Shearing, plastic deformation, and friction

$$A = \frac{F_N}{y}$$

$$F_L = \tau \cdot A$$

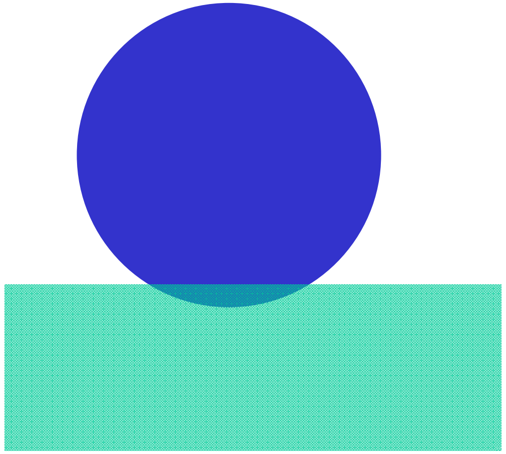
$$\mu = \frac{F_L}{F_N} = \frac{\tau}{y}$$

y – Yield strength
τ – Shear strength

$$\mu = \frac{shear\ strength}{yield\ strength}$$

Metals: μ = 0.4 – 0.6

Shearing, elastic deformation, and friction



$$F_L = \tau \cdot A$$

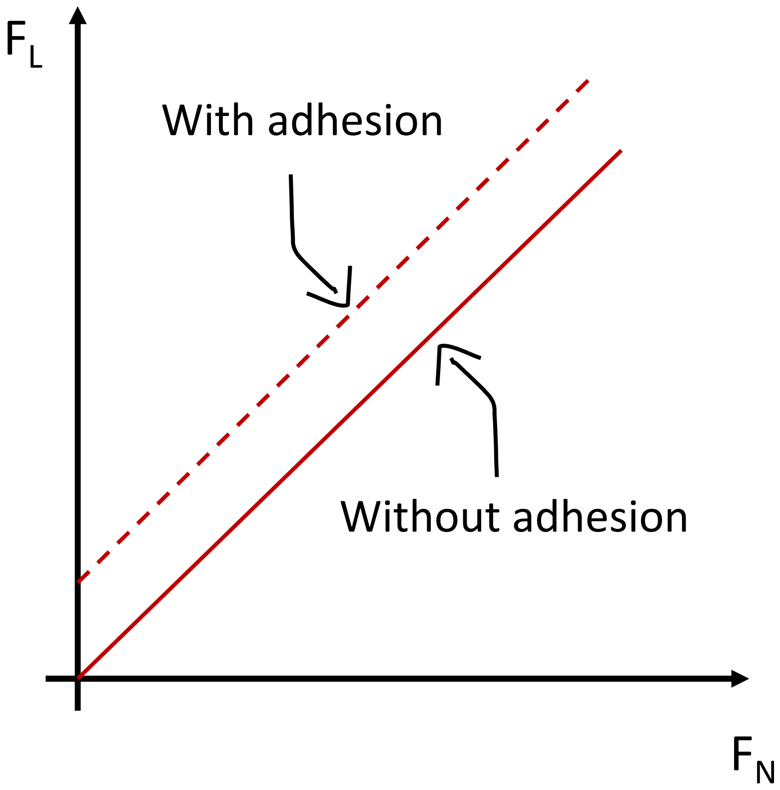
Elastic deformation described by contact mechanics

Hertz model

(sphere on flat, no adhesion)

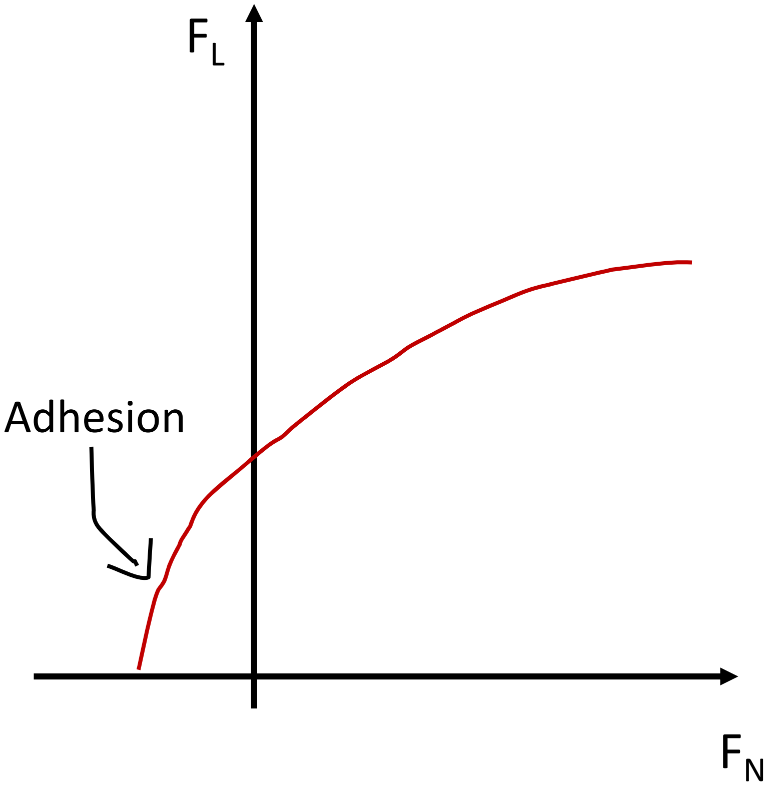
$$\boxed{F_L \propto {F_N}^{2/3}}$$

Friction vs. load curves



Macroscopic

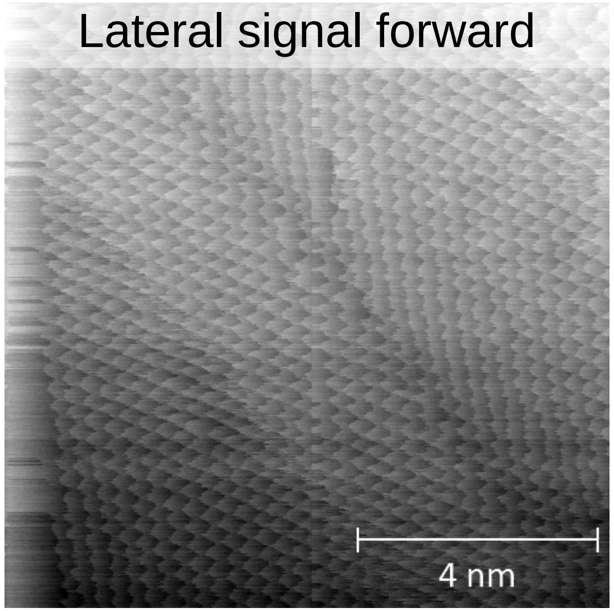
$$\boxed{F_L \propto F_N}$$

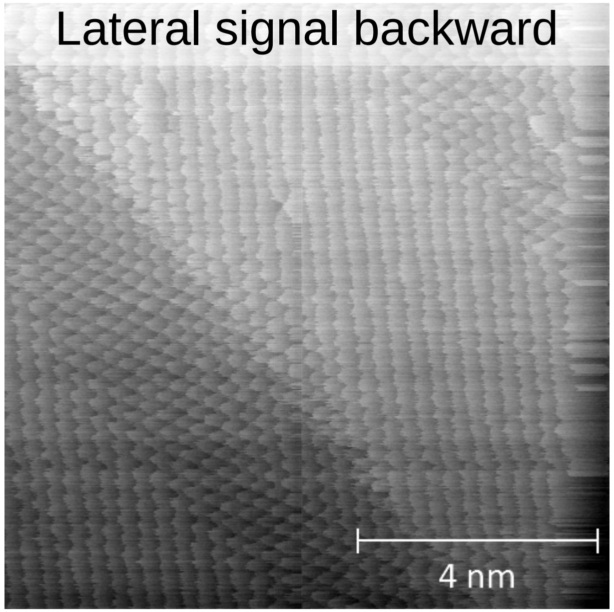


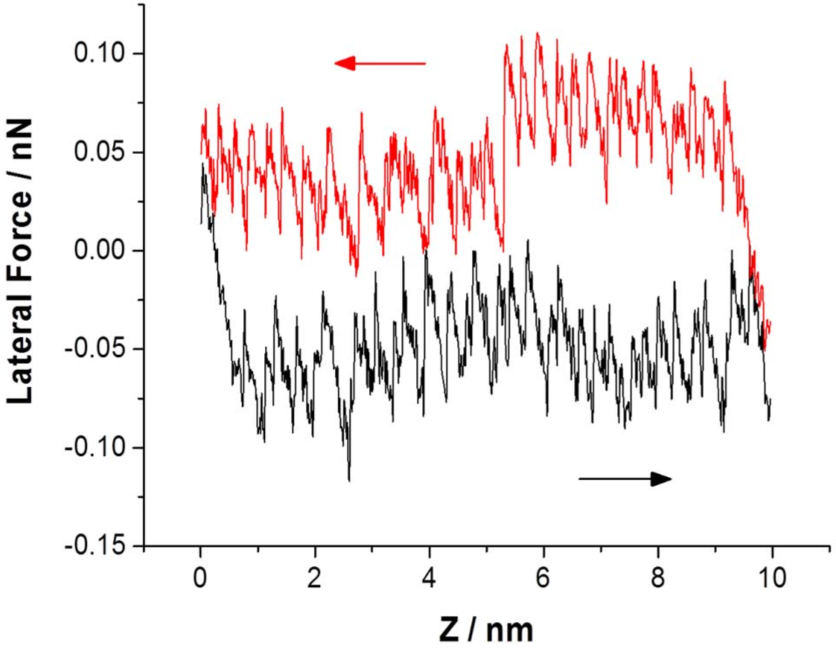
Single asperity, elastic

$$\boxed{F_L \propto F_N^{2/3}}$$

FFM image of atomic stick slip





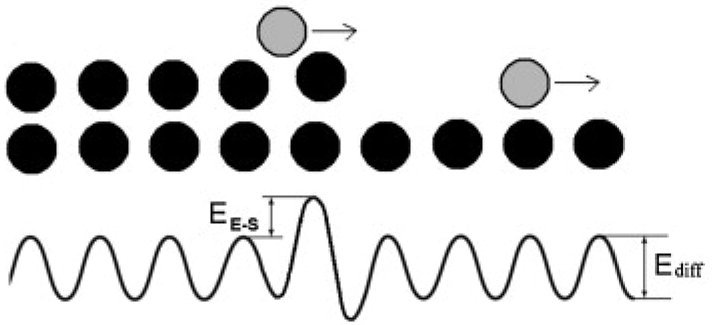


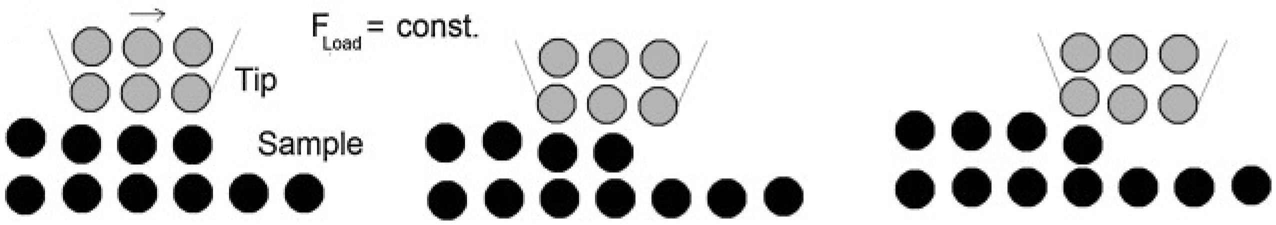
Diamond tip on Au(111)
Friction force ~0.05 nN

Typical artifacts in FFM

Ehrlich–Schwoebel barrier $E_{\text{E-S}}$

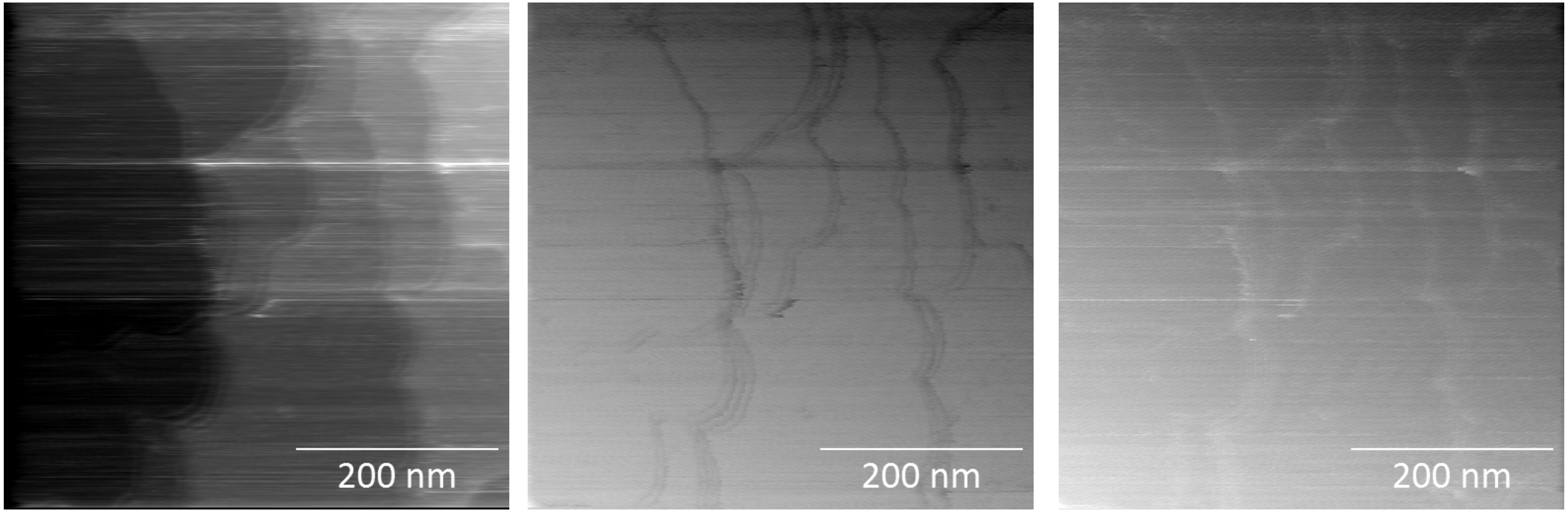
Diffusion barrier E_{diff}

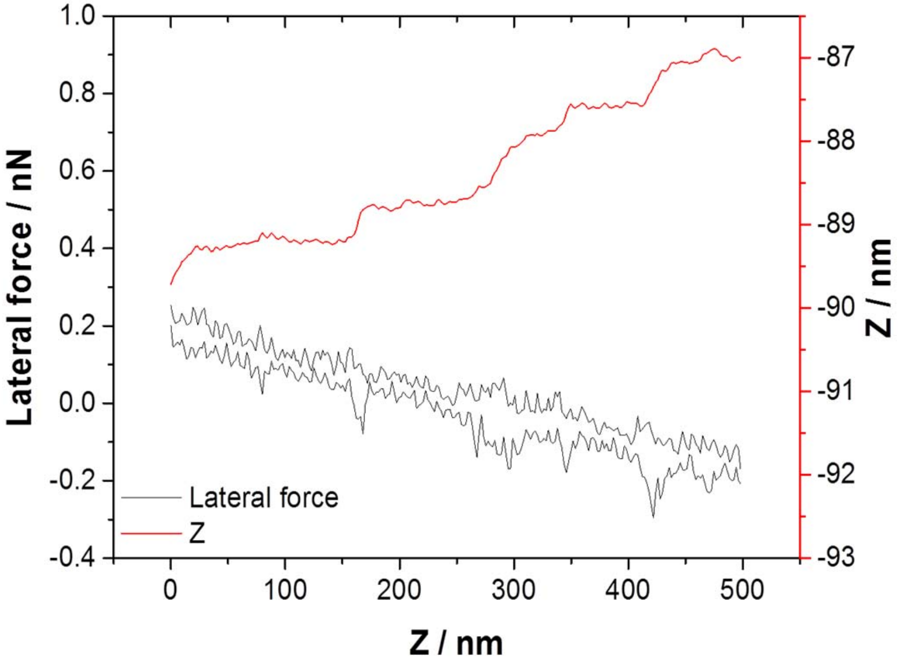




Relaxation of atomic structures at the interface between the sample and the probing tip during FFM scanning in the region of step edge. The change of effective area of interaction results in significant changes of distribution of pressure and local relaxation.

