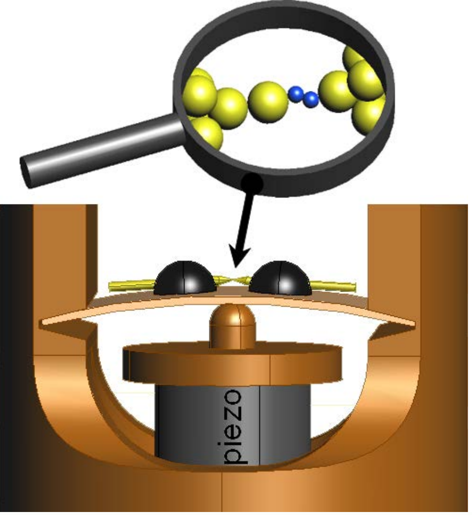


From nanophysics research labs to cell phones

Dr. András Halbritter
Department of Physics
associate professor

Curriculum Vitae

Birth: 1976.




High-school graduation: 1994.




Master degree: 1999.



PhD: 2003.

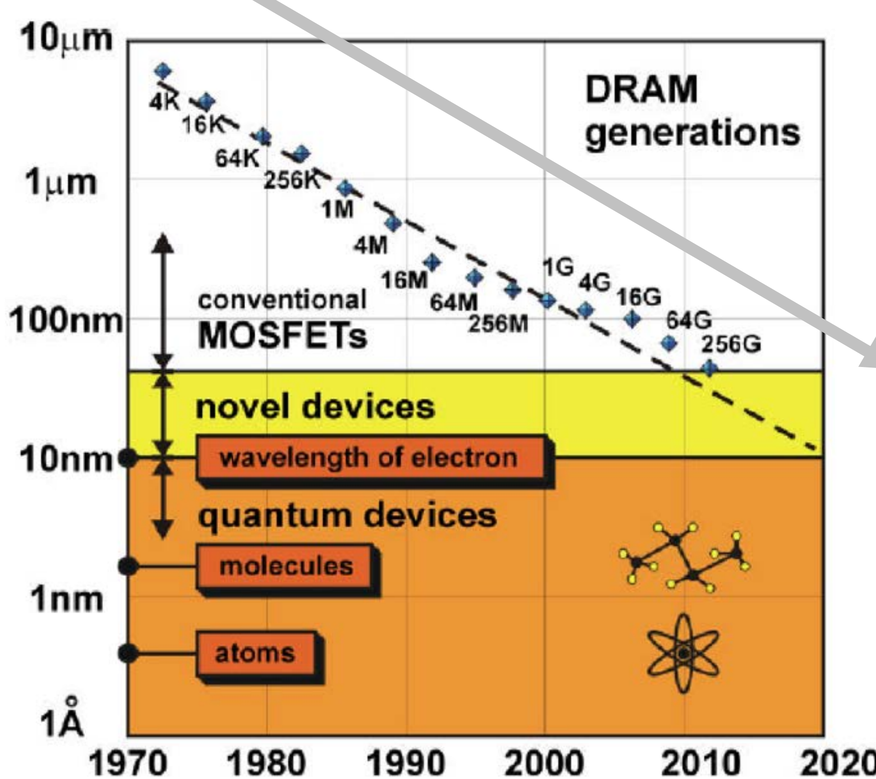

Nanocircuits in our pocket

First semiconductor transistor

Shockley, Bardeen , Brattain

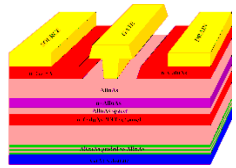
Nobel prize 1956.

Moore's law: the characteristic size of electronic building blocks (e.g. transistors) decreases by one order of magnitude within less than 20 years

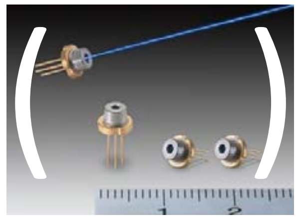


Nobel prize science in a cell phone

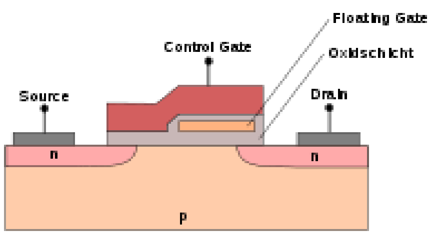
GHz communication, high electron mobility transistor, semiconductor laser

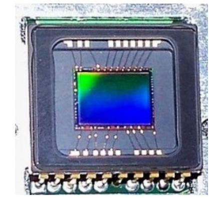


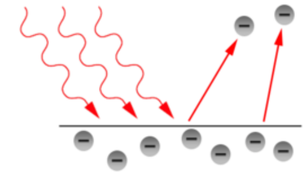
Alferov, Kroemer- Nobel prize 2000. (semiconductor nanostructures)



SIM card,
electron tunneling
Esaki - Nobel prize 1973.





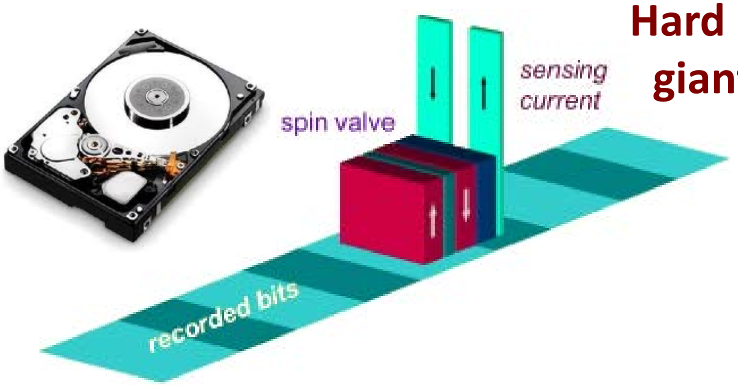


CCD camera

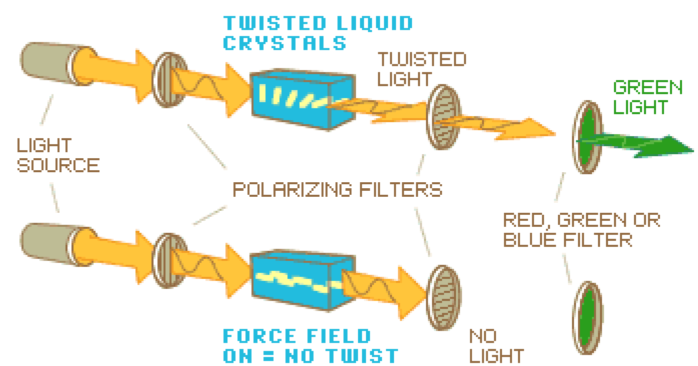
Einstein - Nobel prize 1921. (photo effect)

Boyle, Smith - Nobel prize 2009. (CCD sensor)

LCD display,
de Gennes - Nobel-prize 1991. (liquid crystal)

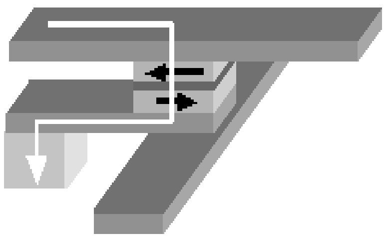


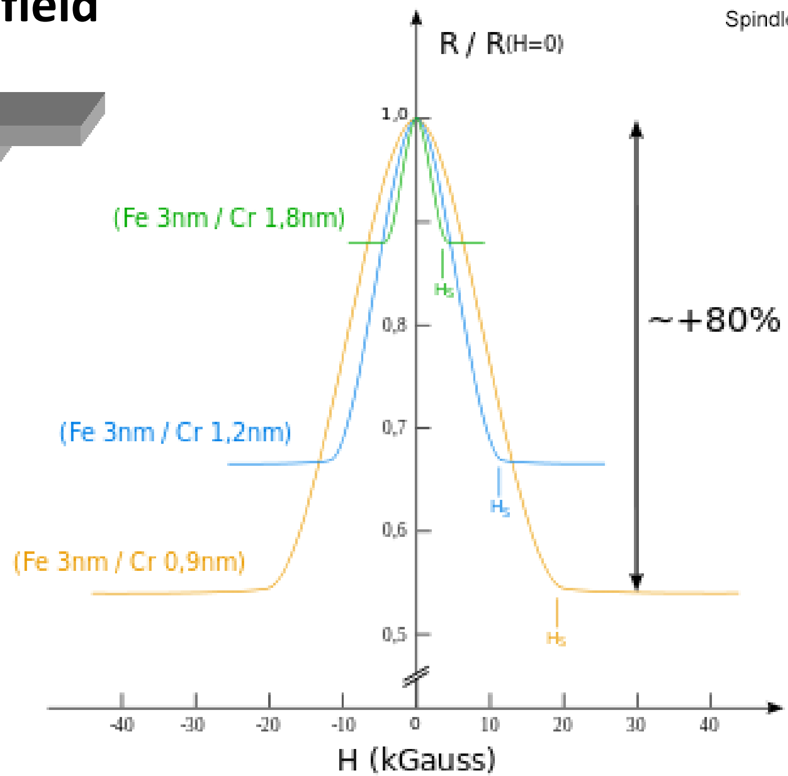
Hard disk drive read head - giant magnetoresistance (GMR)
Fert, Grünberg - Nobel prize: 2008.

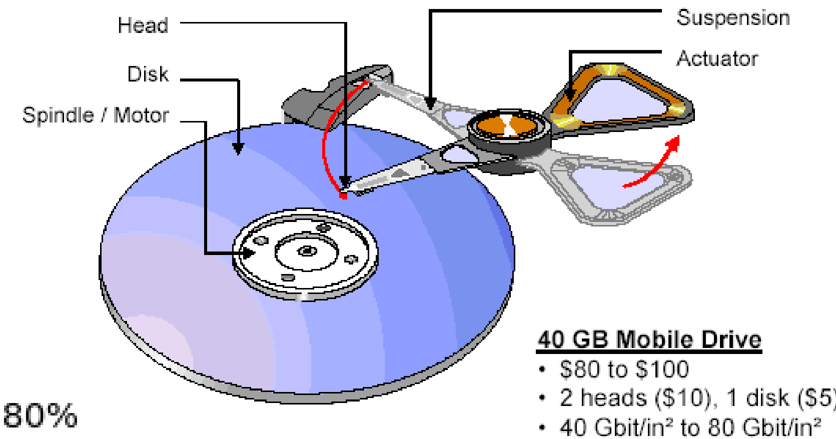


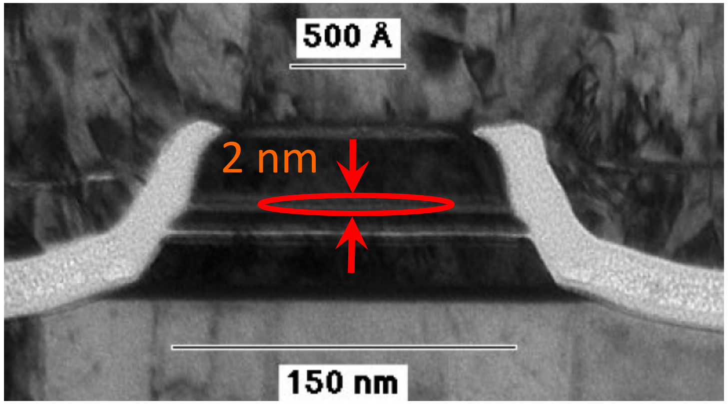
Spin valve sensor

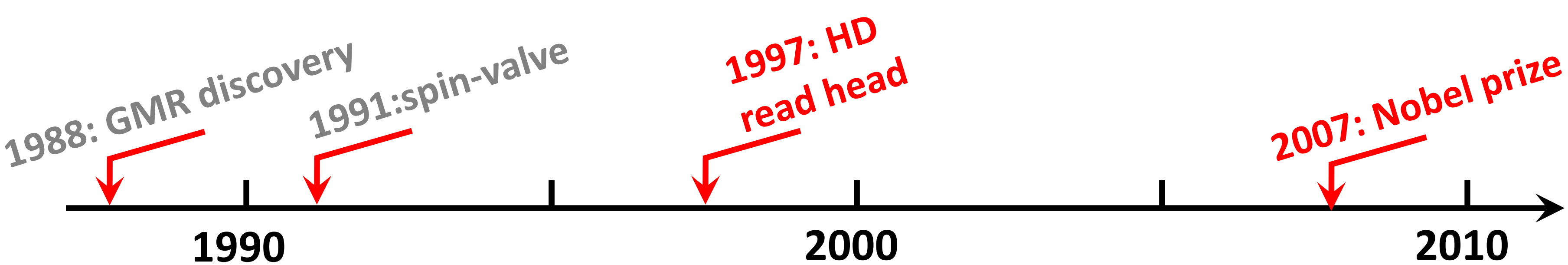
Application: measurement of magnetic field



