Sławomir Kulesza
Uniwersytet Warmińsko-Mazurski w Olsztynie
Wydział Matematyki i Informatyki
kulesza@matman.uwm.edu.pl

Atomic Force Microscopy: touching invisibles

There’s plenty of room at the bottom

Richard Feynman,
Meeting of the American Physics Society at Cal-Tech, 29/12/1959

Plenty of Room at the Bottom

Richard P. Feynman
(Dated: Dec. 1959)

This is the transcript of a talk presented by Richard P. Feynman to the American Physical Society in Pasadena on December 1959, which explores the immense possibilities afforded by miniaturization.

I imagine experimental physicists must often look with envy at men like Kamerlingh Onnes, who discovered a field like low temperature, which seems to be bottomless and in which one can go down and down. Such a man is then a leader and has some temporary monopoly in a scientific adventure. Percy Bridgman, in designing a way to obtain higher pressures, opened up another new field and was able to move into it and to lead us all along. The development of ever higher vacuum was a continuing development of the same kind.

I would like to describe a field, in which little has been done, but in which an enormous amount can be done in principle. This field is not quite the same as the others in that it will not tell us much of fundamental physics (in the sense of, "What are the strange particles?") but it is more like solid-state physics in the sense that it might tell us much of great interest about the strange phenomena that occur in complex situations. Furthermore, a point that is most important is that it would have an enormous number of technical applications.

What I want to talk about is the problem of manipulating and controlling things on a small scale.

As soon as I mention this, people tell me about miniaturization, and how far it has progressed today. They tell me about electric motors that are the size of the nail on your small finger. And there is a device on the market, they tell me, by which you can write the Lord's Prayer on the head of a pin. But that's nothing; that's the most primitive, halting step in the direction I intend to discuss. It is a staggeringly small world that is below. In the year 2000, when they look back at this age, they will wonder why it was not until the year 1960 that anybody began seriously to move in this direction.

Why cannot we write the entire 24 volumes of the Encyclopedia Brittanica on the head of a pin?

Let's see what would be involved. The head of a pin is …

can easily be adjusted in size as required by the photoengraving, and there is no question that there is enough room on the head of a pin to put all of the Encyclopedia Brittanica.

Furthermore, it can be read if it is so written. Let's imagine that it is written in raised letters of metal; that is, where the black is in the Encyclopedia, we have raised letters of metal that are actually 1/25,000 of their ordinary size. How would we read it?

If we had something written in such a way, we could read it using techniques in common use today. (They will undoubtedly find a better way when we do actually have it written, but to make my point conservatively I shall just take techniques we know today.) We would press the metal into a plastic material and make a mold of it, then peel the plastic off very carefully, evaporate silica into the plastic to get a very thin film, then shadow it by evaporating gold at an angle against the silica so that all the little letters will appear clearly, dissolve the plastic away from the silica film, and then look through it with an electron microscope!

There is no question that if the thing were reduced by 25,000 times in the form of raised letters on the pin, it would be easy for us to read it today. Furthermore; there is no question that we would find it easy to make copies of the master; we would just need to press the same metal plate again into plastic and we would have another copy.

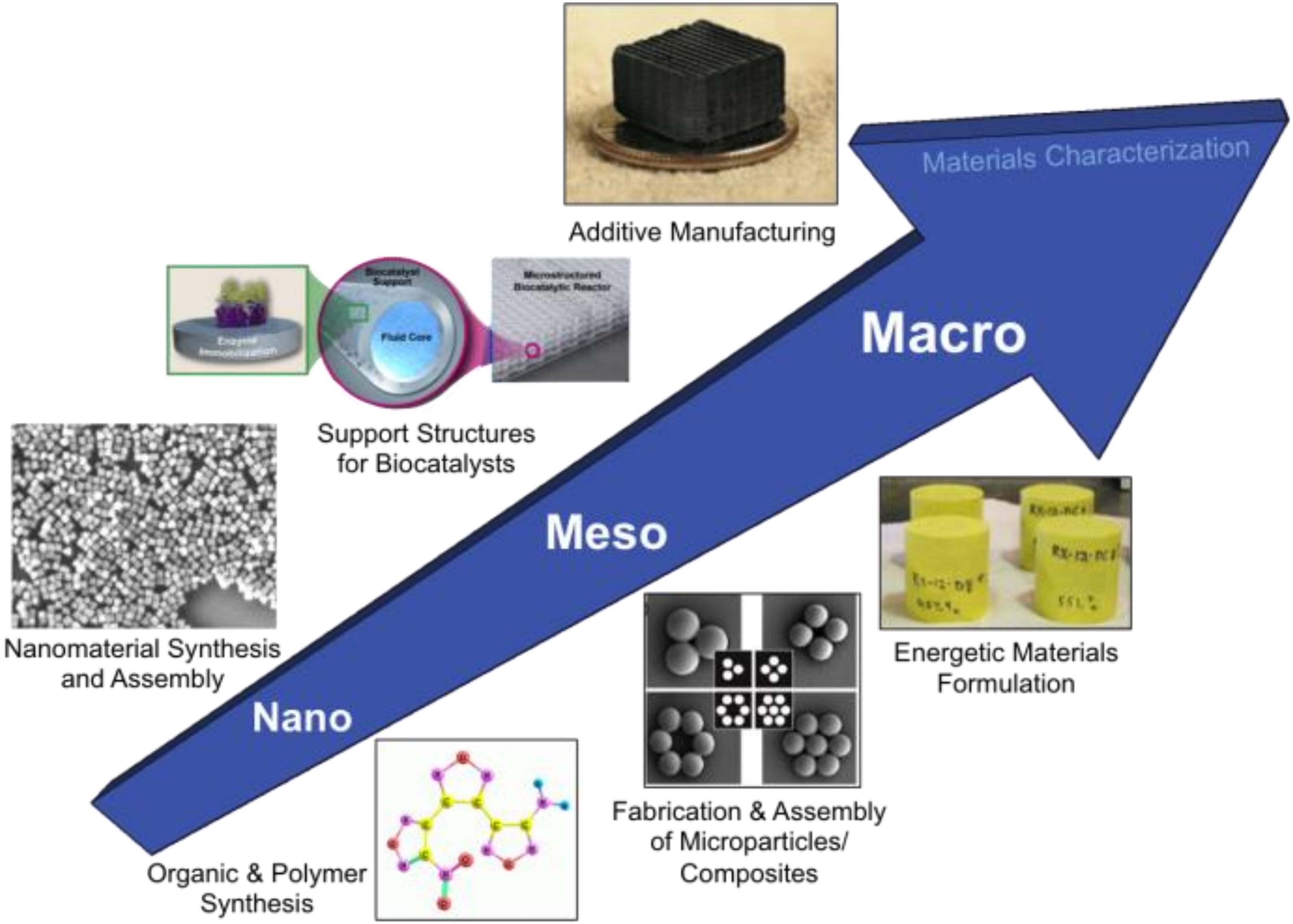
How do we write small?

The next question is: How do we write it? We have no standard technique to do this now. But let me argue that it is not as difficult as it first appears to be. We can reverse the lenses of the electron microscope in order to demagnify as well as magnify. A source of ions, sent through the microscope lenses in reverse, could be focused to a very small spot. We could write with that spot like we write in a TV cathode ray oscilloscope, by going across in lines, and having an adjustment which determines the amount of material which is going to be deposited as we scan in lines.

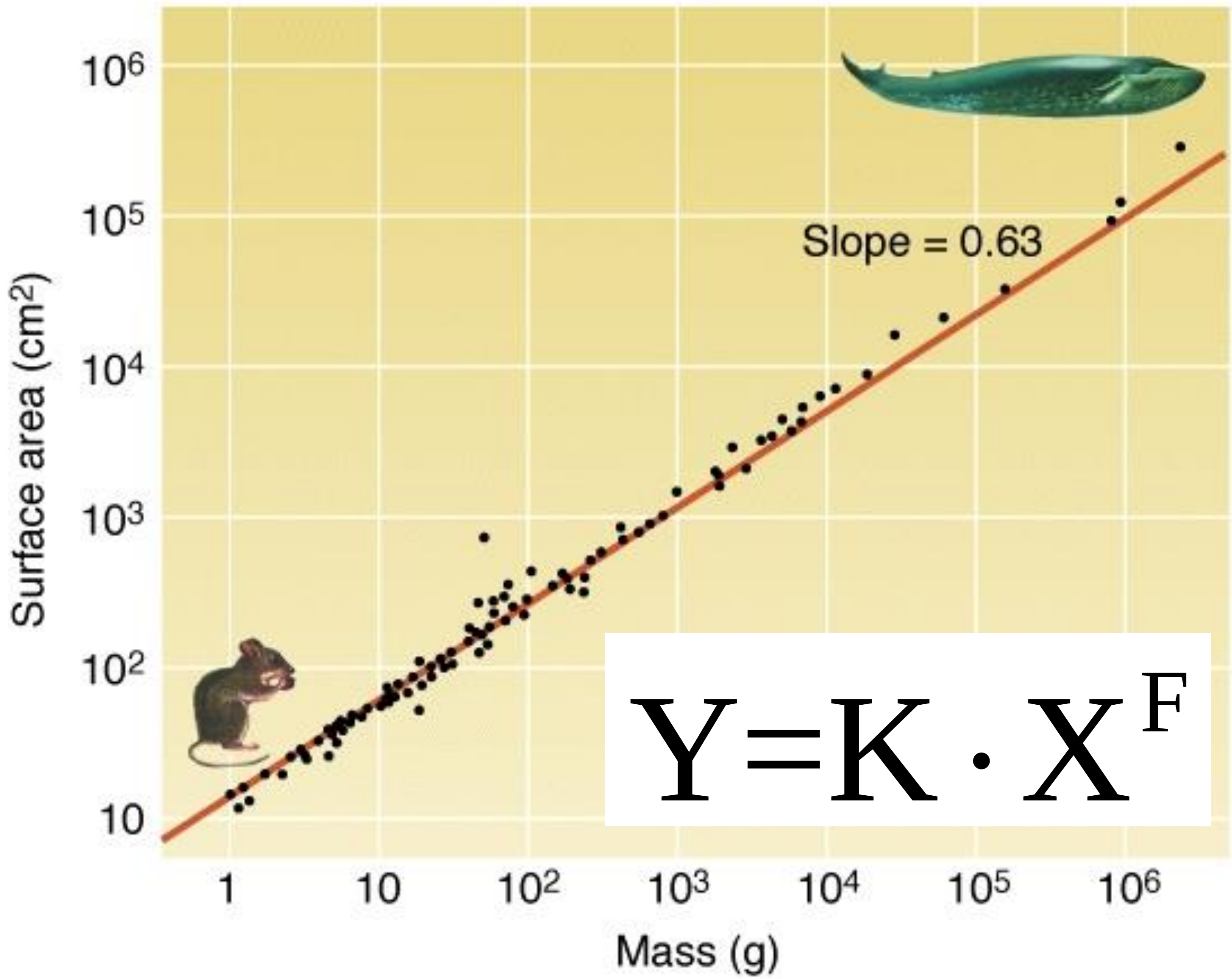
This method might be very slow because of space charge limitations. There will be more rapid methods. We could first make, perhaps by some photo process, a screen which has holes in it in the form of the letters. Then we would strike an arc behind the holes and draw metallic ions through the holes; then we could again use our system of lenses and make a small image in the form of ions, which would deposit the metal on the pin.

A simpler way might be this (though I am not sure it

What is the length scale?



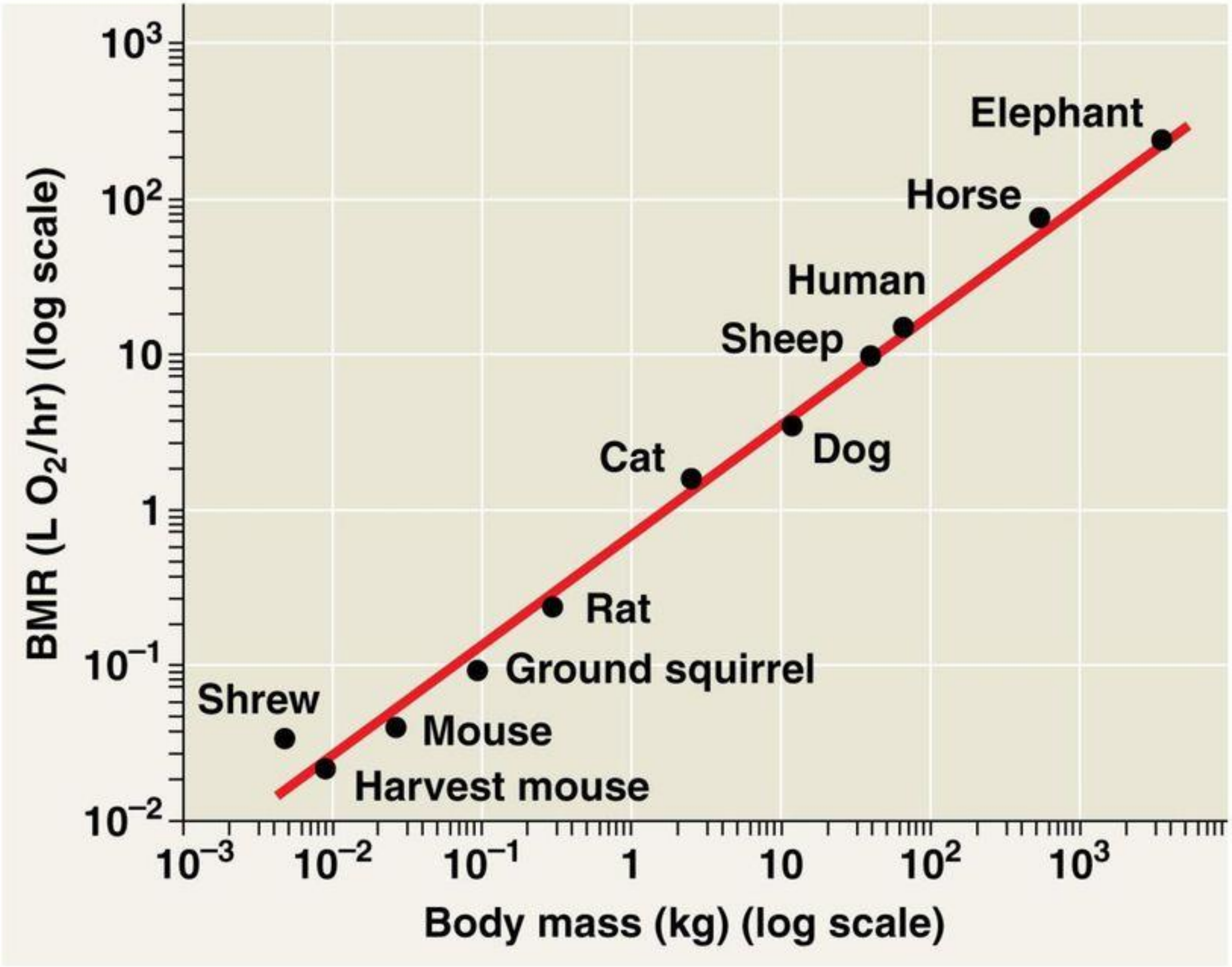
Problem – non-linear scaling



$$Y = K \cdot X^F$$

Allometric scaling

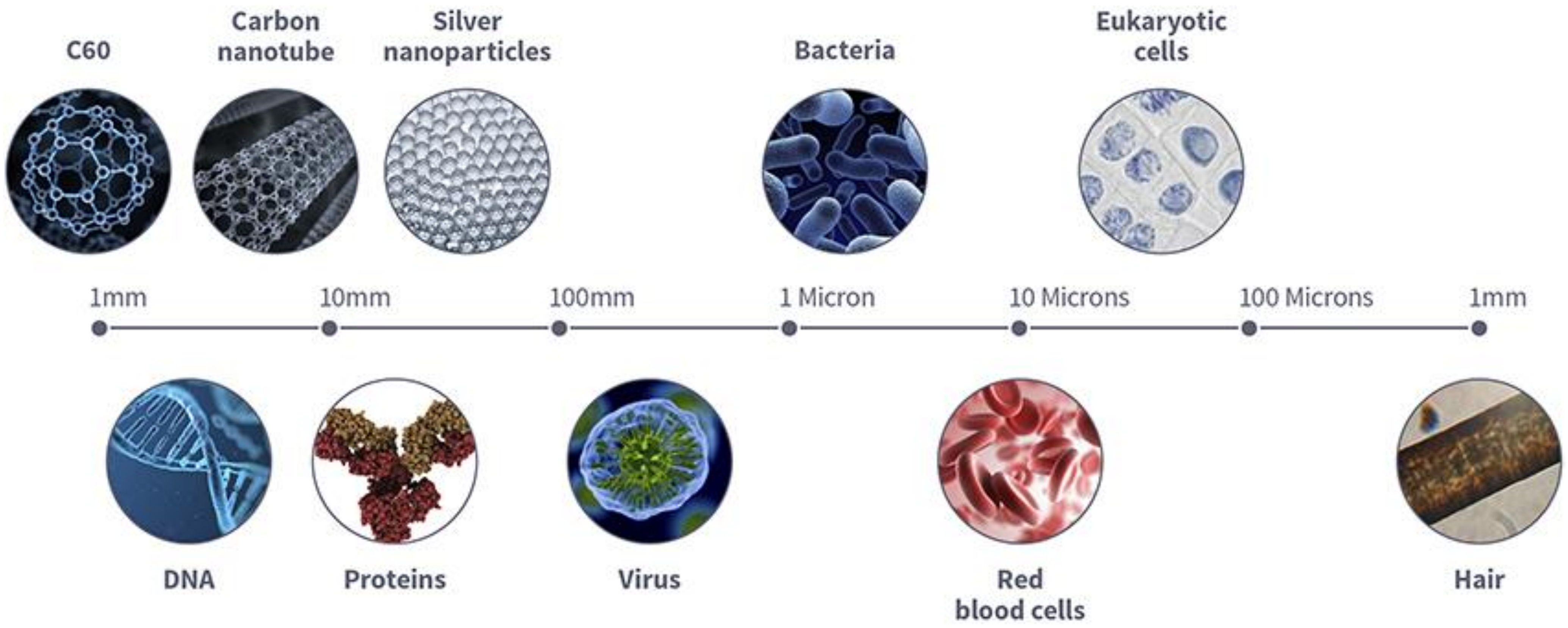
Figure 40.19a



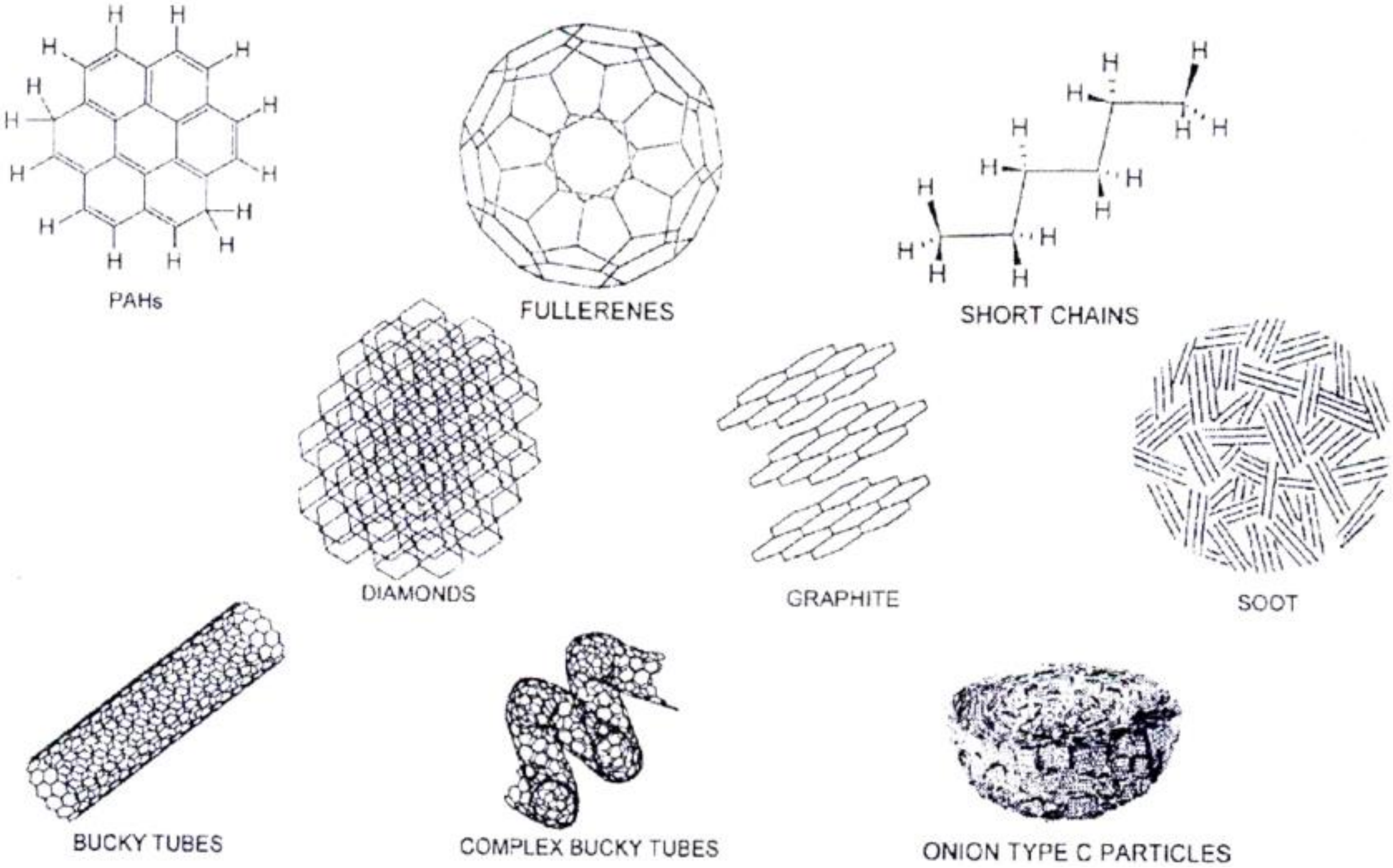
(a) Relationship of basal metabolic rate (BMR) to body size for various mammals

Things change with the scale!

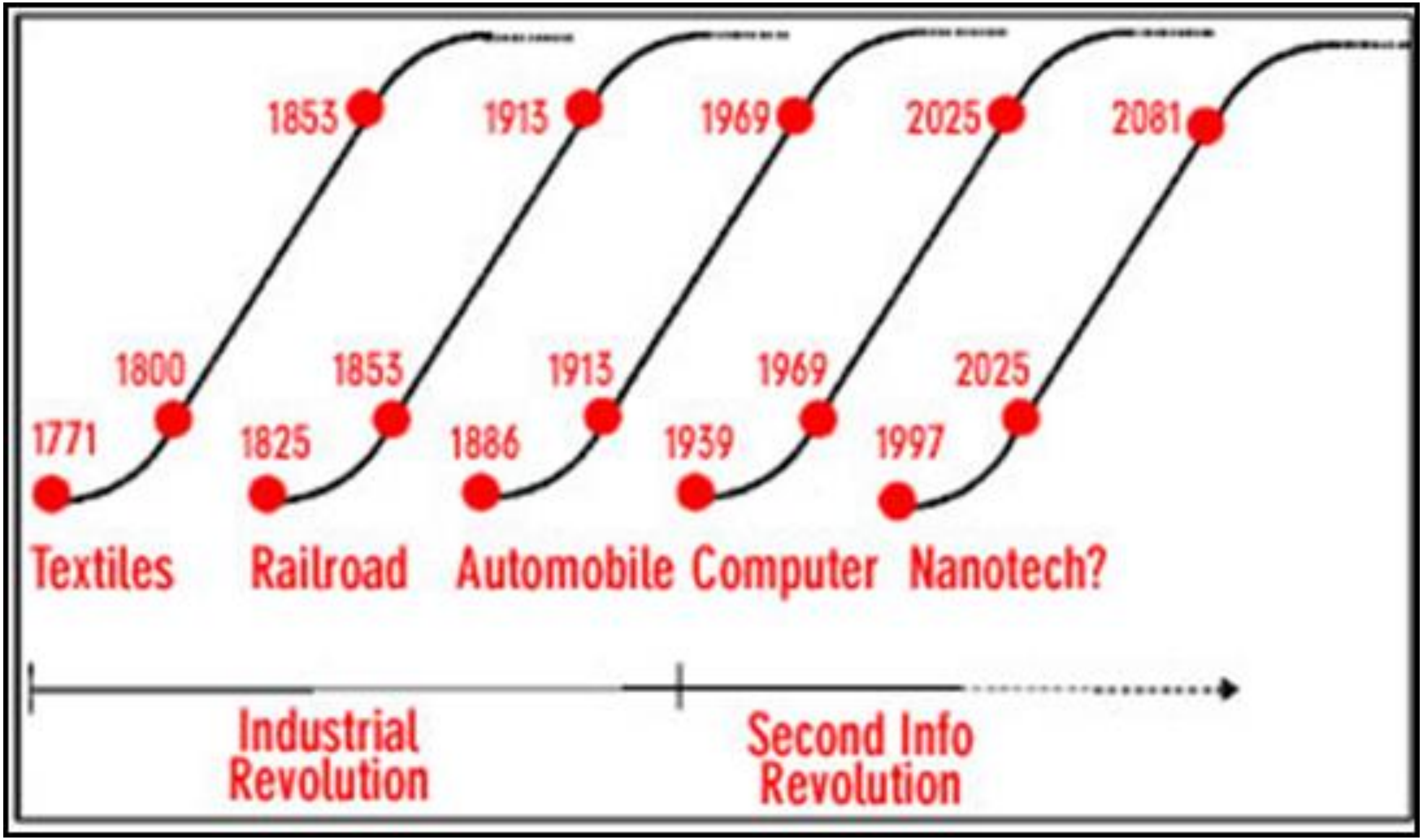
How small is 1 nanometer?