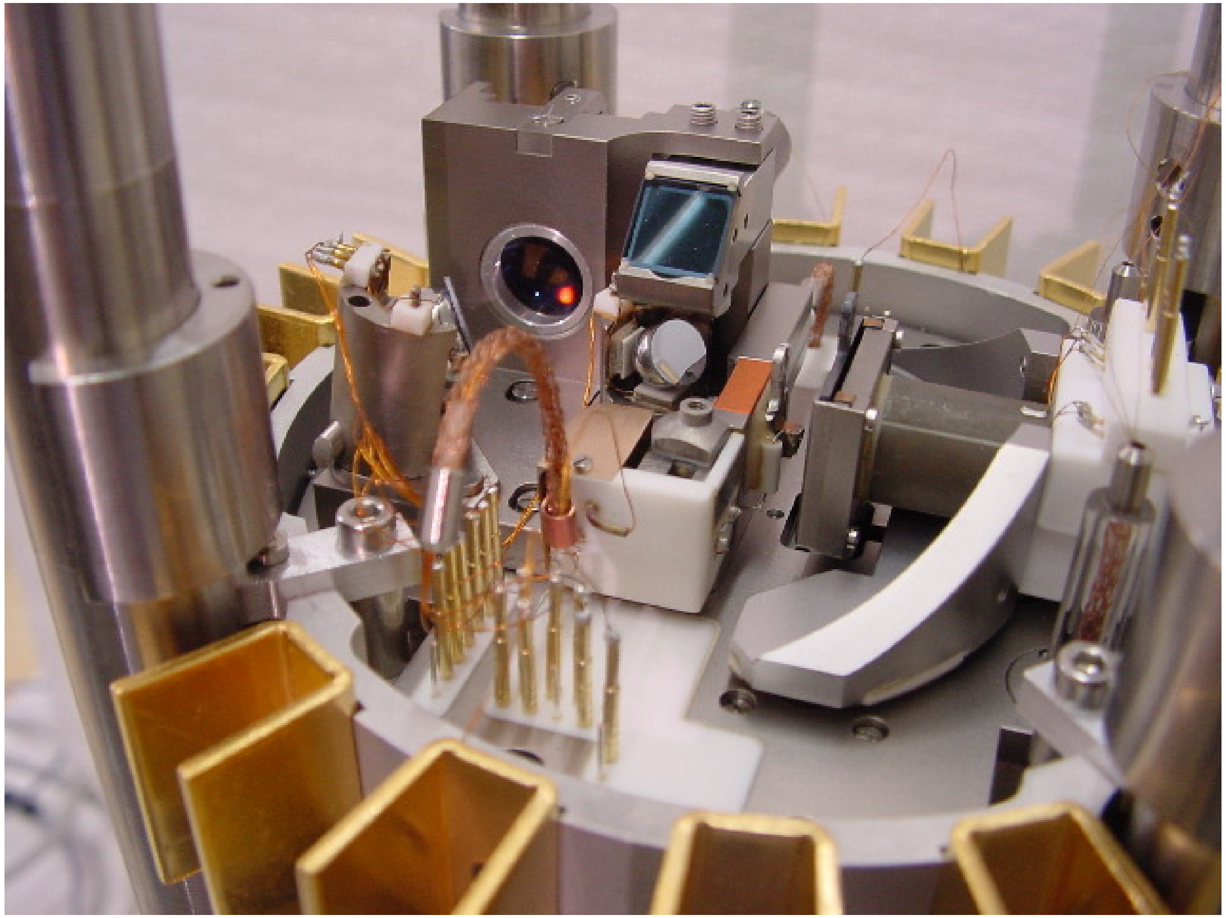
F. Gołek, P. Mazur, Z. Ryszka, S. Zuber, *AFM image artifacts,* Applied Surface Science 304 (2014) 11-19





SiO_2 tip on Au(111)
Friction force ~0.05 nN

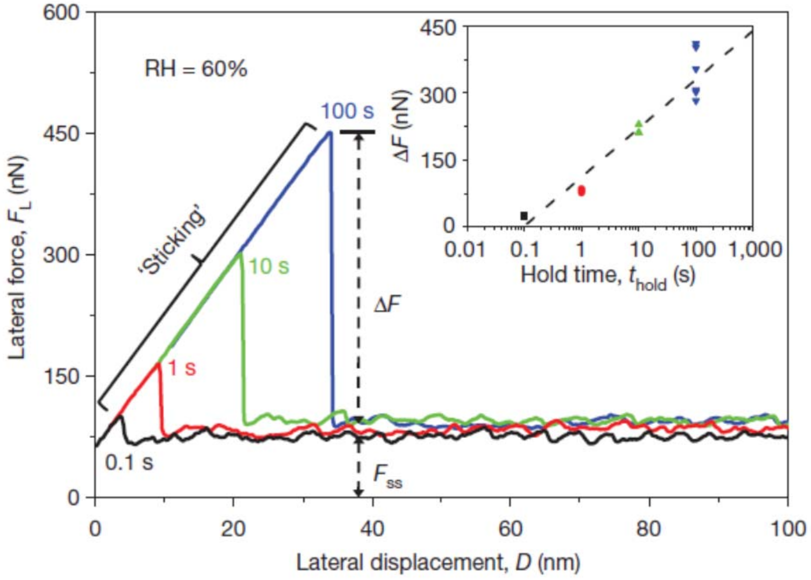
High-bandwidth friction force microscope



- Measurement of forces with 3 MHz bandwidth
- Superluminescent diode for high spatial stability.

Friction and contact ageing on pure metal surfaces

- In air, contact ageing has great influence on static friction (friction drop)[1]



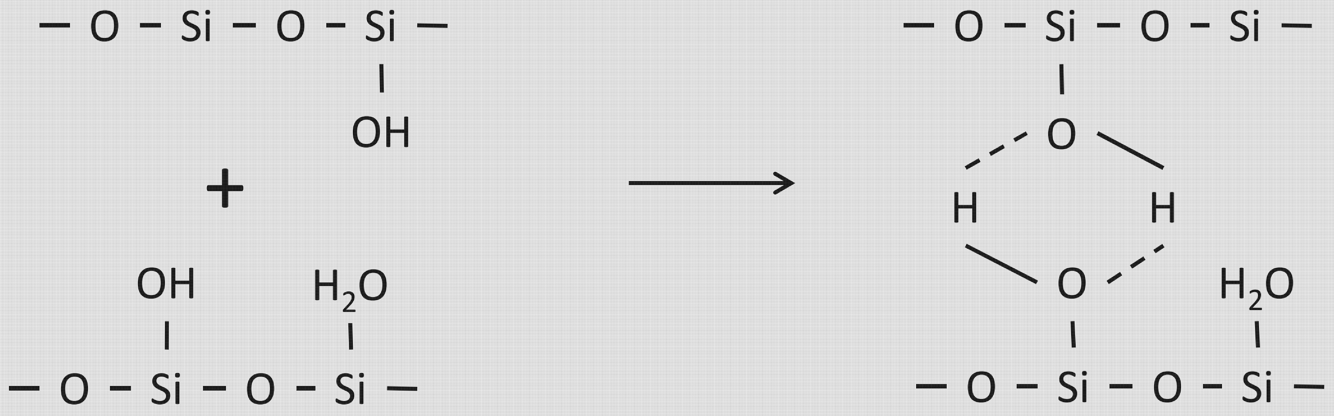
Si tip vs. Si surface
Measured in air (60% humidity)

- Reason: asperity creep or time-dependent strengthening of bonding at contact points[1]
- In UHV conditions, cold welding of Au contacts[2] and transfer of matter between AFM tip and probed surface[3] have been observed

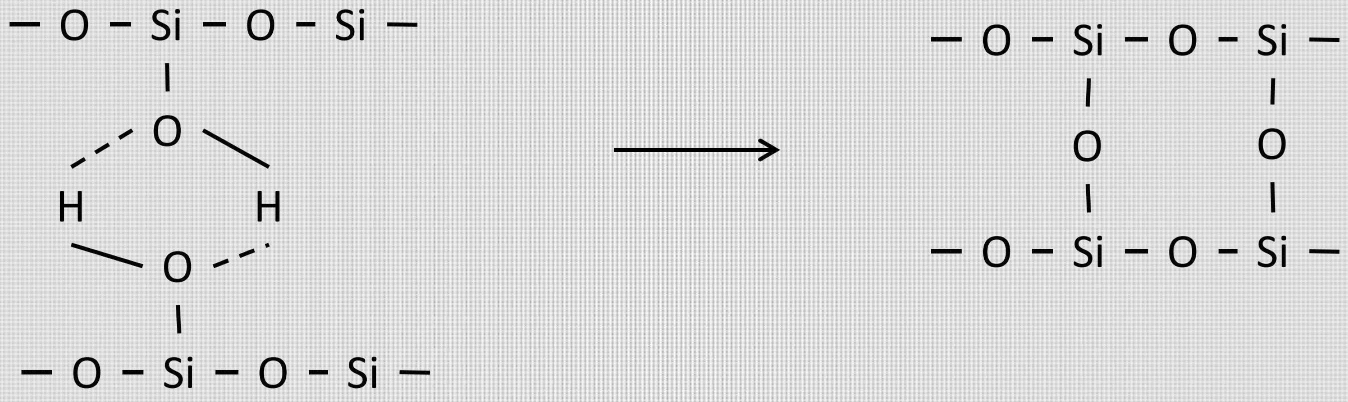
[1] Li Q et al., Nature 480 (2011) 233; [2] Budakian R et al., Phys Rev B 65 (2002) 235429; [3] Gosvami NN et al., Phys Rev Lett 107 (2011) 144303

Effect of atmosphere

In humid environment: hydrogen bonding between 2 hydroxylated silica surfaces



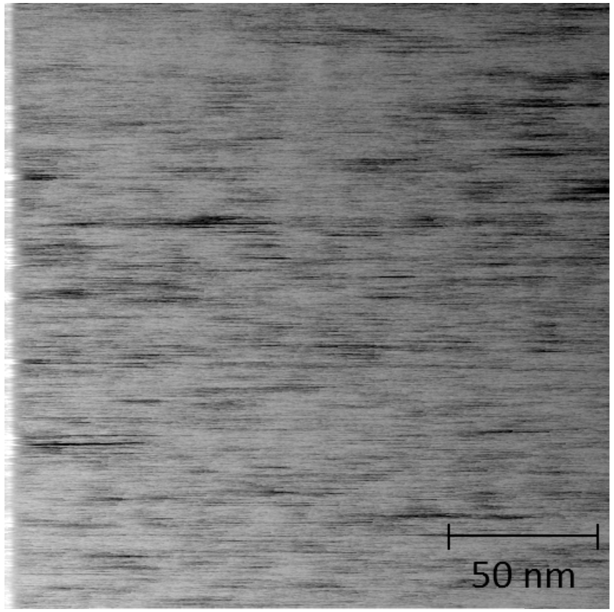
Increased T by pressure and friction: siloxane bonds can be formed

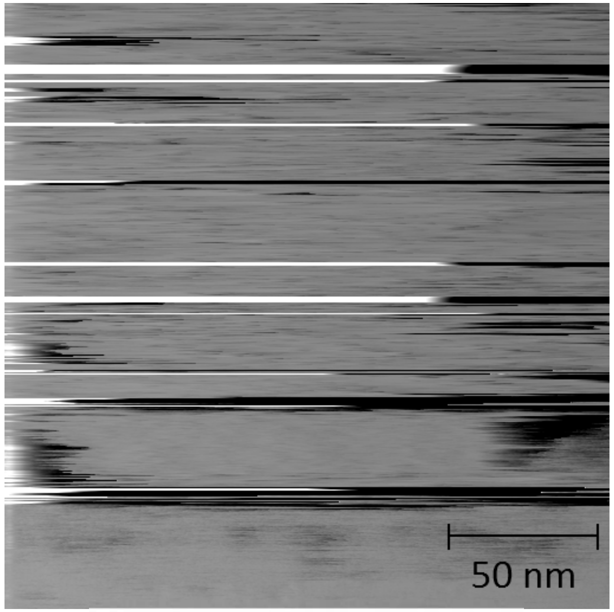


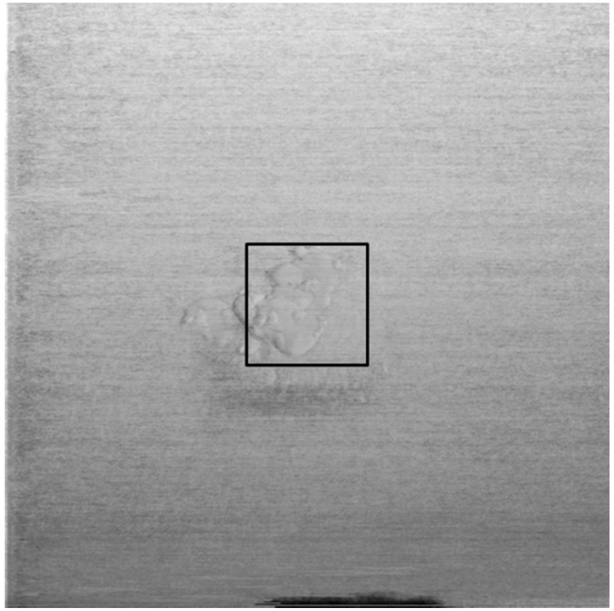
Li Q et al., Frictional ageing from interfacial bonding and the origins of rate and state friction. Nature 488 (2011) 233

Friction and contact ageing on pure metal surfaces

- Contact ageing in UHV?

