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ICTP/FANAS Conference on trends in Nanotribology

19 - 24 October 2009

Controlling single cluster dynamics at the nanoscale

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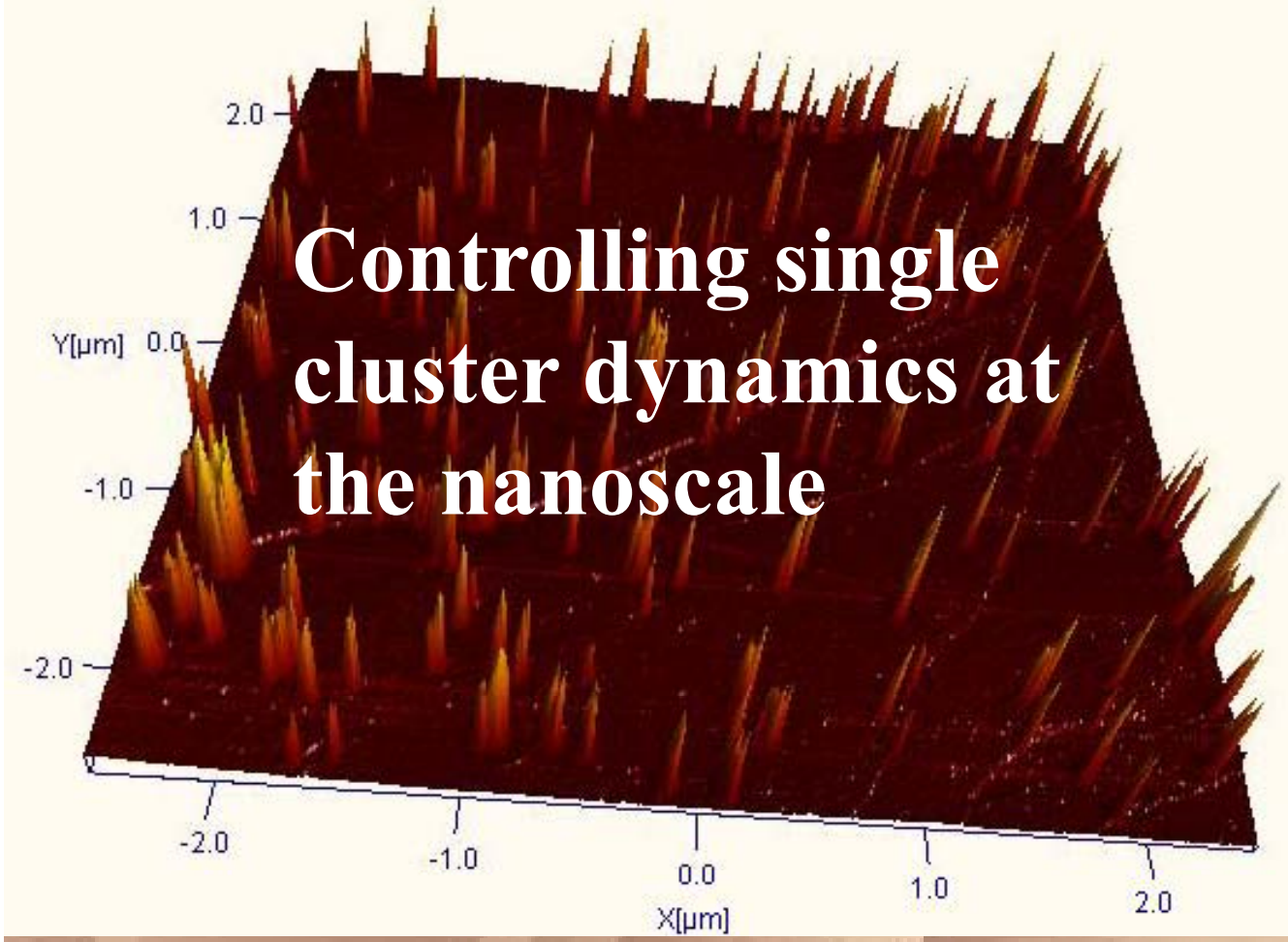

Controlling single cluster dynamics at the nanoscale

Outline :

- **Introduction**
- **Experimental method**
- **Detachments**
- **Movements**
- **Conclusions**

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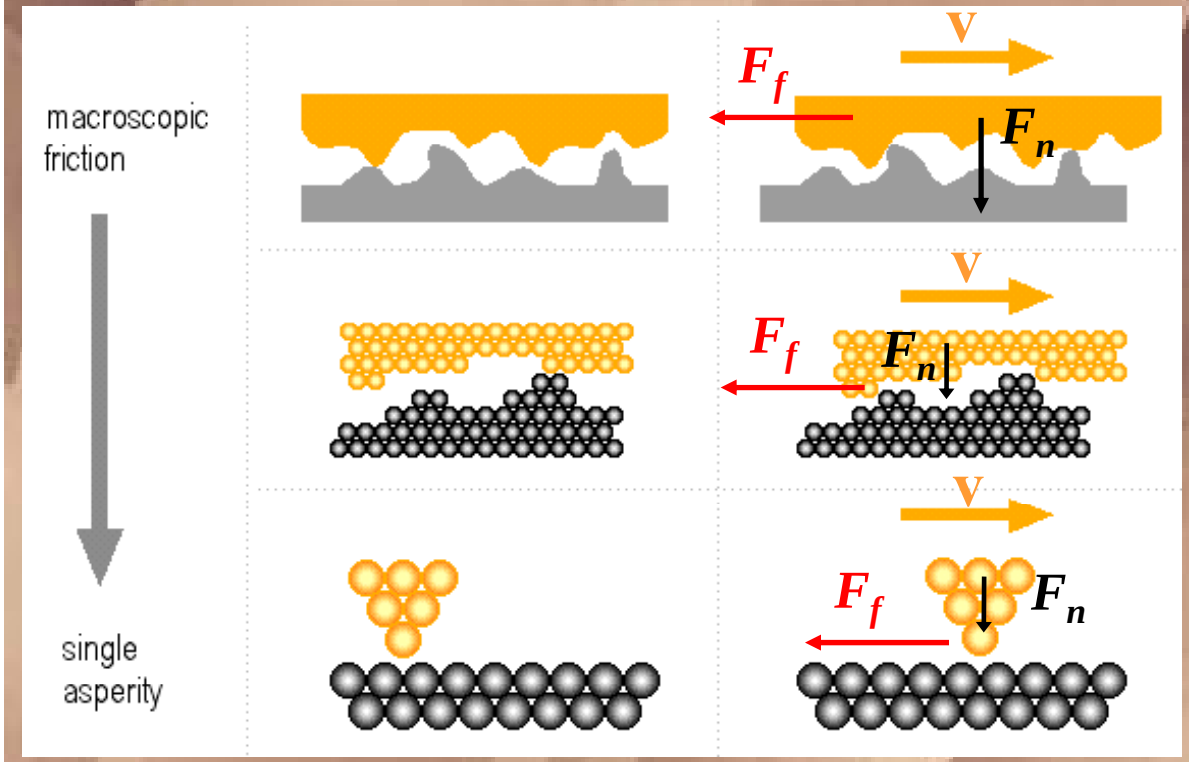
Introduction

