The Abdus Salam International Centre for Theoretical Physics

United Nations Educational, Scientific and Cultural Organization

IAEA International Atomic Energy Agency

2063-21

ICTP/FANAS Conference on trends in Nanotribology

19 - 24 October 2009

Ultrasonic nanolithography on hard substrates

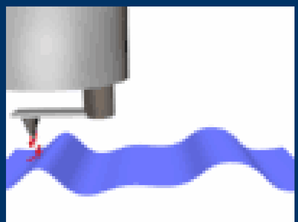
Teresa Cuberes

University of Castilla La Mancha
Almaden
Spain

Strada Costiera 11, 34151 Trieste, Italy - Tel.+39 040 2240 111; Fax +39 040 224 163 - sci_info@ictp.it

ULTRASONIC NANOLITHOGRAPHY ON HARD SUBSTRATES

Teresa Cuberes



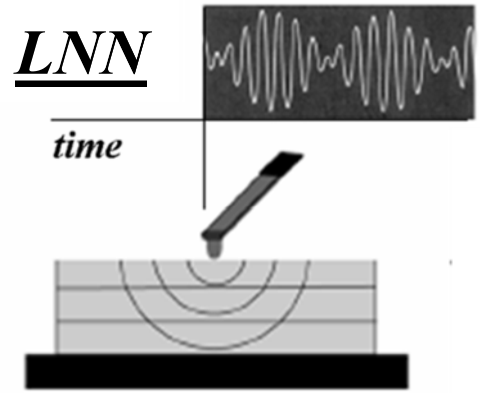
teresa.cuberes@uclm.es

UCLM
UNIVERSIDAD DE CASTILLA-LA MANCHA

http://www.uclm.es/organos/vic_investigacion/gruposweb/nanotecnologia/

The Laboratory of Nanotechnology, Almaden, SPAIN

LNN



Outline

- ***Mechanical-diode-mode Ultrasonic AFM***

  -The Mechanical-Diode (MD) effect: UFM, HFM, IC-HFM

- ***Tribology with ultrasonic-AFM***

  - Study of adhesion hysteresis and energy dissipation with UFM

  - Study of friction and lubrication with MD- UFFM

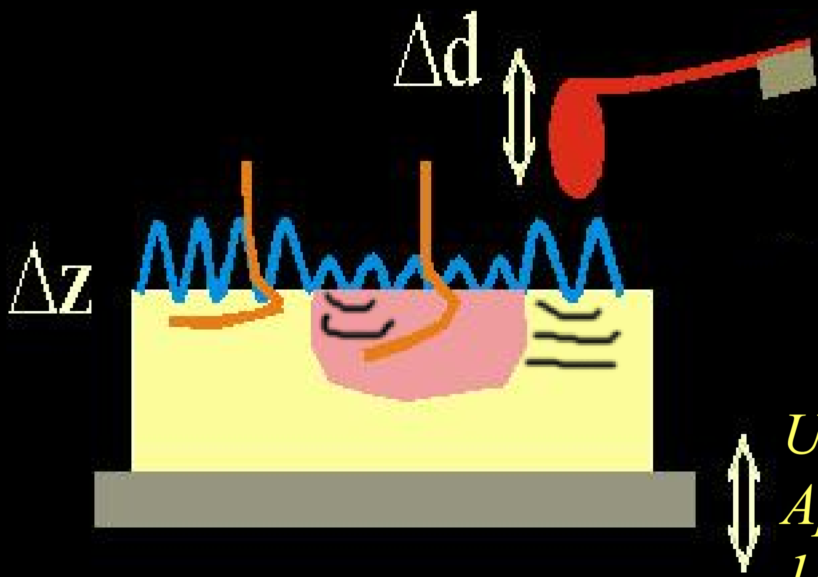
  - Control of friction and generation of wear using ultrasound

- ***Ultrasonic nanolithography on hard substrates***

  - Results on Si(111)

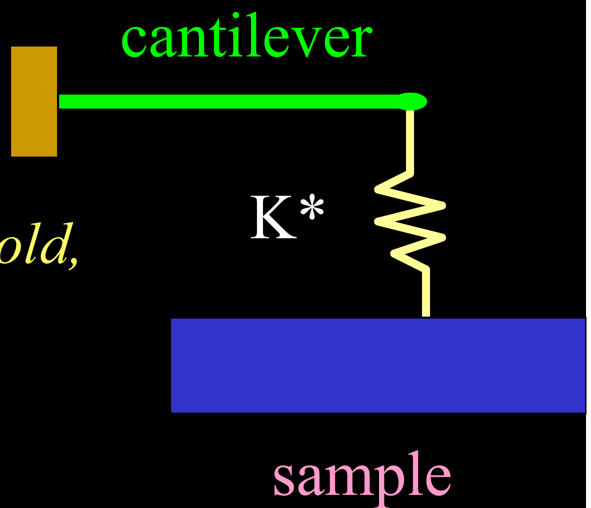
- ***Summary***

ACOUSTIC ATOMIC FORCE MICROSCOPY (AFAM)



The cantilever can support high-frequency resonant modes

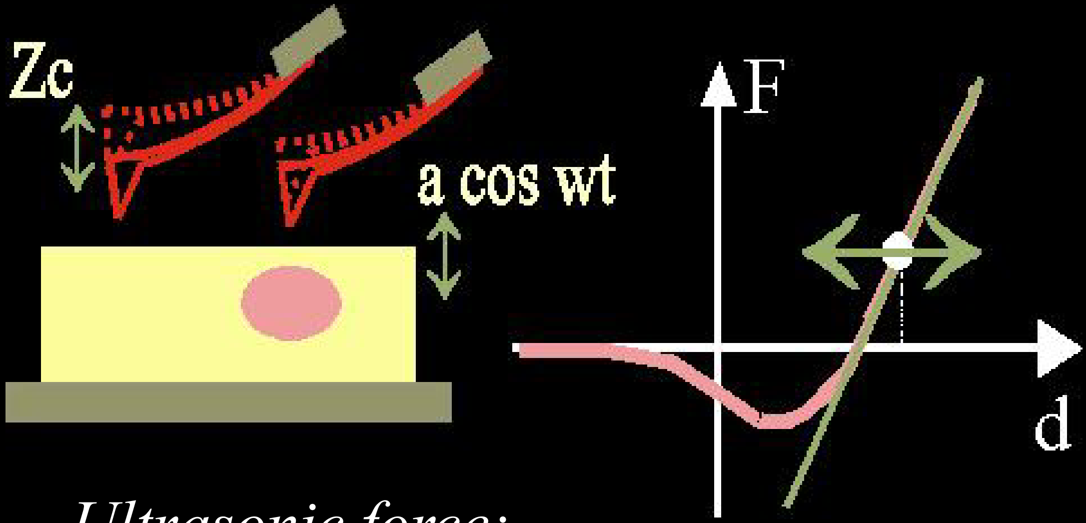
U. Rabe and W. Arnold, Appl. Phys. Lett. 64, 1493 (1993)

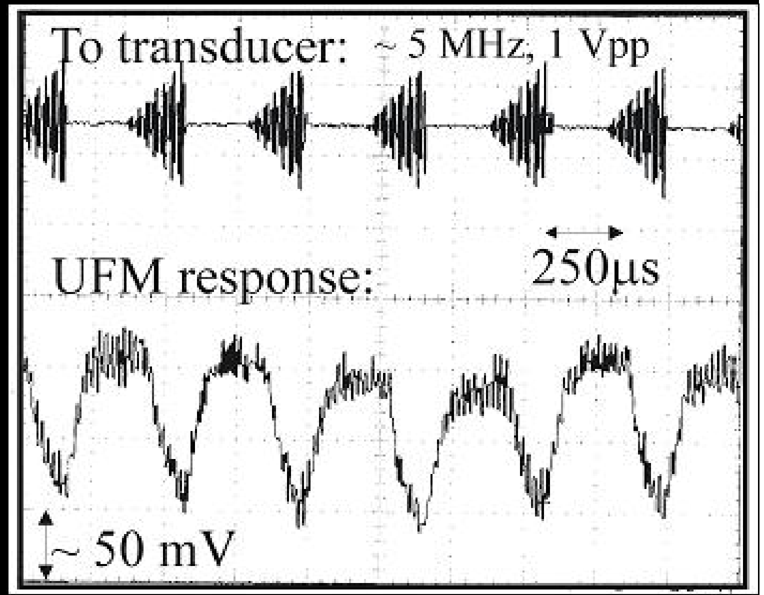


The tip-sample interaction is kept in the linear tip-sample force regime

AFAM *provides information about* sample elasticity with nanoscale lateral resolution. Measured magnitude: *Resonance frequency of the cantilever high-order modes* (the contact stiffness and the Young modulus can be evaluated)

ULTRASONIC FORCE MICROSCOPY





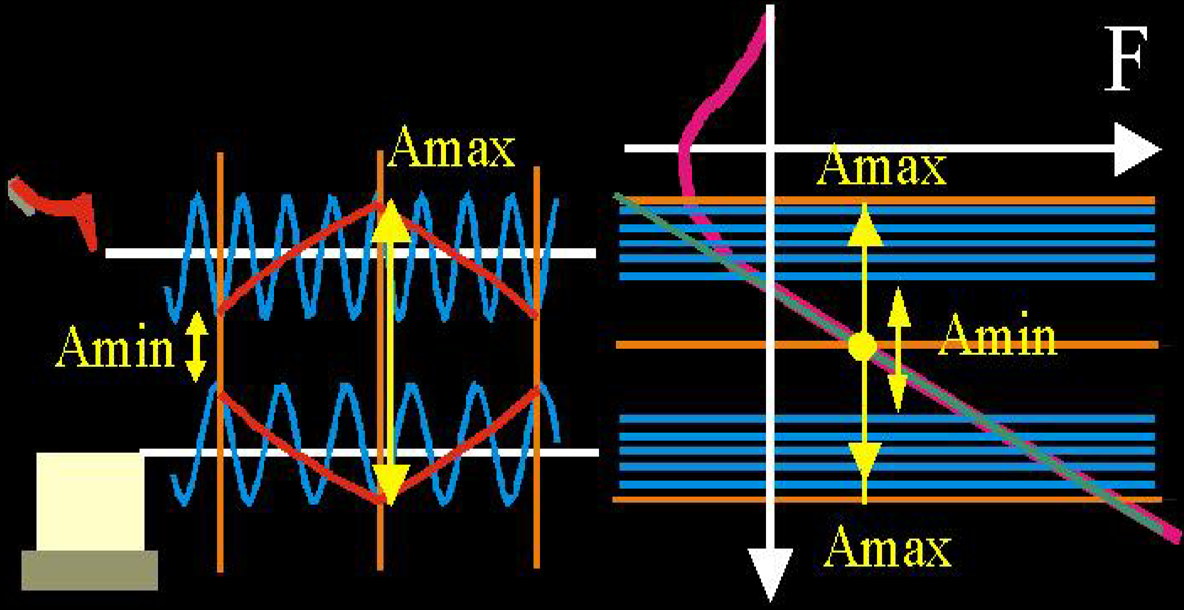
Ultrasonic force:

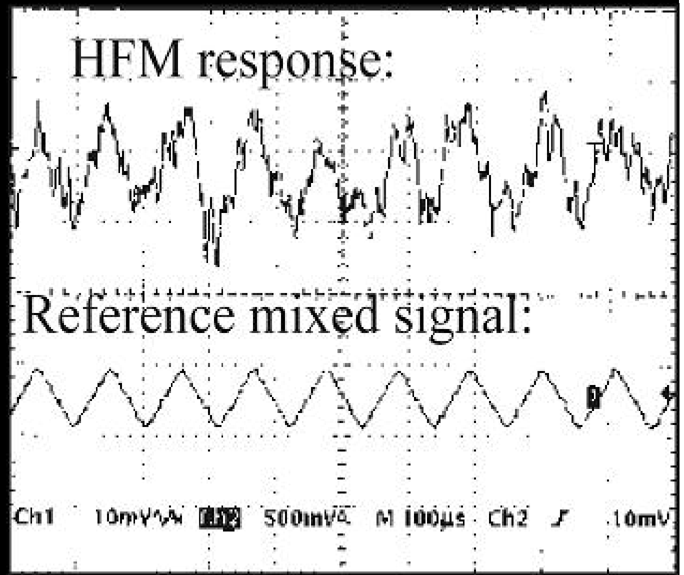
$$kz_c = \frac{1}{T}\int_0^T F(z_c - z_s - A\cos wt)\,dt$$

O. Kolosov and K. Yamanaka, Jpn. J. Appl. Phys. 32, L1095 (1993)

UFM *provides information about* sample elasticity and adhesion with nanoscale lateral resolution. Measured magnitude: static cantilever displacement induced by the *ultrasonic force*.

