



The Abdus Salam
International Centre for Theoretical Physics



2063-3

ICTP/FANAS Conference on trends in Nanotribology

19 - 24 October 2009

To slide or not to slide: Frictional duality of nanoparticles

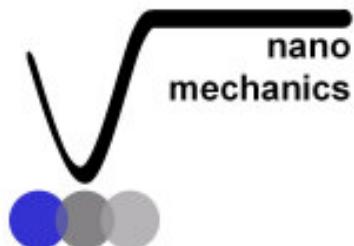
SCHIRMEISEN André
*Westfälische Wilhelms-Universität
Institut Fur Physikalische Chemie
Schlossplatz 4
D48149 Münster
GERMANY*

“To slide or not to slide” Frictional duality of nanoparticles

André Schirmeisen

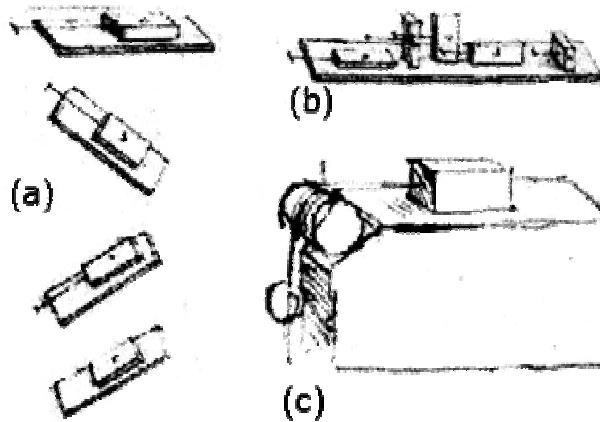
*Institute of Physics & CeNTech (Center for Nanotechnology)
University of Münster, Germany*

<http://www.centech.de/nanomechanics>



Historic laws of friction...

Leonardo daVinci (1452-1519)
Guillaume Amontons (1663-1705)

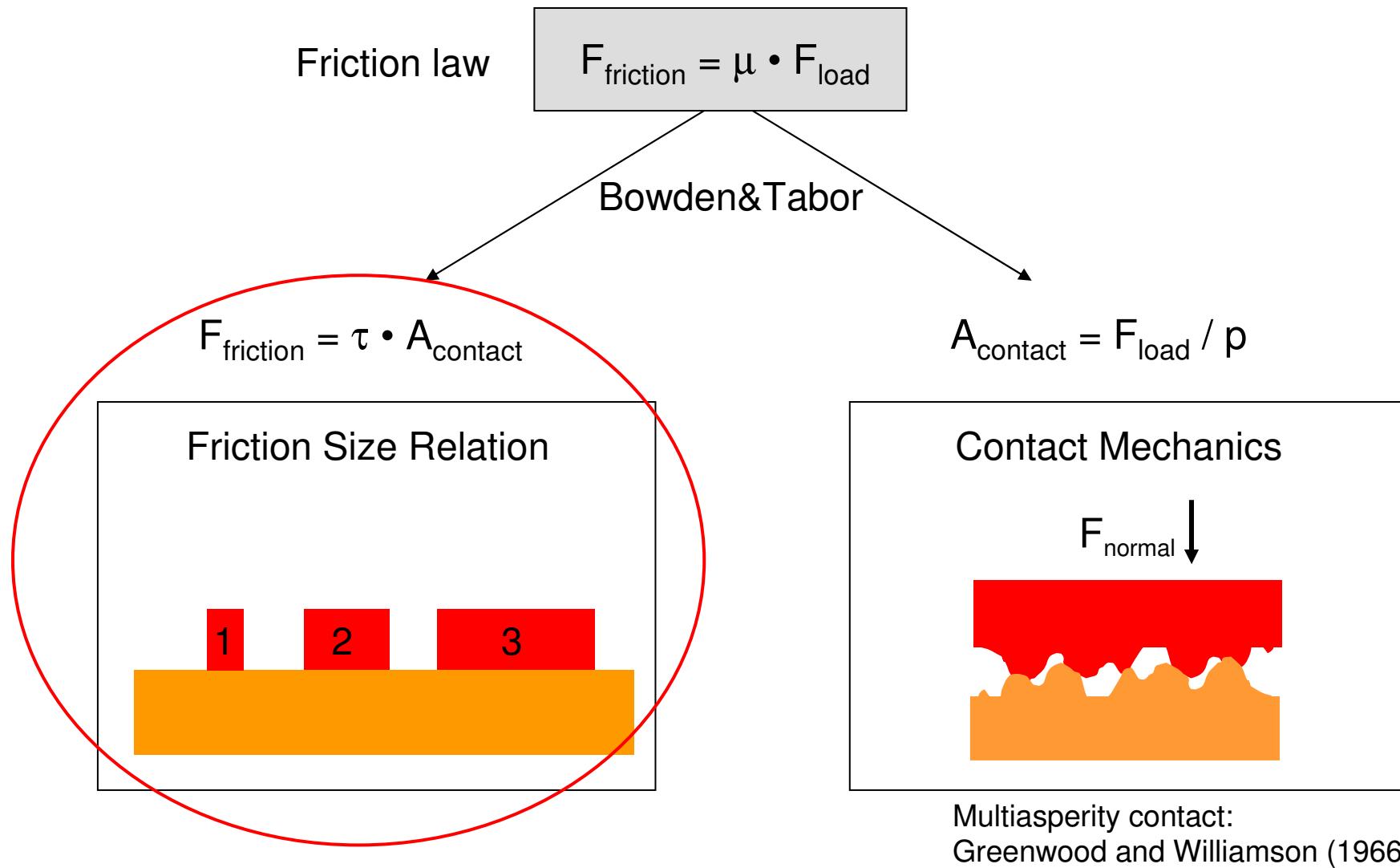


Charles Augustin Coulomb
(1736-1806)

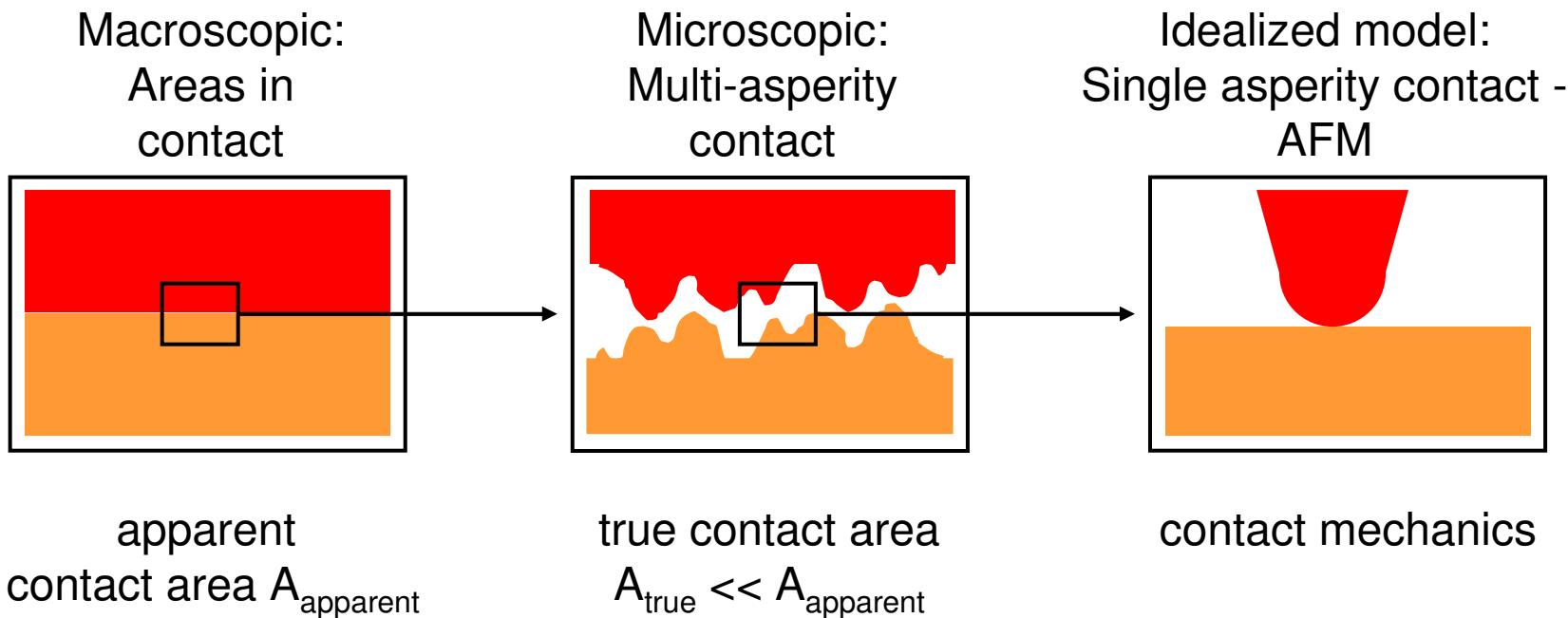
- 1. Friction is independent of the contact area**
- 2. Friction is proportional to the normal load**
- 3. Friction is independent of sliding speed**

What are the microscopic origins of these friction laws?

Macroscopic friction law decomposed

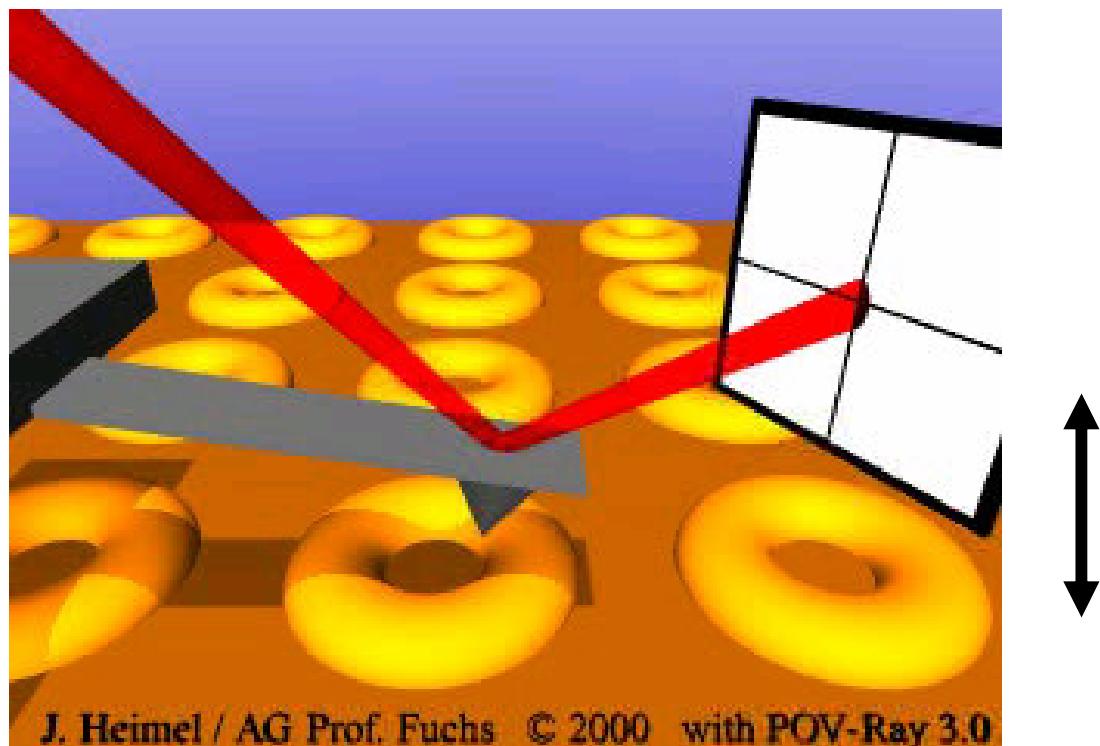
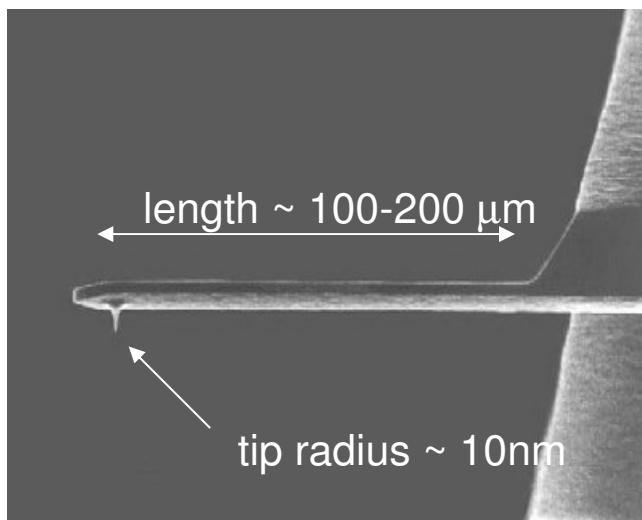


