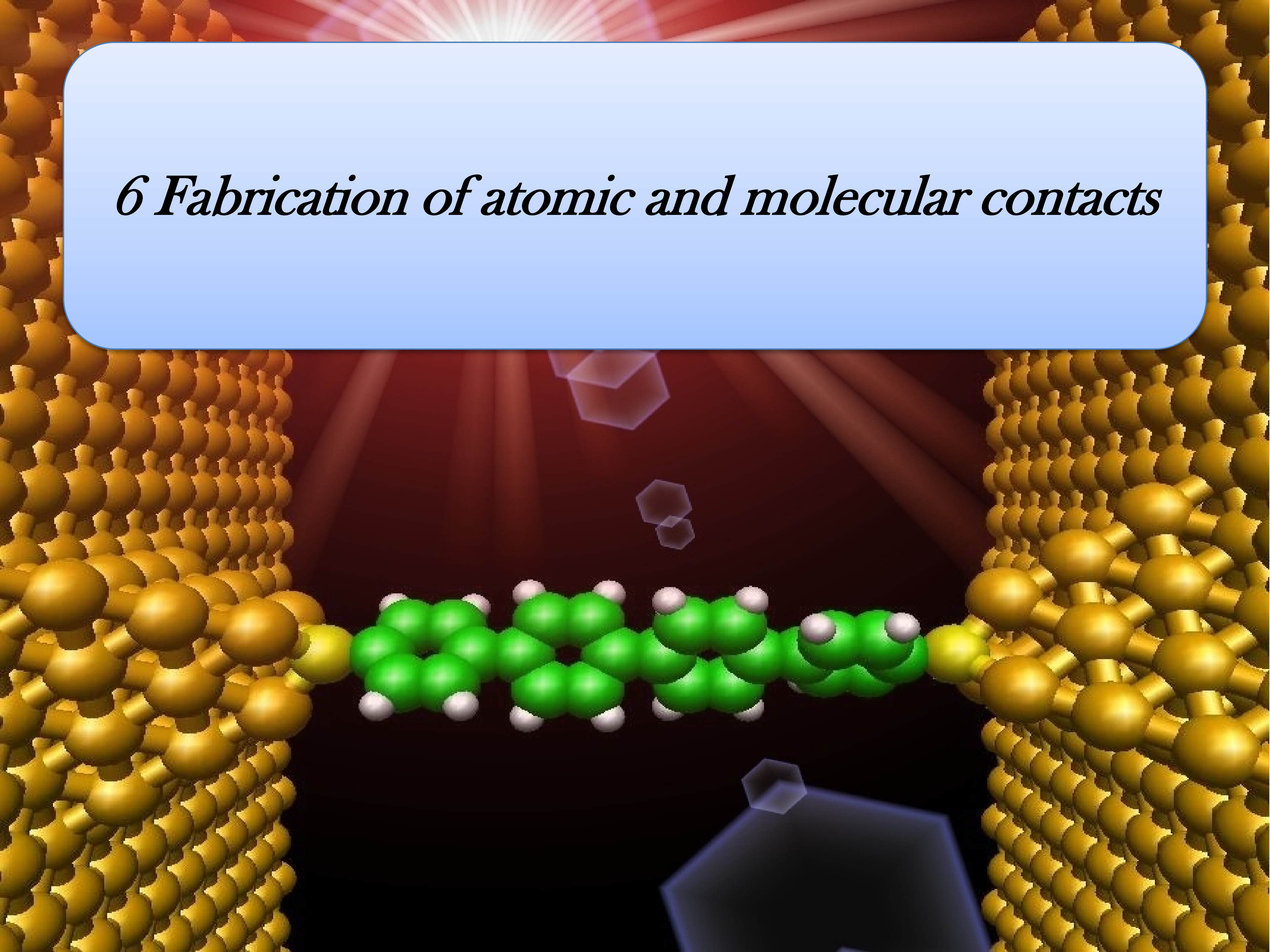
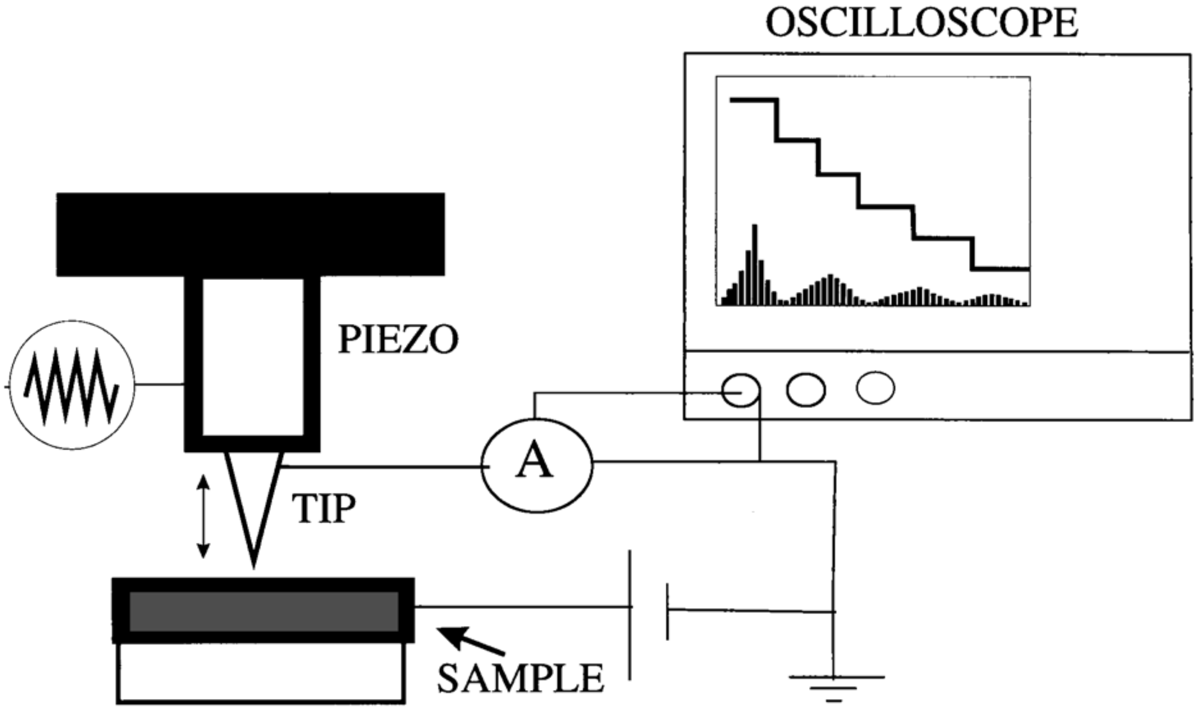
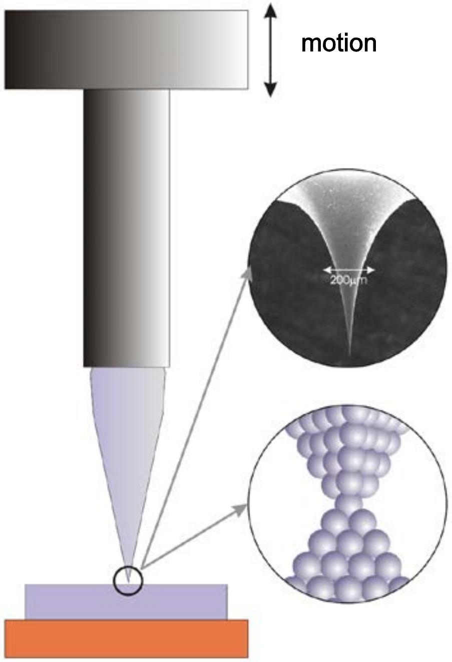
6 Fabrication of atomic and molecular contacts



6.1 Fabrication of atomic-size contacts

6.1.0 Scanning tunneling microscopy (STM)

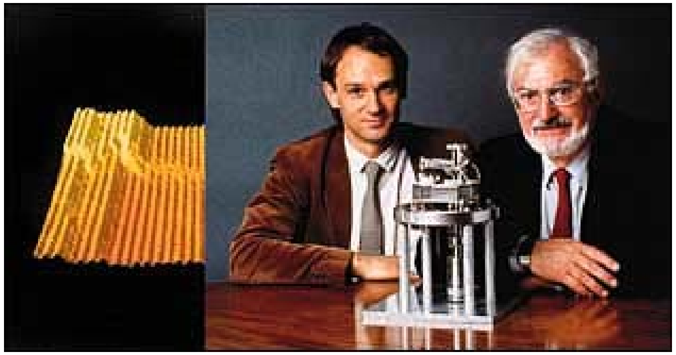




+ large variability of materials + fast + imaging

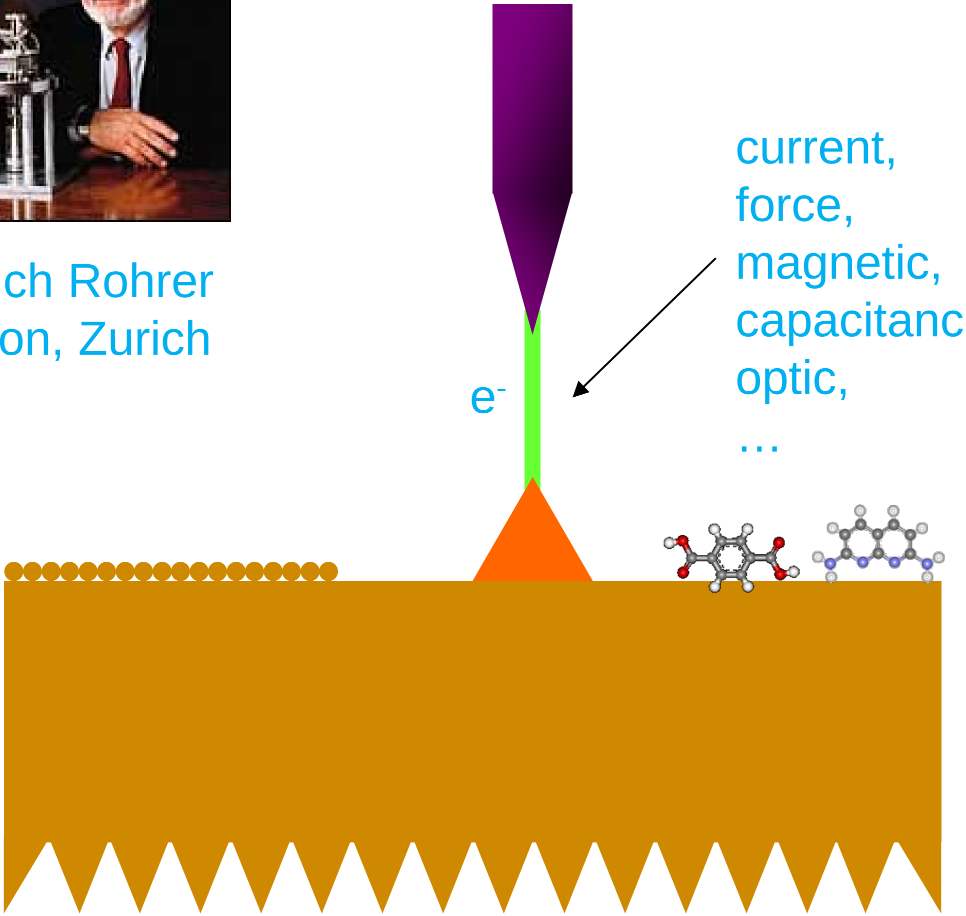
6.1 Scanning tunneling microscopy

Scanning probe microscopy



Gerd Binnig & Heinrich Rohrer
IBM Research Division, Zurich

1986



current,
force,
magnetic,
capacitance,
optic,
…

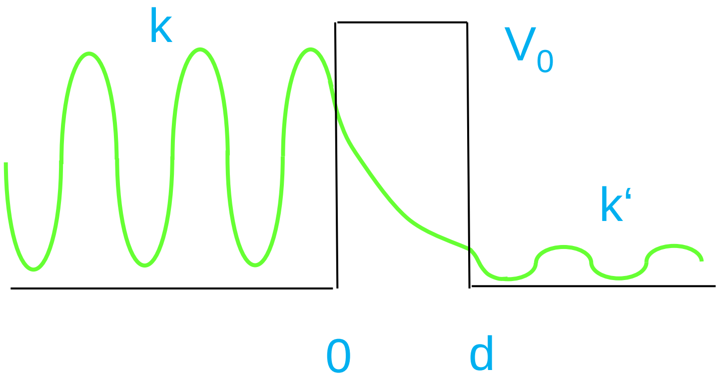
for conducting samples

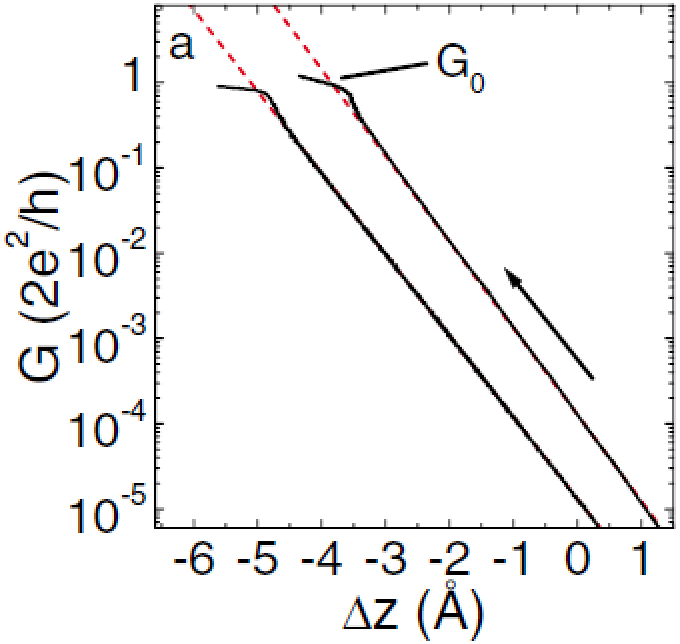
local investigation of surfaces

Courtesy: G. Costantini, MPI Stuttgart

Tunnel current through a 1-dim rectangular barrier

Current-distance curves or G vs Δz curves





Ag on Ag 111 or Cu on Cu 111
Limot et al, PRL94, 126102 (2004)