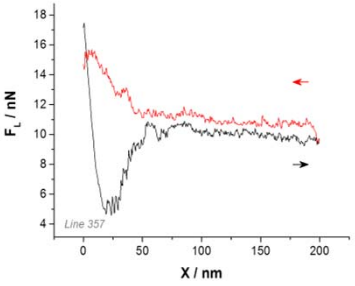


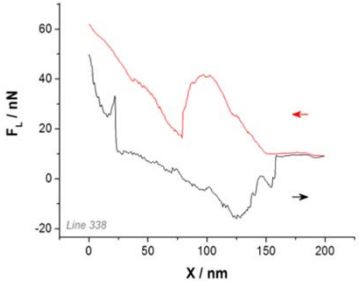




FF-image (FW) 046

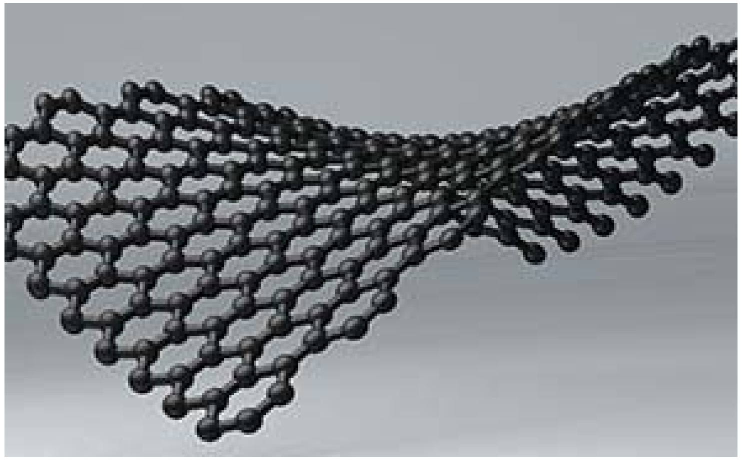
200 nm



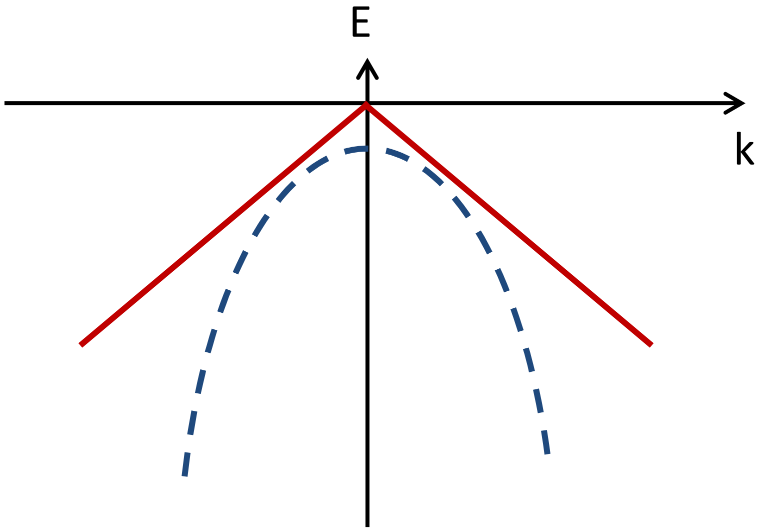


Petzold C et al. unpublished results

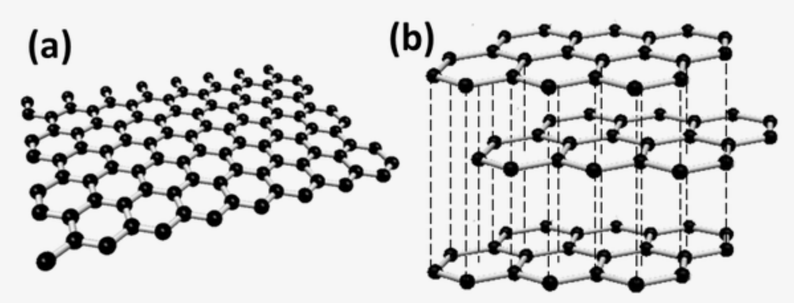
Graphene – Superstar material



http://graphene-flagship.eu/



Graphite (b) is a great solid lubricant (except in vacuum), what about graphene (a)?

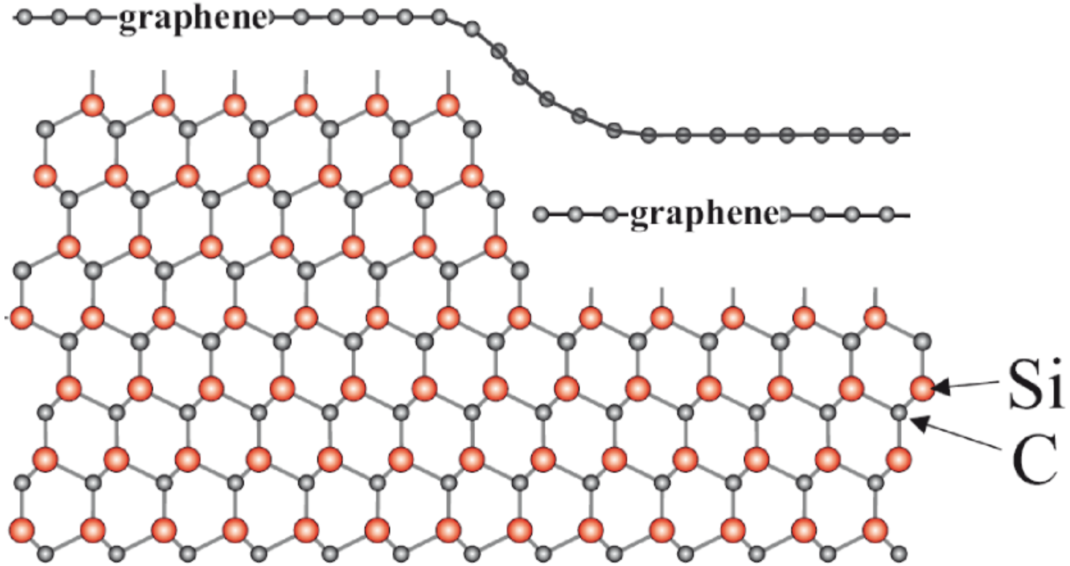


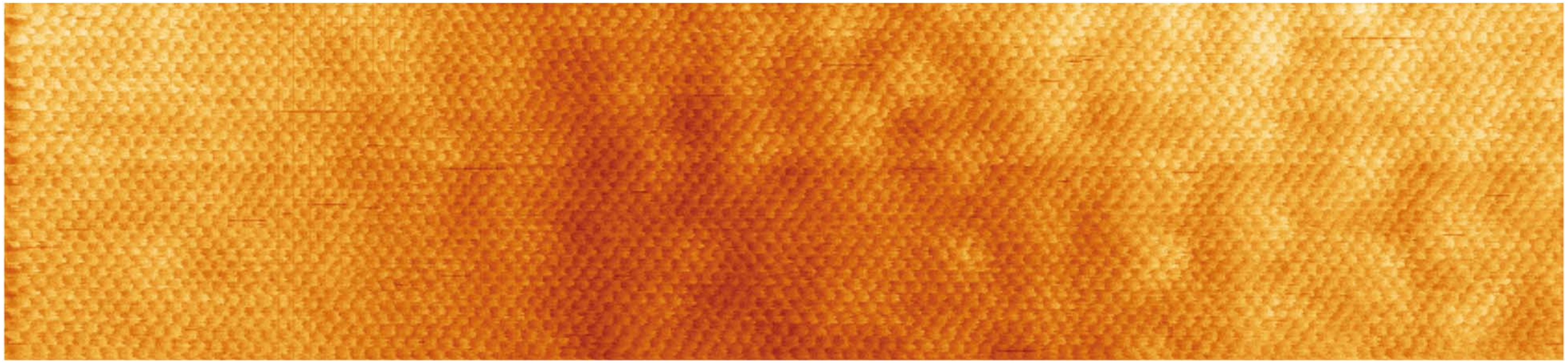
Bandgap of graphite vs. graphene

- Infinitesimal for graphene
- Zero-bandgap-semiconductor
- E – Electron energy
- k – Momentum (wave vector)

Epitaxial graphene on SiC(0001)

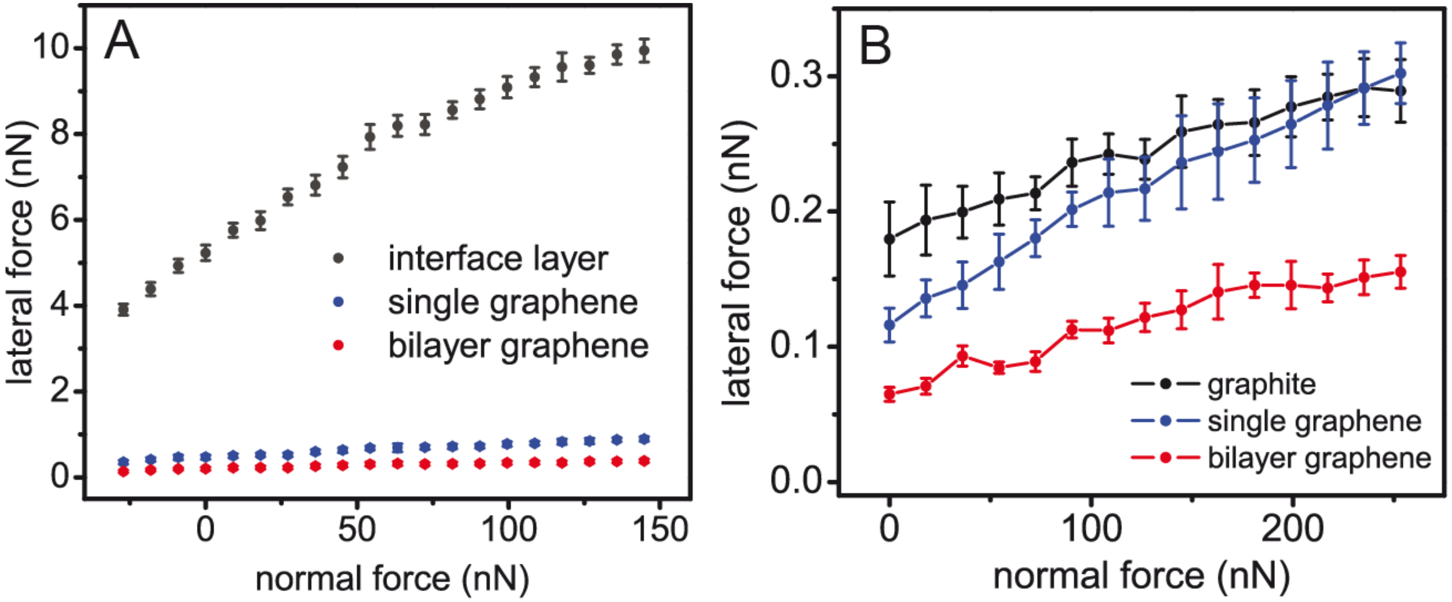
- Graphene grown by thermal decomposition in Argon atmosphere
- Top layer of graphene covers substrate steps like a carpet
- Atomic friction reveals structure of the glide plane





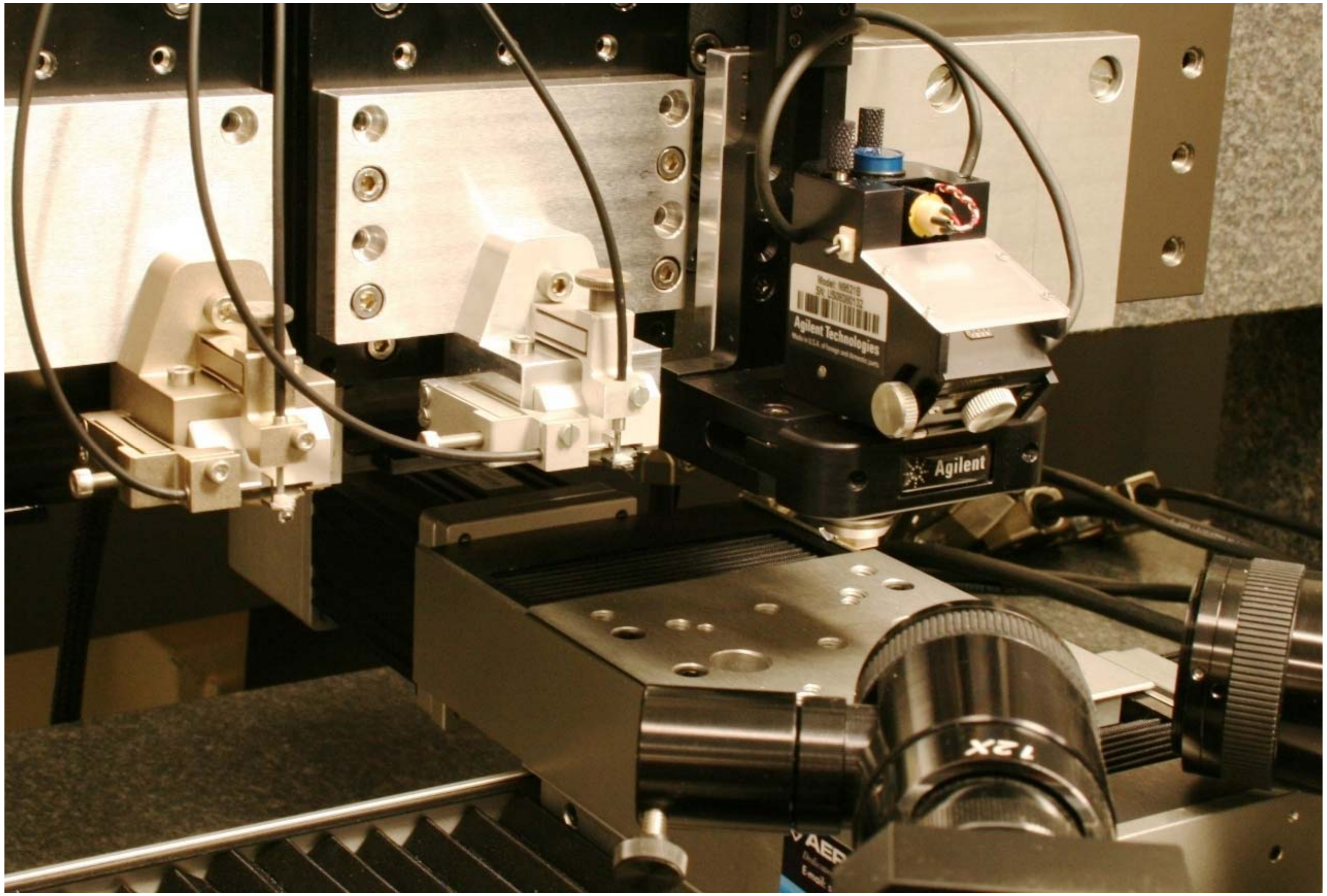
Friction on graphene vs. graphite

- Huge decrease of friction compared to (contaminated) interface layer.
- Factor of two in friction between single and bilayer graphene.
- Bilayer outperforms graphite as solid lubricant due to lower adhesion.