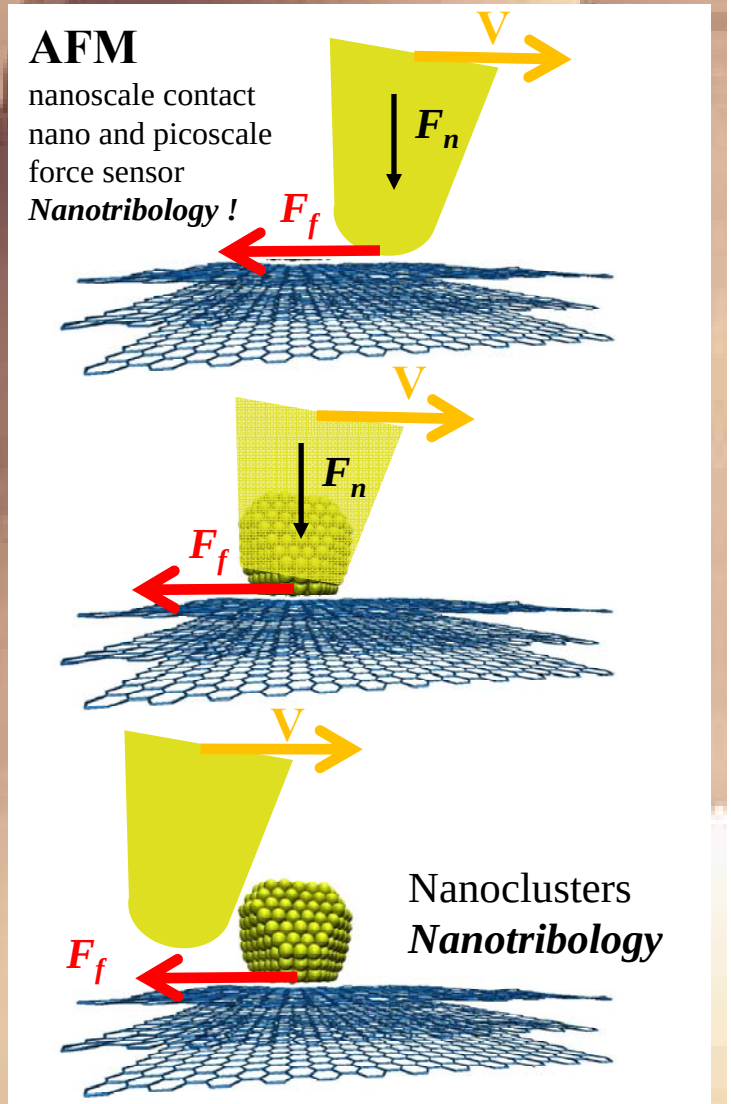
Tribology



Tribology at the atomic scale

Experimental method

AFM
nanoscale contact
nano and picoscale
force sensor
Nanotribology !



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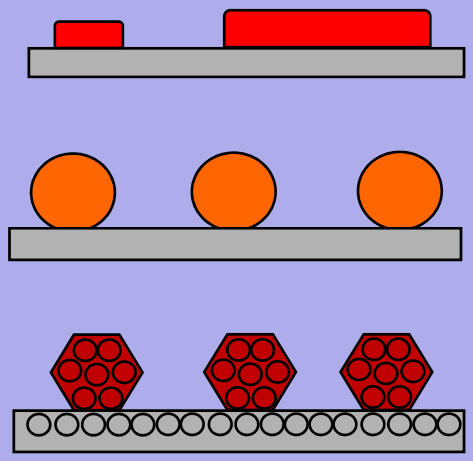
Introduction

Nanoclusters represent "specialised tool" to study friction at the nanoscale:

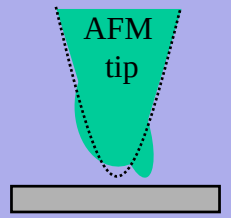
- ***Controlled and variable contact size, range: 10- 200 nm***
- ***Controlled and variable compositions at the contact interface***
- ***Well defined cristalline interface***
- ***Dynamical behaviour***



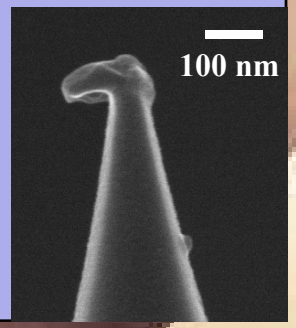
Defined contact areas at the nanometer scale can be obtained by using island deposited on surface.

Statistical analysis may be performed on a uniform size clusters deposition

Commensurabilty effects on cristalline interface



Is difficult to control AFM tip shape during the microscope operation



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System

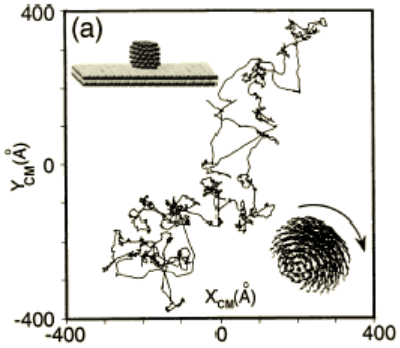
Gold /antimony nanoclusters on graphite (*HOPG*) possess peculiar *dynamical* characteristics:

-very high diffusion coefficient

L. Bardotti et al Phys. Rev. Lett. 74 (1995) 4694

- distinctive motion features :

- ***pinnig effects***
- ***Lévy flights***
- ***rotation***



W.D. Luedtke and U. Landman Phys. Rev. Lett. ***82*** *(1999) 3835*
L. Lewis et al Phys. Rev. B ***61*** *(2000) 16084*
S. Pisov et al J.Phys.: Condes. Matter ***19*** *(2007) 305015*

superlubric translations

D. Dietzel et al
Phys. Rev. Lett. ***101****, 125505 (2008)*

Tribology interest at the nanoscale

Experiment

CONDITIONS

- **Gold clusters ∅ 10-50 nm**
- **Ambient conditions**
- **AFM induced translations**

OBJECTVES

- ***controlled movements***
- ***static friction versus contact area***

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Experimental details

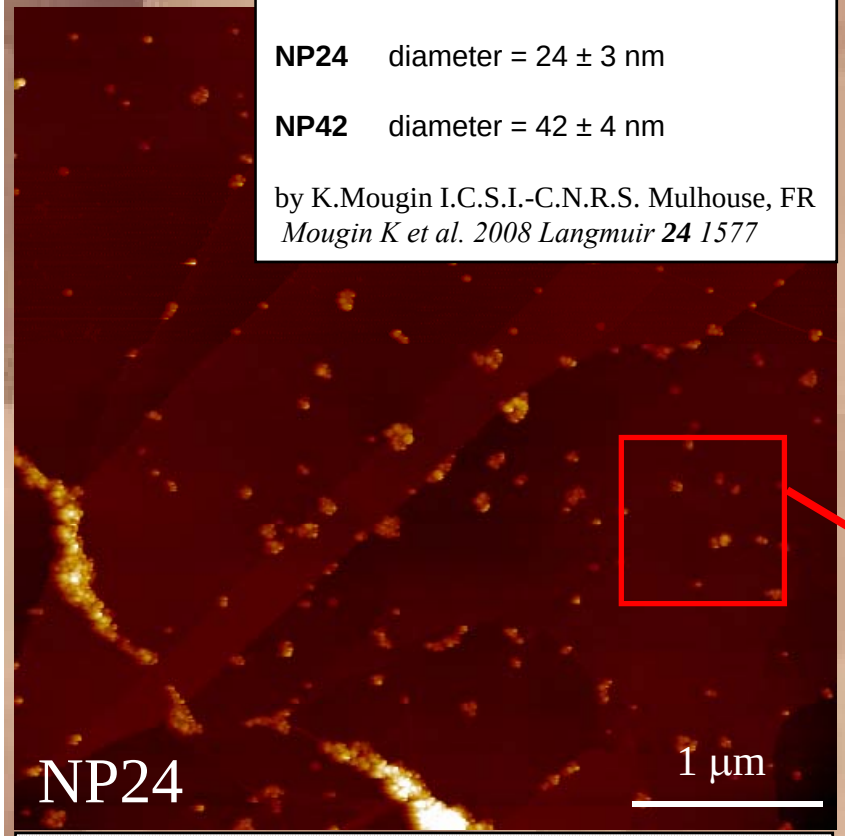
Three different cluster sizes were used :