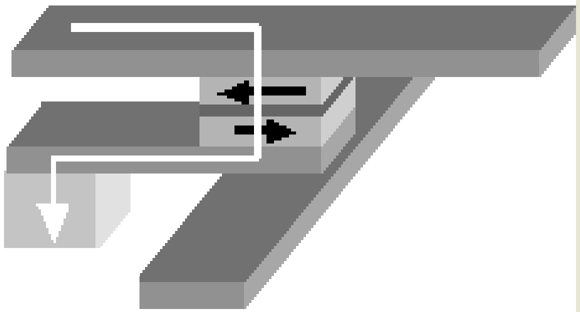






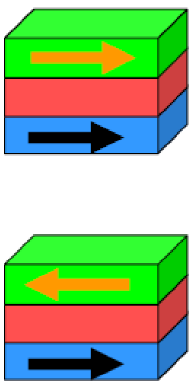


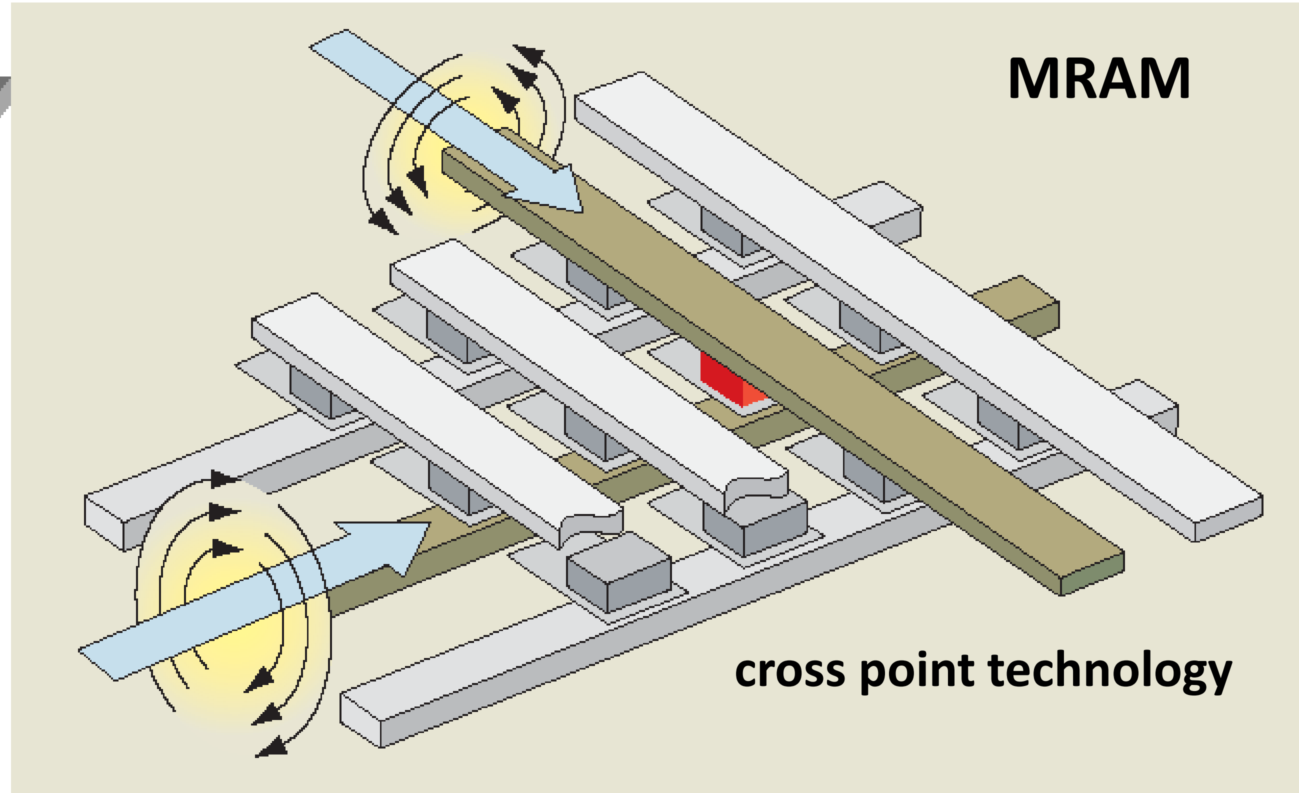
Spin valve memory



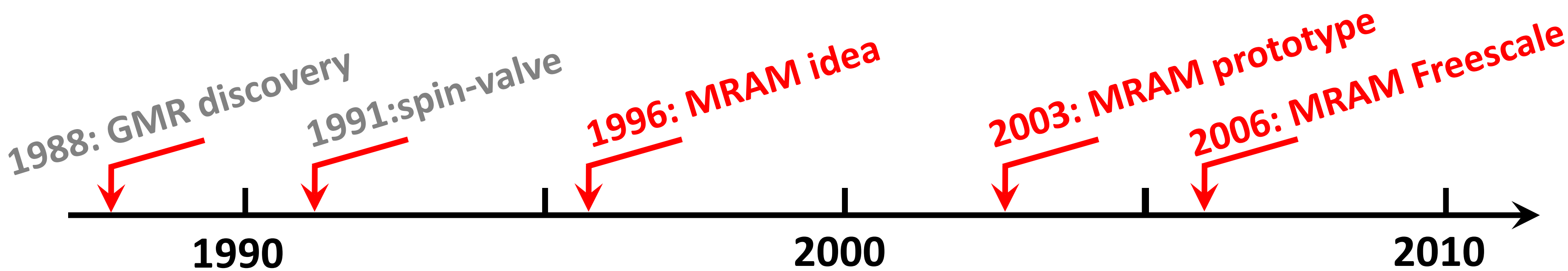
"0"

"1"



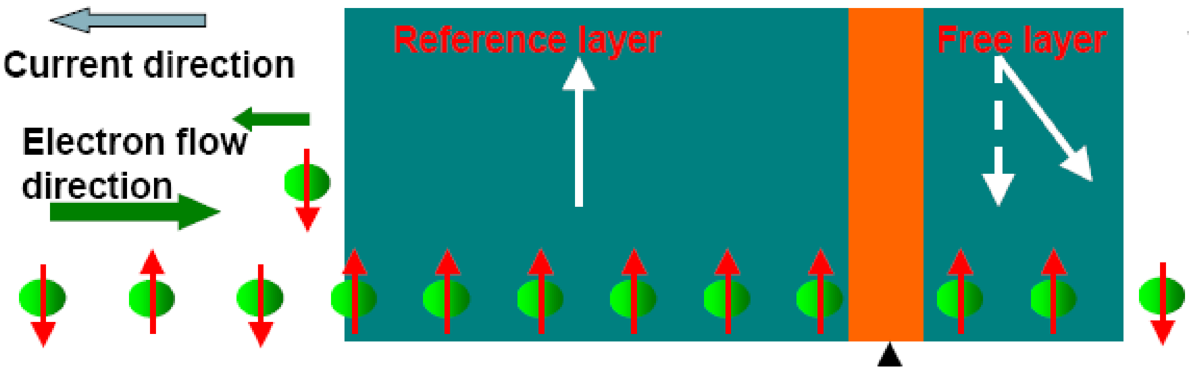


Magnetoresistive **R**andom **A**ccess **M**emory



Switching a spin valve by its current

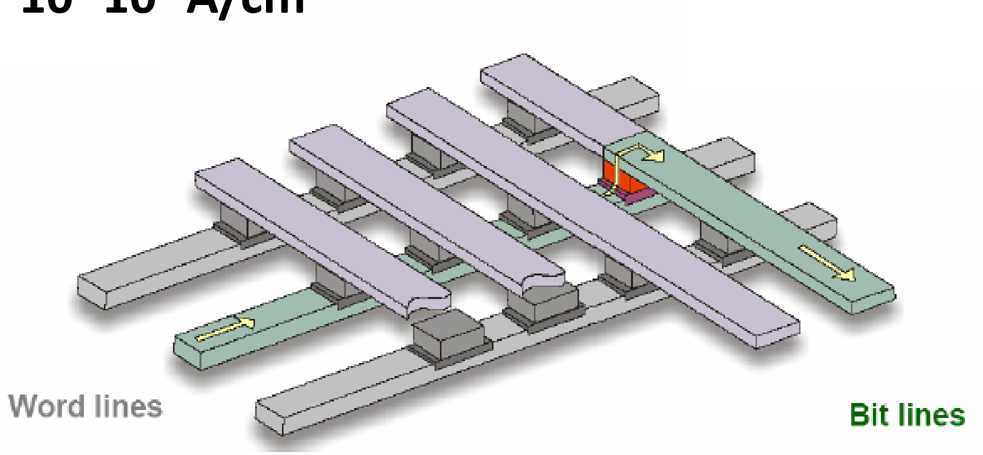
Spin transfer torque (STT)