HETERODYNE FORCE MICROSCOPY





Phase-HFM makes possible to study dynamic relaxation processes in *nanometre volumes* with a *time-sensitivity of nanoseconds*

M. T. Cuberes et al. J. Phys. D. Appl. Phys. 33, 2347 (2000)

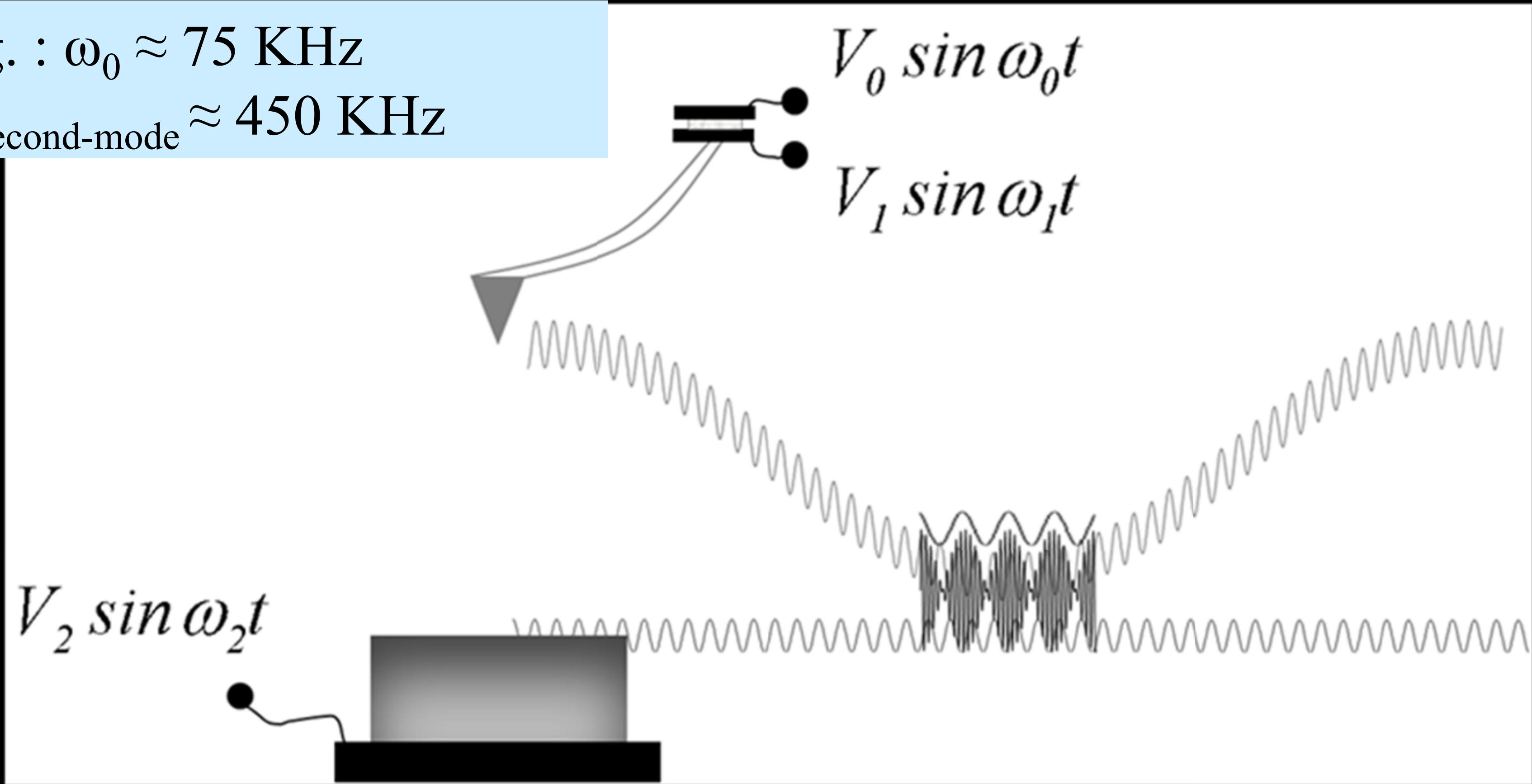
SCANNING NEAR FIELD ULTRASOUND HOLOGRAPHY

Phase-SNFUH provides elastic information of buried features with *great sensitivity.*

Shekhawat and Dravid. Science 310, 90 (2005)

INTERMITTENT-CONTACT HETERODYNE FORCE MICROSCOPY

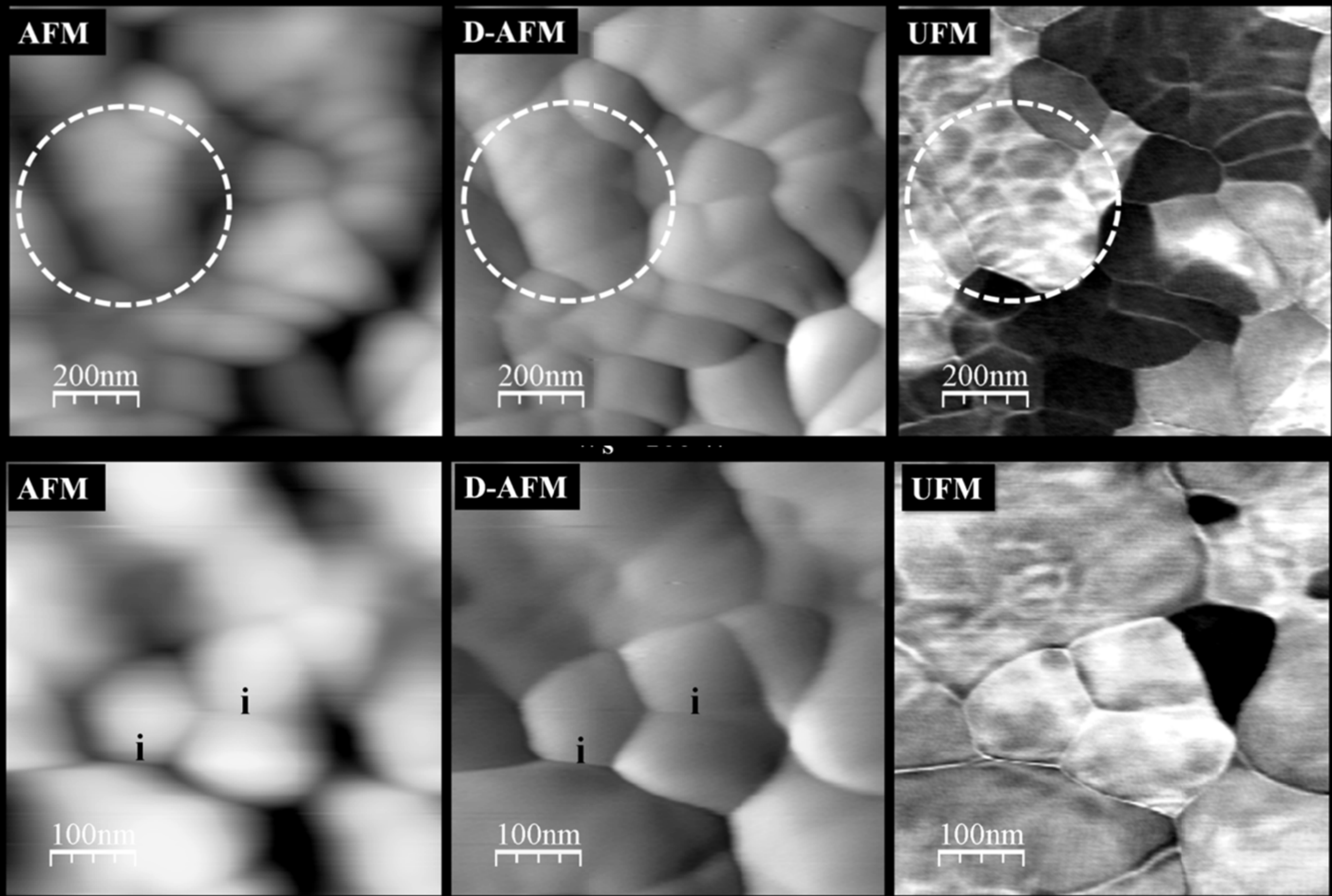
e. g. : $\omega_0 \approx 75$ KHz
$\omega_{second\text{-}mode} \approx 450$ KHz



Principle: the cantilever is driven at *its fundamental flexural eigenmode.* Ultrasonic vibration in the megahertz range is additionally input at the tip-sample contact *from the cantilever base and from the back of the sample.* The ultrasonic frequencies are such *that their difference is coincident with the second cantilever eigenmode.*

M. T. Cuberes, J. of Nanomaterials (2009)

ULTRASONIC FORCE MICROSCOPY ON TiN COATINGS



J. A. Hidalgo, C. Montero-Ocampo, and M. T. Cuberes, Nanoscale Res Lett (2009)

Outline

- **Mechanical-diode-mode Ultrasonic AFM**

  -The Mechanical-Diode (MD) effect: UFM, HFM, IC-HFM

- **Tribology with ultrasonic-AFM**

  - Study of adhesion hysteresis and energy dissipation with UFM

  - Study of friction and lubrication with MD- UFFM

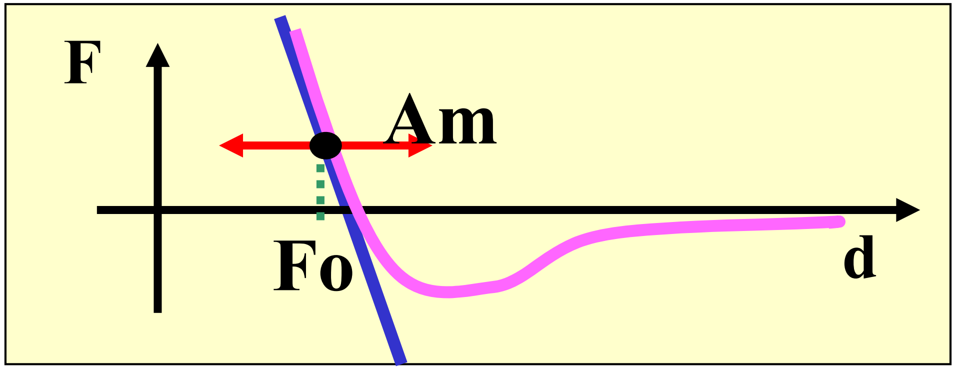
  - Control of friction and generation of wear using ultrasound

- **Ultrasonic nanolithography on hard substrates**

  - Results on Si(111)

