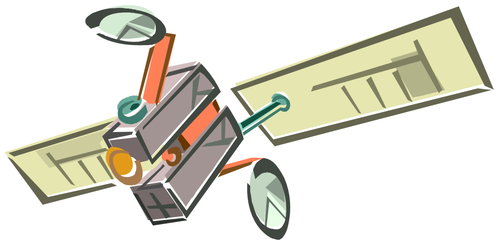
Lectures 14+15

Electronics

microlectronics

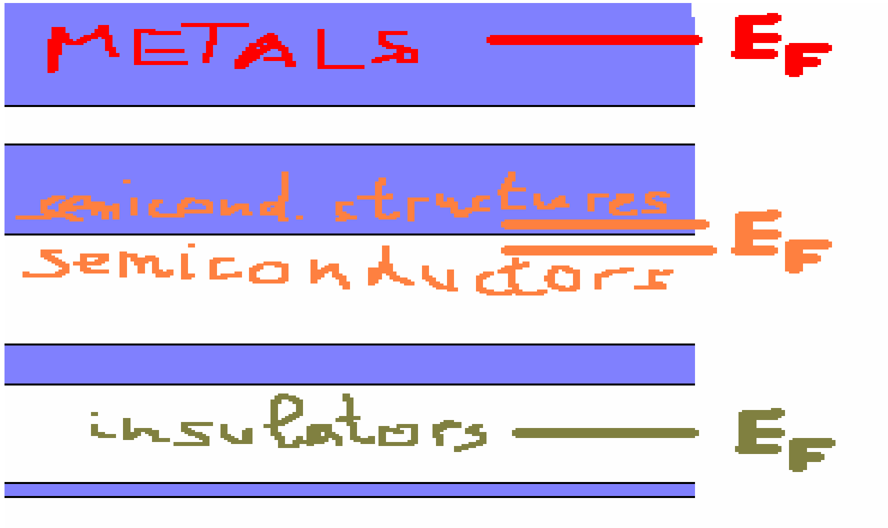
nanolectronics



Electronics =
electronic transport + sensitivity of transport characteristics to external conditions:
magnetic field,
temperature,
electromagnetic environment.

Electronics materials:
Semiconductors and semiconductor heterostructures
Normal and Ferromagnetic metals, Superconductor

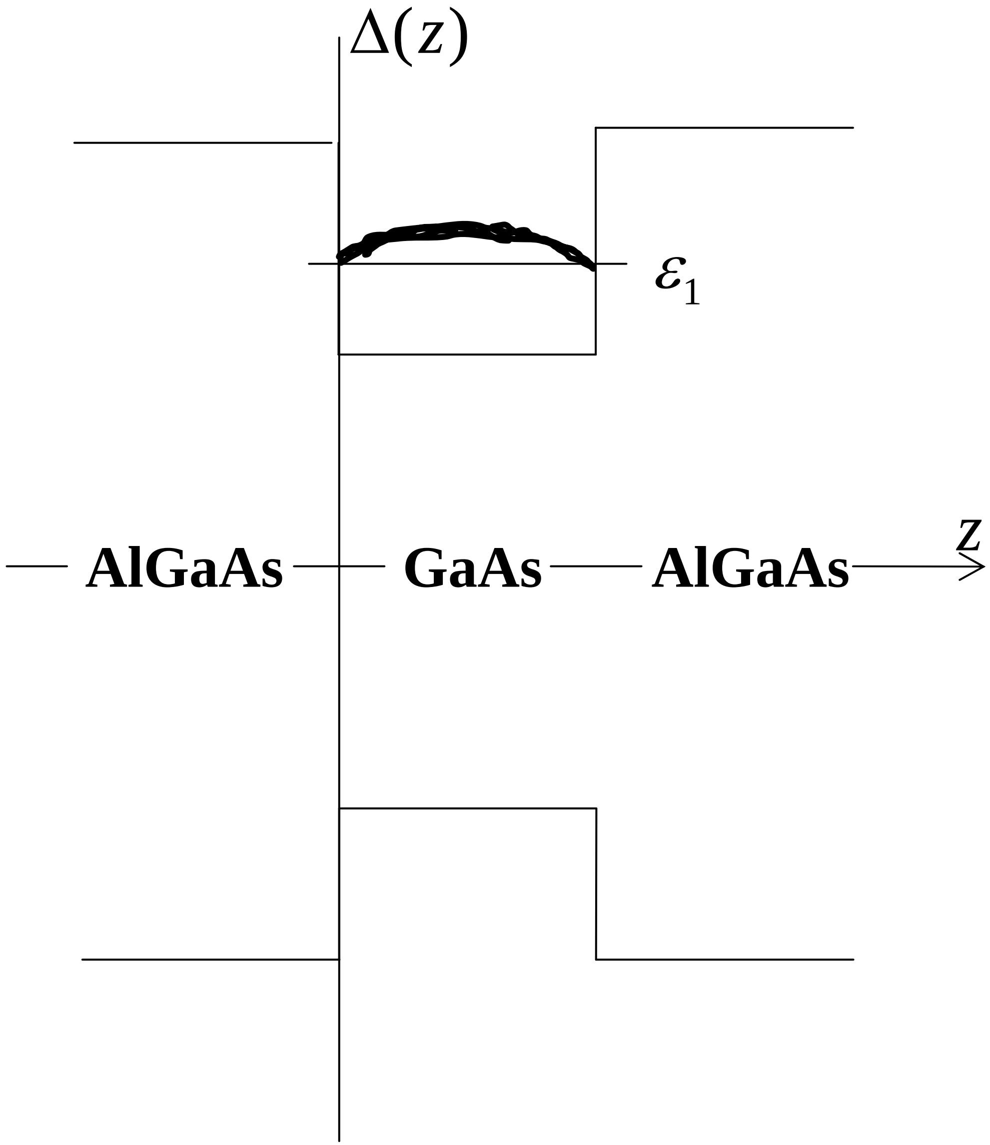
Electron dynamics in each material is determined by



band structure ~1eV

correlations <1meV

Semiconductor quantum wells



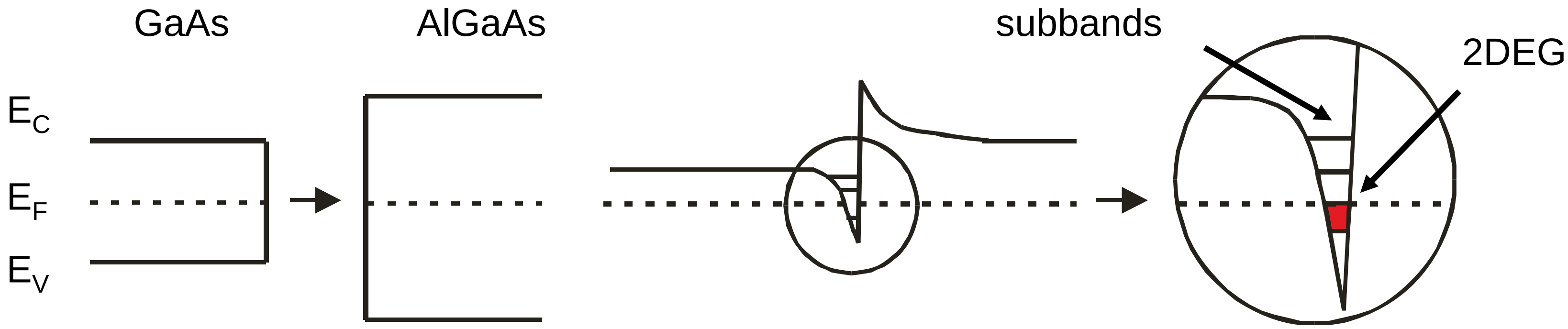
$$\varepsilon_1 = \frac{\pi^2\hbar^2}{2mw^2} \qquad \psi_1 \sim \sin\frac{\pi z}{w}$$

