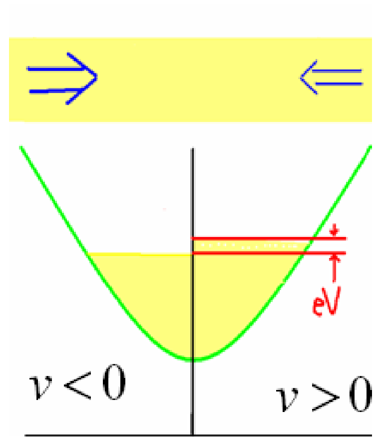
Lectures 21: Scanning Tunneling Microscopy

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

ballistic 1D wire ballistic 1D wire

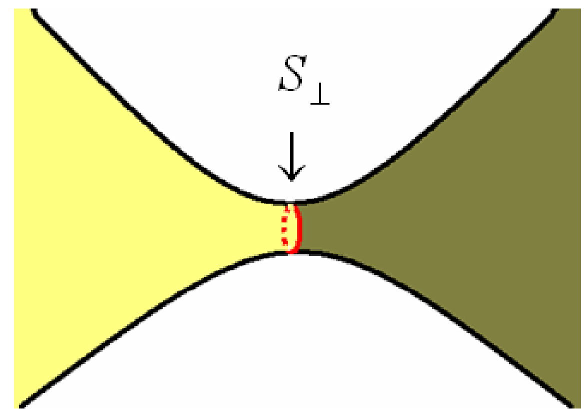


$$G = \frac{2e^2}{h} w_{12}(\varepsilon_F)$$

Landauer, Buttiker 1984

$w_{12}=1$ full transmission for open channels	$w_{12} \sim exp(-k^* d)$ almost completely blocked channels

