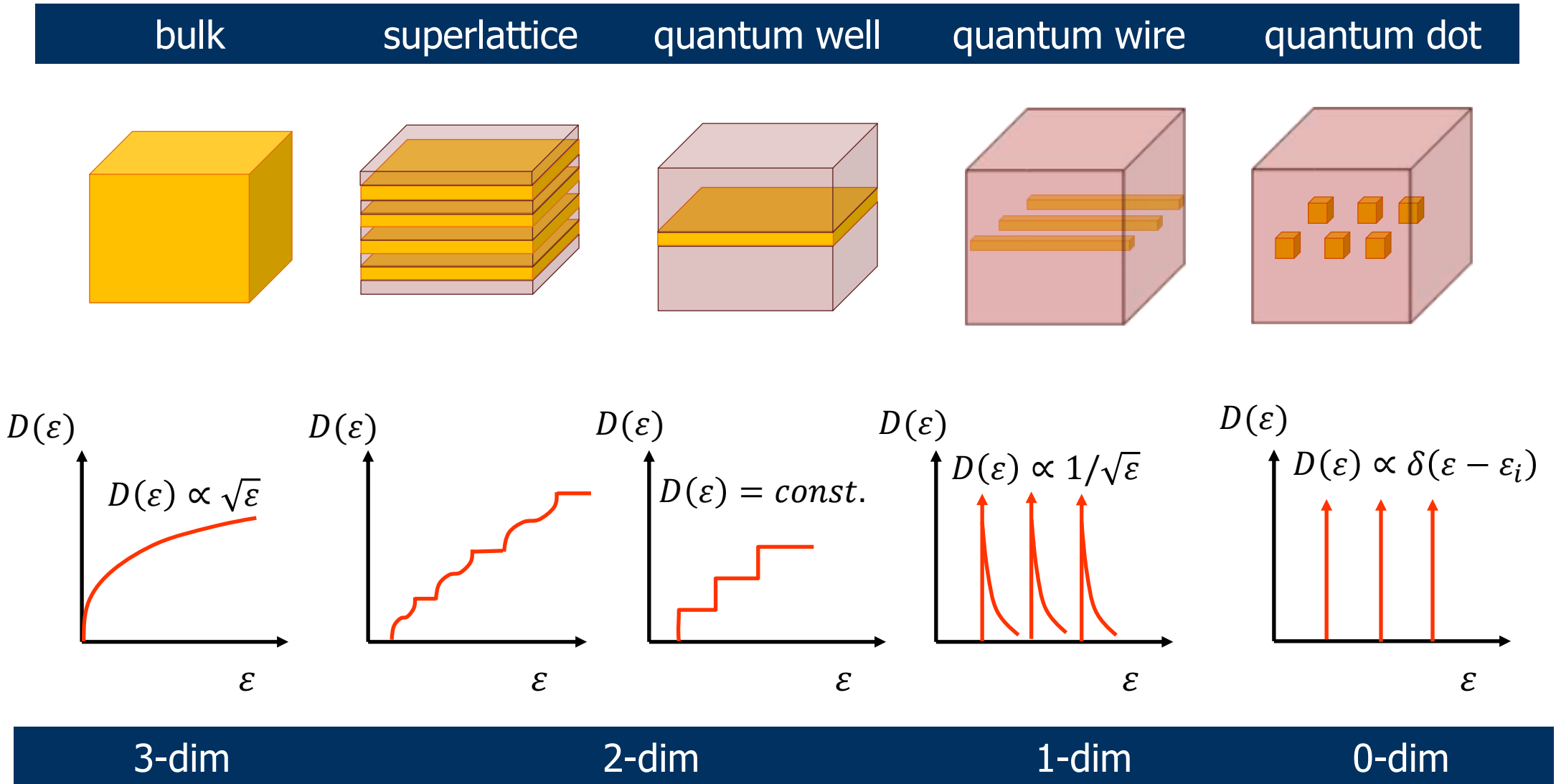
for semiconductors:

$$n \approx 10^{16} - 10^{19} \text{ cm}^{-3} \rightarrow \lambda_F \approx 10 - 100 \text{ nm}$$

- single charge/flux effects: $\frac{e^2}{2C} > k_B T, \frac{\Phi_0^2}{2L} > k_B T$

II.1.4 Characteristic Energy Scales

- size quantization: DOS in 3D, 2D, 1D, and 0D

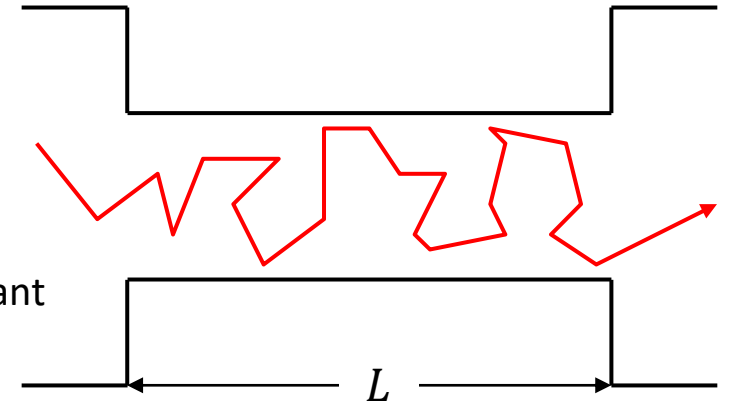


II.1.4 Characteristic Energy Scales

• Thouless energy

- how long does it take for an electron to diffuse through a sample of length L

$$L = \sqrt{Dt} \quad \Rightarrow \quad t = \frac{L^2}{D} \quad D = v^2\tau: \text{diffusion constant}$$



- mean diffusion time is related to the characteristic energy (uncertainty relation)

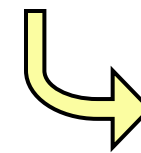
$$\epsilon_{\text{Th}} = \frac{\hbar}{t} = \frac{\hbar D}{L^2} \quad (\text{Thouless energy})$$

- macroscopic samples: $\epsilon_{\text{Th}} \ll k_B T$
- mesoscopic samples: $\epsilon_{\text{Th}} > k_B T$

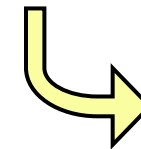
- ballistic transport regime (see below):

$$t = \frac{L}{v_F} \quad \Rightarrow \quad \epsilon_{\text{Th}} = \frac{\hbar}{t} = \frac{\hbar v_F}{L}$$

$(v_F: \text{Fermi velocity})$



$$L < \sqrt{\frac{\hbar D}{k_B T}}$$

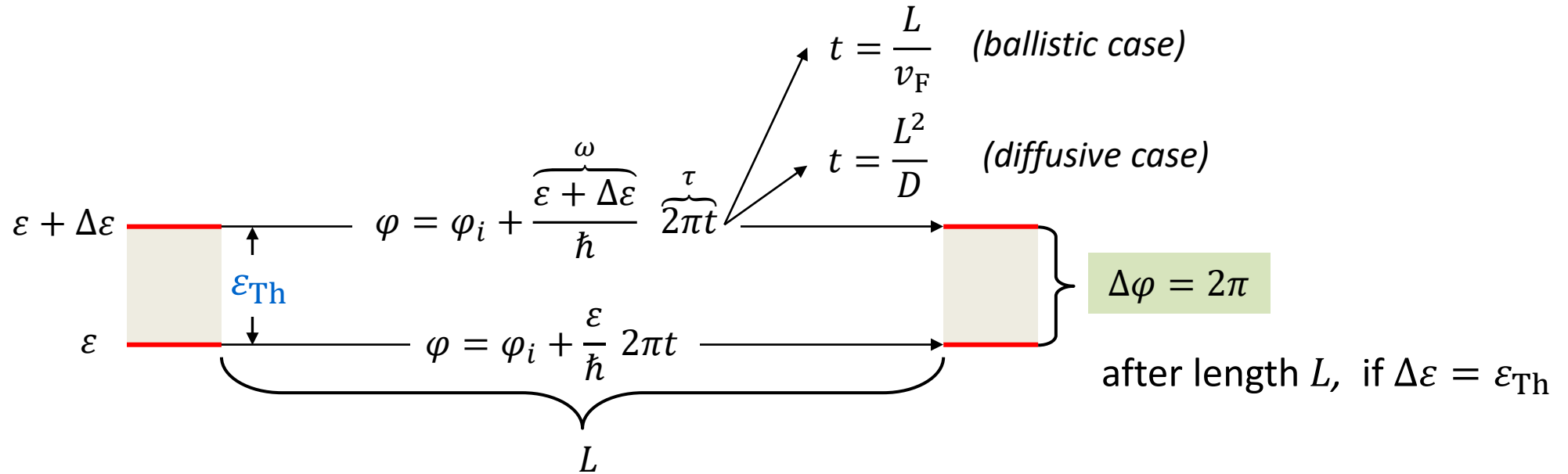


- low T
- small L
- clean samples (large D)

II.1.4 Characteristic Energy Scales

- physical meaning of the Thouless energy

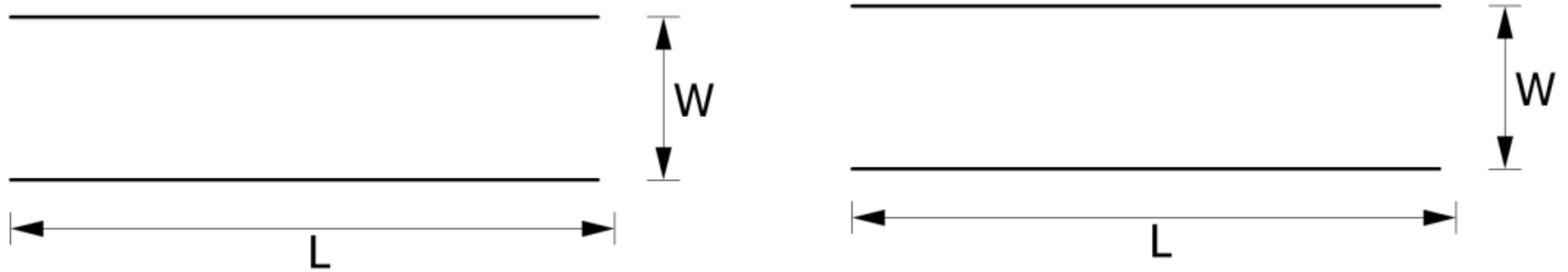
$$\varepsilon_{\text{Th}} = \frac{\hbar}{t} = \frac{\hbar D}{L^2} \rightarrow \text{electrons in energy interval } \Delta\varepsilon = \varepsilon_{\text{Th}} \text{ stay phase coherent in sample of length } L$$



if $\Delta\varepsilon \leq \varepsilon_{\text{Th}}$, the acquired phase shift is less than 2π

example: $D = 10^3 \text{ cm}^2/\text{s}$, $L = 1 \text{ }\mu\text{m}$ $\rightarrow \varepsilon_{\text{Th}} / k_B \approx 1 \text{ K}$

II.1.5 Transport Regimes



<i>macroscopic sample</i>	<i>mesoscopic sample</i>
diffusive: $L, W \gg \ell$	ballistic: $L, W < \ell$
	quasi-ballistic: $W < \ell$
incoherent: $L \gg L_\phi$	coherent: $L < L_\phi$

- @ 300 K: $\ell \sim 10 \text{ nm}$ due to e-ph scattering
- @ at low T : ℓ is limited by impurity and e-e scattering \rightarrow sample quality matters
- L_ϕ is limited by inelastic processes: e-ph and e-e scattering:
 strong T dependence: L_ϕ increases with decreasing T
 $L_\phi \approx 1 \mu\text{m} @ 1\text{K}$

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II.5 Coulomb Blockade



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II.2.1

Electron Waves and Waveguides

(true only in vacuum)

$$\Psi(\mathbf{r}, t) = \frac{1}{\sqrt{V}} \exp\left(i\mathbf{k} \cdot \mathbf{r} - \frac{i}{\hbar} \varepsilon(\mathbf{k})t\right)$$

$\Psi(\mathbf{r}, t)$ wave function

$|\Psi(\mathbf{r}, t)|^2$ probability to find electron at position \mathbf{r} at time t

V normalization volume

\mathbf{k} wave vector

$\mathbf{p} = \hbar\mathbf{k}$ momentum

$\varepsilon(\mathbf{k}) = \frac{\hbar^2 k^2}{2m}$ energy

II.2.1 Electron Waves and Waveguides

- electrons as fermions:

→ Pauli principle (state either occupied by single electron or empty)

→ density of states in k -space: $2 \frac{V}{(2\pi)^3}$ (factor 2 due to *spin*)

→ fraction of filled states: $f(\mathbf{k}, T)$

- important quantities:

$$\begin{array}{l} \text{density} \\ \text{energy density} \\ \text{current density} \end{array} = \begin{bmatrix} \rho \\ \varepsilon \\ \mathbf{J} \end{bmatrix} = 2 \int \frac{d^3k}{(2\pi)^3} \begin{bmatrix} 1 \\ \varepsilon(\mathbf{k}) \\ e\mathbf{v}(\mathbf{k}) \end{bmatrix} f(\mathbf{k})$$

- f determined by statistics:

$$f(\mathbf{k}, T) = \left[\exp\left(\frac{\varepsilon(\mathbf{k}) - \mu}{k_B T}\right) + 1 \right]$$

*Fermi statistics
for electrons*

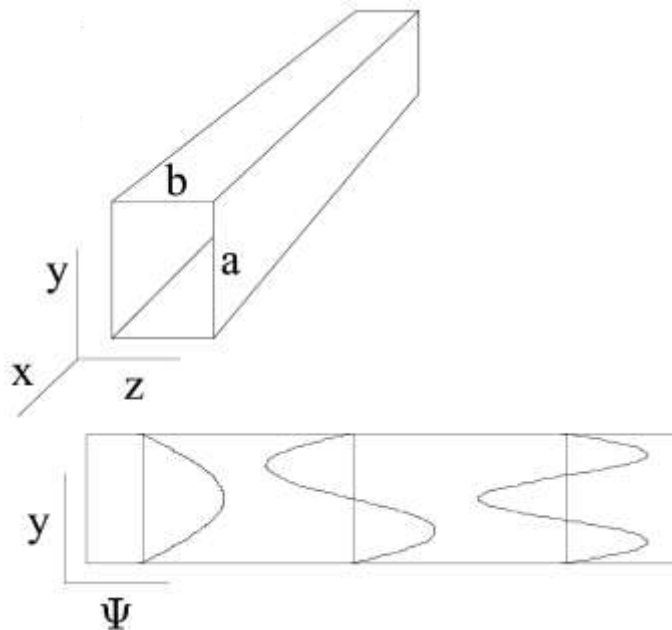
II.2.1 Electron Waves and Waveguides

- ballistic conductor as waveguide

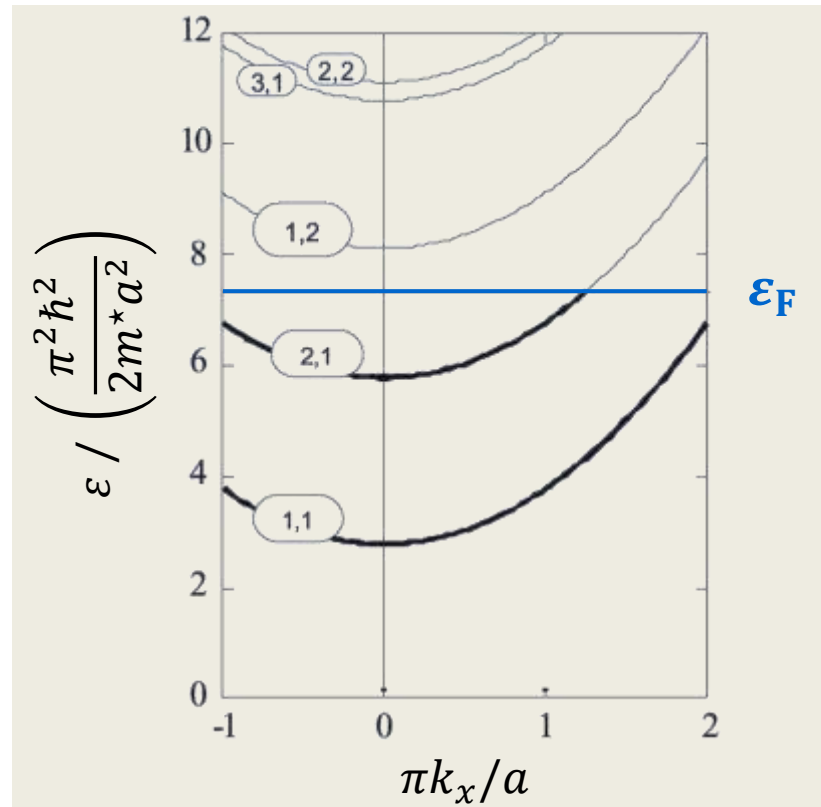
- example: 1D free motion of charge carriers, e.g. in x -direction with confinement in y, z -direction

$$\Psi_{k_x, n, m}(\mathbf{r}, t) = \phi_{n, m}(y, z) \exp[i(k_x x - \omega t)]$$

\uparrow mode index n, m \uparrow standing wave \uparrow plane wave



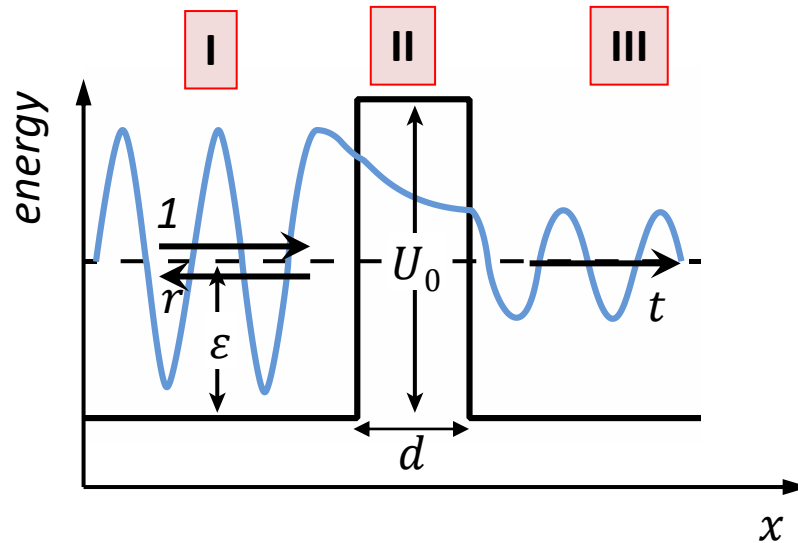
$$\epsilon_{n, m}(k_x) = \frac{\hbar^2 k_x^2}{2m^*} + \epsilon_{n, m} \quad \epsilon_{n, m} = \frac{\pi^2 \hbar^2}{2m^*} \left(\frac{n_y^2}{a^2} + \frac{m_z^2}{b^2} \right)$$



Source: Handouts Nazarov, TU Delft

II.2.1 Electron Waves and Waveguides

- wave guide with potential barrier



$$\varepsilon_{n,m}(k_x) = \frac{\hbar^2 k_x^2}{2m^*} + \varepsilon_{n,m}(0)$$

$$\varepsilon_{n,m}(k_x) - U_0 = \frac{\hbar^2 \kappa^2}{2m^*}$$

I $\Psi(x) = 1 \cdot \exp(ik_x x) + r \cdot \exp(-ik_x x)$

II $\Psi(x) = A \cdot \exp(ikx) + B \cdot \exp(-ikx)$

III $\Psi(x) = t \cdot \exp(ik_x x)$

4 unknown variables:

A, B, r, t

t: transmission amplitude

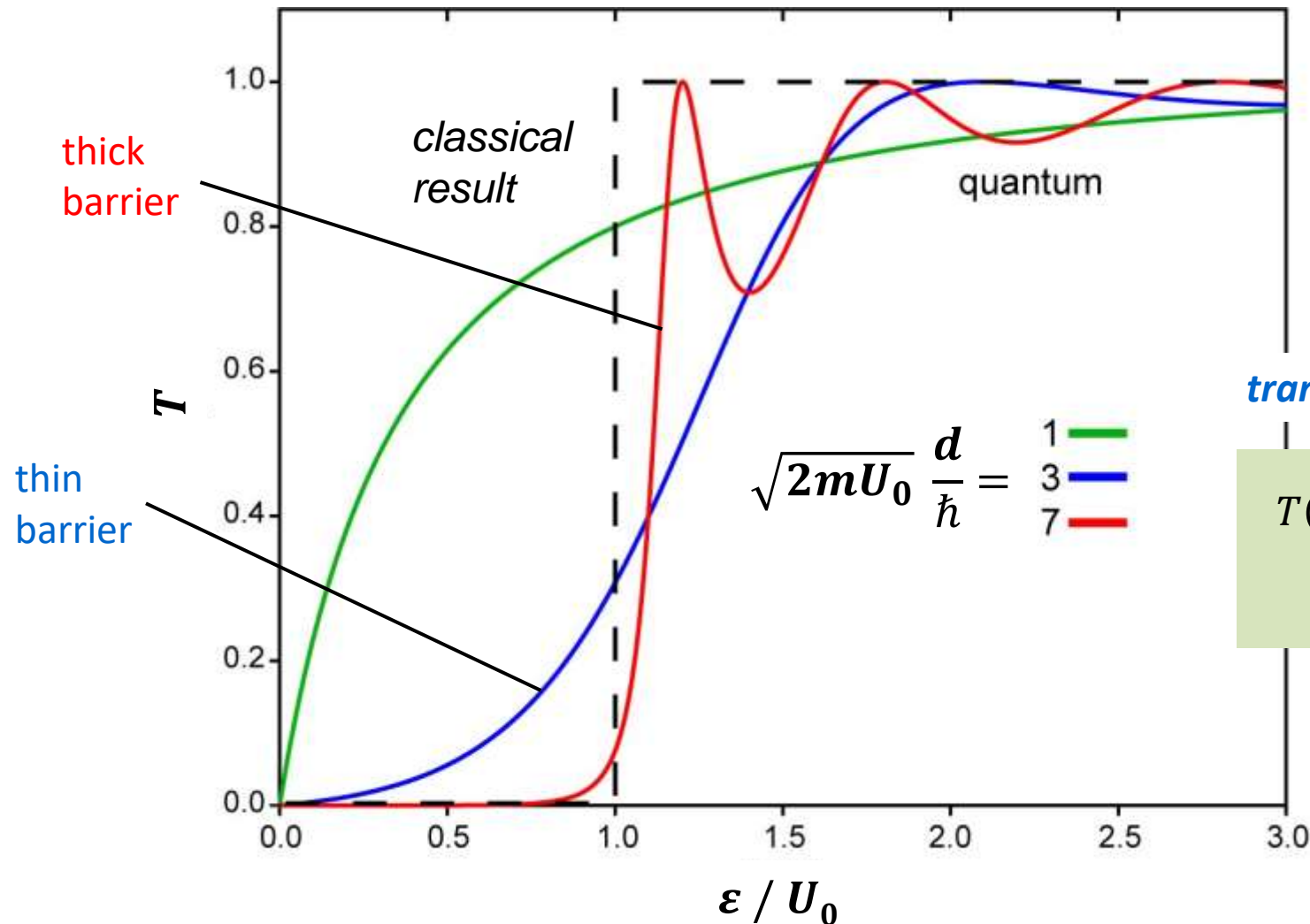
r: reflection amplitude

4 equations

**(wave function matching
at interfaces)**

II.2.1 Electron Waves and Waveguides

- wave guide with potential barrier → example: rectangular barrier



transmission probability/coefficient:

$$T(\varepsilon) \equiv |t^2| = \frac{1}{1 + \left(\frac{k_x^2 - \kappa^2}{2k_x\kappa}\right)^2 \sinh^2 \kappa d}$$

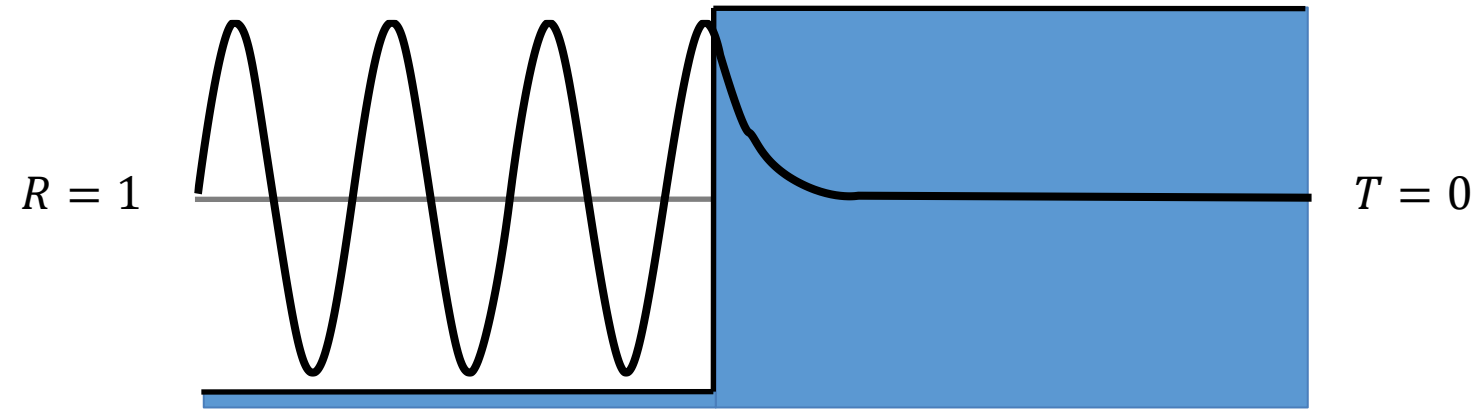
for $\kappa d \gg 1$:

$$\sinh^2(\kappa d) = [\exp(\kappa d) - \exp(-\kappa d)]^2 \approx \exp(2\kappa d)$$

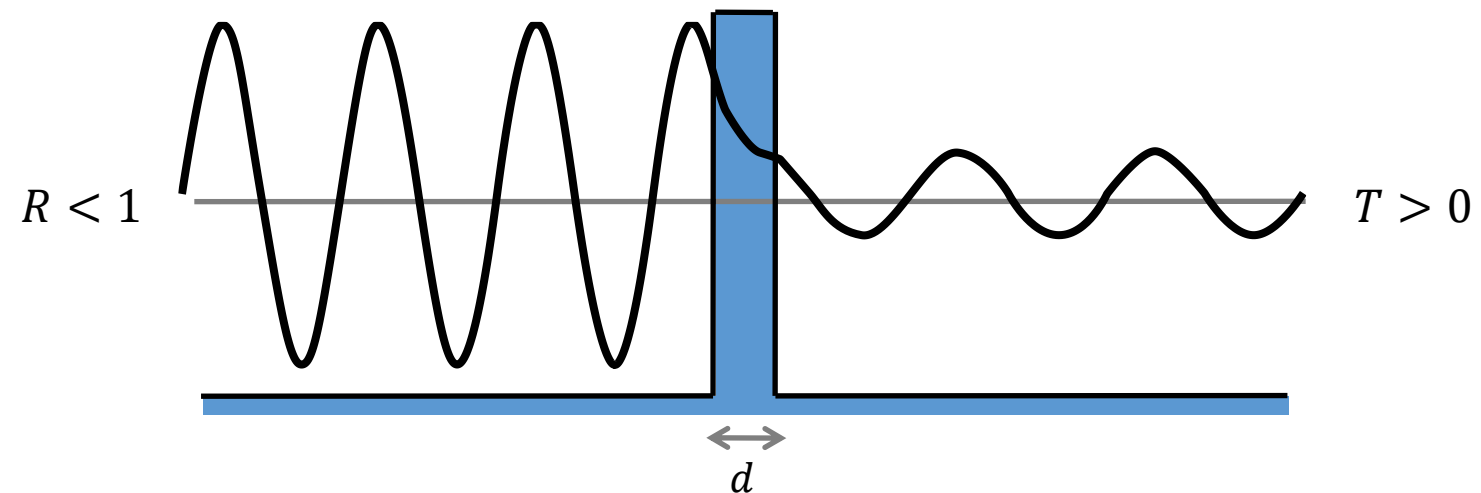
II.2.1 Electron Waves and Waveguides

- quantum tunneling through a thin potential barrier

– total reflection at boundary
(barrier with infinite thickness)

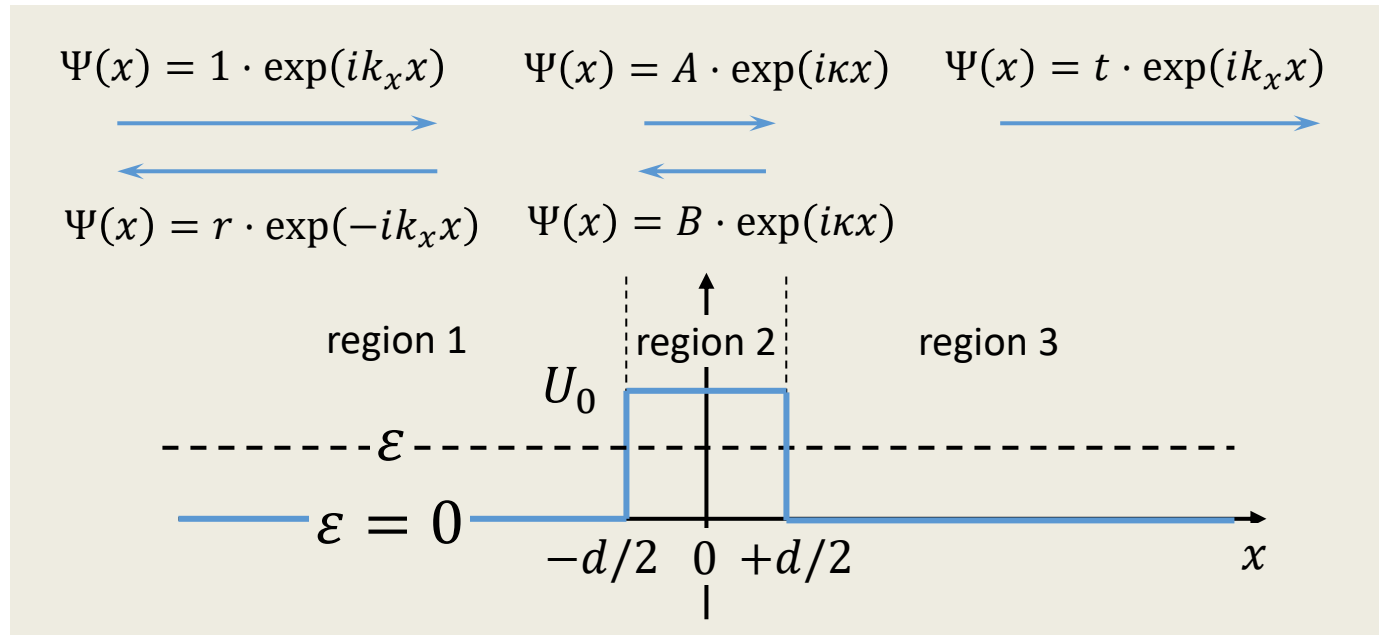


– partial reflection/tunneling
at barrier of finite thickness



II.2.1 Electron Waves and Waveguides

- quantum tunneling through a thin potential barrier: a rectangular barrier

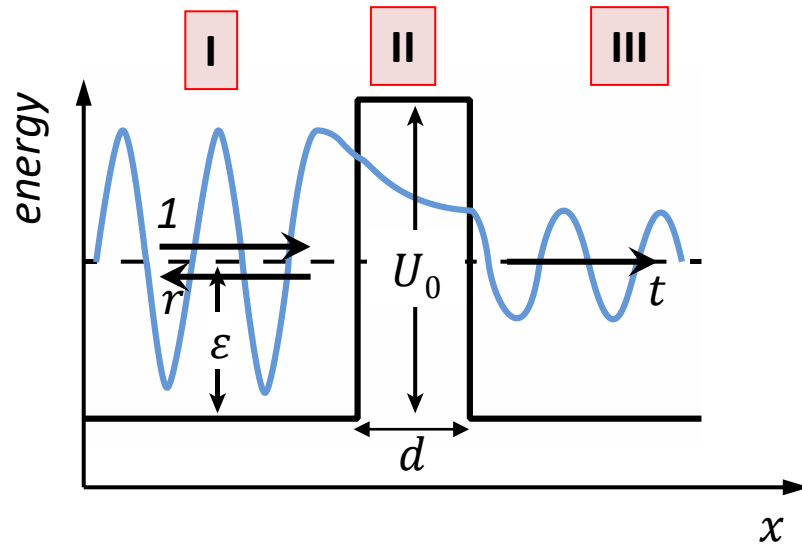


– in regions 1 and 3: $-\frac{\hbar^2}{2m} \frac{\partial^2 \Psi}{\partial x^2} = \varepsilon \Psi(x) \quad \Rightarrow \quad k_x^2 = \frac{2m\varepsilon}{\hbar^2}$

– in region 2: $-\frac{\hbar^2}{2m} \frac{\partial^2 \Psi}{\partial x^2} = (\varepsilon - U_0) \Psi(x) \quad \Rightarrow \quad \kappa^2 = \frac{2m(\varepsilon - U_0)}{\hbar^2}$

II.2.1 Electron Waves and Waveguides

- quantum tunneling through a thin potential barrier: a rectangular barrier



$$T(\varepsilon) \equiv |t^2| = \frac{1}{1 + \left(\frac{k_x^2 - \kappa^2}{2k_x\kappa}\right)^2 \sinh^2 \kappa d}$$

$$T(\varepsilon) \equiv |t^2| = \frac{1}{1 + \frac{U_0^2}{4\varepsilon(U_0 - \varepsilon)} \sinh^2 \kappa d}$$

for $\kappa d \gg 1$:

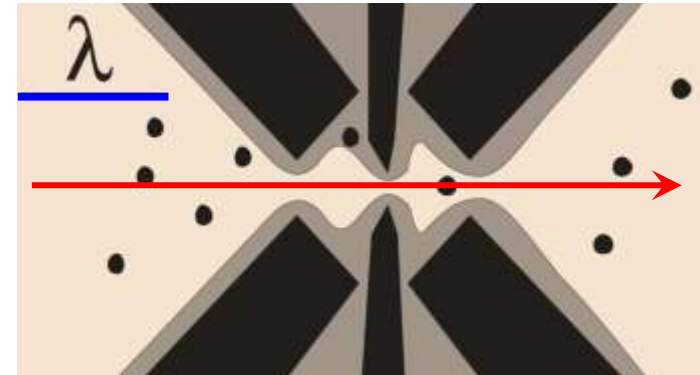
$$\sinh^2(\kappa d) = [\exp(\kappa d) - \exp(-\kappa d)]^2 \simeq \exp(2\kappa d)$$

$$T(\varepsilon) \equiv |t^2| = \frac{1}{1 + \frac{U_0^2}{4\varepsilon(U_0 - \varepsilon)} \exp(2\kappa d)}$$

II.2.1 Electron Waves and Waveguides

- modelling of nanostructures as complex waveguides

→ *transport channels + potential barrier*

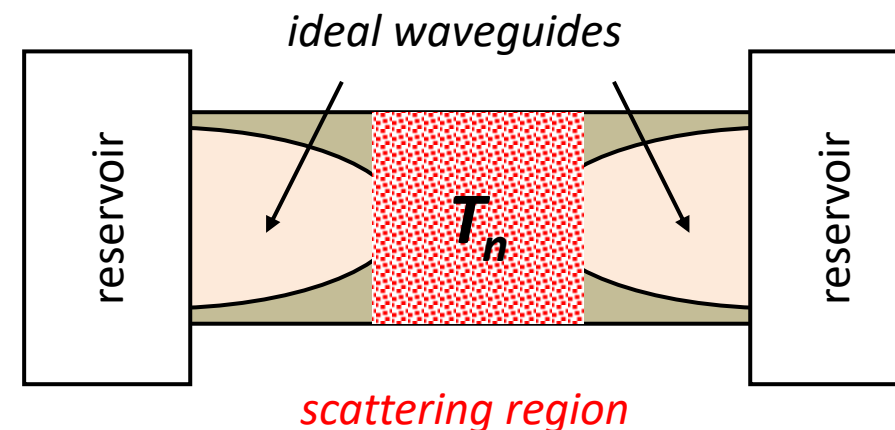


- description of transport by a *set of transmission coefficients T_n*

sufficient to describe transport !!

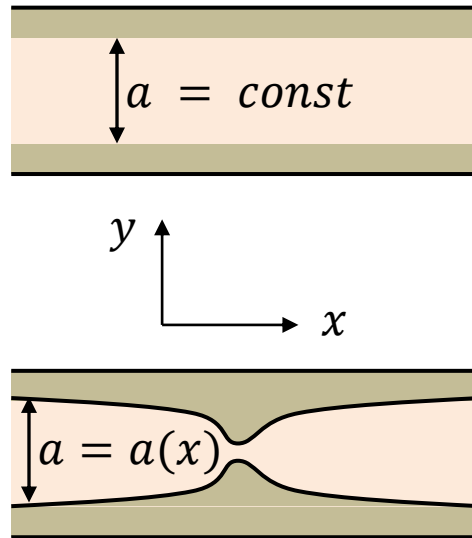
examples:

- (i) adiabatic quantum transport
- (ii) quantum point contact



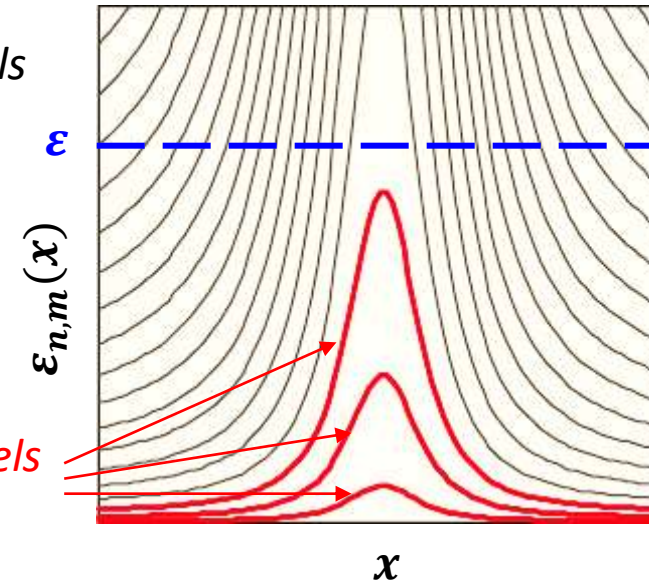
II.2.1 Electron Waves and Waveguides

- modelling of nanostructures as complex waveguides
 - example: **adiabatic quantum transport** → *constriction as a potential barrier*



closed channels
 $T = 0$

3 open channels
 $T = 1$



$$\varepsilon_{n,m}(k_x, x) = \frac{\hbar^2 k_x^2}{2m^*} + \frac{\pi^2 \hbar^2}{2m^*} \left(\frac{n_y^2}{a^2(x)} + \frac{m_z^2}{b^2(x)} \right)$$

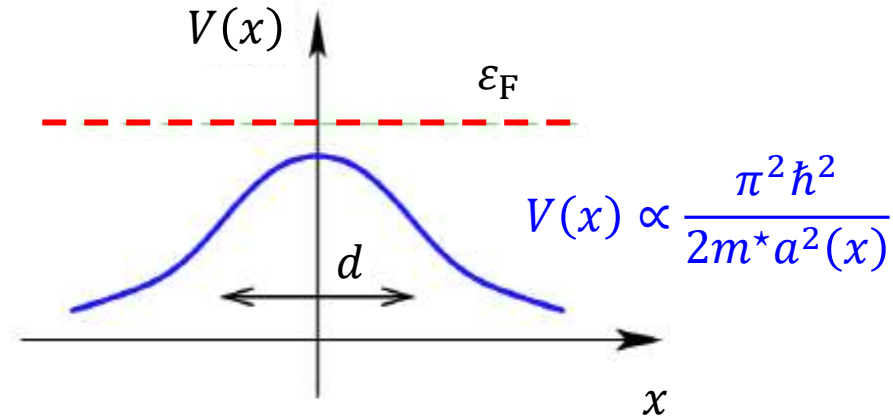
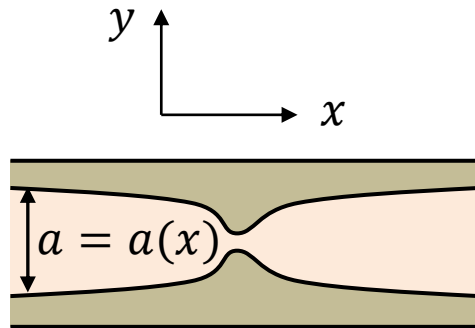
adiabatic waveguide:

variation of dimensions occurs on length scale large compared to width

→ waveguide walls can be assumed parallel locally

II.2.1 Electron Waves and Waveguides

- modelling of nanostructures as complex waveguides
 - example: *adiabatic quantum transport* → *constriction as a potential barrier*



$$\varepsilon_{n,m}(k_x, x) = \frac{\hbar^2 k_x^2}{2m^*} + \underbrace{\frac{\pi^2 \hbar^2}{2m^*} \left(\frac{n_y^2}{a^2(x)} + \frac{m_z^2}{b^2(x)} \right)}_{=V(x)}$$

- parabolic approximation of potential step

$$V(x) \simeq V_0 - \frac{1}{2} m \Omega^2 x^2$$

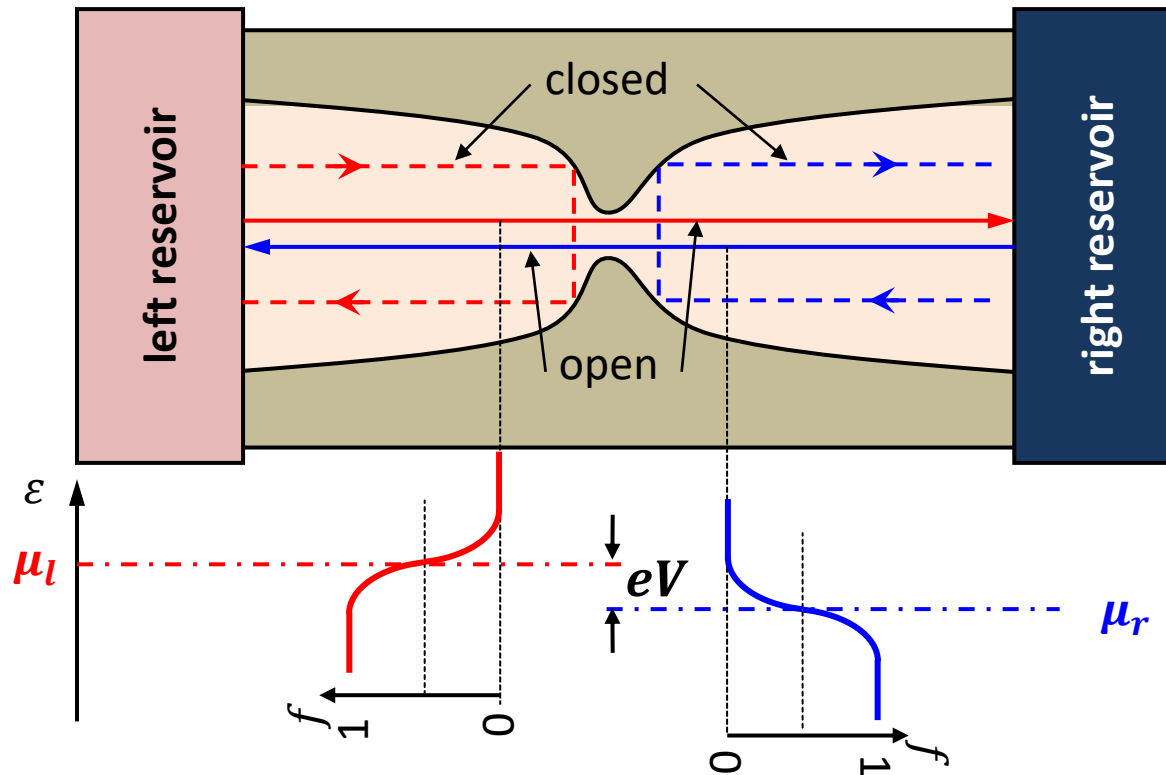
transmission probability:

$$T(\varepsilon_F) = \frac{1}{\exp\left(-\frac{2\pi\varepsilon_F}{\hbar\Omega}\right) + 1}$$

E.C. Kemble, 1935

II.2.1 Electron Waves and Waveguides

- modelling of nanostructures as complex waveguides
 - example: *quantum point contact*



net current:

$$I = I_l - I_r$$

$$I_l = T \frac{2}{2\pi} \int dk_x e v_x f_l(k_x)$$

spin

$$I_r = T \frac{2}{2\pi} \int dk_x e v_x f_r(k_x)$$

$$v_x = \frac{1}{\hbar} \frac{\partial \epsilon}{\partial k_x}$$

open channel: $T = 1$

closed channel: $T = 0$

$$I = \frac{2e}{2\pi\hbar} \sum_{\text{open ch}} \int d\epsilon \underbrace{[f_l(\epsilon) - f_r(\epsilon)]}_{= \mu_l - \mu_r} = \frac{2e}{2\pi\hbar} N_{\text{open}} \underbrace{(\mu_l - \mu_r)}_{= eV} = 2 \underbrace{\frac{e^2}{\hbar}}_{= G_Q} N_{\text{open}} V$$

quantized conductance !!