NP13 diameter = 13 ± 2 nm

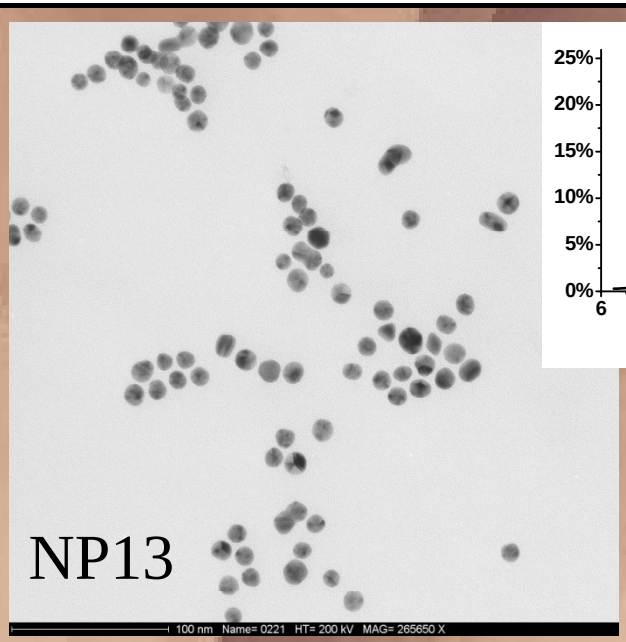
NP24 diameter = 24 ± 3 nm

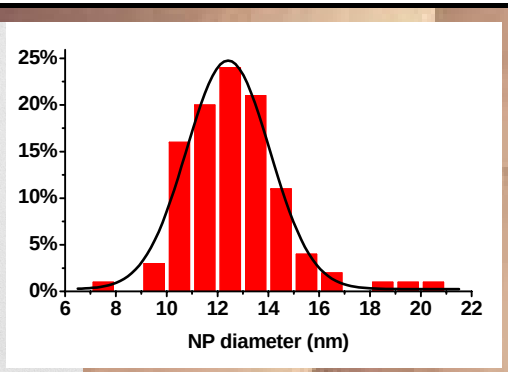
NP42 diameter = 42 ± 4 nm

by K.Mougin I.C.S.I.-C.N.R.S. Mulhouse, FR
*Mougin K et al. 2008 Langmuir **24** 1577*



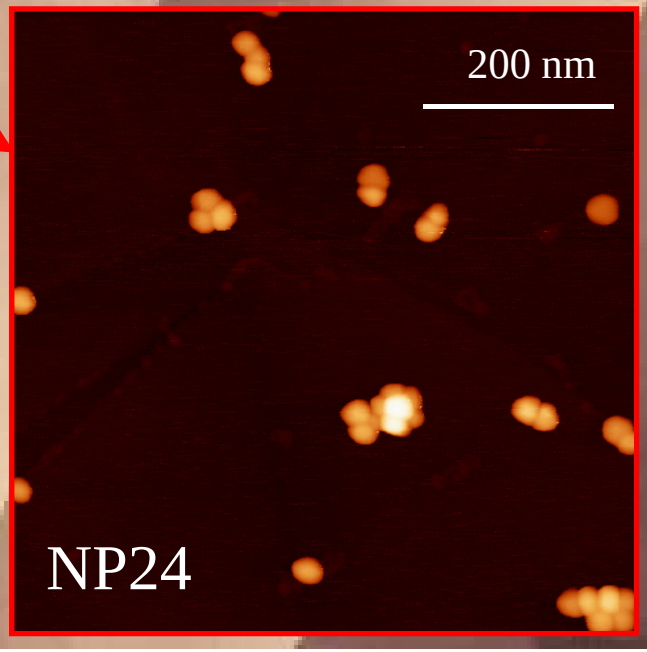
Gold nanoclusters deposited on a freshly cleaved HOPG surface
A droplet of suspension containing nanoclusters of well defined size is deposited onto the surface (air, RT) then dried with a nitrogen flux.





Height distribution corresponds to diameter distribution obtained by TEM

Spherical shape



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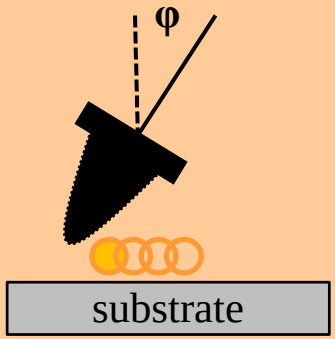
Experimental method

Contact AFM



- **Torsional bending (φ)**
- **Force measurement**

➢**Standard FFM**

Dynamic AFM

- **Amplitude oscillations**
- **Phase**
- **Frequency**

➢**Damping effects**

- Tip + cantilever + sample are in a **dynamic equilibrium state.**

$$\langle P_{dis} \rangle = \langle P_{in} \rangle - \langle P_0 \rangle$$

- The system is a **point mass driven oscillator with damping**
- actuator and tip oscillate like simple **sinusoidal waves**
- $\langle P_0 \rangle = \frac{1}{2}\alpha\omega^2 A^2 \quad \alpha = effective\ damping\ coefficient = \frac{k}{Q\omega_0}$

$$\rightarrow \langle P_{dis} \rangle = \frac{1}{2}\frac{\omega k A}{Q}\left(QA_d \sin\phi - A\frac{\omega}{\omega_0}\right)$$

At the resonance $\omega = \omega_0$, $A_0 = QA_d$; normalised to the period T

$$\rightarrow \langle E_{dis} \rangle = \frac{\pi k A^2}{Q}\left(\frac{A_0}{A}\sin\phi - 1\right)$$

- T. Trevethan *et al.* Phys Rev. Lett. **98**, 028101 (2007)
-R. Garcia *et al.* Nature Materials **6**, 405 (2007)
-H. Hölscher Appl. Phys. Lett. **89**, 123109 (2006)
-N.F. Martinez and R. Garcia Nanotechnology **17**, S167 (2006)
-R.Garcia *et al.* Phys Rev. Lett. **9**, 016103 (2006)
- B. Anczykowski *et al.* Appl. Surf. Science **140,** 376 (1999)