- **Summary**

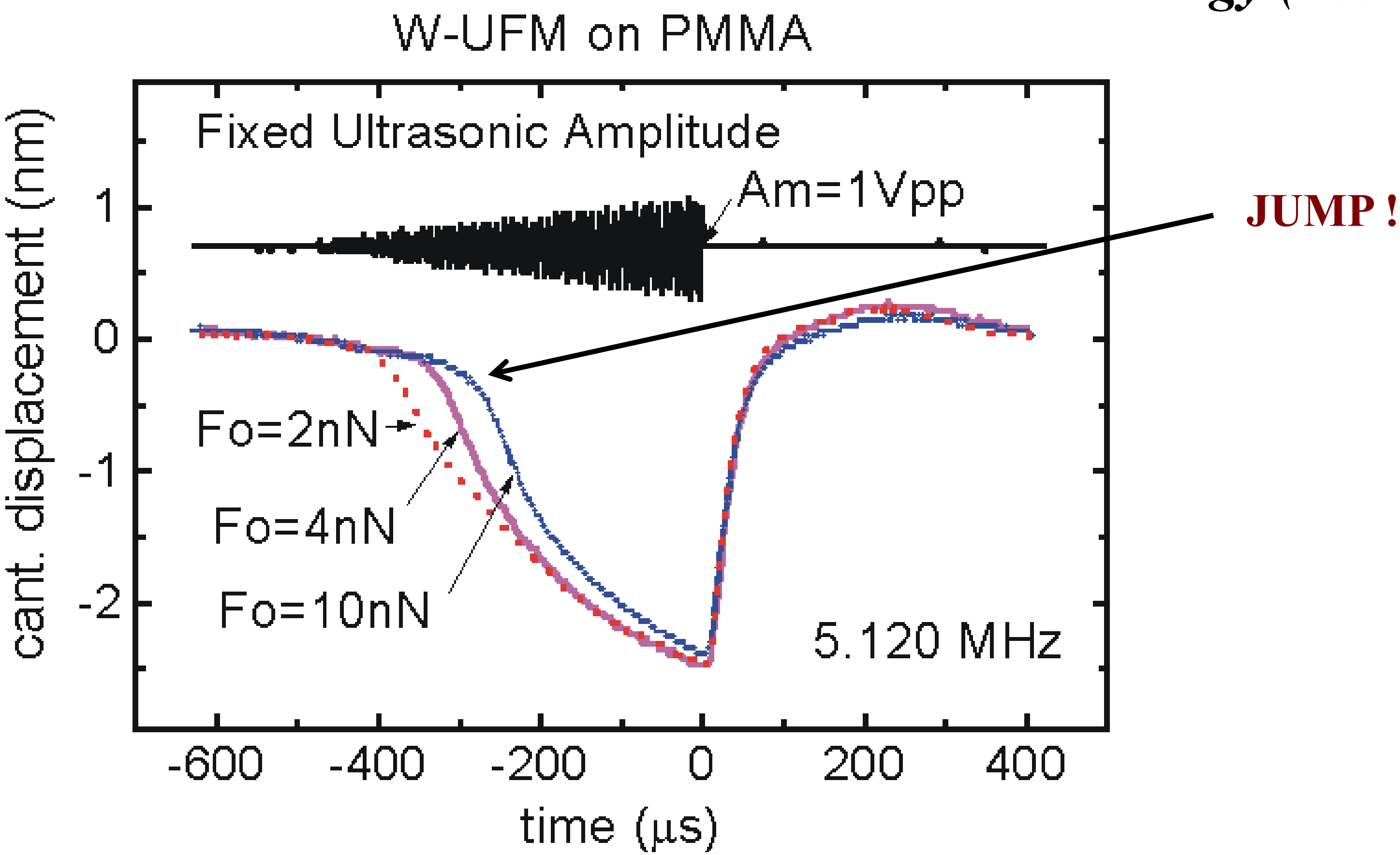
UFM: ADHESION HYSTERESIS AND ENERGY DISSIPATION



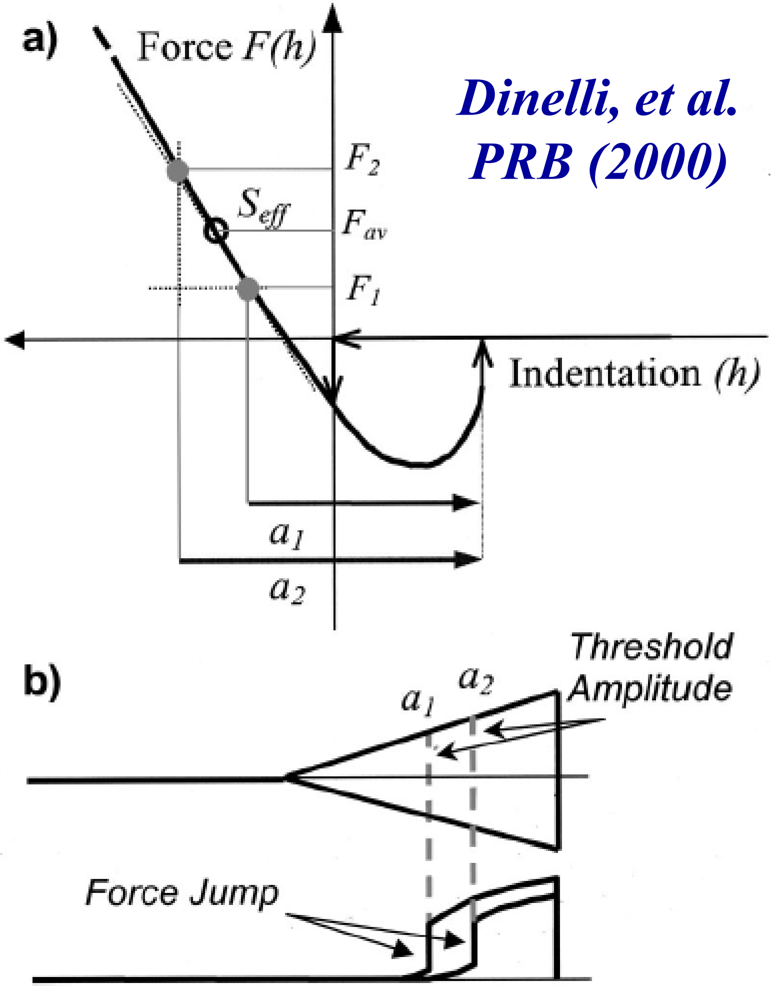
ULTRASONIC CURVES

O. Kolosov and K. Yamanaka, Jpn. J. Appl. Phys. (1993)

M. T. Cuberes et al. Nanotechnology (2001)

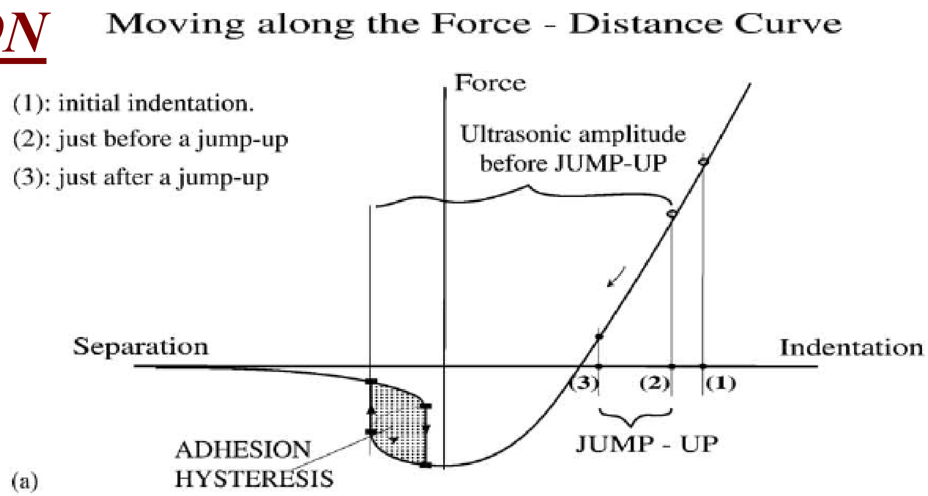


ELASTIC MODULUS AND ADHESION

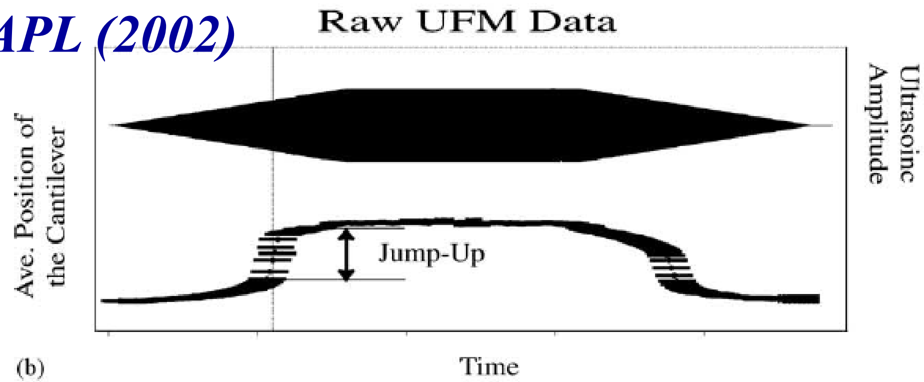


Dinelli, et al. PRB (2000)

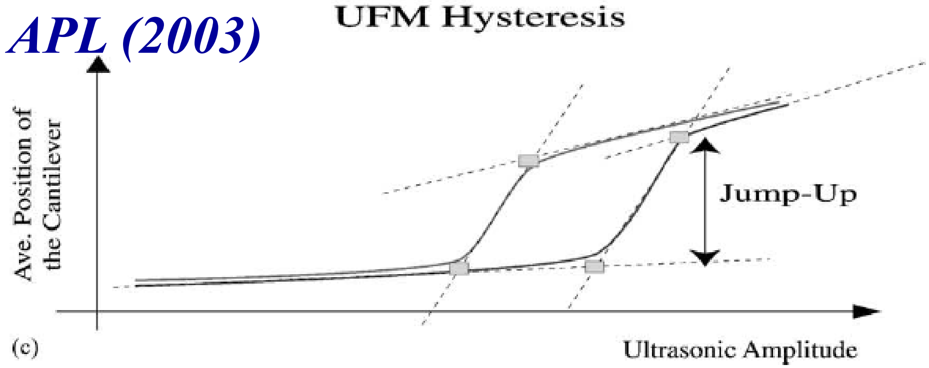
$$S_{eff}(F_{av}) = \frac{F_2 - F_1}{a_2 - a_1}$$



Inagaki et al. APL (2002)