II.2.1 Electron Waves and Waveguides

- what is the meaning of the quantity $G = \frac{I}{V} = 2 \frac{e^2}{h} N_{\text{open}} = 2 G_Q N_{\text{open}}$
 - for ballistic transport and reflectionless contacts ($T = 1$) there should not be any resistance!
 - where does the resistance come from ?
 - contact resistance from the interface between the ballistic conductor and the contact pads
 - resistance is denoted as **contact resistance**

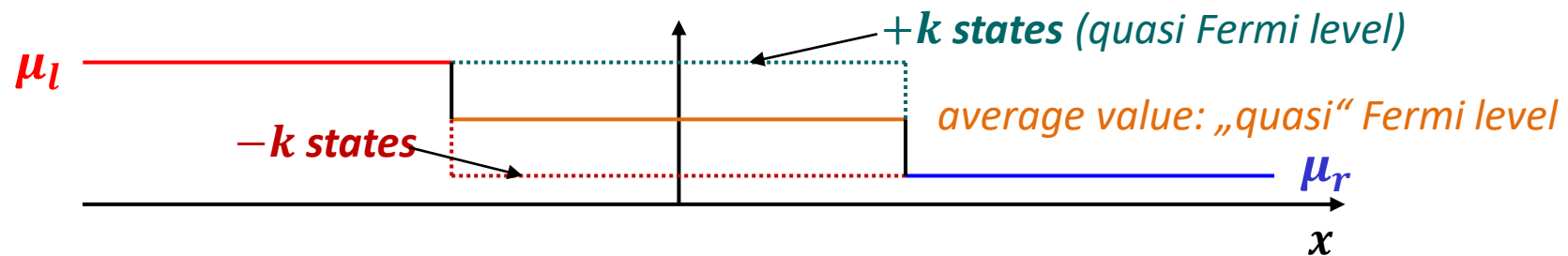
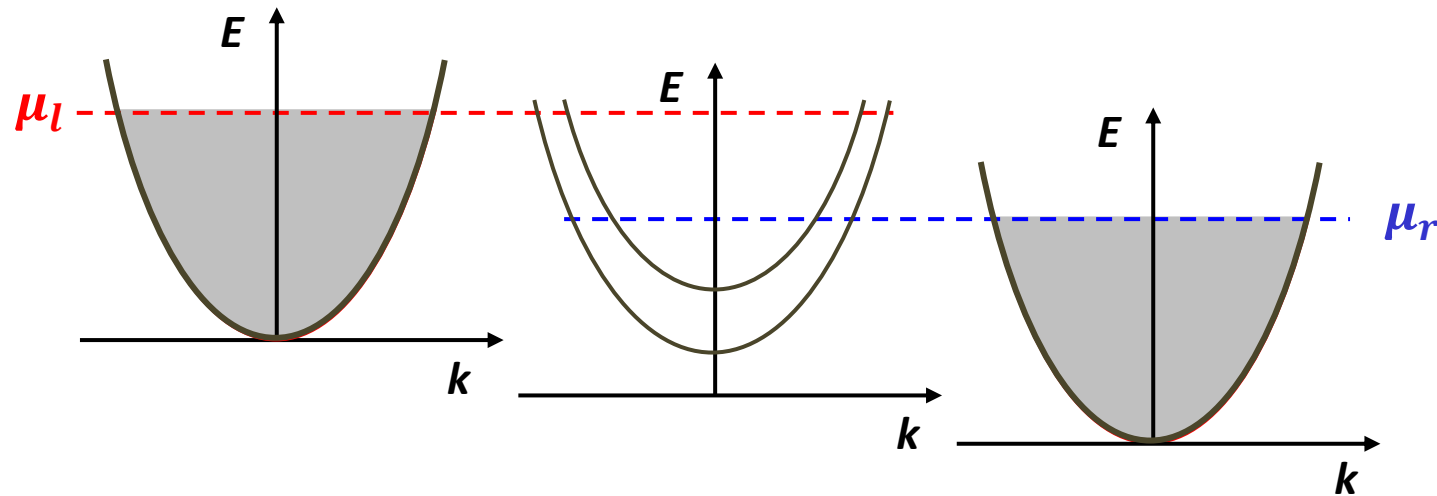
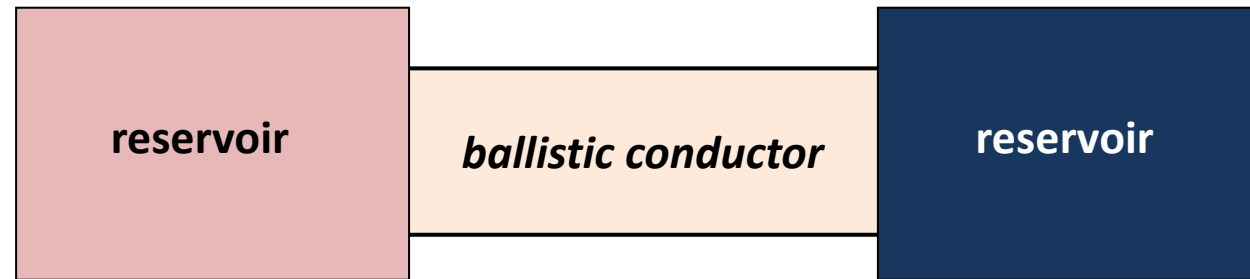
$$G_c^{-1} = \frac{h}{e^2} \frac{1}{2N_{\text{open}}} = G_Q^{-1} \frac{1}{2N_{\text{open}}}$$

\swarrow quantum resistance
25 812.807 $\Omega = 1$ Klitzing

\nwarrow number of available modes

- G_Q determined by fundamental constants, does not depend on materials properties, geometry or size of nanostructure

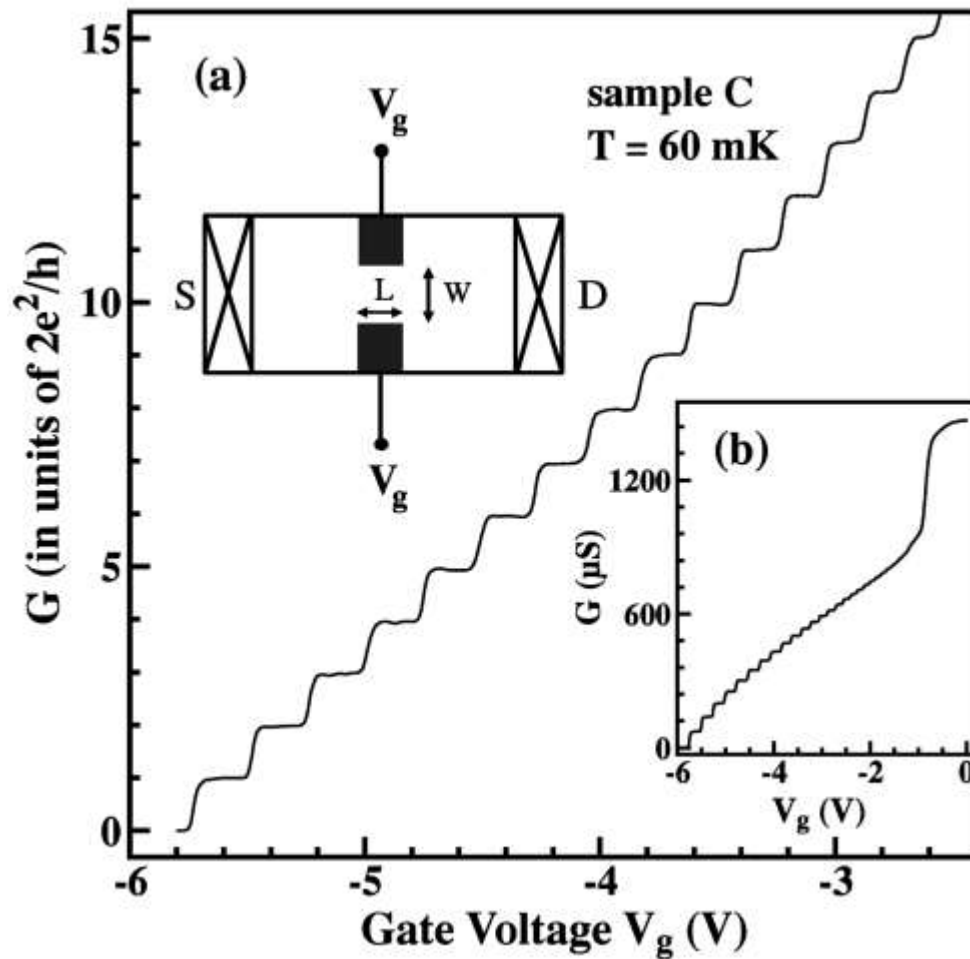
II.2.1 Electron Waves and Waveguides



→ voltage drop at interfaces (contact resistance) !!

II.2.1 Electron Waves and Waveguides

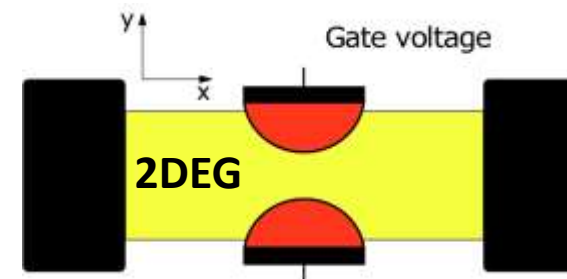
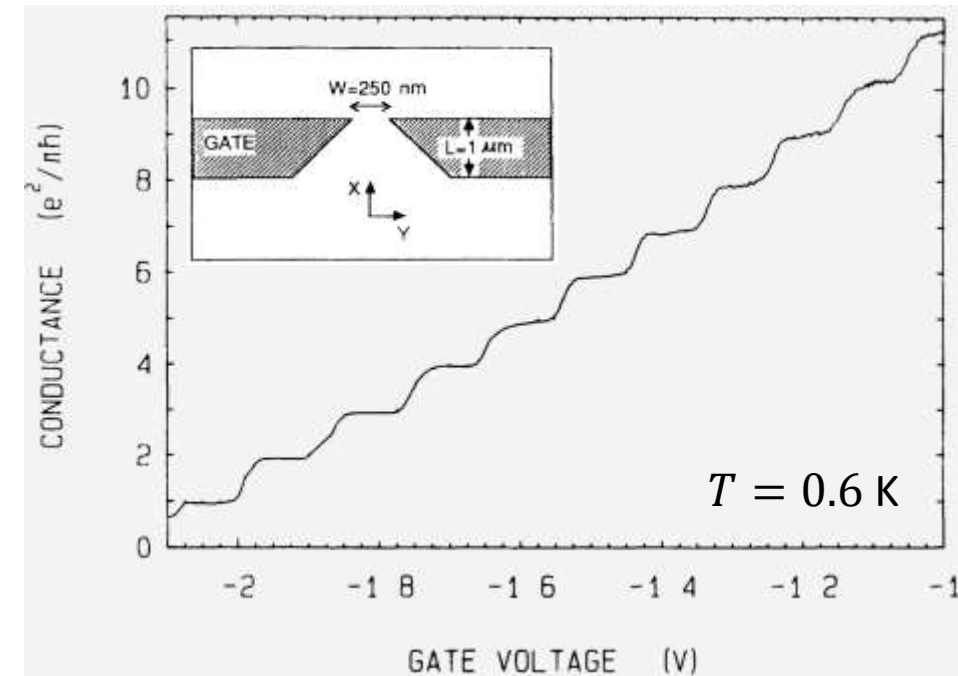
- quantum point contact: experimental results



K.J. Thomas *et al.*, Phys. Rev. B **58**, 4846 (1998)

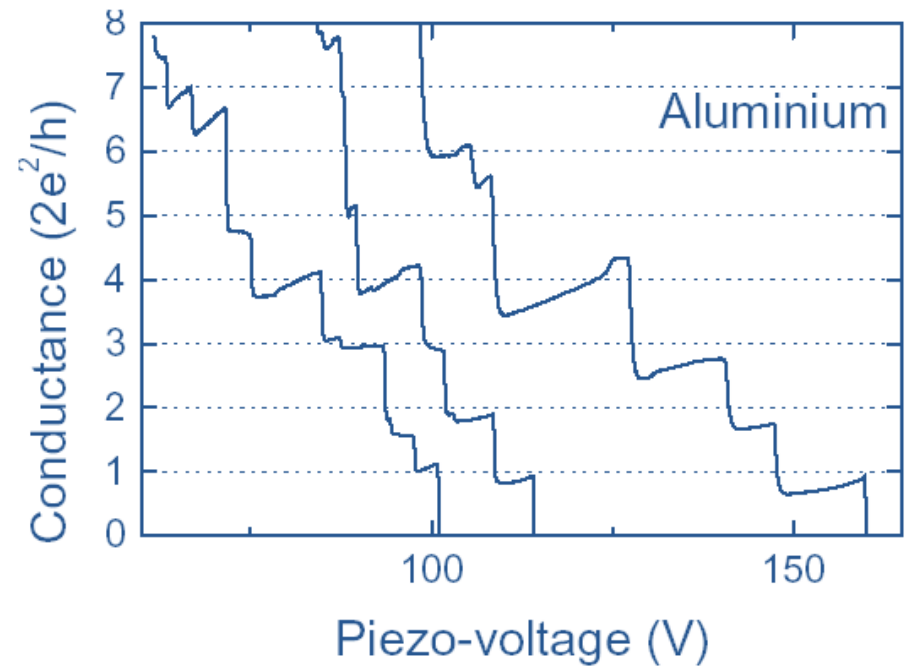
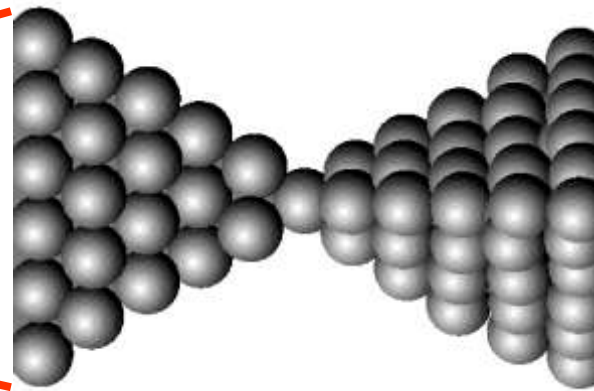
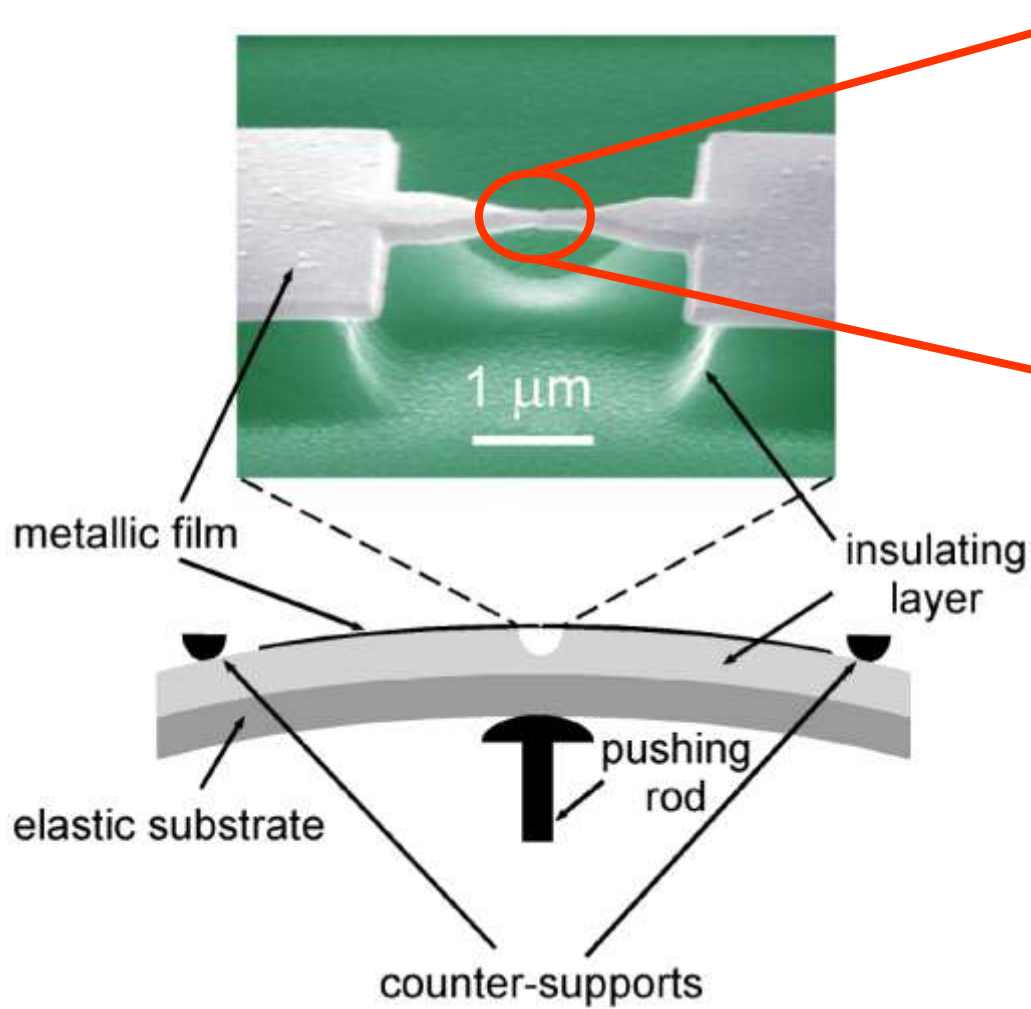
first experiment by

Van Wees *et al.*, Phys. Rev. Lett. **60**, 848 (1988)



increasing gate voltage
narrows channel
→ reduction of N_{open}

II.2.1 Electron Waves and Waveguides

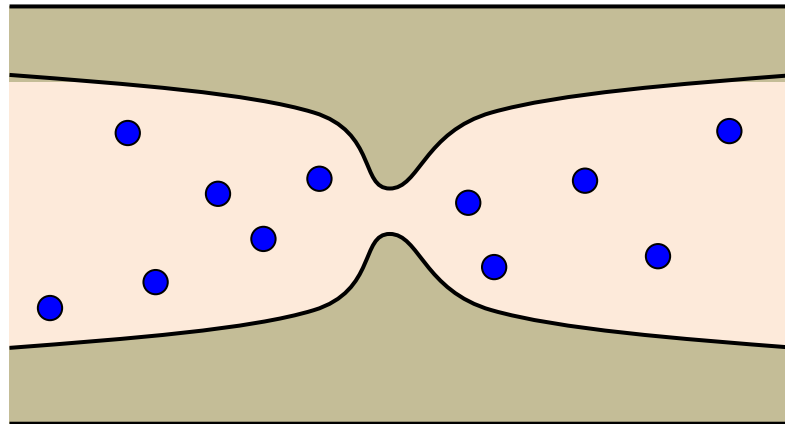


conduction through a single atom !

(Elke Scheer, Univ. Konstanz)

II.2.2 Landauer Formalism

- considered examples have been too simple: T only 1 (open) or 0 (closed)
- more complicated situation: *ideal sample + scattering sites*



transmission probability
of the different modes
will no longer be only 0 or 1

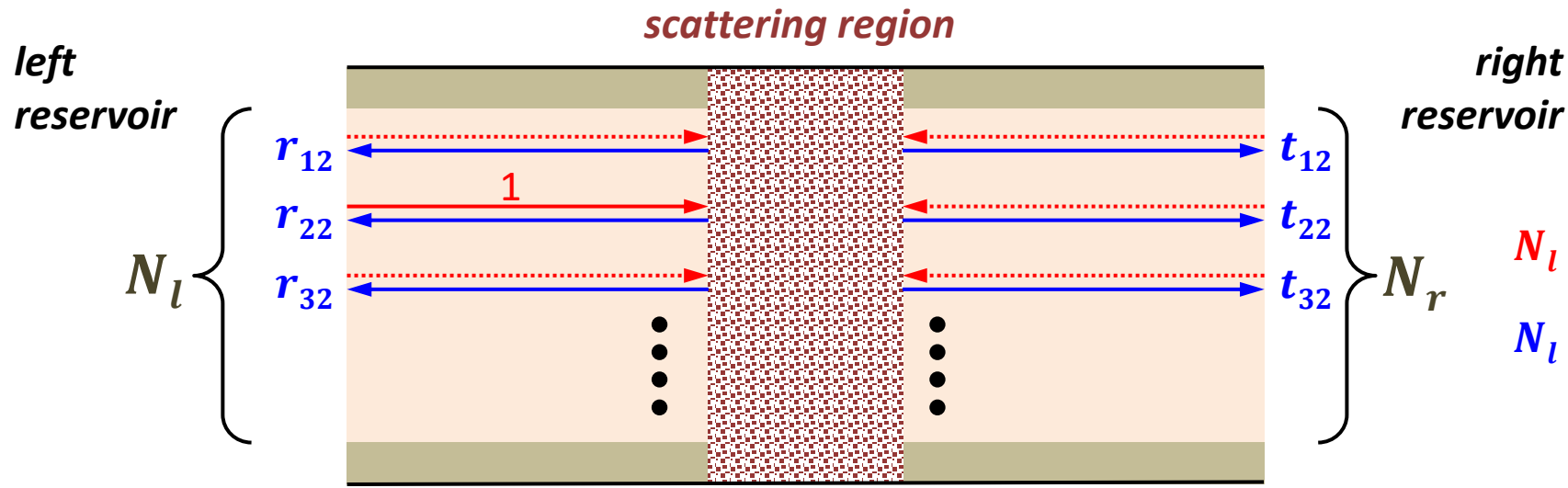


„dusty waveguide“

$$0 \leq T \leq 1$$

- T represents the **average probability** that an electron injected at one end will be **transmitted** to the other end
- treatment of the situation by a *scattering matrix*

II.2.2 Landauer Formalism



$N_l \times N_l$ reflection matrix \hat{r} $N_l \times N_r$ transmission matrix \hat{t}

$$\mathbf{b} = \hat{\mathbf{S}} \mathbf{a} \quad \Rightarrow \quad \begin{bmatrix} \mathbf{b}_l \\ \mathbf{b}_r \end{bmatrix} = \underbrace{\begin{bmatrix} \hat{S}_{ll} & \hat{S}_{lr} \\ \hat{S}_{rl} & \hat{S}_{rr} \end{bmatrix}}_{\text{scattering matrix}} \begin{bmatrix} \mathbf{a}_l \\ \mathbf{a}_r \end{bmatrix} = \begin{bmatrix} \hat{r} & \hat{t}' \\ \hat{t} & \hat{r}' \end{bmatrix} \begin{bmatrix} \mathbf{a}_l \\ \mathbf{a}_r \end{bmatrix}$$

scattering matrix

→ relates amplitudes of outgoing waves with those of incoming waves

transfer matrix \hat{M} :

$$\begin{bmatrix} \mathbf{b}_r \\ \mathbf{a}_r \end{bmatrix} = \hat{M} \begin{bmatrix} \mathbf{a}_l \\ \mathbf{b}_l \end{bmatrix} = \begin{bmatrix} \hat{t} - \hat{r}'\hat{t}'^{-1}\hat{r} & \hat{r}'\hat{t}'^{-1} \\ -\hat{t}'^{-1}\hat{r}' & \hat{t}'^{-1} \end{bmatrix} \begin{bmatrix} \mathbf{a}_l \\ \mathbf{b}_l \end{bmatrix}$$

relates amplitudes of waves right of the scatterer with those left of the scatterer

→ “transfers” states across the scatterer

II.2.2 Landauer Formalism

$$\hat{s} = \begin{bmatrix} \hat{r} & \hat{t}' \\ \hat{t} & \hat{r}' \end{bmatrix}$$

- properties of the scattering matrix

– for given time reversal symmetry: $\hat{t}^T = \hat{t}' \implies \hat{s}^T = \hat{s}$ *symmetric matrix*

– electrons do not disappear: $\underbrace{\sum_{n'} |r_{nn'}|^2}_{R_n} + \underbrace{\sum_m |t_{mn}|^2}_{T_n=1-R_n} = (\hat{s}^\dagger \hat{s})_{nn} = 1$

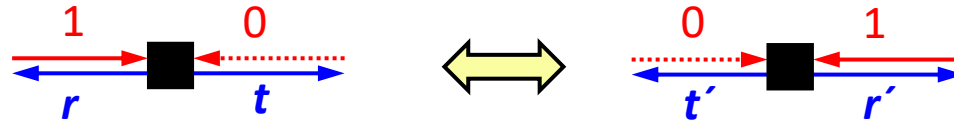
$R_n = (\hat{r}^\dagger \hat{r})_{nn}$
 $T_n = (t^\dagger \hat{t})_{nn}$

conjugate transpose of \hat{s}

$\implies \hat{s}^\dagger \hat{s} = \hat{1}$ *unitary matrix*

II.2.2 Landauer Formalism

- properties of the scattering matrix
 - example: *one channel scatterer*



$$\begin{bmatrix} \mathbf{b}_l \\ \mathbf{b}_r \end{bmatrix} = \begin{bmatrix} r & t' \\ t & r' \end{bmatrix} \begin{bmatrix} \mathbf{a}_l \\ \mathbf{a}_r \end{bmatrix}$$

r, t, r', t' are **complex numbers**

condition of unitarity

→ *only three independent parameters*

$$\hat{S} = \begin{bmatrix} r & t' \\ t & r' \end{bmatrix} = \begin{bmatrix} \sqrt{R} e^{i\theta} & \sqrt{T} e^{i\eta} \\ \sqrt{T} e^{i\eta} & -\sqrt{R} e^{i(2\eta-\theta)} \end{bmatrix}$$

$$R = |r|^2 = 1 - |t|^2 = 1 - T$$

follows from condition of unitarity

- the phases θ and η do not manifest themselves in transport across a single scatterer
 - lead to **quantum interference effects** in multi-scatterer configurations

II.2.2 Landauer Formalism

- properties of the scattering matrix: condition of unitarity: $\hat{S}^\dagger \hat{S} = \hat{1}$

$$\begin{bmatrix} \hat{r}^* & \hat{t}'^* \\ \hat{t}^* & \hat{r}'^* \end{bmatrix} \cdot \begin{bmatrix} \hat{r} & \hat{t} \\ \hat{t}' & \hat{r}' \end{bmatrix} = \begin{bmatrix} \overbrace{|r|^2 + |t'|^2}^{=1} & \overbrace{r^*t + t'^*r'}^{=0} \\ \underbrace{t^*r + r'^*t'}_{=0} & \underbrace{|t|^2 + |r'|^2}_{=1} \end{bmatrix} = \hat{1}$$

$$\hat{s} = \begin{bmatrix} r & t' \\ t & r' \end{bmatrix} = \begin{bmatrix} \sqrt{R} e^{i\theta} & \sqrt{T} e^{i\eta} \\ \sqrt{T} e^{i\eta} & -\sqrt{R} e^{i(2\eta-\theta)} \end{bmatrix}$$

(i) $r^*t + t'^*r' = 0$

$$\begin{aligned} \sqrt{R} e^{-i\theta} \sqrt{T} e^{i\eta} - \sqrt{T} e^{-i\eta} \sqrt{R} e^{i(2\eta-\theta)} &= \\ \sqrt{T R} e^{-i(\theta-\eta)} - \sqrt{T R} e^{-i(\theta-\eta)} &= 0 \quad !! \end{aligned}$$

(ii) $t^*r + r'^*t' = 0$

$$\begin{aligned} \sqrt{T} e^{-i\eta} \cdot \sqrt{R} e^{i\theta} - \sqrt{R} e^{-i(2\eta-\theta)} \cdot \sqrt{T} e^{i\eta} &= \\ \sqrt{T R} e^{i(\theta-\eta)} - \sqrt{T R} e^{i(\theta-\eta)} &= 0 \quad !! \end{aligned}$$

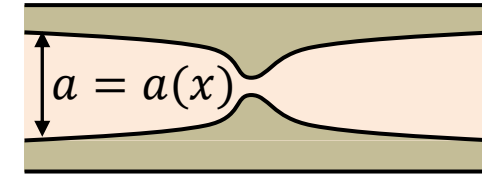
II.2.2 Landauer Formalism

- description of transport properties by scattering matrix

- expression for the current:

$$I = 2e \sum_n \sum_{k_x} v_x(k_x) f_n(k_x) = 2e \sum_n \int_{-\infty}^{\infty} \frac{dk_x}{2\pi} v_x(k_x) f_n(k_x)$$

spin \nearrow $2e$
 \nearrow \sum_n sum over transport channels
 \nwarrow $f_n(k_x)$ occupation probability



- occupation probabilities for right- and left-moving electrons (for current in the left waveguide):

- $k_x > 0$: $f_l(\epsilon)$ (electrons moving to the right)
- $k_x < 0$: $R_n f_l(\epsilon) + (1 - R_n) f_r(\epsilon)$ (electrons moving to the left)

$$I = 2e \sum_n \left\{ \int_0^{\infty} \frac{dk_x}{2\pi} v_x(k_x) f_l(\epsilon) + \int_{-\infty}^0 \frac{dk_x}{2\pi} v_x(k_x) [R_n f_l(\epsilon) + (1 - R_n) f_r(\epsilon)] \right\}$$

$$1 - R_n = \sum_m |t_{mn}|^2 = T_n = (t^\dagger \hat{t})_{nn}$$

$$\sum_n (t^\dagger \hat{t})_{nn} = \text{Tr} [t^\dagger \hat{t}]$$

$$I = 2e \sum_n \int_0^{\infty} \frac{dk_x}{2\pi} v_x(k_x) (1 - R_n) [f_l(\epsilon) - f_r(\epsilon)] \stackrel{\substack{\leftarrow \\ dk_x = d\epsilon / \hbar v_x}}{=} \frac{2e}{2\pi \hbar} \int_0^{\infty} d\epsilon \text{Tr} [t^\dagger \hat{t}] [f_l(\epsilon) - f_r(\epsilon)]$$

II.2.2 Landauer Formalism

- description of transport properties by scattering matrix
 - $\text{Tr} [t^\dagger \hat{t}]$ can be represented by sum of ,transmission‘ eigenvalues T_p of Hermitian matrix $\hat{t}^\dagger \hat{t}$ (for each energy ε)

- expression for the current:

$$I = \frac{2e}{2\pi\hbar} \sum_p \int d\varepsilon T_p(\varepsilon) \cdot [f_l(\varepsilon) - f_r(\varepsilon)] = 2G_Q \underbrace{\sum_p T_p}_{\text{Landauer formula}} \cdot V$$

can usually assumed to be independent of ε

this gives just the number of open channels, if T_p is either 0 or 1



Rolf Wilhelm (William) Landauer
 born 4. February 1927 in Stuttgart
 † 27. April 1999 in Briarcliff Manor, N.Y.

Einstein relation ↔ Landauer formula

$$\sigma = 2e^2 N(\varepsilon_F) D \quad \Leftrightarrow \quad G = 2 \frac{e^2}{h} N T$$

single spin DOS diffusion constant number of modes transmission probability

Landauer formula → ‘mesoscopic version’ of Einstein relation

II.2.2 Landauer Formalism

- description of transport properties by scattering matrix: plausibility consideration

- consider a conductor with a single conduction channel
- reservoir biased at V sends out the following number of electrons:

$$N(t) = \underbrace{Z(k)\Delta k}_{\text{number}} \cdot \underbrace{\frac{1}{\hbar} \frac{\Delta \varepsilon}{\Delta k}}_{\text{velocity}} \cdot \underbrace{t}_{\text{time}} = \frac{\overset{\text{spin}}{2}}{2\pi} \Delta k \cdot \frac{eV}{\hbar \Delta k} \cdot t = 2 \cdot \frac{eV}{h} \cdot t$$

emission frequency

- the chance to pass is T_0 , then the passed charge is just $Q(t) = eT_0N(t)$

- the average current is charge per time:

$$I = \frac{Q}{t} = 2 \frac{e^2}{h} T_0 V$$

- many channels: just sum up to obtain

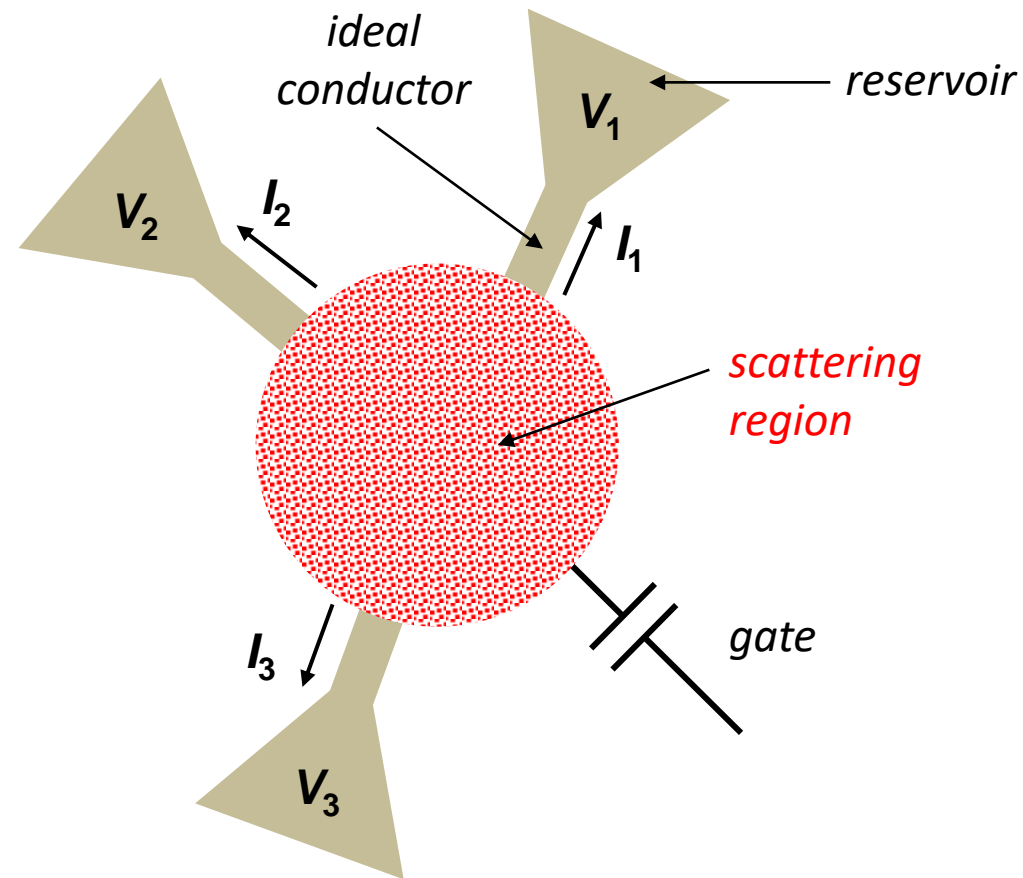
$$I = 2G_Q \sum_p T_p V$$

II.2.2 Landauer Formalism

- description of transport properties by scattering matrix: limitations and restrictions
 - *restrictions:*
 - only *elastic* scattering (electrons pass the conductor at constant energy)
 - *no interactions* between electrons
 - *limitations:*
 - low temperatures and low voltages
 - short conductors (shorter than inelastic scattering length)

II.2.3 Multi-terminal Conductors

- Landauer formalism: multi-terminal conductors
 - so far discussion of two-terminal systems, extension to multi-terminal conductors?



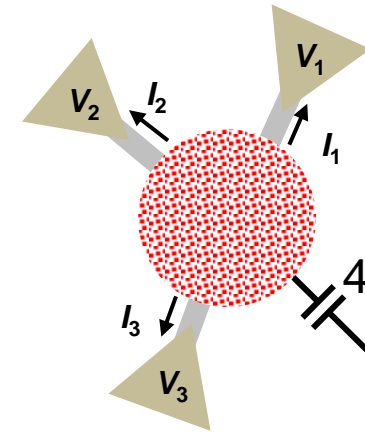
how to express currents in terms of voltages using the Landauer formalism ?

II.2.3 Multi-terminal Conductors

- Landauer formalism: multi-terminal conductors

- conduction matrix G_{kl}

$$\begin{pmatrix} I_1 \\ \vdots \\ I_n \end{pmatrix} = \begin{pmatrix} G_{11} & \cdots & G_{1n} \\ \vdots & \ddots & \vdots \\ G_{n1} & \cdots & G_{nn} \end{pmatrix} \begin{pmatrix} V_1 \\ \vdots \\ V_n \end{pmatrix}$$



$$I_k = \sum_l G_{kl} V_l$$

- properties of conduction matrix:

→ *current conservation (Kirchhoff's law):*

$$\sum_{k=1}^n I_k = 0 \Rightarrow \sum_{k=1}^n G_{kl} = 0$$

sum of conduction coefficients in each column must be zero

→ *no current, if potential is shifted by the same amount in all leads*

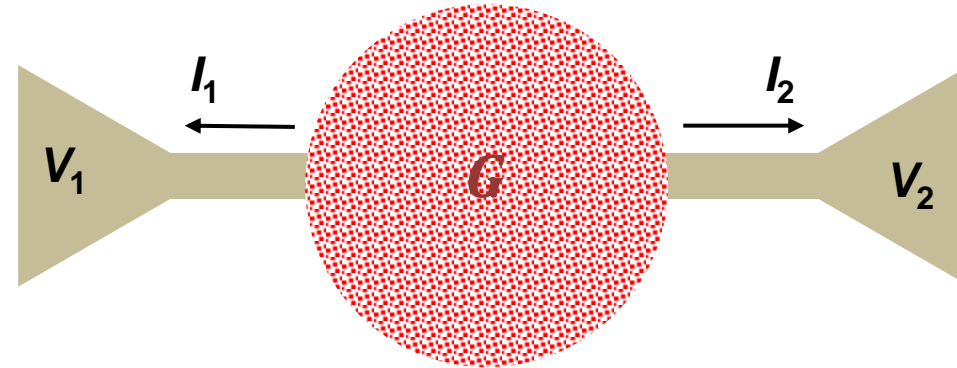
$$\sum_{l=1}^n G_{kl} = 0$$

sum of conduction coefficients in each row must be zero

- consequence of the sum rules: currents I_k voltage differences

II.2.3 Multi-terminal Conductors

- Landauer formalism: multi-terminal conductors
 - simplest case: two-terminal conductor



- the conduction matrix only has a *single independent element*:

$$\begin{bmatrix} I_1 \\ I_2 \end{bmatrix} = \begin{bmatrix} -G & G \\ G & -G \end{bmatrix} \begin{bmatrix} V_1 \\ V_2 \end{bmatrix}$$

$$I_1 = G(V_2 - V_1)$$

$$I_2 = G(V_1 - V_2)$$

II.2.3 Multi-terminal Conductors

- Landauer formalism: multi-terminal conductors

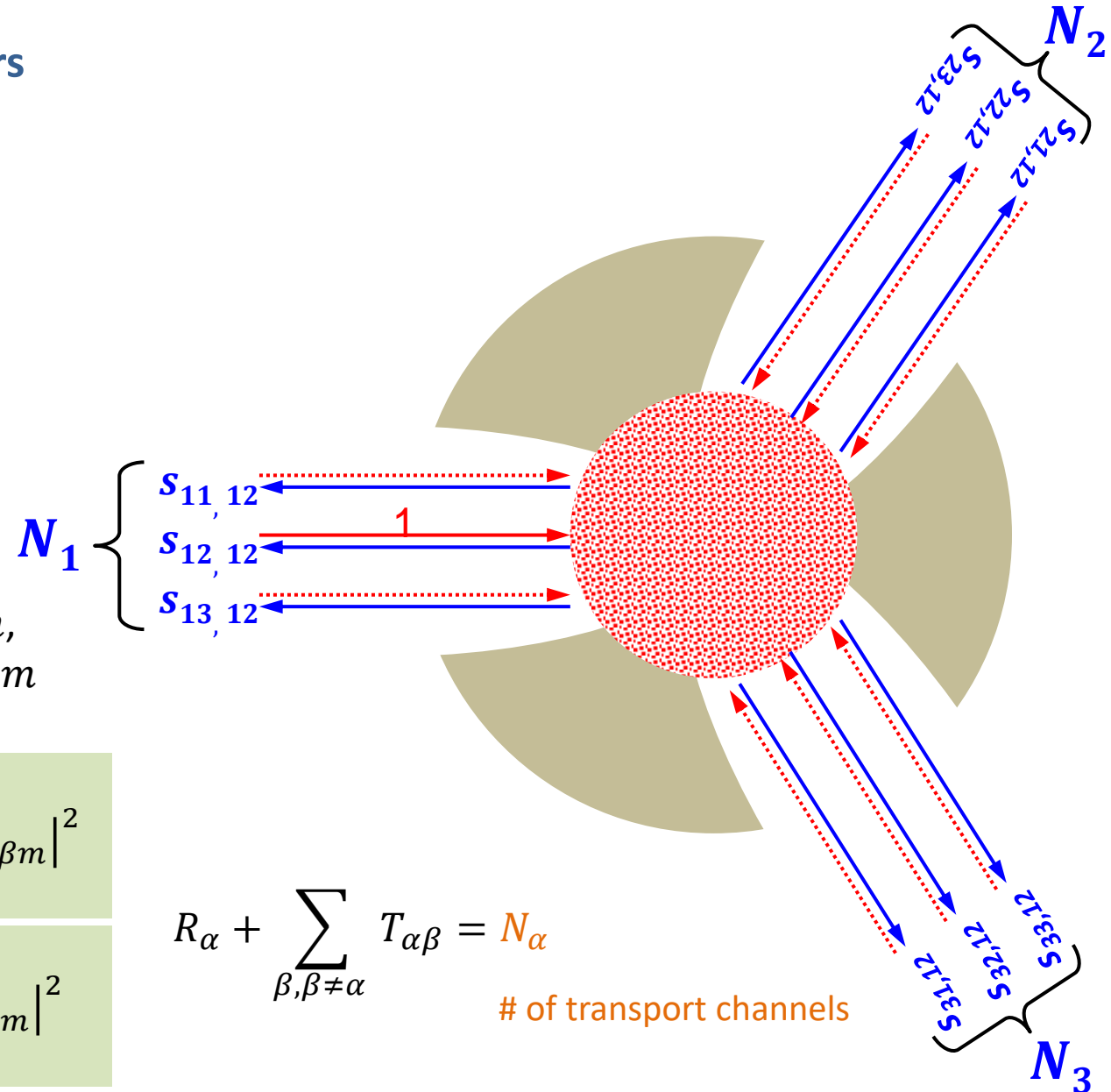
- scattering matrix for *multi-terminal* conductors
- number of modes: $N = N_1 + N_2 + N_3 + \dots$
 → scattering matrix is $N \times N$ matrix
- meaning of $s_{\beta m, \alpha n}$: $b_{\beta m} = s_{\beta m, \alpha n} a_{\alpha n}$
 → propagation amplitude from terminal α , transport channel n , to the terminal β , transport channel m

- transmission probability from lead α to β :

$$T_{\alpha\beta} = \sum_{n=1}^{N_\alpha} \sum_{m=1}^{N_\beta} |s_{\alpha n, \beta m}|^2$$

- reflection probability from lead α into α :

$$R_\alpha = \sum_{n=1}^{N_\alpha} \sum_{m=1}^{N_\alpha} |s_{\alpha n, \alpha m}|^2$$



$$R_\alpha + \sum_{\beta, \beta \neq \alpha} T_{\alpha\beta} = N_\alpha$$

of transport channels

II.2.3 Multi-terminal Conductors

- Landauer formalism: multi-terminal conductors

- properties of scattering matrix:

- reflection back into same lead α : $S_{\alpha n, \alpha m}$

- transmission from lead β to lead α : $S_{\alpha n, \beta m}$

- current conservation requires

$$\hat{S}^\dagger \hat{S} = \hat{1} \quad (\text{unitary matrix})$$

$$\sum_{\alpha n} S_{\alpha n, \gamma l}^* S_{\alpha n, \beta m} = \delta_{\gamma \beta} \delta_{l m}$$

- time reversibility relation

- we know: if $\Psi(\mathbf{r}, \mathbf{B})$ solves Schrödinger equation then also $\Psi^*(\mathbf{r}, -\mathbf{B})$

- application to asymptotic scattering states: taking complex conjugate of scattering state b , then the incoming state a becomes the complex conjugate of b^* → corresponds to reversal of time direction

$$\left. \begin{aligned} b = s(\mathbf{B})a &\Rightarrow b^* = s^*(\mathbf{B}) a^* \\ a^* = s(-\mathbf{B})b^* &\Rightarrow s^{-1}(-\mathbf{B})a^* = s^{-1}(-\mathbf{B})s(-\mathbf{B})b^* \Rightarrow s^{-1}(-\mathbf{B})a^* = b^* \end{aligned} \right\} \Rightarrow s^{-1}(-\mathbf{B}) = s^*(\mathbf{B}) = s^\dagger(\mathbf{B})$$

due to unitarity

$$S_{\alpha n, \beta m}(\mathbf{B}) = S_{\beta m, \alpha n}(-\mathbf{B})$$

II.2.3 Multi-terminal Conductors

- Landauer formalism: multi-terminal conductors

– sum rules:

$$R_\alpha + \sum_{\beta, \beta \neq \alpha} T_{\alpha\beta} = N_\alpha$$

of transport channels in lead α

$$R_\beta + \sum_{\alpha, \alpha \neq \beta} T_{\beta\alpha} = N_\beta$$

of transport channels in lead β

$$T_{\alpha\beta} = \sum_{n=1}^{N_\alpha} \sum_{m=1}^{N_\beta} |S_{\alpha n, \beta m}|^2$$

$$R_\alpha = \sum_{n=1}^{N_\alpha} \sum_{m=1}^{N_\alpha} |S_{\alpha n, \alpha m}|^2$$

– example: **two-terminal conductor**

	$\beta = 1$	$\beta = 2$	$\sum =$
$\alpha = 1$	R_1	T_{12}	N_1
$\alpha = 2$	T_{21}	R_2	N_2
$\sum =$	N_1	N_2	

$$R_1 + T_{12} = R_1 + T_{21} \Rightarrow T_{12} = T_{21}$$

transmission function is reciprocal !
→ time reversal symmetry

II.2.3 Multi-terminal Conductors

- Landauer formalism: multi-terminal conductors

- multi-terminal expression of Landauer formula relates currents to voltages via a scattering matrix (cf. page 42)

$$I_\alpha = 2e \sum_n \left\{ \int_0^\infty \frac{dk_x}{2\pi} v_x(k_x) f_\alpha(\varepsilon) + \int_{-\infty}^0 \frac{dk_x}{2\pi} v_x(k_x) \sum_{\beta m} |s_{\alpha n, \beta m}|^2 f_\beta(\varepsilon) \right\}$$

$$I_\alpha = 2e \sum_n \int_0^\infty \frac{dk_x}{2\pi} v_x(k_x) \sum_{\beta m} \{ |s_{\alpha n, \beta m}|^2 - \delta_{\alpha\beta} \delta_{mn} \} f_\beta(\varepsilon) \stackrel{dk_x = d\varepsilon / \hbar v_x}{=} \underbrace{\frac{2e}{2\pi\hbar}}_{=G_Q/e} \int_0^\infty d\varepsilon \sum_{\beta mn} \{ |s_{\alpha n, \beta m}|^2 - \delta_{\alpha\beta} \delta_{mn} \} f_\beta(\varepsilon)$$

- probability for transmission from α to β :

$$I_\alpha = -\frac{G_Q}{e} \int_0^\infty d\varepsilon \sum_\beta \text{Tr} \{ \delta_{\alpha\beta} \delta_{mn} - \hat{s}_{\alpha\beta}^\dagger \hat{s}_{\alpha\beta} \} f_\beta(\varepsilon)$$

- trace includes all possible transport channels

- if all $f_\beta(\varepsilon)$ are the same, e.g. in thermal equilibrium and no voltages applied, then $\sum_\beta = 0$ (current conservation, follows from unitarity)

- we apply voltage V_γ to terminal γ and keep all other at ε_F \rightarrow the only surviving term in \sum_β is the one for $\beta = \gamma$ and the integral yields eV_γ

$$I_\alpha = -\frac{G_Q}{e} \text{Tr} \{ \delta_{\alpha\gamma} \delta_{mn} - \hat{s}_{\alpha\gamma}^\dagger \hat{s}_{\alpha\gamma} \} eV_\gamma = G_{\alpha\gamma} V_\gamma$$

$$\Rightarrow G_{\alpha\gamma} = -G_Q \text{Tr} \{ \delta_{\alpha\gamma} \delta_{mn} - \hat{s}_{\alpha\gamma}^\dagger \hat{s}_{\alpha\gamma} \}$$

**multi-terminal
Landauer formula**

II.2.3 Multi-terminal Conductors

- Summary: Landauer formalism: multi-terminal conductors

- linear transport regime: $G_{\alpha\gamma} = -G_Q \text{Tr} \{ \delta_{\alpha\gamma} \delta_{mn} - \hat{S}_{\alpha\gamma}^\dagger \hat{S}_{\alpha\gamma} \}$

- relation to two-terminal expression: $\alpha, \gamma = l, r$

$$G_{lr} = G_Q \text{Tr} \{ \hat{S}_{lr}^\dagger \hat{S}_{lr} \} = G_Q \text{Tr} [t^\dagger \hat{t}]$$

- time reversal symmetry: $G_{\alpha\gamma}(\mathbf{B}) = G_{\gamma\alpha}(-\mathbf{B})$

this is in agreement with Onsager symmetry relations !

