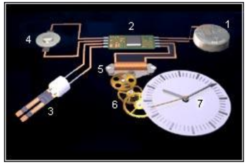
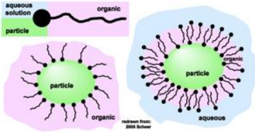
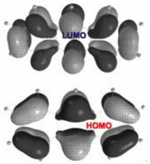
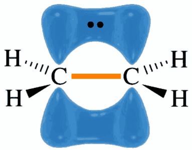
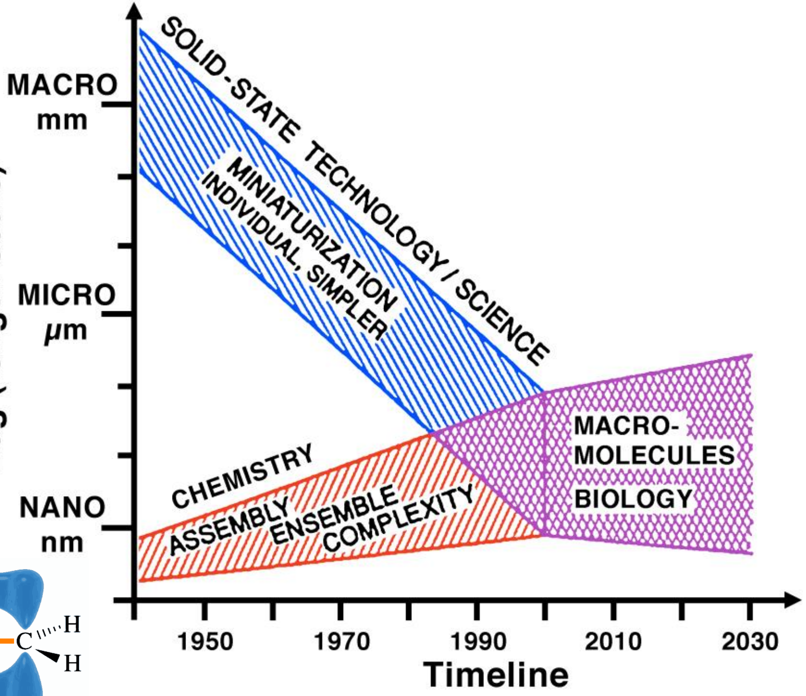
Welcome to our Nanotechnology course MICRO-530

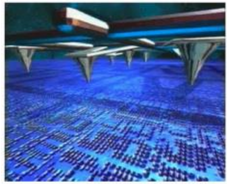


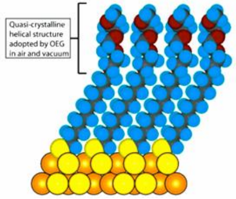


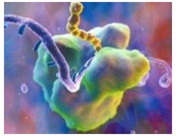












Agenda for today

- Introduction to the course
- Teachers, schedule, activities
- Course objectives
- Exam information

- Lecture start
  - some scaling considerations
  - micro-engineered nano-tools

The teaching team

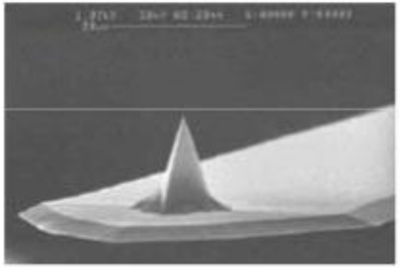
Juergen Brugger
Micro/Nanofabrication
MEMS/NEMS

Giovanni Boero
Physical electronics
Nanoscale phenomena

About myself - J. Brugger

- Born, primary and high-schools in Germany
- University of Neuchatel/Switzerland “Physical Electronics”
- PhD Uni Neuchatel (Atomic Force Microscopy)
- Hitachi Research Laboratory, Tokyo
- IBM Research Laboratory, Zürich
- University of Twente, The Netherlands

- Since 2001 @ EPFL
- Office: BM 3.107
- https://people.epfl.ch/juergen.brugger



MEMS & Atomic Force Microscope tip

About – G. Boero

- Schools in Italy
- Laura in Physics (University of Genova, Italy)
- Worked at Fermilab (Chicago, USA) and CERN (Geneva, Switzerland)
  (Gas beams for particle physics experiments)
- PhD in Technical Sciences (EPFL, Switzerland)
  (Nuclear magnetic resonance, integrated electronics)
- Present research interests: Methods and devices for Nuclear Magnetic Resonance (NMR), Electron Spin Resonance (EPR), FerroMagnetic Resonance (FMR) spectroscopy and imaging on «small» samples.

- Coordinates: BM-3-110, +36675, giovanni.boero@epfl.ch
  http://people.epfl.ch/giovanni.boero

Course objectives

- Nanoscientific phenomena necessary to understand nanotechnology
- Nanotechnology in relation to advanced engineering
- Basis of the emergent field nanotechnology (we are still ~~at the beginning~~ in a ~~growing~~ stabilizing mode)
- Get you prepared for new jobs requiring knowledge on nanotechnology
- Help in filtering information from the media: hype & danger
- Contribute to open discussion on potentials & risks of nanotechnology

JB (2024): "Nanotech was 30 years ago what AI is today"

Content overview

- **Basis (GB)**
  - Nanoscale phenomena
  - Quantum Mechanics
  - From Atom to solids
  - Scaling laws
- **Nanoimaging and nanofabrication (JB)**
  - Microscopy and lithography
  - 3 categories: optical, electron, scanning nanoprobes
  - Lithography (optical, DUV, resolution enhancement, EUV, emerging nanopatterning)
  - Focused ion beam systems
  - Scanning probe systems
  - *Self-assembly… (tbc)*

- Q: start the class at 9h15? Instead of 8h15?

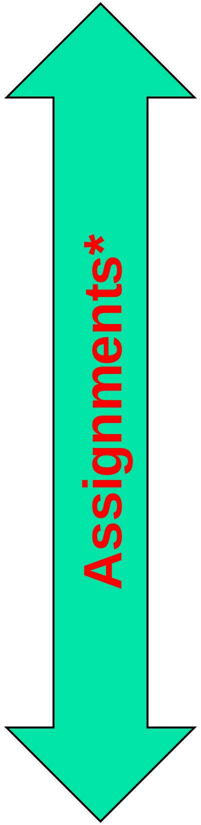
Please fill out the google form on moodle by next week.

Supporting and teaching material

- Hand-outs of lecture slides on Moodle as PDF
- Everything will be on Moodle
- Some assignments/quizzes (not graded, but effective for learning, self-assessment, feedback)
- References to books / papers
- MOOC (EBL, AFM)
- Recorded videos from 2021 class
- chatGPT or Gemini as “sparring” partner

Schedule 2025

Date	Content	Teacher
Feb 19	Intro	JB
Feb 26	Nano Phen	GB
Mar 05	Nano Phen	GB
Mar 12	Nano Phen	GB
Mar 19	Nano Phen	GB
Mar 26	Nano Phen	GB
Apr 02	Nano Phen	GB
Apr 09	Nano Phen	GB
Apr 16	Nano Imag & Fab	JB
Apr 23	Easter Break	
Apr 30	Nano Imag & Fab	JB
May 07	Nano Imag & Fab	JB
May 14	Nano Imag & Fab	JB
May 21	Nano Imag & Fab	JB
May 28	Nano Imag & Fab	JB



***Assignments:**
Quizzes
Group-based topical reading
Short pitches
Peer reviewing
Paper selection
Final presention in last week

Group based learning activities

Besides the lectures (ex-cathedra) …

- **Week 1-2: Group Formation & Topic Selection**
- Week 2-7: Weekly Guided Reading & Quizzes
- Week 3-7: Interactive Discussion Challenges on Moodle
- Week 5: Mid-Point Mini Peer Assessment (tbc)
- Week 8: Paper Selection & Voting
- Week 10: Elevator Pitches & Peer Feedback
- Week 11-12: Hands-On Simulation (tbc)
- Week 13-14: Final Nano "Proposal" possibly with industry guest 'jury' (tbc)

Knowledge tests

- Oral exam (in principle as planned,… tbc)
- Set of questions will be provided during the semester
  - 15-20 min preparation without course docs
  - 15-20 min oral exam using document projector

Nanotechnology is touching many / all disciplines

- Nano-Science
- Nano-Technology
- Nano-Engineering
- Nano-Manufacturing

- Nano-electronics
- Nano-mechanics
- Nano-optics
- Nano-fluidics
- Nano-magnetism
- Nano-biology
- ...

Nano is not only small size…

Nano offers new functionalities that do not exist at micro/macro scale

In-class question

- Q1: When was the term Nanotechnology for the first time used?

Answer

- Q2: What is different in scaling laws when going sub-micrometer, 100nm, 10nm 1nm, 1A ?

Answer

Scope and Outline (GB lectures)

EPFL

Scope:

- **Basic understanding of some physical and chemical phenomena relevalant at nanoscale.**

Outline:

- **Introduction**
- **Basics of quantum mechanics**
- **Atomic structure**
- **Molecular structure**
- **Band structure in 0D, 1D, 2D, 3D**
- **Intermolecular forces**
- **Physi- and chemi-absorption,**
- **Surface tension**
- **Examples of nanoscale phenomena and devices.**

References:

Books

P. Atkins, J. de Paula, Atkins' physical chemistry, Oxford Univ. Press, 2006.

J. N. Israelachvily, Intermolecular and surface forces, Academic Press, 2011.

Web resources

IUPAC guide to chemical nomenclature: http://goldbook.iupac.org

E. F. Schubert, Physical foundation of solid state devices, http://homepages.rpi.edu/~schubert/

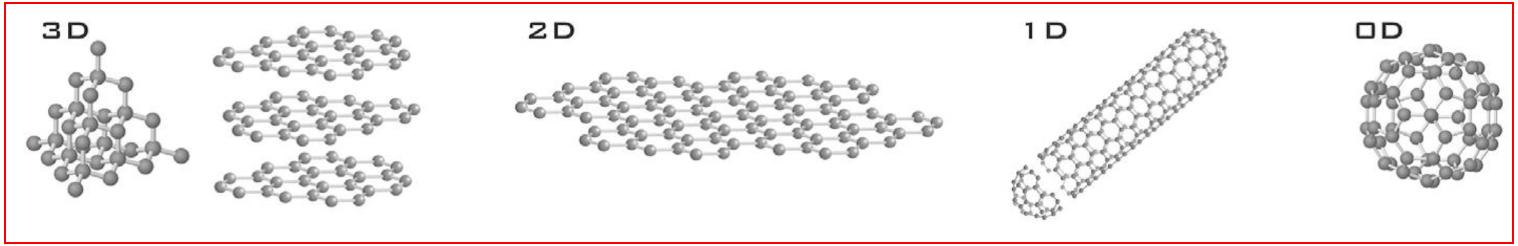
Links to other courses:

Scaling laws (from macro to micro….but not down to nano) are extensively treated in: "Scaling of MEMS", Ph. Renaud & H. Shea

Nanoscience and nanotechnology: definitions (GB)

- **Nanoscience**: study of phenomena and manipulation of materials at the atomic, molecular and macromolecular scale (nanometer range), where properties differ significantly from those at larger scale.
- **Nanotechnologies** are the design, characterization, production and application of structures,devices, and systems by controlling shape and size at nanometer range.
- **Nanometer range**: from 100 nm down to 0.2 nm in at least one dimension.

Only **one** dimension (2D):	Thin films, thin surface coatings, quantum wells, ..
Only **two** dimensions (1D):	Nanotubes, nanowires, quantum wires,…
All **three** dimensions (0D):	Nanoparticles,quantum dots, nanodots….



http://www.grin.com/object/external_document.241594/4faa9d200d87a21c1cd800b5b38f9153_LARGE.png

Nanoscience and nanotechnologies: opportunities and uncertainties, The Royal Society & The Royal Academy of Engineering, July 2004, www.nanotech.org.uk

Why it is interesting to study nanoscale «objects» ? (GB)

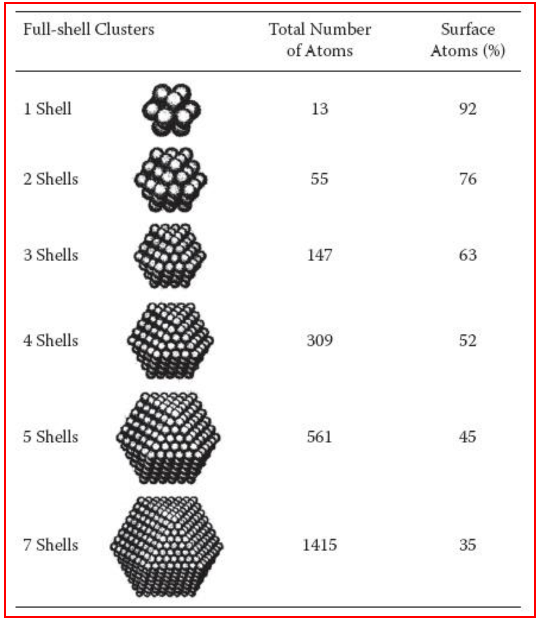
- Nanosized «objects» exhibit **different properties** than larger «objects» of the same material.
- Understanding the behavior of nanoscale «objects» requires **new theories** with respect to those used for the behavior of larger «objects».
- Nanoscale «objects» are **useful** in several fields (fundamental and applied research, medicine, consumer electronics, ….)

Properties of nanoscale «objects» (GB)

Micrometer scale «objects» have properties typically identical to those of larger «objects» (i.e., they have "bulk" properties).

Which properties might be significantly different in nanoscale «objects» ?

- Optical (color, transparency,….)
- Electrical (conductivity,….)
- Mechanical (hardness,…)
- Thermal (melting point,…)
- Chemical (reactivity, reaction rates, …)
- Magnetic (superparamagnetism,…)



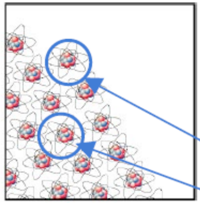
Full-shell Clusters	Total Number of Atoms	Surface Atoms (%)
1 Shell	13	92
2 Shells	55	76
3 Shells	147	63
4 Shells	309	52
5 Shells	561	45
7 Shells	1415	35

Why properties of nanoscale «objects» are different from those of macroscopic «objects » ?