From Macroscopic to Nanoscopic Friction

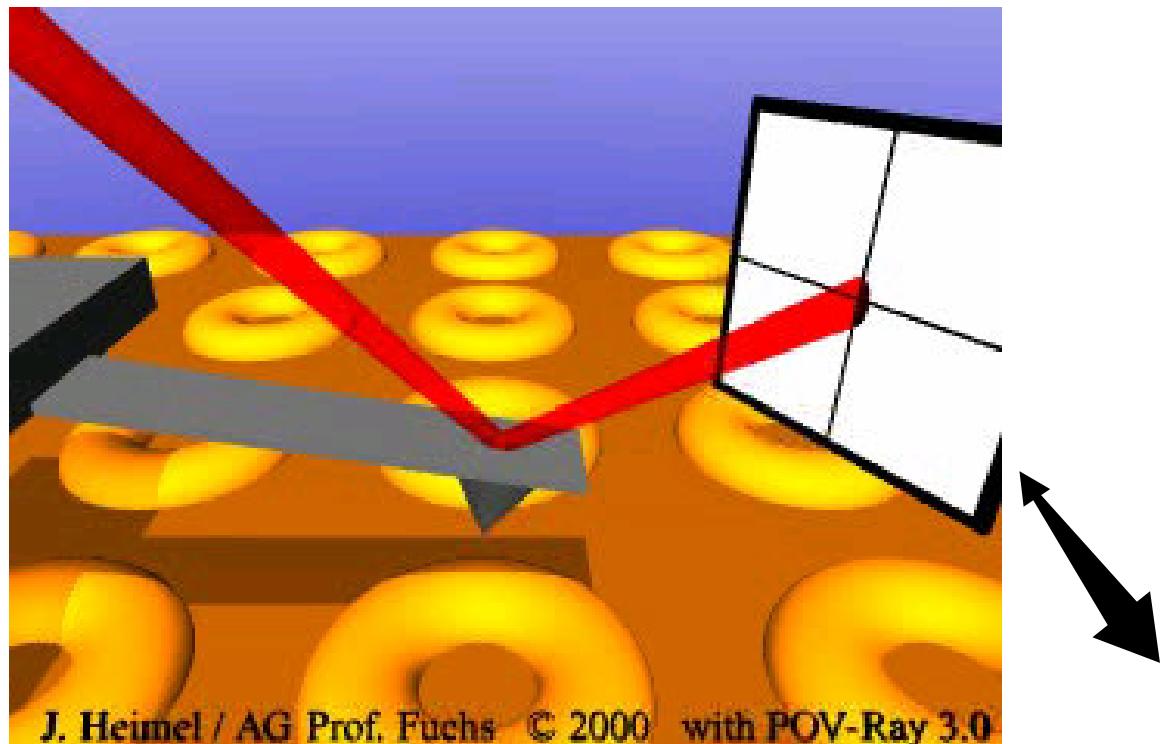
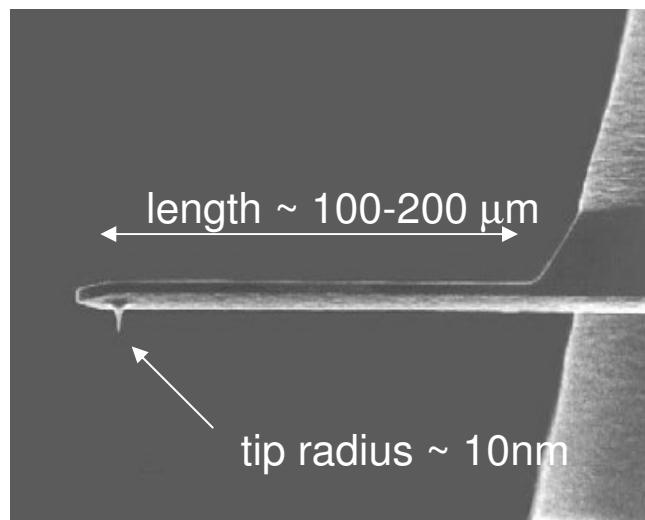


Are macroscopic friction laws still valid at
microscopic scales?

Atomic Force Microscope

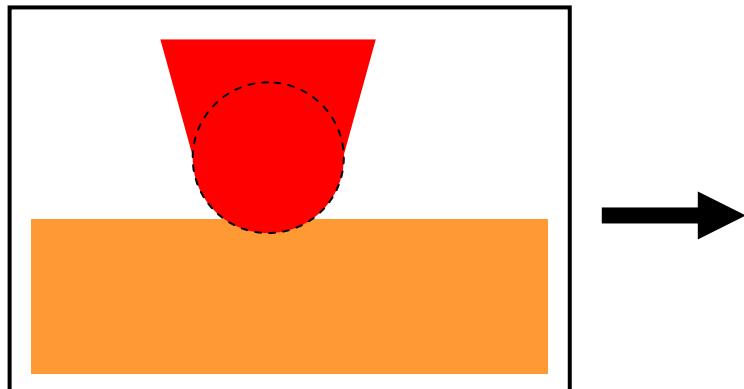


Friction Force Microscope



Friction versus contact size: Spherical tips

Idealized spherical
mono-contact



Hertz contact model
 $A_{\text{contact}} = \pi \cdot (R F_{\text{load}} / K)^{2/3}$

TEM preparation of spherical tips
(amorphous carbon layers)

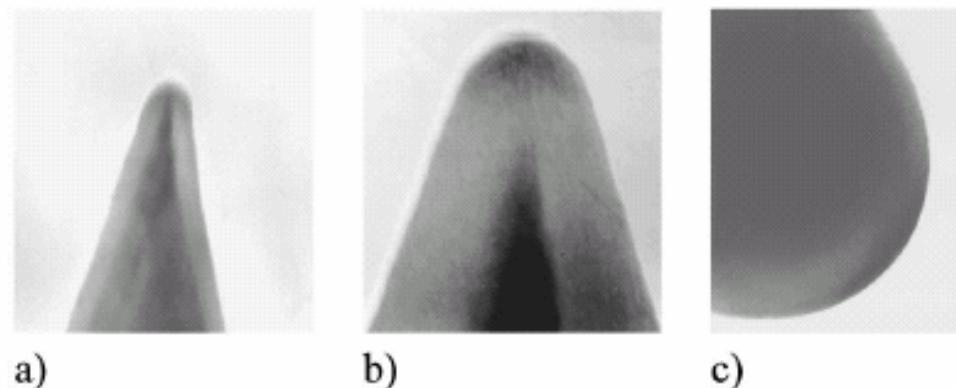
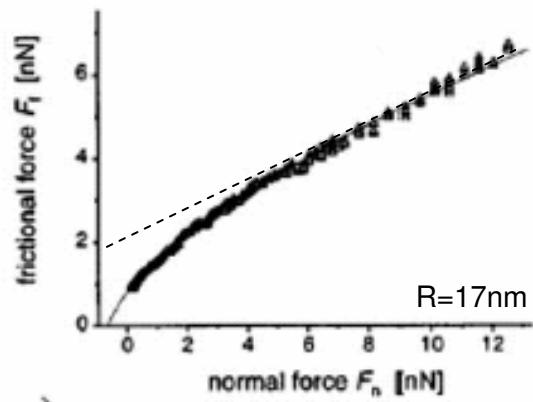


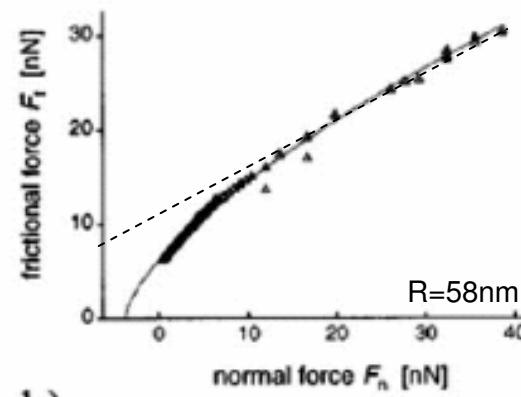
FIG. 4. Transmission electron micrographs of three different tips with spherical apexes prepared according to the procedure described in the text. The apex of the tip presented in (a) has a radius of (21 ± 5) nm, the radius of the tip end displayed in (b) is (35 ± 5) nm, and the tip shown in (c) has an apex radius of (112 ± 5) nm.

The case of a spherical single asperity contact

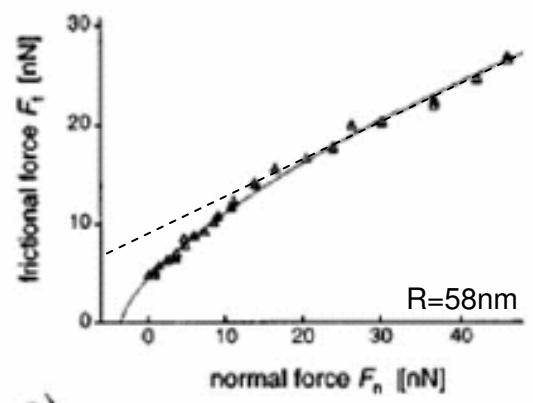
Friction-load relation follows: $F_f = \tilde{C} R^{2/3} (F_n - F_{\text{off}})^{2/3}$ with $\tilde{C} = 0.16 \text{ nN}^{1/3}/\text{nm}^{2/3}$



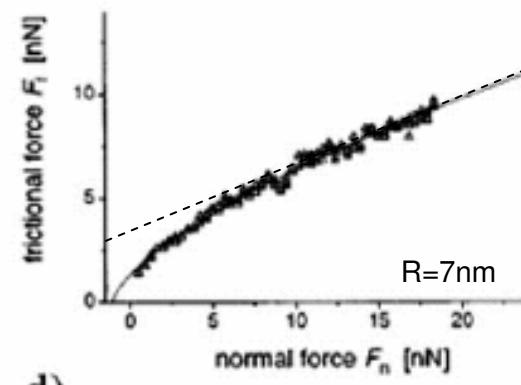
a)



b)



