Dynamic Atomic Force Microscopy: Basic Concepts

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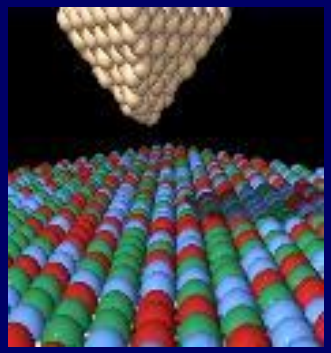
http://www.uam.es/spmth



Curso "Introducción a la Nanotecnología"

Máster en física de la materia condensada y nanotecnología

References

R. García and R. Pérez, Surf. Sci. Rep. 47, 197 (2002)

F.J. Giessibl, Rev. Mod. Phys. 75, 949 (2003)

W. Hofer, A.S. Foster & A. Shluger , Rev. Mod. Phys. 75, 1287 (2003)

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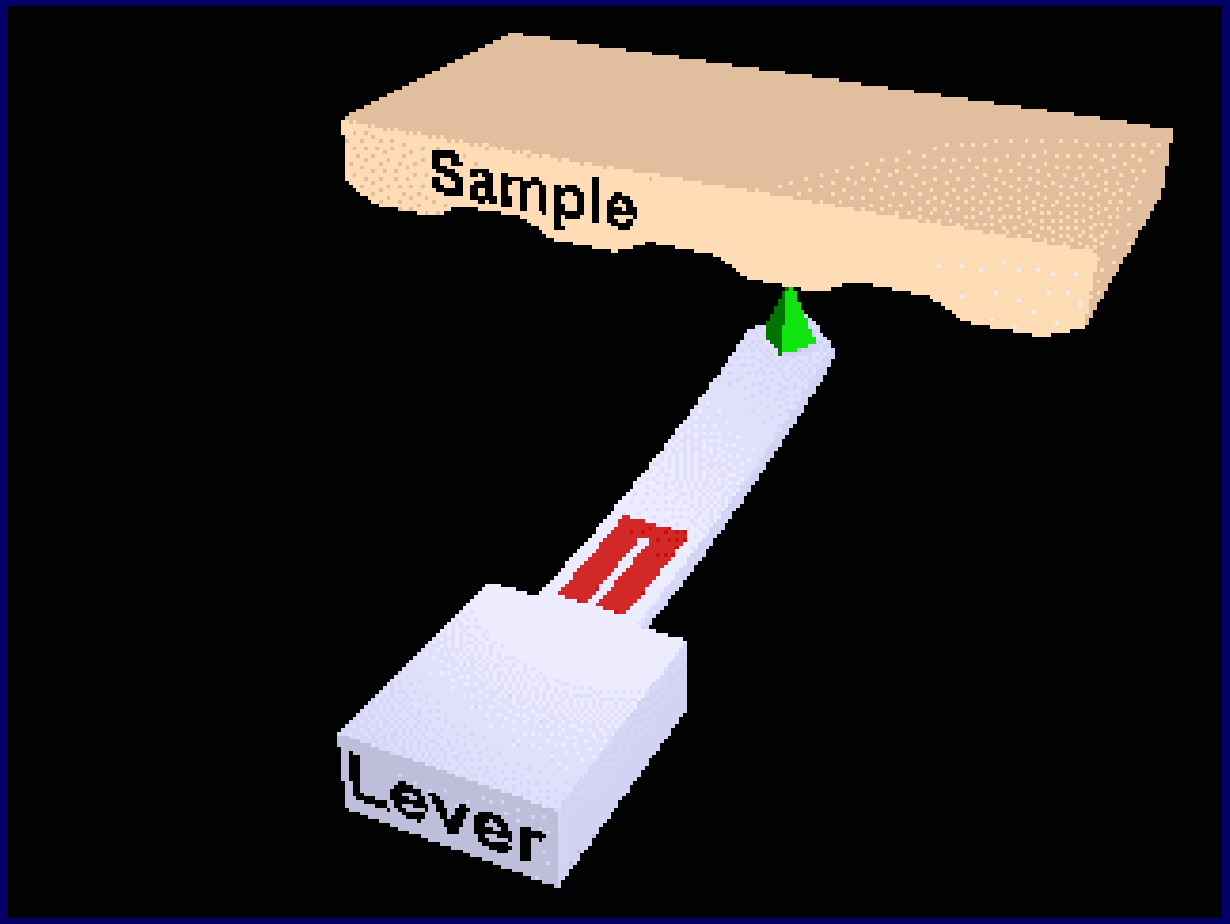
Outline

- Static vs Dynamic AFM: AM-AFM & FM-AFM.
- Amplitude Modulation AFM
- Frequency Modulation AFM

Static vs Dynamic AFM: Amplitude Modulation (AM) & Frequency Modulation (FM).

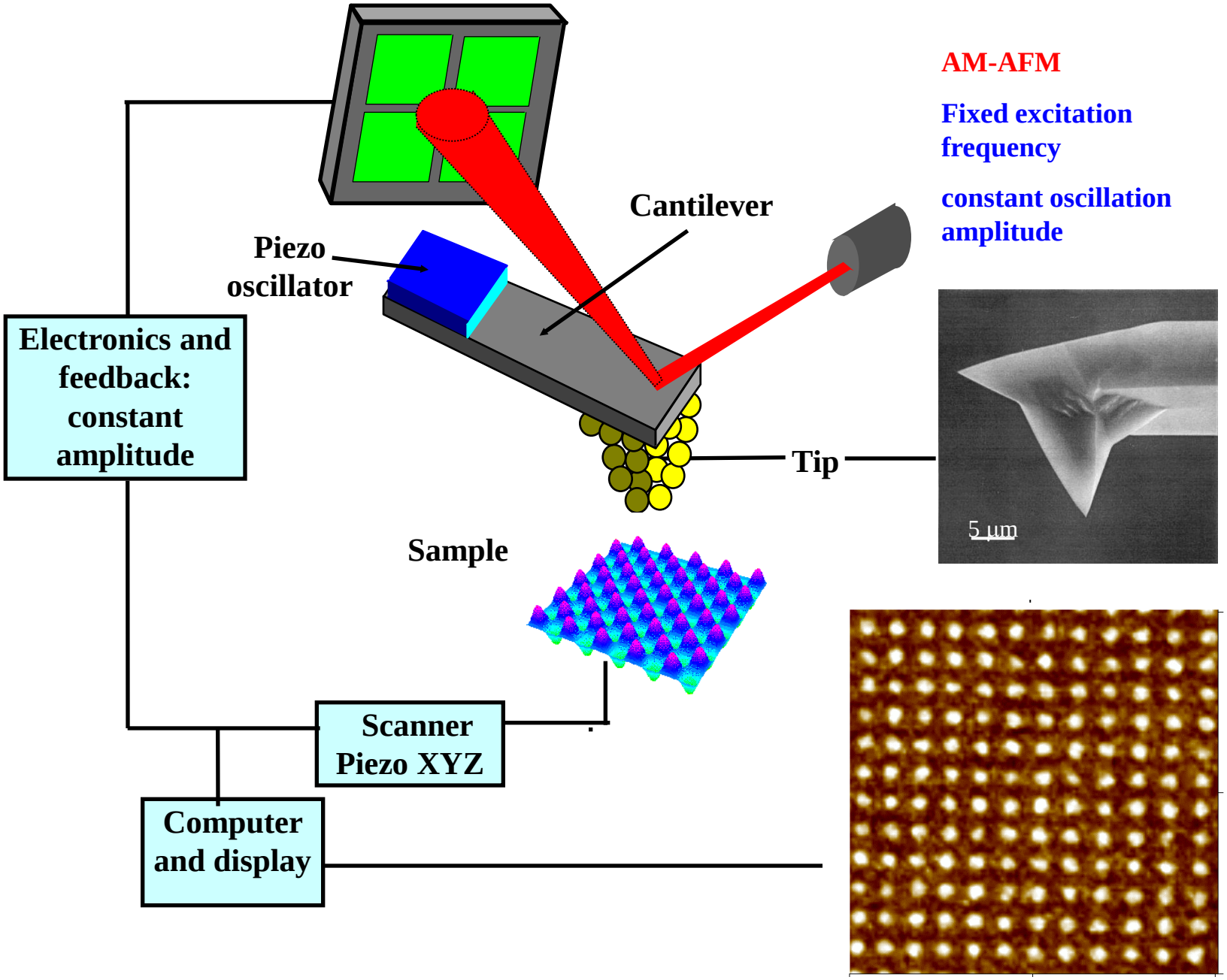
ATOMIC FORCE MICROSCOPY (AFM)

G. Binnig, C. Gerber & C. Quate, PRL 56 (1986) 930

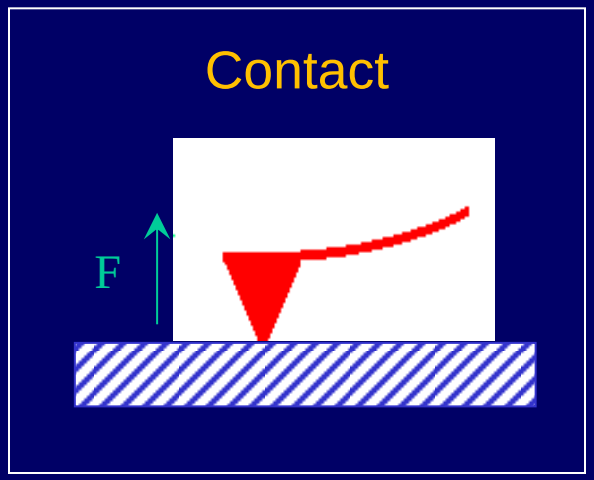


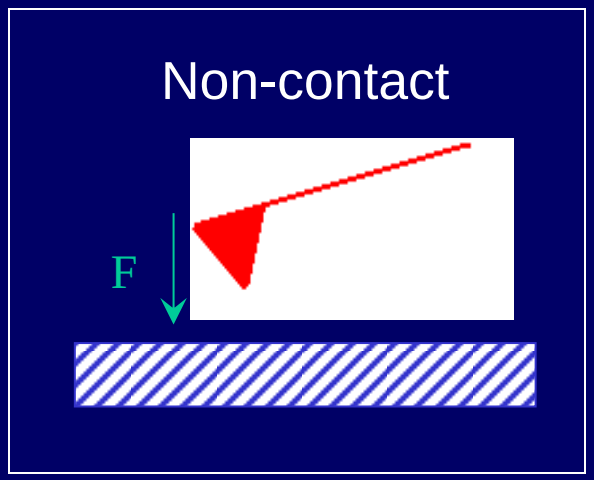
2nd most cited PRL: +5000 citations !!!

http://monet.physik.unibas.ch/famars/afm_prin.htm


AM-AFM
Fixed excitation frequency
constant oscillation amplitude
Cantilever
Piezo oscillator
Electronics and feedback: constant amplitude
Tip
5 µm
Sample
Scanner Piezo XYZ
Computer and display

Limitations of static AFM





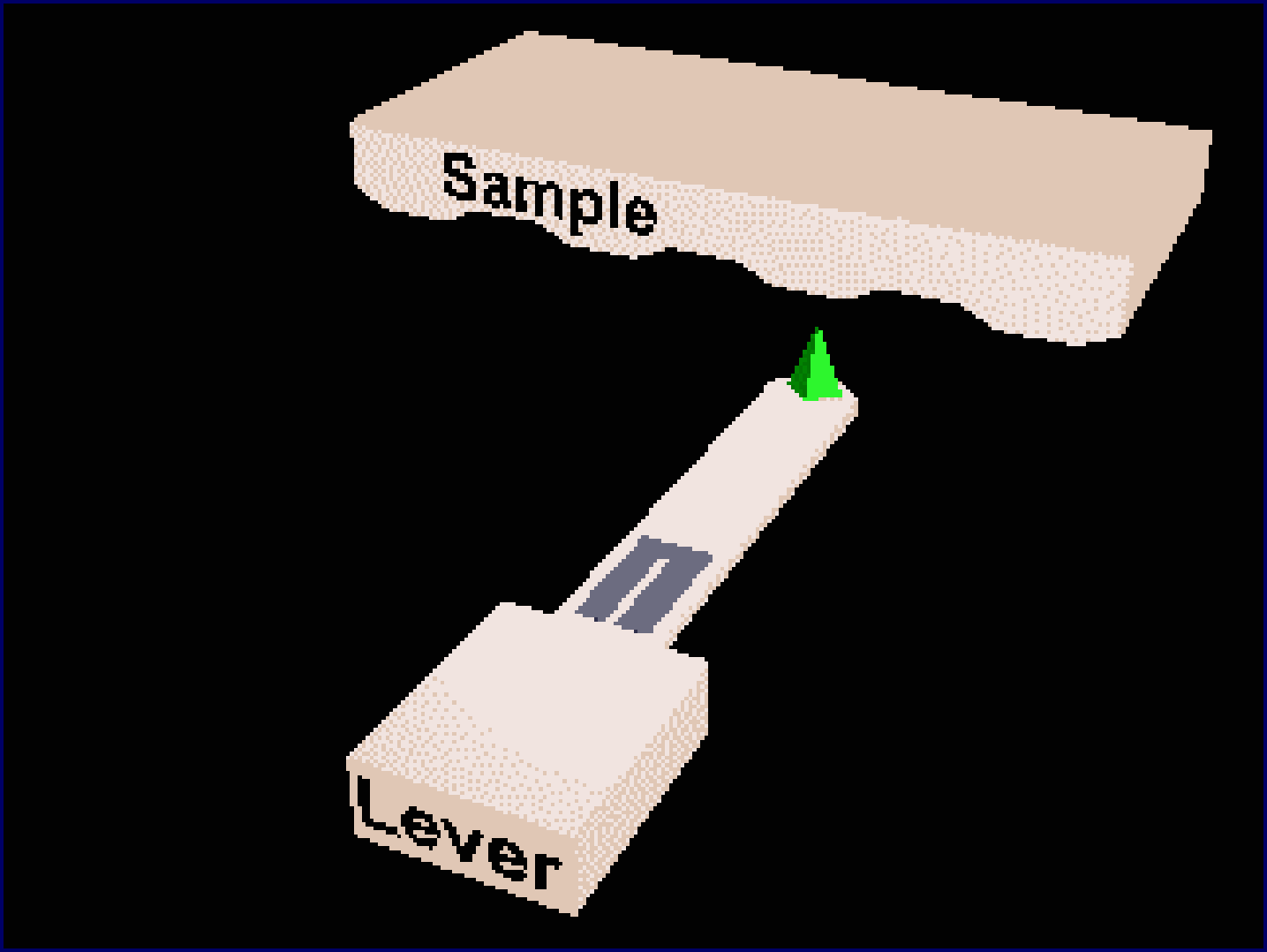
- Deformation, Friction
- No point defects observed

Atomic Resolution?

- Detection of small forces: soft cantilevers.
- "Jump to contact" : stiff cantilevers

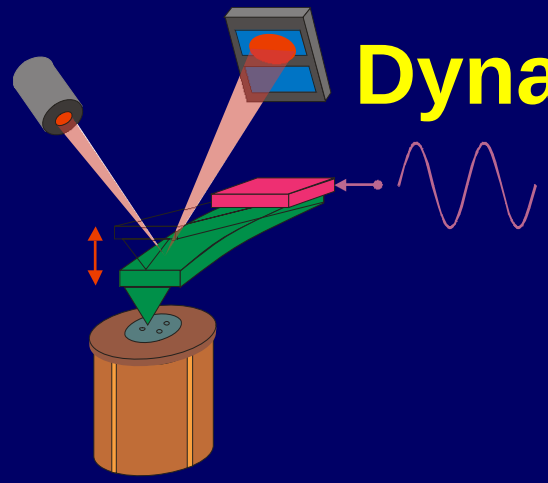
AFM: G. Binnig, C. Gerber & C. Quate, PRL 56 (1986) 930

Dynamic AFM

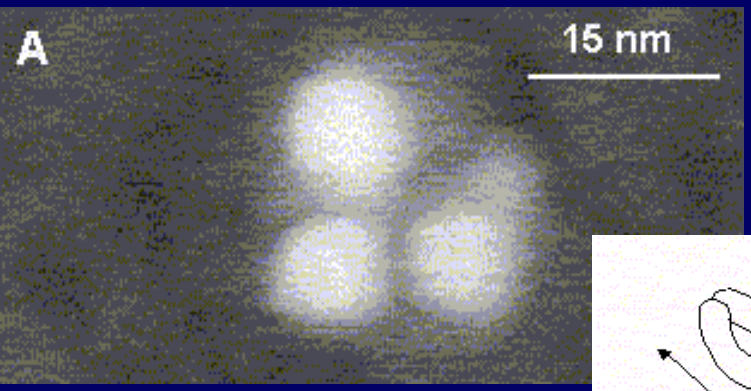


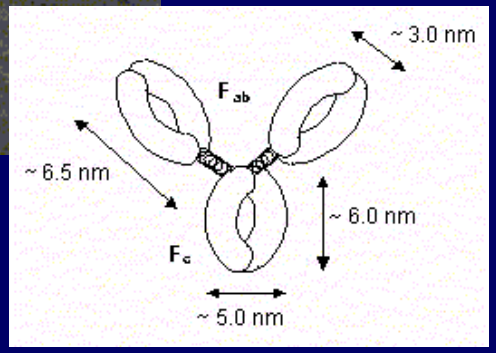
http://monet.physik.unibas.ch/famars/afm_prin.htm

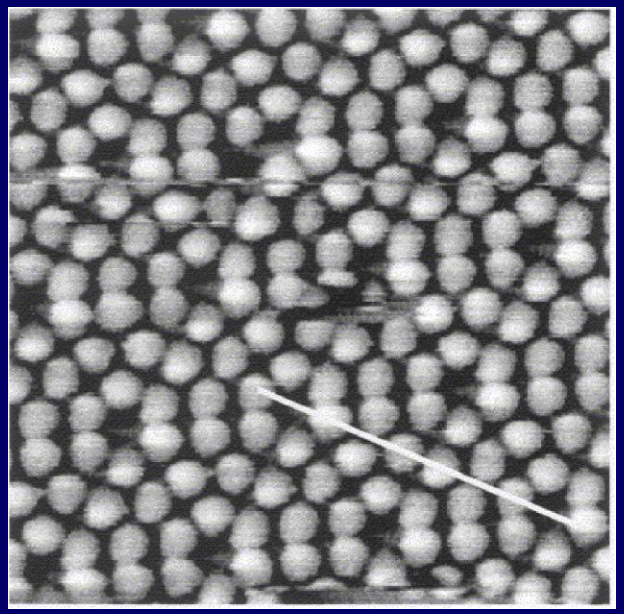
Dynamic AFM: Our Goal



Why changes observed in the dynamic properties of a vibrating cantilever with a tip that interacts with a surface make possible to:







AM-dAFM

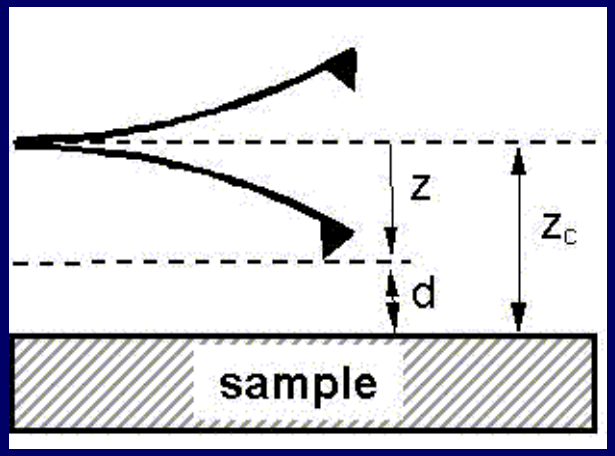
• Obtain molecular resolution images of biological samples in ambient conditions.

•Resolve atomic-scale defects in UHV.