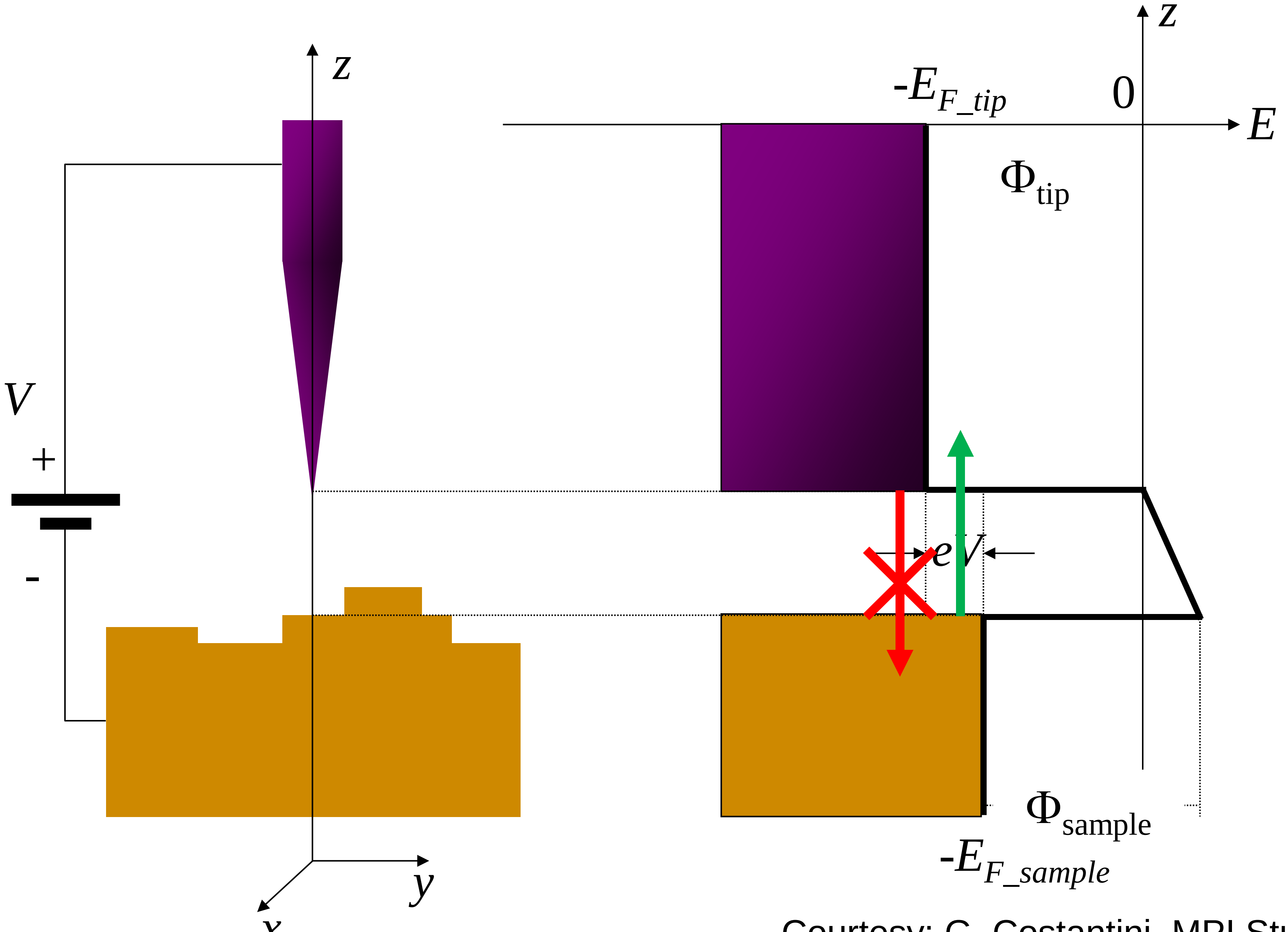
Solution of time-independent Schrödinger eq.:

$$T = \frac{j_{aus}}{j_{ein}} \approx e^{-2\kappa d} \quad \text{with} \quad \kappa = \sqrt{2m(V_0 - E)/\hbar}$$

T: tunneling probability

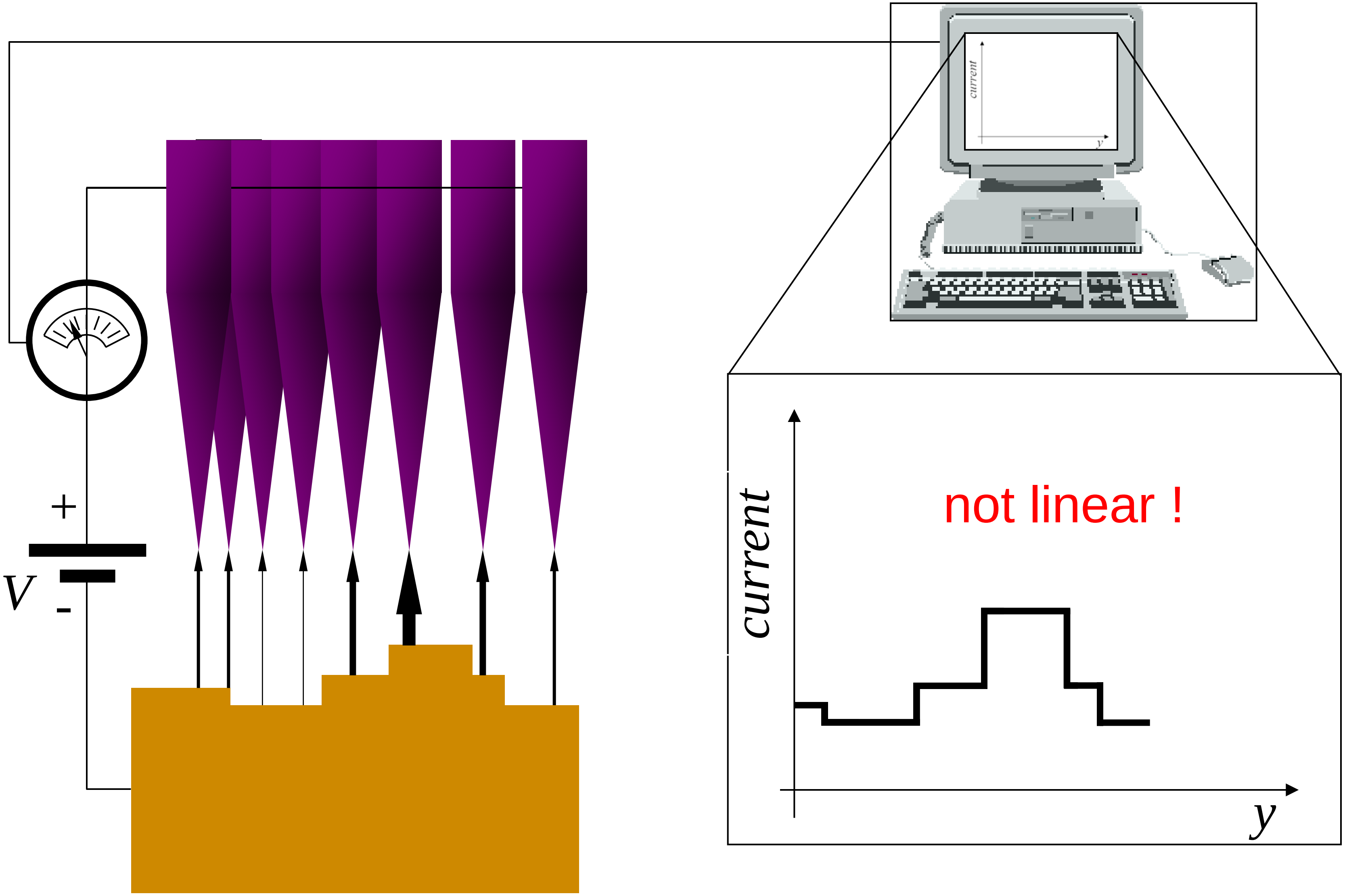
Courtesy: G. Costantini, MPI Stuttgart

STM: the working principle(s)



Courtesy: G. Costantini, MPI Stuttgart

STM: the working principle(s)

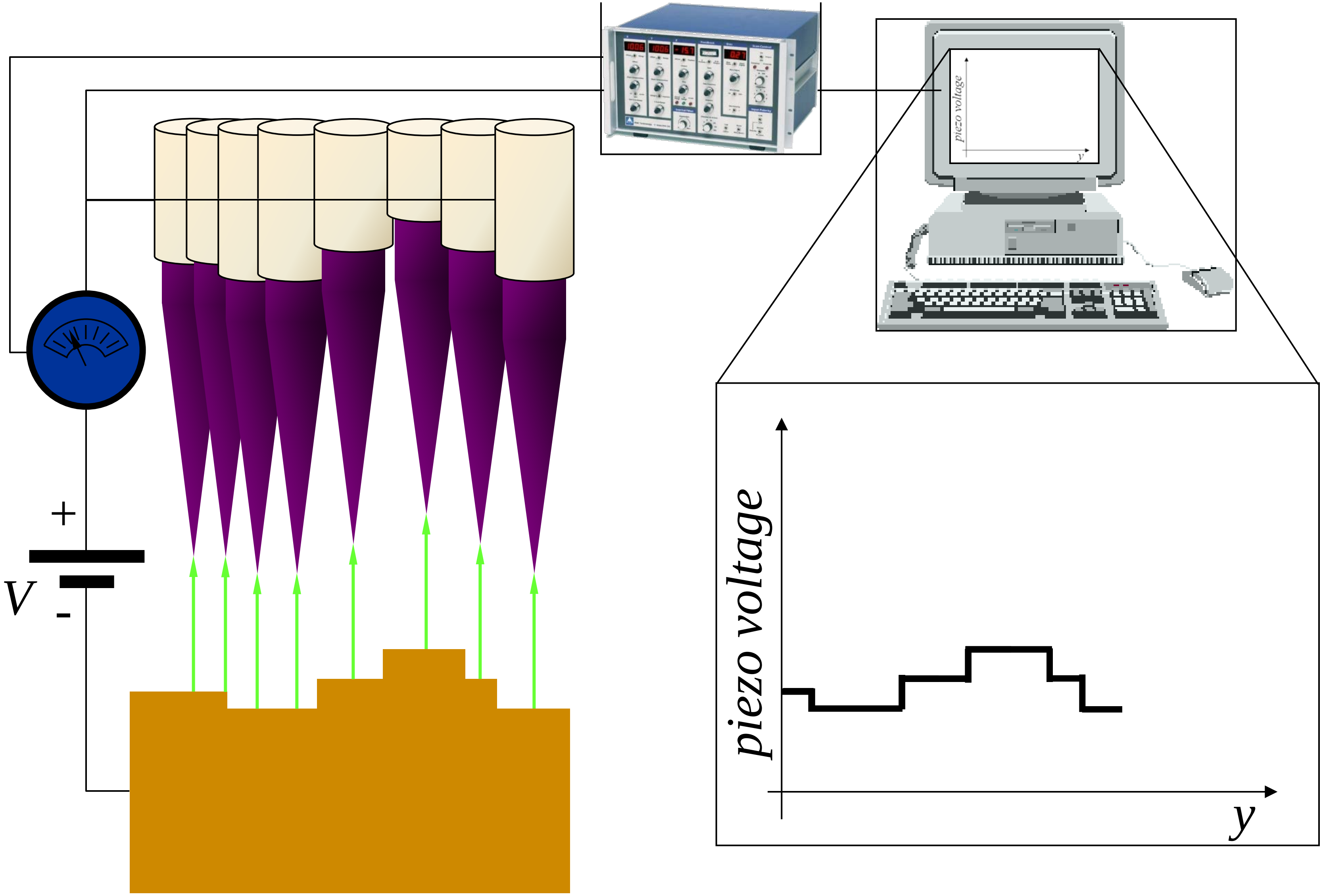


not linear !

Constant height mode

Courtesy: G. Costantini, MPI Stuttgart

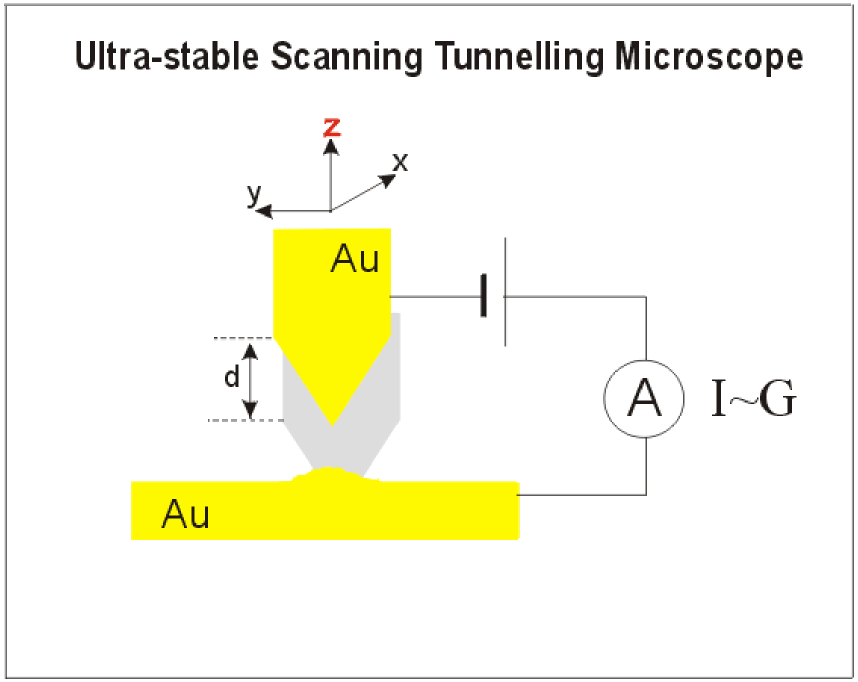
STM: the working principle(s)