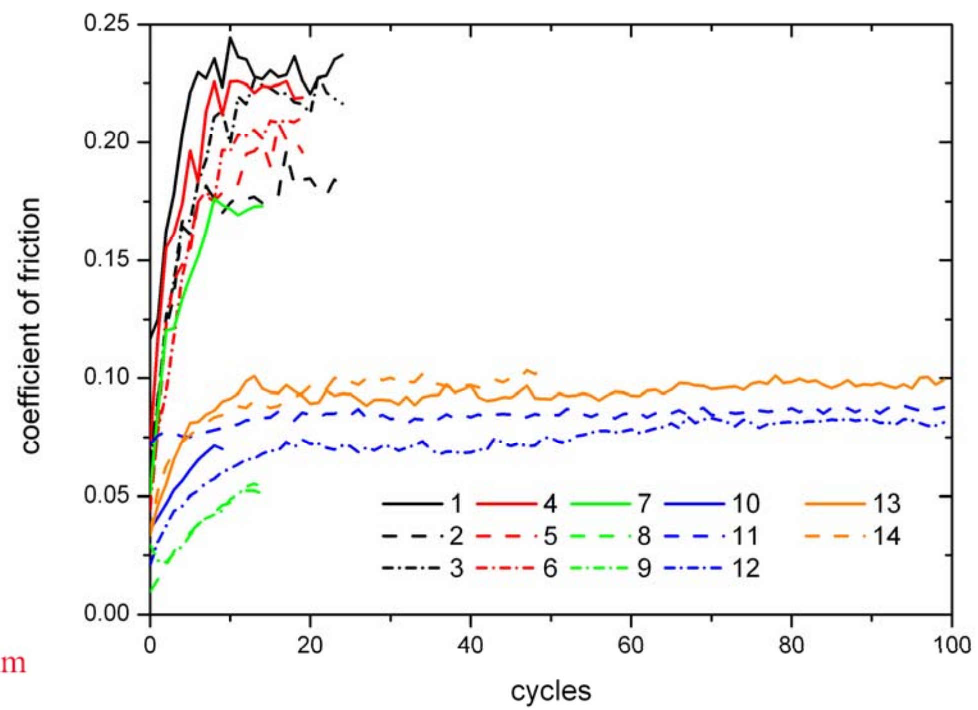
T. Filleter et al., Phys. Rev. Lett. 102 (2009) 086102.

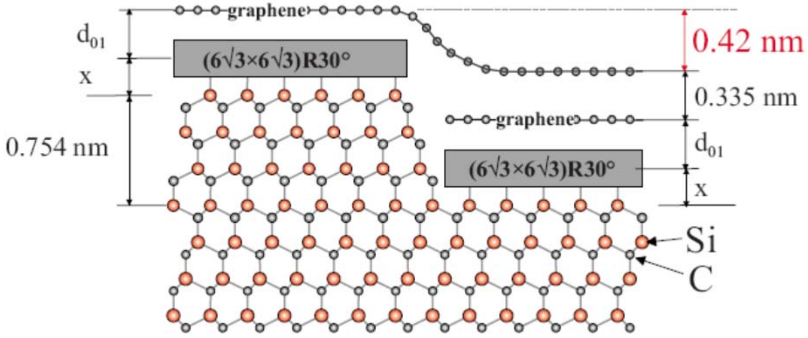
Multi-scale tester MuScaT



Microtribometer experiments

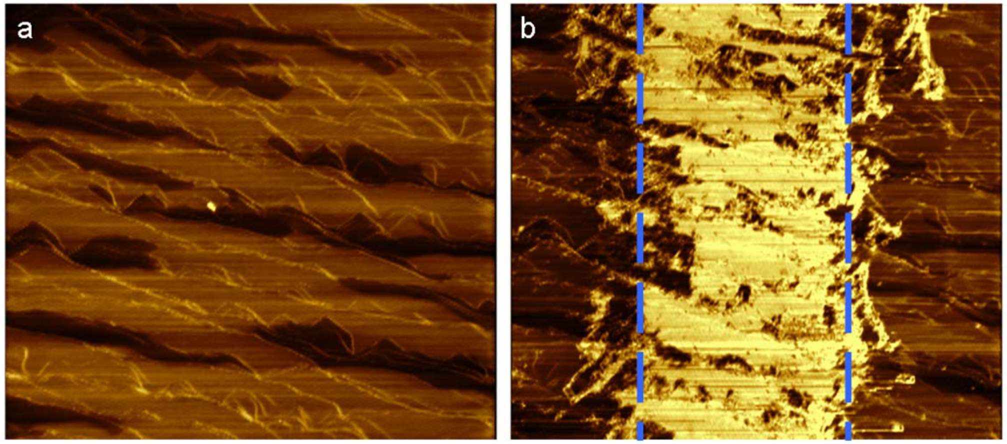
- 500 µm ruby sphere in reciprocal sliding over 400 µm.
- Very low initial friction.
- Steady-state friction coefficient still lower than on SiC.
- Poor reproducibility between experiments is caused by variations in the sphere, not the surface.





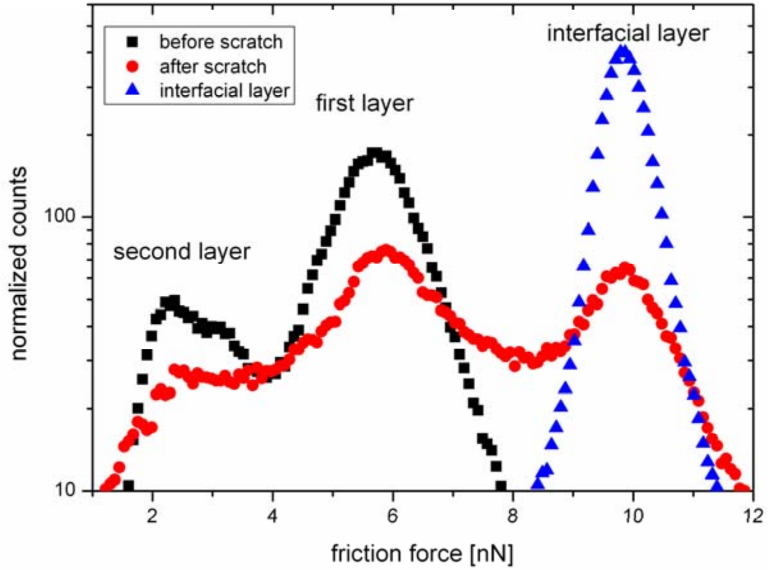
F. Wählisch et al., Wear 300 (2013) 78

Friction force microscopy of track



- Friction force microscopy reveals contrast between single and bilayer graphene.
- Sliding track exhibits higher constant friction, except for low-friction patches.
- Substrate steps not affected.

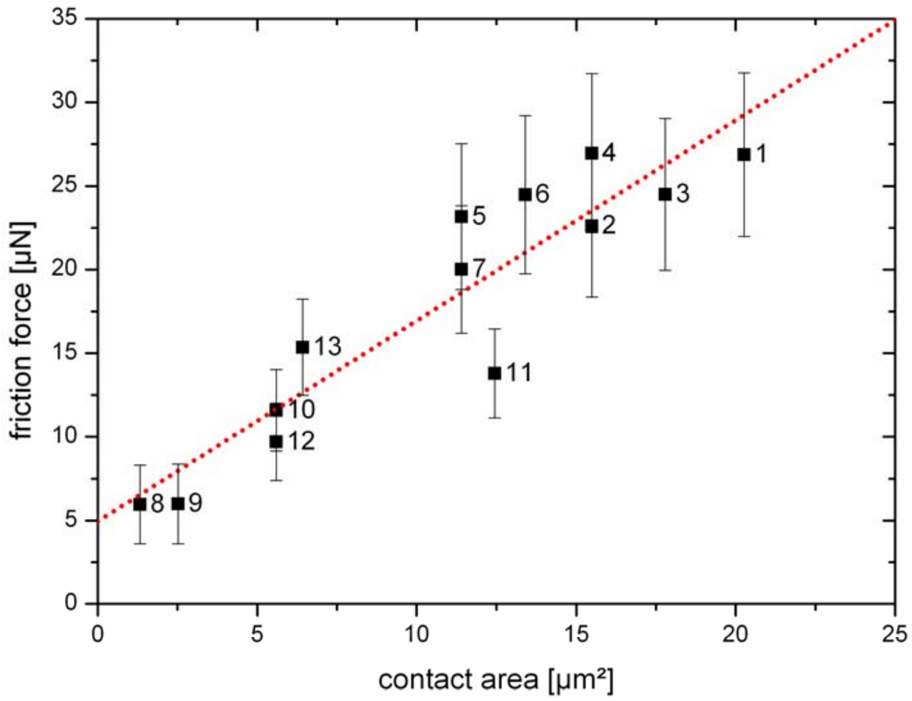
- Histogram of friction forces confirms that surface exposed in the sliding track is the carbon-rich interface layer.



F. Wählisch et al., Wear 300 (2013) 78.

Sorting results by contact area

$F_L = \boxed{\tau \cdot} A$

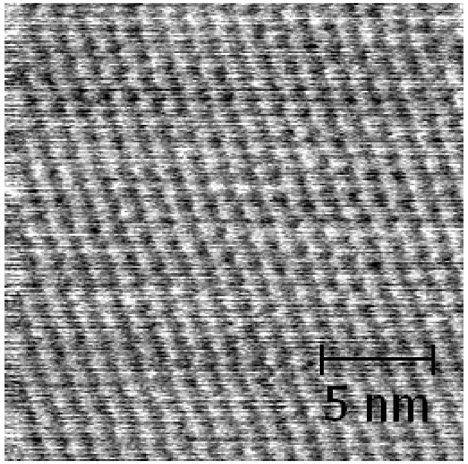


- Friction force microscopy shows varying contact width for different experiments.
- Friction force is proportional to contact area, calculated from width of sliding track.
- Shear strength of 1.2 MPa for the contact between the ruby sphere and the graphitic interfacial layer.

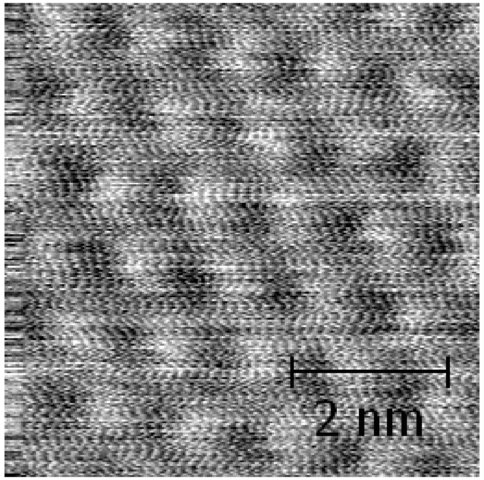
F. Wählisch et al., Wear 300 (2013) 78.

Friction on graphene/Pt(111)

- Ultrahigh-vacuum atomic force microscopy
- Modulation of lateral force.
- Periodicity too large for graphene structure.
- Friction follows Moiré pattern.



http://nickyhamlyn.com/images-4/



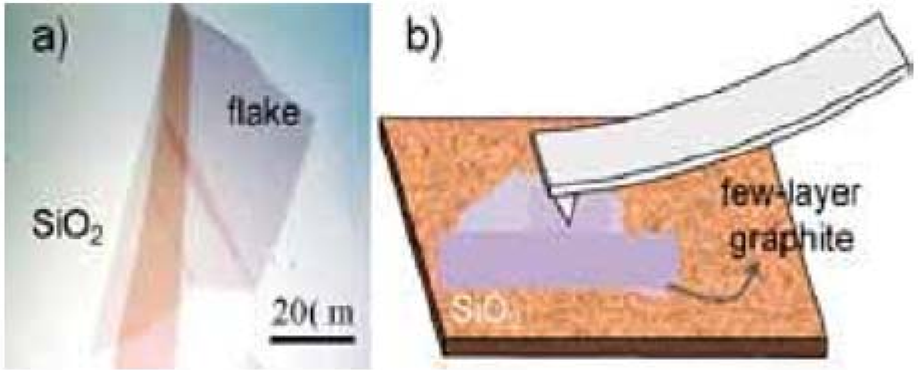


Fig. 3 (a) Optical image of exfoliated graphene on SiO_2/Si, showing the dimension and thickness contrast of the flake; (b) a schematic of an AFM tip scanning over a flake containing areas with different thicknesses. Li Q et al., Physica Status Solidi (b) 247 (2010) 2909

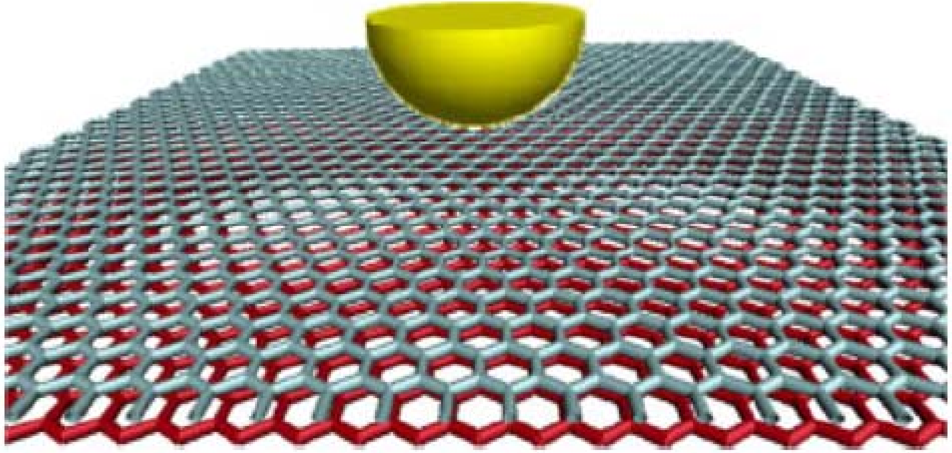


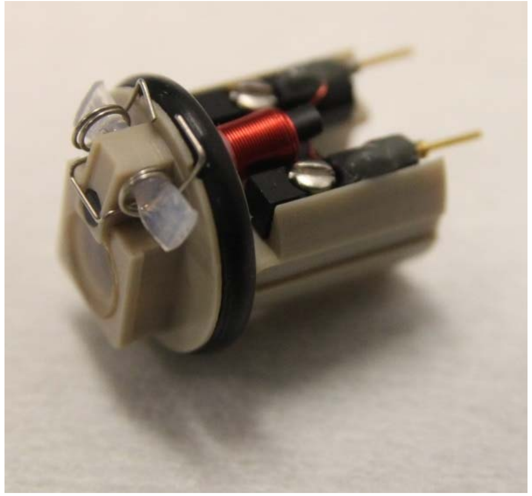
Fig. 2 Simulation of a spherical nanoasperity sliding over a graphene film (gray bonds) supported by a substrate of rigid atoms (red bonds).