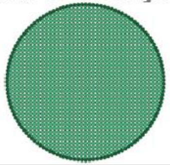
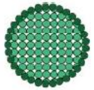
- Surface-to-volume ratios are larger
- Gravitational force is negligible
- Quantum effects might be important
- Random thermal molecular motion is more important
- …

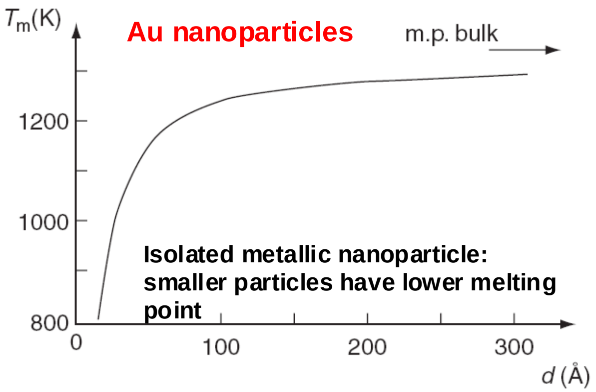
Example: Nanoparticles melting point (GB)

- **Melting Point (Microscopic Definition)**
  - Temperature at which the atoms, ions, or molecules in a substance have enough energy to overcome the intermolecular forces that hold the them in a "fixed" position in a solid

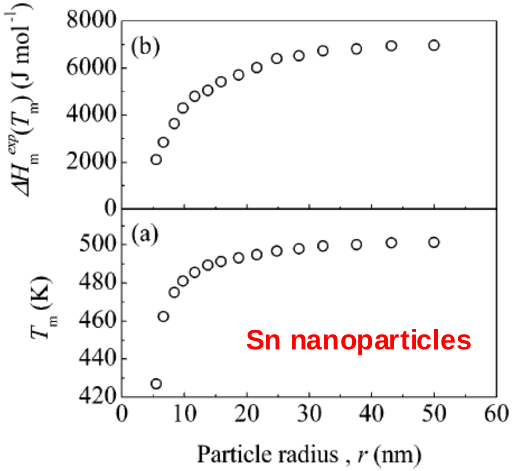


  - Surface atoms require *less* energy to move because they are in contact with *fewer* atoms of the substance

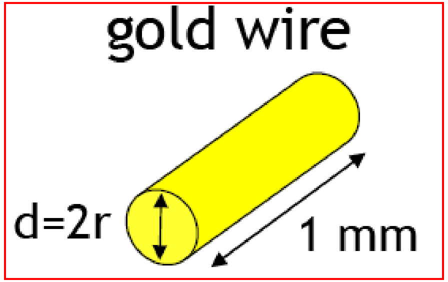
	At the macroscale	At the nanoscale
The majority of the atoms are…	…almost all on the inside of the object 	…split between the inside and the surface of the object 
Changing an object's size…	…has a very small effect on the percentage of atoms on the surface	…has a big effect on the percentage of atoms on the surface
The melting point…	…doesn't depend on size	… is lower for smaller particles



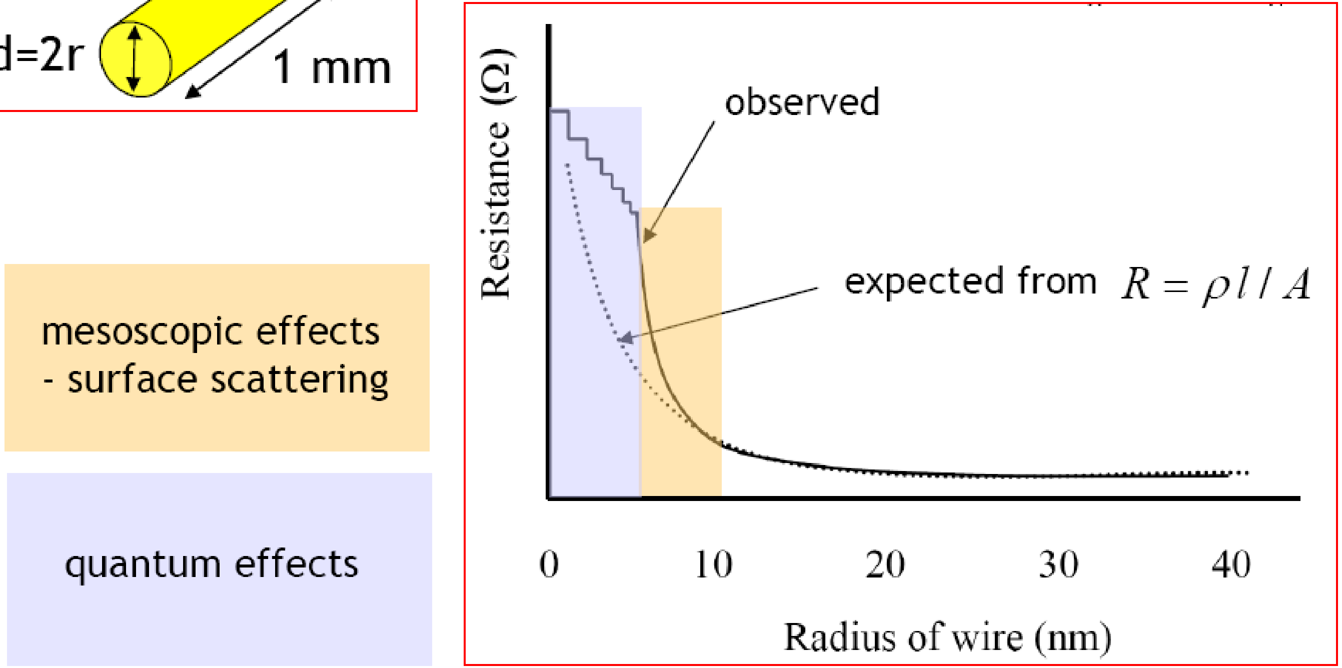
(Note: Metallic nanocrystals in a continuous matrix: smaller particles have higher melting point)



Conductance quantization: experimental evidence (GB)

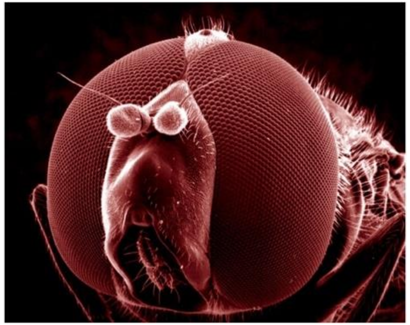


Conductance quantization: first observed in 1988.
1. B. J. van Wees et al."Quantized Conductance of Point Contacts in a Two-Dimensional Electron Gas" *Physical Review Letters* 60, 848-850, 1988.
D. A. Wharam et. Al. "One-dimensional transport and the quantisation of the ballistic resistance," *Journal of Physics C: Solid State Physics* 21, L209-L214, 1988.

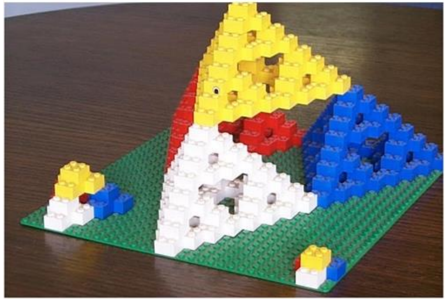


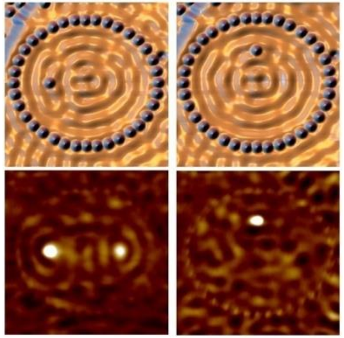
Imaging - a feeling for scales

For science and engineering, we need to develop a sense for scales we wish to interact with. Sometimes the scale is obvious (reference), but the best practice is to add a scale bar. The way images are shown (or the scale) mostly indicate also what microscope was used to take the image. But it is not always obvious.



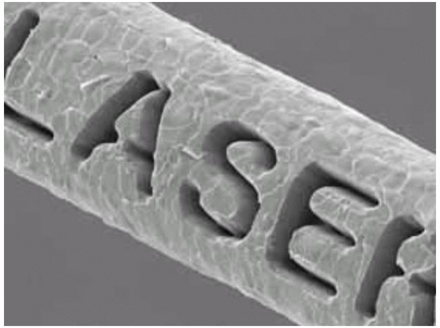
Scale?

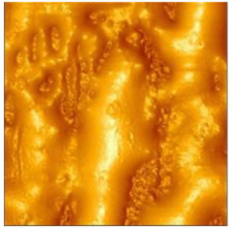


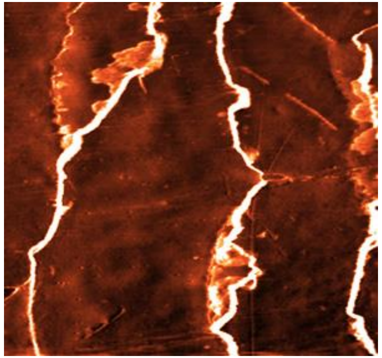


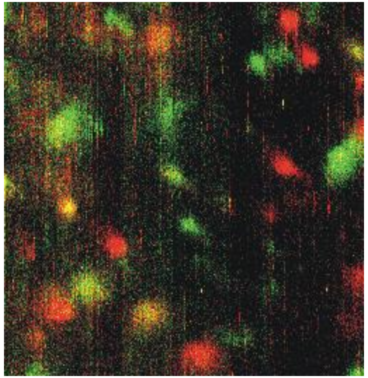
Scale?

What is the scale?



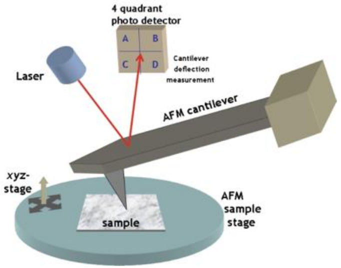






Three types of instruments to view nanoscale

A microscope is a tool that 'probes' a surface or material and the interaction with it provides some information. Often microscopes are surface instruments, but not only, depending how deep the 'probe' can penetrate into the material and re-exit to be detected by a monitoring system (eye, detector, sensor). The 'probe' may also alter the specimen.



Optical ("light") microscope
'Probe': Light that is reflected from or transmitted through sample.

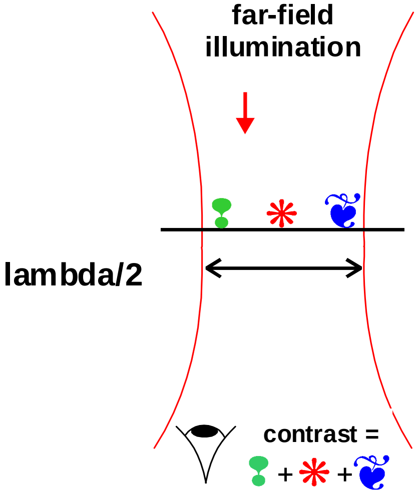
Electron microscope
'Probe': Electrons (shorter wavelength) that are re-emitted from or transmitted through sample.

Scanning Probe microscope
'Probe': tip that interacts locally with surface (forces, electrons, photons)

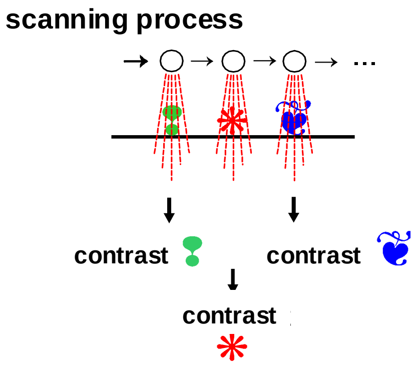
- Q3: How is is possible to detect single molecules with optical methods (that are limited by diffraction)?

Far-field versus near-field

- Far-field
  - wavelength
  - Resolution by diffraction limit

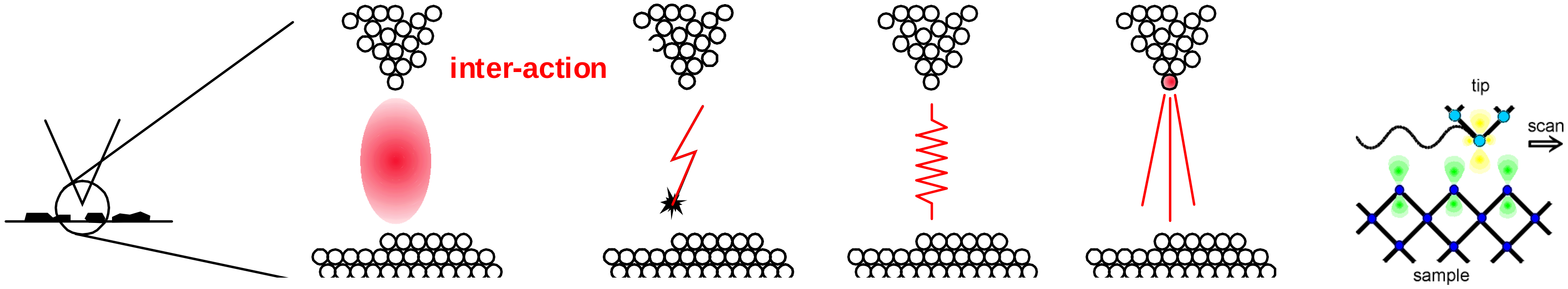


- Nearfield (probe)
  - Scanning probe
  - spatial dimension
  - resolution = f (tip size, distance,…)



Different kinds of SPMs

- SPM = scanning probe microscope
- the nature of the interaction determines the sample property that is observed
- the magnitude of the interaction determines whether we observe or modify: SPM as a **microscope** (to observe) or a **tool** (to modify the surface).