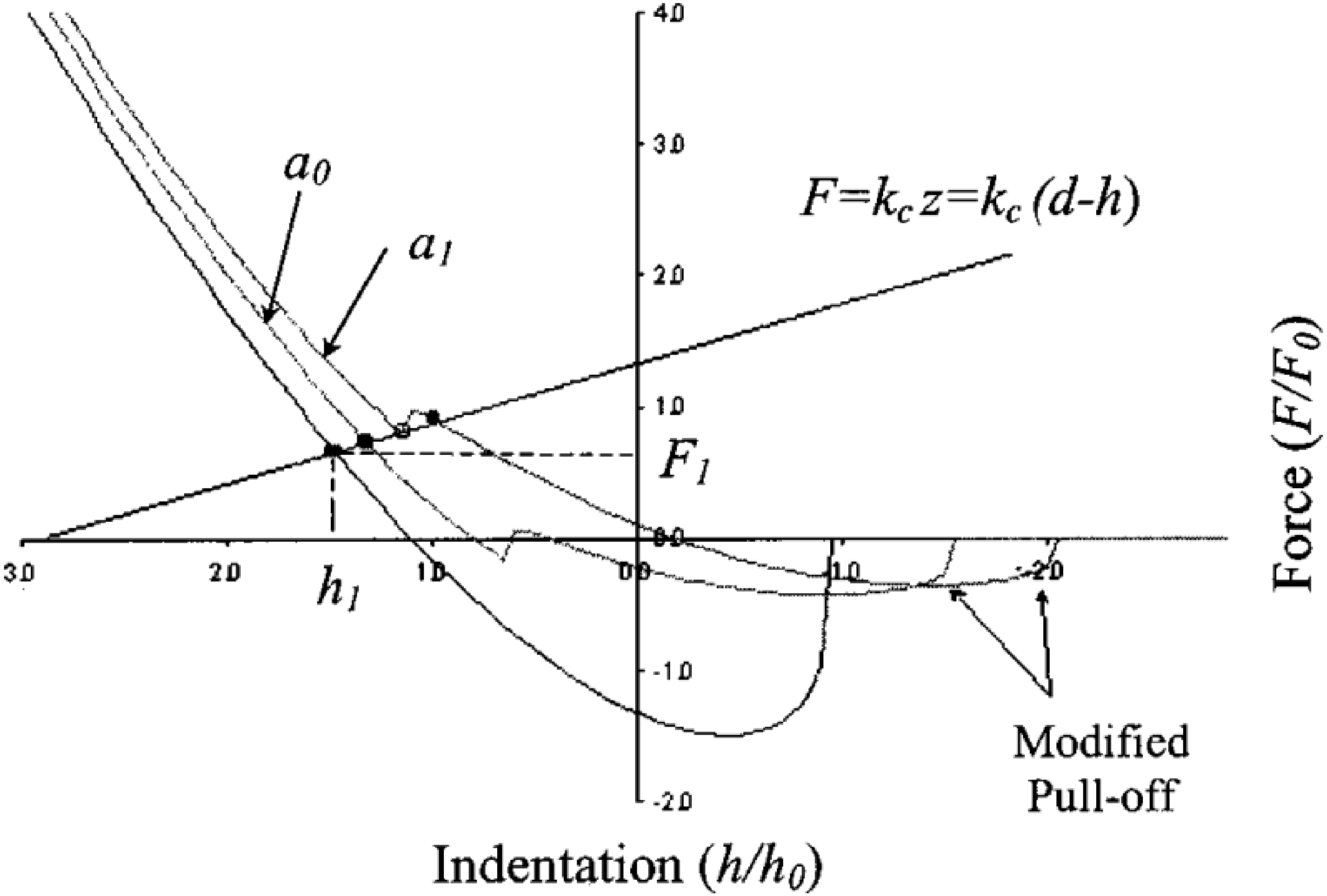


Szoskiewicz et al. APL (2003)

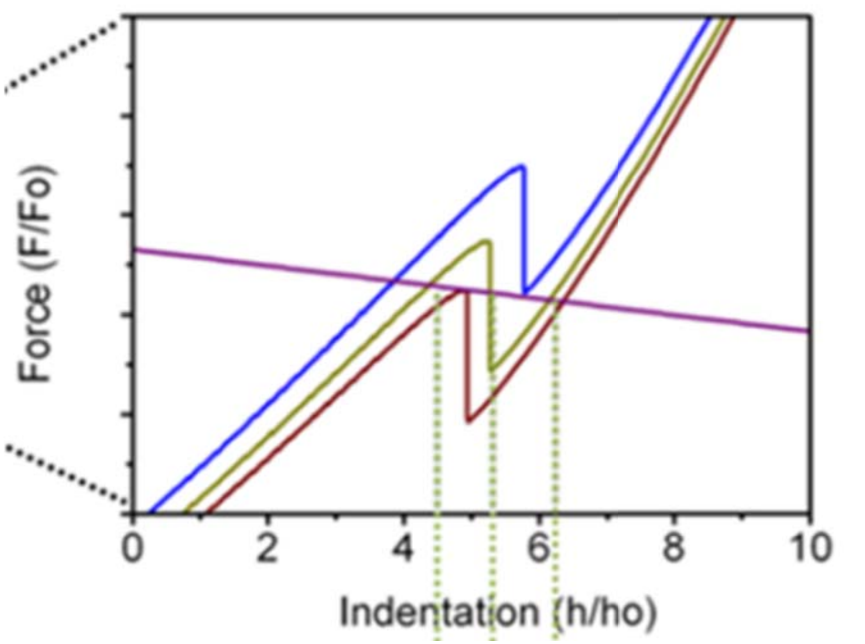


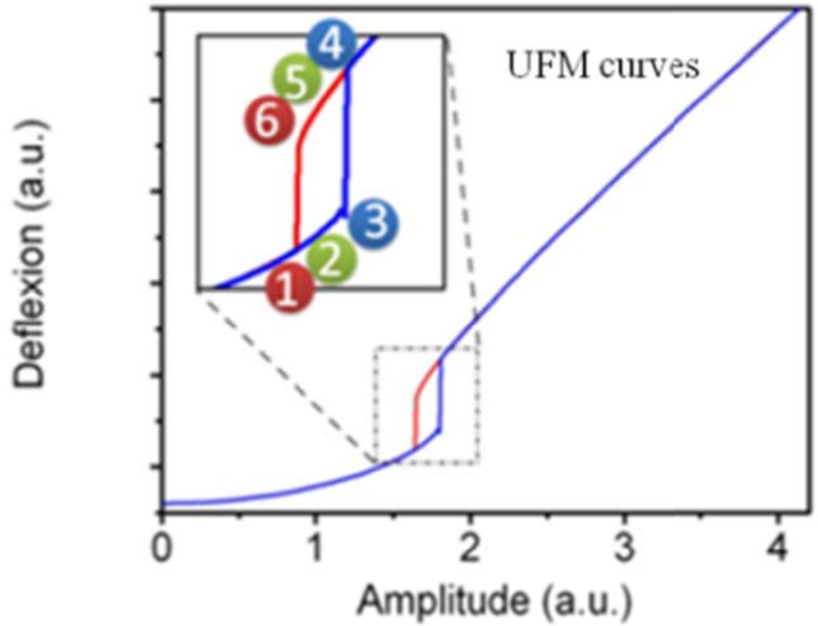
Simulations of the *ultrasonic force* versus *ultrasonic amplitude* curves:

ULTRASONIC-AMPLITUDE DEPENDENT TIP-SAMPLE FORCE CURVES

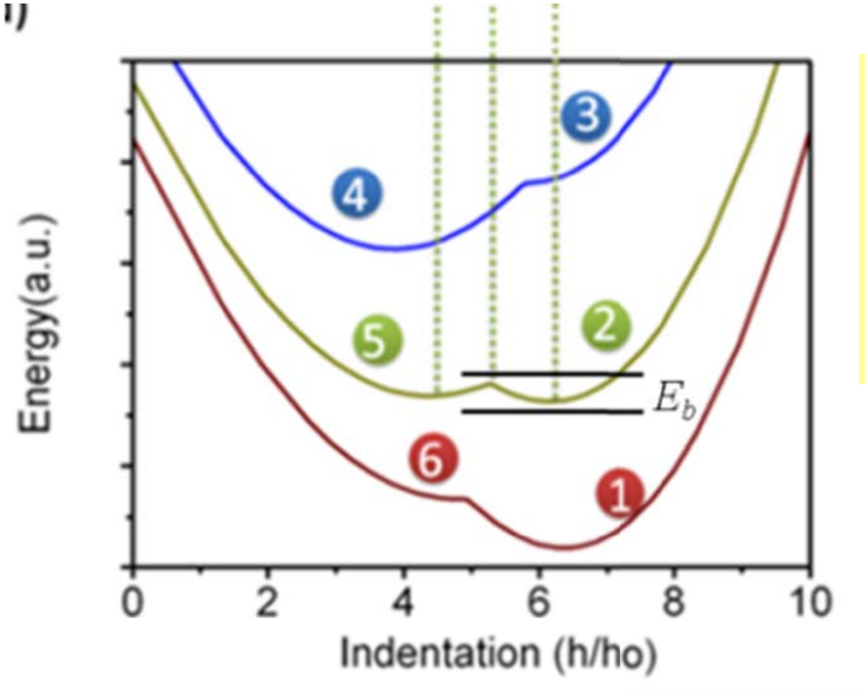


Dinelli, Biswas, Briggs, and Kolosov, Phys. Rev. B (2000), 13995





ULTRASONIC-AMPLITUDE DEPENDENT POTENTIAL ENERGY CURVES

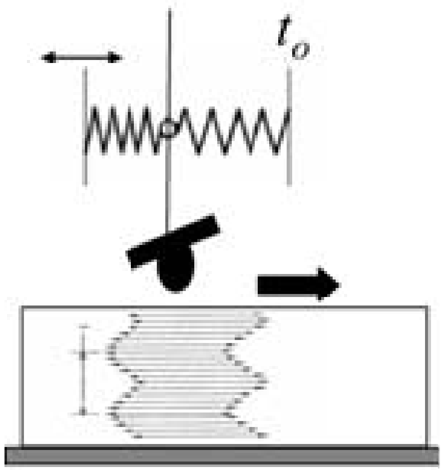


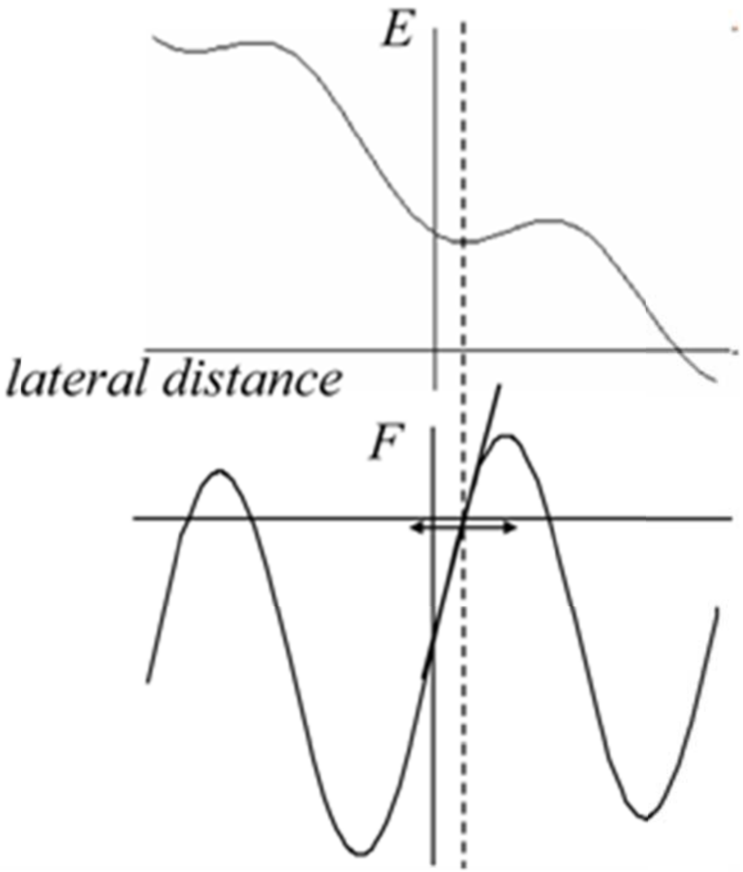
For certain ultrasonic amplitudes, the modified tip-sample forces lead to **two quasi-static equilibrium states separated by en energy barrier.**