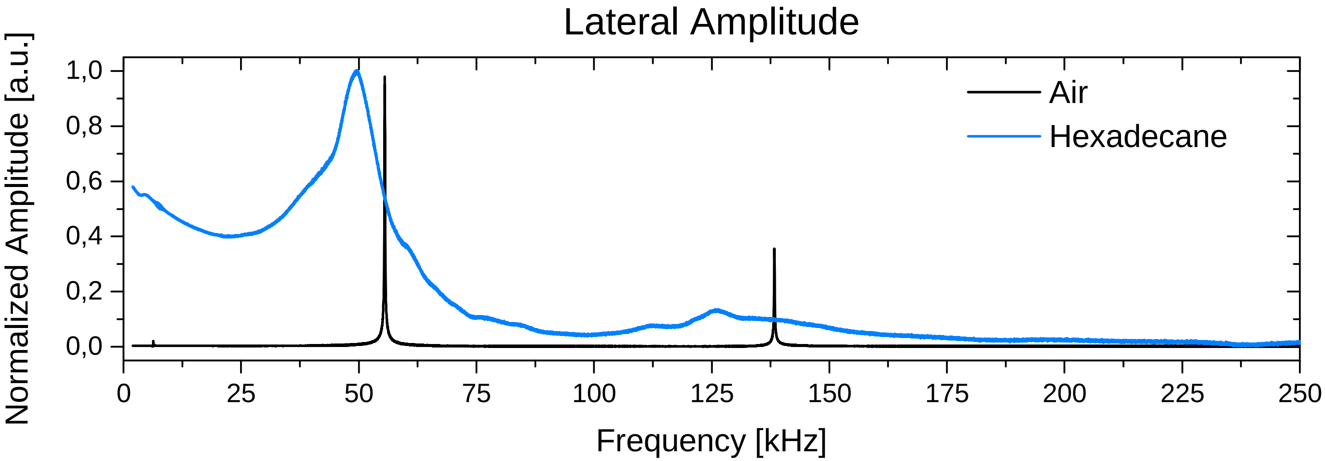
Sandoz-Rosado E J et al., Carbon 50 (2012) 4078

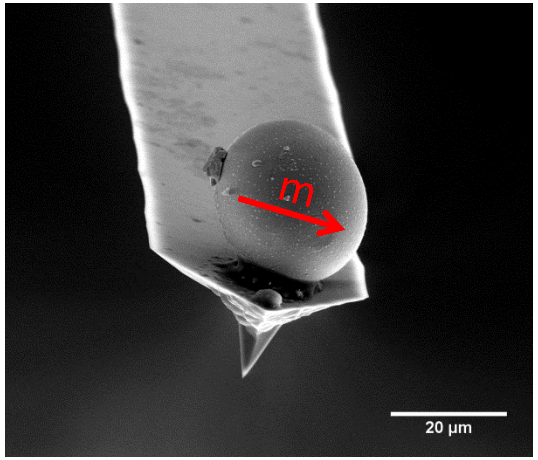
Penkov O et al., Int J Precision Eng Manufacturing 15 (2014) 577

Magnetically activated torsional oscillations

- Magnetic particle attached to the back side of the cantilever
- Magnetic field in z-direction creates a torque on the bead
- AC-driven solenoid excites cantilever to torsional oscillations (MAC Mode Nose)







N. N. Gosvami et al., Appl. Phys. Lett. 105, 093101 (2014)

Layering of ionic liquids in AFM

At the interface: solvation and designing ionic liquids

Robert Hayes,[a] Gregory G. Warr[b] and Rob Atkin*[a]

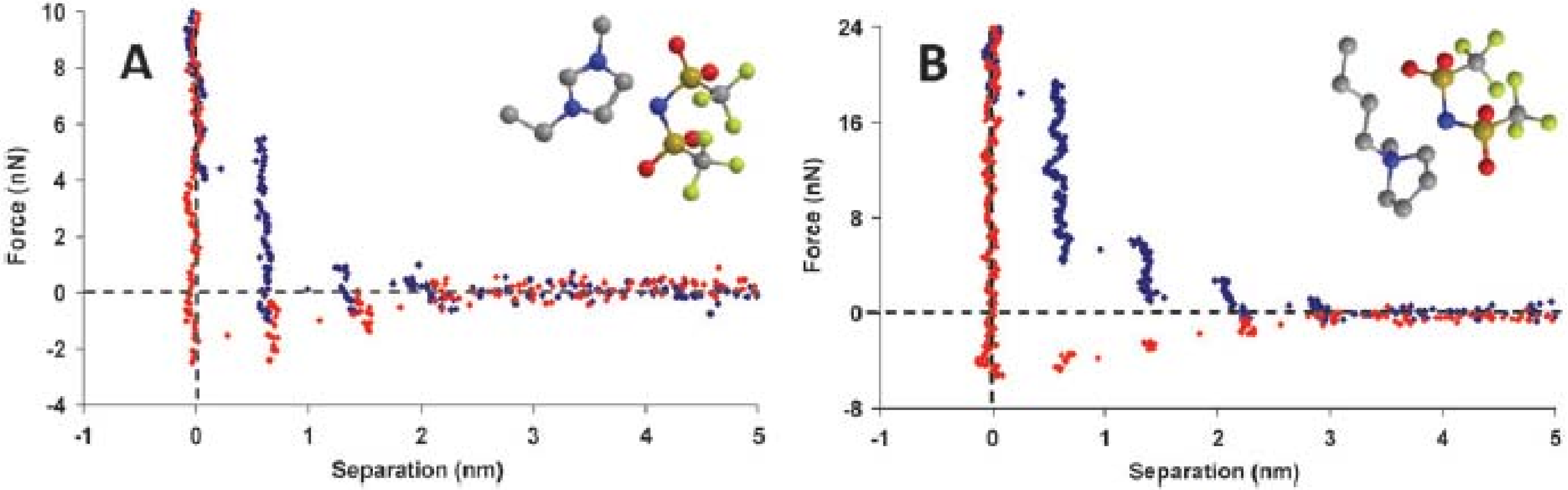
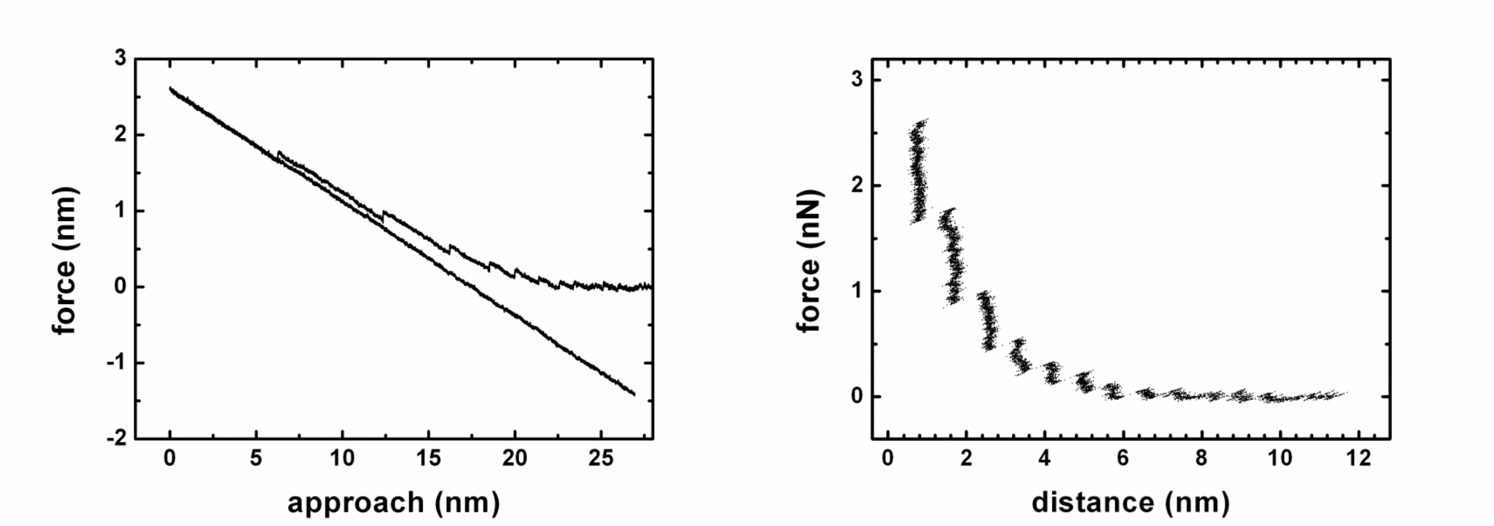


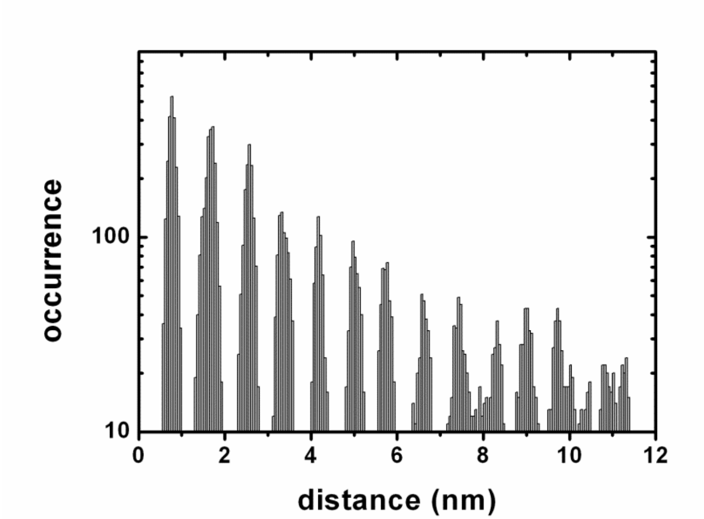
Fig. 8 Force *versus* distance profile for an AFM tip approaching (blue) and retracting from (red) a gold (111) surface in (A) [EMIm]TFSA and (B) [BMP]TFSA at 21 °C. Reproduced with permission from ref. 77.

Phys. Chem. Chem. Phys., 2010, **12**, 1709-1723

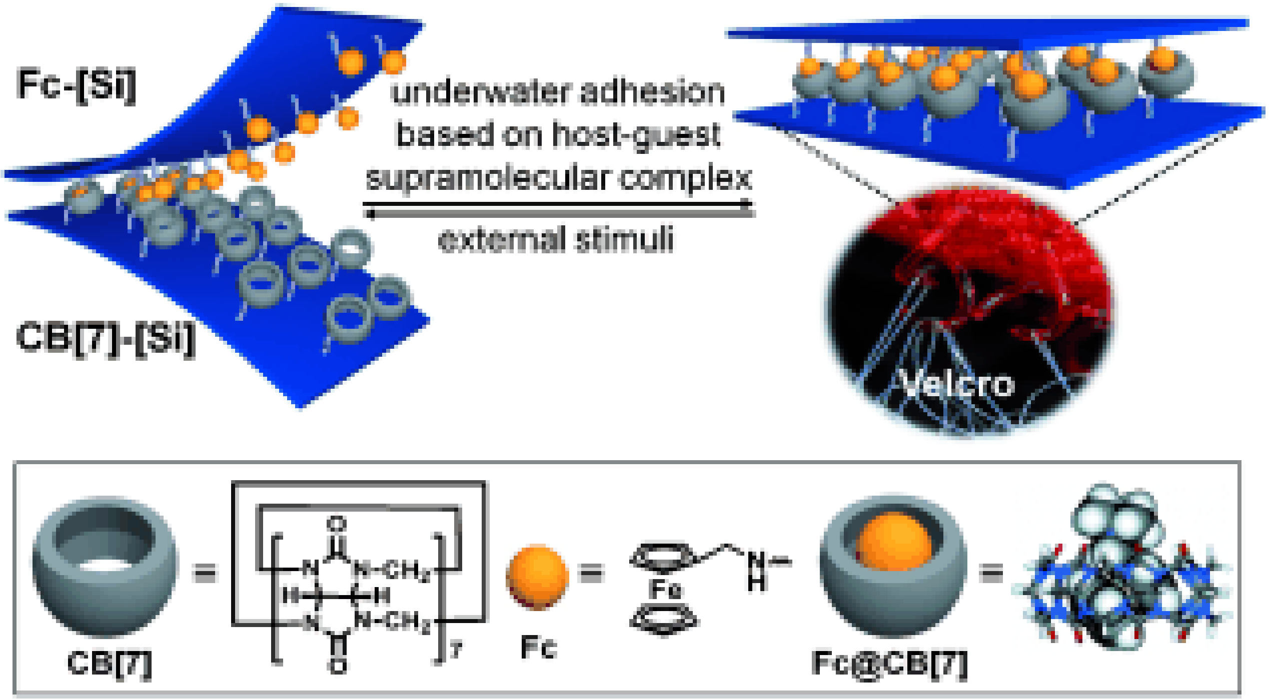
Layering of ionic liquids in AFM



- Ionic liquids exhibit layering of up to 12 layers.