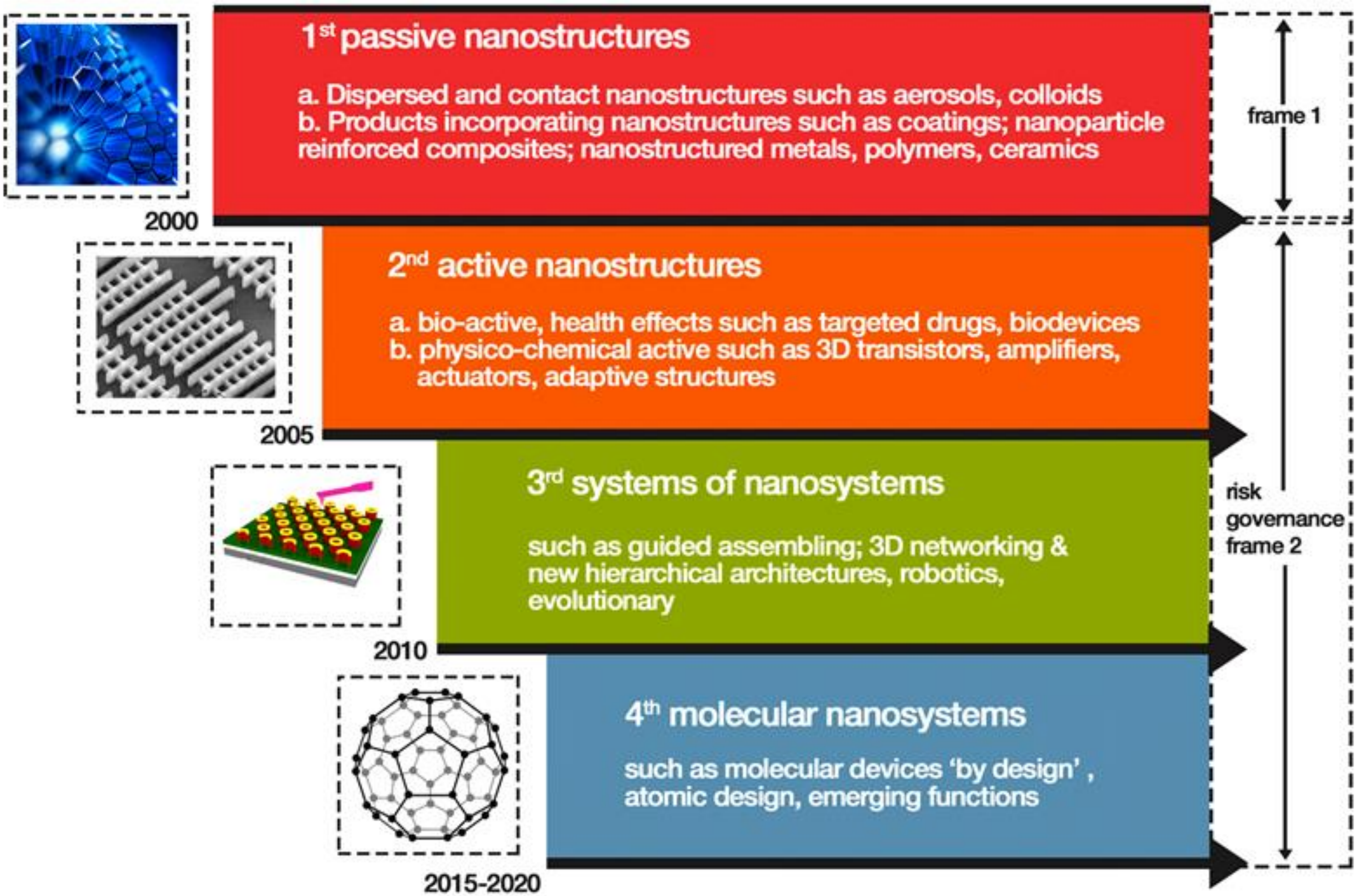
Particle configuration matters



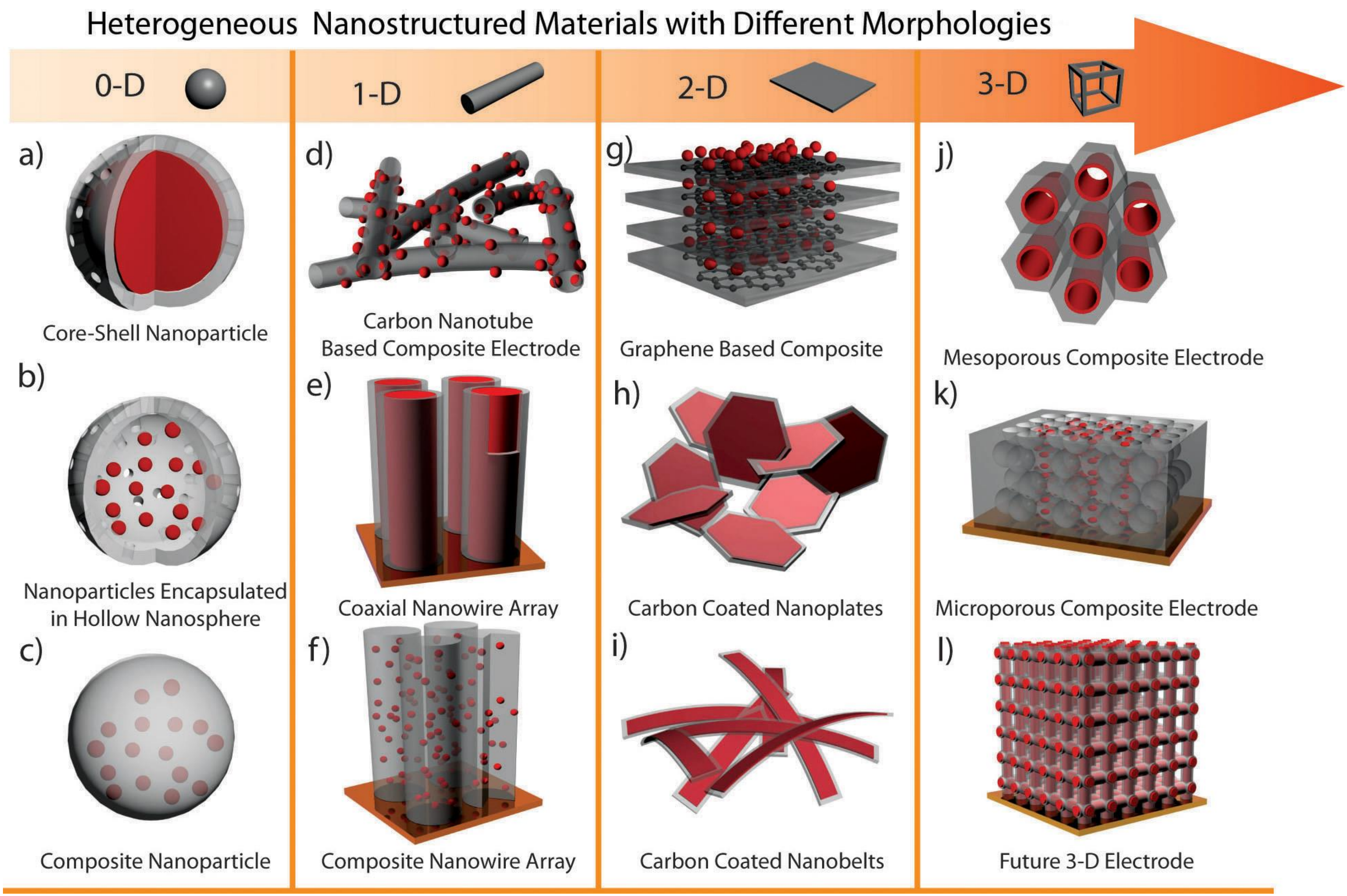
Nanotechnology – revolution of modern era



4 generations of nanostructures



Abundance of nanostructures

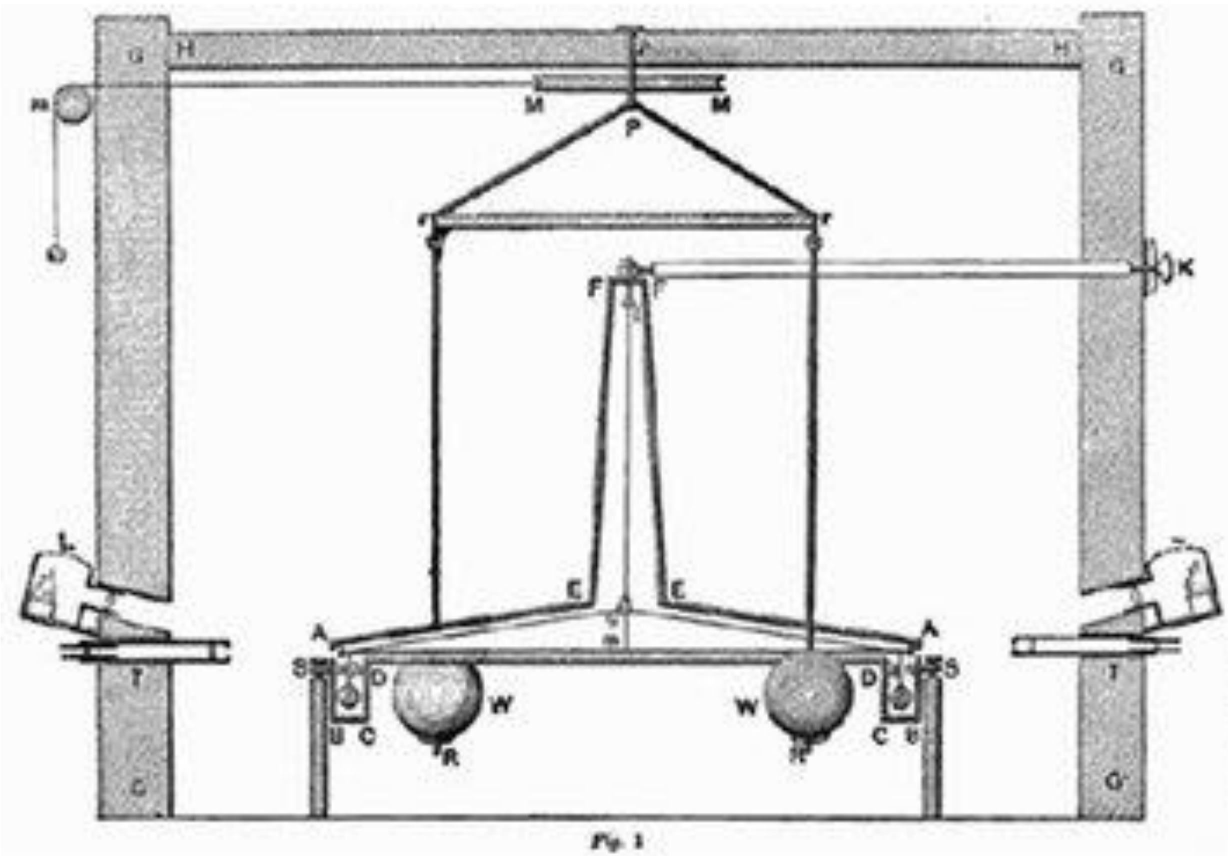


How to study the structure of solids?

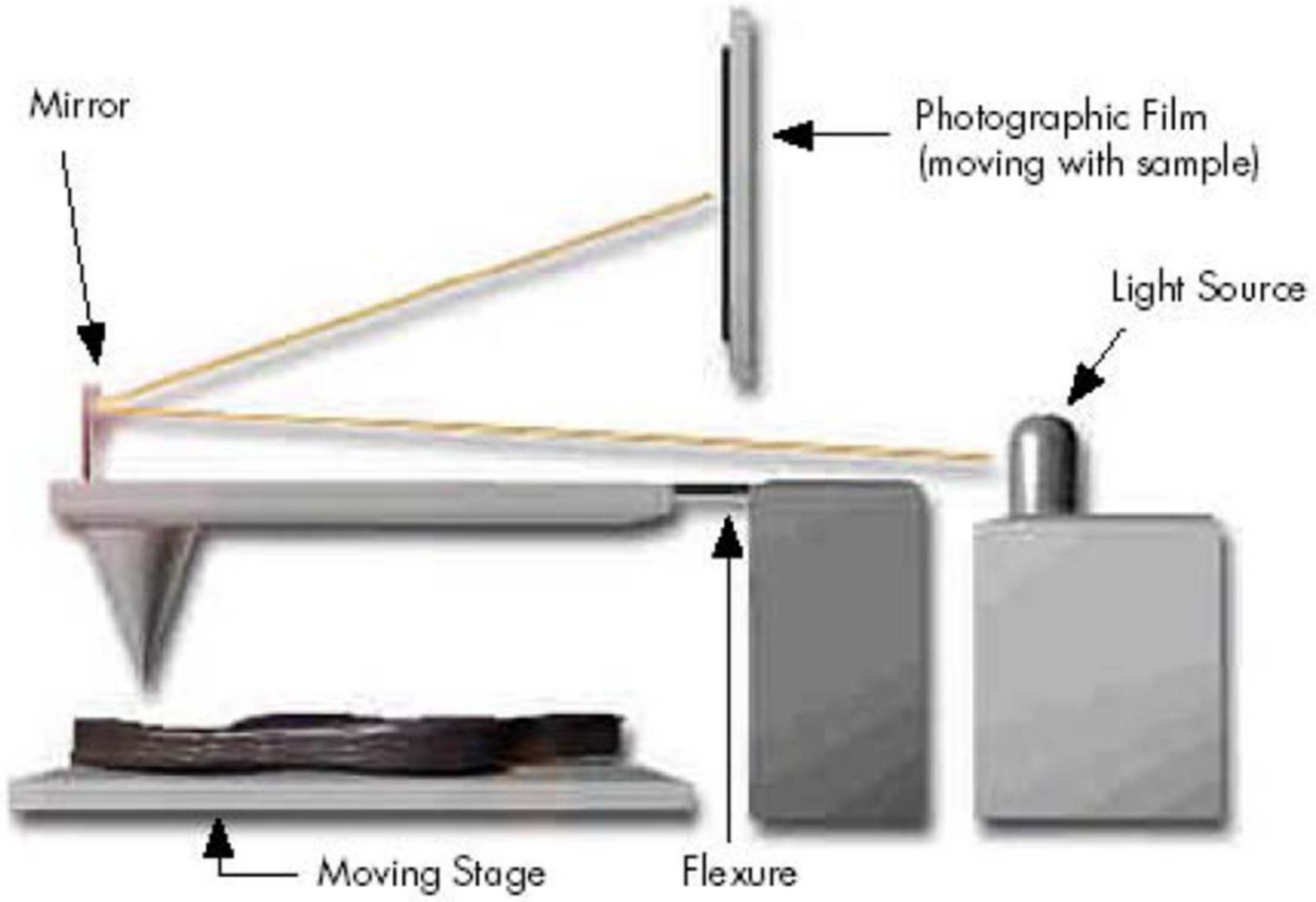
- By sight – microscopes: optical, (SNOM), TEM, SEM
- Wave phenomena: transmission, reflection, secondary emission

- By touch – scanning probes: STM, AFM, MFM, EFM, LFM etc.
- Particle interactions: attractive, repulsive

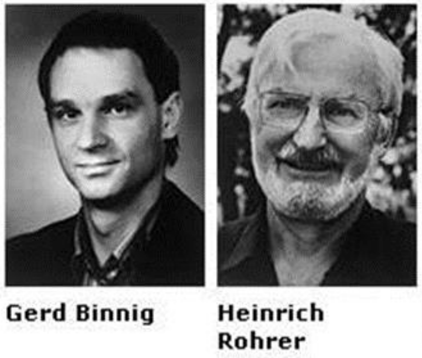
Torsion balance – Cavendish (1798)



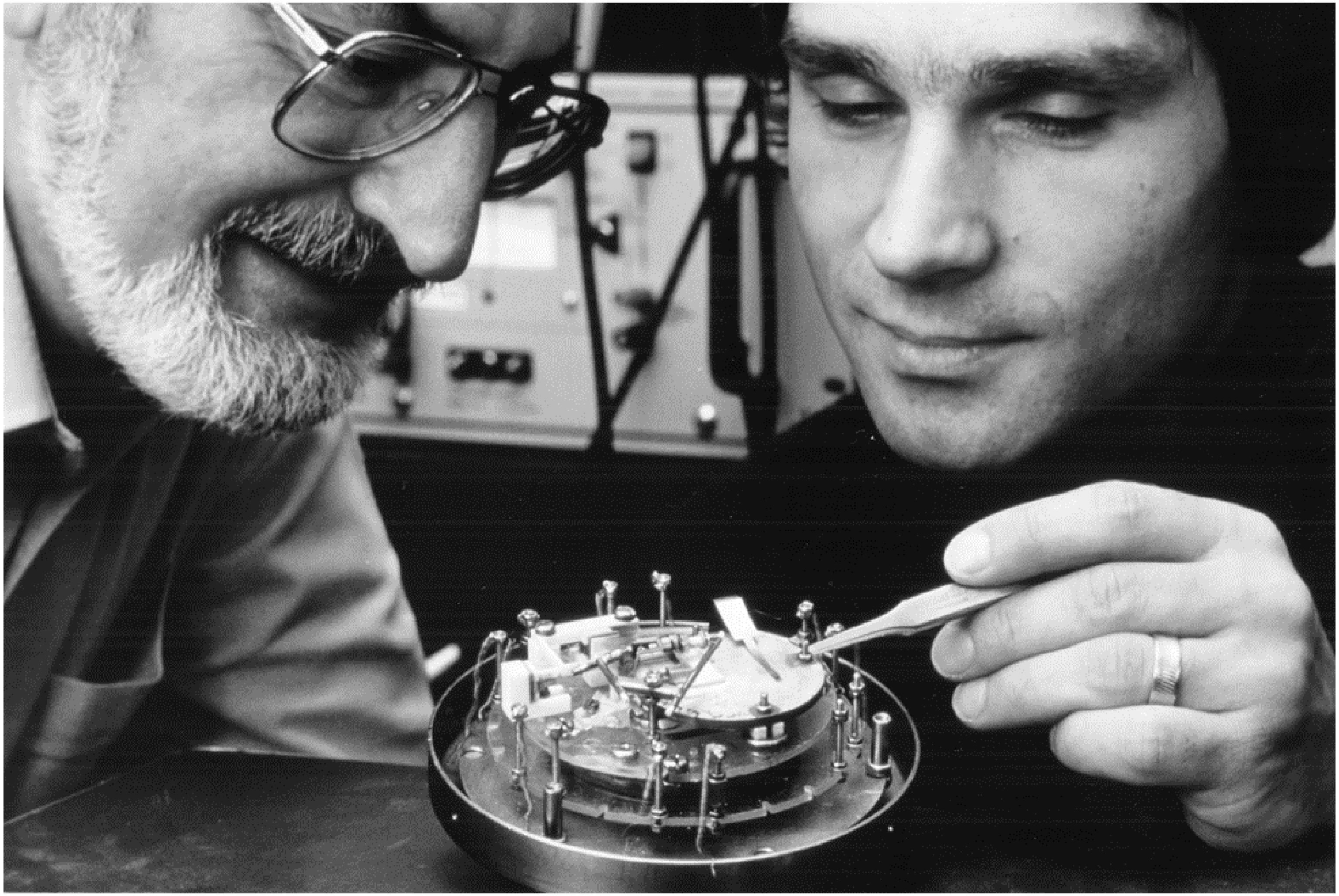
Profilometer – Schmalz (1929)



STM – Rohrer, Binnig (1981)

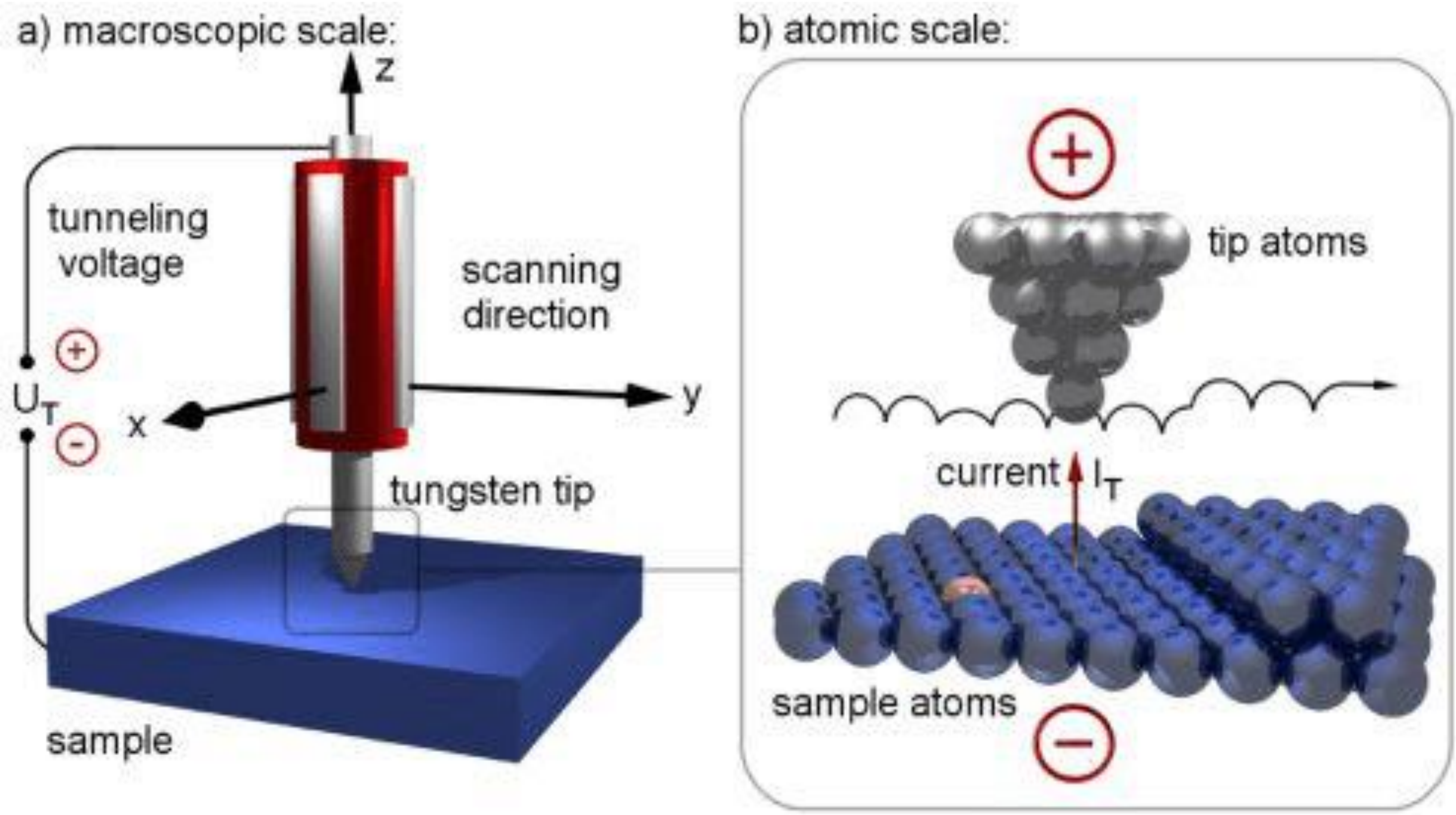


(IBM Zürich)

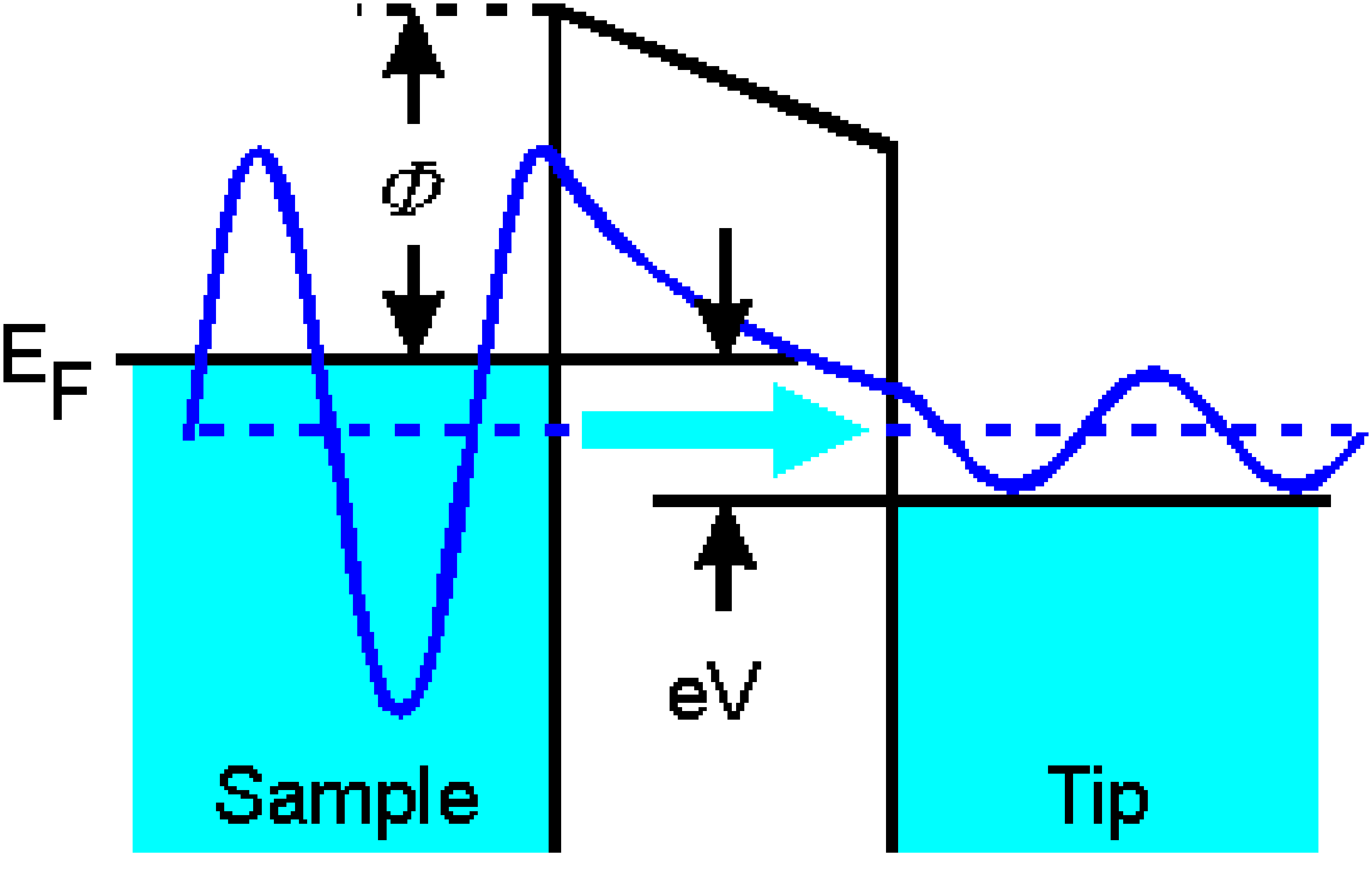


Nobel Prize in physics in 1986 – (semi-) conducting materials.