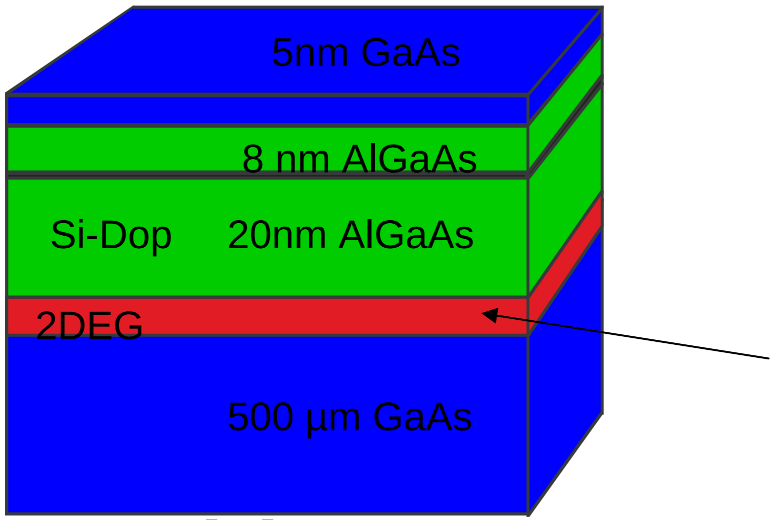
$$\varepsilon_2 = \frac{4\pi^2\hbar^2}{2mw^2} \qquad \psi_2 \sim \sin\frac{2\pi z}{w}$$

$$\varepsilon_3 = \frac{9\pi^2\hbar^2}{2mw^2} \qquad \psi_3 \sim \sin\frac{3\pi z}{w}$$

$$\varepsilon = \varepsilon_n + \frac{p_{\parallel}^2}{2m} \quad \textbf{subbands}$$

Semiconductor heterostructures





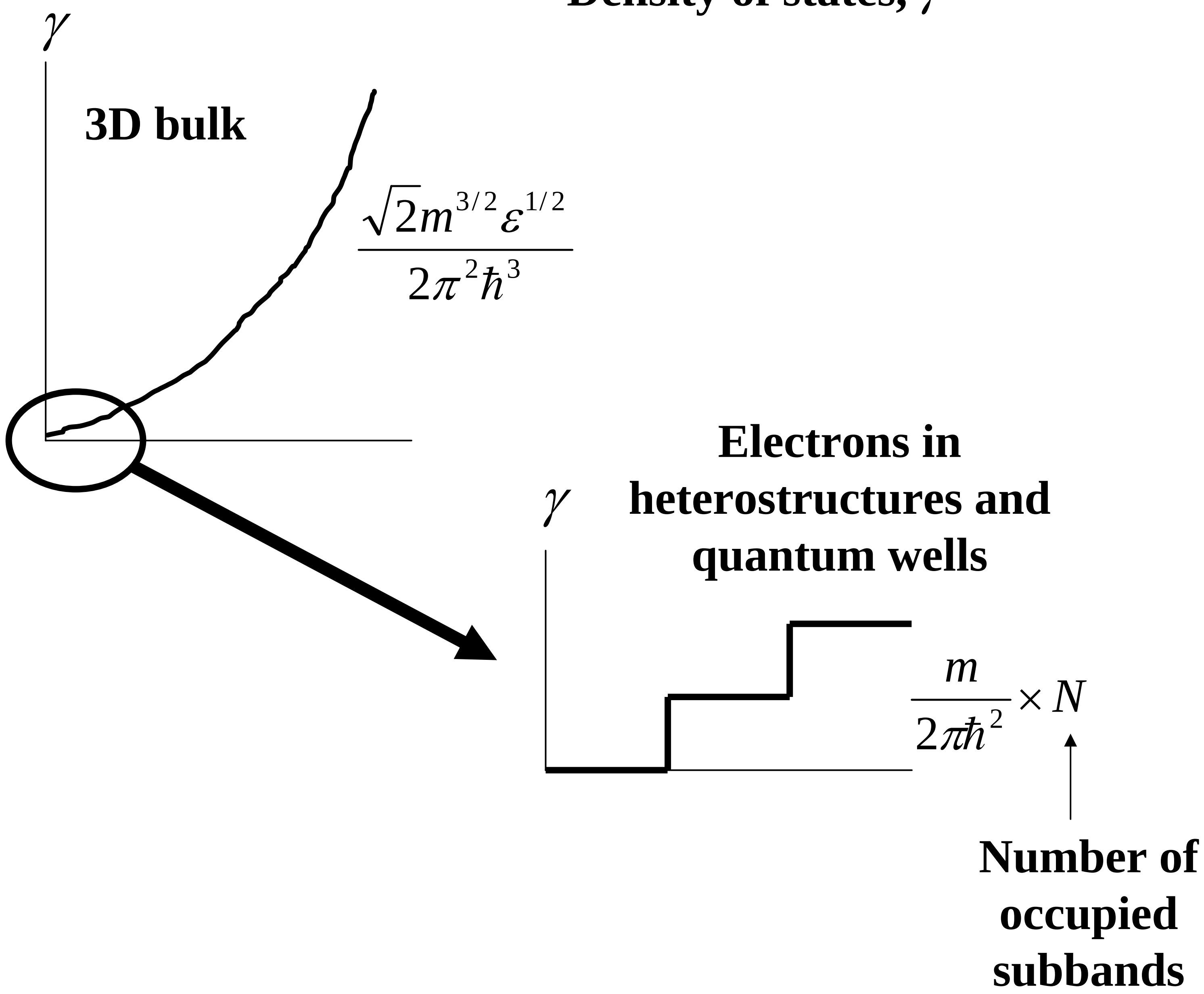
made by MBE:
molecular beam epitaxy

band-edge discontinuity produces a triangular well ➡ 2DEG

2DEG is a metal with a very low density

$$n_{2DEG} \sim 10^{10} - 10^{12}\, cm^{-2}$$

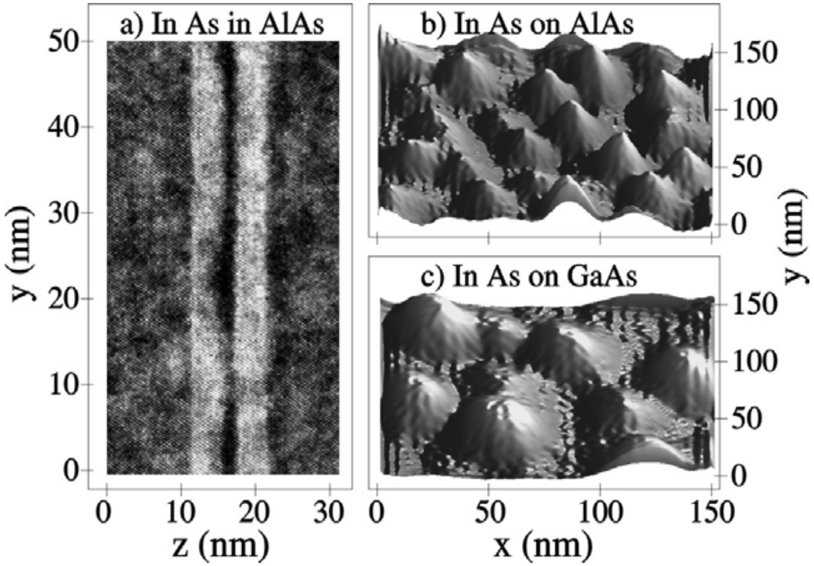
Density of states, γ



Micro/Nanotructures: wires (1D) and dots (0D)