'Point contact' between two bulk 3D metals



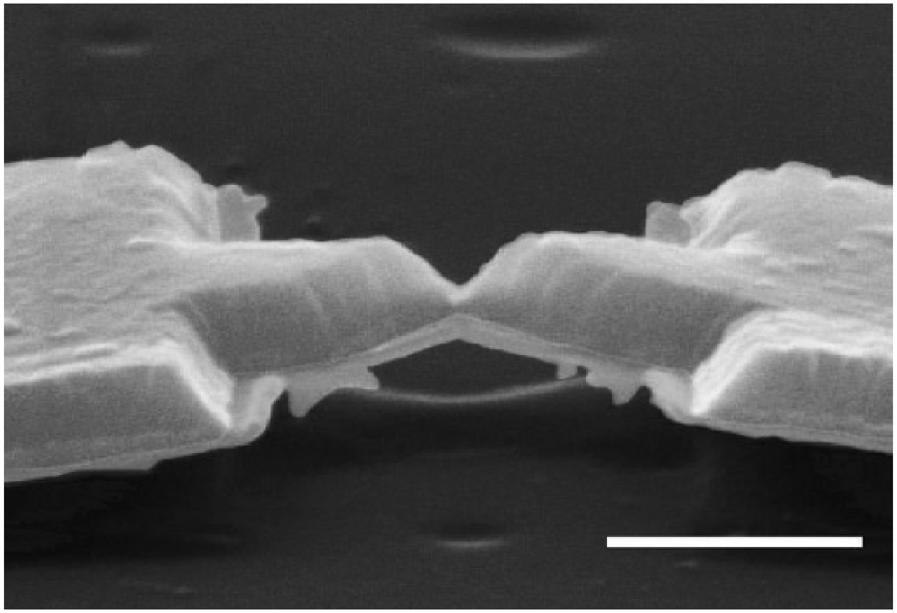
$$G = \frac{2e^2}{h} N_{ballistic}$$

$\uparrow$

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

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

Sharvin 1982



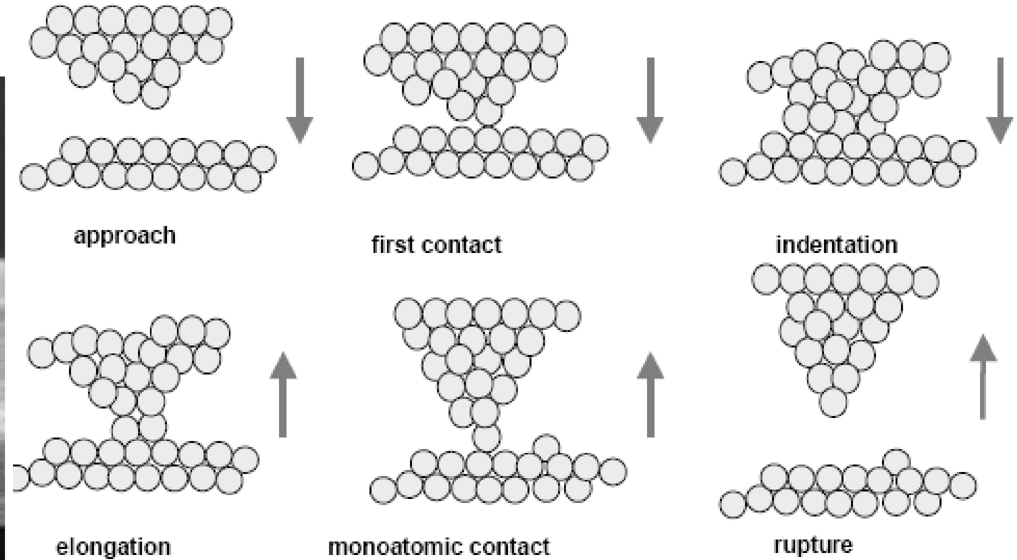
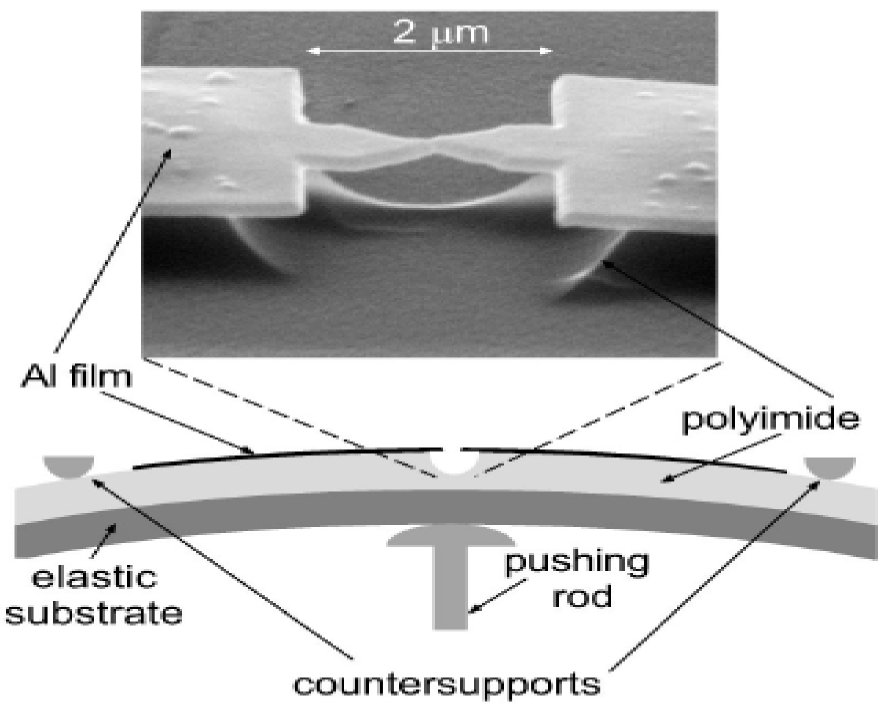
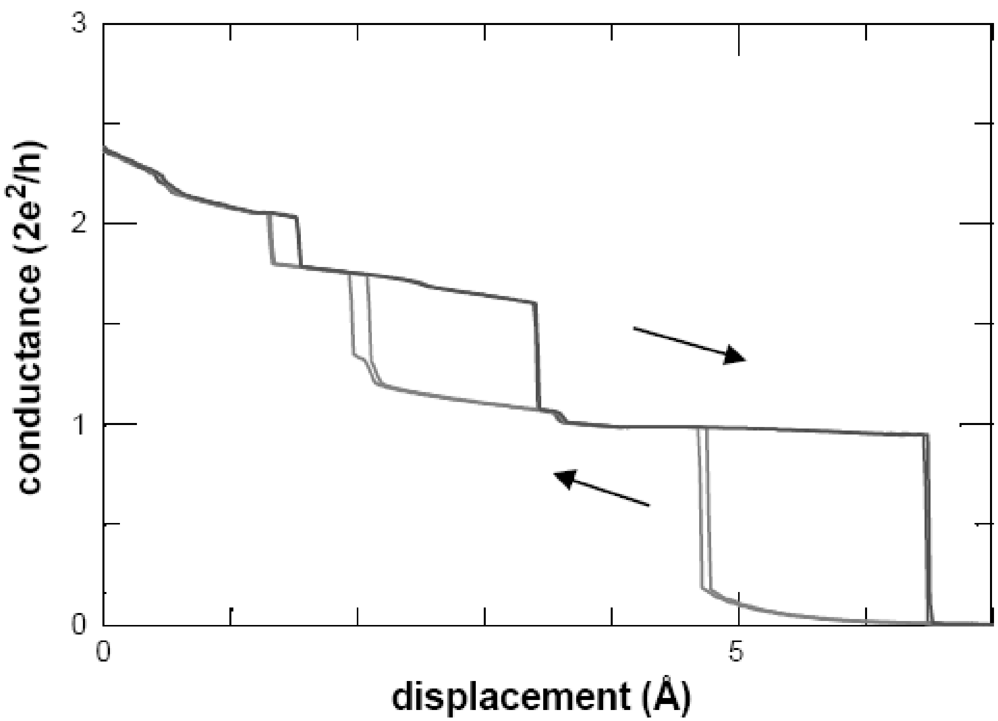
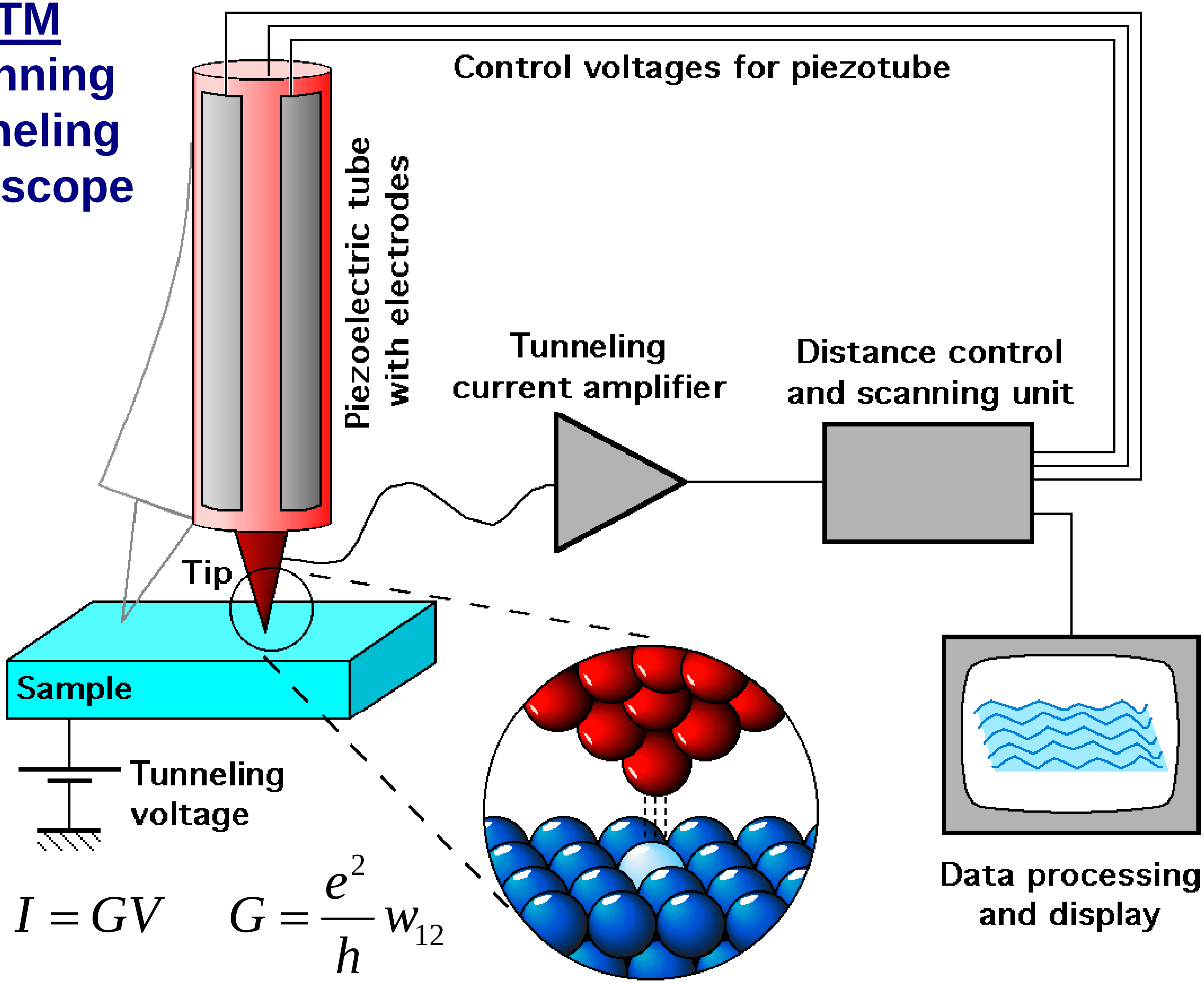