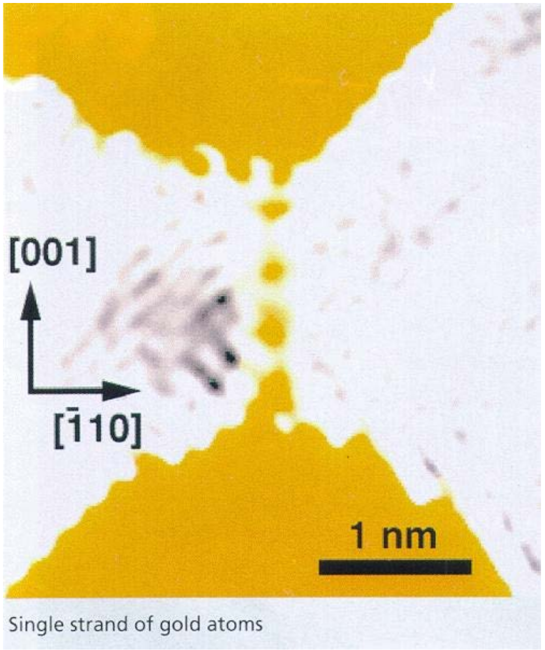


constant current mode

Courtesy: G. Costantini, MPI Stuttgart

6.1.2 STM-based methods for fabricating single-atom contacts



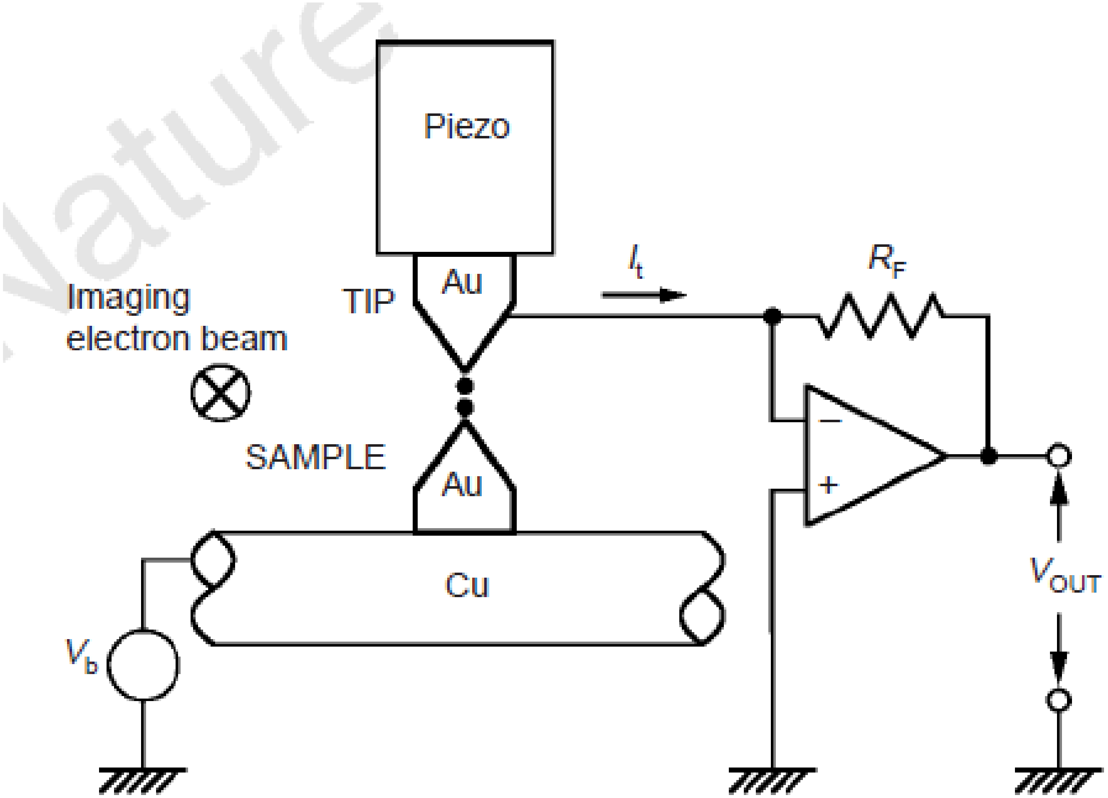


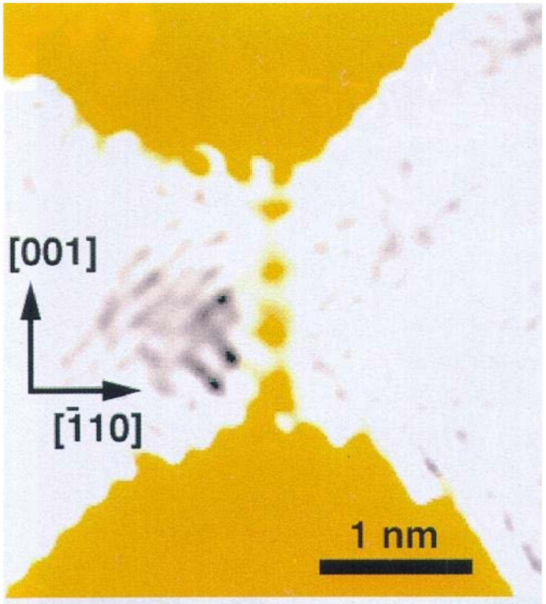
Single strand of gold atoms

+ large variability of materials
+ simultaneous imaging of envrironment

+ fast -> good statistics
- short lifetime of individual contacts

STM in Transmission Electron Microscope (TEM)

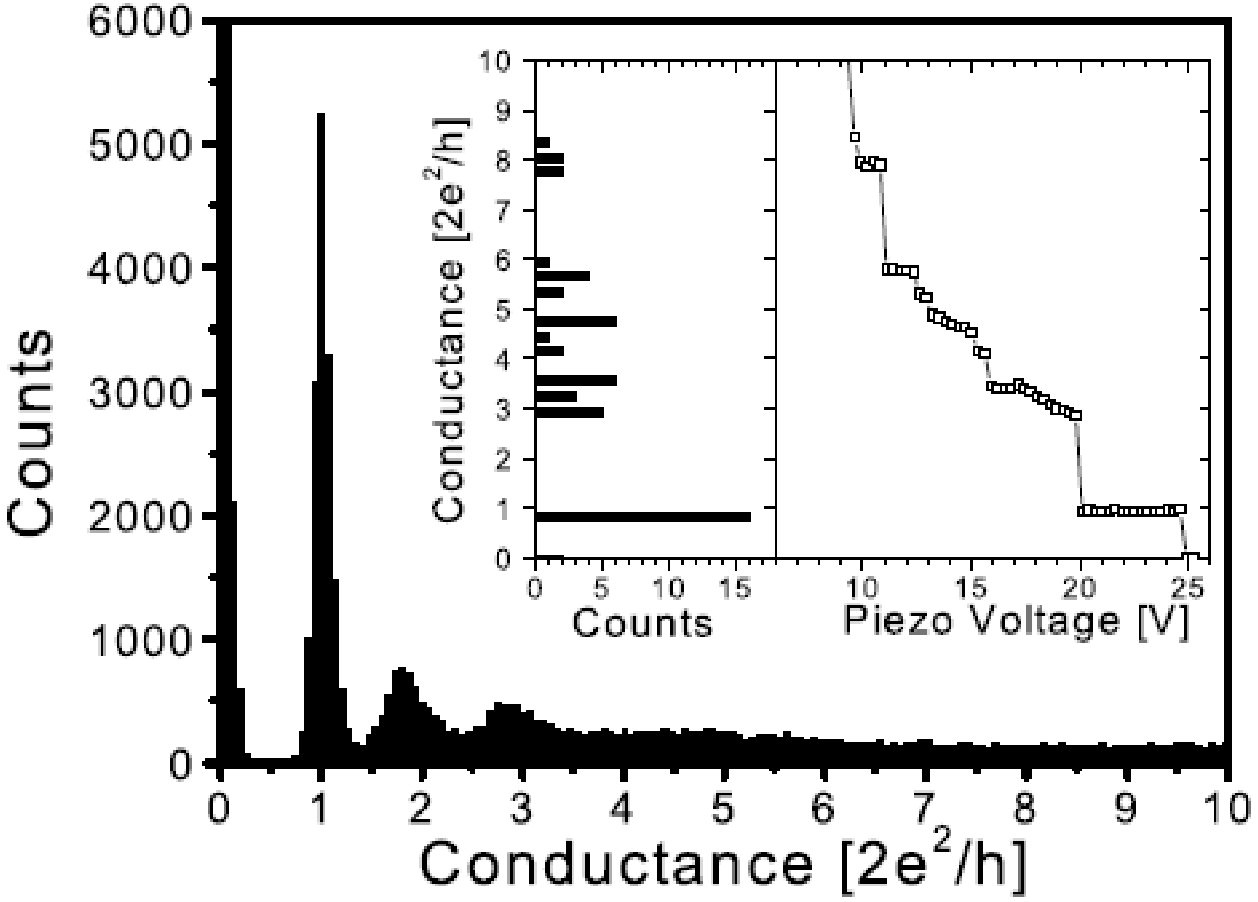




Single strand of gold atoms

Ohnishi et al., 1998

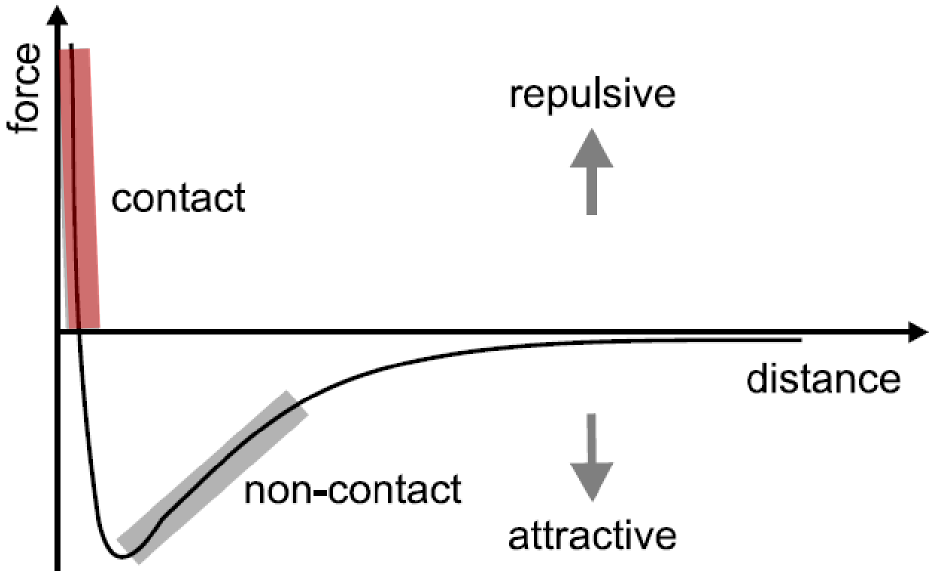
Conductance histograms

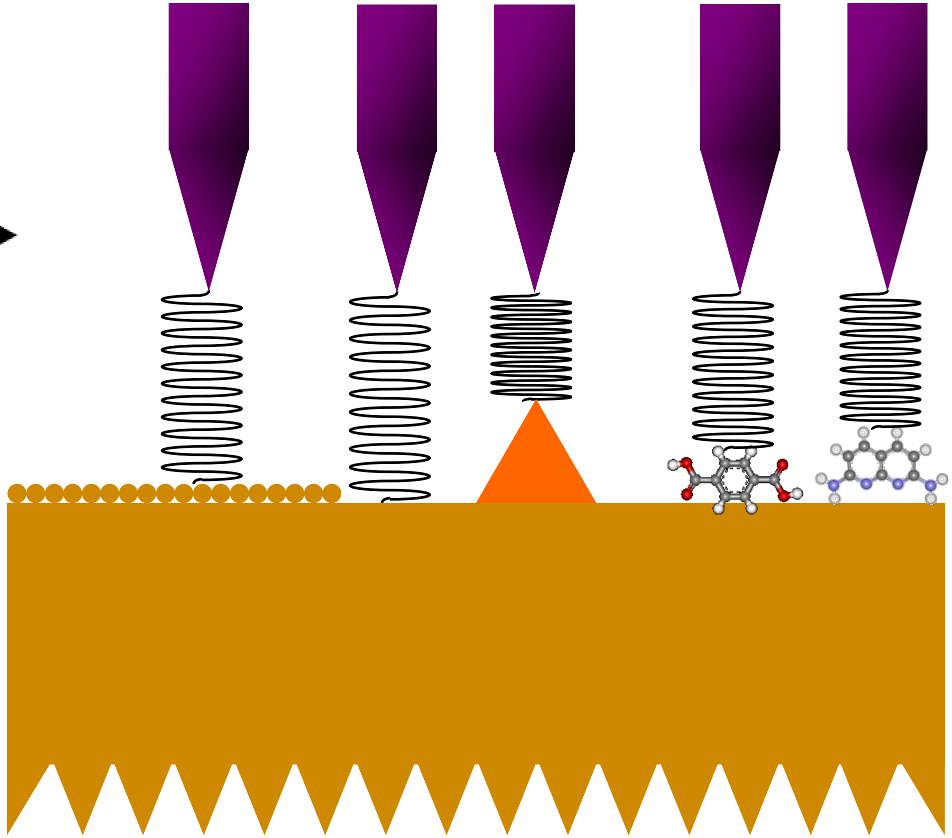


R. Smit, PhD Thesis, Leiden 2002

6.1.3 Techniques using the atomic-force microscope (AFM)

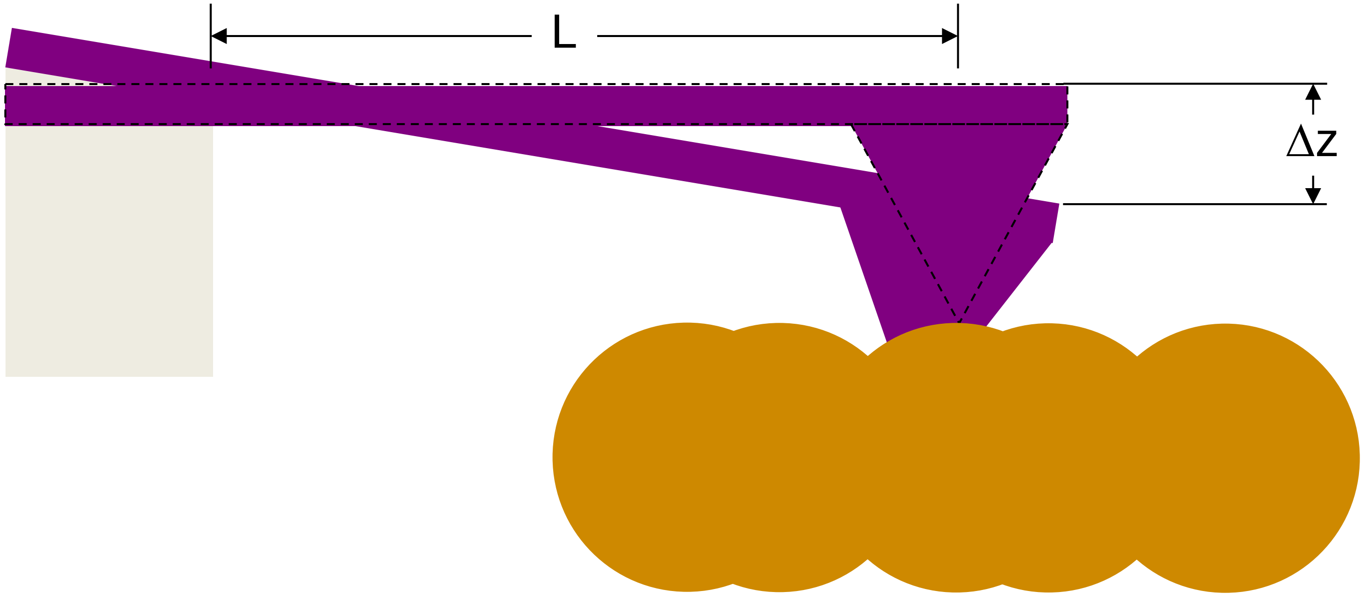
Atomic Force Microscopy (AFM)