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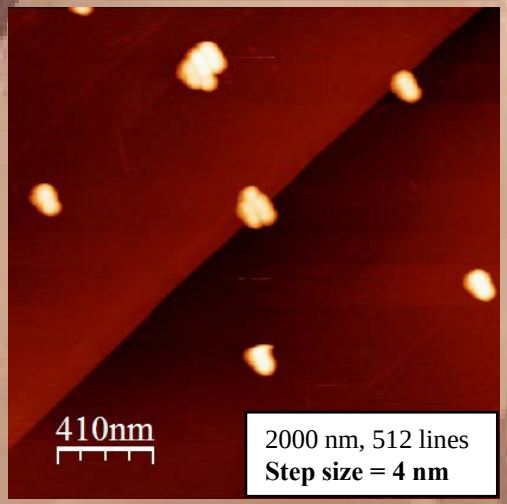
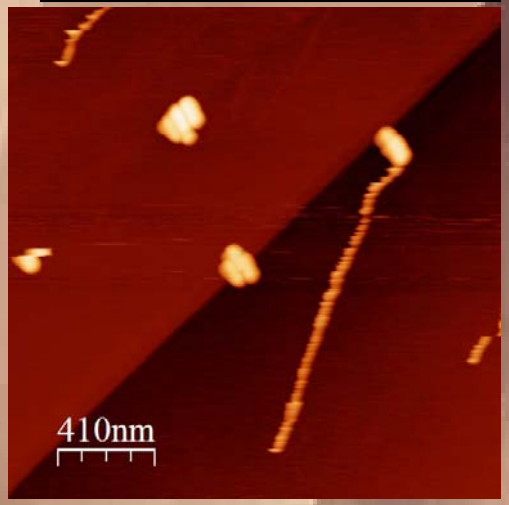
Amplitude Modulation - AFM *Tapping mode*

NP 42

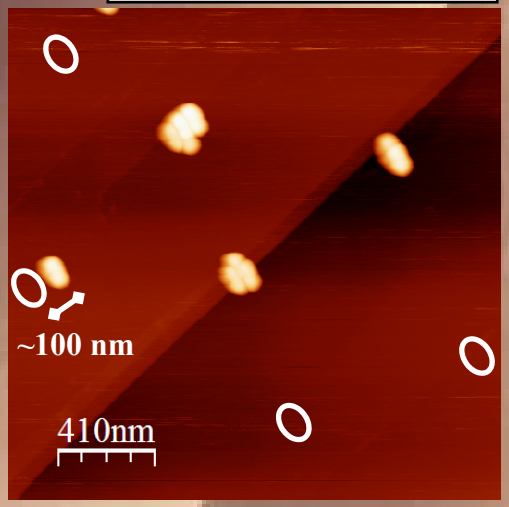
Initial image, *topography*
A_0 =13 nm, A = 10 nm



Manipulation scan, *topography*
A_0 =15 nm, A = 10 nm



Final image, topography
A_0 =13 nm, A = 10 nm



Tip and cantilever act as external exitation sources and they may induce clusters detachments and movements

Movements are intentionally induced using a tip amplitude oscillation A_0 larger than that optimised for imaging purpose.

Controlling parameter is the energy dissipation signal measured on clusters

$$\langle E_{dis} \rangle = \frac{\pi k A^2}{Q}\left(\frac{A_0}{A}\sin\phi - 1\right)$$

cluster –substrate properties

- G. Paolicelli *et al.* Appl. Phys. Lett. **95,** 143121 (2009)
- A. Rao, *et al.* Nanotechnology **20**, 115706 (2009)
- G. Paolicelli *et al.* J.Phys.:Condens. Matter **20**, 354011 (2008)
- K. Mougin *et al.* Langmuir, **24**, 1577 (2008)
- C. Ritter *et al.* Phys. Rev. B **71,** 085405 (2005)

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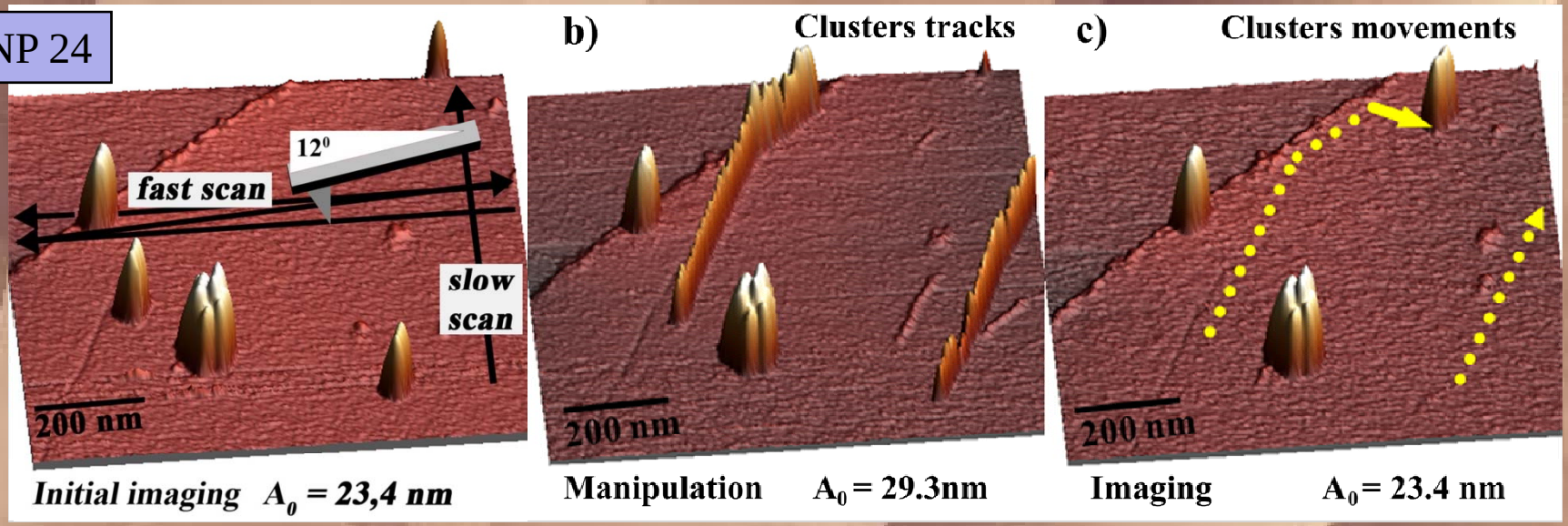
NP 24



Appl. Phys. Lett. **95,** 143121 (2009)

Clusters initially sitting on a graphite step remain pinned on their positions
Typical behaviour of surface defects

Clusters move towards the slow scan direction by small steps

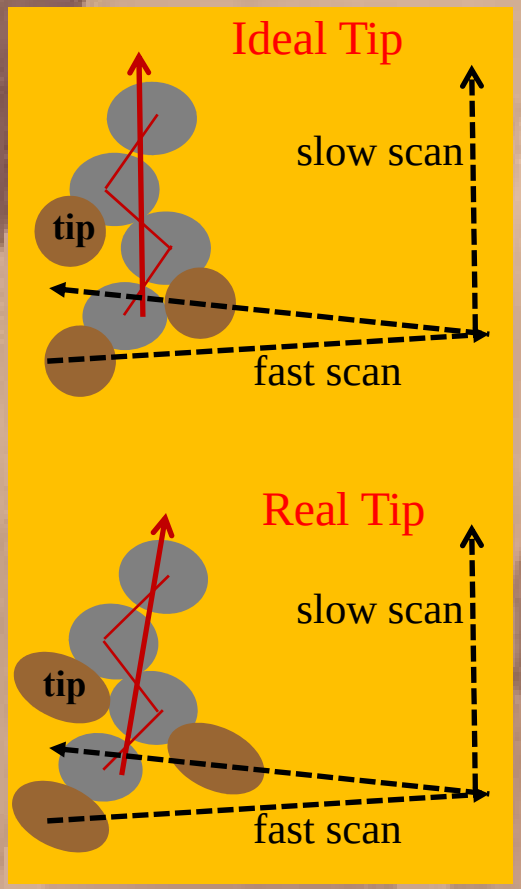
Clusters usually do not cross the steps and trajectories are modified on their proximity

We have found few large jumps
*Our results seem to agree with recent measurements by D. Dietzel et al. (Phys. Rev. Lett. **101**, 125505 (2008)) who observed, by contact AFM, superlubric translations of antimony island on HOPG graphite.*

Interaction mechanisms ?