Fig. 3. Cartoon representation of contact fabrication using an STM.





STM
Scanning Tunneling Microscope

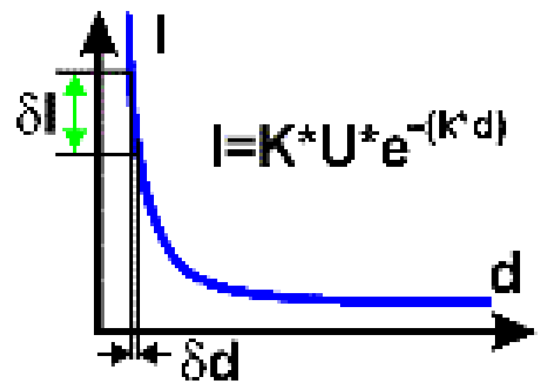


$$I = GV \qquad G = \frac{e^2}{h} w_{12}$$

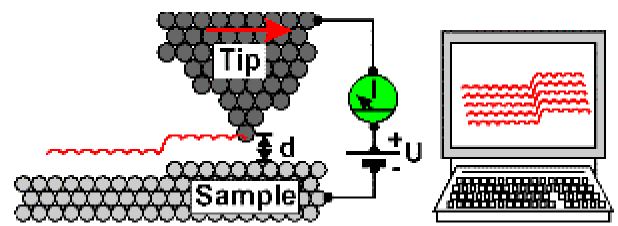
Scanning Tunneling Microscope

Heinrich Rohrer
Gerd Binnig
Nobel Prize 1986

Tunneling current starts to flow when a sharp tip approaches a conducting surface at a distance of approximately 1nm (10Angstrom).

