Dissipation from contact and non-contact

Ernst Meyer, Remy Pawlak, Thilo Glatzel, Sweetlana Fremy,
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Outline

- Contact force microscopy combined contact resonance force microscopy
- Pendulum AFM on superconductors: The influence of electronic friction
- LT-AFM: Rotation of single molecules by AFM

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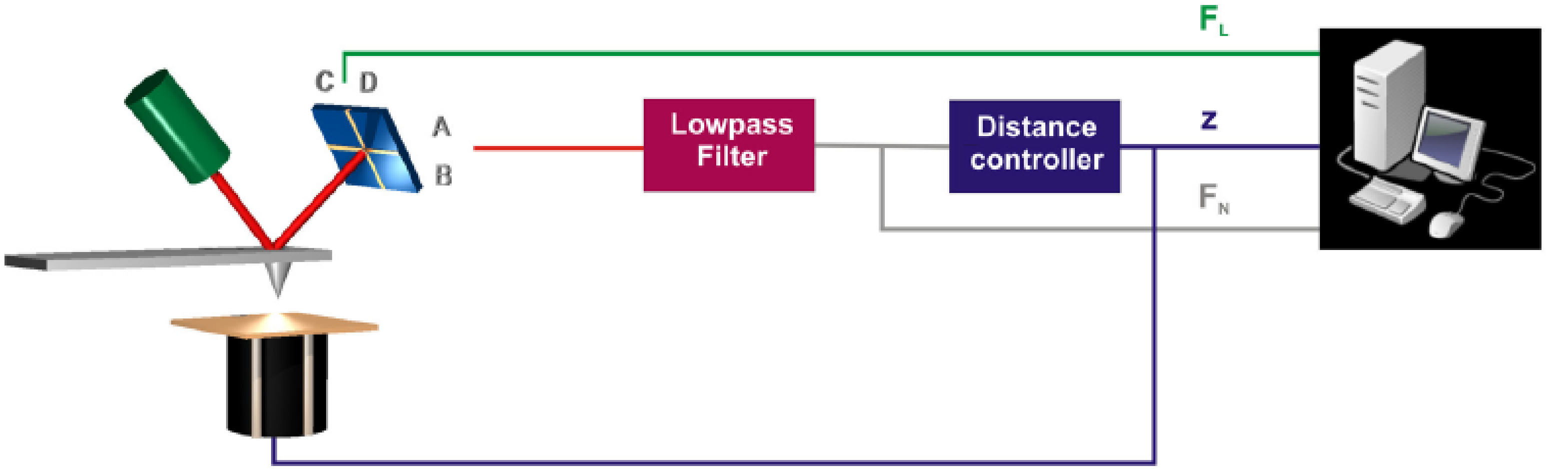
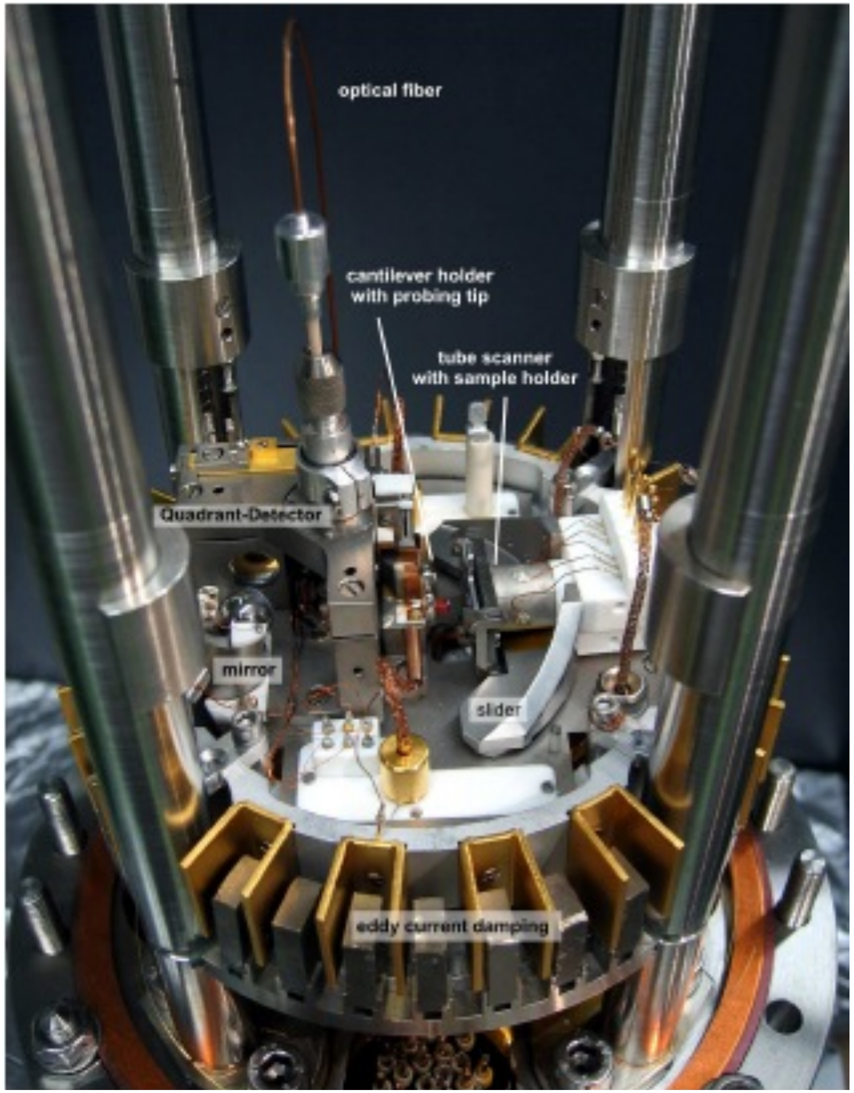
1st ESF NANOTRIBOLOGY WORKSHOP
PORTOVENERE (I) 19 - 23 OCTOBER 2002

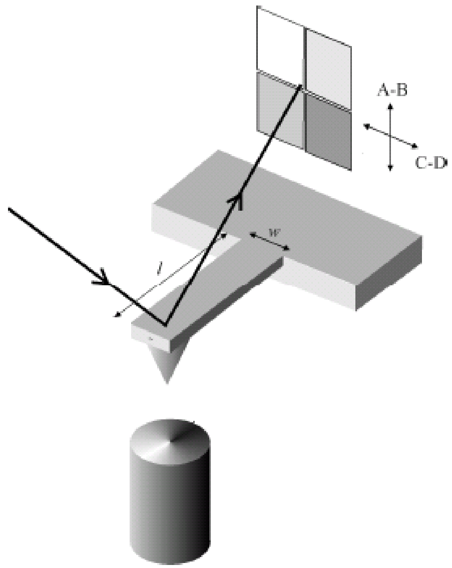
Contact AFM



Ultrahigh Vacuum Force Microscopy



- UHV- chamber with base pressure < 10 $^{-10}$ mbar
- room temperature



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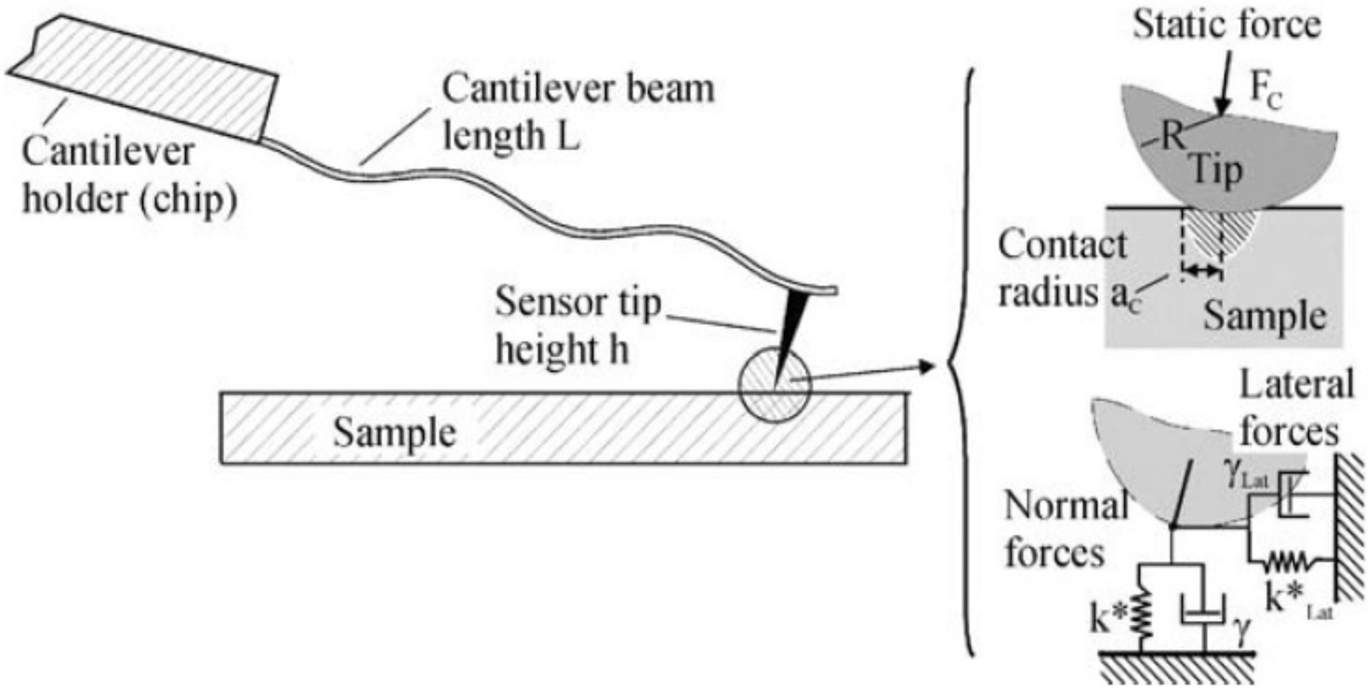
Contact resonance frequencies vs.normal & lateral contact stiffnesses and dampings