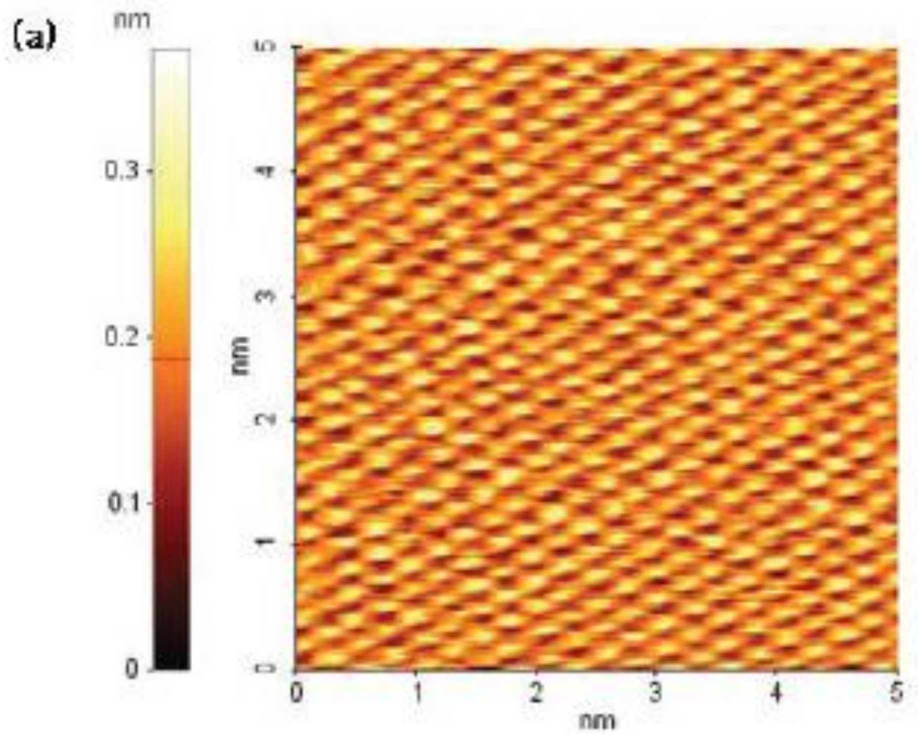
Scanning Tunneling Microscope



Electron tunneling

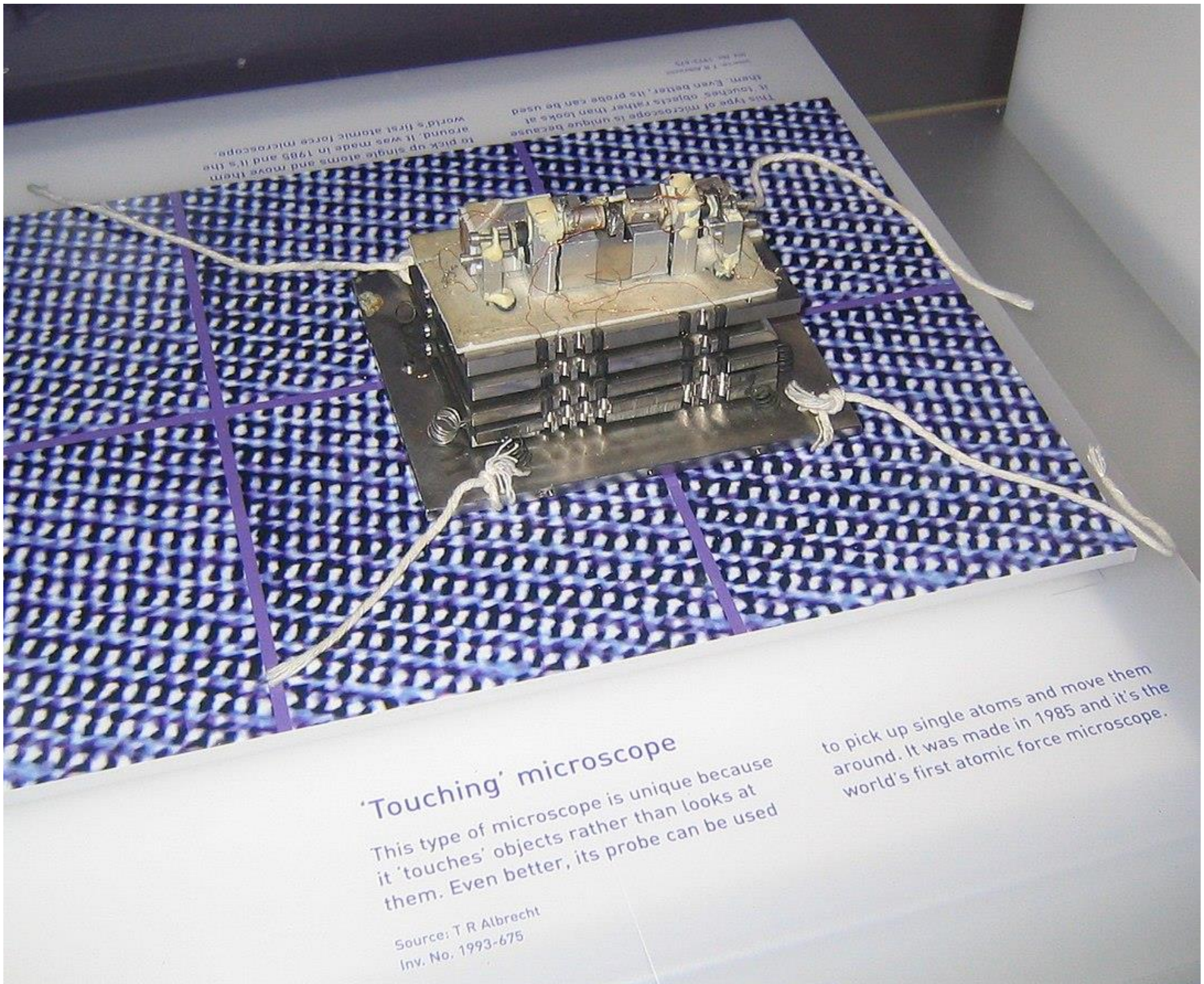


Atomic resolution in STM



Binnig, Quate, Gerber (1986)

AFM – improved STM

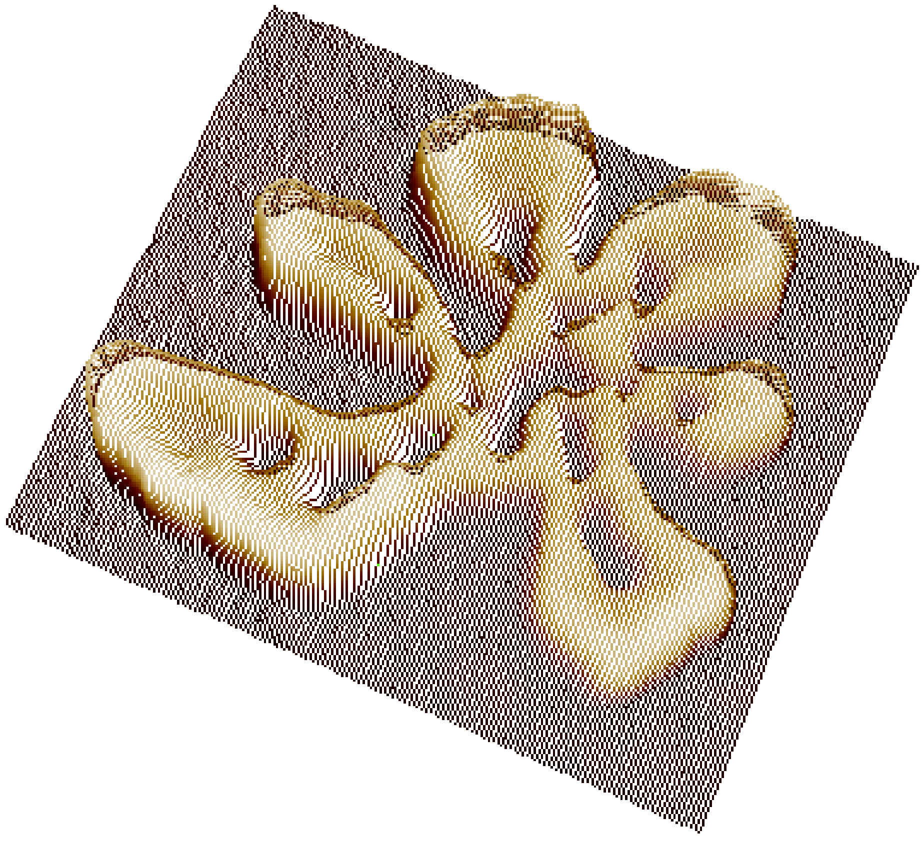


Comparison

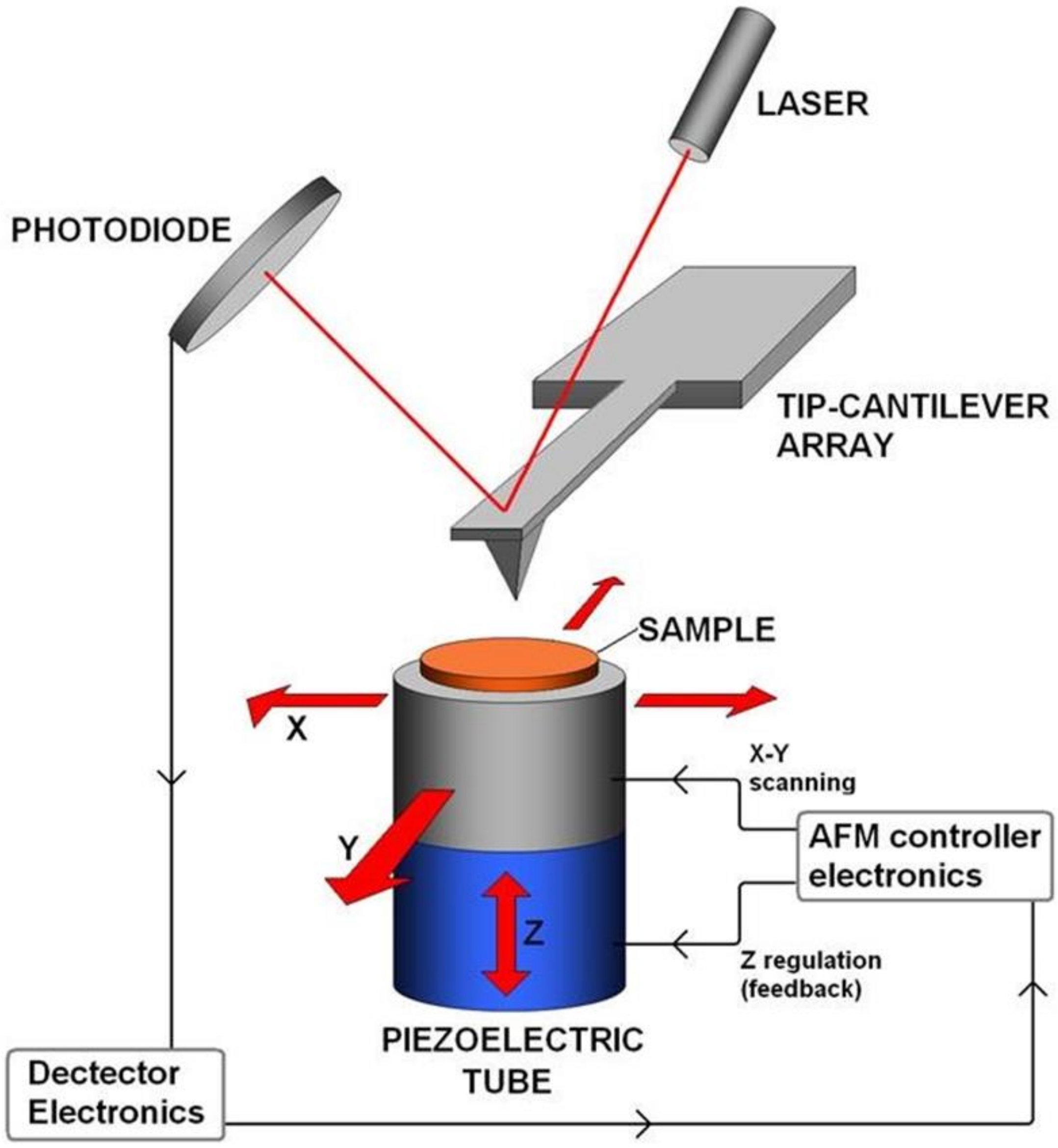
		Optical Microscopy	SEM	TEM	AFM
Resolution	XY	200 nm	2 nm	0.1 nm	1 nm
	Z	500 nm	NA	NA	0.1 nm
Depth of focus		Poor	High	Moderate	High
Sample prep.		Simple	Moderate	Skilled	Simple
Works in Liquid?		Yes	Limited	No	Yes
Ambient Atmosphere		Variable	Vacuum	Vacuum	Variable
Damage to sample		Low	High	High	Low
Speed		Fast	Moderate	Slow	Moderate
Skill required		Low	Moderate	Advanced	Moderate
Data interpretation		Easy	Moderate	Moderate	Easy

What is AFM?

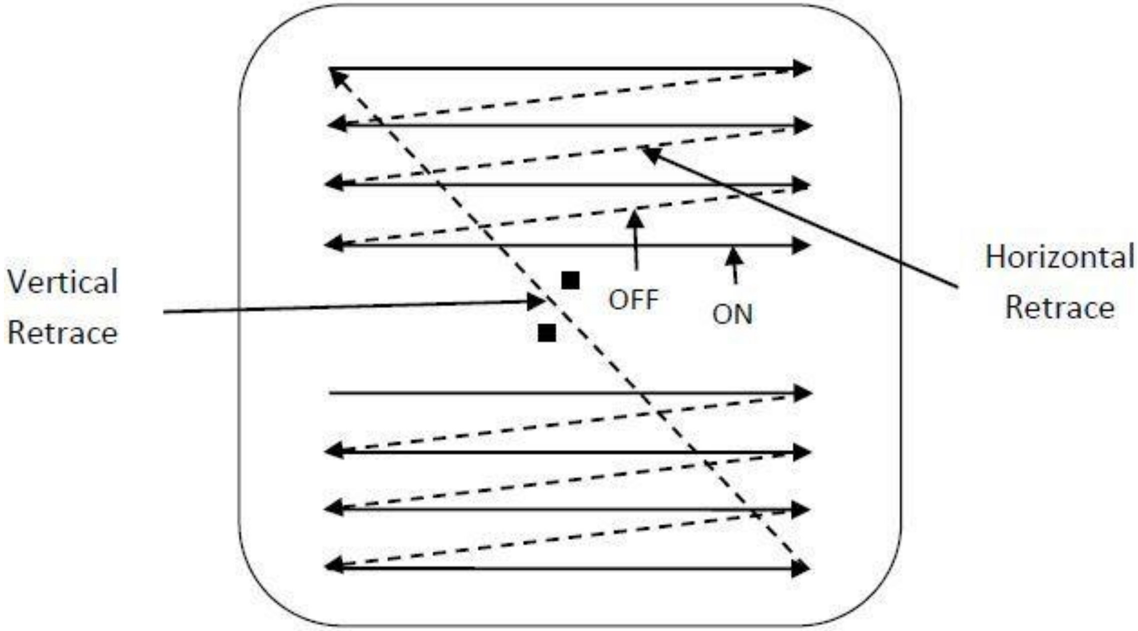
AFM images are surface property maps taken by sampling interactions occurring between surface and a sharp scanning tip (R ≥ 1nm).

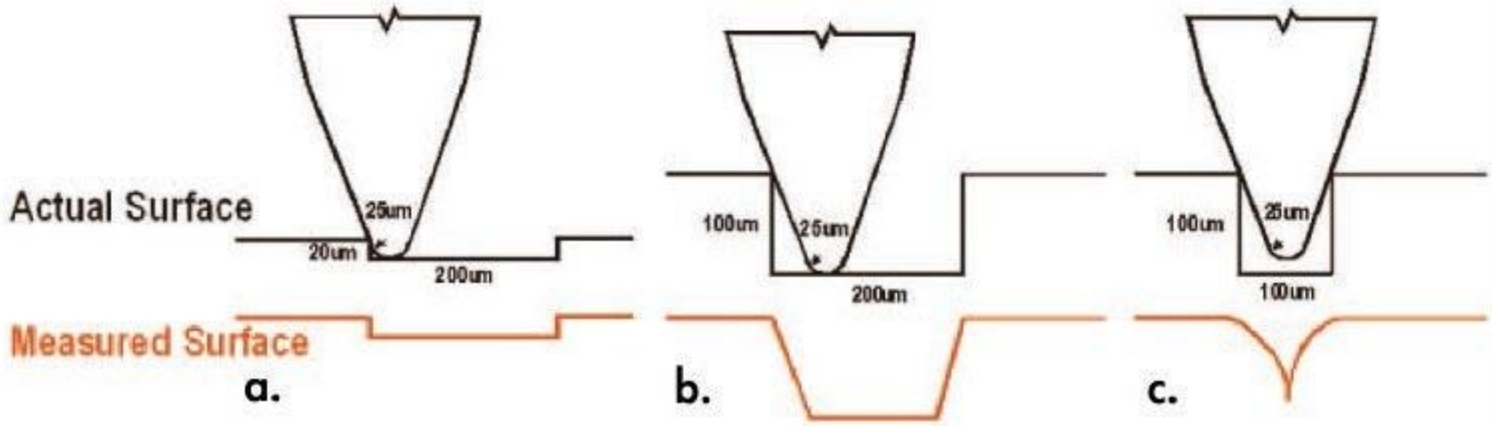


How AFM works?

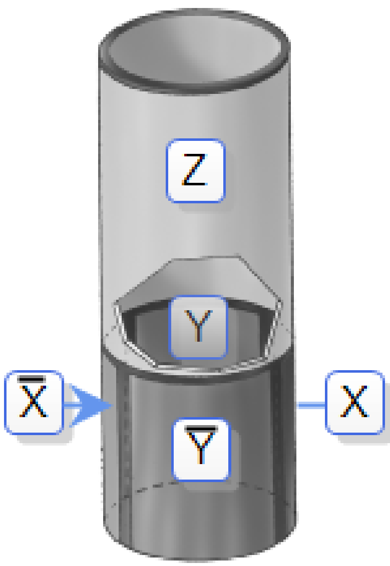


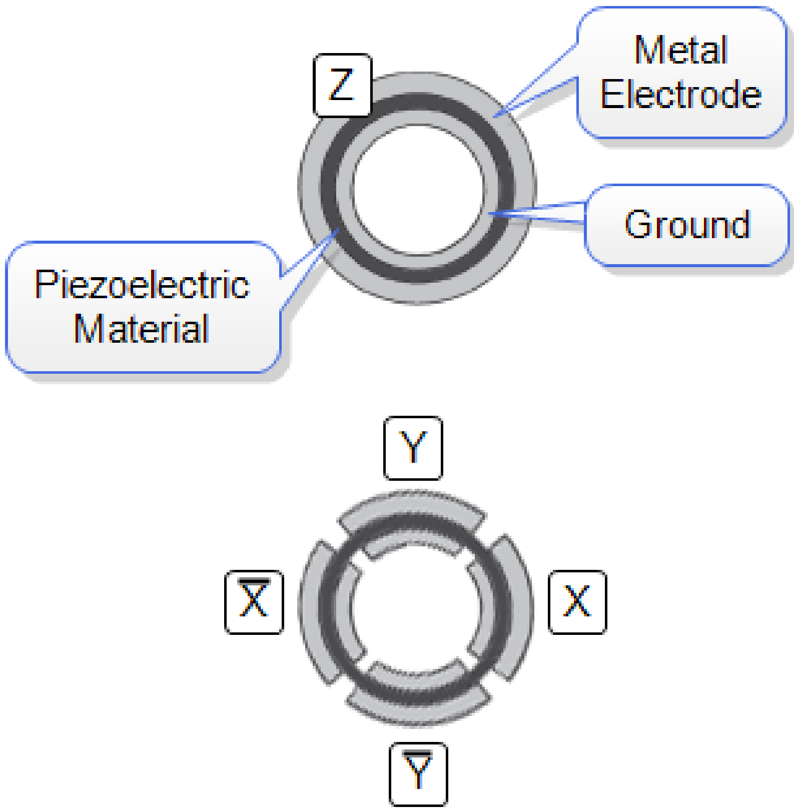
AFM = raster scanning + height profiling