FM-dAFM

R. García and R. Pérez, Surf. Sci. Rep. 47, 197 (2002)

Dynamic description



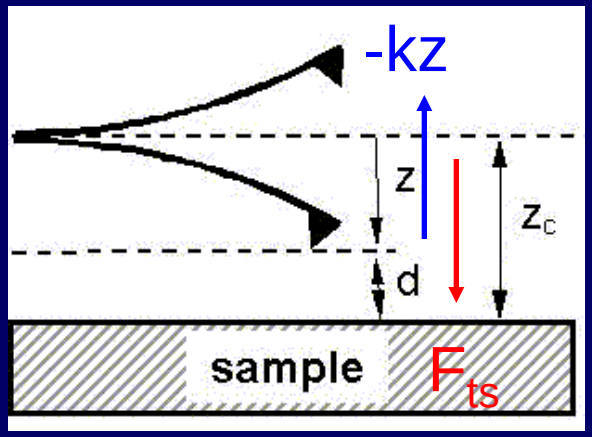
Cantilever-tip ensemble as a point mass spring described by a non-linear 2nd order differential equation

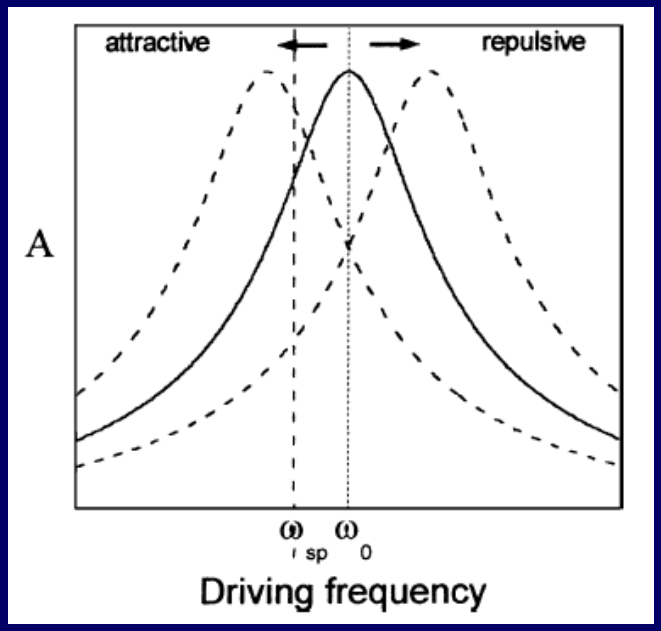
$$\ddot{z}(t) + \frac{\omega_0}{Q}\dot{z}(t) + \omega_0^2 z(t) - \frac{\omega_0^2}{k} F_{ts}\left[z_c + z(t)\right] = \omega_0^2 A_{exc}(t)$$

Amplitude
Resonance Frequency
Phase shift

} link the dynamics of a vibrating tip to the tip-surface F_{ts} interaction.

Why do A and Δf ($\Delta\omega$) depend on F_{ts}? (simple quasi-harmonic argument)





For small amplitudes and large distances

$$\omega = \sqrt{\frac{k + k_{ts}}{m}}$$

$$k_{ts} = -\frac{dF_{ts}}{dz}\left[z = z_c\right]$$

$$\frac{\Delta\omega}{\omega_0} = \frac{k_{ts}}{2k}$$

$$k >> k_{ts}$$

New $\omega \Rightarrow$ new resonance curve $\Rightarrow$ New amplitude for given ω_{exc}

BUT: Large amplitudes $\Rightarrow$ Force gradient varies considerably during oscillation $\Rightarrow$ Non-linear features in the dynamics

Two major modes: AM-AFM and FM-AFM

Amplitude Modulation AFM

- Excitation with constant amplitude A_{exc} and frequency ω_{exc} close or at its FREE resonance frequency ω_0.
- Oscillation amplitude A as feedback for topography.
- Phase shift ϕ between excitation and oscillation: compositional contrast.
- Air and liquid environments.

Y. Martin et al, JAP 61, 4723 (1987)

Q. Zhong et al, SS 290, L688 (1993)

Frequency Modulation AFM

- Constant oscillation amplitude at the current resonance frequency (depends on F_{ts}).
- Frequency shift Δf as feedback for topography.
- Excitation amplitude A_{exc} provides atomic-scale information on dissipation.
- UHV (now also liquids !)

T.R. Albrecht et al, JAP 69, 668 (1987)

F.J. Giessibl, Science 267, 68 (1995)

Amplitude Modulation (AM) AFM

Outline: AM-AFM

(or Tapping mode AFM)

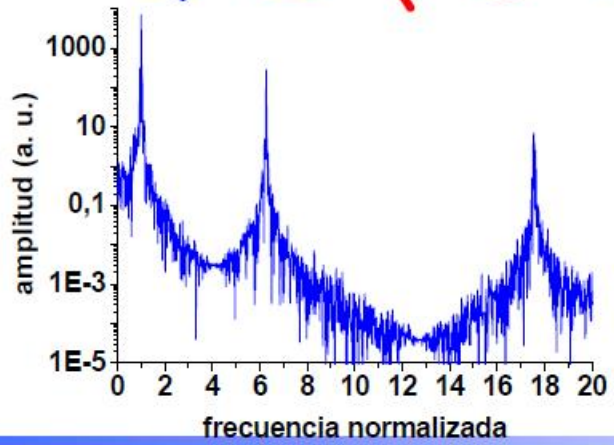
- Operation Parameters.
- Non-linear dynamics: Existence of two oscillation states (L & H): implications for imaging.
- Understanding amplitude reduction.
- Imaging materials properties: phase shifts and dissipation.
- Summary: things to remember...

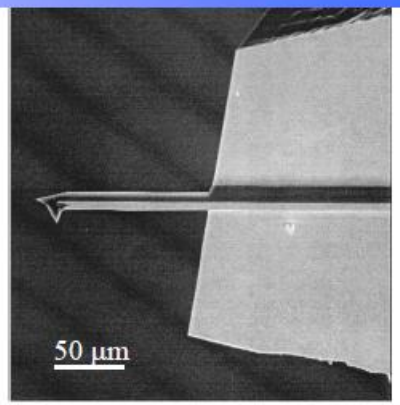
Microcantilevers

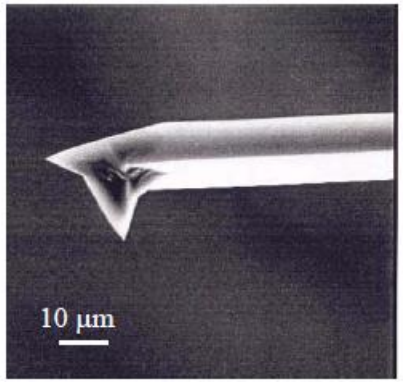
Mechanical device to detect and amplify tip-surface interactions, Si or Si_3N_4

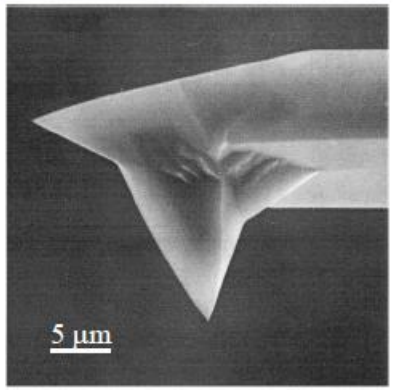
The dynamic response of the μcantilever is characterized by three quantities: force constant k_n , resonant frequency f_n and quality factor Q_n

There are several resonances (eigenmodes) in a cantilever

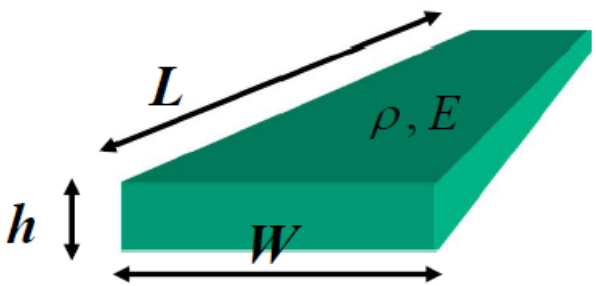


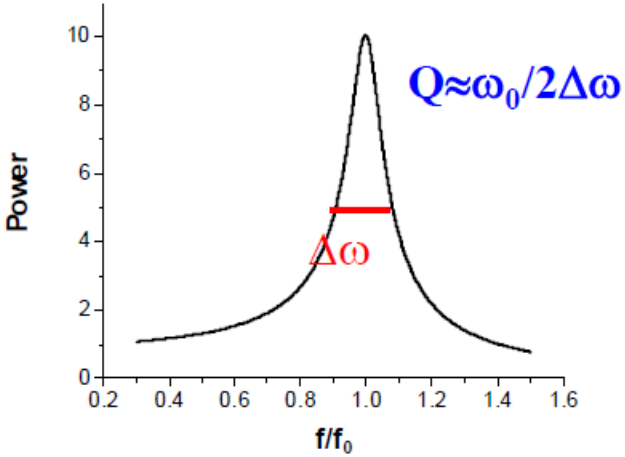






Microcantilevers





$$f_n = \frac{1}{2\pi}\sqrt{\frac{k_n}{m_n}} = \frac{C_n^2}{2\pi}\frac{h}{L^2}\sqrt{\frac{E}{\rho}}$$

$$k = \frac{3\,EI}{L^3} = \frac{EWh^3}{4\,L^3}$$

Resonace frequency	Force constant	Q-factor
10^4-4x 10^5 Hz	0.01-50 N/m	1-10^5

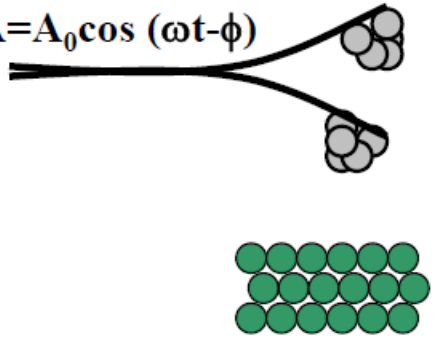
Forces: Equation of motion

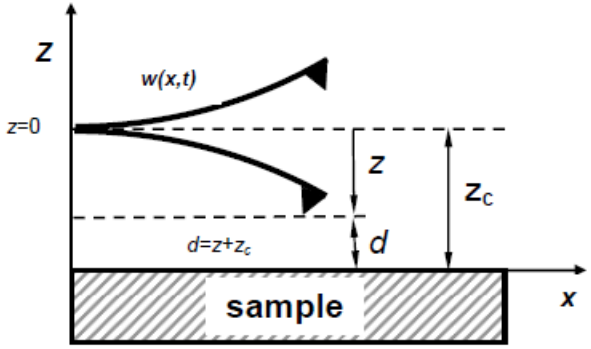
Contact AFM

$$F_{ts} = -kz$$

dynamic AFM (amplitude modulation)

$A = A_0 \cos(\omega t - \phi)$





Point-mass model of the microcantilever

Respuesta elástica

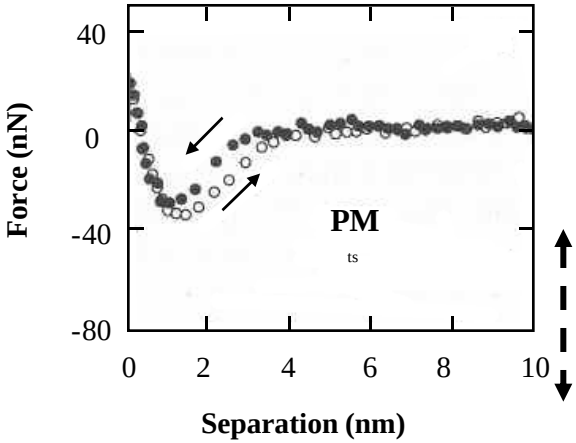
Interacciones

$$m\frac{d^2z}{dt^2} = -kz - \frac{m\omega_0}{Q}\frac{dz}{dt} + F_{ts} + F_0 \cos \omega t$$

Amortiguamiento del medio

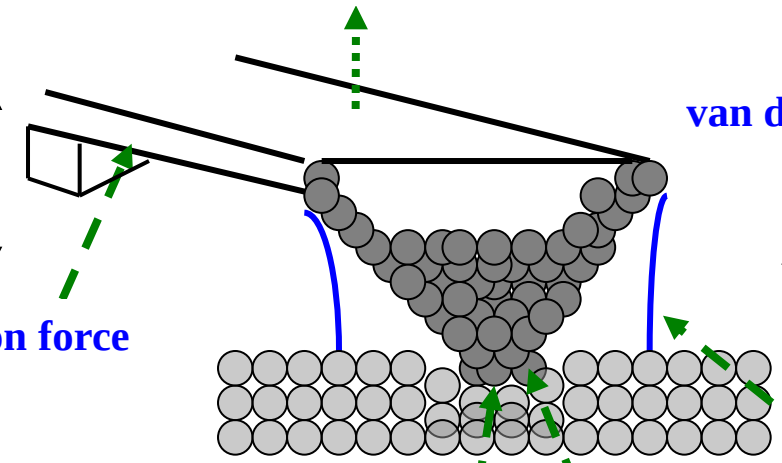
Fuerza externa

Forces in AFM



Restoring force cantilever

$F_c = -kz$



van der Waals forces

$$F_{vdw} = \frac{HR}{6d^2}$$

Excitation force

$F_0 \cos \omega t$

Capillary forces

Hidrodynamic forces

$$F_h = \frac{m\omega_0}{Q}\frac{dz}{dt}$$

Adhesion forces

$F_a = 4\pi\gamma R$

Short range repulsive forces (DMT)

$$F_{DMT} = E^* \sqrt{R}\delta^{3/2}$$

Forced damped harmonic oscillator

$$m\ddot{z}(t)+\frac{mQ}{\omega_0}\dot{z}(t)+kz(t)=kA_{exc}\cos(\omega_{exc}t)$$

$$\omega_0=\sqrt{\frac{k}{m}}$$

Q ≡ Quality factor (cantilever damping)

$$\gamma=\frac{\omega_0}{2Q}$$

$$z(t)=C\exp(-\gamma t)\cos(\omega_\gamma t+\delta)+$$

(transient)

$$+\frac{\omega_0^2 A_{exc}}{\sqrt{\left(\omega_0^2-\omega_{exc}^2\right)^2+\left(\omega_0\omega_{exc}/Q\right)^2}}\cos(\omega_{exc}t-\phi)$$

$\omega_0=\omega_{exc} \Rightarrow A = QA_{exc}$ (resonance)

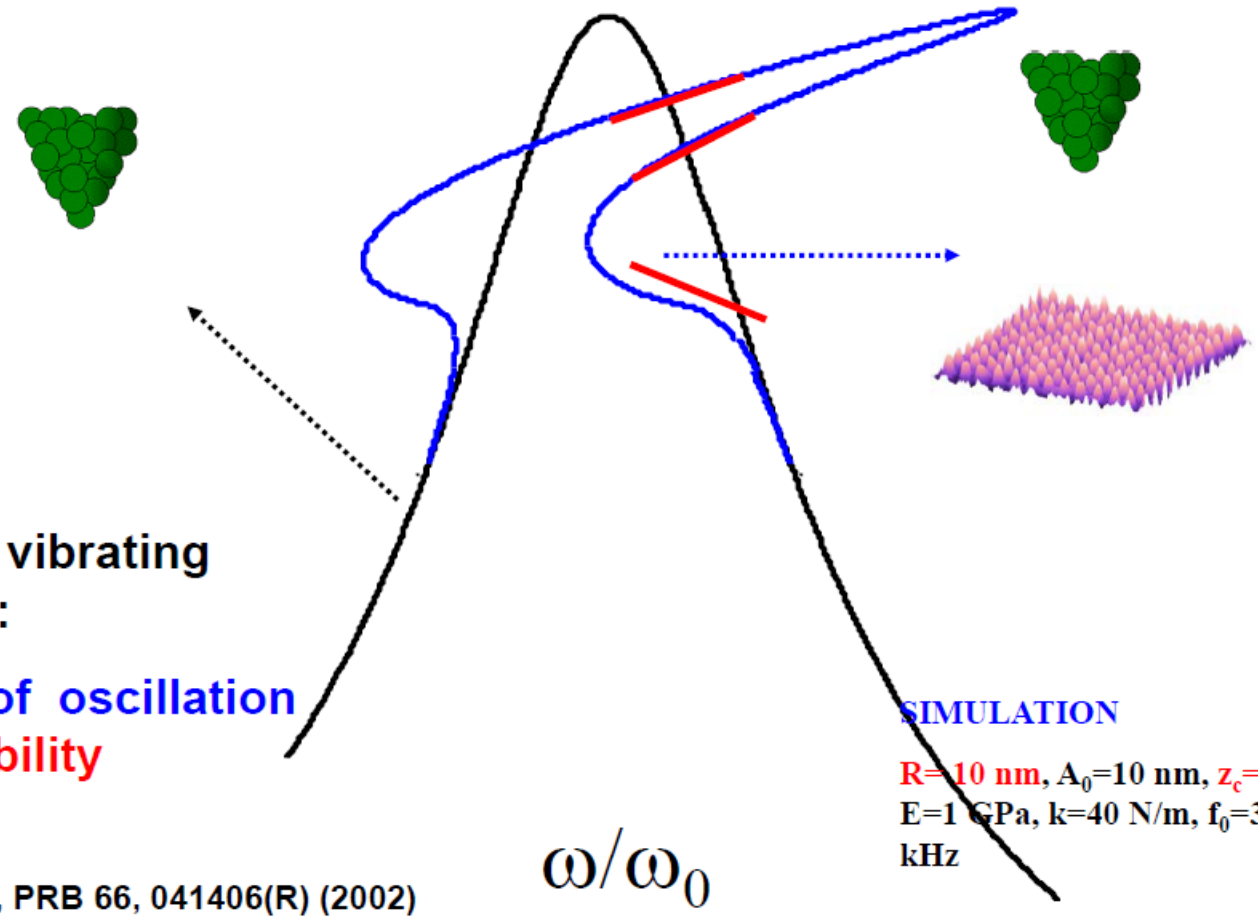
$$\tan\phi=\frac{\omega_0\omega_{exc}/Q}{\omega_0^2-\omega_{exc}^2}$$

BUT F_{ts} is nonlinear
$\Rightarrow$ anharmonic effects

Resonance Curves

Free oscillating tip (10 nm)

Interacting tip (10 nm size)



Mechanics of vibrating nanosystems:

Coexistence of oscillation states: Bi-stability

SIMULATION

R=10 nm, A_0=10 nm, z_c=8 nm, E=1 GPa, k=40 N/m, f_0=325 kHz

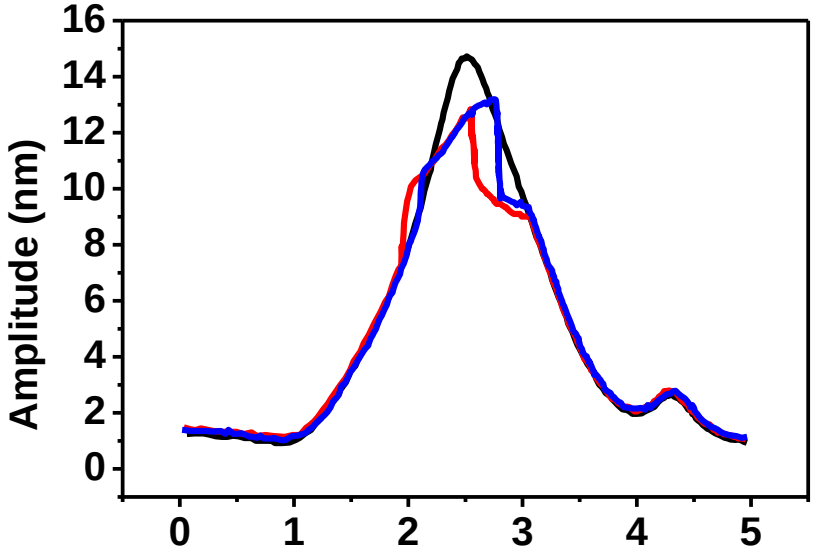
AS Paulo, R García, PRB 66, 041406(R) (2002)

