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Atomic friction: ways to determine the elastic and viscous properties of nano-contacts

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Atomic Friction: Ways to determine elastic and viscous properties of nano-contacts

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- Atomic-scale stick slip
  - loading dependence
  - multiple slips and estimation of damping

- Simultaneous measurement of normal and lateral contact stiffnes

- Control of friction
  -actuation of nano-contacts

Acknowledgement


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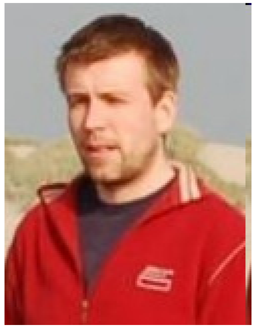
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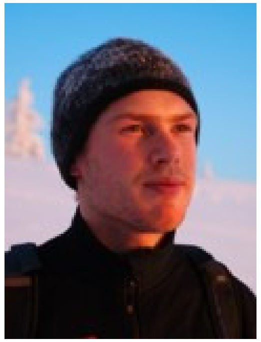
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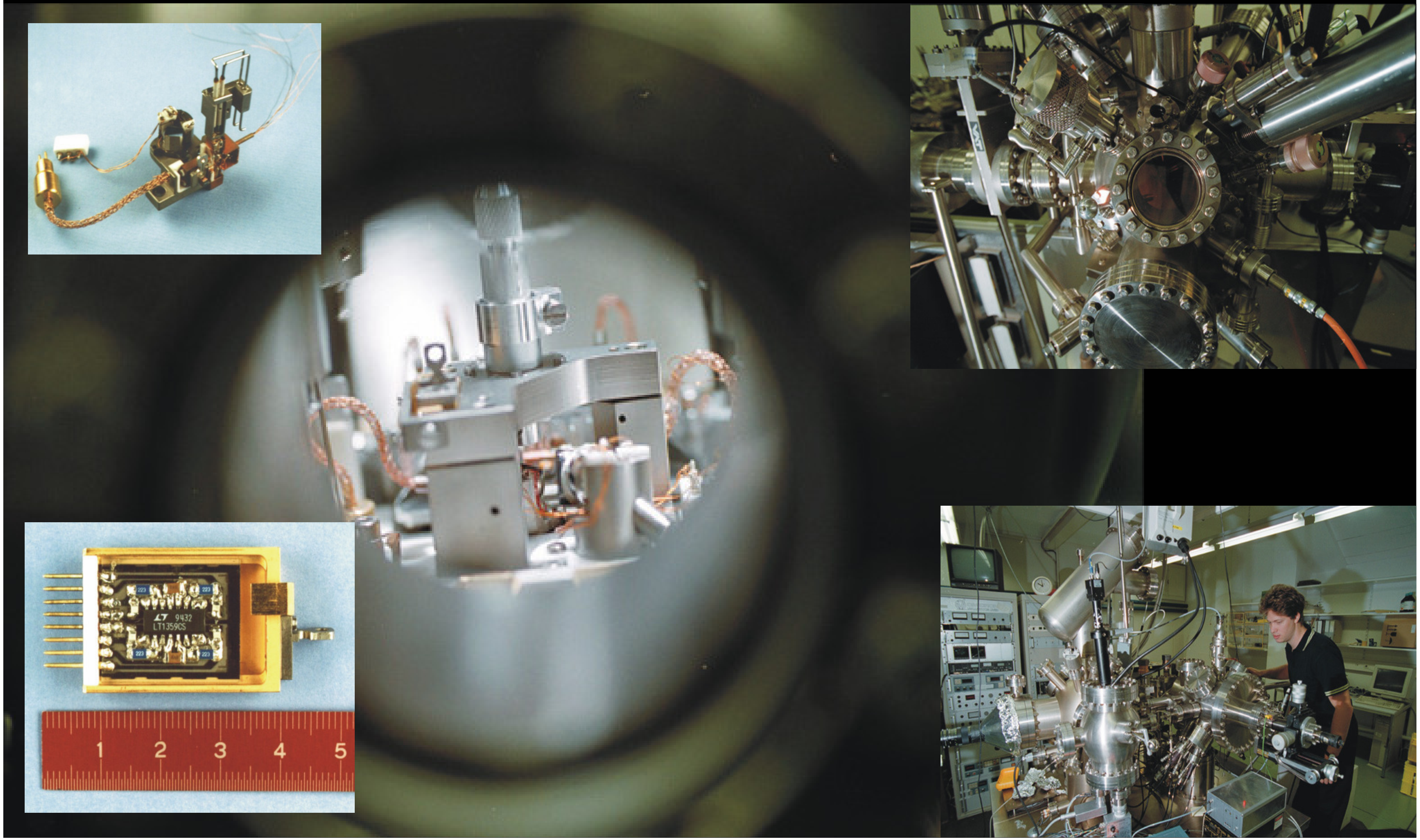
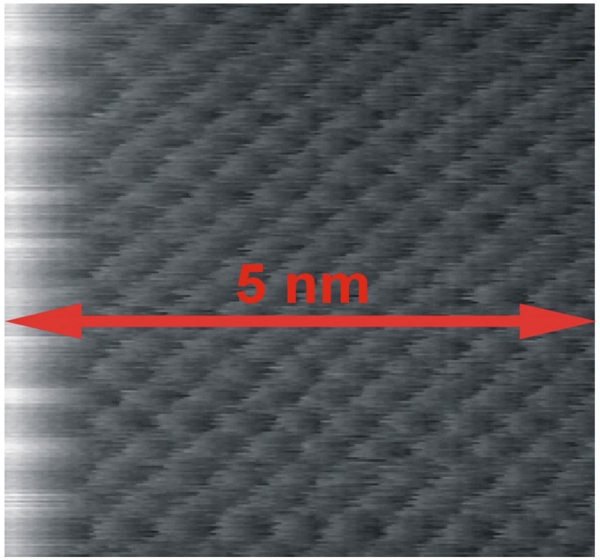
(Glas Troesch)

UHV-Force microscope with in-situ preamplifier



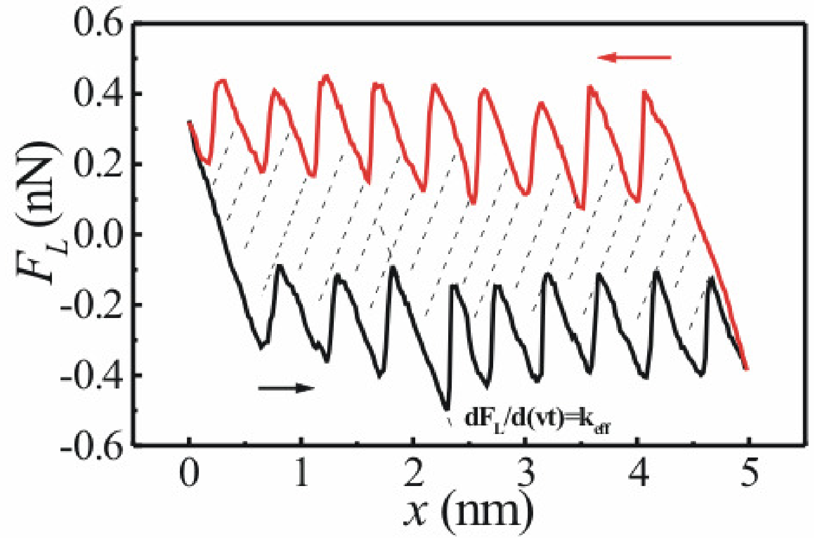
Friction on the Nanometer-scale: Atomic-Stick Slip

Atomic stick-slip



KBr(001)-crystal

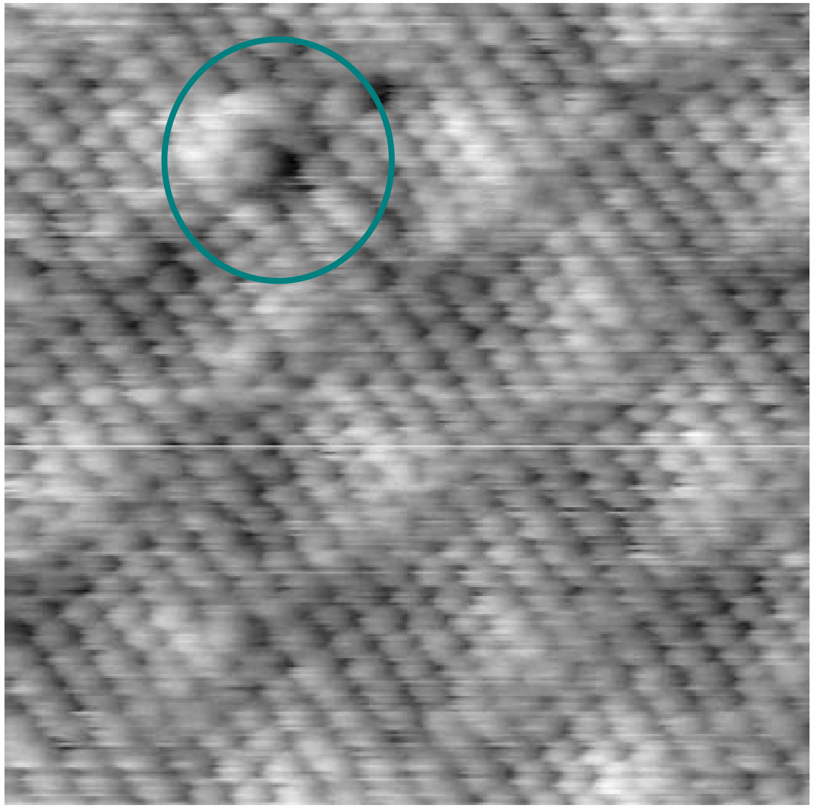
Friction loop

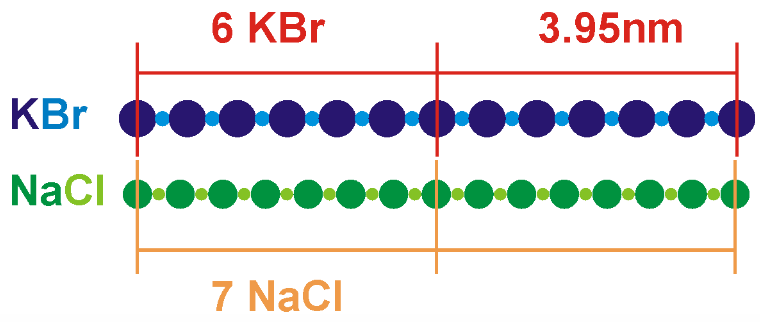


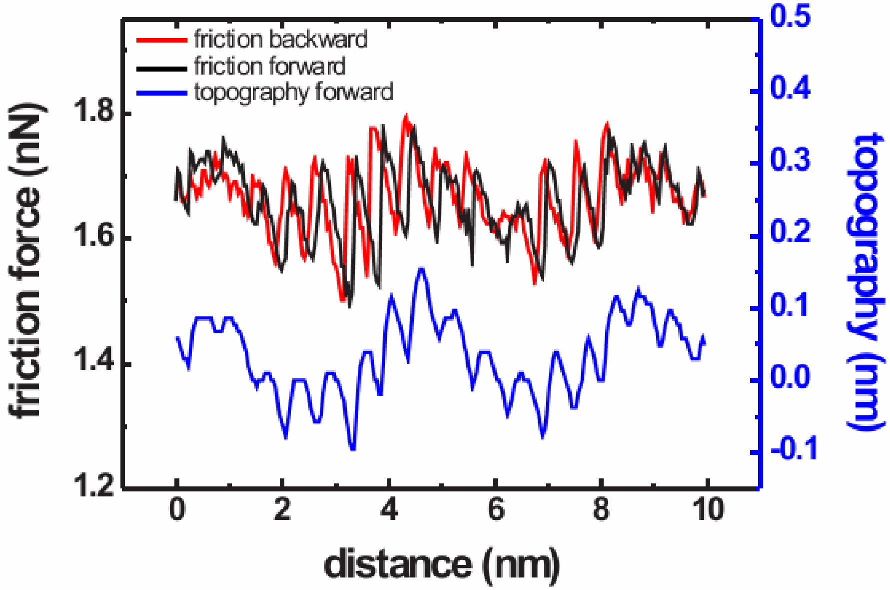
$F_N = 0.44$ nN

$E_{diss} = 1.4$ eV
(per slip)

Observation of defects and superstructure of KBr on NaCl(001)