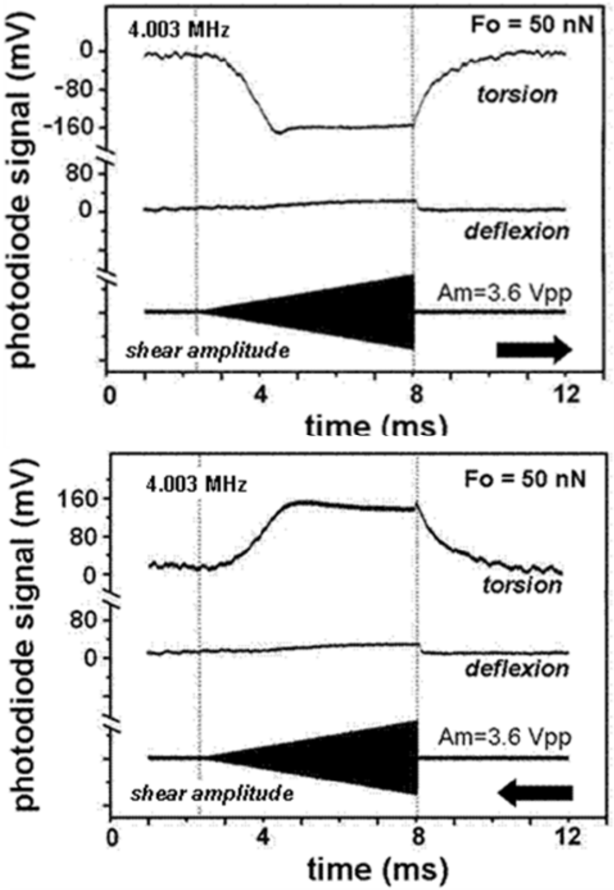
J. J. Martínez and M. T. Cuberes, Mater. Res. Soc. Symp. Proc. Vol. 1085 (2008)

MD-UFFM: NANOSCALE FRICTION AND LUBRICATION

MD-ULTRASONIC FRICTION FORCE MICROSCOPY





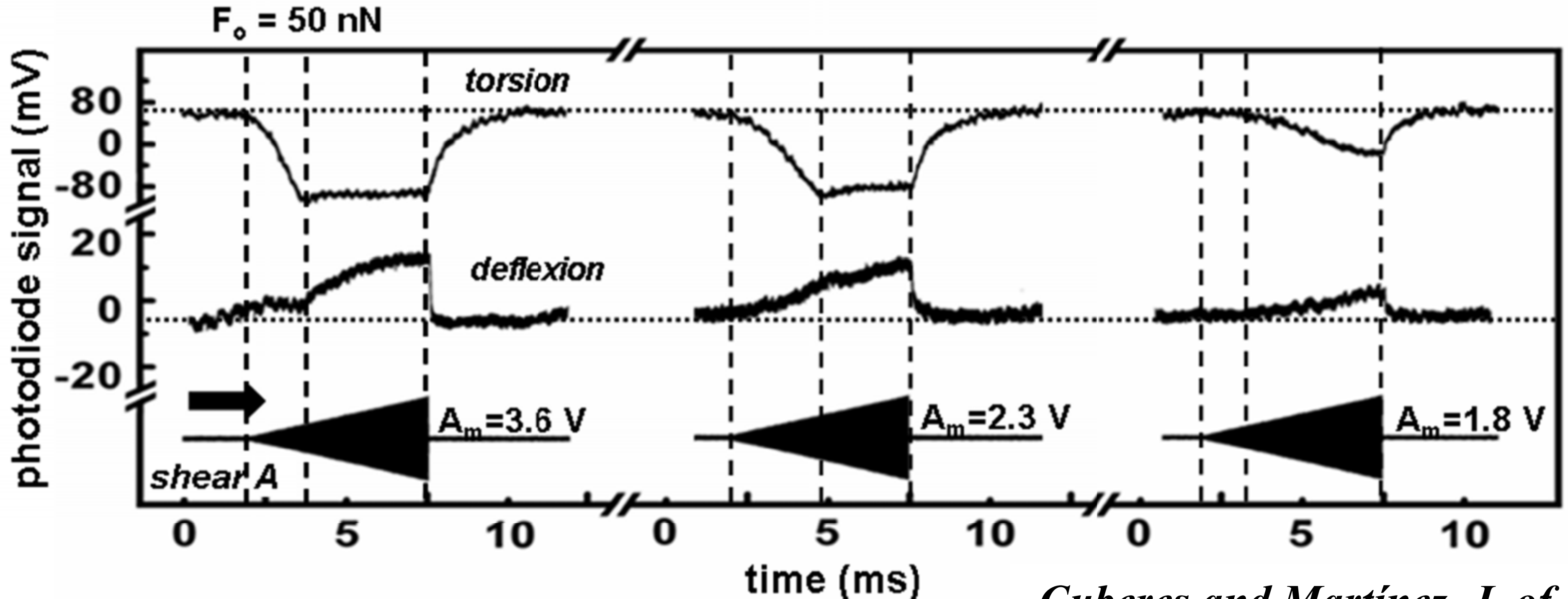


Lateral Mechanical Diode Effect!

M. T. Cuberes and J. J. Martínez, J. of Phys.: Conf. Ser. (2007)

MD-UFFM ***provides information about*** **sample shear elasticity and friction at the nanoscale**. **Measured magnitude**: **static cantilever torsion** induced by the ***lateral ultrasonic force***.

Dependence on the ultrasonic amplitude: ***MD-UFFM on Si(111)***



Cuberes and Martínez, J. of Phys.: Conf. Ser. (2007)

Physical origin of the lift-off?

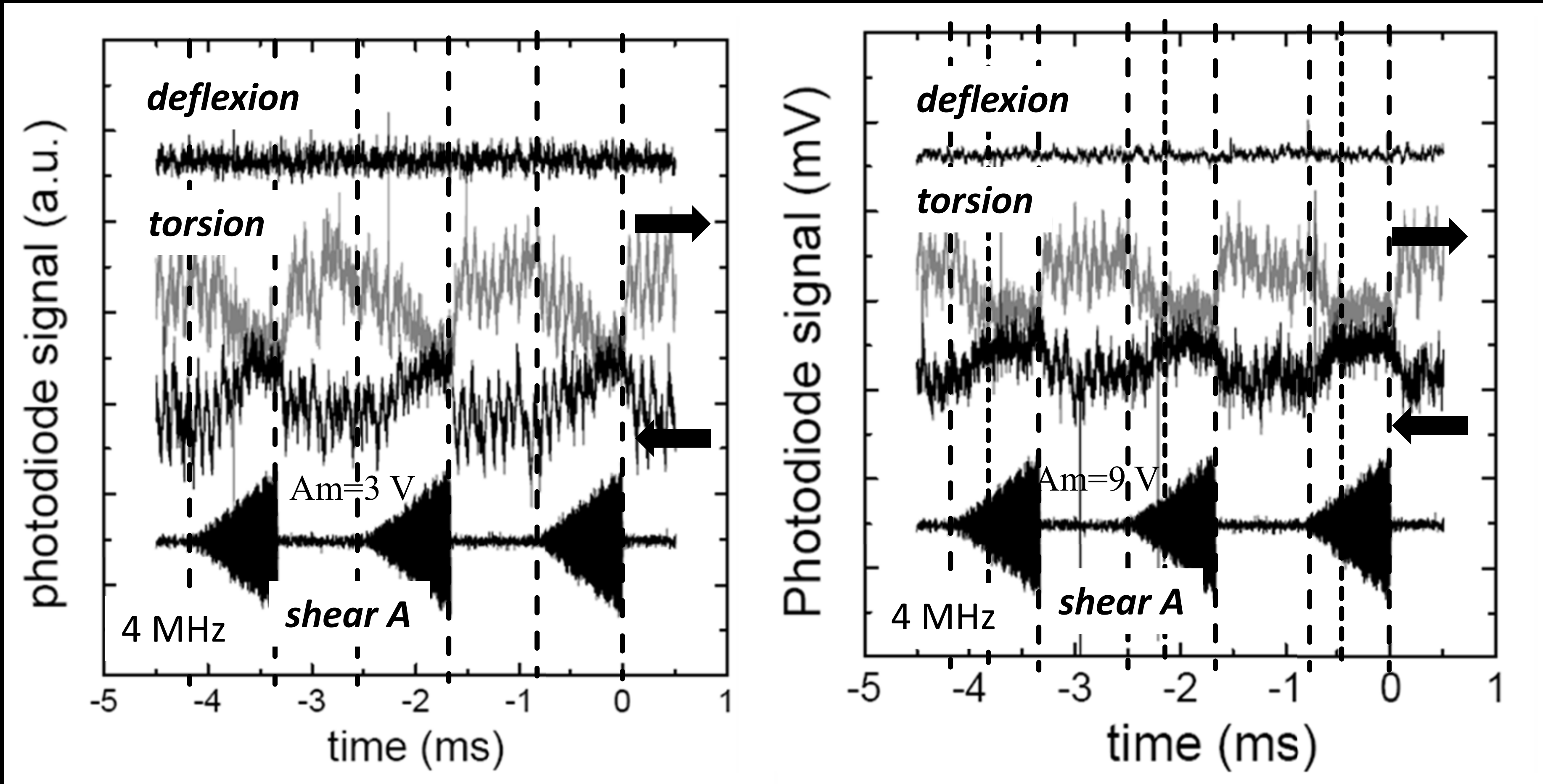
When **increasing the sliding velocity**, the minimum thickness of a viscous squeezed liquid layer increases according to EHD theory, and the ***hydrodynamic pressure may support the tip*** and reduce friction.

$$h_{\min} = 1.79 R^{0.47} \alpha^{0.49} \eta_0^{0.68} U^{0.68} E^{-0.12} W^{-0.07}$$

V. Scherer, W. Arnold, and B. Bhushan. Surf. Interface Anal. (1999)

CONTROL OF FRICTION

MD-UFFM on HOPG



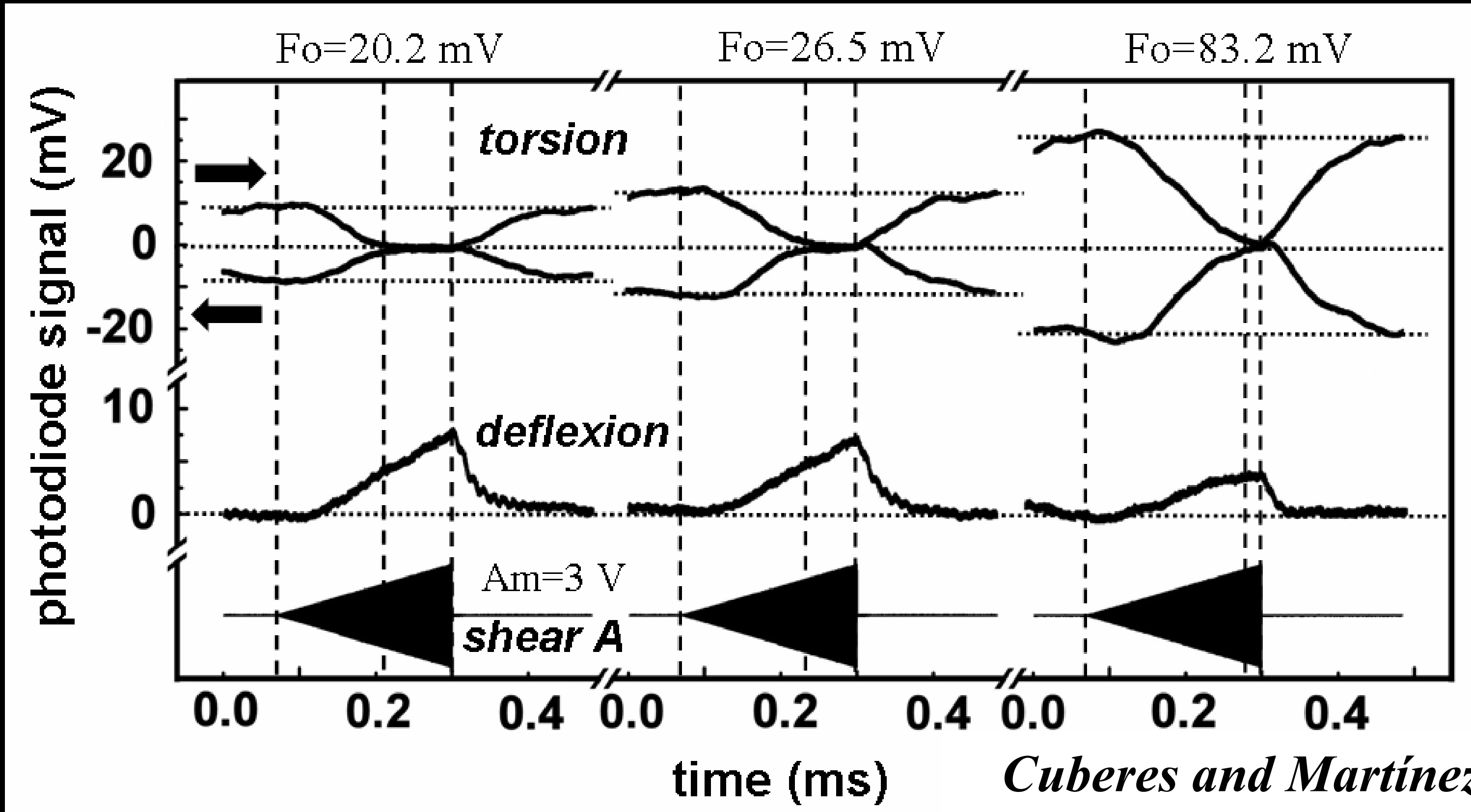
No lift-off is observed on HOPG!