U. Rabe in Applied Scanning Probe Methods II, p. 39ff
Eds. H. Fuchs, B. Bhushan, Springer-Verlag, Berlin

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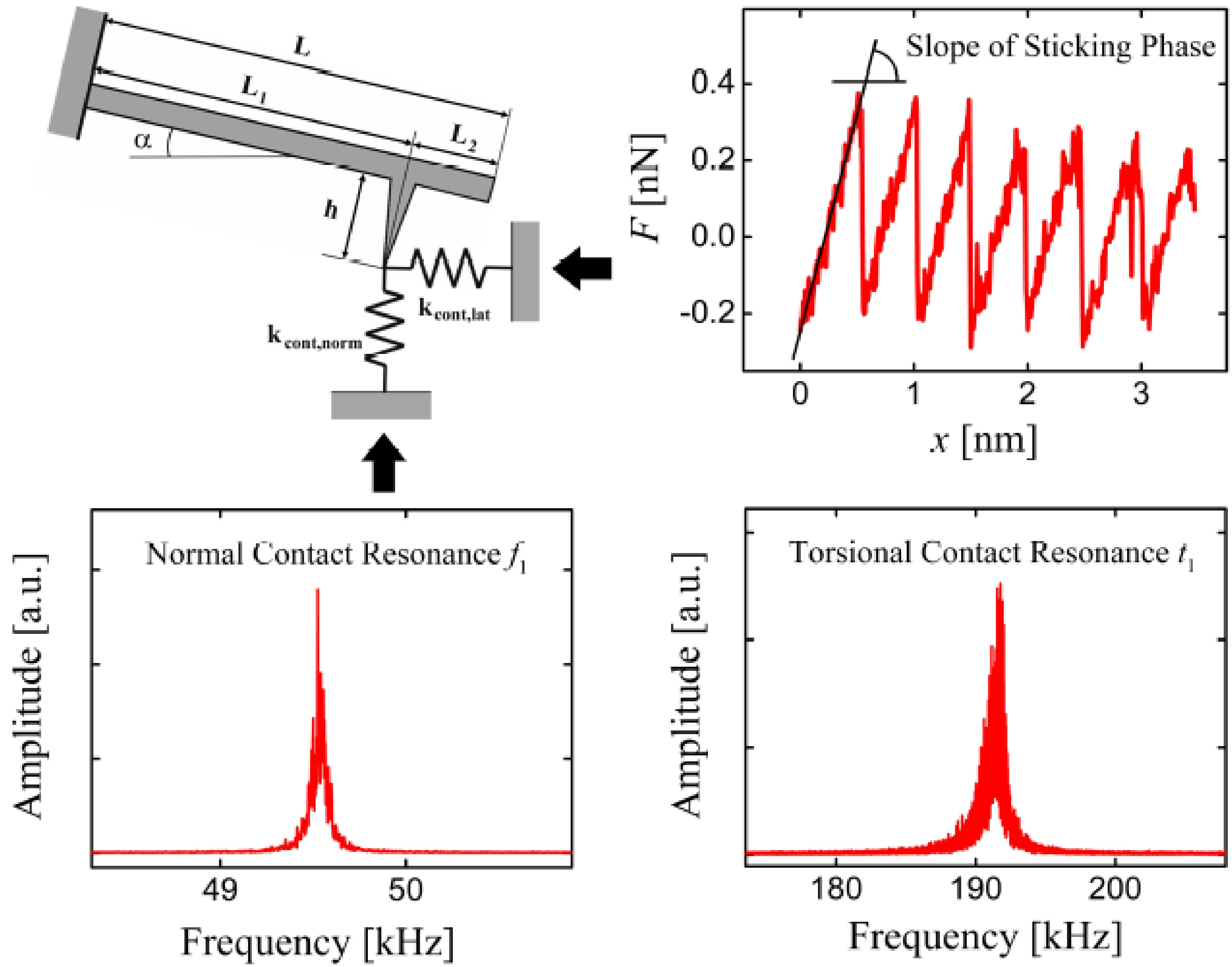
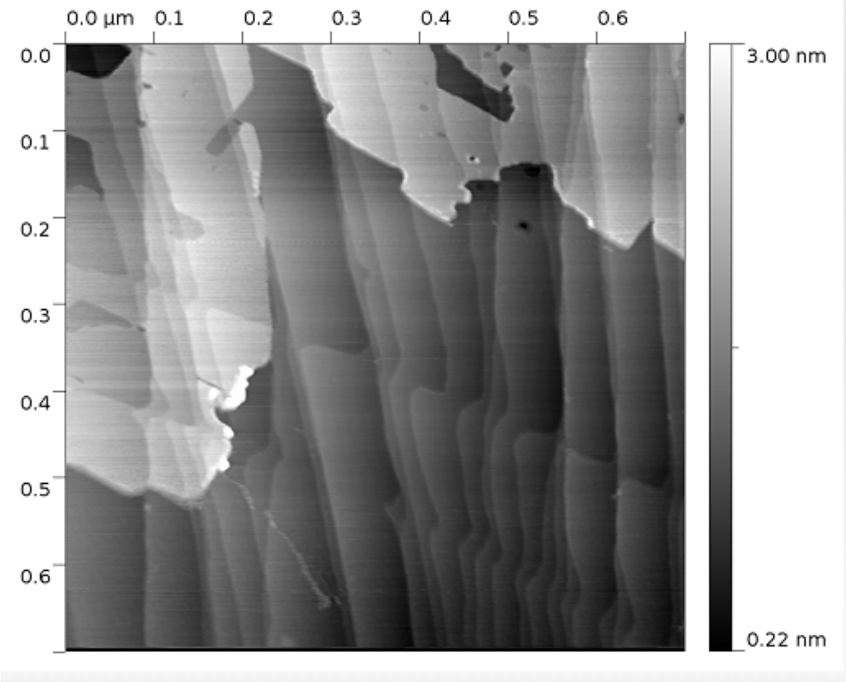
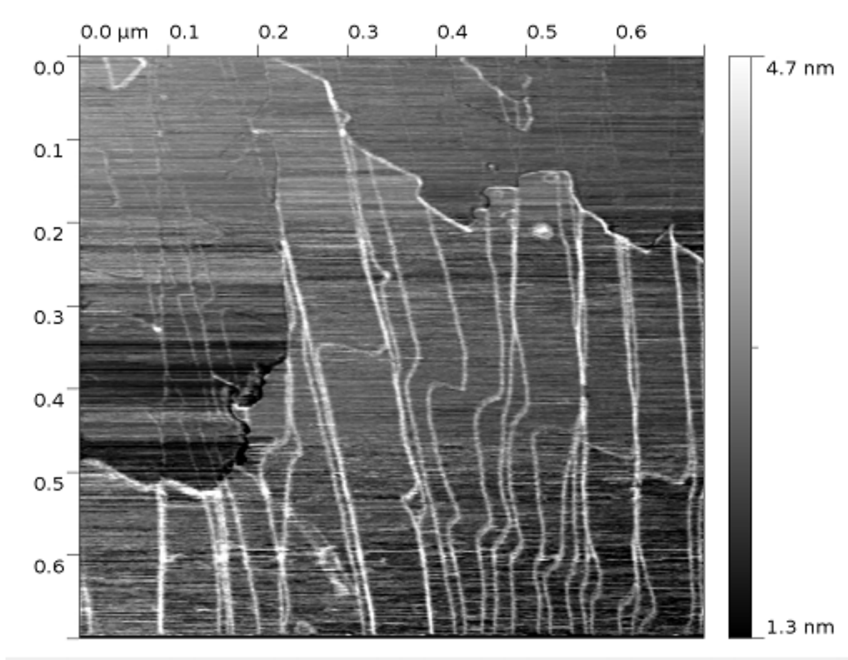
Simultaneous determination of lateral and normal contact stiffnesses k_N, k_L = $-dF_N/dz$, dF_L/dx



Contact mode imaging with excitation of NaCl(001) on Cu(111) and amplitude measurement at contact resonance



Topography



Lock-in amplitude at 56.2kHz

Fixed frequency: 56.2kHz
Lock-In measurement of amplitude

⇒Local variations of normal contact stiffness

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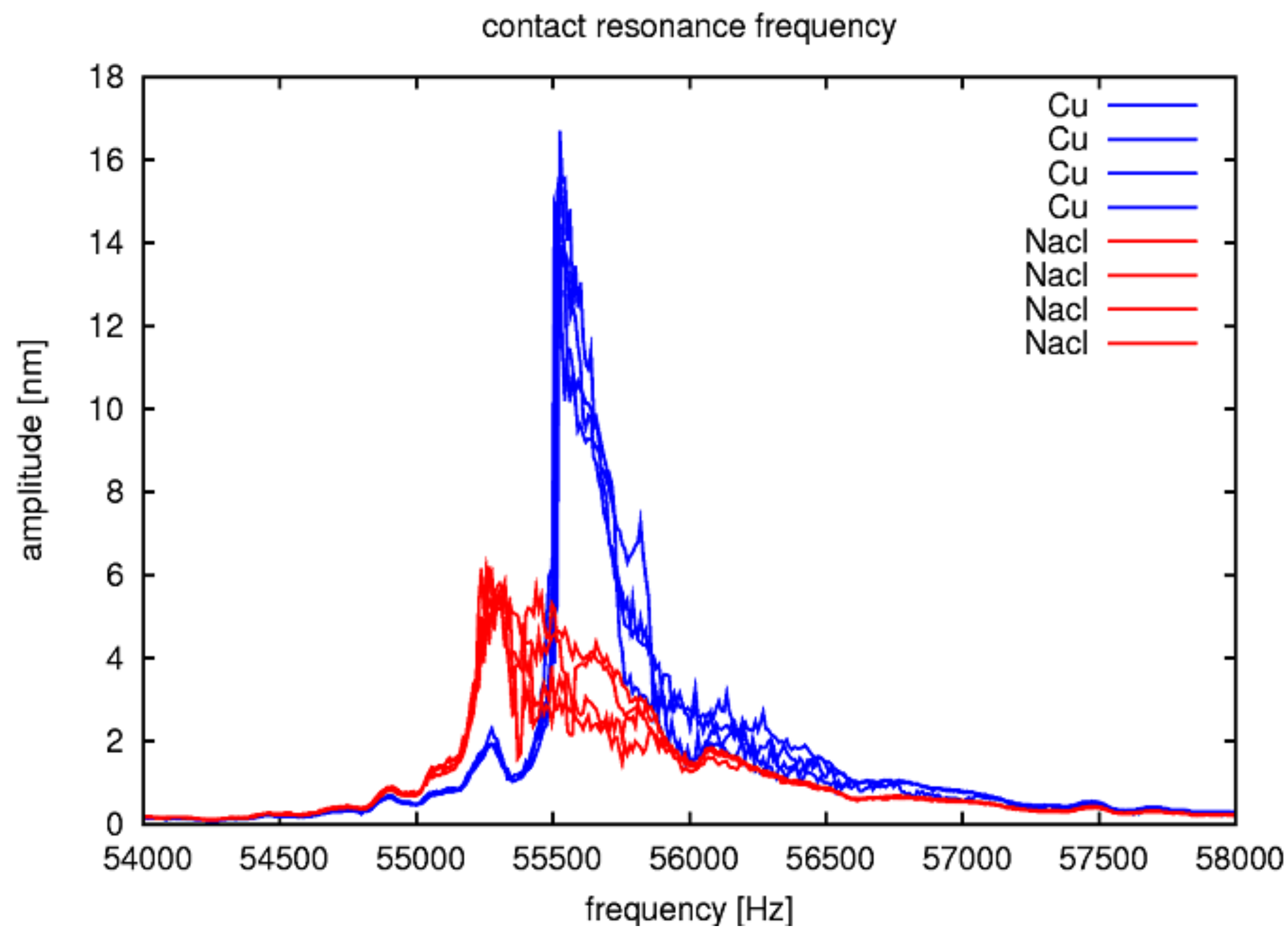
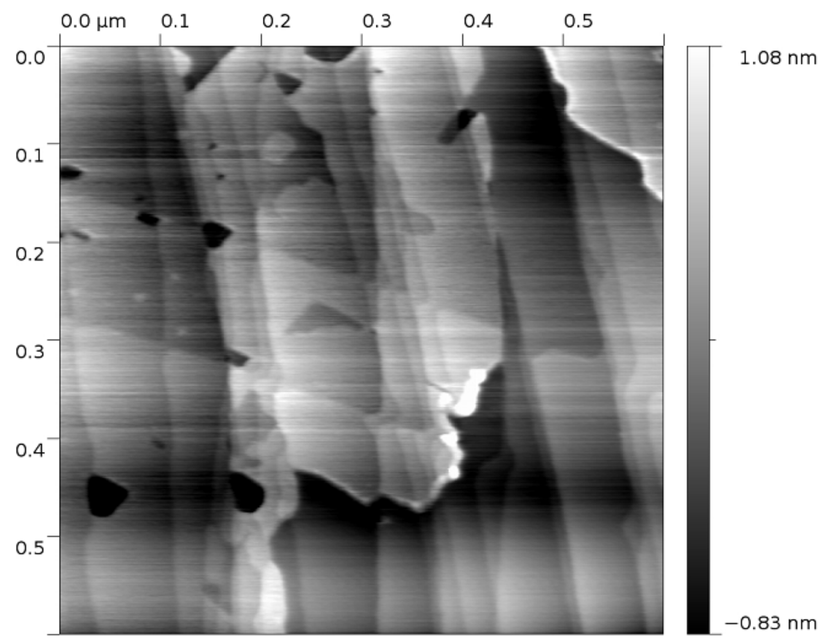
Contact Resonances

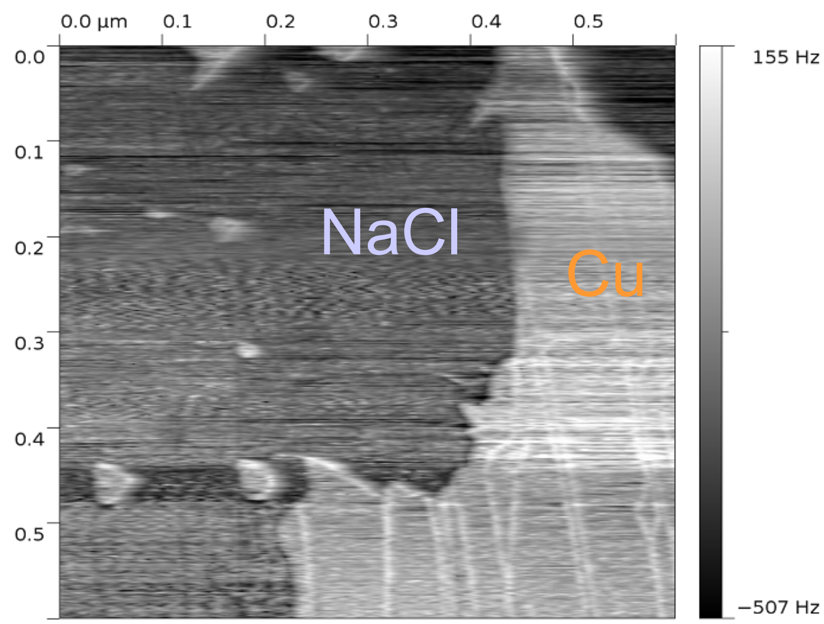


Free cantilever: 11325Hz; In Contact: 55.3kHz and 55.5kHz

Imaging of contact resonance by PLL
NaCl(001) on Cu(111)