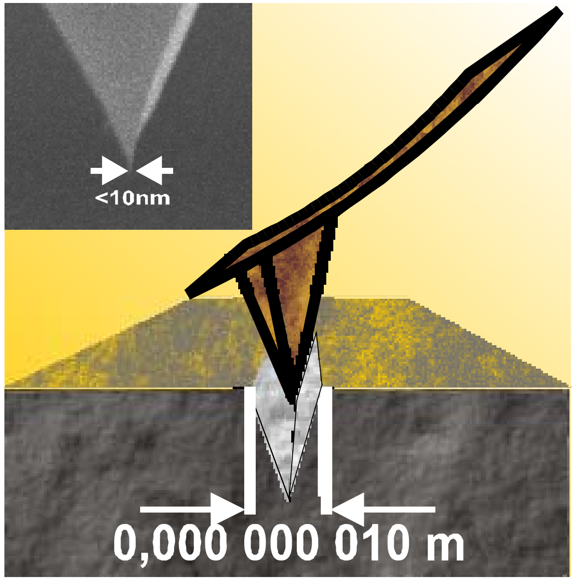
optical lithography (1-10microns)
electron beam lithography (0.1-1micron)
direct writing with AFM (10-100nm)

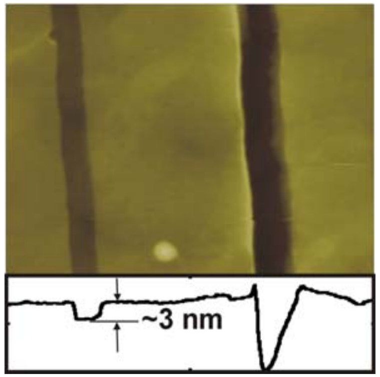
self-organized growth - InAs quantum dots
in AlAs matrix



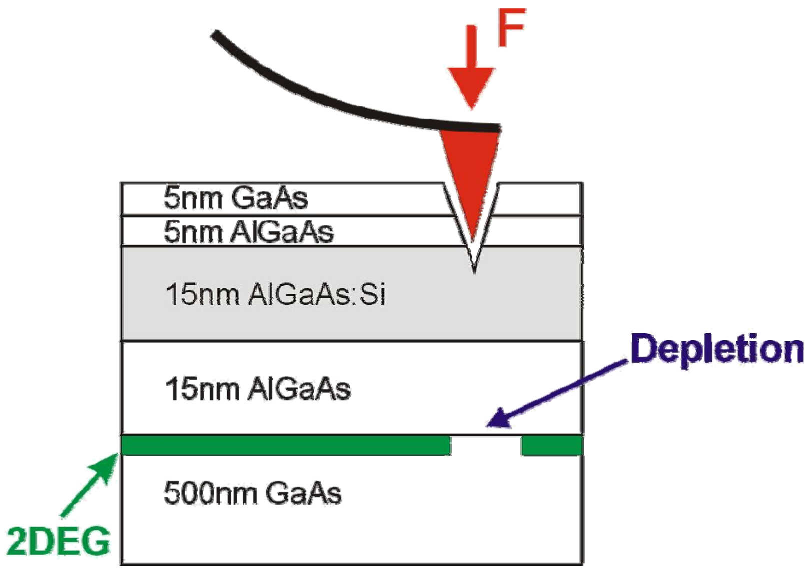
Surface Modification with an AFM

nanomachining



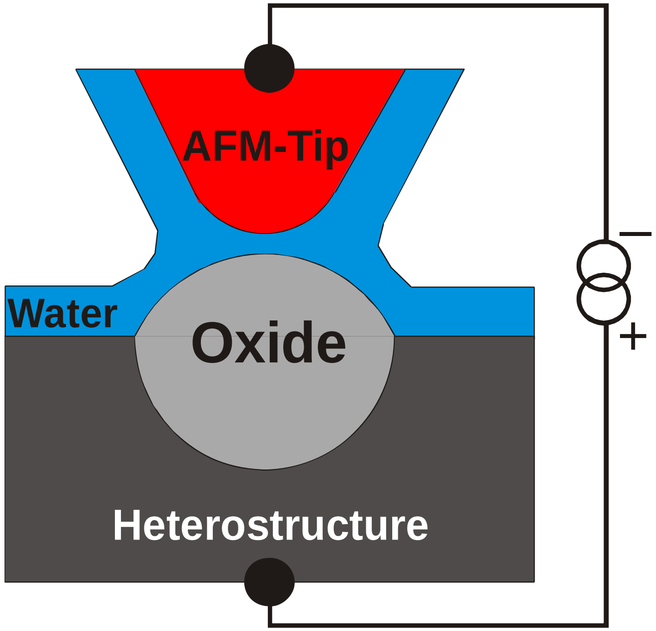


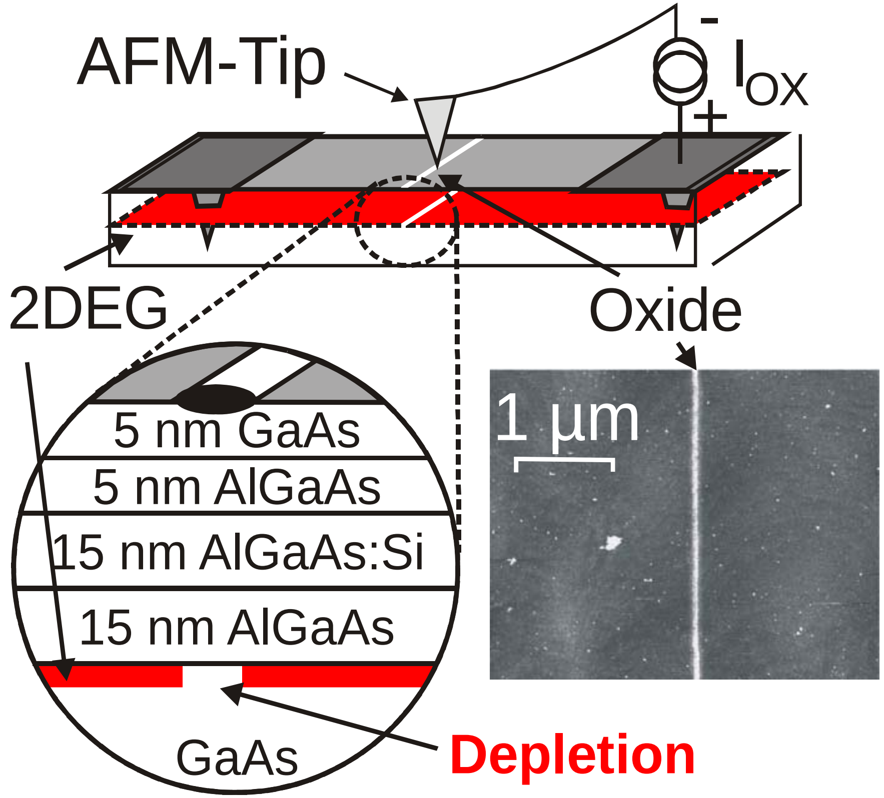
application:
GaAs/AlGaAs-heterostructure



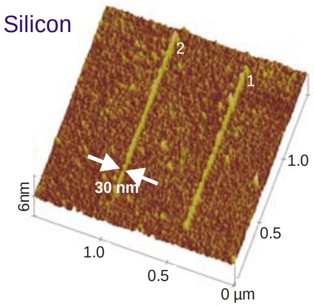
Haug et al, Appl. Phys. Lett. 75, 1107 (1999)