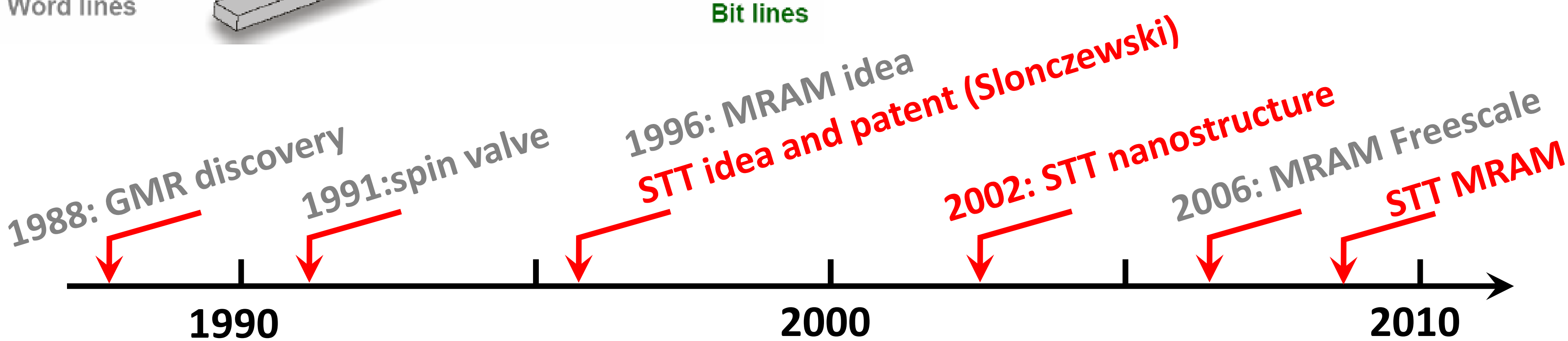


small current – readout

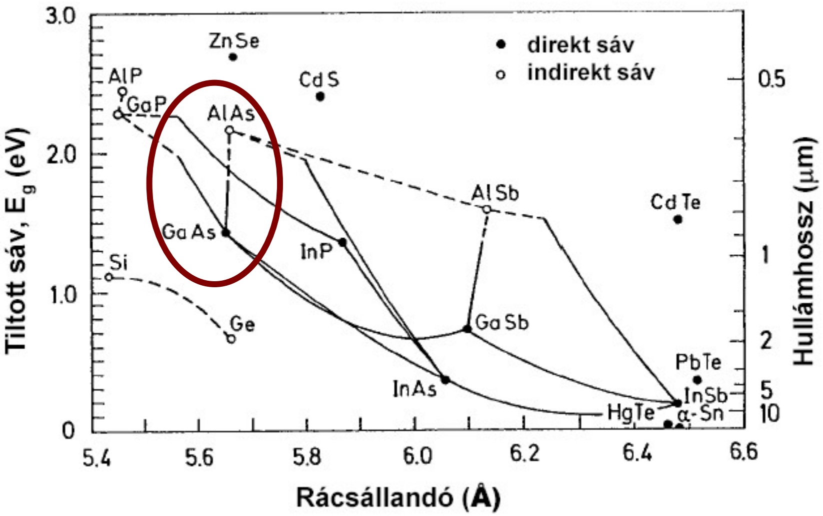
Large current – data storage

10^8-10^9 A/cm^2

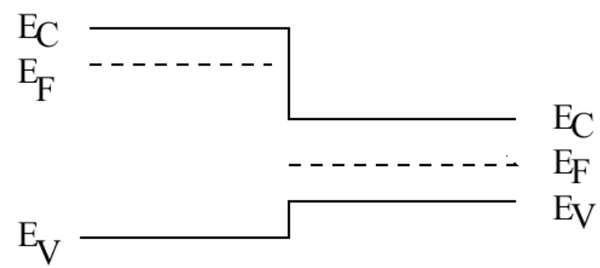




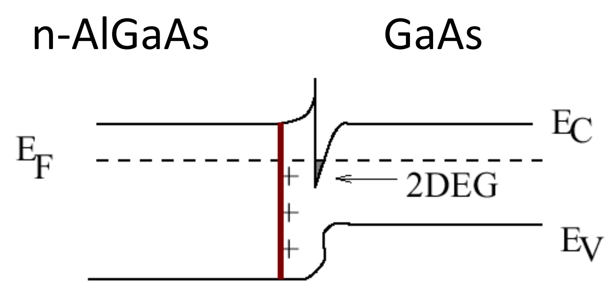
2D electron gas in $Ga_xAl_{1-x}As$ heterostructures

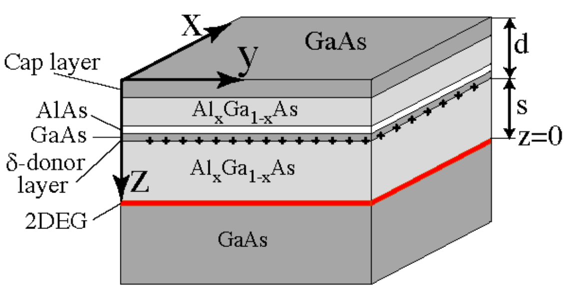


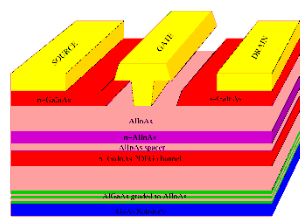
The gap of GaAs and AlAs strongly differs, but their lattice constant is the same with <0.15% precision, therefore they can be grown above each other epitaxially, without lattice defects. If $Ga_xAl_{1-x}As$ is grown with coevaporation than the gap can be continously tuned with x (band engineering).



At the interface of AlGaAs and GaAs a two dimensional electron gas (2DEG) is formed, i.e. At the inerface the electrons can freely propagate.







Applications: High Electron Mobility Transistor, with frequencies up to 600GHz; semiconductor lasers

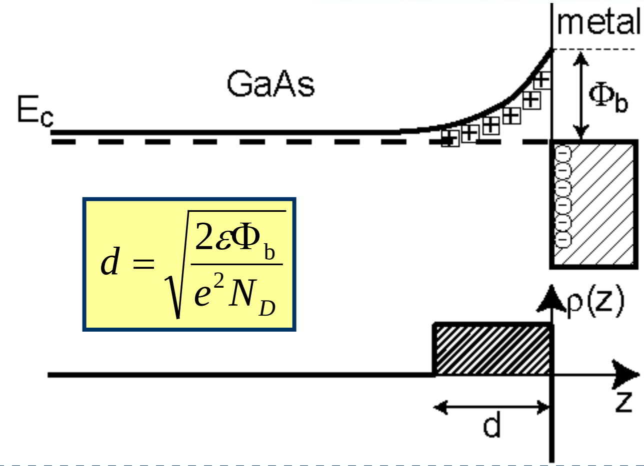
Doping is performed further away from the interface, thus the doping atoms do not disturb the motion of the electrons in the 2DEG. Due to this and the epitaxial growth the electrons can travel extremely long distances in the 2DEG without scattering -> high mobility.

2D electron gas in $Ga_xAl_{1-x}As$ heterostructures

Gate electrodes – Schottky barrier

Between a metal and the semiconductor a depleted layer forms. The electrons can only cross this layer by thermal excitation or electron tunneling.

With the gate voltage one can tune the electron density in the 2DEG.



$$d = \sqrt{\frac{2\varepsilon\Phi_b}{e^2 N_D}}$$

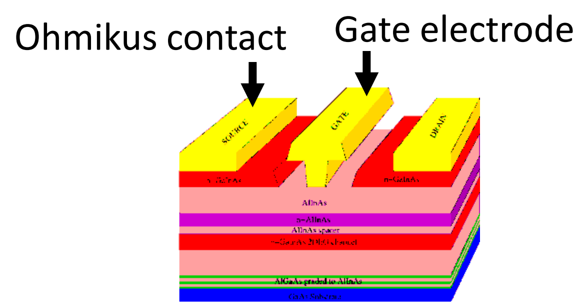
Ohmic contacts

With strong doping the Schottky barrier can be destroyed, and so ohmic contacts can be formed.

Au + 12% Ge
GaAs

450 ^{O}C →

Ge is placed to Ga sites



„Split gate" technique

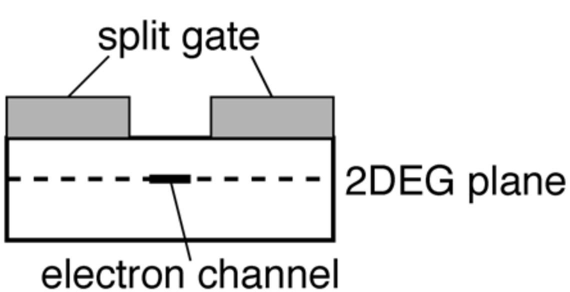
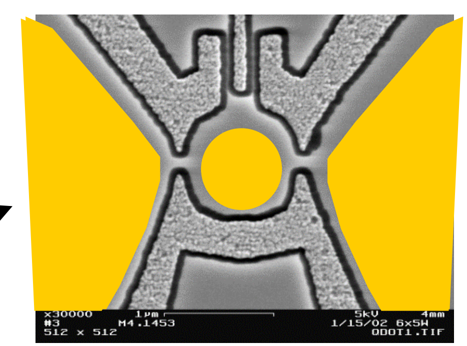


Photo or electron beam lithography is used to place gate electrodes on the top of the 2DEG. With proper gate voltage the electron gas can be depleted underneath the gates.

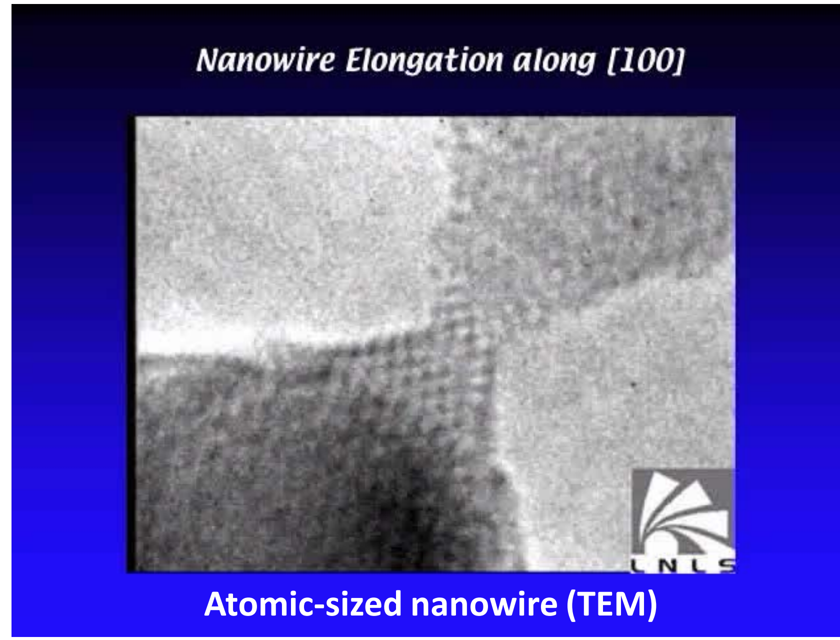
quantum dot

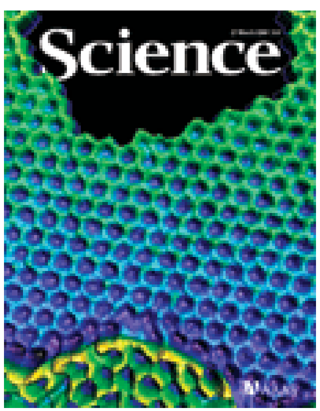


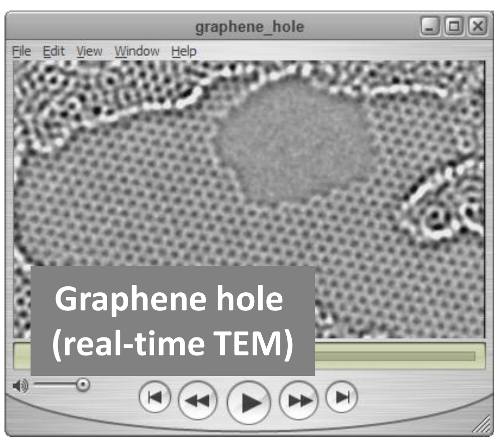
Scanning and transmission electron microscope (SEM / TEM)

• SEM: the sample is scanned by a focused electron beam, reflected electrons or secondary electrons are detected. 1-5 nm resolution.

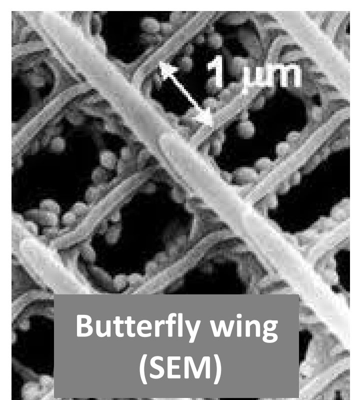
• TEM: the electron beam is transmitted through an ultra thin layer, the picture is magnified by electron optics.