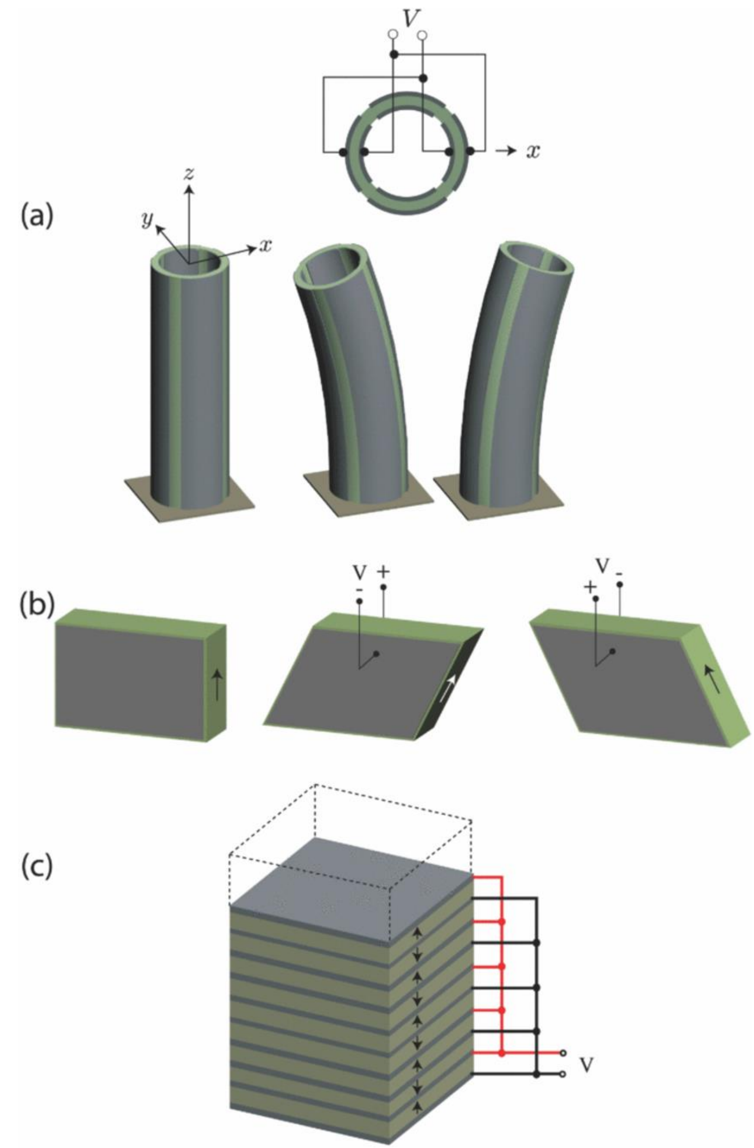




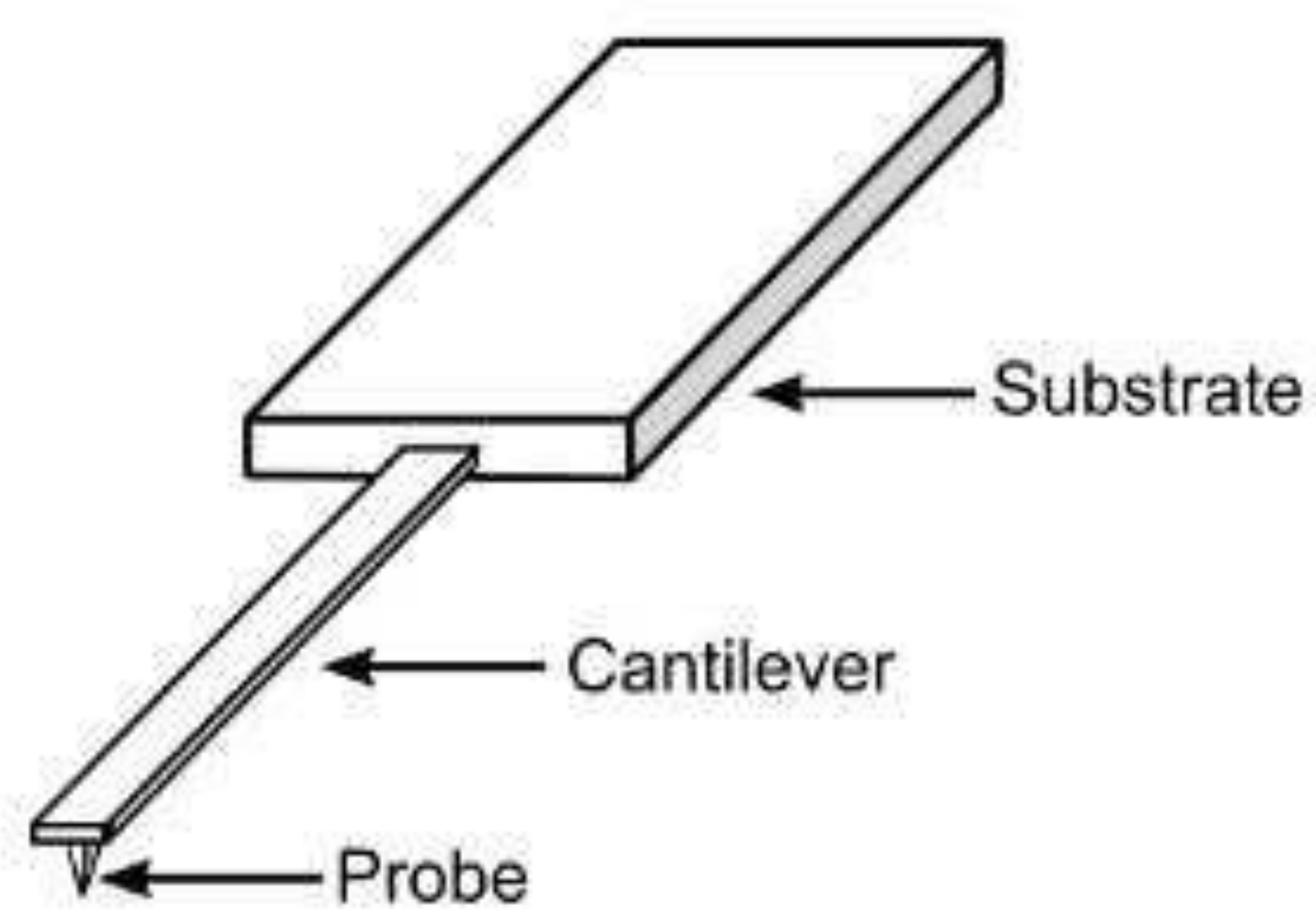
Piezoelectric scanner



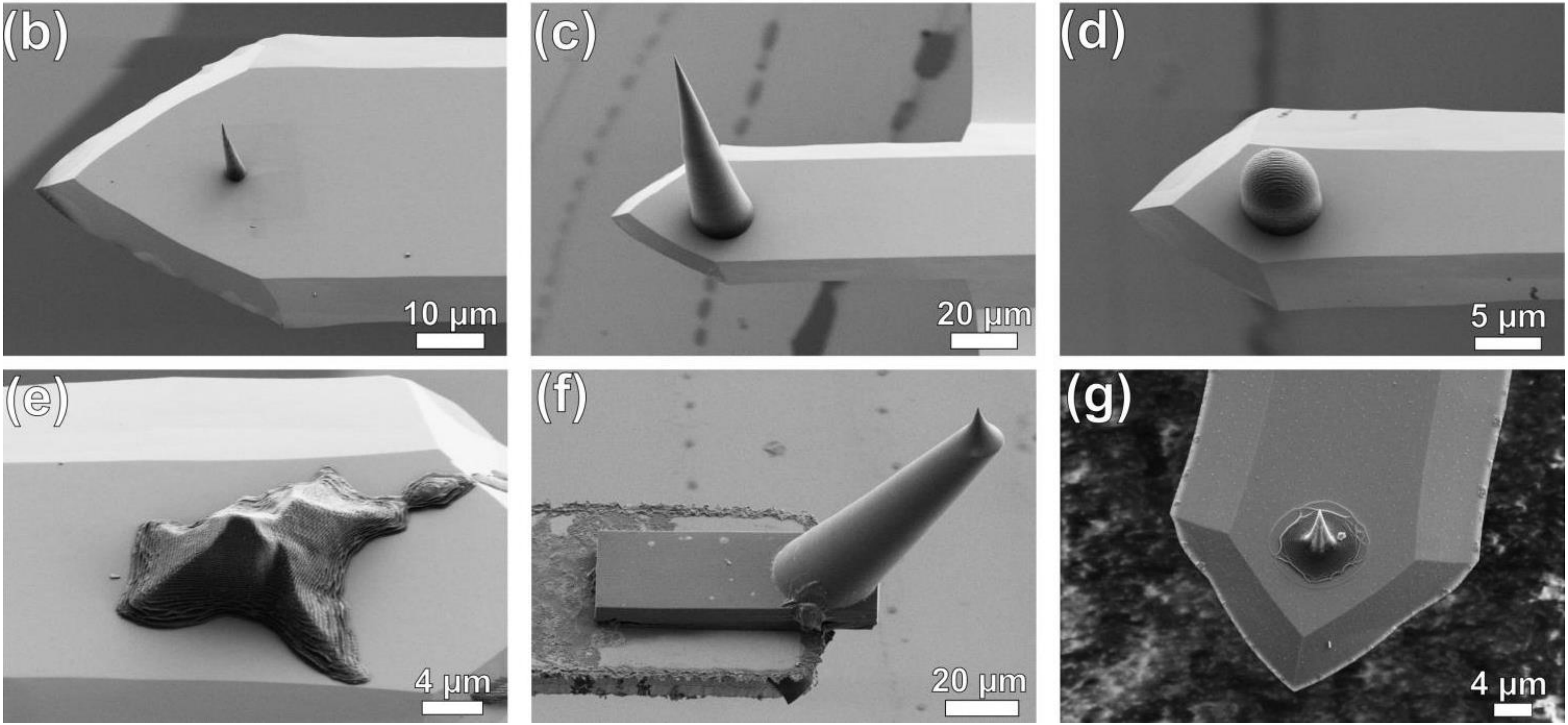




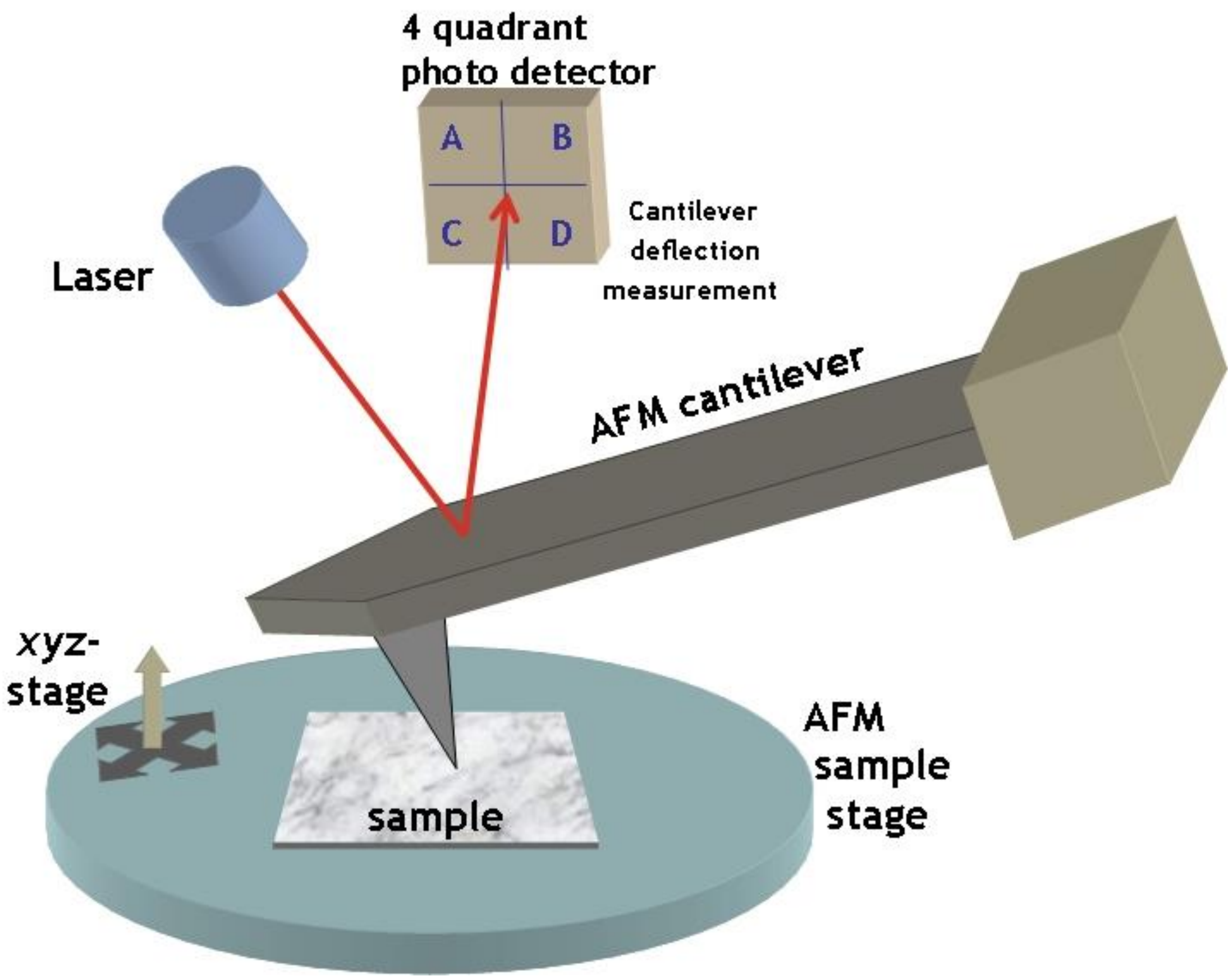
Scanning probe



Scanning tips



Detection of a lever deflection



Deflection modes

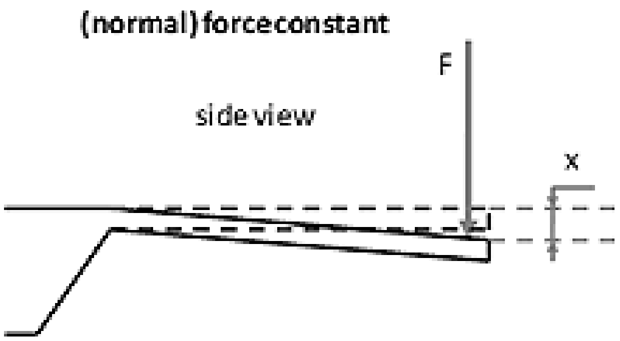


Fig. 1: Schematic side view of an AFM cantilever

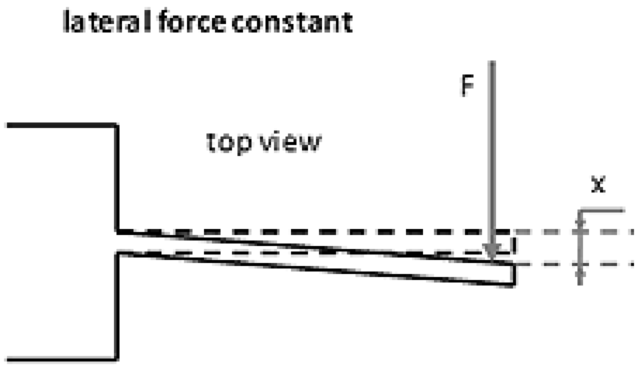


Fig. 2: Schematic top view of an AFM cantilever

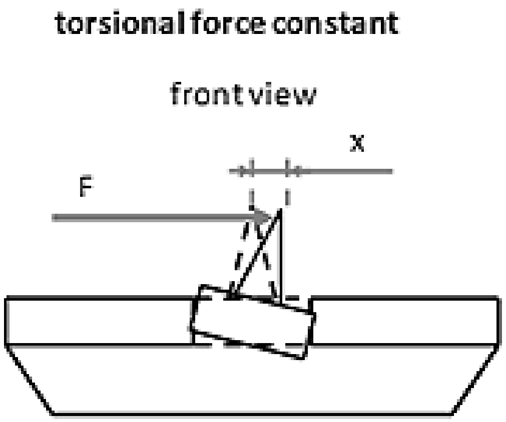


Fig. 3: Schematic front view of an AFM cantilever

Imaging modes

- **Contact** mode: repulsive tip-sample interaction due to close approach (less than 1 nm)
- **Tapping** mode: intermittent tip-sample contact due to tip oscillation (distance between 1 and 10 nm)
- **Non-contact** mode: attractive tip-sample interaction at a distance larger than 10 nm

Contact mode

Advantage	Disadvantage
• High scan speeds • Rough samples with extreme changes in vertical topography can sometimes be scanned more easily	• Lateral (shear) forces may distort features in the image • In ambient conditions may get strong capillary forces due to adsorbed fluid layer • Combination of lateral and strong normal forces reduce resolution and mean that the tip may damage the sample, or vice versa

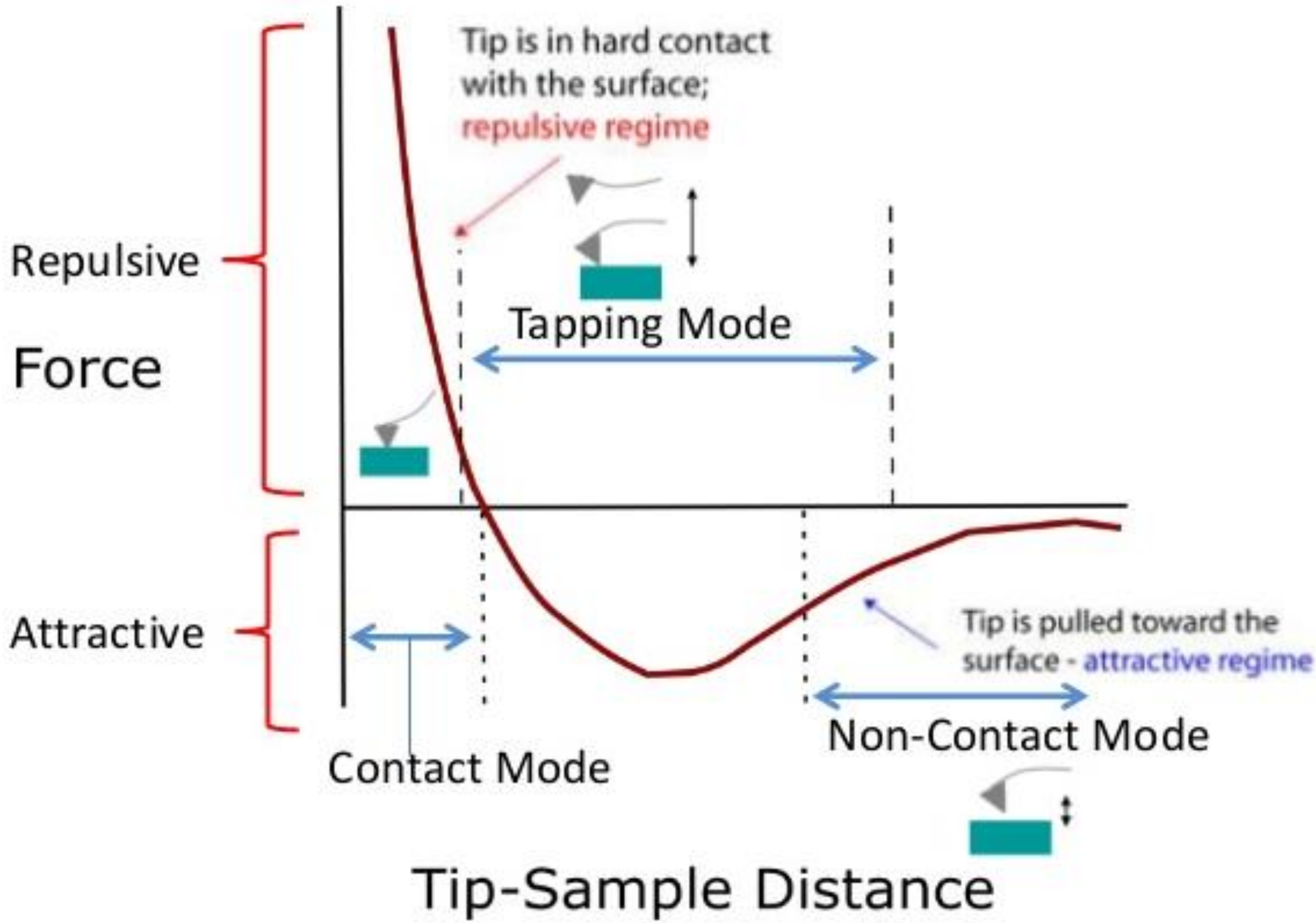
Tapping mode

Advantage	Disadvantage
• Lateral forces almost eliminated • Higher lateral resolution on most samples • Lower forces so less damage to soft samples or tips	• Slower scan speed than in contact mode

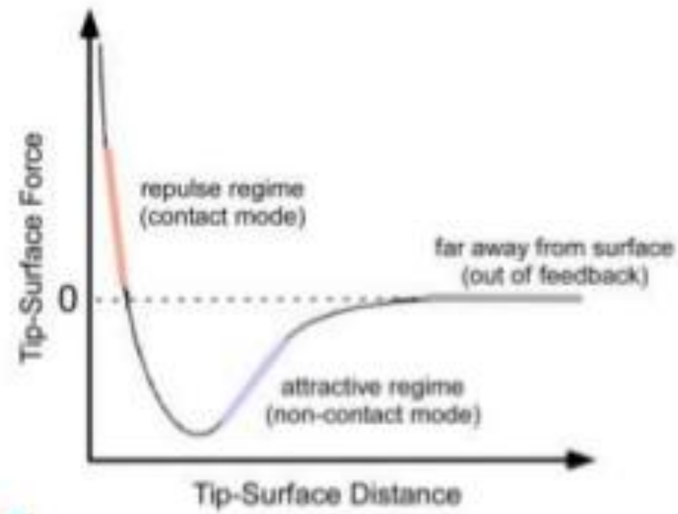
Non-contact mode

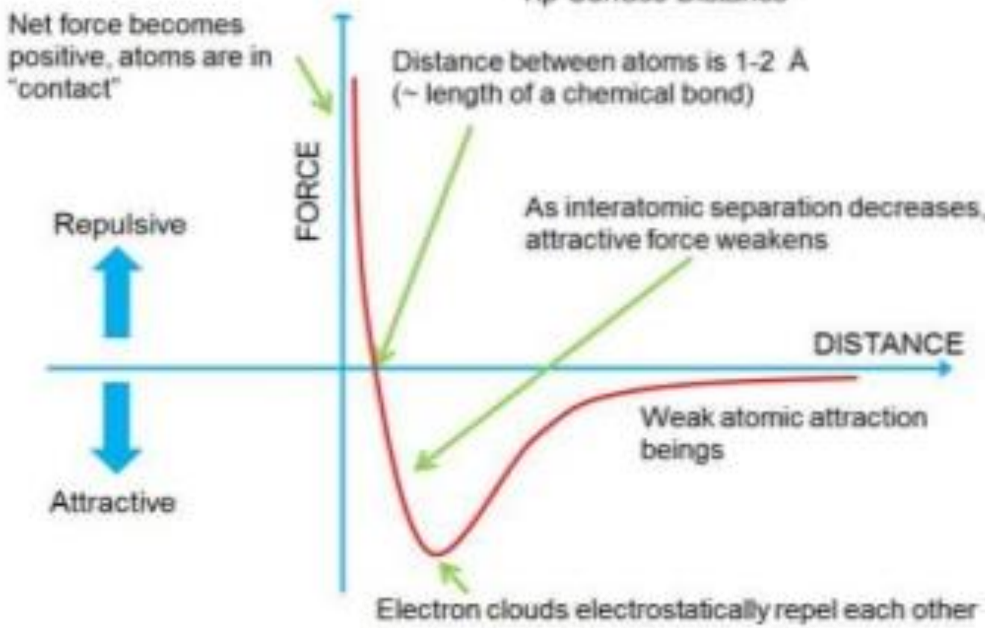
Advantage	Disadvantage
• Both normal and lateral forces are minimized, so good for measurement of very soft samples • Can get atomic resolution in a UHV environment	• In ambient conditions the adsorbed fluid layer may be too thick for effective measurements • Slower scan speed than tapping and contact modes to avoid contacting the adsorbed fluid layer

Imaging modes

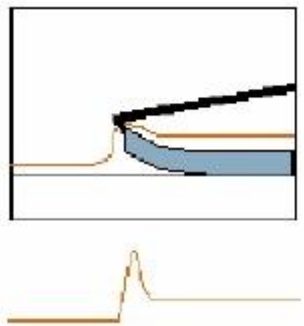
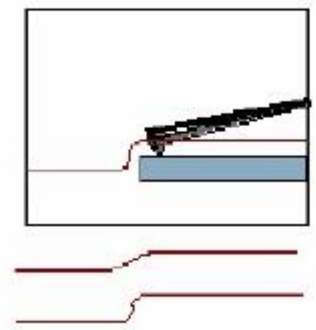
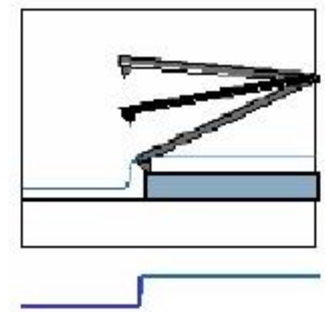


Tip-sample interactions

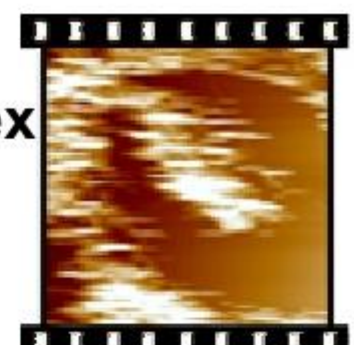


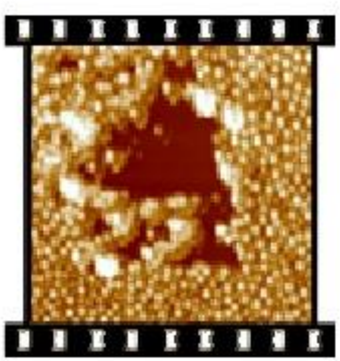


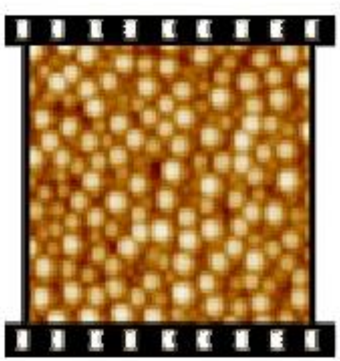
Imaging modes

	Contact	Noncontact	Vibrating (tapping)
			
•Cantilever	soft	hard	hard
•Force	1-10nN	0.1-0.01nN	
•Friction	large	small	small
•Distance	<0.2nm	~ 1nm	>10nm
•Damage	large	small	small
•Surface	hard surface	soft or elastic surface	