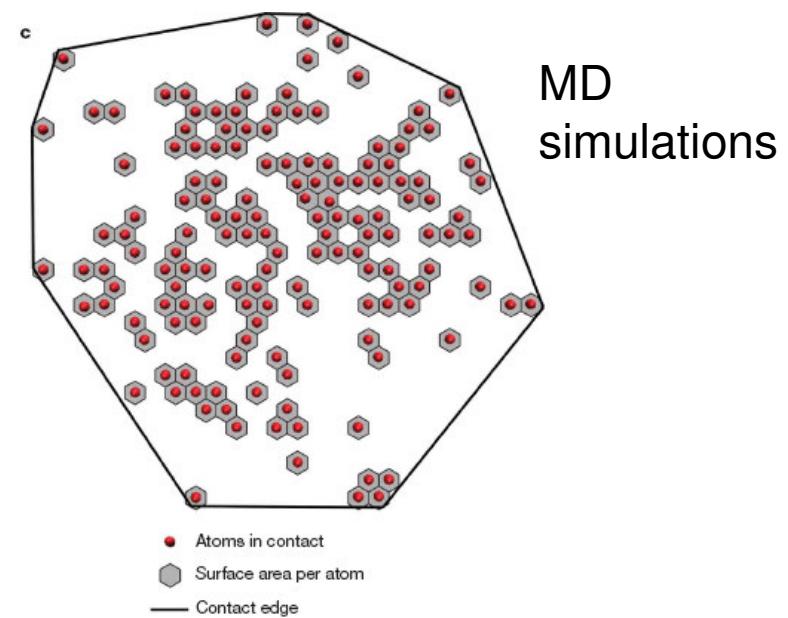
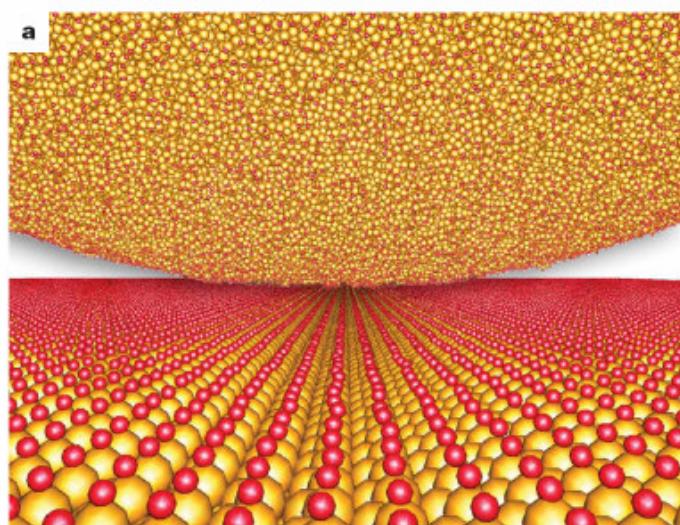
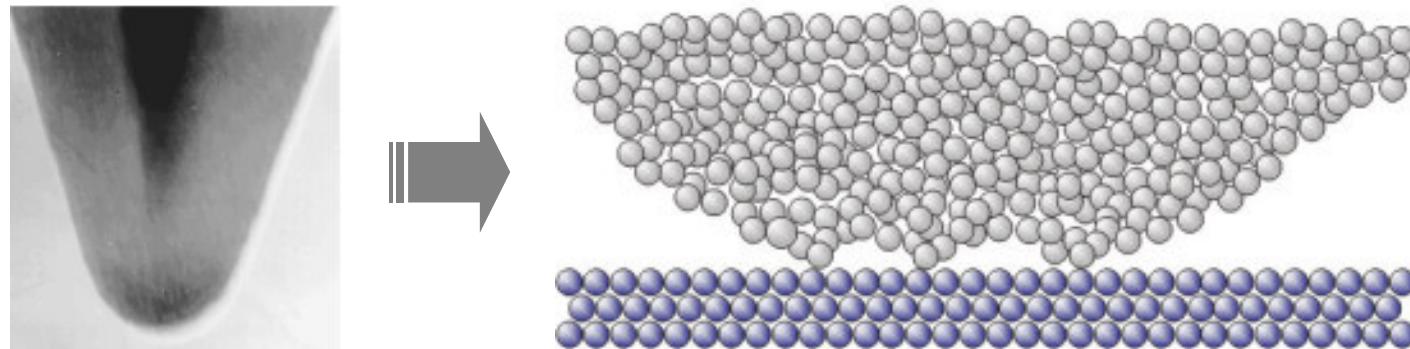
c)



d)

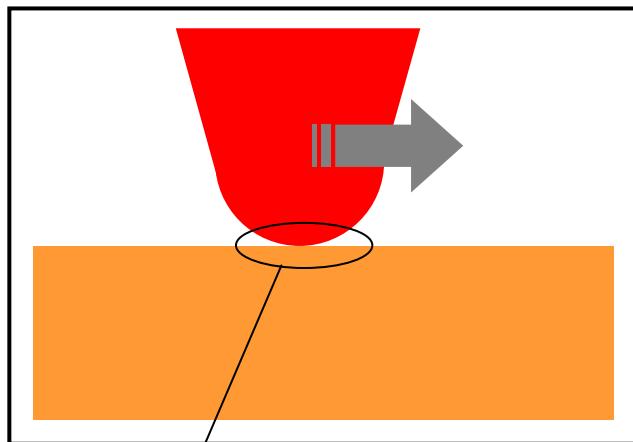
1. Exact interface geometry important!
2. Extension to larger contact areas?
3. Use different materials!

Spherical Amorphous AFM Tip

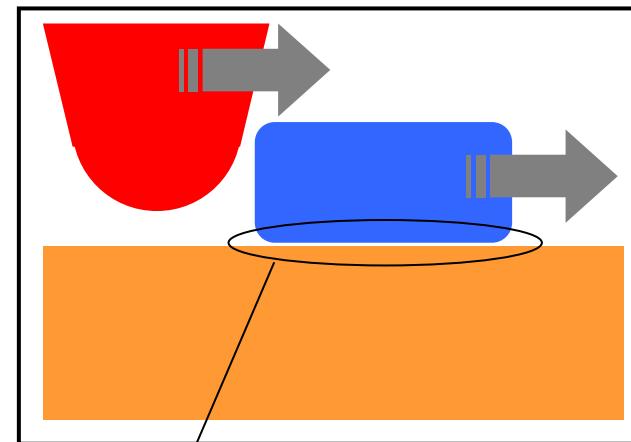


Mo et al., Nature 457, 1116 (2009)

Interface geometry – towards nanoparticle manipulation



relevant interface

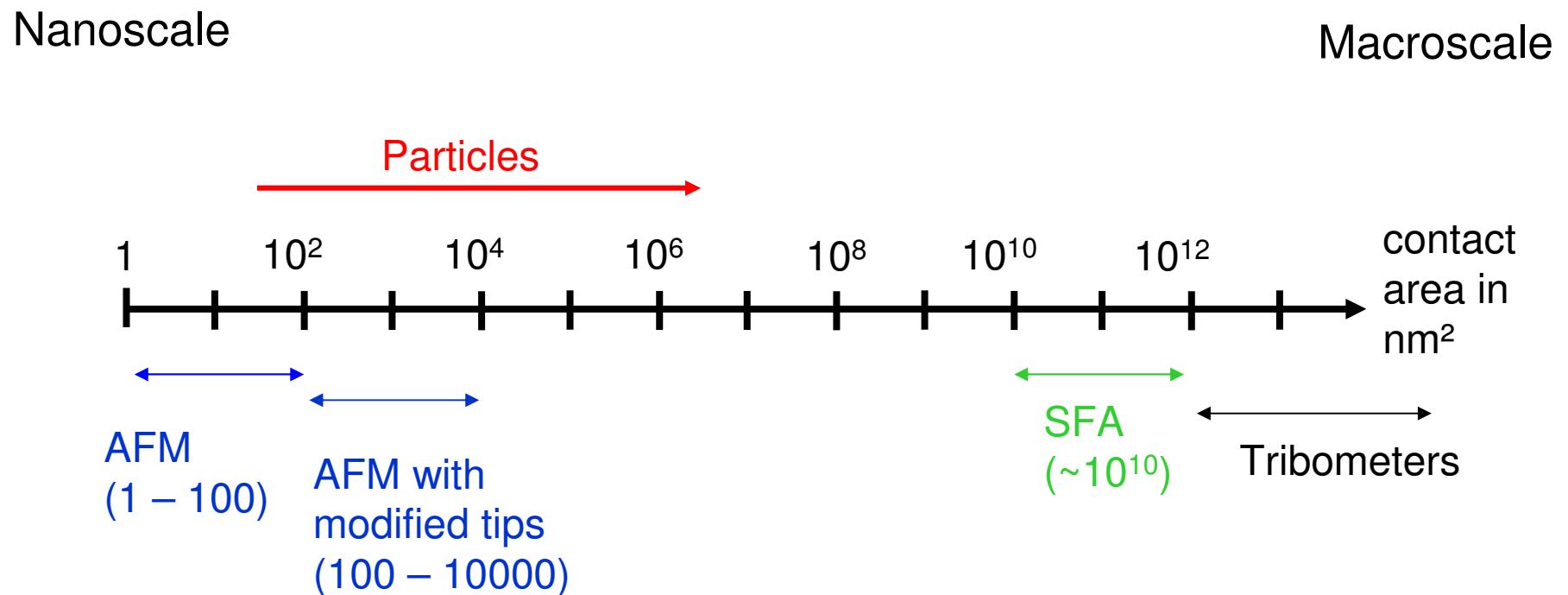


relevant interface

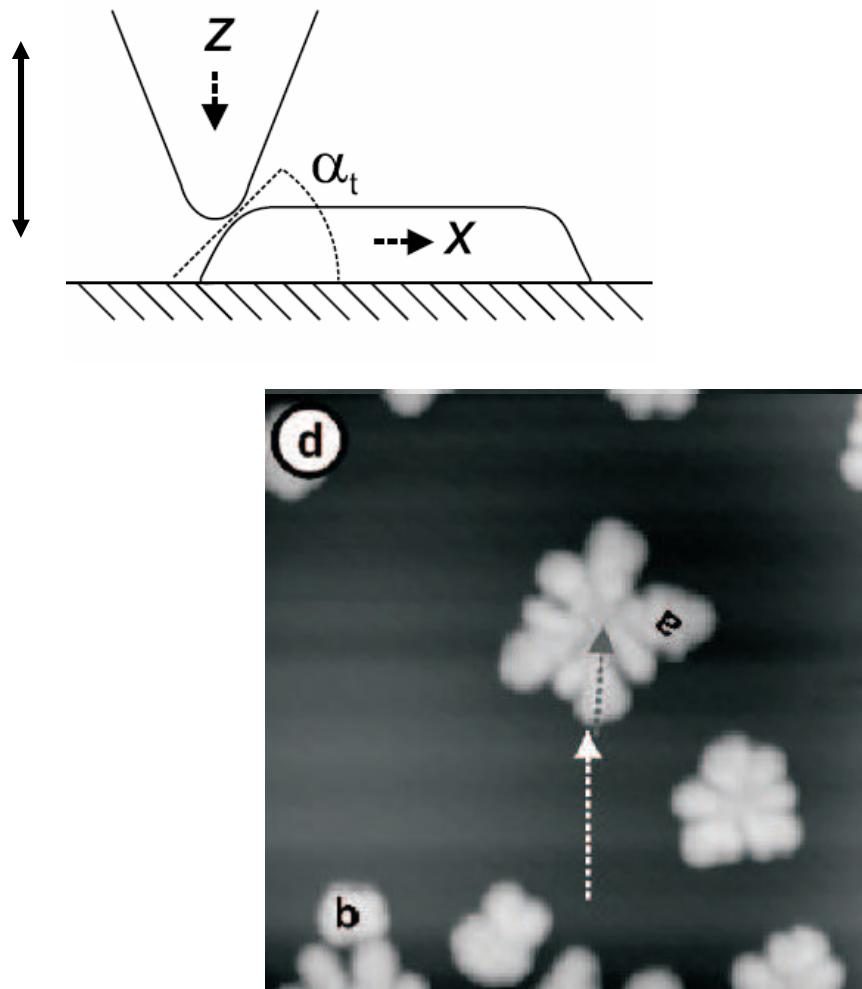
Area dependence of friction: Measure friction as a function of particle size

Particle manipulation with AFM: C₆₀ islands (Lüthi et al., Science (1994)), MoO₃ particles (Sheehan and Lieber, Science (1996)), Nanotubes (Falvo et al., Nature (1999)), etc...