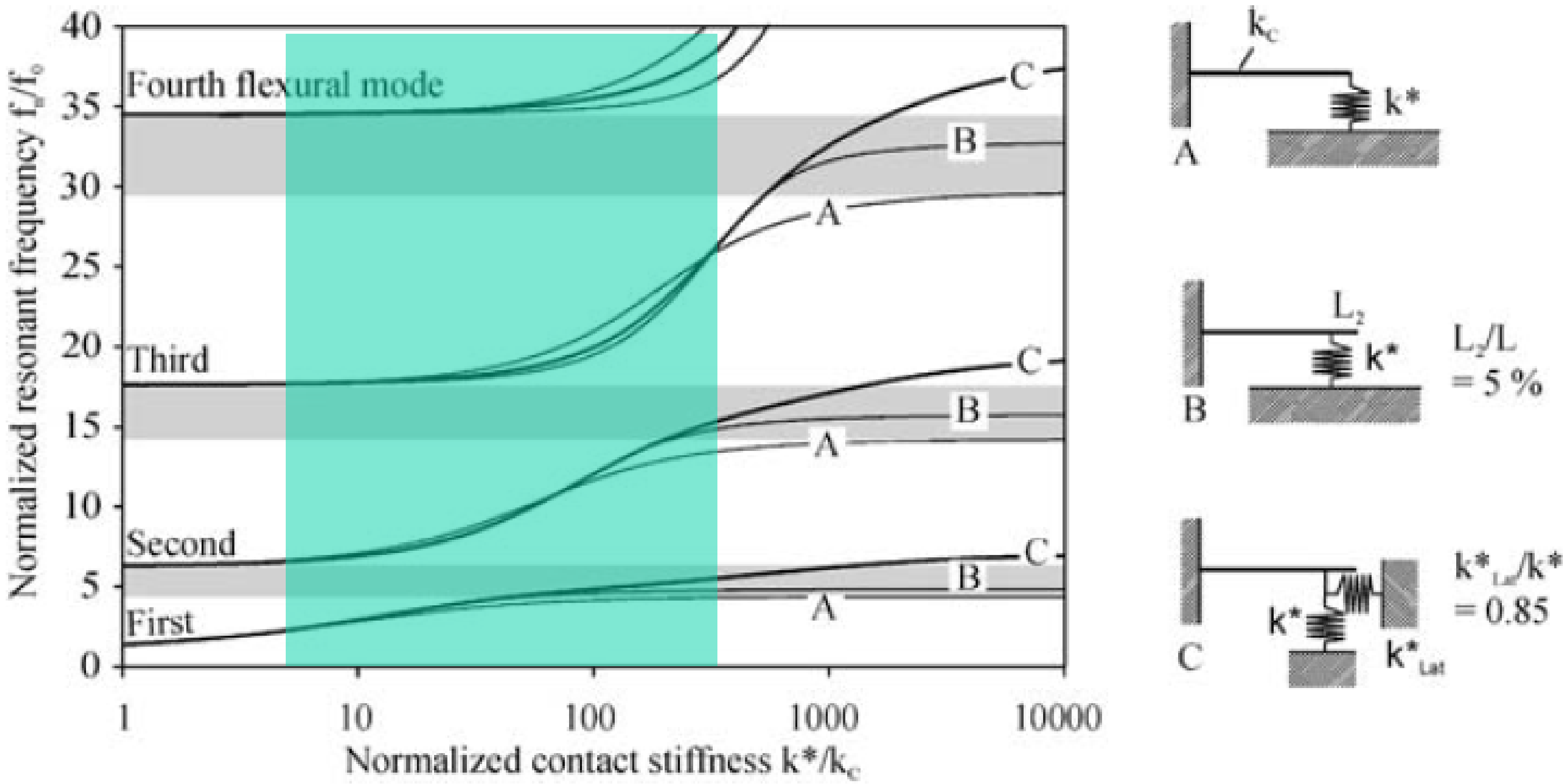
Topography



Frequency shift
measured by PLL
Amplitude=400pm

Contrast between copper and NaCl: 195Hz
Free cantilever: 11325Hz; In Contact: 55.3kHz and 55.5kHz

Contact resonance frequencies as a function of normalized contact stiffness $k^* \equiv k_N$



Sensitive to tip offset from lever end in the nearly pinned limit,
Most sensitive measurement in intermediate (shaded) range

U. Rabe in Applied Scanning Probe Methods II, p. 39ff, Springer-Verlag, Berlin

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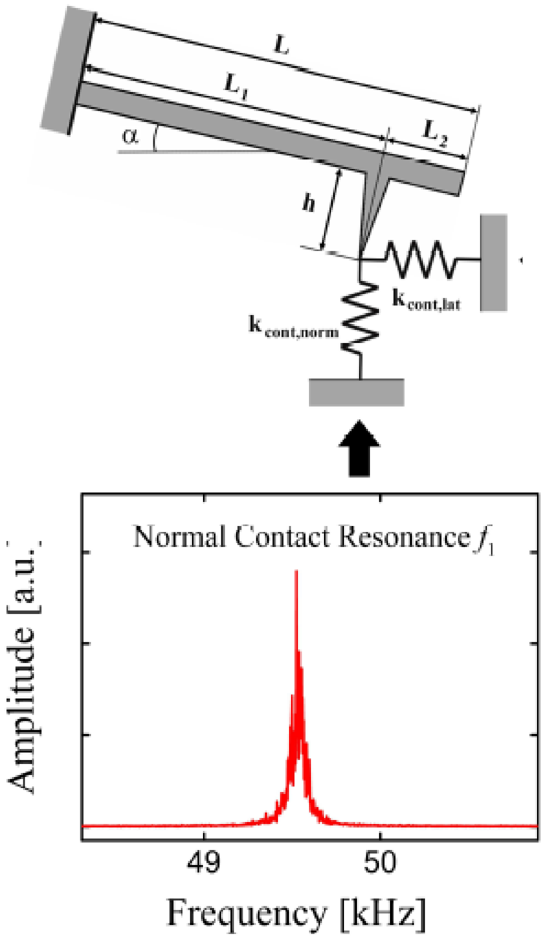
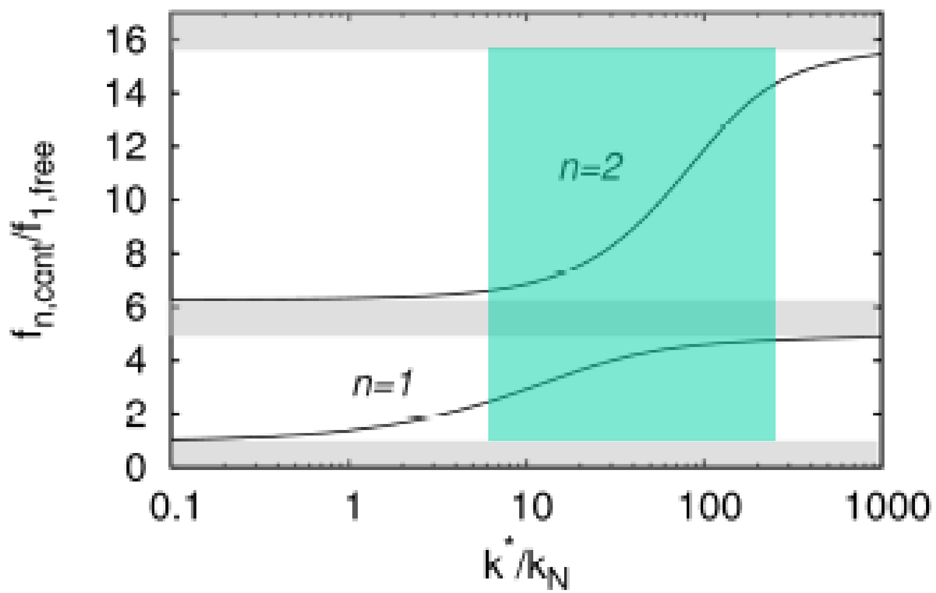
Determination of normal contact stiffness





$$\frac{k_{\mathrm{cont,norm}}}{k_{\mathrm{norm}}} = \frac{-B \pm \sqrt{B^2 - 4AC}}{6A}.$$

$$A = \left(\frac{k_{\mathrm{cont,lat}}}{k_{\mathrm{cont,norm}}}\right)\left(\frac{h}{L_1}\right)^2 (1 - \cos(x_{\mathrm{n}} L_1)\cosh(x_{\mathrm{n}} L_1)) \times (1 + \cos(x_{\mathrm{n}} L_2)\cosh(x_{\mathrm{n}} L_2)),$$

$$B = B_1 + B_2 + B_3,$$

$$C = 2(x_{\mathrm{n}} L_1)^4 (1 + \cos(x_{\mathrm{n}} L)\cosh(x_{\mathrm{n}} L)),$$

k_N=0.095N/m, f_1=49.5kHz f_1^0=10.2kHz

$$x_1 L = x_1^0 L \sqrt{\frac{f_1}{f_1^0}},$$

D. Hurley & J. Turner, J. Appl. Phys. 102, 033509 (2007)

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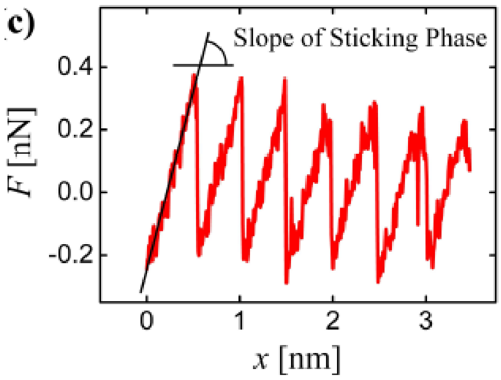
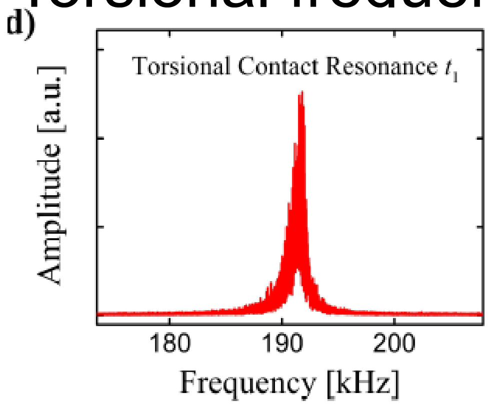
Determination of lateral contact stiffness from friction force loop vs. torsional resonance frequency

Friction force loop



k_L =5.55N/m

Torsional frequency



$$\frac{k_{\text{cont,lat}}}{k_{\text{tors}}} = -\frac{y_1 L \cos(y_1 L)}{\sin(y_1 L_1)\cos(y_1 L_2)}.$$

$$y_1 L = \frac{\pi}{2}\frac{t_1}{t_1^0}.$$

⇒ Consistent independent determinations

⇒ Moreover, torsional k_T=59.4N/m >> lateral contact stiffnesses k_L ~ 1-6N/m)

Torsional frequencies: t_1 in contact
$t^0{}_1$ out of contact

k_L =5.18N/m

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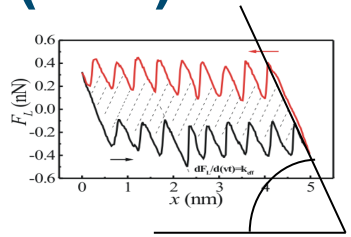
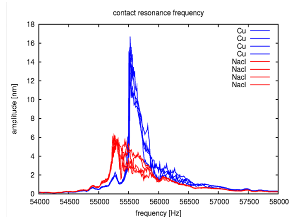
Simultaneous determination of normal and lateral contact stiffness on NaCl(001) /Cu(111)

Lateral contact stiffness:
k_L on Cu(111): 3.2N/m;
k_L on NaCl(001): 2N/m (1.7-2.3N/m)





Contact resonances:
Free cantilever: 11325Hz;
In Contact on Cu(111): 55.5kHz and on KBr(001): 55.3kHz

⇒Normal contact stiffness estimates with Rabe-model:
Cu(111): 50N/m ; NaCl(001): 40N/m

Normal contact stiffness is much larger than lateral contact stiffness!

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Comparison of lateral and normal contact stiffness

sample	k_N [N/m]	η	κ [N/m]	k_{eff} [N/m] (k cont lat)	k^* [N/m] (k cont norm)	$\frac{k^*}{\kappa}$	$\frac{k^*}{k_{eff}}$ ($\frac{k_{\text{cont norm}}}{k_{\text{cont lat}}}$)
NaCl(100)	3.1	5.7	1.72	2.07	13.1	7.6	6.33
NaCl(100)	0.095	4.9	1.24	1.49	21.1	17.1	14.16
NaCl(100)	0.082	4.0	1.43	1.83	19.0	13.0	10.38
KBr(100)	0.082	1.3	0.96	1.72	14.9	15.5	8.68
Cu(111)	0.091	5.7	2.72	3.20	40.4	14.9	12.63
NaCl(100) on Cu(111)	0.091	3.1	1.65	2.18	32.7	19.8	15.00

$$\eta = \frac{2\pi F_L^{max}}{k_{exp} a} - 1; \qquad k_{eff} = \frac{\eta + 1}{\eta} \cdot \kappa$$

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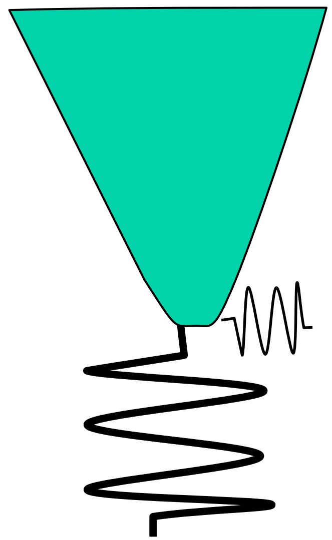
Comparison of lateral and normal contact stiffness

Lateral contact stiffness under atomic stick slip condition (F_N=0.1-1nN; η=3-5):

k_L=1-3N/m



Normal contact stiffness determined from contact resonances:

k^*=13-40N/m

Ratio of normal to lateral contact stiffness:

k^*/k_L=6-15

Normal contact stiffness is larger than lateral contact stiffness

From continuum models a ratio of E/G=2-4 is expected!