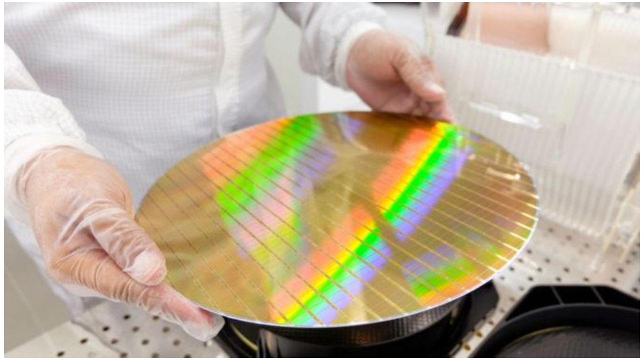


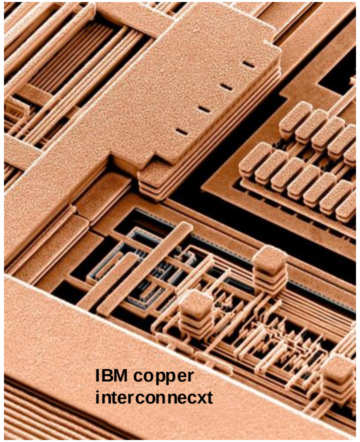
Manufacturing at the nanoscale:

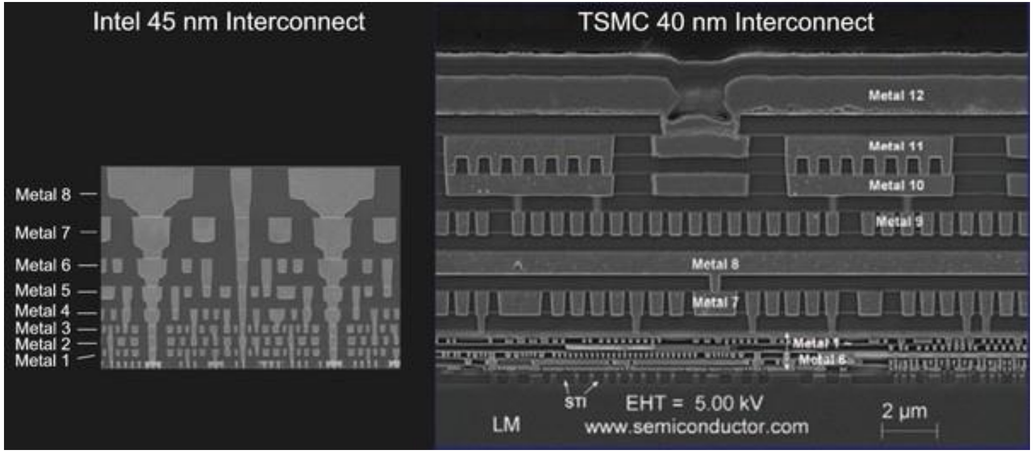
Top-down.
Bottom-up.
Both together.

Top down fabrication/lithography (CMOS)

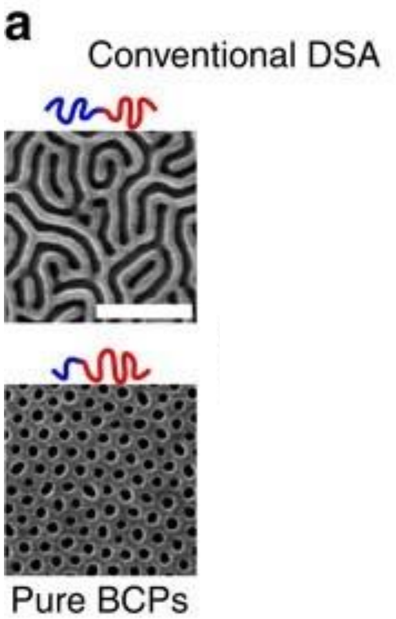
- Lithography
- Thin film processing
- Deposition
- Etching
- New materials
  - SOI wafers
  - 2D materials
- Moore's 'law' limits
  - Always pushed by new technological advances





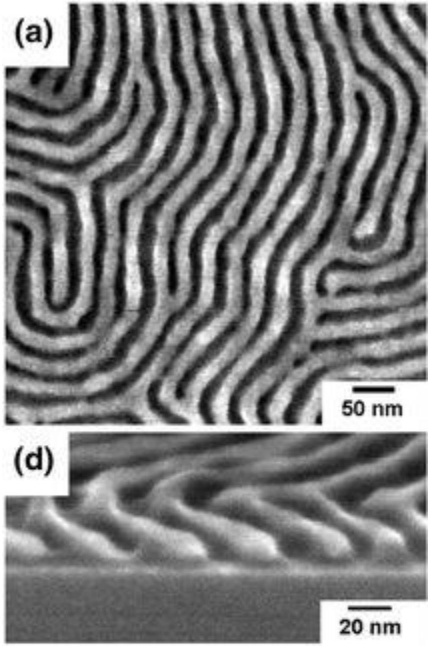


Bottom-up (self-assembly)



Stein, A., Wright, G., Yager, K. *et al.* Selective directed self-assembly of coexisting morphologies using block copolymer blends. *Nat Commun* 7, 12366 (2016). https://doi.org/10.1038/ncomms12366

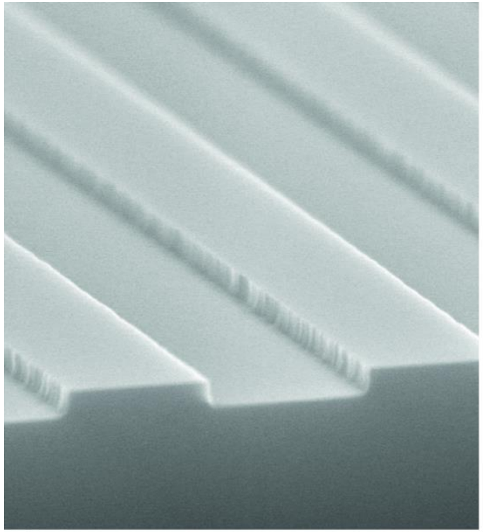
Block co-polymer
Random features



DOI: 10.1117/1.JMM.11.3.031306]

Bottom-up (self-assembly) and top-down

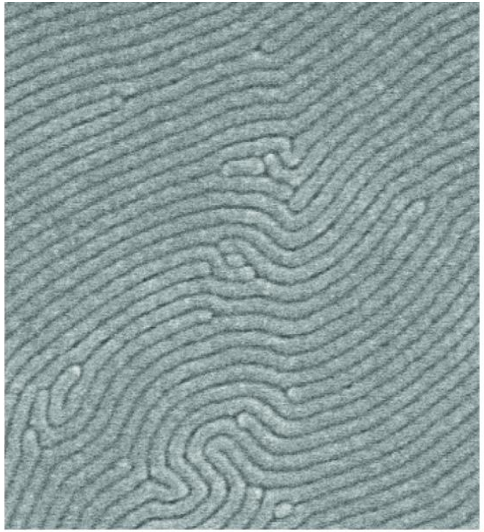
Micro template



Lithographically-defined substrate

+

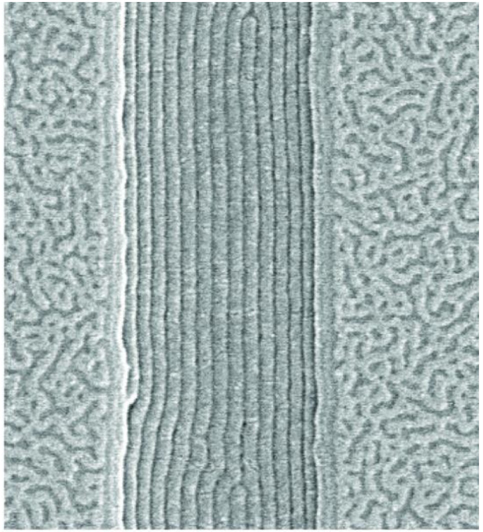
Self-assembly



Self-Assembly of diblock copolymers

=

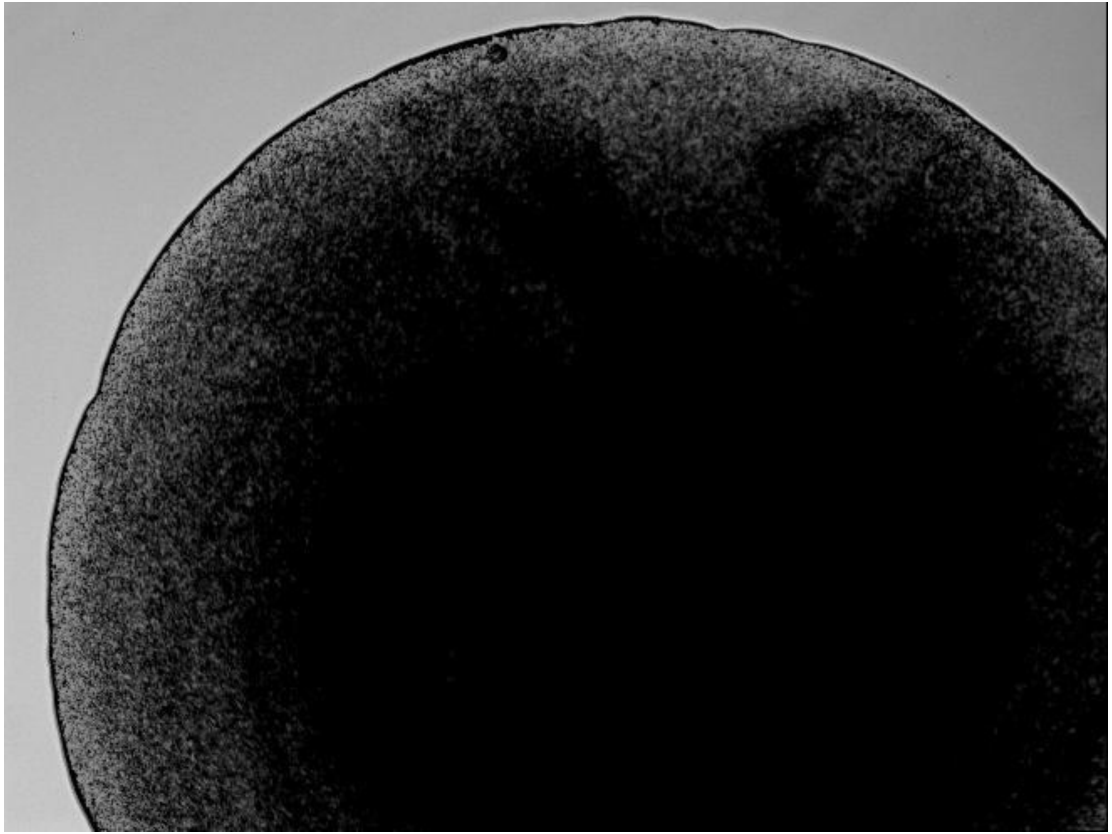
Templated self-assembly



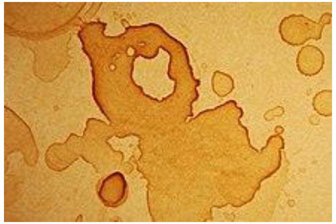
Directed Self-Assembly

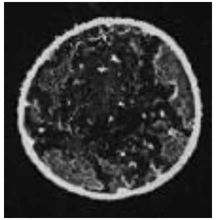
http://polynano.snu.ac.kr/research_research.htm

Capillary assembly of nanoparticles (bottom-up)

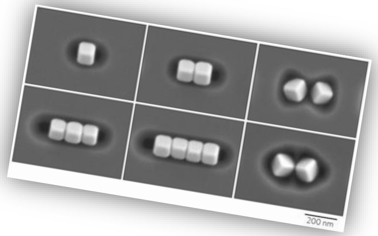


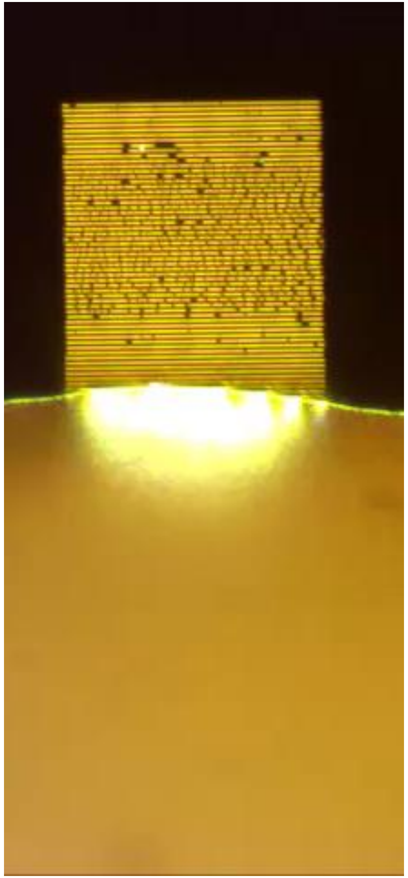
Still *et al.*, *Langmuir* 2012



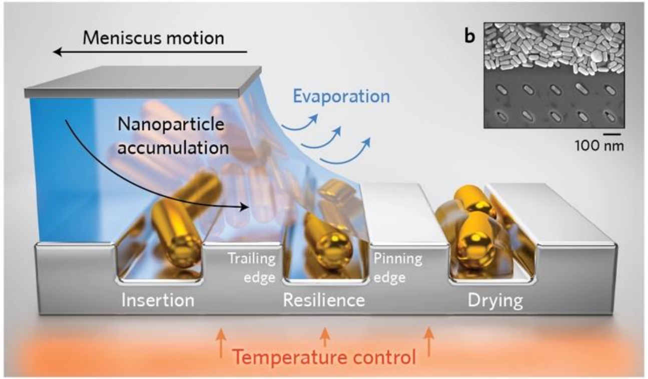


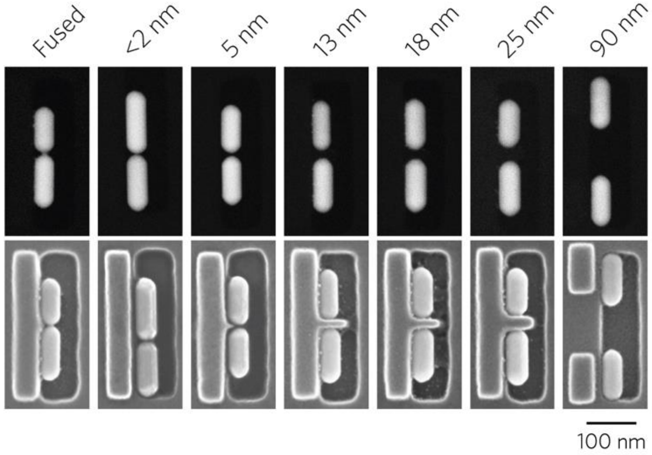
Capillary assembly of nanoparticles (top down and bottom up)