II.2.3 Multi-terminal Conductors

- Landauer formalism: multi-terminal conductors
 - example: **three-terminal scattering element**

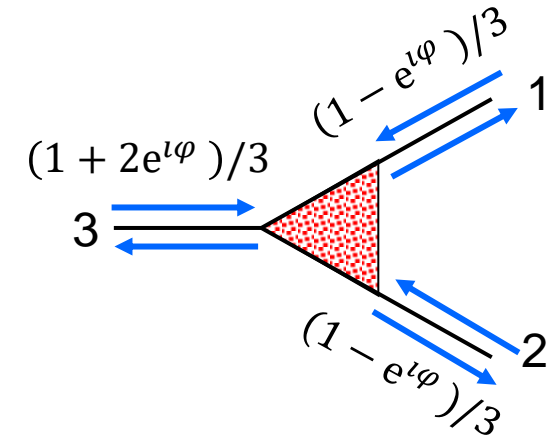
scattering matrix for fully symmetric beam splitter:

$$\hat{S}_{\text{BS}} = \frac{1}{3} \begin{pmatrix} 1 + 2e^{i\varphi} & 1 - e^{i\varphi} & 1 - e^{i\varphi} \\ 1 - e^{i\varphi} & 1 + 2e^{i\varphi} & 1 - e^{i\varphi} \\ 1 - e^{i\varphi} & 1 - e^{i\varphi} & 1 + 2e^{i\varphi} \end{pmatrix}$$

diagonal elements: $R = |1 + 2e^{i\varphi}|^2 = [5 + 4 \cos \varphi]/9$

$R = 1$ for $\varphi = 0$ (total reflection)

$R = 1/3$ for $\varphi = \pi$ (equal division)



fully symmetric ideal beam splitter

II.2.3 Multi-terminal Conductors

- Landauer formalism: multi-terminal conductors

- example: **three-terminal scattering element**

scattering matrix:
$$\hat{s}_{BS} = \begin{pmatrix} -\sin^2\left(\frac{\varphi}{2}\right) & \cos^2\left(\frac{\varphi}{2}\right) & \sin\left(\frac{\varphi}{2}\right) \\ \cos^2\left(\frac{\varphi}{2}\right) & -\sin^2\left(\frac{\varphi}{2}\right) & \sin\left(\frac{\varphi}{2}\right) \\ \sin\left(\frac{\varphi}{2}\right) & \sin\left(\frac{\varphi}{2}\right) & -\cos\varphi \end{pmatrix}$$

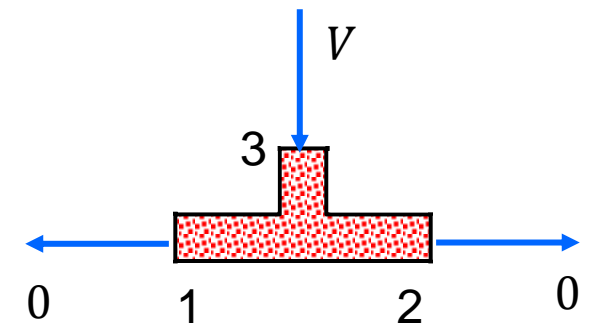
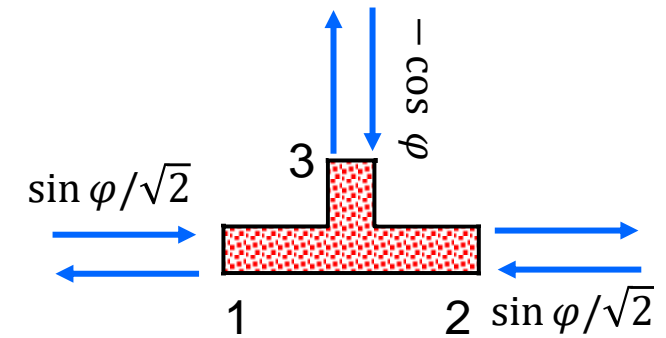
for $\varphi = \pi/2$:
$$\hat{s}_{BS} = \begin{pmatrix} -1/2 & 1/2 & 1/\sqrt{2} \\ 1/2 & -1/2 & 1/\sqrt{2} \\ 1/\sqrt{2} & 1/\sqrt{2} & 0 \end{pmatrix}$$

conductance matrix:
(for $\varphi = \pi/2$)

$$G_{\alpha\beta} = G_Q \begin{pmatrix} -3/4 & 1/4 & 1/2 \\ 1/4 & -3/4 & 1/2 \\ 1/2 & 1/2 & 1 \end{pmatrix}$$

example: $I_3 = G_Q V$, $I_1 = I_2 = -G_Q V/2$

T-type symmetric ideal beam splitter





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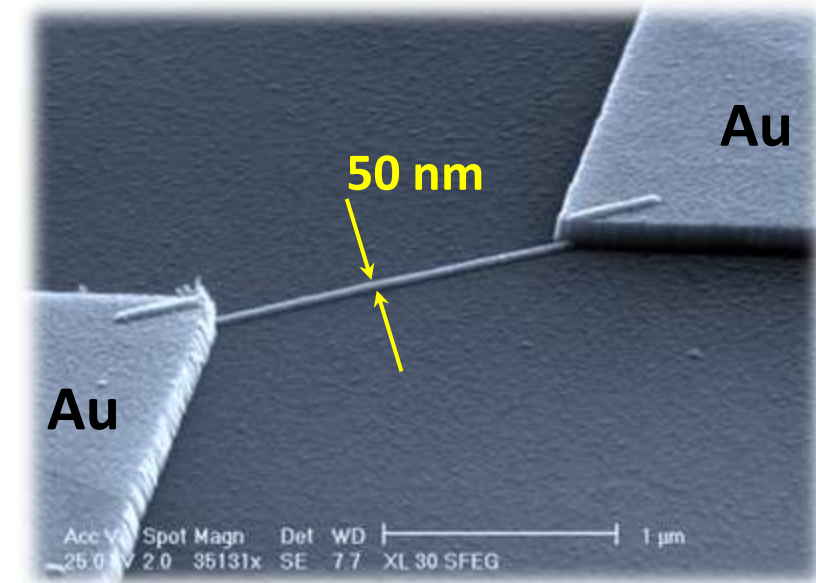
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Superconductivity and Low Temperature Physics II



Lecture No. 9

R. Gross

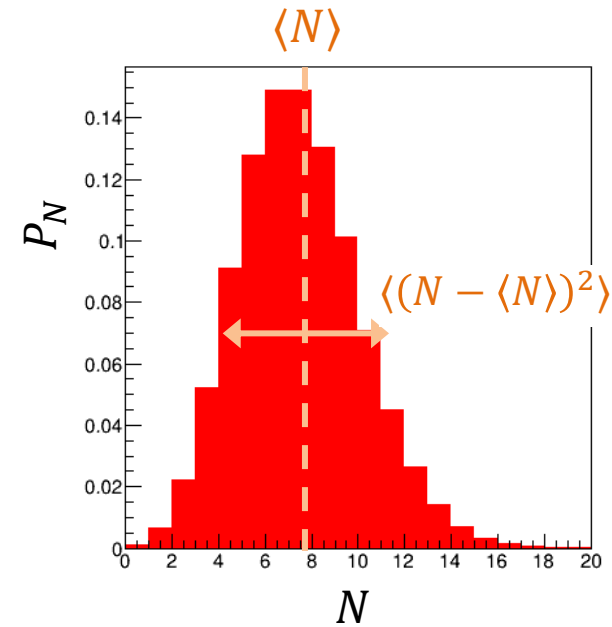
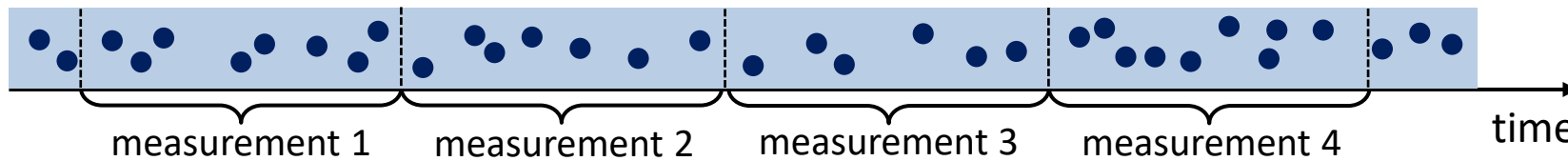
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II.2.4 Statistics of Charge Transport

- Landauer formalism: counting electrons

- electron transfer is a stochastic process

→ *measured number of electrons transferred in time interval Δt is random*



- **important aspects:**

- averaging allows to get rid of fluctuations of individual measurements
- study of statistics provides additional information on transport through nanostructure

- probability P_N to count N electrons: $\sum_N P_N = 1$ normalization of distribution

$$\langle N \rangle = \sum_N N P_N \quad \text{average number (1st cumulant)}$$

$$\langle (N - \langle N \rangle)^2 \rangle = \sum_N N^2 P_N - \left(\sum_N N P_N \right)^2 \quad \text{variance (2nd cumulant)}$$

II.2.4 Statistics of Charge Transport

- Moment generating function of a random variable N

$$M_N(t) = \langle e^{tN} \rangle = 1 + t\langle N \rangle + \frac{t^2}{2!} \langle N^2 \rangle + \frac{t^3}{3!} \langle N^3 \rangle + \dots$$

$$M_N(t) = \langle e^{tN} \rangle = 1 + m_1 t + m_2 \frac{t^2}{2!} + m_3 \frac{t^3}{3!} + \dots = 1 + \sum_{n=1}^{\infty} m_n \frac{t^n}{n!} = \exp\left(\sum_{n=1}^{\infty} \kappa_n \frac{t^n}{n!}\right) = \exp(K_N(t))$$

moments m_i

$$m_1 = \langle N \rangle$$

$$m_2 = \langle N^2 \rangle$$

$$m_3 = \langle N^3 \rangle$$

⋮

example: normal distribution $f(N) = \frac{1}{\sqrt{2\pi\sigma^2}} \exp\left(-\frac{(N-\mu)^2}{2\sigma^2}\right)$

$$M_N(t) = \exp\left(\mu t + \frac{1}{2}\sigma^2 t^2\right) \quad \mu = \langle N \rangle \text{ (mean value), } \sigma^2 = \langle (N - \langle N \rangle)^2 \rangle \text{ (variance)}$$

for a discrete probability density function: $M_N(t) = \langle e^{tN} \rangle = \sum_{n=0}^{\infty} P_n e^{tN_n}$

The moment-generating function of a real-valued random variable N is an alternative specification of its probability distribution P_N .

The moment-generating function can be used to compute a moments of a distribution.

k^{th} moment: differentiate expansion k -times with respect to t and evaluate result at $t = 0$

$$m_n = \left. \frac{\partial^n}{\partial t^n} M_N(t) \right|_{t=0}$$

example: 1st moment

$$\left. \frac{\partial}{\partial t} M_N(t) \right|_{t=0} = m_1 + m_2 t + \dots \Big|_{t=0} \stackrel{\text{}}{=} m_1 = \langle N \rangle$$

II.2.4 Statistics of Charge Transport

- cumulant generating function of a random variable N

$$K_N(t) = \ln M_N(t) = \ln \langle e^{tN} \rangle = \sum_{n=1}^{\infty} \kappa_n \frac{t^n}{n!} = \kappa_1 t + \kappa_2 \frac{t^2}{2} + \dots$$

$$K_N(t) = \langle e^{tN} \rangle = 1 + t\kappa_1 + \frac{t^2}{2!}\kappa_2 + \frac{t^3}{3!}\kappa_3 + \dots$$

cumulants κ_i

$$\kappa_1 = m_1 = \langle N \rangle \quad \text{average value}$$

$$\kappa_2 = m_2 - m_1^2 = \langle (N - \langle N \rangle)^2 \rangle \quad \text{variance}$$

$$\kappa_3 = m_3 - 3m_2m_1 + 2m_1^3 = \langle (N - \langle N \rangle)^3 \rangle \quad \text{skewness}$$

⋮

example: normal distribution $f(N) = \frac{1}{\sqrt{2\pi\sigma^2}} \exp\left(-\frac{(N-\mu)^2}{2\sigma^2}\right)$

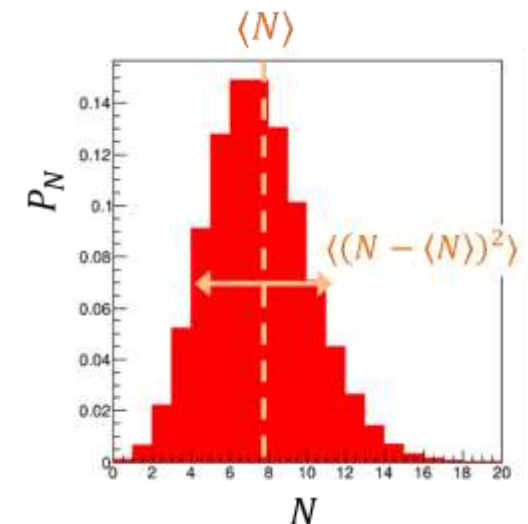
$$K_N(t) = \mu t + \frac{1}{2}\sigma^2 t^2 \quad \mu = \langle N \rangle \text{ (mean value)}, \quad \sigma^2 = \langle (N - \langle N \rangle)^2 \rangle \text{ (variance)}$$

k^{th} cumulant: differentiate expansion k -times with respect to t and evaluate result at $t = 0$

$$\kappa_n = \left. \frac{\partial^n}{\partial t^n} K_N(t) \right|_{t=0}$$

example: 1st cumulant

$$\left. \frac{\partial}{\partial t} K_N(t) \right|_{t=0} = \kappa_1 + \kappa_2 t + \dots \Big|_{t=0} \stackrel{\text{}}{=} \kappa_1 = \langle N \rangle$$



II.2.4 Statistics of Charge Transport

- characteristic function of a random variable N

$$H_N(t) = \ln \langle e^{itN} \rangle = \sum_{n=1}^{\infty} \kappa_n \frac{(it)^n}{n!} = \kappa_1 it - \kappa_2 \frac{t^2}{2} + \dots$$

cumulants κ_i

$$\kappa_1 = \mu = \langle N \rangle \quad \text{average value}$$

$$\kappa_2 = \sigma^2 = \langle (N - \langle N \rangle)^2 \rangle \quad \text{variance}$$

$$\kappa_3 = \langle (N - \langle N \rangle)^3 \rangle \quad \text{skewness}$$

example: normal distribution $f(N) = \frac{1}{\sqrt{2\pi\sigma^2}} \exp\left(-\frac{(N-\mu)^2}{2\sigma^2}\right)$

$$H_N(t) = i\mu t - \frac{1}{2}\sigma^2 t^2$$

for a discrete probability density function

$$\exp H_N(t) = \langle e^{itN} \rangle = \sum_{n=0}^{\infty} P_n e^{itN_n}$$

(Fourier transform of the probability density function)

k^{th} cumulant: differentiate expansion k -times with respect to it and evaluate result at $t = 0$

$$\kappa_n = \frac{1}{i^n} \frac{\partial^n}{\partial t^n} H_N(t) \Big|_{t=0}$$

example: 1st cumulant

$$\frac{1}{i} \frac{\partial}{\partial t} H_N(t) \Big|_{t=0} = \kappa_1 + i\kappa_2 t + \dots \Big|_{t=0} \stackrel{\text{}}{=} \kappa_1 = \langle N \rangle$$

II.2.4 Statistics of Charge Transport

- characteristic function (1)

- use of **characteristic function** $H_N(t) = \ln \langle e^{tN} \rangle = \ln \sum_{n=0}^{\infty} P_n e^{tn}$

($\langle e^{tN} \rangle$ = Fourier transform of the probability density function)

- application to statistics of electron transfer:

- we assume large measurement time Δt so that $\langle Q \rangle = \langle I \rangle \Delta t \gg e$
- we divide Δt into very small intervals dt so that $\langle Q \rangle = \langle I \rangle dt \ll e$
 - ➔ probability to transfer one electron within dt : $\Gamma dt \ll 1$ (Γ = transfer rate)
 - ➔ probability to transfer no electron within dt : $1 - \Gamma dt$
- we assume that all electrons move in the same direction
- we neglect probability to transfer two (or more) electrons within dt ($\mathcal{O}(\Gamma dt)^2$)

$$\langle e^{tN} \rangle_{N,dt} = \sum_N P_N e^{tN} = \underbrace{(1 - \Gamma dt)}_{N=0} + \underbrace{(\Gamma dt)e^{t}}_{N=1} + \dots = 1 + \underbrace{\Gamma dt(e^t - 1)}_{\ll 1} + \dots \simeq \exp[\Gamma dt(e^t - 1)]$$

$$\langle e^{tN} \rangle_{N,\Delta t} \stackrel{\text{independent events}}{\equiv} [\langle e^{tN} \rangle_{N,dt}]^{\Delta t/dt} = \{\exp[\Gamma dt(e^t - 1)]\}^{\Delta t/dt} = \exp\left[\underbrace{\Gamma \Delta t}_{=\bar{N}}(e^t - 1)\right] = \exp[\bar{N}(e^t - 1)]$$

characteristic function of Poisson distribution

$$M_N(t) = \langle e^{tN} \rangle = \sum_{n=0}^{\infty} P_n e^{tn}$$

$$P_N = \int_0^{2\pi} \frac{dt}{2\pi} \langle e^{tN} \rangle_{N,\Delta t} e^{-iNt} \simeq \int_0^{2\pi} \frac{dt}{2\pi} e^{[\bar{N}(e^{it}-1)]} e^{-iNt} = \frac{\bar{N}^N}{N!} e^{-\bar{N}\Delta t}$$

k^{th} cumulant: differentiate expansion k -times with respect to it and evaluate result at $t = 0$

$$\kappa_n = \frac{1}{i^n} \frac{\partial^n}{\partial t^n} H_N(t) \Big|_{t=0}$$

example: 1st cumulant

$$\frac{1}{i} \frac{\partial}{\partial t} H_N(t) \Big|_{t=0} = \kappa_1 + i\kappa_2 t + \dots \Big|_{t=0} \stackrel{\equiv}{=} \kappa_1 = \langle N \rangle$$

Poisson distribution

individual transfer processes are not correlated since $\Gamma dt \ll 1$

II.2.4 Statistics of Charge Transport

- characteristic function (2)

- opposite example: **ideally transmitting channel**

- since there is no scattering, the total momentum of all electrons does not change → **current does not fluctuate**

$$P_N = \delta(N - \bar{N}) \quad \Rightarrow \quad \langle e^{itN} \rangle = \sum_N P_N e^{itN} = e^{it(N - \bar{N})}$$

- intermediate case: $0 < T_p < 1$: ➤ the transmitted electrons are correlated, but not fully

- characteristic function is given by **Levitov formula**

L. S. Levitov and G. B. Lesovik,
JETP Lett. **58**, 230 (1993)

$$\ln \langle e^{itN} \rangle = 2 \Delta t \int \frac{d\varepsilon}{2\pi\hbar} \sum_p \ln \{ 1 + T_p (e^{it} - 1) f_l(\varepsilon) [1 - f_r(\varepsilon)] + T_p (e^{-it} - 1) f_r(\varepsilon) [1 - f_l(\varepsilon)] \}$$

note:

- the transfer processes from left to right and vice versa are correlated
- for $f_l(\varepsilon) = f_r(\varepsilon) = 1$, the total current is zero
 - ➔ if there are no correlations, this would result in current fluctuations
 - ➔ electrons moving left are blocked by electrons filling the state and vice versa

- limiting case: $k_B T \ll eV$: integral over energy gives eV

$$\ln \langle e^{itN} \rangle = \pm \frac{2eV\Delta t}{2\pi\hbar} \sum_p \ln \{ 1 + T_p (e^{\pm it} - 1) \}$$

± for different sign of voltage

II.2.4 Statistics of Charge Transport

- calculation of cumulants

- starting point is Levitov formula

$$\ln\langle e^{itN} \rangle = 2 \Delta t \int \frac{d\varepsilon}{2\pi\hbar} \sum_p \ln\{1 + T_p(e^{it} - 1) f_l(\varepsilon)[1 - f_r(\varepsilon)] + T_p(e^{-it} - 1) f_r(\varepsilon)[1 - f_l(\varepsilon)]\}$$

- **1st cumulant:** $\langle N \rangle = \left. \frac{\partial \ln\langle e^{itN} \rangle}{\partial(it)} \right|_{t=0} = \frac{2eV\Delta t}{2\pi\hbar} \sum_p \int d\varepsilon T_p(\varepsilon)[f_l(\varepsilon) - f_r(\varepsilon)]$

$$I = e \frac{\langle N \rangle}{\Delta t} = \frac{2eV}{2\pi\hbar} \sum_p \int d\varepsilon T_p(\varepsilon)[f_l(\varepsilon) - f_r(\varepsilon)] \quad \text{Landauer formula}$$

- **2nd cumulant:** $\langle (N - \langle N \rangle)^2 \rangle = \left. \frac{\partial^2 \ln\langle e^{itN} \rangle}{\partial(it)^2} \right|_{t=0}$

$$\langle (N - \langle N \rangle)^2 \rangle = \frac{2e\Delta t}{2\pi\hbar} \sum_p \int d\varepsilon \{ T_p(\varepsilon)[f_l(\varepsilon)(1 - f_l(\varepsilon)) + f_r(\varepsilon)(1 - f_r(\varepsilon))] + T_p(\varepsilon)(1 - T_p(\varepsilon))(f_l(\varepsilon) - f_r(\varepsilon))^2 \}$$

Case 1: equilibrium: $V = 0$ ($f_l(\varepsilon) = f_r(\varepsilon)$):

$I = 0$ for $f_l(\varepsilon) = f_r(\varepsilon)$

$$\langle (Q - \langle Q \rangle)^2 \rangle_{\text{eq}} = \underbrace{\frac{2e^2\Delta t}{2\pi\hbar}}_{=2G_Q\Delta t} k_B T \underbrace{\sum_p T_p}_{=1} = 2G_Q k_B T \Delta t$$

Nyquist-Johnson noise

II.2.4 Statistics of Charge Transport

- Nyquist-Johnson noise

- interpretation of result $\langle (Q - \langle Q \rangle)^2 \rangle_{\text{eq}} = 2G_Q k_B T \Delta t$

- if Δt is large enough, variance of the transmitted charge can be interpreted as zero-frequency current noise with $\Delta I = \Delta Q / \Delta t$ we obtain the current fluctuation $\Delta I^2 = \langle (Q - \langle Q \rangle)^2 \rangle_{\text{eq}} / \Delta t^2 = 2G_Q k_B T / \Delta t$

- with the current noise power spectral density $S_I(0) = \Delta I^2 / 2\Delta t = \frac{\Delta I^2}{\text{BW}}$, we obtain

$$S_I(0) = 4G_Q k_B T$$

Nyquist-Johnson noise

- **Wiener–Khinchin theorem:** relates the autocorrelation function $AC_I(\tau)$ to the power spectral density $S_I(\omega)$

$$AC_I(\tau) = \frac{1}{2\pi} \int_{-\infty}^{\infty} S_I(\omega) e^{i\omega\tau} d\omega$$

$$S_I(\omega) = \int_{-\infty}^{\infty} AC_I(\tau) e^{-i\omega\tau} d\tau = \int_{-\infty}^{\infty} d\tau e^{-i\omega\tau} \langle I(t)I(t + \tau) \rangle$$



$$AC_I(\tau) = \langle I(t) \hat{I}^*(t + \tau) \rangle = \lim_{\Delta t \rightarrow \infty} \int_{-\Delta t}^{+\Delta t} dt I(t) \hat{I}^*(t + \tau)$$

II.2.4 Statistics of Charge Transport

- shot noise

$$\langle (N - \langle N \rangle)^2 \rangle = \frac{2e\Delta t}{2\pi\hbar} \sum_p \int d\varepsilon \left\{ T_p(\varepsilon) [f_l(\varepsilon)(1 - f_l(\varepsilon)) + f_r(\varepsilon)(1 - f_r(\varepsilon))] + T_p(\varepsilon) (1 - T_p(\varepsilon)) (f_l(\varepsilon) - f_r(\varepsilon))^2 \right\}$$

Case 2: $eV \gg k_B T \rightarrow$ only 2nd term on rhs survives (we assume $T_p(\varepsilon) = \text{const.}$)

$$\langle (Q - \langle Q \rangle)^2 \rangle_{eV \gg k_B T} = 4eG_Q V \Delta t \sum_p T_p (1 - T_p)$$

with $S_I = \langle (Q - \langle Q \rangle)^2 \rangle_{\text{eq}} / \Delta t^2$

$$S_I(\omega) = 4eG_Q V \sum_p T_p (1 - T_p)$$

with $\langle I \rangle = 2G_Q V \sum_p T_p$

$$S_I(\omega) = 2e\langle I \rangle \left[\frac{\sum_p T_p (1 - T_p)}{\sum_p T_p} \right]$$

Schottky expression

$$F = 1$$

no correlations in transmission: Poisson process

Fano factor

$$0 \leq F \leq 1$$

takes into account correlations in the transmission processes

ideal quantum point contact:

only open ($T_p = 1$) or closed ($T_p = 0$) channels

\rightarrow no shot noise !

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- II.3.5 Universal Conductance Fluctuations

II.4 From Quantum Mechanics to Ohm's Law

II.5 Coulomb Blockade

II.3 Quantum Interference Effects

charge carriers are phase coherent if $L_\varphi > L$

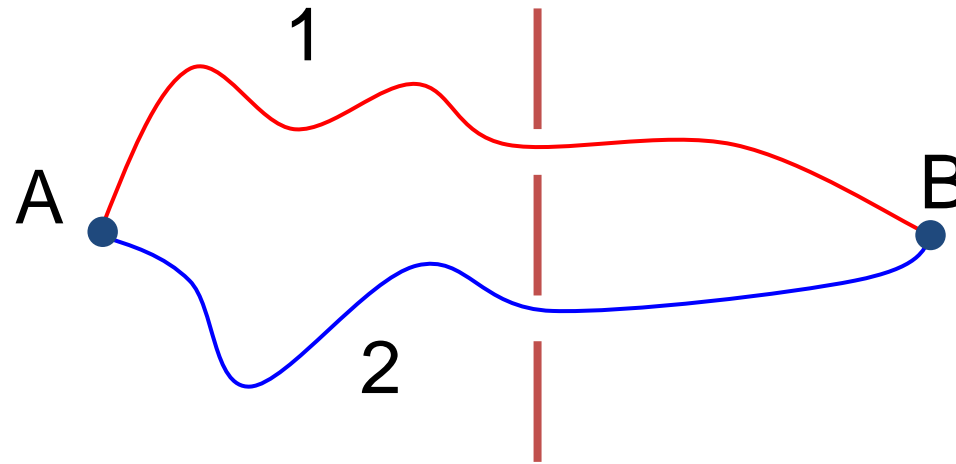
- low temperatures ($\rightarrow L_\varphi$ gets large), nanoscale samples (L gets small)
 - interference of multiply scattered charge carriers
 - *corrections to the classical conductance*

- *macroscopic and mesoscopic samples:*
 - weak localization (WL)*

- *mesoscopic samples:*
 - Aharonov-Bohm (AB) oscillations*
 - Universal Conductance Fluctuations (UCFs)*

II.3.1 Double Slit Experiment

- effect of quantum coherence: transmission through double slit



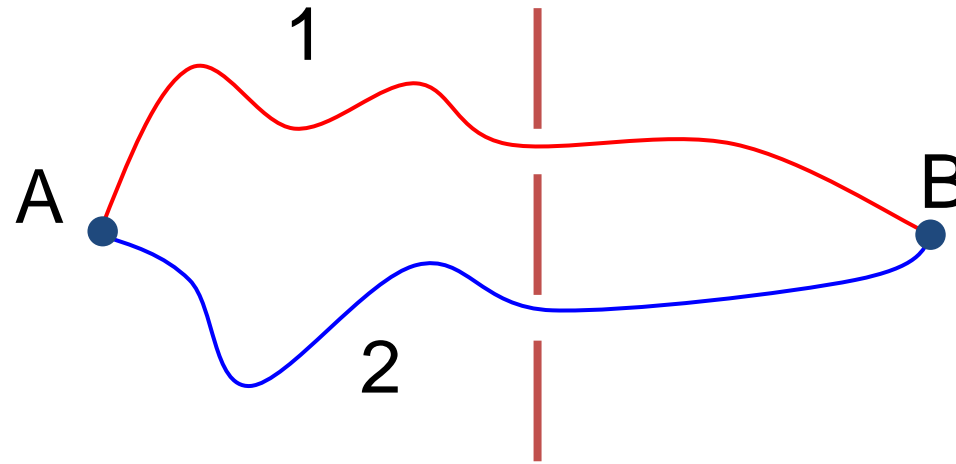
- basic quantum mechanics: *double slit experiment*
- probability of propagation from point A to point B:

$$P_{AB} = |A_1 + A_2|^2 = \underbrace{|A_1|^2}_{=P_1} + \underbrace{|A_2|^2}_{=P_2} + \underbrace{A_1 A_2^* + A_1^* A_2}_{2\text{Re}[A_1 A_2^*]}$$

classical result
interference term:
quantum mechanical

II.3.1 Double Slit Experiment

- effect of quantum coherence: transmission through double slit



$$P_{AB} = P_{\text{classical}} + 2\sqrt{P_1 P_2} \cos \varphi$$

interference terms may be **destructive** or **constructive**

→ depends on phase shift φ

$$P_1 = P_2: \quad P_{AB} = 2P + 2P \cos \varphi = 2P(1 + \cos \varphi)$$

problem:

calculate phase shift φ as a function of geometry, electric potential, magnetic field, ...

II.3.1 Double Slit Experiment

- phase shifts

- geometric phase:

definition: geometric phase = phase difference acquired when a system is subjected to cyclic adiabatic processes, which results from the geometrical properties of the parameter space of the Hamiltonian
 → geometric phase occurs when system parameters are changed very slowly (adiabatically), and eventually brought back to the initial configuration

example: in quantum mechanics, this could involve rotations but also translations of particles, which are apparently undone at the end

important:

one might expect that the waves in the system return to the initial state (characterized by amplitude and phase). However, if the parameter excursions correspond to a loop instead of a self-retracing back-and-forth variation, then it is possible that the initial and final states differ in their phases. This phase difference is the geometric phase, and its occurrence typically indicates that the system's parameter dependence is singular (its state is undefined) for some combination of parameters.

- we consider eigenstate $\psi(t_0) = |m[\mathbf{R}(t_0)]\rangle$ with energy $\varepsilon_m(t_0)$ and change system parameter \mathbf{R} adiabatically along path Γ

$$\gamma_m(t) = i \int_{t_0, \Gamma}^t \underbrace{\langle m[\mathbf{R}(t)] | \nabla_{\mathbf{R}} | m[\mathbf{R}(t)] \rangle}_{\mathbf{A}_m(\mathbf{R})} \cdot d\mathbf{R}$$

Mead–Berry Vector Potential

geometric phase or Berry phase

II.3.1 Double Slit Experiment

- phase shifts

- dynamical phase** (phase shift due to energy or potential):

we consider wave function of electron in semi-classical approximation

$$\psi(x) = \exp[i\varphi(x)] = \exp[ik(x)x] \implies \frac{d\varphi}{dx} = k(x) = \sqrt{2m[\varepsilon - V(x)]} / \hbar$$

local wave vector at position x

(i) $V(x) = \text{const.}$

$$\Delta\varphi = \int_A^B \frac{d\varphi}{dx} dx = \int_A^B k(x) dx = \varphi(B) - \varphi(A) \stackrel{V(x)=\text{const}}{=} kL$$

usually, absolute value of phase is not interesting, but the relative phase shift between different paths

(ii) $V(x) \neq \text{const.}$

$$\frac{d\varphi}{d\varepsilon} = \frac{d\varphi}{dk} \frac{dk}{d\varepsilon} \stackrel{v=\frac{1}{\hbar} \frac{d\varepsilon}{dk}}{=} \frac{d\varphi}{dk} \frac{1}{\hbar v(x)} = \int_A^B \frac{dx}{\hbar v(x)} = \int_{t_A}^{t_B} \frac{dt}{\hbar} = \frac{\tau}{\hbar}$$

time of flight between points A and B at energy ε

$$\Delta\varphi = \frac{d\varphi}{d\varepsilon} \Delta\varepsilon = \int_A^B \varepsilon(x) \frac{dx}{\hbar v(x)} \stackrel{V(x)=\text{const}}{=} \int_{t_A}^{t_B} \varepsilon(x(t)) \frac{dt}{\hbar} = \frac{\varepsilon}{\hbar} \tau$$

depends on the state's energy and the time it takes the system to propagate from A to B

II.3.1 Double Slit Experiment

- phase shifts

- Aharonov-Bohm phase (charged particle in magnetic field)

- canonical momentum: $\mathbf{p} = m\mathbf{v} + q\mathbf{A}$

$$\mathbf{k}(x) \rightarrow \mathbf{k}(x) - \underbrace{\frac{q}{\hbar}\mathbf{A}(x)}$$

results in phase shift φ_{mag} due to vector potential $\mathbf{A}(x)$

$$\varphi_{\text{mag}} = \frac{e}{\hbar} \int_A^B \mathbf{A} \cdot d\mathbf{x} = \frac{e}{\hbar} \int_{t_A}^{t_B} \mathbf{A} \cdot \mathbf{v}(t) dt \quad (q = -e)$$

opposite phase shift for time-reversed path

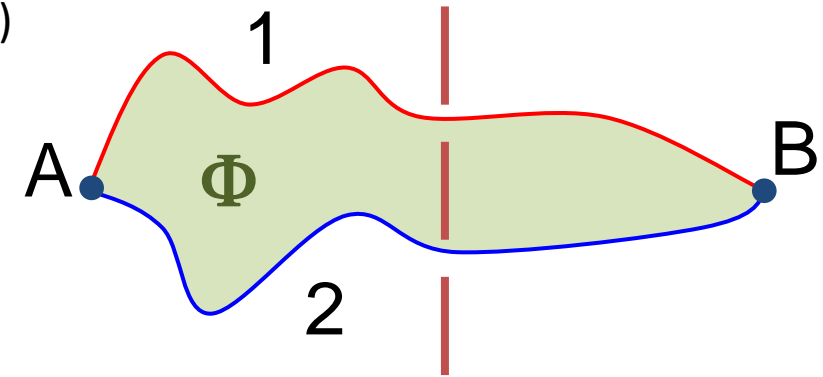
note: φ_{mag} depends on gauge $\mathbf{A} \rightarrow \mathbf{A} + \nabla\chi(x)$ and is therefore unphysical and not observable

- gauge invariant quantity is the phase accumulated along a closed path (electron returns to the same point):

Aharonov-Bohm phase

$$\varphi_{AB} = \frac{e}{\hbar} \oint \mathbf{A} \cdot d\mathbf{x} \stackrel{\text{Stokes theorem}}{=} \frac{e}{\hbar} \int \mathbf{B} \cdot d\mathbf{F} = 2\pi \frac{\Phi}{\Phi_0}$$

$\Phi_0 = \frac{h}{e}$ („normal“ flux quantum)
(in superconductors we have $q_s = -2e$ and therefore $\Phi_0 = h/2e$)



phase difference $\Delta\varphi = \varphi_1 - \varphi_2$ between 1 and 2 corresponds to φ_{AB} due to opposite sign of phase shift on time-reversed path

II.3.2 Double Tunnel Junction

- quantum interference effect in a double tunnel junction

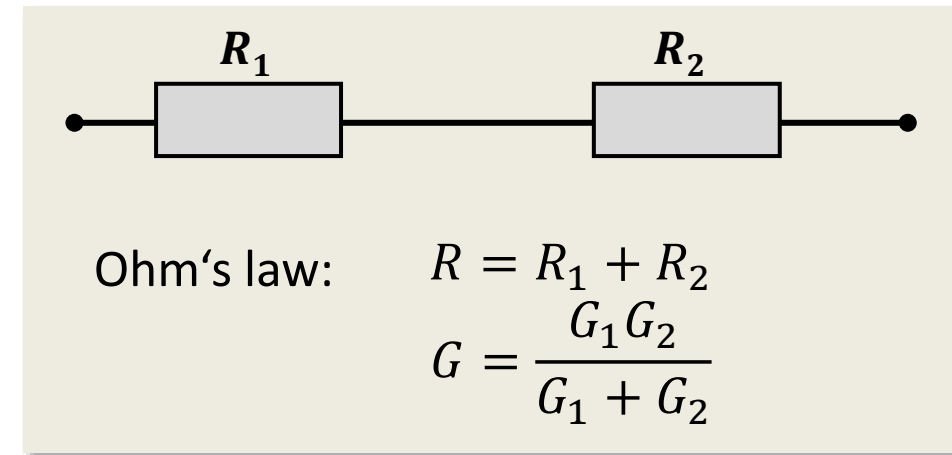
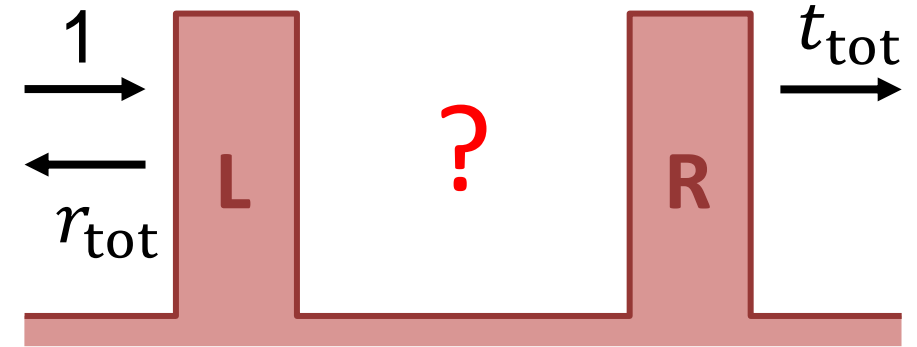
- we consider only a single conductance channel
- no magnetic field

- „classical“ expectation:

(tunneling) resistances are added

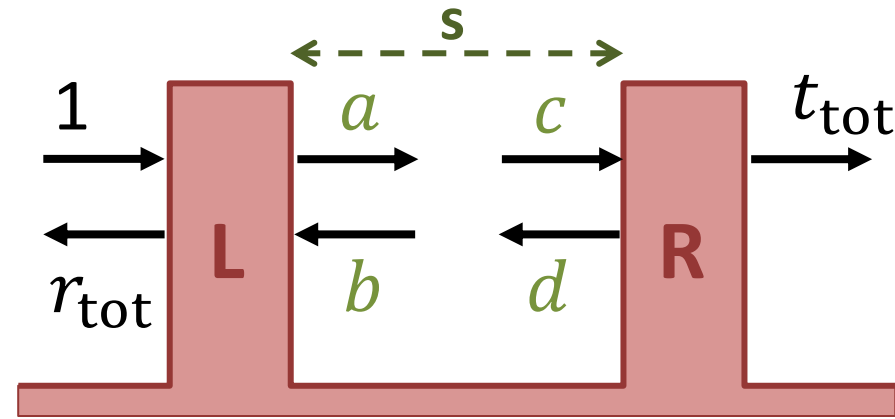
multiplication of transmission probabilities $T_L \cdot T_R$

- what is the role of **quantum interference**?
- how do individual *scattering matrices* have to be *combined*?