G. Binning, C.F. Quate and C. Gerber, PRL 56, 930 (1986)

Cantilever spring



Resolution needed

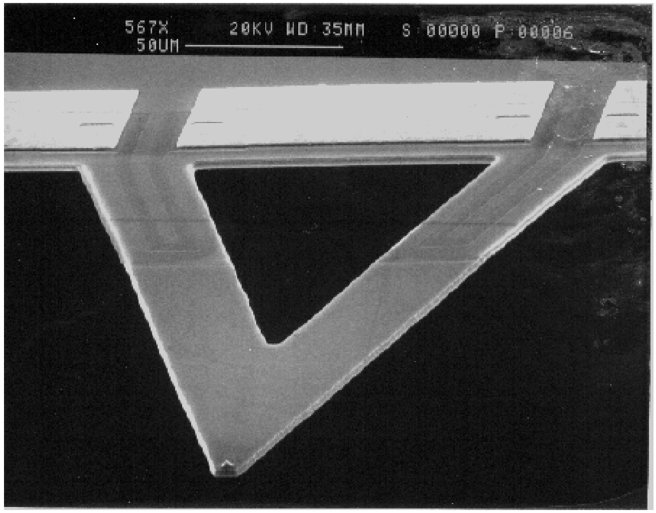
$\Delta z \sim 1$ Å

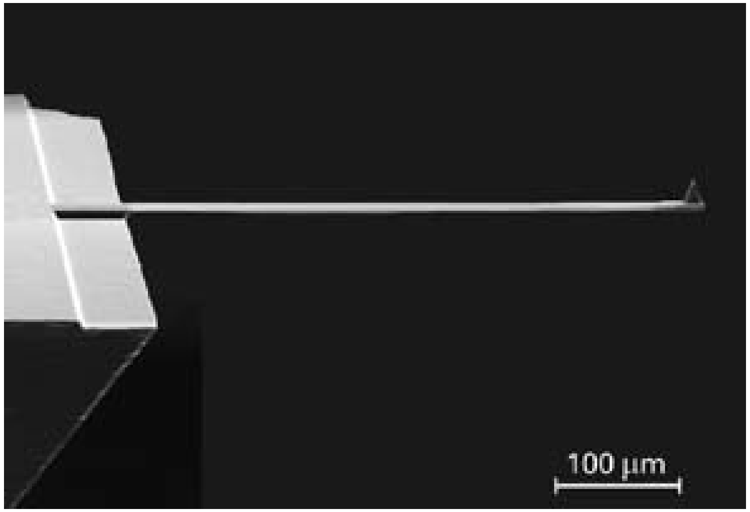
$L \sim 100\ \mu m$

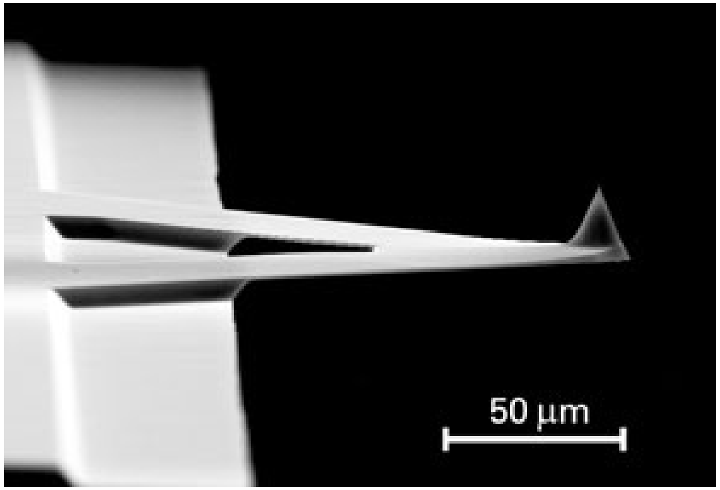
→

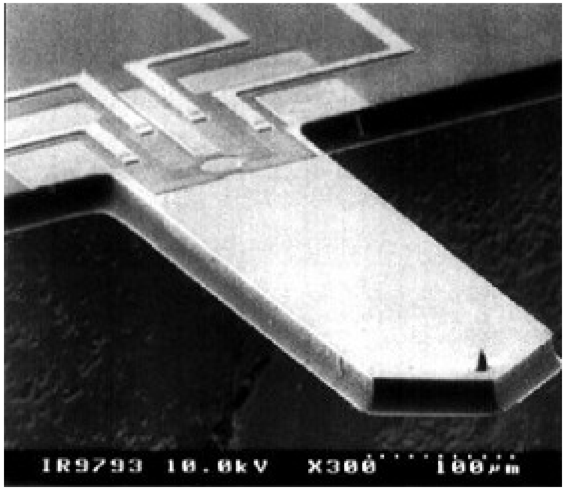
bending angle $\theta \sim 10^{-6}$

Forces ~ nN

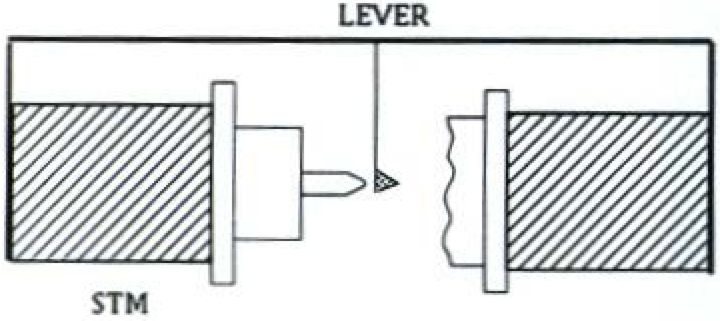

567X 20KV WD 35MM S 00000 P 00006
50UM


100 µm

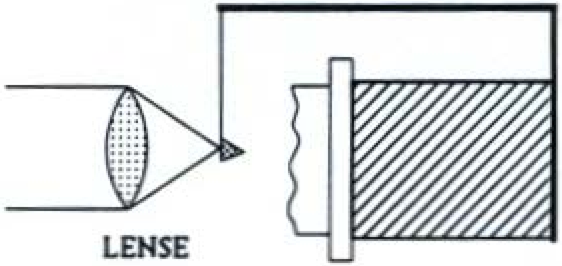

50 µm


IR9793 10.0kV X300 100µm

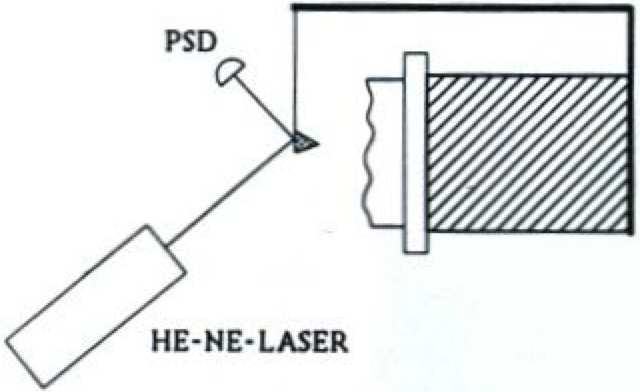
Detection schemes



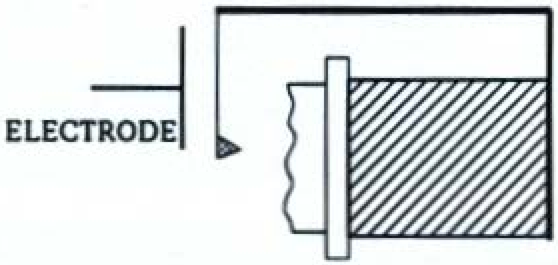
electron tunneling



optical interferometry

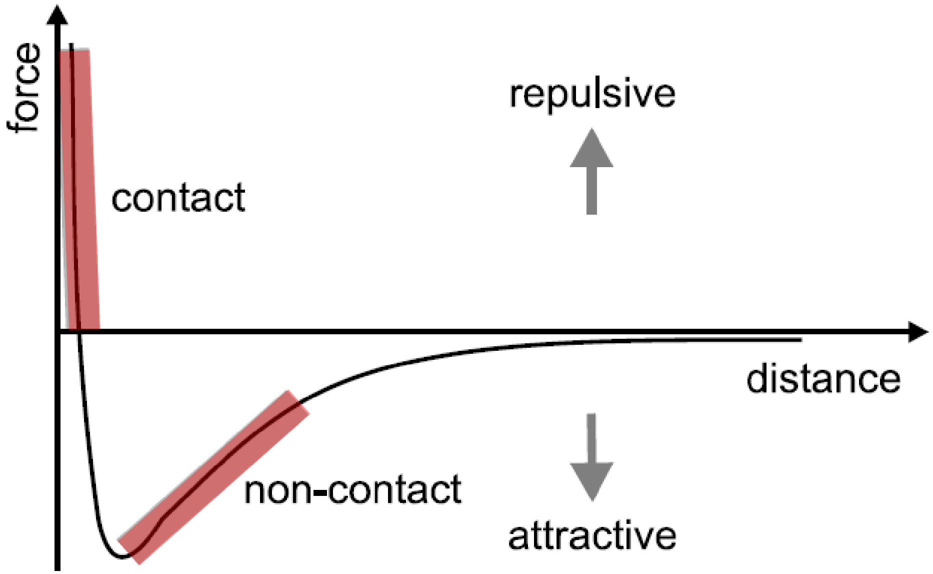


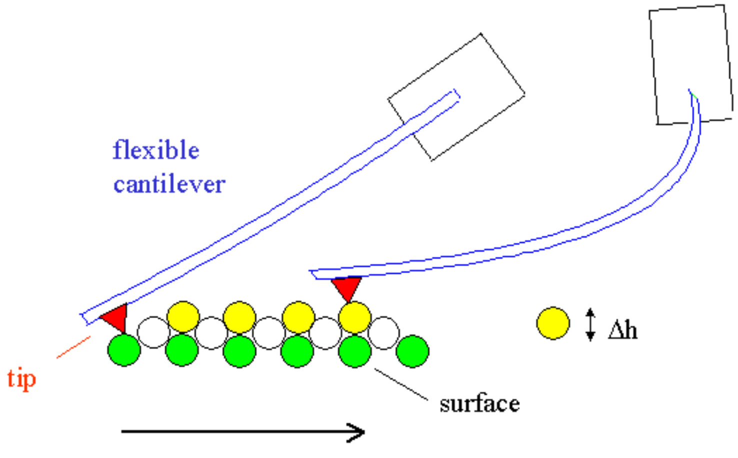
laser beam deflection

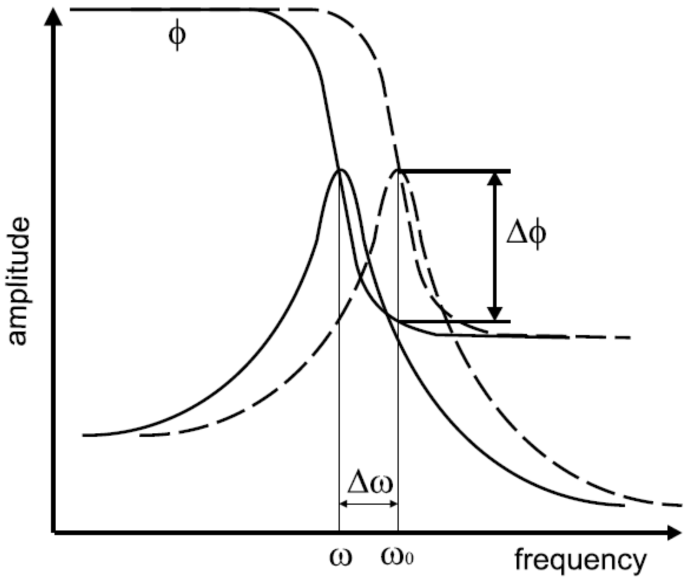


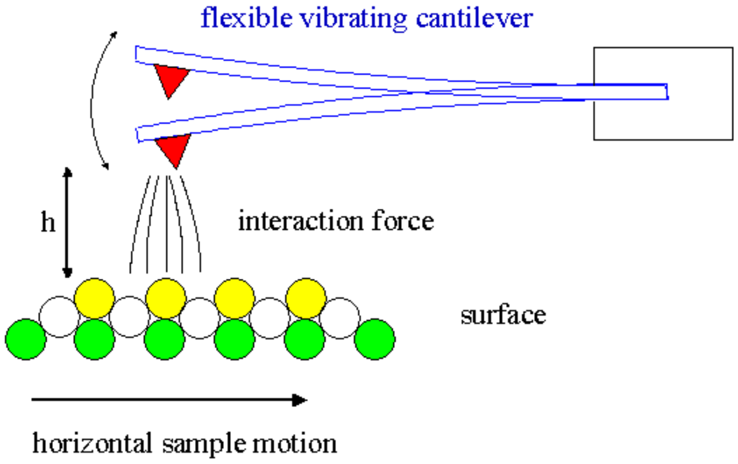
capacitance method

Non-contact mode



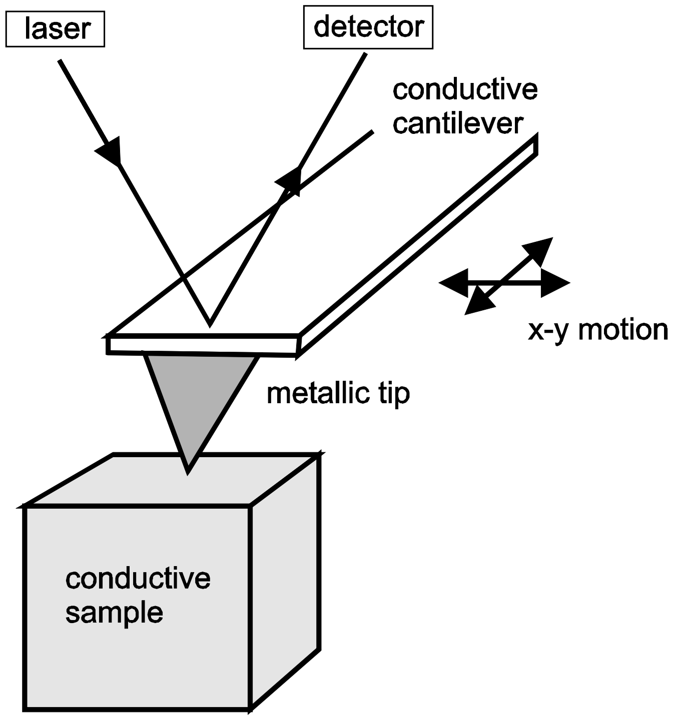




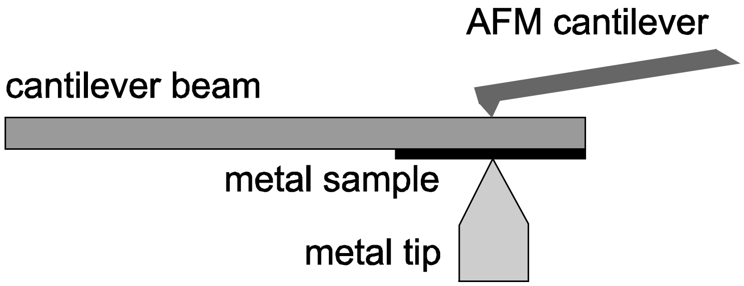


Conductive AFM (cAFM)

(a)



(b)



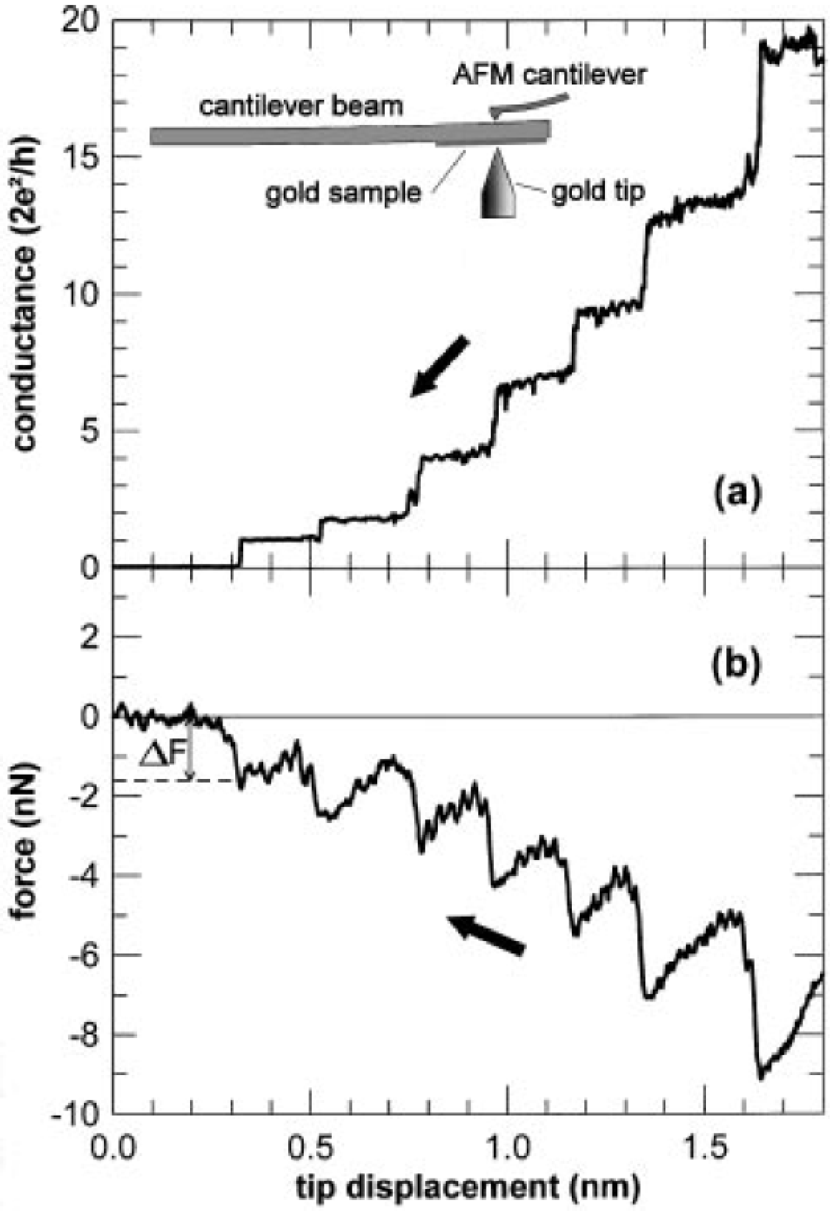
+ simultaneous conductance and force measurements
+ large variability of materials
+ fast
+ imaging
- short lifetime of individual contact
- mostly larger contacts (~ 100 atoms)