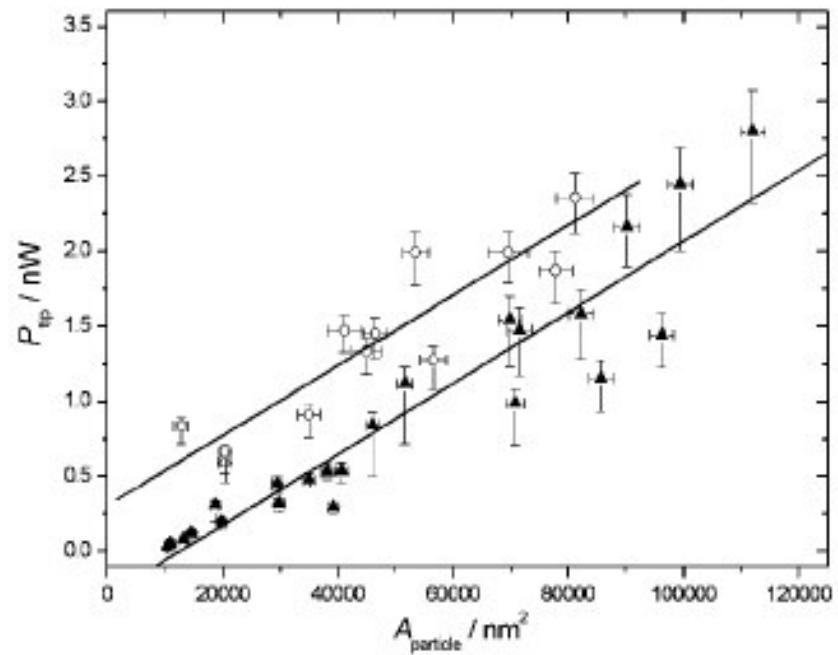
Bridging the size gap of contact areas



Moving Antimony islands with dynamic AFM in air

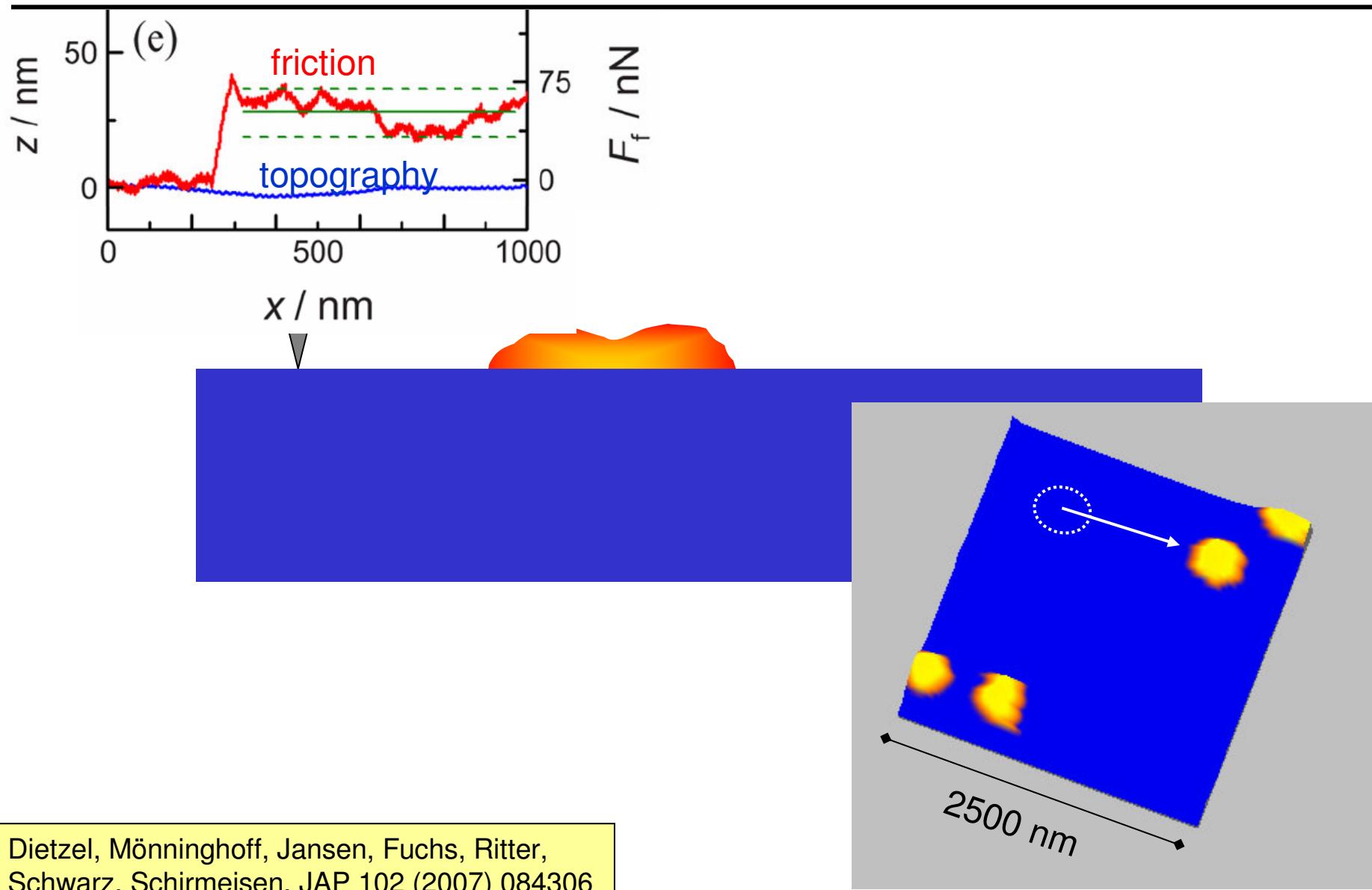


Dissipated power versus island size



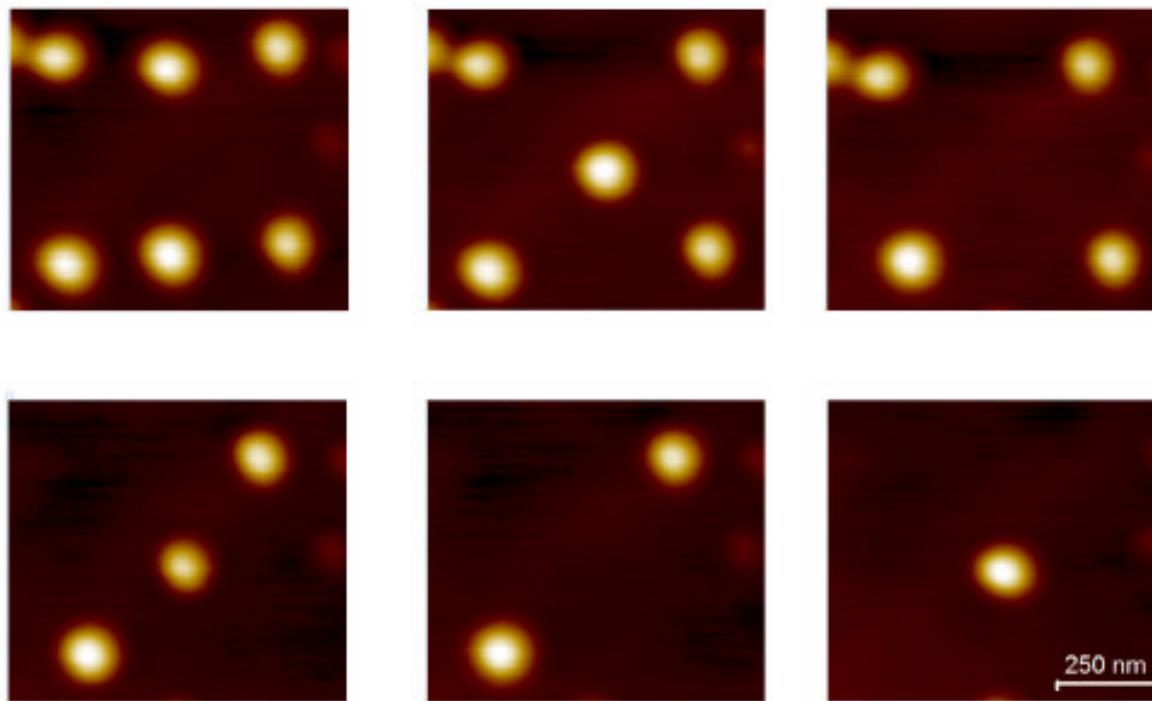
- Dissipated power P_{diss} only indirect measurement of friction
- In air –water molecules/oxidation

Moving Nanoparticles by Atomic Force Microscopy



Controlled Nanoparticle Manipulation

Sb on HOPG



Full Control over particle positioning! (Precision \approx 30nm)

Moving Nanoparticles by Atomic Force Microscopy



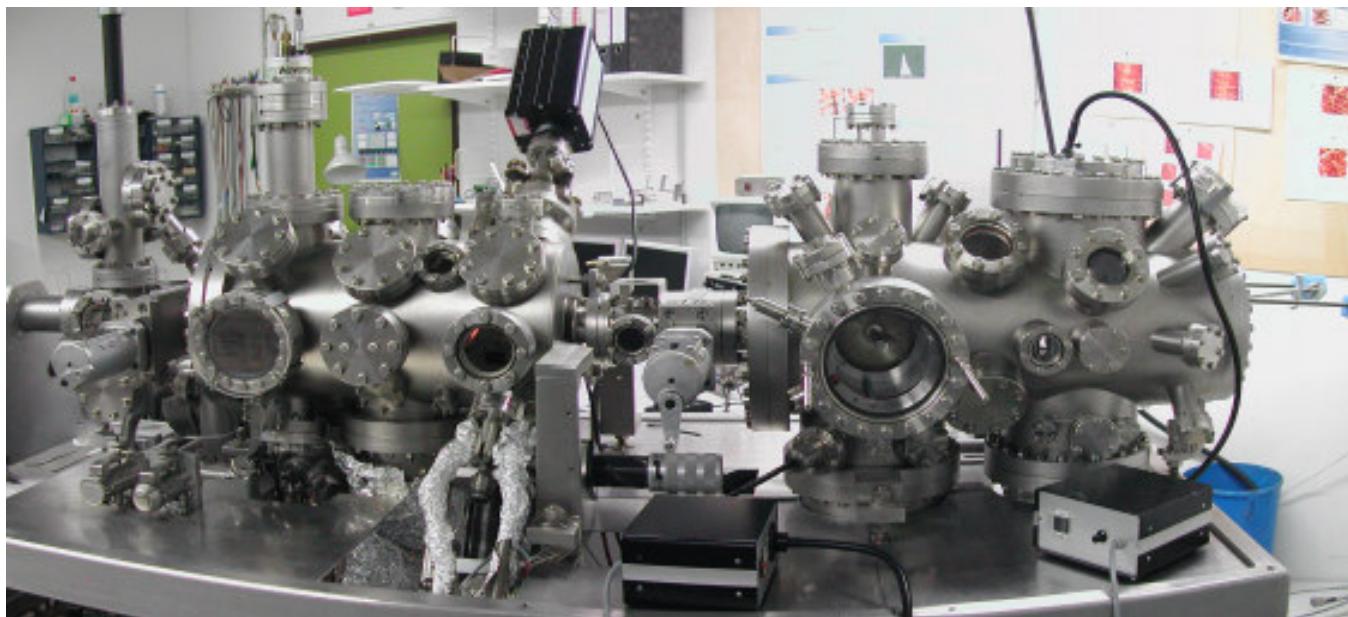
Invited MiniReview

'Measuring the Friction of Nanoparticles:
A New Route towards a Better
Understanding of Nanoscale Friction'

