ICTP/FANAS Conference on trends in Nanotribology

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Ultrasonic nanolithography on hard substrates

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ULTRASONIC NANOLITHOGRAPHY ON HARD SUBSTRATES

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The Laboratory of Nanotechnology, Almaden, SPAIN
• **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

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)

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

ULTRASONIC FORCE MICROSCOPY

Ultrasonic force:

\[ k z_c = \frac{1}{T} \int_{0}^{T} F(z_c - z_s - A \cos \omega t) \, dt \]


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**

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**SCANNING NEAR FIELD ULTRASOUND HOLOGRAPHY**

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

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*M. T. Cuberes et al.*

*Shekhawat and Dravid.*
*Science 310, 90 (2005)*
**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

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• **Summary**
ULTRASONIC CURVES

O. Kolosov and K. Yamanaka,

M. T. Cuberes et al.
Nanotechnology (2001)
ELASTIC MODULUS AND ADHESION

Dinelli, et al.  
PRB (2000)

Moving along the Force - Distance Curve

(1): initial indentation.  
(2): just before a jump-up  
(3): just after a jump-up

Inagaki et al.  
APL (2002)

Szoskiewicz et al.  
APL (2003)

\[ S_{\text{eff}}(F_{\text{av}}) = \frac{F_2 - F_1}{a_2 - a_1} \]
Simulations of the *ultrasonic force* versus *ultrasonic amplitude* curves:

**ULTRASONIC-AMPLITUDE DEPENDENT TIP-SAMPLE FORCE CURVES**

ULTRASONIC-AMPLITUDE DEPENDENT POTENTIAL ENERGY CURVES

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

MD-UFFM: NANOSCALE FRICTION AND LUBRICATION

MD-ULTRASONIC FRICTION FORCE MICROSCOPY

Lateral Mechanical Diode Effect!


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

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


Friction reduces for increasing shear ultrasonic amplitudes; above a critical value, the lateral ultrasonic force remains constant. No lift-off is observed on HOPG!

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

REDUCTION OF FRICTION BY LATERAL ULTRASONIC VIBRATION

**Results on HOPG**

Without ultrasound

Shear ultrasonic $A = 1.7 \, \text{V}$

Shear ultrasonic $A = 9 \, \text{V}$

**SUPERLUBRICITY:** Registry between the sliding surfaces

Normal mechanical resonances

Dienwiebel et al. PRL (2004)

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MANIPULATION OF SUBSURFACE DISLOCATIONS IN HOPG

(a) AFM
(b) AFM with us
(c) AFM with us

700 nm x 700 nm
Fo: 105 nN    Cantilever stiffness: 0.35 Nm⁻¹

Wear of HOPG is observed after repeatedly scanning over the same surface region in the presence of ultrasound 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

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- **Summary**
Advantages for nanofabrication

It is possible to \textit{indent hard materials} with a \textit{soft cantilever}.

\textit{A soft cantilever can be dynamically stiffened!}

\textit{Friction at the nanometer scale vanishes} in the presence of ultrasonic vibration of sufficiently high amplitude.

\textit{Sonolubrication at the nanoscale!}

\textbf{Ultrasonic-AFM}


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,
**SCRATCHES on Si(111):** 50, 75 and 100 lines with $F_n=37\ nN$, $f=5\ MHz$, $A_m=0.5\ V$

**AFM:** $F_0=13\ nN$

**OLYMPUS Si$_3$N$_4**

$K_c=0.11\ N\ m^{-1}$ $\omega=22\ KHz$

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)
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