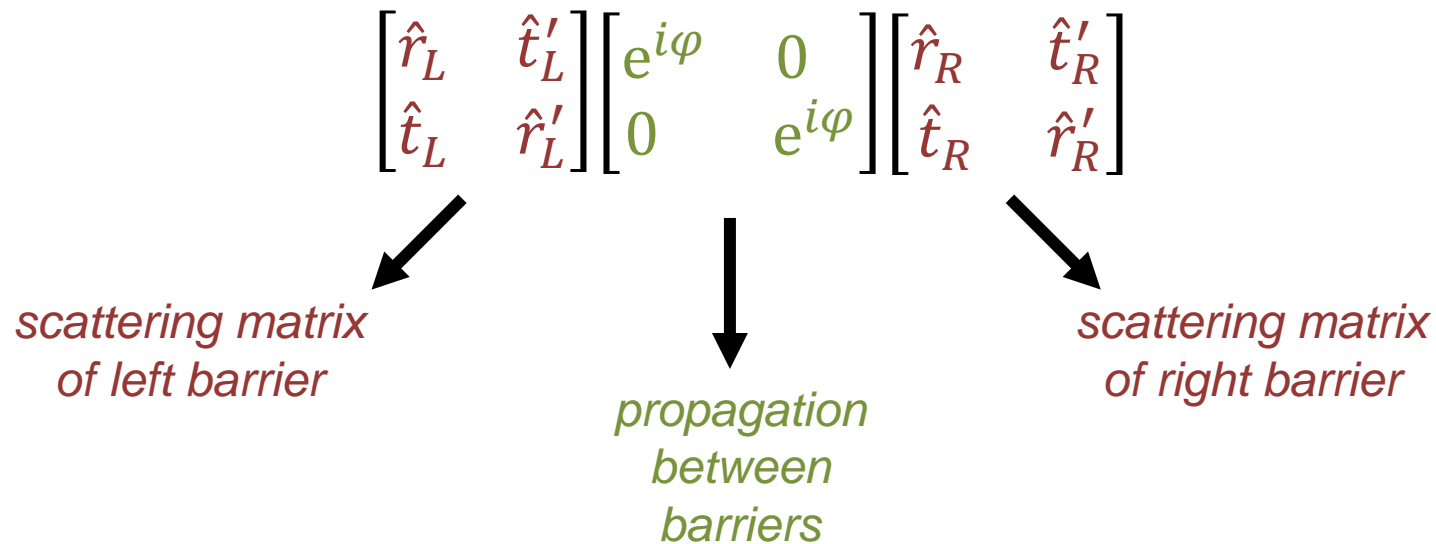
II.3.2 Double Tunnel Junction

- quantum interference effect in double tunnel junction



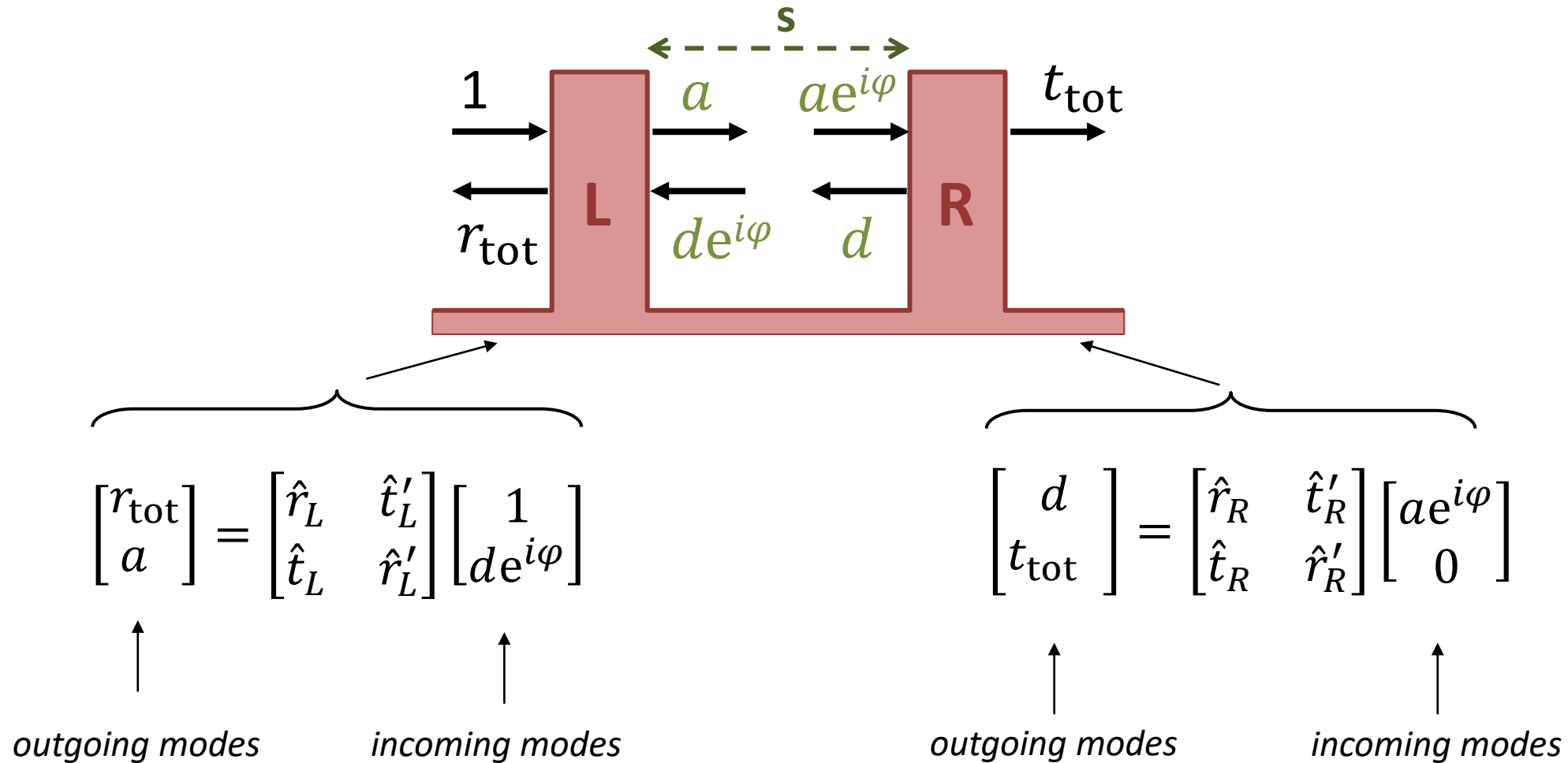
acquired phase during propagation between barriers

$$\varphi = k \cdot s$$



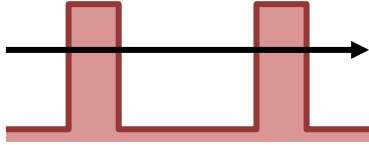
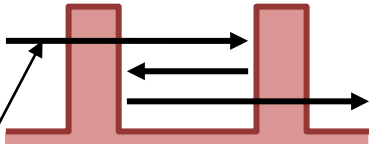
II.3.2 Double Tunnel Junction

- quantum interference effect in double tunnel junction



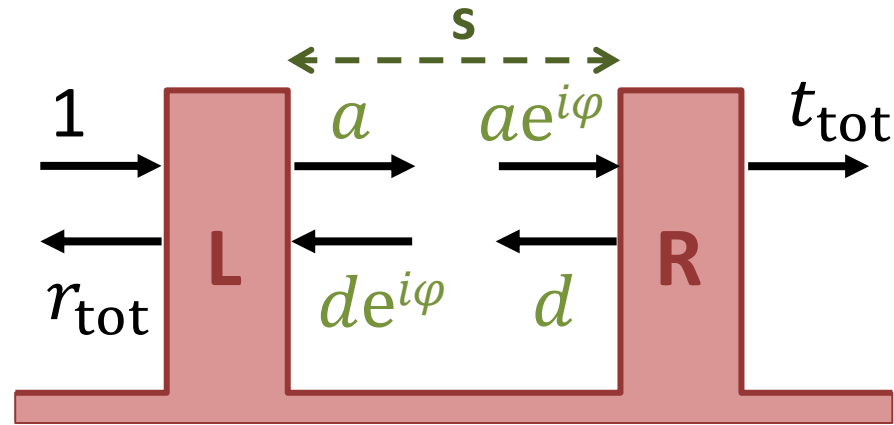
II.3.2 Double Tunnel Junction

- quantum interference effect in double tunnel junction

process	amplitude	probability
	$t_L t_R e^{i\varphi}$	$T_L T_R$
	$t_L t_R r'_L r_R e^{i3\varphi}$	$T_L T_R R_L R_R$
...
<p>path can be viewed as Feynman path</p>	sum of all amplitudes:	sum of all probabilities:
coherent	$t_{\text{tot}} = \frac{t_L t_R}{1 - r'_L r_R e^{i2\varphi}}$	$T_{\text{classical}} = \frac{T_L T_R}{1 - R_L R_R}$
	$T_{\text{tot}} = t_{\text{tot}} ^2$	incoherent
		<p>for $T_{L,R} \ll 1$:</p> $G_{\text{class}} = G_Q T_{\text{class}} = \frac{G_L G_R}{G_Q [1 - (1 - T_L)(1 - T_R)]}$ $G_{\text{class}} \simeq \frac{G_L G_R}{G_Q [T_L + T_R]} = \frac{G_L G_R}{G_L + G_R}$

II.3.2 Double Tunnel Junction

- quantum interference effect in double tunnel junction



$$t_{\text{tot}} = \frac{t_L t_R}{1 - r'_L r'_R e^{i2\phi}}$$

$$T_{\text{tot}}(\varepsilon) = |t_{\text{tot}}|^2 = \frac{T_L T_R}{1 + R_L R_R - 2\sqrt{R_L R_R} \cos \chi(\varepsilon)}$$

phase accumulated during the round trip

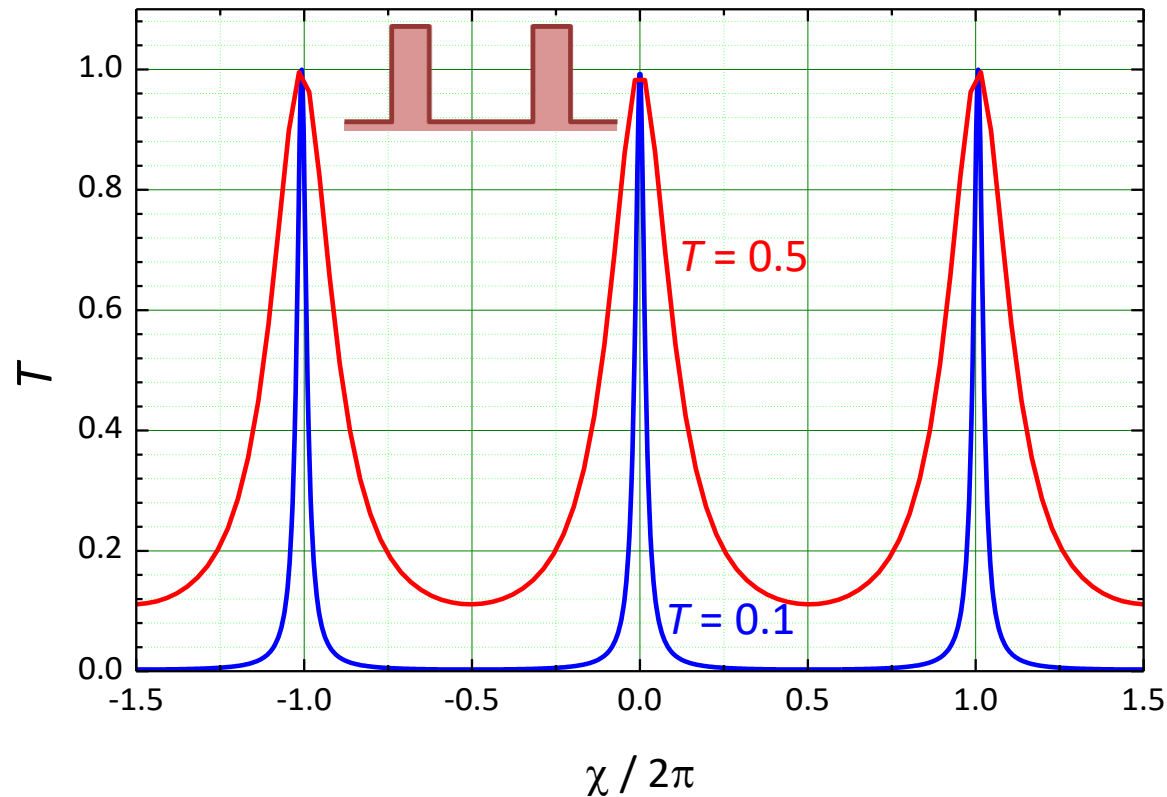
$$\chi(\varepsilon) = 2\phi(\varepsilon) = 2k(\varepsilon)s$$

$$k(\varepsilon) = \sqrt{\frac{2m\varepsilon}{\hbar^2}}$$

II.3.2 Double Tunnel Junction

- quantum interference effect in double tunnel junction

– transmission coefficient *depends on energy*



$$T_{\text{tot}}(\varepsilon) = |t_{\text{tot}}|^2 = \frac{T_L T_R}{1 + R_L R_R - 2\sqrt{R_L R_R} \cos[2k(\varepsilon)s]}$$

assume $T_L = T_R = T \ll 1$,
 $R_L = R_R = R \simeq 1$

between peaks: $T(\varepsilon) \approx T^2$

maximum value: $T_{\text{max}} = \frac{T_L T_R}{(1 - \sqrt{R_L R_R})^2} \simeq 1$ @ $\chi = n \cdot 2\pi$

maximum value: $T_{\text{min}} = \frac{T_L T_R}{(1 + \sqrt{R_L R_R})^2} \ll 1$ @ $\chi = (n + \frac{1}{2}) \cdot 2\pi$

→ **resonant tunneling**
 (or Fabry-Perot resonances)

- double barrier structure behaves as an **optical interferometer**
- resonant tunneling is **quantum interference effect**

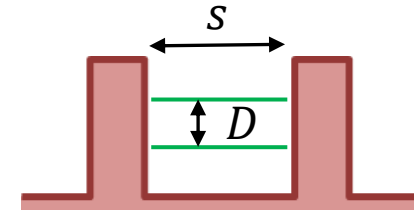
II.3.2 Double Tunnel Junction

- quantum interference effect in double tunnel junction

- how does the transmission $T(\varepsilon)$ look like close to the transmission resonances?

$$\cos \chi = \cos(2ks) \simeq 1 - \frac{1}{2} (2ks)^2 \quad \text{for } \chi \ll 1$$

$$\cos \chi \simeq 1 - \frac{\varepsilon - \varepsilon_{\text{res}}}{2D} \quad \text{with } (2ks)^2 = \frac{8ms^2(\varepsilon - \varepsilon_{\text{res}})}{\hbar^2} = \frac{\varepsilon - \varepsilon_{\text{res}}}{D}$$



D = level spacing in potential well of width s

- after some math:

$$T(\varepsilon) = \frac{T_L T_R}{\left(\frac{T_L + T_R}{2}\right)^2 + \left(\frac{\varepsilon - \varepsilon_{\text{res}}}{D}\right)^2}$$

transmission assumes Lorentzian shape

$$T(\varepsilon) = \frac{D^2 T_L T_R}{\left(\frac{D(T_L + T_R)}{2}\right)^2 + (\varepsilon - \varepsilon_{\text{res}})^2}$$

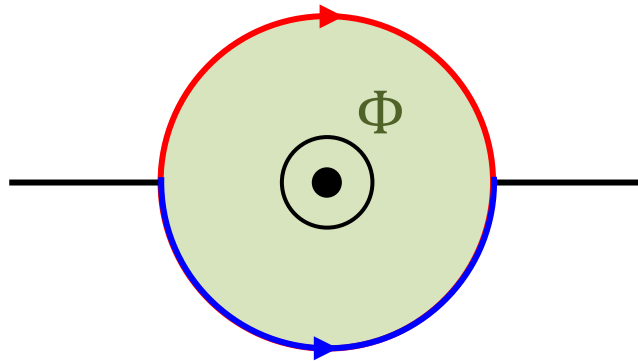
energy width of transmission resonance: $d = D (T_L + T_R)$

- interpretation in terms of a particle that moves back and forth between the two potential wells and escapes at a certain tunneling rates Γ_L and Γ_R
- with $d = \hbar(\Gamma_L + \Gamma_R)$ according to uncertainty relation we obtain well-known **Breit-Wigner formula**

II.3.3 Aharonov-Bohm Effect

- quantum interference effects in multiply connected conductors, e.g. rings
 - phase shift due to magnetic field

two trajectories enclosing magnetic flux



all quantities are periodic in Φ/Φ_0 , even if there is NO magnetic field at the trajectories!

accumulated phase with vector potential: $\mathbf{k}(x) \rightarrow \mathbf{k}(x) - \frac{q}{\hbar} \mathbf{A}(x)$

$$\varphi_{1,2} = kL_{1,2} + \frac{e}{\hbar} \int_{1,2} \mathbf{A} \cdot d\mathbf{x} \quad (q = -e)$$

$$\varphi_2 - \varphi_1 = k(L_2 - L_1) + \frac{e}{\hbar} \oint \mathbf{A} \cdot d\mathbf{x}$$

$$\varphi_{AB} = \frac{e}{\hbar} \oint \mathbf{A} \cdot d\mathbf{x} \stackrel{\substack{\text{Stokes} \\ \text{theorem}}}{=} \frac{e}{\hbar} \int \mathbf{B} \cdot d\mathbf{F} = 2\pi \frac{\Phi}{\Phi_0}$$

$$\Phi_0 = \frac{h}{e} \quad (\text{„normal“ flux quantum})$$

(in superconductors we have $q_s = -2e$ and therefore $\Phi_0 = h/2e$)

II.3.3 Aharonov-Bohm Effect

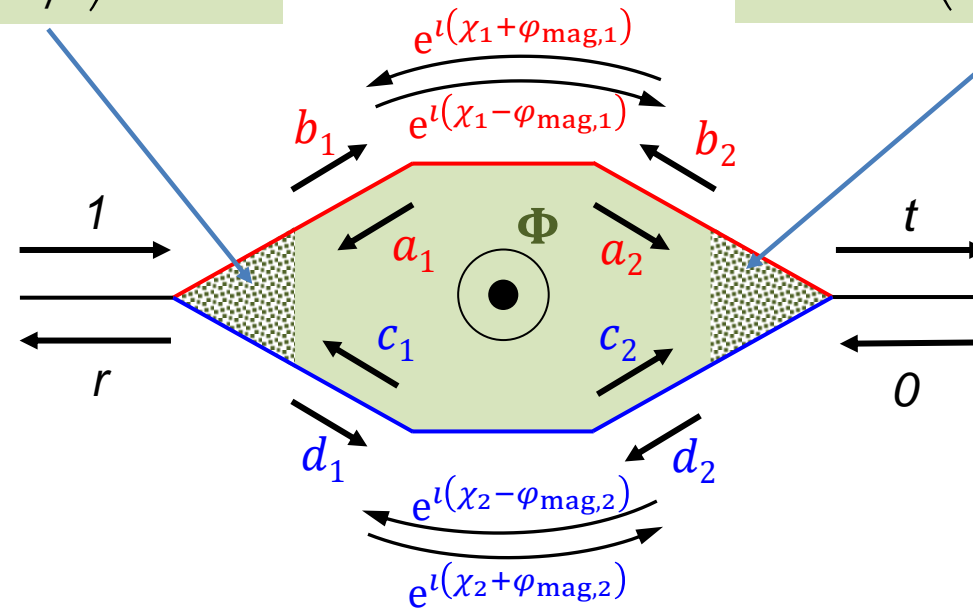
- description of Aharonov-Bohm ring by two beam splitters and loop

$$\begin{pmatrix} r \\ b_1 \\ d_1 \end{pmatrix} = \begin{pmatrix} 0 & 1/\sqrt{2} & 1/\sqrt{2} \\ 1/\sqrt{2} & -1/2 & 1/2 \\ 1/\sqrt{2} & 1/2 & -1/2 \end{pmatrix} \begin{pmatrix} 1 \\ a_1 \\ c_1 \end{pmatrix}$$

left beam splitter

$$\begin{pmatrix} t \\ b_2 \\ d_2 \end{pmatrix} = \begin{pmatrix} 0 & 1/\sqrt{2} & 1/\sqrt{2} \\ 1/\sqrt{2} & -1/2 & 1/2 \\ 1/\sqrt{2} & 1/2 & -1/2 \end{pmatrix} \begin{pmatrix} 0 \\ a_2 \\ c_2 \end{pmatrix}$$

right beam splitter



dynamical phase:

$$\chi_{1,2} = kL_{1,2}$$

magnetic phase:

$$\varphi_{\text{mag},1} + \varphi_{\text{mag},2} = \varphi_{\text{AB}} = 2\pi \frac{\Phi}{\Phi_0}$$

$$\begin{pmatrix} 0 & e^{i(\chi_1 + \varphi_{\text{mag},1})} \\ e^{i(\chi_1 - \varphi_{\text{mag},1})} & 0 \end{pmatrix}$$

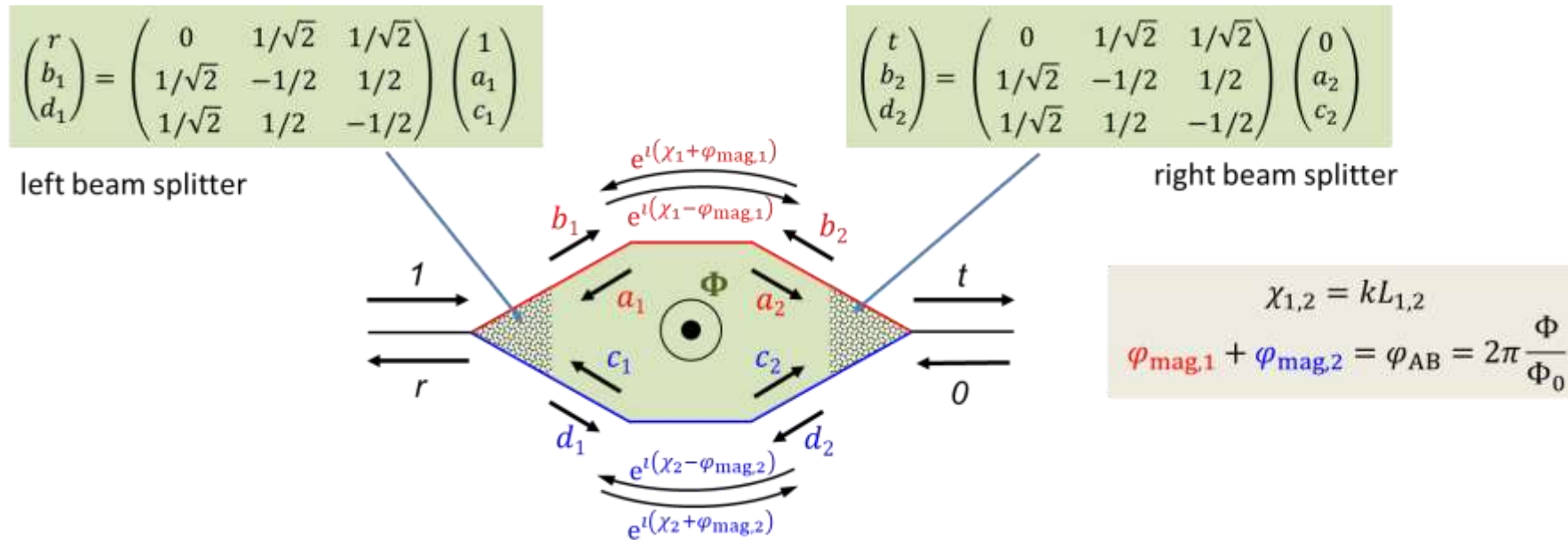
upper arm (1)

$$\begin{pmatrix} 0 & e^{i(\chi_2 - \varphi_{\text{mag},2})} \\ e^{i(\chi_2 + \varphi_{\text{mag},2})} & 0 \end{pmatrix}$$

lower arm (2)

II.3.3 Aharonov-Bohm Effect

- description of Aharonov-Bohm ring by two beam splitters and loop



- **example 1:** electron enters from left, takes lower path and goes out to the right:

$$t_1 = \frac{1}{\sqrt{2}} e^{i(\chi_2 + \varphi_{\text{mag},2})} \frac{1}{\sqrt{2}} = \frac{1}{2} e^{i(\chi_2 + \varphi_{\text{mag},2})}$$

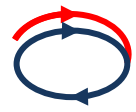
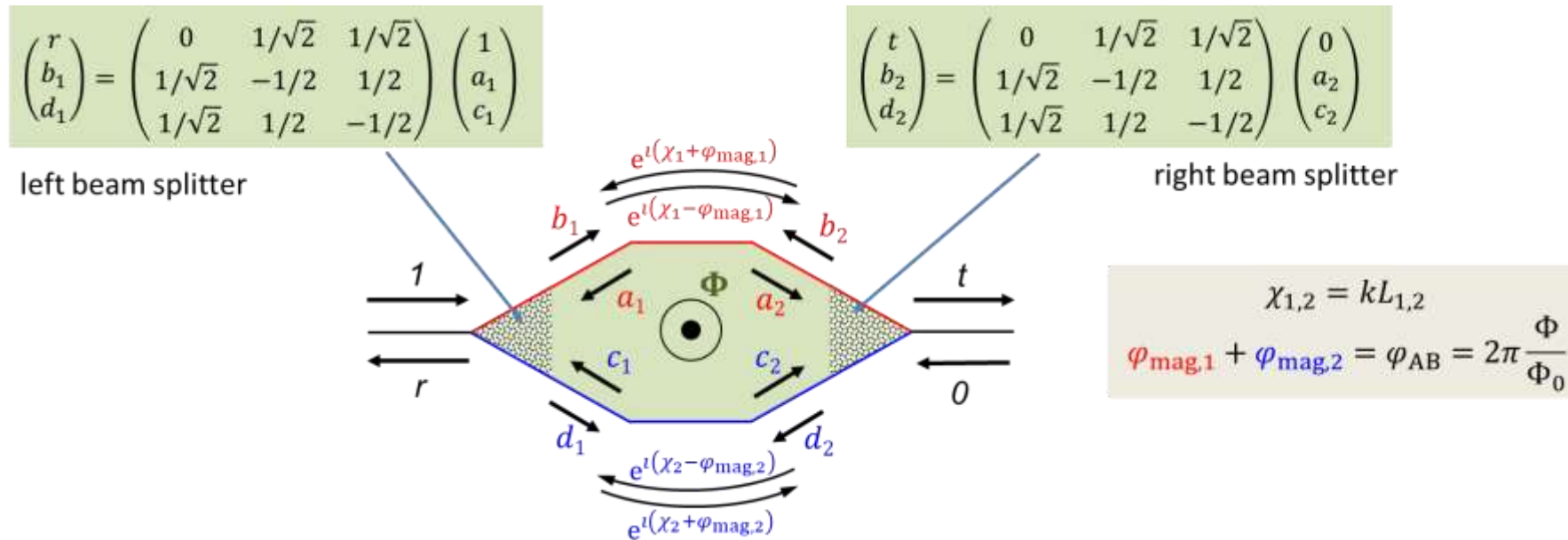
- **example 2:** electron enters from left, takes upper path and goes out to the right:

$$t_2 = \frac{1}{\sqrt{2}} e^{i(\chi_1 - \varphi_{\text{mag},1})} \frac{1}{\sqrt{2}} = \frac{1}{2} e^{i(\chi_1 - \varphi_{\text{mag},1})}$$

➔ phase difference in two paths: $\chi_2 - \chi_1 + \varphi_{\text{mag},2} + \varphi_{\text{mag},1} = \chi_2 - \chi_1 + \varphi_{\text{AB}}$ (depends on dynamical phases χ_2, χ_1)

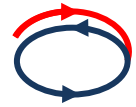
II.3.3 Aharonov-Bohm Effect

- description of Aharonov-Bohm ring by two beam splitters and loop



- **example 3:** electron takes upper path + full clockwise turn:

$$t_3 = \frac{1}{\sqrt{2}} e^{i(\chi_1 - \varphi_{mag,1})} \frac{1}{2} e^{i(\chi_2 - \varphi_{mag,2})} \frac{1}{2} e^{i(\chi_1 - \varphi_{mag,1})} \frac{1}{\sqrt{2}} = \frac{1}{8} e^{i(2\chi_1 + \chi_2 - 2\varphi_{mag,1} - \varphi_{mag,2})}$$



- **example 4:** electron takes upper path + full counter-clockwise turn (time-reversed path):

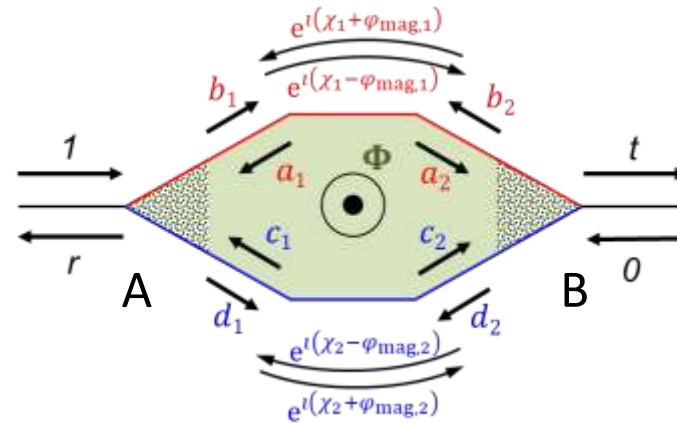
$$t_4 = \frac{1}{\sqrt{2}} e^{i(\chi_1 - \varphi_{mag,1})} \left(-\frac{1}{2}\right) e^{i(\chi_1 + \varphi_{mag,1})} \frac{1}{2} e^{i(\chi_2 + \varphi_{mag,2})} \frac{1}{\sqrt{2}} = -\frac{1}{8} e^{i(2\chi_1 + \chi_2 + \varphi_{mag,2})}$$

➔ phase difference in two paths: $2\varphi_{mag,2} + 2\varphi_{mag,1} = 2\varphi_{AB}$ (independent of dynamical phases χ_2, χ_1)

II.3.3 Aharonov-Bohm Effect

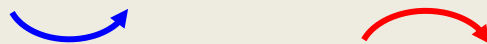
- description of Aharonov-Bohm ring by two beam splitters and loop

$$P_{AB} = P_{\text{classical}} + 2\sqrt{P_1 P_2} \cos \Delta\varphi$$



$$\chi_{1,2} = kL_{1,2}$$

$$\varphi_{\text{mag},1} + \varphi_{\text{mag},2} = \varphi_{AB} = 2\pi \frac{\Phi}{\Phi_0}$$



$$\Delta\varphi = \chi_2 - \chi_1 + \varphi_{AB}$$

$$P_{AB} \propto \cos(\chi_2 - \chi_1 + \varphi_{AB})$$

universal conductance fluctuations

- P_{AB} depends on dynamical phases
- configuration of scattering sites matters
- removed by ensemble averaging
- $\cos(2\pi \Phi/\Phi_0)$: flux period $\Phi_0 = h/e$



$$\Delta\varphi = 2\varphi_{AB}$$

$$P_{AB} \propto \cos(2\varphi_{AB})$$

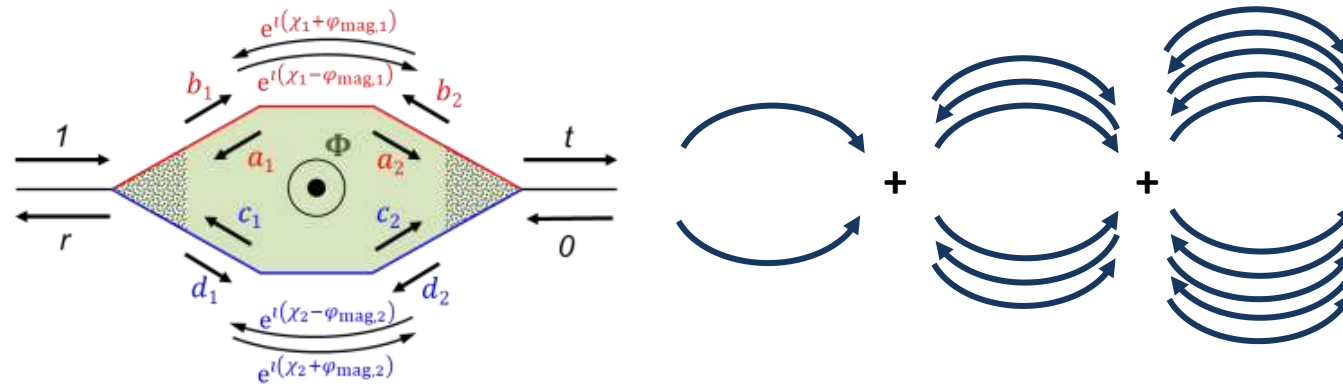
Altshuler-Aronov-Spivak oscillations

- P_{AB} independent of dynamical phases
- configuration of scattering sites does not matter
- survives ensemble averaging
- $\cos(4\pi \Phi/\Phi_0)$: flux period $\Phi_0/2 = h/2e$

+ many other trajectories

II.3.3 Aharonov-Bohm Effect

- description of Aharonov-Bohm ring by two beam splitters and a loop
 - summing up (without closed loops):



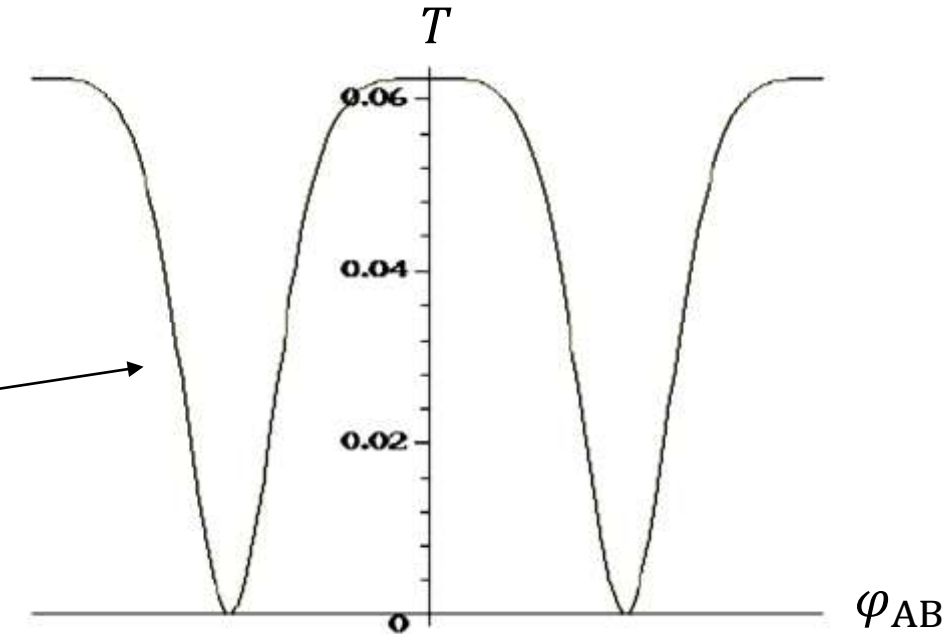
$$\chi_1 = \chi_2 = \chi = kL_{1,2} = kL$$

$$\varphi_{mag,1} = \varphi_{mag,2} = \varphi_{mag}$$

$$\varphi_{mag,1} + \varphi_{mag,2} = \varphi_{AB} = 2\pi \frac{\Phi}{\Phi_0}$$

$$T = \frac{(1 - \cos 2\chi)(1 + \cos^2 \varphi_{AB})}{\sin^2 2\chi + \left[\cos 2\chi - \frac{1}{2}(1 + \cos \varphi_{AB}) \right]^2}$$

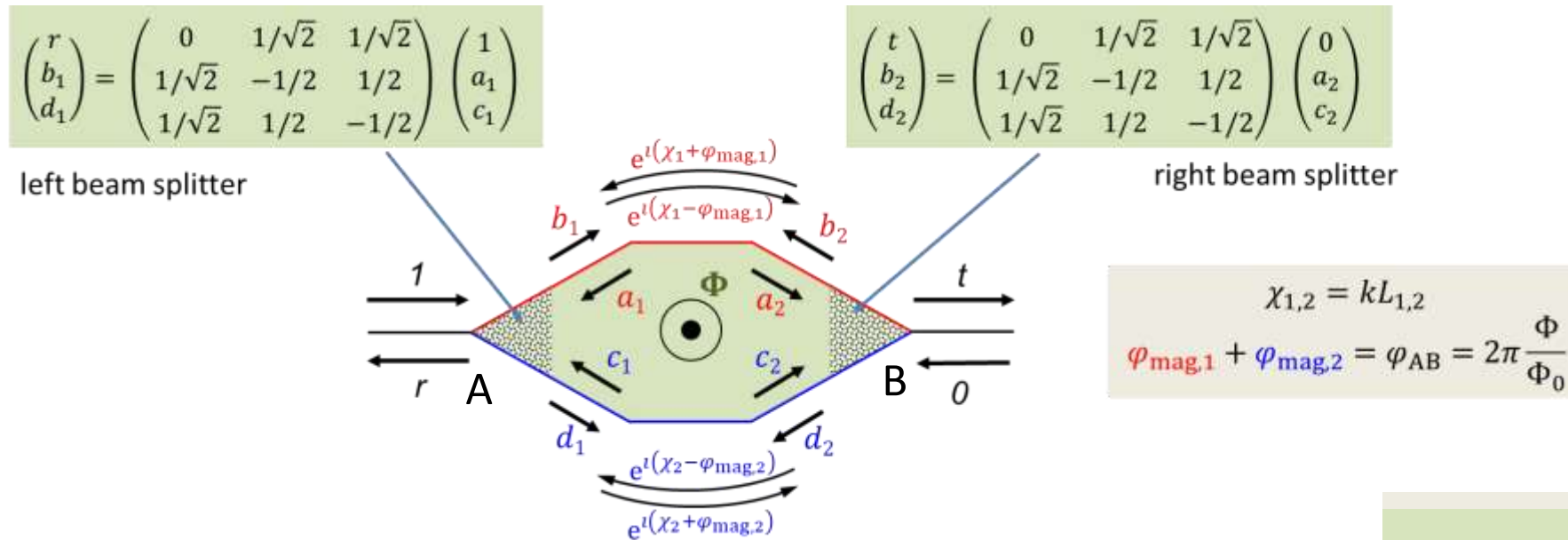
$$2\chi = \frac{\pi}{4} \Rightarrow T = \frac{(1 + \cos^2 \varphi_{AB})}{1 + \frac{1}{4}[1 - \cos \varphi_{AB}]^2}$$



Aharonov-Bohm effect: flux dependent transmission

II.3.4 Weak Localization

- description of Aharonov-Bohm ring by two beam splitters and a loop



R. Gross © Walther-Meißner-Institut (2004 - 2024)



➤ **example 5:** electron takes full clockwise turn:

$$r_3 = \frac{1}{\sqrt{2}} e^{i(\chi_1 - \varphi_{mag,1})} \frac{1}{2} e^{i(\chi_2 - \varphi_{mag,2})} \frac{1}{\sqrt{2}} = \frac{1}{4} e^{i(\chi_1 + \chi_2 - \varphi_{mag,1} - \varphi_{mag,2})}$$



➤ **example 6:** electron takes full counter-clockwise turn (time-reversed path):

$$r_4 = \frac{1}{\sqrt{2}} e^{i(\chi_2 + \varphi_{mag,2})} \frac{1}{2} e^{i(\chi_1 + \varphi_{mag,1})} \frac{1}{\sqrt{2}} = \frac{1}{4} e^{i(\chi_1 + \chi_2 + \varphi_{mag,1} + \varphi_{mag,2})}$$

$$P_{AA} \propto \cos \Delta\varphi \propto \cos \left(4\pi \frac{\Phi}{\Phi_0} \right)$$

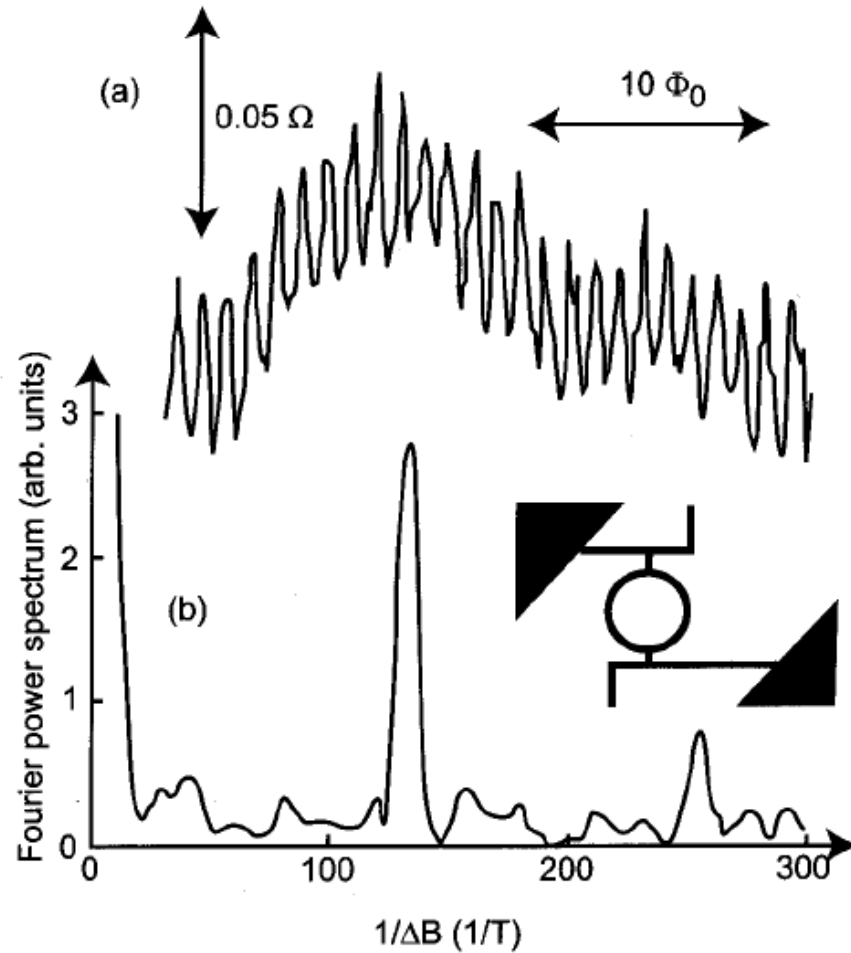
@ $B = 0$: enhanced back-scattering due to time-reversed paths

➔ **weak localization**

➔ phase difference in two paths: $2\varphi_{mag,2} + 2\varphi_{mag,1} = 2\varphi_{AB}$ (independent of dynamical phases χ_2, χ_1)

II.3.3 Aharonov-Bohm Effect

- Aharonov-Bohm effect: experiments



R. Webb et al, PRL **54**, 2696 (1985)

Aharonov-Bohm (AB) oscillations:

- period: $\Phi = \Phi_0 = h/e$
- amplitude: $G_Q = 2e^2/h$
- one channel in Landauer model

Fourier analysis shows that there are also weak oscillations with half period

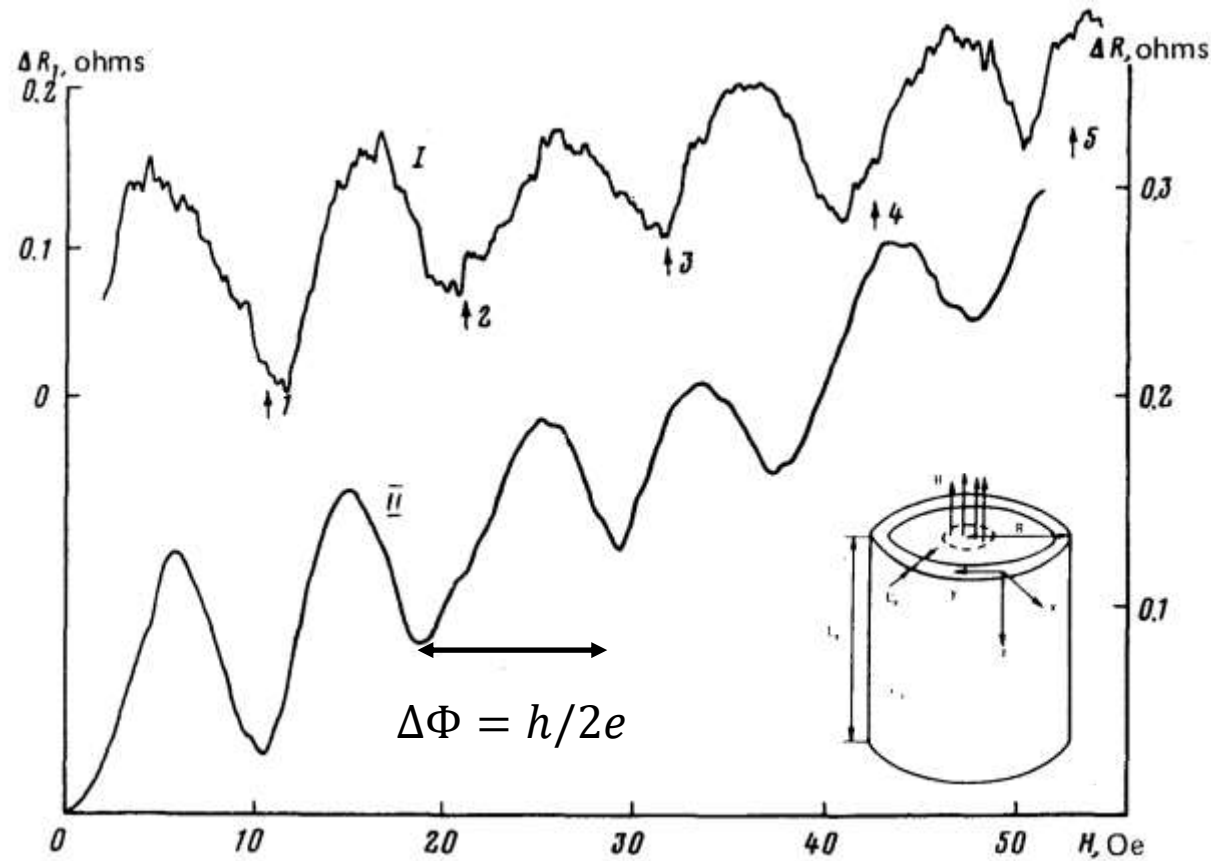
→ higher order interferences:

Altshuler-Aronov-Spivak (AAS) oscillations

- period: $\Phi = \Phi_0/2 = h/2e$
- Interference of time-reversed traces
- constructive interference for $B = 0$
- coherent backscattering

II.3.3 Aharonov-Bohm Effect

- Aharonov-Bohm effect: experiments

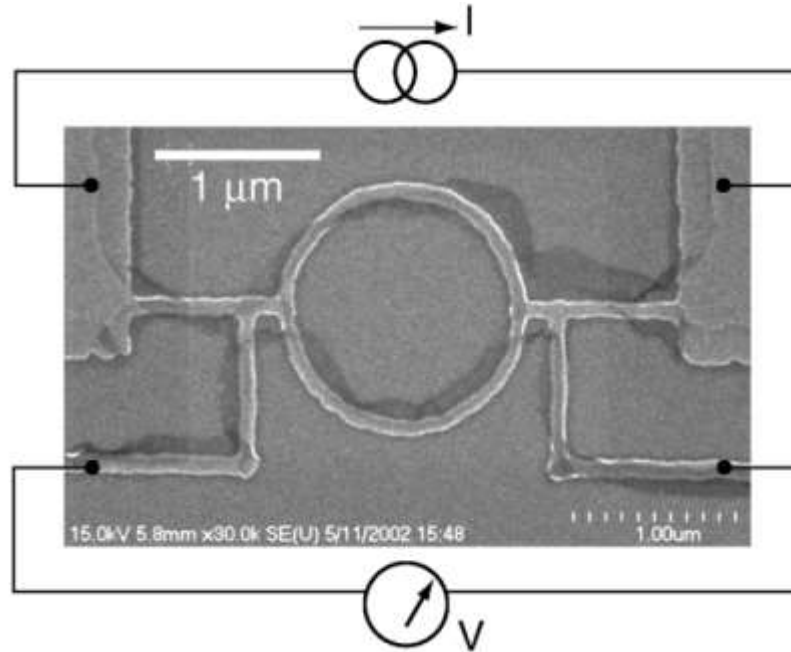


Aharonov-Bohm like magneto-conductance oscillations (*Altshuler-Aronov-Spivak (AAS) oscillations*) observed in normally conducting Mg cylinders of diameter $1.5 \mu\text{m}$. Left and right resistance scales correspond to samples 1 and 2, respectively. The periodicity of the oscillations corresponds to $\Delta\Phi = h/2e$.