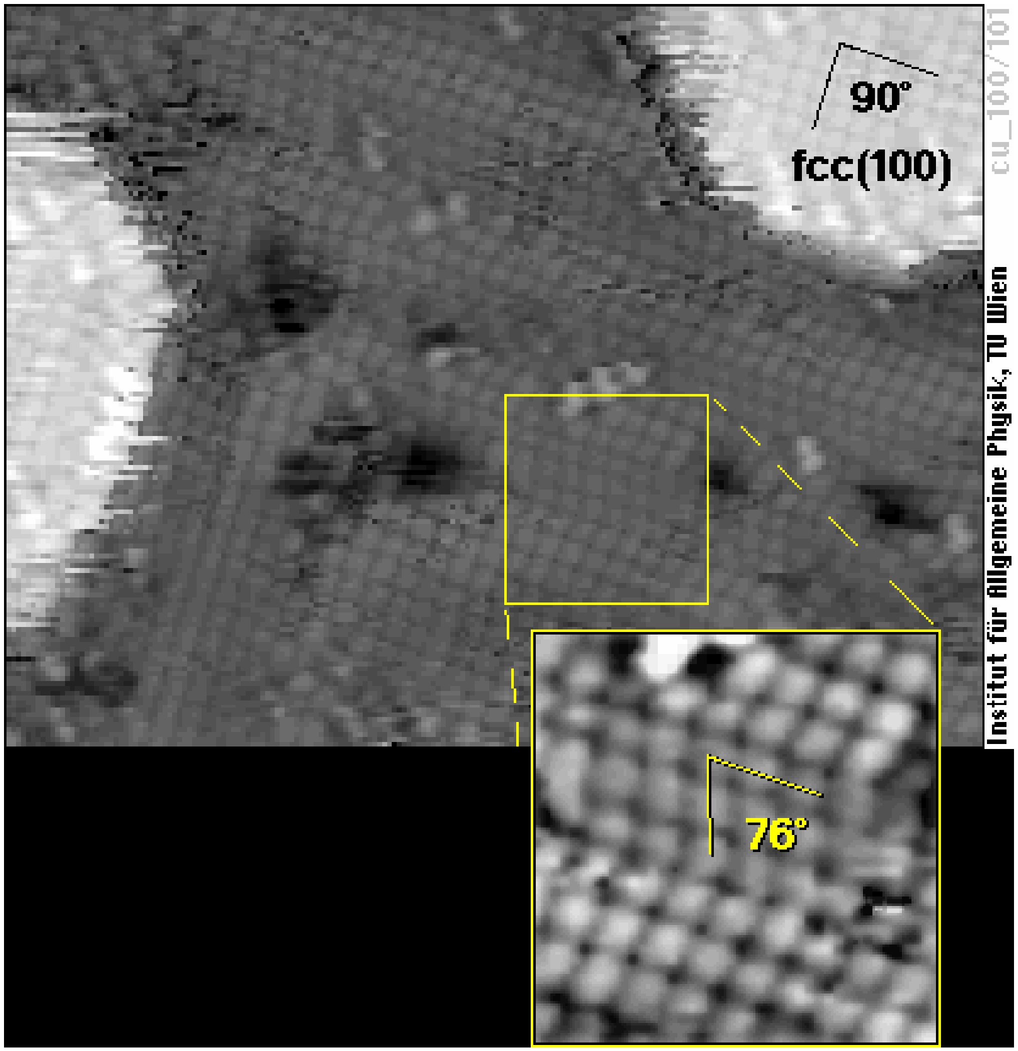


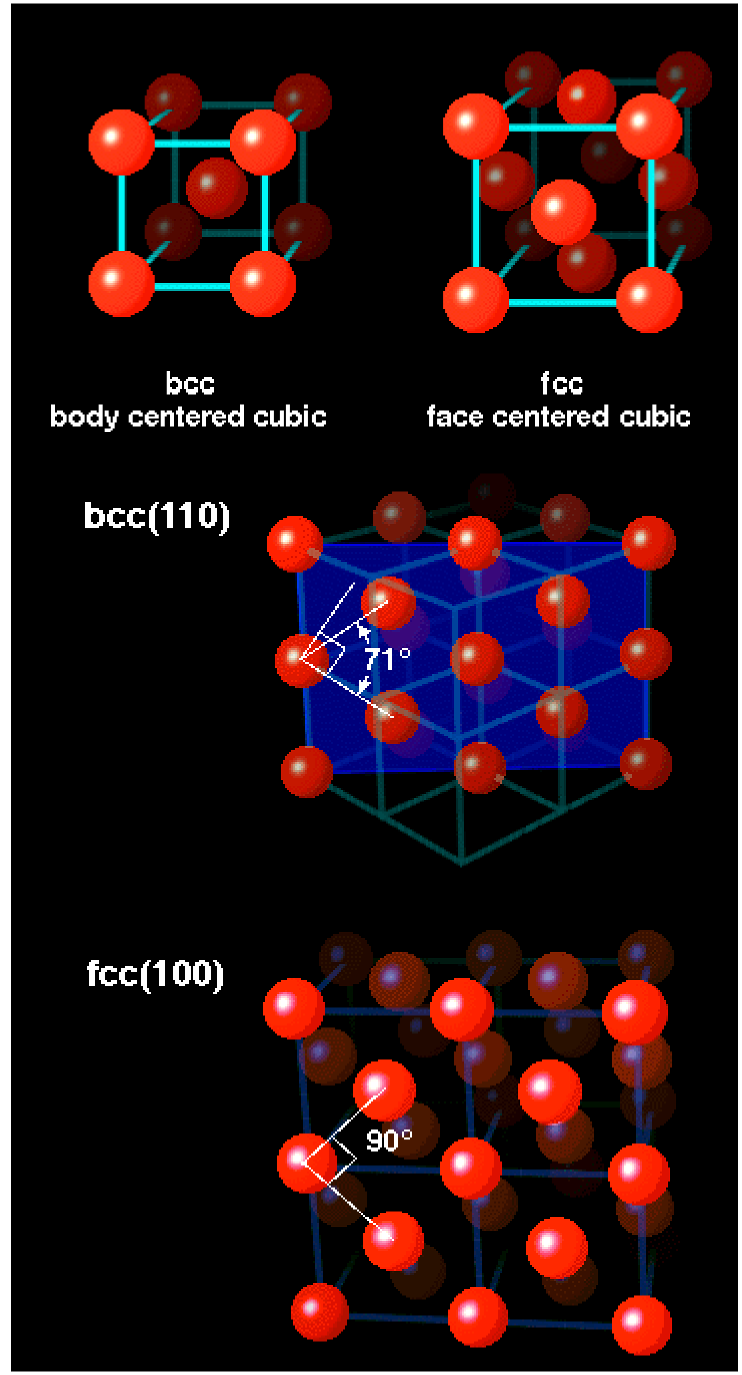
The tip is mounted on a piezoelectric tube, which allows tiny movements by applying a voltage at its electrodes. The electronics control the tip position to keep tunneling current and, hence, the tip-surface distance constant, while at the same time scanning a small area of the sample surface.



This movement is recorded and can be displayed as an image of the surface topography. Under ideal circumstances, the individual atoms of a surface can be resolved and displayed.