A. Schirmeisen and U.D. Schwarz
ChemPhysChem 14, 2358 (2009)

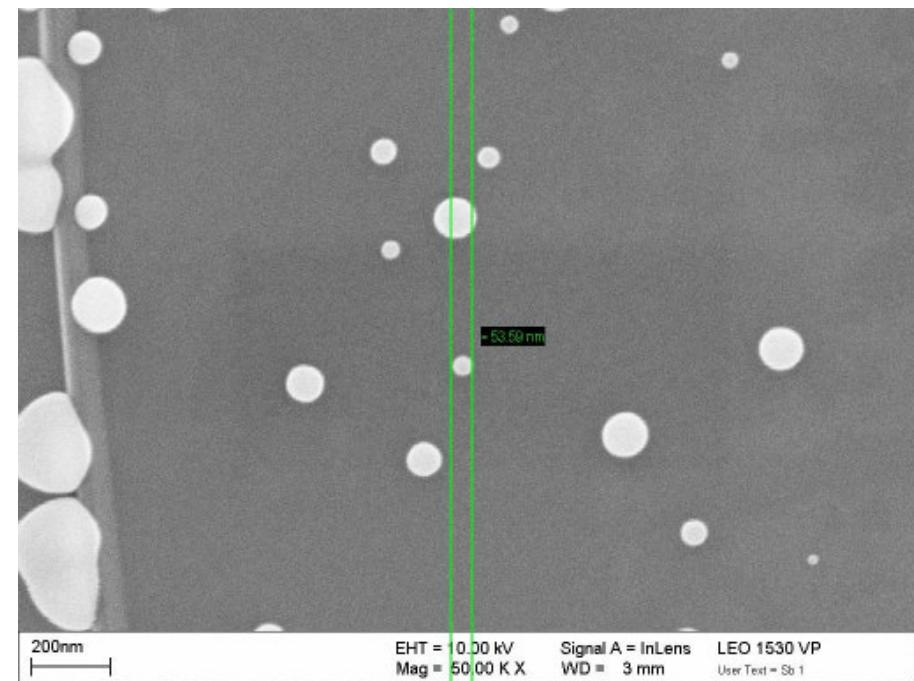
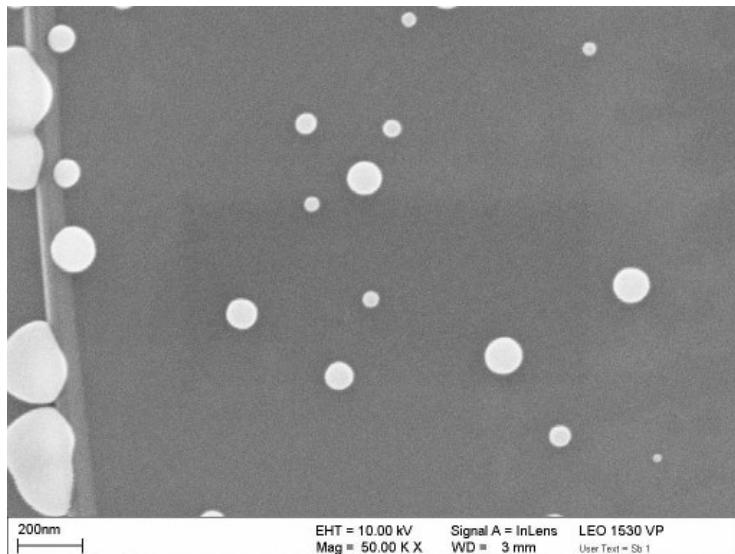
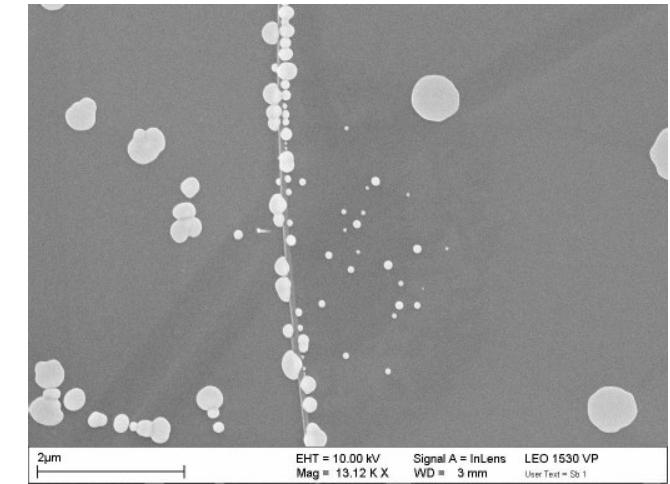
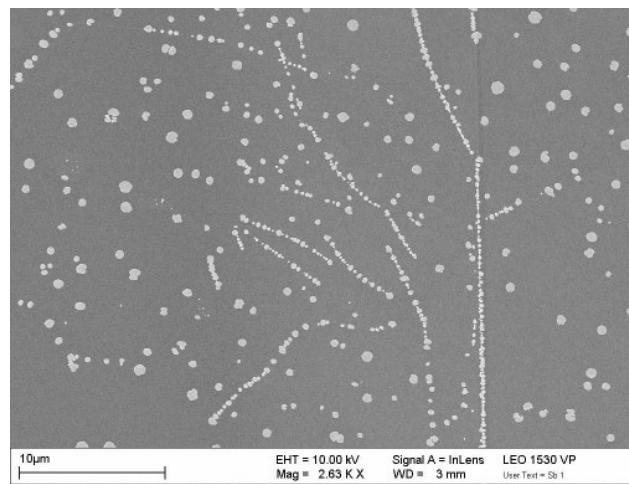
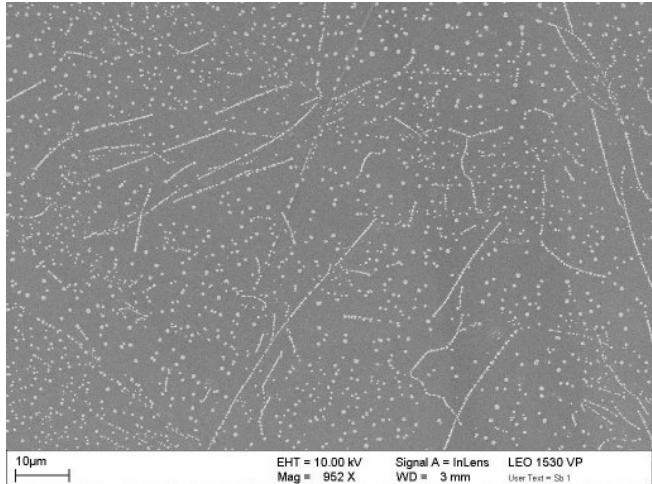
Metallic Antimony nanoscale islands by sublimation

Omicron room temperature
AFM in UHV

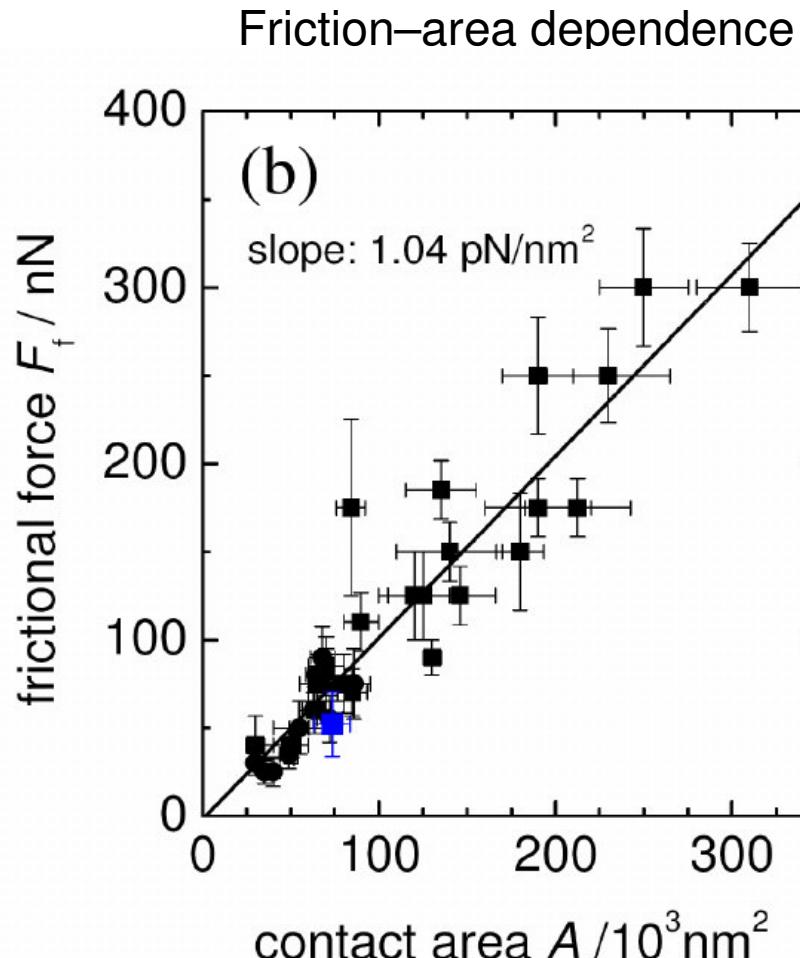


In-situ
preparation Sb
particles

Metallic Antimony nanoscale islands by sublimation



High Friction Branch - Linear correlation



Friction scales linearly
with contact area!

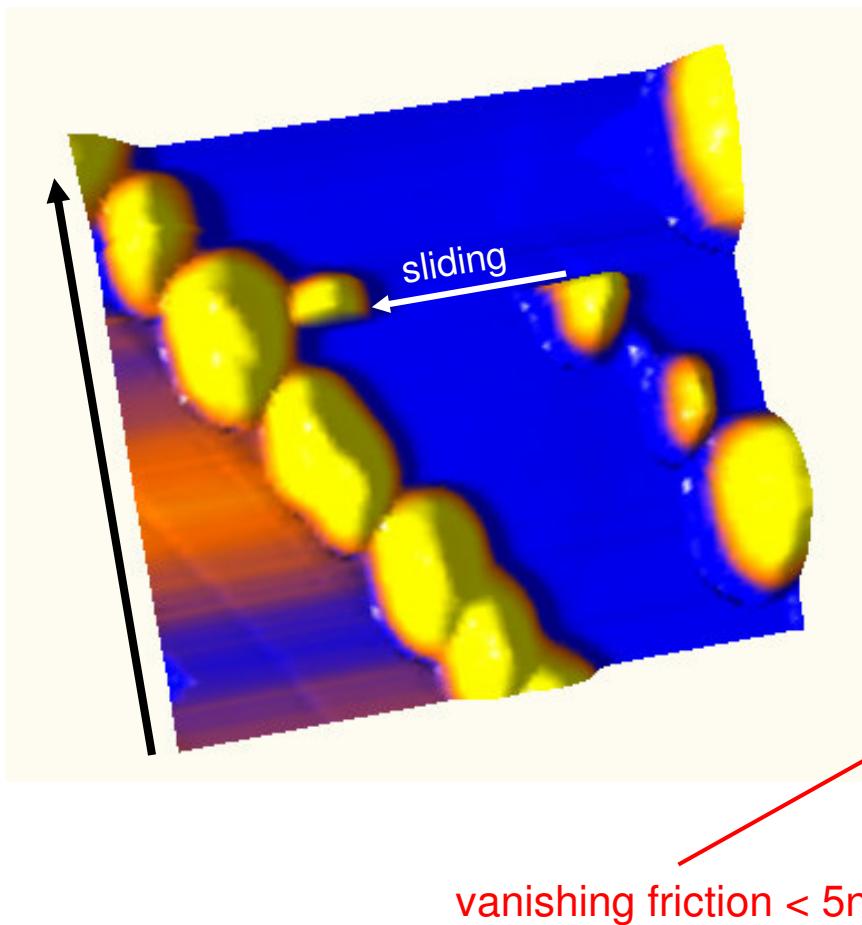
$$F_{\text{friction}} = \tau \cdot A_{\text{contact}}$$