M. T. Cuberes (in preparation for issue in Tribology Letters)

Friction reduces for increasing shear ultrasonic amplitudes; *above a critical value, the lateral ultrasonic force remains constant.*

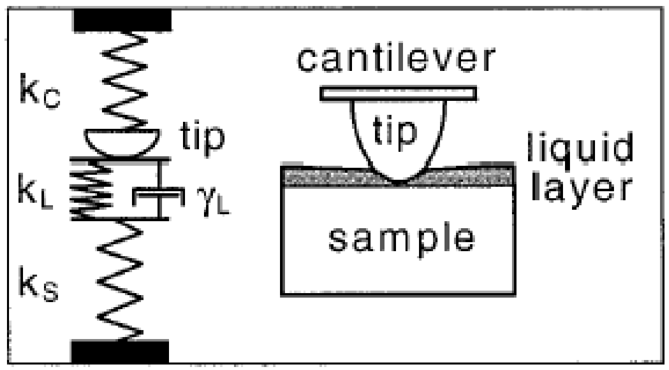
CONTROL OF FRICTION

MD-UFFM on Si(111)



Cuberes and Martínez (2007)

➡ Reduction of friction by out-of-plane vibrations and lubricant layers



Supresion of solvation force and **development of liquid-like dynamics**

Dinelli , Biswas et al. APL (1997)

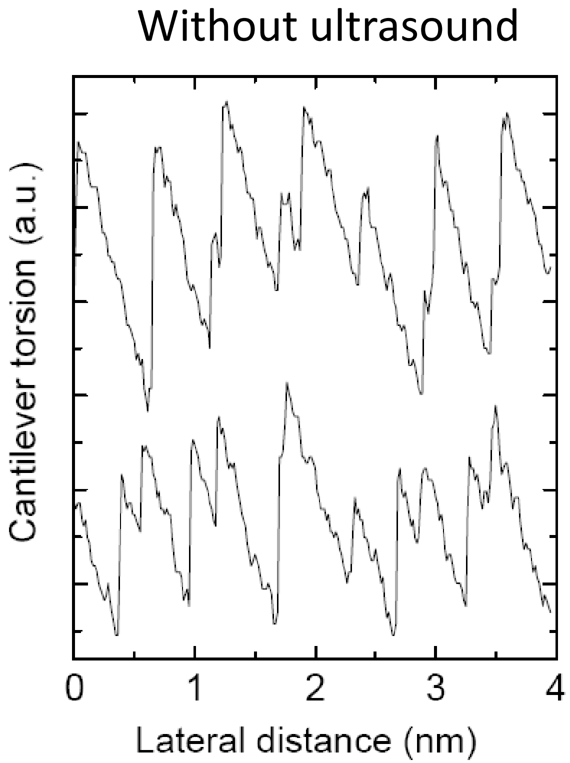
Gao et al. J. Phys. Chem. B (1998)

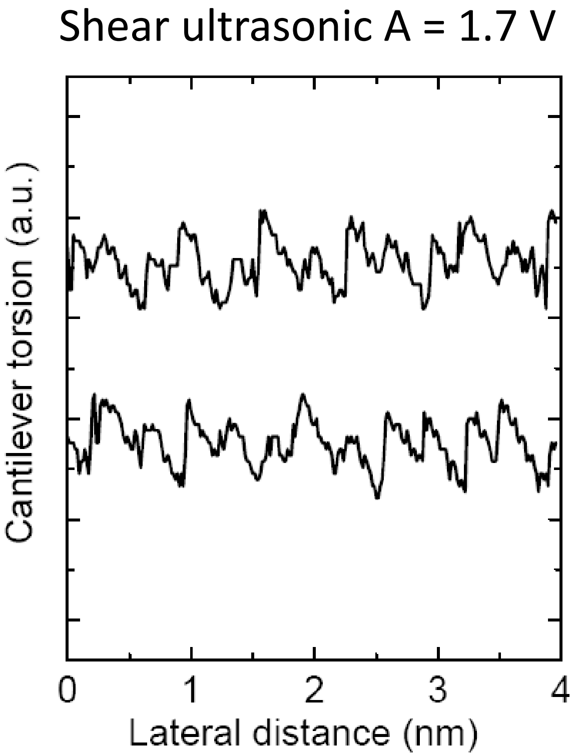
Heuberger et al. J. Phys. Chem. (1998)

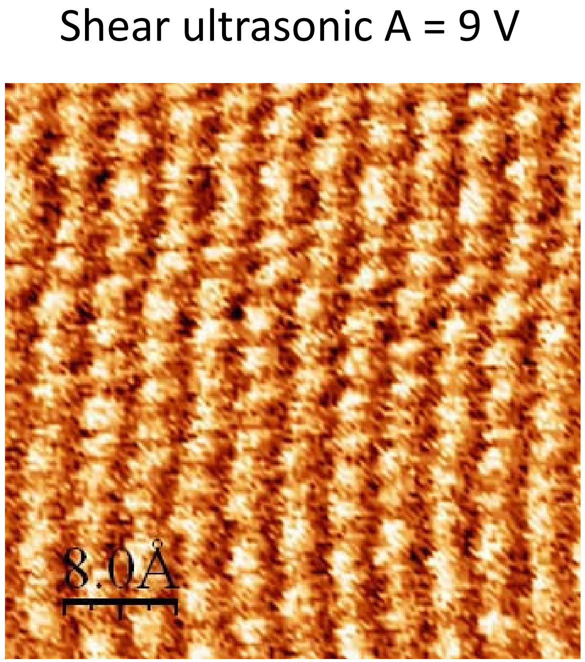
CONTROL OF FRICTION

Results on HOPG

REDUCTION OF FRICTION BY LATERAL ULTRASONIC VIBRATION

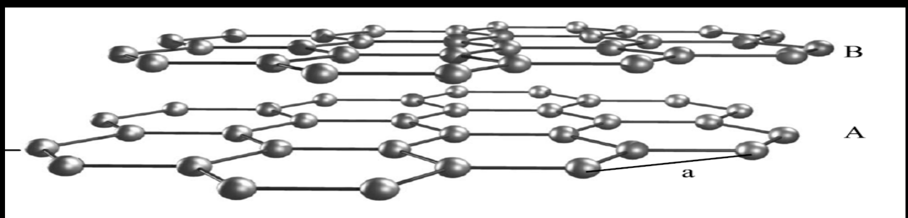






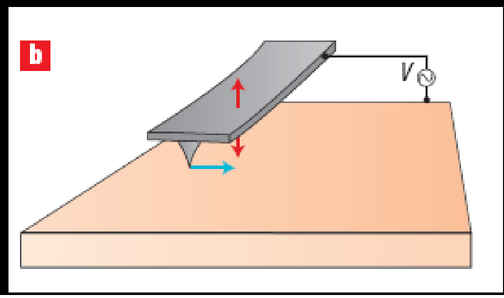
M. T. Cuberes (in preparation for issue in Tribology Letters)

SUPERLUBRICITY: *Registry betwen the sliding surfaces*



Dienwiebel et al. PRL (2004)

Normal mechanical resonances



Socoliuc et al. Science (2006)

The Abdus Salam
International Centre for Theoretical Physics

United Nations
Educational, Scientific and
Cultural Organization

IAEA
International Atomic Energy Agency

2063-21

ICTP/FANAS Conference on trends in Nanotribology

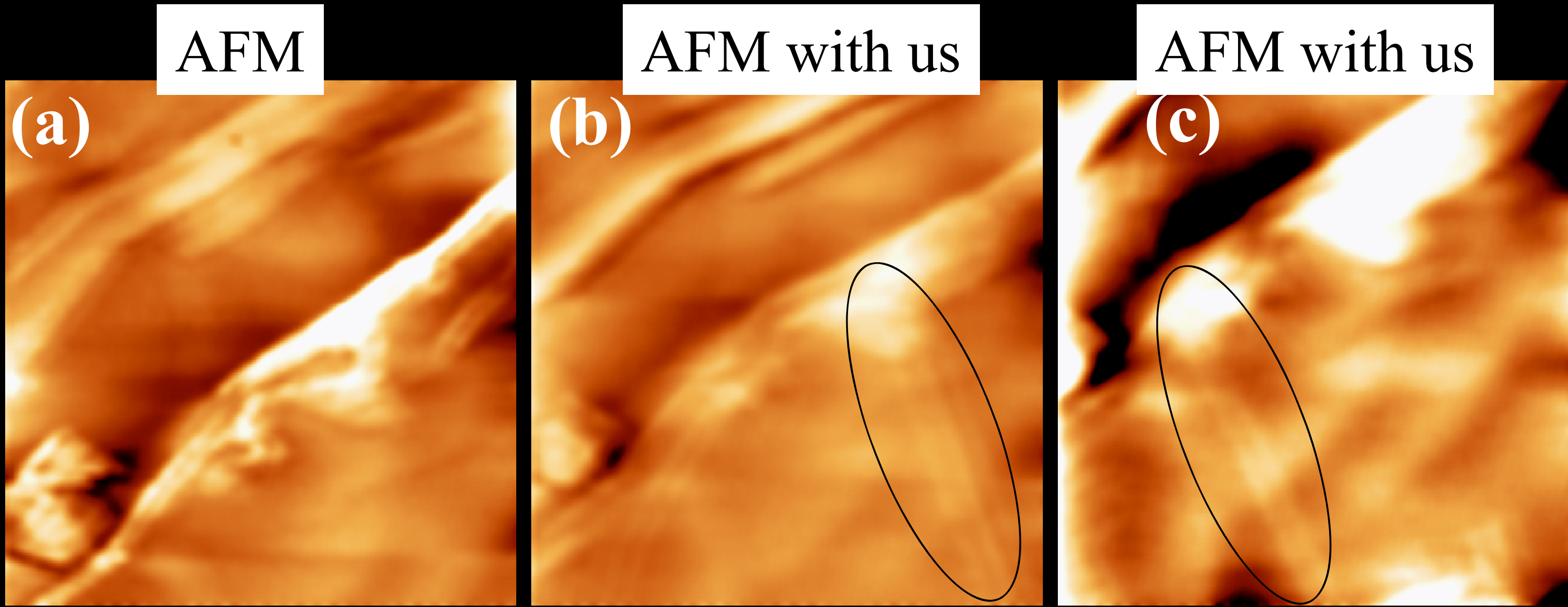
19 - 24 October 2009

Ultrasonic nanolithography on hard substrates

Teresa Cuberes

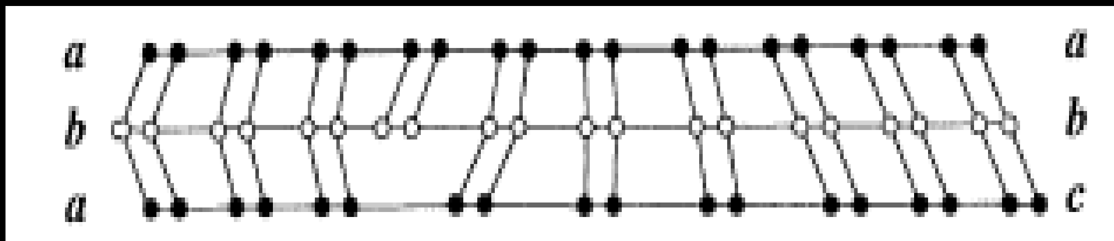
University of Castilla La Mancha
Almaden
Spain