Beaker with NP





V. Flauraud et al., *Nat. Nanotechnol.* 2017

Nano-technology in commercial advanced chip technology

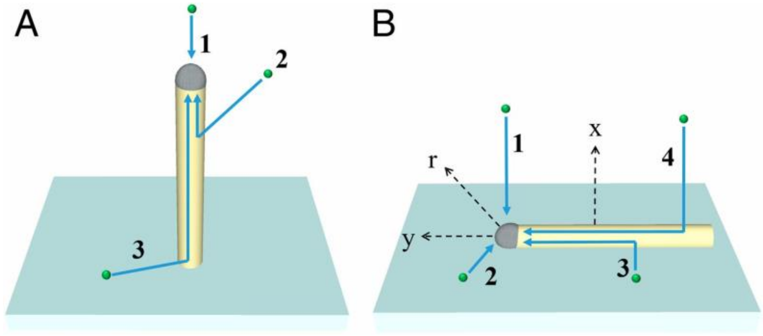
- Key technologies:

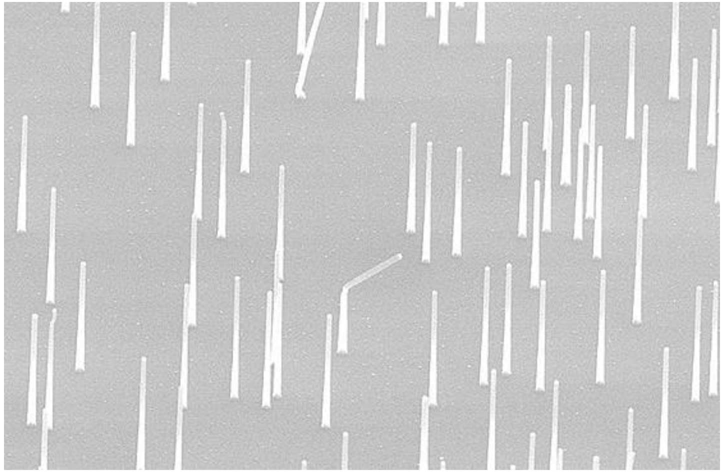
- CPU, processor chip
  - Still mainly silicon (mono-crystalline!)
  - Strained silicon to improve mobility
- Memory (SSD) using silicon FET … or (HD) magnetic materials for switching
- Ndvia chip nano?

How is a silicon wafer grown?

- Seed crystal
- Controlled process (saturation, temperature, speed, etc.)

Growth of 1D nanowires (bottom up)



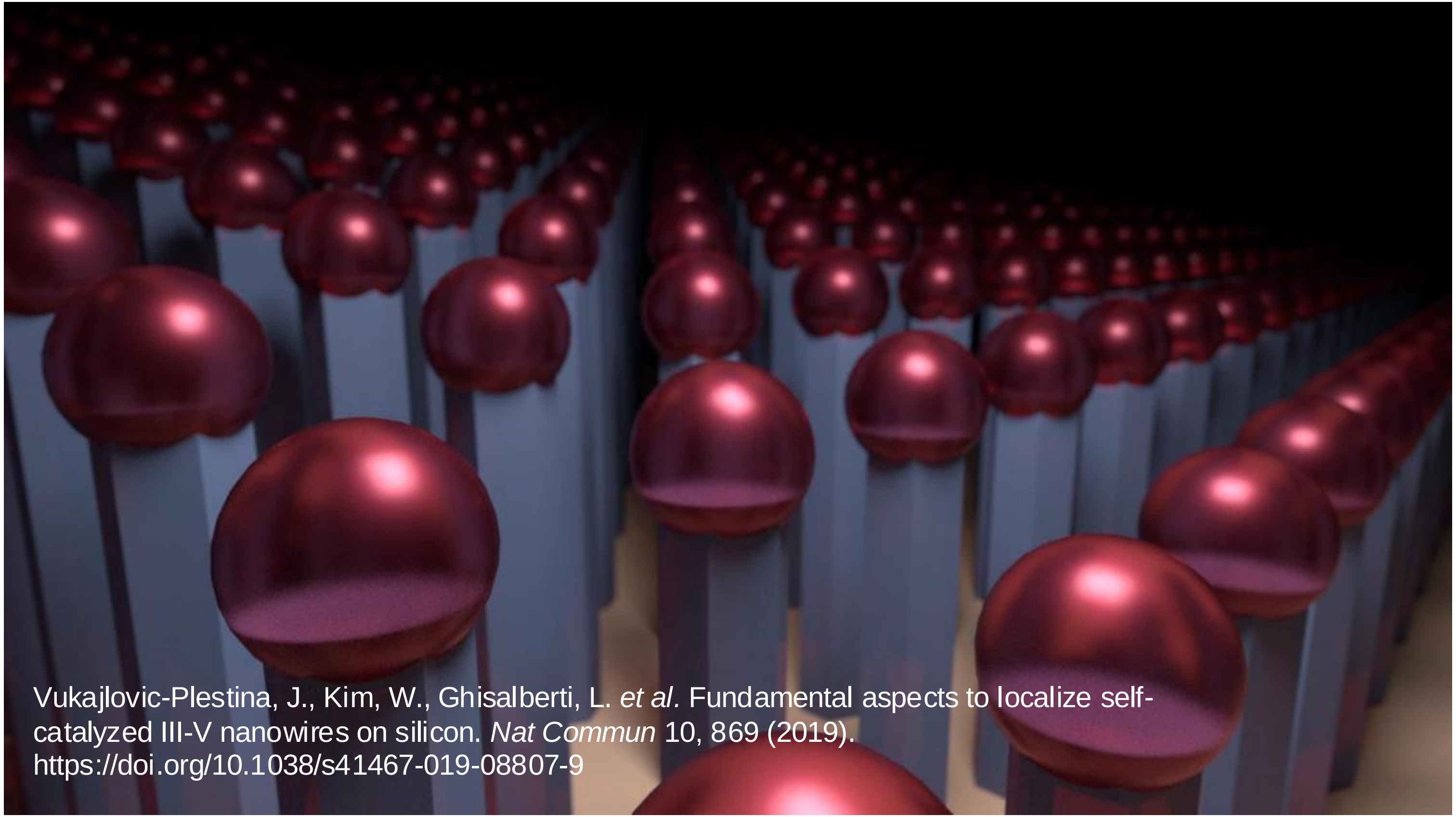


Kristian Molhave/Opensource Handbook of Nanoscience and Nanotechnology

These are all single crystalline rods and wires!

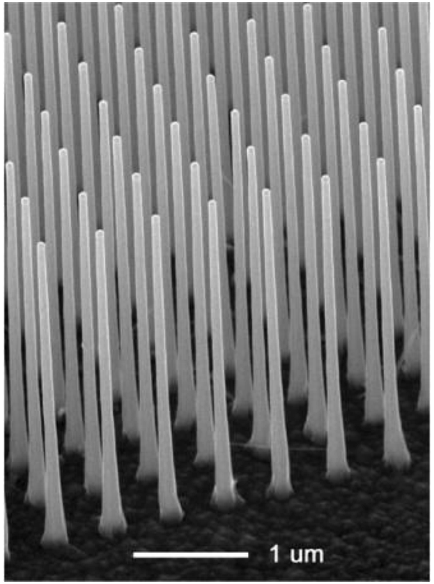
Various materials (metal, semiconductor)

Nanowire growth (@Epfl)

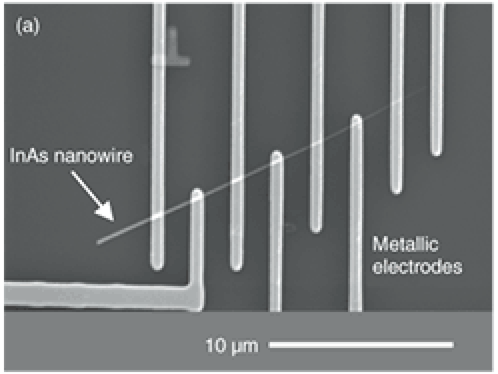


Vukajlovic-Plestina, J., Kim, W., Ghisalberti, L. *et al.* Fundamental aspects to localize self-catalyzed III-V nanowires on silicon. *Nat Commun* 10, 869 (2019). https://doi.org/10.1038/s41467-019-08807-9

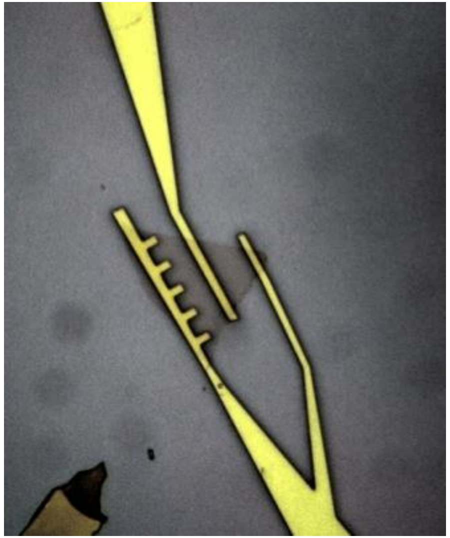
1D/2D nanodevices, with atomic precise crystal planes



Nanowire as device



Graphene, MoS_2, …



Left: https://doi.org/10.1016/j.physe.2004.06.030
Middle: Guoqiang Zhang†, Kouta Tateno, Hideki Gotoh, and Tetsuomi Sogawa, NTT technical review
Right: Dong Sun, Grant Aivazian, Aaron M. Jones, Jason S. Ross, Wang Yao, David Cobden and Xiaodong Xu. Nature Nanotechnology, 15 Jan 2012.

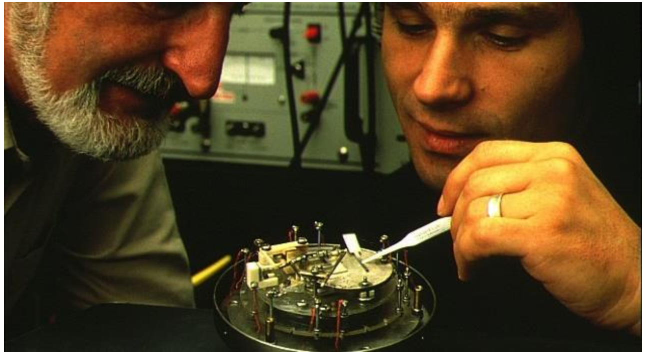
Agenda for today

- Introduction to the course
- Teachers, schedule, activities
- Course objectives
- Exam information

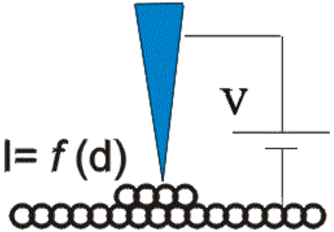
- Lecture start
  - some scaling considerations
  - micro-engineered nano-tools

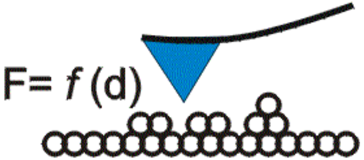
History of surface profiling

- Profilometry (~ 1976)
  - high resolution for vertical axis (thin films), but lacking mechanical precision, feedback, sharp tip, …
- STM (1981)
  - Scanning Tunneling Microscopy (STM): G. Binnig, H. Rohrer, Ch. Gerber and E. Weibel; Phys. Rev. Lett. 49, 57 (1982)
  - Imaging of <u>individual</u> atoms in space and time; tunneling; quantum mechanics “visible”
- AFM / SFM (1985)
  - Atomic Force Microscopy (AFM):
Scanning Force Microscopy (SFM): G. Binnig, C.F. Quate, and Ch. Gerber, Phys. Rev. Lett. 56, 930 (1986)
  - Insulating surfaces, atomic resolution, ‘true’ atomic resolution



http://nobelprize.org/physics/laureates/1986/





The original STM paper (Binnig et al.)

VOLUME 50, NUMBER 2 PHYSICAL REVIEW LETTERS 10 JANUARY 1983

7 × 7 Reconstruction on Si(111) Resolved in Real Space

G. Binnig, H. Rohrer, Ch. Gerber, and E. Weibel
IBM Zurich Research Laboratory, 8803 Rüschlikon-ZH, Switzerland
(Received 17 November 1982)

The 7×7 reconstruction on Si(111) was observed in real space by scanning tunneling microscopy. The experiment strongly favors a modified adatom model with 12 adatoms per unit cell and an inhomogeneously relaxed underlying top layer.

PACS numbers: 68.20.+t, 73.40.Gk

Exact copy of first Scanning Tunneling Microscope of Binnig and Rohrer (original has not preserved).