with shear stress:
 $\tau = (1.04 \pm 0.06) \text{ MPa}$

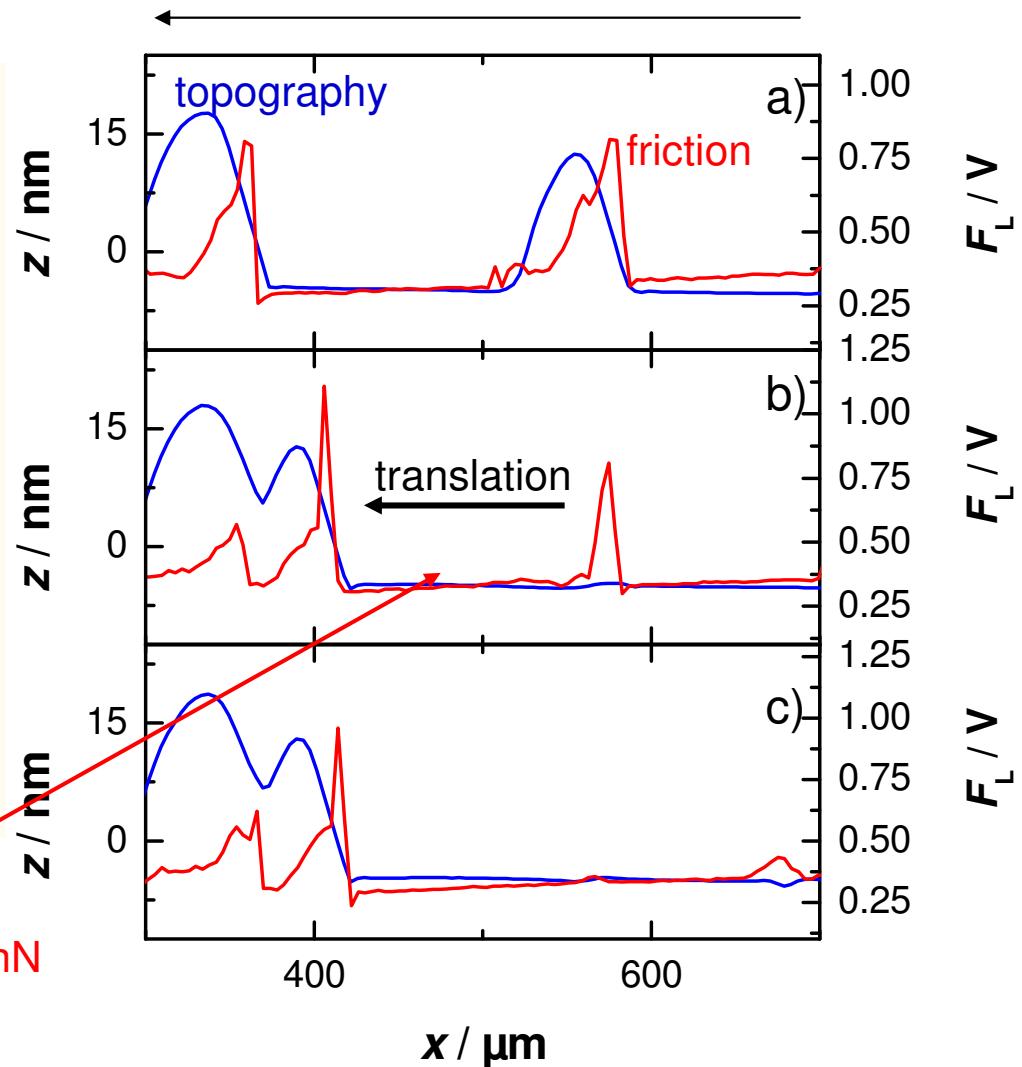
Cd arachidate islands ($\tau \approx 1 \text{ MPa}$)
 MoO_3 nanocrystals ($\tau \approx 1.1 \text{ MPa}$)
 C_{60} islands displaced on NaCl ($\tau \approx 0.15 \text{ MPa}$)

Vanishing friction?

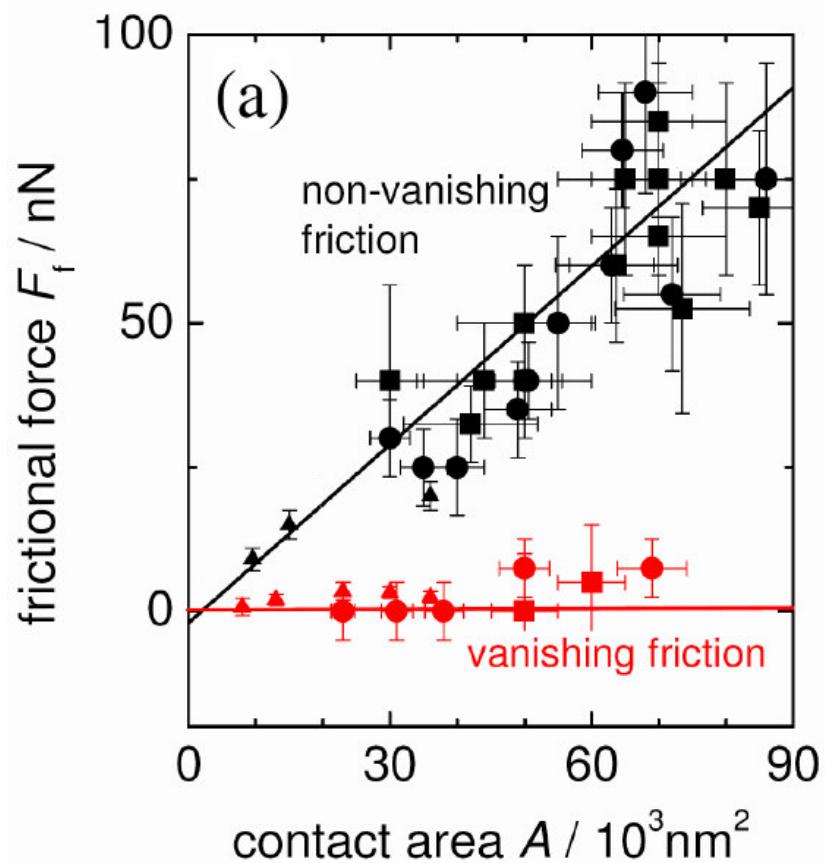
Topography



Retraces

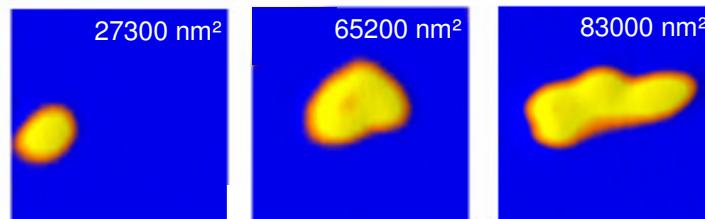


Frictional Duality: 'To Slide or not to Slide'

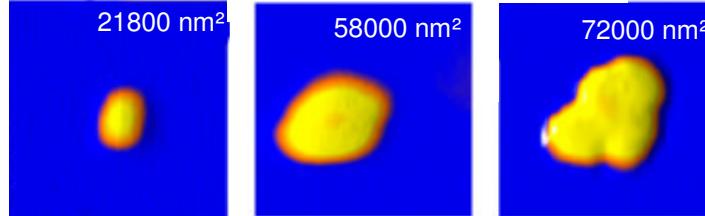


Particle shapes: No apparent differences

a vanishing friction particles



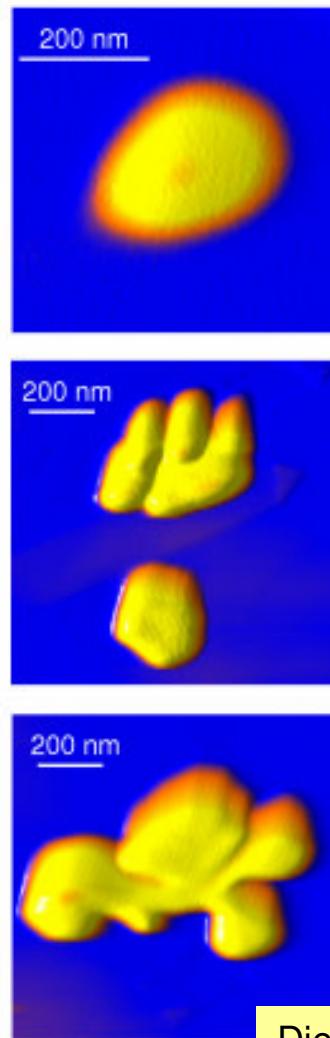
b non-vanishing friction particles



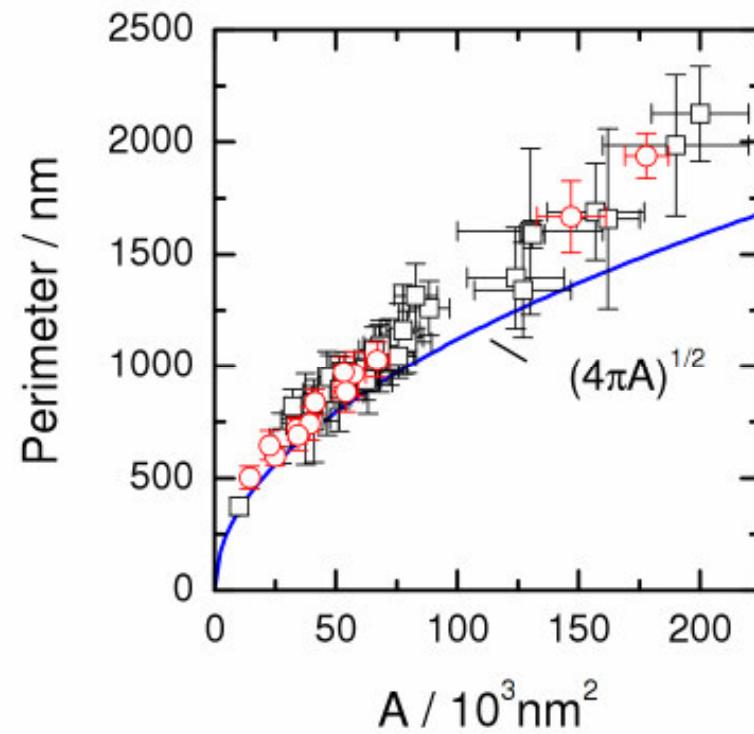
size

Influence of Particle Shape?