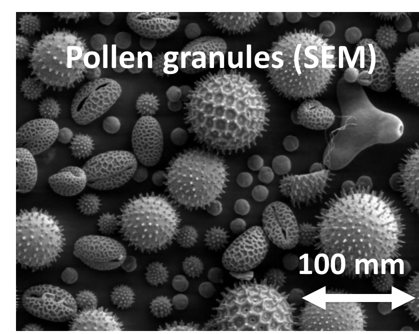




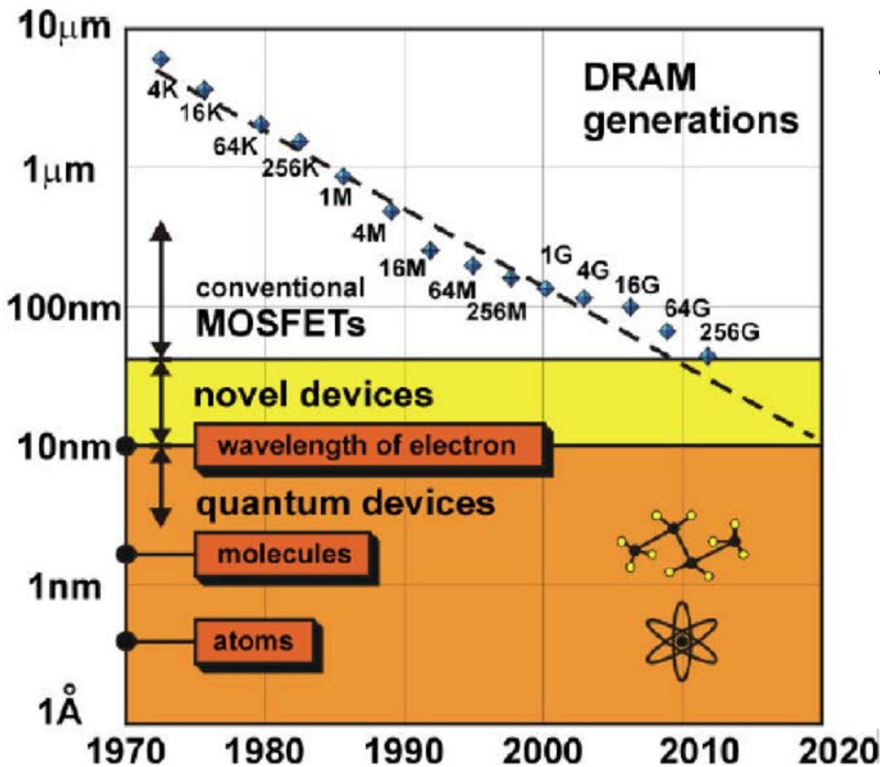


Girit et al. Science **323,** 1705 (2009)

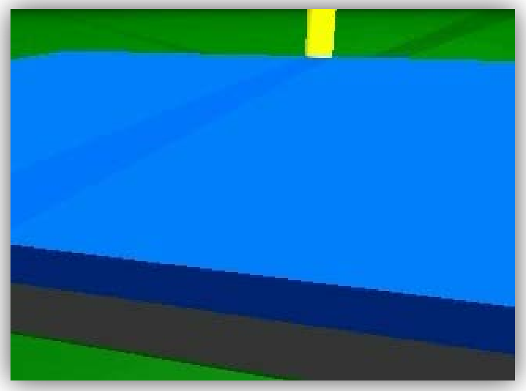




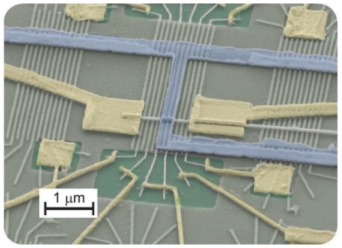
How can we fabricate nanocircuits?



Scanning electron microscope in the BME – MFA joint laboratory



Electron beam lithography

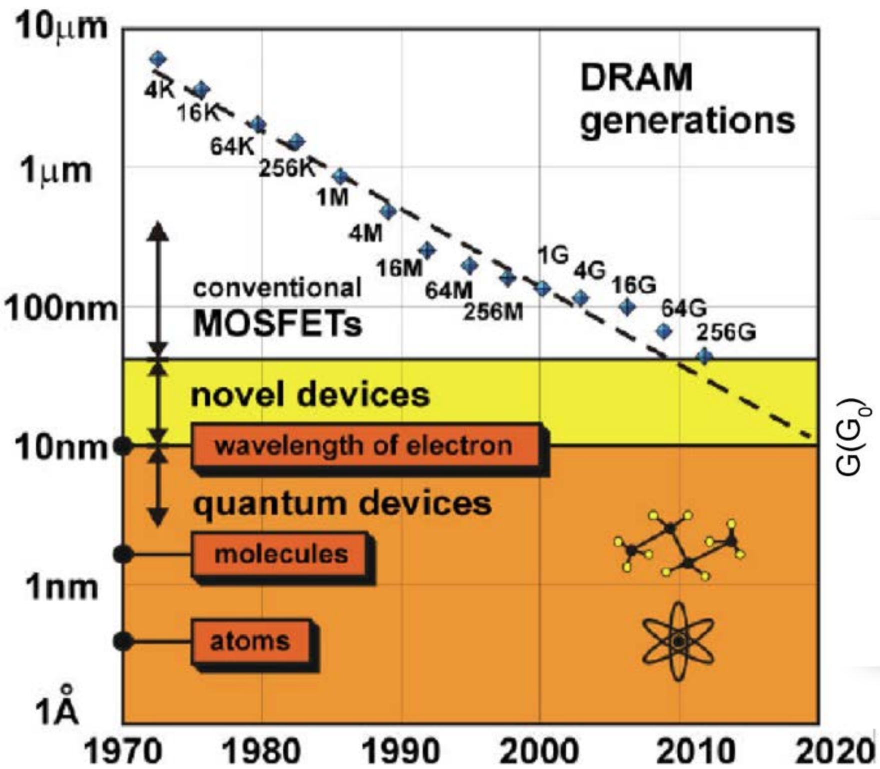


Ernst Ruska, Nobel prize 1986.

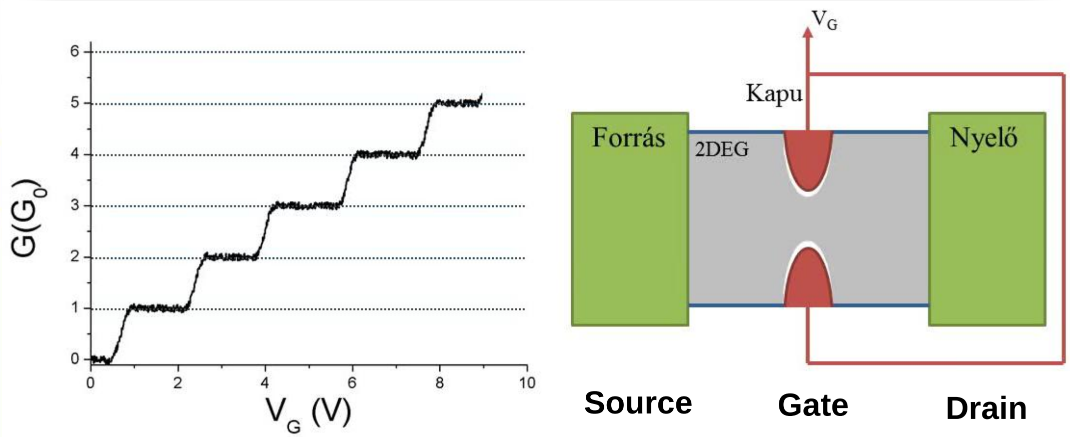
„for his fundamental work in electron optics, and for the design of the first electron microscope”

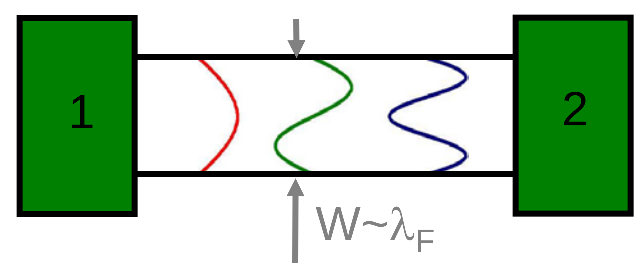
A silicion substrate is covered by a polimer (PMMA) film. The structure of the PMMA changes where it is shined by the e-beam. At these regions the PMMA can be removed with a solvent. Afterwards metal is evaporated, and finally the rest of the PMMA (with the metal on the top) is removed by an other solvent. A metal wire is left, where the structure was shined by e-beam.

Surprising phenomena at nanoscale



Wave nature of electrons, conductance quantization

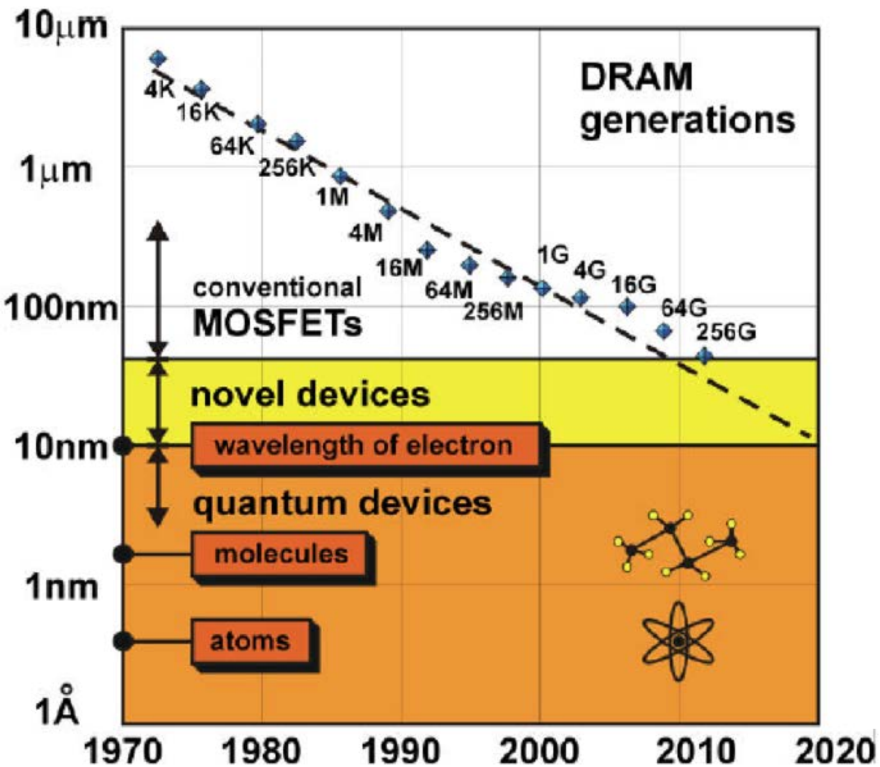




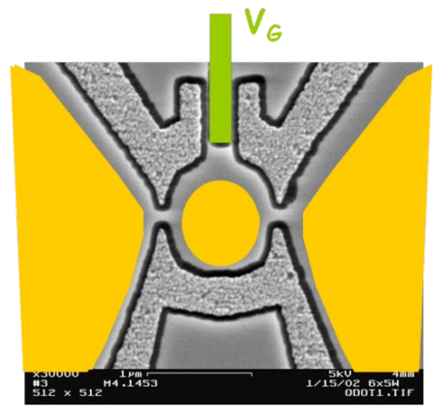
The conductance of a two dimensional electron gas changes in steps of $G_0=2e^2/h$ as the width of the chanel is tuned by gate electrodes, if the channel width is in the order of the electron wavelength. The conductance steps correspond to the opening of discrete conductance channels, which are related to transverse standing waves.

In semiconductors the electron wavelength is λ_F>10 nm, smaller devices are not conducting!