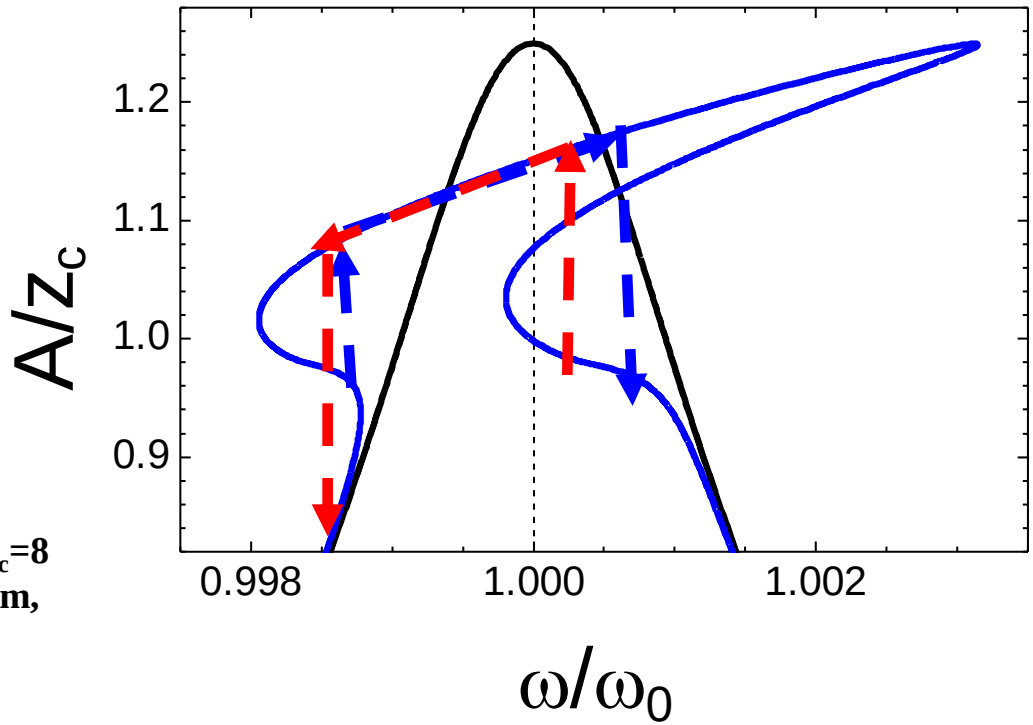
EXPERIMENT

Silicon, A_0=15 nm, A=13 nm, f_0=295.64 kHz

Low to high

high to low



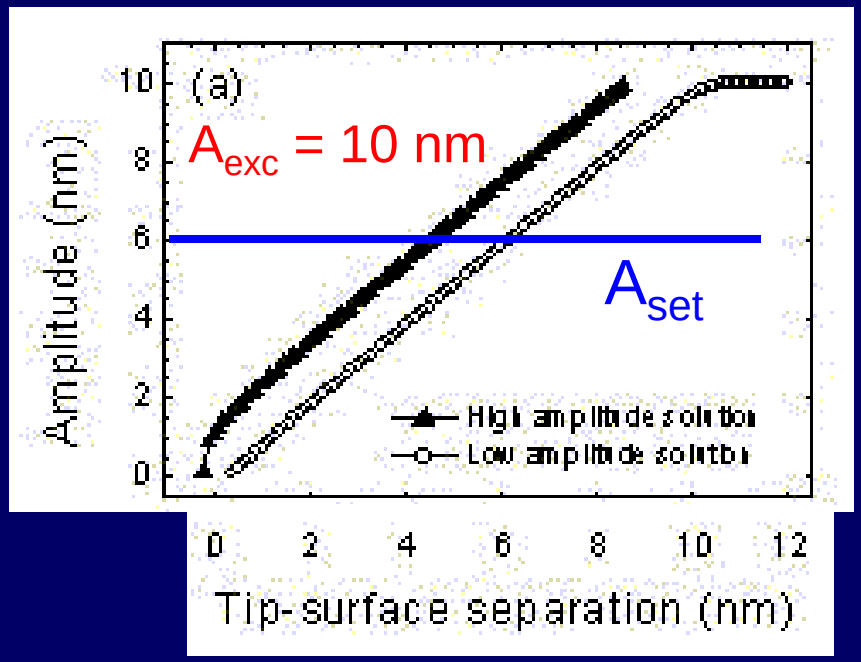


SIMULATION

R= 10 nm, A_0=10 nm, z_c=8 nm, E=1 GPa, k=40 N/m, f_0=325 kHz

AM-AFM: Two stable oscillation states

$$z_{H(L)}(t) = z_c + A_{H(L)} \cos(\omega_{exc} t - \phi_{H(L)})$$



(two steady state solutions)

H: high amplitude state

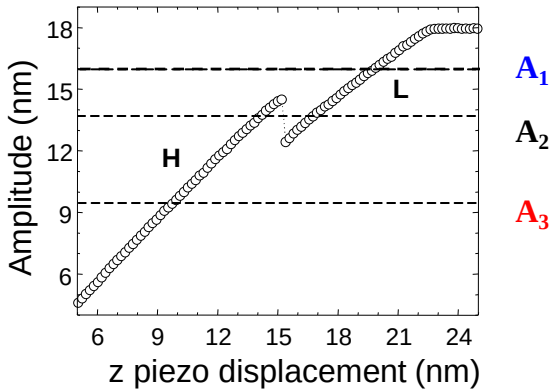
L: low amplitude state

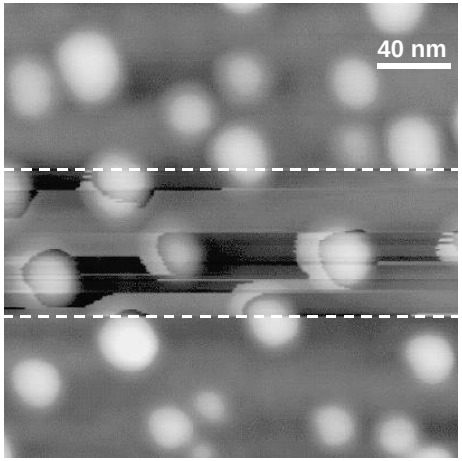
Amplitude curves: $A_{H(L)}$ vs z_c

- Collection of L and H solutions gives rise to L and H branches.
- $A_{H(L)}$ decreases linearly with z_c for both branches.
- Ambiguity in the operation: both branches can match the set amplitude A_{set} .

Experimental implications of the coexistence of states (I): Noise and stability

Sample: InAs quantum dots





A_1 low amplitude branch

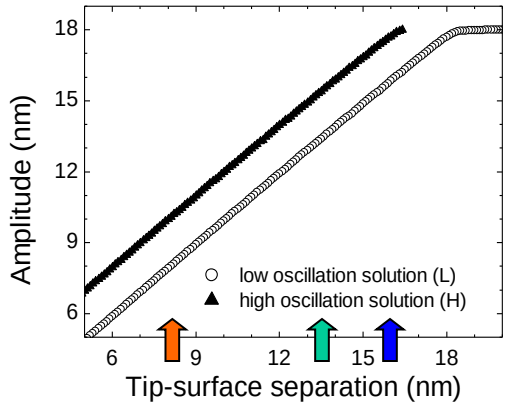
A_2

A_3 high amplitude branch

García, San Paulo,
PRB 61, R13381 (2000)

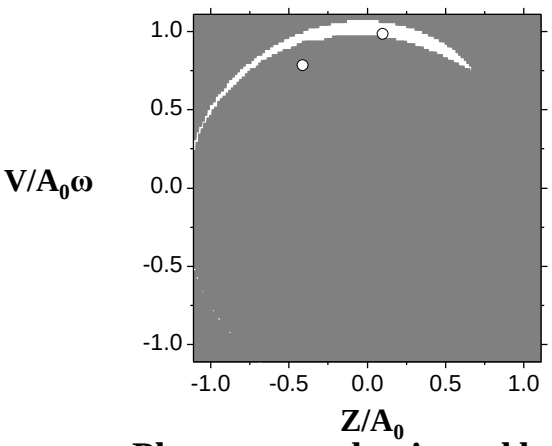
Are both solutions equally accessible ?

García and San Paulo, Phys. Rev. B 61, R13381 (2000)



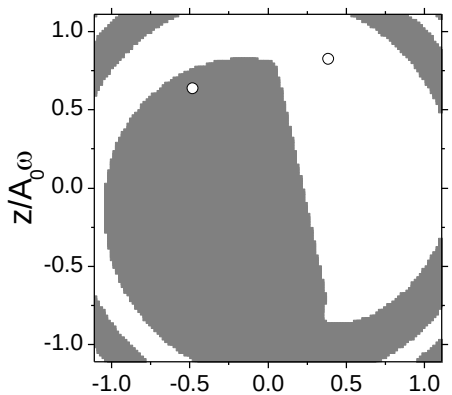
Phase space diagrams: Representation of the tip final state as a function of the initial velocity and positions

Z_c=16 nm



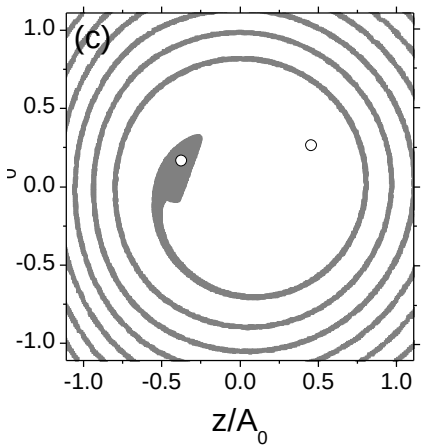
Phase space dominated by the L state=stable operation

Z_c=14.5 nm



Phase space diagram with significant H and L contributions=unstable operation

Z_c=7.5 nm

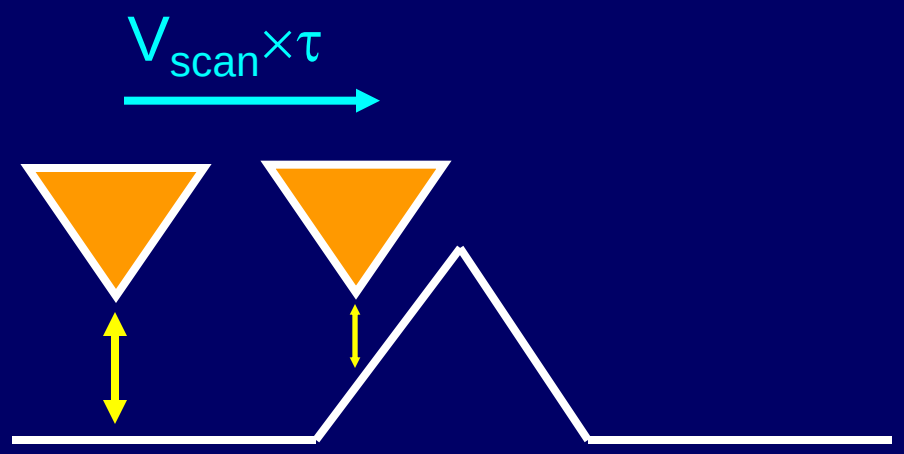


Phase space diagram dominated by the H state basin of attraction=stable operation

Tip should stay always on the same branch (deterministic) BUT…

NOISE: Implications for scanning

Mechanical, electronical,thermal and feedback perturbations...



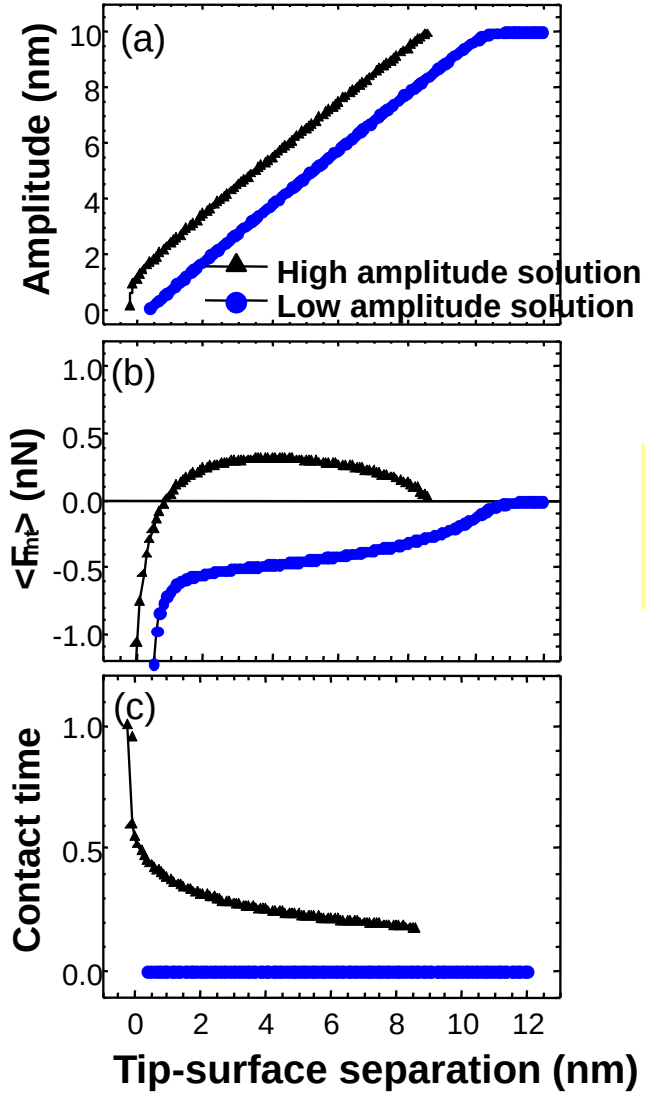
Finite time response of the feedback ($\tau \cong 10^{-4}$ s)

Change in separation can lead to transitions before the feedback takes over

- AM-AFM would operate properly if initial (unperturbed) and intermediate state belong to the same branch, otherwise instabilities and image artifacts will appear.
- Stable operation when one of the states dominates the phase space (tip oscillates in the state with the largest attraction basin).

Characterizing the physical properties of the two states....

H and L states have different properties

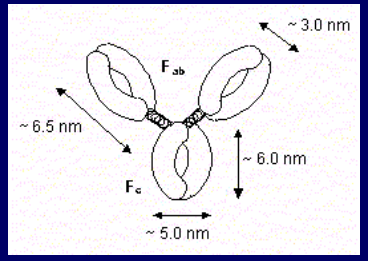


$$\langle F_{ts} \rangle = \frac{1}{T} \oint F_{ts}(t)dt$$

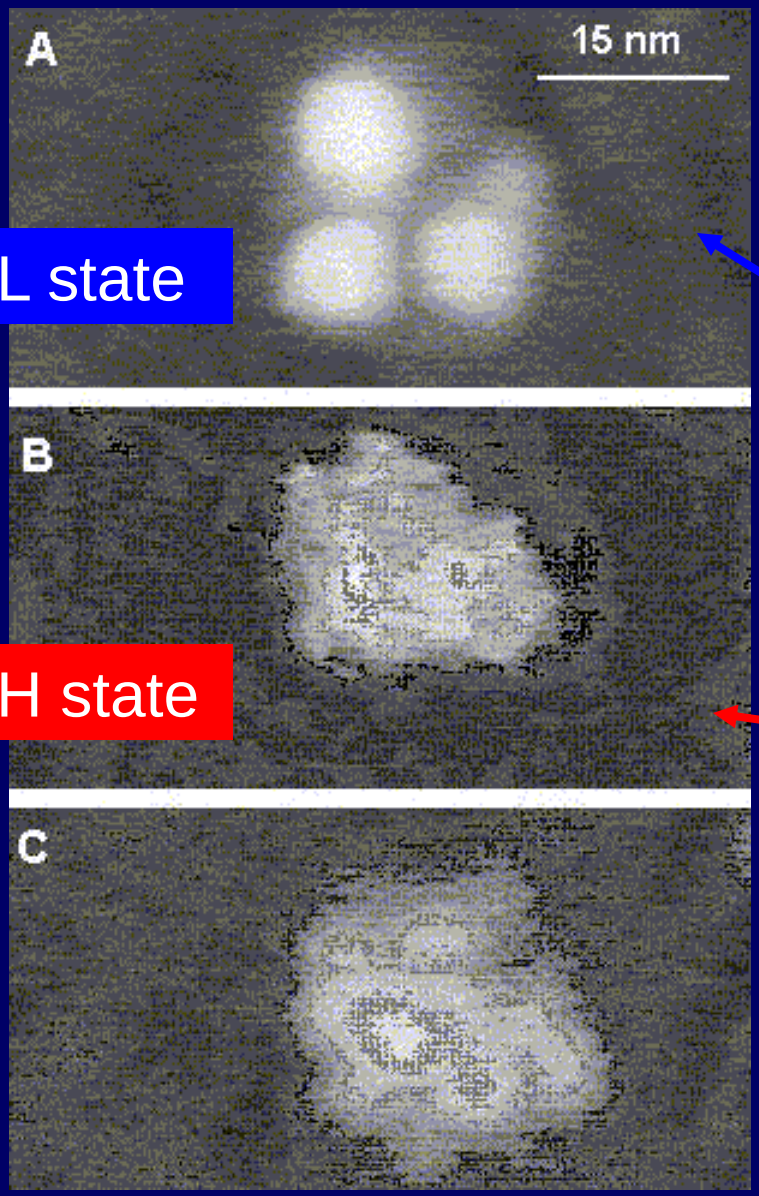
Simulation data: R=20 nm
f_0=350 kHz, Q=400, H=6.4x10^{-20},
E^*=1.52 GPa

García, Pérez, Surf. Sci. Rep. 47, 197 (2002)

Does resolution depend on the oscillation state chosen?



a-HSA antibody on mica



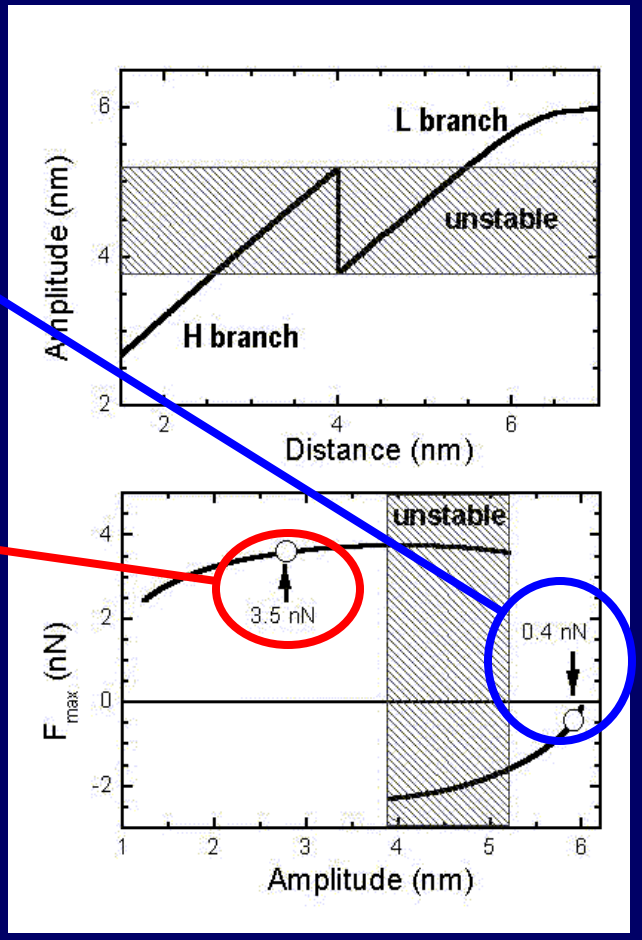
L state

H state

Morphology and dimensions of fragments clearly resolved

No domain structure

Irreversible deformation after imaging on H state



Analytical Approximations

(Understanding the amplitude reduction…: related to $\langle F_{ts} \rangle$??)