R. Roth et al.

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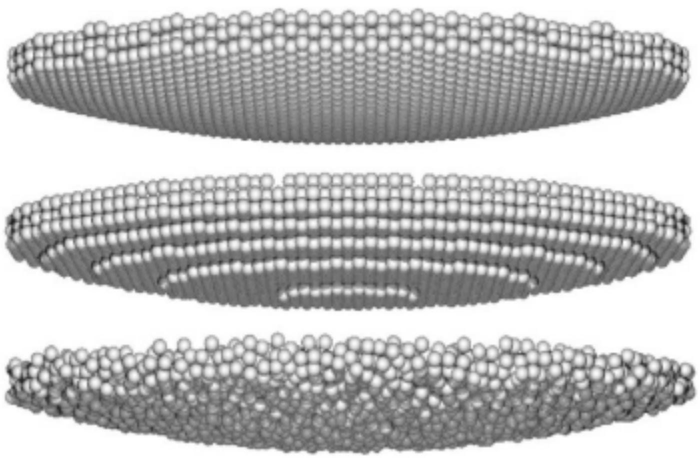
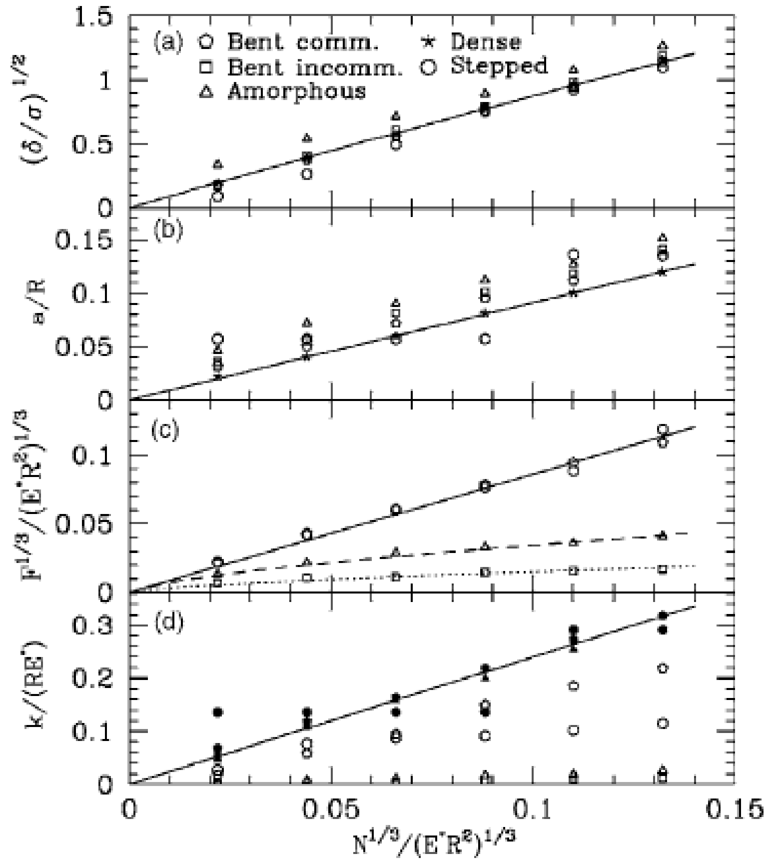
Normal and lateral contact stiffness





-Normal contact stiffness in reasonable agreeement with continuum models

-Lateral contact stiffness differs from the continuum model for small radii

B. Luan and M. Robbins, Phys. Rev. E 74, 026111 (2006).

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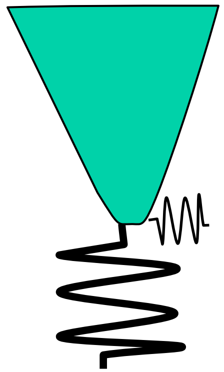
Contact area from normal contact resonance frequencies measurements

$k_{cont,\ norm}$=32N/m on NaCl(001)/Cu(111)
$k_{cont.\ norm}$=40N/m on Cu(111)

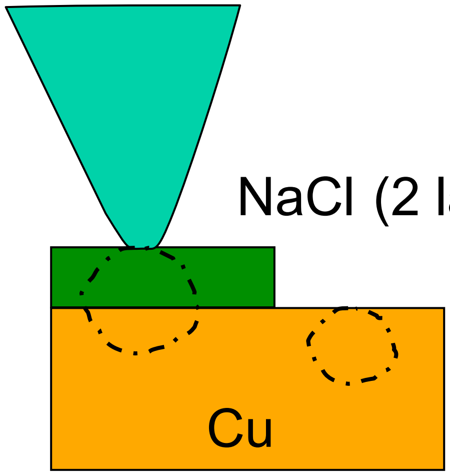


Application of Continuum model (flat punch):

$$2a = \frac{k_{cont\ norm}}{E^*} = \ 0.9\text{nm} / 0.5\text{nm}$$

$$\frac{1}{E^*} = \left(\frac{1-\nu_{tip}^2}{E_{tip}}\right) + \left(\frac{1-\nu_{sample}^2}{E_{sample}}\right)$$

E_{tip}=169GPa ν_{tip}=0.33
E_{sample}=40GPa/120GPa ν_{sample}=0.25/0.34



⇒Area from normal contact stiffness seems in agreement with resolution

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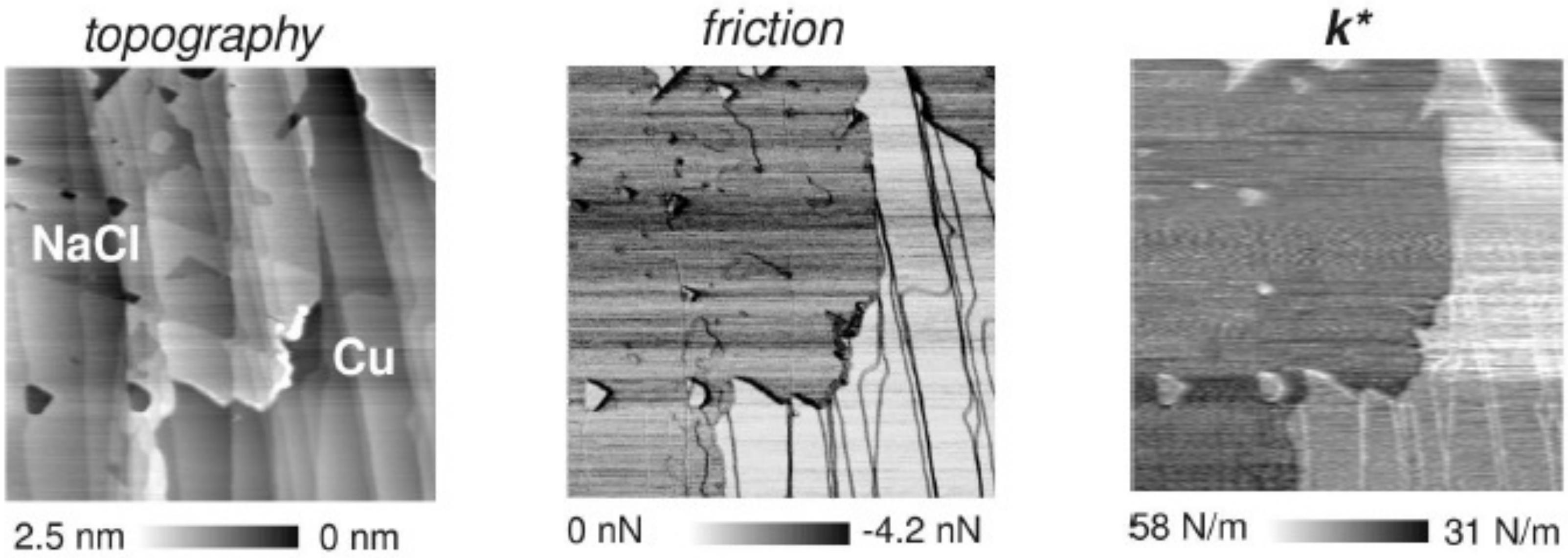
Simultaneous imaging of lateral forces and normal contact stiffness: NaCl(001) on Cu(111)



Lowest friction on Cu(111)
Contact stiffness on NaCl k*(NaCl)=32N/m
Contact stiffness on Cu(111) k*(Cu)=40N/m
Contact diameter: 2a=k*/E*=0.9nm (0.5nm)
Contact stiffness rather independent of number of layers

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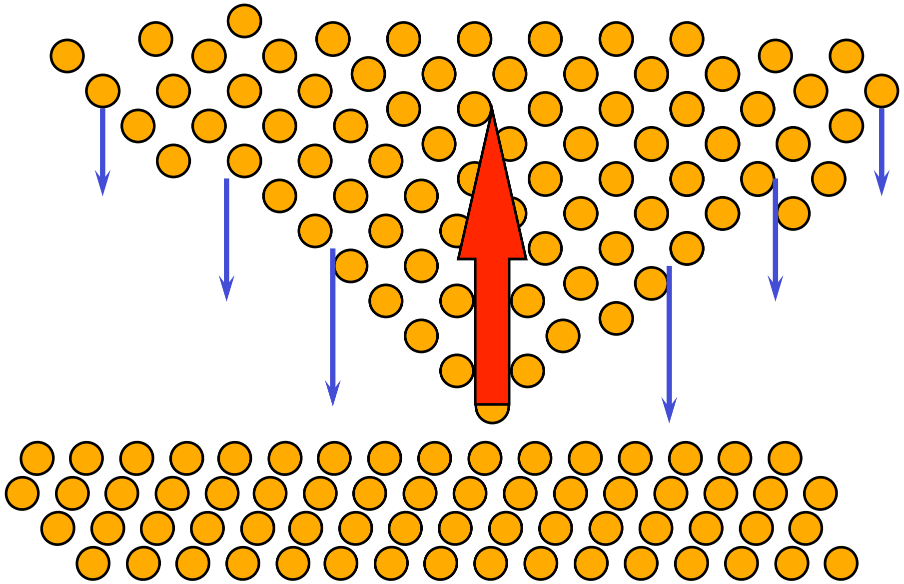
Contact force microscopy: Balance of long- and short-range forces



- **Typical long-range forces:**
  - **in air: 10-100nN**
  - **in liquids: 1-100pN**
  - **in ultra-high vacuum: 0.1-10nN**

- **Long-range forces are compensated by short-range repulsion. Bending of the cantilever can reduce the repulsive forces.**

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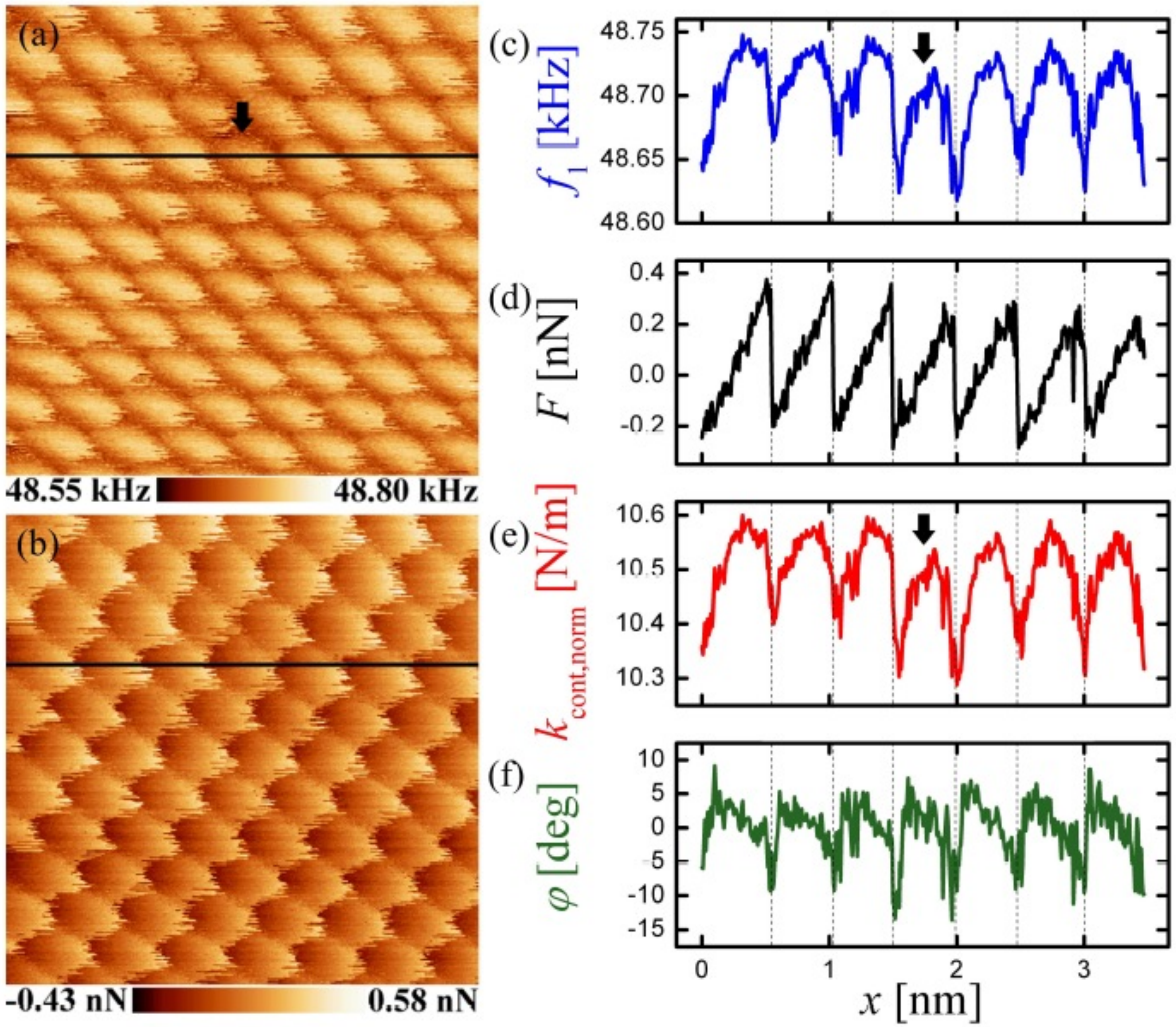
Simultaneous measurement of atomic stick slip and normal contact resonances on NaCl(001)

Contact resonance

Friction



Atomic-scale resonance frequency modulation more sensitive to defects, e.g. ⇓ than lateral F