Surprising phenomena at nanoscale



Particle nature of electrons: quantum dots, single electron transistor

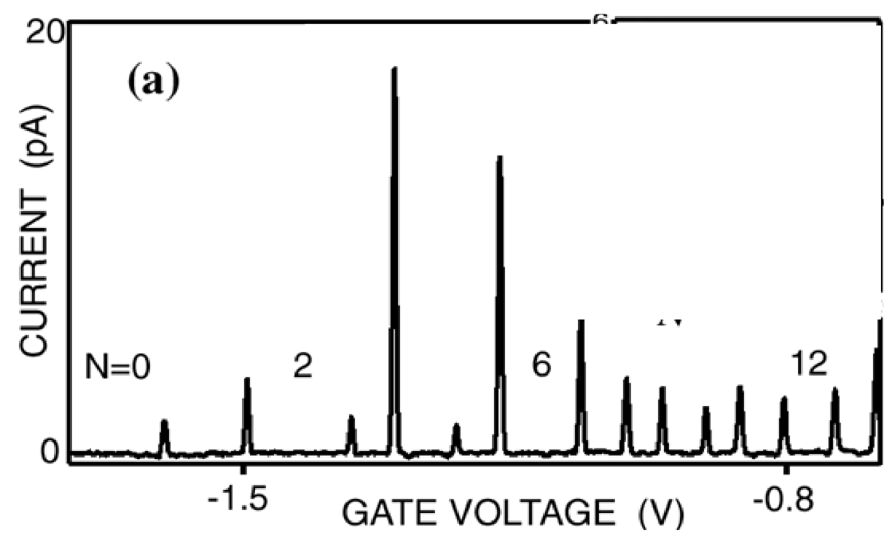


$$E_{\text{Coulomb}}(N) = \frac{e^2 N^2}{2C}$$

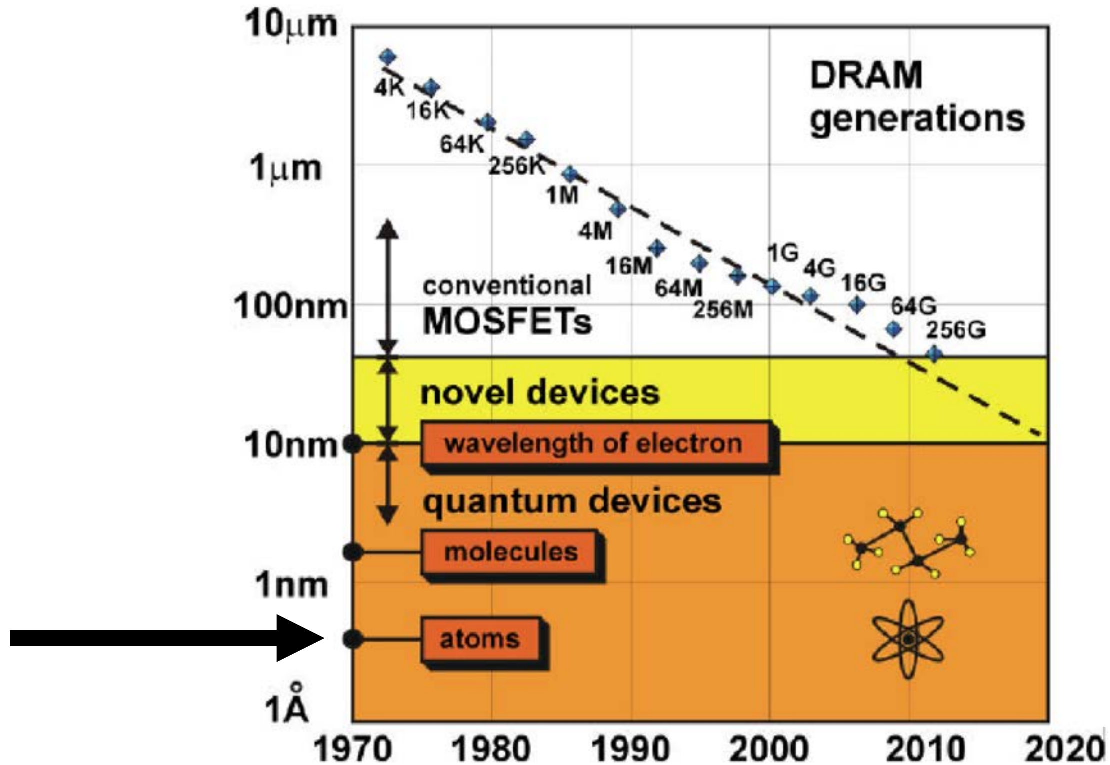
The energy required to add a single electron (charging energy):

$$\Delta E_c \approx \frac{e^2}{C} \sim 1\text{meV} \approx 11\text{K}$$

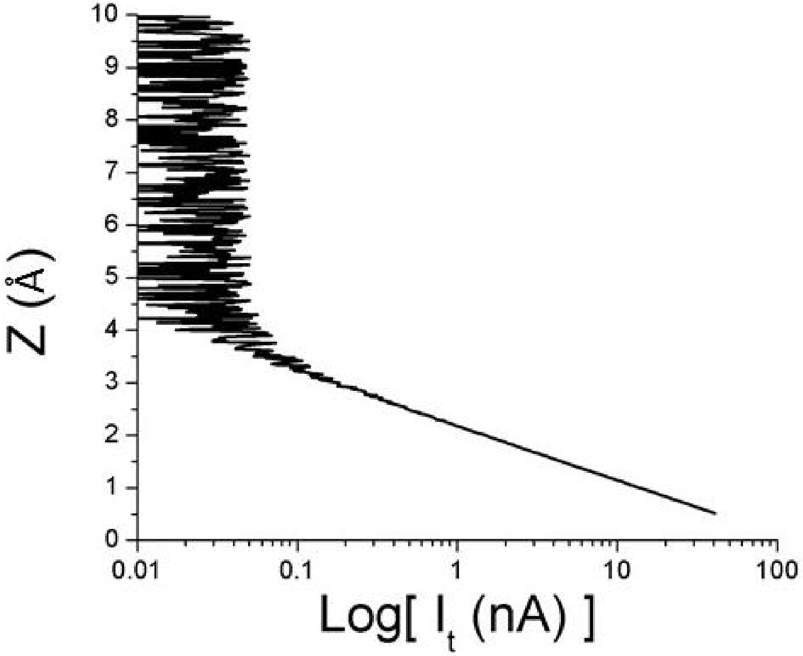
A metallic island is connected to the source and drain electrodes via tunnel barriers. The addition of an extra electron to the island costs Coulomb energy, therefore at low temperature ($kT<E_C$) the current through the quantum dot is blocked. However, by gate tuning the electrostatic potential of the dot one can set discrete potential values where the presence of N or N+1 electron is energetically equivalent, and so current can flow through the dot.

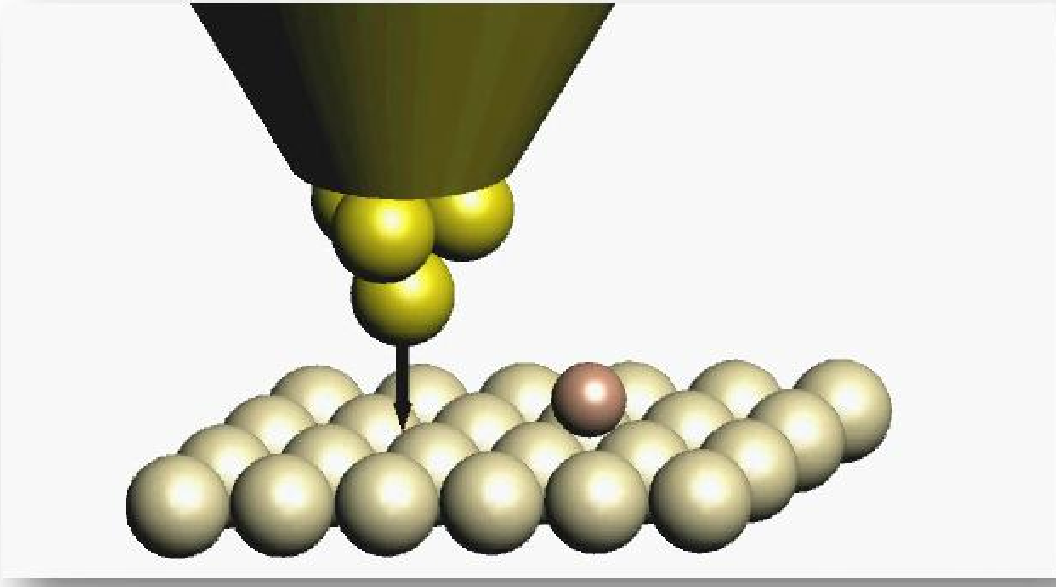


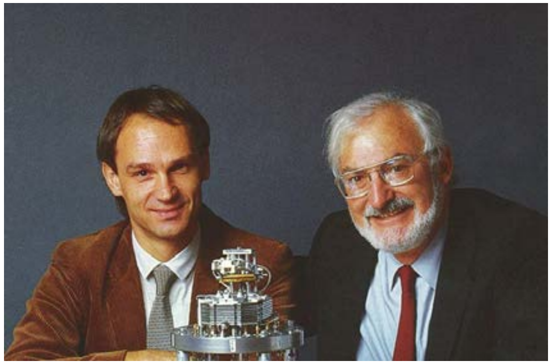
Atomic-sized structures?



Scanning tunneling microscope (STM)





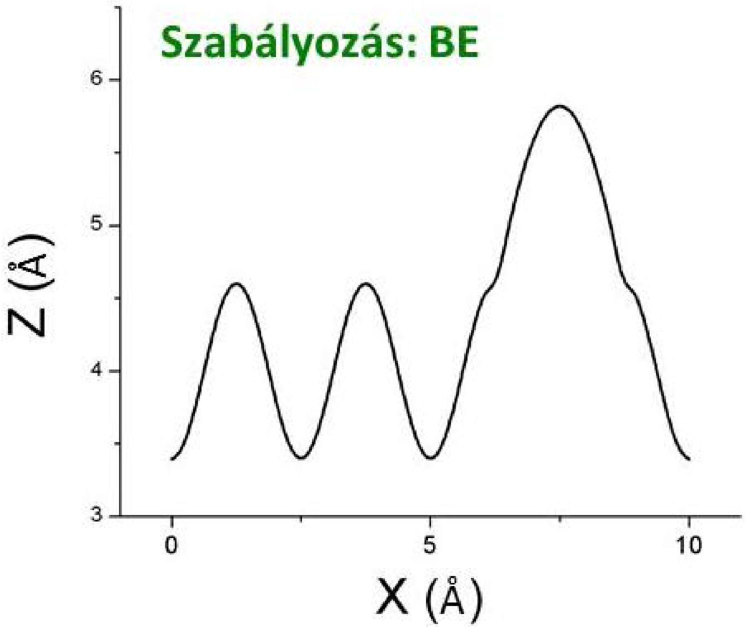


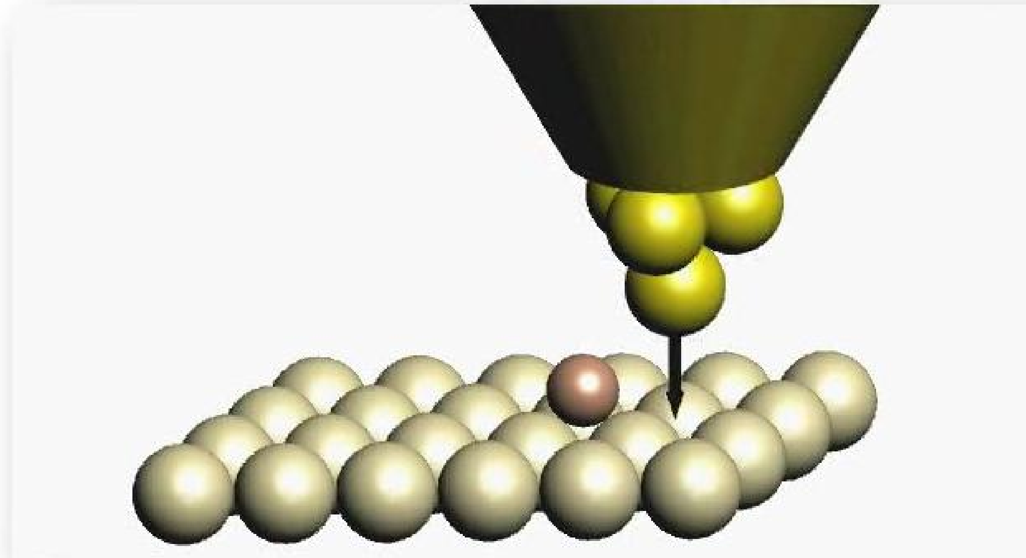
Gerd Binnig, Heinrich Rohrer
Nobel prize 1986.