San Paulo and García, PRB 64, 193411 (2001)

The virial theorem and energy consideration allows to derive an analytical approximation

$\omega=\omega_0$ and $A>>z_0$

$$\cos\phi = \frac{2Q}{k_c A A_0}\left[\frac{<F_{ts}>^2}{k_c} - <F_{ts}\cdot z> + \frac{1}{2}k_c A^2\left(1-\frac{\omega^2}{\omega_0^2}\right)\right] \Rightarrow \cos\phi \approx -\frac{2Q<F_{ts}\cdot z>}{k_c A A_0}$$

$$\sin\phi = \frac{A\omega}{A_0\omega_0} + \frac{2QP_{ts}}{k_c A A_0 \omega}$$

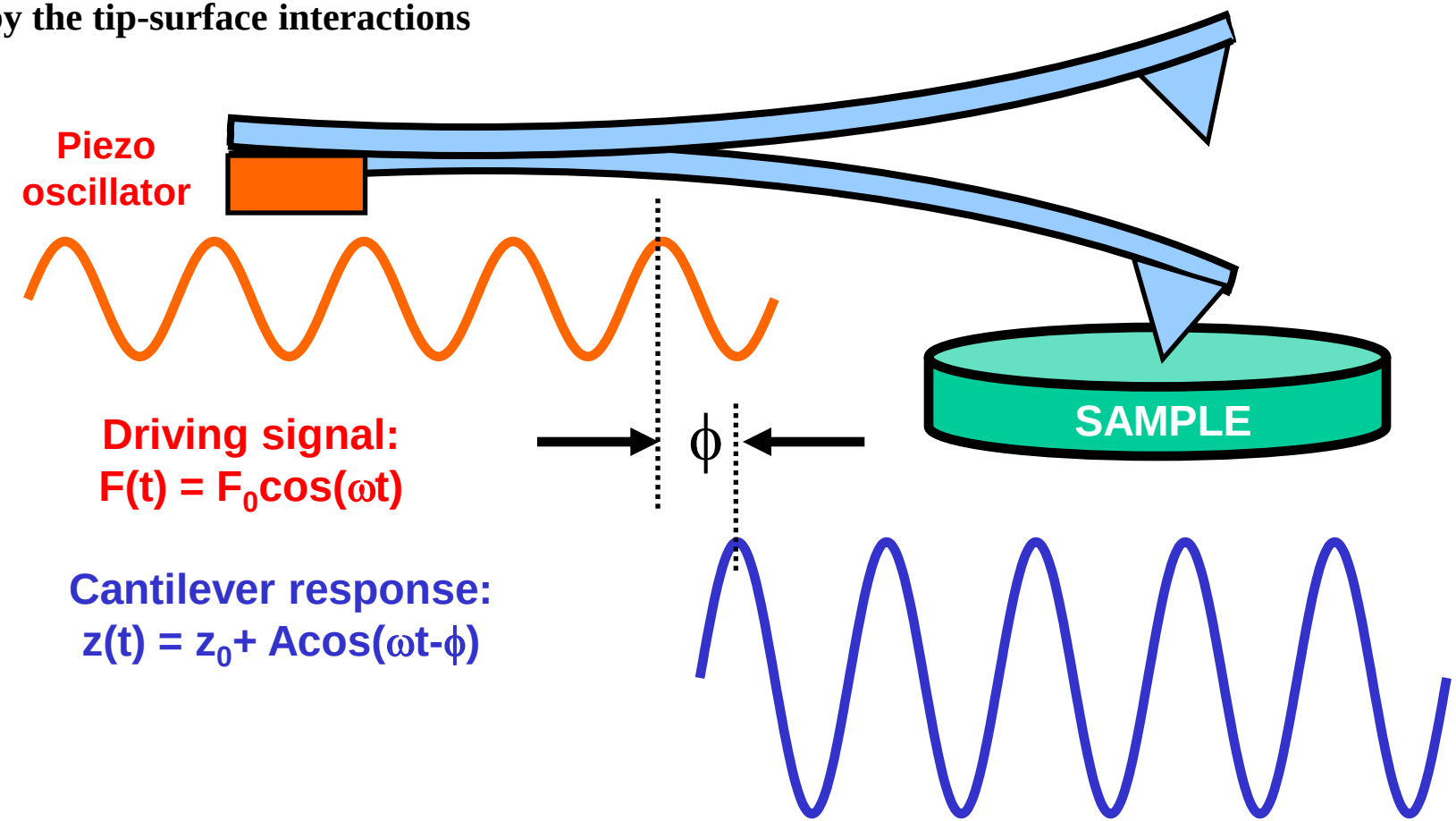
Negligible power dissipation

$$A \approx \frac{A_0}{\sqrt{2}}\left(1-\frac{2P_{ts}}{P_{med}} \pm \sqrt{1-\frac{4P_{ts}}{P_{med}} - 16\left(\frac{<F_{ts}\cdot z>}{F_0 A_0}\right)^2}\right)^{1/2} \Rightarrow A \approx \frac{A_0}{\sqrt{2}}\left(1 \pm \sqrt{1-16\left(\frac{<F_{ts}\cdot z>}{F_0 A_0}\right)^2}\right)^{1/2}$$

$$A \approx A_0\left(1-4\left(\frac{<F_{ts}>}{F_0}\right)^2\right)^{1/2}$$

Phase Imaging

The dynamic response of the cantilever is modified by the tip-surface interactions

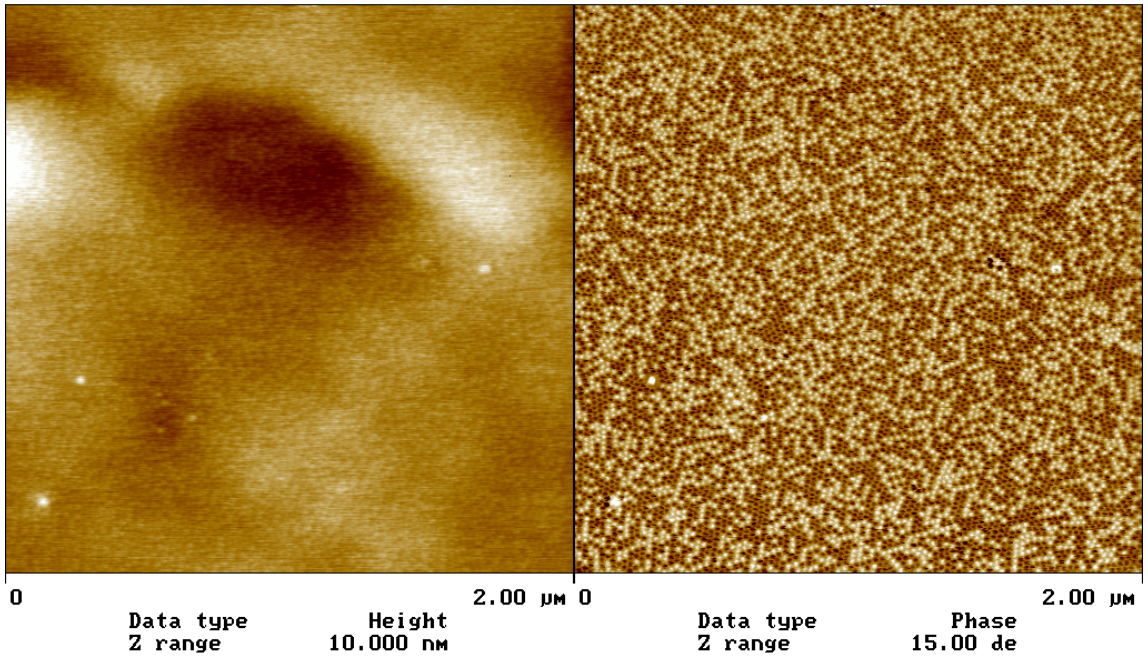


Driving signal:
$F(t) = F_0\cos(\omega t)$

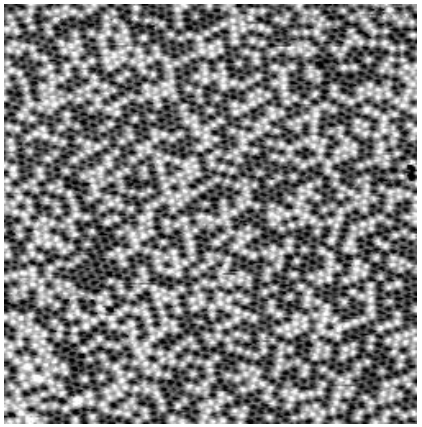
Cantilever response:
$z(t) = z_0 + A\cos(\omega t - \phi)$

Polymers: Morphology and Structure

Amplitude image Phase image



Polymer morphology and structure as a function of temperature. Hydrogenated diblock copolymer (PEO-PB). Crystallisation of PEO blocks occurs individually for each sphere (light are crystalline, dark amorphous**). Reiter et al., Phys. Rev. Lett. 87, 2261 (2001)**



Phase Image, size $1\mu m^2$

PHASE SHIFT AND ENERGY DISSIPATION IN AMPLITUDE MODULATION AFM

Steady solution

$$z(t) = A(\omega)\cos(\omega t - \phi)$$

Dynamic equilibrium in AM -AFM (tapping mode)

$$E_{EXT} = E_{med} + E_{dis}$$ **energy per period**

$$E_{EXT} = \oint F_0 \cos(\omega t)\frac{dz}{dt}dt = (1/Q)\pi k A_0 A(\omega)\cdot\sin\varphi$$

$$E_{med} = \oint\left(\frac{m\omega_0}{Q}\frac{dz}{dt}\right)\frac{dz}{dt}dt = \frac{\pi k\omega A^2(\omega)}{Q\omega_0}$$

$$E_{dis} = \oint(F_{TS})\frac{dz}{dt}dt$$

$$\sin\phi = \frac{\omega}{\omega_0}\frac{A_{sp}}{A_0} + \frac{QE_{dis}}{\pi k A_0 A_{sp}}$$

Cleveland et al. APL 72, 2613(1998)

Tamayo, García APL73, 2926 (1998)

García et al. Surf. Int. Anal. 27, 1999)

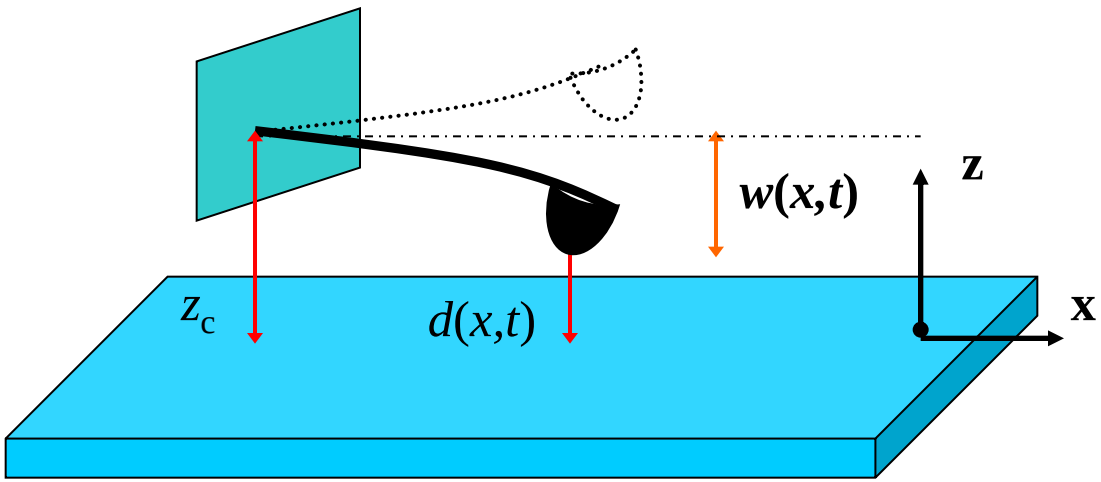
At A_{sp}=constant phase shifts are linked to tip-surface inelastic interactions

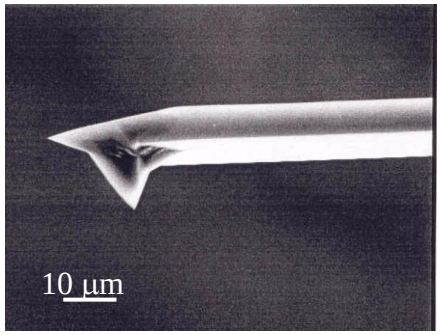
CONTRIBUTIONS TO CONTRAST IN PHASE IMAGES

PHASE CONTRAST

- **ELASTIC CONTRIBUTIONS**
  - **TOPOGRAPHIC EFFECTS**
  - **TAPPING ↔ NON CONTACT TRANSITIONS**
  - **YOUNG MODULUS**
    (In presence of dissipative channels)
- **INELASTIC CONTRIBUTIONS**
  - **VISCOELASTICITY**
  - **ADHESION HYSTERESIS**
  - **CAPILLARY FORCES**
  - **HIDROPHILIC/HIDROPHOBIC INTERACTIONS**

Continuous Model for the Cantilever

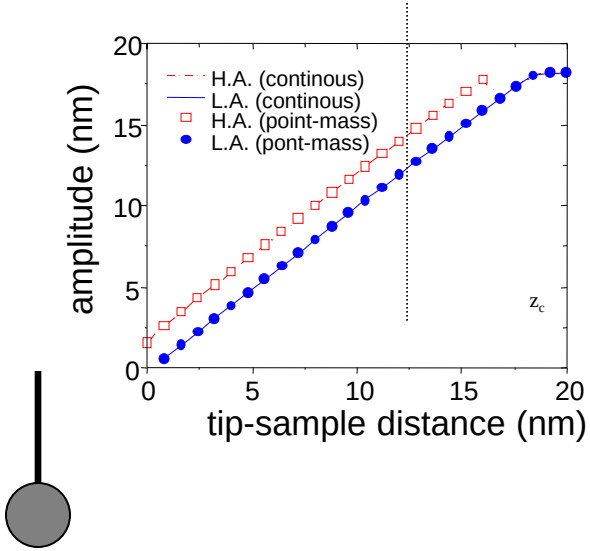


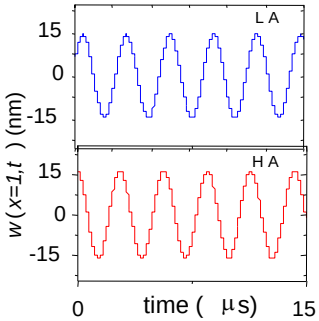


$$\frac{EI}{L^4}\frac{\partial^4}{\partial x^4}\left[w(x,t)\right] + bh\rho\frac{\partial^2 w(x,t)}{\partial t^2} = F_{ext} + F_{med} + F_{ts}$$

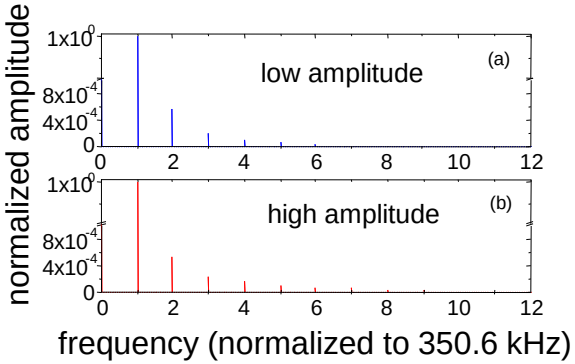
$$w(x,t)\Big|_{x=0} = \frac{\partial w(x,t)}{\partial x}\Big|_{x=0} = \frac{\partial^2 w(x,t)}{\partial x^2}\Big|_{x=1} = \frac{\partial^3 w(x,t)}{\partial x^3}\Big|_{x=1} = 0$$

Rodríguez and García, Appl. Phys. Lett. 80, 1646 (2002)

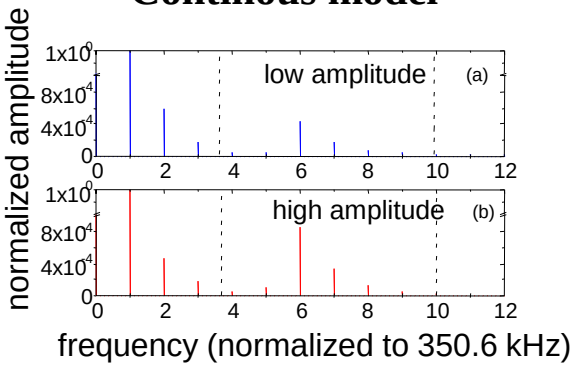




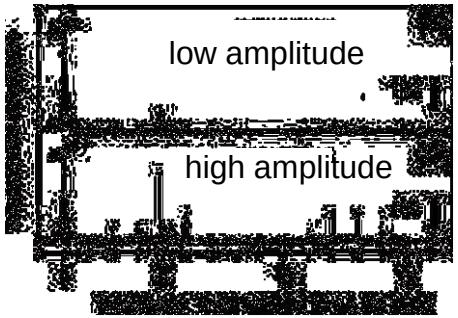
Point -mass model



Continous model



Experimental results
(Triangular cantilever)

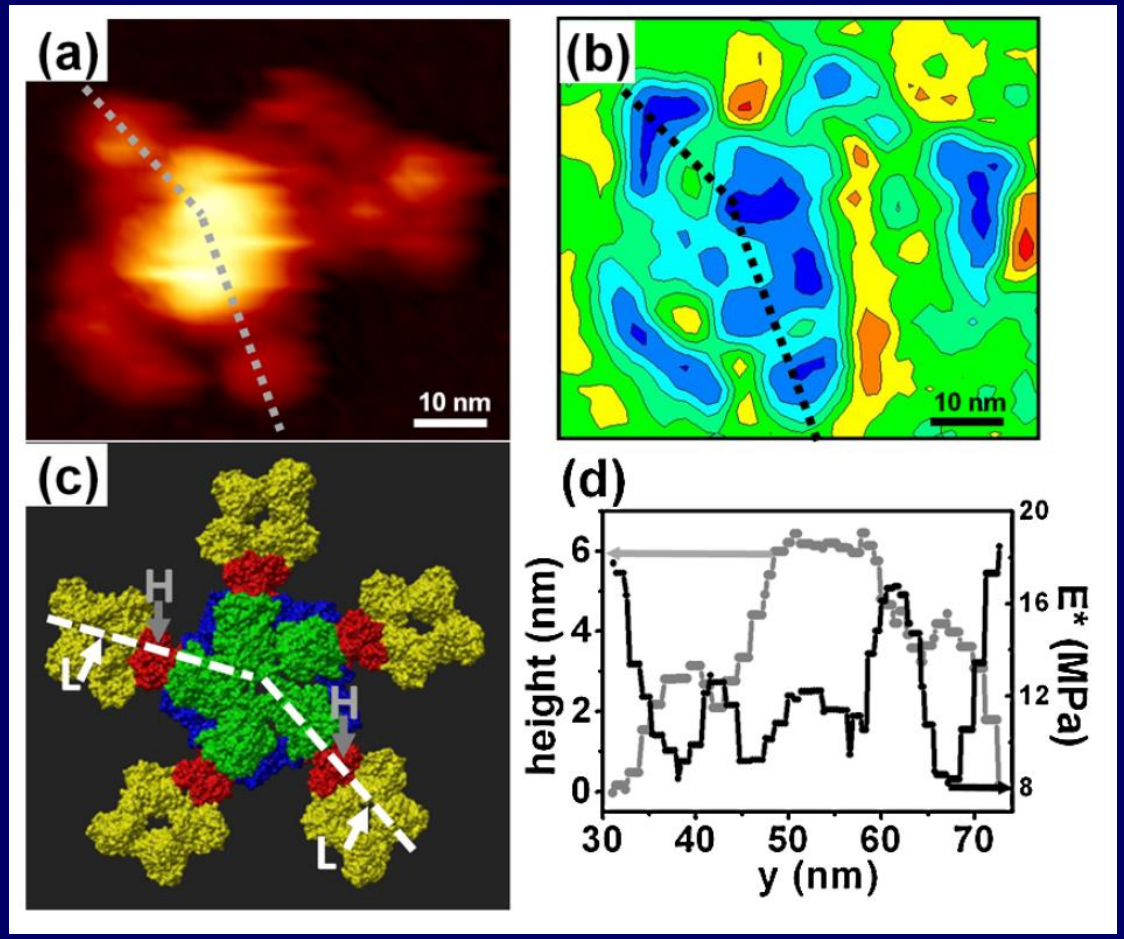


Stark et al. APL 77, 3293 (2000)

Parámetros de la simulación:
f_0= 350.6 kHz k= 40 N/m, A_0= 18.22 nm Q= 400 (masa puntual, ajusta el primer modo libre).
l=119 μm, h=3.6 μm, b=33 μm, E=170 Gpa, r_c =2320 kg/m^3, F=1.85 nN, a_0=1.28·10^{-3} kg/m·s,
a_1=0.2 ns, a_2=10.037 (modelo continuo que ajusta la curva A vs. f experimental libre)
R=30 nm, H= 6.4·10^{-20} J, E^*=1.51 Gpa, d_0= 0.165 nm

Bimodal FM-AFM on Antibodies(IgM)

Noninvasive Protein Structural Flexibility Mapping



D. Martinez et al, PRL106, 198101(2011)

AM-AFM: Things to remember...

- Operation Parameters (OP): A_{exc}, ω_{exc}, $z_{c.}$& A_{set}
- Two stable oscillation states: L (H) = low (large) amplitude.
- Chose OP to ensure that one state dominates phase space $\Rightarrow$ stable imaging.
- Image soft materials with L state (avoid damage).
- Image stiff materials with H state (improved contrast).
- Amplitude reduction related to $\langle F_{ts} \cdot z \rangle$.
- Imaging material properties: Phase imaging.
- Phase shift related to $\langle P_{ts}^{diss} \rangle = \langle F_{ts} \cdot dz/dt \rangle$.
- Nanometric resolution (both amplitude and phase images).

Frequency Modulation (FM) AFM

Outline: FM-AFM

- Dynamic AFM: AM-AFM vs FM-AFM.
- Cantilever dynamics: Δf vs F_{ts}.

  Perturbation theory for the frequency shifts
  Normalized frequency shift

- Atomic scale contrast and F_{ts}: tip as the key player.
  - Separation of long- and short-range interactions.
  - semiconductors, alkali halides, oxides, metals, nanotubes,…
- Recent developments.