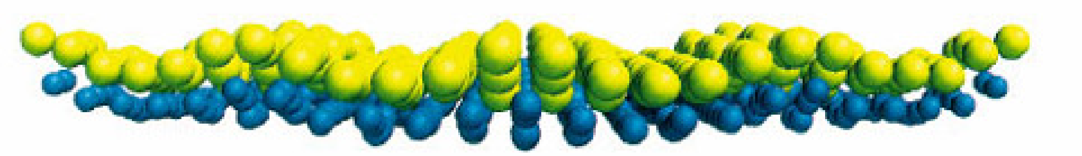


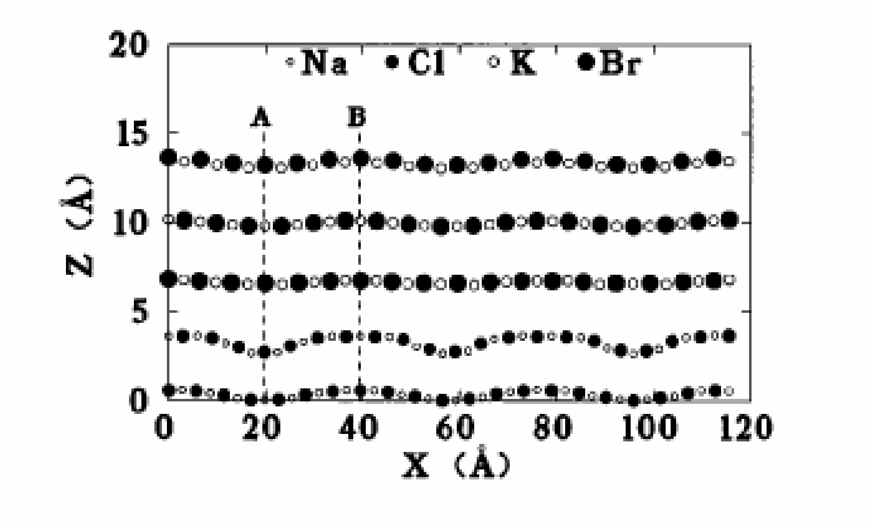


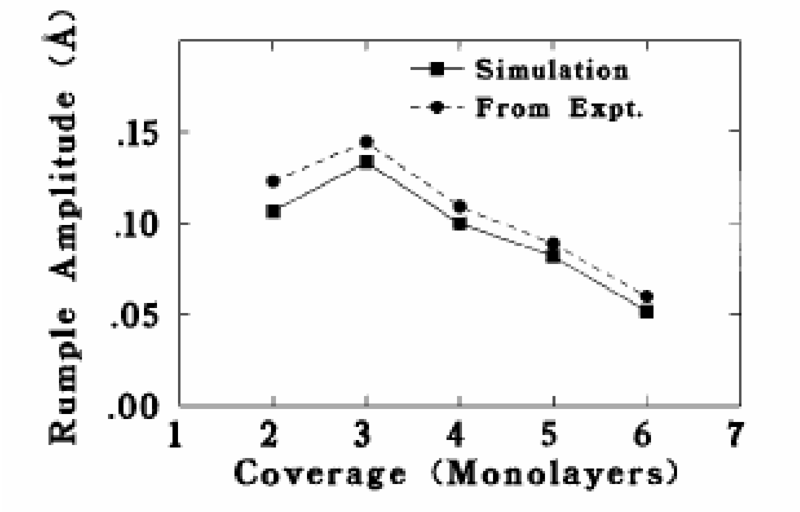
Contact size ist smaller than 10 atoms
Contact stiffness is about 1N/m
$F_{max} \approx 0.1$nN

Monte Carlo Simulations of KBr/NaCl(001)

J. Baker and P.A. Lindgard, *Phys. Rev. B* **54**, R 11137 (1996)





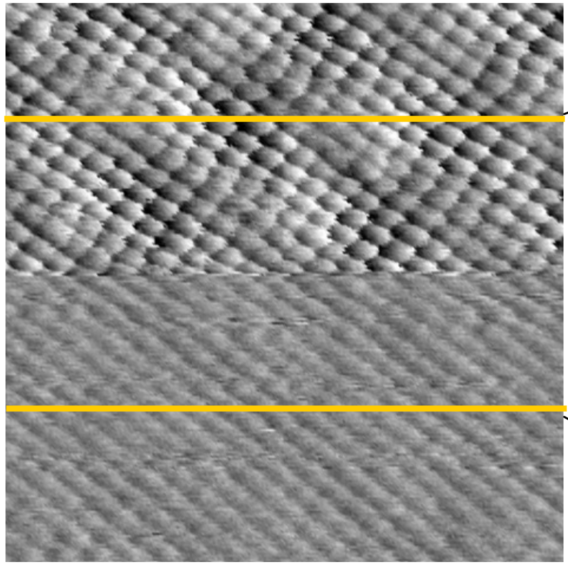


17% misfit leads to superstrucutre
6 KBr-units fit on 7 NaCl-units

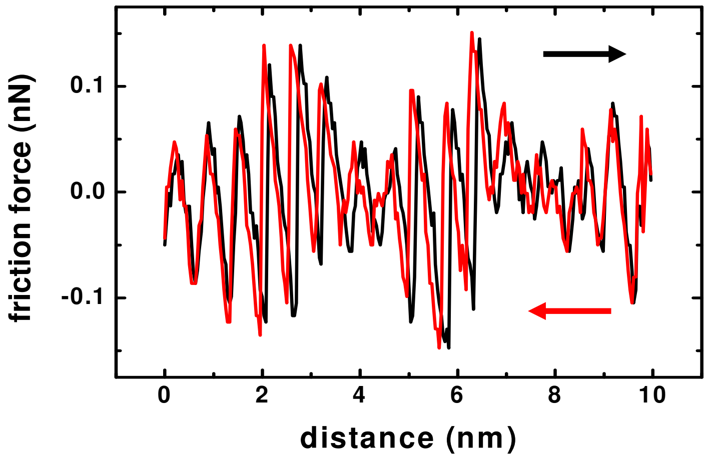
Rumpling of NaCl-interface is observed on the KBr-surface (0.01nm for 2ML)

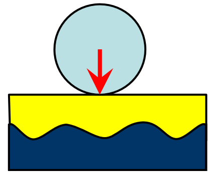
Agreement with Helium scattering data; Duan et al. *Surf. Sci.* **272**, 220 (1992)

Loading dependence of atomic friction: KBr/NaCl(001) superstructure

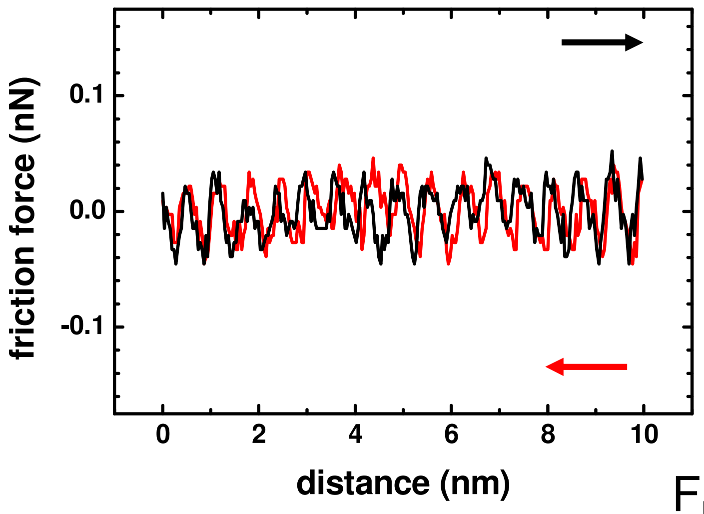


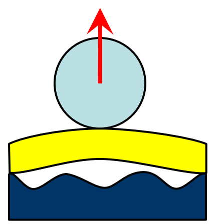
10x10nm^2:
Friction force map at 2 loads





F_N=0.01 nN

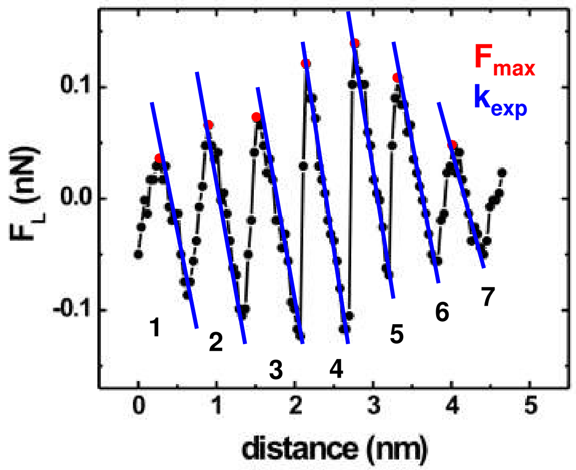




F_N=-0.31 nN
Close to jump-off

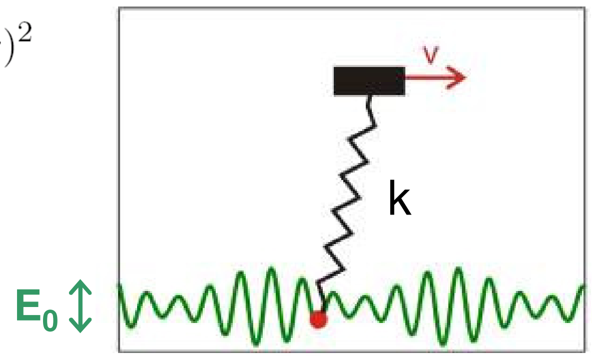
Superstructure is less pronounced at lower loads
Influence of the buried interface?

Modification of the Tomlinson Model

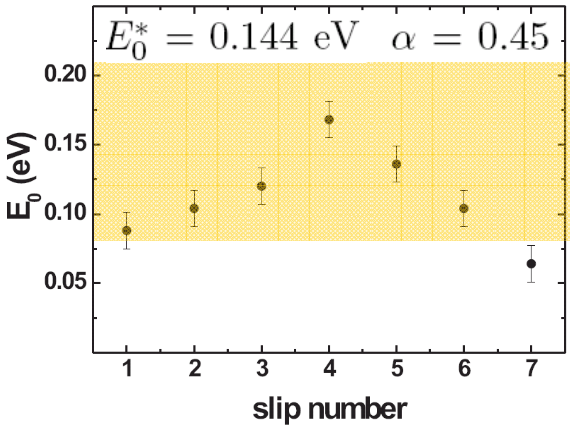


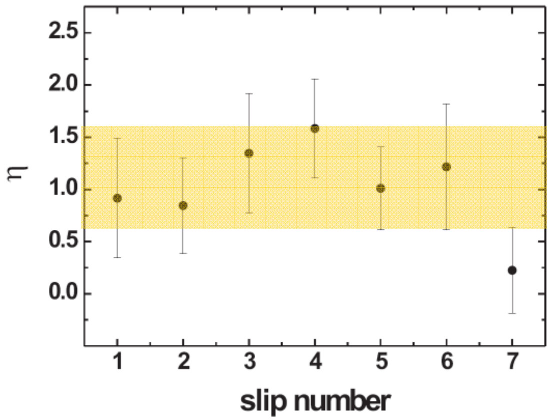
$$V = -\frac{E_0}{2}\cos\left(2\pi\frac{x_{tip}}{a}\right) + \frac{1}{2}k(x_{tip}-x)^2$$

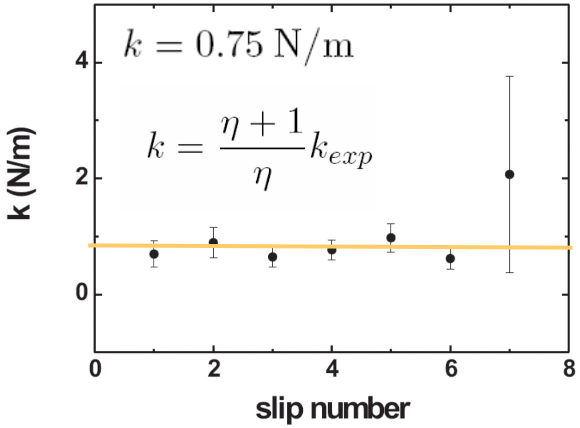
$$E_0 = E_0^*\left(\alpha\cos\left(\frac{2\pi x_{tip}}{b}\right)+1\right)$$



⇨ Modulation of the stiffness k or energy corrugation E_0



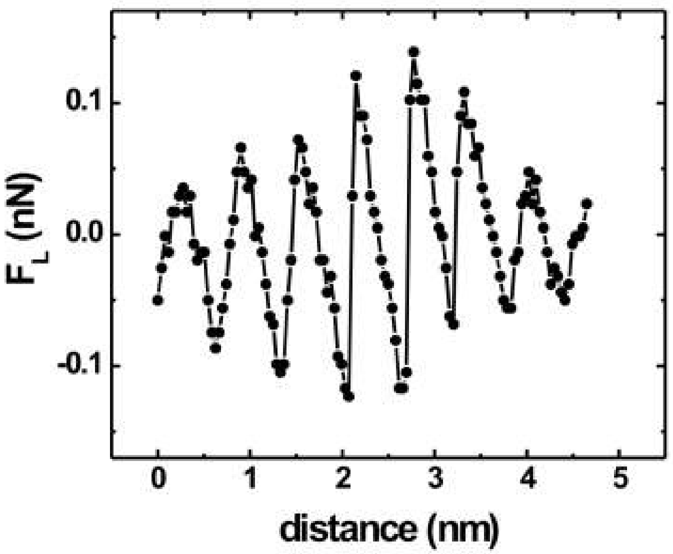




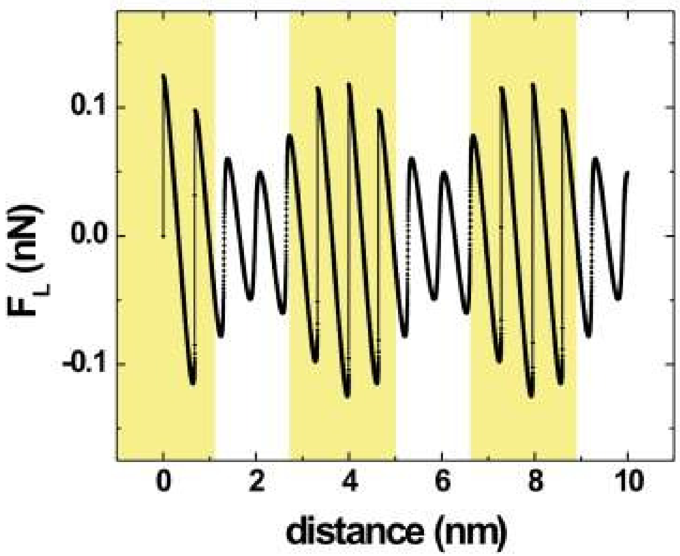
S. Maier et al., Phys. Rev. B **78**, 045432 (2008).