Local Oxidation

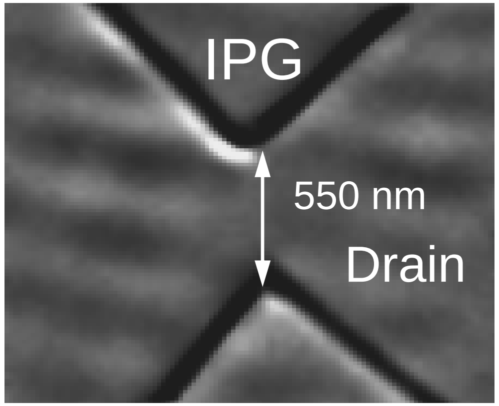


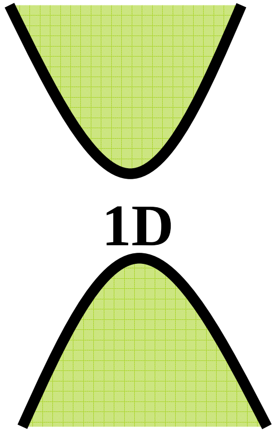


Ishii, Matsumoto (1995), Held et al. (1998)

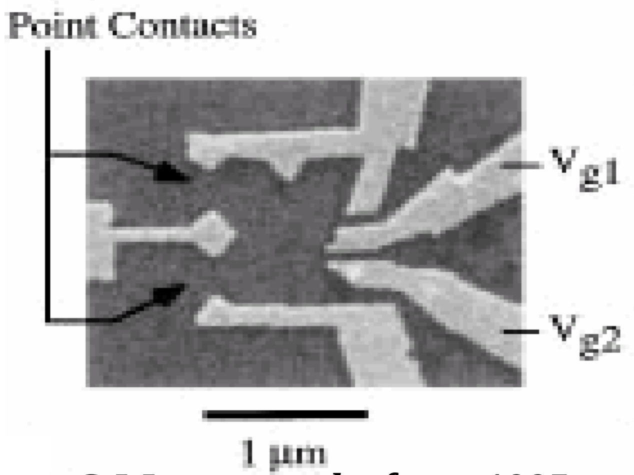


Quantum transport effects

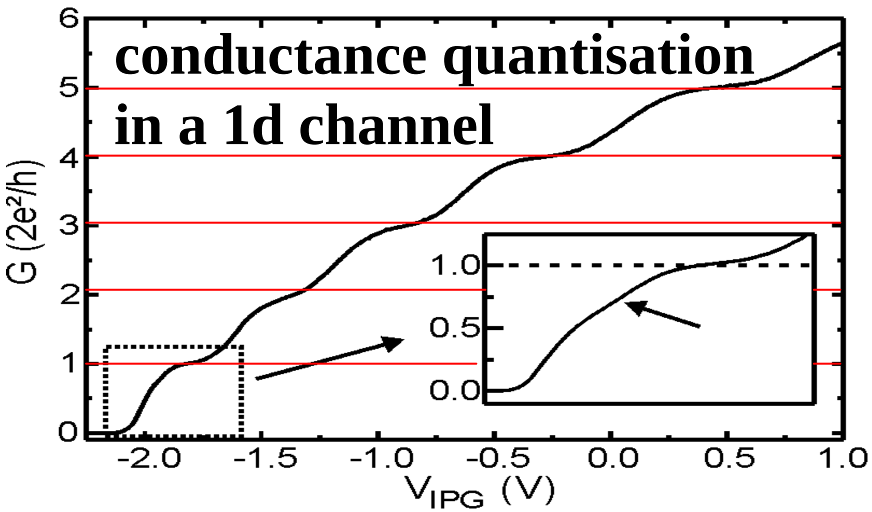


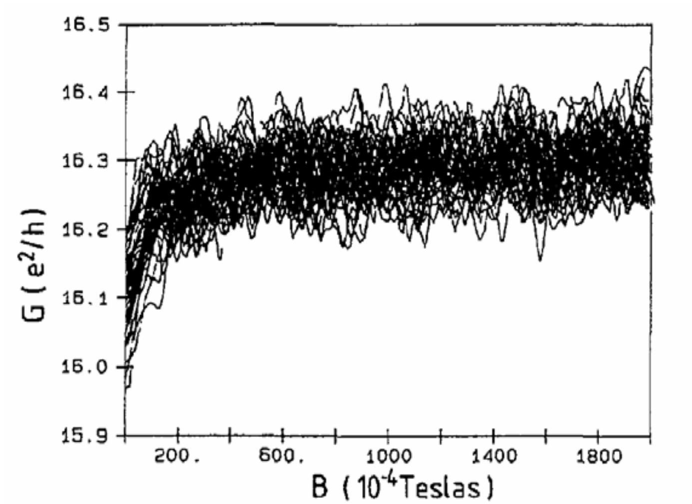


Haug *et al*, Appl. Phys. Lett.81, 2023 (2002)