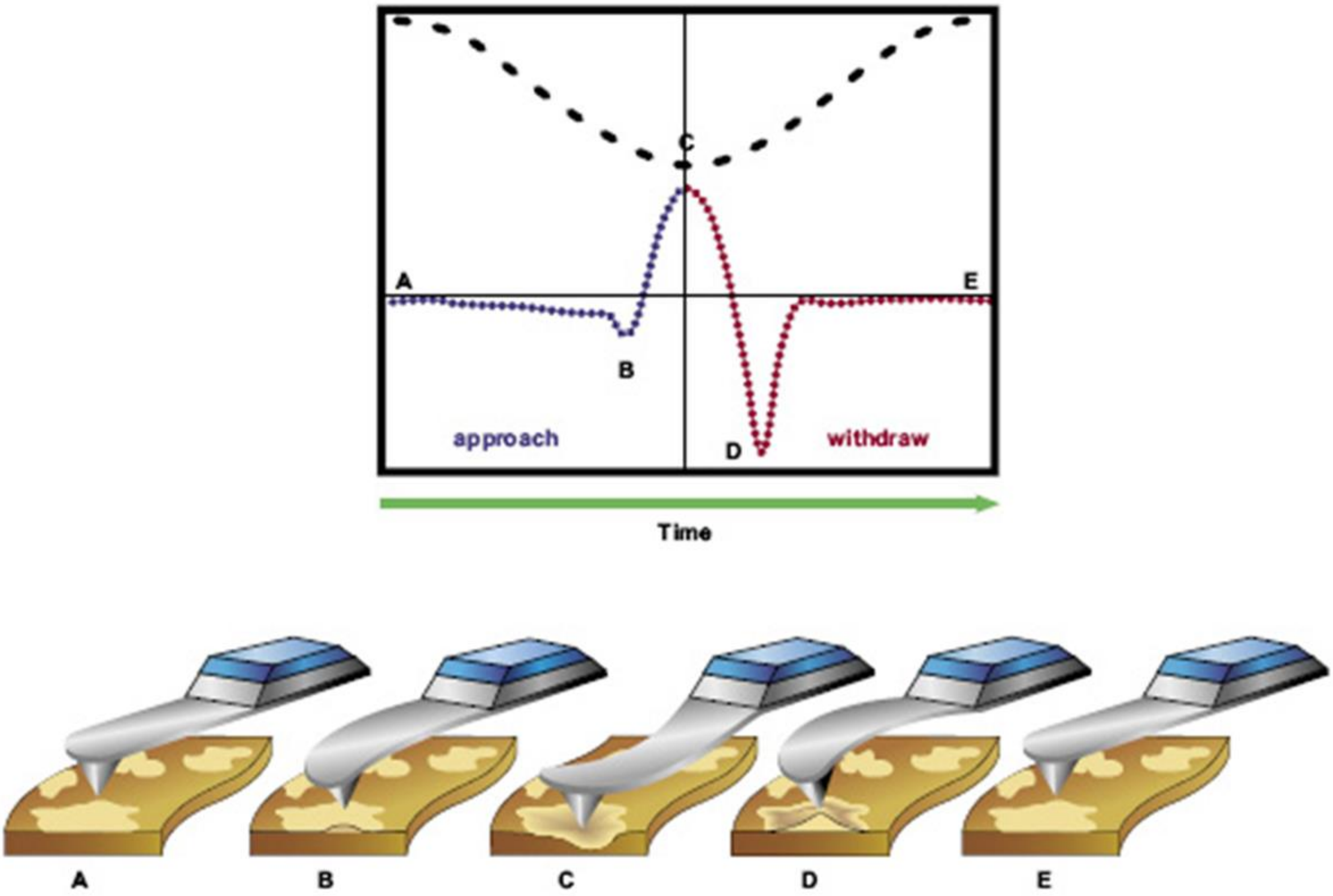
Polymer latex particle on mica



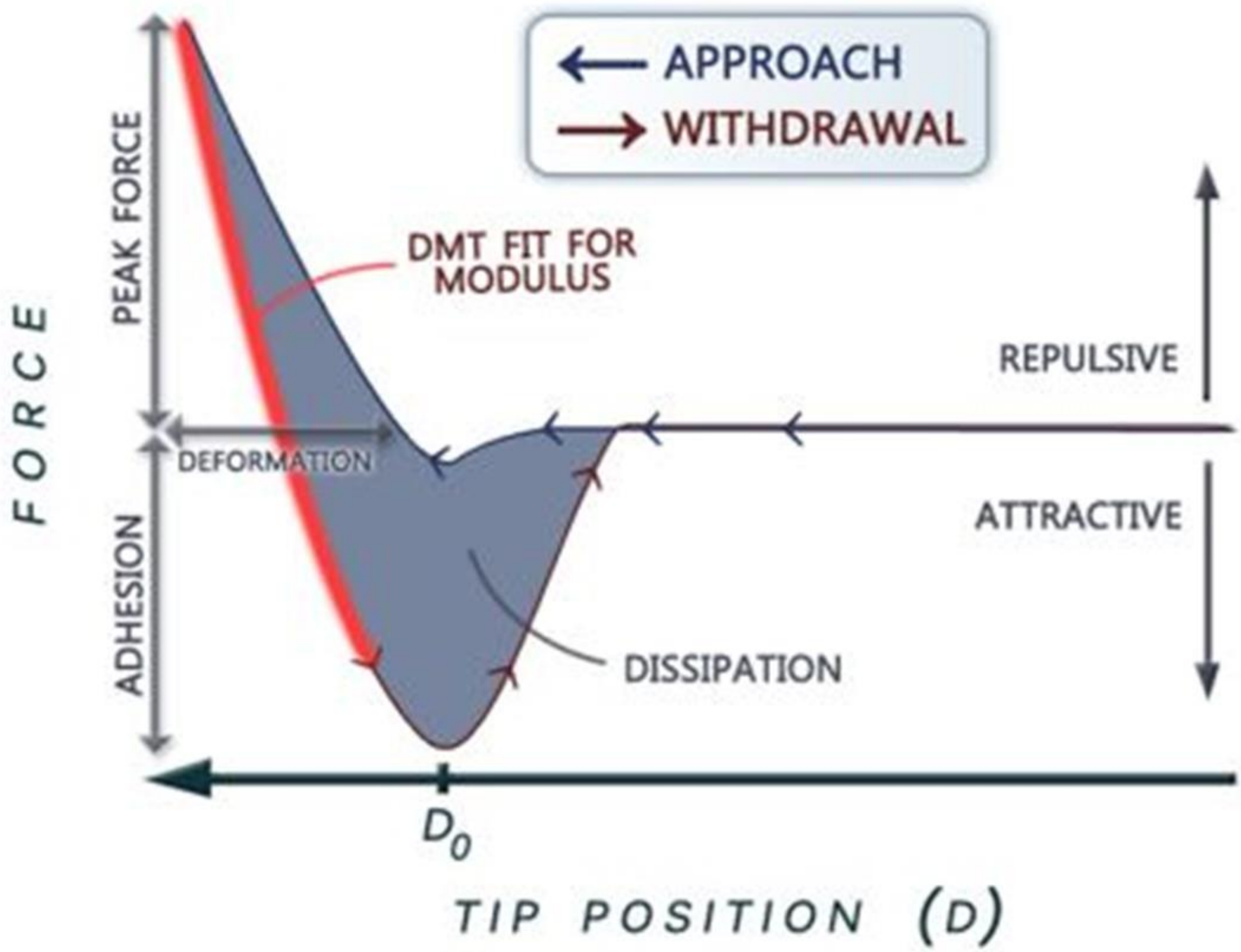




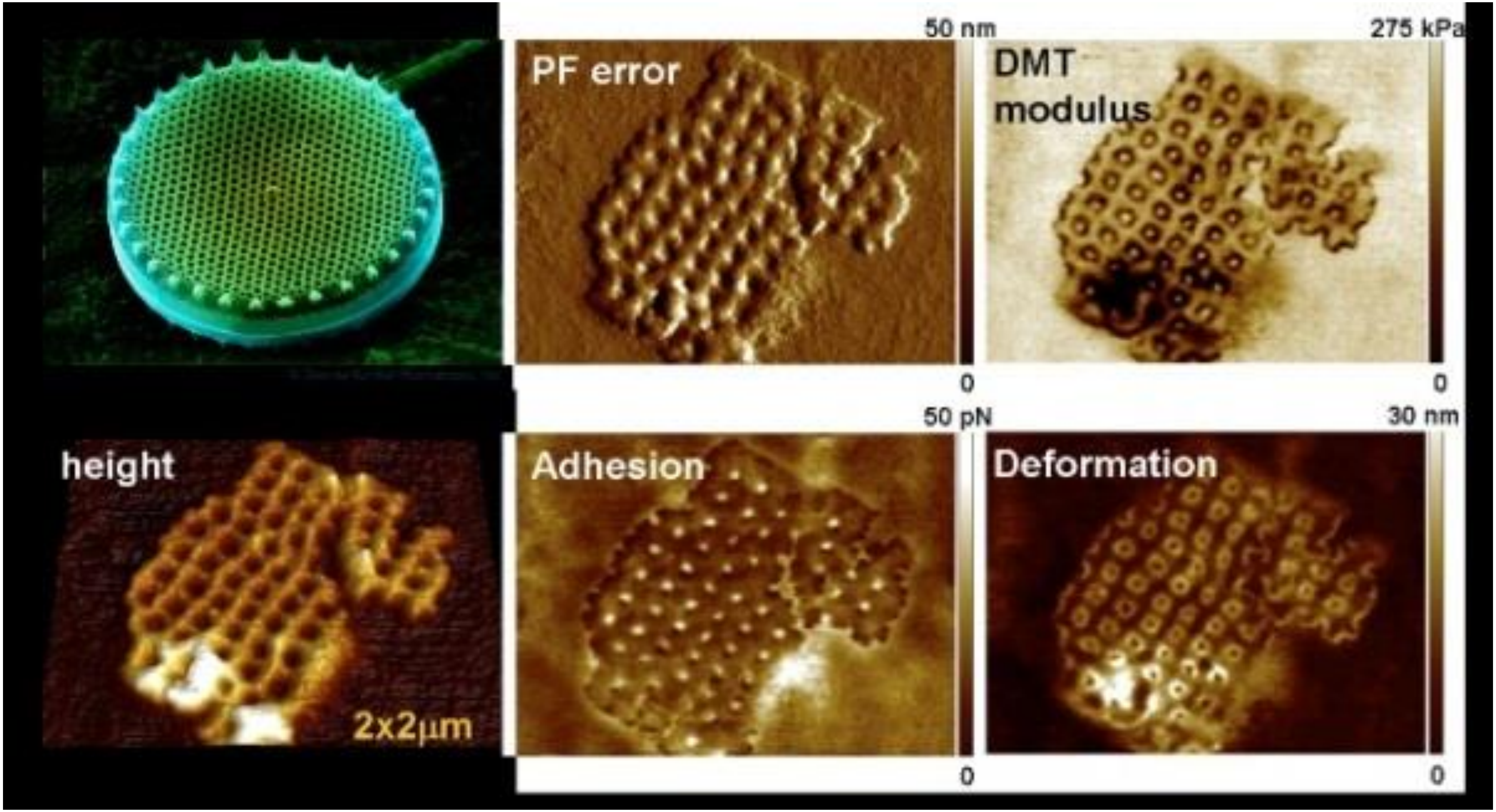
PeakForce AFM



Quantitative Nanomechanical Mapping



Quantitative Nanomechanical Mapping

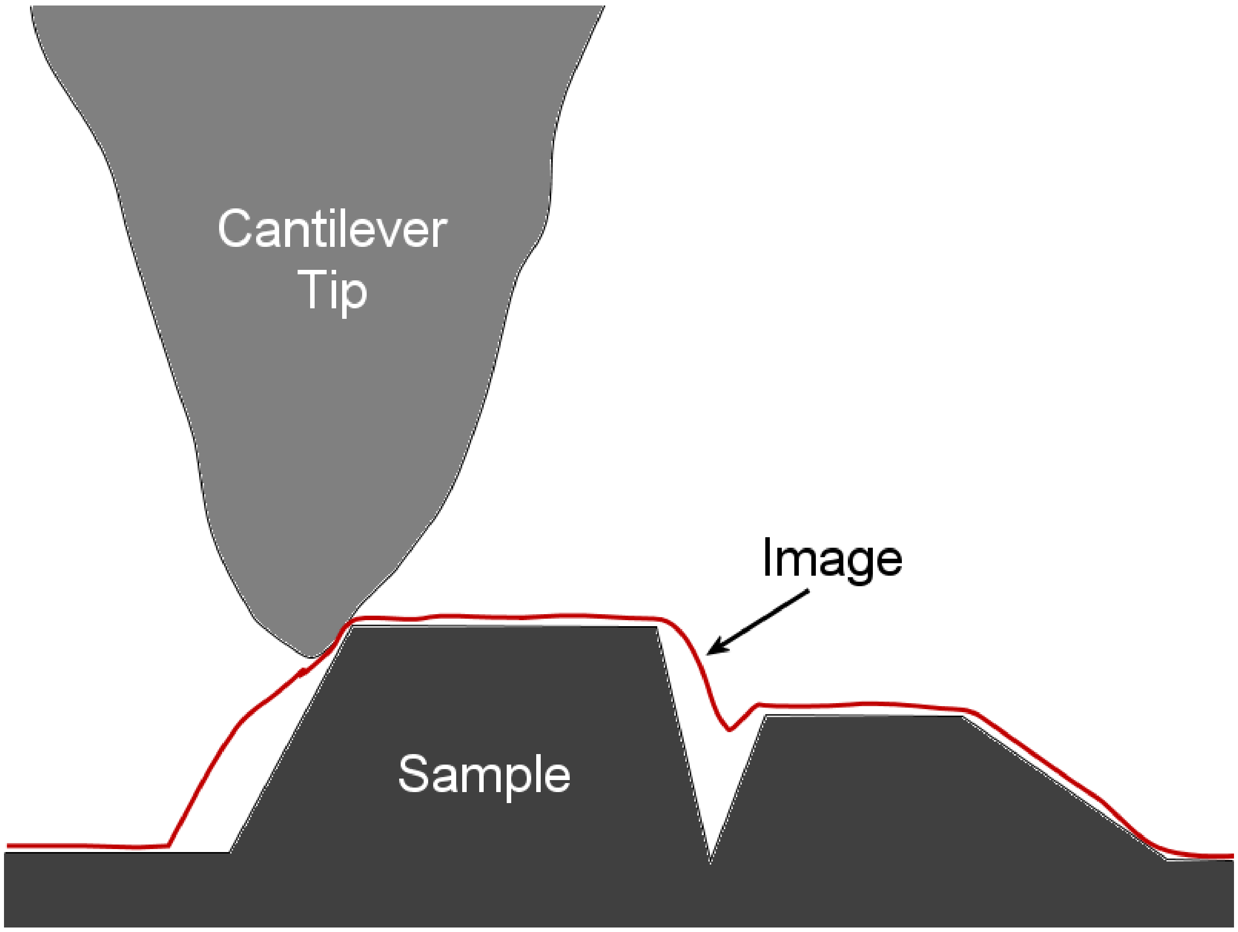


Measurement resolution

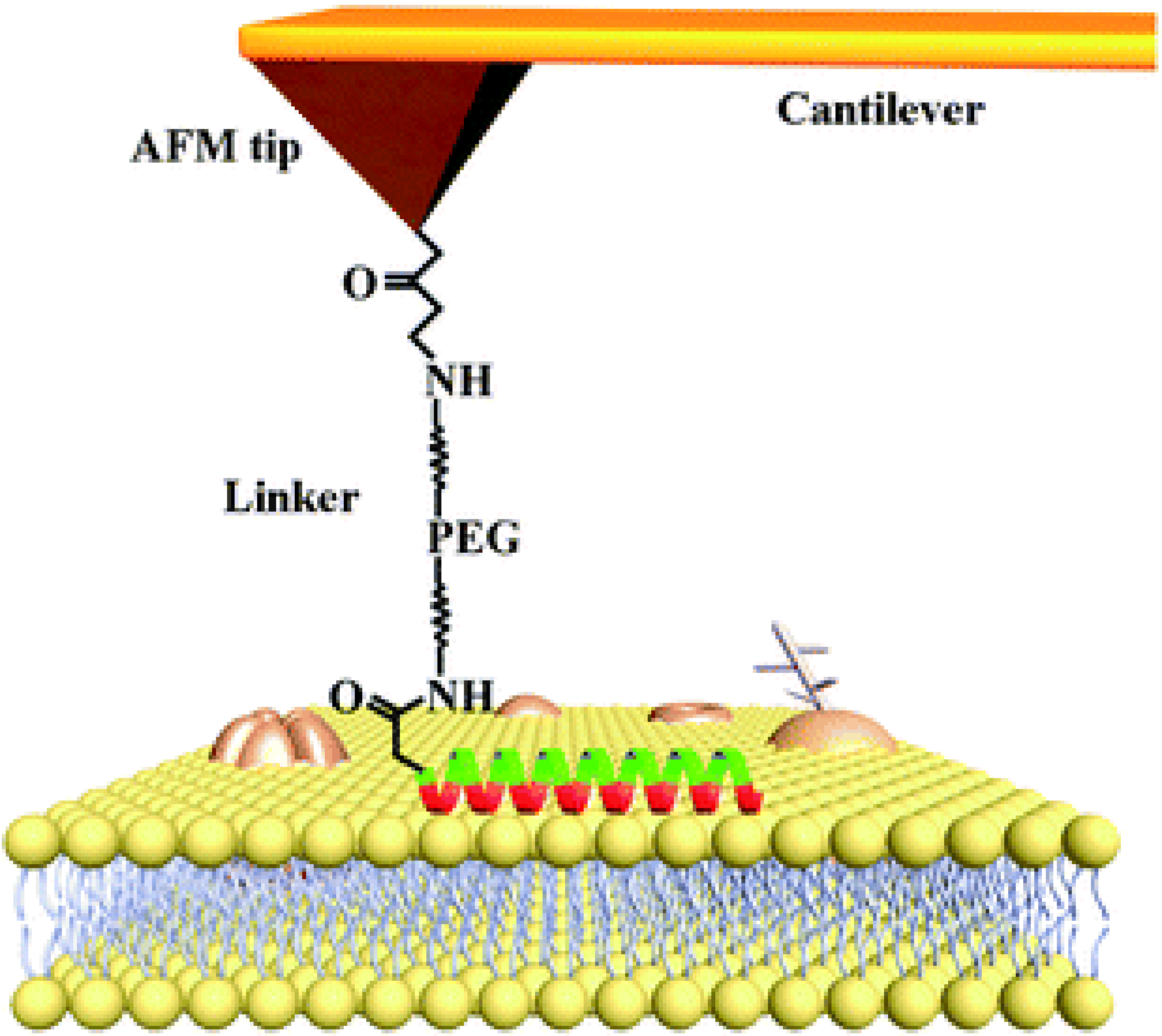
- Scanning tip geometry
- Curvature radius, tip apex
- External disturbances
- Thermal noise, acoustic vibrations, capillary forces
- Scanner characteristics
- Sensitivity, linearity, stability, repeatibility

What you get is **not** what you can see

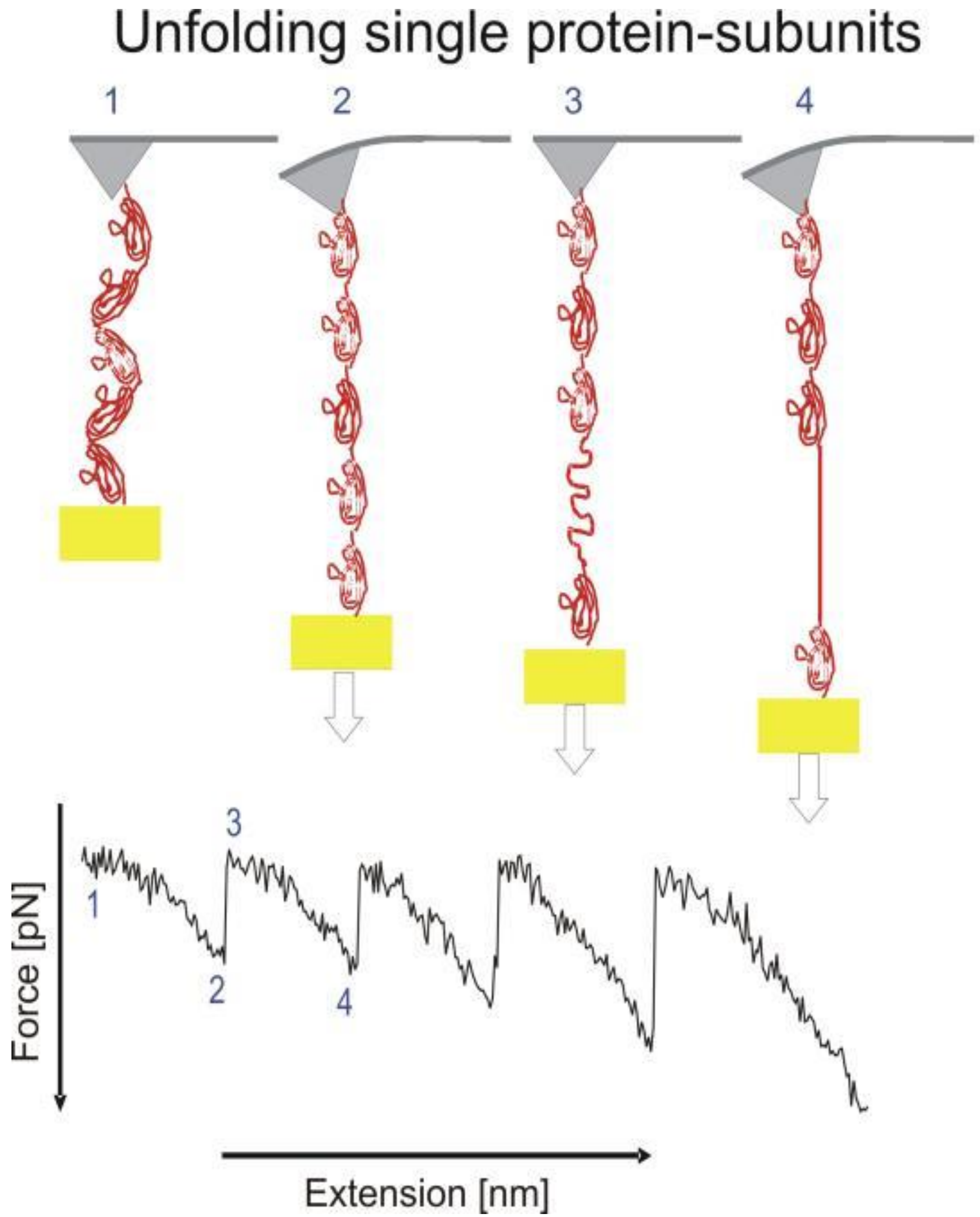
AFM images are convolution of surface topography and tip geometry



Tip functionalization

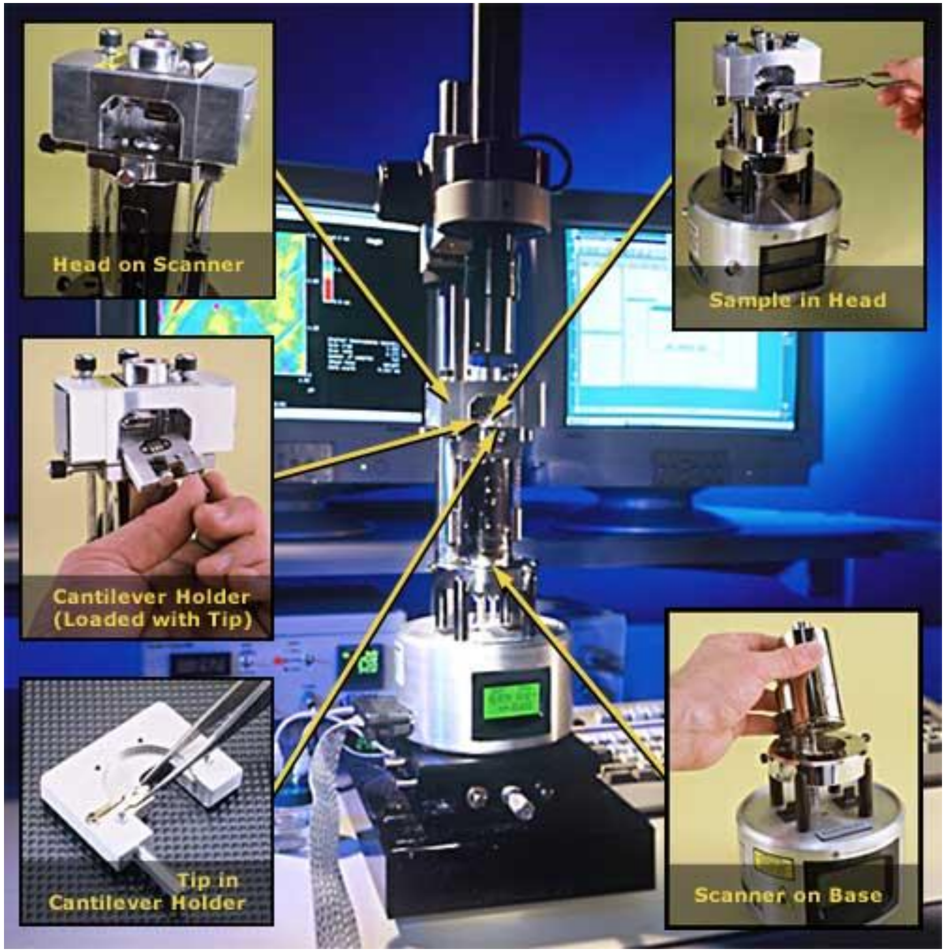


Atomic Force Spectroscopy

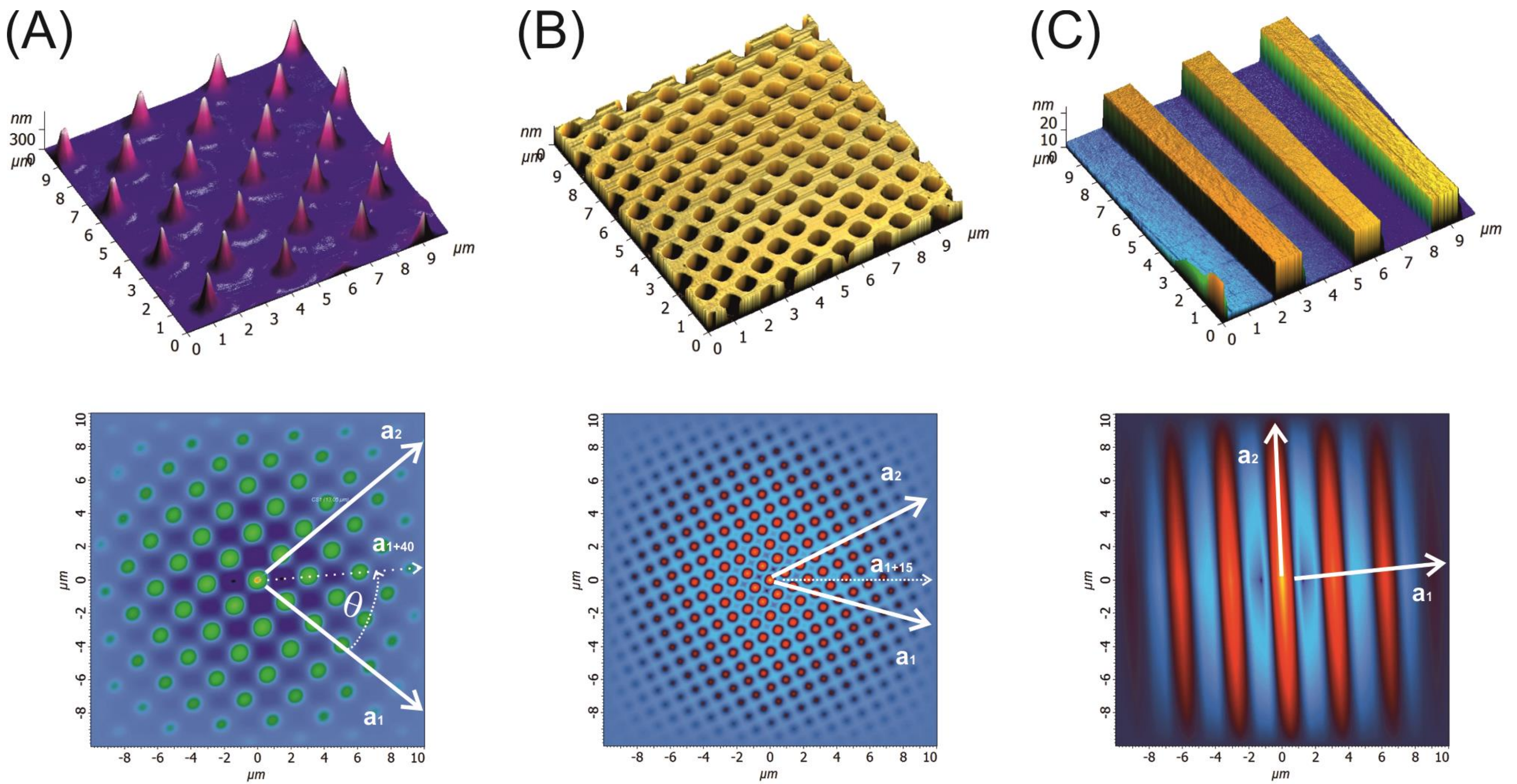


AFM @ WMiI

Multimode 8 + Nanoscope V (Bruker)
AFM + MFM + LFM + KPFM + CAFM
Imaging in air/liquid
Modes: contact, tapping, peak-force tapping
Tips: Scan-Asyst, SNL-10 (2 nm)
What you get is not what you could see: tip-surface convolution