J. Hoth, F. Hausen, M.H. Müser, R. Bennewitz, J. Phys. Cond. Mat. 26 (2014) 284110

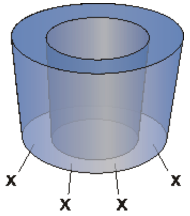


Ahn Y et al., *Supramolecular Velcro for Reversible Underwater Adhesion.* Angew. Chem. 2013, 125, 3222.

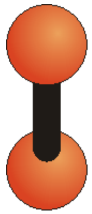
Molecular toolkit for controlling friction

- Our building blocks:

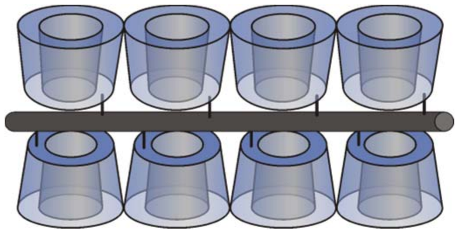
Functionalized CDs



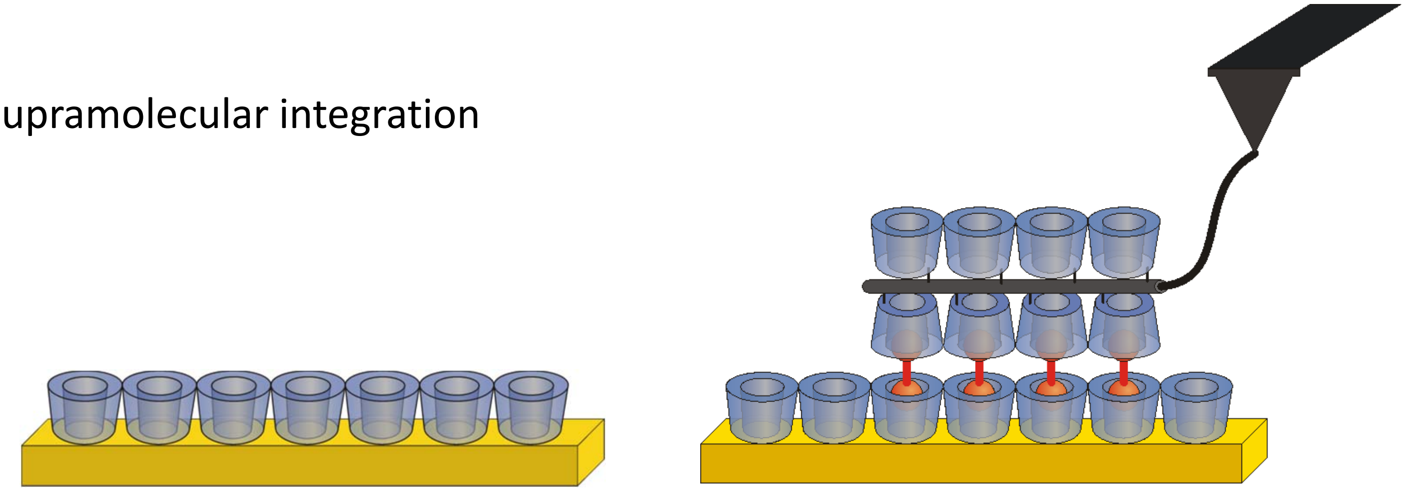
Connectors



CD polymers



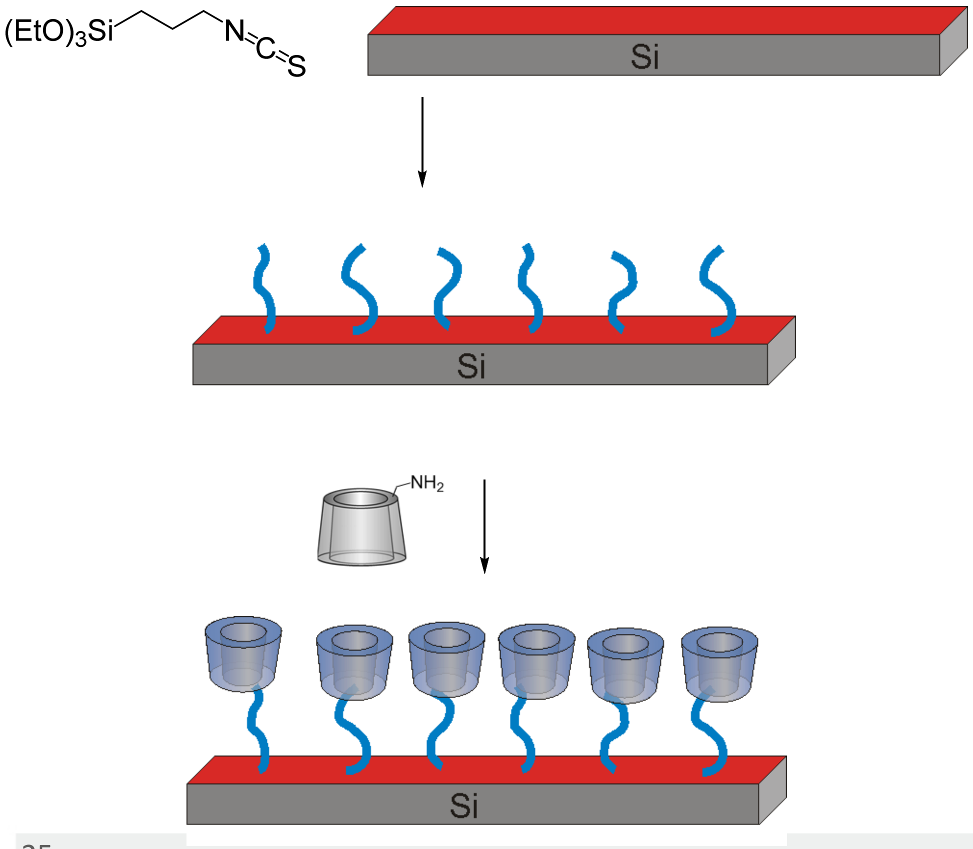
Supramolecular integration



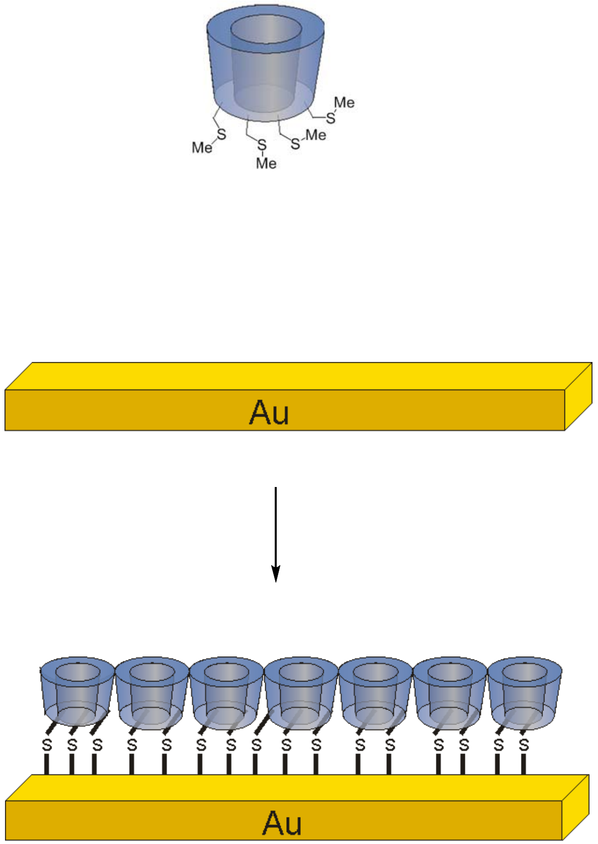
Synthesis (AG Prof. Wenz)

- Surface modification

oxidized Silicon



Gold

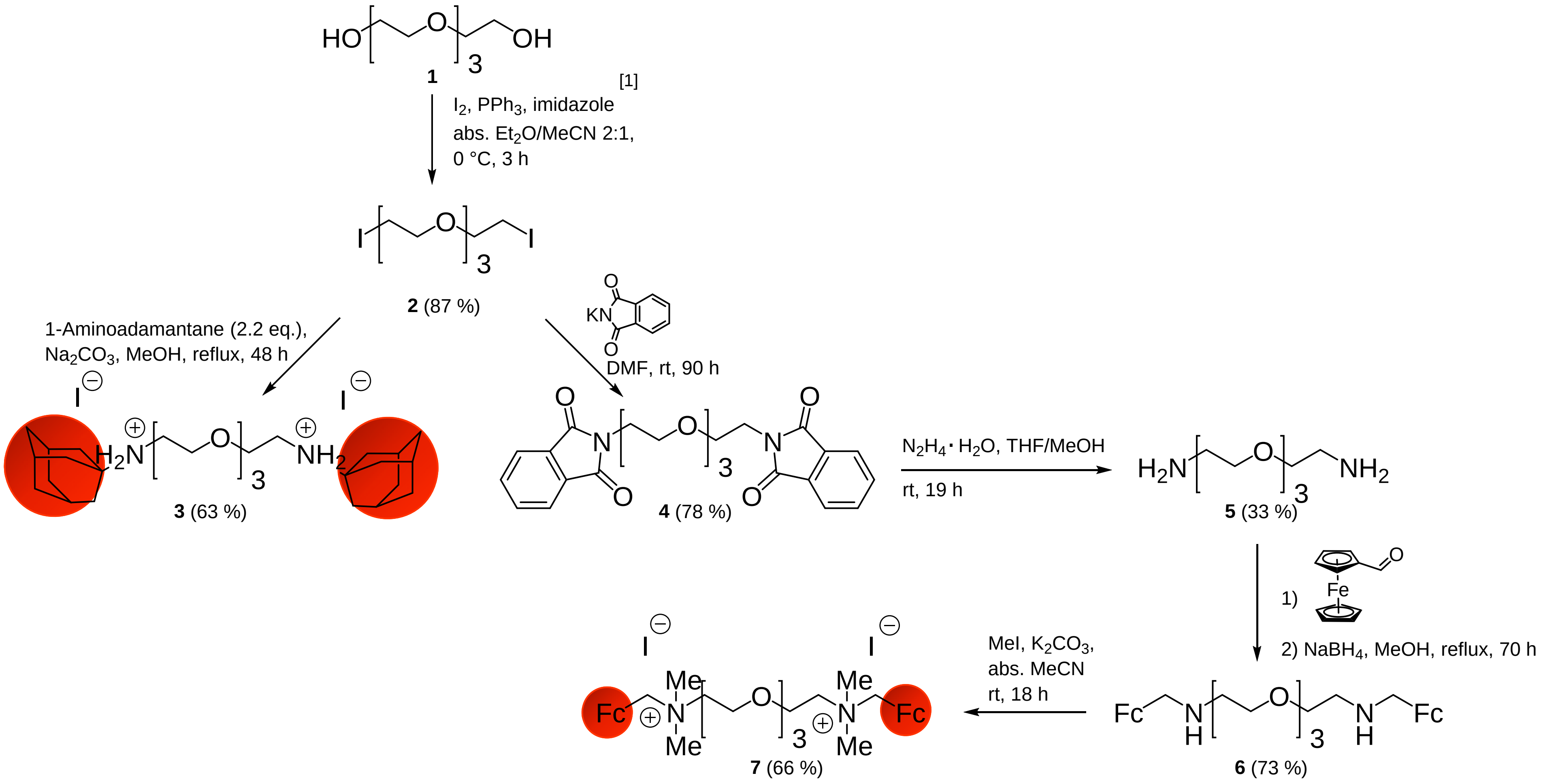


Synthesis (AG Prof. Wenz)

- Connectors

Adamantane

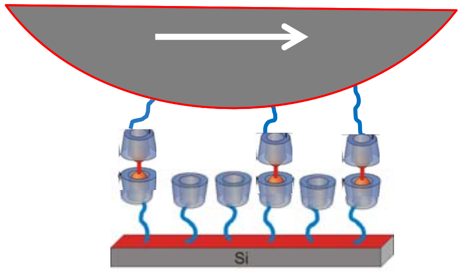
Ferrocene

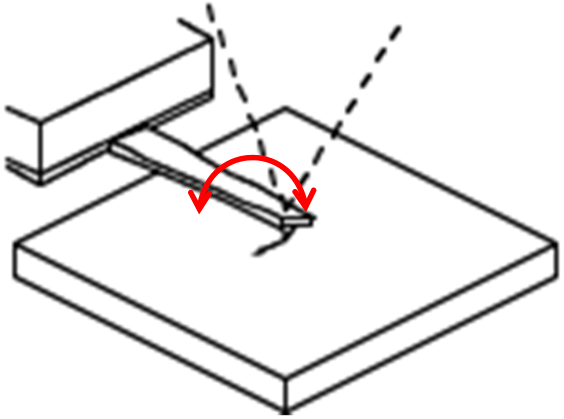


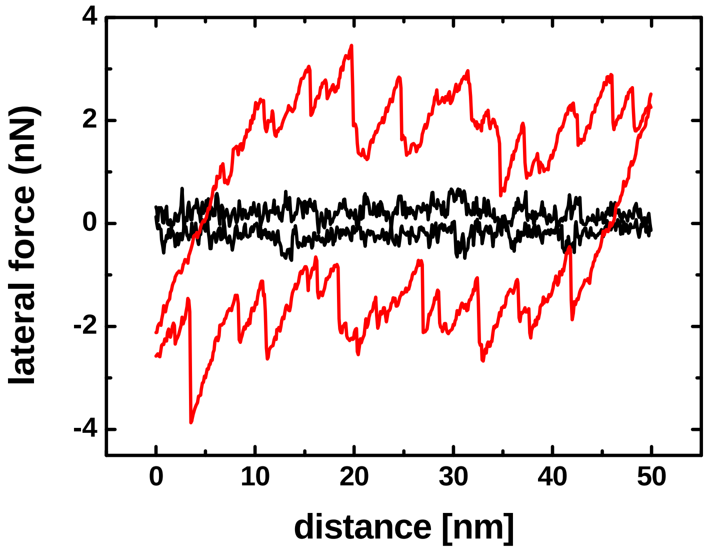
[1] L. S. Beall, N. S. Mani, A. J. P. White, D. J. Williams, A. G. M. Barrett, B. M. Hoffman, *J. Org. Chem.* **1998**, *63*, 5806-5817.

Friction force microscopy

- Friction loops:
  Lateral force signal for back and forth scan of AFM tip.
- Stronger friction with typical molecular detachment features in guest solution.
- Friction forces similar to adhesion forces.
- Reproducible details in lateral force signal in pure water indicate inhomogeneous film growth.