Deduced k_N

Phase Locked Loop error signal unavoidable near slips

⇒ Maximum normal contact resonance is observed for F_L=0

P. Steiner et al., Nanotechnology, **20**, (495701), (2009)

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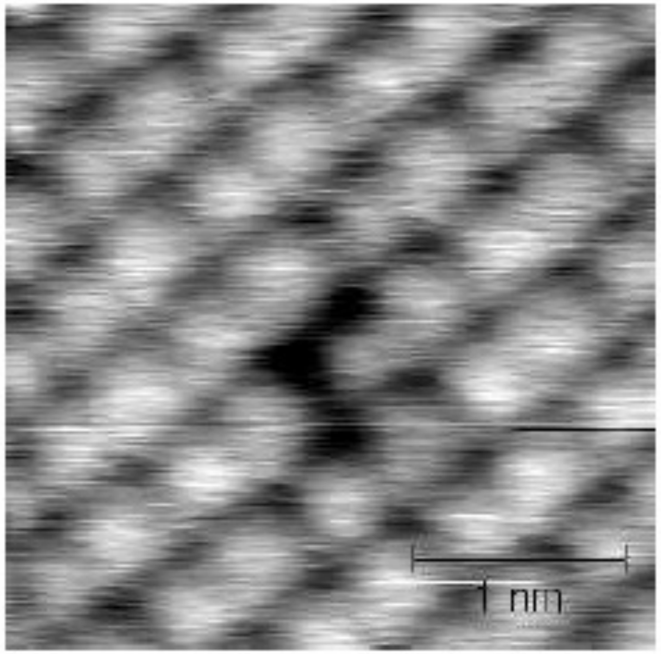
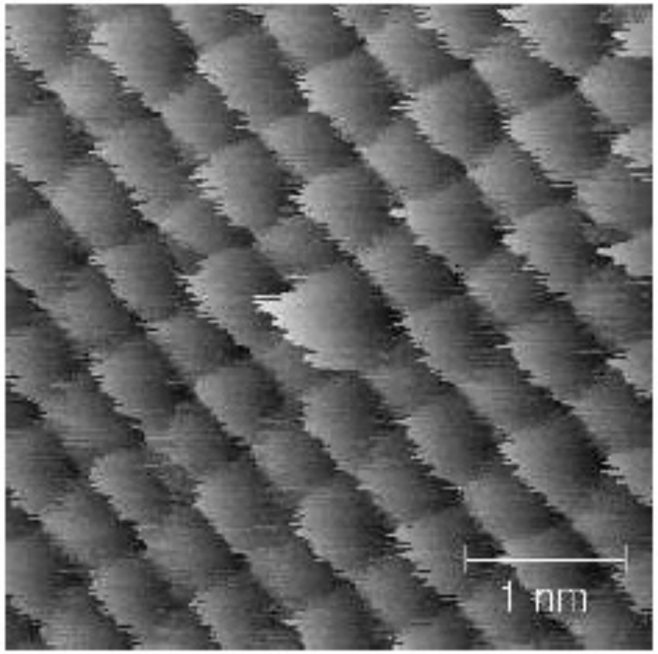
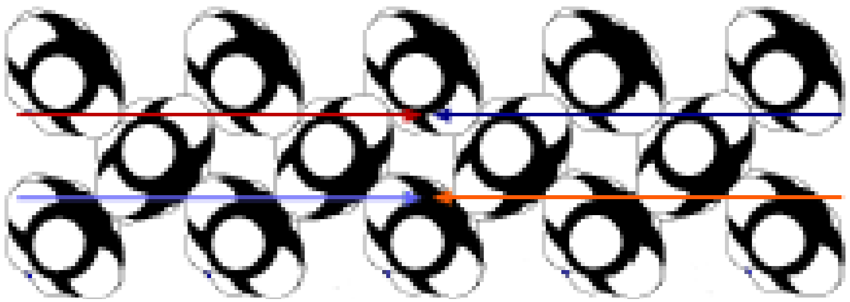
Friction force microscopy on a novel layered molecular crystal: [Benzylammonium]$_2$[Cu(oxalate)$_2$] BNL





Topography

Friction



G. Fessler et al.
S. Decurtins, Uni Berne

Appl. Phys. Lett., **98**, 083119 (2011)

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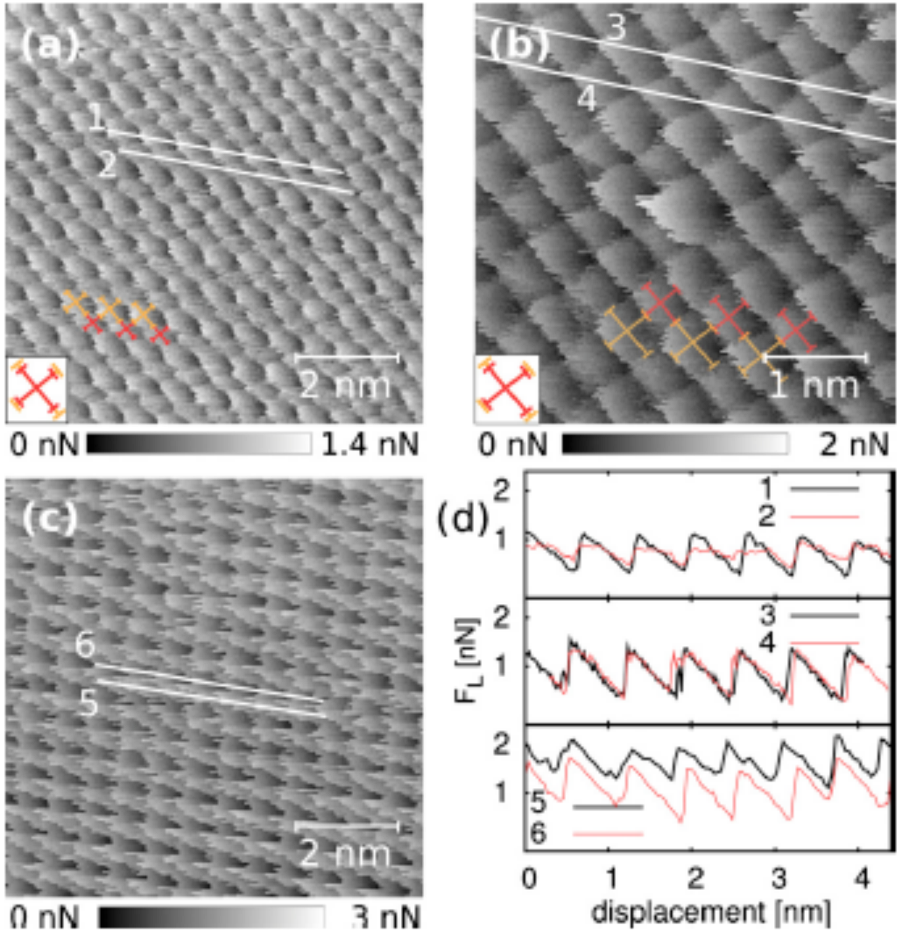
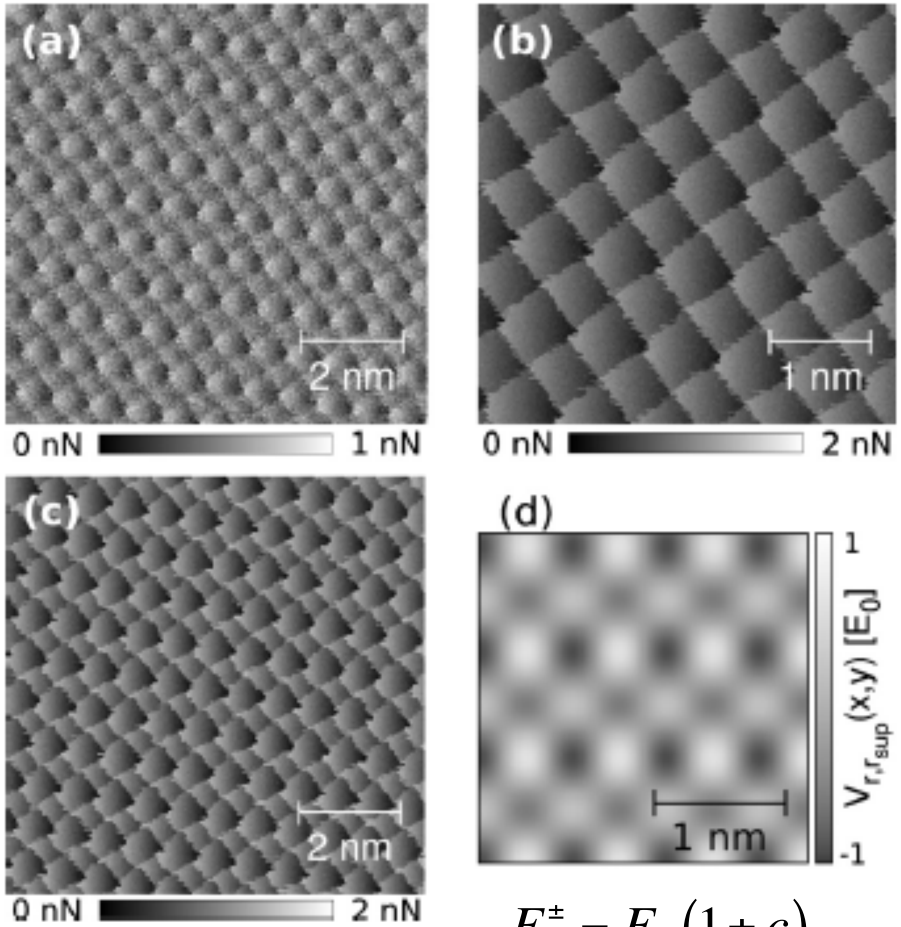
Friction on molecules:
Comparison with PT-model





$$E_0^{\pm} = E_0\left(1 \pm c\right)$$

Good agreement at low loads (c=0.15-0.35) deviations at higher loads

G. Fessler et al., Appl. Phys. Lett. 98, 0831191 (2011)

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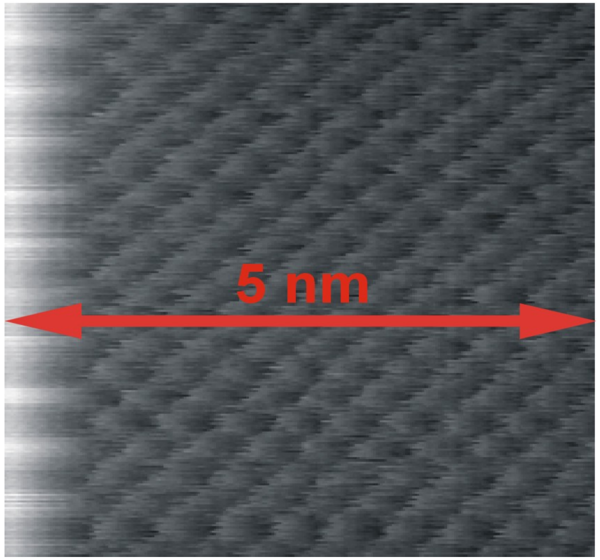
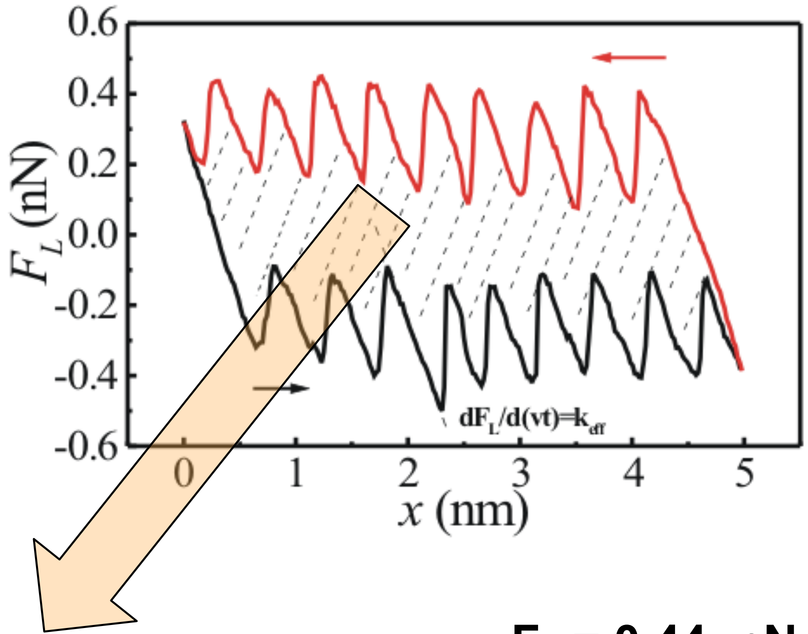
Friction on the Nanometer-scale: Atomic-Stick Slip

Atomic stick-slip



KBr(001)-crystal

Friction loop



What are the dissipation channels?