D.Y. Sharvin, Y.V. Sharvin, *Sov. Phys. JETP Lett.* **34**, 272 (1981).

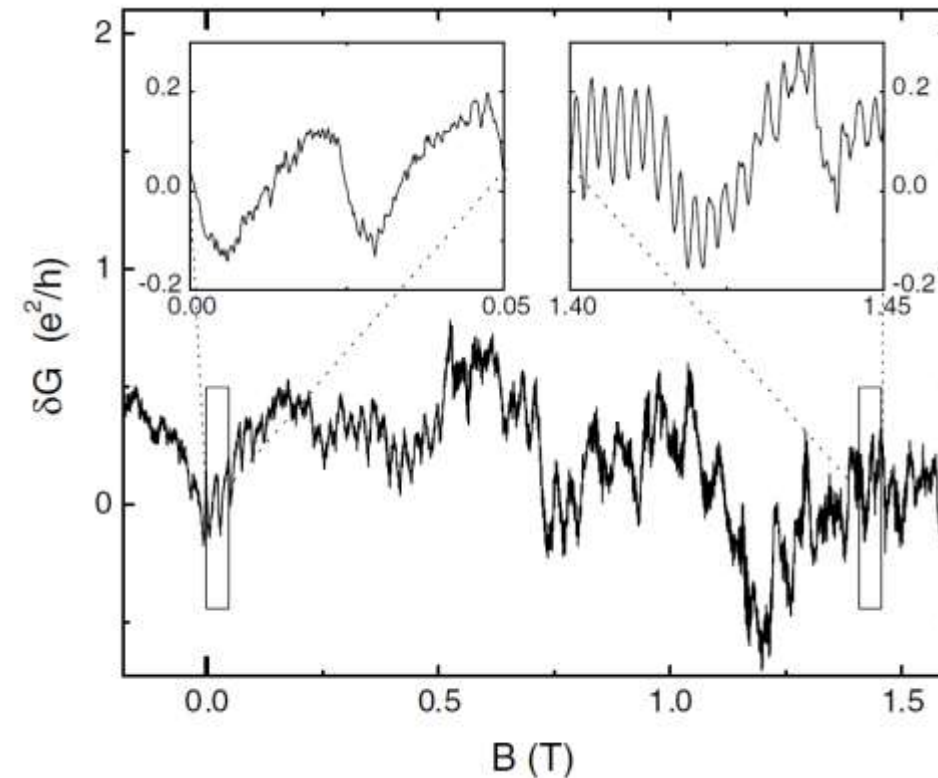
II.3.3 Aharonov-Bohm Effect

- Aharonov-Bohm effect: experiments



- conductance of a Cu ring in units of $G_Q = e^2/h$, as a function of magnetic field at $T = 100$ mK.
- narrow AB oscillations $\Delta B \approx 2.5$ mT are superimposed on larger and broader *universal conductance fluctuations*.

Cu ring on Si, width 80 nm

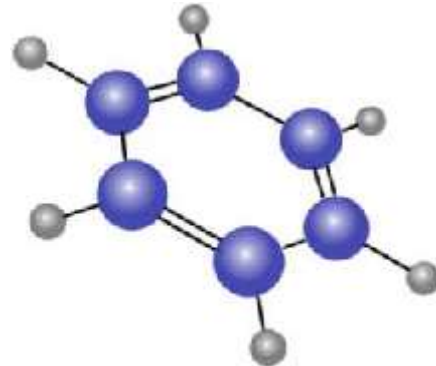


F. Pierre et. al., PRL **89**, 206804 (2002)

II.3.3 Aharonov-Bohm Effect

- Aharonov-Bohm effect: experiments

Benzene ring



0.5 nm

10^{13}

Large Electron Positron Collider at CERN (Geneva)



ring accelerator

AB effect: one flux quantum (h/e) through ring area:

$$\frac{h/e}{\pi r^2} = 5000 T$$

$$\frac{h/e}{\pi r^2} = 7 \times 10^{-23} T$$



Walther
Meißner
Institut

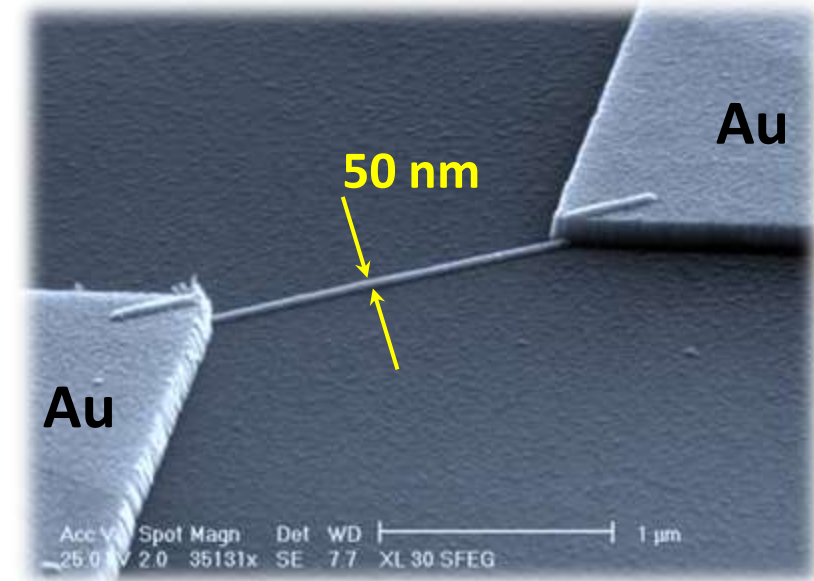
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München

TUM

Superconductivity and Low Temperature Physics II



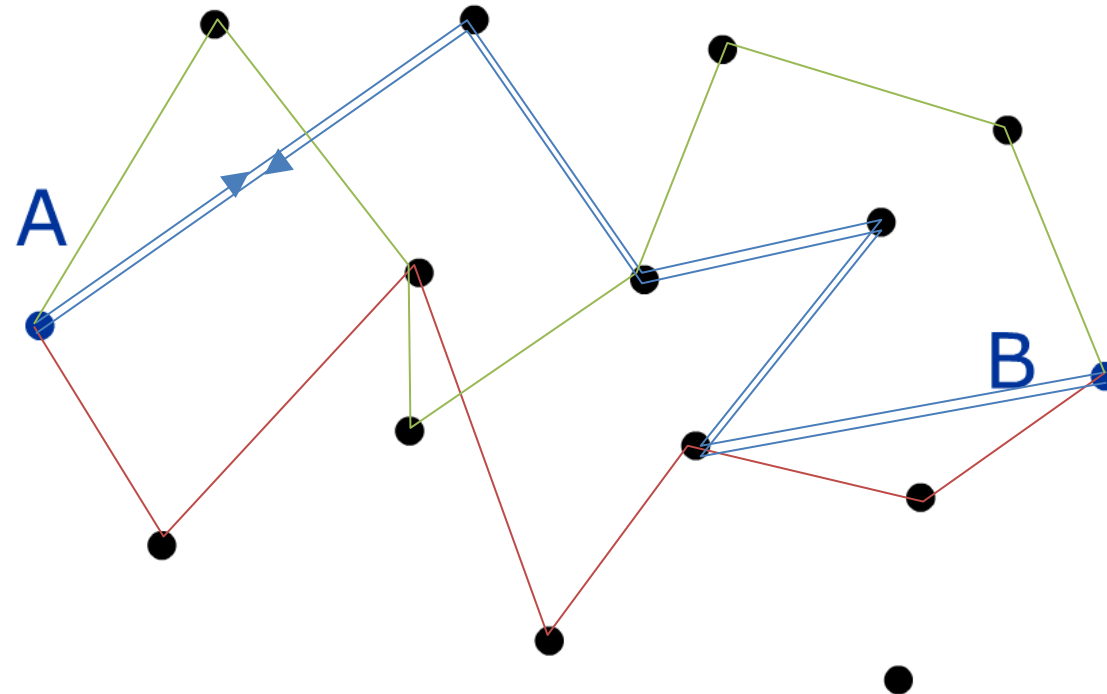
Lecture No. 10

R. Gross

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Weak localization:

interference of time reversed electron paths



II.3.4 Weak Localization

- quantum interference of time-reversed trajectories

$$P_{AB} = |A_1 + A_2|^2 = \underbrace{|A_1|^2}_{=P_1} + \underbrace{|A_2|^2}_{=P_2} + \underbrace{A_1 A_2^* + A_1^* A_2}_{2\text{Re}[A_1 A_2^*]}$$

classical result
interference term: quantum mechanical

$2|A_1 A_2| \cos \Delta\phi$
 $\langle \cos \Delta\phi \rangle = 0 \text{ !?}$

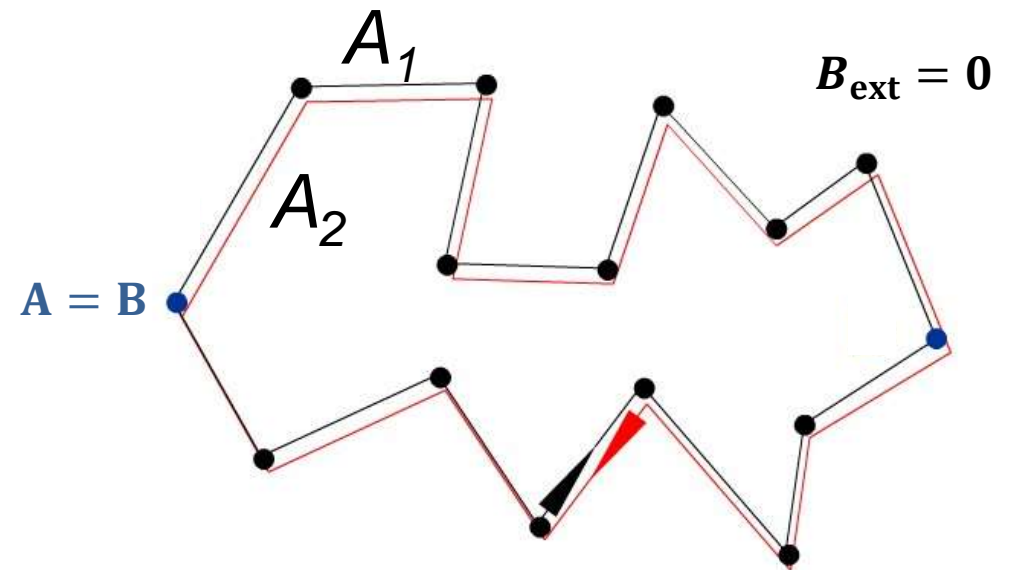
does averaging over many paths destroy interference effects in diffusive conductor?

time-reversed trajectories:

we consider a closed loop with $A = B$

→ the amplitude A_2 is just a time reversal of A_1

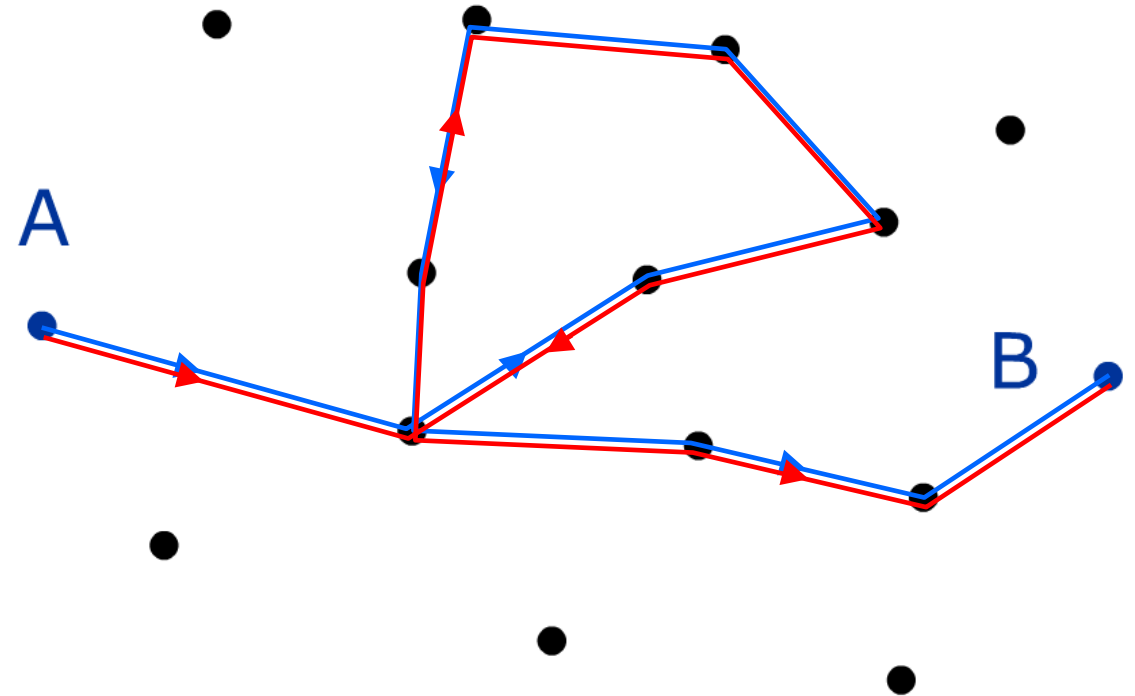
$$|A_1 + A_2|^2 = |A_1 + A_1^*|^2 = 4 |A_1|^2$$



- the backscattering probability is enhanced by factor **2** for all time-reversed paths!!!
- this is a predecessor of **localization**

II.3.4 Weak Localization

- quantum interference of time-reversed trajectories
 - increased backscattering probability to original position makes **self-intersecting scattering paths** important
 - interference effects make it more likely that a charge carrier is doing closed paths than without any interference
 - **increased net resistivity**
 - applied magnetic field reduces backscattering probability
 - **decrease of resistivity with increasing field**



II.3.4 Weak Localization

- magnetic field dependence of weak localization

- calculate phase difference of time reversed paths:

$$\varphi_{\text{mag},A_2} - \varphi_{\text{mag},A_1} = \frac{2e}{h} \oint \mathbf{A} \cdot d\mathbf{s} = 2\varphi_{AB}$$

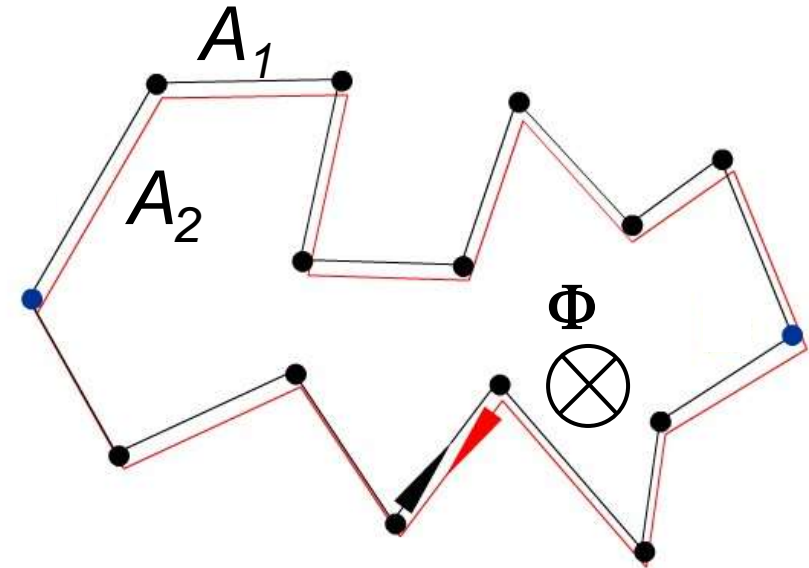
- loss of constructive interference due to additional φ_{AB}

$$\varphi_{\text{mag},A_2} - \varphi_{\text{mag},A_1} = \frac{2e}{h} \oint \mathbf{A} \cdot d\mathbf{s} = 2\varphi_{AB} = 4\pi \frac{\Phi}{\Phi_0}$$

$\Phi = B_{\text{ext}} \cdot F = \text{flux enclosed in the loop}$
 $F = \text{area of the enclosed loop}$

- characteristic field defined by $\varphi_{\text{mag},A_2} - \varphi_{\text{mag},A_1} = 2\pi$ (complete dephasing):

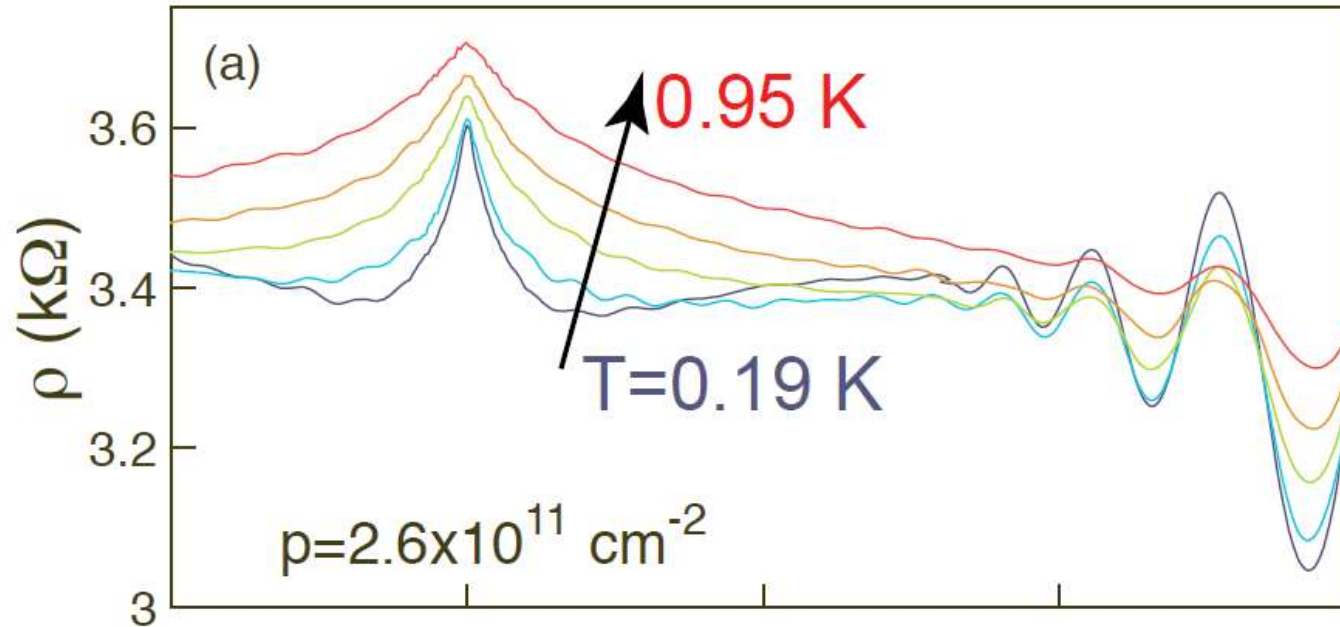
$$B^* = \frac{\Phi_0}{2F} = \frac{\Phi_0}{2\pi L_\phi^2} = \frac{\hbar}{2eL_\phi^2}$$



II.3.4 Weak Localization

- weak localization: important facts
 - coherent backscattering: called the **weak localization** (the relative number of contributing closed loops is **small**)
 - effect is important, since it is **sensitive to weak magnetic** fields:
 - **small fields**: contributions of large rings oscillate rapidly, phase difference in small rings almost unchanged
 - the **larger the field**, the fewer loops/rings contribute to constructive backscattering
 - resistance drops to classical value for large fields, if phase shift in smallest rings is about 2π
 - weak localization has to be distinguished from strong localization (due to strong disorder)

- weak localization: experiments



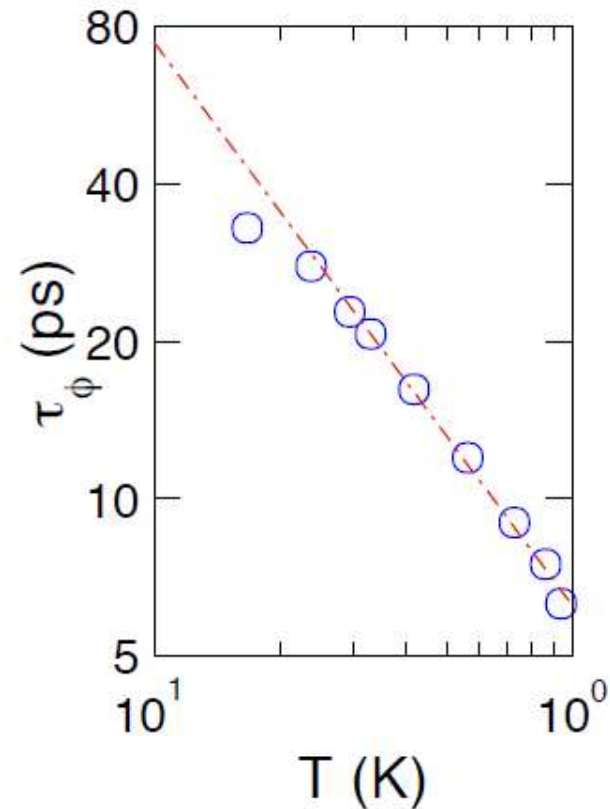
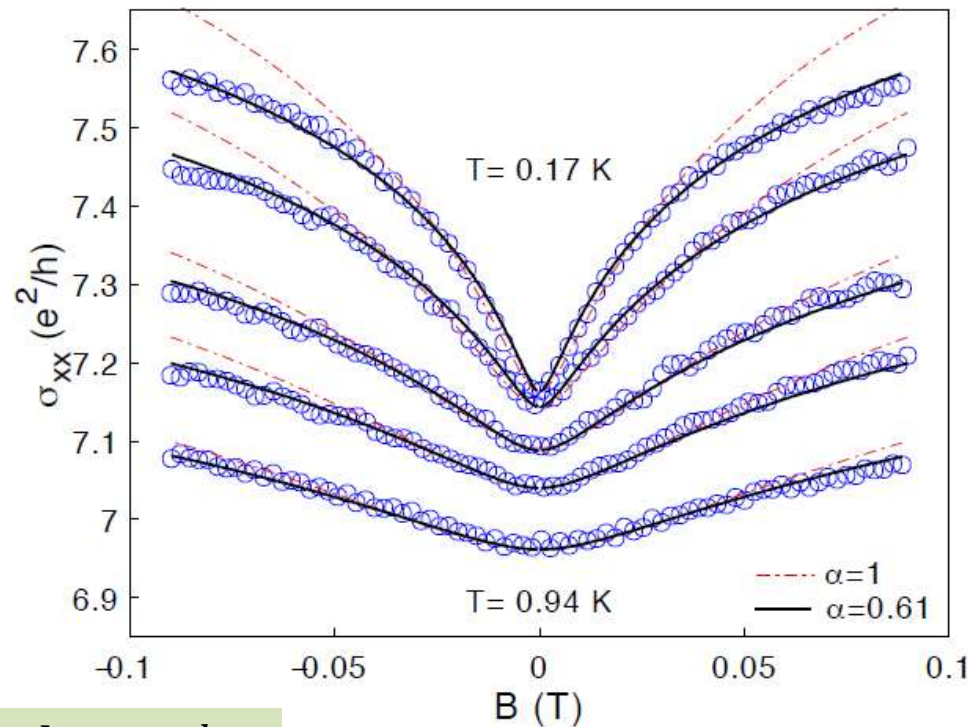
weak localization
in SiGe 2-dimensional quantum well
with hole gas

V. Senz, Ph.D. Thesis, ETH Zürich (2002)

- **requirement:**
sample larger than elastic scattering length: $L > \ell$ (diffusive transport)
- **observations:**
 - conductivity is reduced by $\approx 2e^2/h$ for $B_{\text{ext}} = 0$
 - large B_{ext} : Shubnikov de-Haas oscillations

II.3.4 Weak Localization

- weak localization: measurement of phase coherence time
 - as dependence of magnitude of WL on the coherence time is known to be $\tau_\phi \simeq L_\phi^2/D$
 - ➔ *weak localization experiments can be used to determine τ_ϕ*

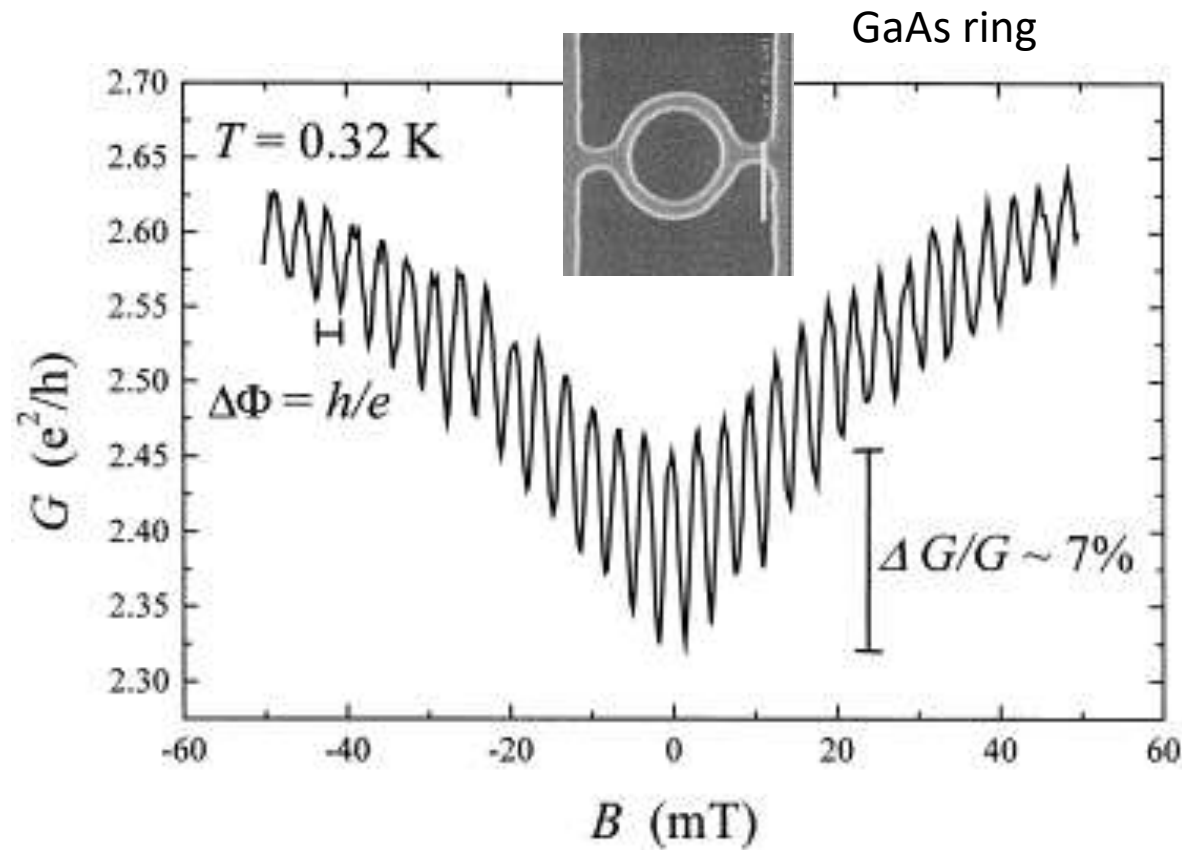


$$B^* = \frac{\Phi_0}{2F} = \frac{\Phi_0}{2\pi L_\phi^2} = \frac{\hbar}{2eL_\phi^2}$$

Senz et al., PRB **61**, 5082 (2000)

II.3.3 Aharonov-Bohm Effect

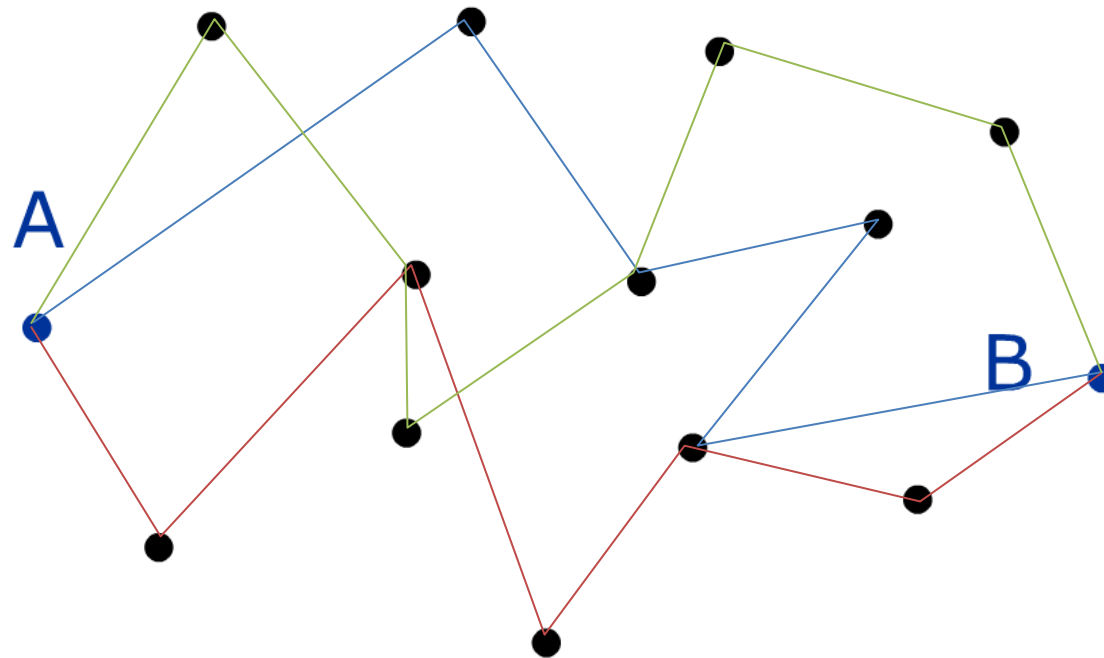
- weak localization: in combination with Aharonov-Bohm effect



S. Pedersen, A.E. Hansen, A. Kristensen, C.B. Sørensen, P.E. Lindelof, Aharonov-Bohm effect in GaAs/GaAlAs ring interferometers, Materials Science and Engineering: B **74**, 234-238 (2000)

Universal Conductance Fluctuations:

fluctuation of conductance due to different configuration of scatters



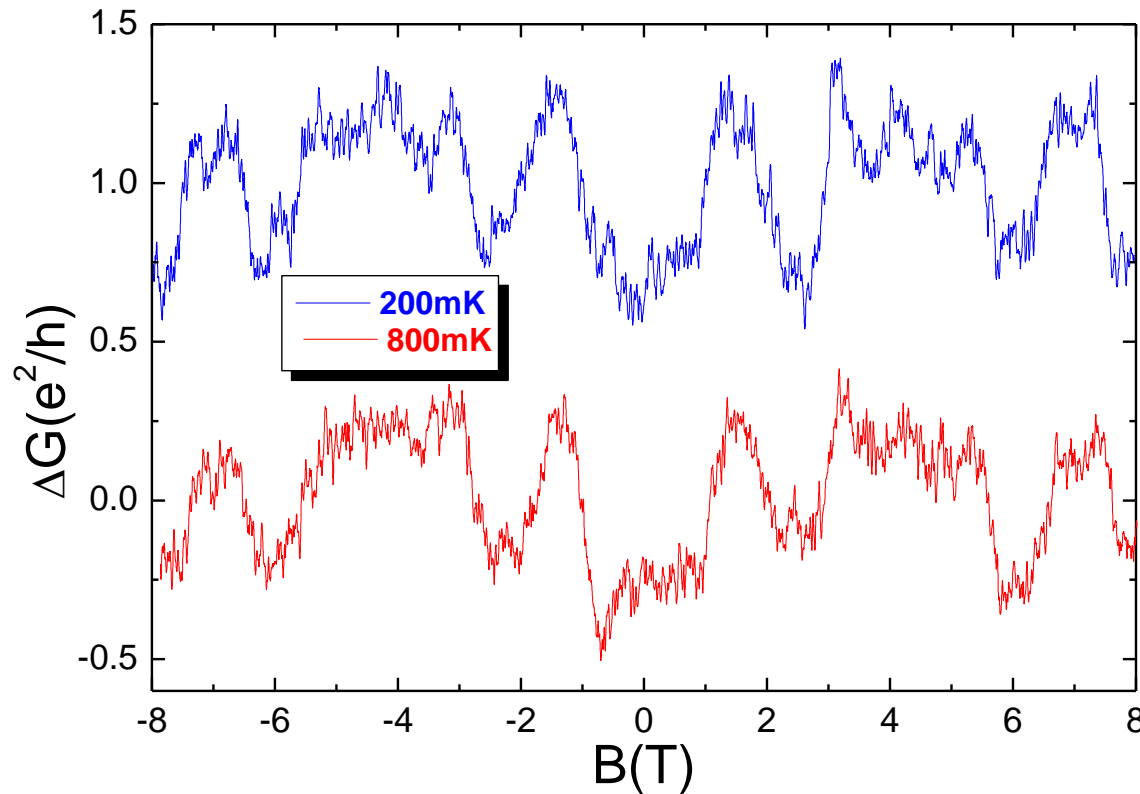
$$P_{AB} = \left| \sum_p A_p e^{i\chi_p} \right|^2 = \sum_p A_p^2 + \left| \sum_{p \neq p'} A_p A_{p'} e^{i(\chi_p - \chi_{p'})} \right|^2$$

phases χ_p depend on specific configuration of scatters in each sample

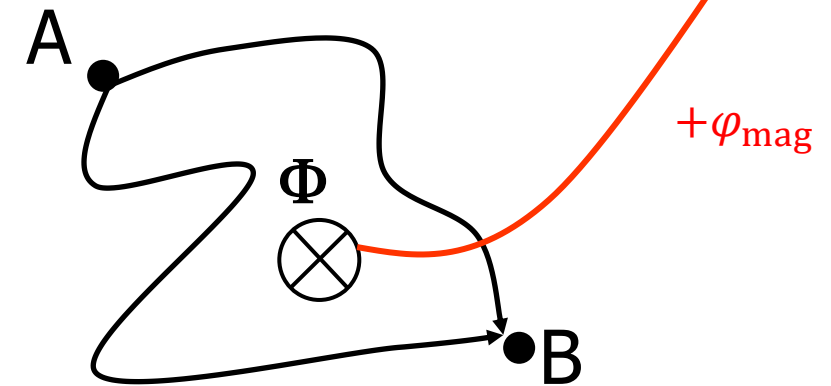
→ P_{AB} and hence conductance is fingerprint of this configuration

II.3.5 Universal Conductance Fluctuations

- experimental study of universal conductance fluctuations
 - would require fabrication of many samples with different (random) configuration of scatters
 - **ergodicity theorem**: same result is obtained for a single sample measured at different applied magnetic fields



$$P_{AB} = \left| \sum_p A_p e^{i\chi_p} \right|^2 = \sum_p A_p^2 + \left| \sum_{p \neq p'} A_p A_{p'} e^{i(\chi_p - \chi_{p'})} \right|^2$$



- ➔ random phase shifts
- ➔ position of scatters becomes important

II.3.5 Universal Conductance Fluctuations

- experimental observations and facts
 - **irregular conductance variations** as a function of field (B), carrier density (n), and voltage (V)
 - **conductance variations are symmetric** with respect to B (2 probe setup)
 - different in each individual sample ("magnetic fingerprint"), fluctuations characterize **impurity configuration**
 - caused by **quantum interference**
 - **amplitude of conductance variations** is of the order e^2/h , **not** noise
 - theory based on ergodicity theorem

variance of ensemble conductance:

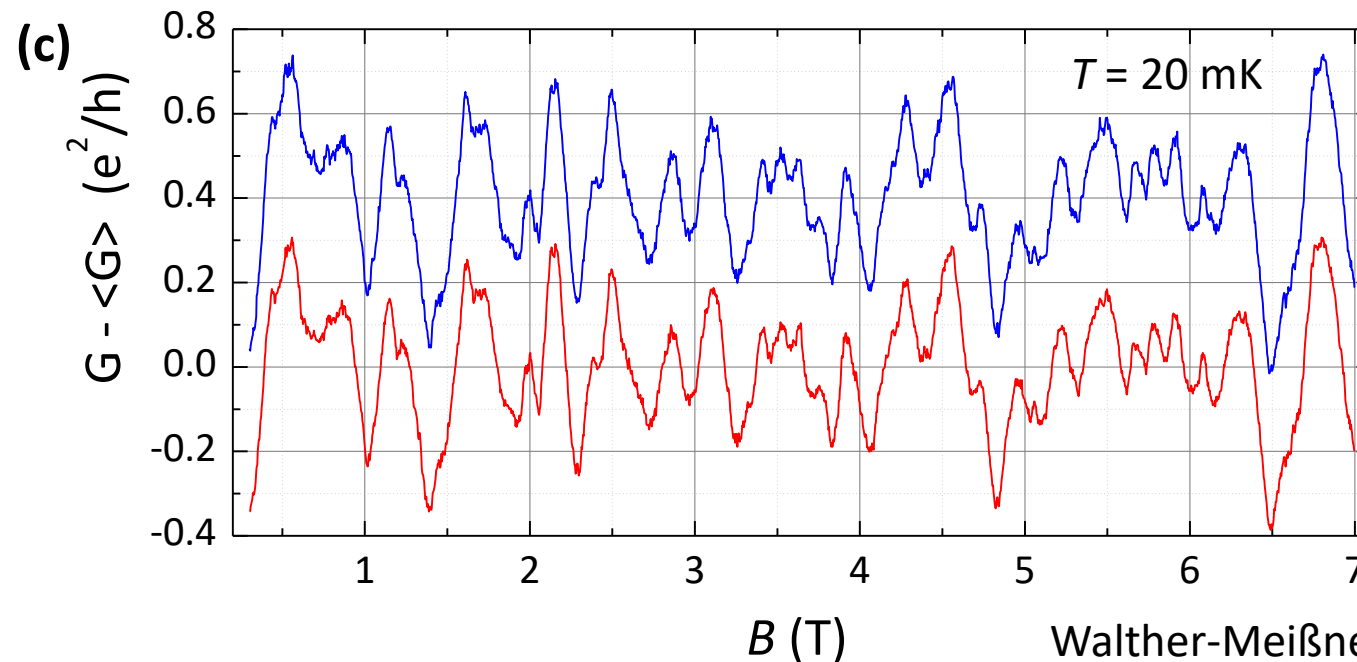
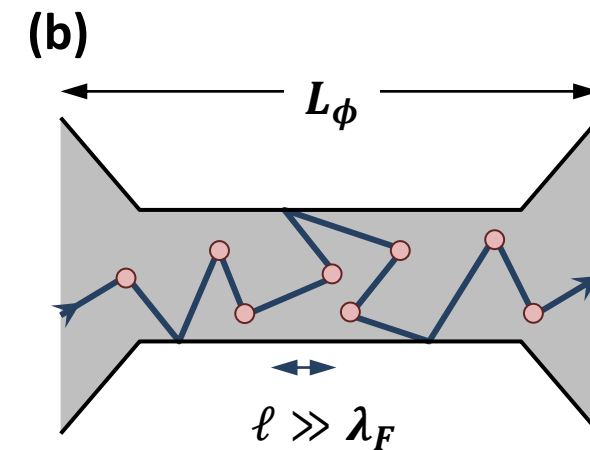
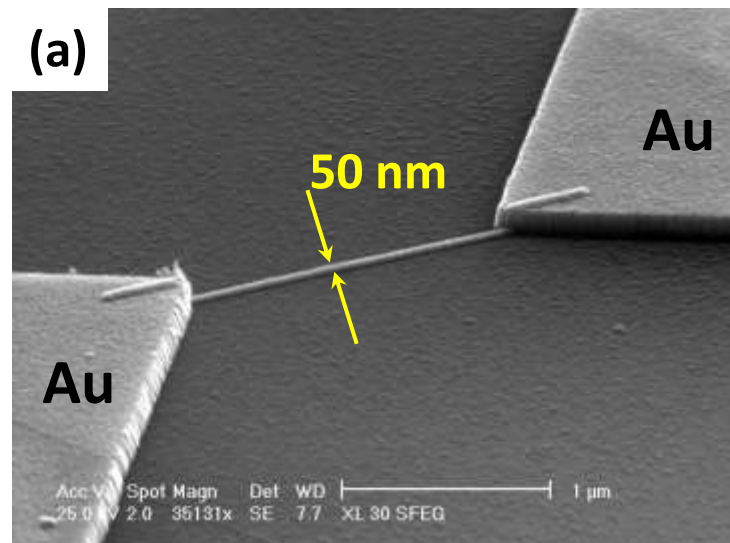
consider an ensemble of **macroscopically identical** but **microscopically different samples** (different configurations of scattering centers)

$$\langle (G - \langle G \rangle)^2 \rangle = \frac{e^4}{h^2} \left\langle \left(\sum_{mn} T_{mn} - \sum_{mn} \langle T_{mn} \rangle \right)^2 \right\rangle \quad T_{mn} = |t_{mn}|^2$$

→ complicated calculation

II.3.5 Universal Conductance Fluctuations

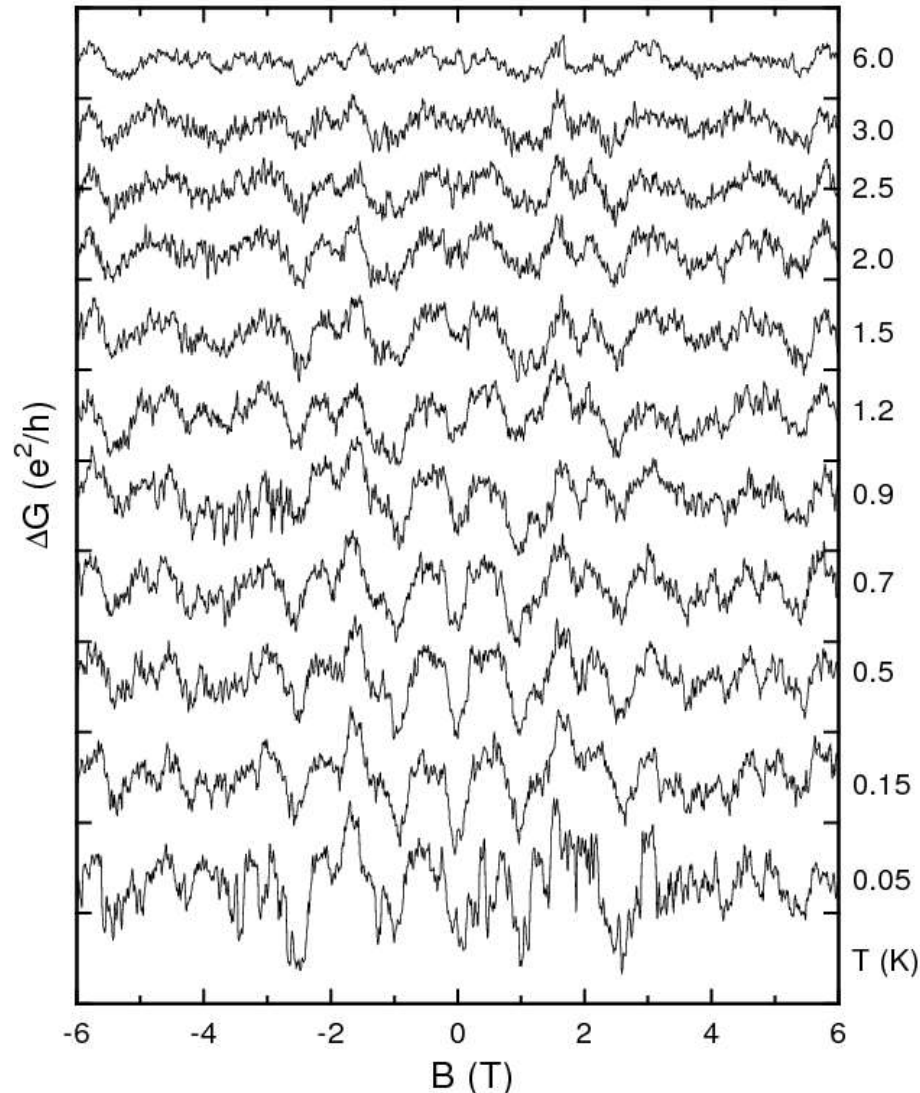
- UCFs in Au wires



red and blue curve taken at different days without warming up the sample
 → no noise effect !!