Modified 1D Tomlinson Model
Comparison with Experimental Results

Experiment



Tomlinson Model

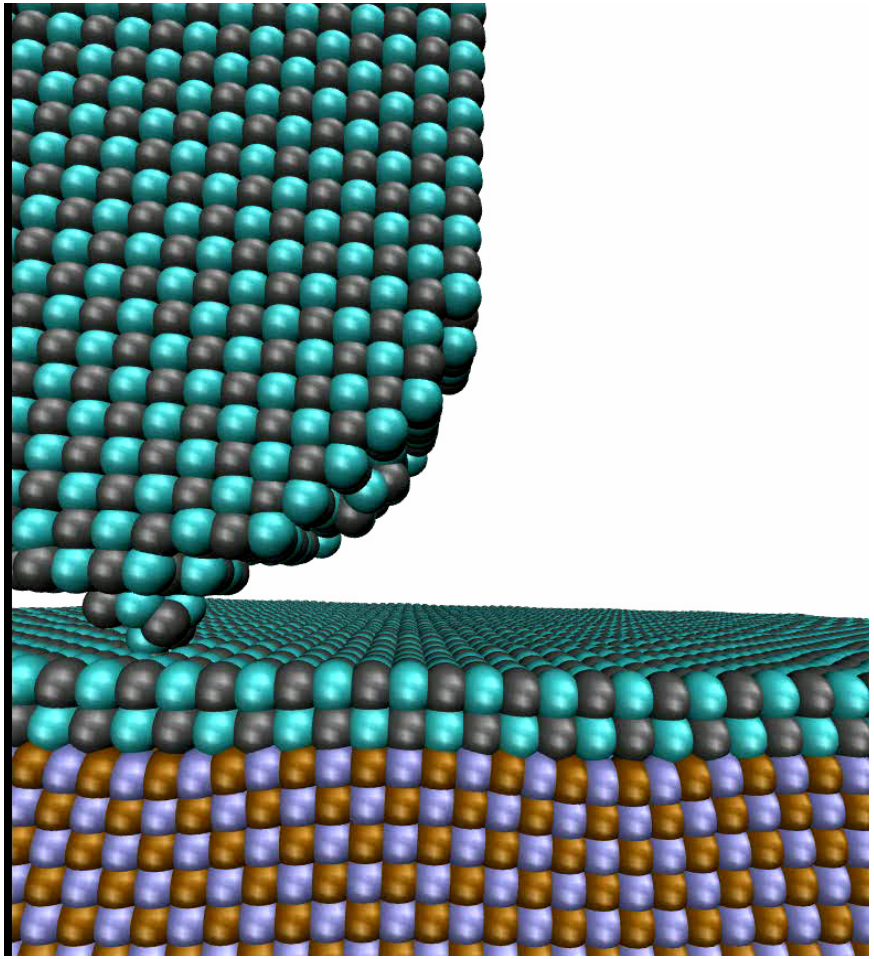


Parameters: E_0*=0.144 eV, α=0.45, k=0.75N/m, v=10nm/s, a=0.66nm

⇒It is possible to observe areas in the superlubricity regime (η<1) and areas with stick slip (η>1) due to the large variations of energy barriers

Atomistic Simulations: KBr/NaCl(001)

A. Ghasemi, S. Goedekker, Uni Basel



Tip (9000 atoms)
KBr/NaCl (70‘000 atoms)

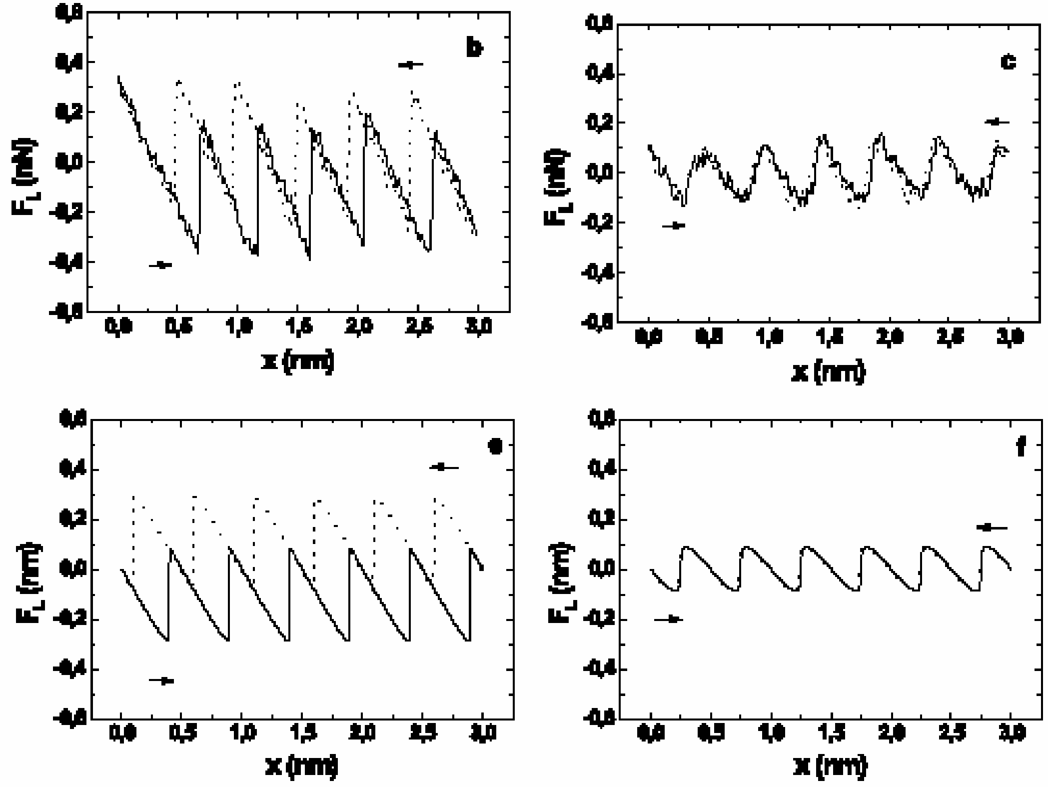
-Superstructure observed

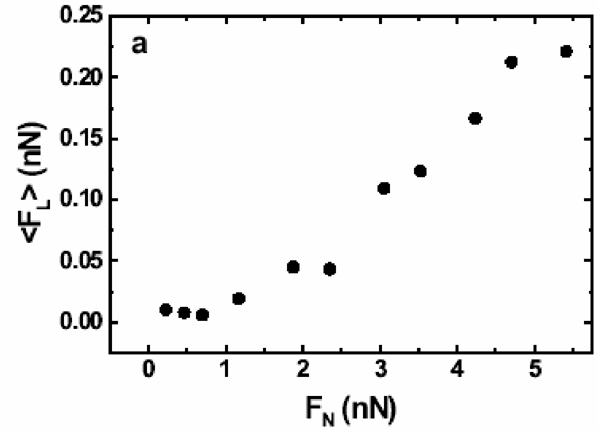
-small topographic changes

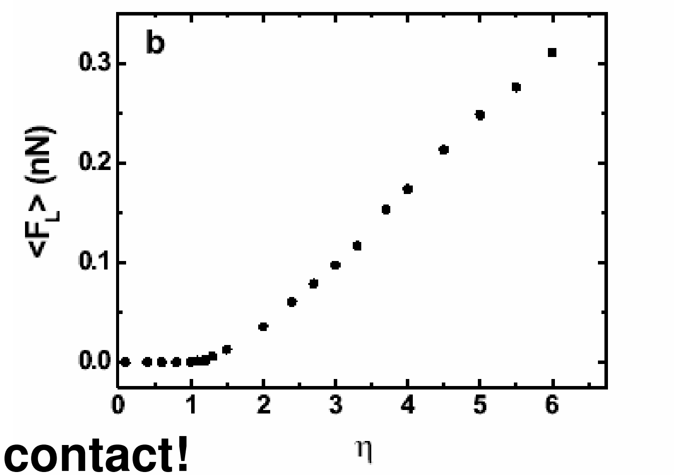
-Interface leads to strong variations of atomic friction

Loading dependence of Friction on NaCl(001)
UHV FFM with sharp tip vs. Prandtl-Tomlinson model

k_x = 29 N/m, k_z = 0.05 N/m, v_x = 3 nm/s, const. z
Scans along [100] showing maximum variation







Stick-slip **Continuous sliding in contact!**

$\eta > 1$ **$\eta < 1$** **mean load $F_N = F_z + 0.7$ nN**

A. Socoliuc et al., *Phys. Rev. Lett.* **92**, 134301 (2004)

1d-Prandtl-Tomlinson-Model

Potential energy:

$$U = -\frac{E_0}{2}\cos\left(2\pi\frac{x_t}{a}\right) + \frac{1}{2}k(x_t - x_s)^2$$

Stability criterion:

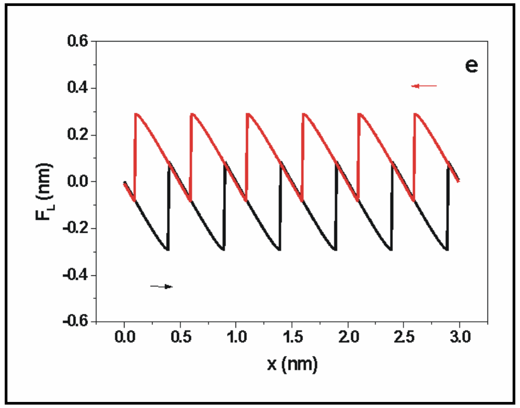
$$\frac{\partial U^2}{\partial x_t{}^2} = \frac{2\pi^2}{a^2}E_0\cos\left(2\pi\frac{x_t}{a}\right) + k > 0$$