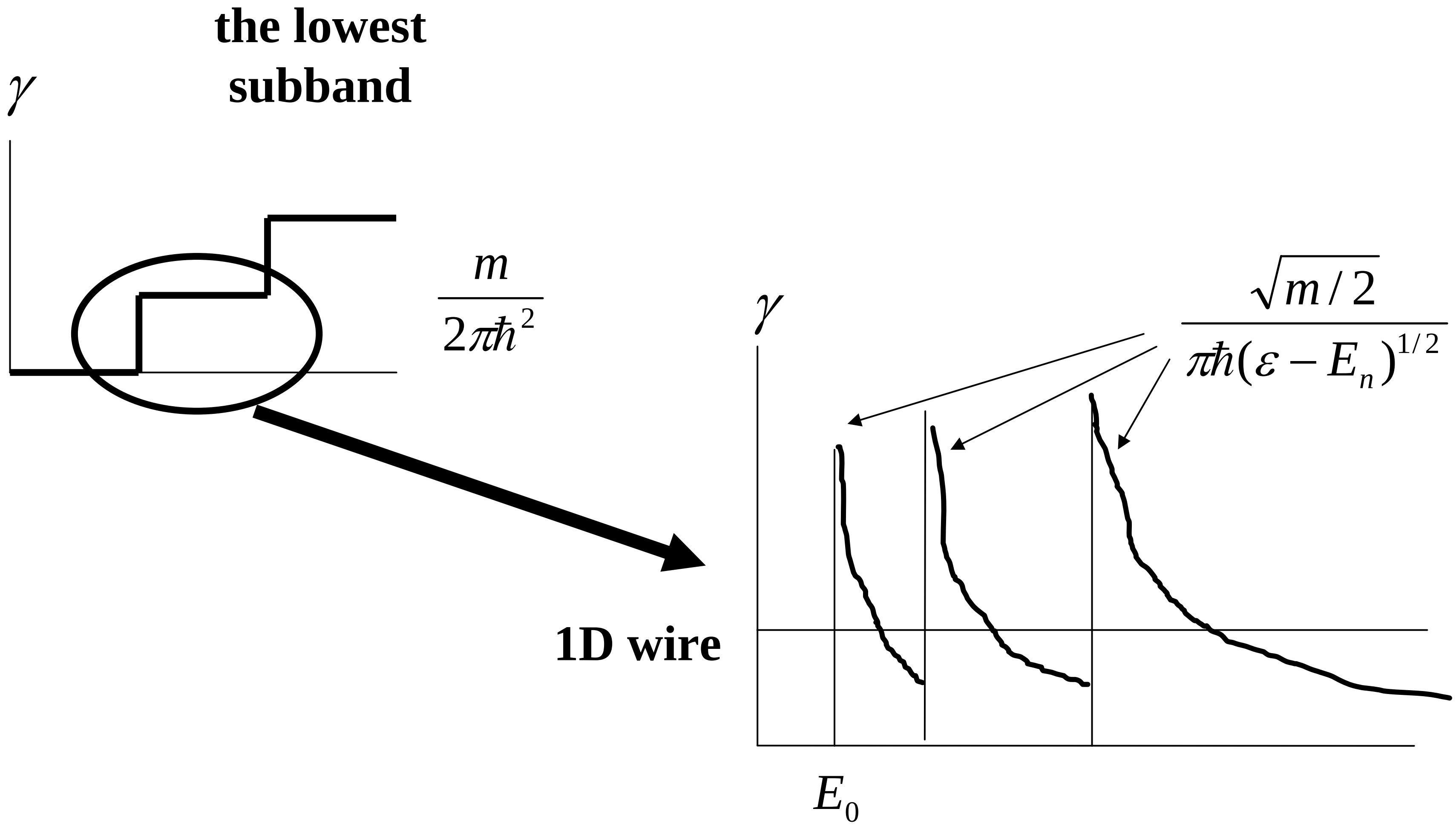
C.Marcus *et al* – from 1995



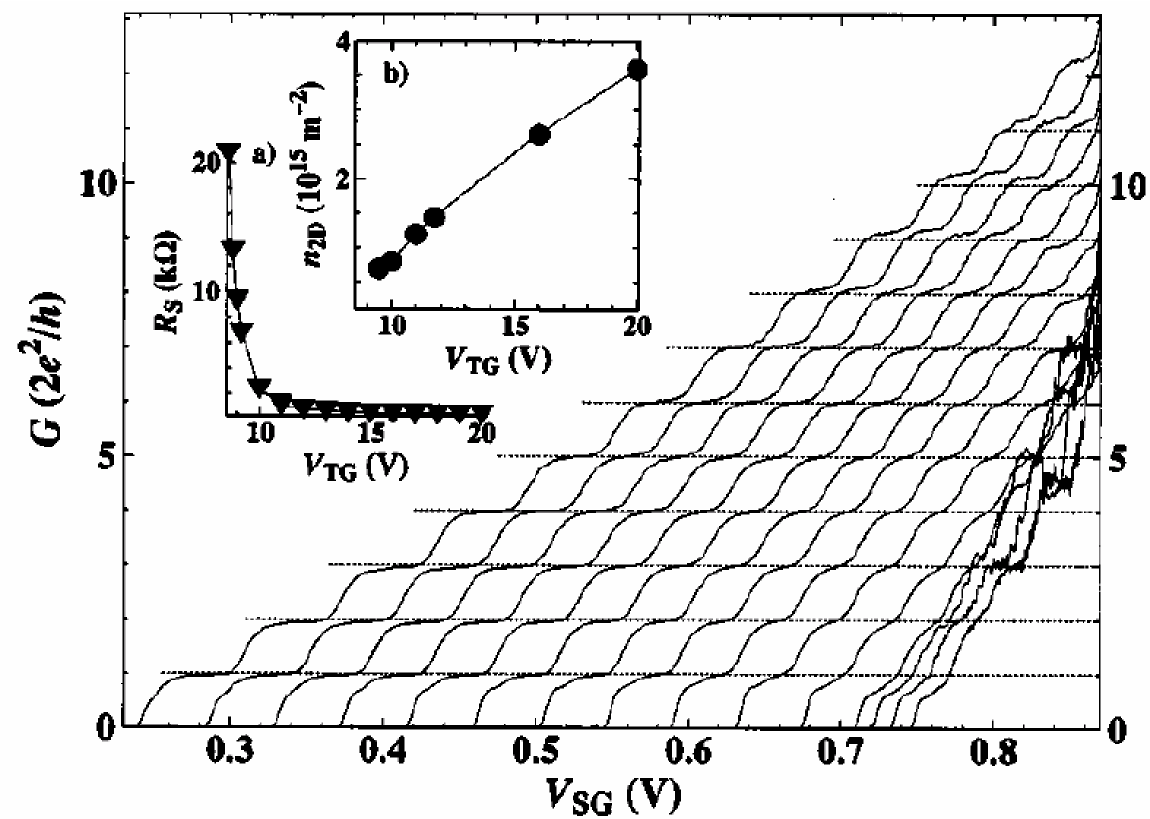


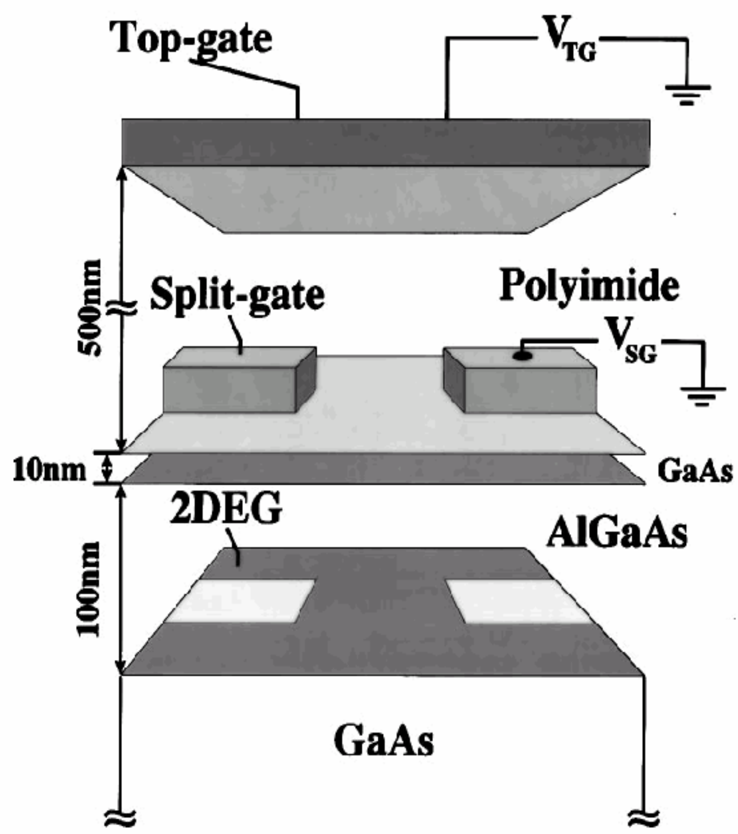
D.Mailly, M.Sanquer - 1992

Density of states, γ



Quantum conductance (resistance)