Quantitative measurements ?

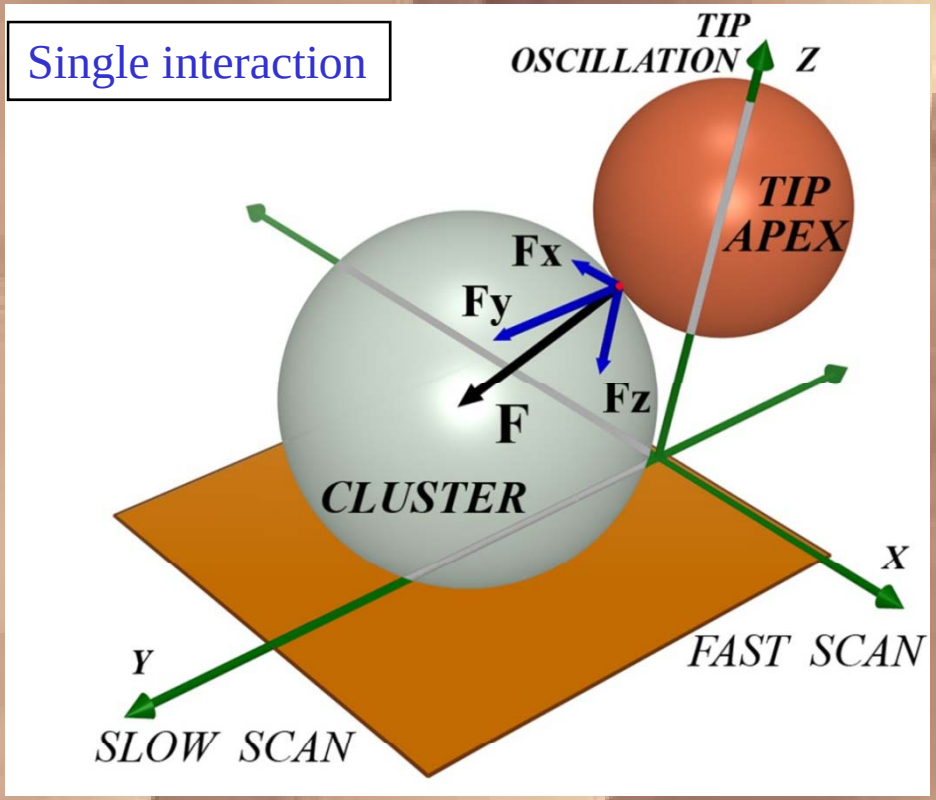
Trajectory



•Comparable tip and clusters dimensions
•Scan step smaller than tip and cluster diameter

A. Rao, E. Gnecco, D. Marchetto, K. Mougin, M. Schönenberger, S.Valeri, and E. Meyer Nanotechnology **20**, 115706 (2009)

Single interaction



•Consider only the final repulsive force acting during the contact **F**
•Spherical shape for both the cluster and tip apex,

Then the force scheme becomes intrinsically anisotropic respect to the substrate surface normal and sensitive to the force components ***Fx ,Fy coplanar to the graphite surface.***

M. S. Marcus, R. W. Carpick, D. Y. Sasaki, and M. A. Eriksson, Phys. Rev. Lett. **88,** 226103 (2002).
D. A. Aruliah, M. H. Muser and U. D. Schwarz Phys. Rev. B **71** 085406 (2005)

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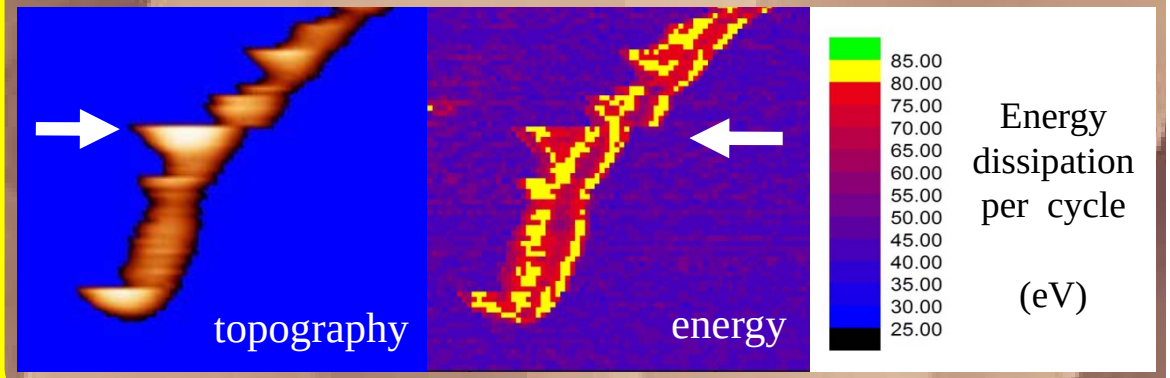
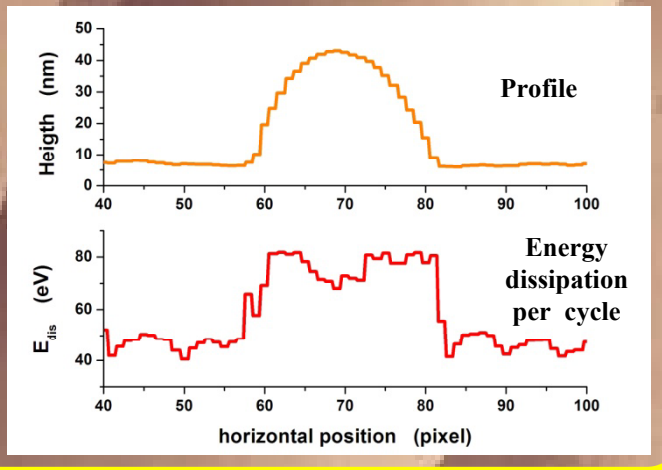
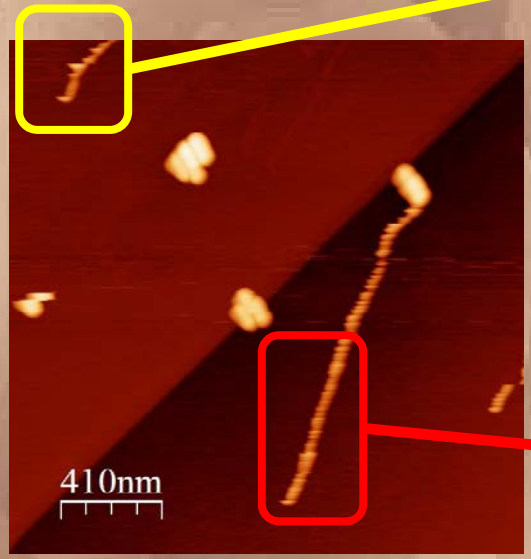
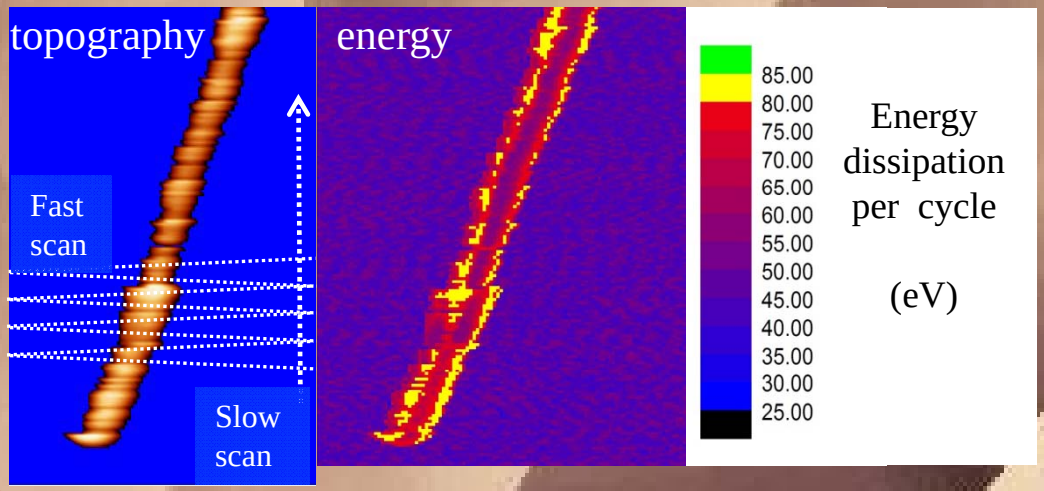