$$\eta = \frac{2\pi^2 E_0}{ka^2} = \pi^2\frac{E_0}{ka^2/2}$$

η < 1: unique sliding solution
η > 1: instabilities

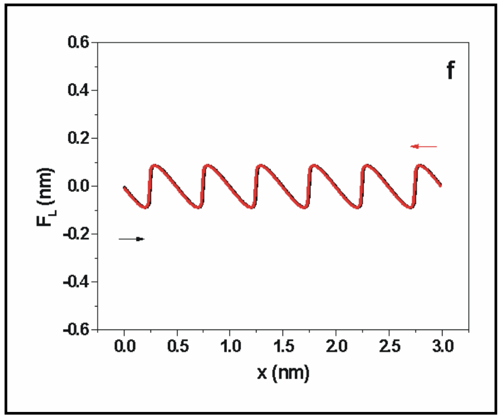
η > 1

η = 3

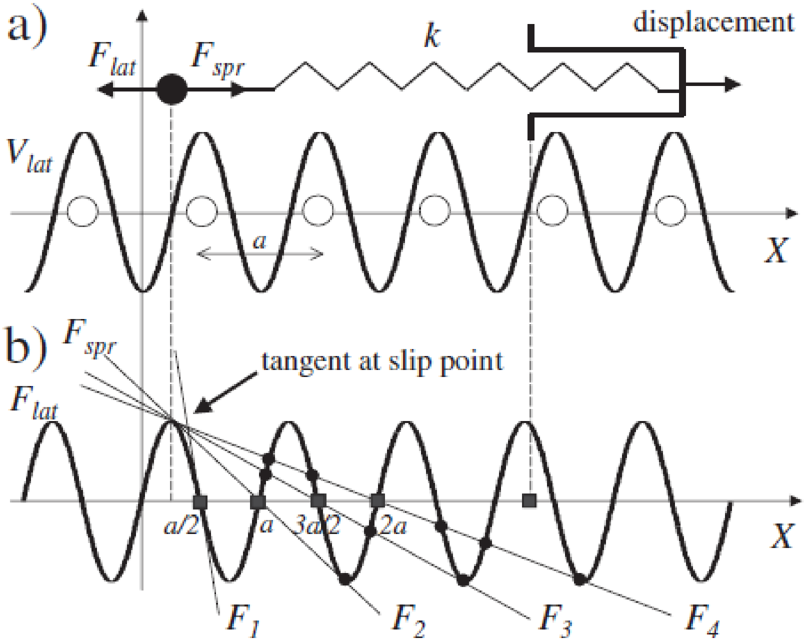


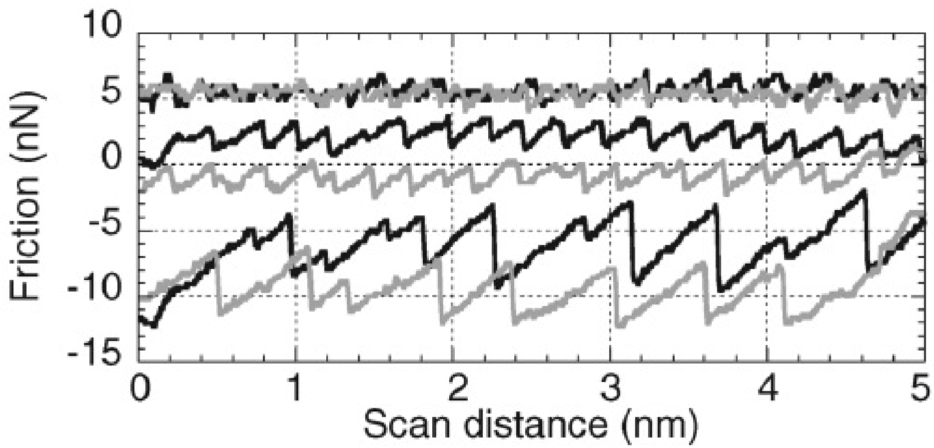
η < 1

η = 1



Multiple Slips





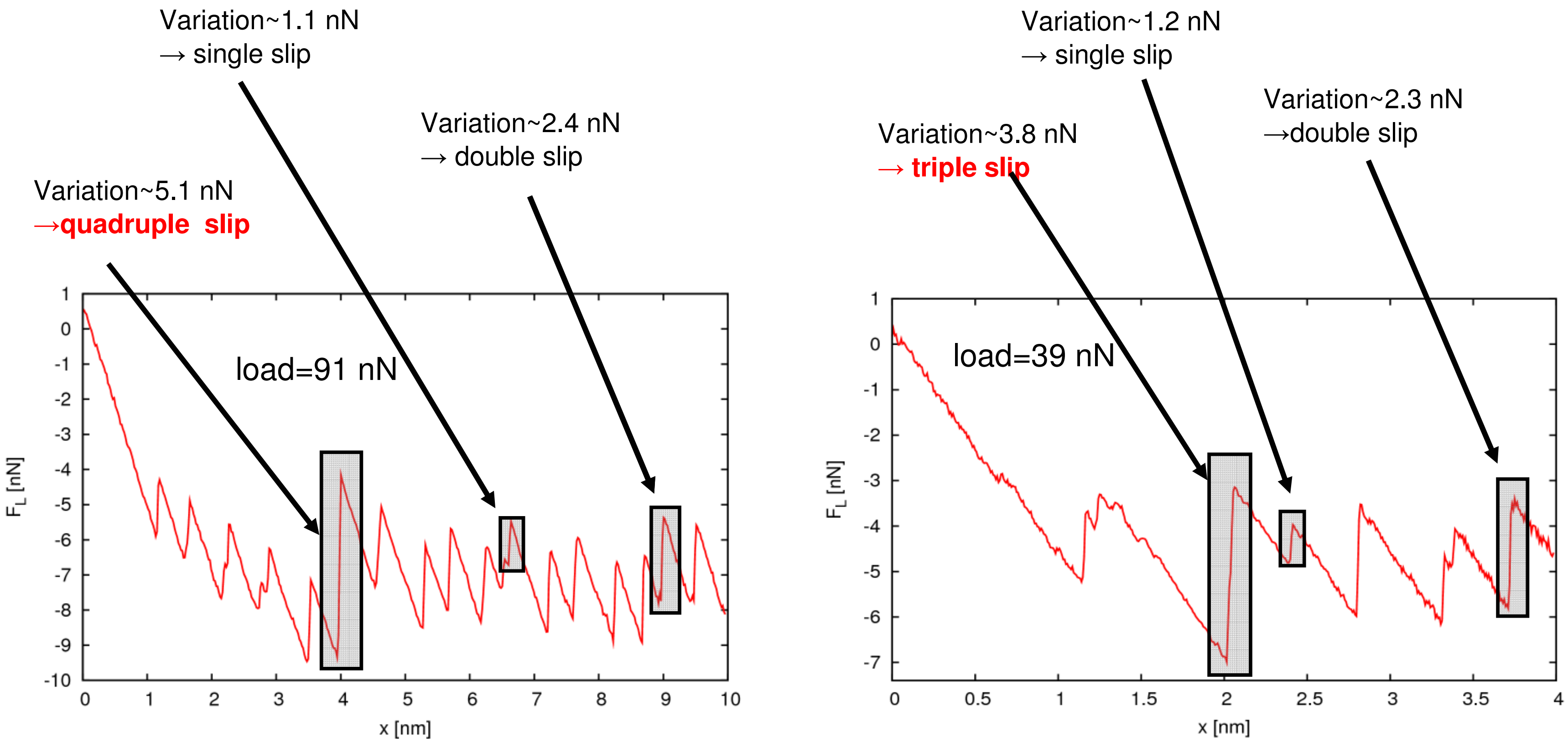
Silicon tip on graphite in air

Transitions for η= 1 / 4.604 / 7.788 / 10.95 / 12.66 ...

... but this is only valid for the quasi-static limit (and 1 dimensional).

S. Medyanik, W. Liu, I. Sung, R. Carpick, Phys. Rev. Lett. 97, 136106 (2006).

Experiments on NaCl(001) in UHV

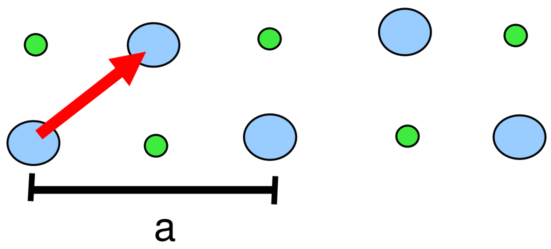


⇨ Multiple slips do happen at relatively high loads, but they are quite rare (single events)

R. Roth et al., Trib. Lett. (09)

Classification of multiple slips on NaCl(001)

single slip

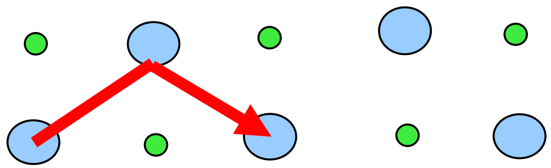


Force-variation= **1/2** a x k_{cont} ~ 1.2 nN

These jumps are nothing special, they also occur at low loads

depends on load ~4.6-5.4 N/m

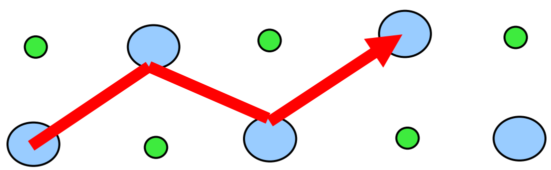
double slip



Force-variation= **1 a** x k_{cont} ~ 2.4 nN

---

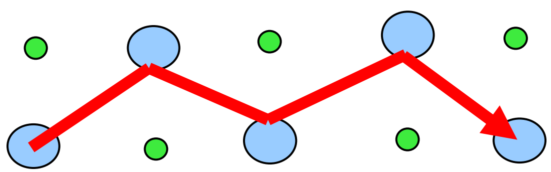
triple slip



Force-variation= **3/2 a** x k_{cont} ~ 3.6 nN

<u>We are looking for these jumps!</u>

quadruple slip

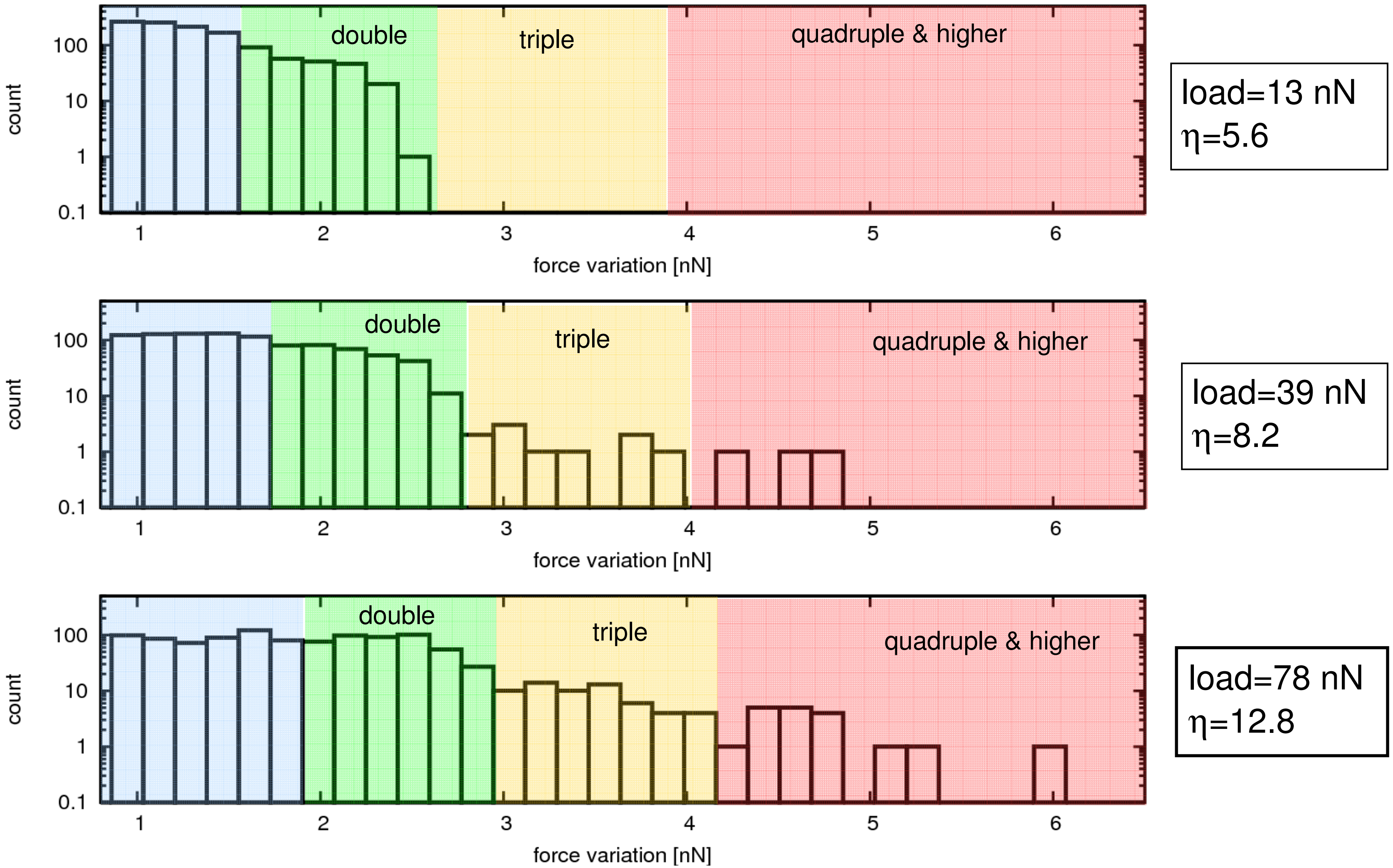


Force-variation= **2 a** x k_{cont} ~ 4.8 nN

etc...

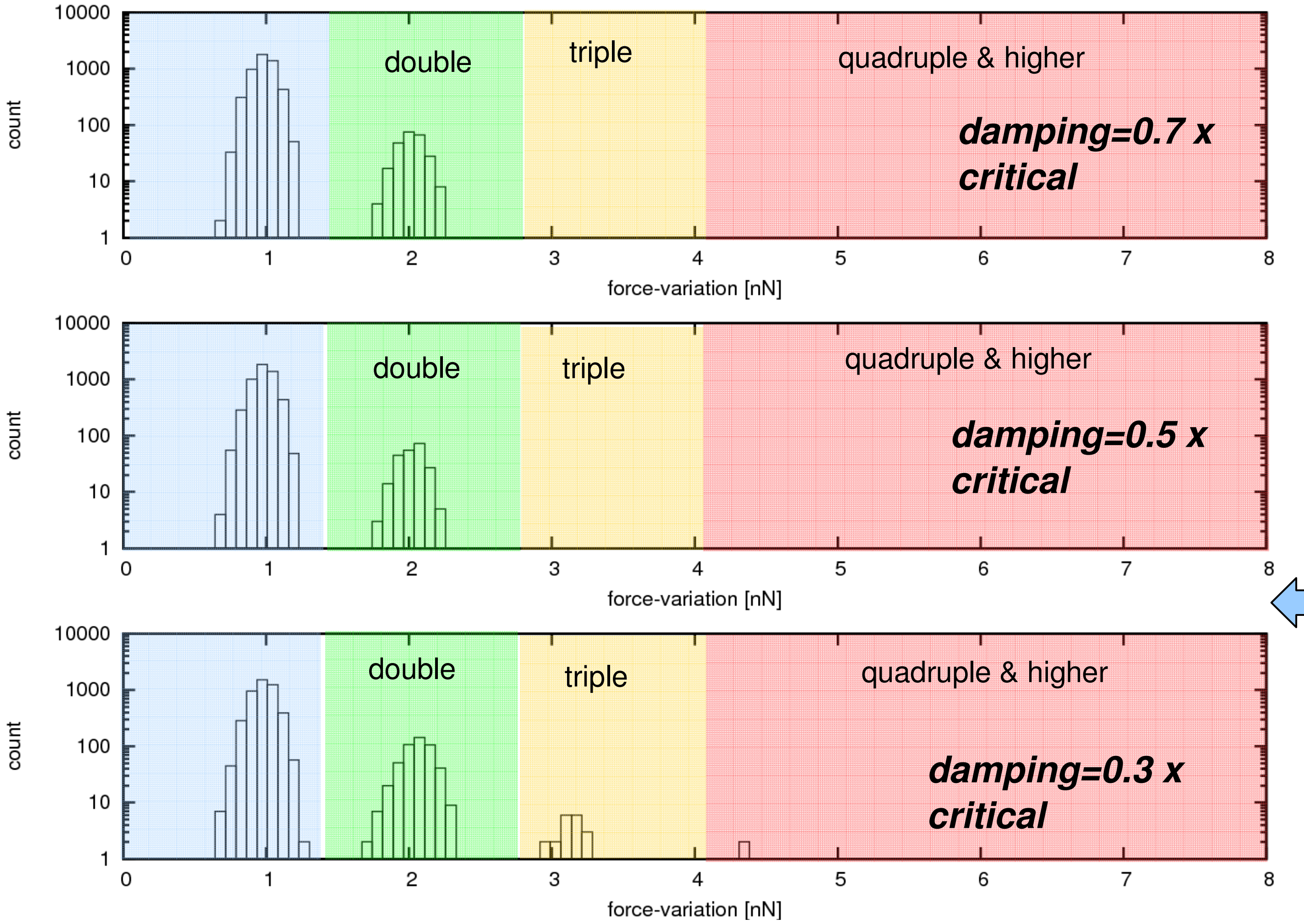
PS: Force variations are upper limits, since jump distance is actually smaller than multiples of a/2