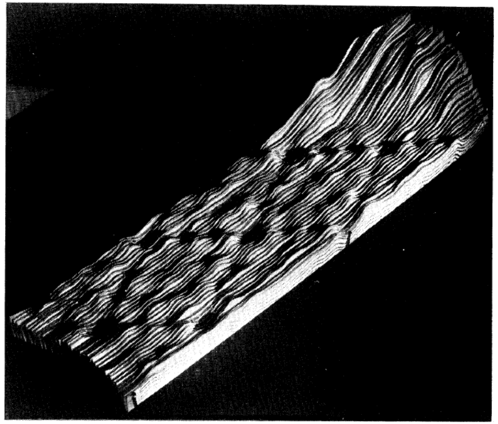
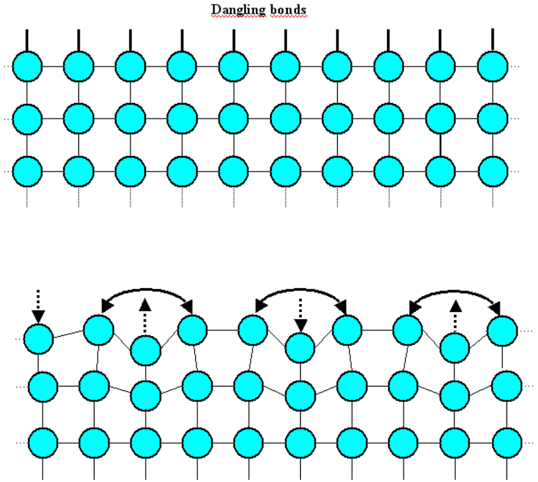
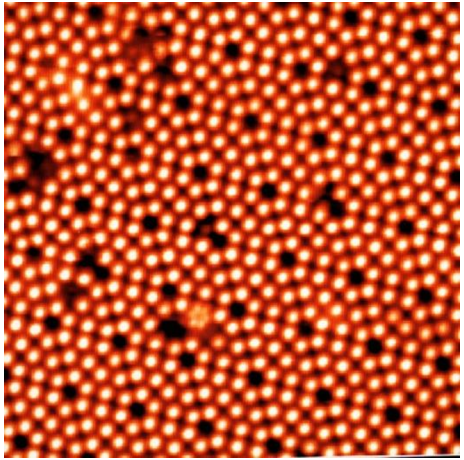


FIG. 1. Relief of two complete 7×7 unit cells, with nine minima and twelve maxima each, taken at 300 °C. Heights are enhanced by 55%; the hill at the right grows to a maximal height of 15 Å. The [$\bar{2}$11] direction points from right to left, along the long diagonal.

Surface reconstruction

Surface reconstruction refers to the process by which atoms at the surface of a crystal assume a different structure than that of the bulk.

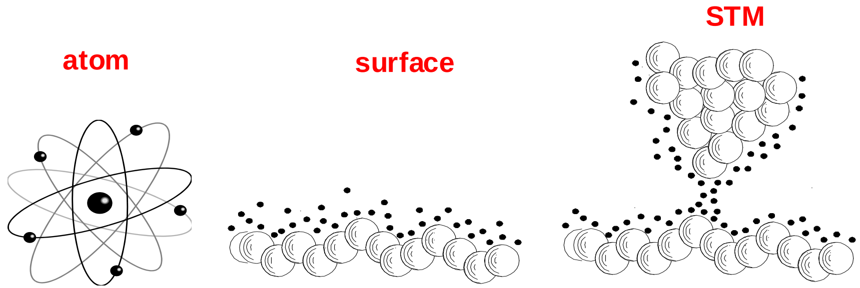




Reconstructed Si {111} surface as seen with the scanning tunneling microscope (STM)

Quantum Mechanical Tunneling

- The tunneling phenomena can also be seen as the interaction between the electron cloud of the tip and the sample.
- A voltage applied between to conducting bodies leads to an electrical current even if the two bodies not quite touch: the tunneling current
- Interaction: (tunneling-) current (down to pA)
  - atomic scale surface topography of electrical conductors
  - electronic properties of the surface (“conductivity”)
- The tunneling current is strongly dependent on the distance of the two bodies: 1 Å changes the current by a factor of 10 !

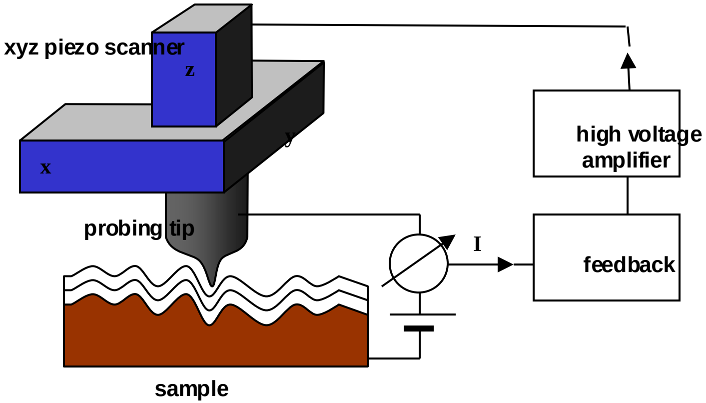


The tunneling effect is the phenomena describing the nonzero probability to have electrons crossing potential barriers. Influencing parameters are:

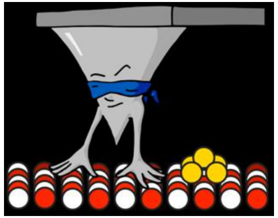
- Voltage applied on the tip.
- Distance between the tip and the sample.
- Difference of work functions. The work function is the energy necessary to extract an electron from a material. Since the material used as a tip is known, it’s possible to identify the nature of the sample.

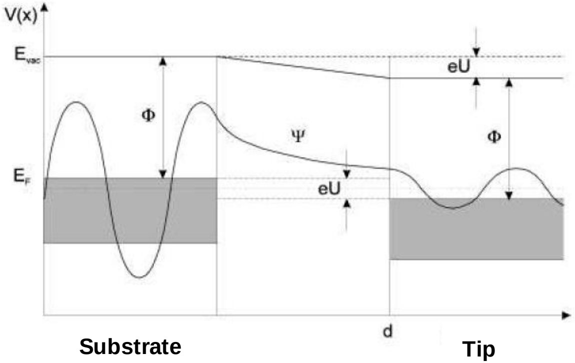
STM set-up (basic)

In an STM, the tip « sees» nothing until it is close enough to interact with the surface. To approach a tip, a voltage is applied between the tip and the sample. When a current is measured, it means that the tunneling effect has started and thus that the distance between the tip and the tip is very close to the surface. At this point, the scanning process can begin.



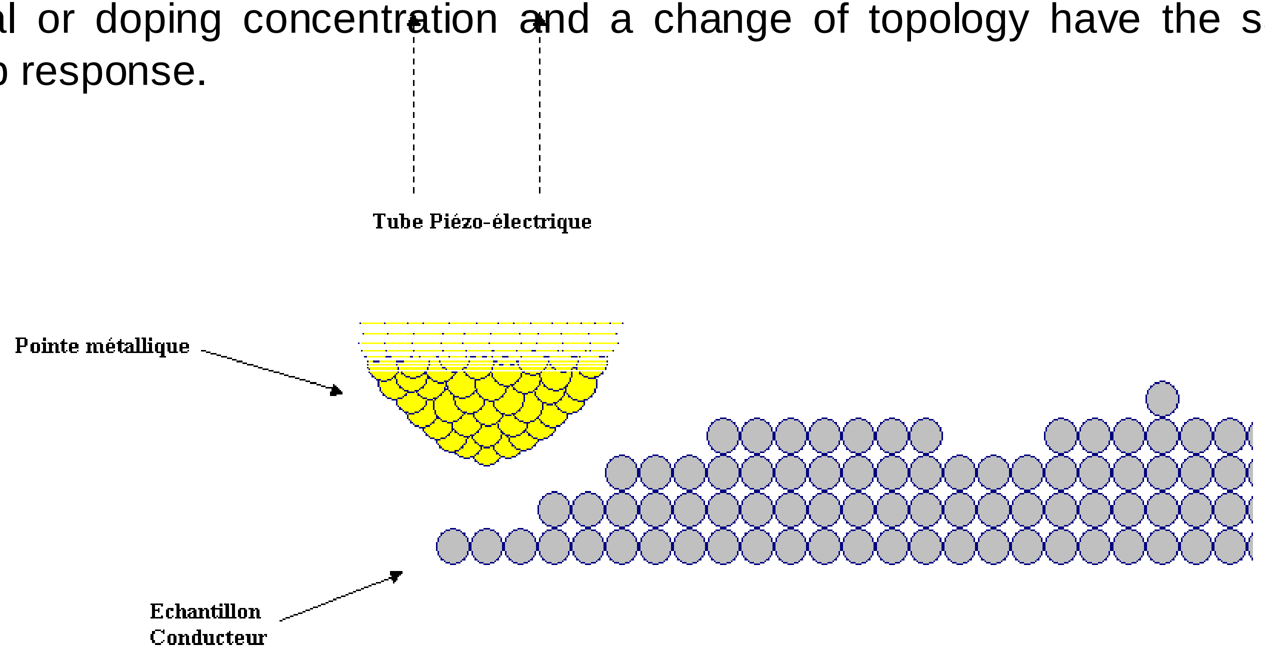
scanning contour of constant tunneling current (≈ pA - nA)



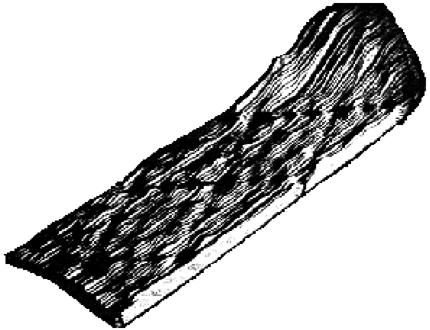


STM: topography versus work-function

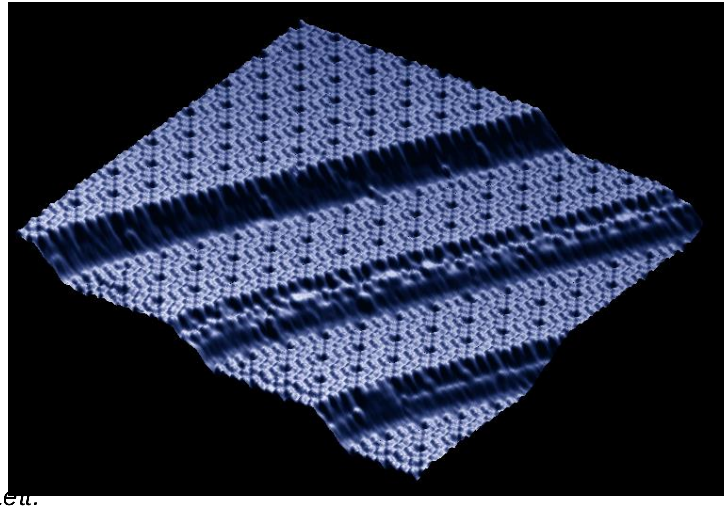
In a STM, the output curves have to be interpreted by the users, since a step corresponds either to a variation of topology or to a variation of work function. Indeed, a change of material or doping concentration and a change of topology have the same influence on the tip response.



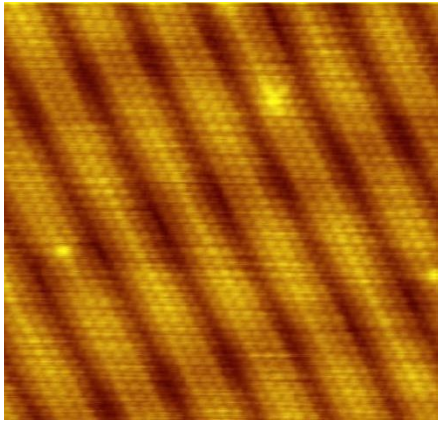
Improvement of STM imaging



(left) The first achievement of STM was the first image of the Si(111)7 × 7 structure at the IBM Research Laboratory Rüschlikon (1981).
(right) Figures A and B show examples of STM images obtained on a Si(111)7 × 7 surface in the presence of multiple-step edges (1990). The Figure shows an overview with three steps between reconstructed terraces.



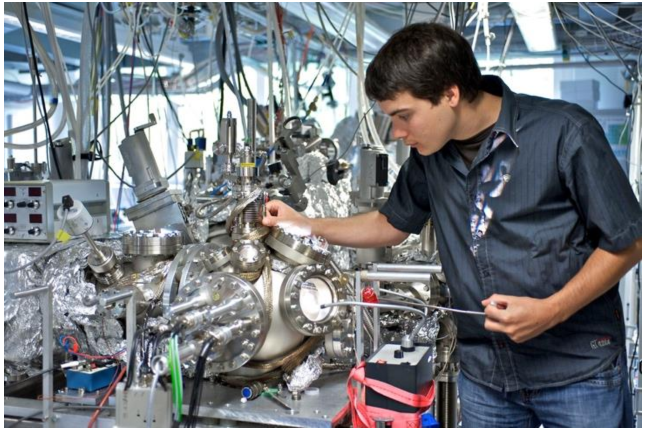
Ref: WIESENDANGER, R., TARRACH, G., BÜRGLER, D. and GÜNTHERODT, H.-J., *Europhys. Lett.* 12 (1990) 57.



- Image of surface reconstruction on a clean Gold (Au(100)) surface, as visualized using scanning tunneling microscopy. The individual atoms composing the material are visible. Surface reconstruction causes the surface atoms to deviate from the bulk crystal structure, and arrange in columns several atoms wide with regularly-spaced pits between them.
- Atomically resolved STM image of clean Au(100). This image is made with an Omicron Low Temperature STM and RHK Technology electronics by Erwin Rossen, Eindhoven University of Technology, 2006. Parameters: p<1e-11 mbar, T=77 K, I_setpoint=6 nA, V_bias=1 mV, Au(100) surface is Ar sputtered (1,5 kV, 2uA, 30 minutes) and annealed (500° C, 30 minutes).