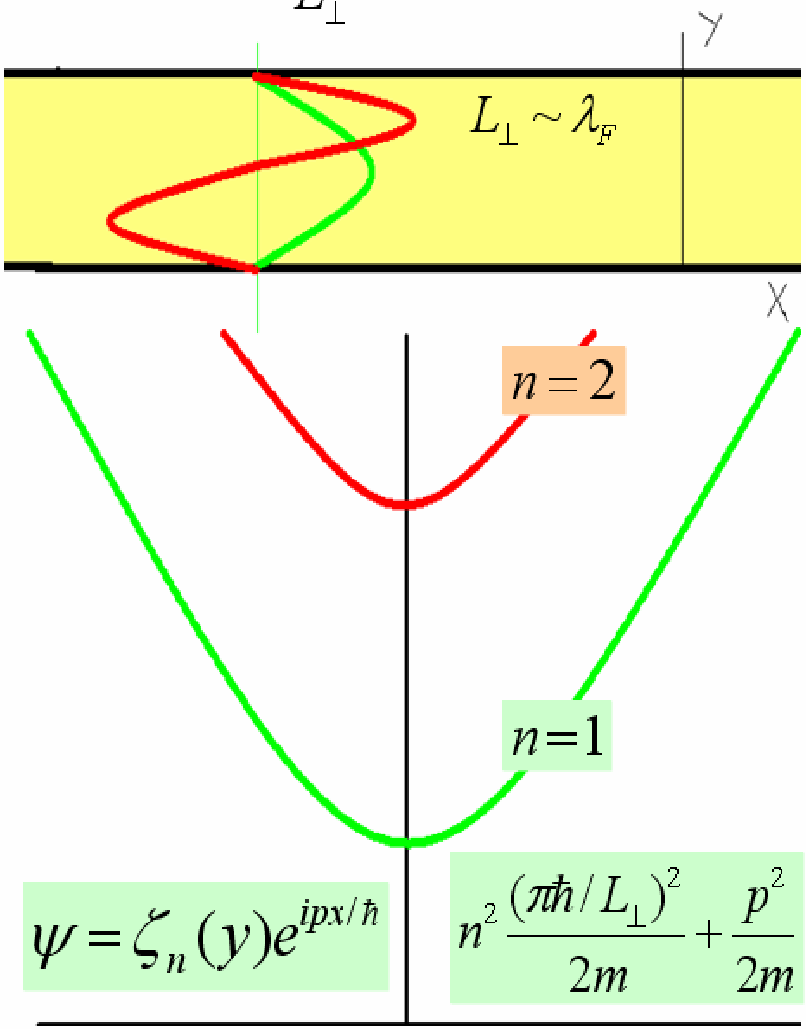


$$G_q = \frac{e^2}{h}$$

$$R_q = \frac{1}{G_q} = \frac{h}{e^2} = 25.812807\ k\Omega$$

Electronic wave-guides

$$\zeta_n(y) \sim \sin\frac{n\pi y}{L_\perp}$$



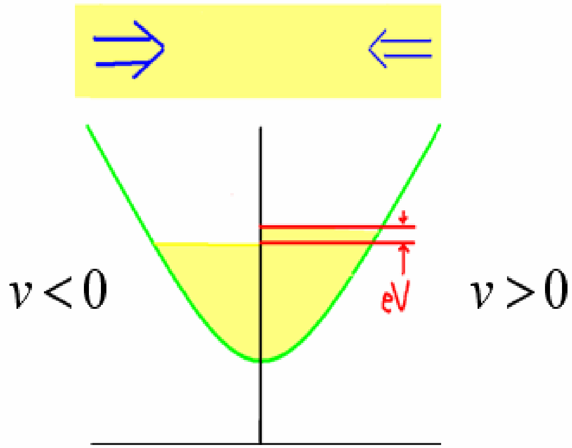
$$\psi = \zeta_n(y)e^{ipx/\hbar}$$

$$n^2\frac{(\pi\hbar/L_\perp)^2}{2m} + \frac{p^2}{2m}$$

One-dimensional sub-bands in a quantum wire

One-dimensional wire

$$\frac{(\pi\hbar/L_\perp)^2}{2m} = E_1 < E_F < E_2 = \frac{4(\pi\hbar/L_\perp)^2}{2m}$$



$$I = e\int_{p(E_F-eV/2)}^{p(E_F+eV/2)} v(k)\frac{dp}{2\pi\hbar} = e\int_{E_F-eV/2}^{E_F+eV/2} d\varepsilon = \frac{e^2V}{h}$$

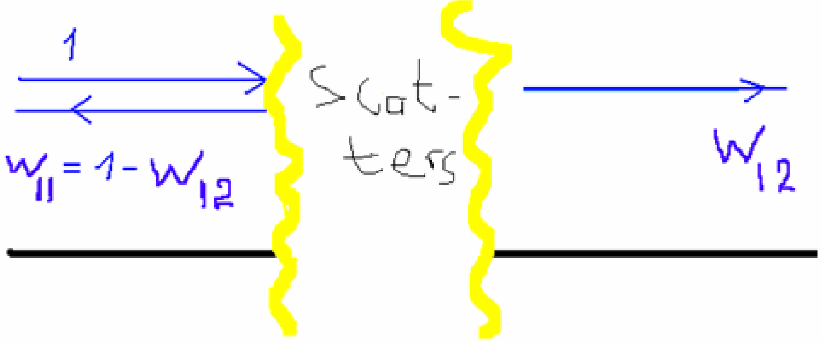
$$v = \frac{d\varepsilon}{dp}$$

$$G_\uparrow = \frac{I_\uparrow}{V} = \frac{e^2}{h}$$

$$G_{\uparrow+\downarrow} = \frac{I_\downarrow + I_\uparrow}{V} = \frac{2e^2}{h}$$

Spin-1/2 (Kramers degeneracy)

$$I = 2e \int_{E_F - eV/2}^{E_F + eV/2} w_{12}(\varepsilon) \cdot V_F v_F \, d\varepsilon = \frac{2e^2 V}{h} w_{12}(\varepsilon_F)$$

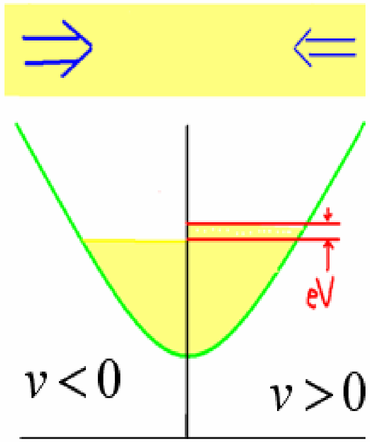


ballistic 1D wire

ballistic 1D wire

$$G = \frac{2e^2}{h} w_{12}(\varepsilon_F)$$

Landauer, Buttiker 1984



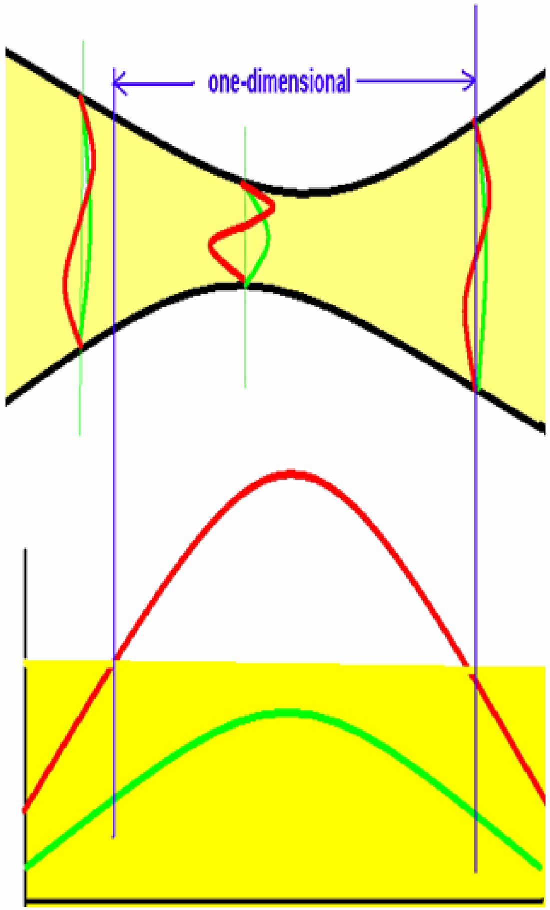
$$w_{12} = 1$$

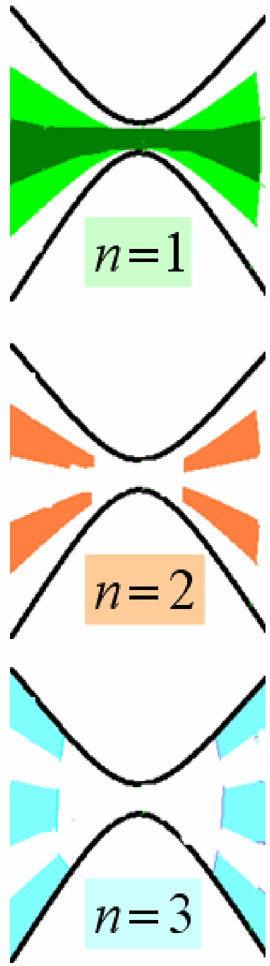
Ballistic and adiabatic constriction:
reflection-less passage from one entry to the other