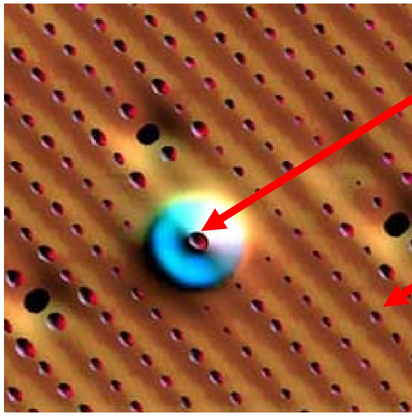
Example:
fcc and bcc Iron in Films





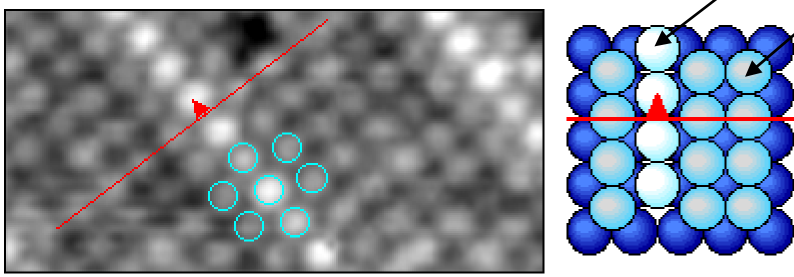
Surface Reconstruction

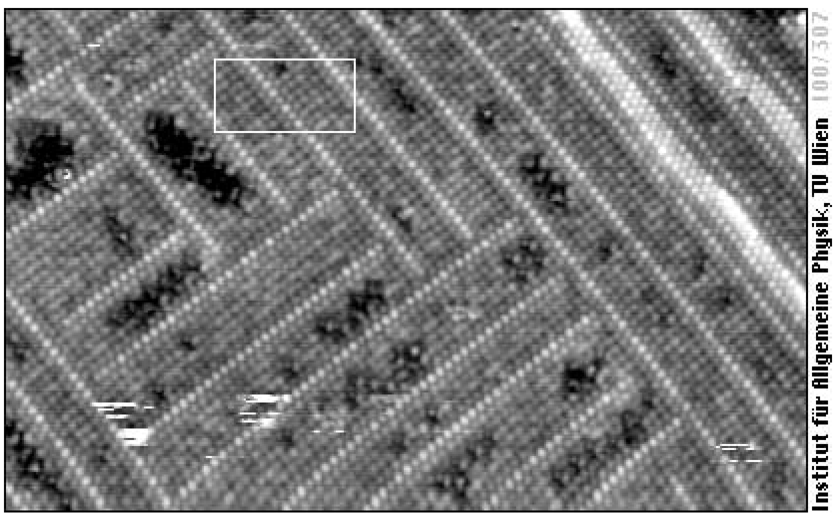
Rearrangement of Atoms at a Surface



Xe atom
on (100)Ni

PtNi



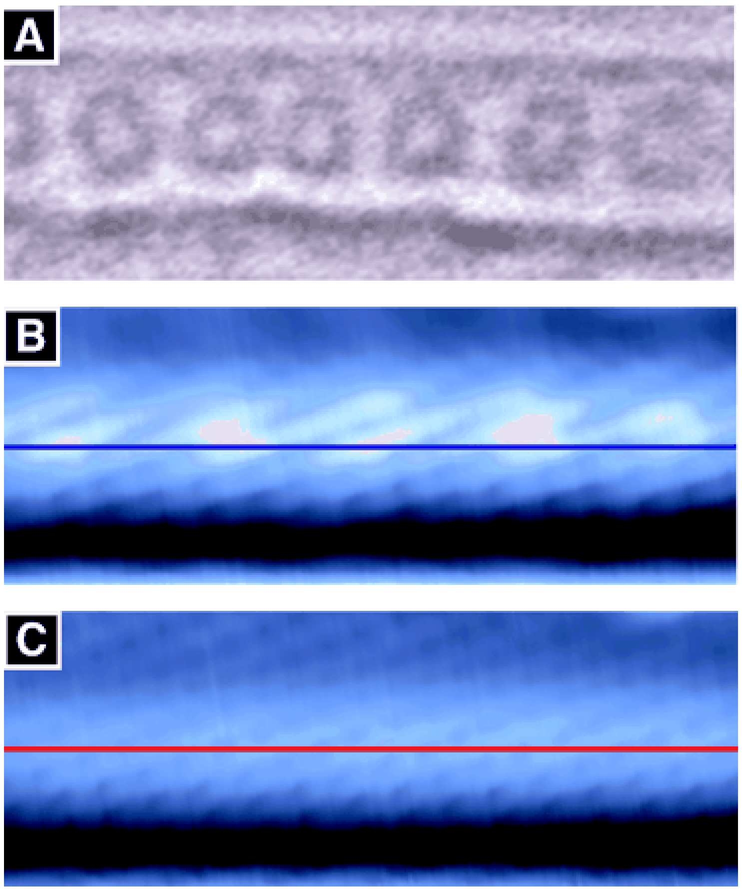


The (100)-oriented surface of Ni is a simple square lattice of atoms, Pt atoms form layer on top of the square lattice of the unreconstructed second layer. And this is what the (100) surface of a PtNi alloy looks like at approx. 68% Pt concentration in the first monolayer.

What you see in the image is a single bright row of atoms shifted by half an interatomic distance in the direction of the rows (red arrow). These atoms have a hexagonal environment (6 nearest neighbours) in the first monolayer, which is already the same local structure as in the 'hex' reconstruction of pure Pt.

Carbon nanotubes stuffed with C60 molecules (carbon peapods)

Hornbaker, Kahng, Misra, Smith, Johnson, Mele, Luzzi, Yazdani - Science 295, 828 (2002)



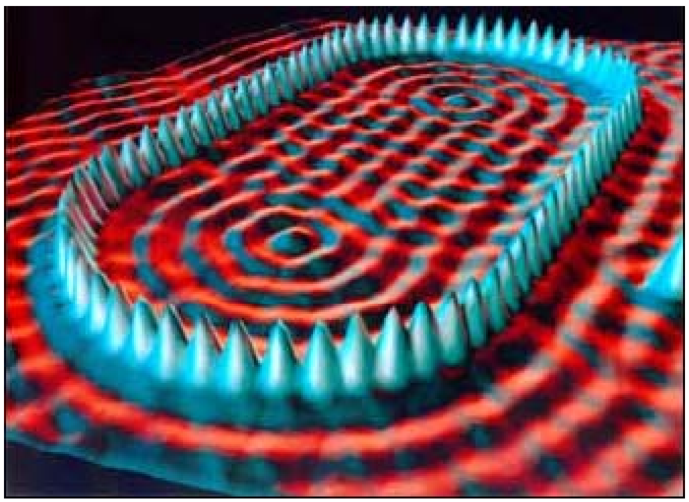
(A) A room temperature TEM image (105 Å by 29 Å) of a peapod, showing the SWNT cage and encapsulated C60 molecules.