Statistics of multiple slips on NaCl(001)



Comparison with simulations (η=8.2)

Same slip-recognition program run with output of 2D thermal Tomlinson simulation program:



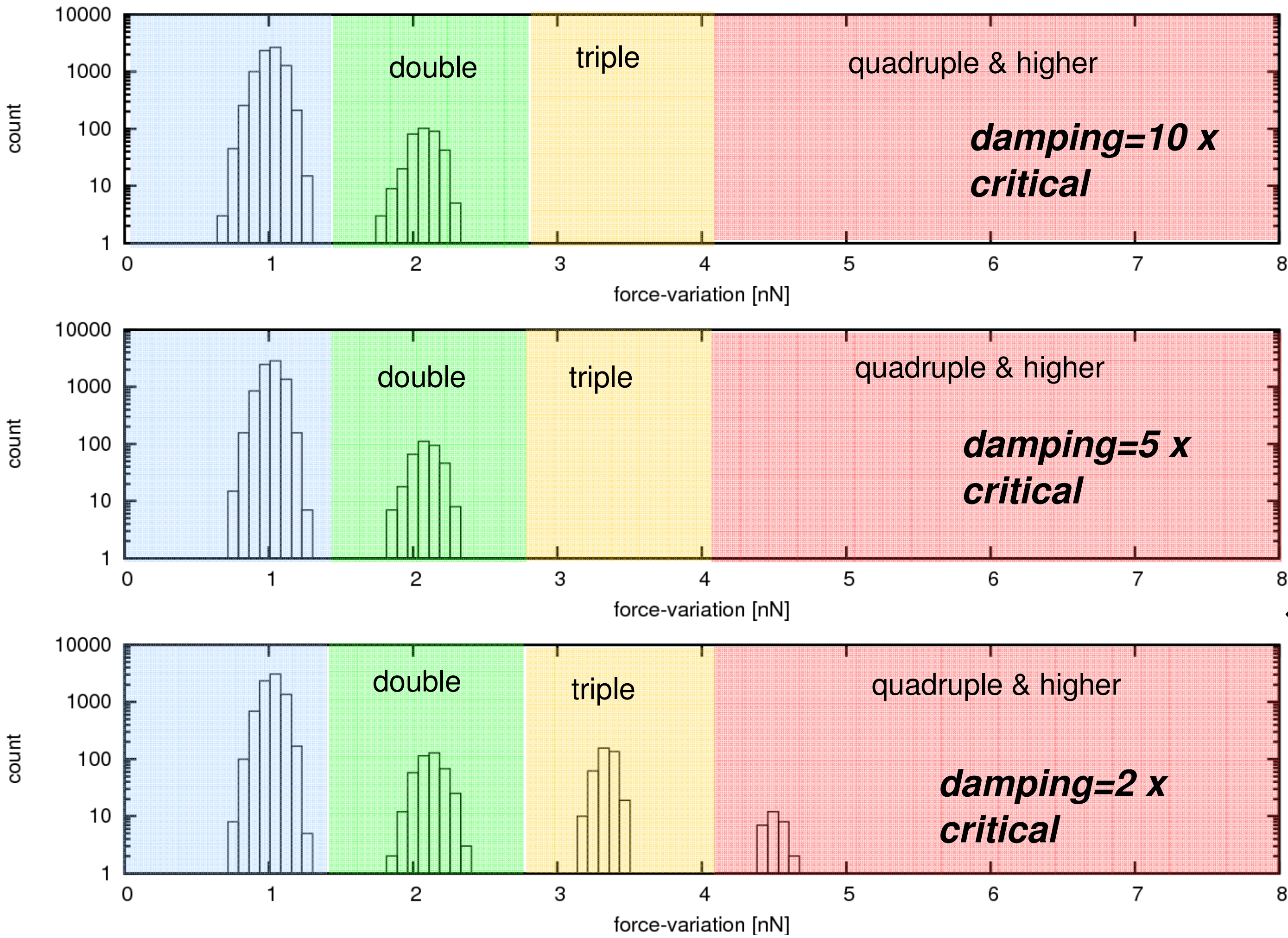
<u>Simulation parameters</u>
E0=3.3 eV
kx=ky=5 N/m
T=293 K
v=10 nm/s
m_tip=1e-12 kg
dt=1e-8 s

Onset of multiple slips!

Damping < 0.5 x critical

Comparison with simulations (η=12.5)

Same slip-recognition program run with output of 2D thermal Tomlinson simulation program:



Simulation parameters

E0=5 eV

kx=ky=5 N/m

T=293 K

v=10 nm/s

m_tip=1e-12 kg

dt=1e-8 s

Onset of multiple slips!

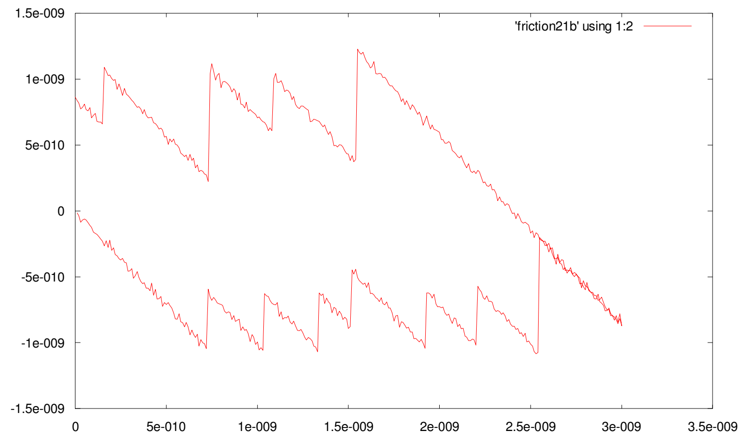
Damping < 5 x critical

Multiple slips: An indicator for damping

$$d^2x_{tip}/dt^2 + \Gamma_{tip}\, dx_{tip}/dt + \omega_{tip}^2 (x_{tip} - x_s) = -(\pi E_0/a) \sin(2\pi x_{tip}/a)$$

$$\omega_{tip} = \sqrt{\frac{k}{m}} \qquad \Gamma_{tip} = \frac{\gamma}{m}$$

Critical damping: $\Gamma_{crit} = 2\sqrt{\frac{k}{m}}$



Observation of multiple slips indicate that the slightly underdamped case is present for intermediate loadings (39nN):

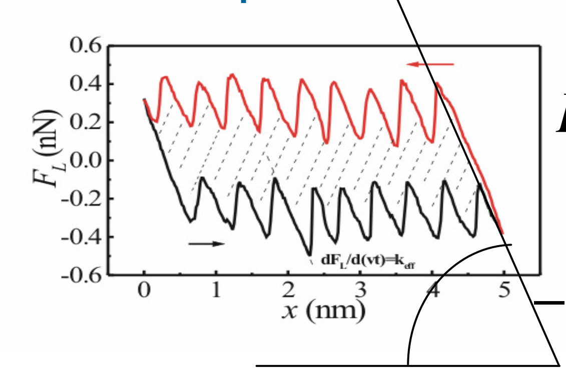
$$\gamma < 0.5\gamma_{crit}$$

At high loads (78nN), there seems to occur a transition to the overdamped case.

$$\gamma < 5\gamma_{crit}$$

R. Roth et al., Trib. Lett. (09)

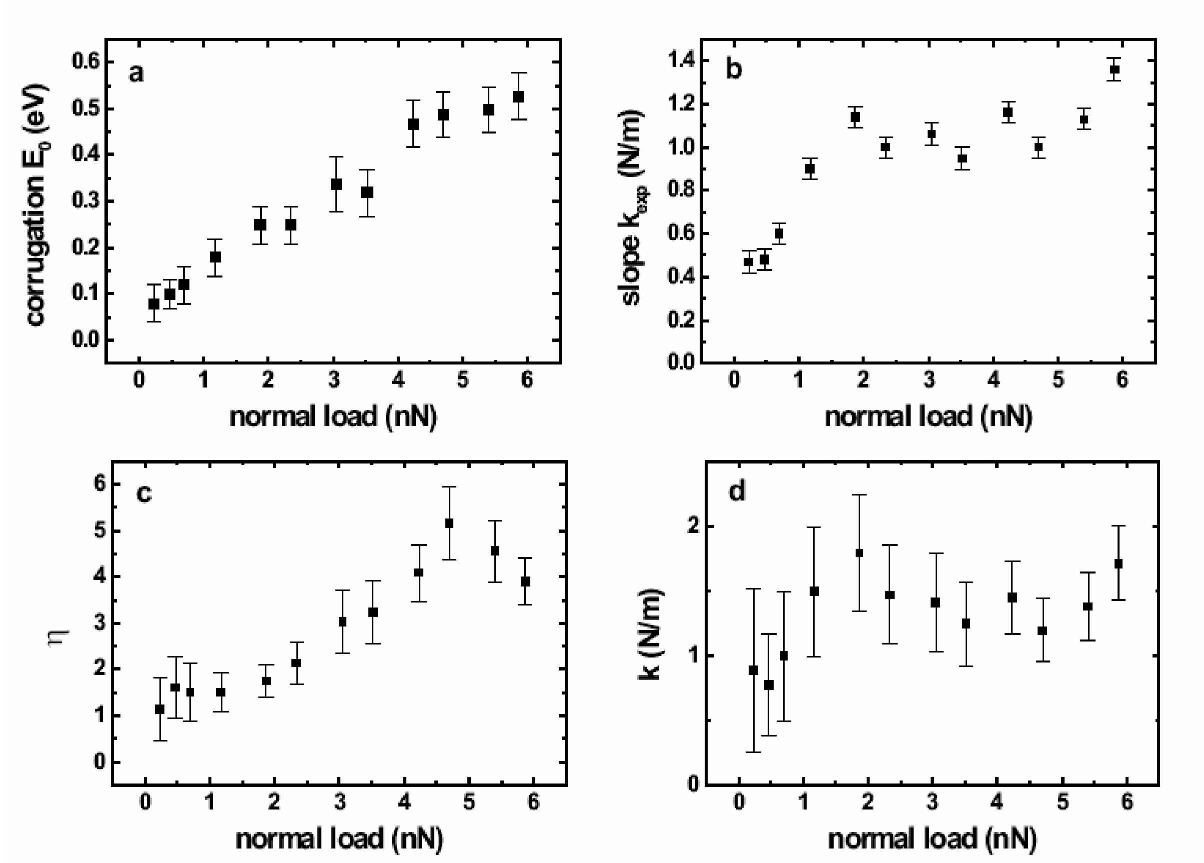
Dependence of Tomlinson Parameters



$$F_L^{max} \rightarrow E_0 = \frac{aF_L^{max}}{\pi}$$

$$-k_{exp} \rightarrow \eta = \frac{2\pi F_L^{max}}{k_{exp}a} - 1$$

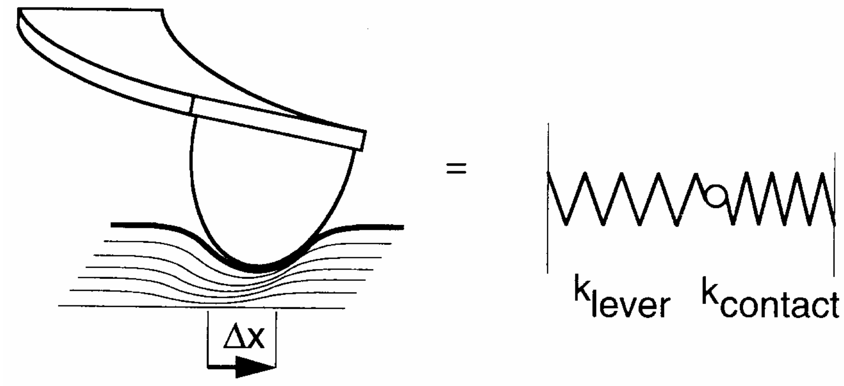
$$k = \frac{\eta + 1}{\eta} k_{exp}$$



E_0: linear increase with normal forces

k: rather independent (contact area const.?)