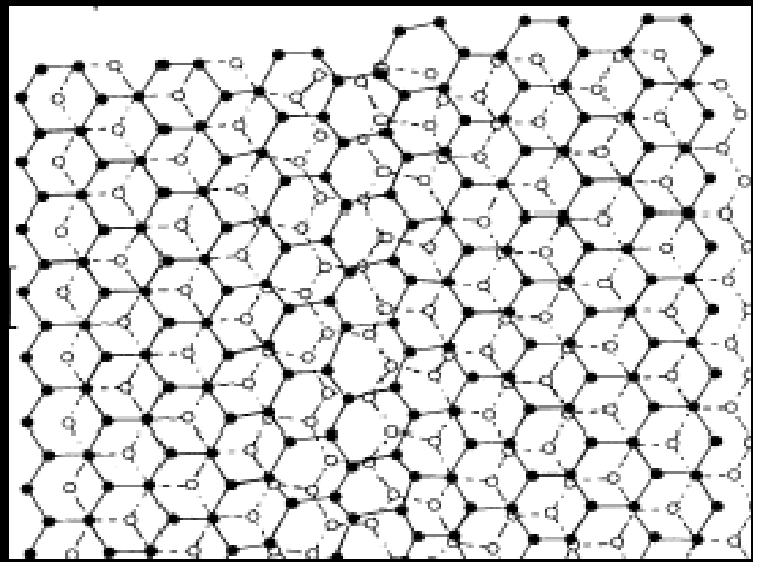
MANIPULATION OF SUBSURFACE DISLOCATIONS IN HOPG



700 nm x 700 nm

Fo: 105 nN *Cantilever stiffness: 0.35 Nm^{-1}*

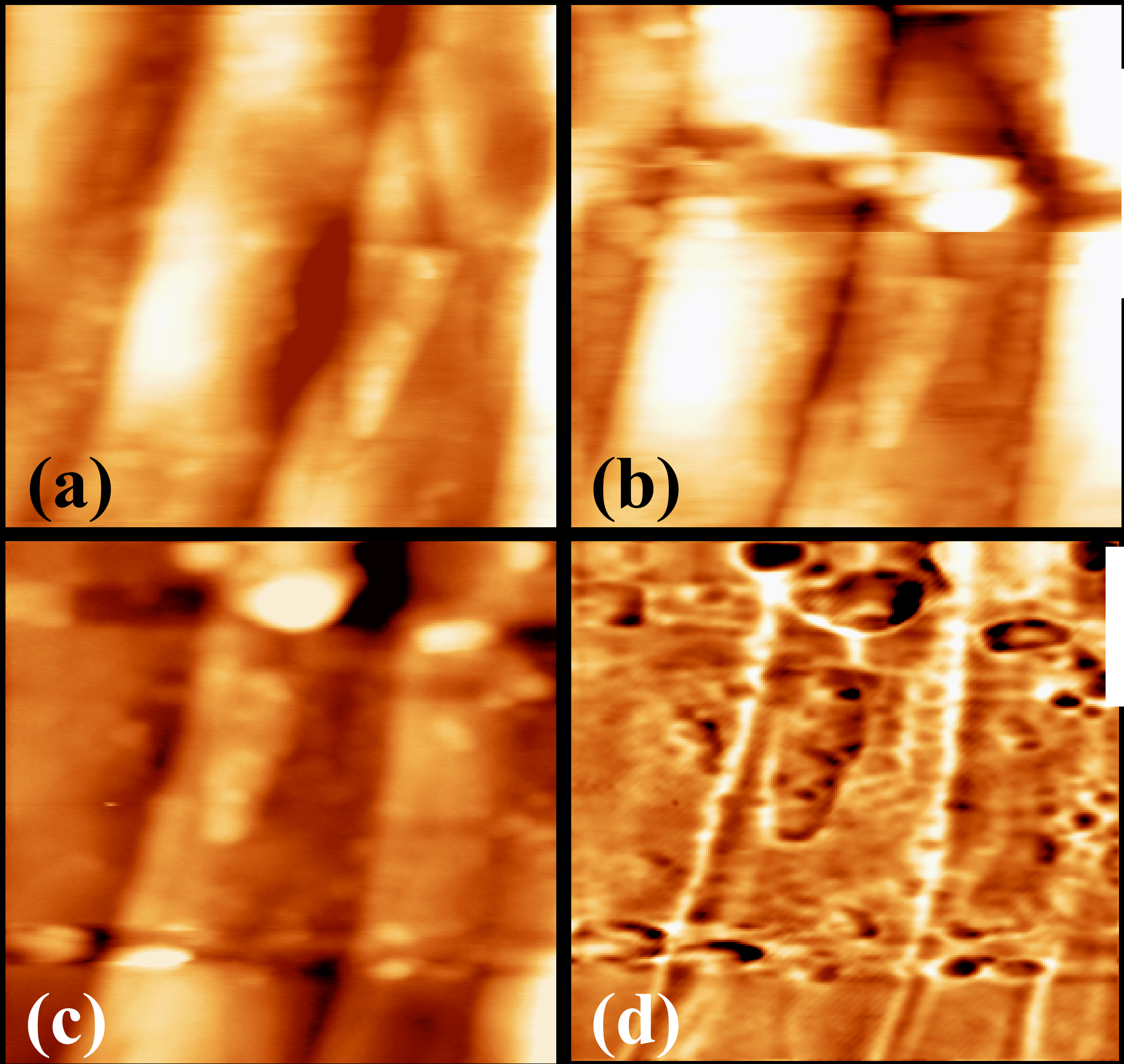




Cuberes J. of Phys. : Conf. Ser. (2007)

ULTRASONIC GENERATION OF WEAR ON HOPG

Wear of HOPG is observed after repeteadly scanning over the same surface region in the presence of us excitation of up to 4.2 nm in A.



(a) and (b) AFM with us A ≈ 1.7 nm *recorded in sequence*

(c) AFM and (d) UFM *simultaneously recorded*

M. T. Cuberes (in preparation for issue in Tribology Letters)

2.5 μm x 2.5 μm; Fo:160 nN

Outline

- ***Mechanical-diode-mode Ultrasonic AFM***

  -The Mechanical-Diode (MD) effect: UFM, HFM, IC-HFM

- ***Tribology with ultrasonic-AFM***

  - Study of adhesion hysteresis and energy dissipation with UFM

  - Study of friction and lubrication with MD- UFFM

  - Control of friction and generation of wear using ultrasound

- ***Ultrasonic nanolithography on hard substrates***

  - Results on Si(111)

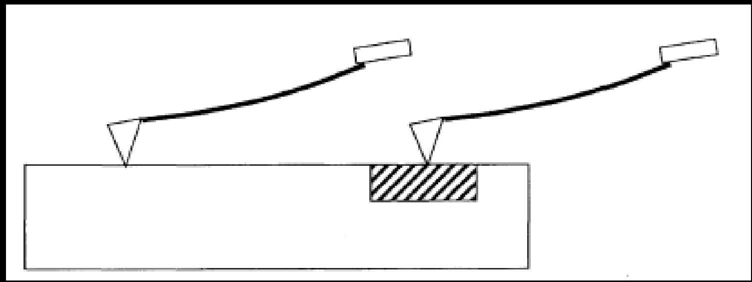
- ***Summary***

Advantages for nanofabrication

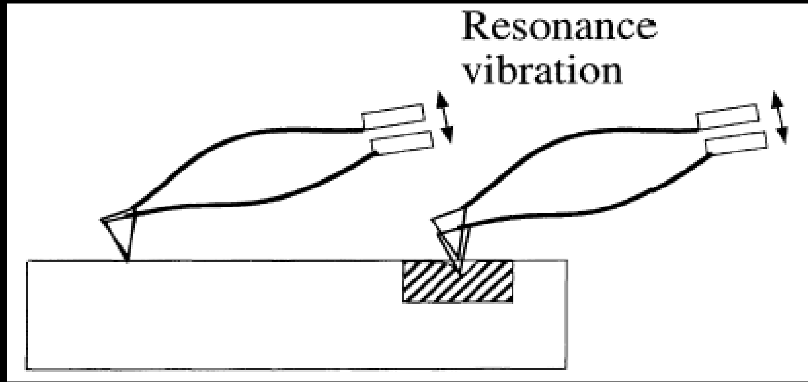
Ultrasonic-AFM

M.T. Cuberes, J. of Phys.: Conf. Ser. 61 (2007) 219

➡ It is possible to ***indent hard materials*** with a ***soft cantilever***

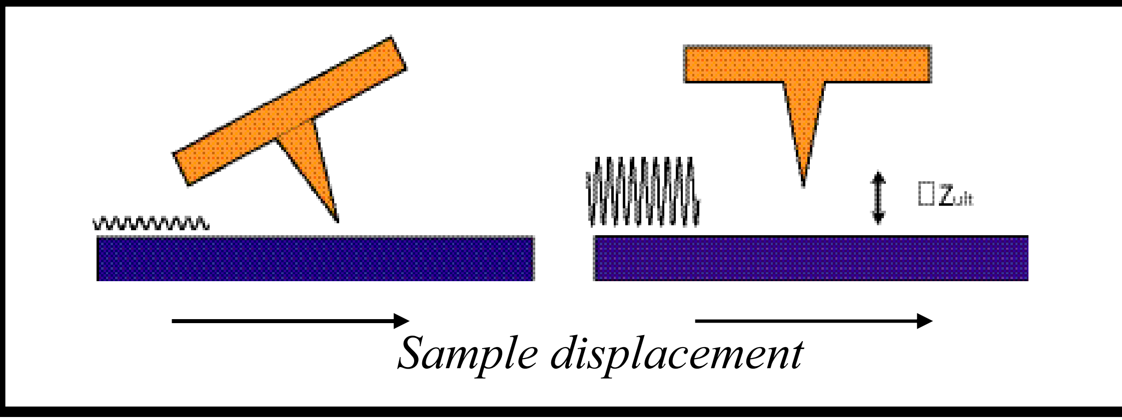


A soft cantilever can be dynamically stiffened!