F_N = 0.44 nN

E_{diss} = 1.4 eV

(per slip)

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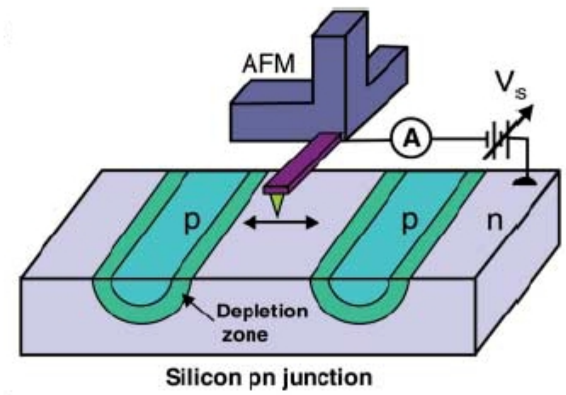
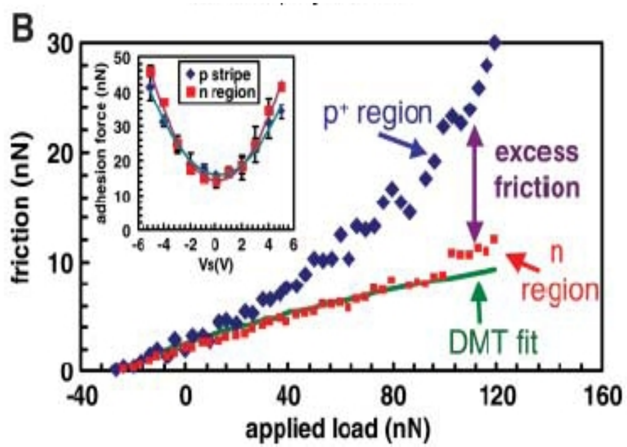
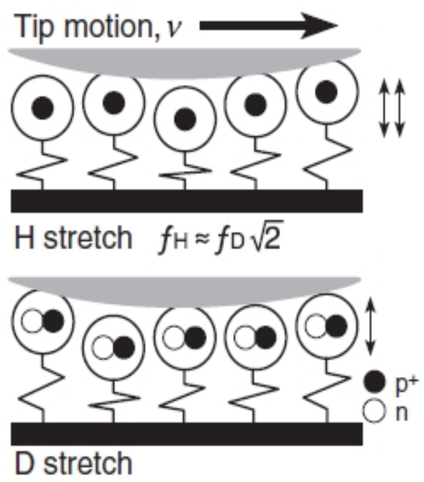
Electronic vs. Phononic Friction Experiments

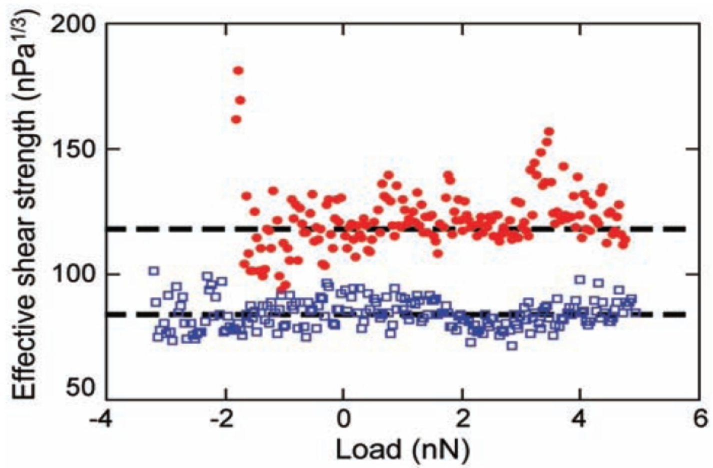
J.Y. Park, D.F. Ogletree, P.A. Thiel, and M. Salmeron, ***Electronic Control of Friction in Silicon pn Junctions,*** Science313, 186 (2006)





R.J. Cannara, M.J. Brukman, K. Cimatu, A.V. Sumant, S. Baldelli, and R.W. Carpick, ***Nanoscale Friction Varied by Isotopic Shifting of Surface Vibrational Frequencies,*** Science318, 780-783 (2007)





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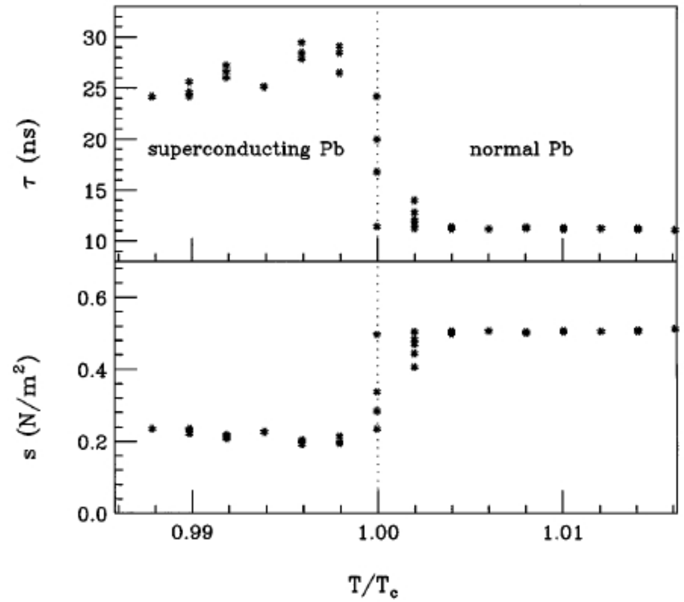
Quartz-Microbalance Experiments

A. Dayo, W. Alnasrallah, and J. Krim, ***Superconductivity-Dependent Sliding Friction***, Phys. Rev. Lett.80, 1690-1693 (1998)



R.L. Renner, J.E. Rutledge, and P. Taborek, ***Quartz Microbalance Studies of Superconductivity-Dependent Sliding Friction***, Phys. Rev. Lett.83, 1261 (1999)

L. Bruschi, G. Fois, A. Pontarollo, G. Mistura, B. Torre, F. Buatier de Mongeot, C. Boragno, R. Buzio, and U. Valbusa, ***Structural Depinning of Ne Monolayers on Pb at T<6.5K***, Phys. Rev. Lett.96, 216101 (2006) – **measurements concluded that adsorbed species stick to the surface**

M. Pierno, L. Bruschi, G. Fois, G. Mistura, C. Boragno, F. Buatier de Mongeot, and U. Valbusa, ***Nanofriction of Neon Films on Superconducting Lead***, Phys. Rev. Lett.105, 016102 (2010) – **measurement employing lighter elements do not show any rise of electronic friction**

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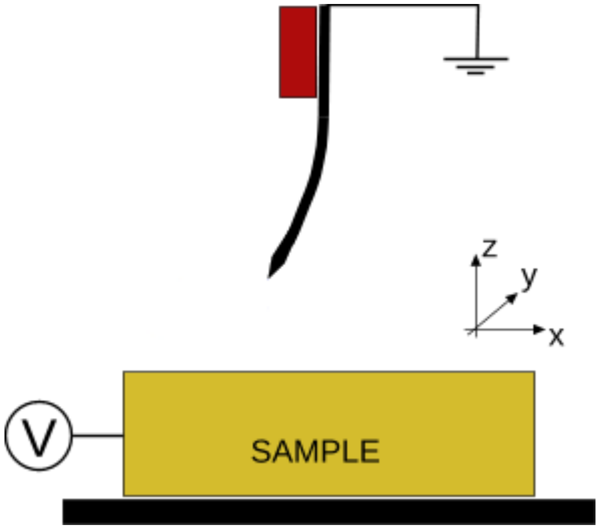
Pendulum AFM



Friction without contact !

The phenomenon reported on both metal and dielectric materials:

B.C. Stipe, H.J. Mamin, T.D. Stowe, T.W. Kenny, and D. Rugar, ***Noncontact Friction and Force Fluctuations between Closely Spaced Bodies***, Phys. Rev. Lett.87, 096801 (2001) – metallic surface

S. Kuehn, R.F. Loring, and J.A. Marohn, ***Dielectric Fluctuations and the Origins of Noncontact Friction***, Phys. Rev. Lett.96, 156103 (2006) – dielectric material

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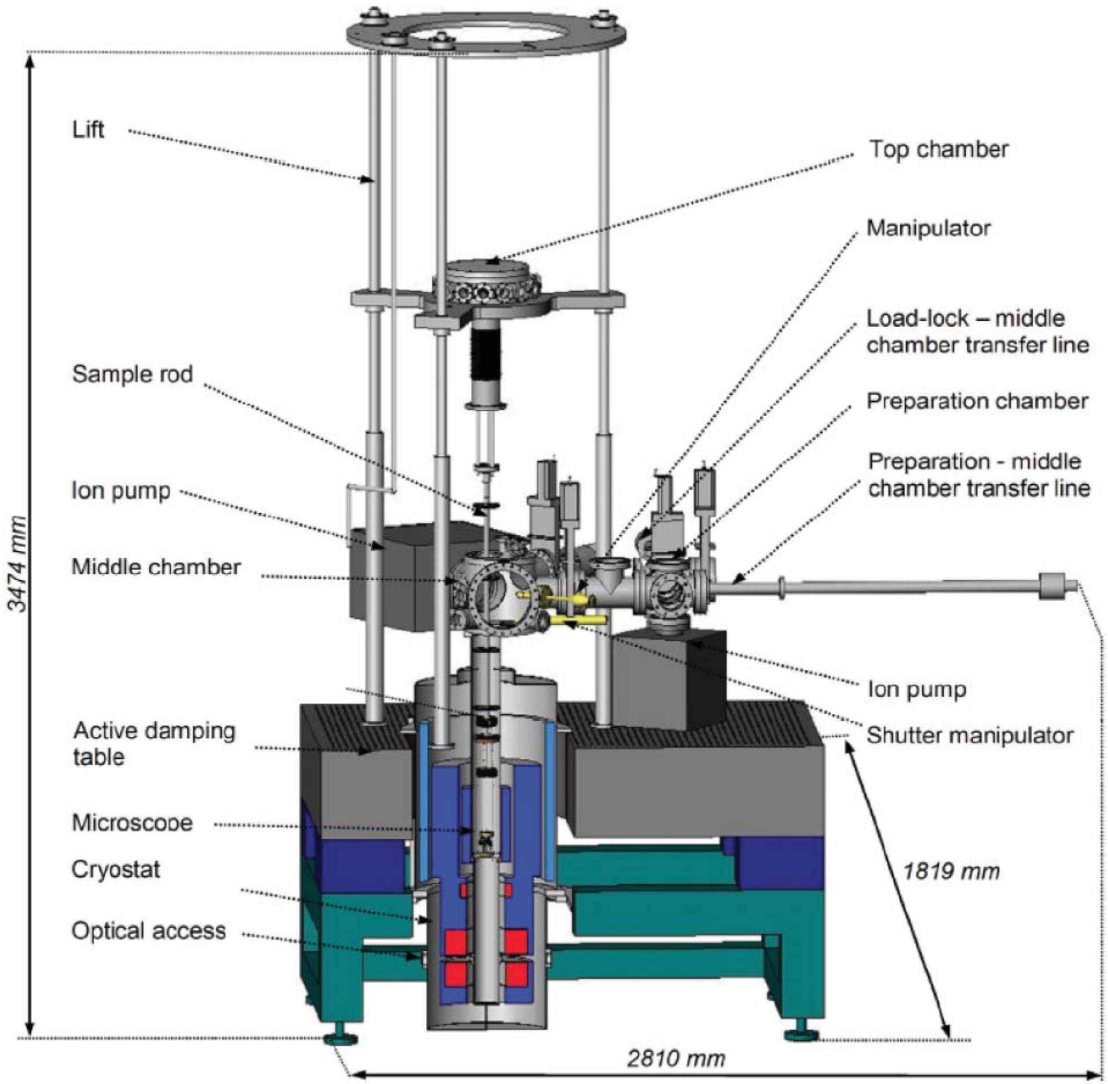
Low temperature pendulum AFM



- Pressure = ~10^{-11}mbar.
- Temperature = 6K.
- Magnetic field = 7T.
- Oscillation amplitude=5nm kept constant with a PLL feedback system.

U. Gysin et al. Rev. Sci. Instrum. 82, 023705 (2011)

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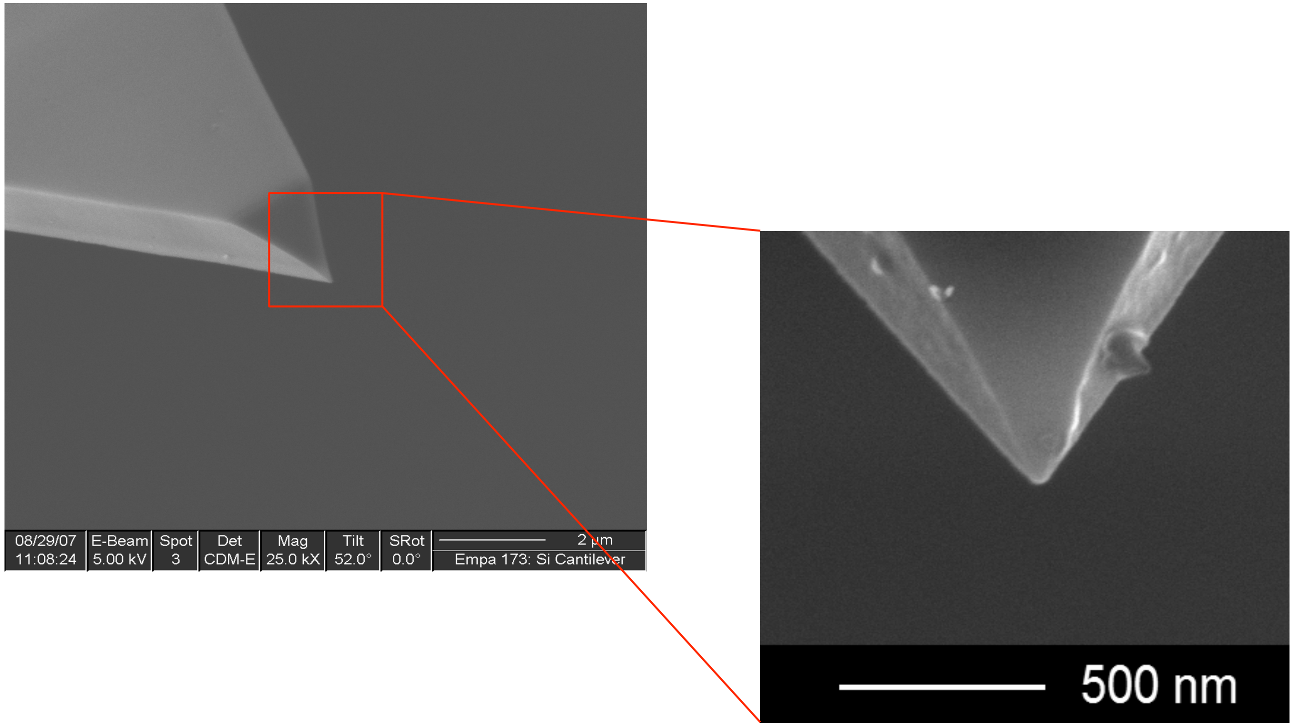
Cantilever preparation