Lateral contact stiffness



$$\frac{1}{k} = \frac{1}{k_{lever}} + \frac{1}{k_{tip}} + \frac{1}{k_{contact}}$$

R. Carpick et al, Appl. Phys. Lett. 70, 1548-1550 (1997)

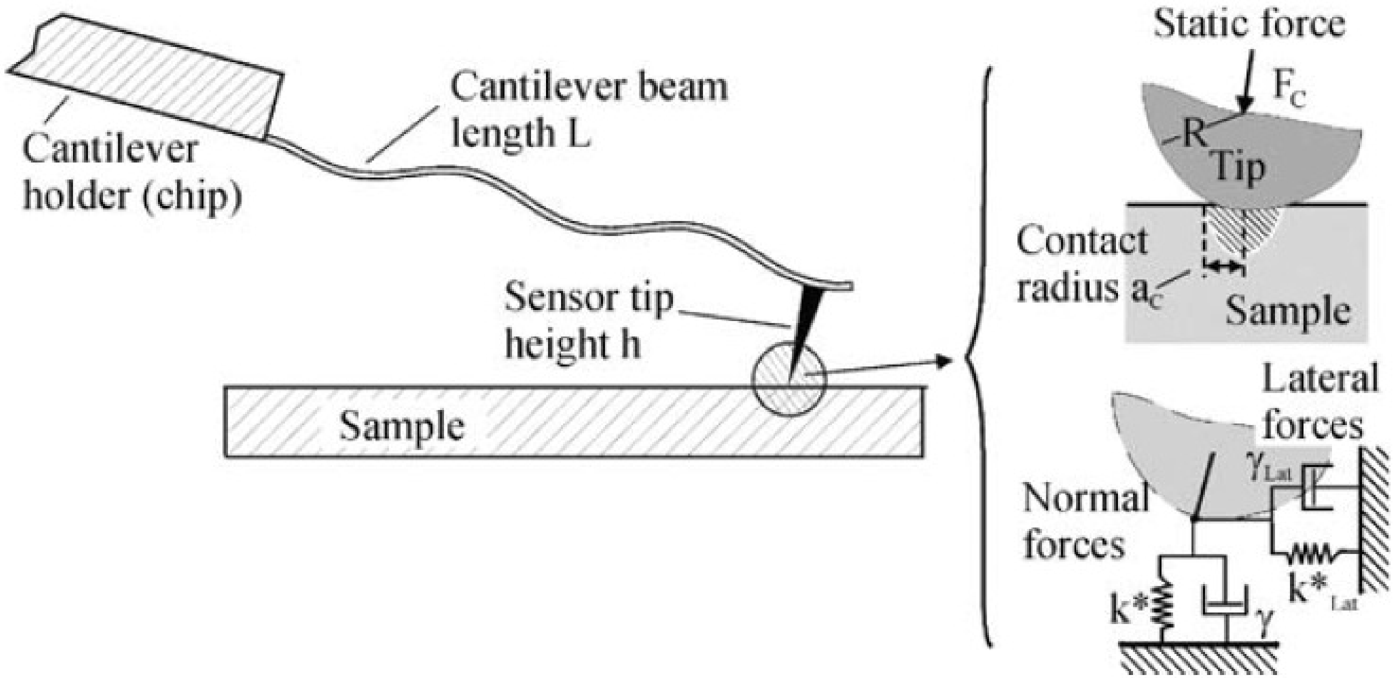
Here: k_{lever}=29N/m » k $\Rightarrow$ $k_{contact} \approx$ 1-2N/m

Continuum model :

$k_{contact}$= 8 a G $\Rightarrow$ a < 1Å ?

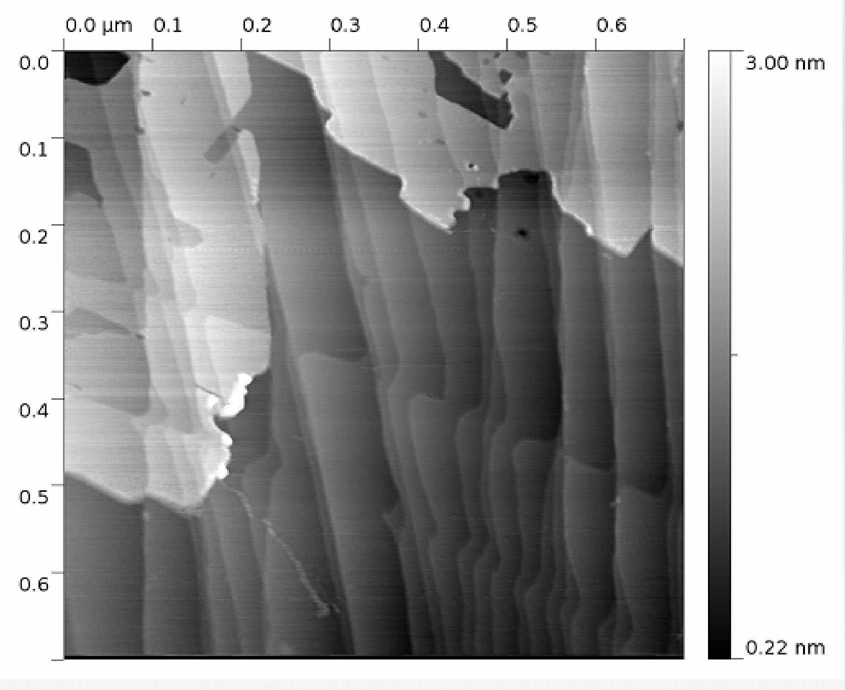
$\Rightarrow$ Atomistic model needed

Contact resonance frequencies and normal stiffness k*

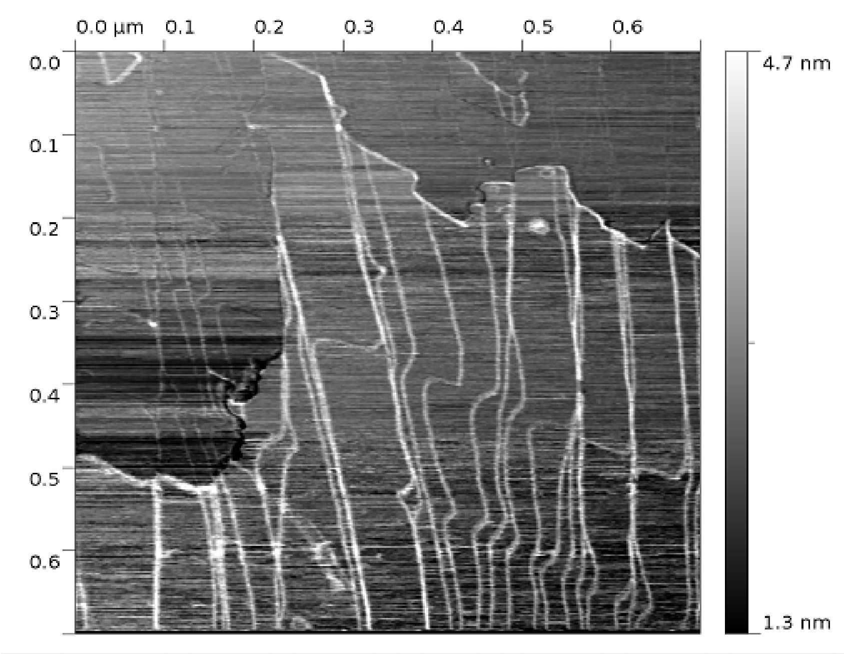


U. Rabe in Applied Scanning Probe Methods II, p. 39ff
Eds. H. Fuchs, B. Bhushan, Springer-Verlag, Berlin

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



Topography

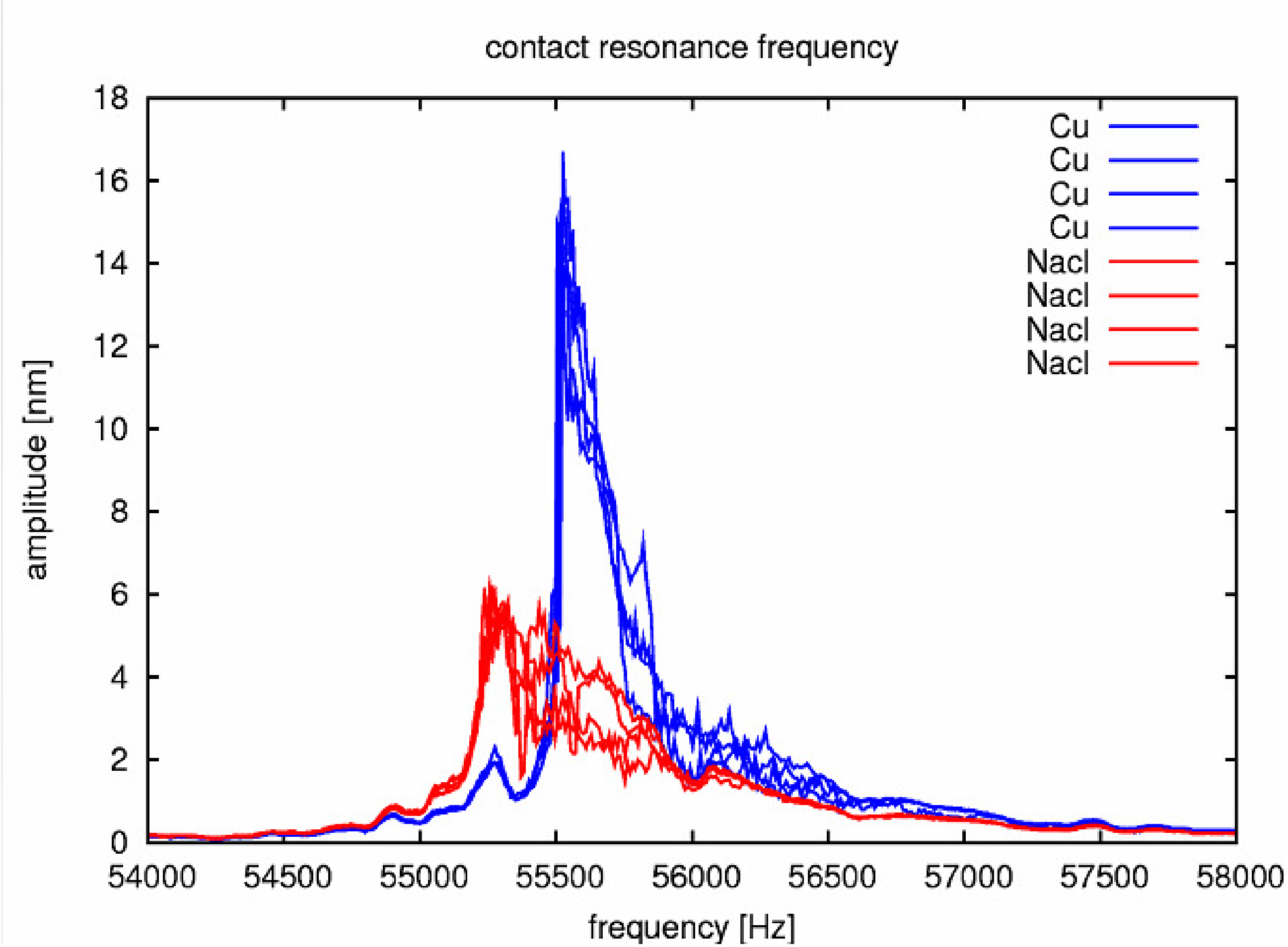


Lock-in amplitude at 56.2kHz

Fixed frequency: 56.2kHz
Lock-In measurement of amplitude

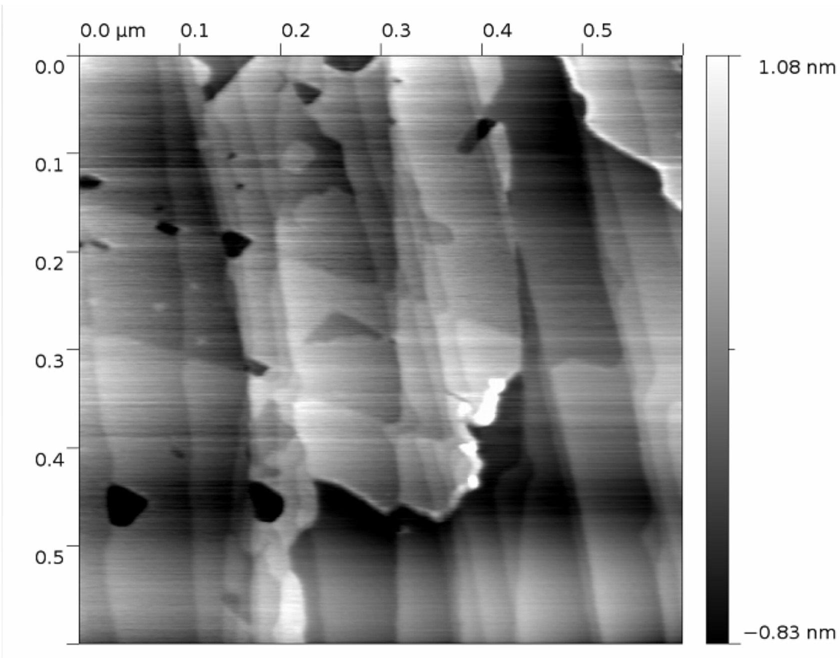
⇒Local variations of normal contact stiffness