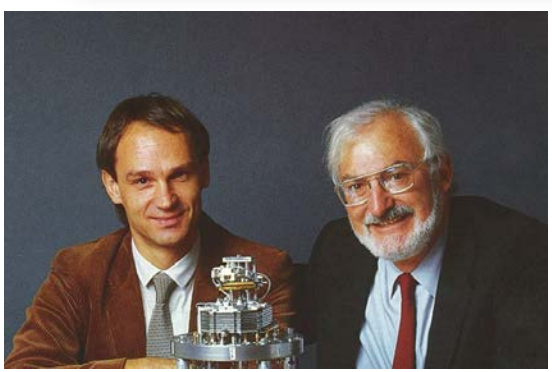
„For their design of the scanning tunneling microscope"

If a biased metallic tip is brought close to a grounded metallic surface a tunnel current flows, though there is an air gap between the tip and the surface. The tunnel current is an exponential function of the tip-surface separation, lifting the tip by a half atom-atom distance (~0.1 nm) causes an order of magnitude decrease in the tunnel current.

Scanning tunneling microscope (STM)







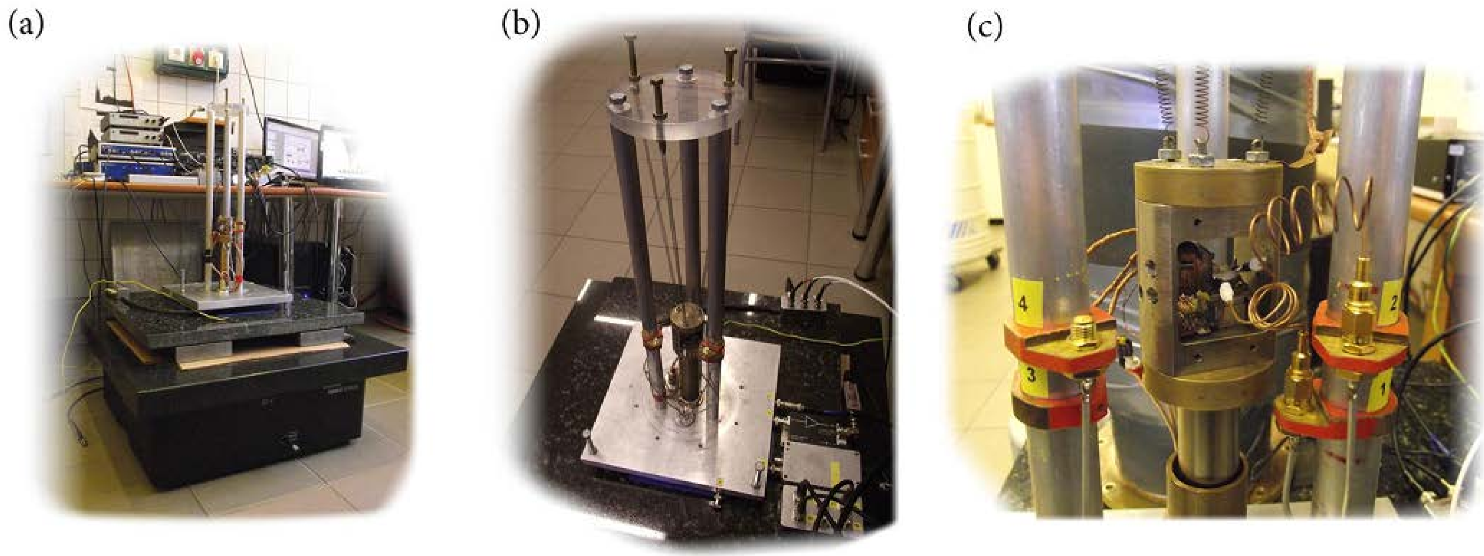
Gerd Binnig, Heinrich Rohrer
Nobel díj 1986.

„For their design of the scanning tunneling microscope"

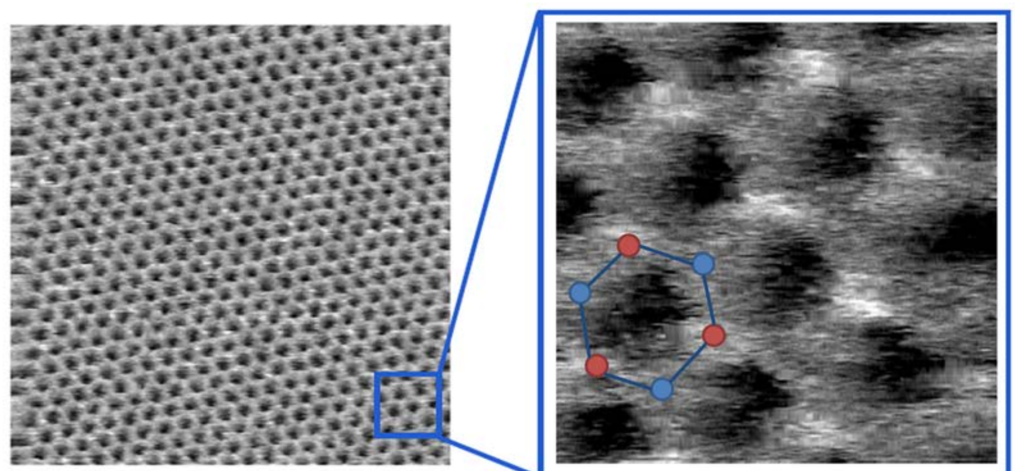
As the tip scans over the surface it is raised or lowered by a feedback loop such that the tunnel curent, i.e. the tip-sample distance remains constant along the scanning. By plotting the z position of the tip as a function of x and y one can map the topography of the surface even with atomic resolution.

Scanning tunneling microscope (STM)

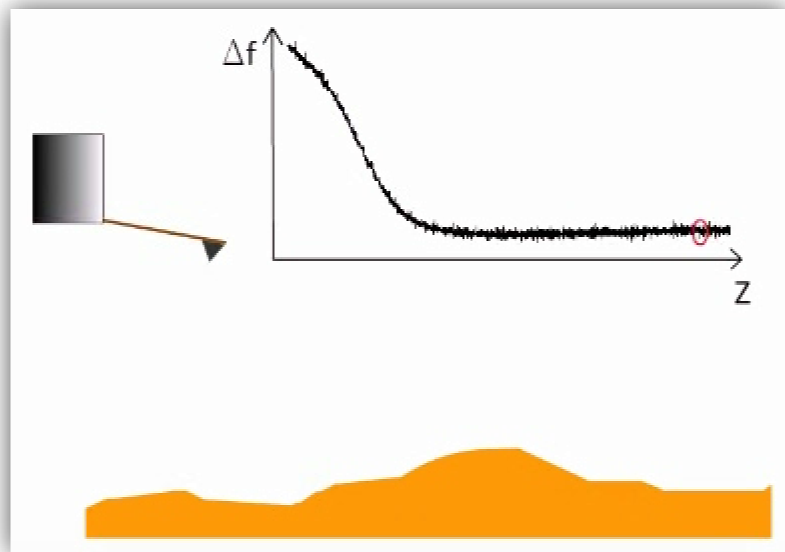
Self-designed STM:

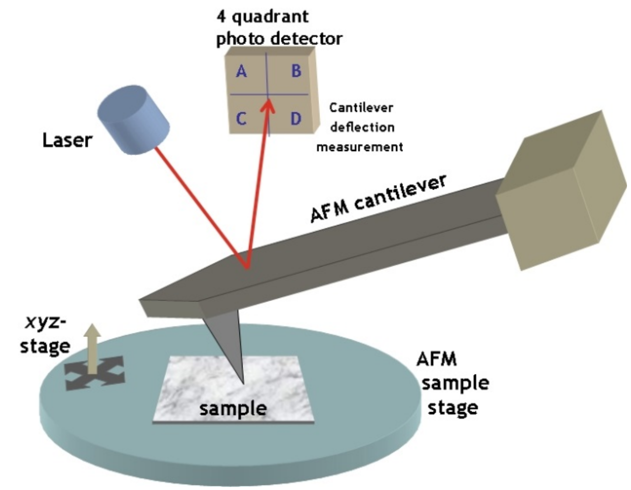


Atomic resolution picture on graphite

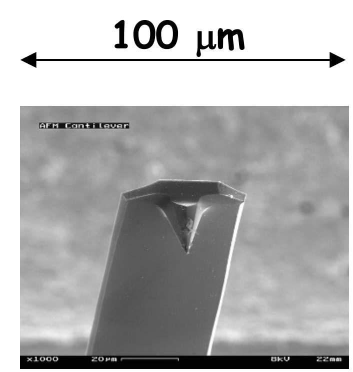


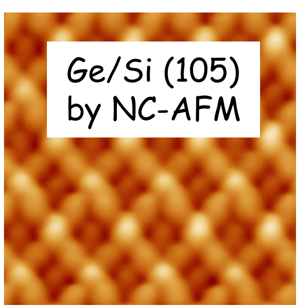
Atomic force microscope

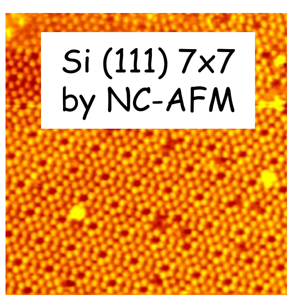


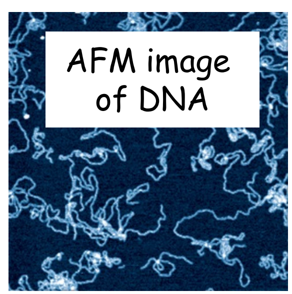


A tip is placed at the end of a cantilever. The tip is raised and lowered by the feedback such that the **force** between the tip and the sample remains constant. The force is determined from the cantilever deflection or the resonance frequency shift. It works also with non-conducting samples.