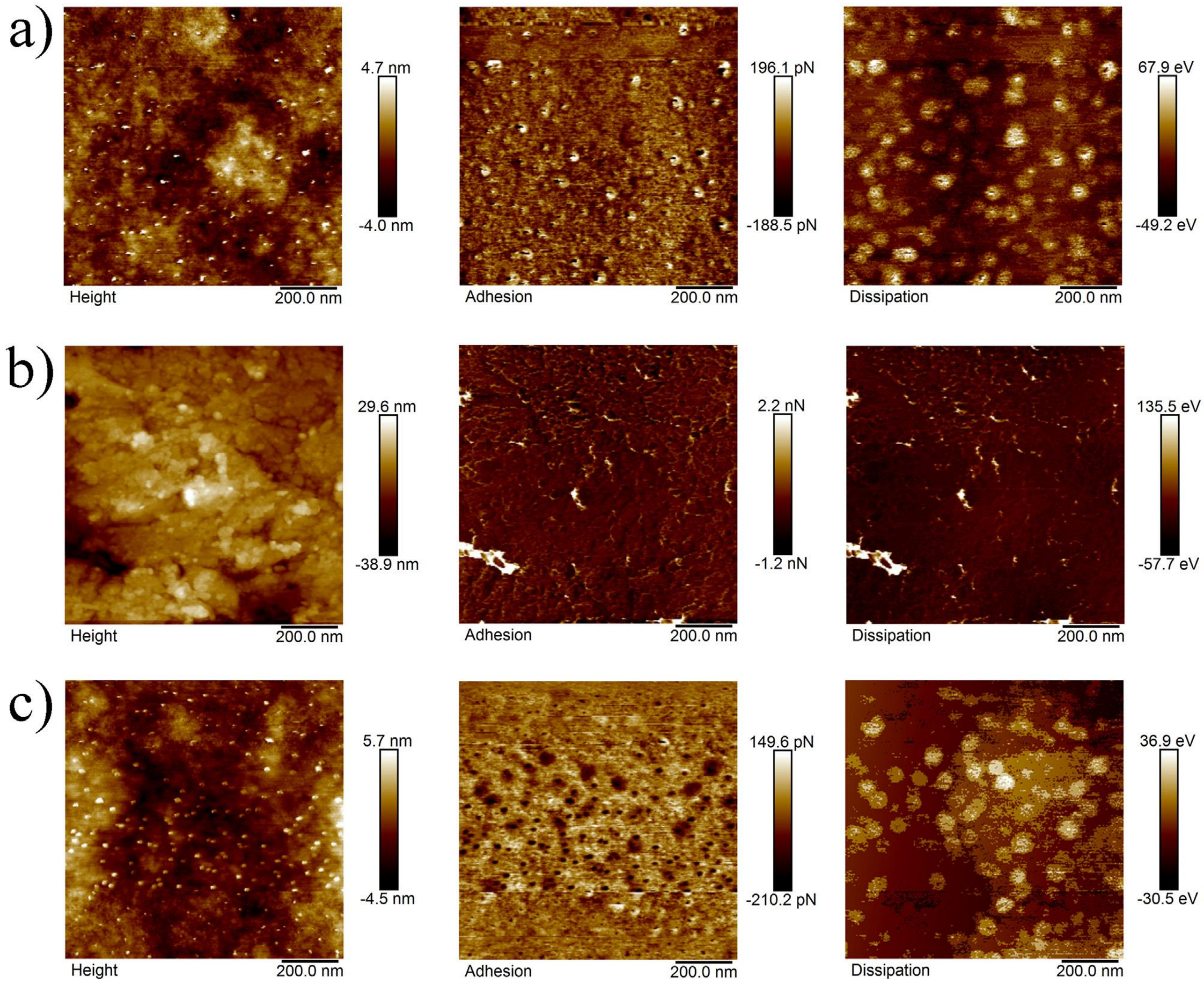
Silicon gratings



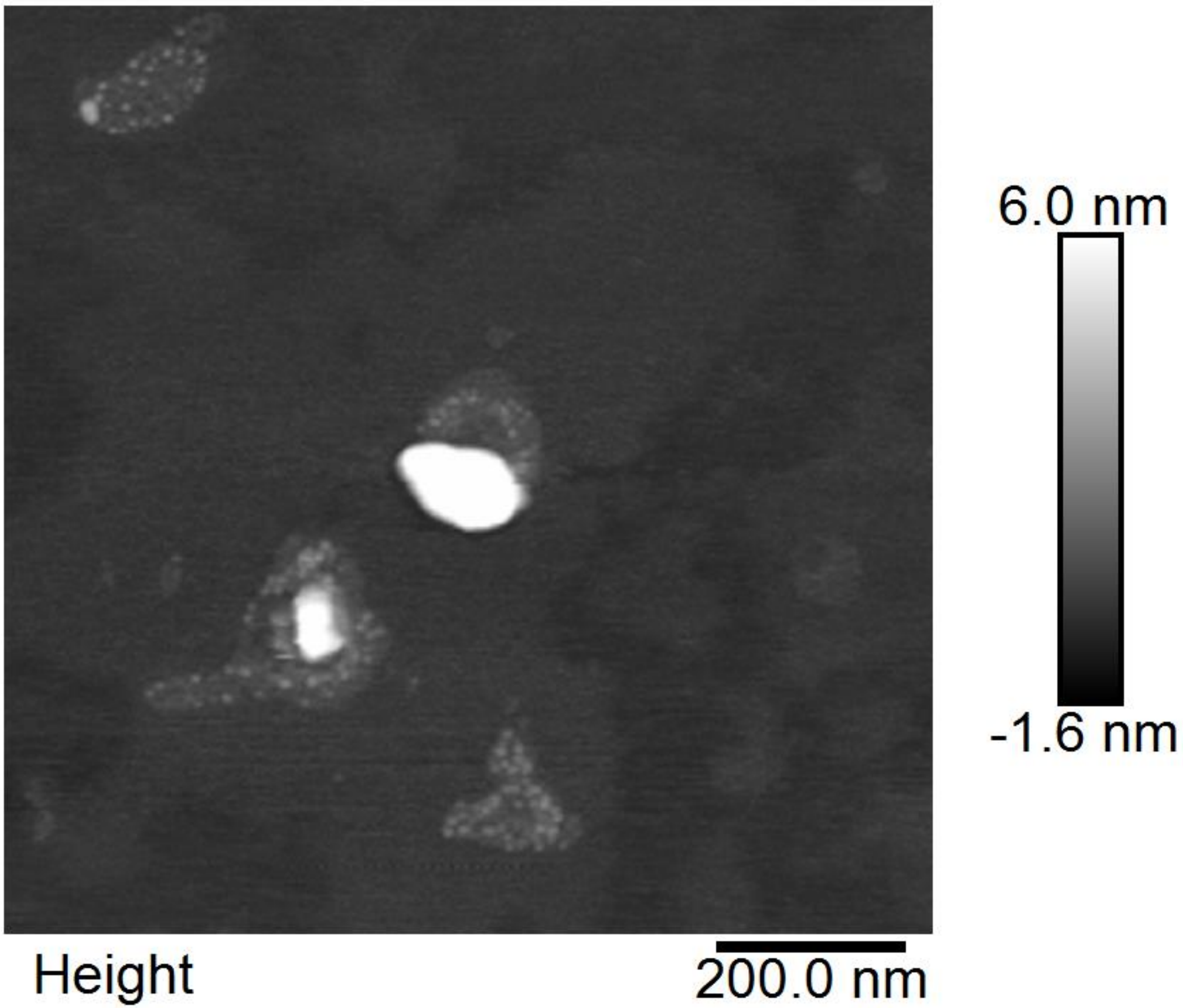
Nanomechanical verification of drugs

S. Wilczyński, M. Petelenz, M. Florek-Wojciechowska, S. Kulesza, Sz. Brym, B. Błońska-Fajfrowska, D. Kruk, *Verification of the authenticity of drugs by means of NMR relaxometry – Viagra® as an example*, Journal of Pharmaceutical and Biomedical Analysis, 135 (2017) 199

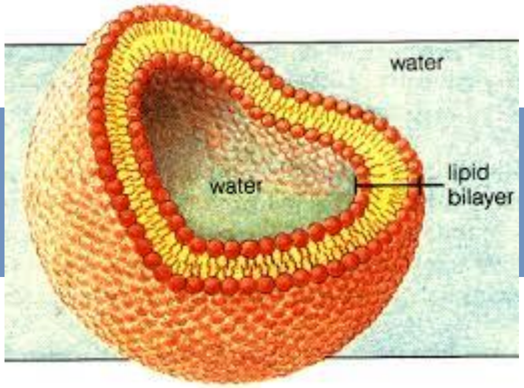
Pure sildenafil, Viagra®, pseudo-Viagra

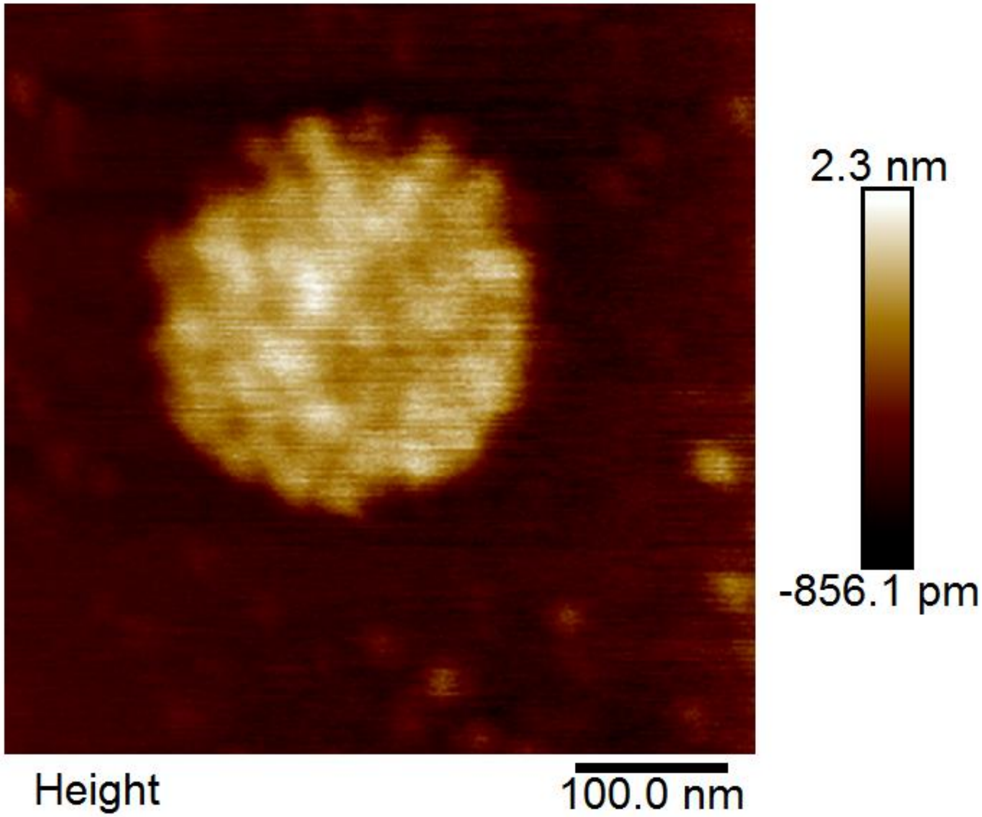


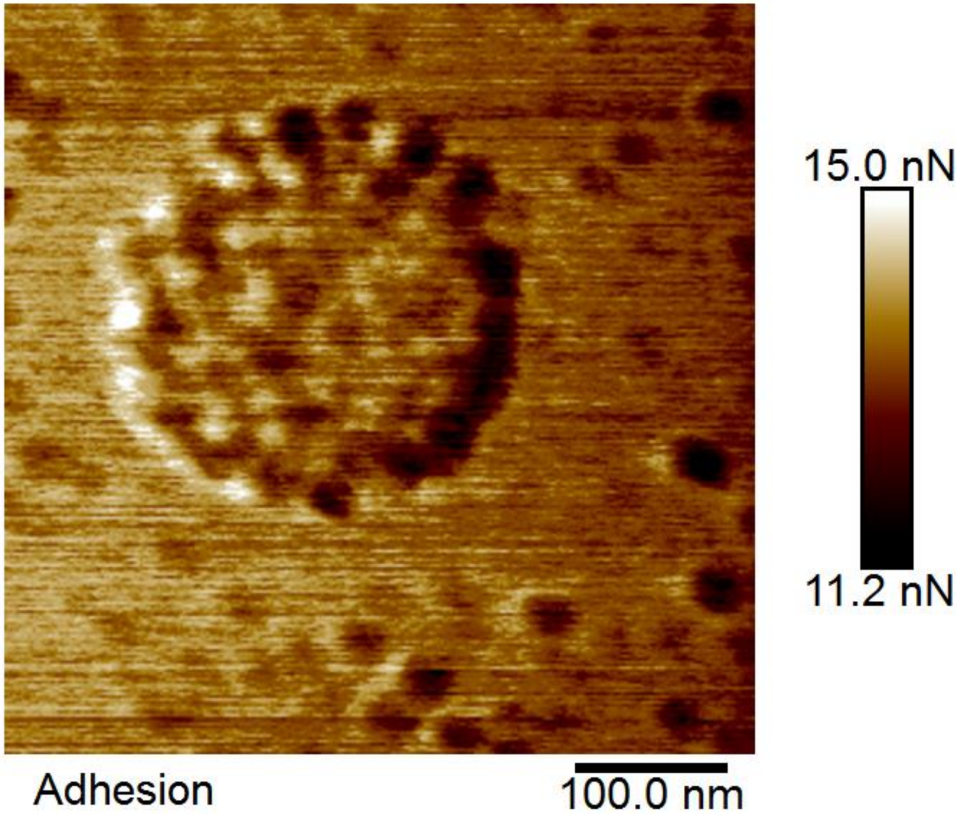
Cu-NPs embedded in glucose



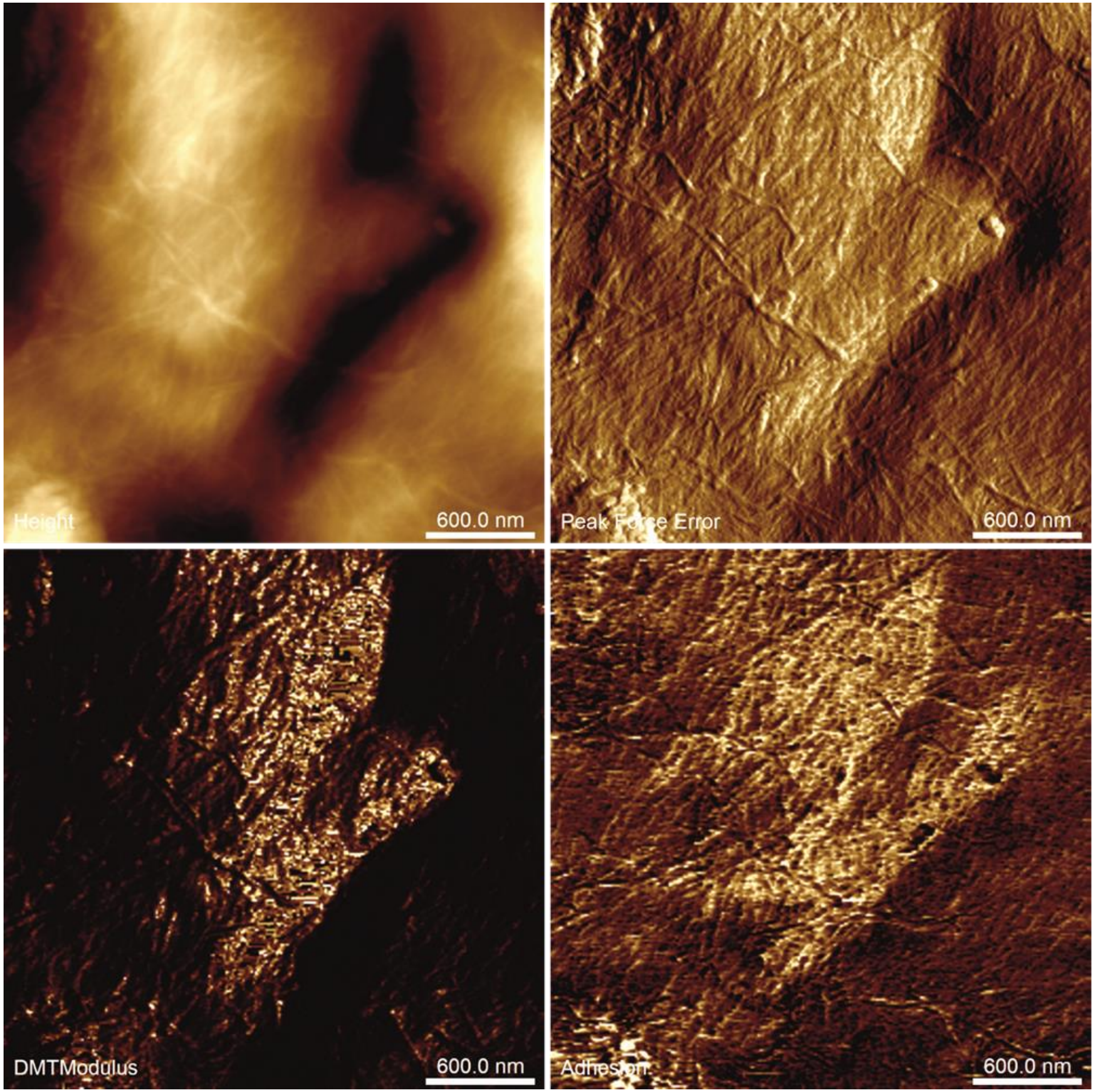
Liposomes


water
water
lipid bilayer

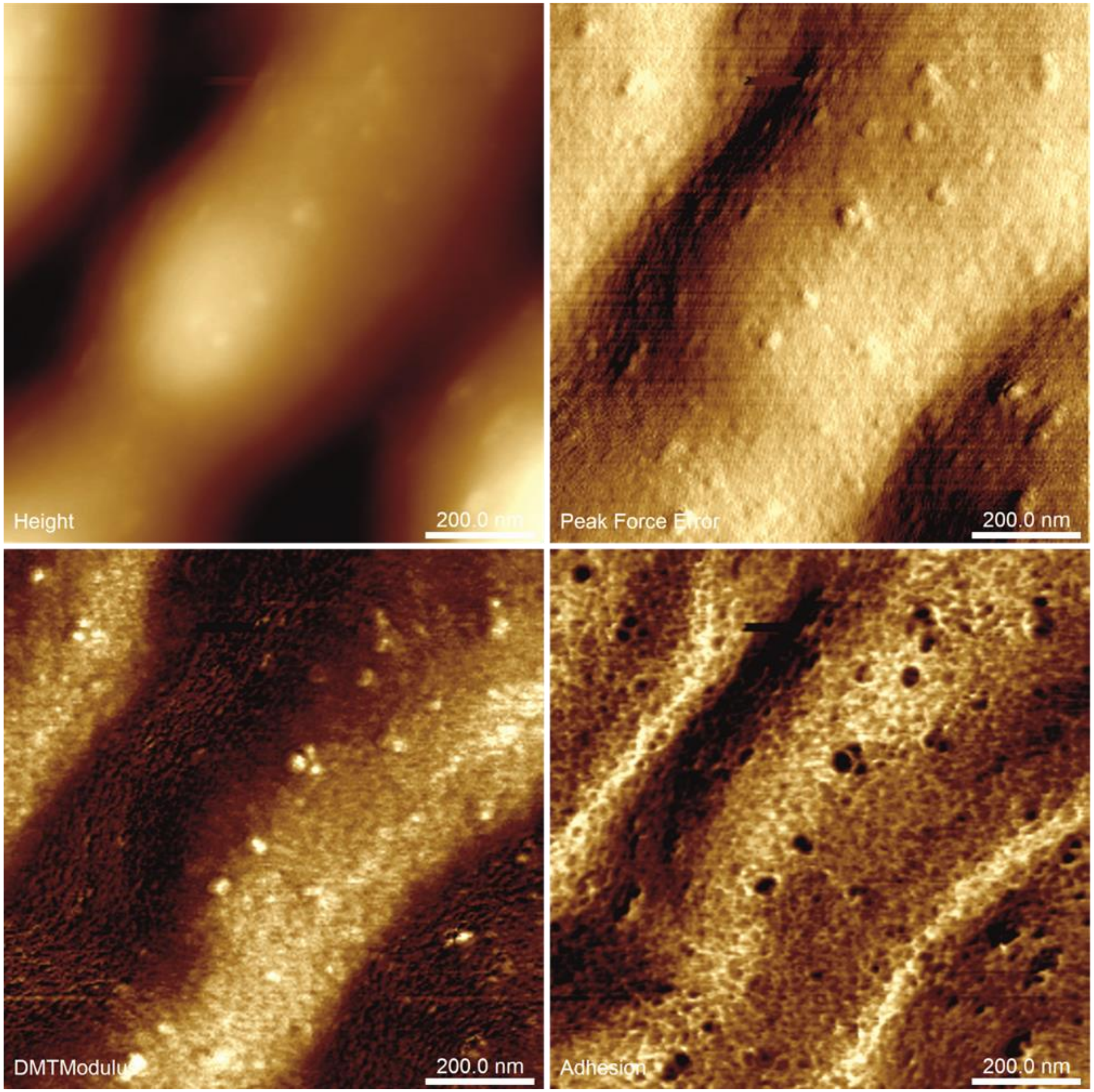

2.3 nm
-856.1 pm
Height
100.0 nm


15.0 nN
11.2 nN
Adhesion
100.0 nm

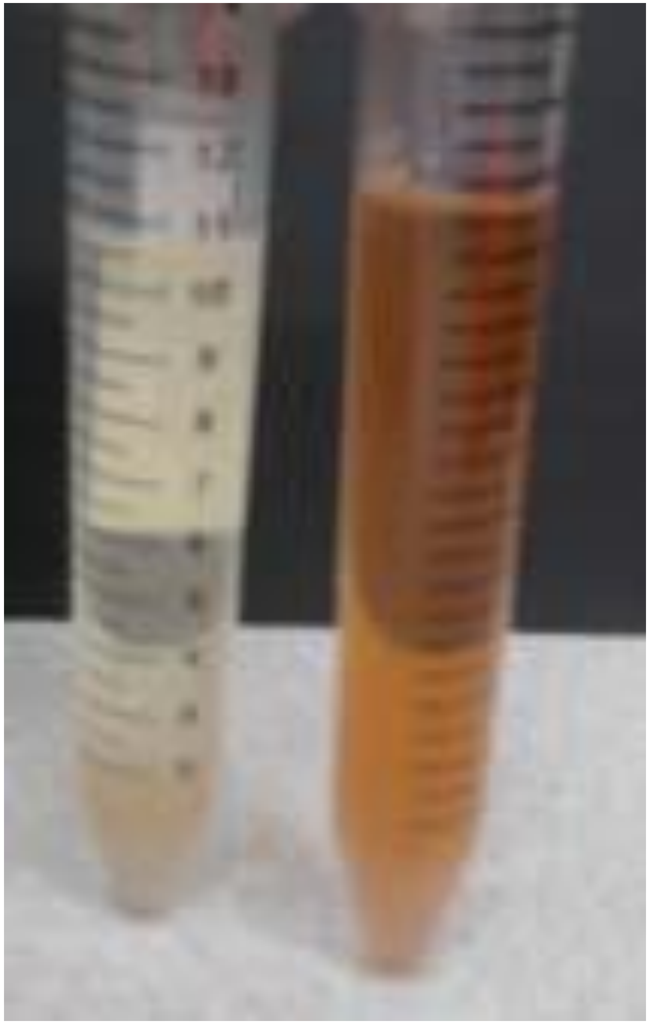
Dried squash of sugar beets without enzymes