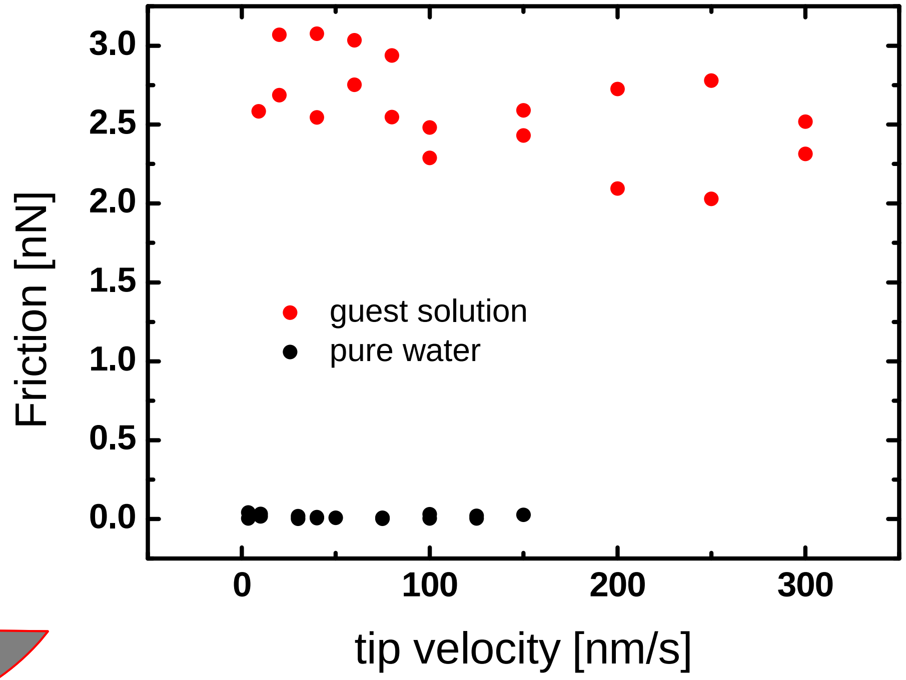


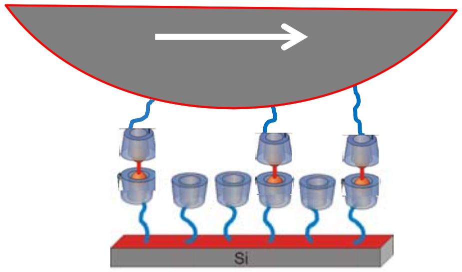




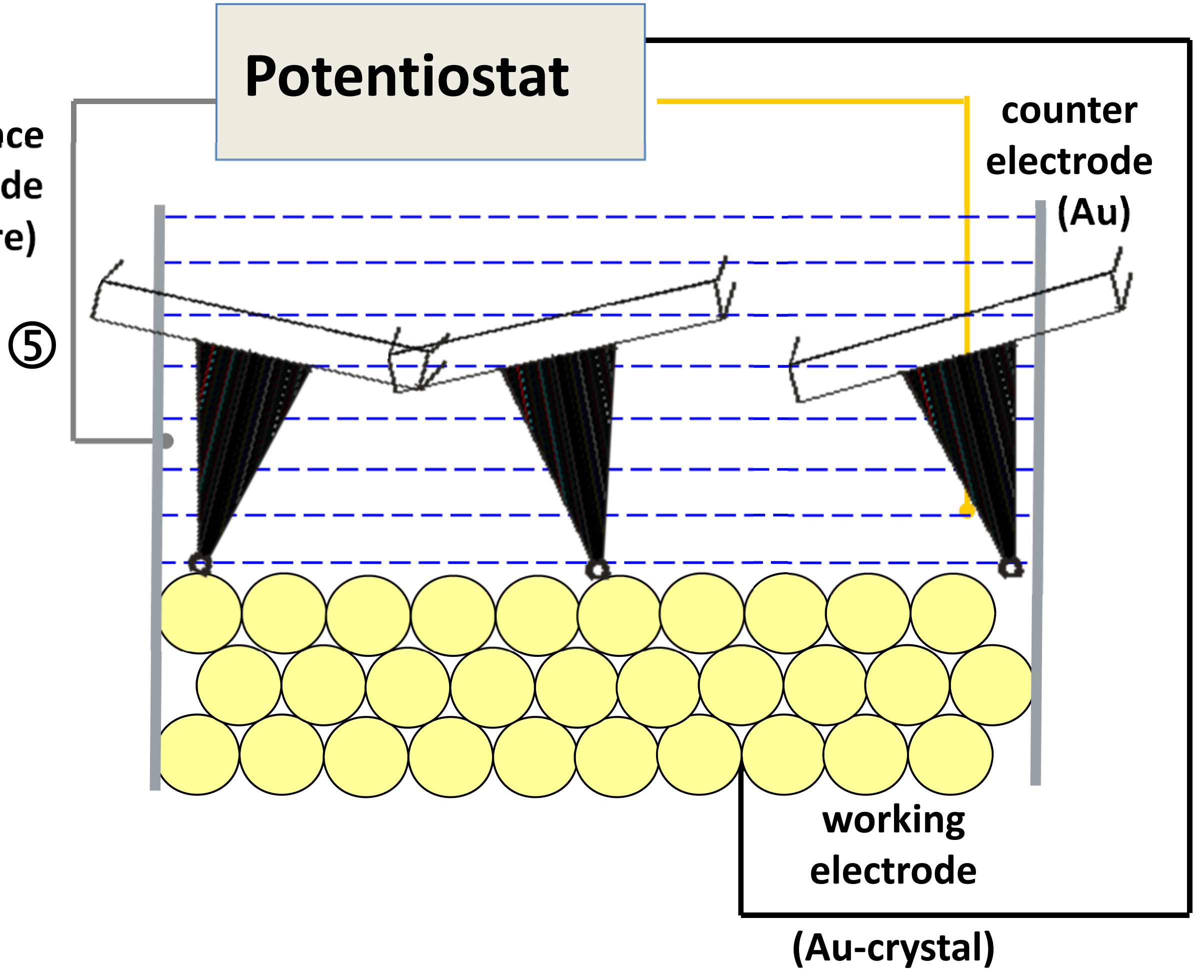
Friction vs. velocity

- Factor of 100 in friction with and without guest molecules.
- Weak velocity dependence indicates equilibrium situation.
- Functionalization of silicon oxide by mono-amino-β-CDs shows larger friction effect than functionalization by hepta-amino-β-CDs.





AFM in an electrochemical cell



Potentiostat

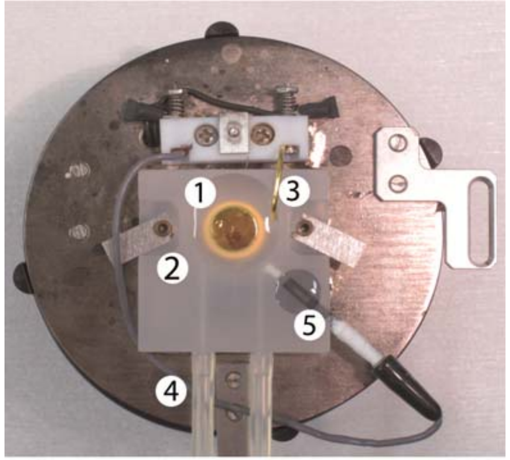
reference electrode (Pt-wire)

⑤

counter electrode (Au)

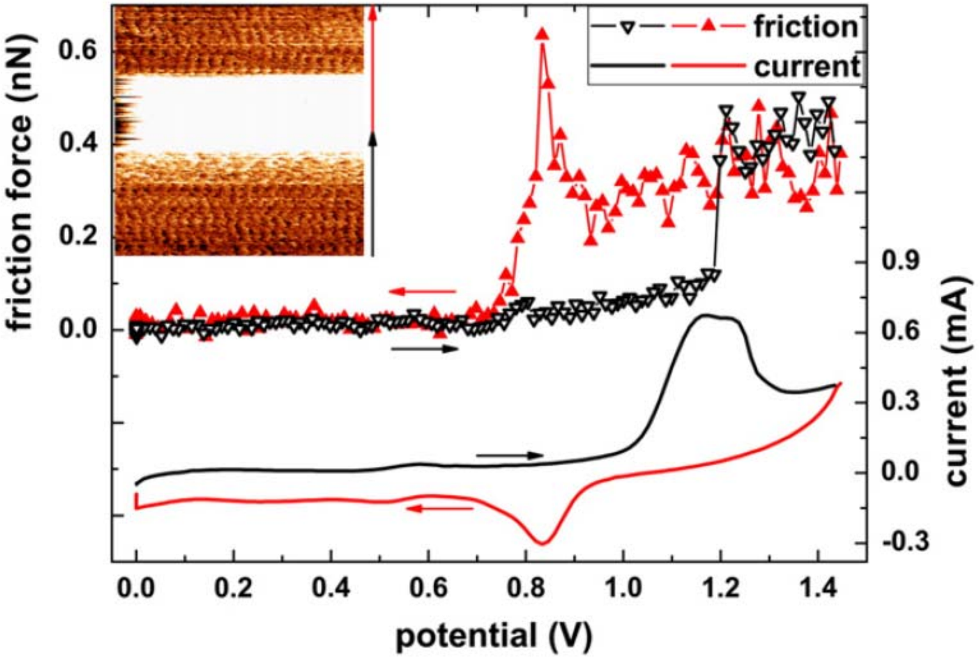
working electrode

(Au-crystal)



Electrochemical oxidation of Au(100)

- Friction increases upon oxidation.
- Friction decreases upon reduction.
- Oxidized surface is roughened, atomic stick-slip reestablished after reduction.



- Au(100) in 0.01 M $HClO_4$

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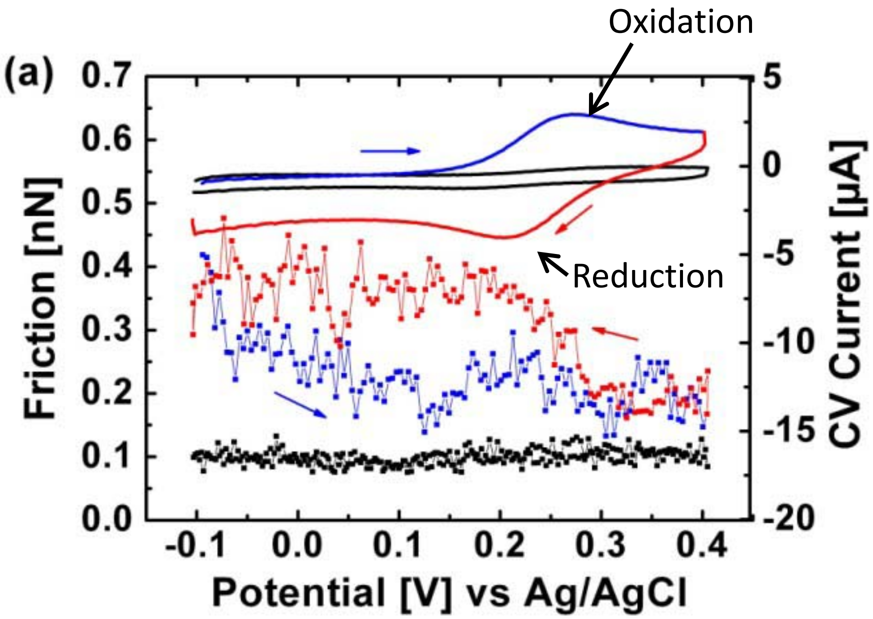
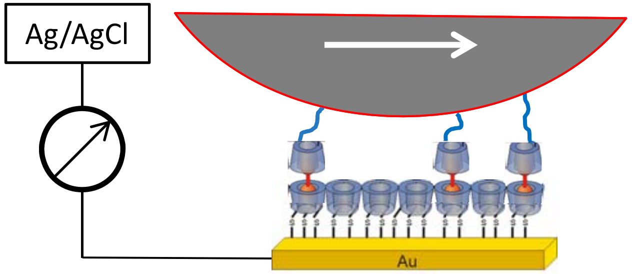
Bianca Bozna, Günther Krämer

Electrochemical control of friction

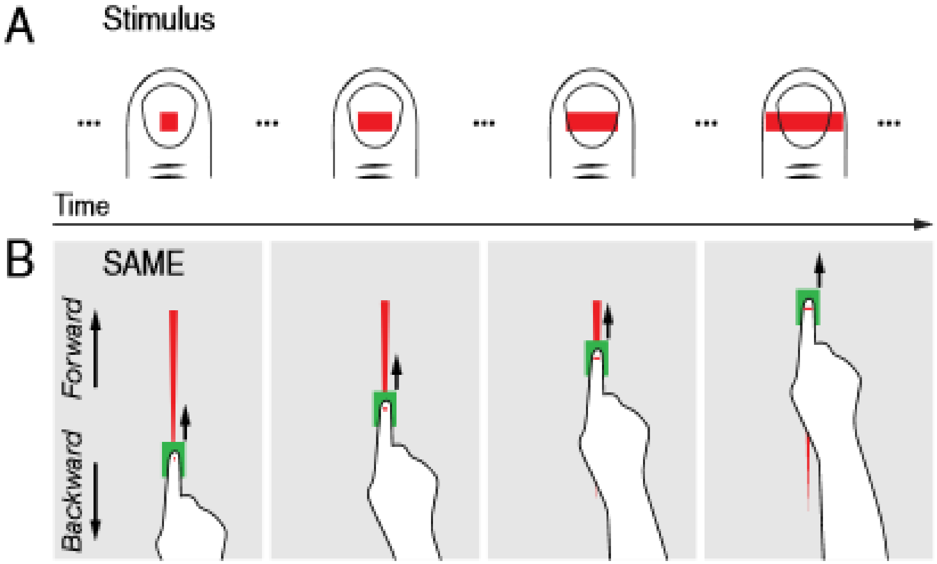
- Fresh preliminary result for ferrocene ditopic guests.
- Solution of 0.1mM ferrocene ditopic guests and 0.05M Na_2SO_4
- Friction change at potential tentatively assigned to Fe/Fe+ oxidation.





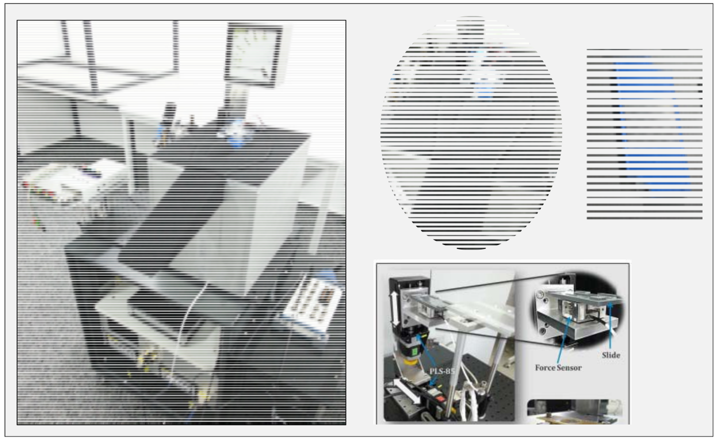
Project TriboBrain

- Measure friction between a fingertip and various materials.
- Simultaneously, measure the neural response by recording EEG signals.
- Question: Can we establish an objective measure for touch and feel of materials?