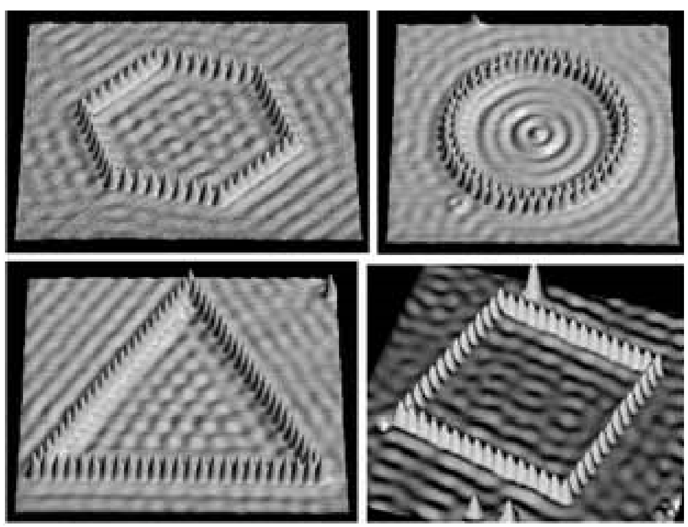
(**B**) STM image (105 Å by 29 Å) of a peapod obtained under positive sample bias (+1.5 V, 700 pA) showing both atomic corrugation of the SWNT and features associated with the encapsulated C60 molecules.

(**C**) An image of the same peapod with a negative bias (-1.5 V, 700 pA) shows only the atomic corrugation of the SWNT.

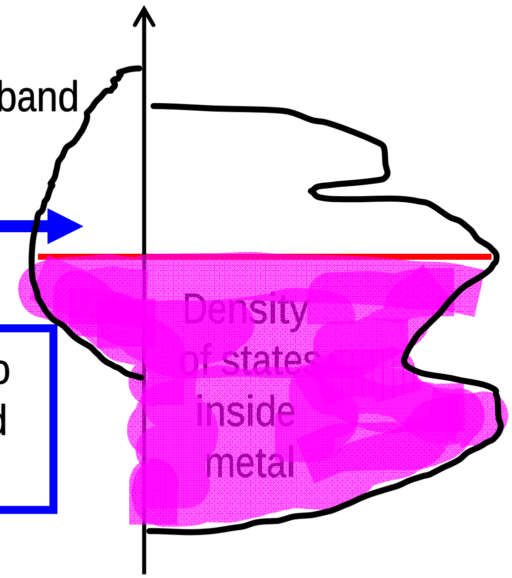
Corrals for surface state electrons

iron atoms on a copper surface.



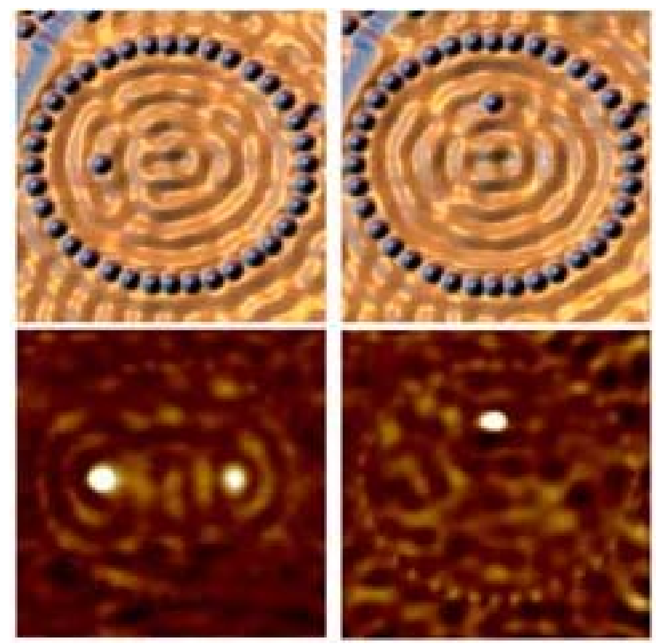


DoS in the surface band



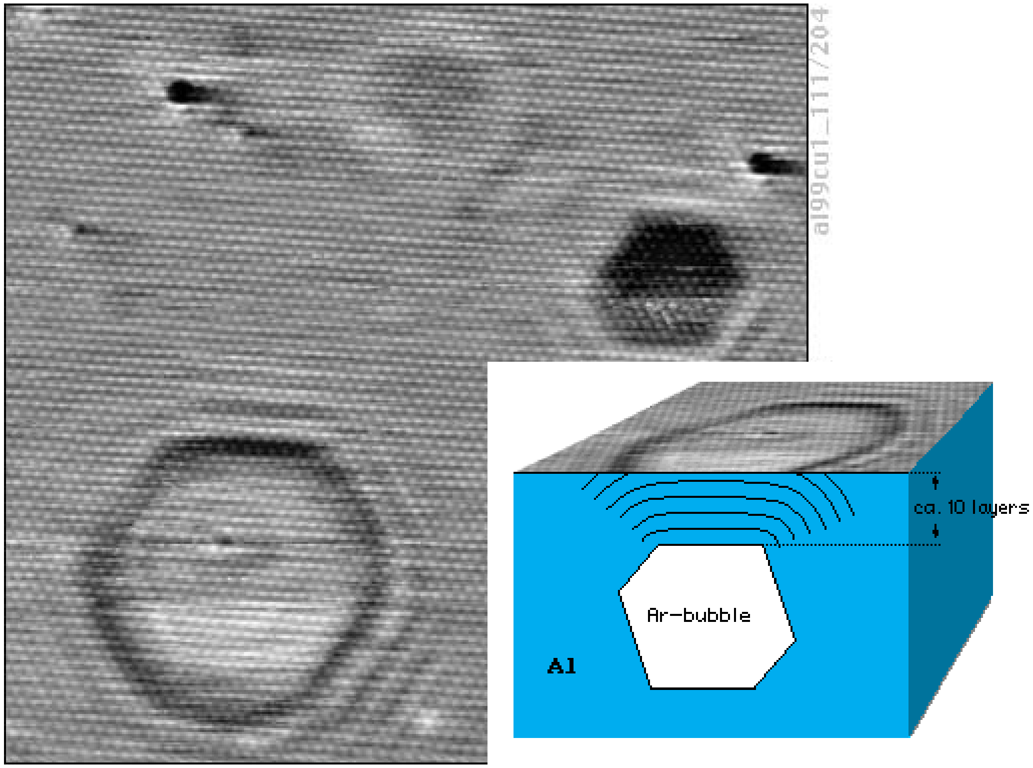
Electrons from the tip tunnel into empty states in the surface band (which are better coupled to it)