Modern STM Instrument (example)

high-performance, low T, UHV, …



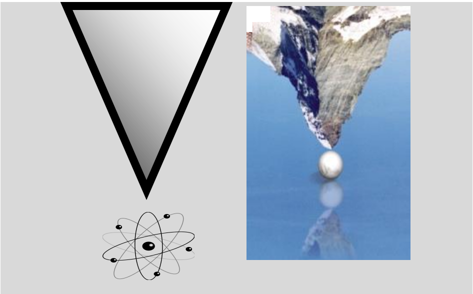
‘affordable aka low-cost’

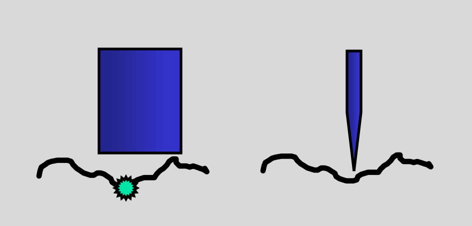
Most of the STMs are research instruments due to their high precision. However, there is almost no industrial application yet. The STM is complex and uses a high vacuum chamber to avoid oxidation and often low temperatures.

The high-performance tool cost around 1’000’000$, whereas the low-cost machine cost 30’000$. But this low-cost instrument is less performing, but excellent for education.

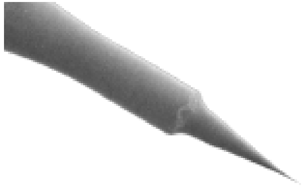
the Tip is the key

- The resolution is determined by:
  - the dimension of the probe ⇒ probes are small
  - the distance of the probe to the sample ⇒ probe is a point





- How to make sharp STM tips?
- Wire of W, Pt-Ir
- 200 um diameter
- cut or etch
- ~ 400 Å diameter tip
- hand-made
- no microfabrication process



Applications and limits of STM

- What are the applications of STM?
  - Fundamental research
  - Material science
  - Conductivity studies at nanoscale
  - Molecular electronics
  - … industrial applications?
    - R&D

- What are the limitation of STM?
  - Conductivity
  - Time for scanning
  - Ideally in vacuum, and low T
  - Difficult to analyse the image

Scanning Force microscopy

Binnig invented the scanning force or atomic force microscope (also abbreviated as AFM) and the first experimental implementation was made by Binnig, Quate and Gerber in 1986. The first commercially available atomic force microscope was introduced in 1989. The AFM is one of the foremost tools for imaging, measuring, and manipulating matter at the nanoscale. The information is gathered by "feeling" the surface with a mechanical probe. Piezoelectric elements that facilitate tiny but accurate and precise movements on (electronic) command enable the very precise scanning.

- Atomic Force Microscope
- Principle of SFM/AFM
- Force sensing
- Cantilevers and probes
- Imaging modes

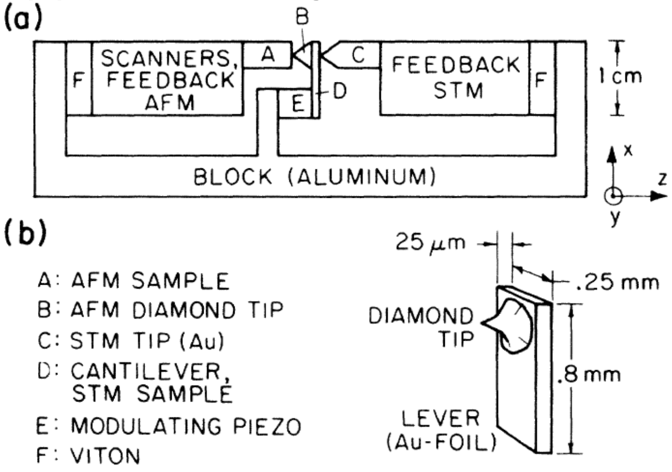


FIG. 2. Experimental setup. The lever is not to scale in (a). Its dimensions are given in (b). The STM and AFM piezoelectric drives are facing each other, sandwiching the diamond tip that is glued to the lever.

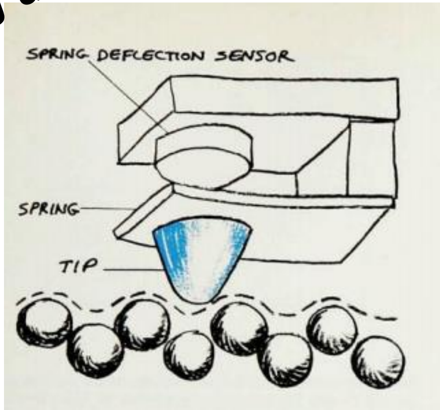
ATOMIC FORCE MICROSCOPY

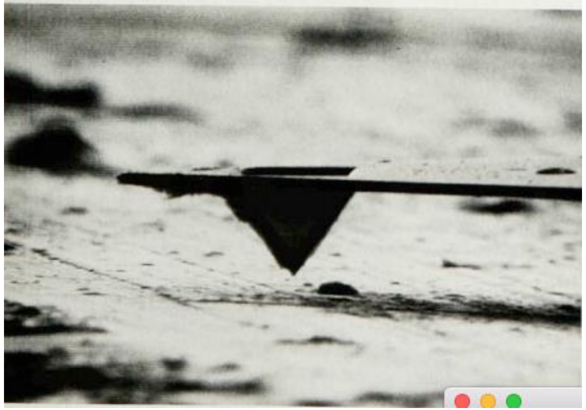
It is surprisingly easy to make a cantilever with a spring constant weaker than the equivalent spring between atoms, allowing a sharp tip to image both conducting and nonconducting samples at atomic resolution.

Daniel Rugar and Paul Hansma

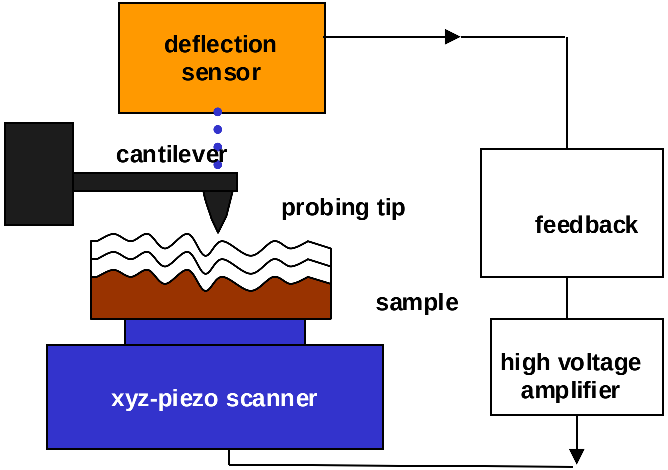
1990 American Institute of Physics
PHYSICS TODAY OCTOBER 1990

Is this drawing at scale?



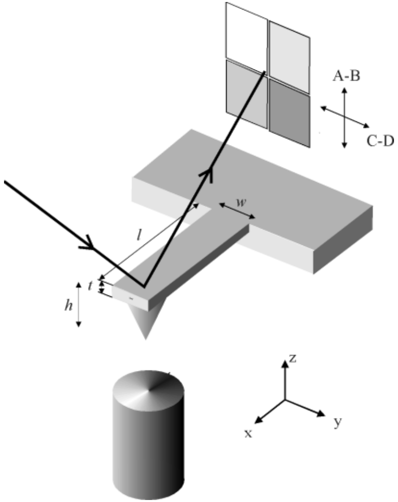


Scanning Force Microscope – basic scheme



Main ingredients:

- **Sensitive detection**
- **Flexible cantilever**
- **Sharp tip**
- **High-resolution tip-sample positioning**
- **Force feedback**



laser beam reflected by cantilever
4-quadrant position sensitive detector PSD

A-B prop. to normal deflection: normal forces
C-D prop. to torsion: lateral forces

Cantilever as force transducer

- Cantilever = force transducer
- Important parameters
- Spring constant k
- Resonance frequency f
- E: Young's modulus (material constant) E_{si} = 1.7 E11 N/m^2
- I: cross sectional moment of inertia (square cross section I = w t^3/12)

Expression general

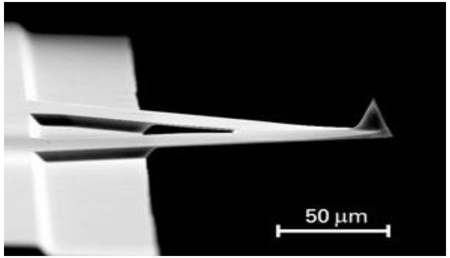
$k = 3\,E\,I\,/\,L^3$

$$f = \frac{1}{2\pi}\sqrt{\frac{k}{m_{eff}}}$$

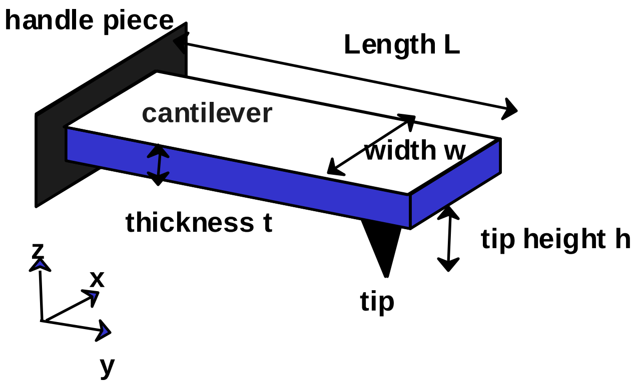
Rectangular shape

$$k = \frac{Ewt^3}{4l^3}$$

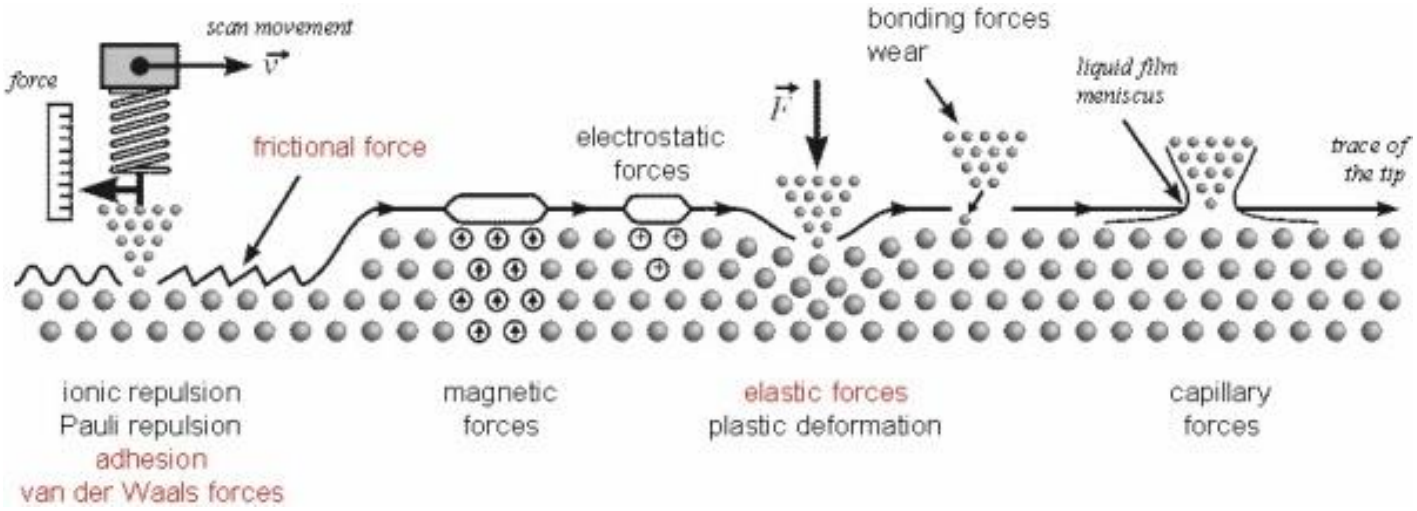
Typical values for AFM
k: 0.001-100 N/m
f: > 10 kHz



Microfabricated AFM cantilever



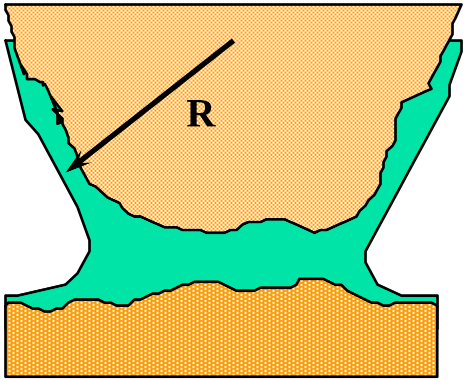
Forces in AFM at a glance



Capillary Forces

$F_{max} = 4\,\pi\,R\,\gamma\,\cos(\Theta)$

$\gamma(H_2O) = 0.074$ N/m tip radius: R = 100 nm
contact angle for hydrophilic surfaces $\Theta \sim 0^\circ$



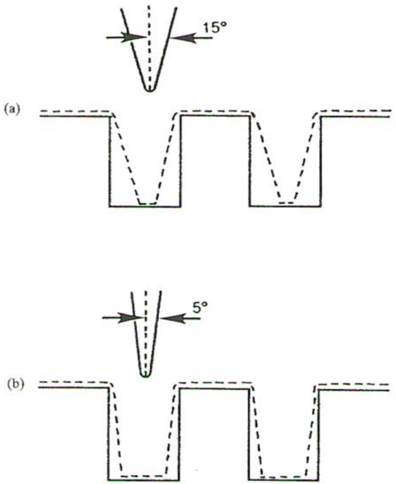
$F_{max} = 90$ nN

Numerical example:
for k = 1 N/m
→ 90 nm cantilever deflection due to liquid meniscus

To avoid capillary forces:
Operate in vacuum
Immerse fully in liquid

Tip effect: convolution, resolution limit

The shape of the tip strongly influences the resolution of the AFM. Only very thin tips are able to scan deep holes. However, the resolution is limited by the fact that tips cannot be made infinitely long. Typical radius dimensions are between 10-100nm. Therefore, to be able to resolve the size of the sample, it is necessary to know with high accuracy the shape of the tip.