Contact Resonances

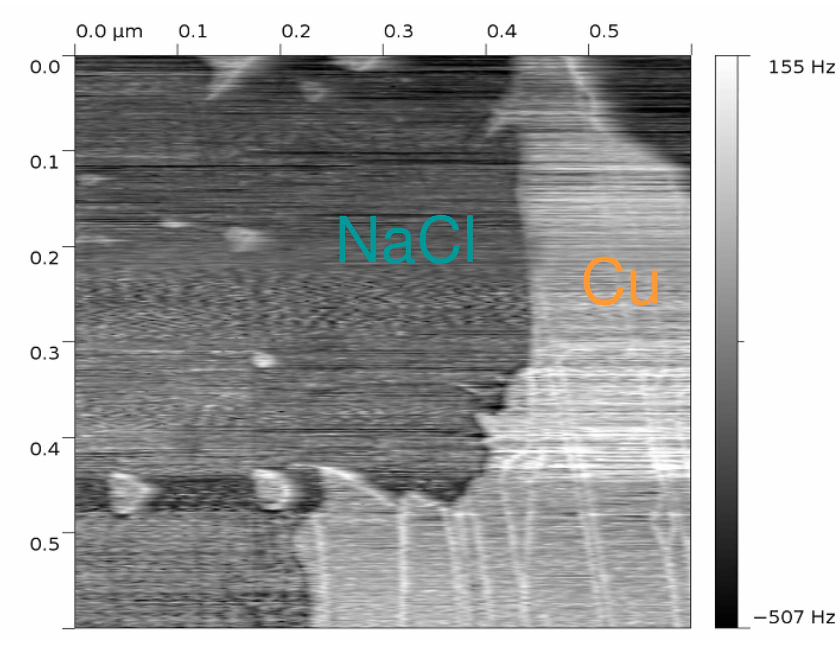


Free cantilever: 11325Hz; In Contact: 55.3kHz and 55.5kHz

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



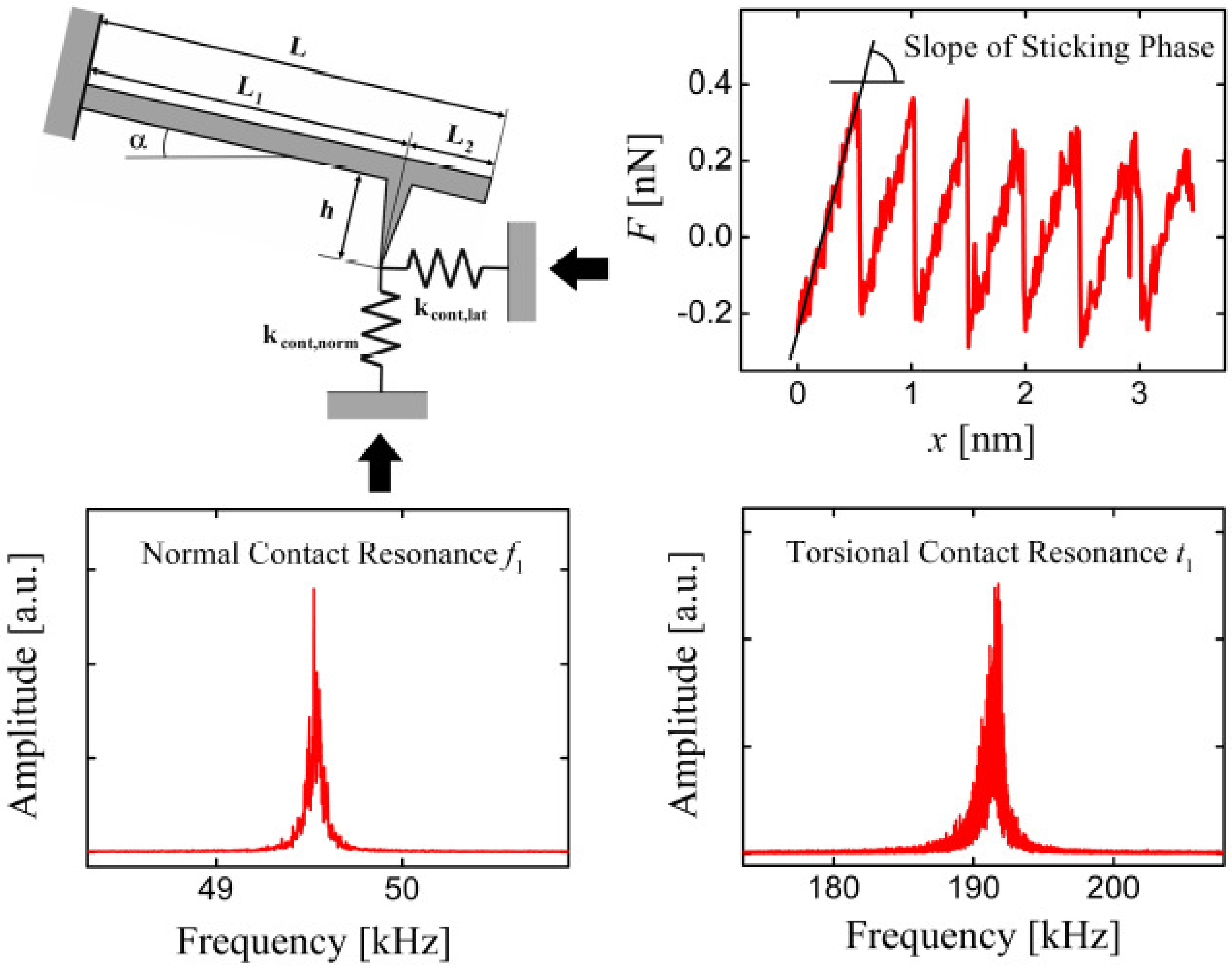
Topography



Frequency shift measured by PLL
Amplitude=400pm

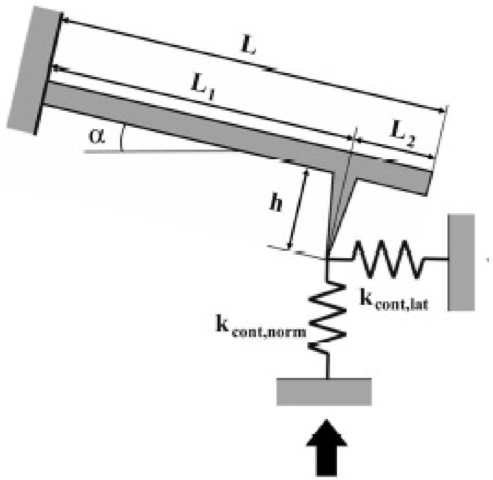
Contrast between copper and NaCl: 195Hz
Free cantilever: 11325Hz; In Contact: 55.3kHz and 55.5kHz

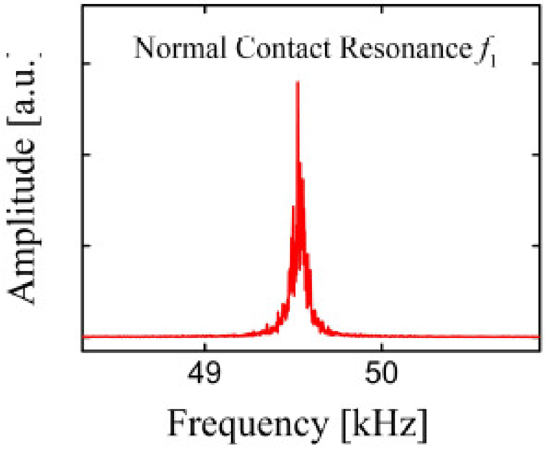
Simultaneous determination of lateral and normal contact stiffness

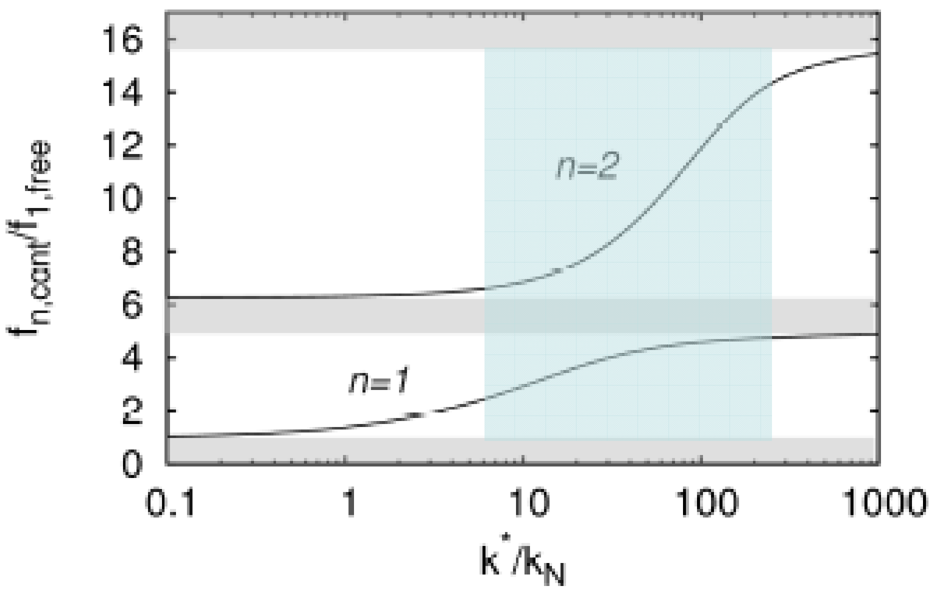


P. Steiner et al., to appear in Nanotechnology

Determination of normal contact stiffness







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

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

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

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

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

k_N=0.095N/m

f_1=49.5kHz f_1^0=10.2kHz

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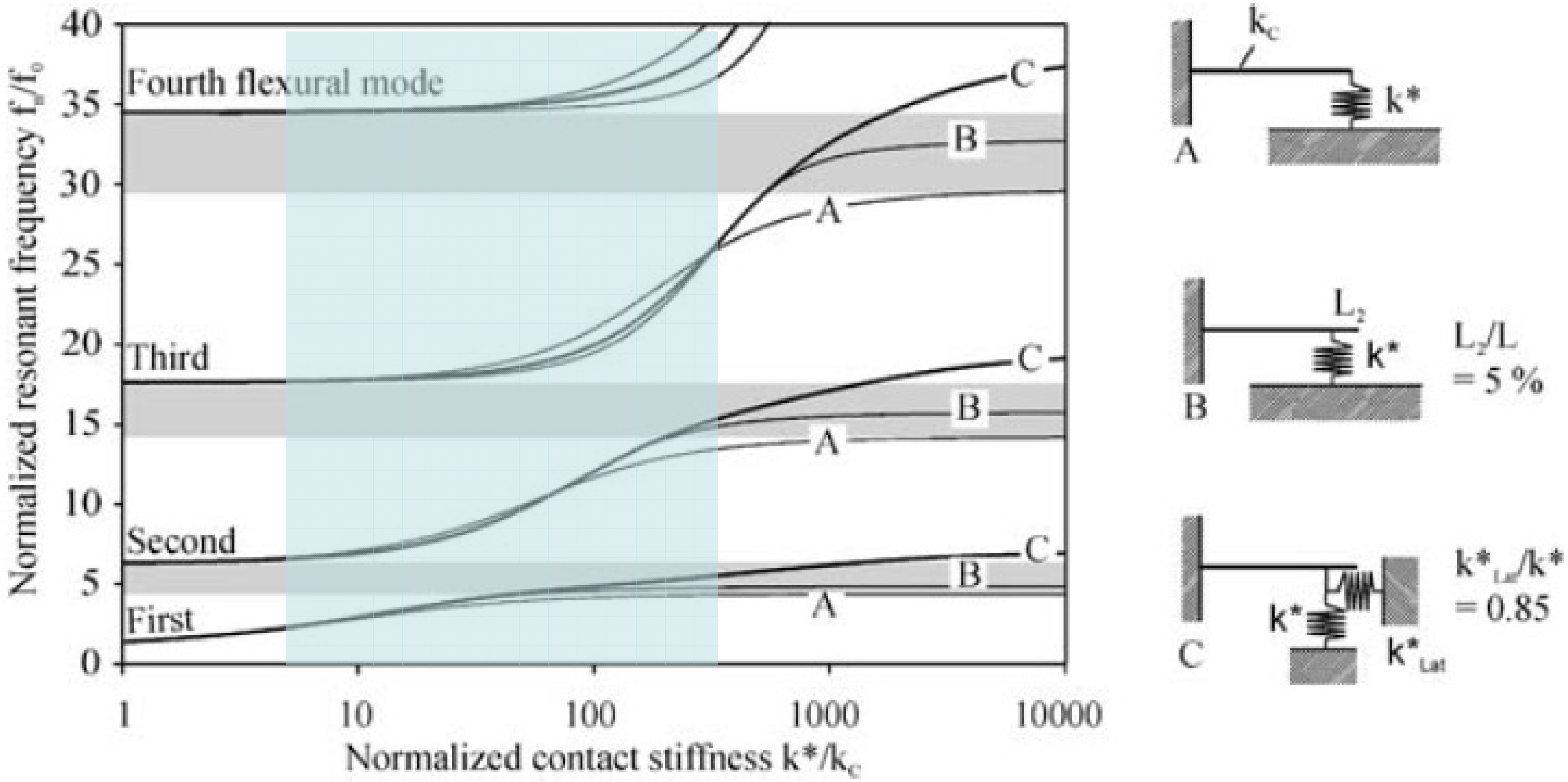
Contact resonance frequencies as a function of normalized contact stiffness



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

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)	$\frac{k^*}{\kappa}$	$\frac{k^*}{k_{eff}}$ ($\frac{k_{cont\ norm}}{k_{cont\ lat}}$)
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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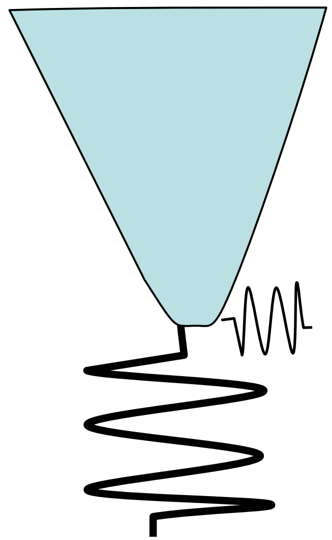
Comparison of lateral and normal contact stiffness

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!