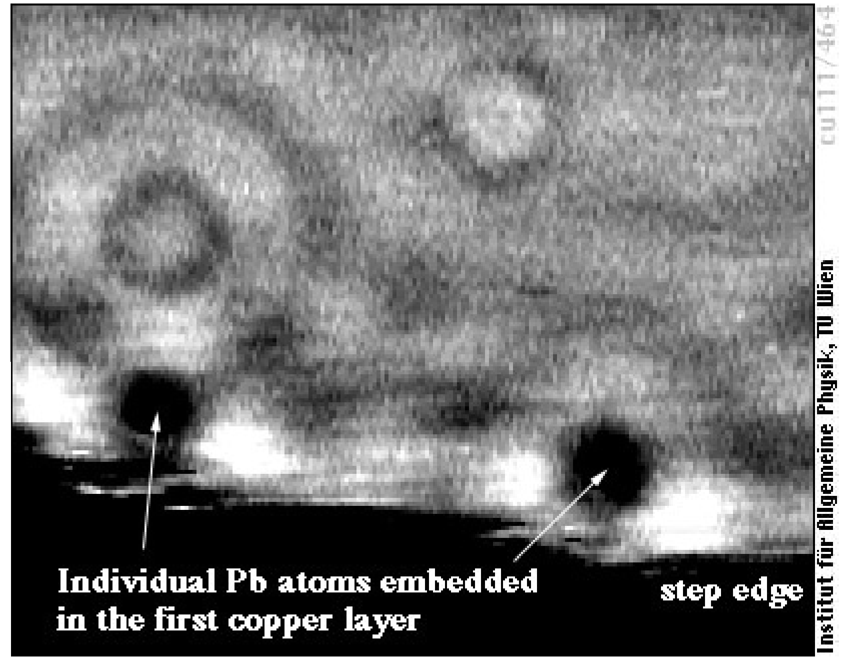
Quantum 'Mirage'