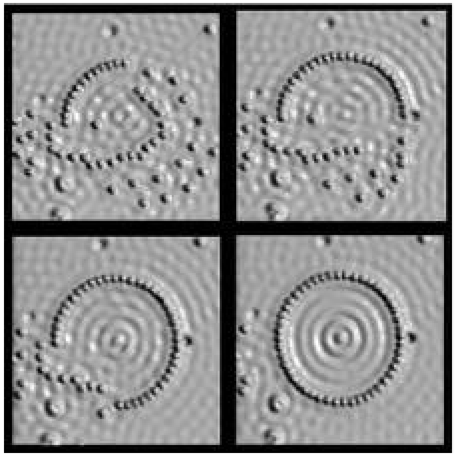




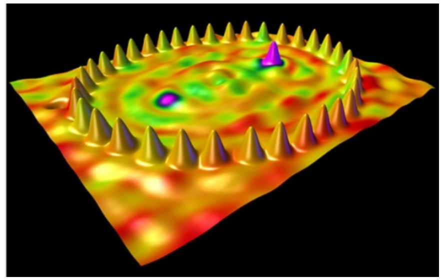




„Building" nanostructures with an STM

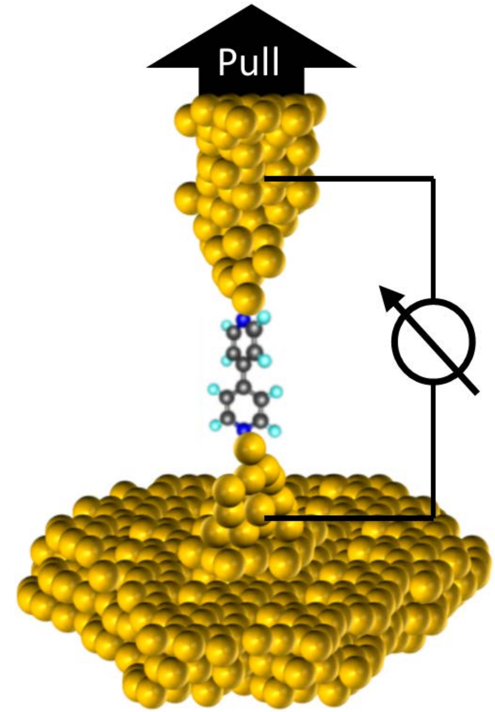


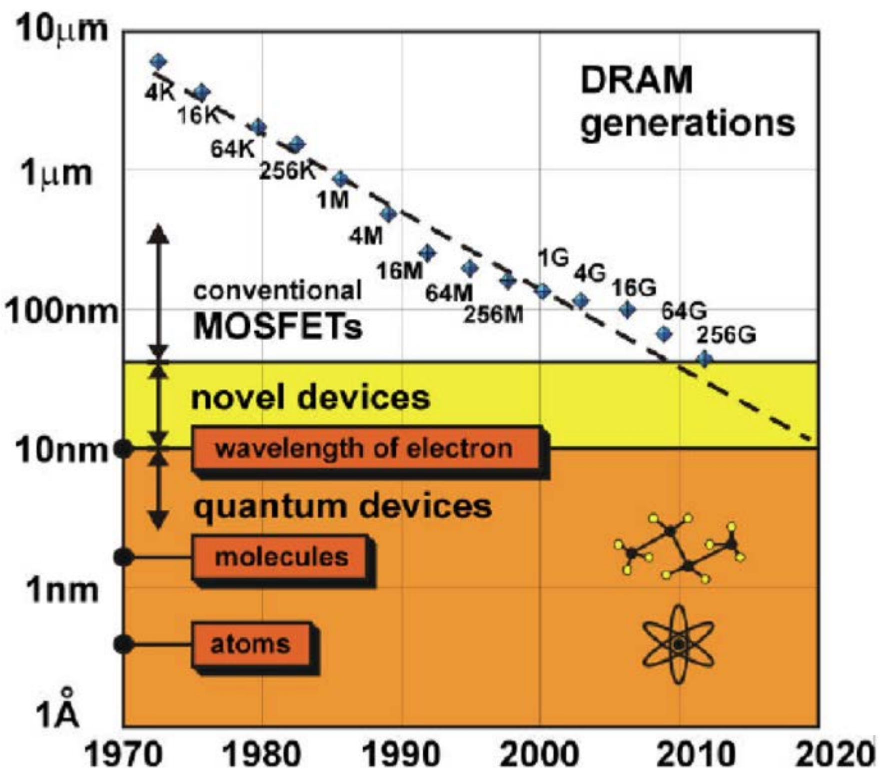
Moving atoms on metal surfaces



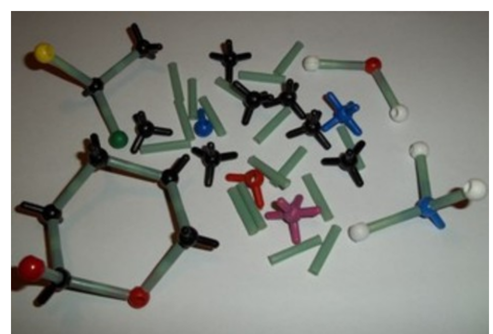
Pulling atomic chains

Molecular electronics?

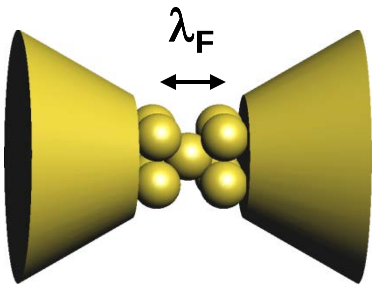




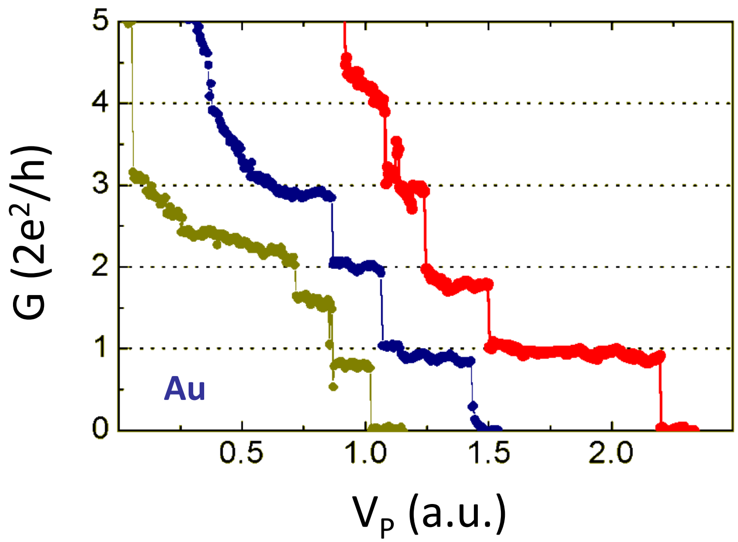
Bottom-up

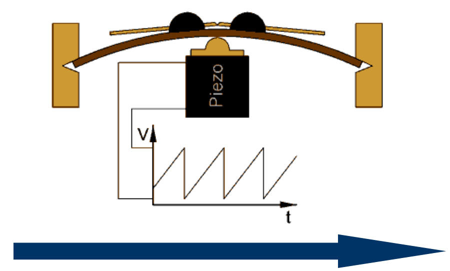


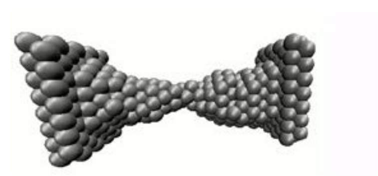
Nanostructures from metals?

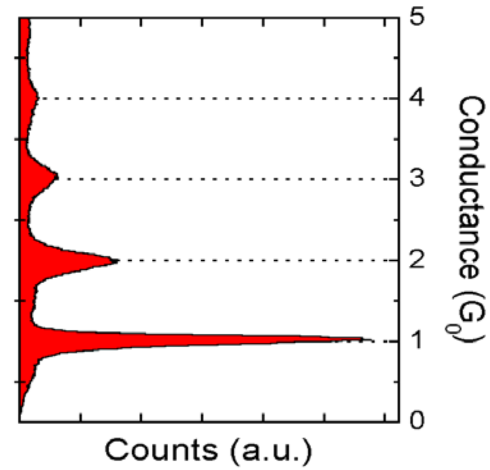


In metals λ_F ~ lattice constant



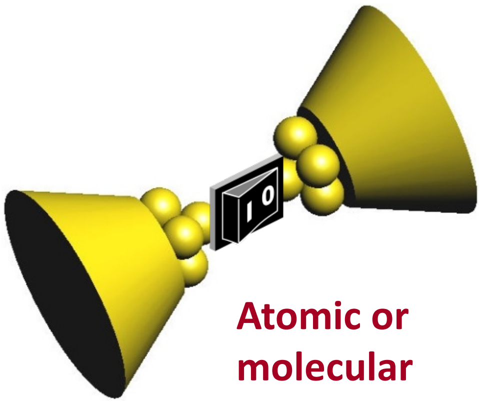






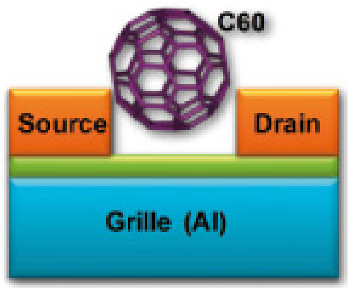
Field effect does not work!

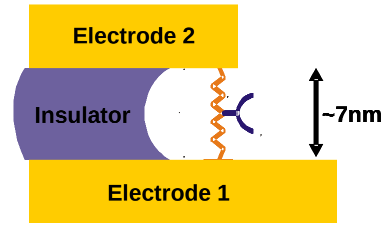
Molecular electronics?