  Tuning forks: small amplitudes to enhance atomic contrast

  Force spectroscopy: Chemical identification.

  Single-atom manipulation, atomic-scale magnetic imaging

  Operation in liquids

- Summary: things to remember...

1. Dynamic AFM:
AM-AFM vs FM-AFM.

Two major modes: AM-AFM and FM-AFM

Amplitude Modulation AFM

- Excitation with constant amplitude A_{exc} and frequency ω_{exc} close or at its FREE resonance frequency ω_0.
- Oscillation amplitude A as feedback for topography.
- Phase shift ϕ between excitation and oscillation: compositional contrast.
- Air and liquid environments.

Y. Martin et al, JAP 61, 4723 (1987)

Q. Zhong et al, SS 290, L688 (1993)

Frequency Modulation AFM

- Constant oscillation amplitude at the current resonance frequency (depends on F_{ts}).
- Frequency shift Δf as feedback for topography.
- Excitation amplitude A_{exc} provides atomic-scale information on dissipation.
- UHV (now also liquids !)

T.R. Albrecht et al, JAP 69, 668 (1987)

F.J. Giessibl, Science 267, 68 (1995)

Why not AM-AFM in UHV?: transient terms!!

$$\delta(\Delta f) = \delta(f - f_0) = \sqrt{\frac{f_0 k_B T B}{4\pi k Q \langle z_{osc}^2 \rangle}}$$

Increase Q to improve resolution
BUT... Q and B (bandwidth) linked in AM-AFM

$$z(t) = C\exp(-\gamma t)\cos(\omega_\gamma t + \delta) +$$

(transient)

$$+ \frac{\omega_0^2 A_{exc}}{\sqrt{\left(\omega_0^2 - \omega_{exc}^2\right)^2 + \left(\omega_0 \omega_{exc} / Q\right)^2}} \cos(\omega_{exc} t - \phi)$$

$$\tau = \frac{1}{\gamma} = \frac{2Q}{\omega_0}$$

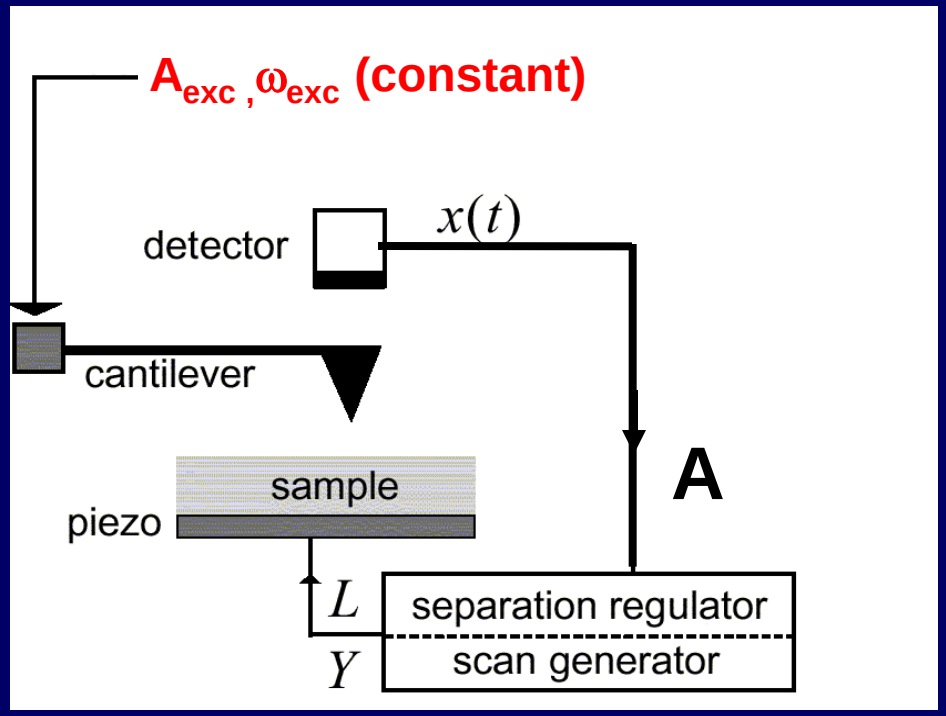
Q (air) = 10^2 –10^3 $\Rightarrow$ τ small

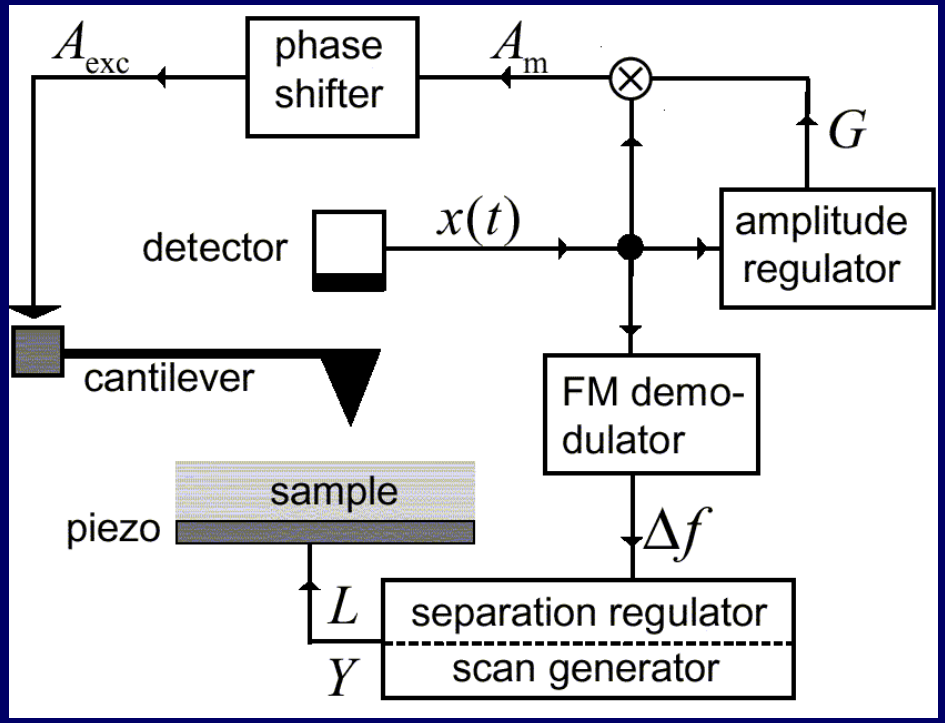
Q (UHV) = 10^4 –10^5 $\Rightarrow$ τ large

(Q=50000, ω_0=50 kHz $\Rightarrow$ τ = 2 s !!!)

We have to wait 2 s to record a single pixel... (small bandwidth)

AM-AFM vs FM-AFM set-ups





FM-AFM: cantilever regulated by electronics $\Rightarrow$ stable and fast response.

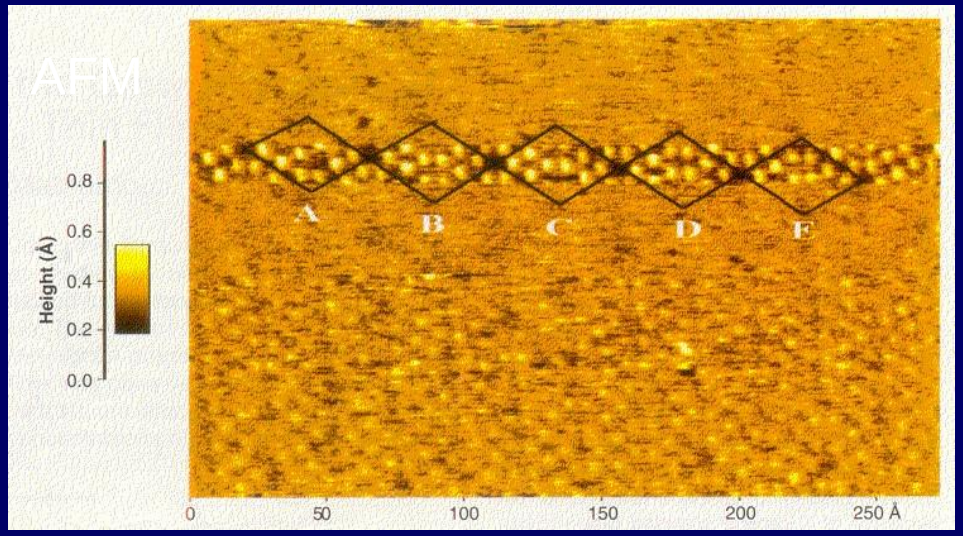
$$\tau_{FM} \approx \frac{1}{\omega_0}$$

Mechanical Stability Conditions

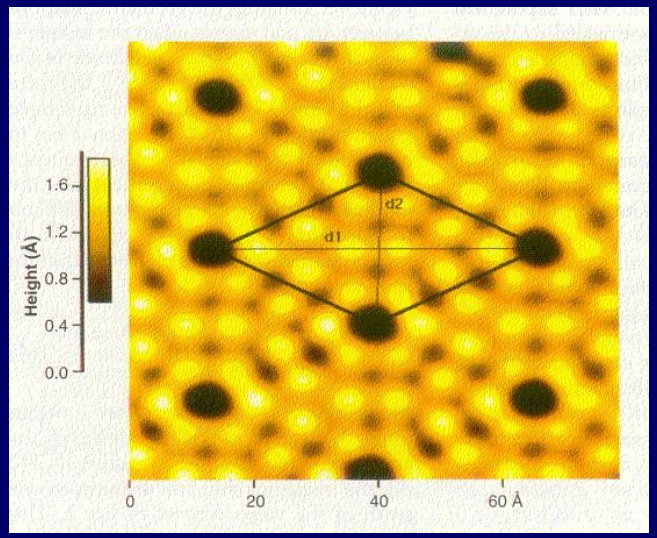
$$\max\left|\frac{d^2 V_{ts}}{dz^2}\right| = k_{ts}^{max} < k$$

$$\max\left|-\frac{dV_{ts}}{dz}\right| = |F_{ts}^{max}| < kA_0$$

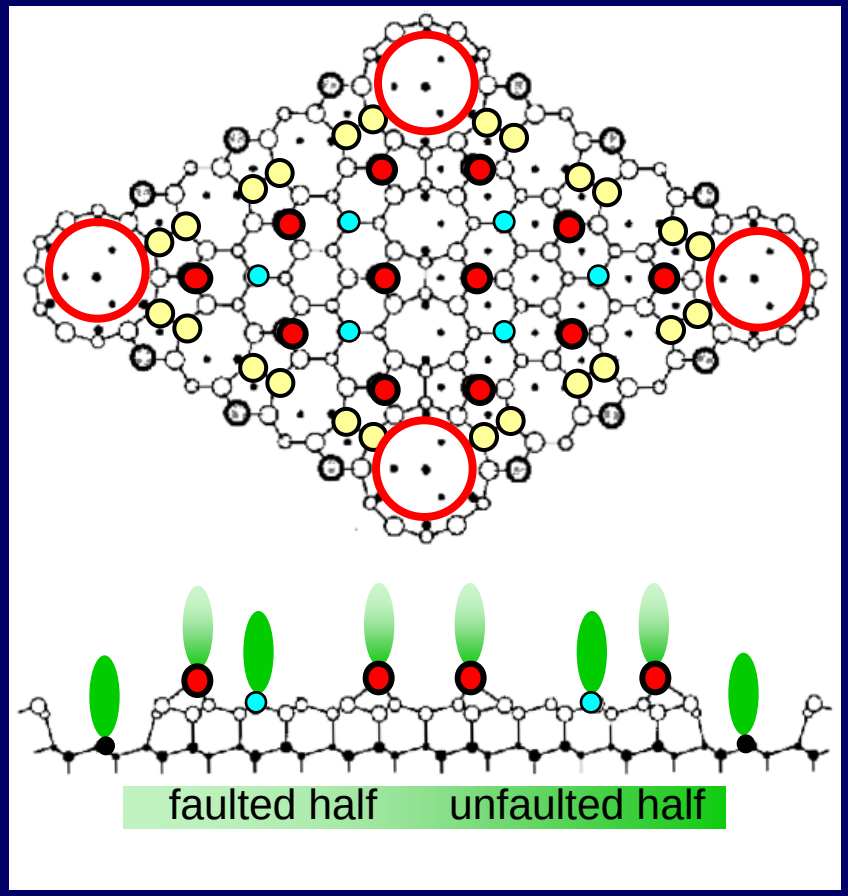
Atomic resolution in FM-AFM:Si(111)-7x7



STM



F.J. Giessibl, Science 267, 68 (1995)



12 adatoms

6 rest atoms

corner hole

dimers

“Classical” FM-AFM operation conditions

Stability Conditions

$$\max\left|\frac{d^2V_{ts}}{dz^2}\right| = k_{ts}^{max} < k$$

$$\max\left|-\frac{dV_{ts}}{dz}\right| = |F_{ts}^{max}| < kA_0$$

k ~ 30 N/m

f_0 ~ 100 kHz

Q ~ 30000

A_0 ~ 200 Å

Δf ~ -(50-100) Hz

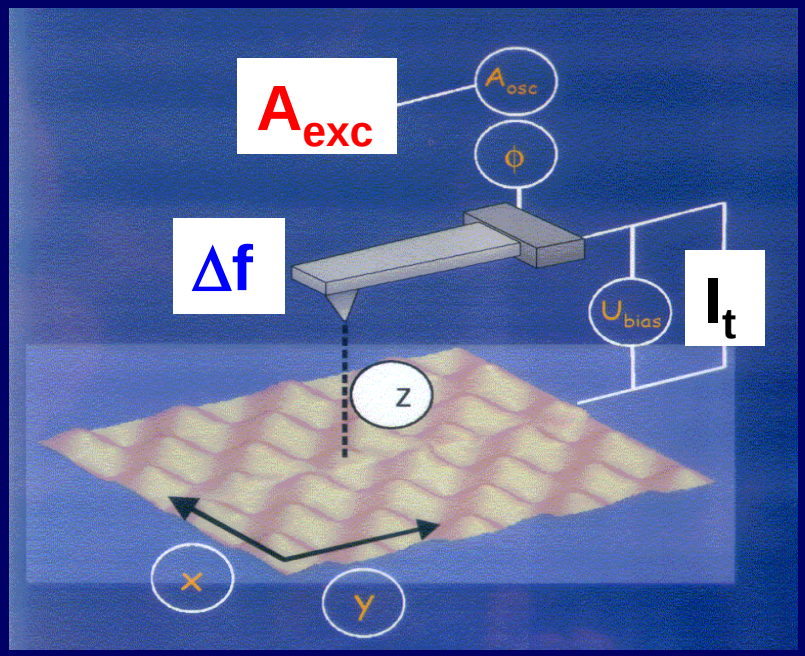
kA_0 ~ 600 nN >> F_{ts} ~ 1-10 nN

(prevents cantilever instabilities)

$1/2kA_0^2$ ~ 3.75 x 10^4 eV >> ΔE_{ts}

(stable oscillation amplitudes)

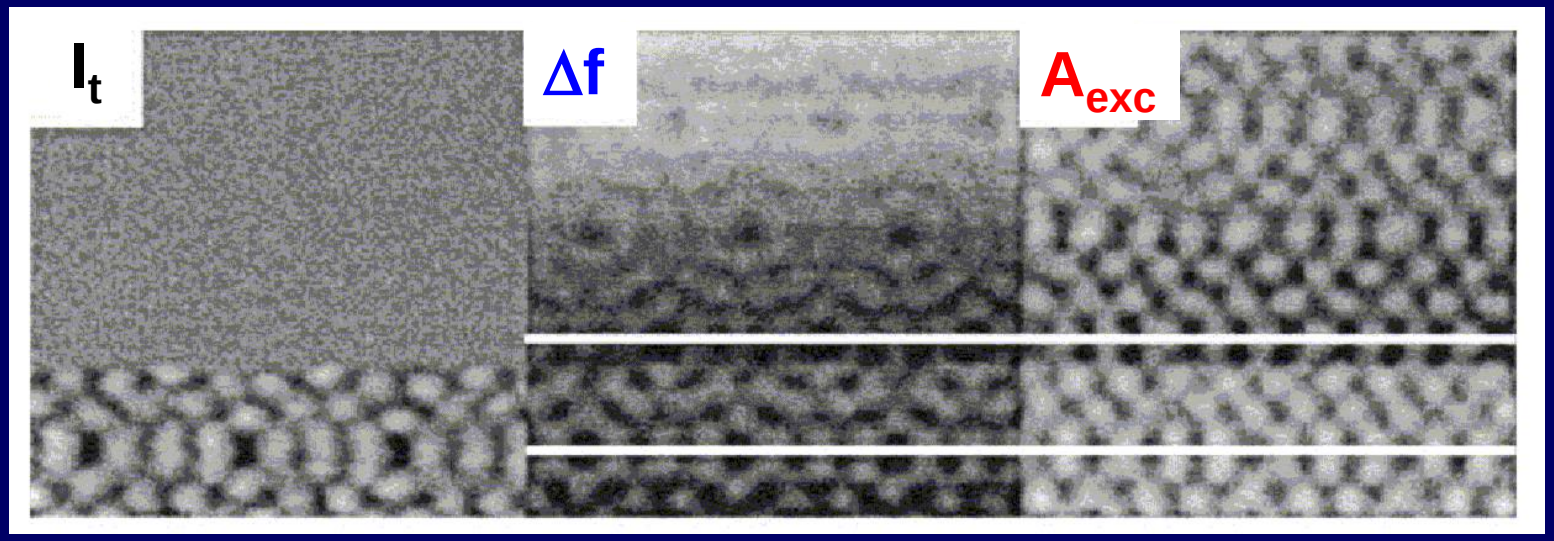
FM-AFM: Contrast sources



Δf: frequency shift

A_{exc}: damping (excitation)

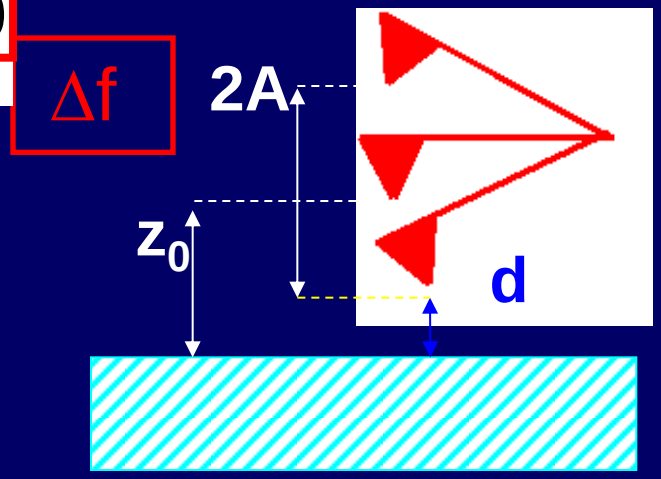
I_t: mean tunneling current



2. Cantilever dynamics : relation between the frequency shift and tip-sample interaction.

Contrast source: frequency shift vs F_{ts}

$$m\ddot{z}(t)+\boxed{\frac{m\omega_0}{Q}\dot{z}(t)}+kz(t)-F_{ts}[z_o+z(t)]=\boxed{kA_{exc}(t)}$$



Electronics cancels damping exactly

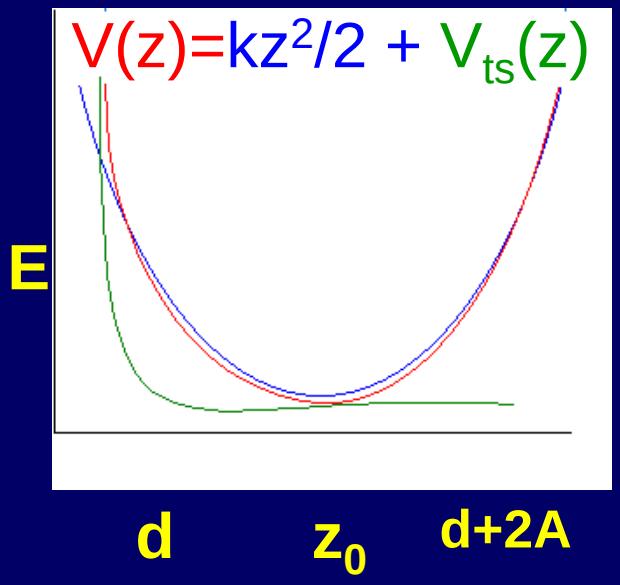
$$m\ddot{z}(t)+kz(t)-F_{ts}[z_o+z(t)]=0$$