II.3.5 Universal Conductance Fluctuations

- UCFs in Au wires



UCF in gold nanowire

$$L = 600 \text{ nm}$$

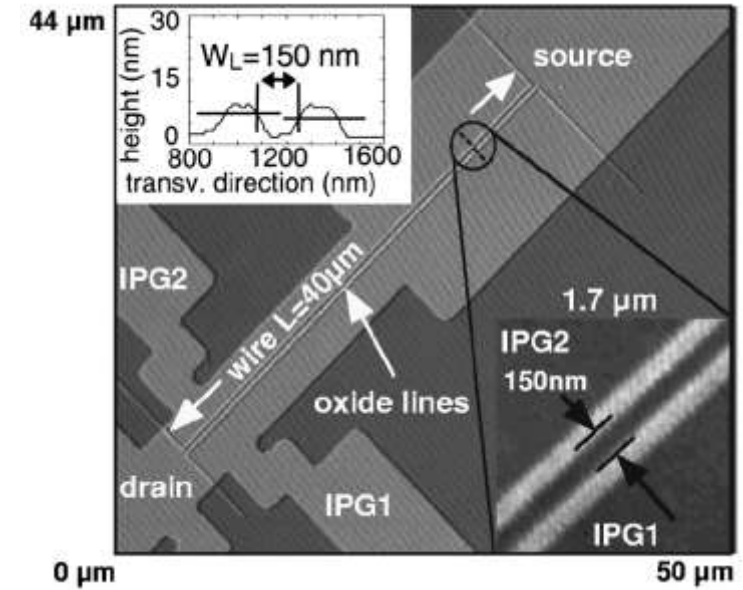
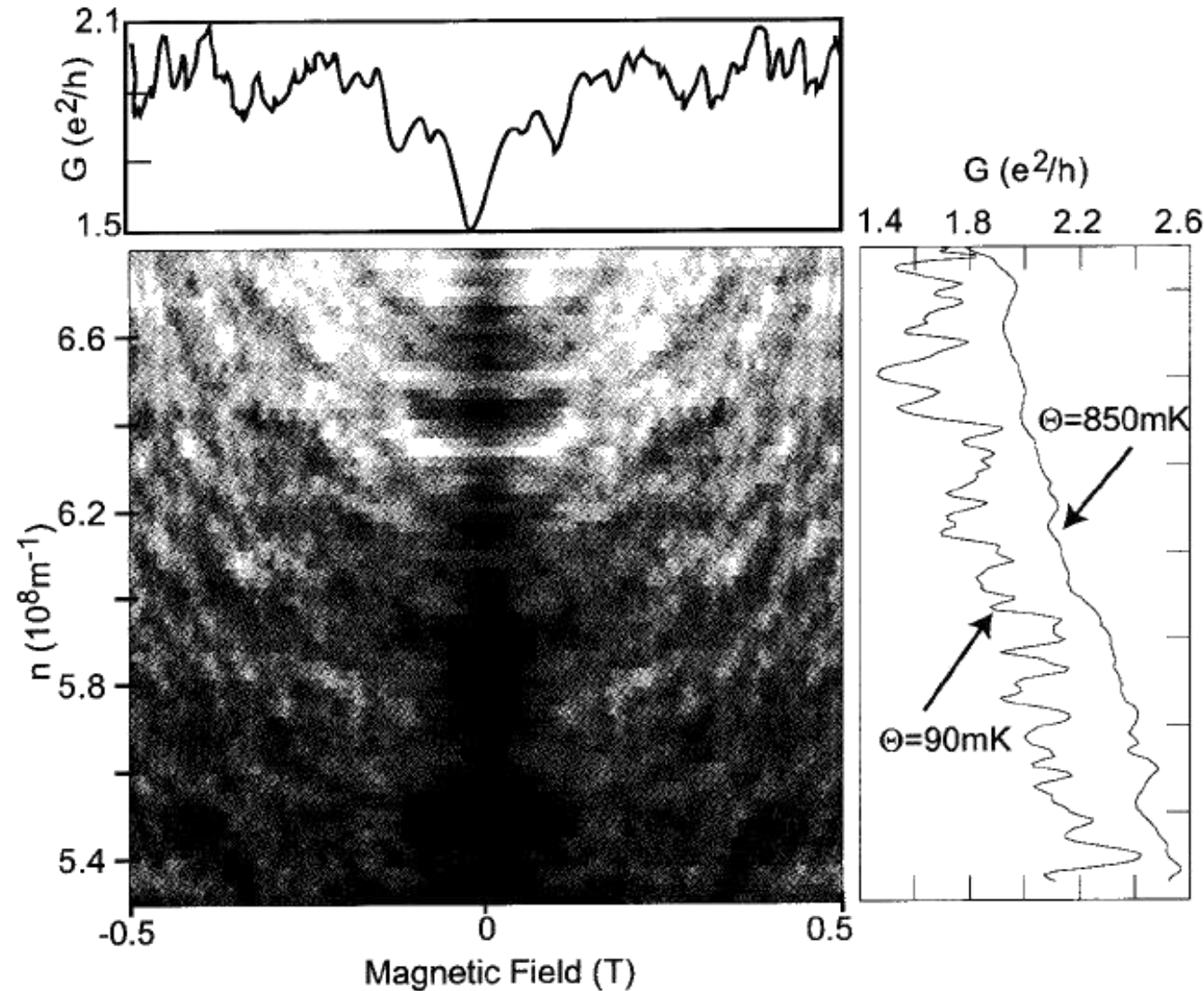
$$W = 60 \text{ nm}$$

UCF amplitude decreases with increasing T as phase coherence length becomes smaller than sample length

H. Hegger, Ph.D. Thesis, Universität zu Köln (1997)

II.3.5 Universal Conductance Fluctuations

- UCFs in GaAs quantum wire



data from Heinzl (2003)

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II.3 Quantum Interference Effects

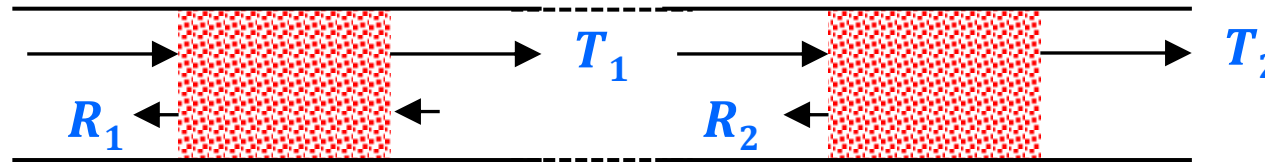
- II.3.1 Double Slit Experiment
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- two different points of view:
 - quantum transport
(electron waves, scattering/transfer matrix)
 - classical transport
(electric currents, charged particles, friction due to scattering, Ohm's law)

What is the bridge between these limiting cases ??

II.4 From Quantum Mechanics to Ohm's Law

- consider two conductors with transmission probabilities T_1 and T_2 connected in series



- what is the transmission probability T_{12} ?
- if $T_{12} = T_1 T_2$, then for a chain of scatterers we would expect the transmission probability to drop exponentially with the length of the chain:

$$T(L) = \exp(-L/L_0)$$

$$\text{as } e^{x_1} \cdot e^{x_2} = e^{x_1+x_2}$$

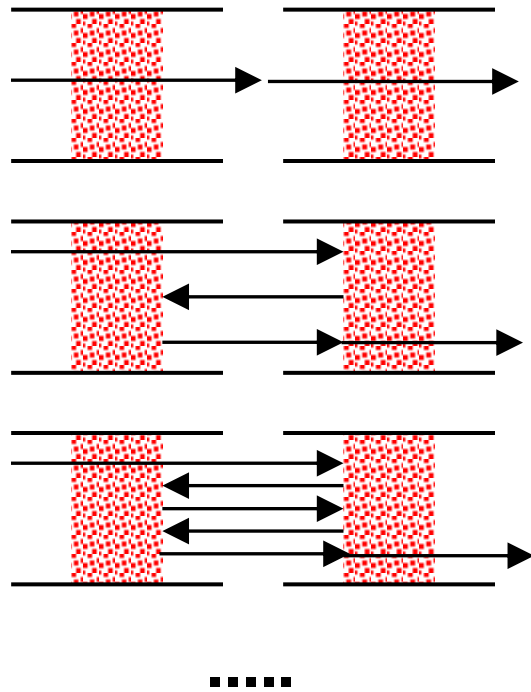
→ **no Ohm's law**

- **problem:** if we assume $T_{12} = T_1 T_2$, then we do not take into account multiple reflections

→ to obtain the correct result we have to add the probabilities of **multiply reflected paths**

II.4 From Quantum Mechanics to Ohm's Law

- two scatterers in series



$$\begin{aligned}
 & T_1 T_2 \\
 & + \\
 & T_1 T_2 R_1 R_2 \\
 & + \\
 & T_1 T_2 R_1^2 R_2^2 \\
 & + \\
 & \dots
 \end{aligned}
 \left. \vphantom{\begin{aligned} & T_1 T_2 \\ & + \\ & T_1 T_2 R_1 R_2 \\ & + \\ & T_1 T_2 R_1^2 R_2^2 \\ & + \\ & \dots \end{aligned}} \right\} \text{transmission probabilities}$$

$$T_{12} = \frac{T_1 T_2}{1 - R_1 R_2}$$

incoherent processes

with $T_1 = 1 - R_1$ and $T_2 = 1 - R_2$

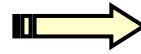
$$\frac{1 - T_{12}}{T_{12}} = \frac{1 - T_1}{T_1} + \frac{1 - T_2}{T_2}$$

additive property

II.4 From Quantum Mechanics to Ohm's Law

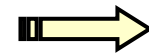
- N scatterers in series

$$\frac{1 - T(N)}{T(N)} = N \frac{1 - T}{T}$$



$$T(N) = \frac{T}{N(1 - T) + T}$$

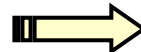
- number of scatterers in conductor of length L can be written as $N = n L$, where n is the linear density



$$T(L) = \frac{L_0}{L + L_0} \quad \text{with} \quad L_0 = \frac{T}{n(1 - T)}$$

- L_0 is of the order of the mean free path ℓ

$$\ell = \frac{1}{n(1 - T)}$$



$$\ell = \frac{1}{n(1 - T)} \simeq \frac{T}{n(1 - T)} = L_0 \quad (\text{for } T \text{ close to } 1)$$

linear density
of scatterers

scattering
probability

II.4 From Quantum Mechanics to Ohm's Law

- quantum conductance for N channels

- wide conductor with $M \approx k_F W / \pi$ modes: $G \approx 2G_Q M T = 2 \frac{e^2}{h} M T \approx \frac{e^2 W}{\pi} T \frac{2k_F}{h}$

- 2D density of transverse modes: $n_{2D} = \frac{1}{2\pi} \frac{2m}{\hbar^2} \implies n_{2D} v_F = \frac{1}{2\pi} \frac{2m}{\hbar^2} \frac{\hbar k_F}{m} = \frac{2k_F}{h}$

$$G \approx \frac{e^2 W}{\pi} T \frac{2k_F}{h} = \frac{e^2 W}{\pi} T n_{2D} v_F$$

- using $T(L) = \frac{L_0}{L+L_0}$ yields:

$$G \approx \frac{W}{L+L_0} \underbrace{e^2 n_{2D} v_F L_0 \pi}_{\approx \sigma \text{ (Einstein relation)}} \approx \text{diffusion constant } D$$

$$\implies G \approx \frac{W}{L+L_0} \sigma$$

or

$$R = \frac{1}{G} \approx \frac{L+L_0}{W} \frac{1}{\sigma} = \frac{L}{\sigma W} + \frac{L_0}{\sigma W}$$

resistance obeying Ohm's law

length independent interface resistance

II.4 From Quantum Mechanics to Ohm's Law

- conclusions
 - Ohm's law is obtained from the expression for the quantum conductance
 - by summing up *probabilities of multiply reflected paths*
 - note that by summing up probabilities *coherence effects are neglected* (of course these are not contained in Ohm's law, incoherent transport)
 - sample size $L \gg$ phase coherence length L_φ : large phase shifts (also affected by disorder)
 - formally identical samples:
 - very different phase shifts,
 - but same ohmic resistance, since interference effects average out for $L \gg L_\varphi$
 - $L < L_\varphi$: interference effects play important role
 - deviation from Ohm's law
 - different resistance for formally identical samples due to different impurity configurations

II.4 From Quantum Mechanics to Ohm's Law

- Where is the resistance ??

- expression for quantum conductance: $G = 2 \frac{e^2}{h} M T$

→ scatterers give rise to resistance by reducing T

- example: waveguide with M modes and a single scatterer

$$\frac{1}{G} = \underbrace{\frac{h}{2e^2} \frac{1}{M}}_{\text{„interface“ resistance}} + \underbrace{\frac{h}{2e^2} \frac{1}{M} \frac{1-T}{T}}_{\text{„scatterer“ resistance}}$$

„interface“ resistance „scatterer“ resistance

→ scatterer resistance determined by properties of scatterer via its transmissivity

- remaining questions:

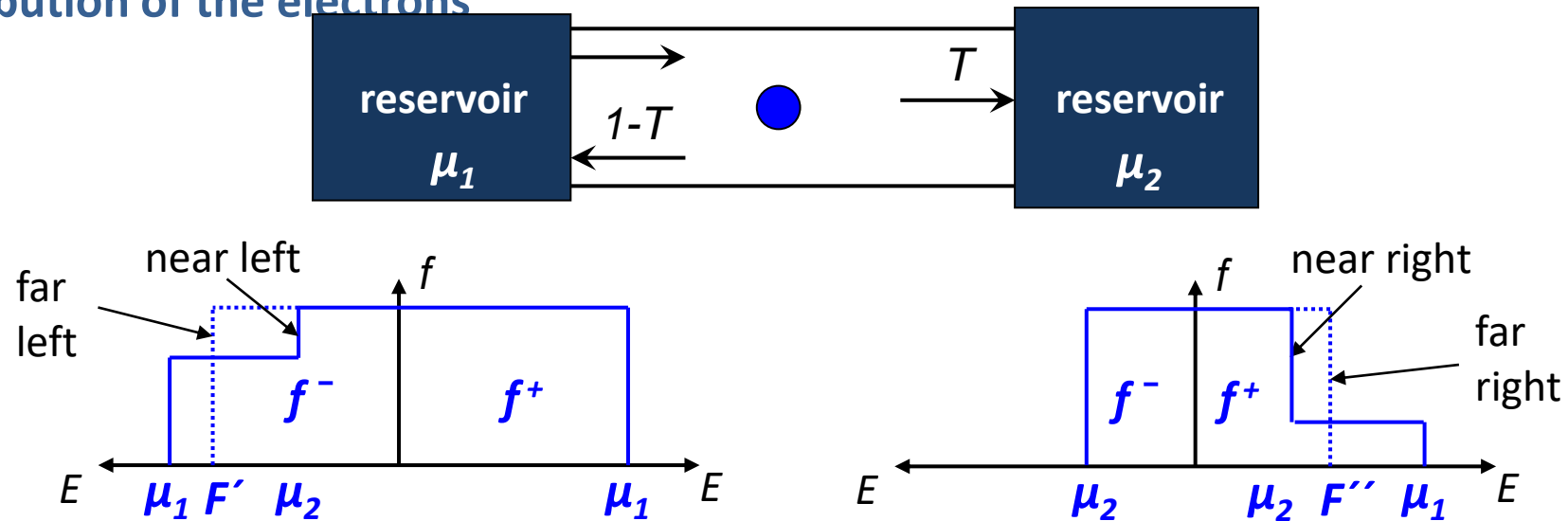
→ can we associate a resistance with the scatterer ?

→ what about the potential drop ? Does it occur across the scatterer ?

→ what about Joule heating ? Dissipation at the scatterer ?

II.4 From Quantum Mechanics to Ohm's Law

- energy distribution of the electrons



- reservoirs: $f^+ = \vartheta(\mu_1 - E)$ $f^- = \vartheta(\mu_2 - E)$ step functions
- near left and right: $f^+ = \vartheta(\mu_1 - E) + T\{\vartheta(\mu_1 - E) - \vartheta(\mu_2 - E)\}$ partial filling
(non-equilibrium) $f^- = \vartheta(\mu_2 - E) + (1 - T)\{\vartheta(\mu_1 - E) - \vartheta(\mu_2 - E)\}$ of states for $\mu_2 < E < \mu_1$
- far left and right: $f^+ = \vartheta(F' - E)$ $f^- = \vartheta(F'' - E)$
(equilibrium) $F' = \mu_2 + (1 - T)\{\mu_1 - \mu_2\}$ $F'' = \mu_2 + T\{\mu_1 - \mu_2\}$
(follows from the conservation of the number of electrons)

II.4 From Quantum Mechanics to Ohm's Law

- spatial variation of the electrochemical potential

- left and right to the scatterer (*after energy relaxation*):

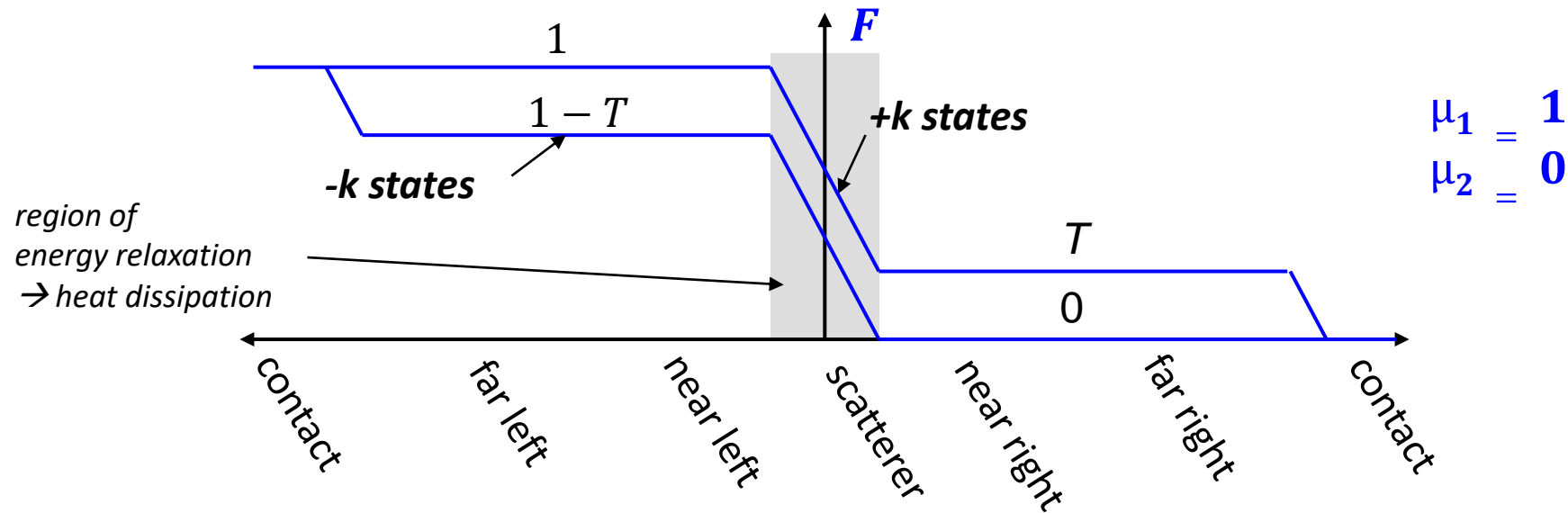
$$F^+ = \mu_1 \quad (\text{left})$$

$$F^- = \mu_2 + (1 - T)\{\mu_1 - \mu_2\} \quad (\text{left})$$

$$F^+ = \mu_2 + T\{\mu_1 - \mu_2\} \quad (\text{right})$$

$$F^- = \mu_2 \quad (\text{right})$$

- close to scatterer (*nonequilibrium distribution, F can be defined via the number of electrons*)



- drop of electrochemical potential across scatterer \rightarrow localized „scatterer“ resistance
- drop close to contact \rightarrow contact resistance

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II.4

From Quantum Mechanics to Ohm's Law

II.5

Coulomb Blockade

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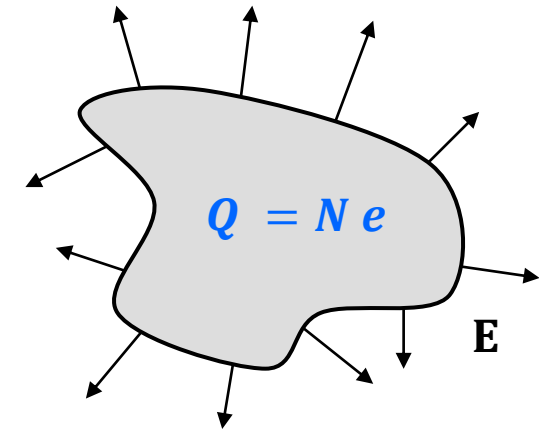
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II.5 Coulomb Blockade

- charge quantization and charging energy
 - **electric charge** is **quantized** for an isolated island
 - charging energy:

$$\varepsilon = \frac{Q^2}{2C} = \frac{N^2 e^2}{2C} = n^2 \varepsilon_c \quad \text{with} \quad \varepsilon_c = \frac{e^2}{2C}$$



- how large is ε_c for island of size L (bring charge e from ∞ to island)

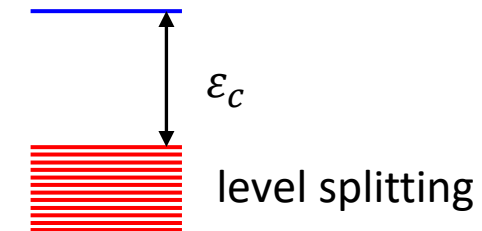
$$\varepsilon_c \approx \frac{e^2}{\epsilon_0 L} \approx \frac{10 \text{ eV}}{L [\text{nm}]}$$

typically in **meV regime** for 100 nm-sized samples

- level splitting in nm-sized island:

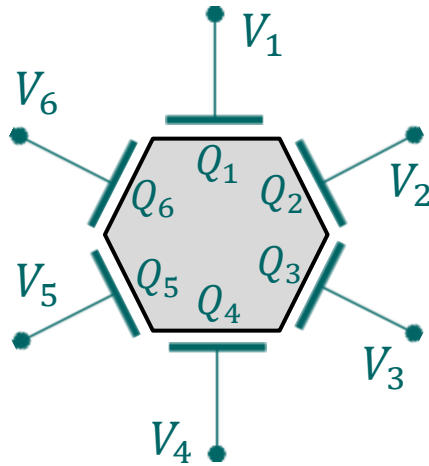
$$\delta\varepsilon \approx \frac{\varepsilon_F}{N_{\text{atom}}} \approx \frac{1 \text{ eV}}{L^3 [\text{nm}^3]}$$

typically **in μeV regime** for 100 nm-sized samples



II.5 Coulomb Blockade

- capacitance model for metallic island



– charge on the island $Q_0 = \sum_{i=1}^k C_i V_i + \bar{Q}_0$ ← charge for all $V_i = 0$ „background charge“

– potential V_0 of the island is not known, but its charge Q_0 is known to be Ne
 → electrostatic potential of the island:

$$V_0(Q_0) = \frac{Q_0 - \bar{Q}_0}{C_\Sigma} - \sum_{i=1}^k \frac{C_i}{C_\Sigma} V_i \quad \text{with} \quad C_\Sigma = \sum_{i=1}^k C_i$$

– electrostatic energy needed to put additional charge $\Delta Q = Ne$ on island

$$\varepsilon_{\text{el}}(N) = \int_{\bar{Q}_0}^{\bar{Q}_0 + Ne} V_0(Q_0) dQ_0 = \frac{(Ne)^2}{2C_\Sigma} - eN \sum_{i=1}^k \frac{C_i}{C_\Sigma} V_i$$

– energy needed to charge the island with one additional charge $\Delta Q = e$

$$\varepsilon_{\text{el}}(N + 1) - \varepsilon_{\text{el}}(N) = \frac{e^2}{C_\Sigma} \left(N + \frac{1}{2} \right) - e \sum_{i=1}^k \frac{C_i}{C_\Sigma} V_i$$

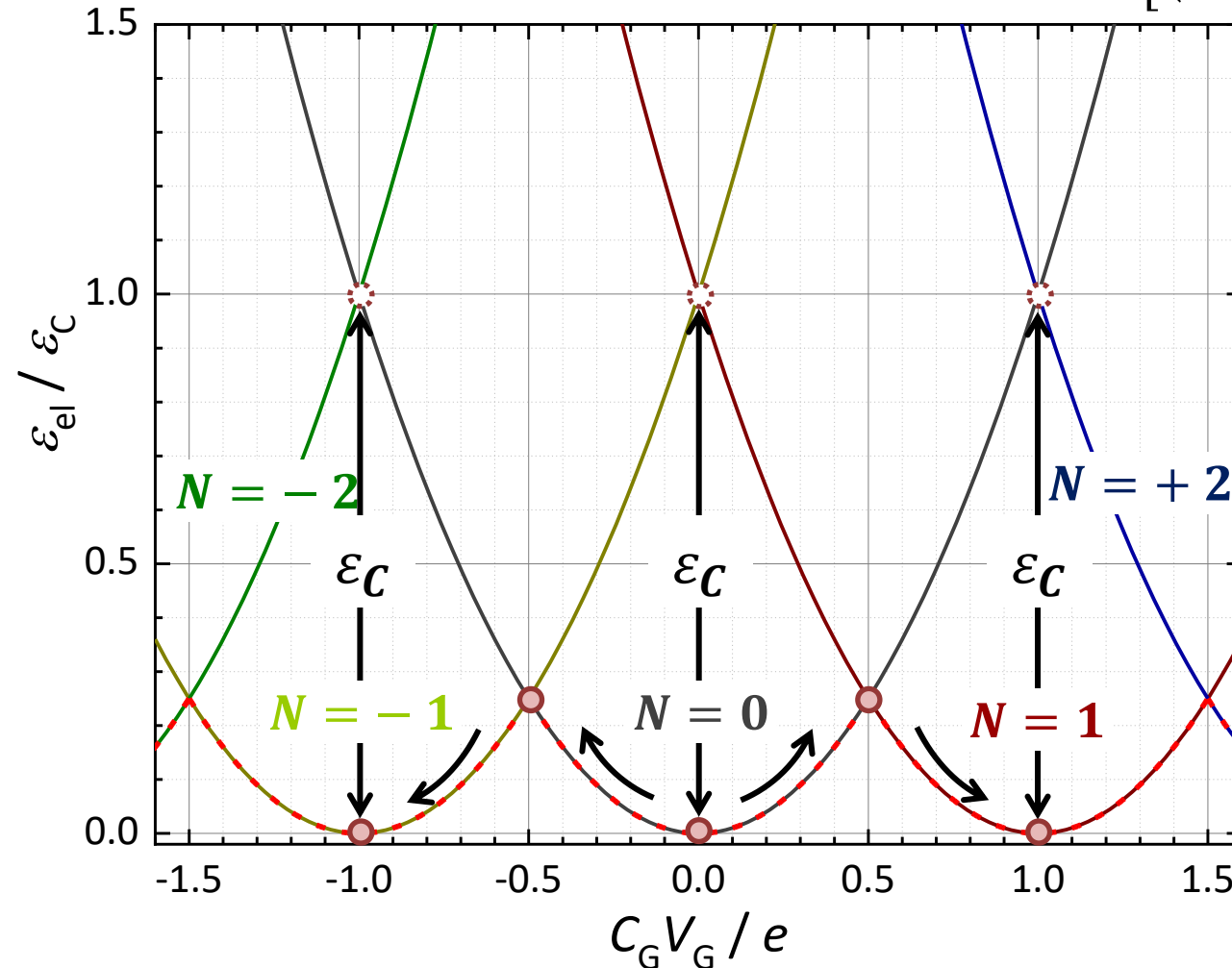
II.5 Coulomb Blockade

$$\epsilon_{el}(\Delta Q = Ne) = \frac{(Ne)^2}{2C_\Sigma} - eN \sum_{i=1}^k \frac{C_i}{C_\Sigma} V_i$$

- capacitance model for metallic island – only a single capacitance ($C_\Sigma = C$)

– electrostatic energy $\epsilon_{el}(\Delta Q = Ne) = \frac{(Ne)^2}{2C} - eNV = \frac{e^2}{2C} \left[\left(N - \frac{CV}{e} \right)^2 - \left(\frac{CV}{e} \right)^2 \right]$

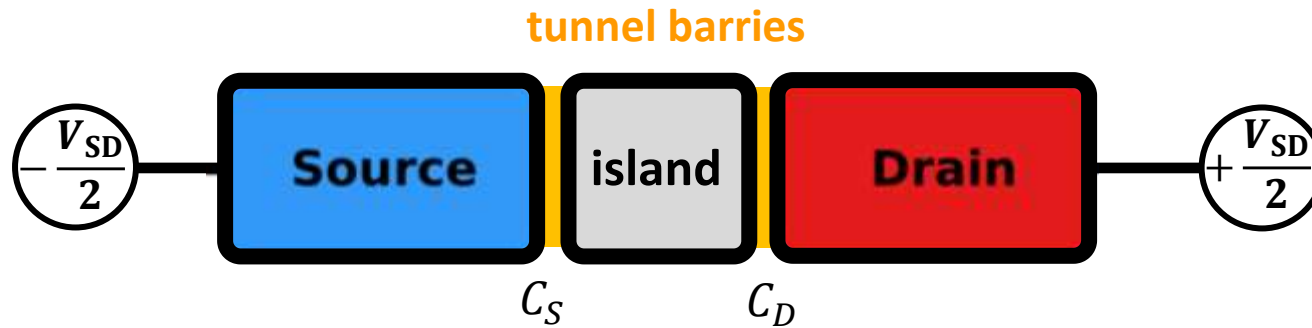
omitted as independent of N



$$\epsilon_{el}(\Delta Q) = \frac{e^2}{2C} \left(N - \frac{CV}{e} \right)^2 = \epsilon_C \left(N - \frac{CV}{e} \right)^2$$

II.5 Coulomb Blockade

- capacitance model for 2-terminal device



$$\varepsilon_{\text{el}}(\Delta Q) = \frac{(Ne)^2}{2C_{\Sigma}} - eN \sum_{i=1}^k \frac{C_i}{C_{\Sigma}} V_i$$

$$C_{\Sigma} = C_S + C_D$$

- electrostatic energy barrier for removing one electron to drain: $\Delta Q = +e$ on island

$$\varepsilon_{\text{el}}(\Delta Q) = \frac{e^2}{2C_{\Sigma}} + e \frac{C_S (-V_{\text{SD}})}{C_{\Sigma} 2} - e \frac{C_D V_{\text{SD}}}{C_{\Sigma} 2} \stackrel{C_S=C_D=C}{=} \frac{e^2}{2C_{\Sigma}} - \frac{eV_{\text{SD}}}{2}$$

- electrostatic energy barrier for adding an electron from source: $\Delta Q = -e$

$$\varepsilon_{\text{el}}(\Delta Q) = \frac{e^2}{2C_{\Sigma}} + e \frac{C_S (-V_{\text{SD}})}{C_{\Sigma} 2} - e \frac{C_D V_{\text{SD}}}{C_{\Sigma} 2} \stackrel{C_S=C_D=C}{=} \frac{e^2}{2C_{\Sigma}} - \frac{eV_{\text{SD}}}{2}$$

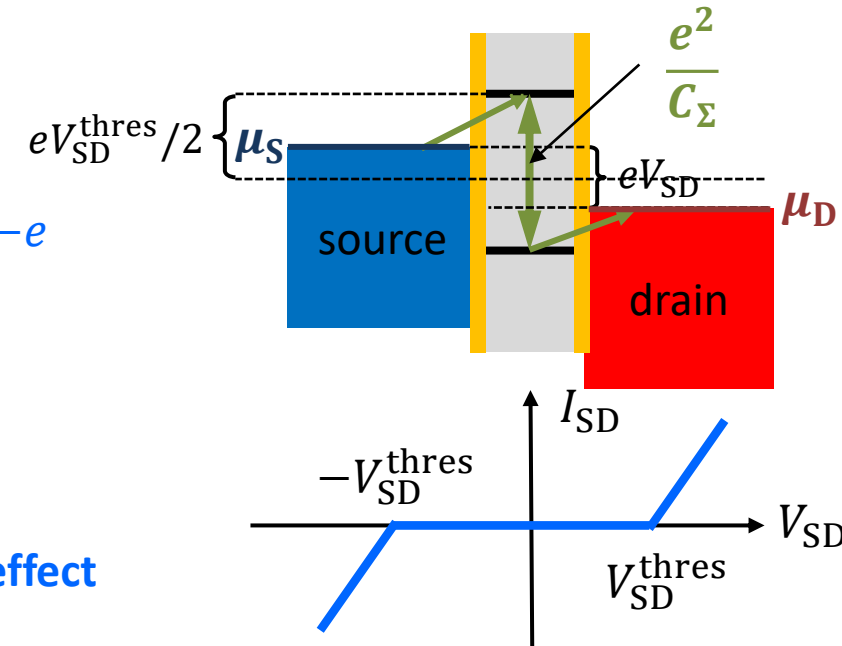
- at $T = 0$, current transport sets in if energy barrier is reduced to zero

threshold SD-voltage:

$$|V_{\text{SD}}^{\text{thres}}| = \frac{e}{C_{\Sigma}}$$

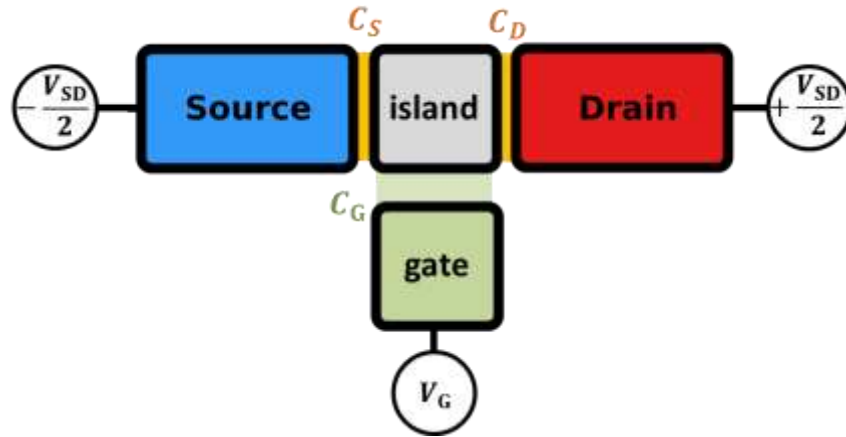
Coulomb blockade effect

for $|V_{\text{SD}}| \leq |V_{\text{SD}}^{\text{thres}}|$



II.5 Coulomb Blockade

- capacitance model for SET: electrostatic energy



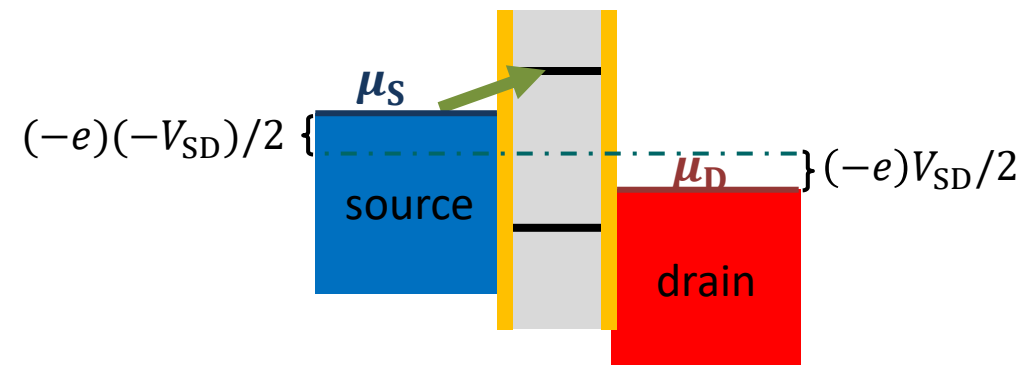
$$\varepsilon_{\text{el}}(\Delta Q) = \frac{(Ne)^2}{2C_{\Sigma}} - eN \sum_{i=1}^k \frac{C_i}{C_{\Sigma}} V_i$$

- charging the neutral island by $\Delta Q = -Ne$ from source at constant V_G

$$\varepsilon_{\text{el}}(\Delta N) = \frac{(-Ne)^2}{2C_{\Sigma}} + Ne \frac{C_S (-V_{\text{SD}})}{C_{\Sigma} 2} - Ne \frac{C_D V_{\text{SD}}}{C_{\Sigma} 2} - Ne \frac{C_G V_G}{C_{\Sigma}} \stackrel{C_S=C_D=C}{=} \frac{(Ne)^2}{2C_{\Sigma}} - Ne \left(\frac{C}{C_{\Sigma}} V_{\text{SD}} + \frac{C_G}{C_{\Sigma}} V_G \right)$$

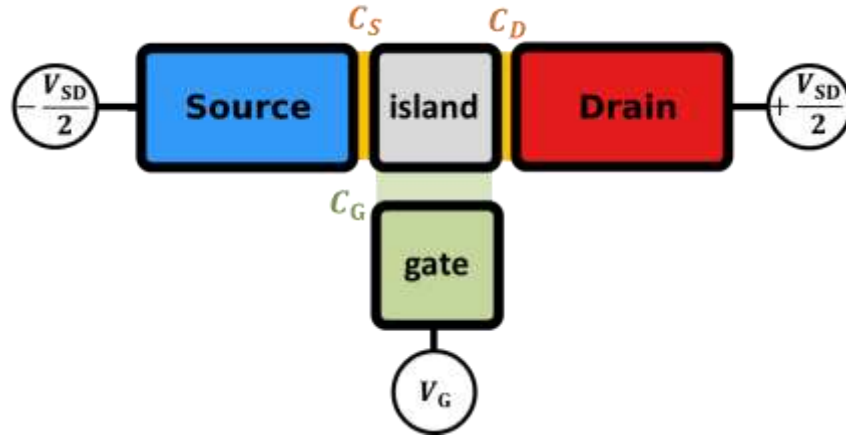
- electrostatic energy difference between adding $\Delta N = N + 1$ and $\Delta N = N$ electrons

$$\varepsilon_{\text{el}}(N + 1) - \varepsilon_{\text{el}}(N) = \left(N + \frac{1}{2} \right) \frac{e^2}{C_{\Sigma}} - e \left(\frac{C}{C_{\Sigma}} V_{\text{SD}} + \frac{C_G}{C_{\Sigma}} V_G \right)$$



II.5 Coulomb Blockade

- capacitance model for SET: electrostatic energy



$$\varepsilon_{\text{el}}(\Delta Q) = \frac{(Ne)^2}{2C_{\Sigma}} - eN \sum_{i=1}^k \frac{C_i}{C_{\Sigma}} V_i$$

- charging the island by removing $\Delta Q = -Ne$ to drain at constant V_G (corresponds to adding $\Delta Q = +Ne$ to island)

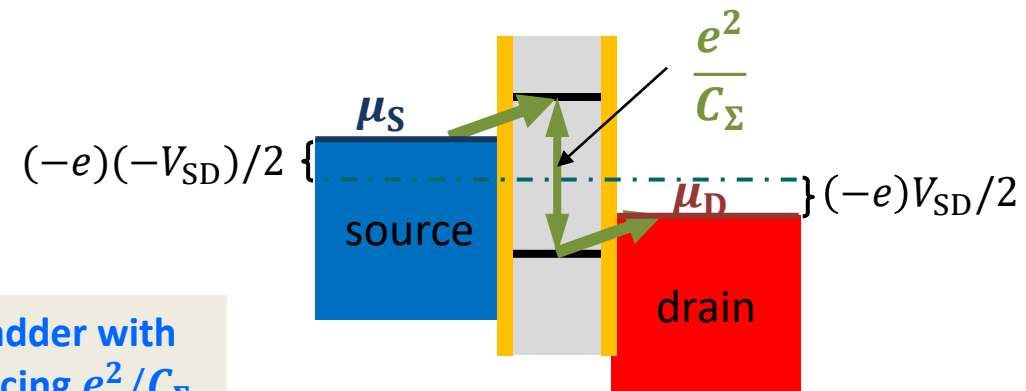
$$\varepsilon_{\text{el}}(\Delta N) = \frac{(\Delta Ne)^2}{2C_{\Sigma}} - Ne \frac{C_S - V_{\text{SD}}}{C_{\Sigma}} + Ne \frac{C_D V_{\text{SD}}}{C_{\Sigma}} + Ne \frac{C_G V_G}{C_{\Sigma}} \stackrel{C_S=C_D=C}{=} \frac{(\Delta Ne)^2}{2C_{\Sigma}} + Ne \left(\frac{C}{C_{\Sigma}} V_{\text{SD}} + \frac{C_G}{C_{\Sigma}} V_G \right)$$

- electrostatic energy difference between removing $\Delta N = N - 1$ and $\Delta N = N$ electrons

$$\varepsilon_{\text{el}}(N) - \varepsilon_{\text{el}}(N - 1) = \left(N - \frac{1}{2} \right) \frac{e^2}{C_{\Sigma}} + e \left(\frac{C}{C_{\Sigma}} V_{\text{SD}} + \frac{C_G}{C_{\Sigma}} V_G \right)$$

$$\varepsilon_{\text{el}}(N + 1) - \varepsilon_{\text{el}}(N) - [\varepsilon_{\text{el}}(N) - \varepsilon_{\text{el}}(N - 1)] = \frac{e^2}{C_{\Sigma}}$$

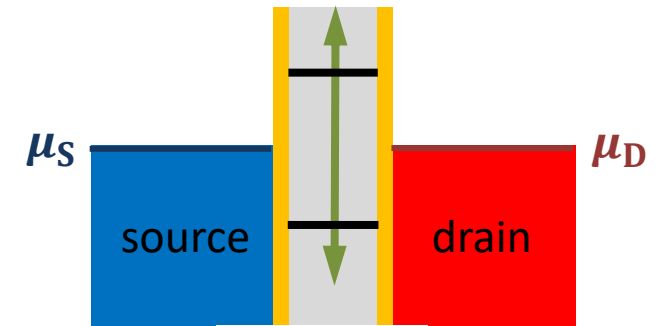
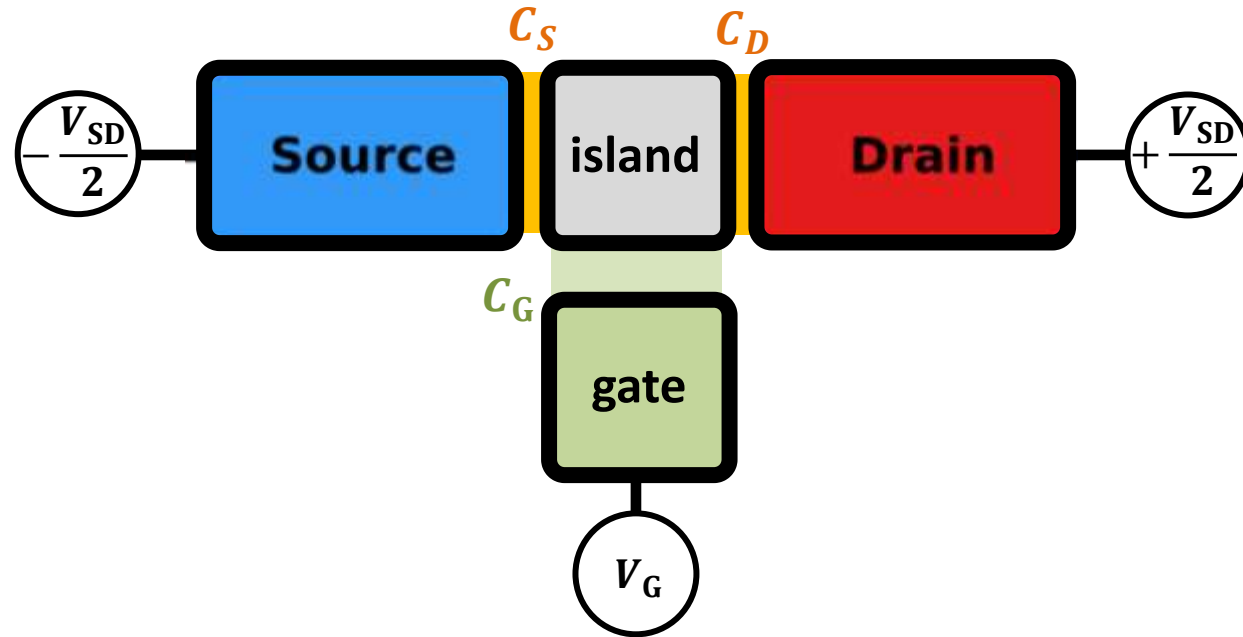
energy ladder with fixed spacing e^2/C_{Σ}



II.5 Coulomb Blockade

- capacitance model for 3-terminal device: single electron transistor (SET)

$$\epsilon_{el}(\Delta Q) = \frac{(Ne)^2}{2C_\Sigma} - eN \sum_{i=1}^k \frac{C_i}{C_\Sigma} V_i$$



additional V_G shifts potential energy of island

- electrostatic energy barrier for removing one electron to drain ($\Delta Q = +e$) [or adding one electron from source ($\Delta Q = -e$)] at finite V_G