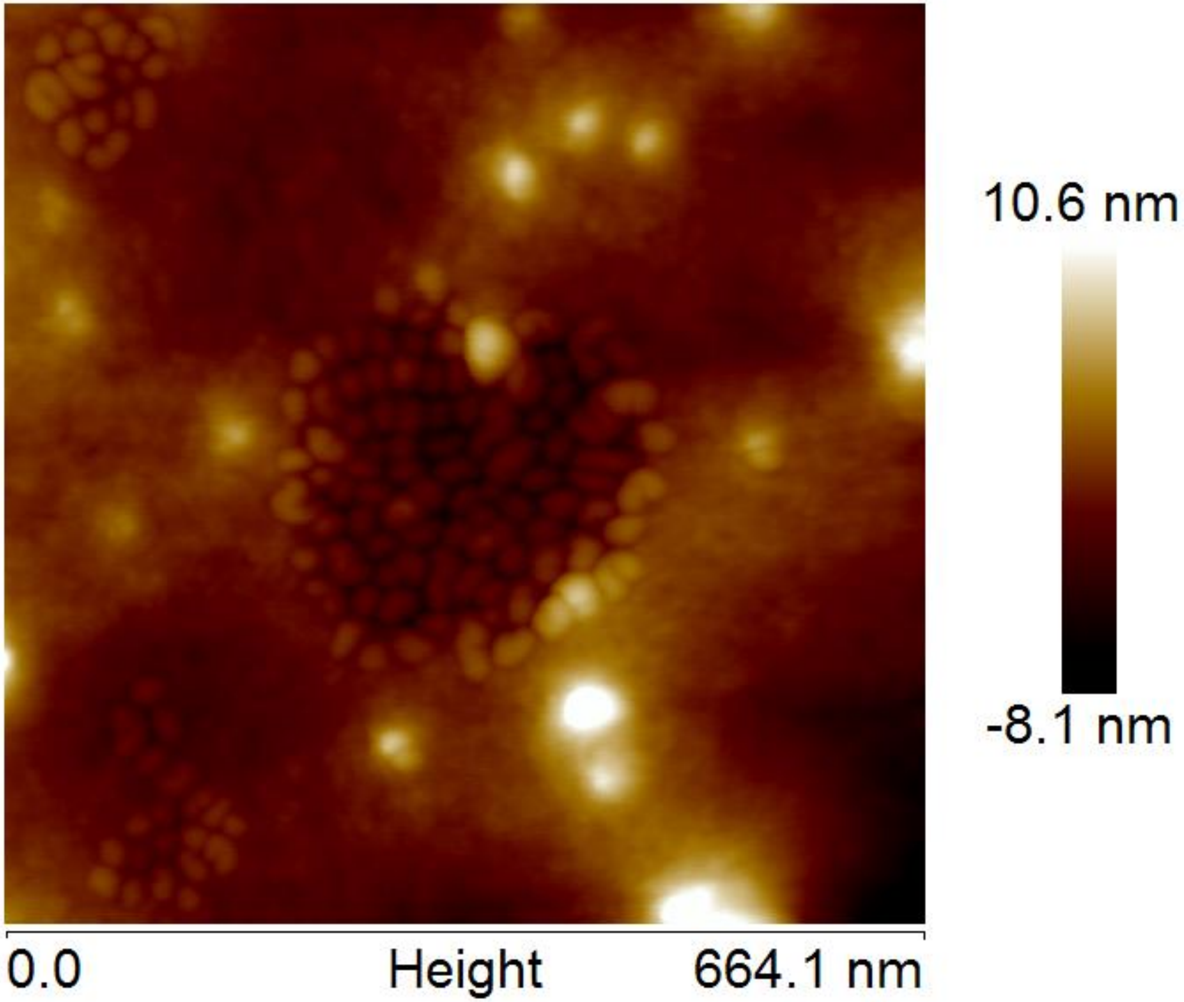


Dried squash of sugar beets with enzymes

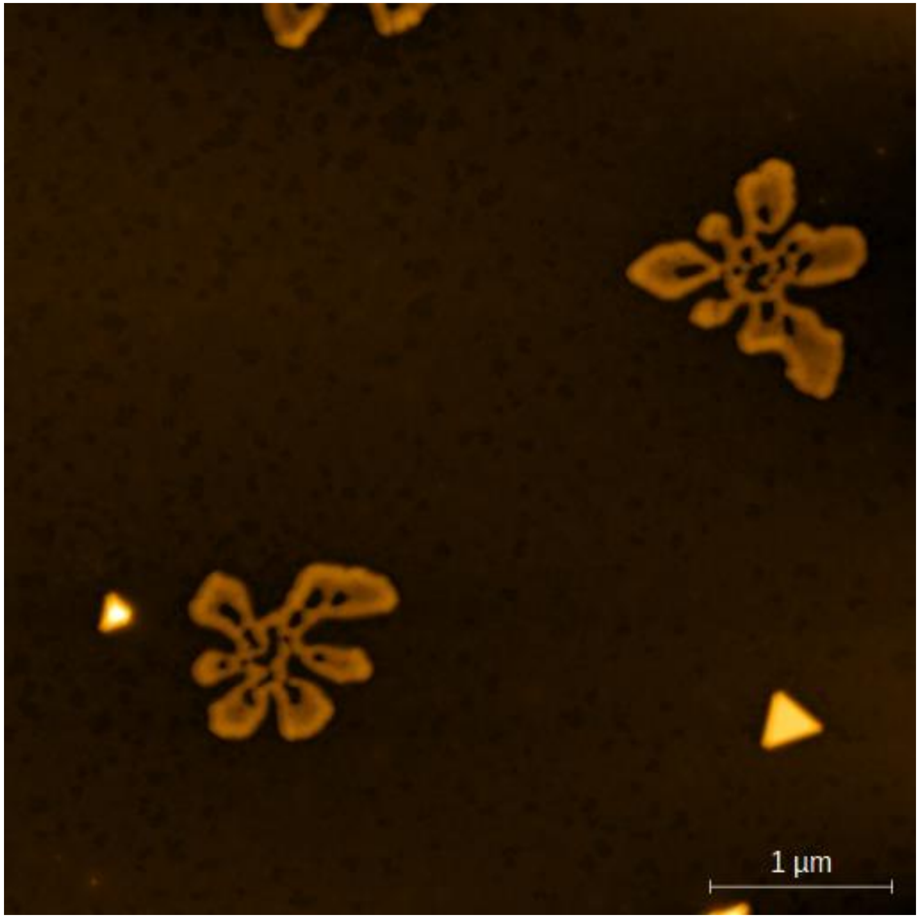


Ag-NPs and the extract of raspberry leaves

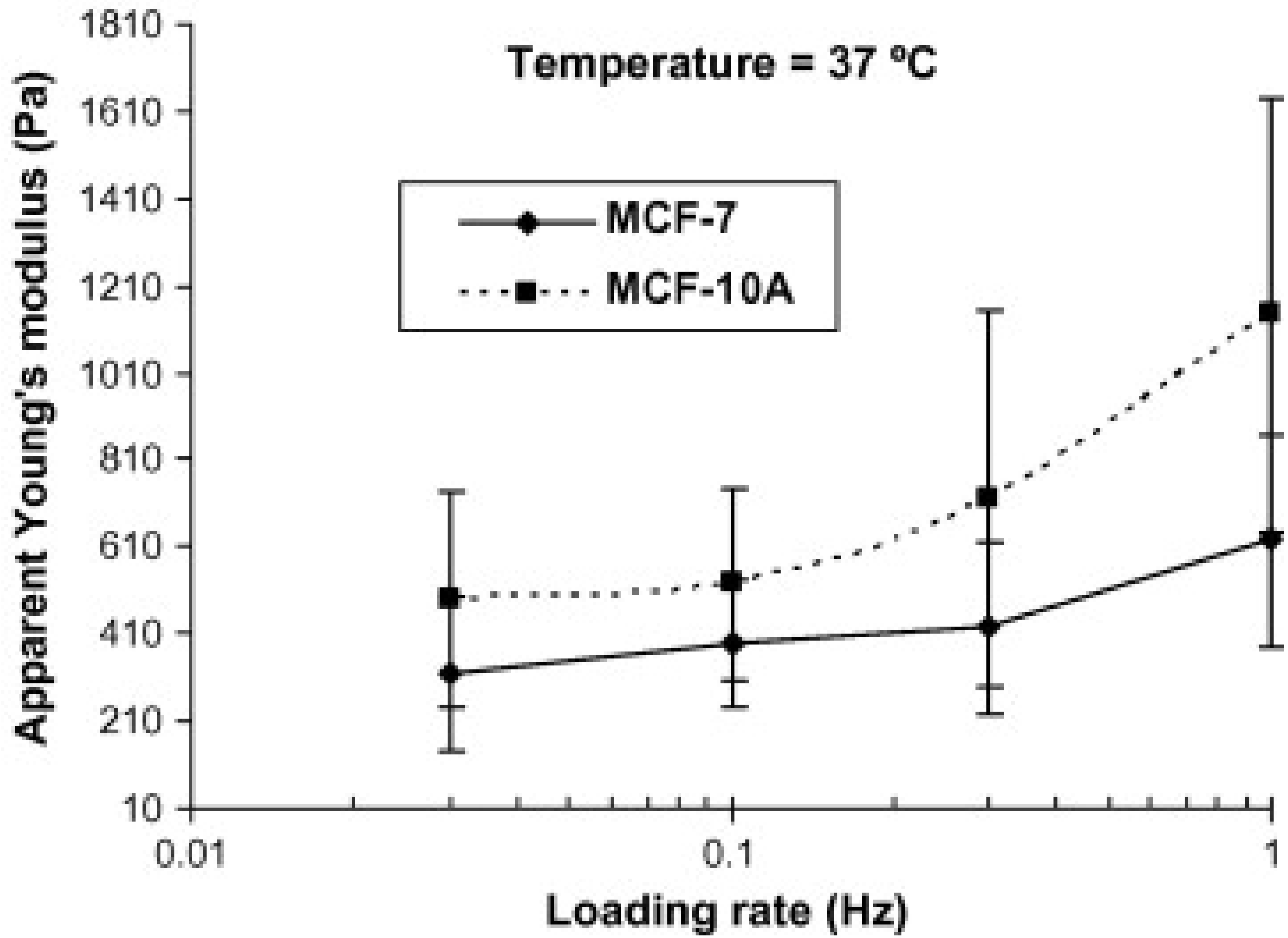




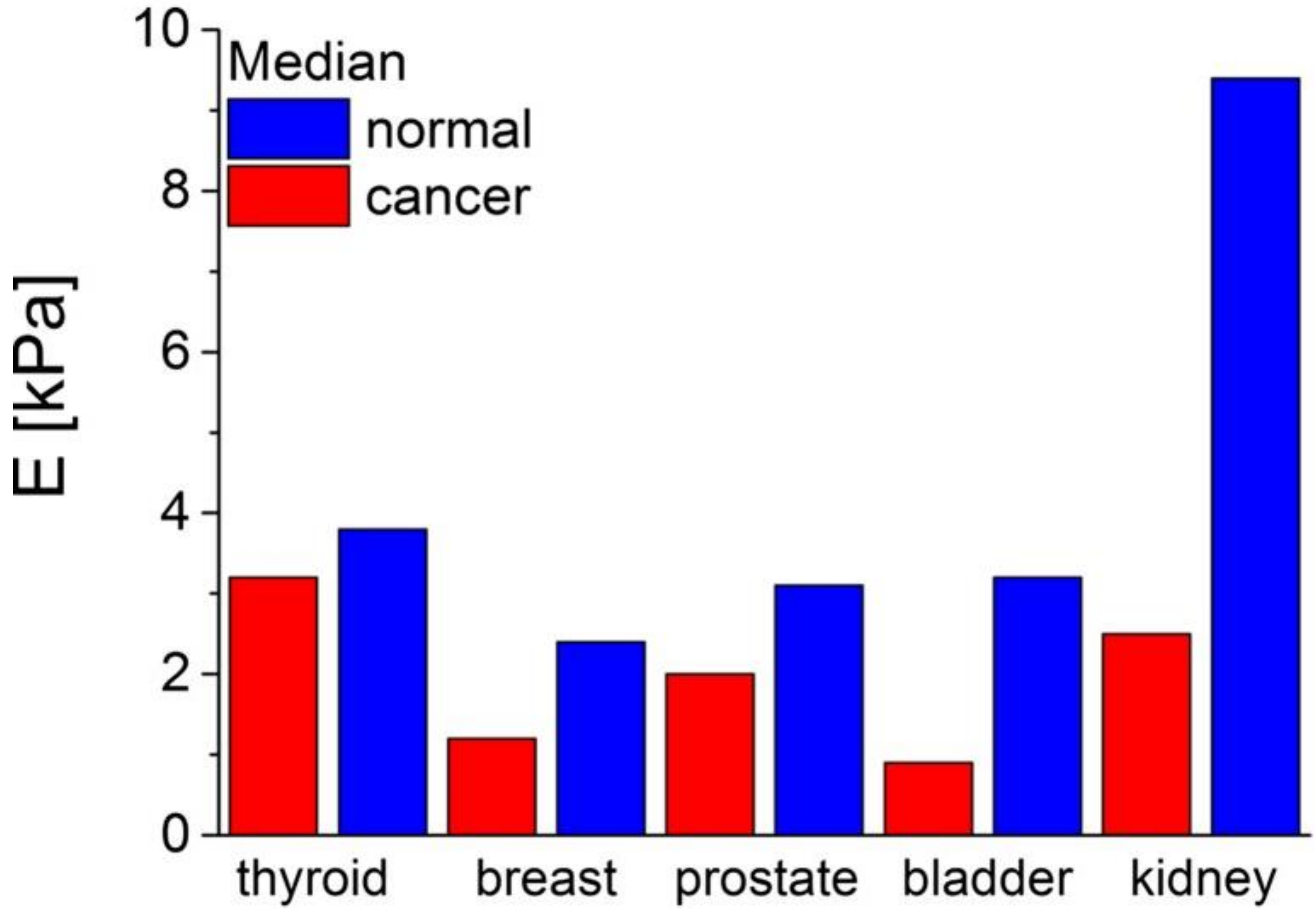
Sample contaminations



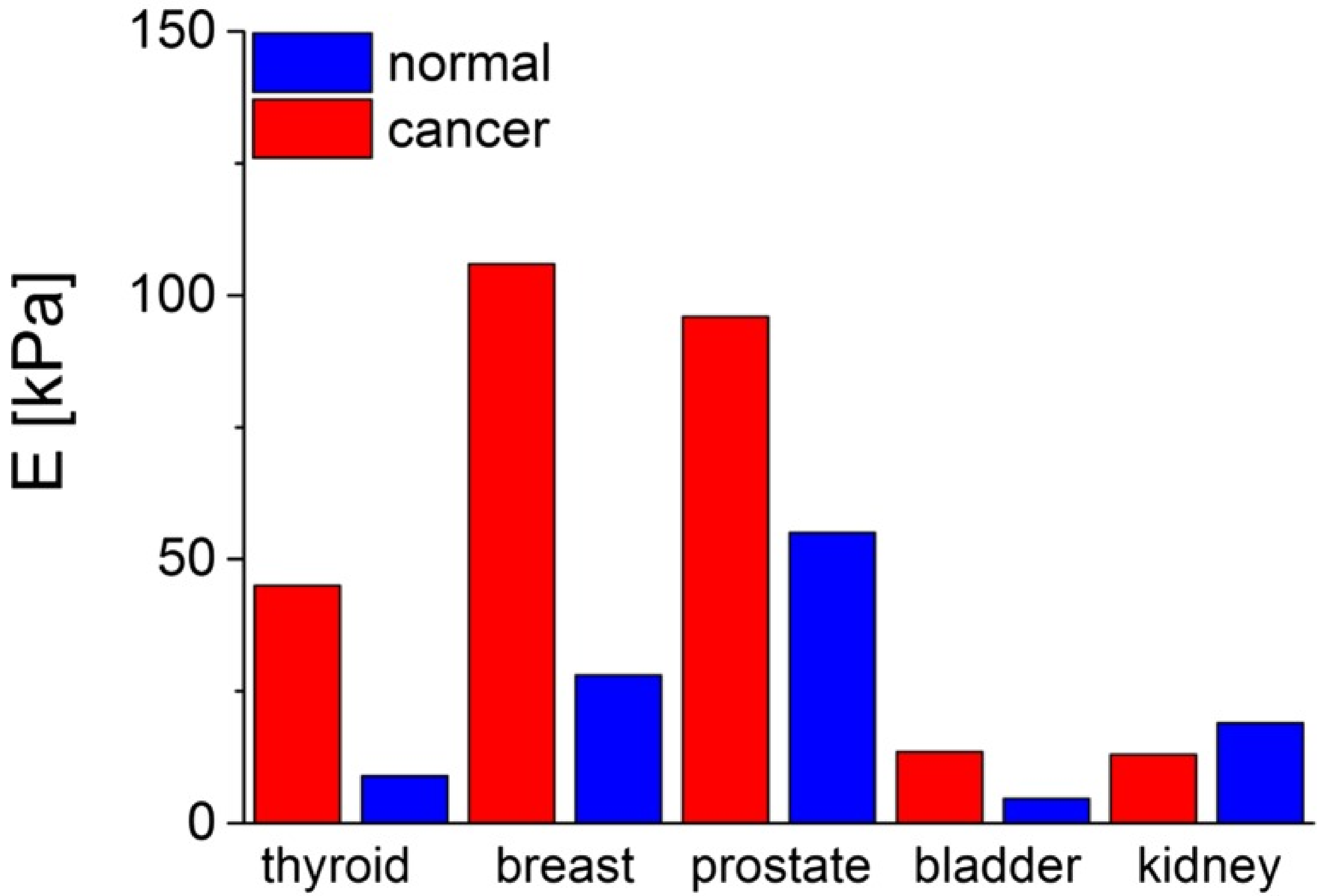
Malignant (MCF-10A) vs. nonmalignant (MCF-7) breast cancer



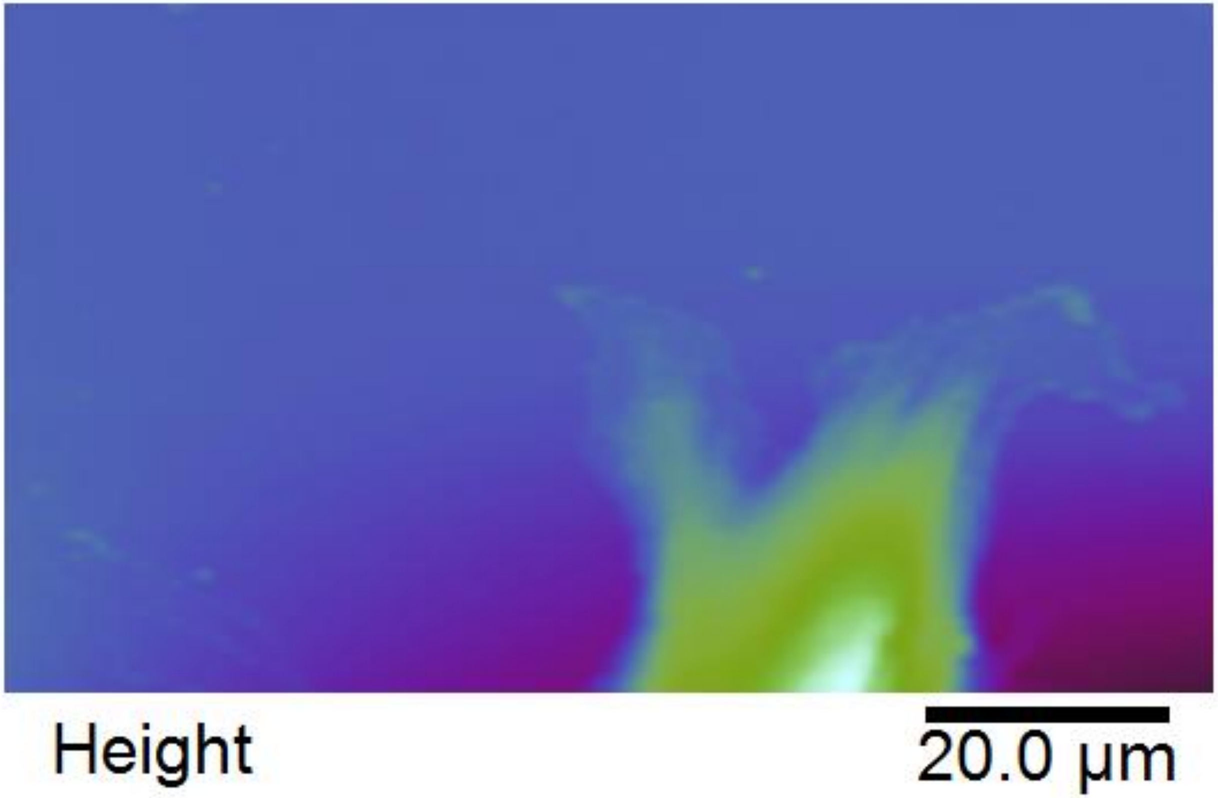
Elasticity of single cells

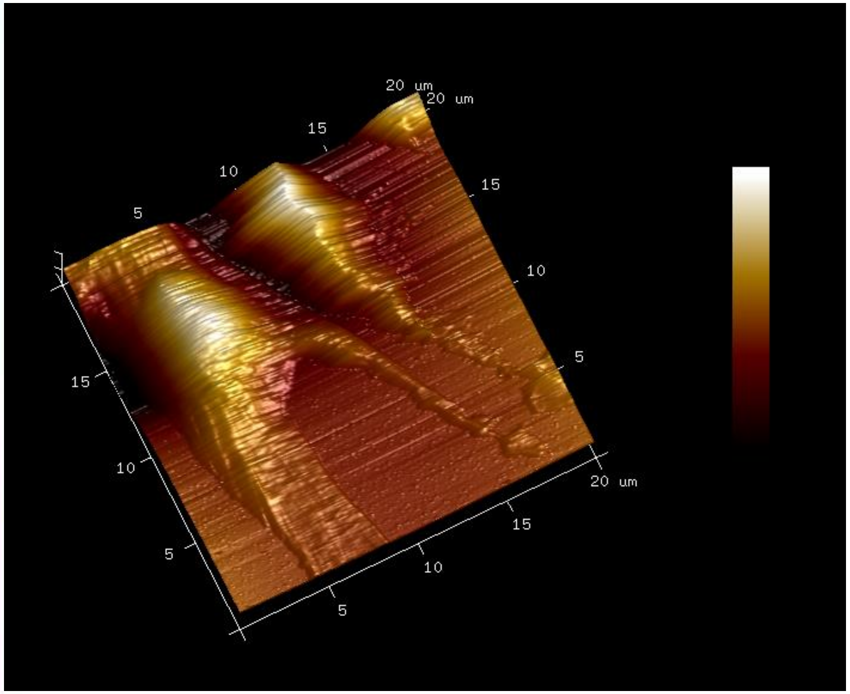


Elasticity of tissues

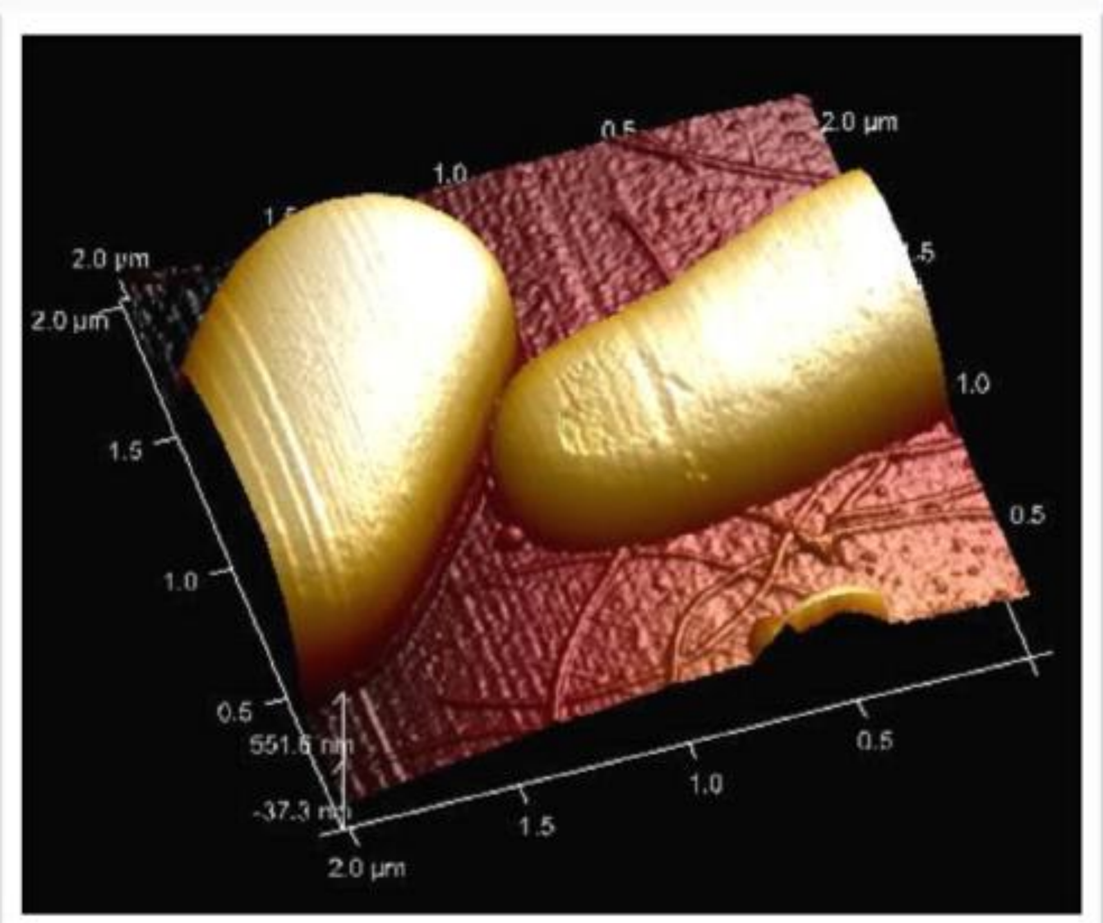


Stem cells

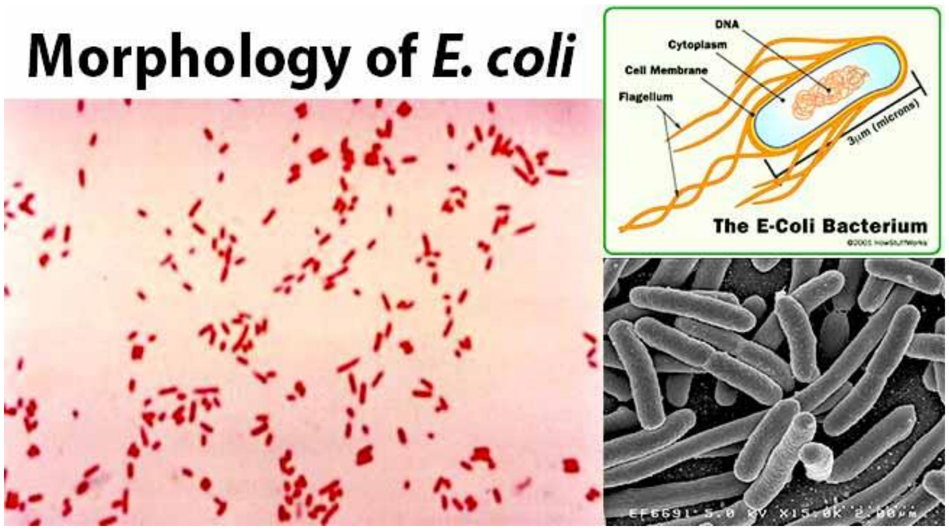




Rod-shaped Escherichia Coli

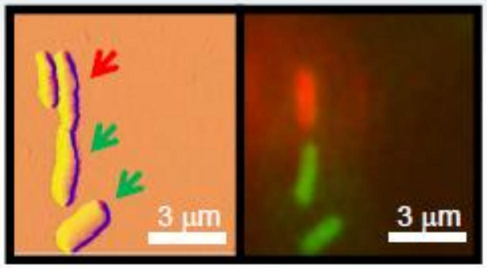


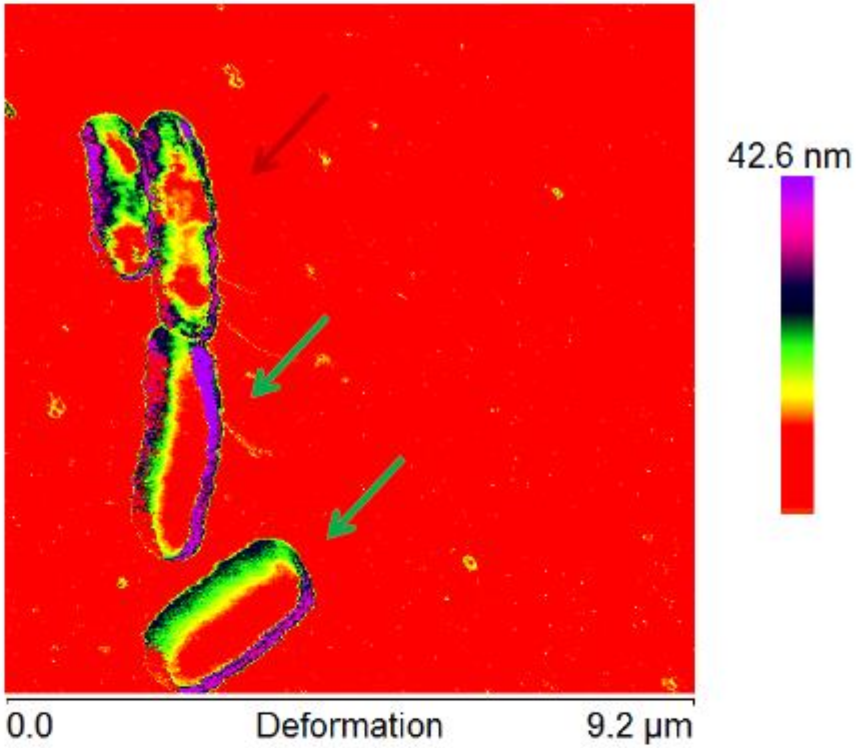
3D Topography image of live E. coli cells. *AFM allows direct observation of the cellular envelope as well as other structures such as flagella and pili . Image was acquired on the Bruker FastScan™ AFM operated in TappingMode™ under fluid conditions (Image = 2 µm).*

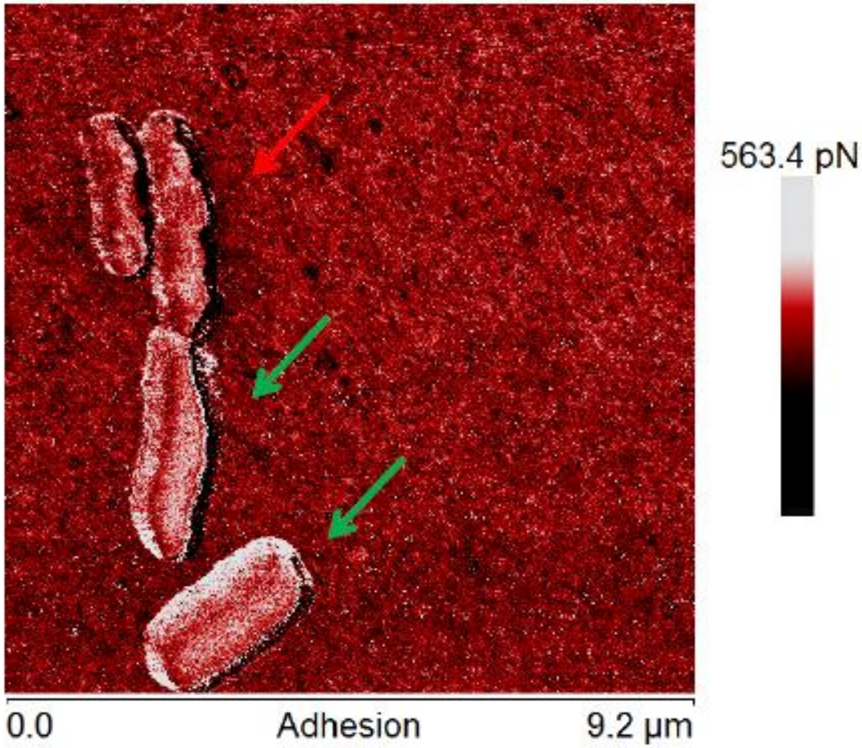


E. coli live vs. dead

- Live *E. coli* cells were fairly uniform in deformation (elasticity) while dead cells were more hetergeneous with areas of increased deformation (softer – less elastic).
- Live and dead cells showed no differences in adhesion.