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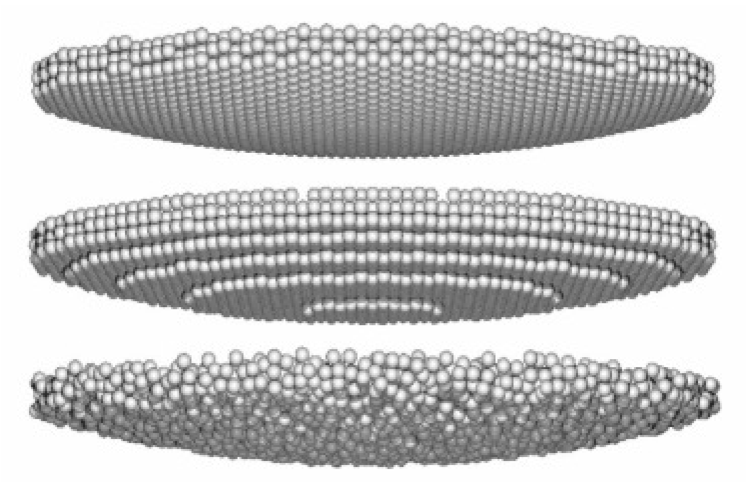
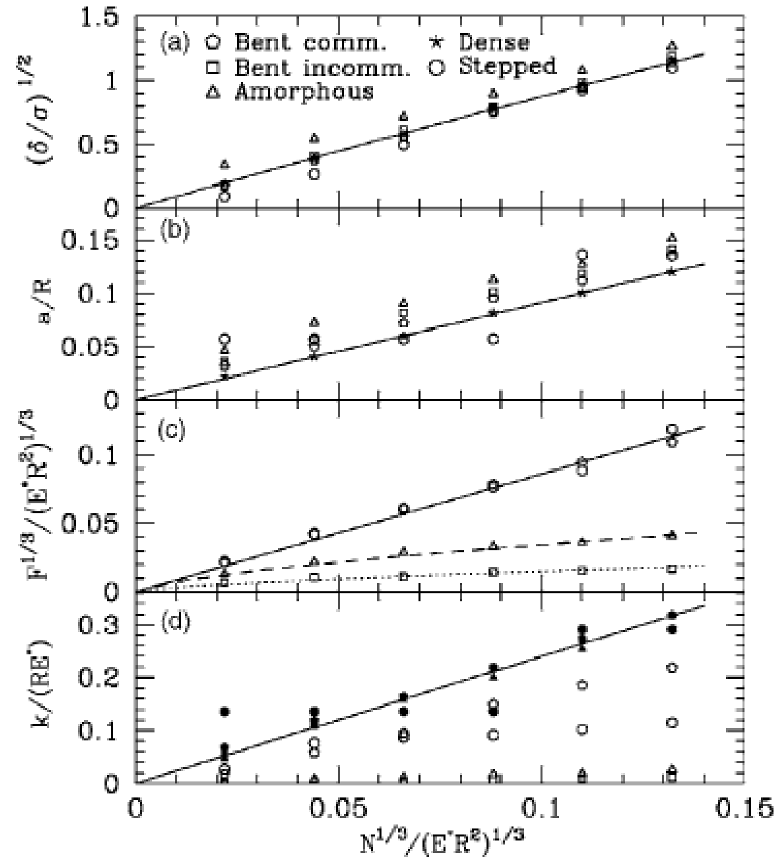
Normal and lateral contact stiffness



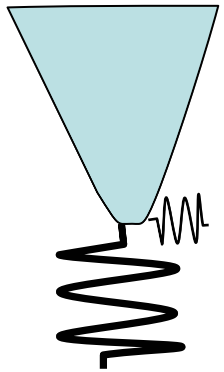


-Normal contact stiffness in reasonable agreeement with continuum models
-Lateral contact stiffness differs from the continuum model for small radii

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

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)

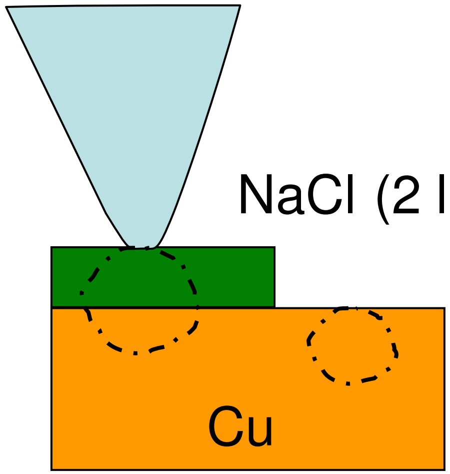


Application of Continuum model (flat punch):

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

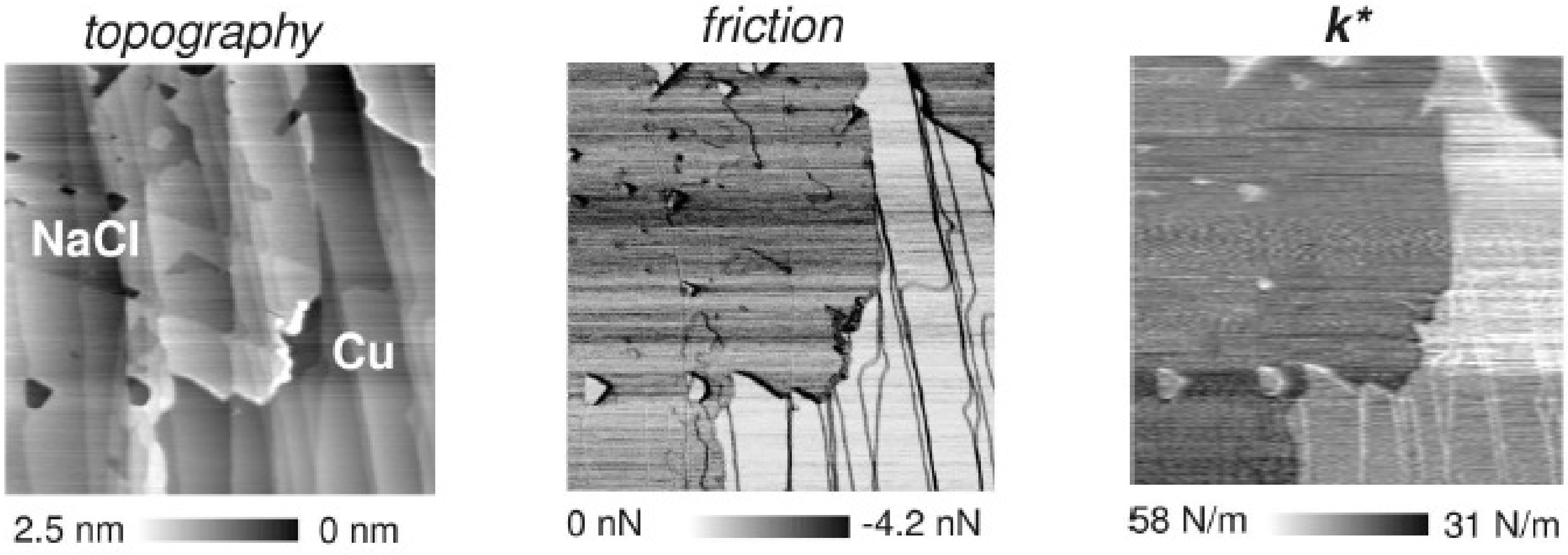
$$\frac{1}{E^*} = \left(\frac{1-\nu_{tip}^2}{E_{tip}}\right) + \left(\frac{1-\nu_{sample}^2}{E_{sample}}\right)$$

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

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

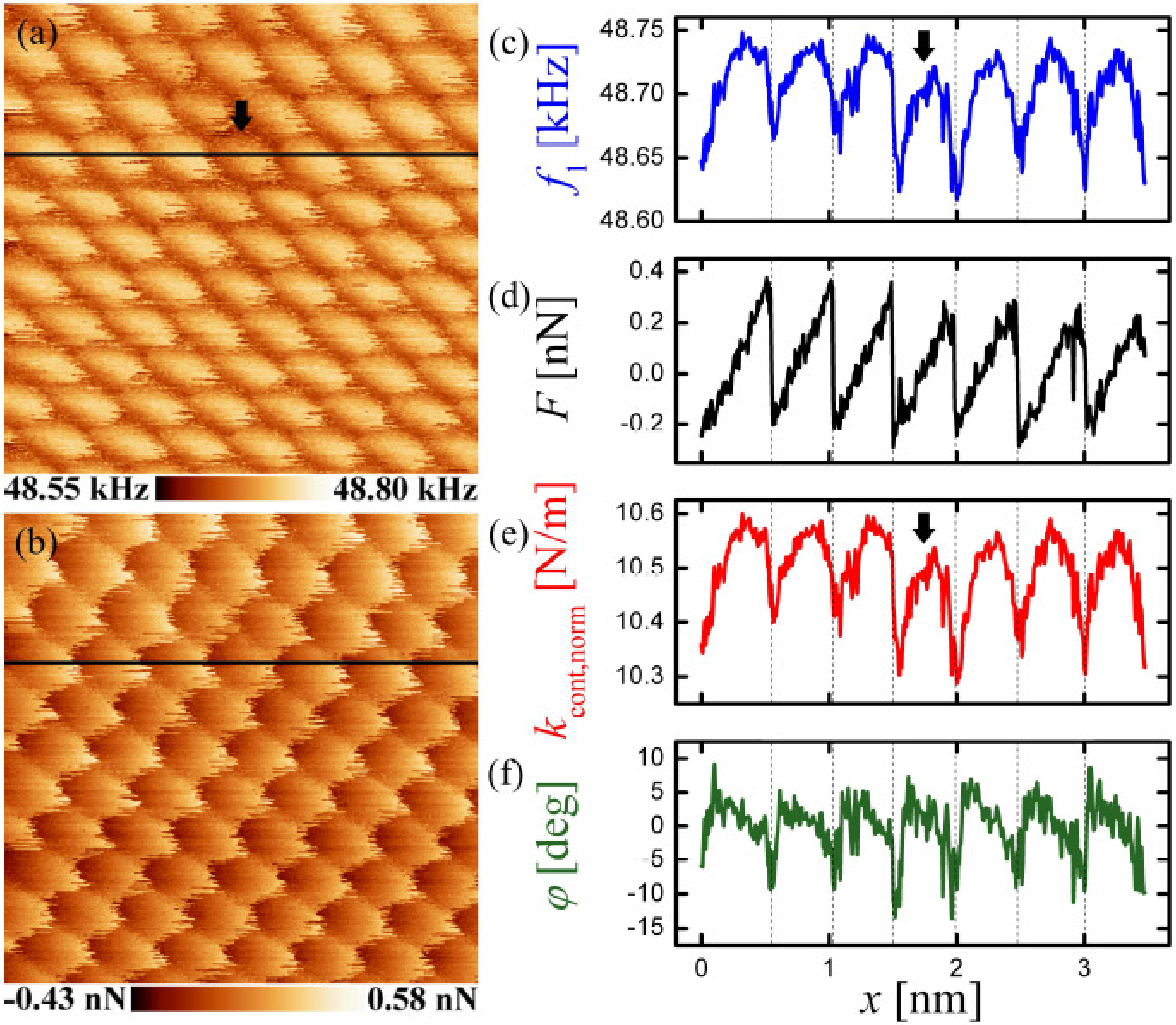


Lowest friction on Cu(111)
Contact stiffness on NaCl k*(NaCl)=32N/m
Contact stiffness on Cu(111) k*(Cu)=40N/m
Contact diameter: 2a=k*/E*=0.9nm (0.5nm)
Contact stiffness rather independent of number of layers

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

Contact resonance

Friction



Defect observed

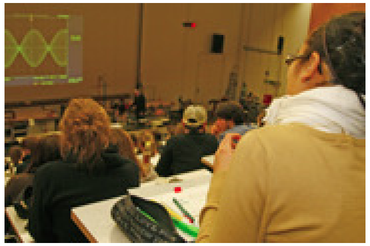
⇒Maximum normal contact resonance is observed for F_L=0

P. Steiner et al., to appear in Nanotechnology

Conclusions

- Observation of atomic-scale stick slip with single molecular and single atomic resolution

•Observation of multiple slips: A tool to estimate damping coefficients



•Simultaneous determination of normal and Lateral contact stiffness by contact resonance frequency measurements