Yamanaka and Nakano., Jpn. J. Appl. Phys. 35, 3787 (1996)

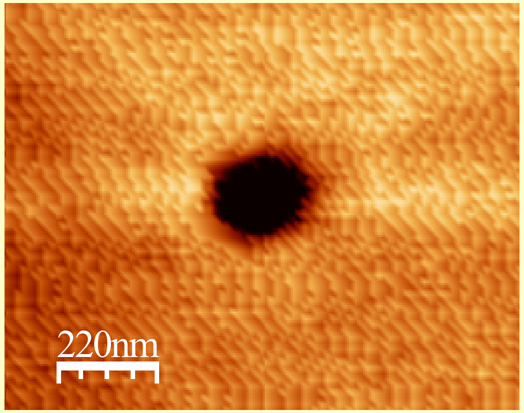
➡ ***Friction at the nanometer scale vanishes*** in the presence of ultrasonic vibration of sufficiently high amplitude

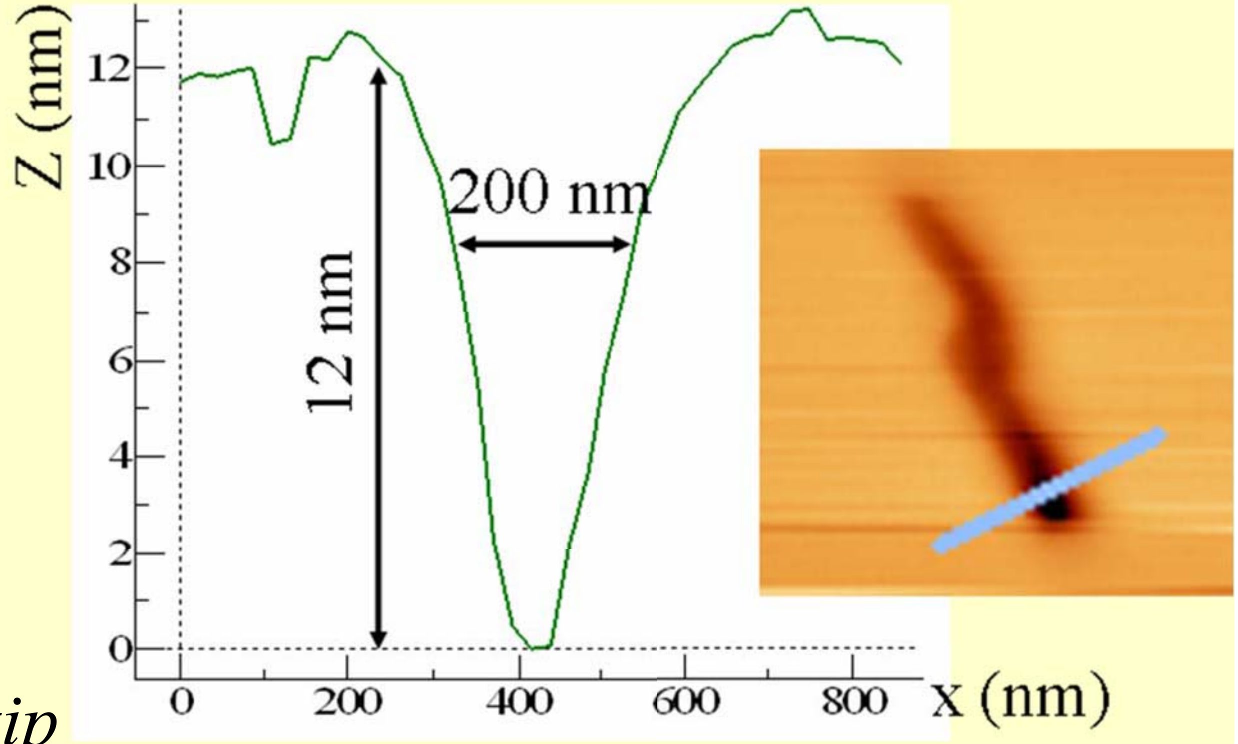


Sonolubrication at the nanoscale!

Dinelli et al. Appl. Phys. Lett. 71 1177 (1997)

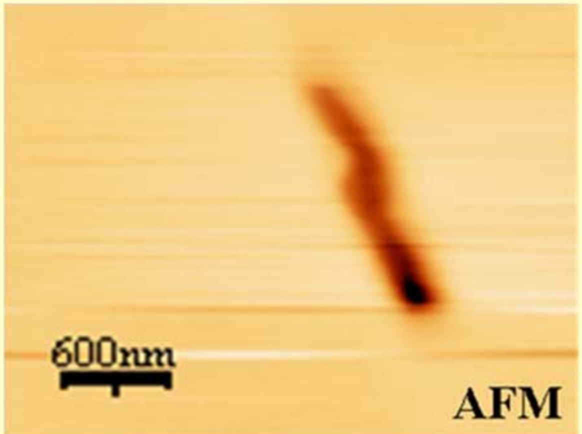
NANO ULTRASONIC MACHINING





Hole and scratch on Si(111) by ultrasonic action with an AFM tip

Diamond-coated tip DCP20, NT-NDT
Rc:35 nm; L:10-15 µm; diamond t: 70 nm;
Kc:28-91 N m^{-1}



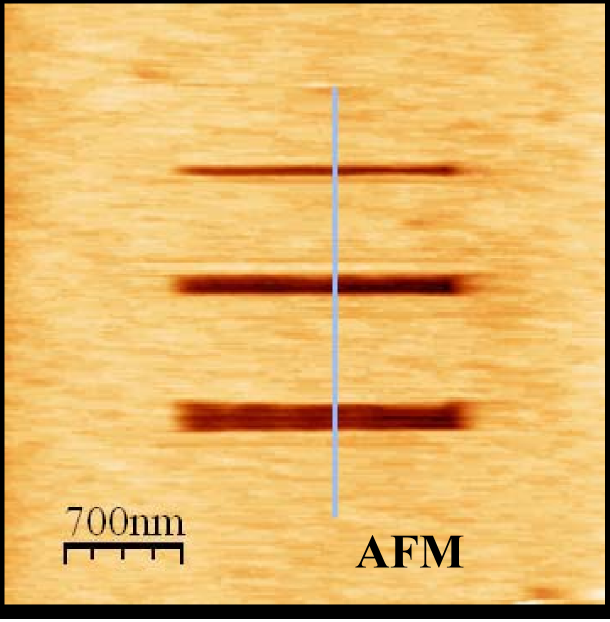
M.T. Cuberes, G. I. T. Imaging & Microscopy 4 (2007) 36

SCRATCHES on Si(111): 50, 75 and 100 lines with Fn=37 nN, *f*=5 MHz, Am=0.5 V

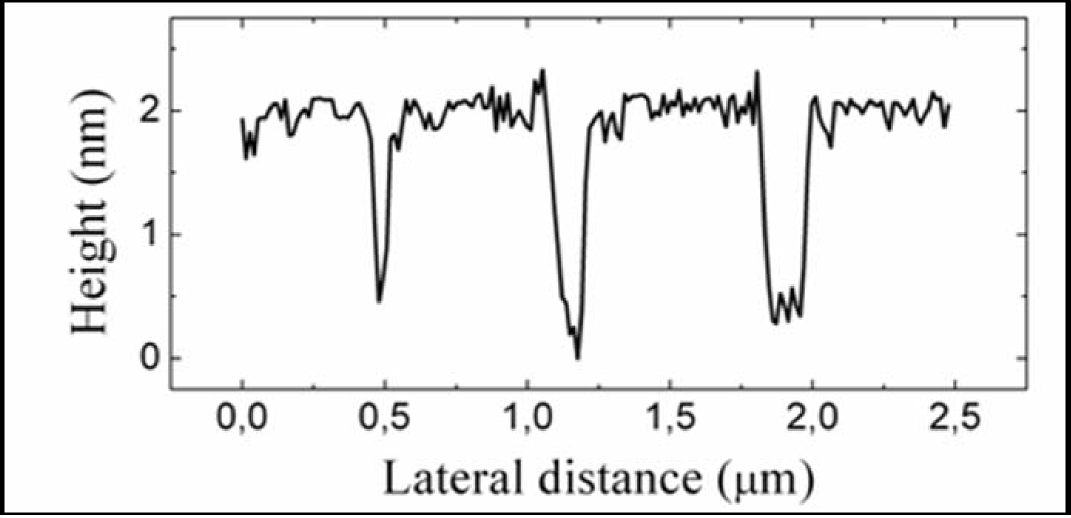
OLYMPUS Si_3N_4

Kc:0.11 N m^{-1} ω: 22 KHz

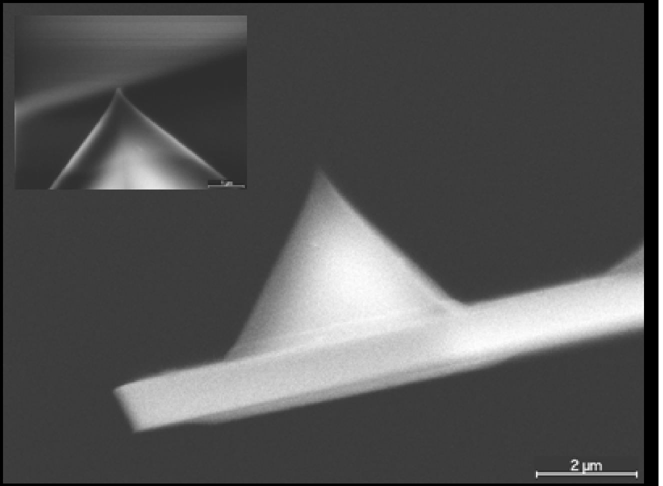
AFM : Fo:13 nN



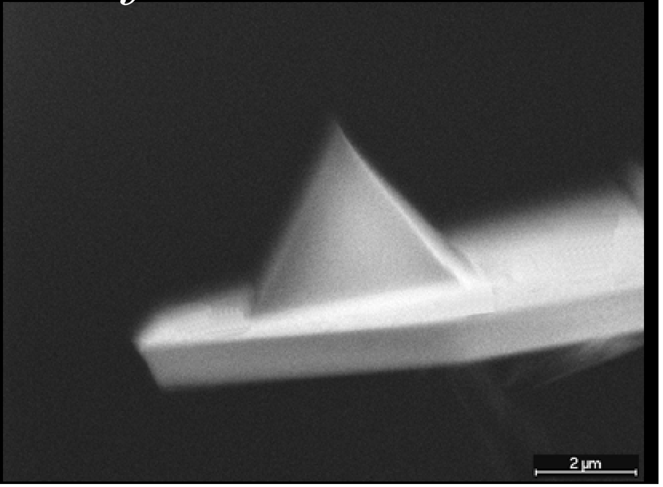
M.T. Cuberes, G. I. T. Imaging & Microscopy 4 (2007) 36



after



before



Summary

- ***Mechanical-diode-mode Ultrasonic AFM***

  -The Mechanical-Diode (MD) effect: UFM, HFM, IC-HFM: MD mode valuable; novel techniques proposed.

- ***Tribology with ultrasonic-AFM***

  - Study of adhesion hysteresis and energy dissipation with UFM: ultrasonic-amplitude-dependent quasistatic energy states

  - Study of friction and lubrication with MD- UFFM: novel technique proposed with results on Si(111) and HOPG.

  - Control of friction and generation of wear using ultrasound: lateral ultrasonic vibration reduces friction; ultrasound facilitates generation of wear

- ***Ultrasonic nanolithography on hard substrates***

  - Results on Si(111): Ultrasound facilitates nanoscratching of Si(111)

ACKNOWLEDGEMENTS

Group of *Nanotechnology and Materials* of the UCLM:

Juanjo Martínez
Carmen Iniesta
Salvatore Marino
Alejandro Rodríguez

http://www.uclm.es/organos/vic_investigacion/gruposweb/nanotecnologia/

Finantial support from **Castilla-La Mancha (JCCM)** ***(projectPBI-08-092)*** is gratefully acknowledged