The cantilever was exposed to FIB to form a sharp pyramidal tip with spherical apex, approximately 50nm in diameter.

k=30mN/m
f=5.3kHz
Q=4.8 10^5
Γ_0=2.0 10^{-12} kg/s @6K
F_{min}=1.76 10^{-17}N/sqrt{Hz} @6K

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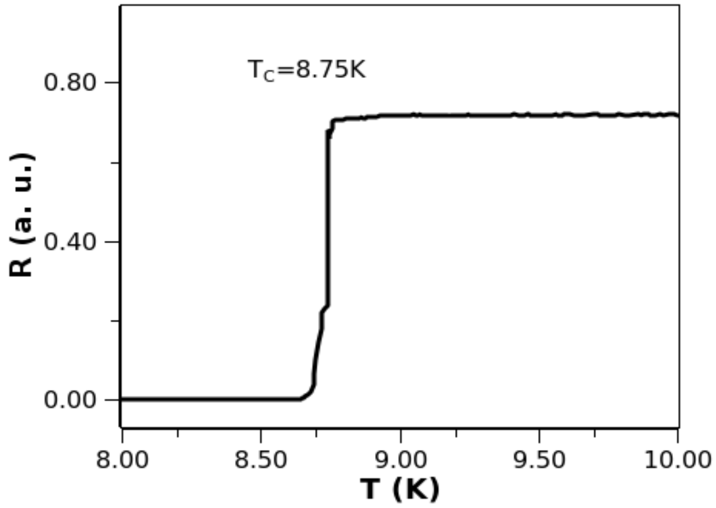
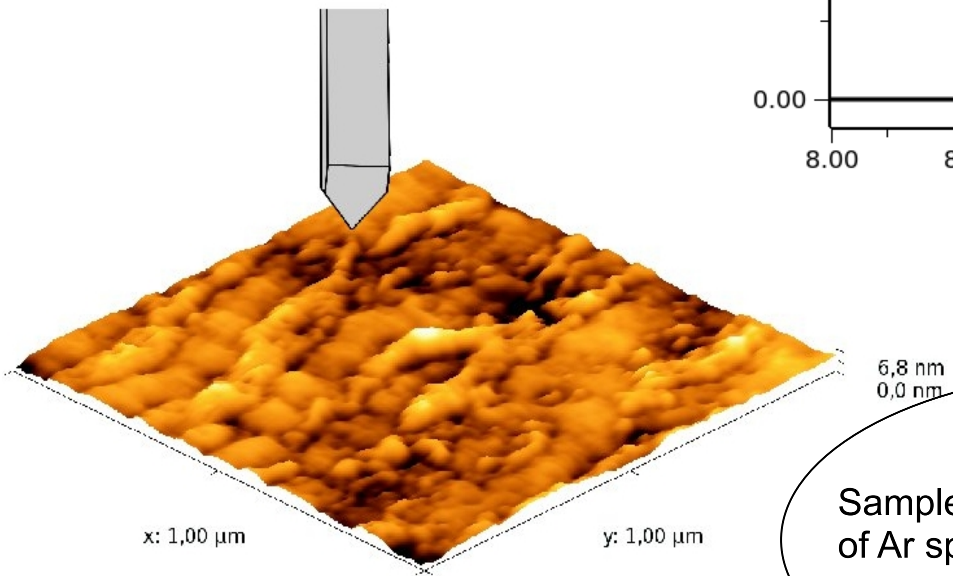
Sample preparation

150nm of Nb deposited on Si(100) substrate by means of Magnetron Sputtering.





Sample cleaned by few cycles of Ar sputtering and annealing Under UHV.

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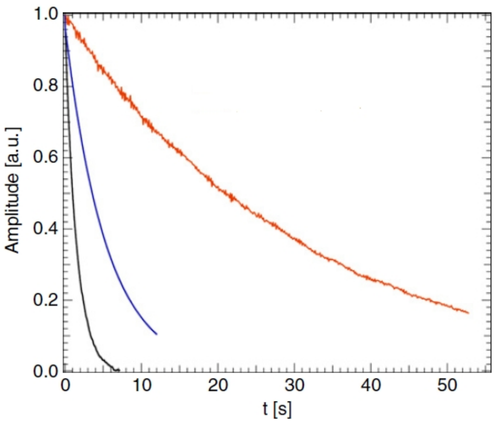
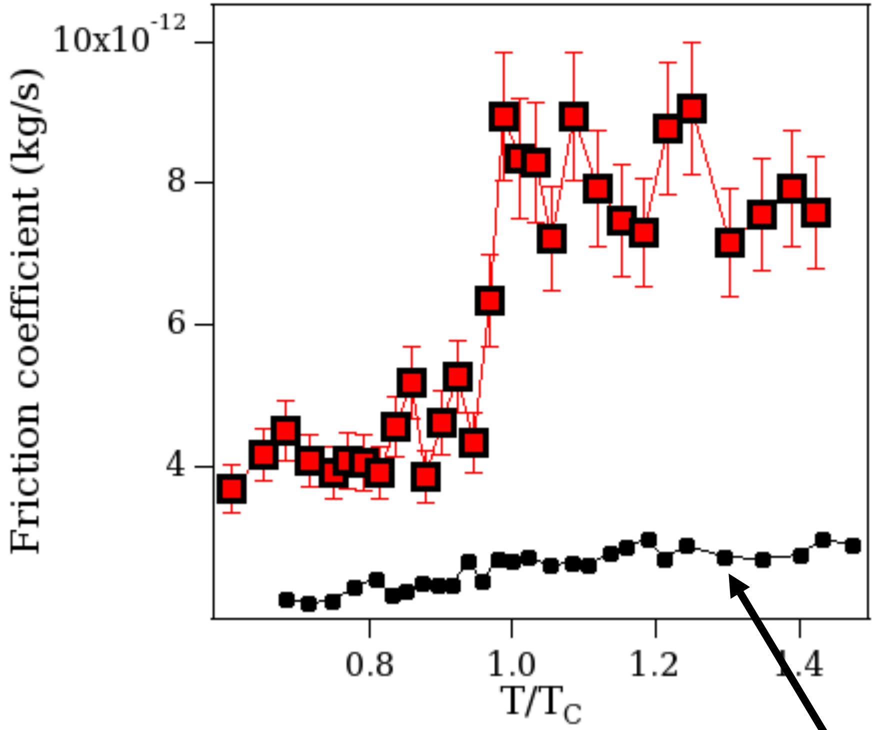
Damping coefficients vs. temperature



$$\Gamma = \frac{k}{2(\pi \cdot f)^2 \tau}$$



$A_{pk-pk} = 5\mathrm{nm}$
$T = 6 - 13\mathrm{K}$
$T_C = 9.2\mathrm{K}$

Constant
Tip – sample
Distance
d=0.5nm

Free cantilever

The damping coefficient is reduceed by a factor of ~3 when the sample enters the superconducting state

M. Marcin et al., *Nature Materials* 10, 119 (2011)

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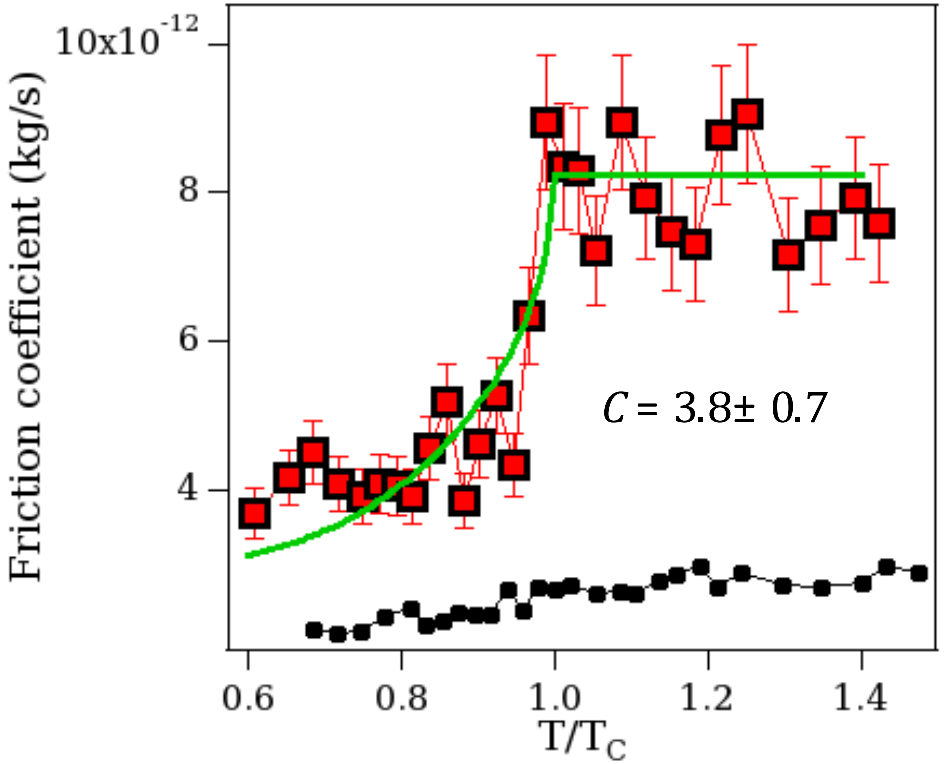
Damping vs. Temperature across the phase transition

The temperature decay of Γ is found to be in good agreement with BCS theory.



$$\frac{\Gamma_{surf}(T)}{\Gamma_{surf}(T_C)} \approx \frac{2}{\exp\left(\frac{\Delta(T)}{kT}+1\right)}$$

$$\Delta(T) = C \cdot \frac{kT_c}{\sqrt{1-\frac{T}{T_c}}}$$

C = 3.52 for all BCS superconductors

B.N.J. Persson, ***Electronic friction on a superconductor surface***, Solid State Comm.115, 145-148 (2000).
J. Bardeen, L.N. Cooper, and J.R. Schrieffer, ***Theory of Superconductivity***, Phys. Rev.108, 1175-1204 (1957).

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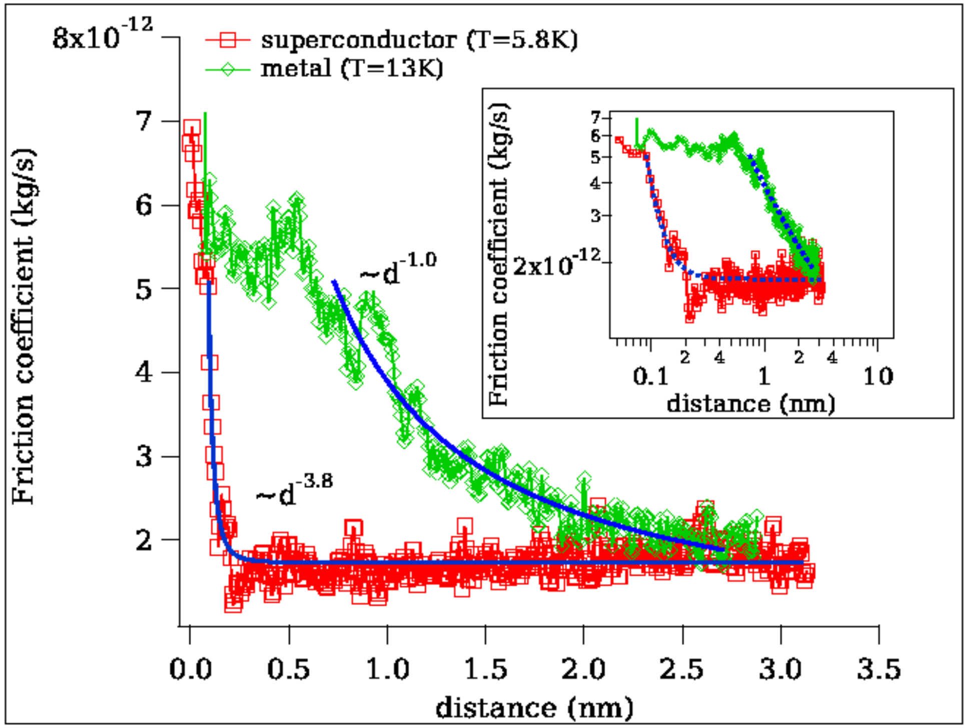
Distance dependence of damping



- A.I. Volokitin, B.N.J. Persson, and H. Ueba, ***Giant enhancement of noncontact friction between closely spaced bodies by dielectric films and two-dimensional systems***, Journ. Exp. Theor. Phys.104, 96-110 (2007)
- B.C. Stipe, H.J. Mamin, T.D. Stowe, T.W. Kenny, and D. Rugar, ***Noncontact Friction and Force Fluctuations between Closely Spaced Bodies***, Phys. Rev. Lett.87, 096801 (2001),

Metal (electronic friction):
For a spherical tip exponent n predicted by the theory (Volokitin et.al.)is n=-1.6, experimentally measured value n=-1.3 for Au (Stipe et. al.)