TriboBrain – Identifying neural response to tribological stimuli.

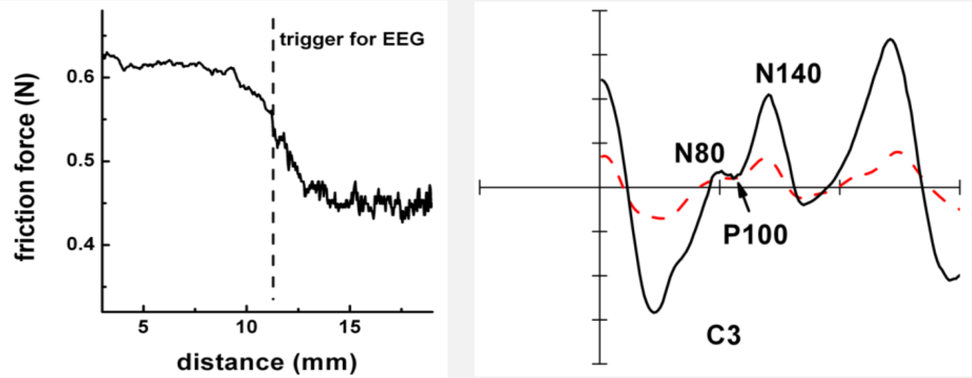
Setup



Approach

Surface under study is moved towards the fingertip until it touches the finger. Then a lateral movement (fwd/bwd) is started while recording friction and EEG.

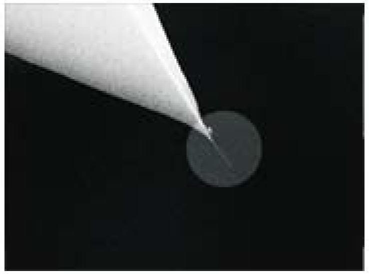
Results

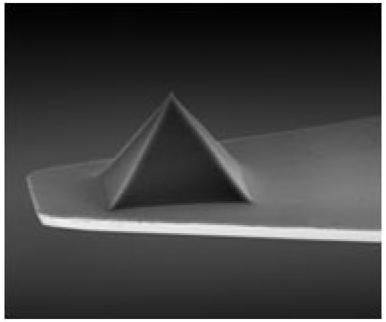


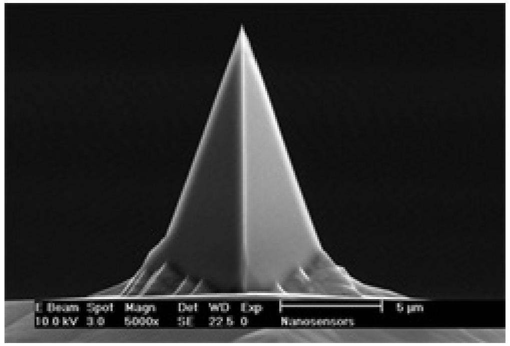
- Friction of a fingertip sliding from a flat to a structured surface. The reduction of friction due to decrease of the contact area and its modulation can be recognized.

- Averaged EEG signal after transition of the sliding fingertip from flat area to a structured surface area, where the relevant peak for the analysis of somatosensory processing are recovered.

Different tips for different applications







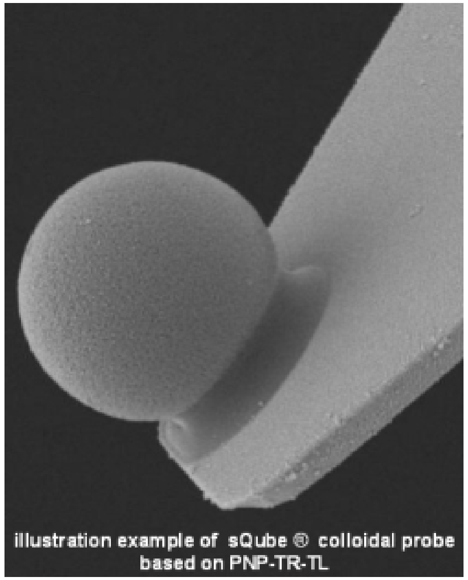
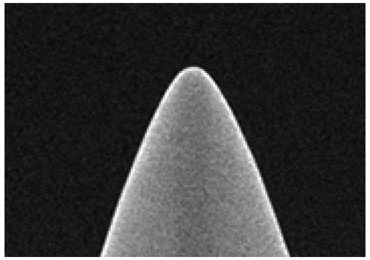
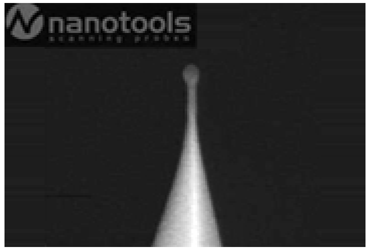
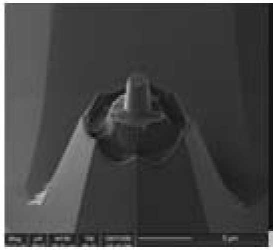
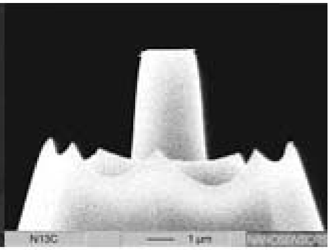


illustration example of sQube ® colloidal probe based on PNP-TR-TL

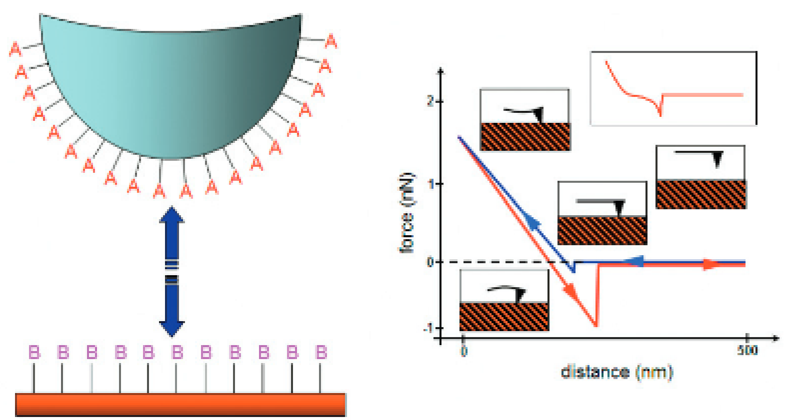






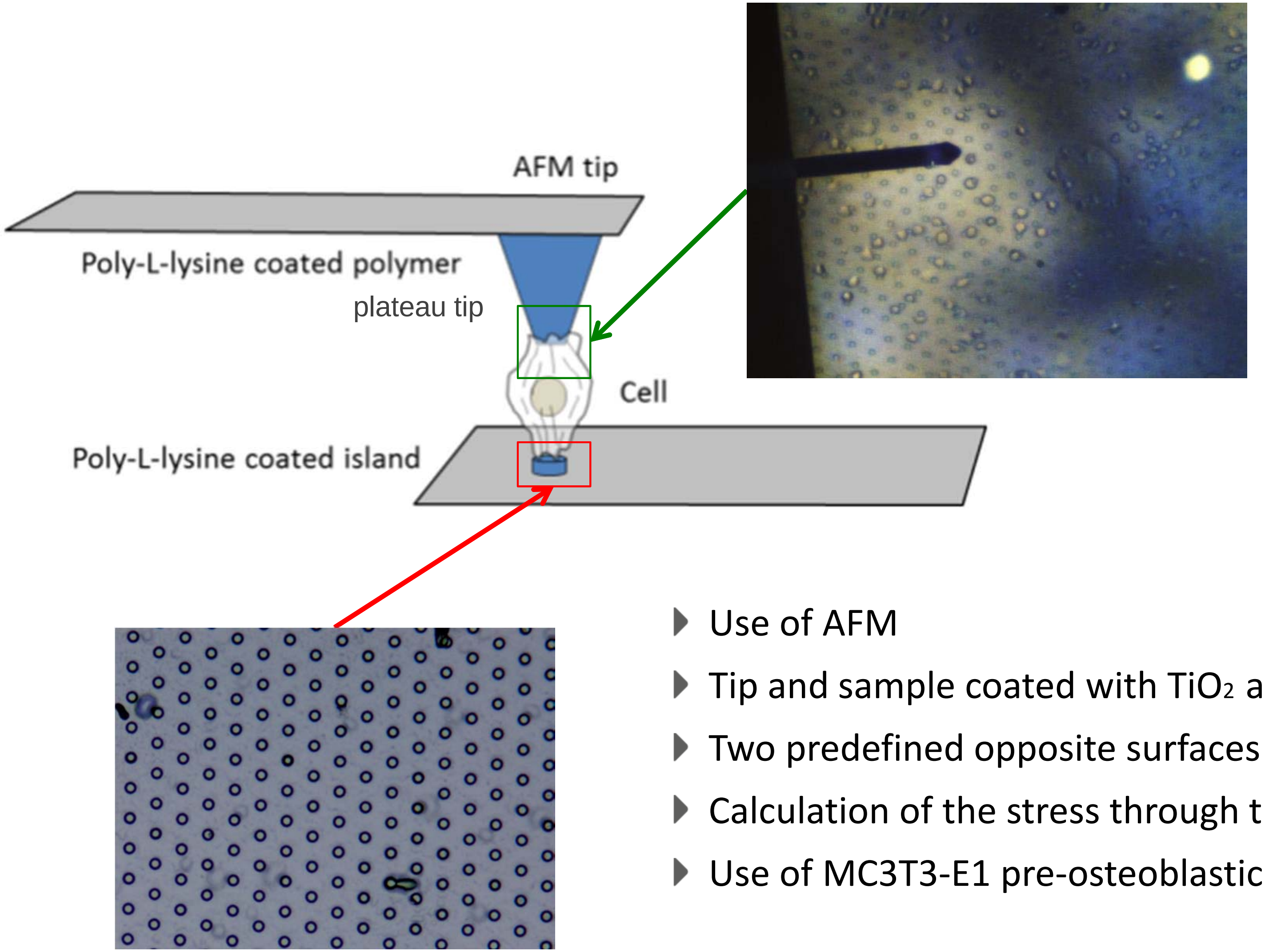


Principle of molecular recognition force measurements



Nanoandmore / Bruker

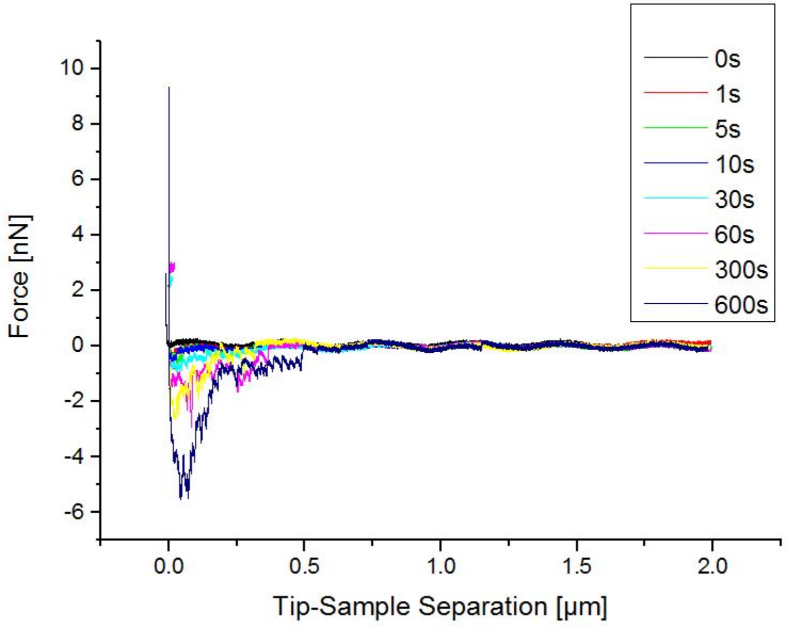
Tensile test on bone cells



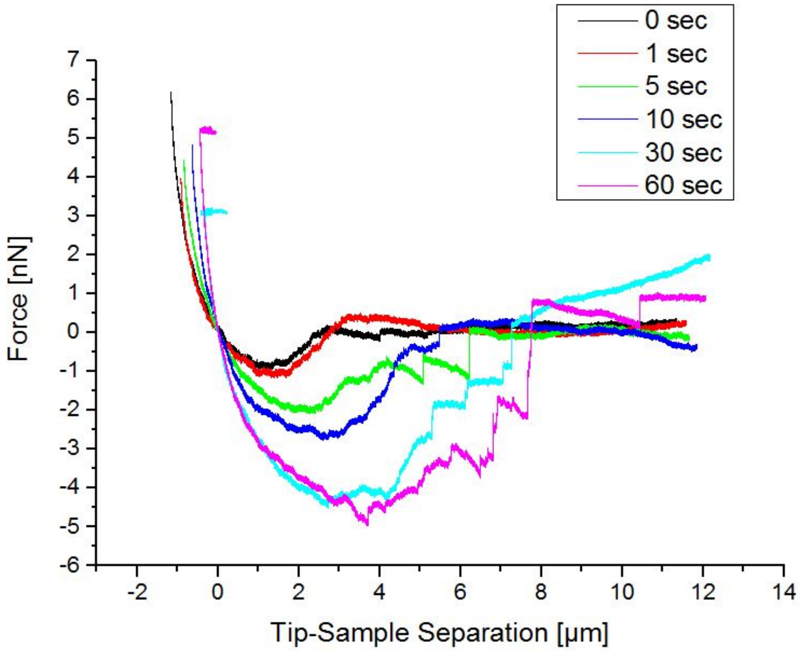
- Use of AFM
- Tip and sample coated with TiO_2 and PLL
- Two predefined opposite surfaces (10 µm)
- Calculation of the stress through the defined area
- Use of MC3T3-E1 pre-osteoblastic cells

Cell adhesive strength

Results force spectroscopy



- Force spectroscopy on PLL using different holding times
- Increasing pull-off force due to contact ageing



- Force spectroscopy on a living cell using different holding times
- Curve progression characteristic for detachment of a cell
- Bond creation after 5 seconds
- Increasing stiffness of the cell