Manipulation scan
A_0 **=15 nm**, A = 10 nm

NP 42

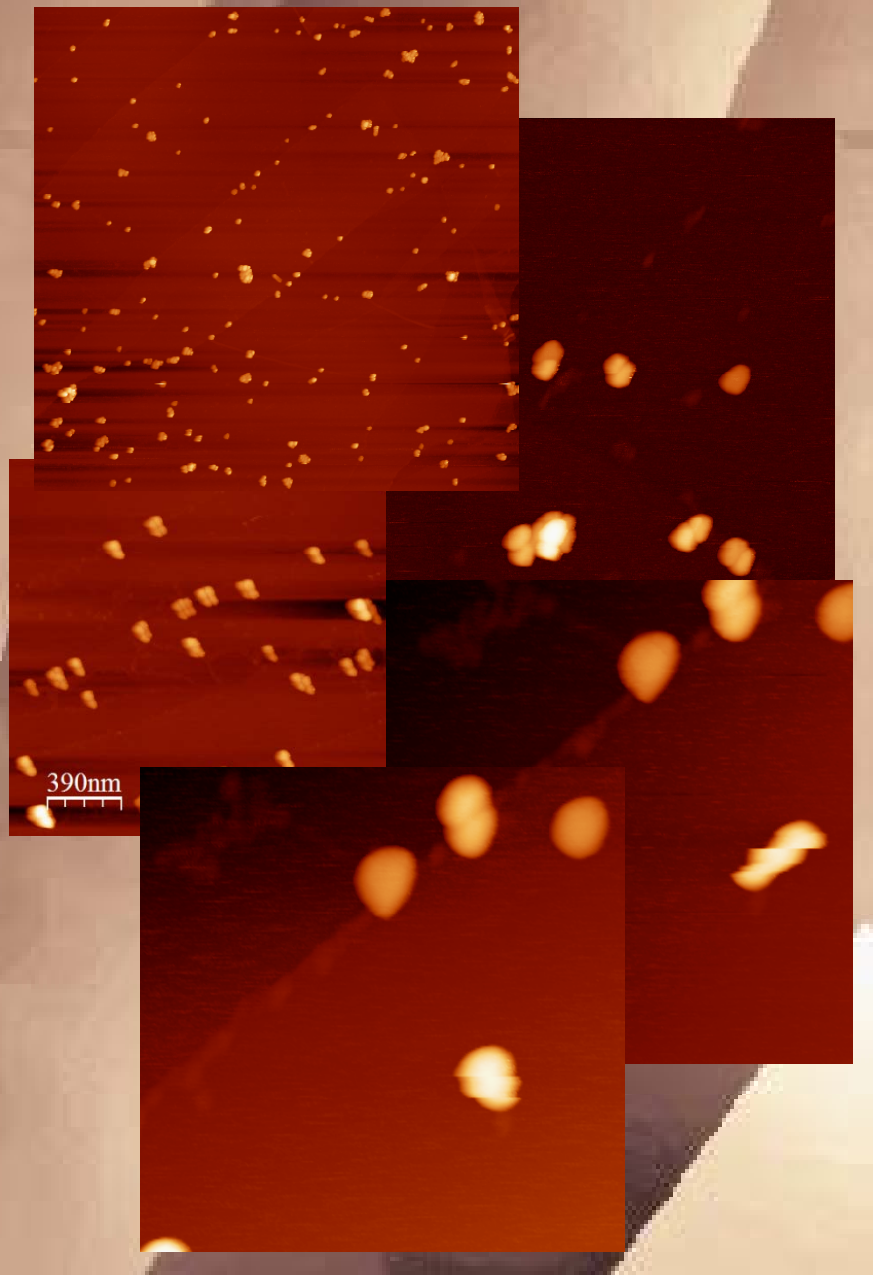
Clusters detachments

We explore an equivalent area of about **10 μm²** for NP13, NP24 and NP42 systems

Each equivalent area contains a total amount of about
140clusters.

About **18 differents tips** were used each of them calibrated according to :
Sader *et al. Rev. Sci. Instrum.* ***70*** *(1999) 3967*