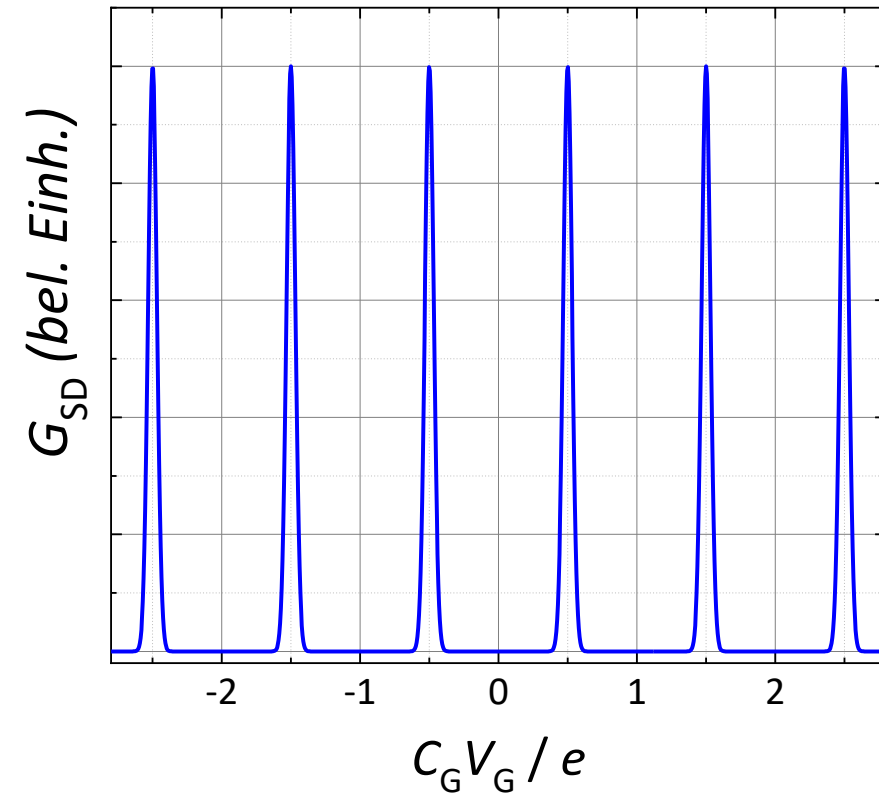
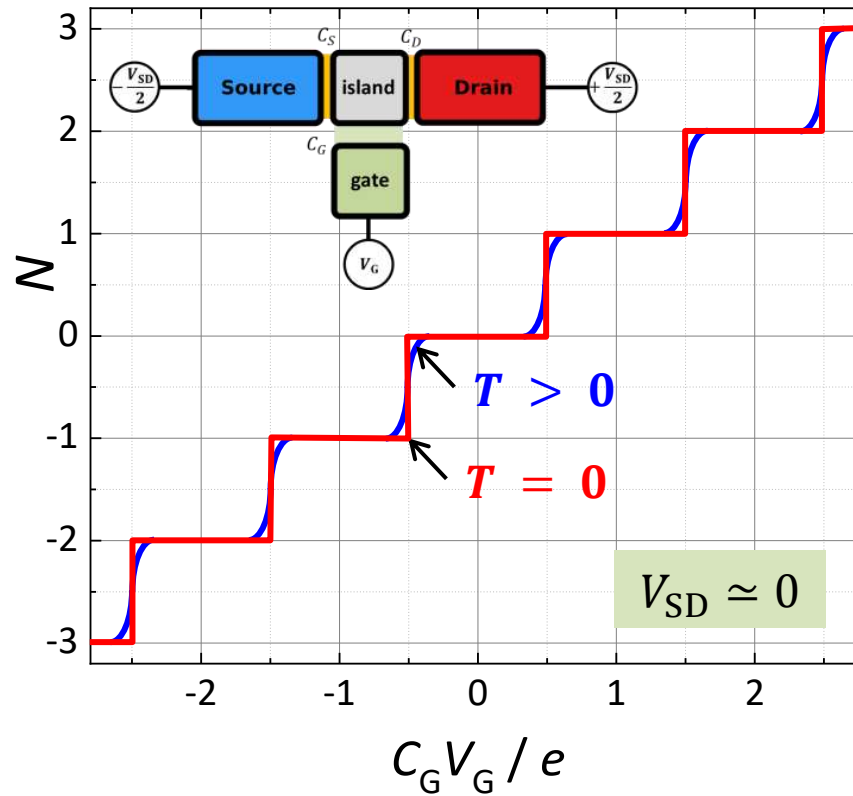
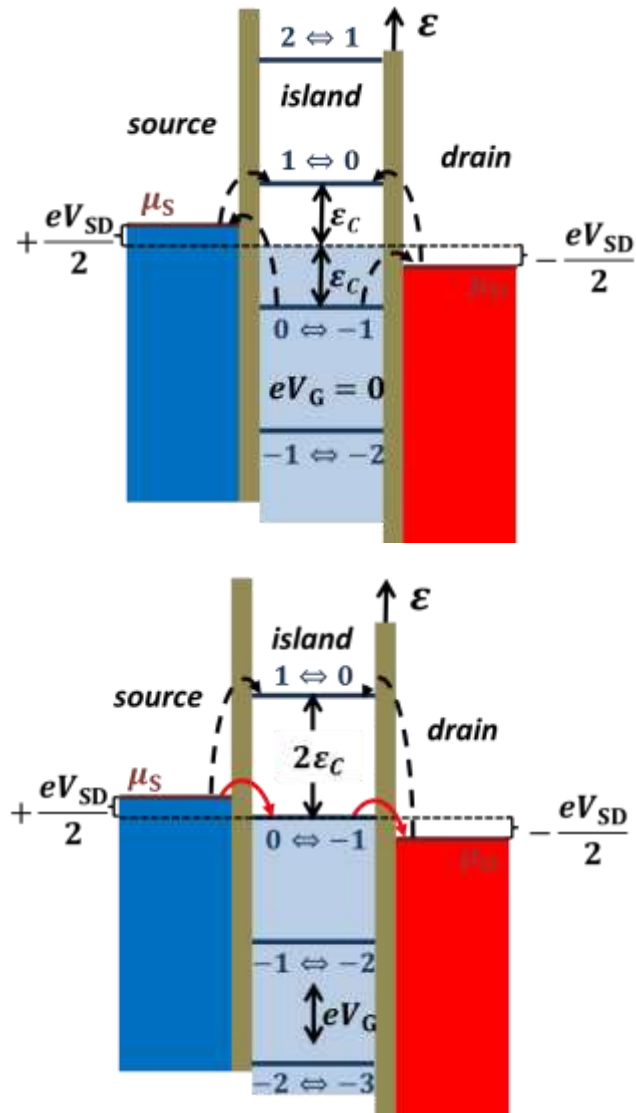
$$\epsilon_{el}(\Delta Q) = \frac{e^2}{2C_\Sigma} + e \frac{C_S - V_{SD}}{C_\Sigma} - e \frac{C_D V_{SD}}{C_\Sigma} - e \frac{C_G V_G}{C_\Sigma} \stackrel{C_S=C_D=C}{=} \frac{e^2}{2C_\Sigma} - eV_{SD} - e \frac{C_G}{C_\Sigma} V_G \quad \text{with } C_\Sigma = C_S + C_D + C_G$$

at $V_{SD} \approx 0$: $\epsilon_{el}(\Delta Q) = \frac{e^2}{2C_\Sigma} - \underbrace{eV_{SD}}_{\approx 0} - e \frac{C_G}{C_\Sigma} V_G \quad \rightarrow \text{transport allowed for } V_G^{\text{trans}} = \frac{e}{2C_G}$

- analog result for adding one electron from source ($\Delta Q = -e$) at finite $V_G \quad \rightarrow \text{periodic peaks in } I_{SD} \text{ at } V_G = N \cdot \frac{e}{2C_G}$

II.5 Coulomb Blockade

- capacitance model for SET: current flow at $V_{SD} \approx 0$ as a function of V_G

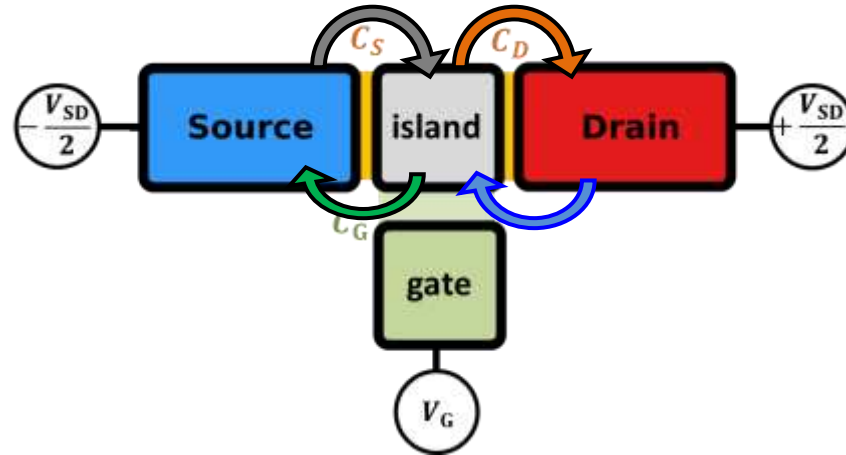


for $V_{SD} \approx 0$:

periodic peaks in SD-current I_{SD} at $V_G = N \cdot \frac{e}{2C_G}$

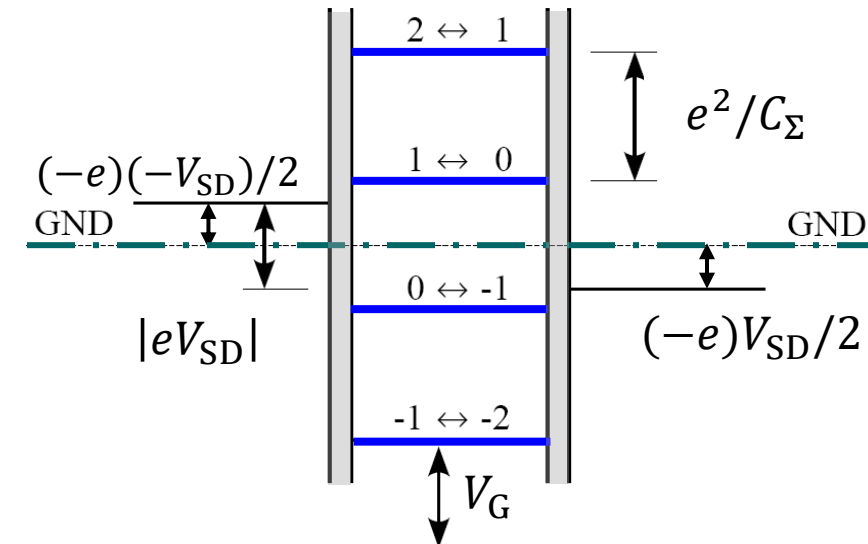
II.5 Coulomb Blockade

- capacitance model for SET: current flow at finite V_{SD} , V_G



at a given N on island, four different electron transfer processes are possible

- | | | |
|--------------------|-----------------------|---|
| 1. from the left: | $N \rightarrow N + 1$ | $\Delta\varepsilon_{FL}(N) = \varepsilon_{el}(N + 1) - \varepsilon_{el}(N)$ |
| 2. to the left: | $N \rightarrow N - 1$ | $\Delta\varepsilon_{TL}(N) = \varepsilon_{el}(N - 1) - \varepsilon_{el}(N)$ |
| 3. from the right: | $N \rightarrow N + 1$ | $\Delta\varepsilon_{FR}(N) = \varepsilon_{el}(N + 1) - \varepsilon_{el}(N)$ |
| 4. to the right: | $N \rightarrow N - 1$ | $\Delta\varepsilon_{TR}(N) = \varepsilon_{el}(N - 1) - \varepsilon_{el}(N)$ |

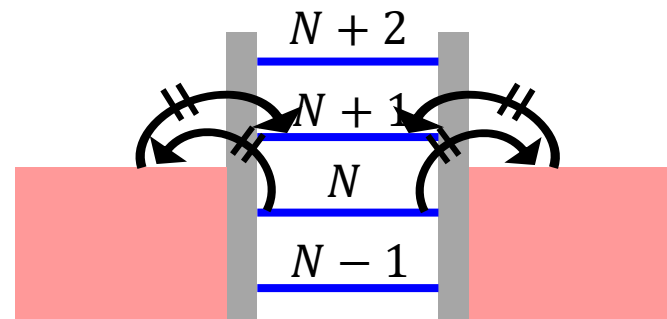


II.5 Coulomb Blockade

- capacitance model for SET: current flow at finite V_{SD}, V_G

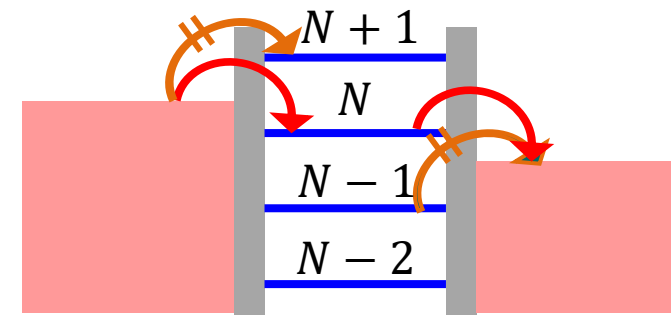
allowed and forbidden electron transfer processes:

- $T > 0$: all transfer processes are allowed (by thermal activation)
- $T = 0$: only transfer processes with $\Delta\varepsilon < 0$ are allowed



Coulomb blockade

$$\Delta\varepsilon_{\text{FL,TL,FR,TR}}(N) > 0$$



single electron tunneling

$$\Delta\varepsilon_{\text{FL}}(N) < 0$$

$$\Delta\varepsilon_{\text{TR}}(N) < 0$$

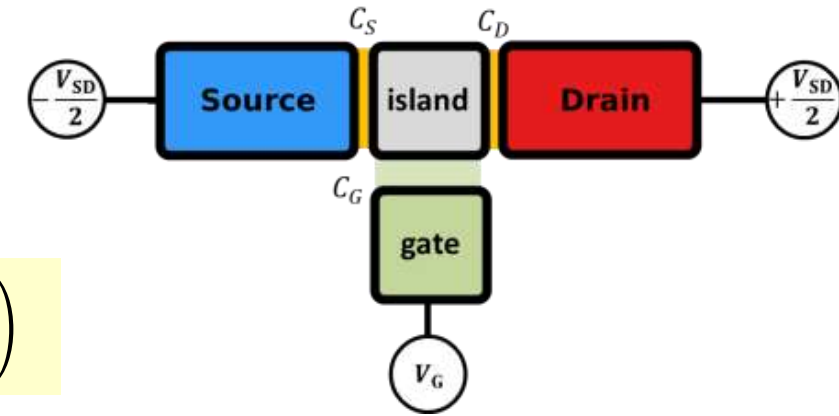
$$\Delta\varepsilon_{\text{FL}}(N+1) > 0$$

$$\Delta\varepsilon_{\text{TR}}(N-1) > 0$$

no second additional or missing electron on island !!

II.5 Coulomb Blockade

- capacitance model for SET: current flow at finite V_{SD} , V_G
 - in which range of V_{SD} and V_G is the electron transport blocked ?
 - assumptions: $C_S = C_D = C$, symmetric SD voltage bias



A
$$\varepsilon_{el}(N + 1) - \varepsilon_{el}(N) = \left(N + \frac{1}{2}\right) \frac{e^2}{C_\Sigma} - e \left(\frac{C}{C_\Sigma} V_{SD} + \frac{C_G}{C_\Sigma} V_G\right)$$

B
$$\varepsilon_{el}(N) - \varepsilon_{el}(N - 1) = \left(N - \frac{1}{2}\right) \frac{e^2}{C_\Sigma} + e \left(\frac{C}{C_\Sigma} V_{SD} + \frac{C_G}{C_\Sigma} V_G\right)$$

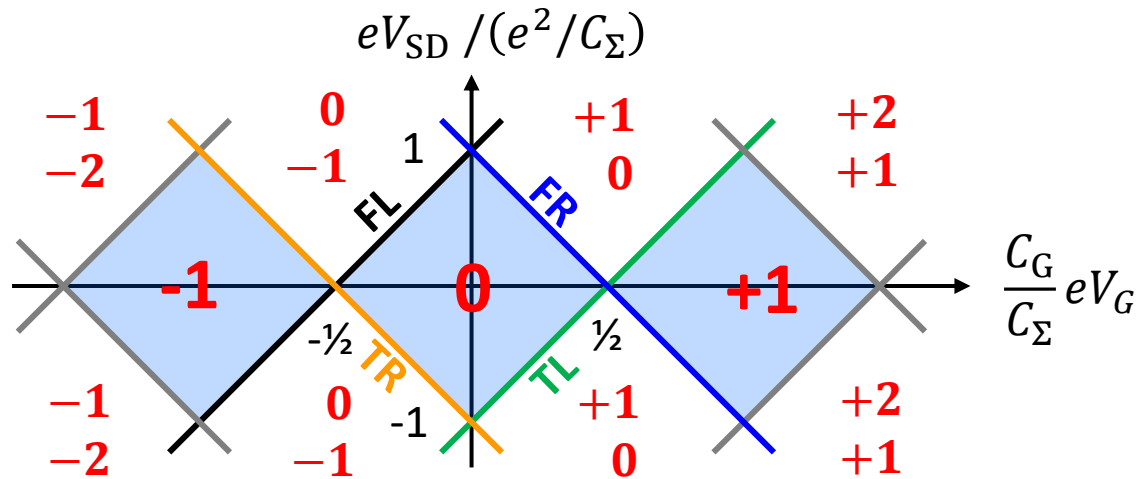
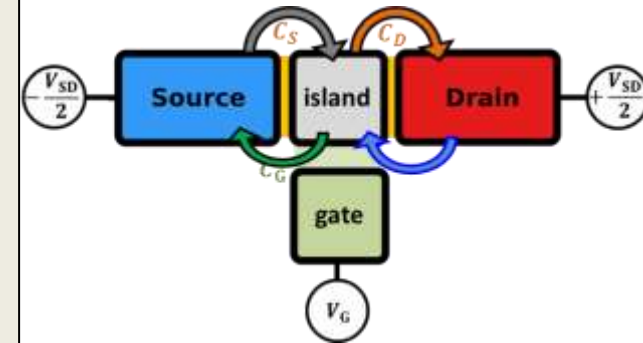
1. from the left:	$N \rightarrow N + 1$	$\Delta\varepsilon_{FL}(0) = \varepsilon(+1) - \varepsilon(0) = -\frac{1}{2} \frac{e^2}{C_\Sigma} - e \left(\frac{C}{C_\Sigma} V_{SD} + \frac{C_G}{C_\Sigma} V_G\right)$	$(N = -1, N + 1 = 0)$ A
2. to the left:	$N \rightarrow N - 1$	$\Delta\varepsilon_{TL}(0) = \varepsilon(-1) - \varepsilon(0) = -\frac{1}{2} \frac{e^2}{C_\Sigma} + e \left(\frac{C}{C_\Sigma} V_{SD} + \frac{C_G}{C_\Sigma} V_G\right)$	$(N = +1, N - 1 = 0)$ B
3. from the right:	$N - 1 \rightarrow N$	$\Delta\varepsilon_{FR}(0) = \varepsilon(0) - \varepsilon(-1) = +\frac{1}{2} \frac{e^2}{C_\Sigma} - e \left(\frac{C}{C_\Sigma} V_{SD} + \frac{C_G}{C_\Sigma} V_G\right)$	$(N - 1 = -1, N = 0)$ A
4. to the right:	$N + 1 \rightarrow N$	$\Delta\varepsilon_{TR}(0) = \varepsilon(0) - \varepsilon(+1) = +\frac{1}{2} \frac{e^2}{C_\Sigma} + e \left(\frac{C}{C_\Sigma} V_{SD} + \frac{C_G}{C_\Sigma} V_G\right)$	$(N + 1 = 1, N = 0)$ B

We consider processes where the final state is always the state with $N = 0$

II.5 Coulomb Blockade

- capacitance model for SET: current flow at finite V_{SD}, V_G

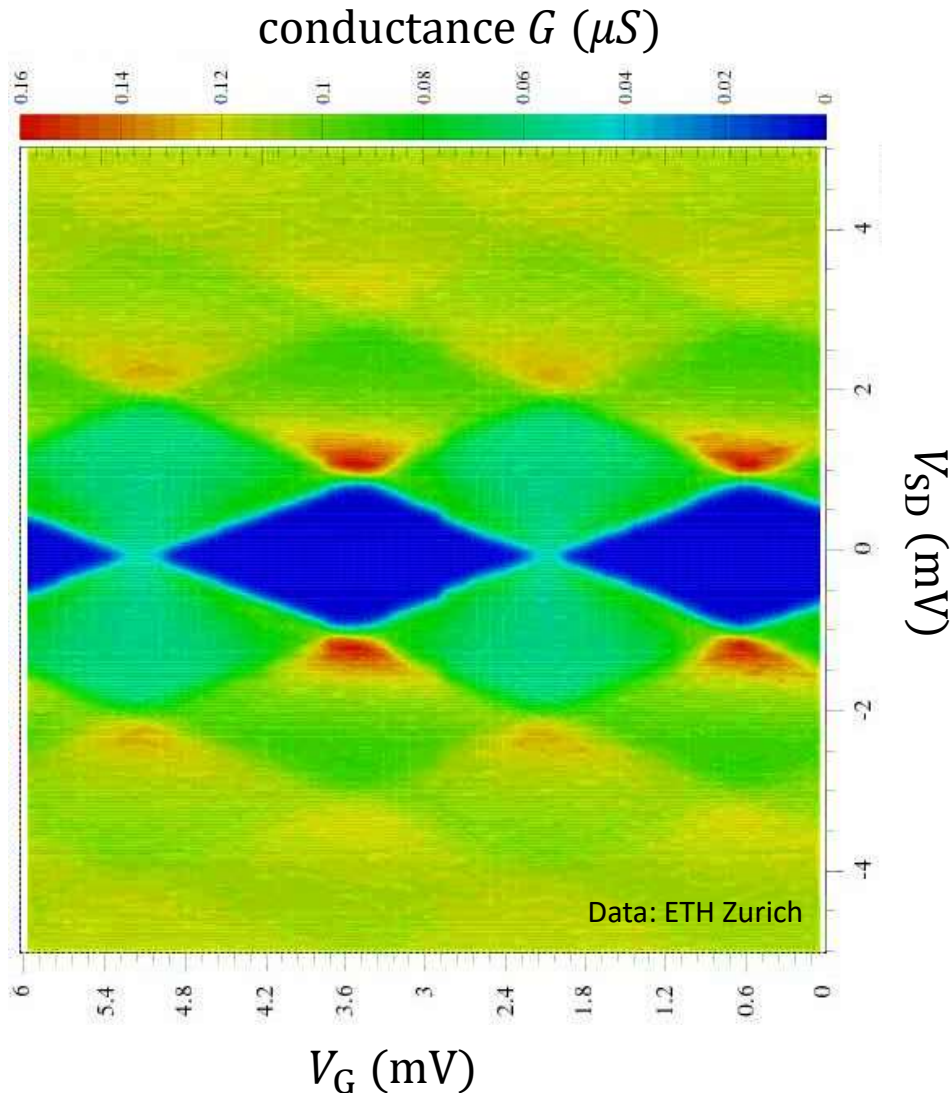
- from the left: $N \rightarrow N + 1$ $\Delta\varepsilon_{FL}(0) = \varepsilon(+1) - \varepsilon(0) = -\frac{1}{2} \frac{e^2}{C_\Sigma} - e \left(\frac{C}{C_\Sigma} V_{SD} + \frac{C_G}{C_\Sigma} V_G \right)$
- to the left: $N \rightarrow N - 1$ $\Delta\varepsilon_{TL}(0) = \varepsilon(-1) - \varepsilon(0) = -\frac{1}{2} \frac{e^2}{C_\Sigma} + e \left(\frac{C}{C_\Sigma} V_{SD} + \frac{C_G}{C_\Sigma} V_G \right)$
- from the right: $N - 1 \rightarrow N$ $\Delta\varepsilon_{FR}(0) = \varepsilon(0) - \varepsilon(-1) = +\frac{1}{2} \frac{e^2}{C_\Sigma} - e \left(\frac{C}{C_\Sigma} V_{SD} + \frac{C_G}{C_\Sigma} V_G \right)$
- to the right: $N + 1 \rightarrow N$ $\Delta\varepsilon_{TR}(0) = \varepsilon(0) - \varepsilon(+1) = +\frac{1}{2} \frac{e^2}{C_\Sigma} + e \left(\frac{C}{C_\Sigma} V_{SD} + \frac{C_G}{C_\Sigma} V_G \right)$



blue areas mark blockade regimes:
„Coulomb diamonds“

II.5 Coulomb Blockade

- capacitance model for SET: current flow at finite V_{SD} , V_G

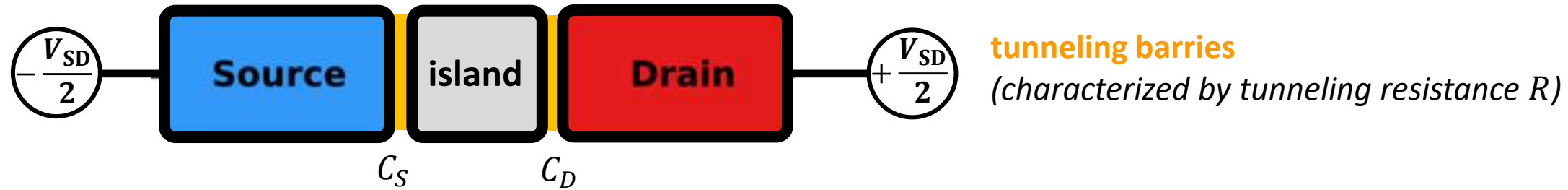


Single Electron Transistor – Coulomb Diamonds:

blue regions of vanishing conductance correspond to the Coulomb blockade regime (no current flow)

II.5 Coulomb Blockade

- capacitance model for SET: current flow at finite V_{SD} , V_G



weak coupling of island to metallic leads (reservoirs)

→ too weak: no electron transfer

→ too strong: no conservation of charge number, no single electron effects



too little



just right



too much

II.5 Coulomb Blockade

- requirements for the experimental observation of the Coulomb blockade:

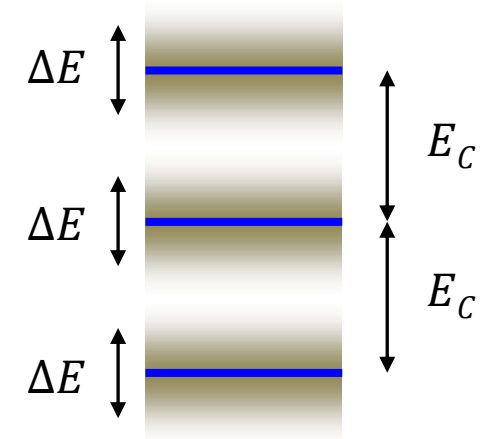
- thermal fluctuations must be small enough:

$$E_c = \frac{e^2}{2C} > k_B T \Rightarrow C < \frac{e^2}{2k_B T} \approx 1 \text{ fF @ 1 K}$$

- quantum fluctuations must be small enough:

$$E_c = \frac{\hbar}{\tau} \simeq \underbrace{\frac{\hbar}{RC}}_{\text{level broadening } \Delta E} \Rightarrow R > \frac{h}{e^2} = R_Q \simeq 25 \text{ k}\Omega$$

$R_Q = \text{quantum resistance}$



- requirement for voltage:

$$E_c > eV \Rightarrow V < \frac{e}{2C} \approx 80 \mu\text{V @ 1 fF}$$

II.5 Coulomb Blockade

- **SET: current-voltage characteristics**
 - facts:
 - (i) charging state is determined by N
 - (ii) no quantum coherence between different states
 - probability $p_N(t)$ to find system in state N at time t :
 - given by *Master equation*

$$\frac{d}{dt} p_N(t) = - \underbrace{[\Gamma_F(N) + \Gamma_T(N)] p_N(t)}_{\substack{\text{tunneling from} \\ \text{and to island} \\ \text{with } N \text{ electrons}}} + \underbrace{\Gamma_T(N-1) p_{N-1}(t)}_{\substack{\text{tunneling to island} \\ \text{with } N-1 \text{ electrons}}} + \underbrace{\Gamma_F(N+1) p_{N+1}(t)}_{\substack{\text{tunneling from island} \\ \text{with } N+1 \text{ electrons}}}$$

with tunneling rates $\Gamma_F = \Gamma_{FL} + \Gamma_{FR}$ and $\Gamma_T = \Gamma_{TL} + \Gamma_{TR}$

- if we know p_N for stationary state, we get currents as

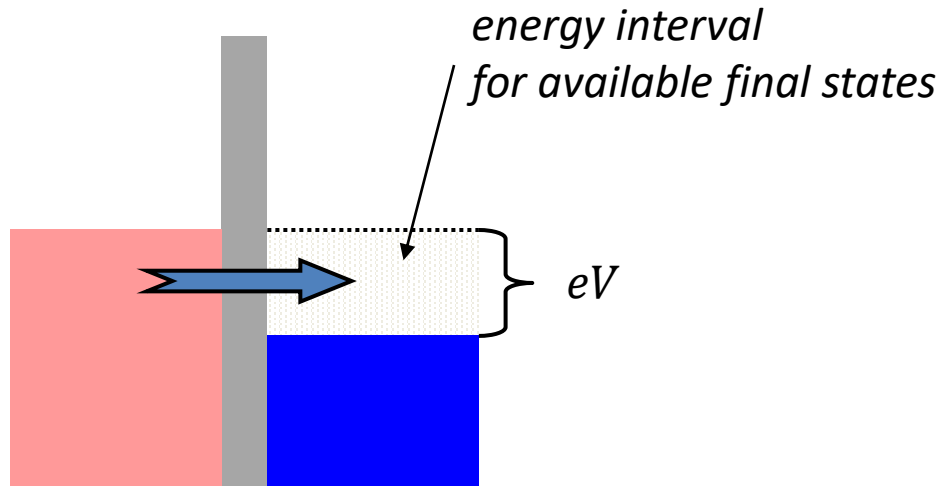
$$\left. \begin{aligned} I_L &= e \sum_N [\Gamma_{FL}(N) - \Gamma_{TL}(N)] p_N \\ I_R &= e \sum_N [\Gamma_{TR}(N) - \Gamma_{FR}(N)] p_N \end{aligned} \right\} I = I_L + I_R$$

II.5 Coulomb Blockade

- SET: current-voltage characteristics

tunneling rates for single tunnel junction:

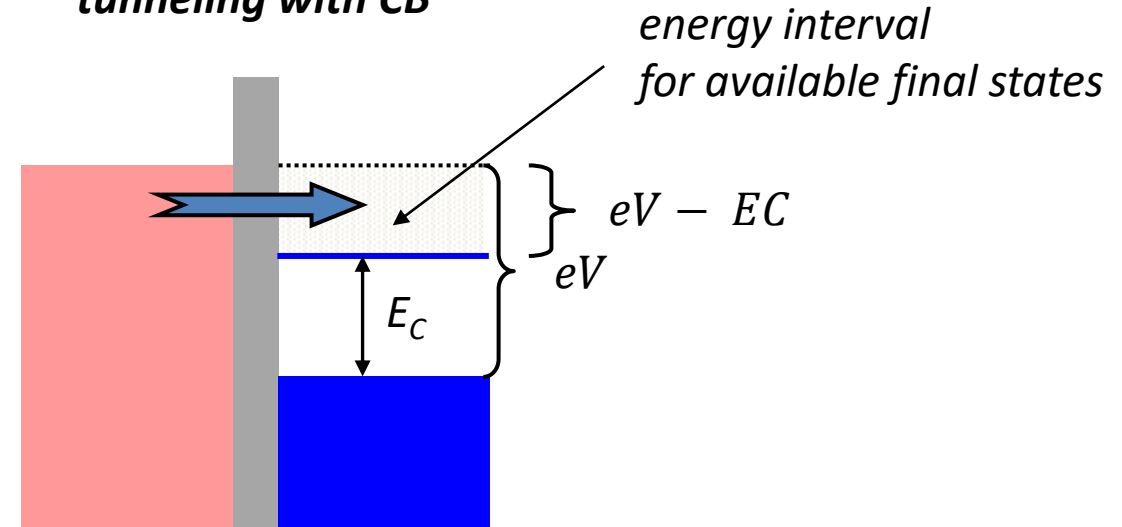
tunneling without CB



$$I = G_{\text{tun}} V$$

tunneling rate: $\Gamma_{\text{tun}} = \frac{I}{e} = \frac{G_{\text{tun}}}{e^2} eV$

tunneling with CB

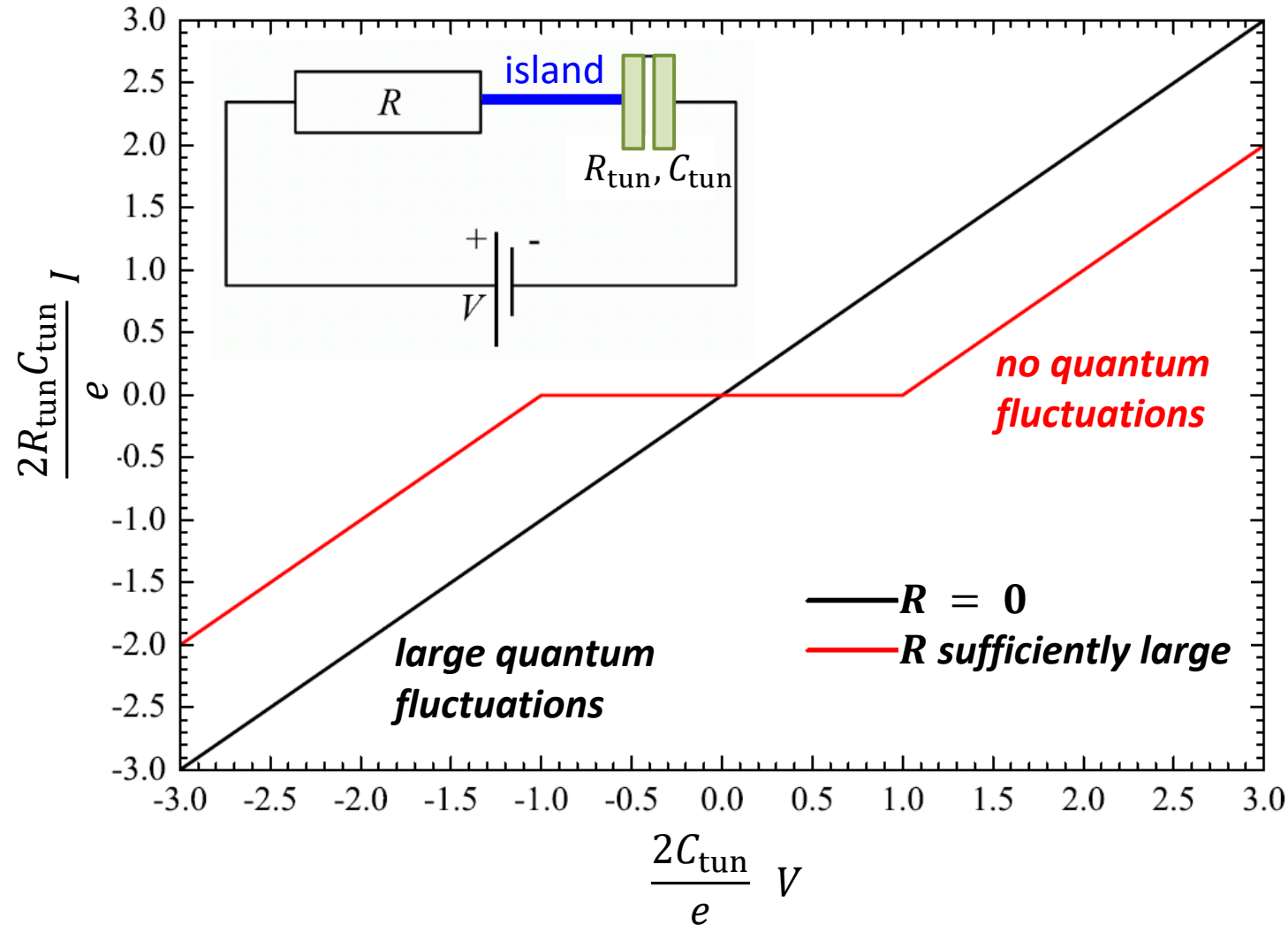


tunneling rate: $\Gamma_{\text{tun}} = 0$ for $eV < E_c$
blockade regime

$$\Gamma_{\text{tun}} = \frac{G_{\text{tun}}}{e^2} (eV - E_c) \quad \text{for } eV > E_c$$

II.5 Coulomb Blockade

- SET: current-voltage characteristics



IVC for tunneling with Coulomb blockade

II.5 Coulomb Blockade

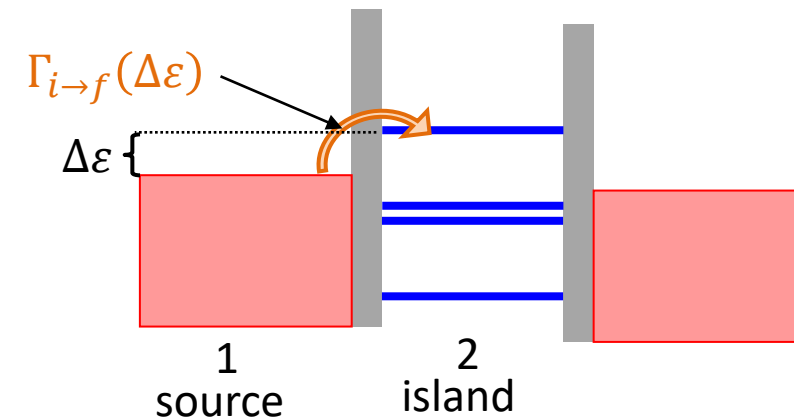
- SET: tunneling rates and IVC

- electrostatic energy changes as electron tunnels
 → determine tunneling rate at electron energy change of $\Delta\varepsilon$:

$$\Gamma_{i \rightarrow f} = \frac{2\pi}{\hbar} |\langle i | H_{\text{tun}} | f \rangle|^2 \delta(\varepsilon_f - \varepsilon_i - \Delta\varepsilon)$$

Fermi's Golden Rule

- total transition rate from conductor 1 (source) to 2 (island):
 - tunneling rate proportional to density of states $D(\varepsilon)$
 - occupation probability given by Fermi functions $f(\varepsilon)$
 - integration over all energies



$$\Gamma_{i \rightarrow f}(\Delta\varepsilon) = \frac{2\pi}{\hbar} \int_{-\infty}^{\infty} d\varepsilon |\langle i | H_{\text{tun}} | f \rangle|^2 \underbrace{D_i(\varepsilon) f(\varepsilon)}_{\text{occupied initial states}} \underbrace{D_f(\varepsilon + \Delta\varepsilon) [1 - f(\varepsilon + \Delta\varepsilon)]}_{\text{empty final states}}$$

II.5 Coulomb Blockade

- SET: tunneling rates and IVC

- simplifying assumptions:

- H_{tun} is energy independent

- $D(\varepsilon)$ is energy independent

$$\Rightarrow f(\varepsilon)[1 - f(\varepsilon + \Delta\varepsilon)] = \frac{f(\varepsilon) - f(\varepsilon + \Delta\varepsilon)}{1 - \exp(\Delta\varepsilon/k_B T)}$$

at low T : Fermi functions \approx step functions

$$\Rightarrow \Gamma_{i \rightarrow f}(\Delta\varepsilon) = \frac{1}{e^2 R_{\text{tun}}} \frac{\Delta\varepsilon}{\exp(\Delta\varepsilon/k_B T) - 1}$$

with

$$R_{\text{tun}} = \frac{\hbar}{2\pi e^2} D^2 |\langle i | H_{\text{tun}} | f \rangle|^2$$

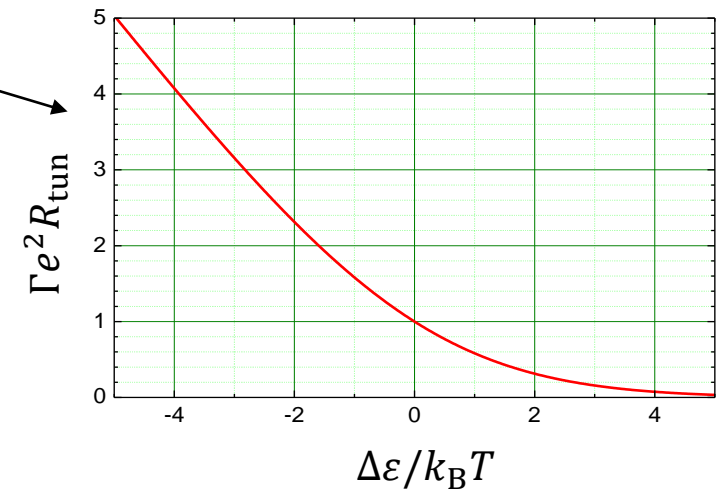
- net current

$$I = e [\Gamma_{1 \rightarrow 2}(\Delta\varepsilon_{1 \rightarrow 2}) - \Gamma_{2 \rightarrow 1}(\Delta\varepsilon_{2 \rightarrow 1})]$$

- current from current source (1) to island (2) in steady state

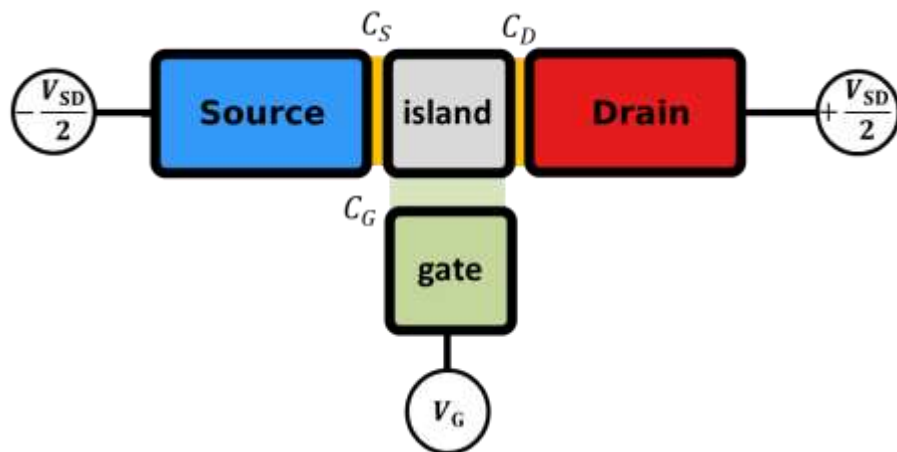
$$I = e \sum_N p(N) \{ \Gamma_{1 \rightarrow 2} [\Delta\varepsilon_{1 \rightarrow 2}(N)] - \Gamma_{2 \rightarrow 1} [\Delta\varepsilon_{2 \rightarrow 1}(N)] \}$$

(equivalent expression for current from island to drain)