Conductive AFM (cAFM)

Example Au-Au contacts

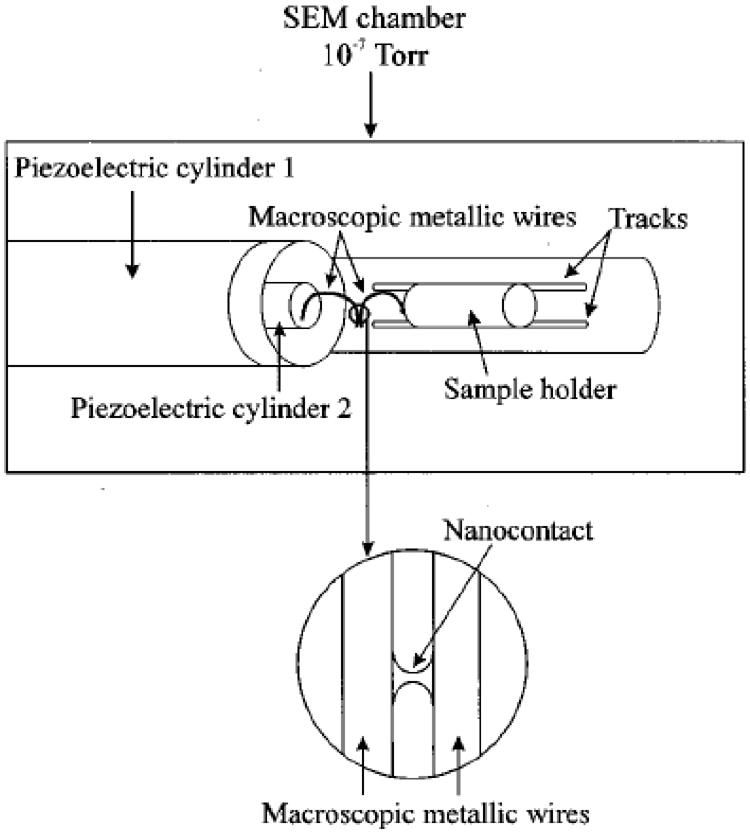
simultaneous conductance and force measurement

Typical measurement mode:
closing or opening traces,
i. e. G(distance) curves



6.1.4 Macroscopic wires

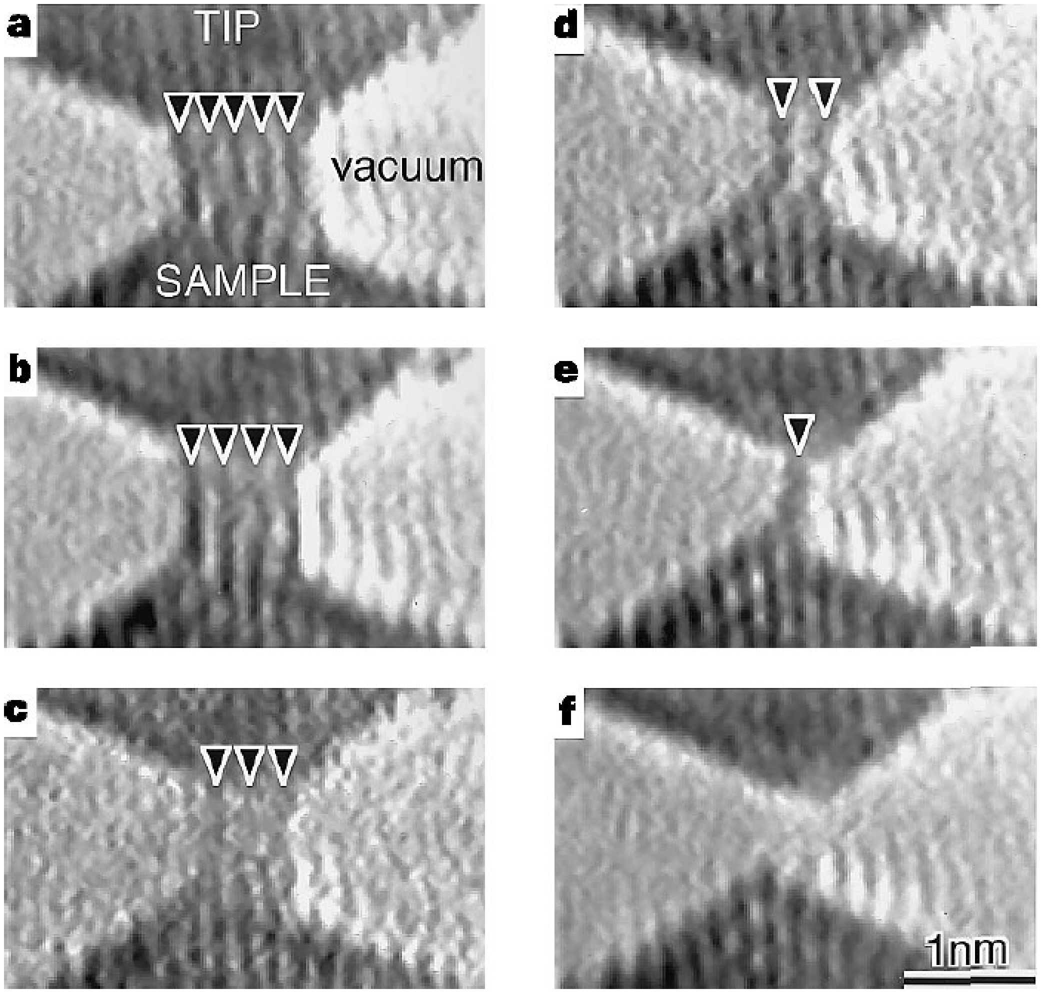
Costa-Krämer et al, PRB 55, 5416 (1997)

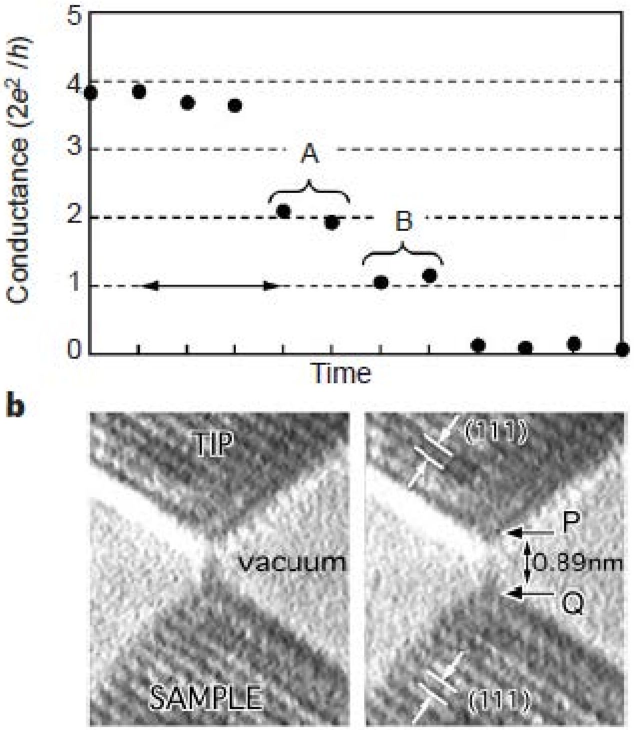


- \+ large variability of materials
- \+ fast
- \- very short lifetime of individual contact
- \- prone to contamination

6.1.5 Transmission Electron Microscope

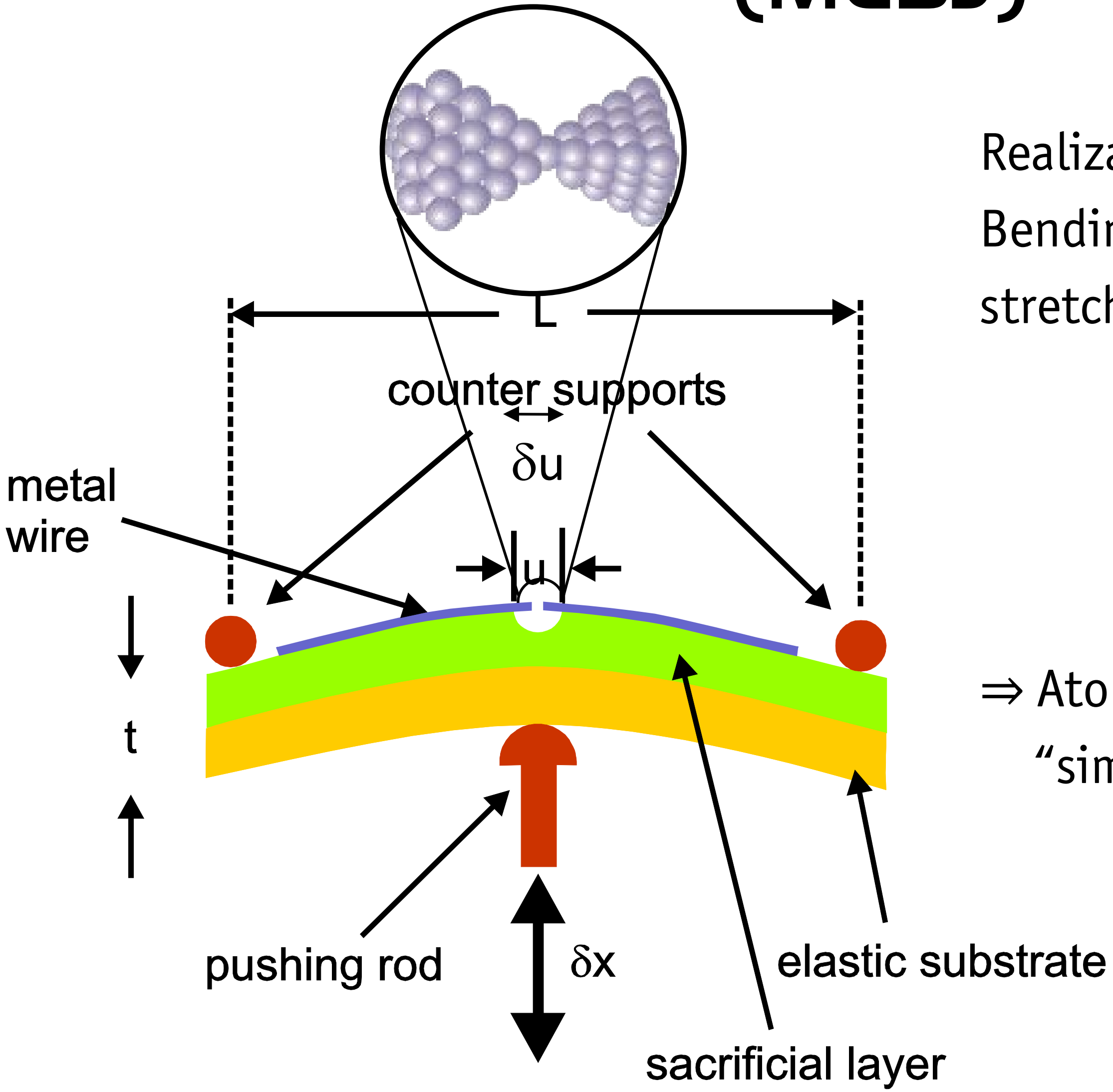
Other possibilibity Highly intensive electron beam melts Au on dewetting surface (glassy carbon):
Film breaks down into small islands: neck formation (Ugarte et al., 1999)





Ohnishi et al., 1998

6.1.6 Mechanically controllable break junctions (MCBJ)



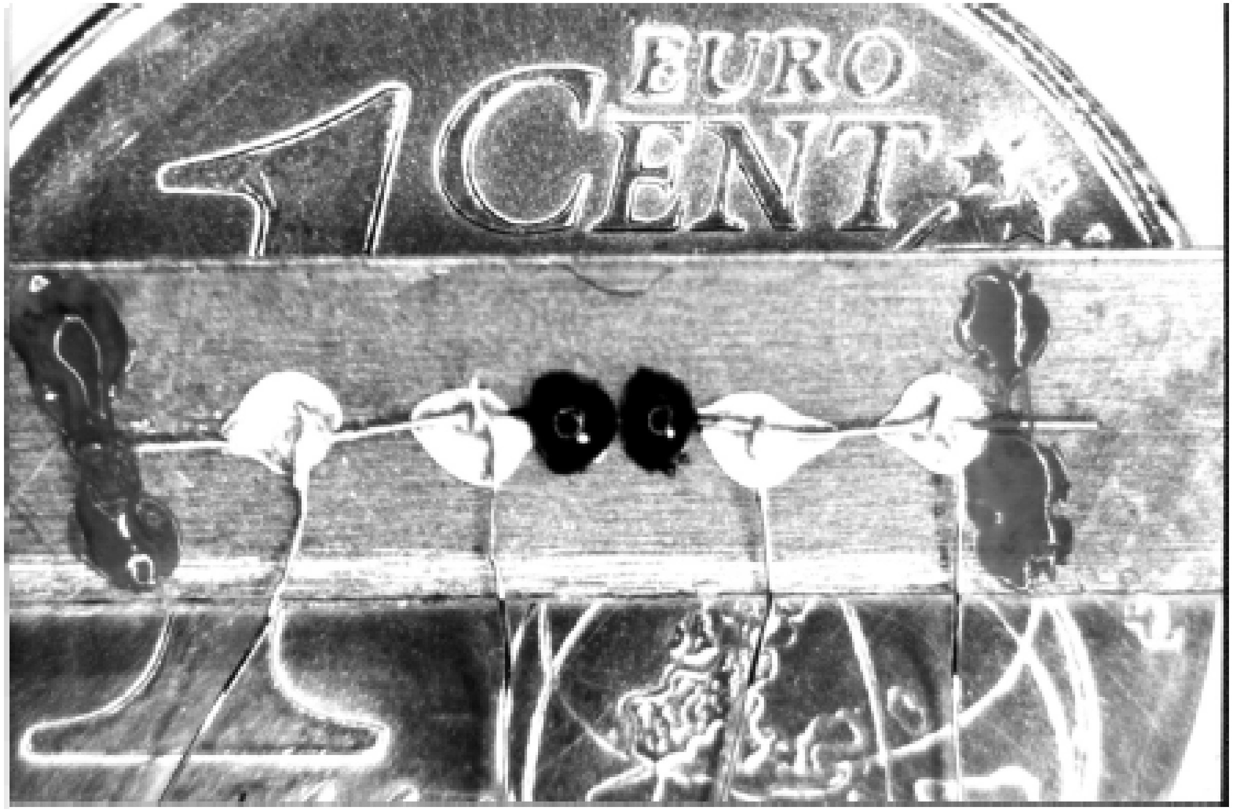
Realization of single-atom contact:

Bending by δx results in a lateral stretching of $\delta u = r\,\delta x$, where

$$r = \frac{6tu}{L^2}$$

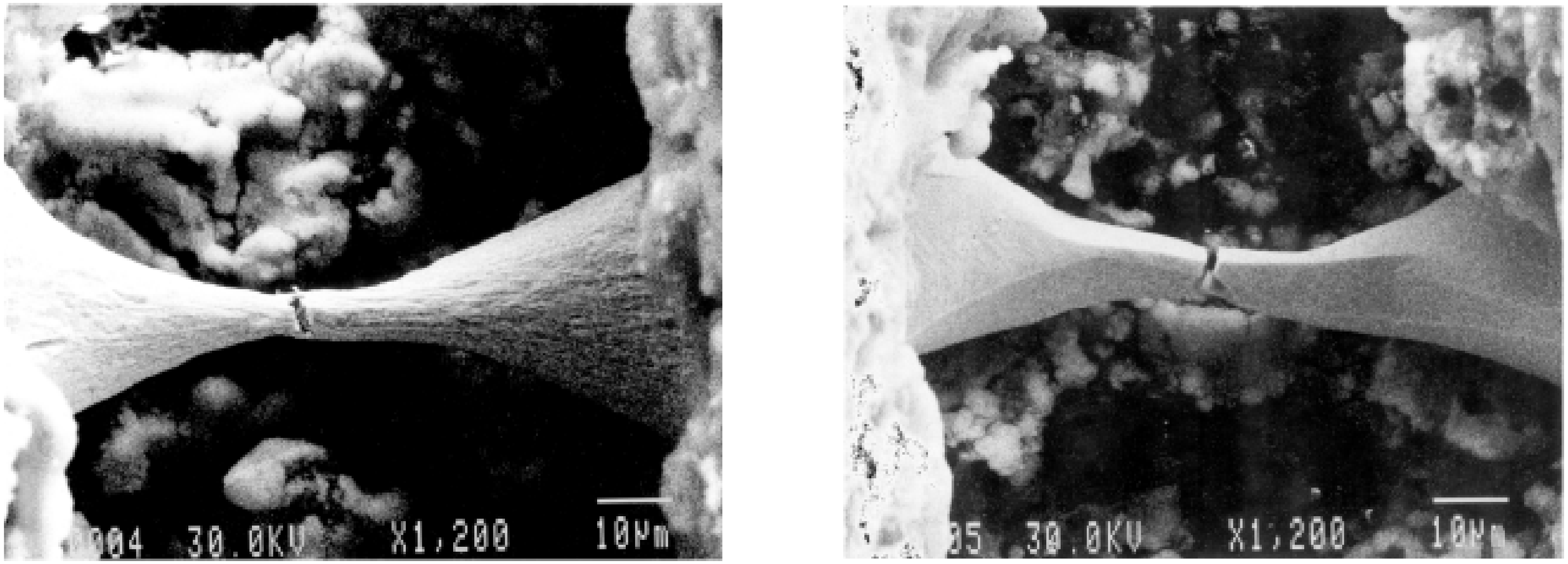
⇒ Atomic resolution possible with "simple" mechanics

Notched-wire MCBJ



+ simple fabrication
+ versatile (works for all metals and some semiconductors)
+ relatively fast drive by piezo control
0 intermediate stability

Notch formation



Here: Iridium notches by ac etching in $CaCl_2$

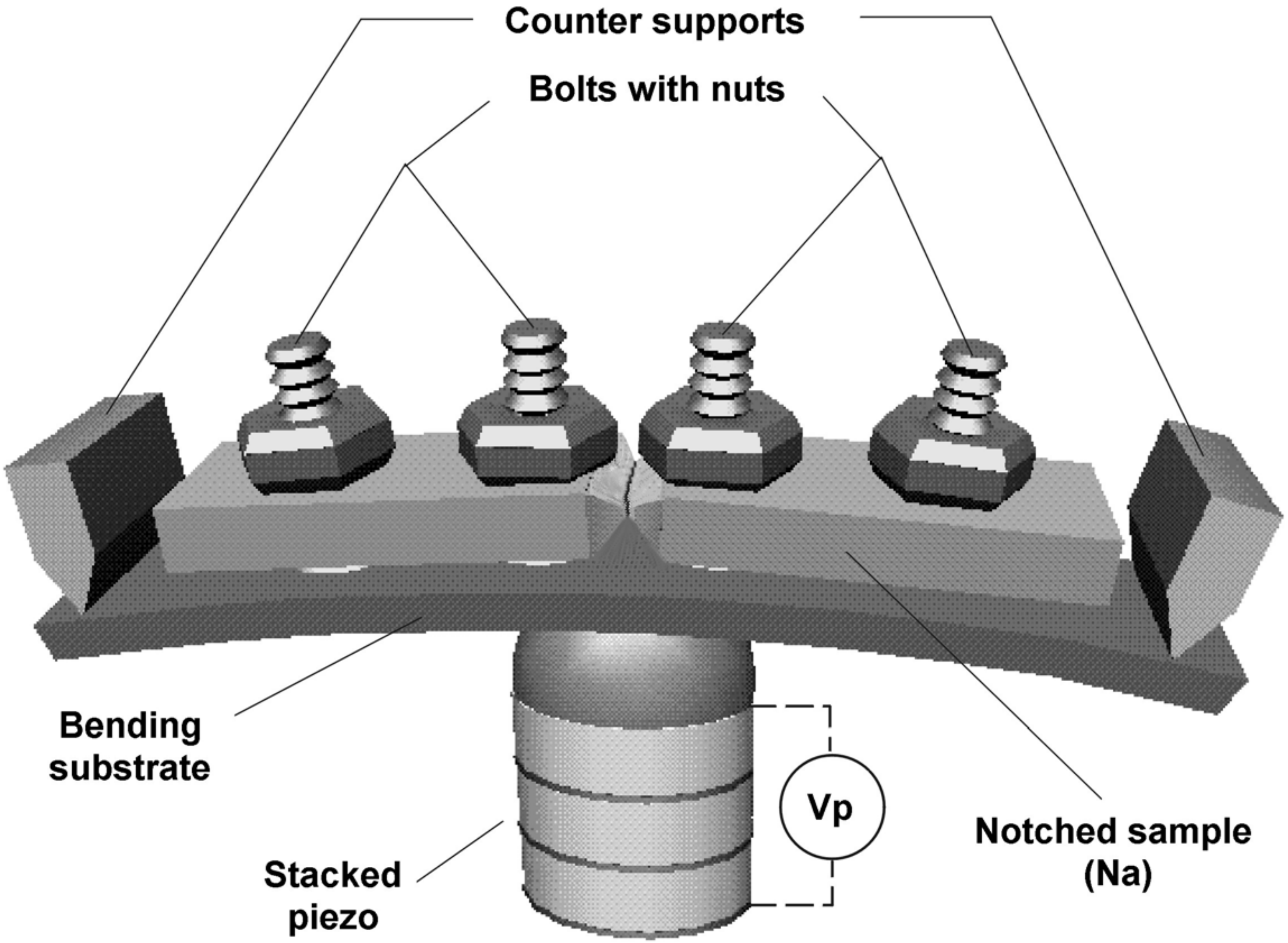
Resistance increase 0.05 Ω corresponding to diameter 6 µm

Left: native material

Right: annealed wire

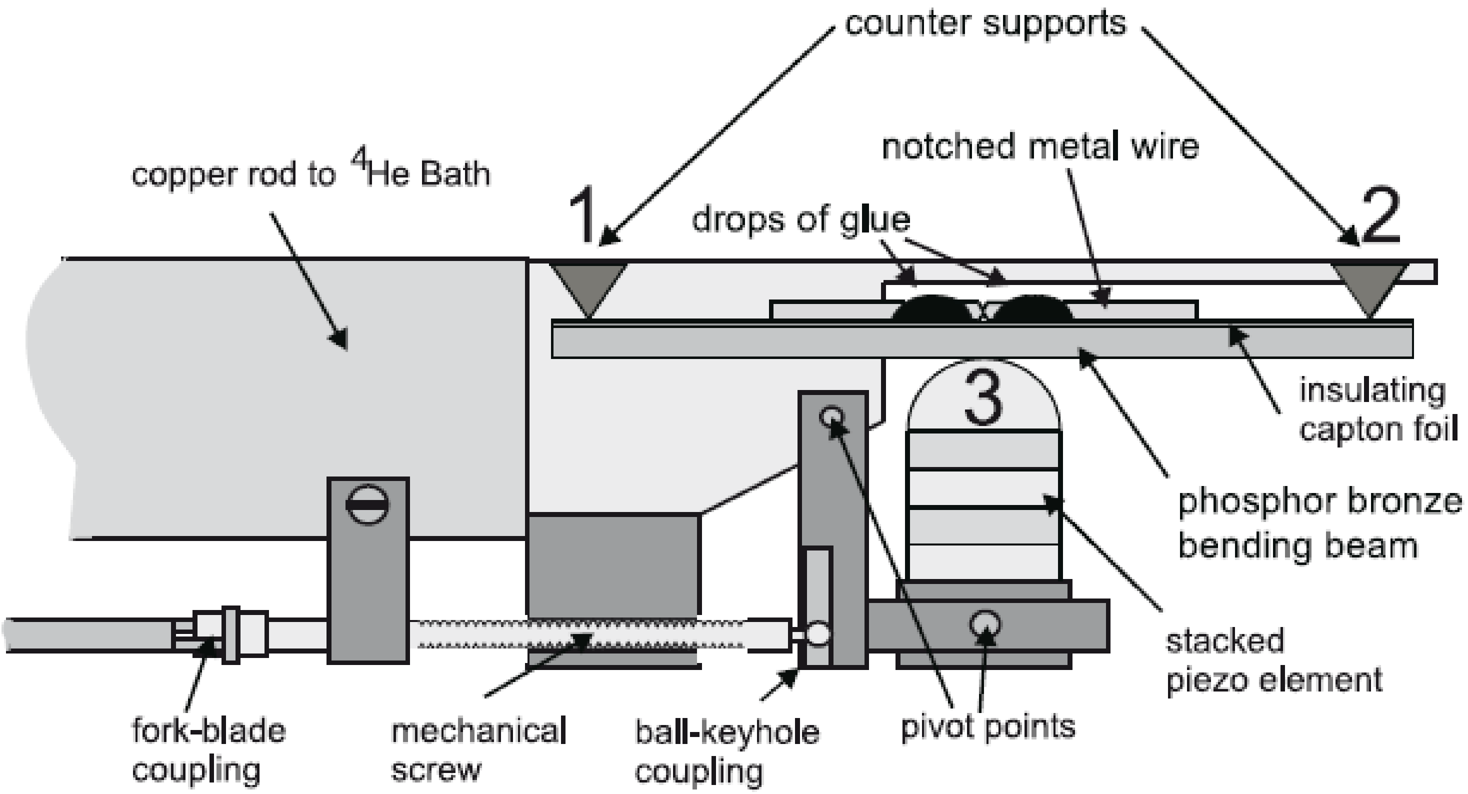
R. Smit, PhD Thesis, Leiden 2002

MCBJ of brittle or reactive materials



MCBJ

The bending mechanism



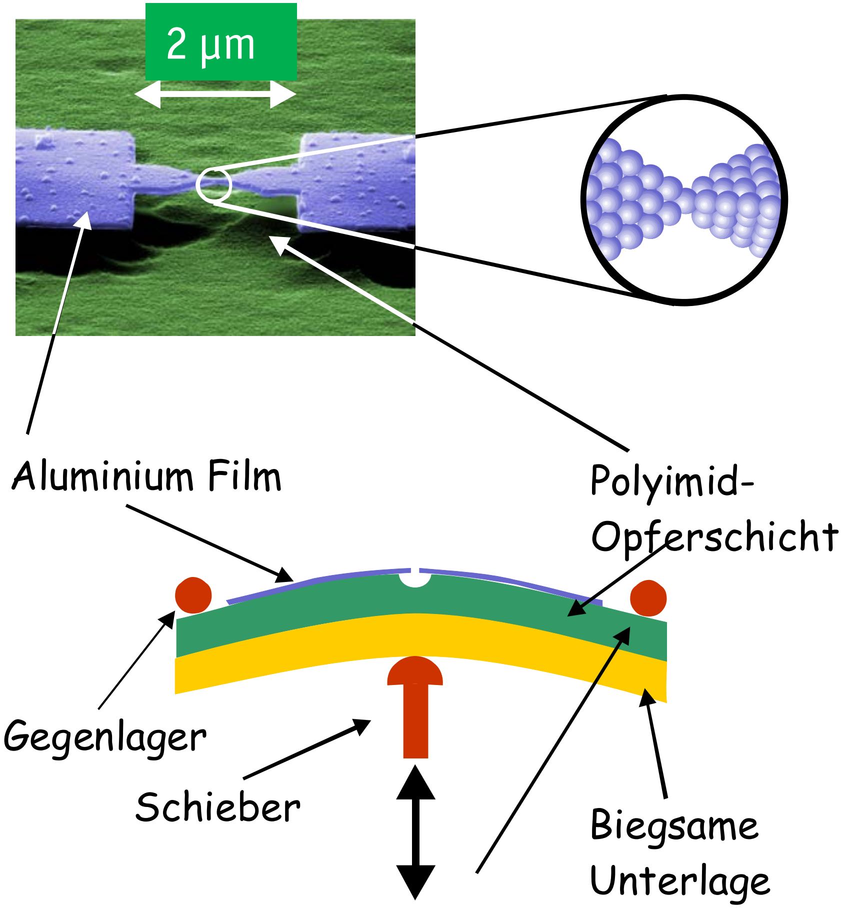
Combination of mechanical drive (coarse approach) and piezo-driven motion