Two kinds of tips (*nominal values*) :
K=3 N/m f=75 kHz
K=40 N/m f=300 kHz



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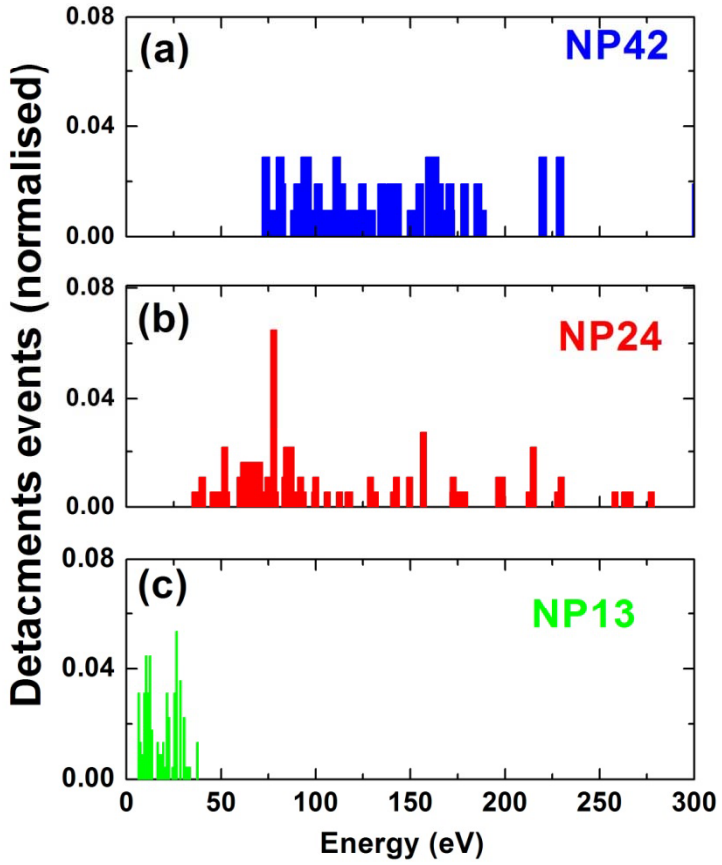
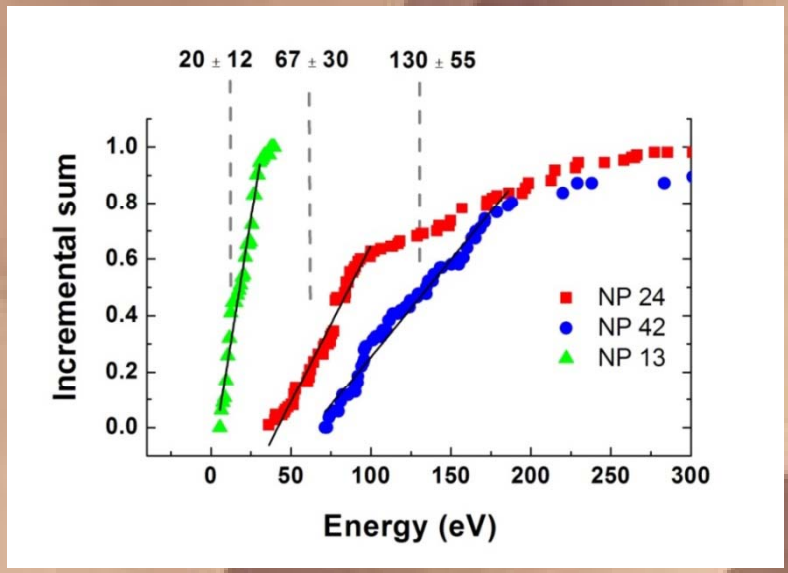
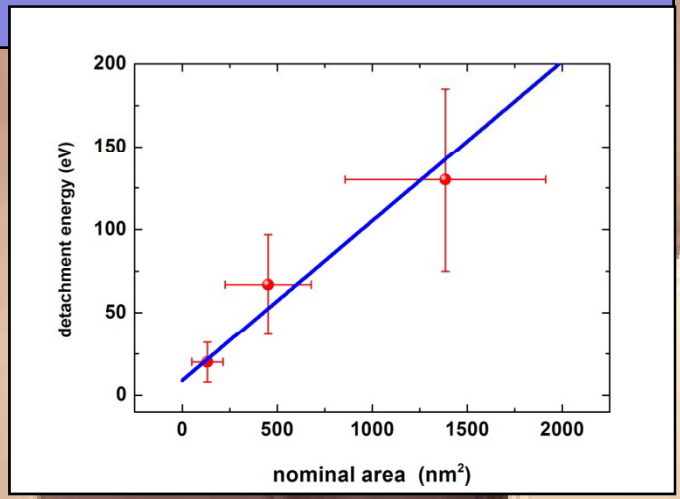
Clusters detachments



Panel (a) , (b) and (c)
Number of detachment events (normalized to the total number of single clusters) and their associated detachment energy sorted by increasing energy .



Incremental sum of detachments events. The linear increase represents regions where detachment occurrence has random uniform probability. Energy thresholds are located in the centre of these regions, while their wid th fix the maximum associated errors .



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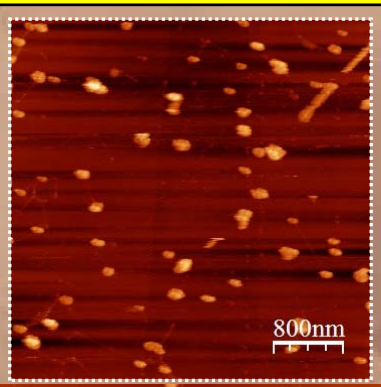
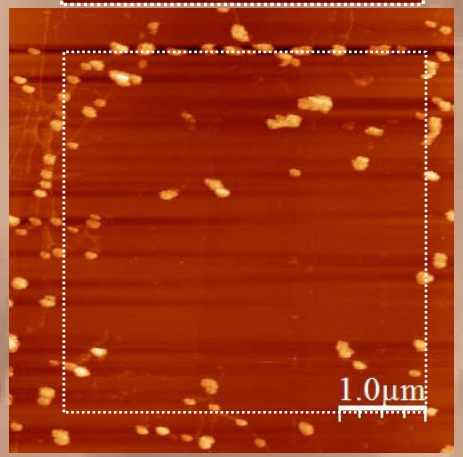
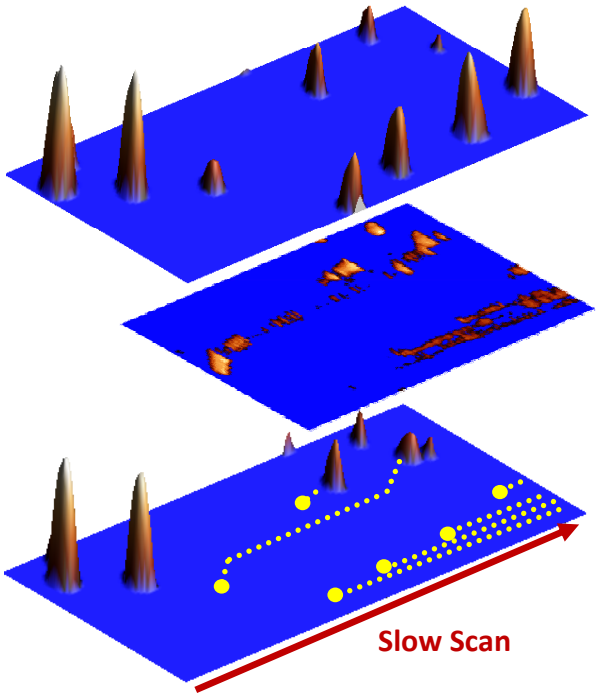
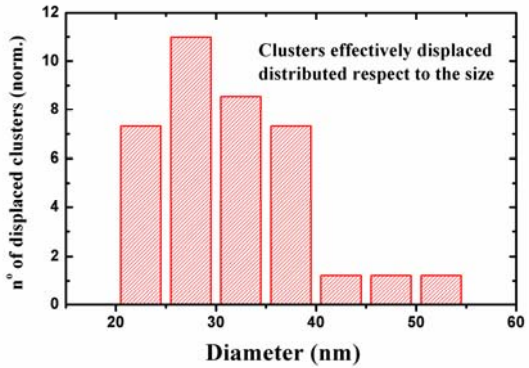
Clusters selection

Deposition of a suspension containing both 24 and 42 diameter particles obtained by stirring equal volumes of the two original liquids.