Perturbation theory

F.J. Giessibl, PRB 58, 10835 (1998)

$$\Delta f\,(d,k,A_0,f_0)=-\frac{f_0}{kA_0^2}\langle F_{ts}z\rangle=$$

$$=-\frac{1}{2\pi}\frac{f_0}{kA_0}\int_0^{2\pi}F_{ts}[d+A_o(1+\cos\varphi)]\cos\varphi\,d\varphi$$



Confirmed by numerical simulations including the control electronics

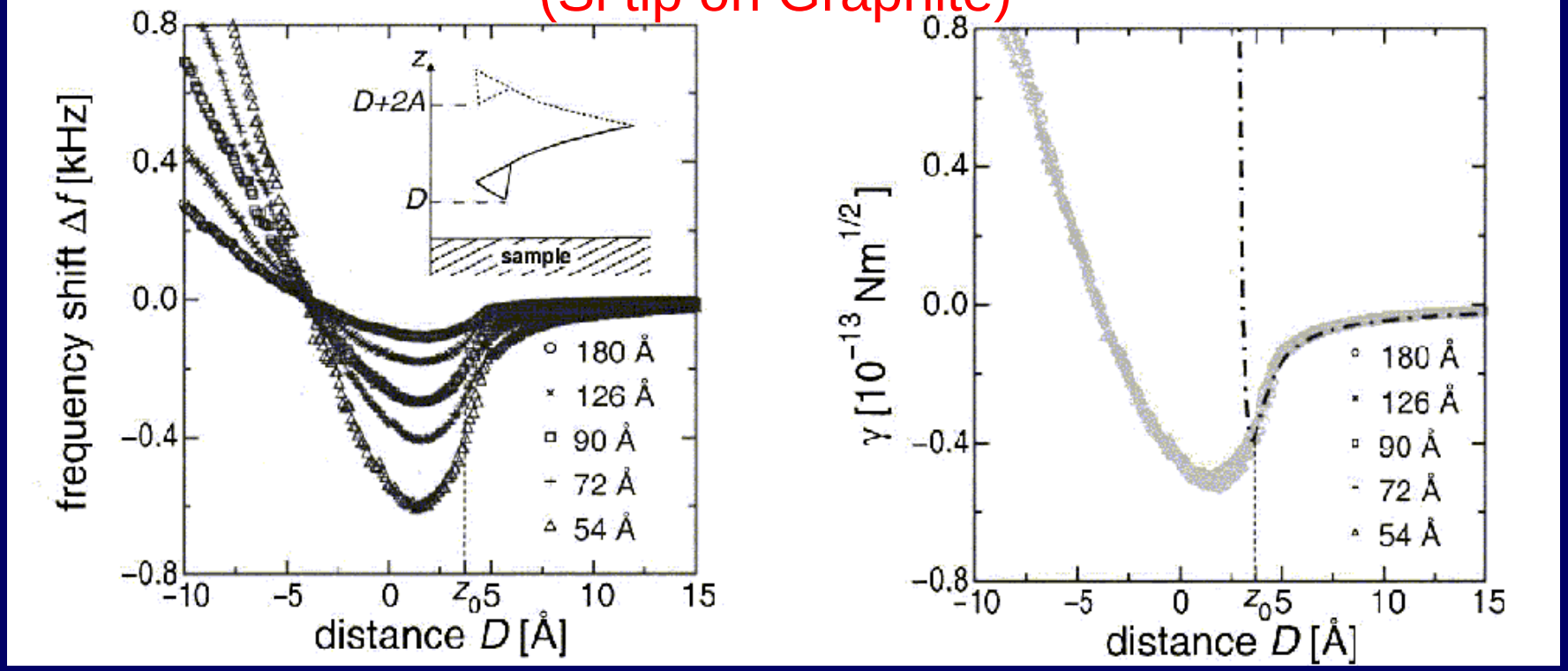
M. Gauthier, R.P., T. Arai, M. Tomitori & M. Tsukada, PRL 87, 096801 (2001)

Normalized frequency shift γ

$$\gamma(d) = \frac{kA_0^{3/2}}{f_0}\Delta f(d, k, A_{0,} f_0)$$

γ extracts the intrinsic contribution coming from F_{ts}

(Si tip on Graphite)



$$\gamma(d) \cong \frac{1}{\sqrt{2\pi}} F_{ts}(d)\sqrt{\frac{V_{ts}(d)}{F_{ts}(d)}}$$

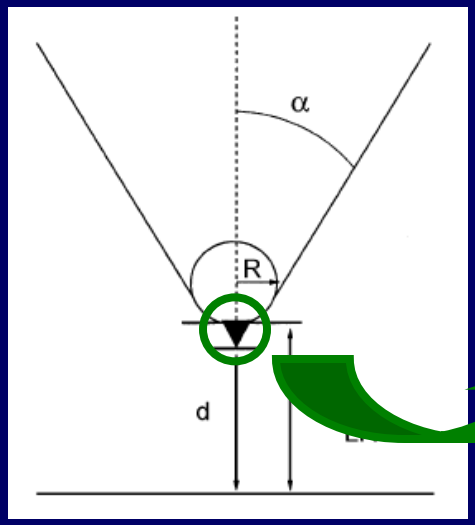
Not accurate for small tip-sample distances (2-3 Å) !!

3. Atomic-scale contrast and tip-sample interaction: tip as the key player

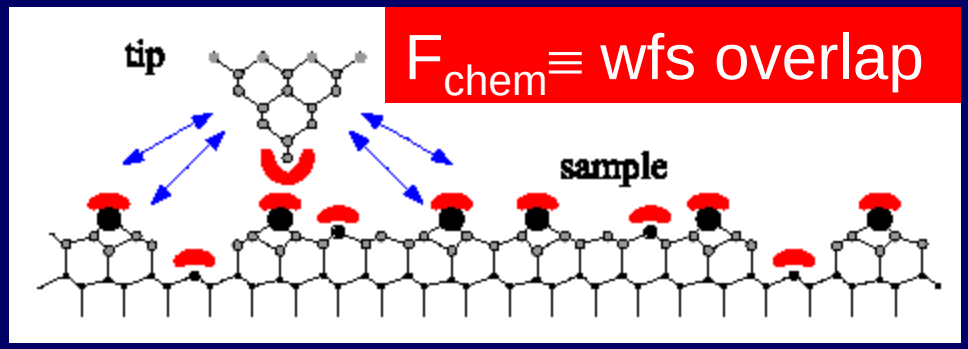
- Separation of LR and SR interactions
- Semiconductors
- Alkali halides & oxides
- Metals, weakly bonded systems & carbon-based materials (graphite, nanotubes, …)

Tip-sample Interaction: $F_V + F_{vdW} + F_{chem}$

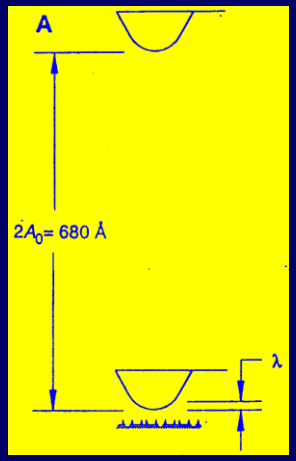
$$F_V = -\pi\epsilon_0 (V_s - V_c)^2 \left\{ \frac{R}{d_{LR}} + s(\alpha)\left[\ln\left(\frac{L}{d_{LR}+R_\alpha}\right) - 1\right] - \frac{R[1 - s(\alpha)\cos^2\alpha/\sin\alpha]}{d_{LR}+R_\alpha} \right\}$$

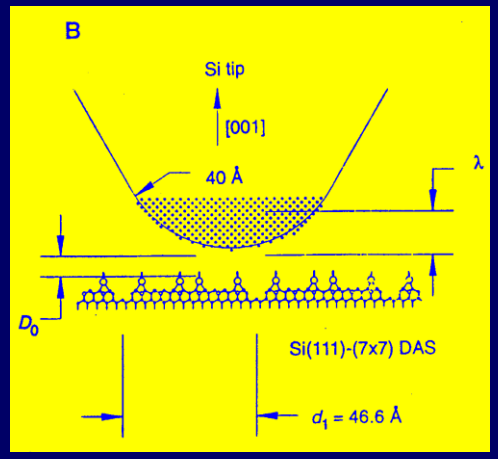


$$F_{vdW} = -\frac{H}{6}\left\{ \frac{R}{d_{LR}^2} + \frac{\tan^2\alpha}{d_{LR}+R_\alpha} - \frac{R_\alpha}{d_{LR}(d_{LR}+R_\alpha)} \right\}$$



$F_{chem} \equiv$ wfs overlap





Exp: A = 340 Å !!!, R = 40 Å

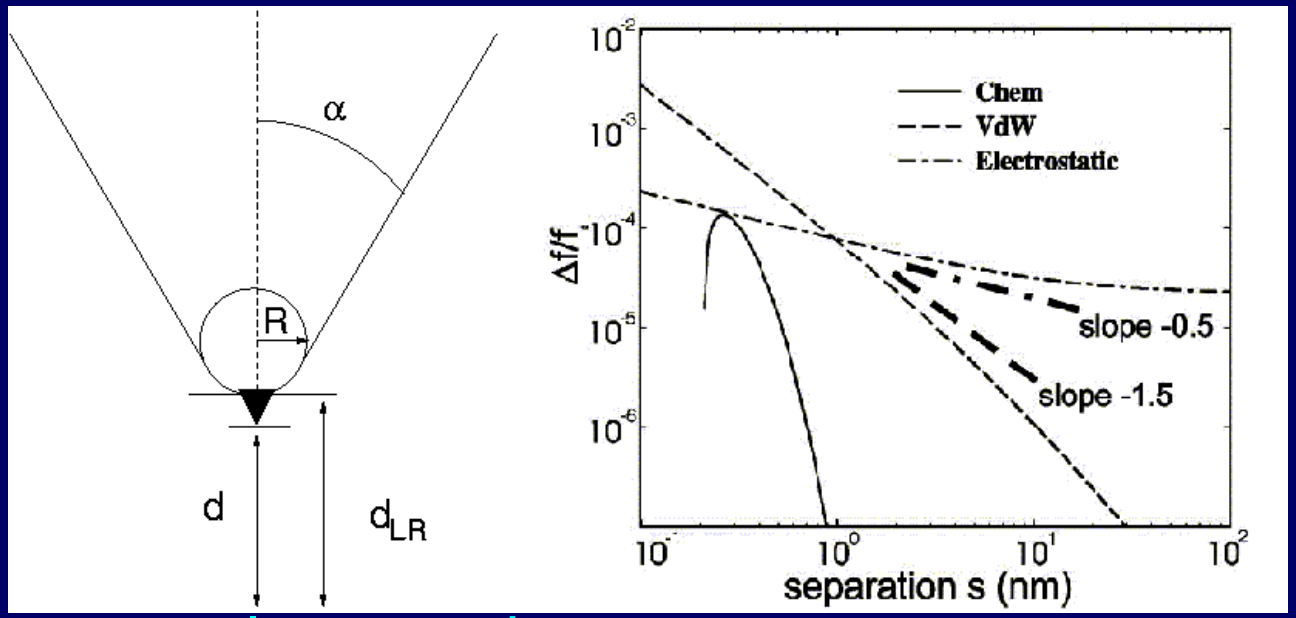
Sensitivity to Short-Range Forces?

$$\Delta f(d) = \frac{f_0}{\pi k a_1}\int_{-1}^{1} F_{ts}[d + a_1(1+u)]u\frac{du}{\sqrt{1-u^2}}$$

$$u = \cos(\omega t)$$

Weak singularity at turning points !!!!

Characterizing the "macroscopic" tip: Separation of interactions

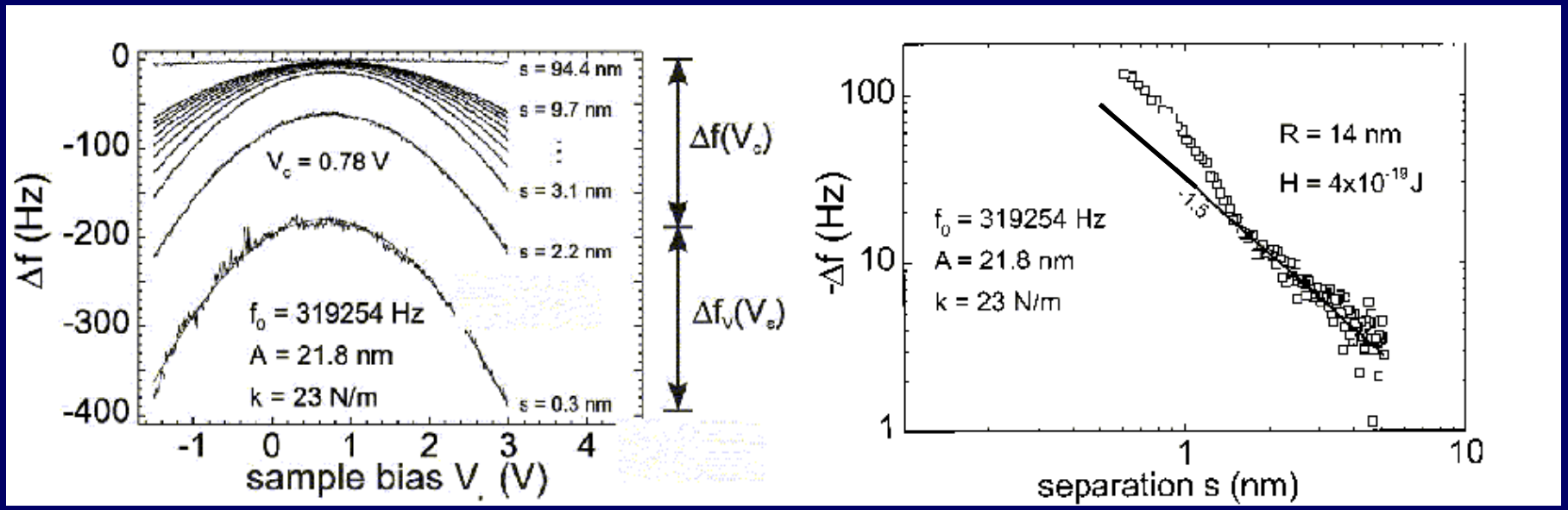


Si tip on Cu(111)

M. Guggisberg et al, PRB 61 (2000) 11151

Electrostatic

VdW

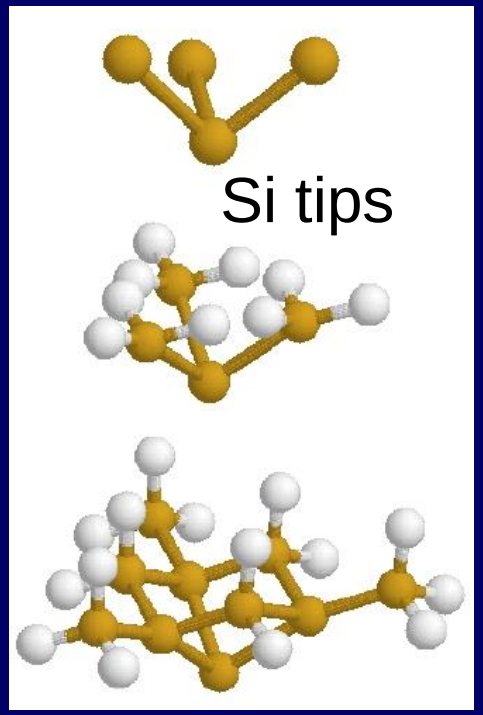


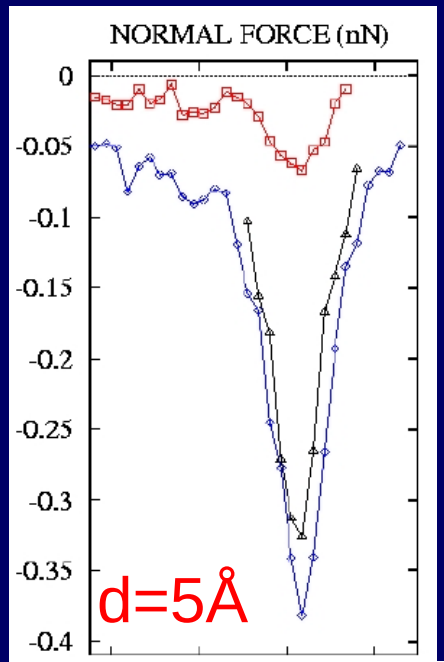
Computational approaches for SR F_{ts}

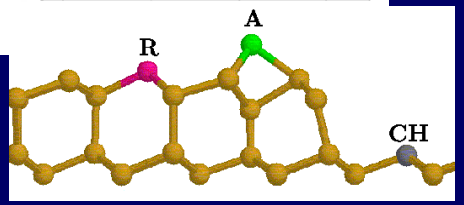
Empirical potentials	OK for ionic bonding Weakly bonded systems??	
Interatomic potentials + some quantum mechanics	about 1,000 atoms dynamics reliable if carefully calibrated	10 x
Simplified and semi-empirical quantum mechanics	about 1,000 atoms simulated annealing, short dynamics many features of first-principles, but faster	100 x
Ab initio quantum mechanics	Necessary for covalent and metallic bonding (semiconductors and metals.)	

Role of SR Covalent Bonding Interactions?

DFT-GGA plane wave pseudopotential calculations

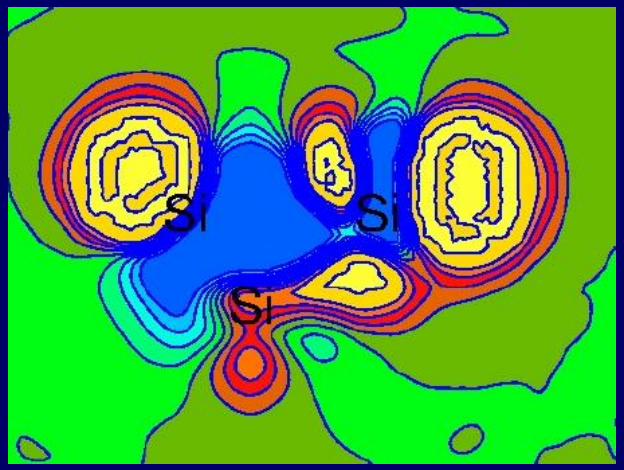




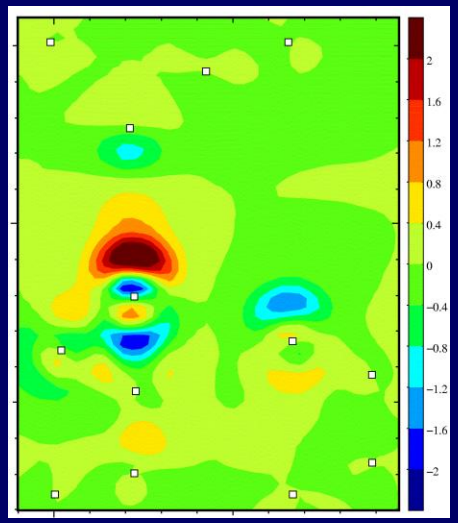


R. P. et al, PRL **78,** 678 (1997)

R. P. et al, PRB **58,** 10 835 (1998)



Charge density difference between tips

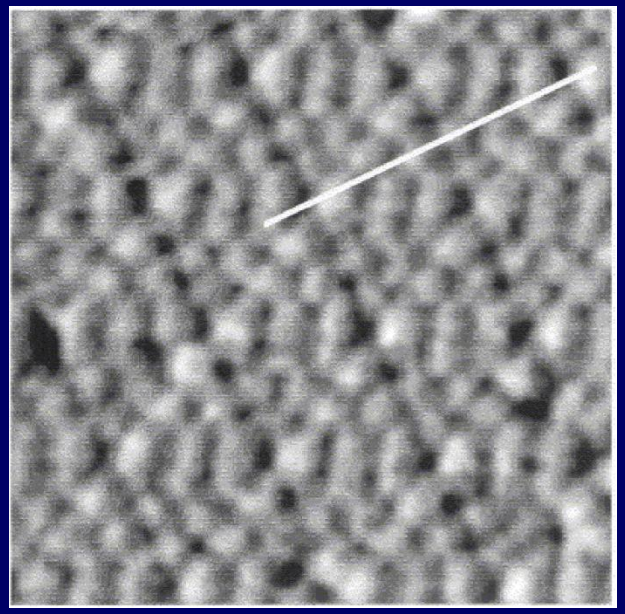


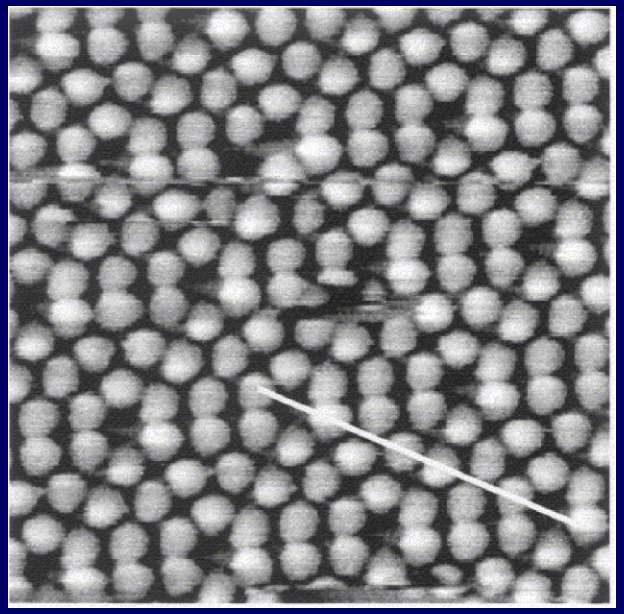
$\rho_{tip+surface} - (\rho_{tip} + \rho_{surface})$