Adiabatic constriction

$$L_\perp \sim \lambda_F << r$$

$$L_\perp\left(\frac{x}{r}\right)$$

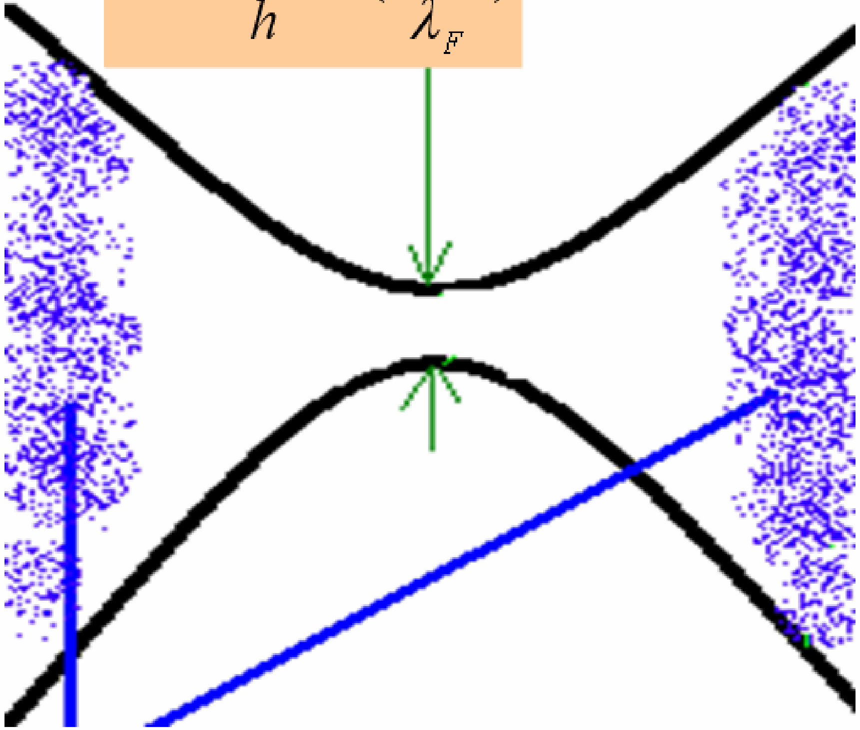




Motion across the wire is quantum, whereas along the wire it is one-dimensional classical: it either passes through without any scattering, or it is fully reflected.

$$G = \frac{2e^2}{h} N\left(\frac{L_\perp^{\min}}{\lambda_F}\right)$$

Landauer-Buttiker formula for ballistic adiabatic wire



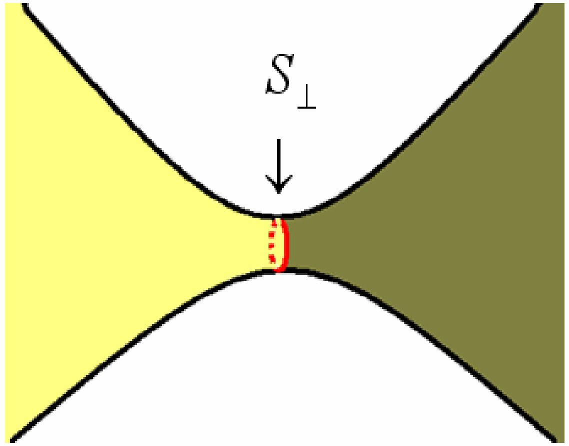
Energy relaxation and scattering between very few ballistically transmitted modes and an infinite number of fully scattered modes (momentum relaxation) take place in reservoirs, far away from the contact.

A finite resistance of a ballistic adiabatic point contact,

$$R = \frac{h}{2e^2 N_{\min}}$$

is formed in the regions where the most of modes arriving from an infinitely large reservoir are reflected back.

'Point contact' between two bulk 3D metals



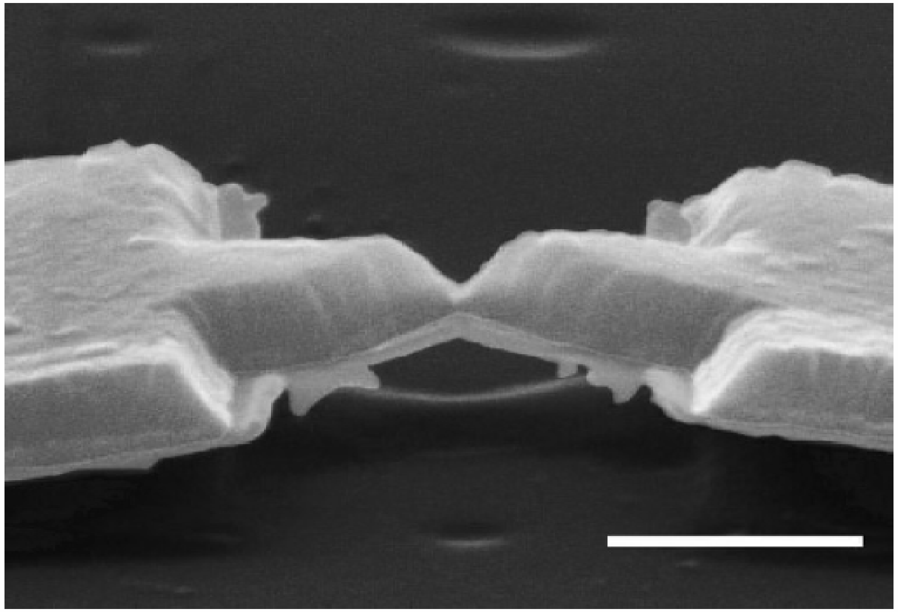
$$G = \frac{2e^2}{h} N_{ballistic}$$

$$\uparrow$$

$$N\left(\frac{S_\perp^{\min}}{\lambda_F^2}\right) \sim \frac{S_\perp^{\min}}{\lambda_F^2}$$