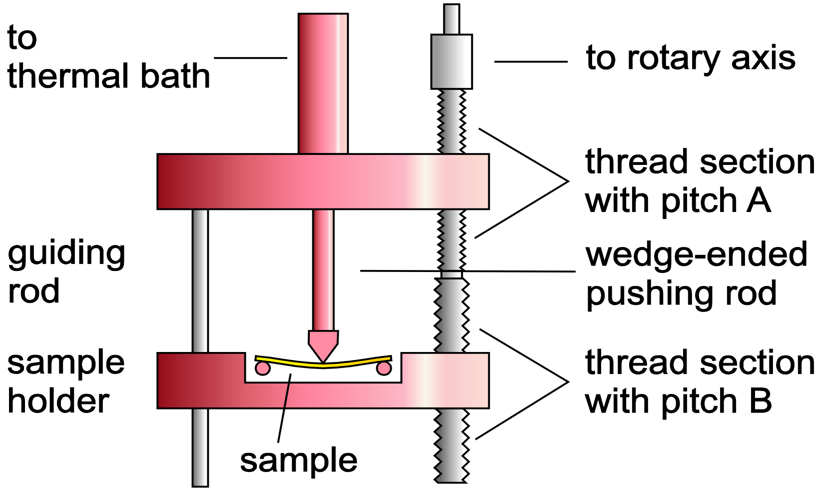
Lithographically fabricated MCBJ

Van Ruitenbeek et al, 1996

$r \approx 10^{-4} \ldots 10^{-5}$

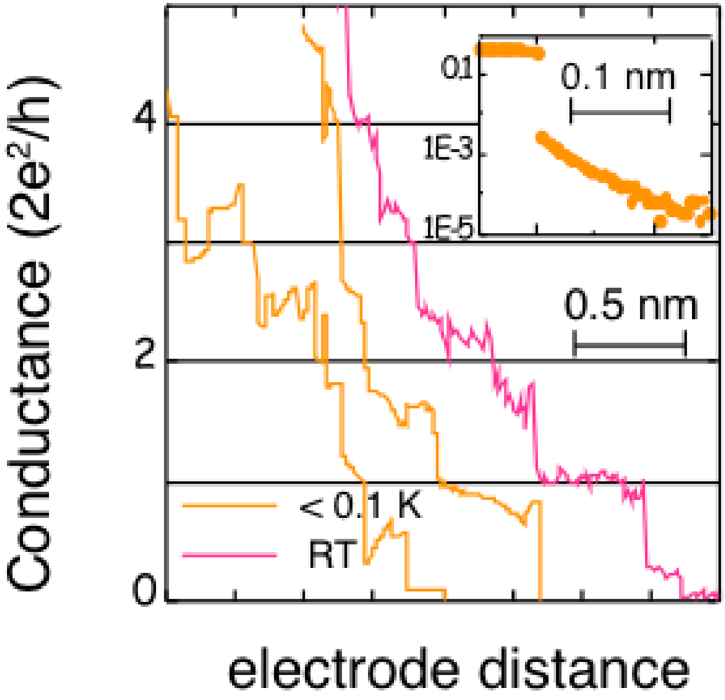
- \+ high stability
- \+ integrateble into ICs
- \- slow
- \- sensitive to voltage shocks
- \- no imaging of contact geometry possible





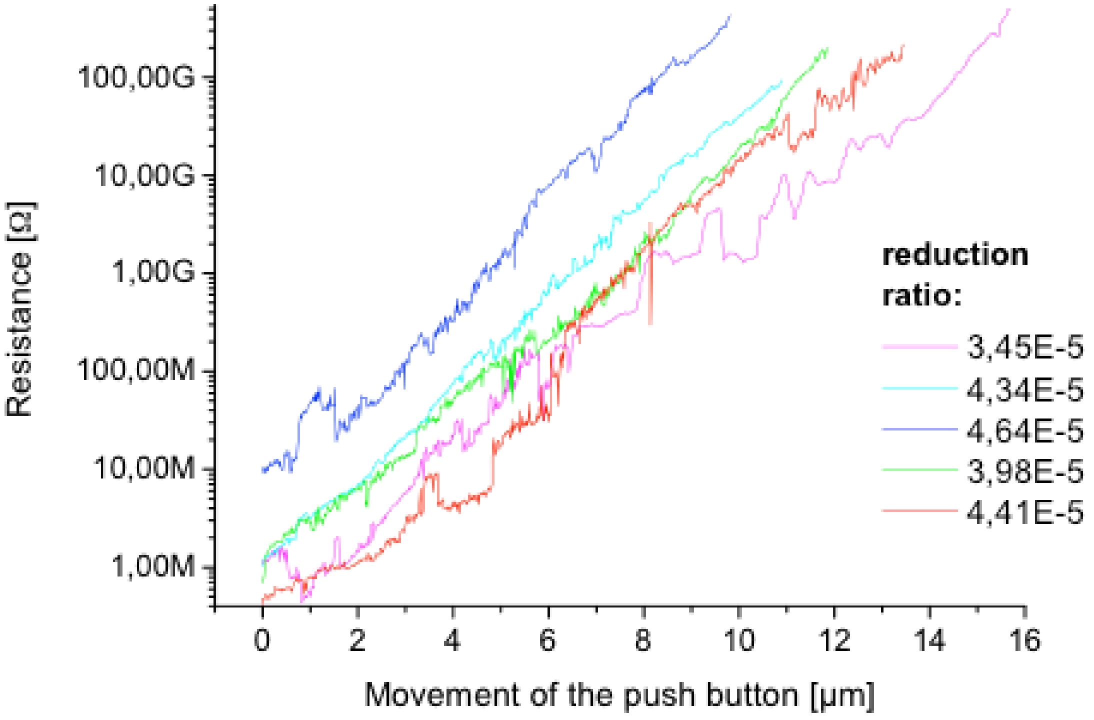
Characterization of gold break junctions

Conductance steps due to atomic configuration

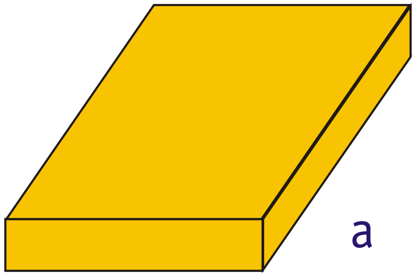


Tunneling regime is used for calibration of the displacement

$$R \propto \exp\left(\frac{2}{\hbar}\sqrt{2m\Phi}\cdot d\right)$$

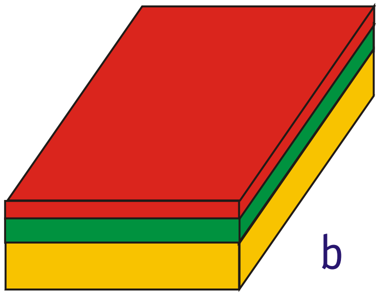


Fabrication litho-MCBJ



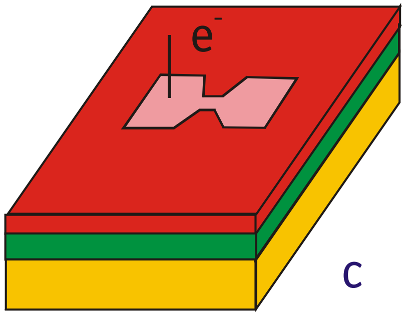
a

polishing of bendable substrate



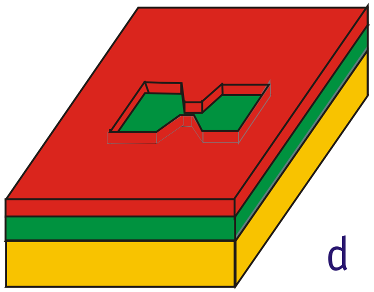
b

spincoating resist



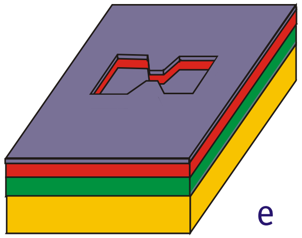
c

electron beam exposure



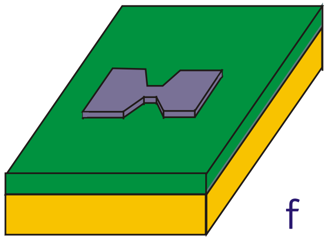
d

development



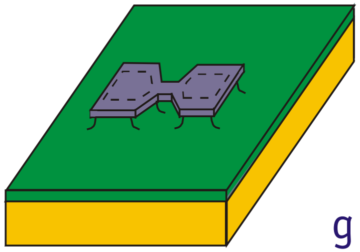
e

metal deposition



f

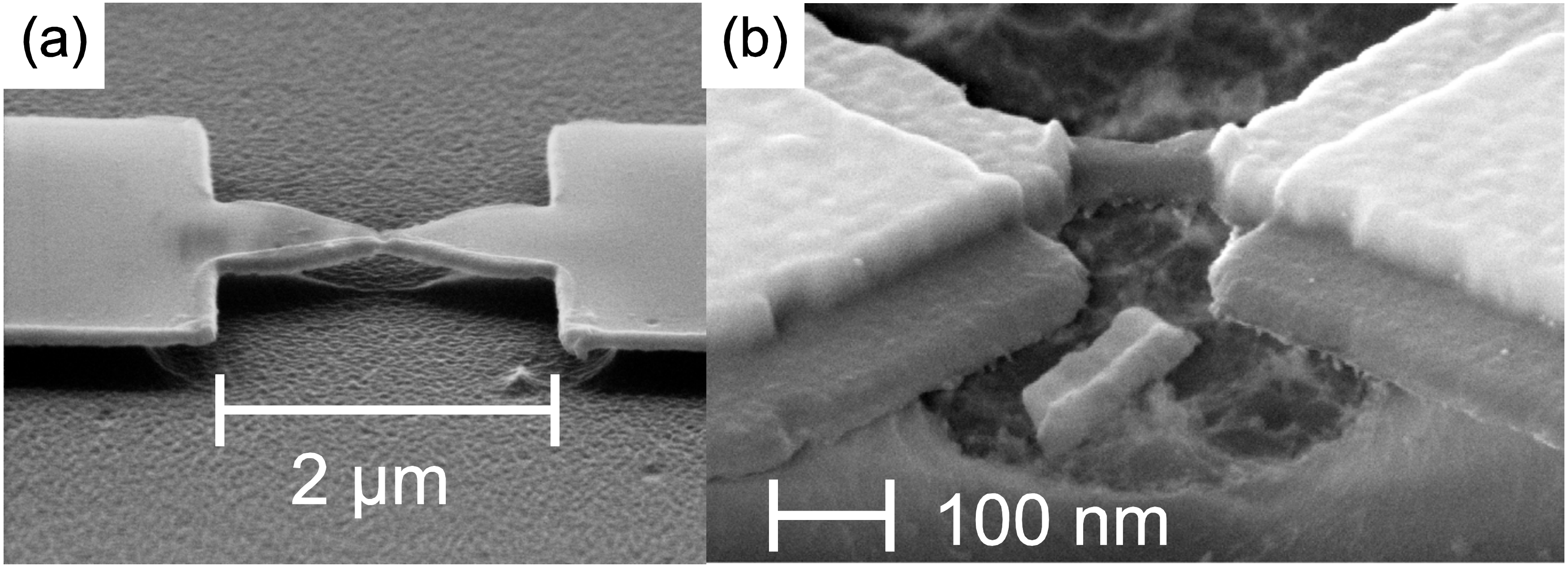
“Lift-off”