Superconductor (phononic friction – lateral oscillations):
For spherical tip $\Gamma \propto F(d)^2$
According to Lifshitz theory the elastic stress caused by van der Waals interaction leads to a force $F(d) \propto d^{-2}$, so the exponent n=-4.0 (Volokitin et. al.)

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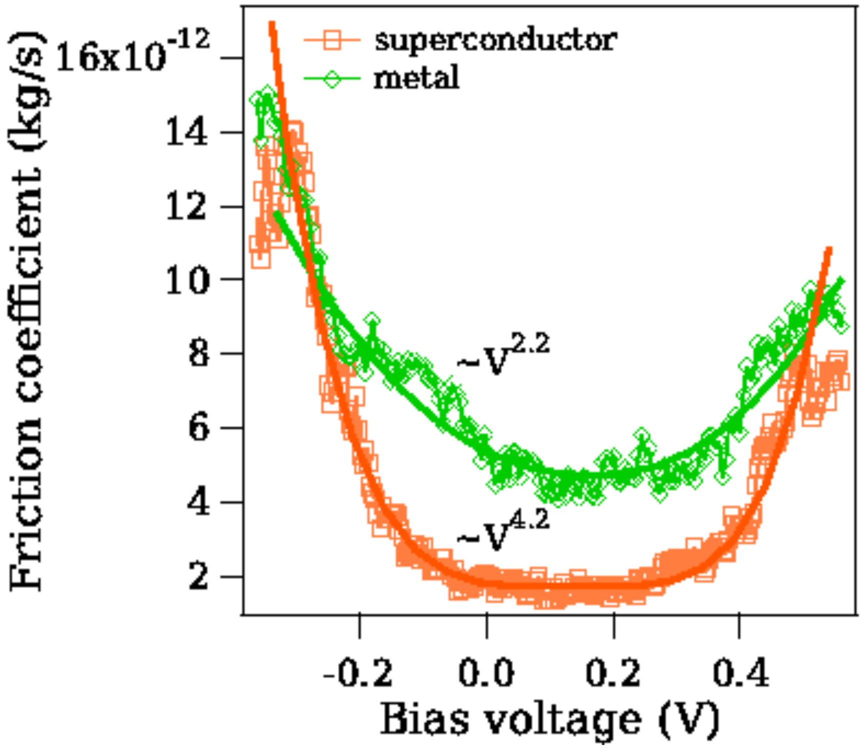
Voltage dependence of damping



- A.I. Volokitin, B.N.J. Persson, and H. Ueba, ***Giant enhancement of noncontact friction between closely spaced bodies by dielectric films and two-dimensional systems***, Journ. Exp. Theor. Phys.104, 96-110 (2007)

$$\Gamma \propto \left(V - V_0\right)^{\alpha}$$

Metal: friction coefficient vary as ~V^2
Superconductor: ~V^4

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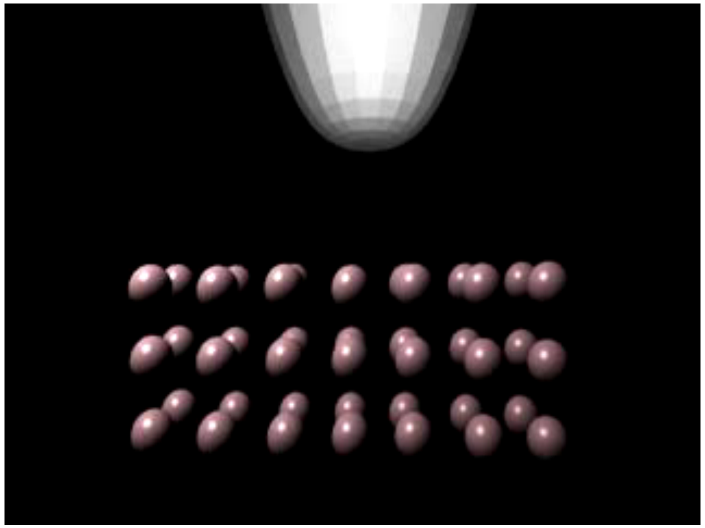
Damping across phase transition

- The friction coefficient Γ is reduced by a factor of three when the sample enters the superconducting state (at 5nm distance).

- The temperature decay of Γ was found to be in good agreement with the BCS theory, meaning that friction has essentially an electronic nature in the metallic state, while phononic friction dominates in the superconducting state.

- Distance and voltage dependent measurement of Γ also indicate that phononic friction becomes dominant below T_C.

M. Marcin et al., Nat. Mat., 10, 119 (2011)



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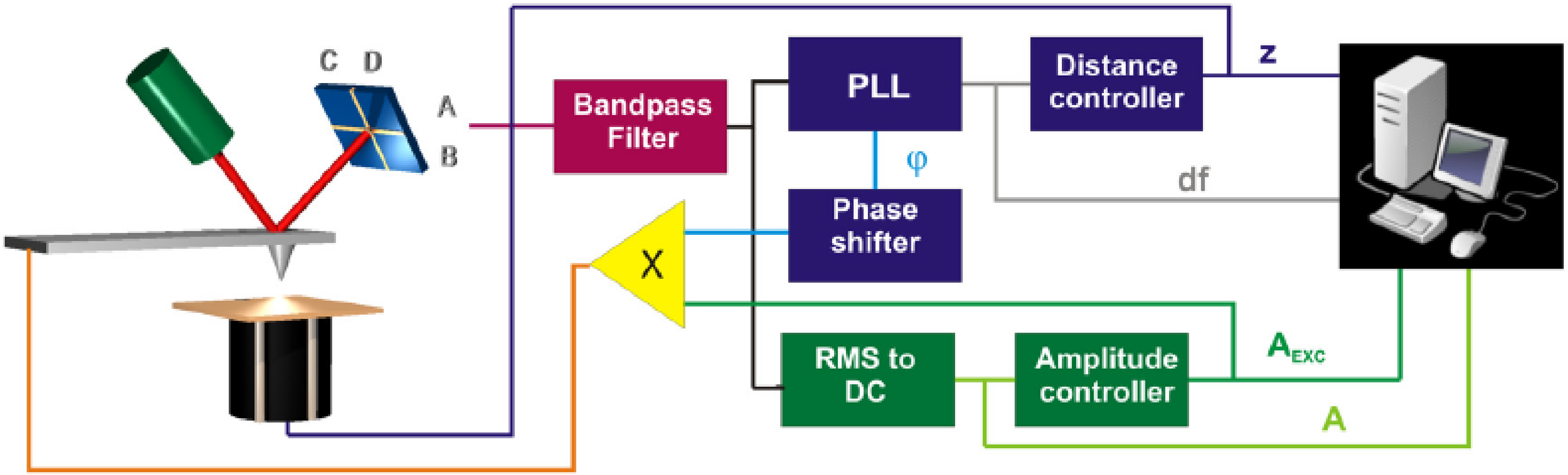
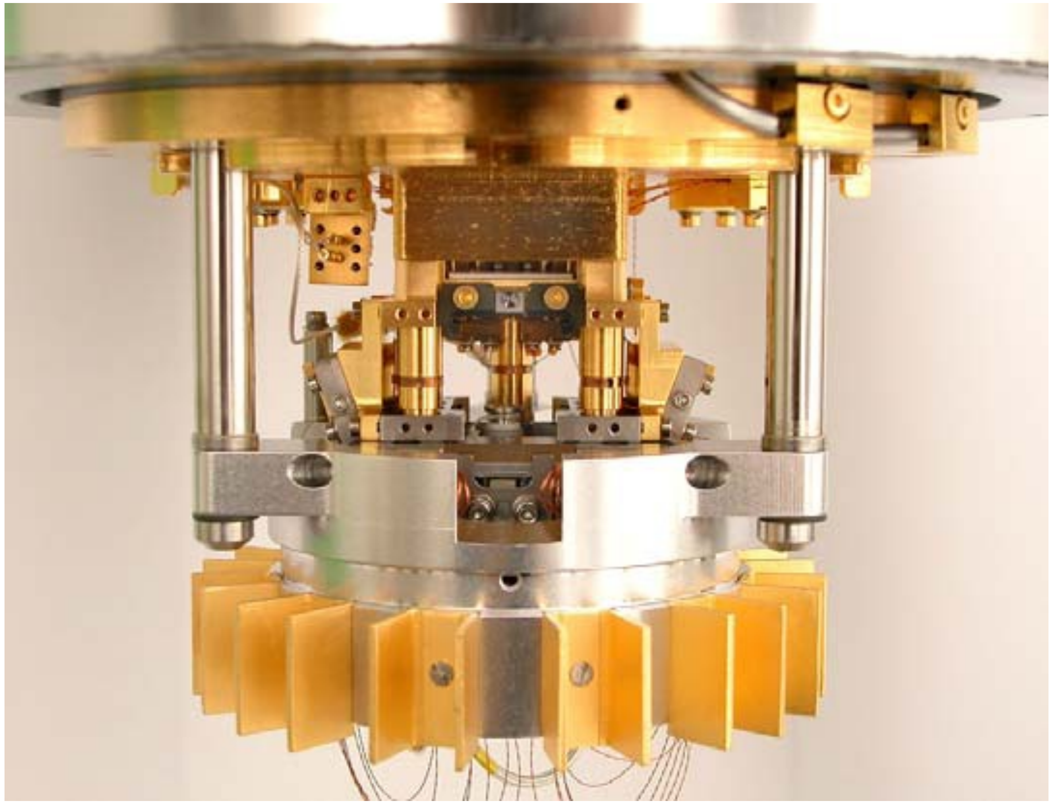
Non-contact AFM



LT-AFM based on tuning fork



Low temperature measurement (5K-77K).

Summary

•Friction force microscopy and contact resonance force microscopy
  -Atomic resolution achieved on solid surfaces

•Pendulum AFM on a superconductor
  -Influence of electronic friction observed

•Controlled rotation of molecules by force interactions

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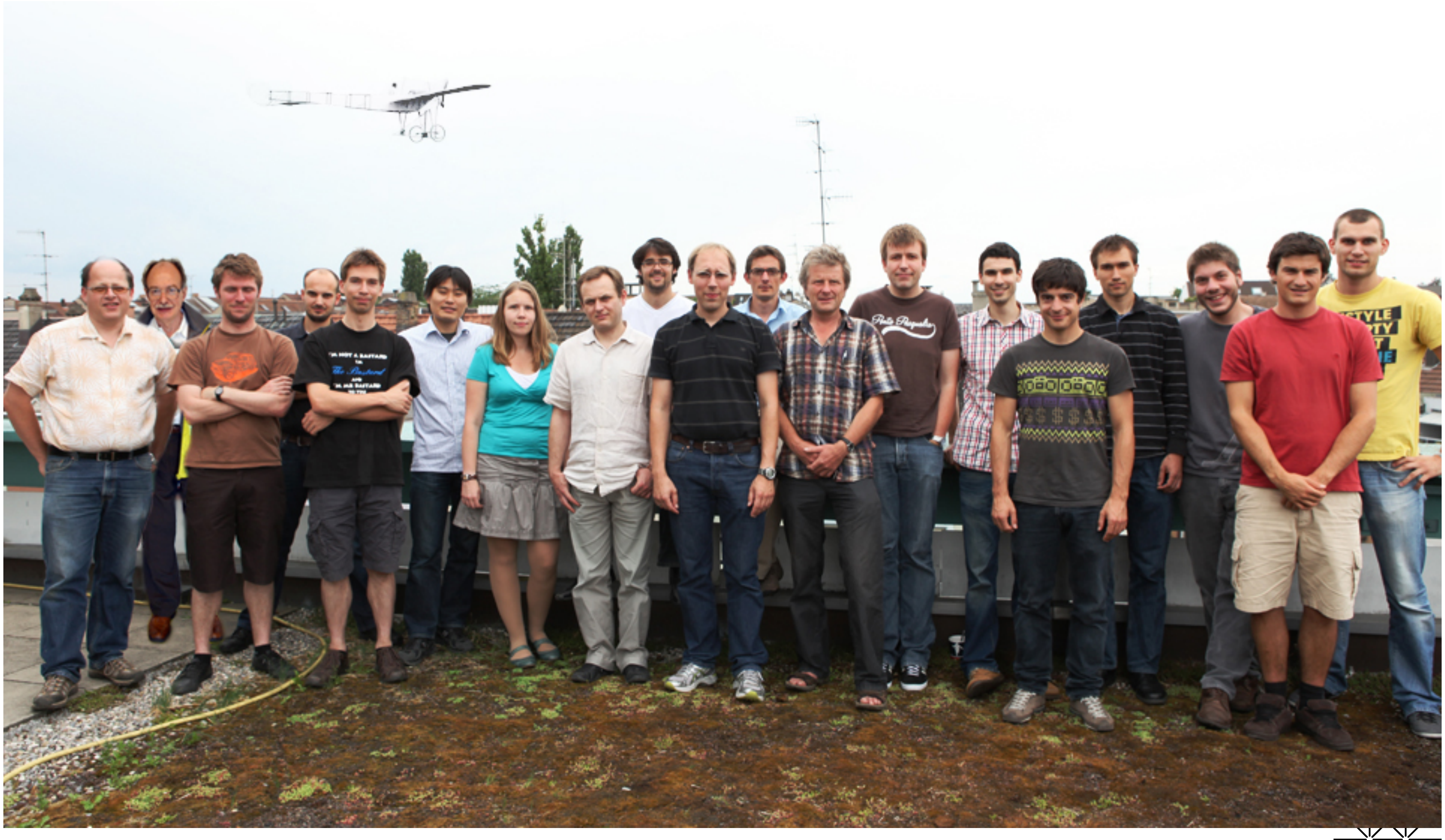
Acknowledgement



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