Spectrum of particle shapes



Shape: Perimeter vs. Contact Area



Red: vanishing friction

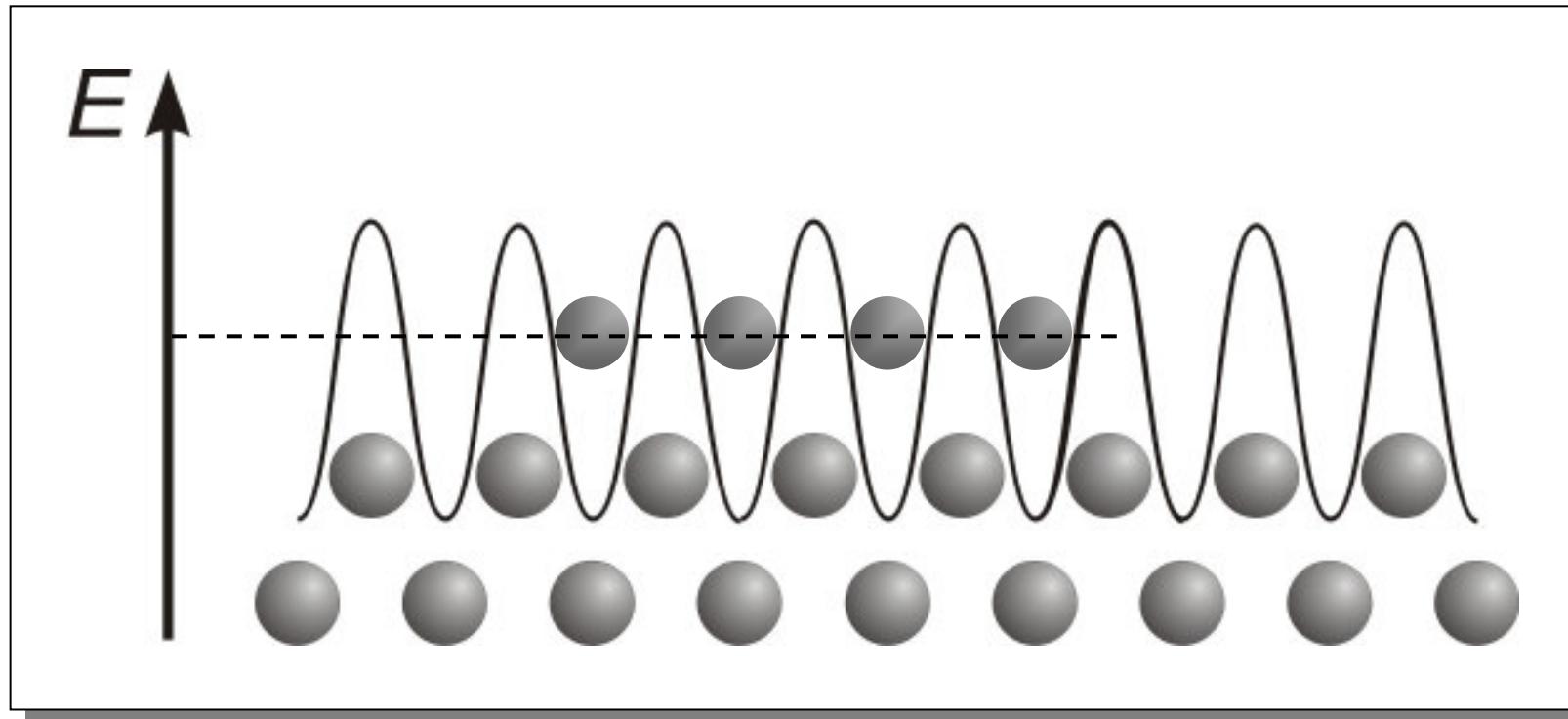
Black: non-vanishing friction

→ No influence of particle shape

Atomistic View: Area Dependence of friction

Commensurate lattices in contact

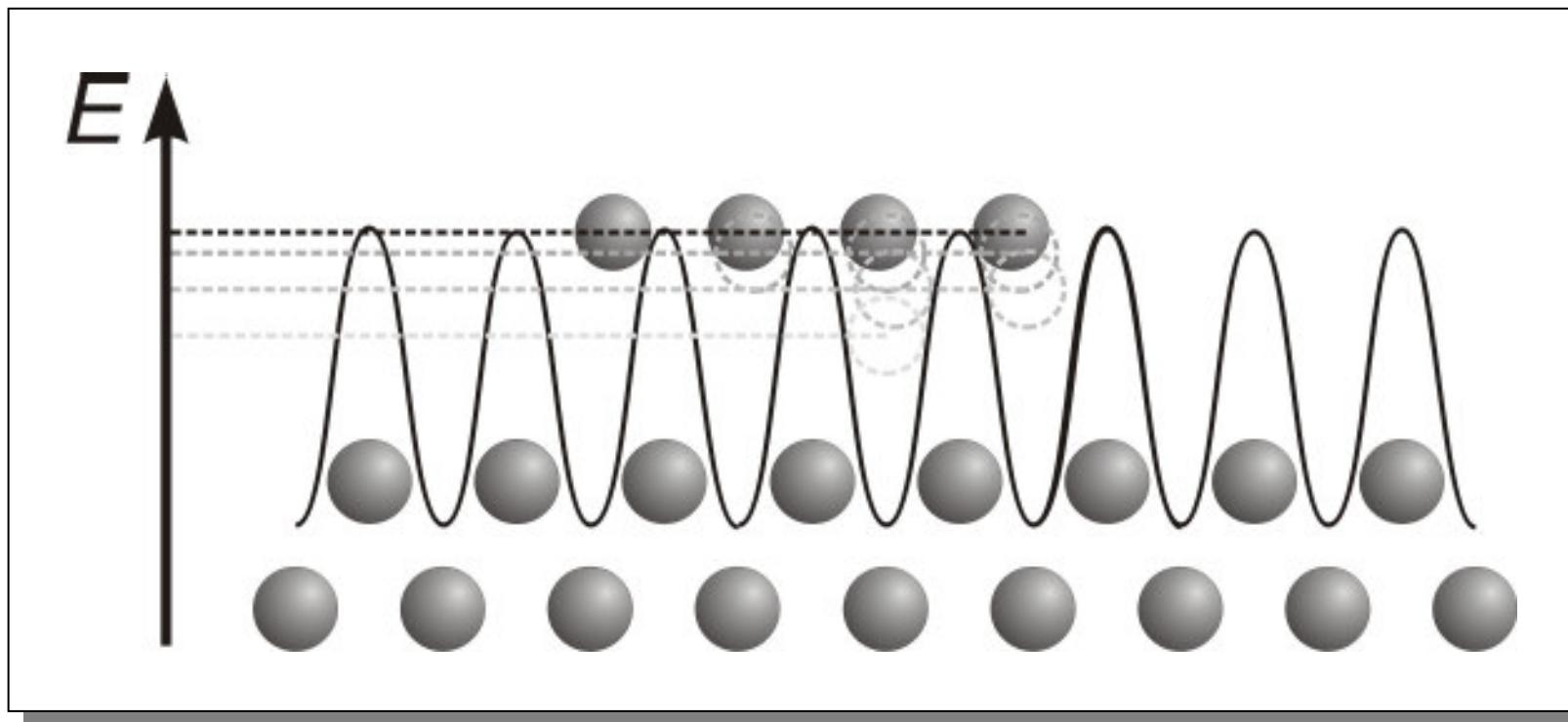
E = potential energy per top atom



$$F_{\text{friction}} = \tau \cdot \# \text{atoms in contact}$$

Atomistic Model for Friction: Superlubricity

Lattice constant 90 % of surface atoms

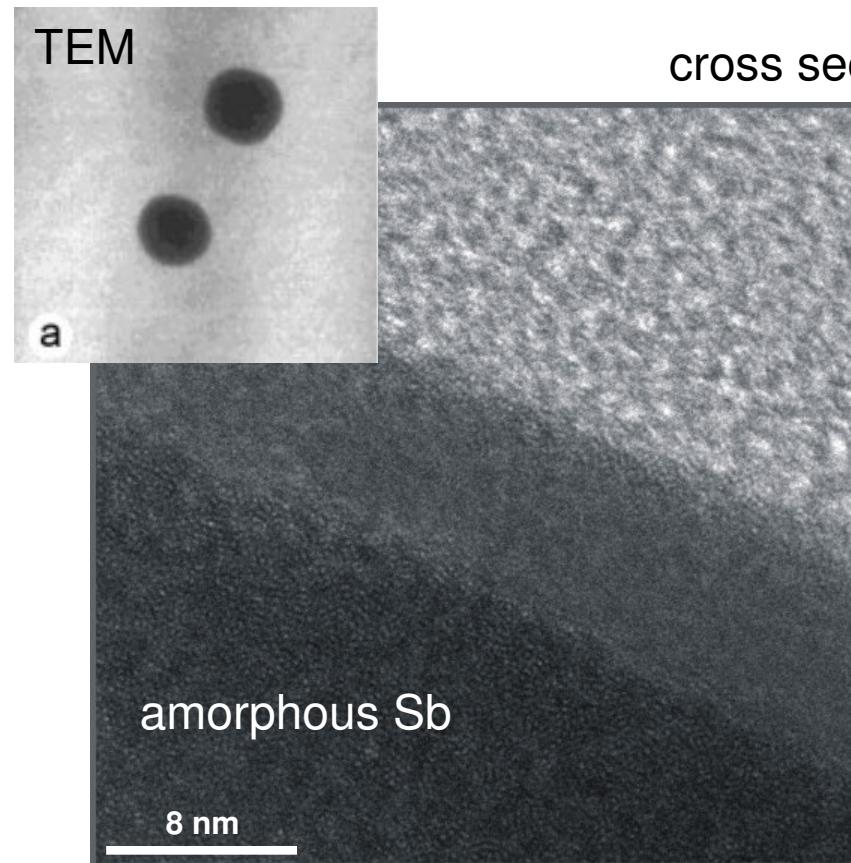


E = potential energy per top atom

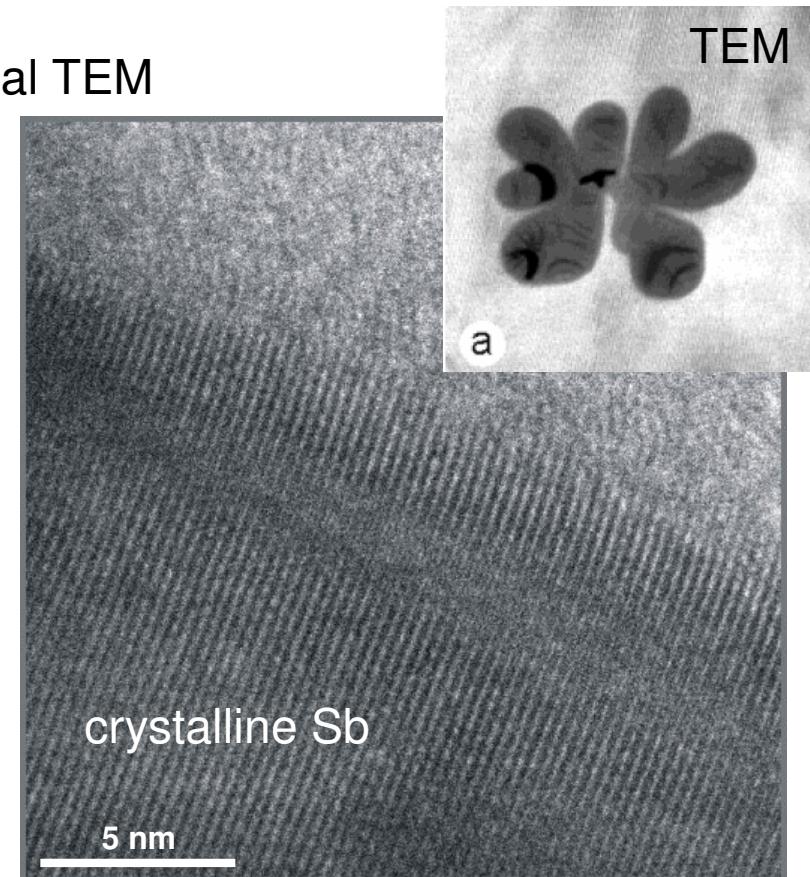
Hirano & Shinjo, PRB 41, 11 837 (1990)
Müser, Wenning, Robbins, PRL 86, 1295 (2001)
Dienwiebel et al., PRL 92, 126101 (2004)

Atomic structure of Antimony particles

Small spherical particles: Amorphous



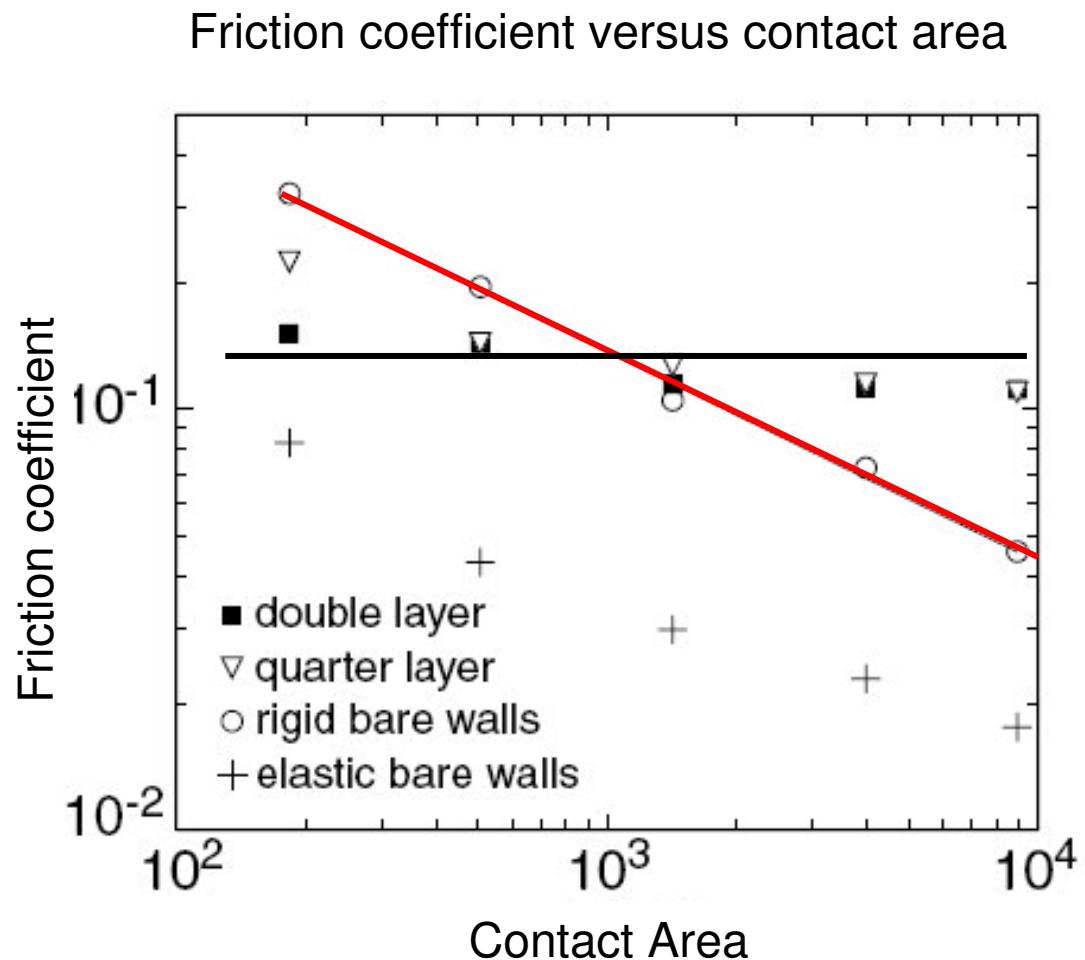
Large branched particles: Crystalline



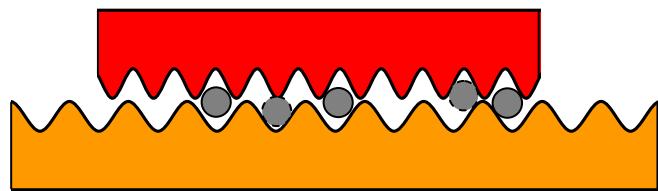
B. Stegemann et al.,
J. Phys. Chem. B 108, 14292 (2004)