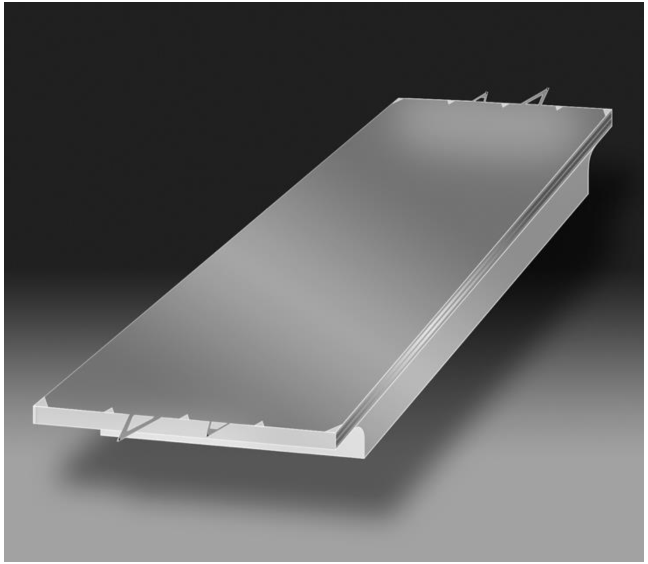


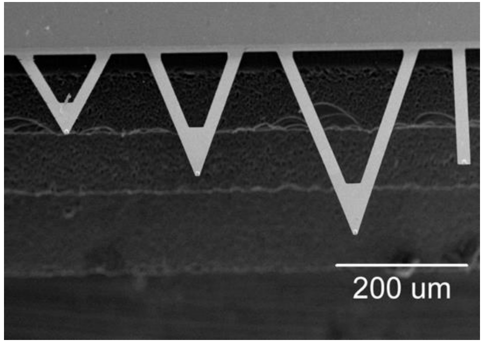
Profil de tranchées larges de 0.75µm et 1µm de profond.

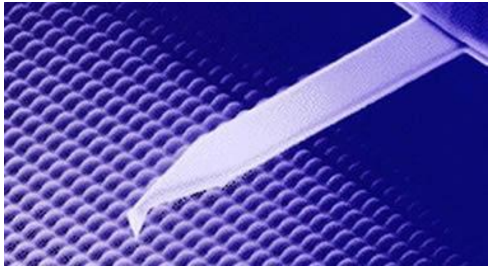
(a) pointe d'apex de rayon 500Å et 15° d'ouverture.

(b) pointe d'apex de rayon 500Å et 5° d'ouverture.

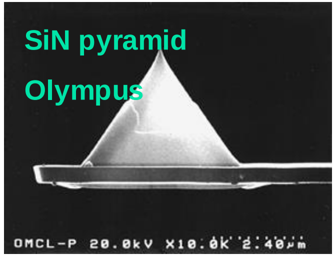
Cantilever, tips, probes

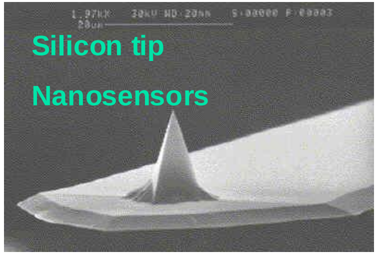






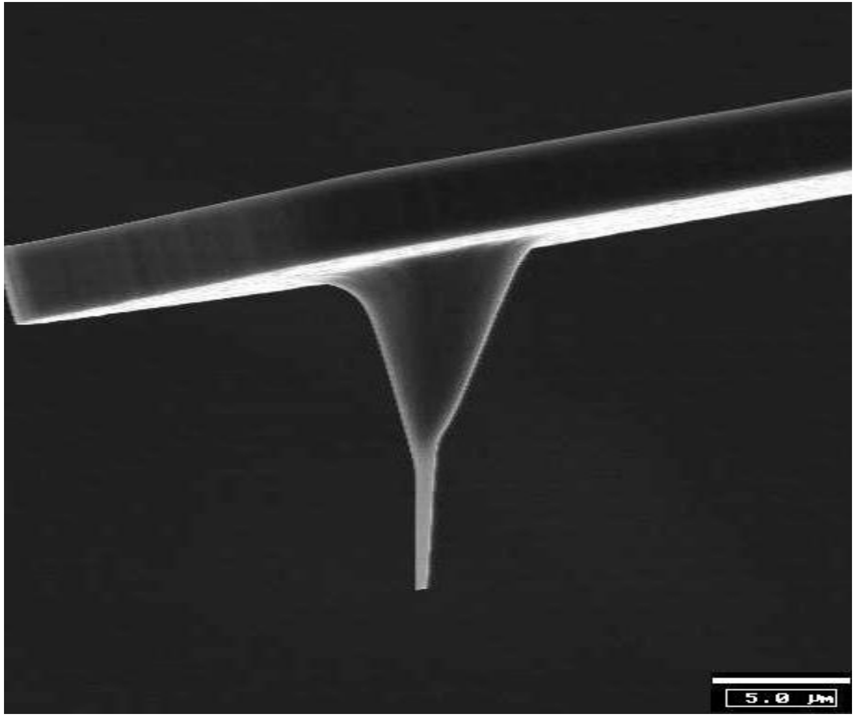
Olympus

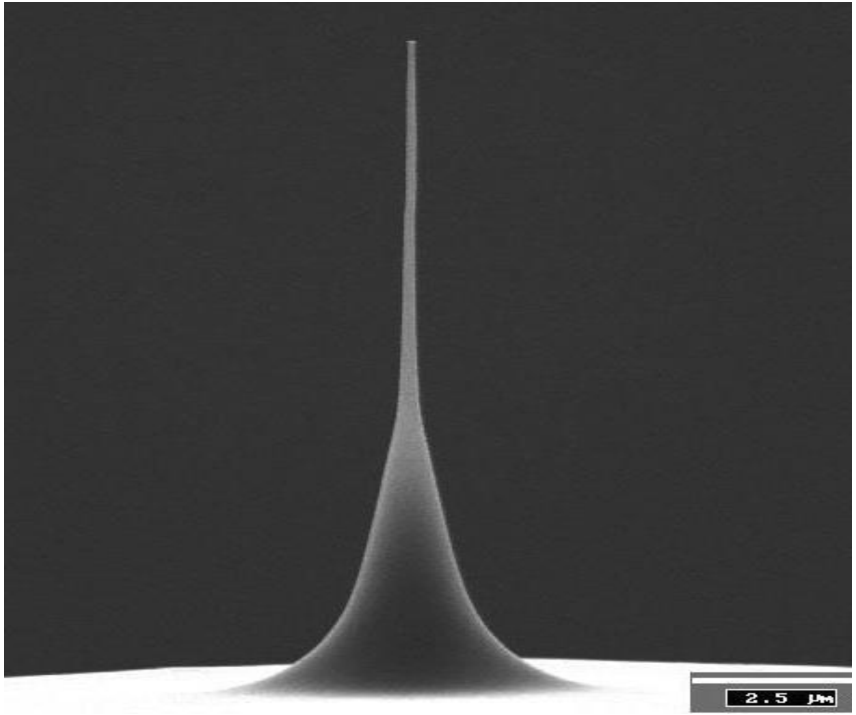




NanoWorld AG

Microfabricated silicon tips for AFM



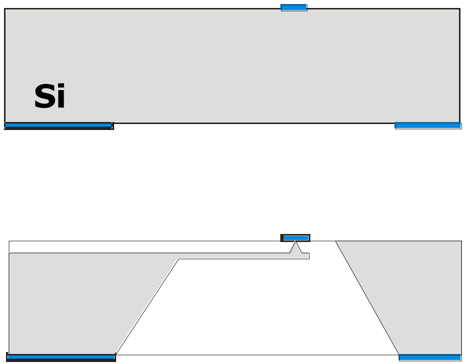


Material properties of SPM cantilever probes

- **Silicon:**
  - High Q-factor -> No intrinsic stress.
  - Semiconductor → piezoresistive, heat
- **Silicon nitride:**
  - Very thin and small cantilevers -> High resonant frequency.
  - Hard and wear resistance -> Robust tips.
- **Polymers:**
  - Low cost > Mass production possible.
  - Biocompatible -> Live science.
  - Soft materials -> High sensitivity, but slow
- **Metals:**
  - Electrically conductive -> Combination of AFM and STM.

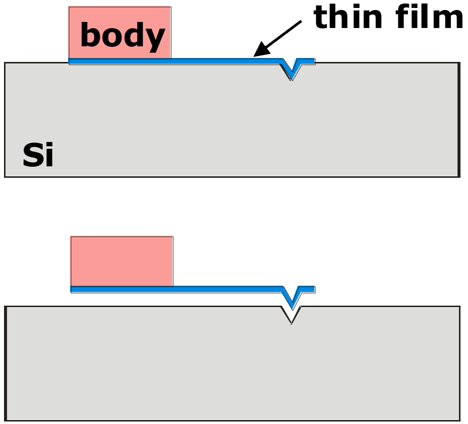
Microfabrication of Nanoprobes

Bulk micromachining



Single crystal material (Si)
High Q
Semiconducting
Oxidation sharpening (tip)
→Tips formed at end of process

Surface micromachining



Thin film (metal, dielectric, polymer)
Oxidation sharpening (mold)
Sacrificial layer
Release process of cantilever is important
→Tips (mold) formed at the beginning of process

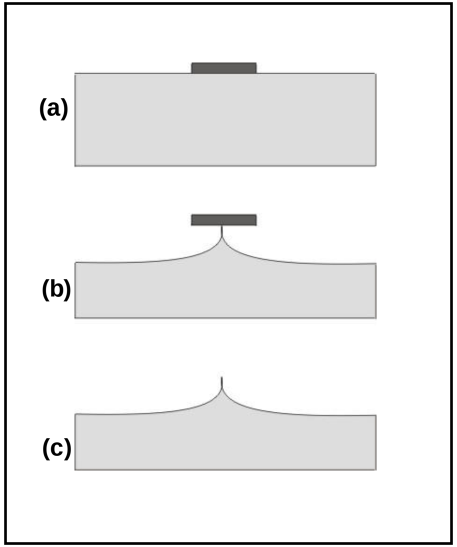
Microfabrication of Nanoprobes

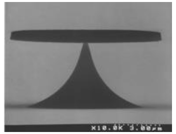
Inspired from Nature

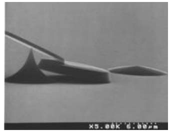
Les Pyramides d'Eusègne
Valais, Switzerland

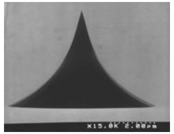
Erosion

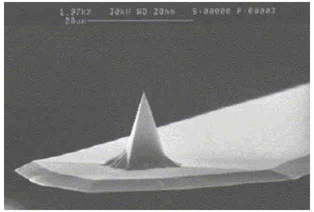
- Material
  - Silicon
- Etch mask (a)
  - nitride, dioxide, resist
- Wet etching (b)
  - potassium hydroxide (KOH), anisotropic
  - HNO3:HF, isotropic
- Dry etching (c)
  - plasma
  - fluorine, chlorine based









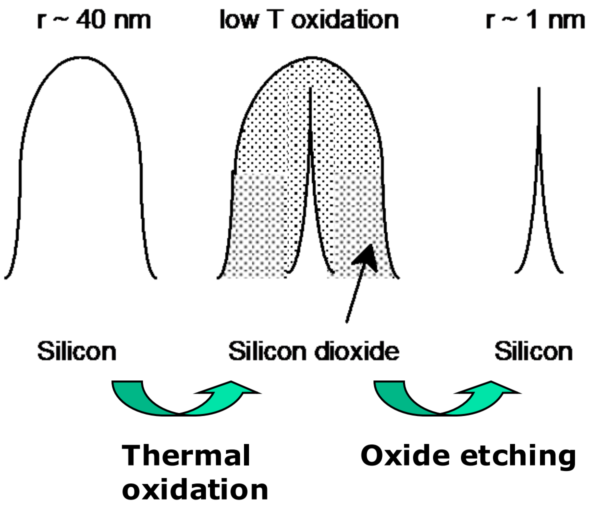


- How does thermal oxidation of silicon works?

Tip Sharpening by Oxidation

- Self-terminating process
- Example: Silicon tip
- 'low' temperature oxidation sharpening T<950 ° C
- Anomalous oxide growth of SiO2 at regions with high curvature radii

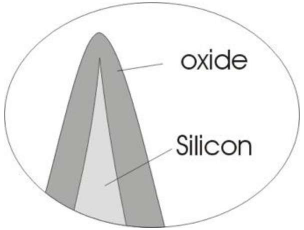
  → exploit this effect to "sharpen" the silicon



There are two ways of forming a SiO_2 layer on the surface of Si. Only oxidation allows sharpening effects:

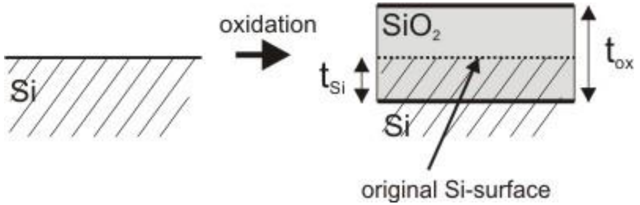
Oxidation:
The oxidation growths a SiO_2 layer as the O_2 reacts with the Si substrate. The SiO_2 layer is roughly 1/3inside the Si layer and 2/3 above it. It is performed at 1100° C.

CVD or sputtering:
The deposition by CVD or sputtering creates a layer 100% on top of the Si substrate. The process is made at 600° C.