Initial : two **large clusters** , more than **40 nm high**, located on left corner plus eight **smaller clusters**, between **15 and 30 nm high**. Blue plane is a 10 nm cut-off introduced for graphical reason.

Central : clusters **movements,** induced using an oscillation energy just above the E_{24} detachment threshold, are shown in the central image.

Lower : the **selection effect** and the trajectories, deduced from the central image, aligned along the slow scan direction.

Appl. Phys. Lett. **95,** 143121 (2009)

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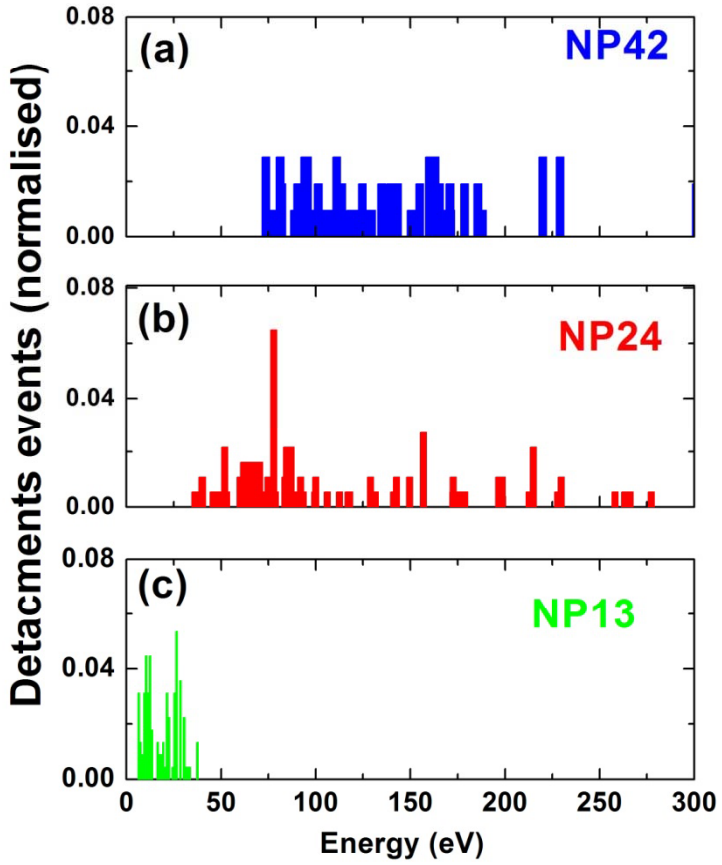
Clusters detachments



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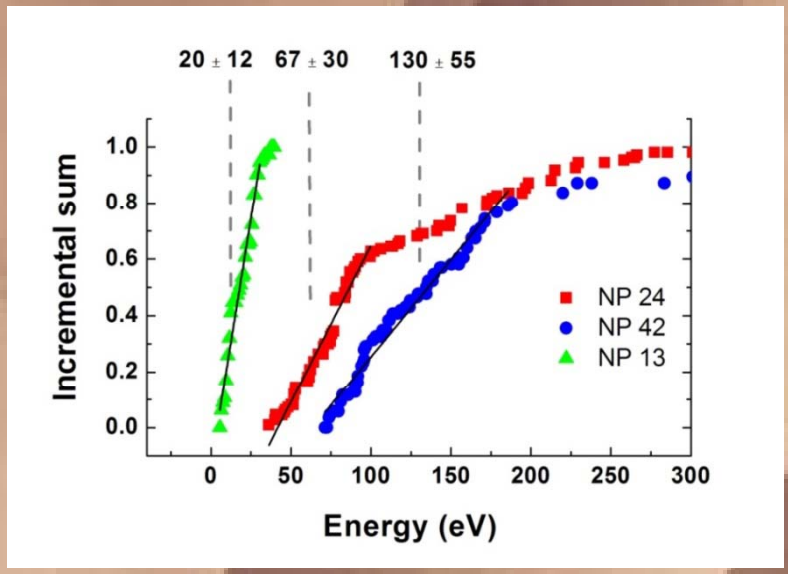
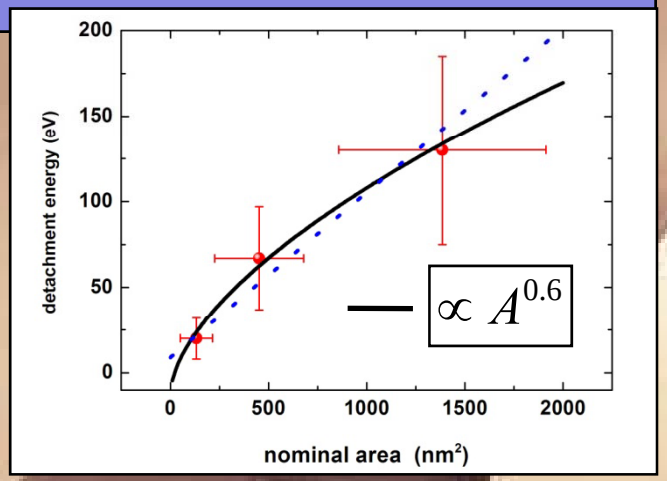
Number of detachment events (normalized to the total number of single clusters) and their associated detachment energy sorted by increasing energy .



Incremental sum of detachments events. The linear increase represents regions where detachment occurrence has random uniform probability. Energy thresholds are located in the centre of these regions, while their wid th fix the maximum associated errors .



Conclusions

• Nanotribology :

Different effects governing nanoclusters forced trajecories can be evaluated and measured using the **AFM with Amplitude Modulation feedback and monitoring the phase shift signal.**

Localised high friction areas like the graphite steps or preferred sliding directions are put in evidence by trajectories analysis.

The method we present allow to distinguish and **measure the energy detachment threshold** for cluster size down to the tenth-nanometer scale.

Results are in qualitative agreement with those of D.Dietzel *et al* (PRL.101 (2008) 125505) but represent a step forward to the direction of measuring nanometer mechanical properties because the corresponding contact areas are two order of magnitude smaller.

• Controlled movements :

Two different gold nanocluster sizes, 24±3 and 42±4 nm of diameters respectively, deposited on HOPG graphite, have been **selectively detached** and **moved** in a controlled way using the **AFM with Amplitude Modulation feedback.**

Control is obtained by tuning the interaction strength between the oscillating tip and clusters. This parameter can be continuously adjusted **varying the amplitude oscillations and monitoring the phase shift signal.**

The existence of a **unique controlling parameter, expressed in terms of energy,** is the key point of this method and allow very reproducible and easily exportable results.

Acknowledgements

People

- **Sergio Valeri**
- **Alberto Rota**
- **Massimo Rovatti**
- **Andrea Vanossi**
- **Antonio Ballestrazzi**
- **Enrico Gualtieri**
- **Luca Marzani**
- **Luca Incerti**

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on nanoStructures and bioSystem at Surfaces

Dipartimento di Fisica,
Università di Modena e Reggio Emilia

Project

Net-Lab ***SUP&RMAN***

Special thanks to **K.Mougin** for providing the gold nanoclusters

This research was partially supported by Net-Lab INTERMECH-SUP&RMAN (PRRIITT Emilia Romagna) and by ESF-FANAS, ACOF and AFRI projects.