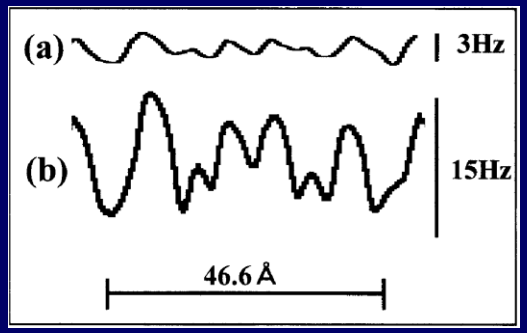
Charge acumulates in the adatom dangling bond

Atomic scale contrast in reactive semiconductor surfaces: chemical tip-surface interaction (between dangling bonds)

Contrast dependence on tip preparation





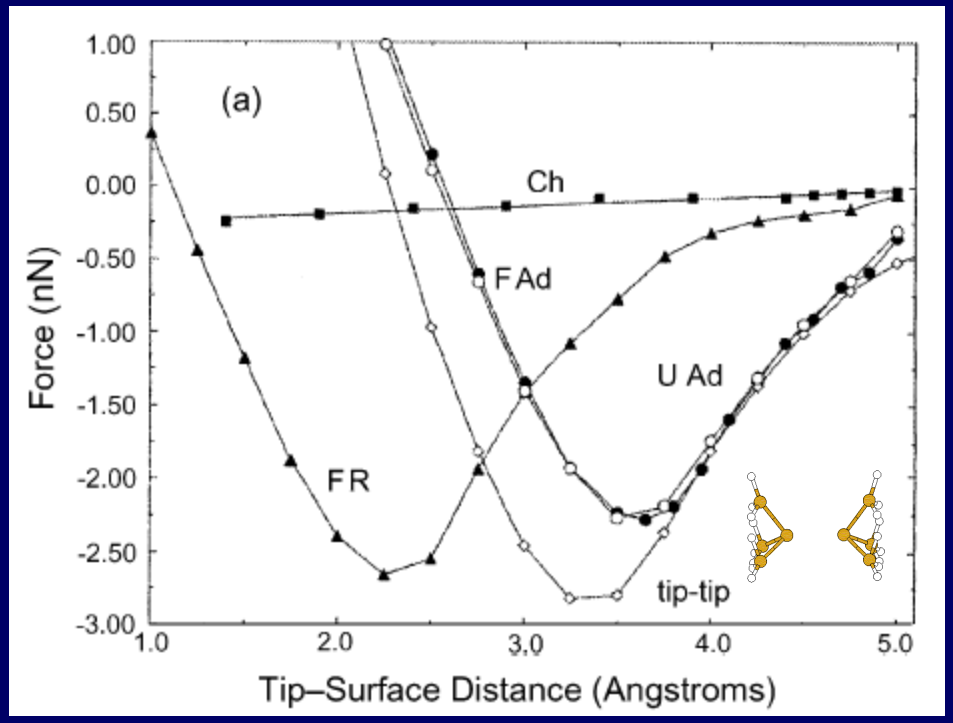


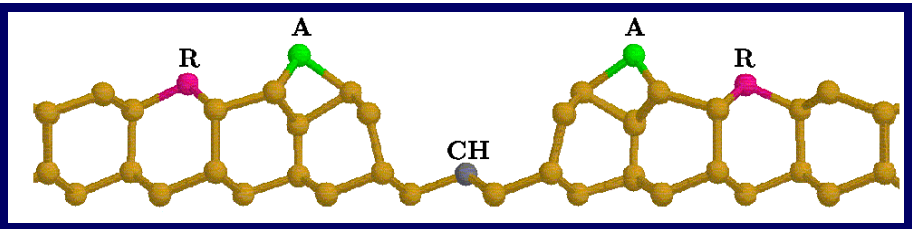
T. Uchihashi et al, PRB 56, 9834 (1997)

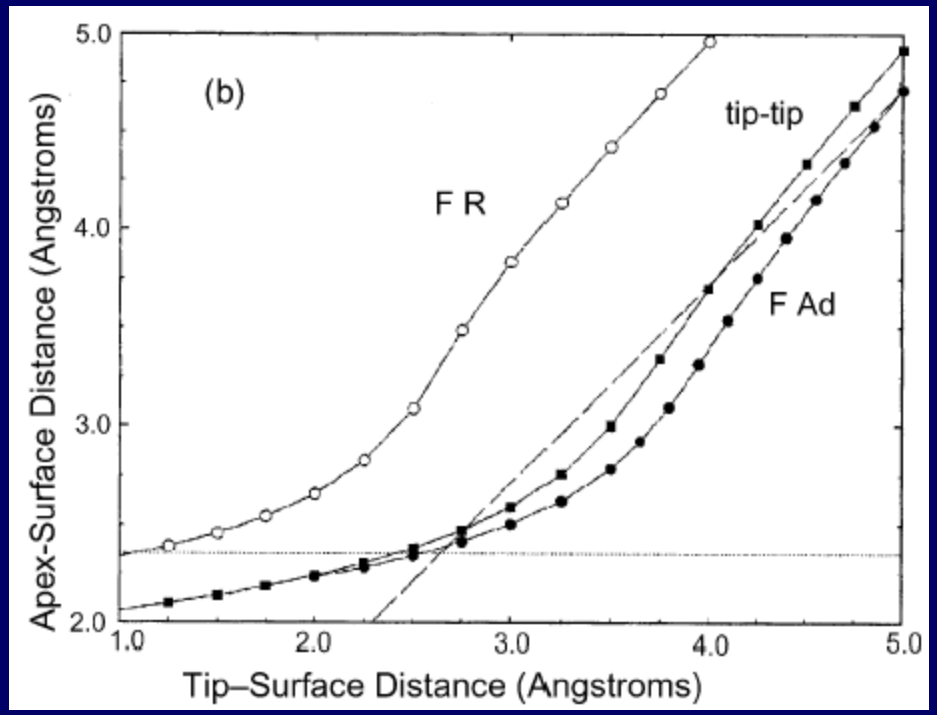
Force-distance curves & Atomic relaxations

R. P. et al, PRB 58, 10835 (1998)

atomic relaxations due to tip-surface interactions!!



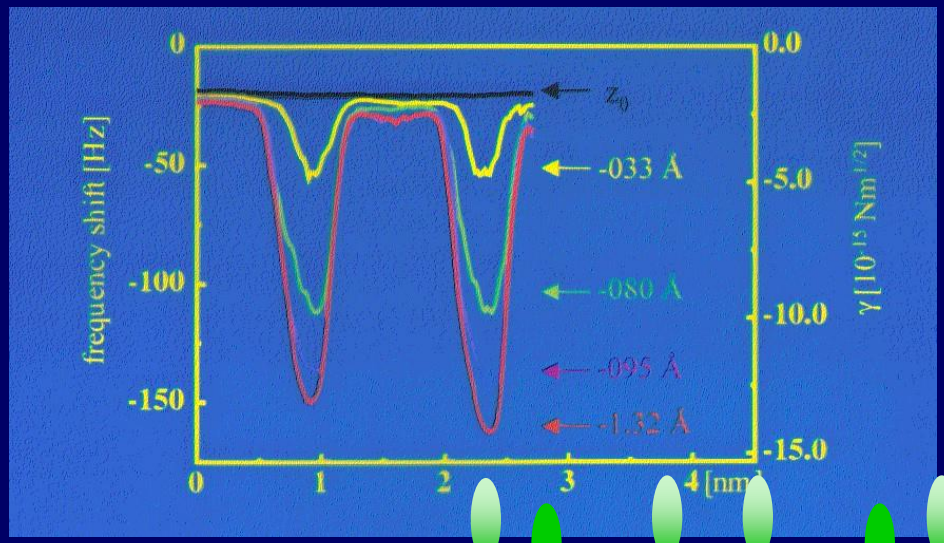


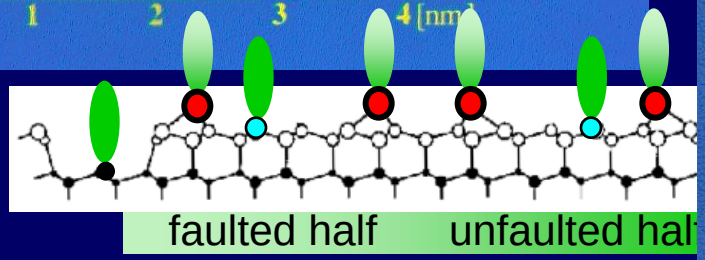


Force vs distance curves → prediction for Δf vs distance

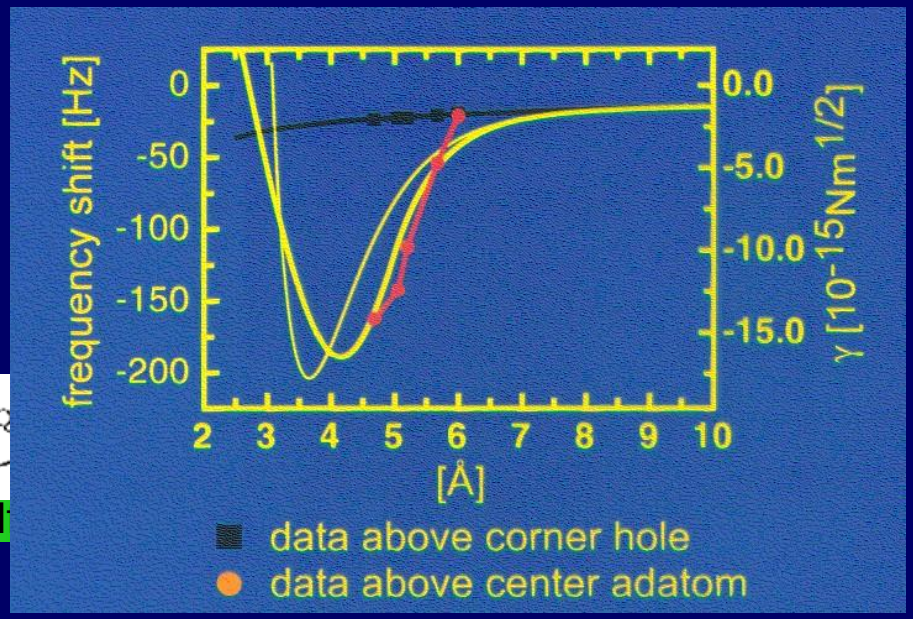
$$\Delta f\,(d) = -\frac{1}{2\pi}\frac{f_0}{kA_0}\int_0^{2\pi} F_{ts}\left[d + A_o(1+\cos\varphi)\right]\cos\varphi\, d\varphi$$

Comparison between theory and low-temperature FM-AFM experiments





M. Lantz et al, PRL 84, 2642 (2000)
M. Lantz et al, Science 291, 2580 (2001)



Separation of VdW and chemical interaction: substracting the corner hole contribution.

Tip-surface interactions

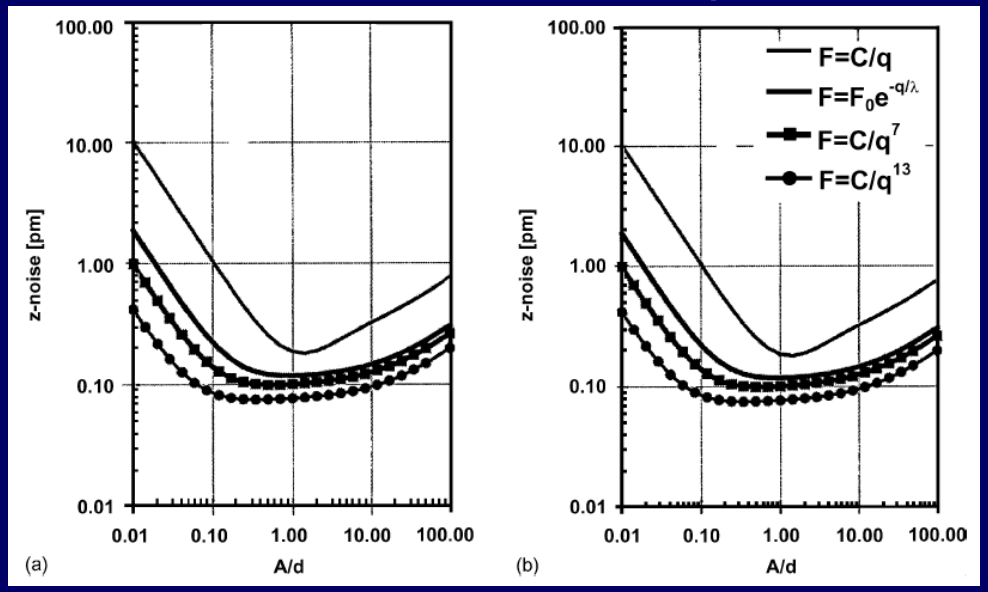
R. Pérez et al , PRL 78, 678 (1997)
R. Pérez et al , PRB 58, 10835 (1998)

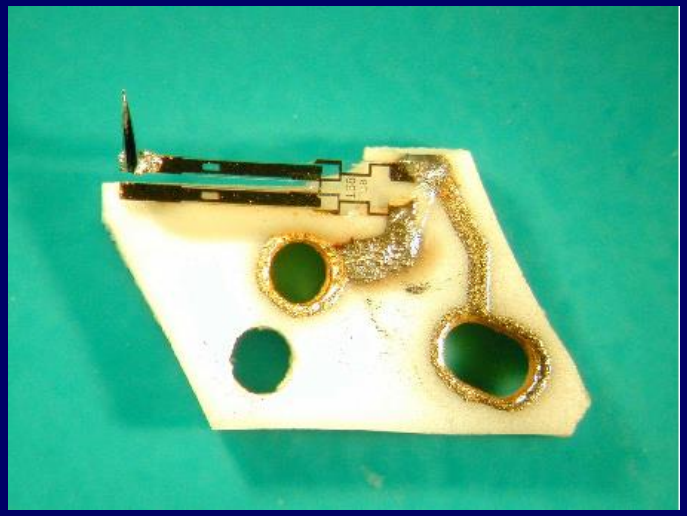
4. Recent developments…

- Tuning forks: small amplitudes to enhance atomic contrast.
- Force spectroscopy: Chemical identification
- Single-atom manipulation at RT
- AFM detection of spin
- True atomic resolution in liquids

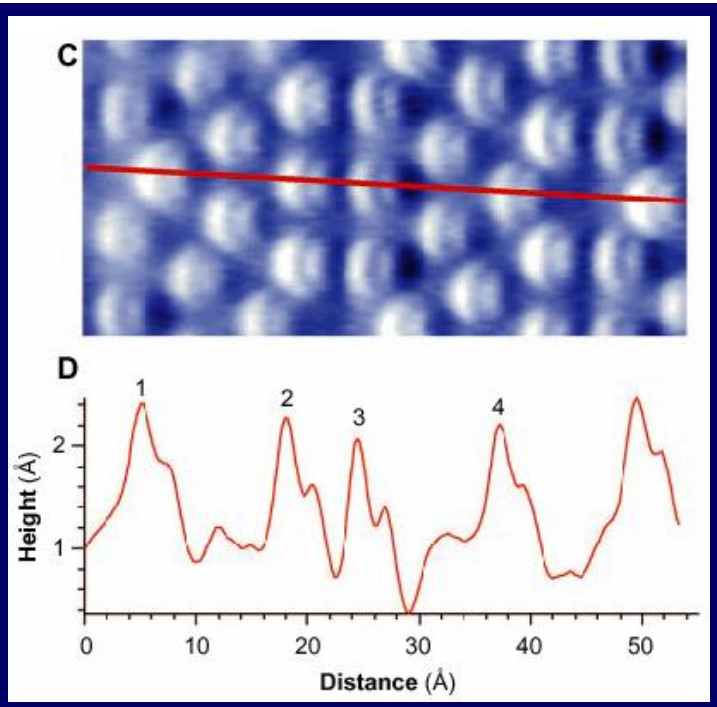
Other operating conditions: qPlus sensor

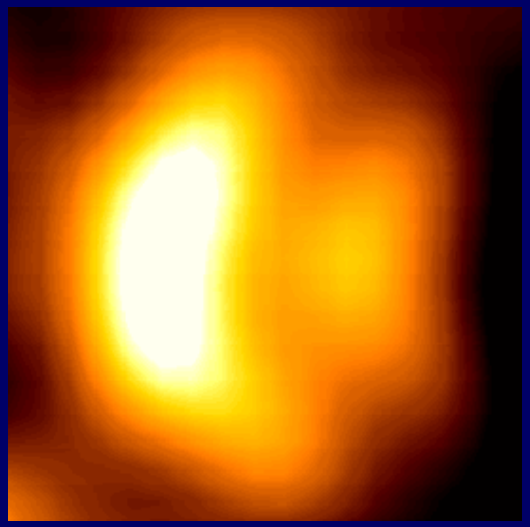
Smallest Noise for Å-size amplitudes!!!





qPlus sensor made from a tuning fork (k ~ 2000 N/m)

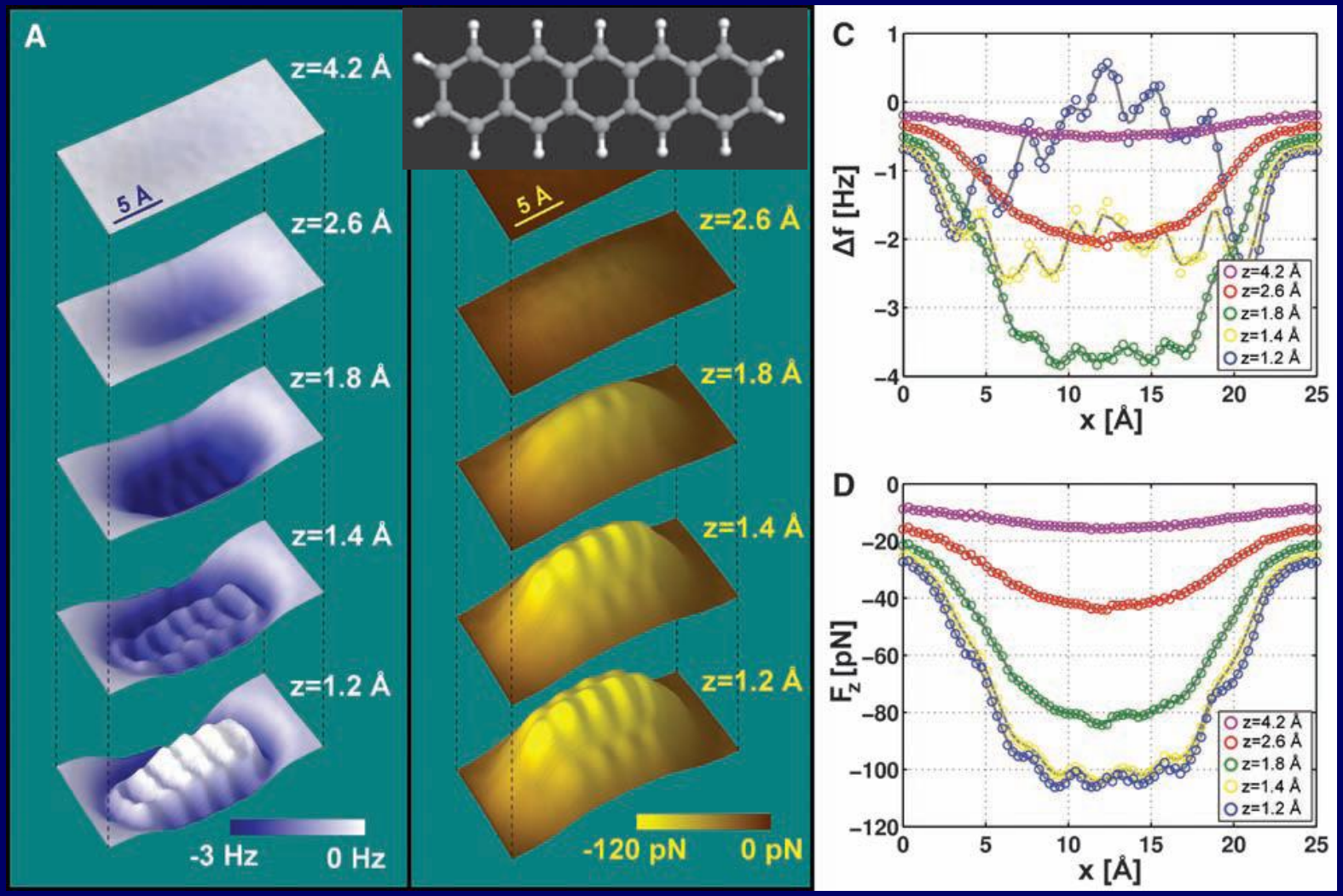




Operating under repulsive SR forces (stabilize by LR electrostatics) !!!