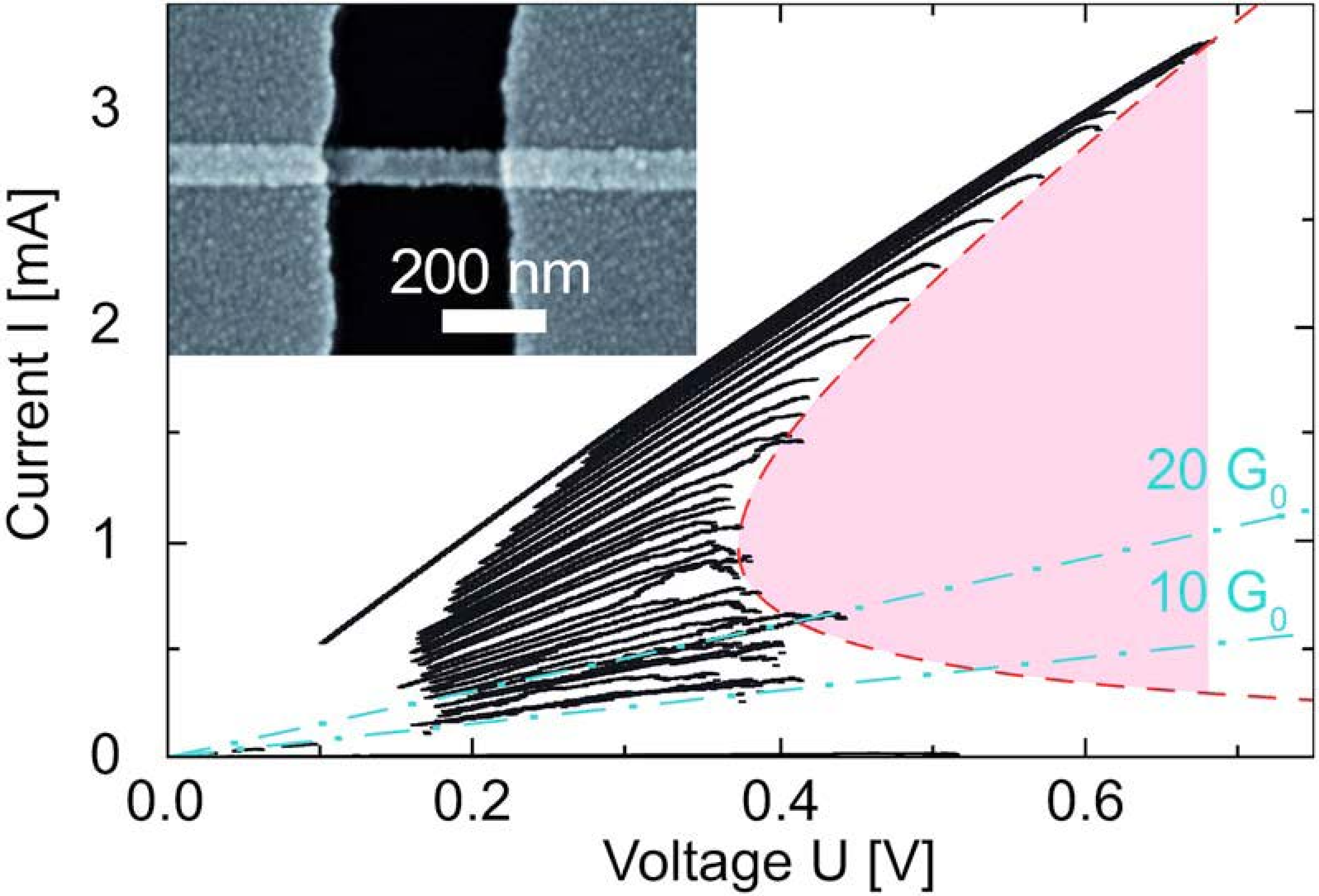
g

Plasma etching

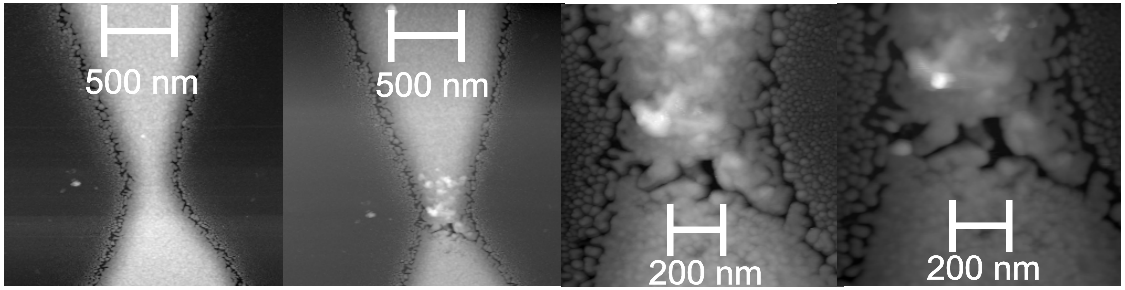
MCBJ with two metals



6.1.7 Single-atom contacts by electromigration



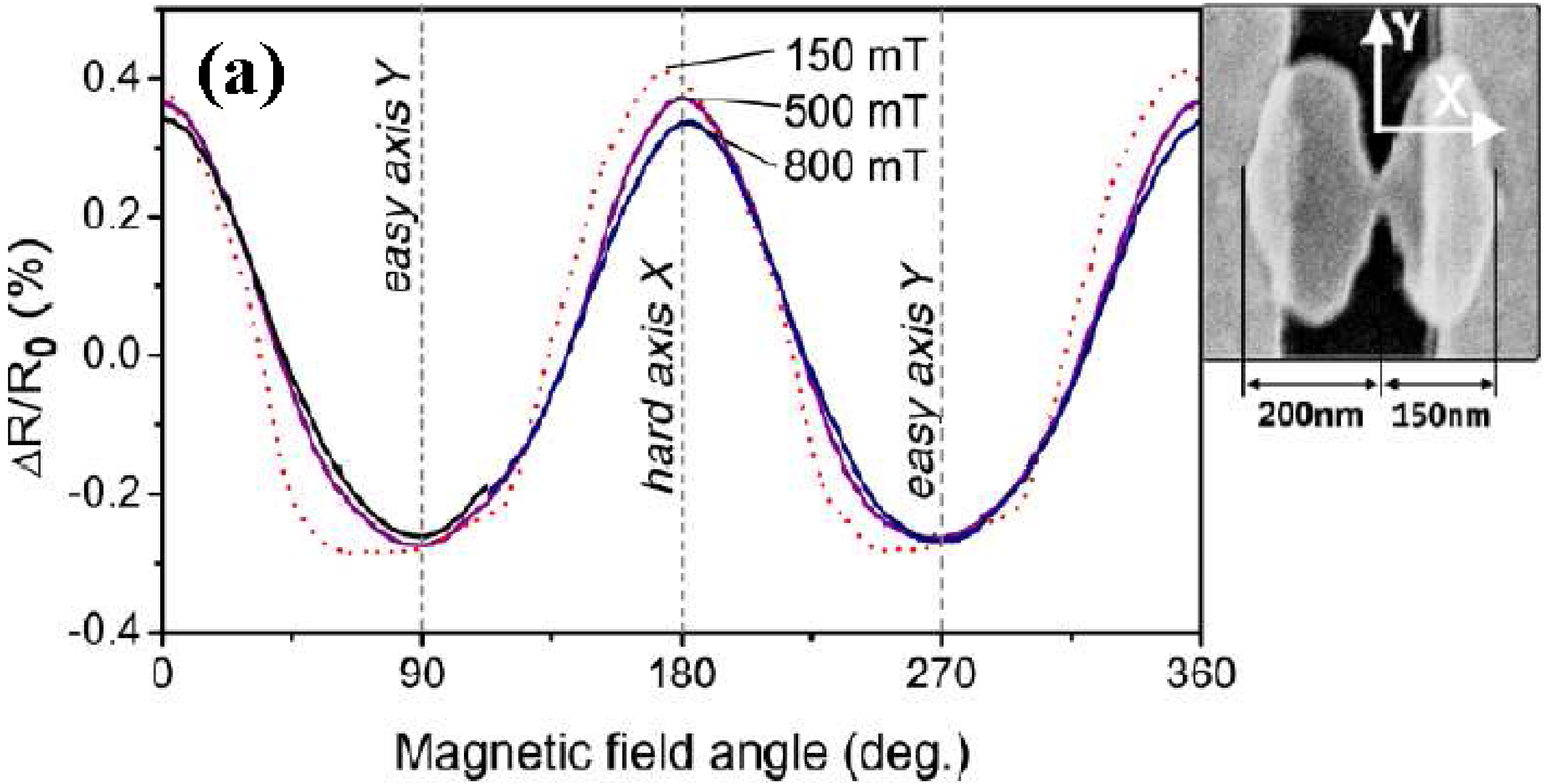
Fabrication by shadow-evaporation to define thin wire and thick electrodes



AFM image of contact after electromigration

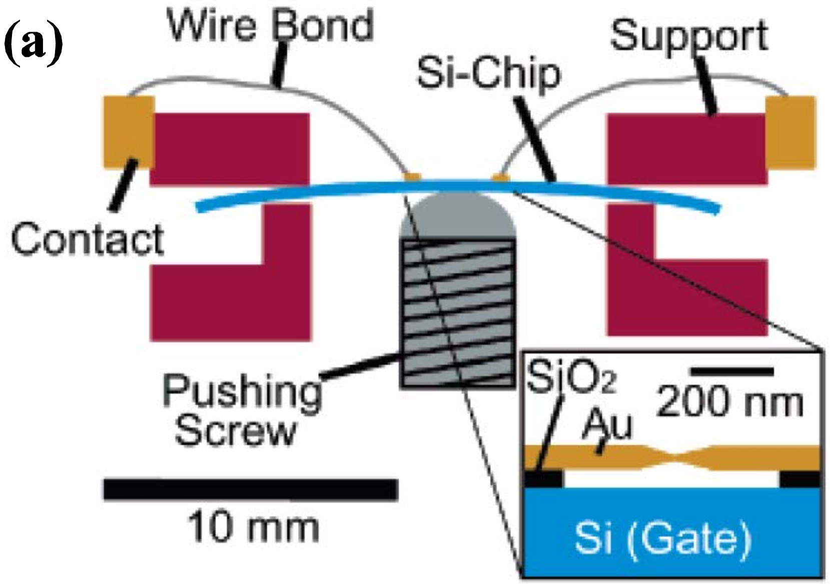
+ mechanically very stable
+ suitable for application of external fields
+ gateble
- low yield,
- single-shot experiment
- no control of contact size

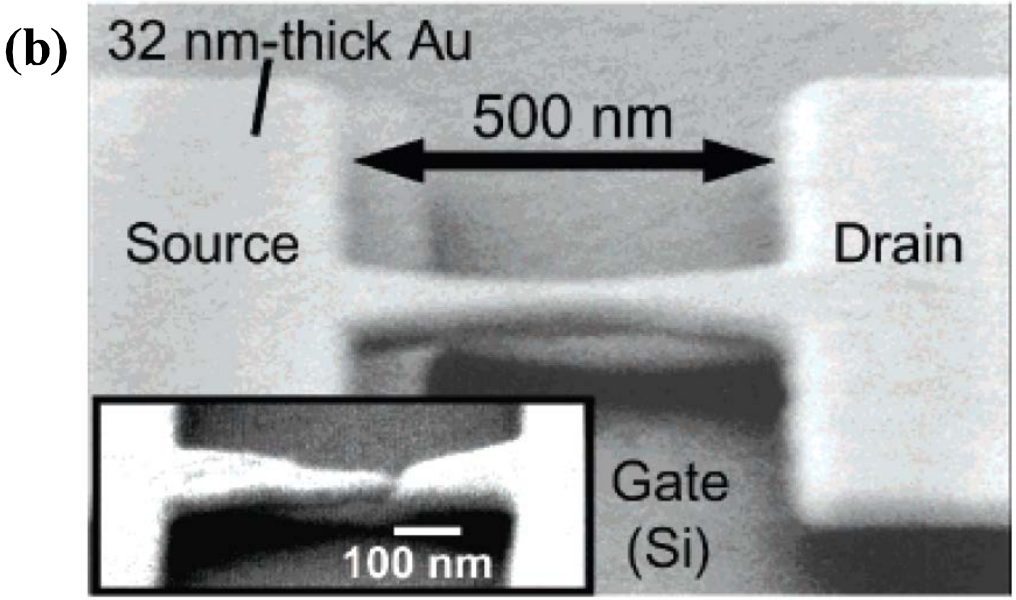
Electro-migrated Py



Bolotin et al., PRL 97, 127202 (2006).

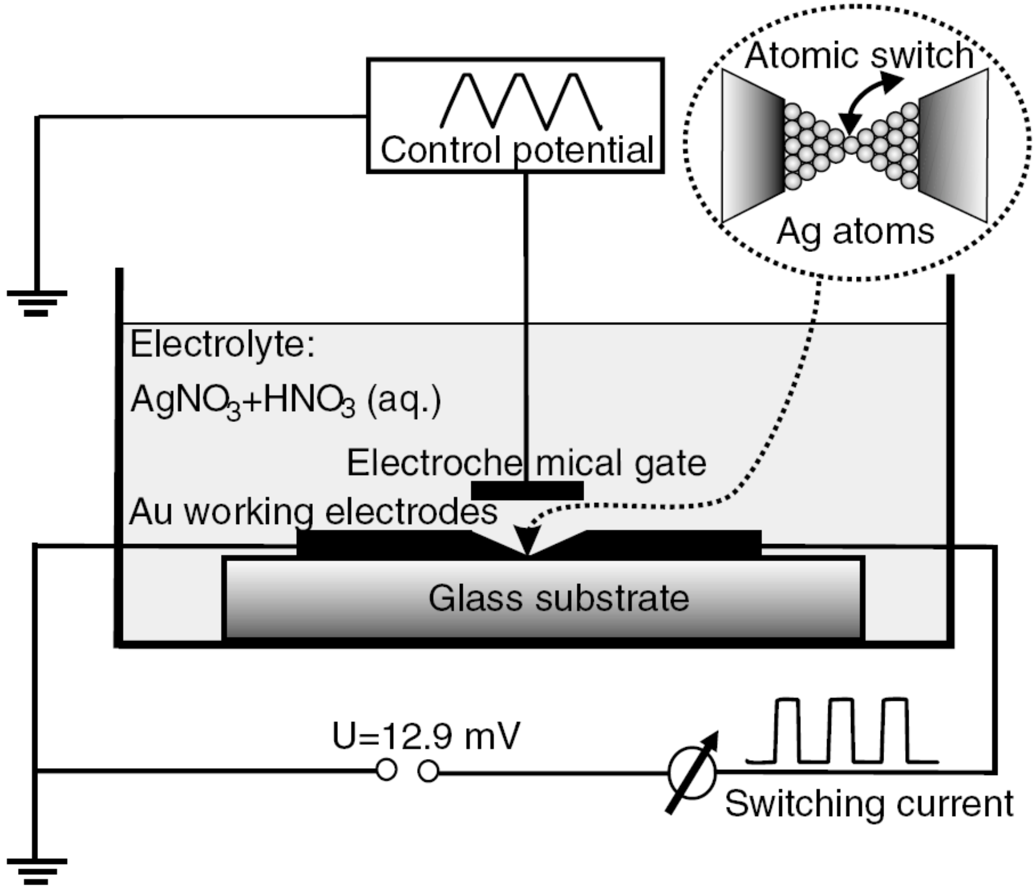
Electromigrated MCBJ with gate





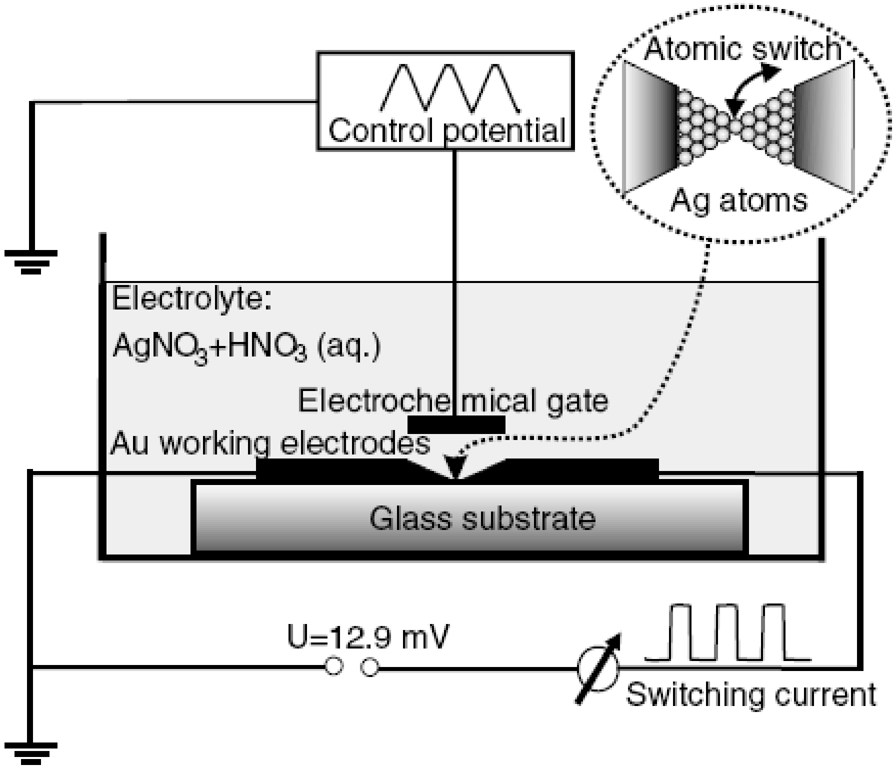
- \+ mechanically stable
- \+ suitable for application of external fields
- \+ silicon technology
- \+ control of contact size
- \+ possibility of three-terminal devices

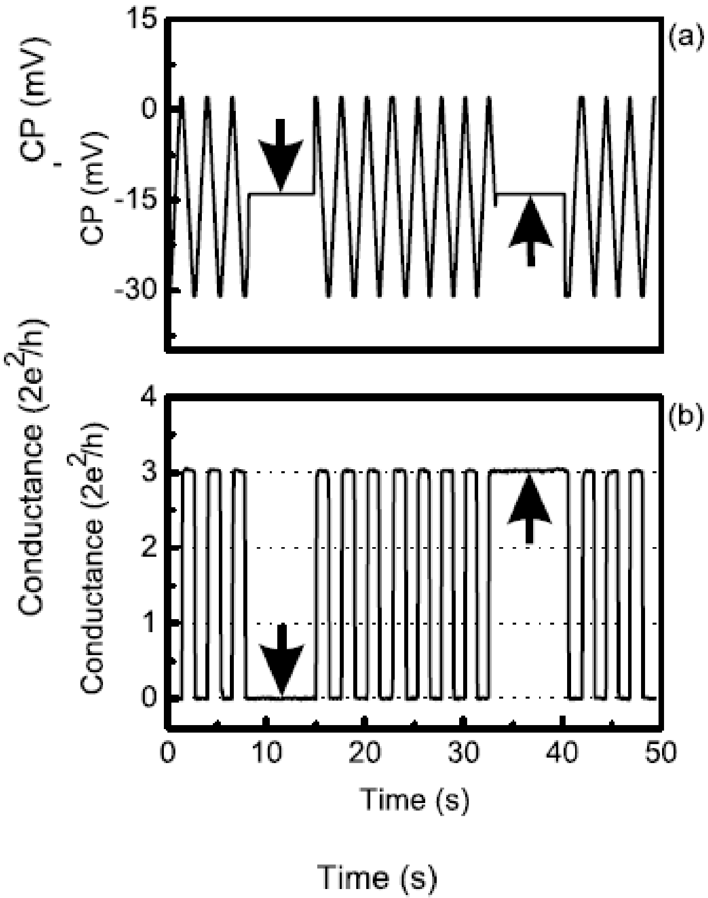
6.1.8 Electrochemical methods



+ simple sample fabrication
+ many repitition possible
+ three terminal device
- Adjustment possible in electrochemical environment

Gate-induced switching of electrochemical contacts





Xie et al, PRL 93, 128303 (2004)