Basics of Thermal Oxidation

- Thermal oxidation of Si
- Si is consumed during growth of SiO_2

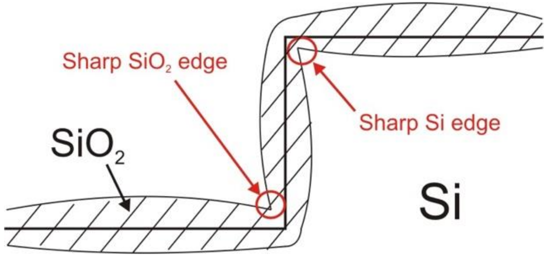


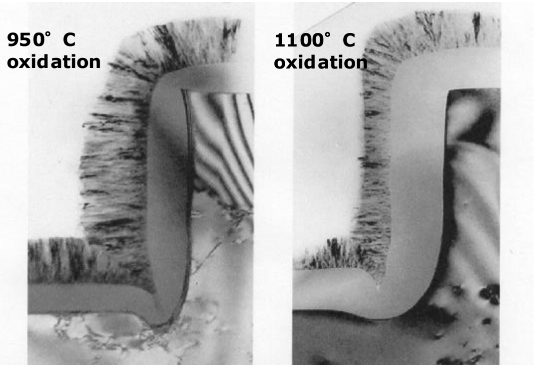
$$t_{Si} = t_{ox} \cdot \frac{N_{ox}}{N_{Si}}$$

N_{ox} : molecular density of SiO_2
N_{Si} : molecular density of Si

$$= t_{ox} \cdot \frac{2.3 \cdot 10^{23}\ \text{molecules/cm}^3}{5 \cdot 10^{22}\ \text{atoms/cm}^3} = 0.46 \cdot t_{ox}$$

- Oxide growth at an edge profile :

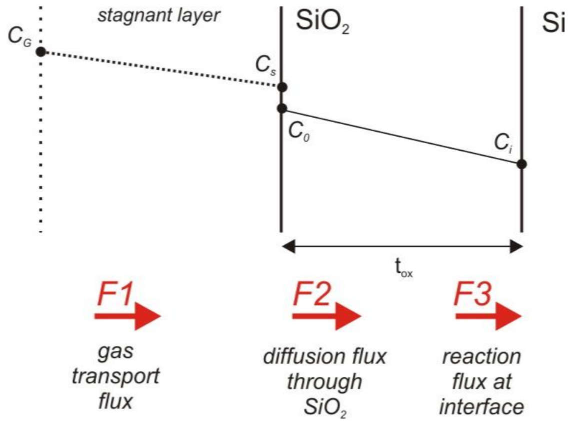


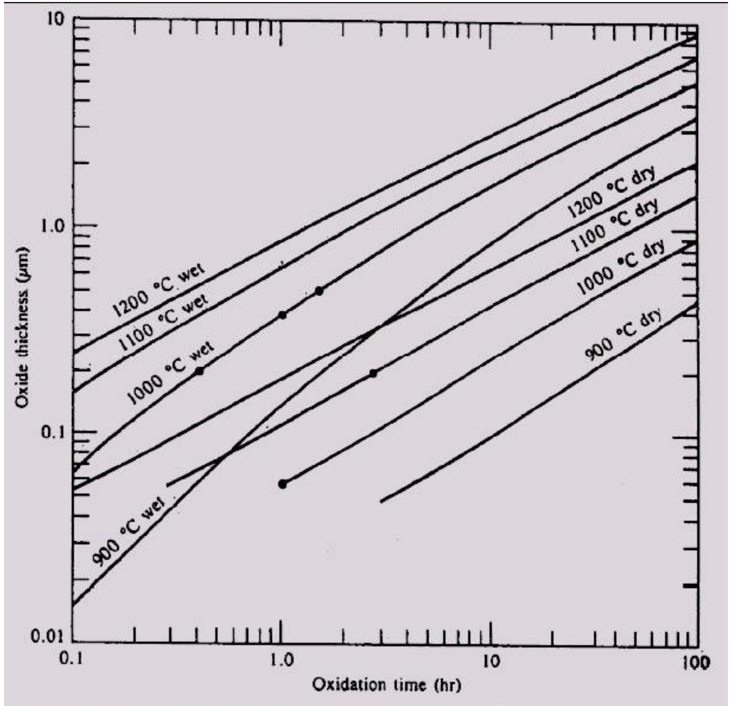


Marcus et al.
http://web.mit.edu

Basics of Thermal Oxidation

- Oxide growth kinetics based on *Deal-Groove Model*
- For short oxidation times: $t_{OX} \sim t$
- For long oxidation times: $t_{OX} \sim \sqrt{t}$
- Oxide growth slows down with increasing thickness

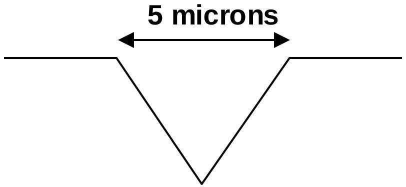


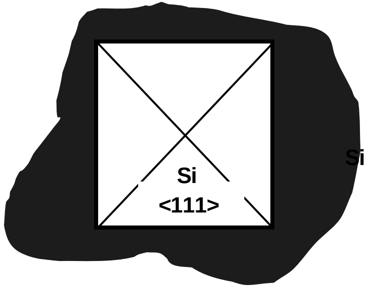


Wet and dry silicon dioxide growth for ⟨100⟩ silicon

Molded Tips for AFM

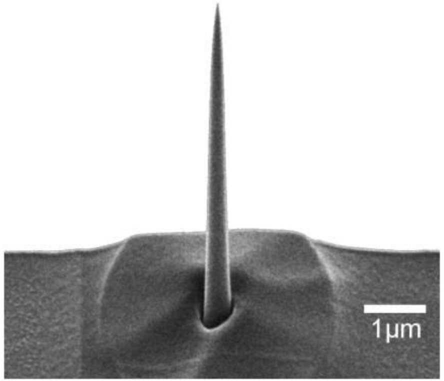
- Molds by anisotropic Si etching (e.g. KOH, TMAH)
- Oxidation of the groove
- Deposition of the tip material (e.g. metals, polymers) into the SiO_2 covered groove



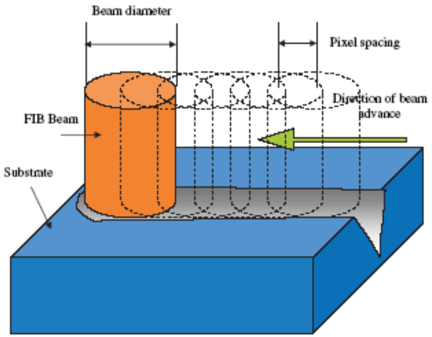


Focused Ion Beam Modified Tips

- Ultra-high aspect ratio silicon AFM tips
- Processed by Focused Ion Beam (FIB)
- Used to image steep structures such as trenches in IC
- allows for accurately imaging of >85º side profiles



Source: ThermoMicroscopes



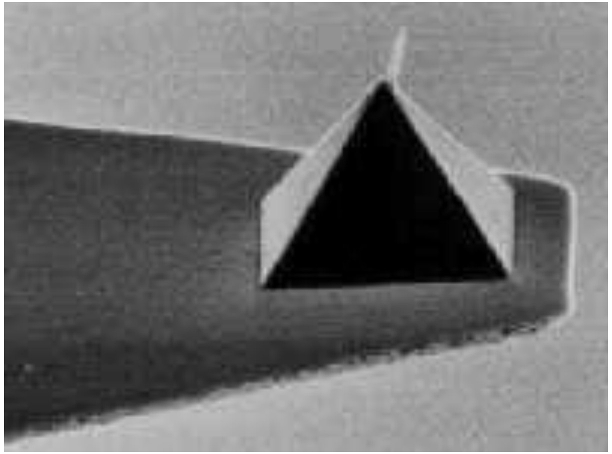
FIB machining using accelerated ions

The FIB works similarly than a SEM, but ions are used instead of electrons. However, since ions have a mass, they will react with the surface. Indeed, a sputtering process will occur and thus material will be extracted.

The FIB can also be used to grow high and sharp tips. But it is a slow process.

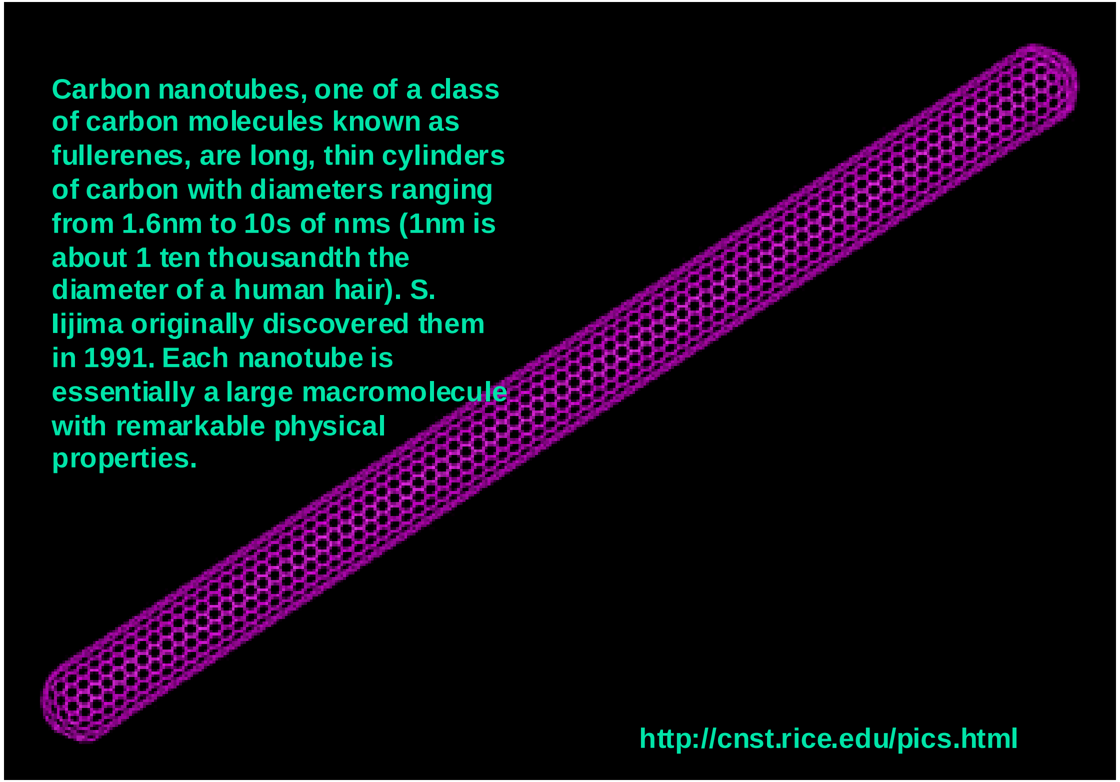
Magnetic Tips (for MFM)

- Carbon contamination needle
- grown on top of pyramidal tip
- Si3N4 cantilever tip
- covered from one side with evaporated 15 nm thick $Co_{80}Ni_{20}$ film
- probe the magnetic stray field above the sample surface

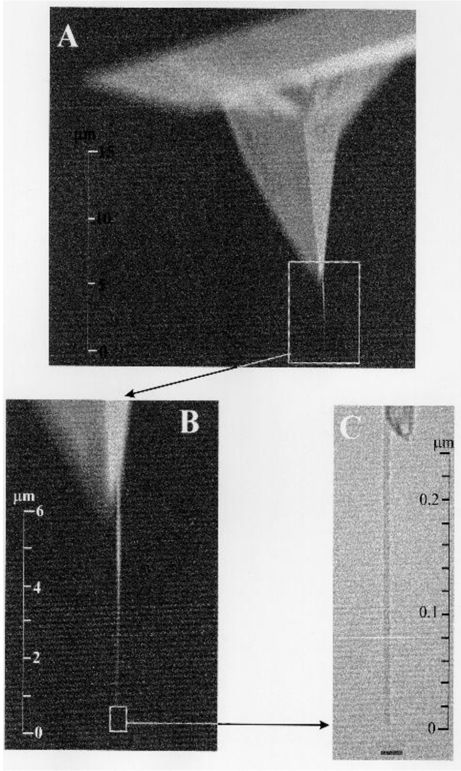


Source: MESA+ Uni Twente

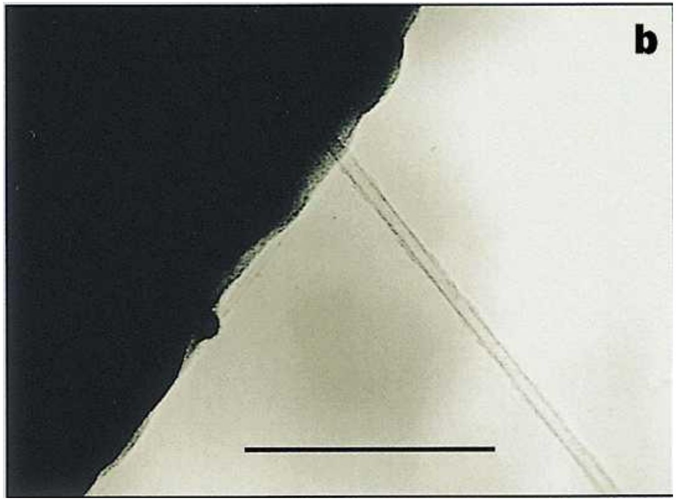
Carbon Nanotubes (CNTs) as Probes



Carbon Nanotube Tips (attached and grown)



- Carbon nanotubes (CNTs) attached to AFM tip after fabrication
- Extremely small diameter and high ascept ratio
- Can be used in very deep trenches



HONGJIE DAI, JASON H. HAFNER, ANDREW G. RINZLER, DANIEL T. COLBERT & RICHARD E. SMALLEY
Nature 384, 147 - 150 (1996)

JASON H. HAFNER, CHIN LI CHEUNG & CHARLES M. LIEBER
Nature | Vol | 398 | 29 April 1999

- Introduction to the course
- Teachers, schedule, activities
- Course objectives
- Exam information

- Lecture start
  - some scaling considerations
  - micro-engineered nano-tools

Monitor the MOODLE activities:

- **Form groups**
- **Use ED stem for Q&A**