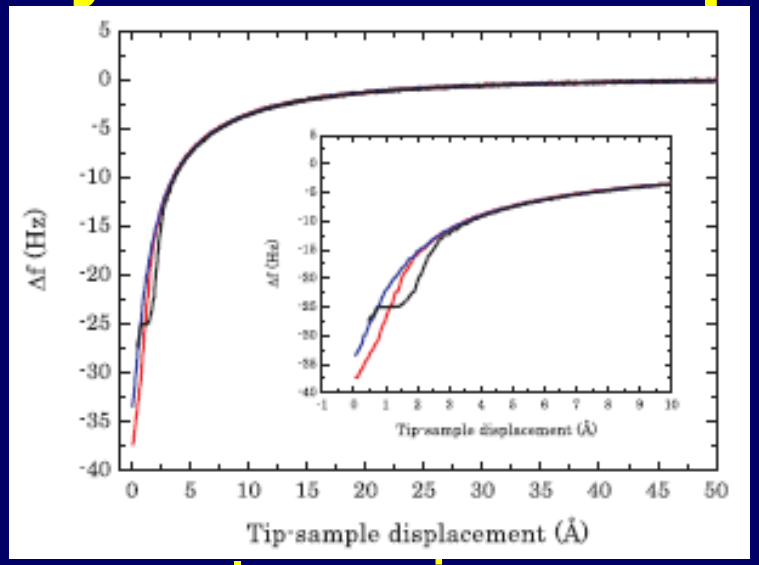
F.J. Giessibl et al,
Science 289 (2000) 422

The Chemical Structure of a Molecule Resolved by Atomic Force Microscopy

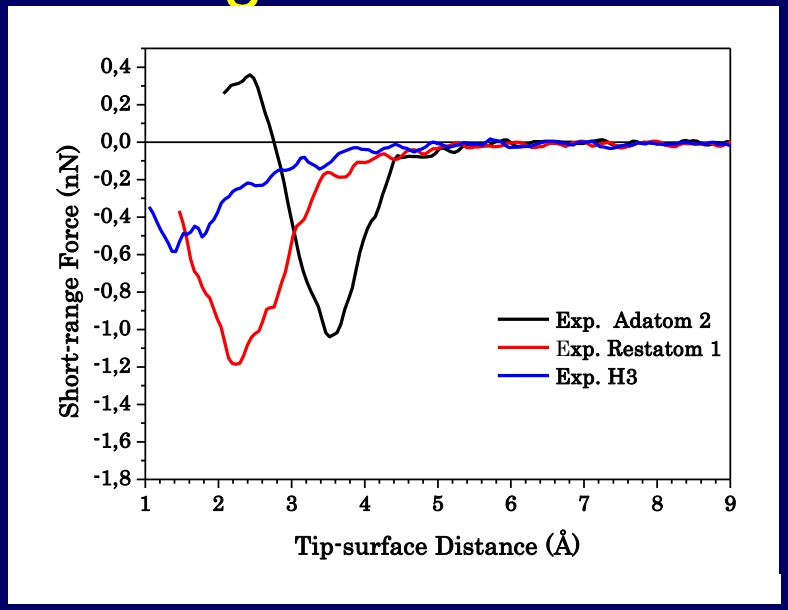


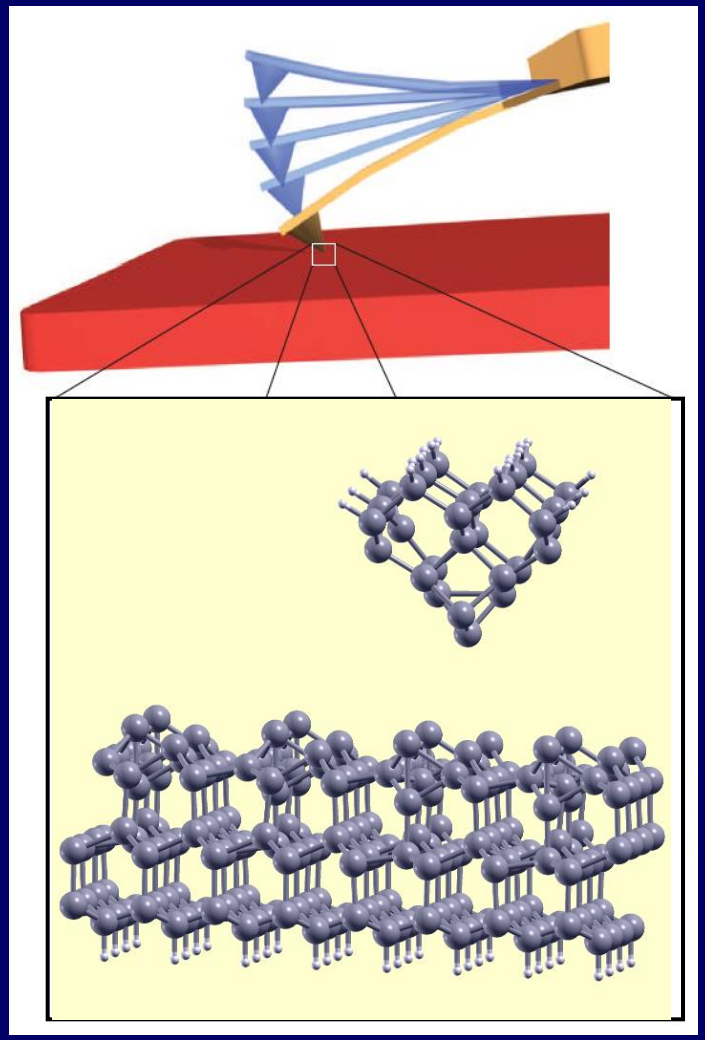
L. Gross et al, Science 325, 1110 (2009)

Dynamic Force Spectroscopy: Access to F_{ts}



Inversion algorithms



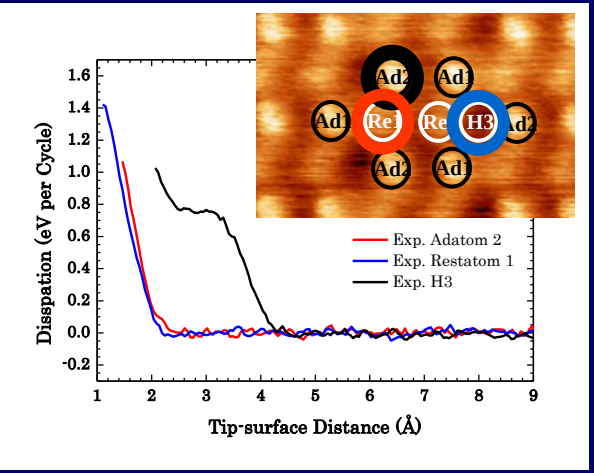


SR forces amenable to ab initio calculations

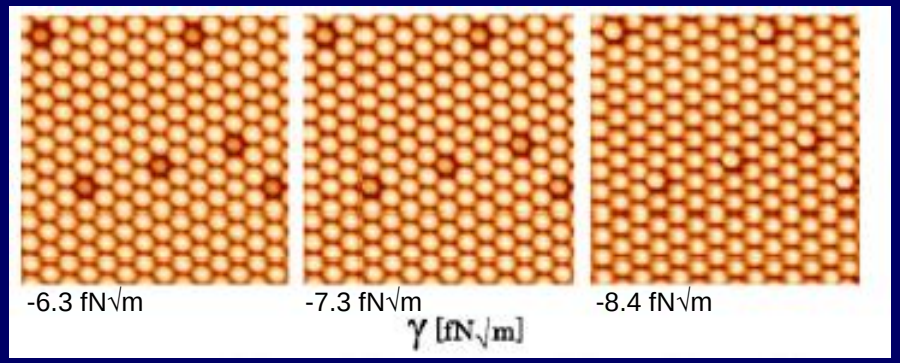
Developments based in Force Spectroscopy

1. DISSIPATION: Characterizing the tip structure and identifying a dissipation channel due to single atomic contact adhesion.

N. Oyabu et al. Phys. Rev. Lett. 96, 106101 (2006).



2. IMAGING: changes in topography: access to the real surface structure?

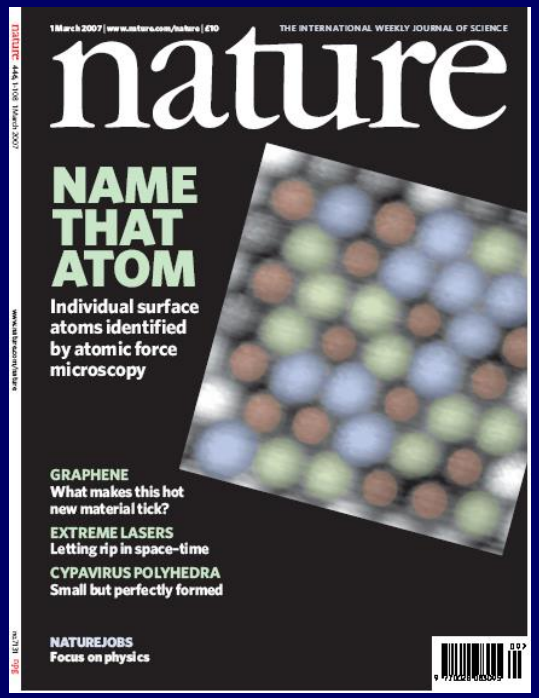


Y. Sugimoto et al
Phys. Rev. B 73, 205329 (2006).

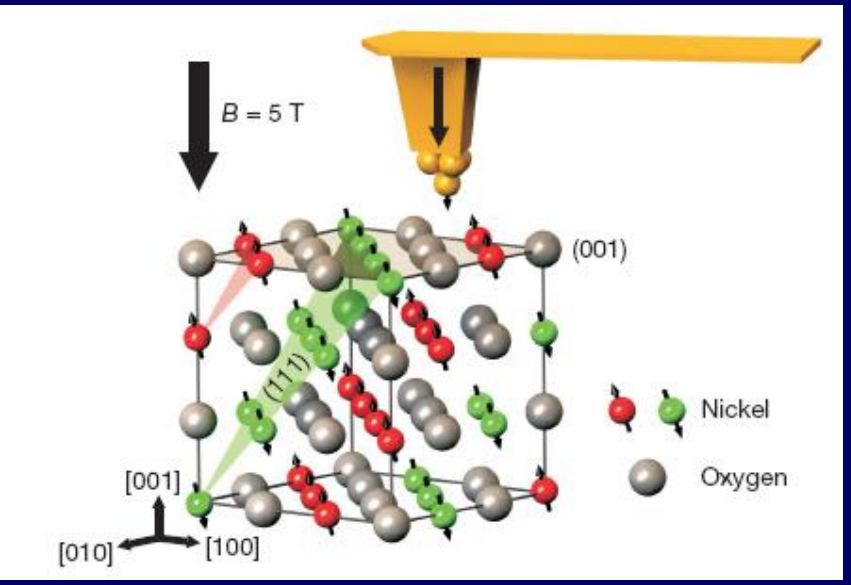
3. CHEMICAL IDENTIFICATION:

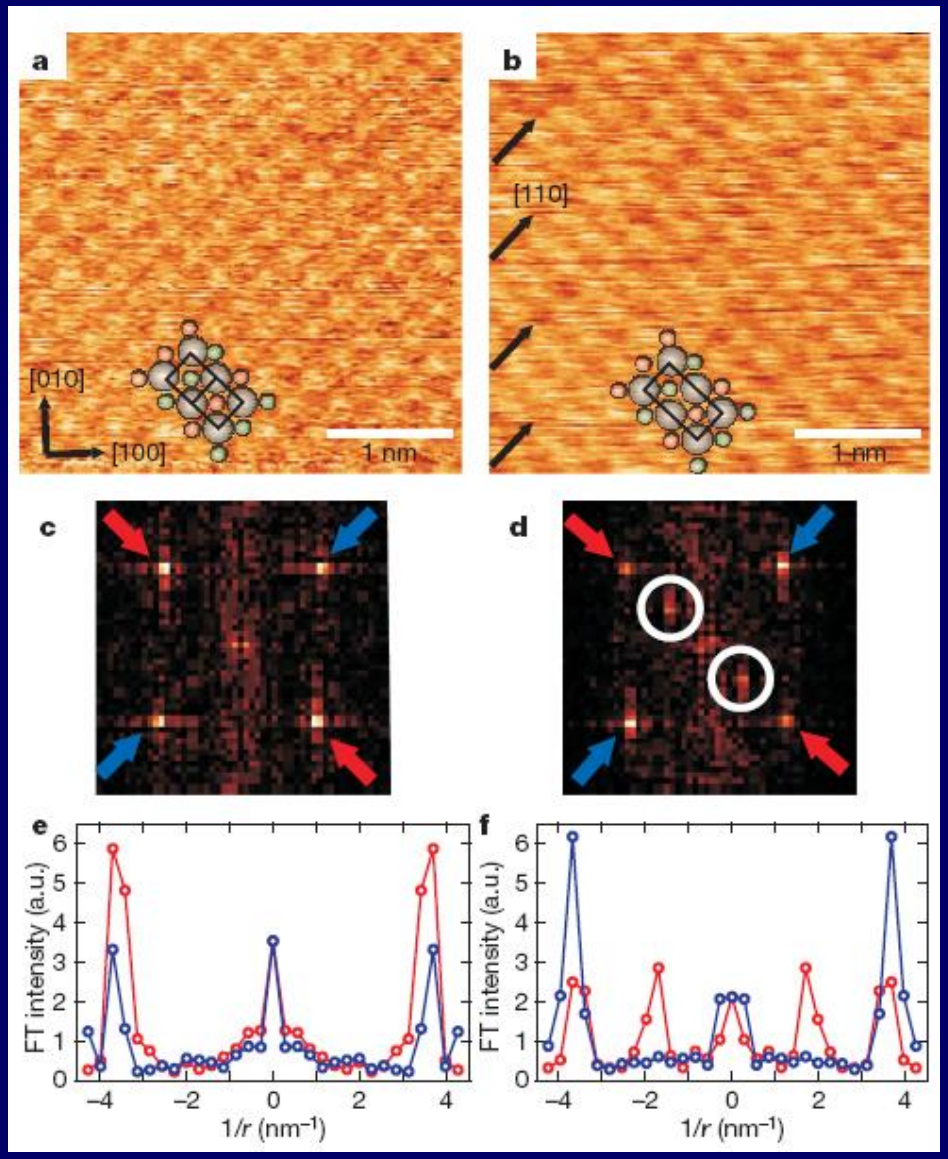
based on the relative interaction ratio of the maximum attractive force measured by dynamic force spectroscopy

Y. Sugimoto et al Nature 446, 64 (2007).



Magnetic exchange force microscopy with atomic resolution



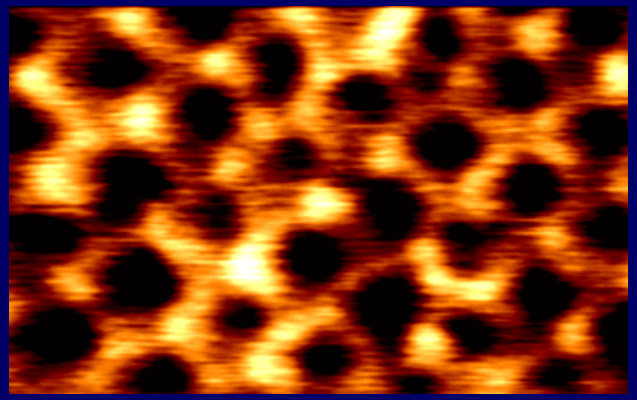


U. Kaiser, A. Schwarz & R. Wiesendanger, Nature 446, 522 (2007)

High-Resolution FM-AFM Imaging in Liquid

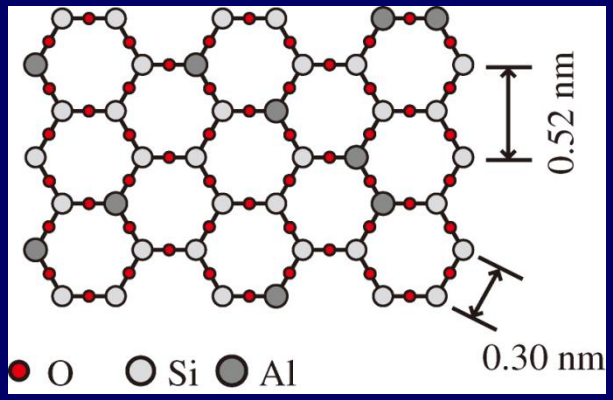
True Atomic Resolution (2005)

FM-AFM Image of Mica in Water



1 nm

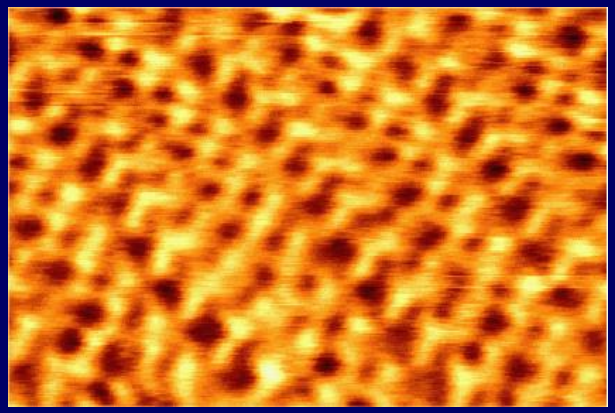
Cleaved Mica Surface



Fukuma *et al.* APL **87** (2005) 034101

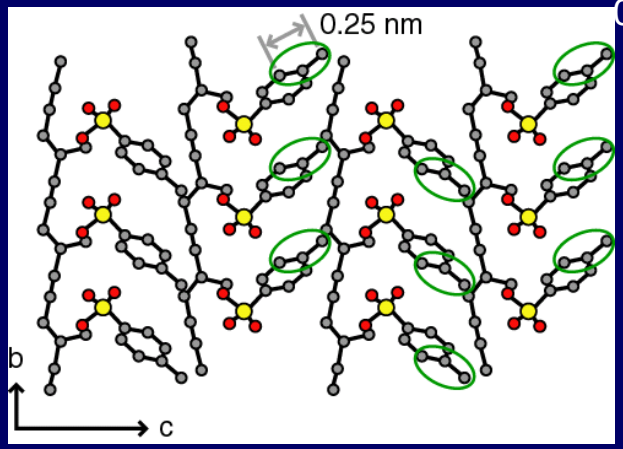
True Molecular Resolution (2005)

Polydiacetylene Single Crystal in Water



1 nm

bc-plane of Polydiacetylene Crystal



Fukuma *et al.* APL **86** (2005) 193108

FM-AFM: Things to remember...

- Frequency shift as the contrast source.
- True atomic resolution. (UHV & Liquids !!!)
- self-driven oscillator: More complicated operation and electronics, but simpler behaviour (amplitude feedback “linearizes” the behaviour).
- Short-range (chemical, electrostatic) interactions are responsible for the atomic resolution.
- Separation of interactions + inversion formulae $\Rightarrow$ spectroscopic capabilities (in combination with theory).
- Different channels (frequency shift, tunneling currents, energy dissipation) recorded simultaneously