$$G = a_{geom} \frac{2e^2}{h} \frac{S_\perp^{\min}}{\lambda_F^2}$$

Sharvin 1982



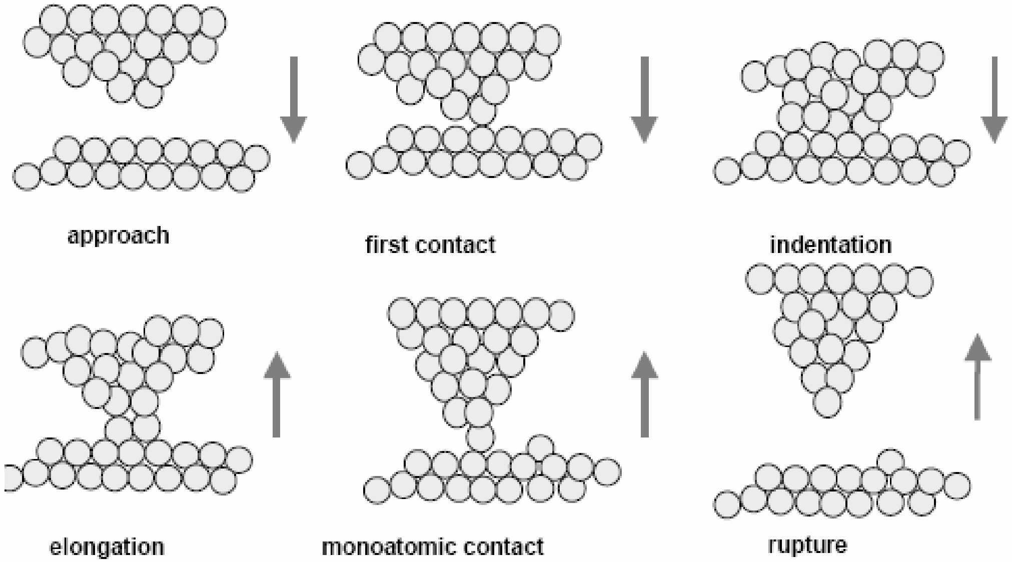
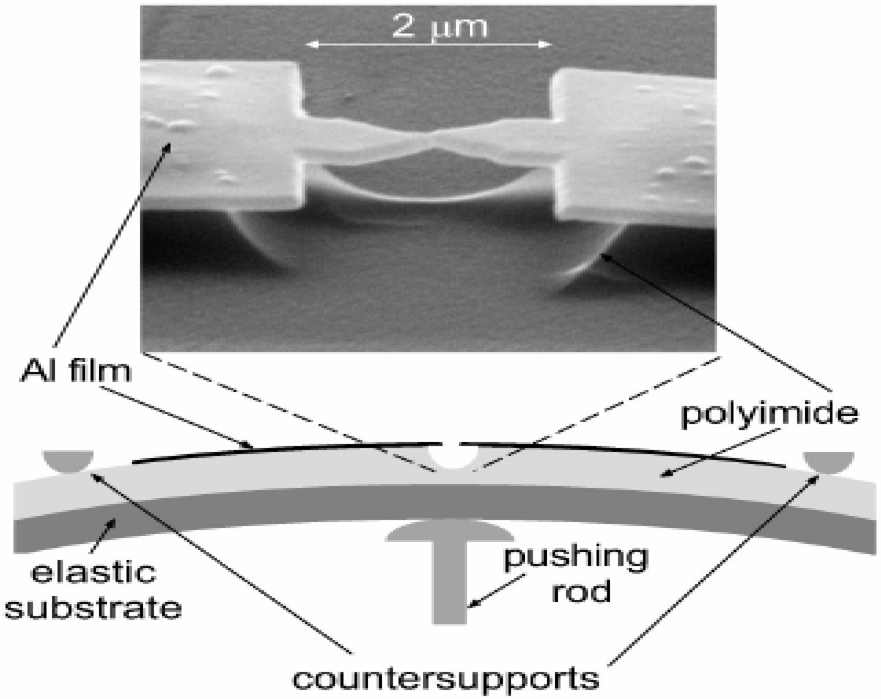
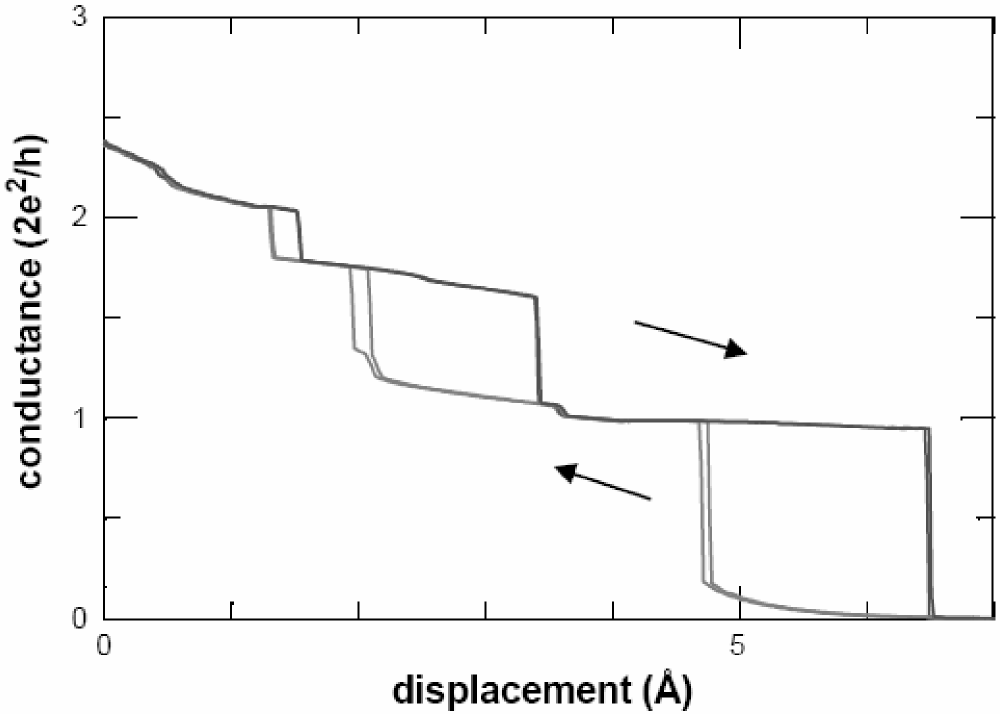


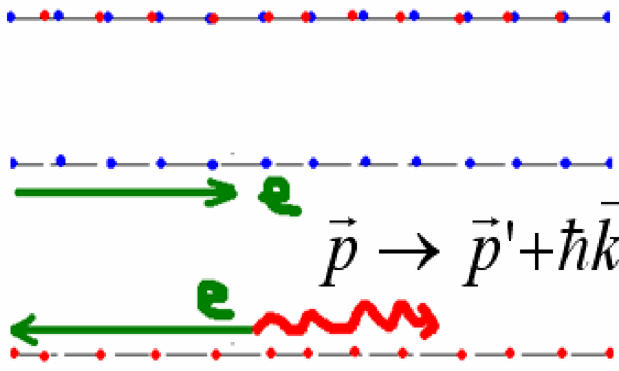
Fig. 3. Cartoon representation of contact fabrication using an STM.





Point contact spectroscopy of electron-phonon interaction

phonons: elementary vibrations of a lattice



$$\vec{p} \rightarrow \vec{p}' + \hbar\vec{k}_{phonon}$$

$$I = \frac{2e}{h} \int_{\varepsilon_F - eV/2}^{\varepsilon_F + eV/2} d\varepsilon \cdot w_{12}(\varepsilon)$$

$$w_{12}(\varepsilon) = 1 - w_{e-ph}(\varepsilon)$$

$$w_{ph-emission}(\varepsilon) = \int_0^{eV} d\omega \, |V_{e-ph}|^2 \, \gamma_{ph}(\omega)$$

$$\frac{d^2 I}{dV^2} = |V_{e-ph}(eV)|^2 \cdot \gamma_{ph}(eV)$$

Exercise

1. Estimate the width of ballistic constriction in a 2DEG with the density $n_e \sim 10^{11} cm^{-2}$ which would have conductance value of the order of conductance quantum, e^2 / h .

2. Estimate the low-T resistance of 10nm-diameter alkali metal ballistic point contact.