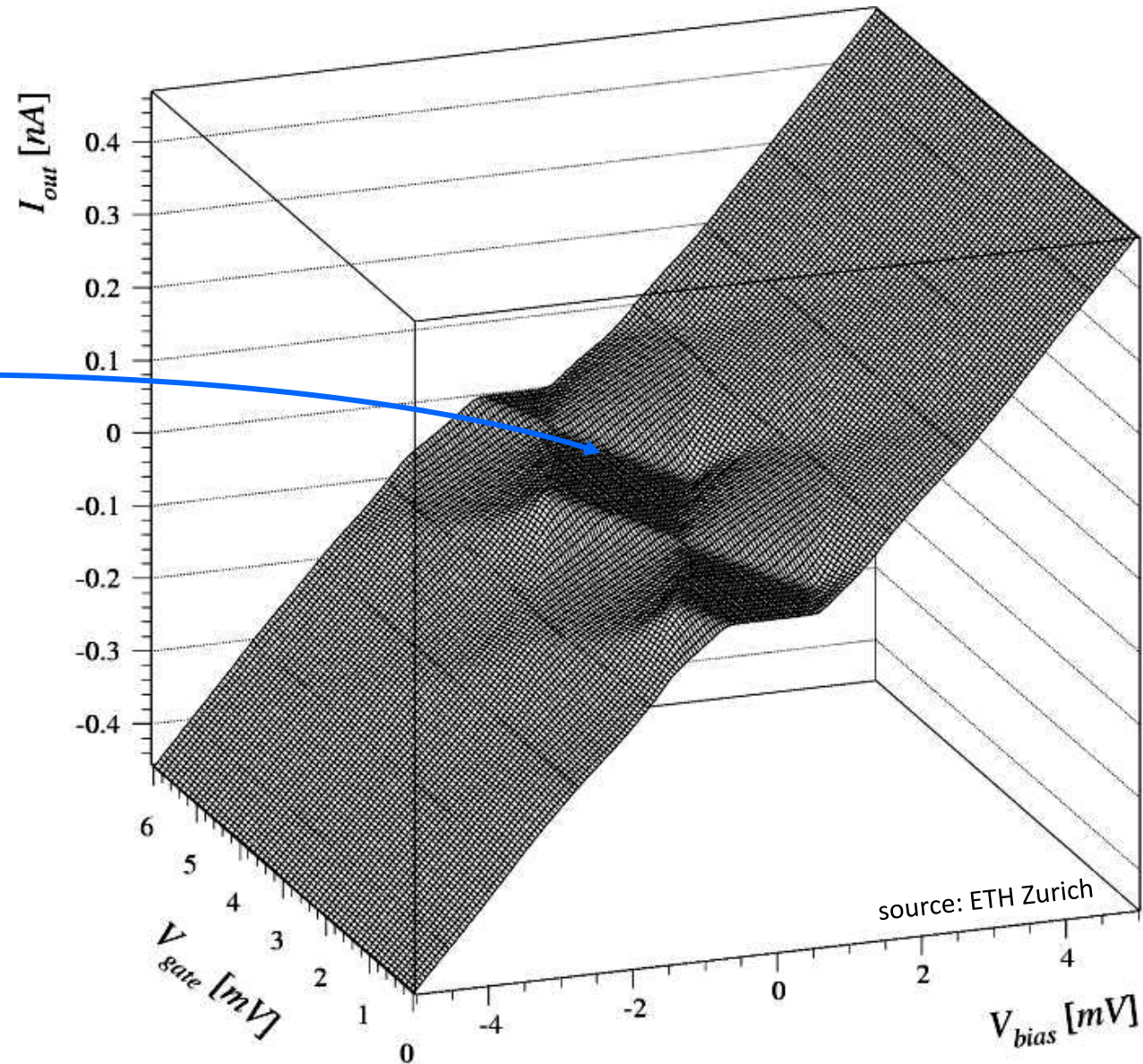


II.5 Coulomb Blockade

- SET: current-voltage characteristics

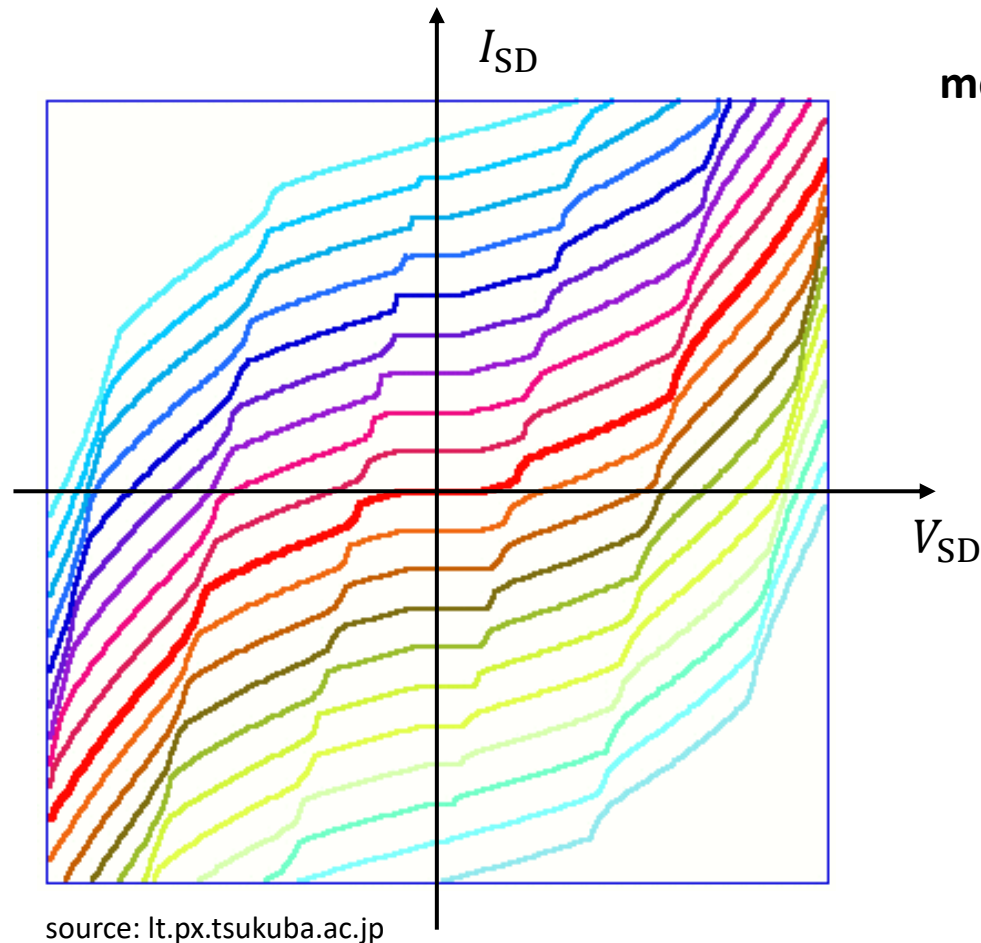


Coulomb diamonds



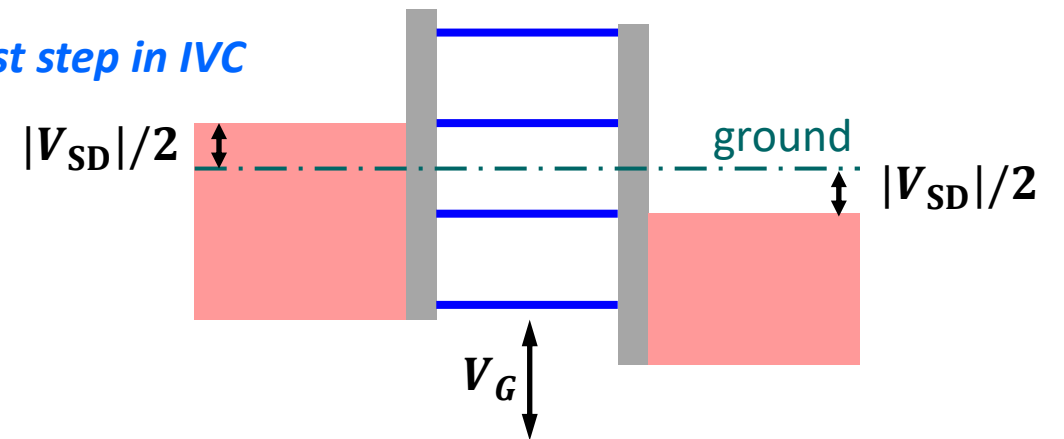
II.5 Coulomb Blockade

- SET: current-voltage characteristics - Coulomb staircase

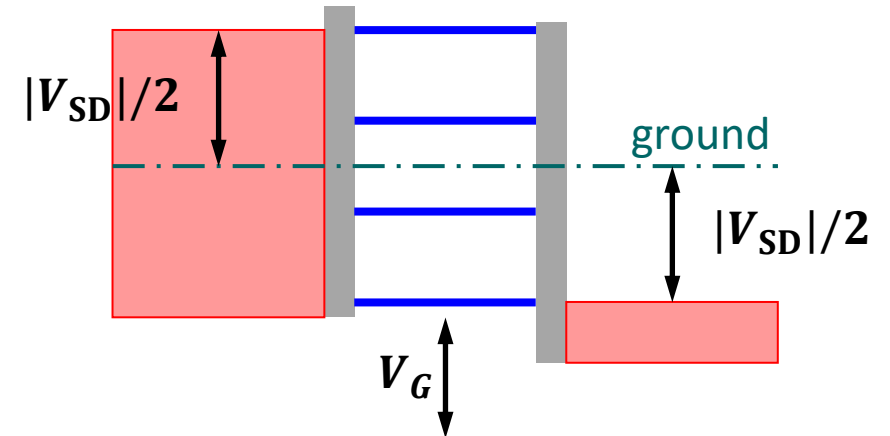


movie shows variation of IVC with varying gate voltage

1st step in IVC

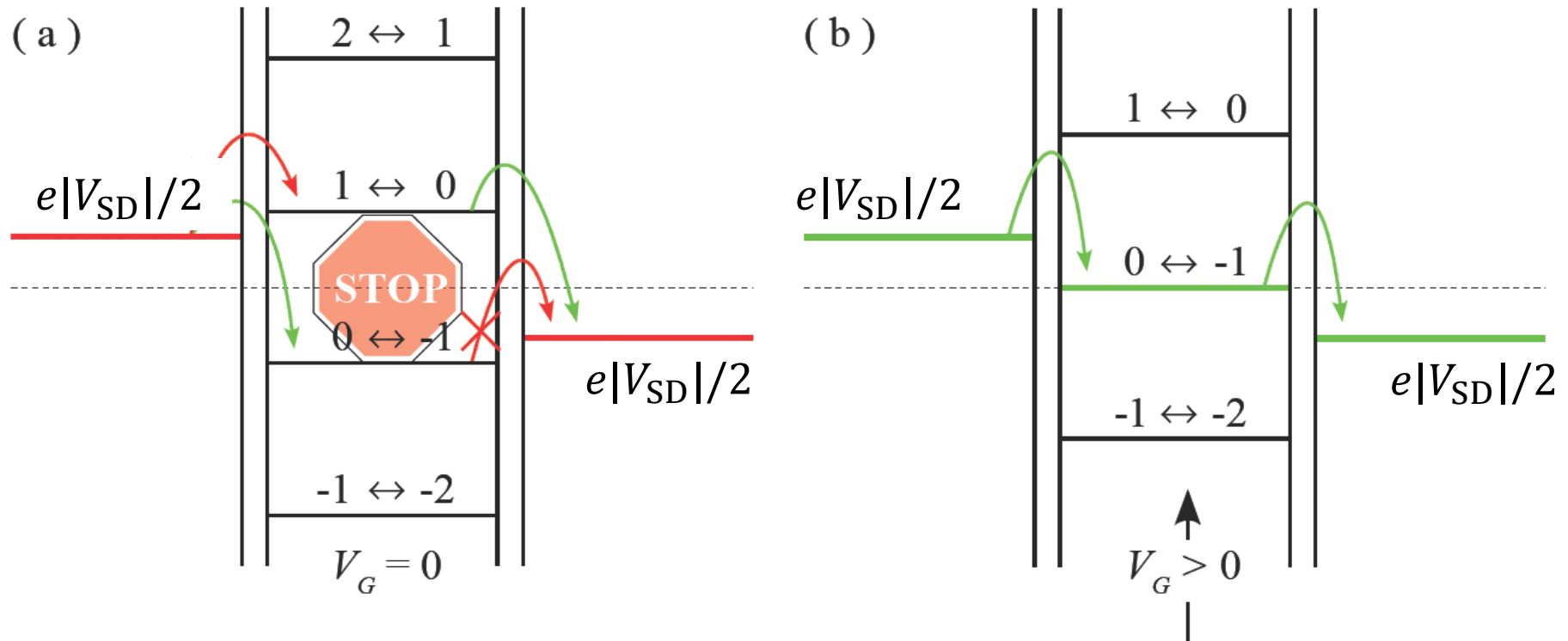


2nd step in IVC



II.5 Coulomb Blockade

- SET: variation of the gate voltage – Coulomb oscillations:

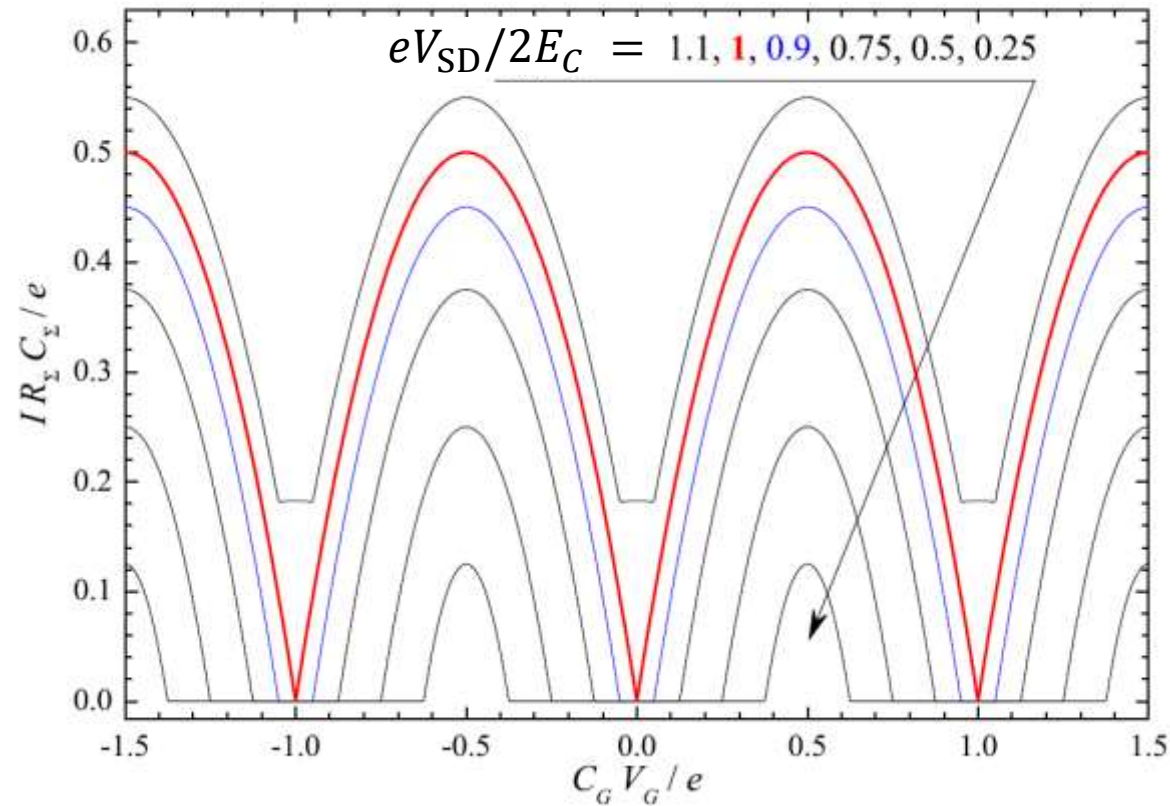


- gate voltage shifts up and down the energy levels of the island
- at small SD-voltages: *conductance can be varied considerably by gate voltage*

→ **Coulomb Oscillations**

II.5 Coulomb Blockade

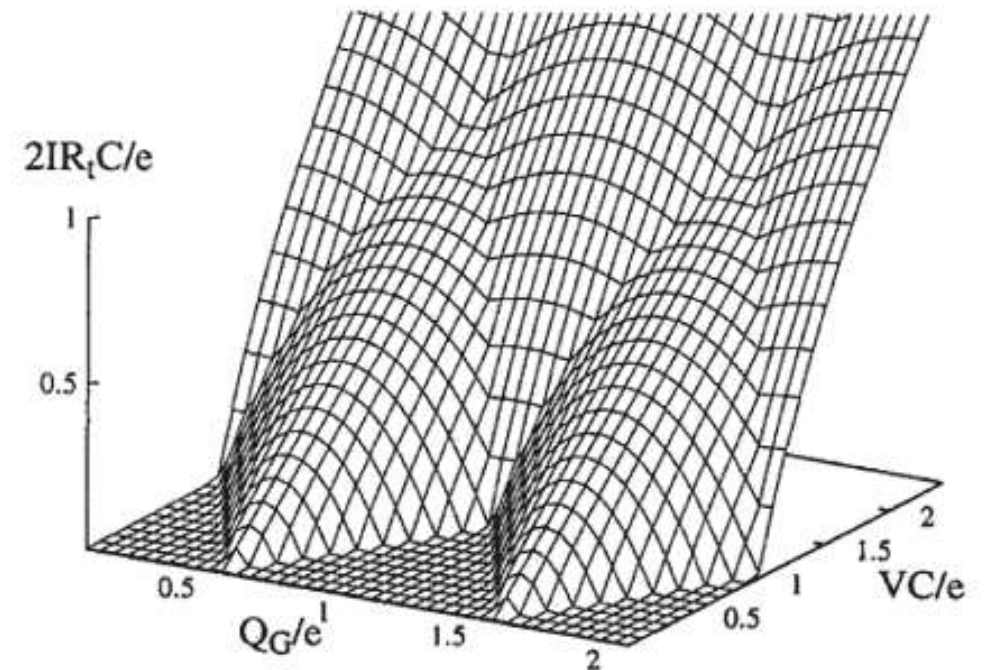
- SET: variation of the gate voltage – Coulomb oscillations:



note:

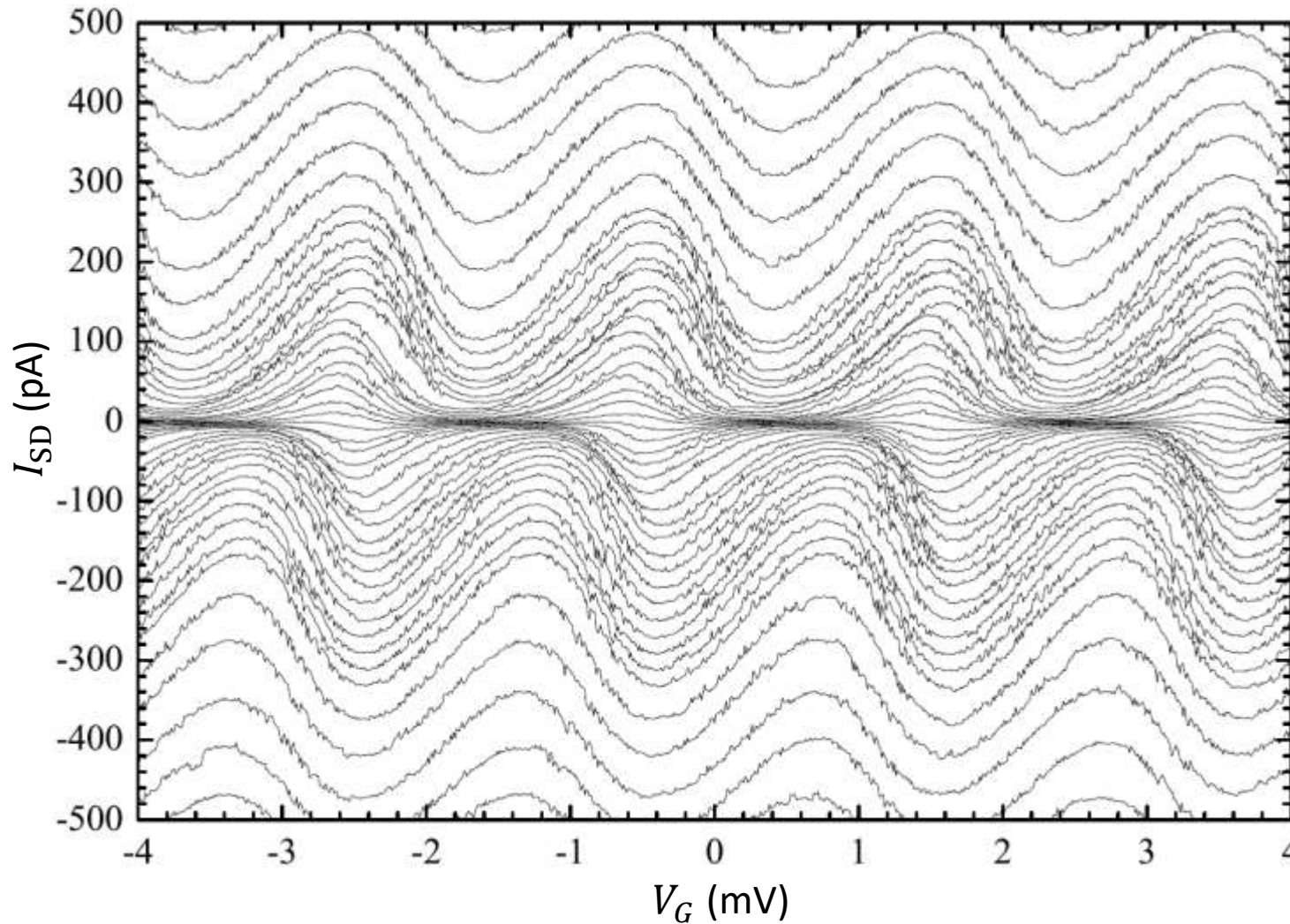
- large dI_{SD} / dV_G

➔ *use as ultra-sensitive electrometer*



II.5 Coulomb Blockade

- SET: variation of the gate voltage – Coulomb oscillations:



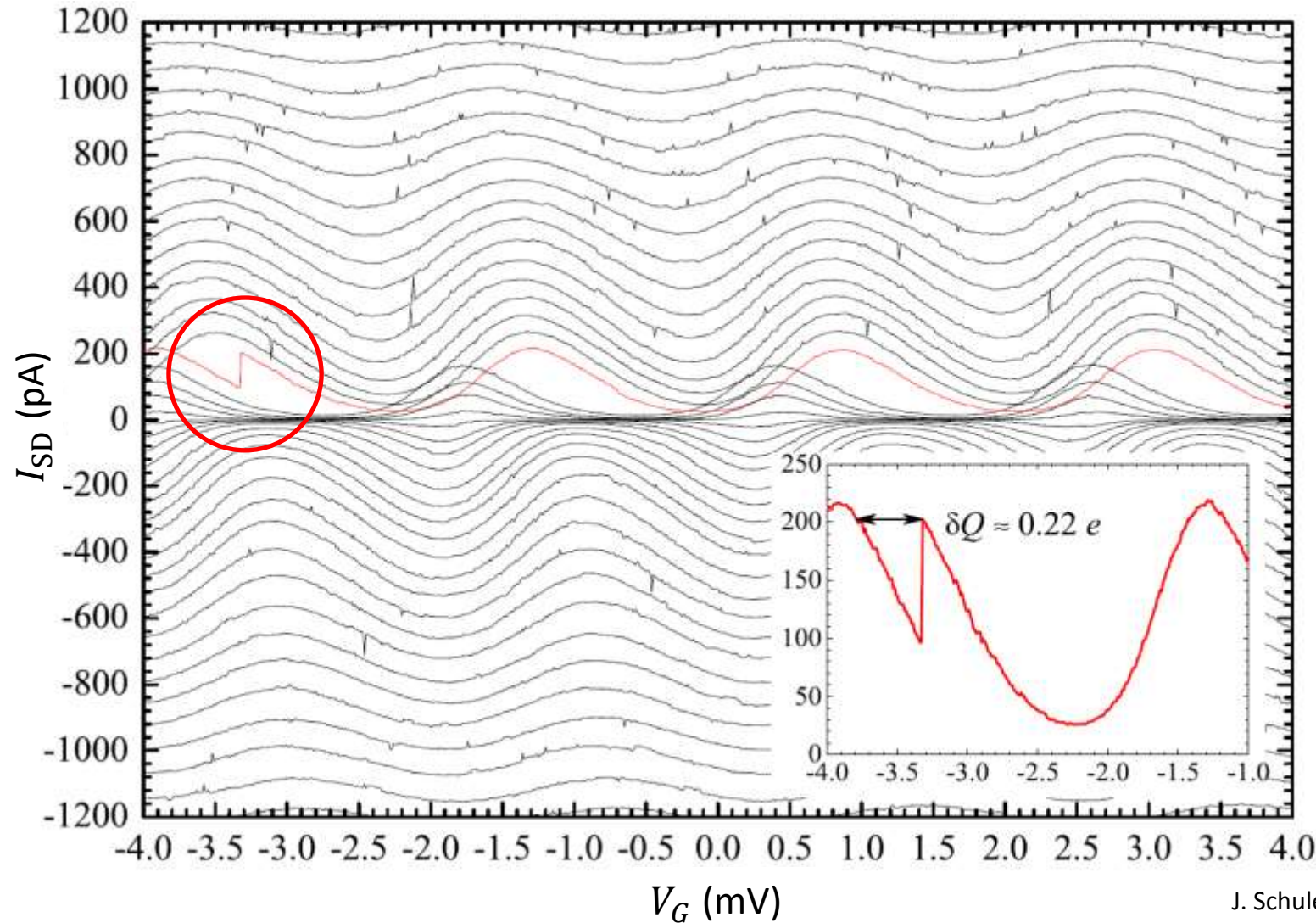
*experimental data on
Al/AIO_x/Al/AIO_x/Al - SET*

V_{SD} is varied for
different curves

J. Schuler, Ph.D. Thesis (WMI 2005)

II.5 Coulomb Blockade

- SET Coulomb oscillations - effect of single fluctuating background charges



$Al/AIO_x/Al/AIO_x/Al$ - SET

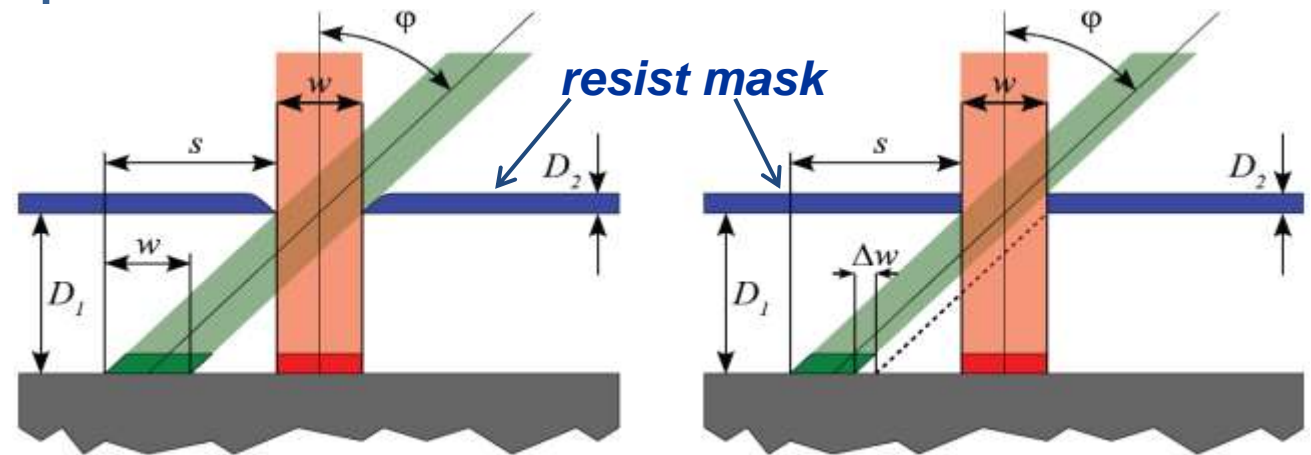
shift of $I_{SD}(V_G)$ curve due to fluctuating background charge

J. Schuler, Ph.D. Thesis (WMI 2005)

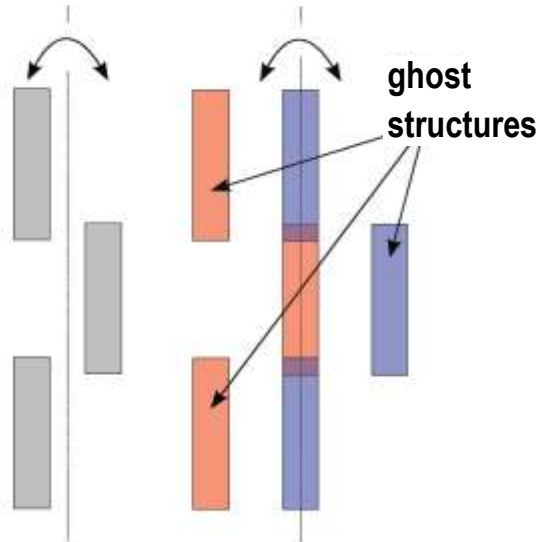
II.5 Coulomb Blockade

- SET fabrication by two-angle shadow evaporation

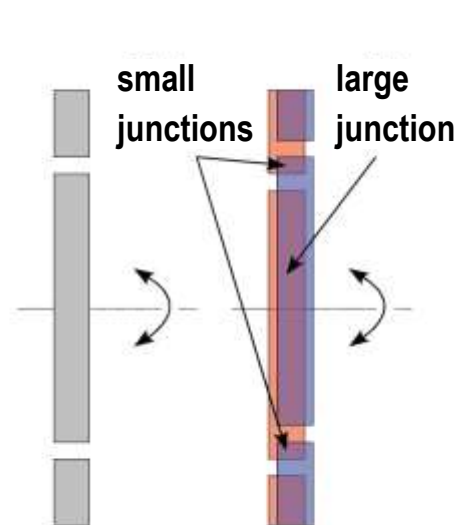
fabrication of sub- μm Josephson Junctions by shadow vaporation technique



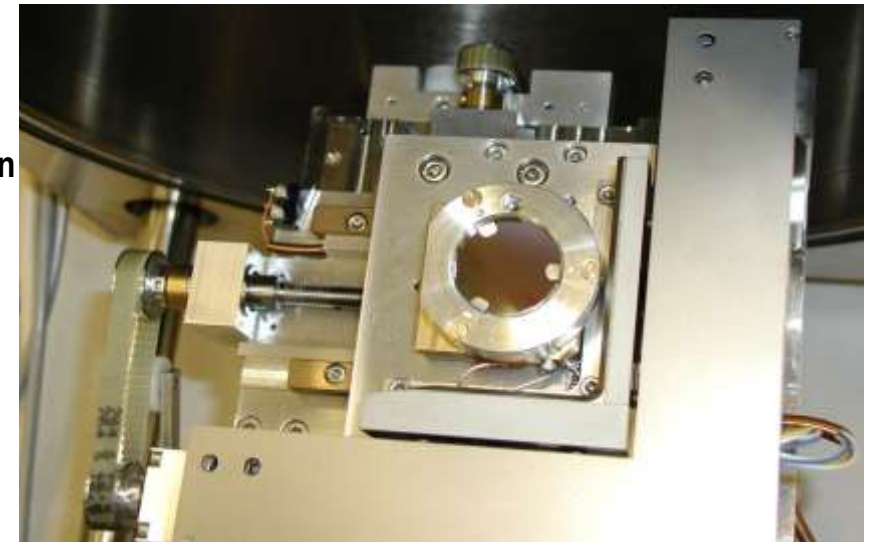
resist mask structure



resist mask structure



resist mask
 first layer
 second layer
 tunnel junction

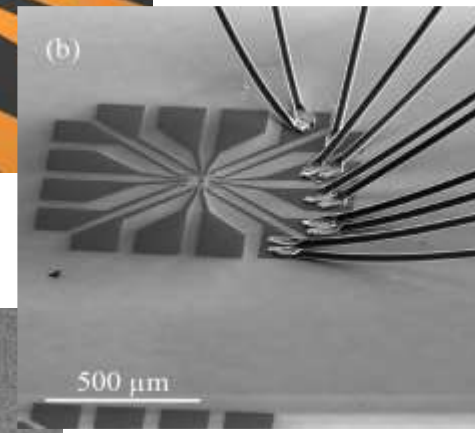


J. Schuler, Ph.D Thesis (2005)

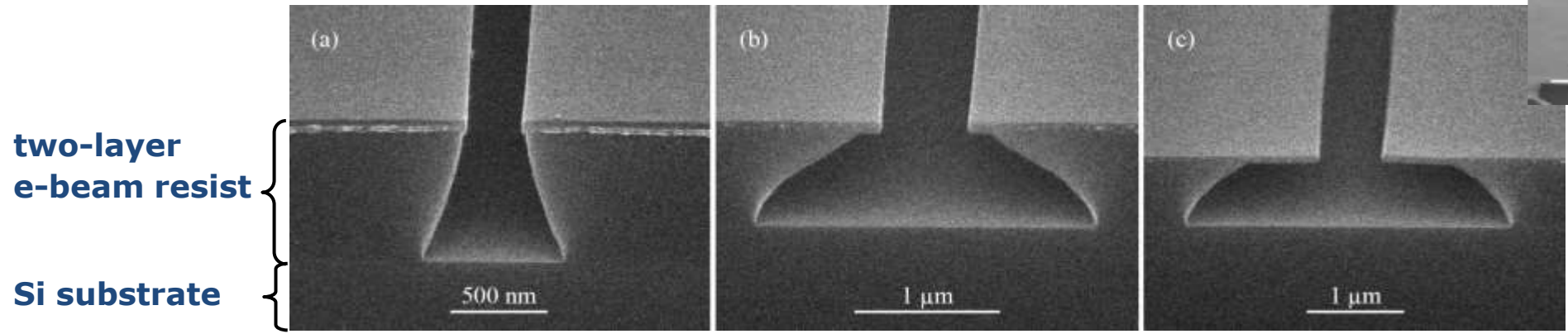
II.5 Coulomb Blockade

- SET fabrication by two-angle shadow evaporation

Optical Lithography

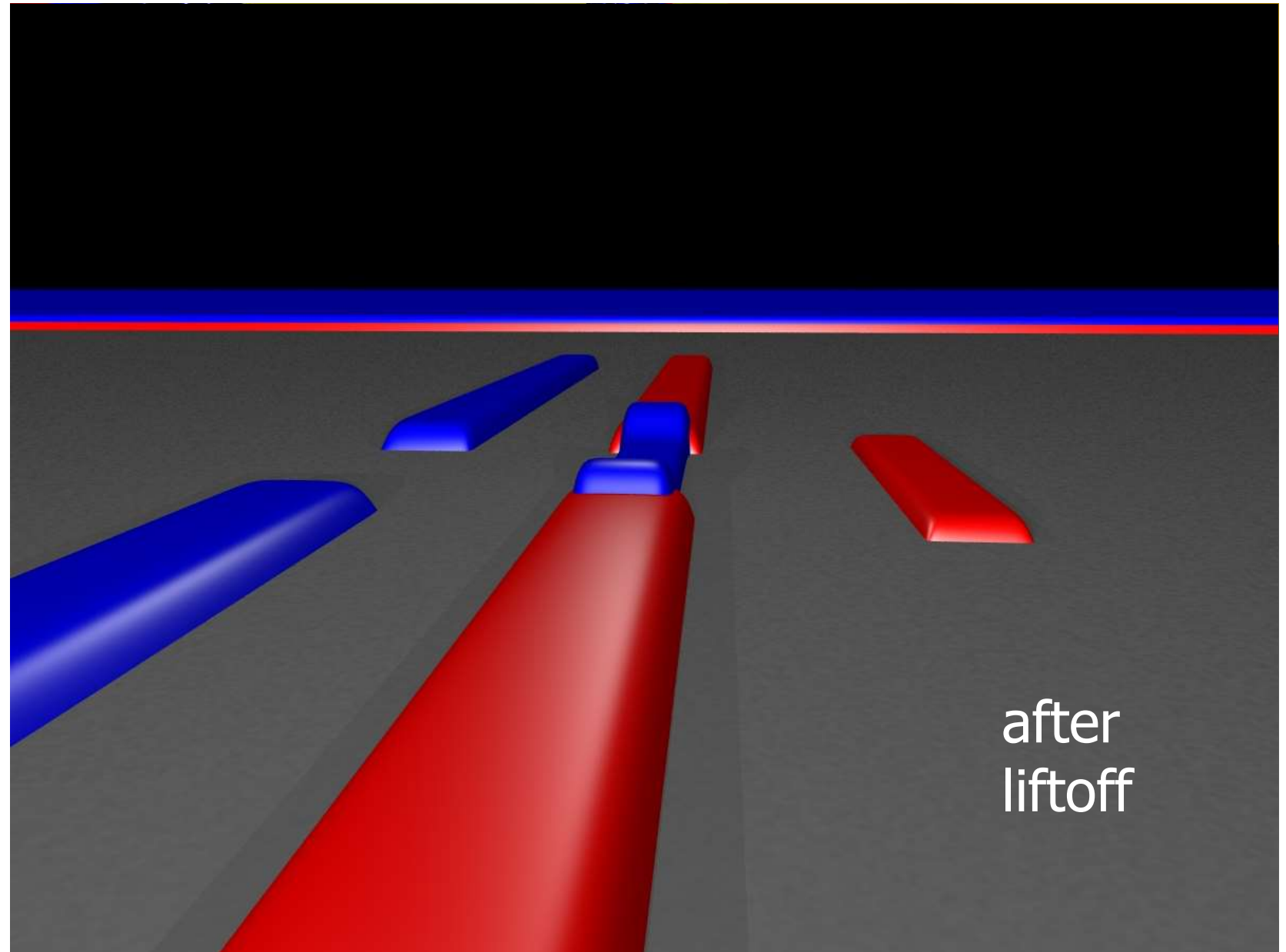


Electron Beam Lithography



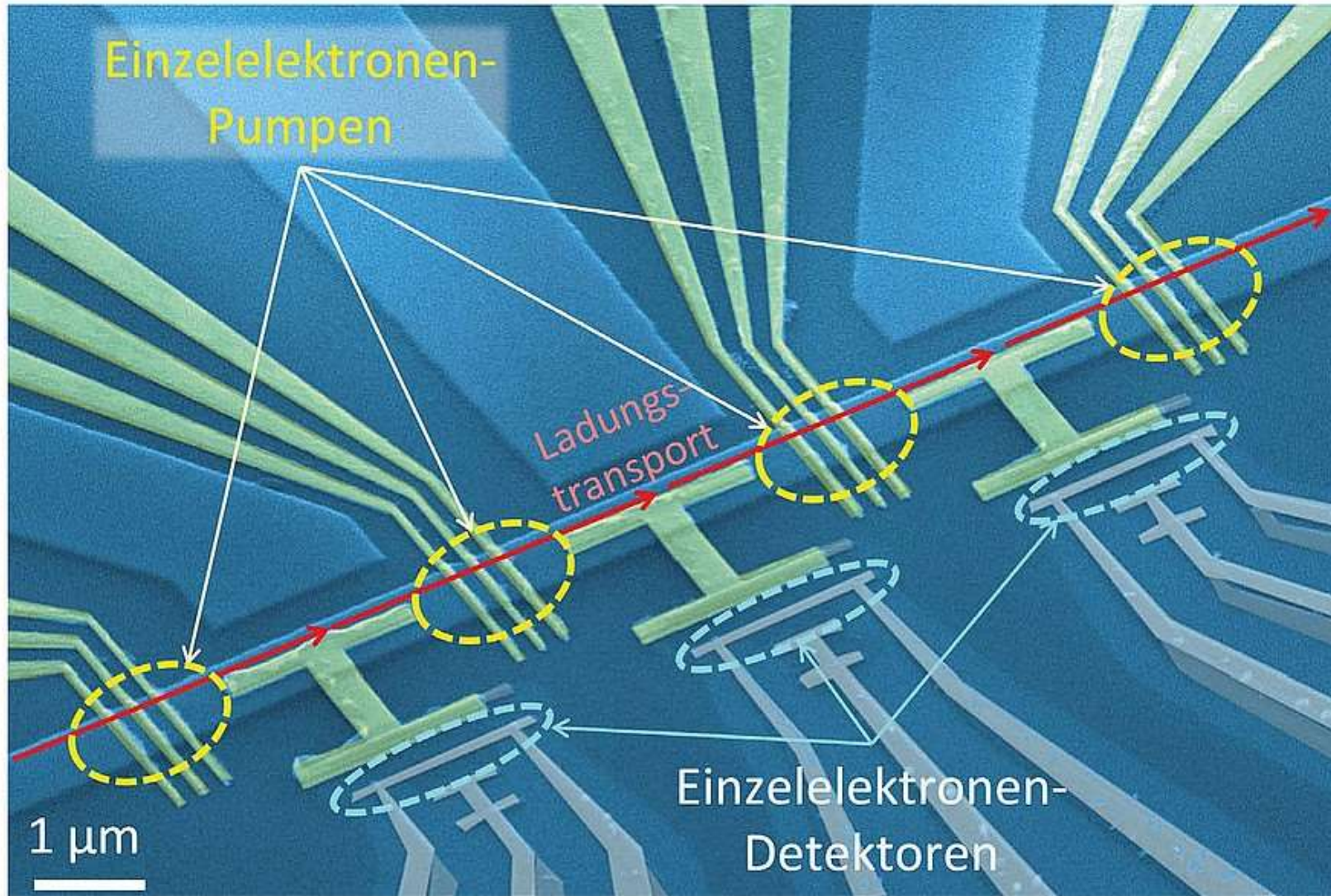
II.5 Coulomb Blockade

- SET fabrication by two-angle shadow evaporation



II.5 Coulomb Blockade

- SET application: single electron detector

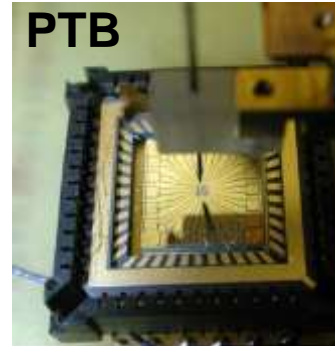


prototype of a self-referenced quantum current source developed at PTB with four semiconductor single-electron current sources (“single-electron pumps”) connected in series and three **metallic single electron detectors**

II.5 Coulomb Blockade

- SET applications

- sensitive electrometers: $\frac{\Delta Q}{Q} \simeq 10^{-5} e$



- electron pumps

- transporting electrons one by one:
counting of electrons

- current standard: $I = e \cdot f$

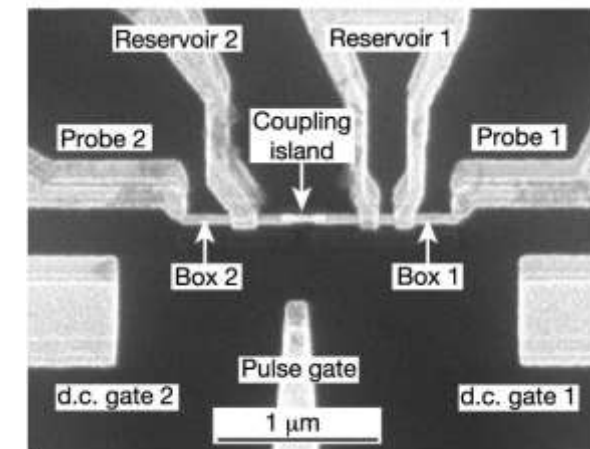
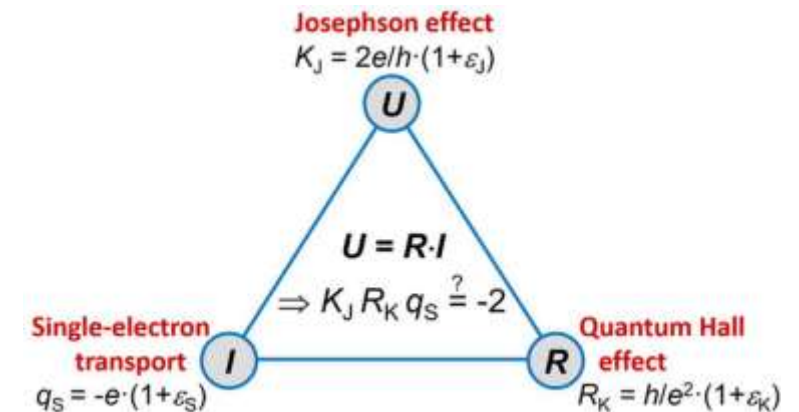
- application of oscillating gate voltage

- charge Qubits

- basic element for quantum information systems

[Quantum oscillations in two coupled charge qubits](#)

Yu. A. Pashkin, T. Yamamoto, O. Astafiev, Y. Nakamura, D. V. Averin and J. S. Tsai
Nature 421, 823-826(20 February 2003)

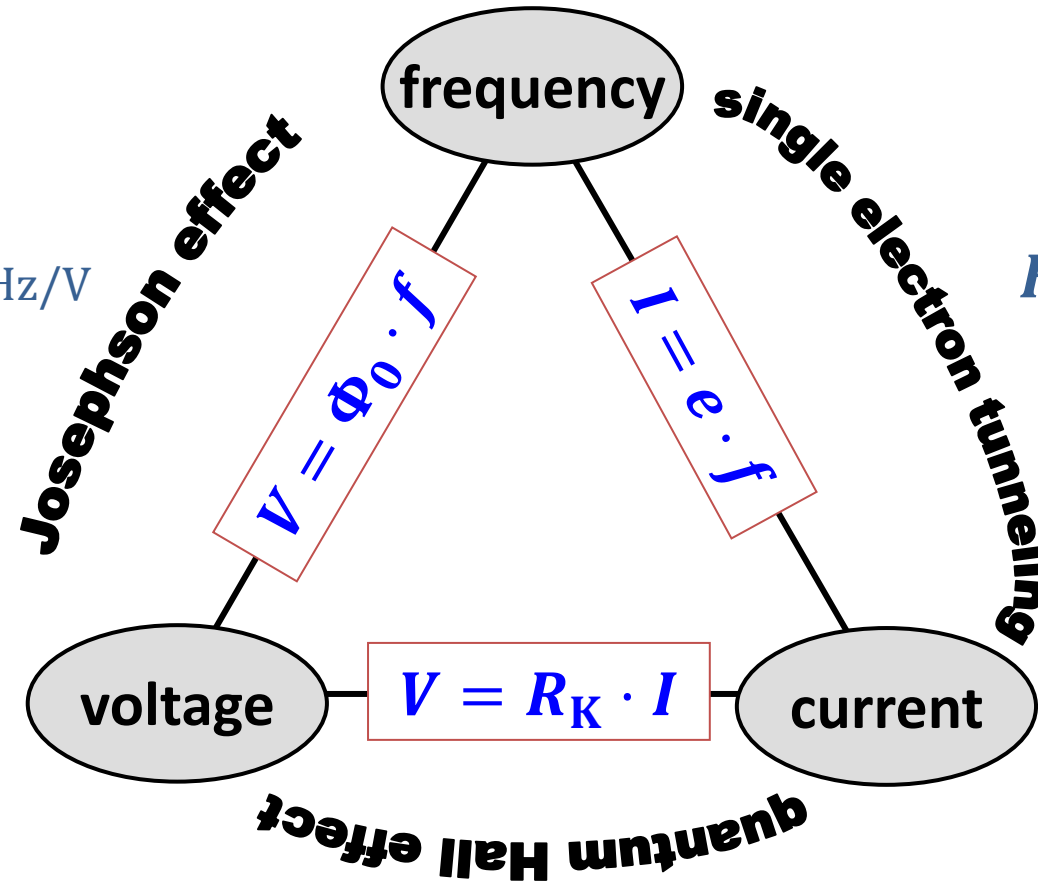


II.5 Coulomb Blockade

- SET applications – the quantum metrology triangle

$$K_J = \frac{2e}{h} = \frac{1}{\Phi_0}$$

$$= 483\,597.848\,4 \dots \text{ GHz/V}$$



$$K_I = 1/e \text{ not yet available}$$

$$R_K = \frac{h}{e^2} = 25\,812.807\,45 \dots \Omega$$