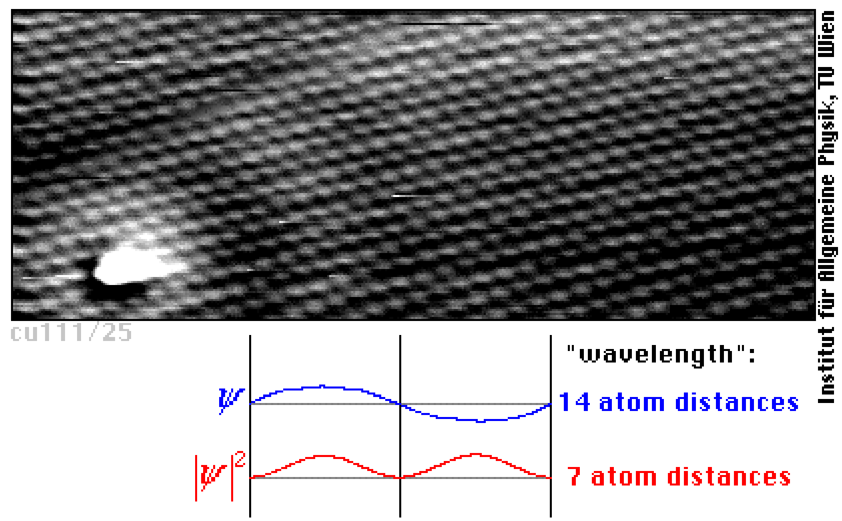


Group of Don Eigler at IBM Almaden Research Center

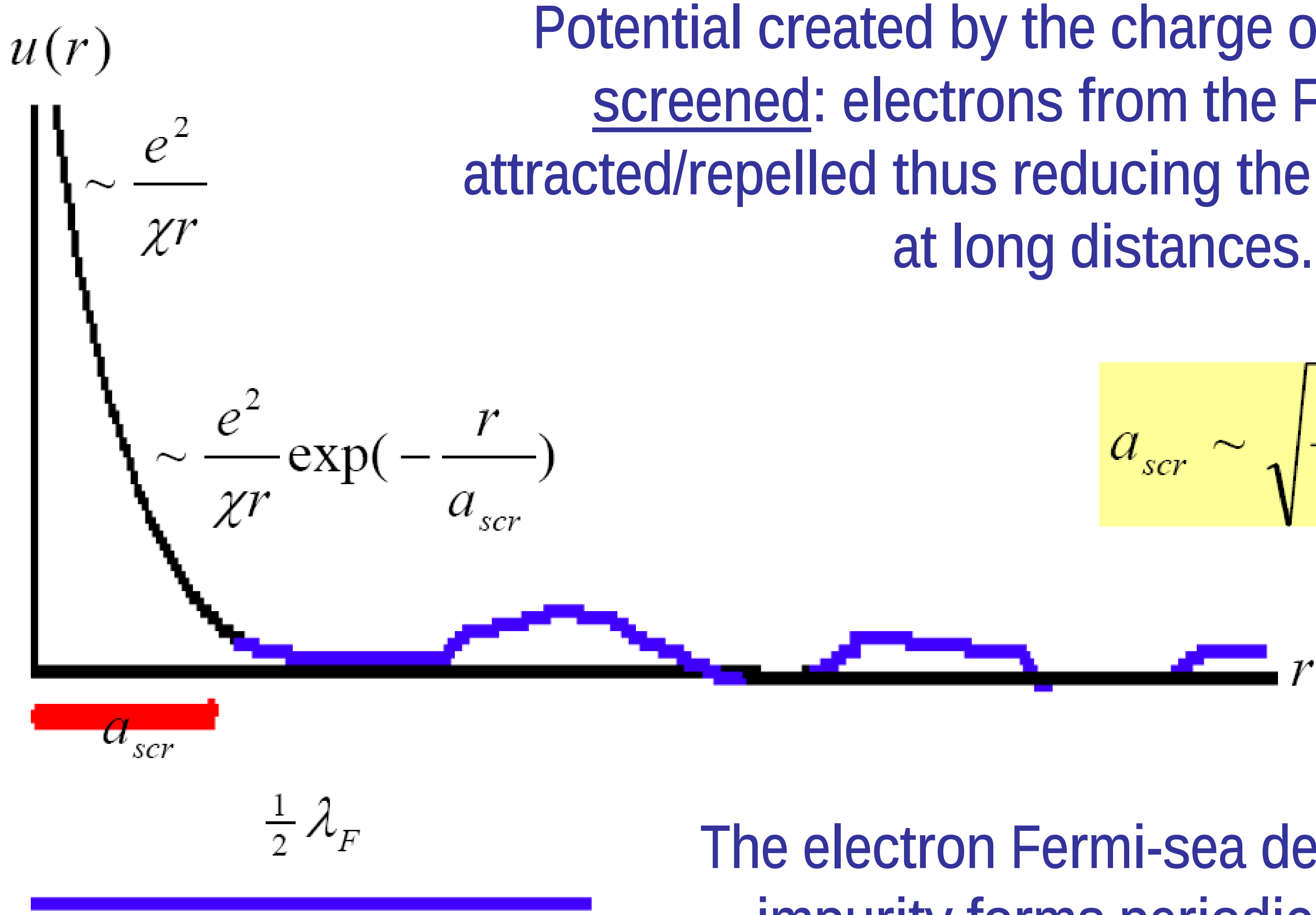
Electron Waves and Interference Phenomena of de Broglie waves of electrons







Friedel oscillations: standing waves of electrons surrounding impurities.



Potential created by the charge of an impurity is <u>screened</u>: electrons from the Fermi sea get attracted/repelled thus reducing the impurity potential at long distances.

$$a_{scr} \sim \sqrt{\frac{\chi}{4\pi e^2 \gamma_F}} \sim \sqrt{\lambda_F a_B}$$

$$a_B = \frac{\chi \hbar^2}{e^2 m}$$

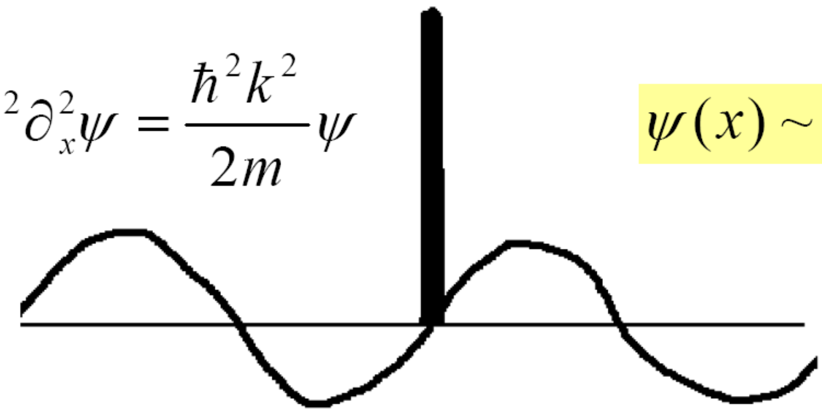
The electron Fermi-sea density around the impurity forms periodic rings with the wavelength of the electron in the metal.

Friedel oscillations in a 1D wire

$$u(x) \approx u\delta(x)$$

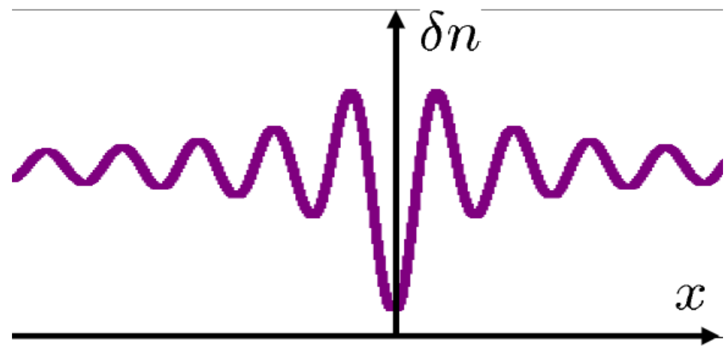
$$\psi(0) = 0$$

$$-\hbar^2 \partial_x^2 \psi = \frac{\hbar^2 k^2}{2m} \psi$$



$$\psi(x) \sim \sin kx$$

$$\delta n_{Friedel}(x) = -\frac{\sin 2k_F x}{8\pi x}$$



$$n_{screening}(x) = \int_0^{k_F} \frac{dk}{2\pi} \sin^2 kx = \int_0^{k_F} \frac{dk}{2\pi} \tfrac{1}{2}[1 - \cos 2kx]$$

$$= \frac{k_F}{4\pi} - \frac{\sin 2kx}{8\pi x}\Bigg|_0^{k_F} = \frac{k_F}{4\pi} - \frac{\sin 2k_F x}{8\pi x}$$

Friedel oscillations of screening electron density

Electrons involved into screening are standing waves with zeros at the position of impurity.

$$\lambda = \frac{2\pi}{k} = \frac{2\pi\hbar}{p}$$

Therefore, the electron density around impurity slightly oscillates (as the function of the distance to it) with the wave number $2k_F$, so that the screened potential oscillates, too:

$$n_{Friedel}(r) = \frac{\sin(2k_F r)}{r^d}$$

d - dimensionality (1,2, or 3)