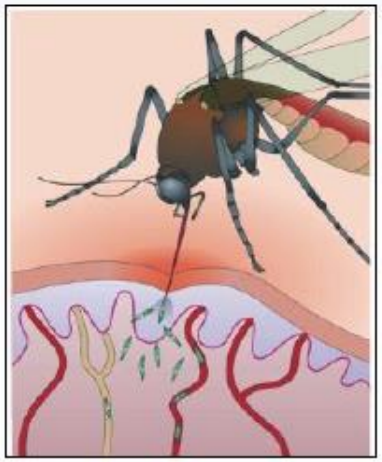


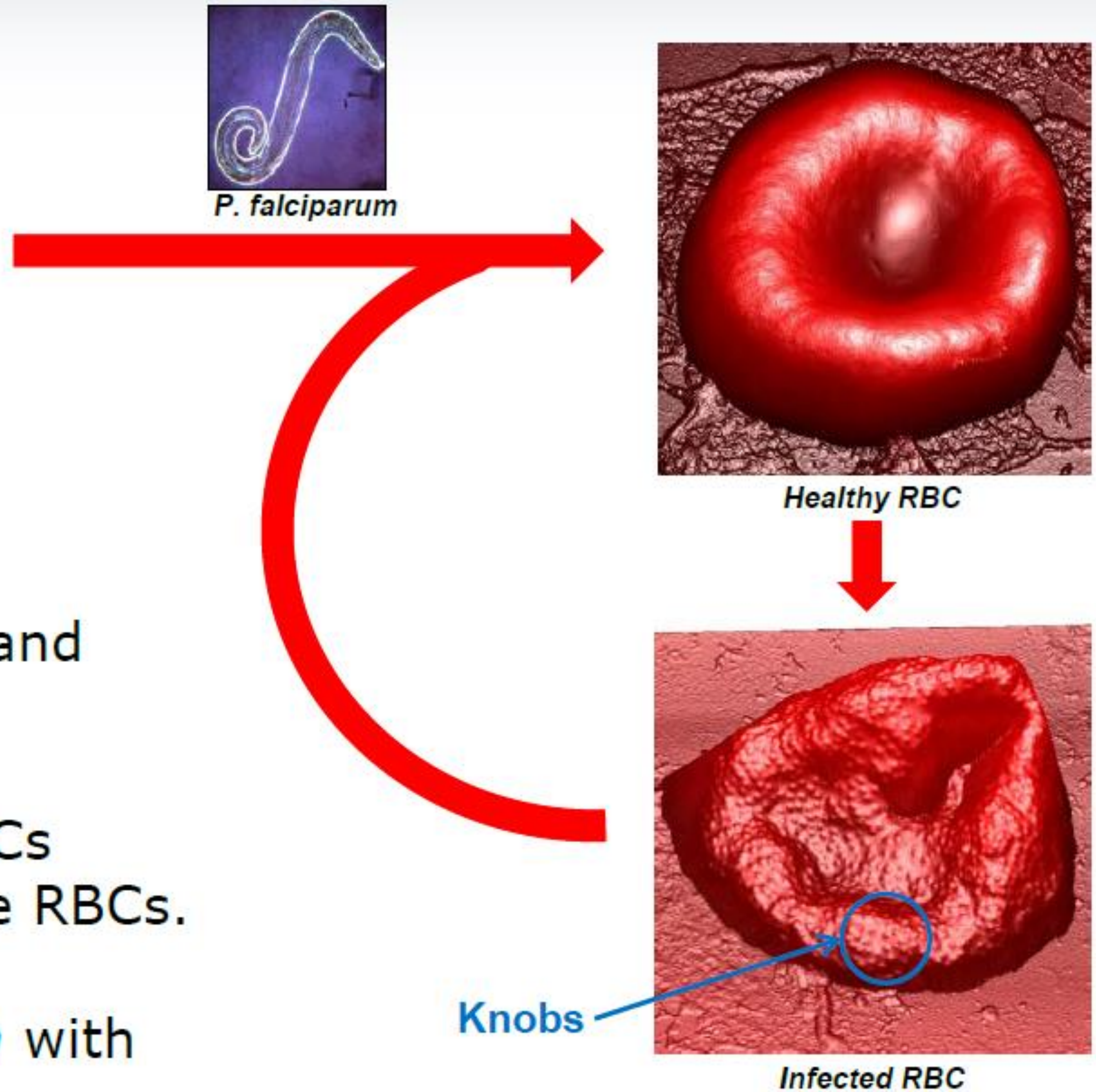




Images were obtained on a BioScope™ Catalyst integrated with a Zeiss Axiovert 200 IOM and operated in PeakForce™ Tapping Mode in fluid. Images courtesy J. Shaw, Bruker-Nano Inc.

Red Blood Cells


Anopheles mosquito

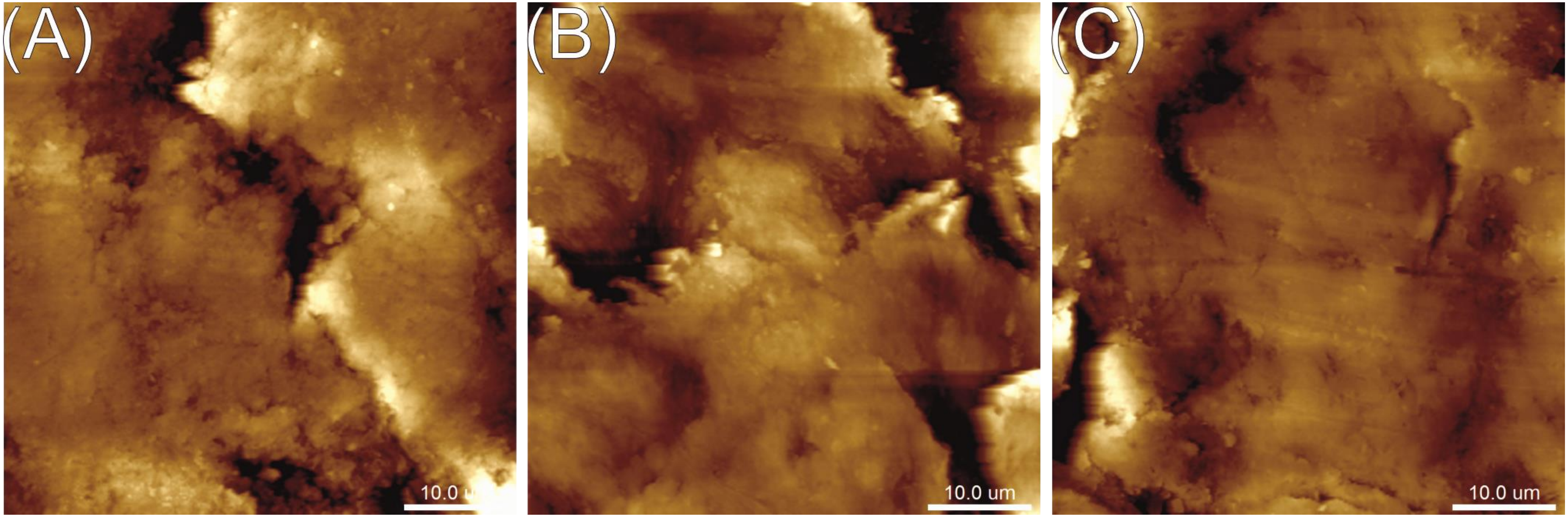


Parasites enter bloodstream and infect RBCs.

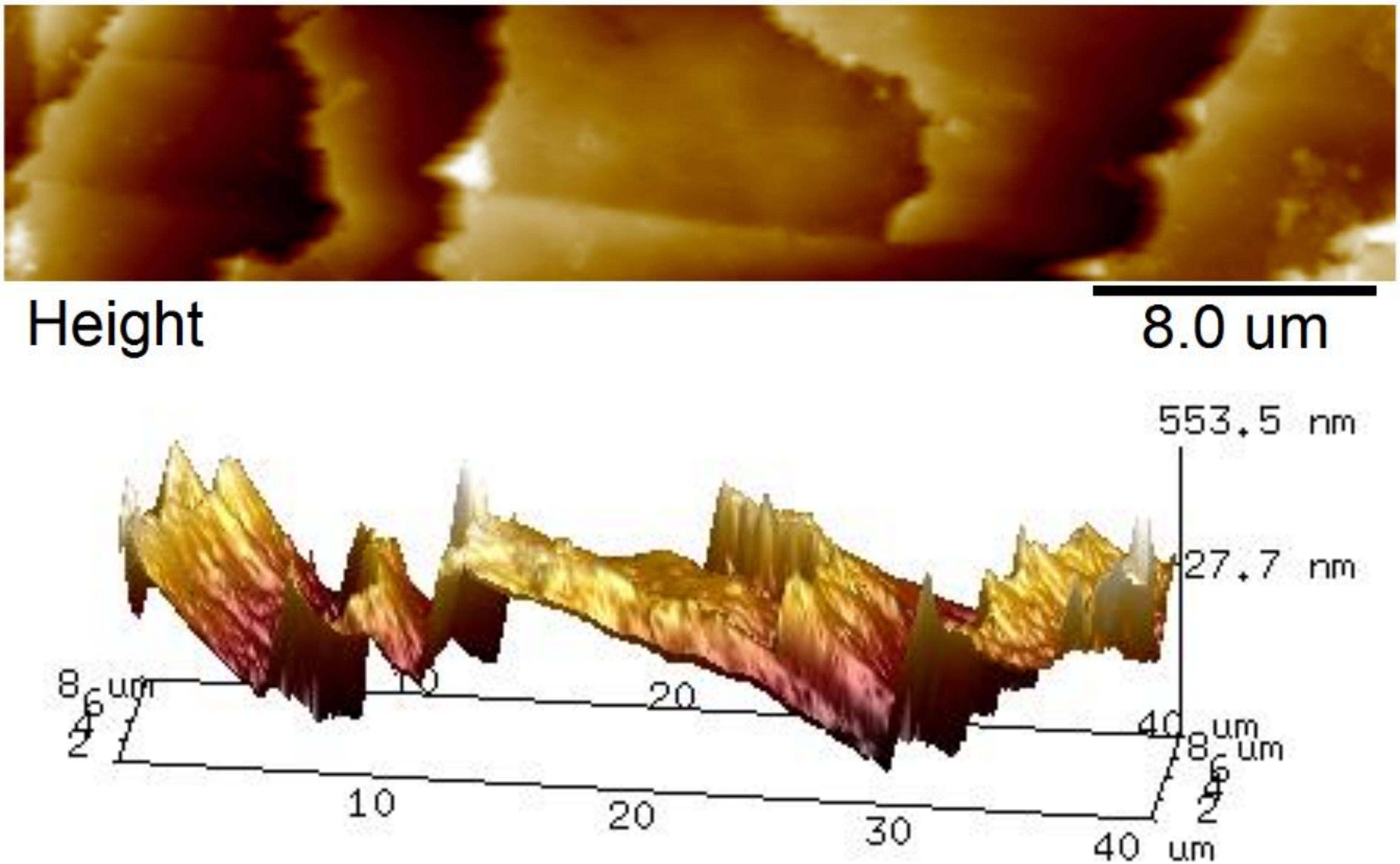
As parasites multiply, the RBCs breaks open and infects more RBCs.

Infected RBCs are *misshapen* with *knob-like structures* on surface.

Human fingernails

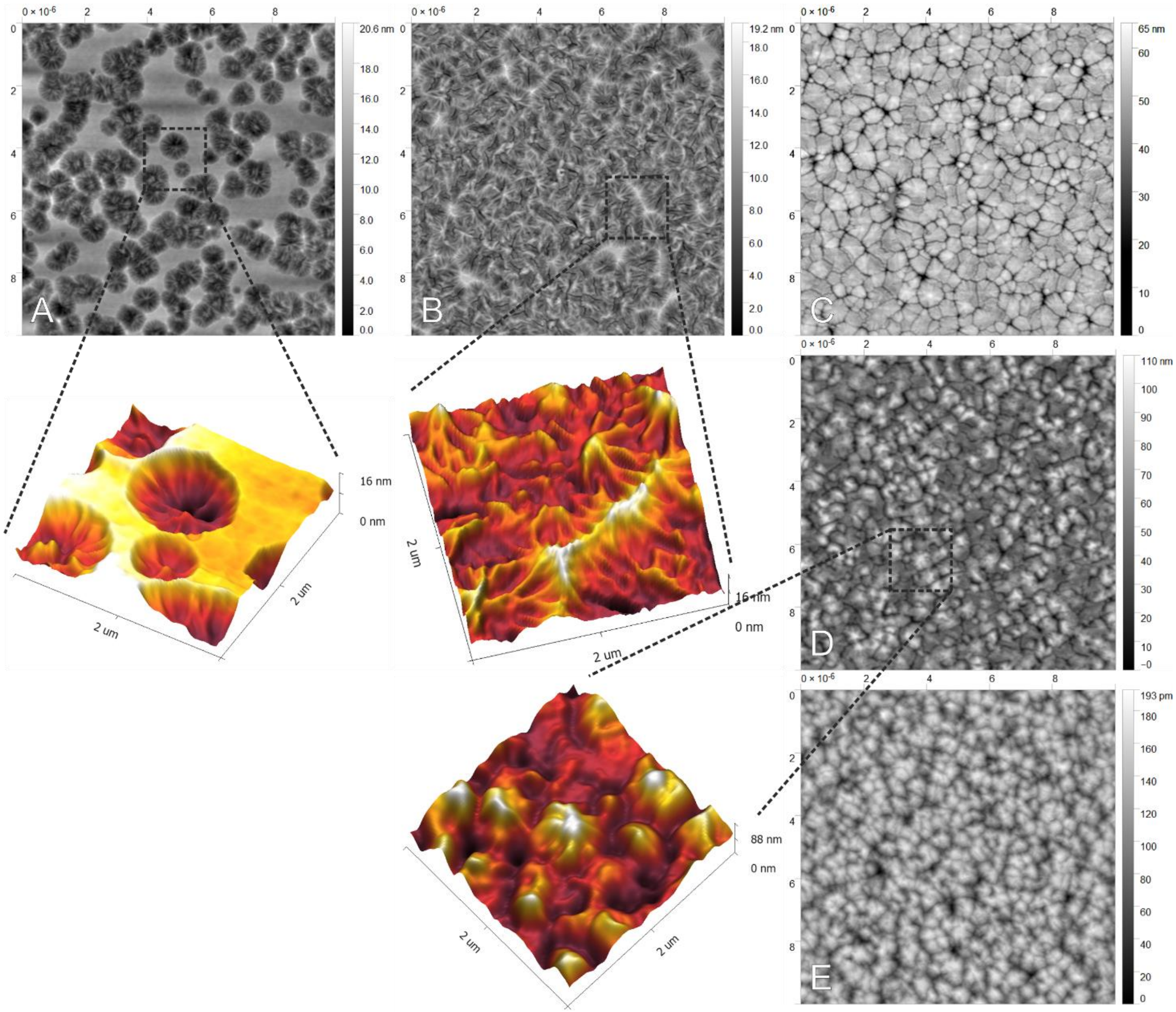


Human hair

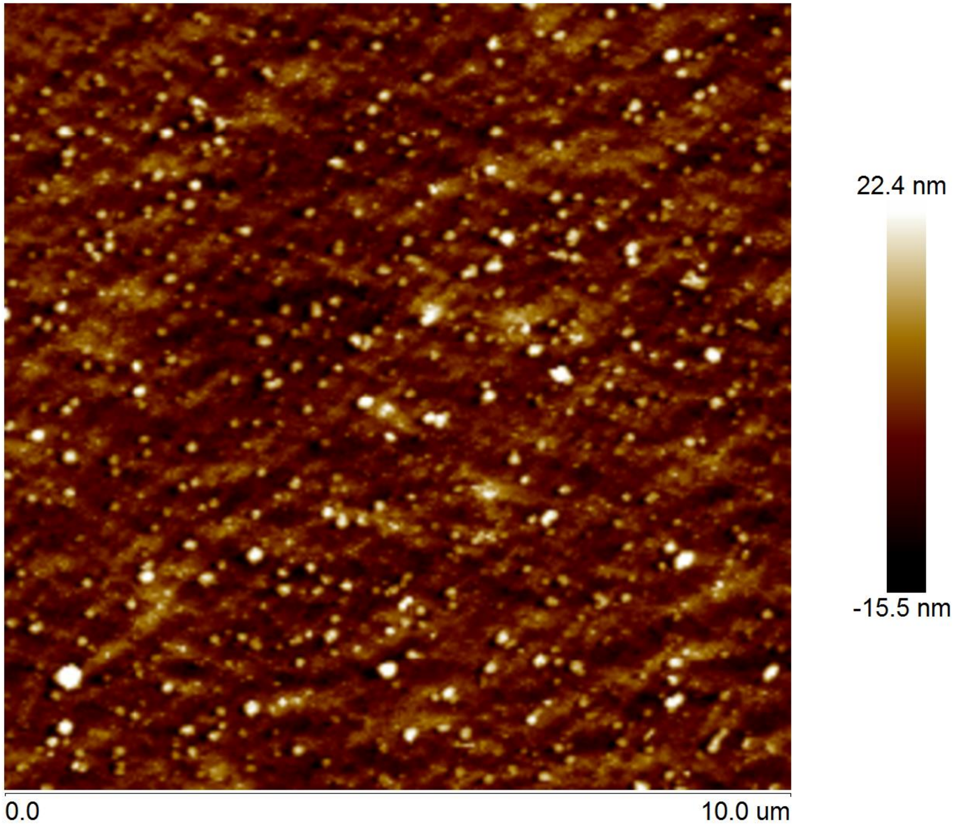


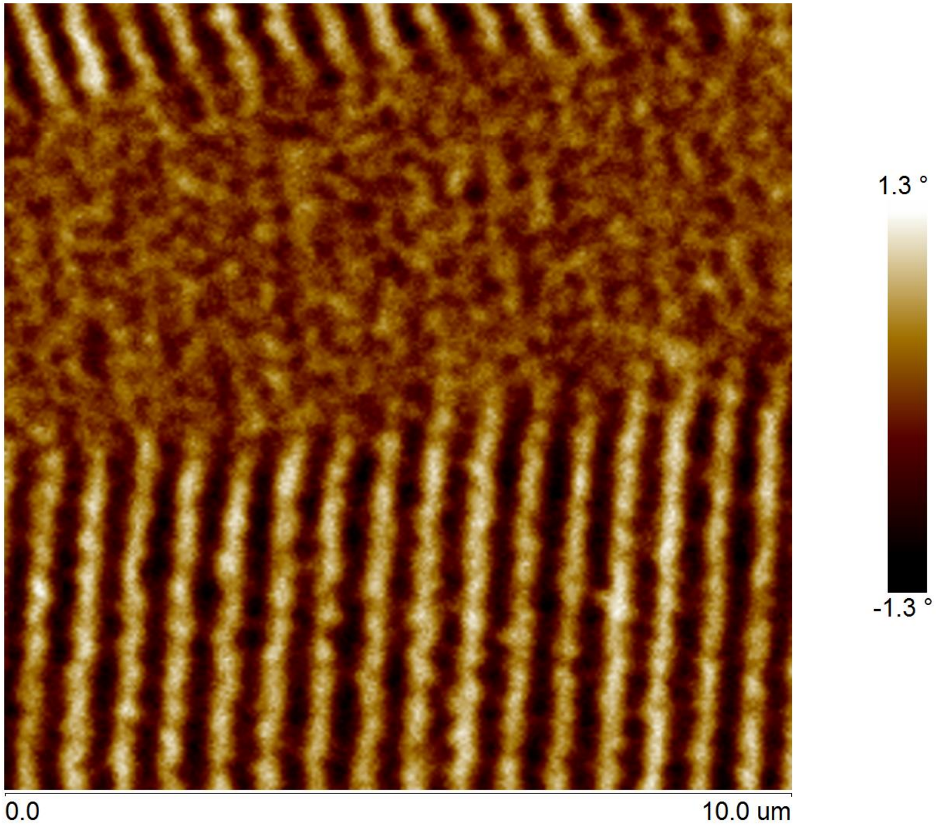
Height
8.0 um
553.5 nm
27.7 nm
8 um
6
4
2
10
20
40 um
8 um
6
4
2
10
20
30
40 um

Hydrxyapatite (HAP)

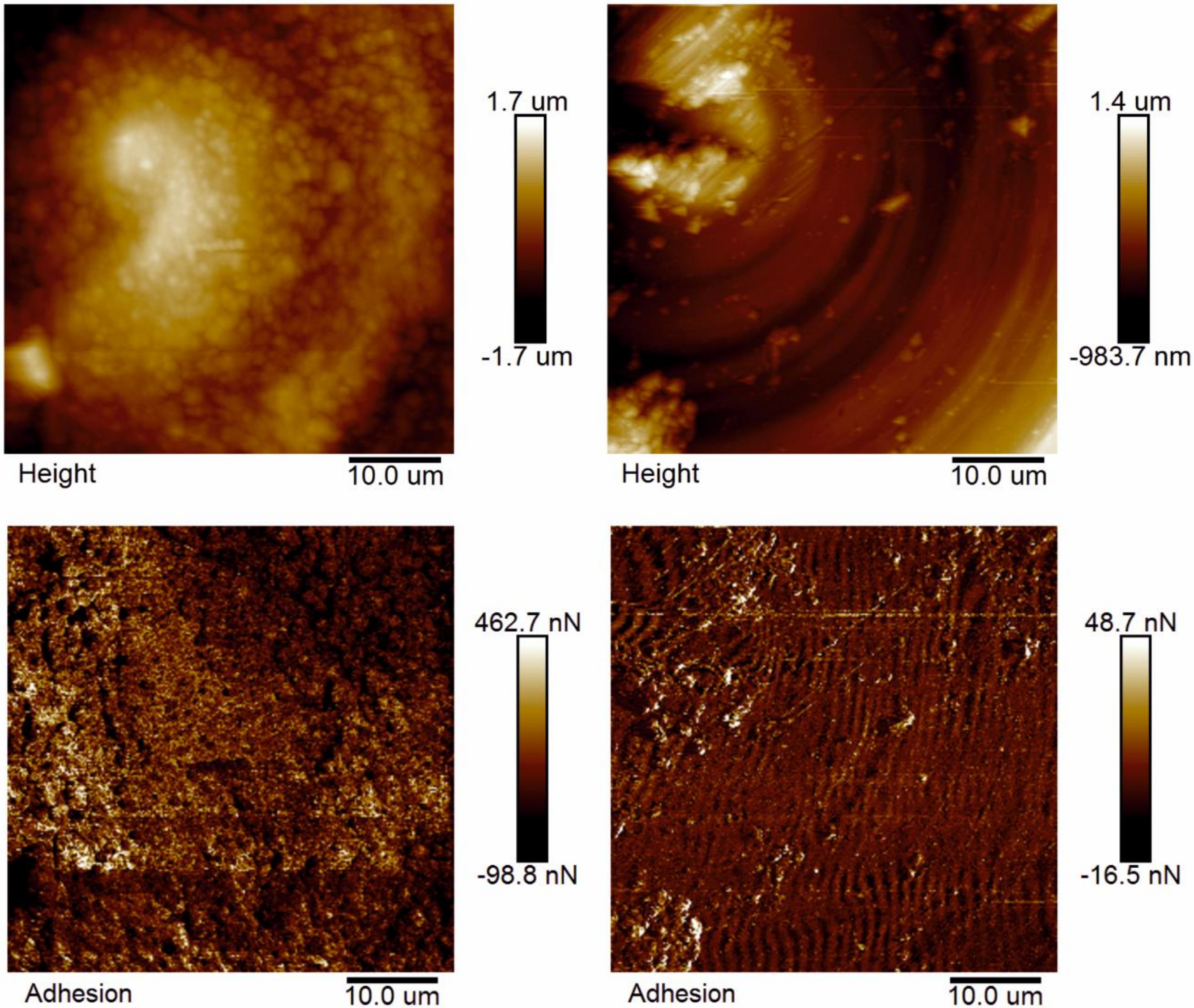


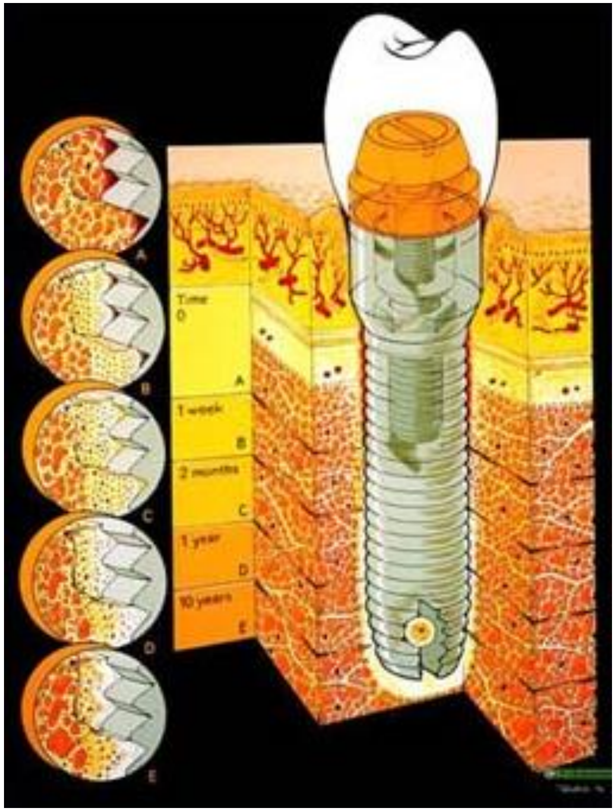
MFM – magnetic tape (VHS)





Ti dental implants





Thank you for your attention!