Sb lattice constant = 0.4307 nm
HOPG lattice constant = 0.246 nm

Molecular Dynamics Simulation: Contamination

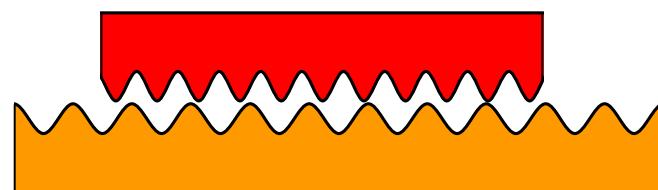


mobile molecules at interface



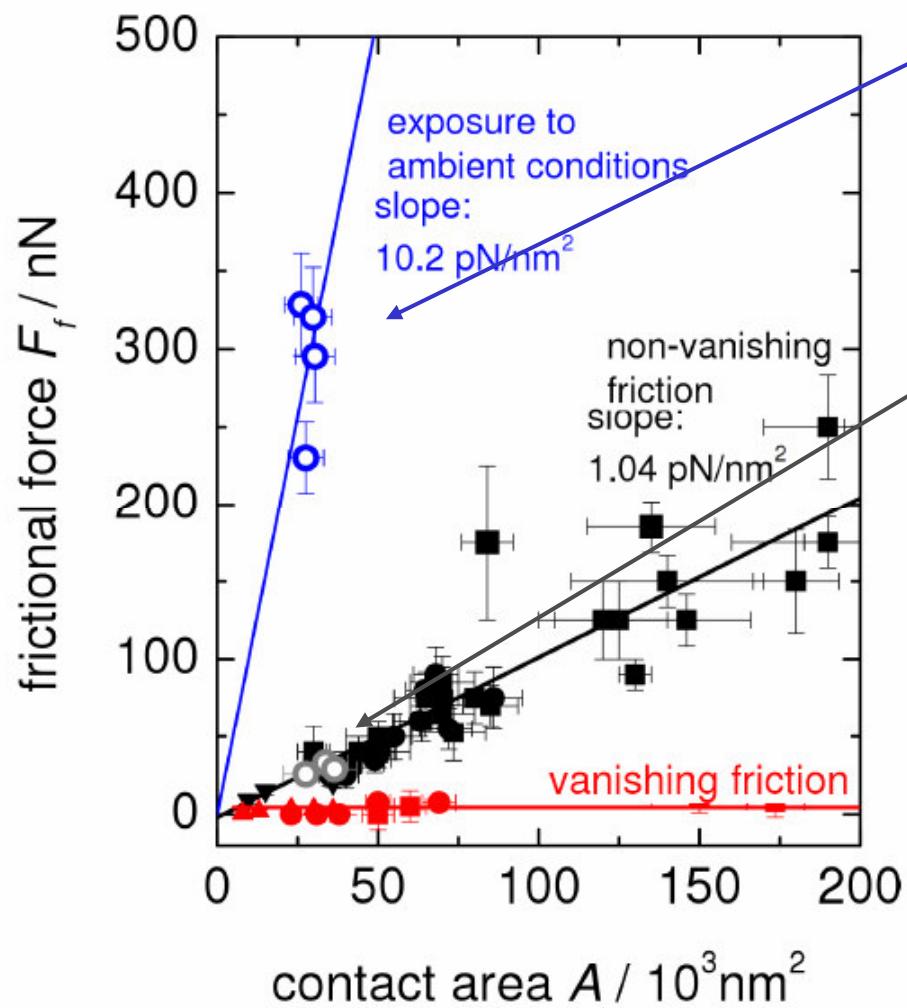
$$\text{friction} = \tau \cdot \text{area}$$

clean amorphous interface



$$\text{friction} = \alpha \cdot \text{area}^{1/2}$$

Further experiments: Particle Oxidation on Air



Upper branch: Friction of oxidized particles increased by over one order of magnitude
(c.f. ambient expt. $\tau = 40 \text{ pN/nm}^2$)

Lower branch: Some particles remain on 'non-vanishing' friction branch

Procedure:

- Particles left in air for two weeks
- Reinserted in UHV
- Annealed at $\sim 150^\circ\text{C}$ for 30 min
- Manipulation in UHV

Perspective: Nanoparticle Mediated Friction

nature
Vol 455 | 2 October 2008

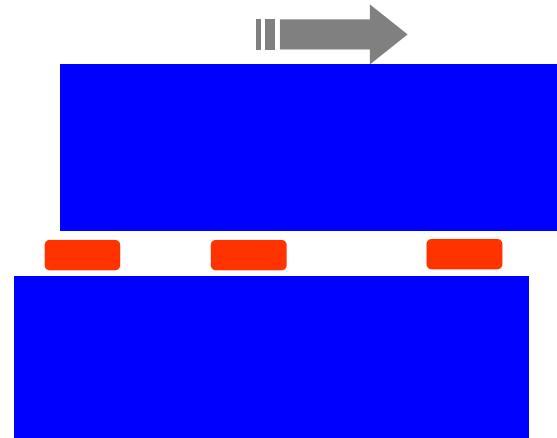
RESEARCH HIGHLIGHTS

MECHANICS

Slippery when clean

Phys. Rev. Lett. **101**, 125505 (2008)

Friction is a familiar force in everyday life, but its nanometre-scale details are obscure. This is because the fundamental mechanisms are subtle and sensitive to contamination,



Frankfurter Allgemeine

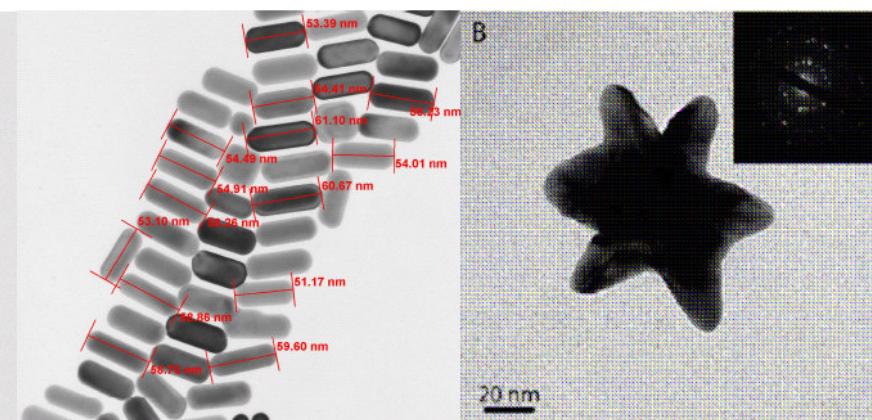
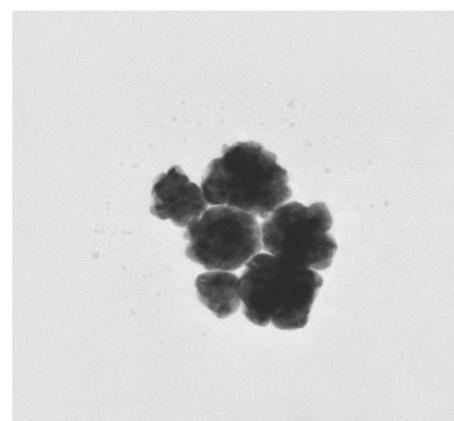
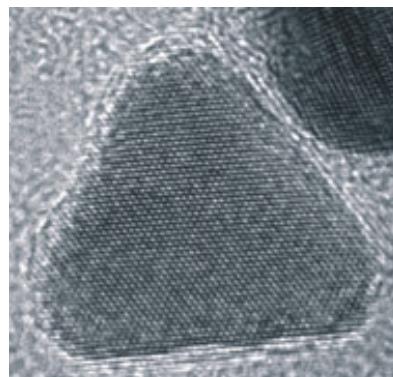
ZEITUNG FÜR DEUTSCHLAND

Frankfurter Allgemeine Zeitung > Natur und Wissenschaft >

Gleiten ohne Widerstand

In der Nanowelt lassen sich winzige Partikeln auf sauberen Graphitoberflächen bisweilen ganz ohne Reibungsverluste verschieben.

Viele vertraute Phänomene unserer Alltagswelt müssen keineswegs auch im Reich der Atome und Moleküle gelten. Ein Beispiel dafür ist die Reibungskraft, die man aufwenden



07.10.2008

K. Mougin, Mulhouse, France

European 'Nanoparticle Manipulation' Team



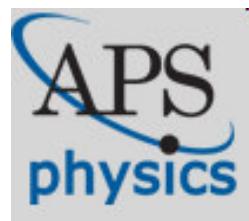
CRP PL: PD Dr. André Schirmeisen
Dr. Gnecco, Basel, Switzerland
Prof. Mougine, Mulhouse, France
Prof. Stich, Bratislava, Slovakia
Dr. Lohmus, Tartu, Estonia
Prof. Reimann, Bielefeld, Germany
Prof. Colaco, Lisbon, Portugal
Prof. Schwarz, Yale, USA
Prof. Erts, Riga, Latvia

Nanoscale Friction Meetings 2010



Regensburg, Germany (21.-26.3.2010)

Special Symposium ,Nanotribology‘ (on Friday morning, 26.3.2010)
organised by A. Schirmeisen and R. Bennewitz



Portland, OR, USA (15.-19.3.2010)

**Focus Topic ,Tribophysics: Friction, fracture and
deformation across length scales‘**

organised by M. Falk, I. Slzufarska, A. Schirmeisen, C. Maloney, E. Riedo

Planned: Nanomanipulation Meeting 2010

1st European Conference on Nanomanipulation

Hotel Bahia, Cascais-Lisbon, Portugal

17.-19. May 2010



Conference organizers:

Enrico Gnecco (Basel University)

Andre Schirmeisen (Muenster University)

Adam Foster (Technical University of Helsinki)

Rogerio Colaco (Technical University of Lisbon)

The People behind the Work...

Münster group

Dirk Dietzel



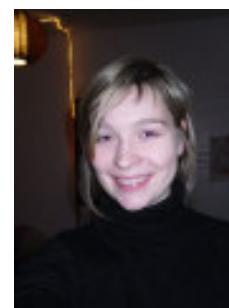
Tristan Mönninghoff



Michael Feldmann



Carina Herding



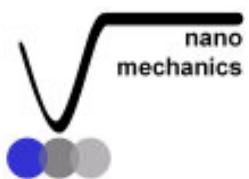
Johannes Sondhauß



Yale group

Claudia Ritter,
Udo D. Schwarz

*Dept. Mechanical
Engineering, Yale
University, USA*



Thank you for your attention!