Atomic or molecular memories

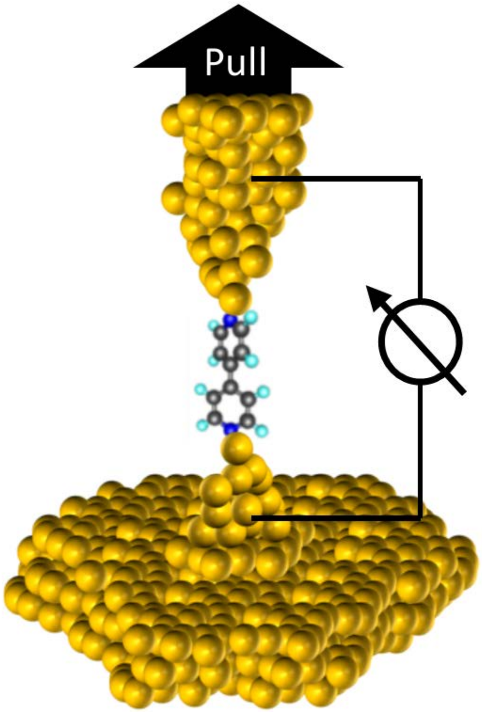
Transistor from a single molecule

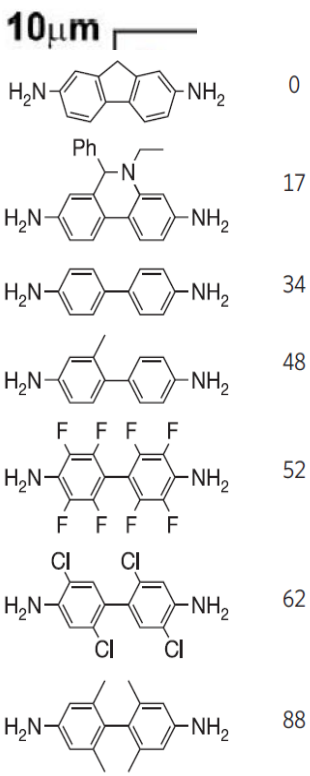


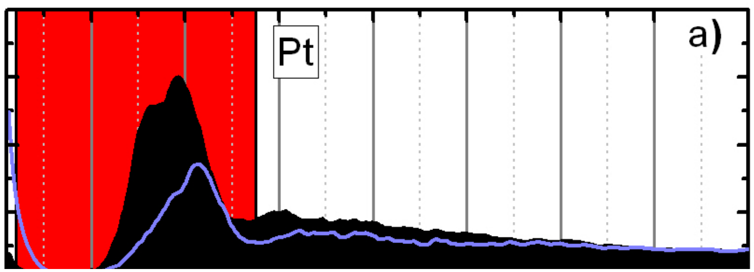


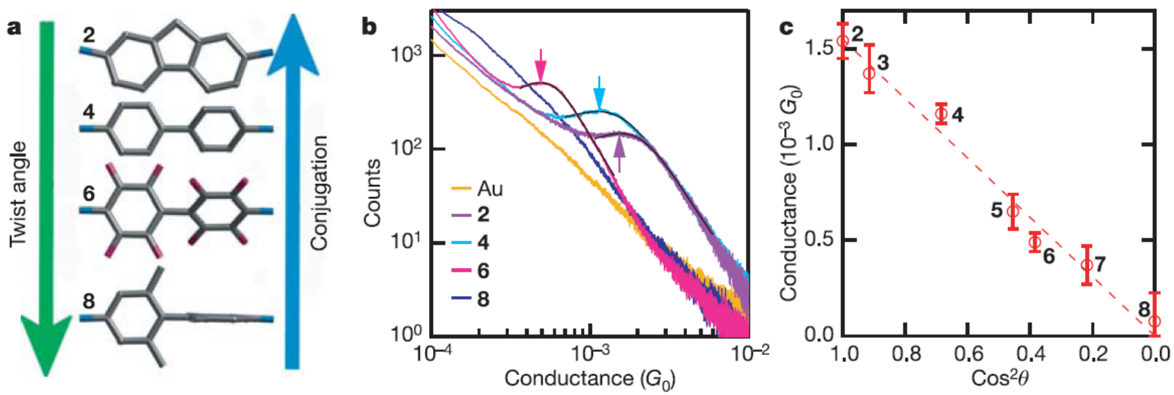
Electrode arrangemen

Sensor from a single molecule



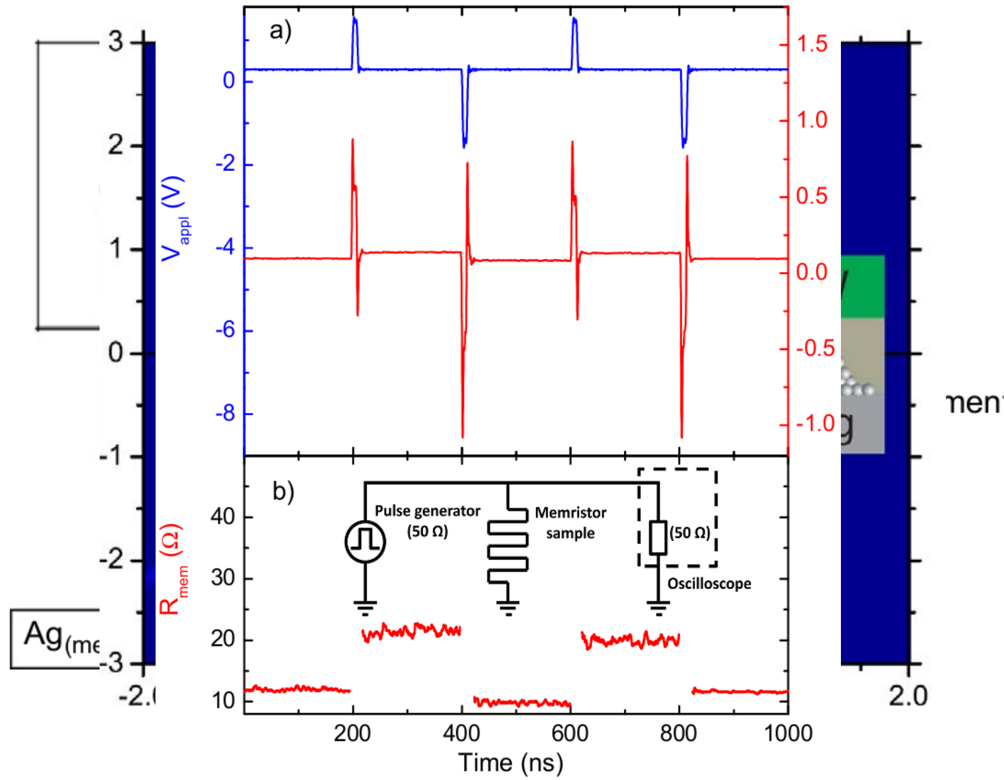


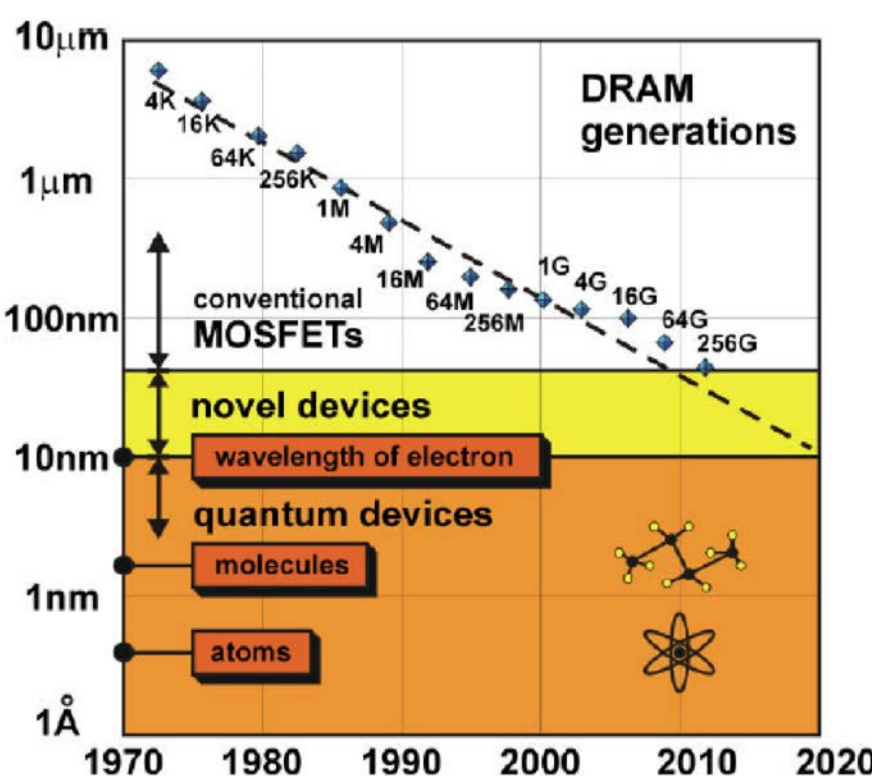




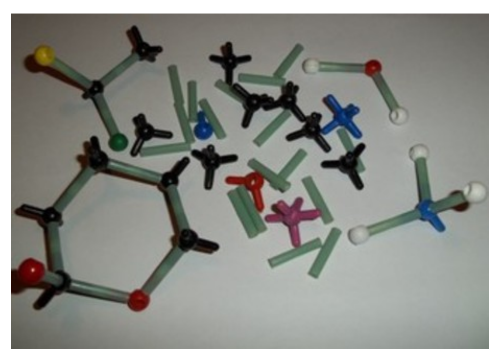
Nanoionics?

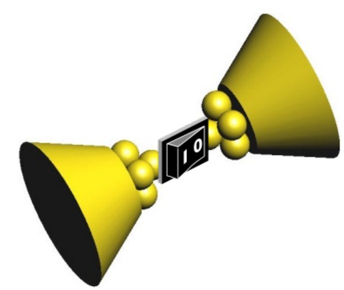
- Atomic-sized memory
- GHz-operation





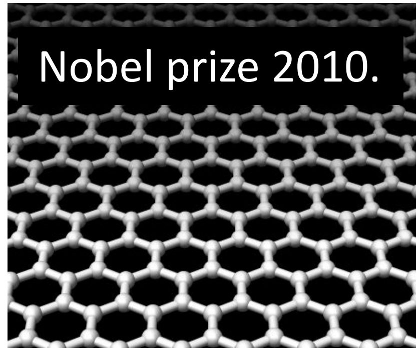
Bottom-up

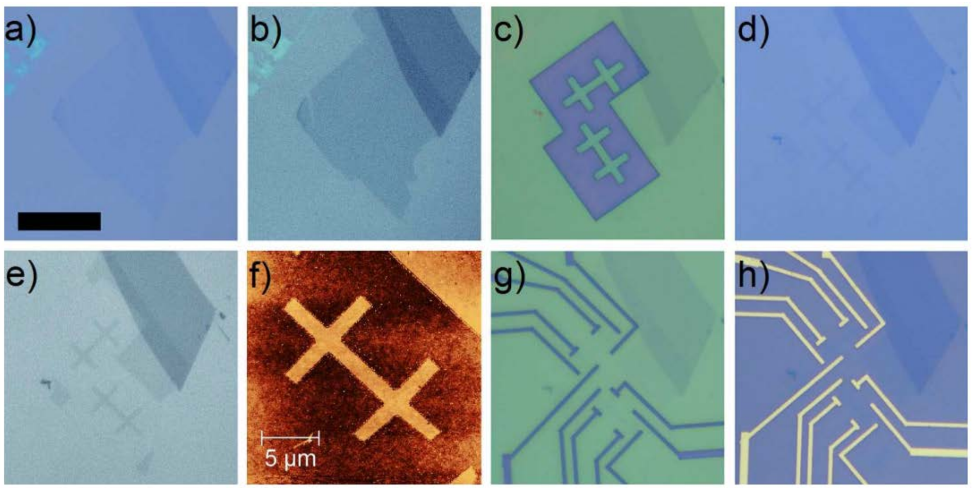


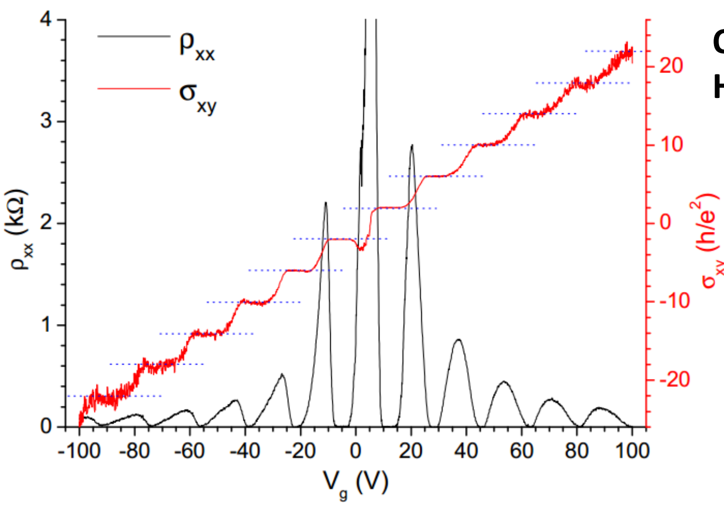


Atomic switch

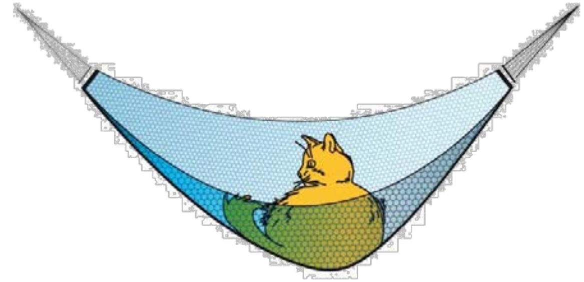
Graphene





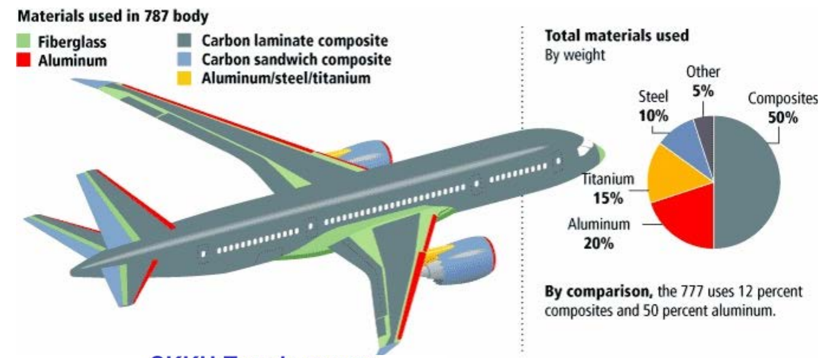


Quantized Hall effect

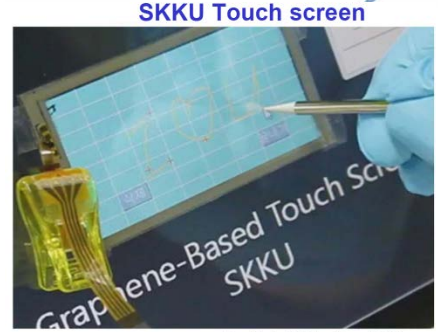


stretchable

strong composit materials



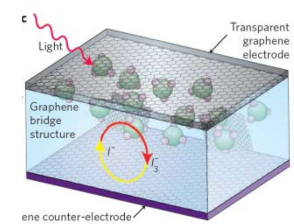
SKKU Touch screen

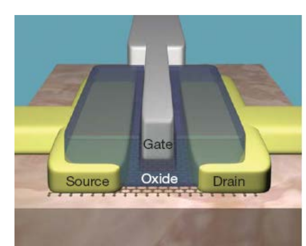


Bae, S. *et al.* Nature Nano (2010)

touch screen (transparent conductor)

photocell





transistor