Atomic force microscopy at the picometer length scale

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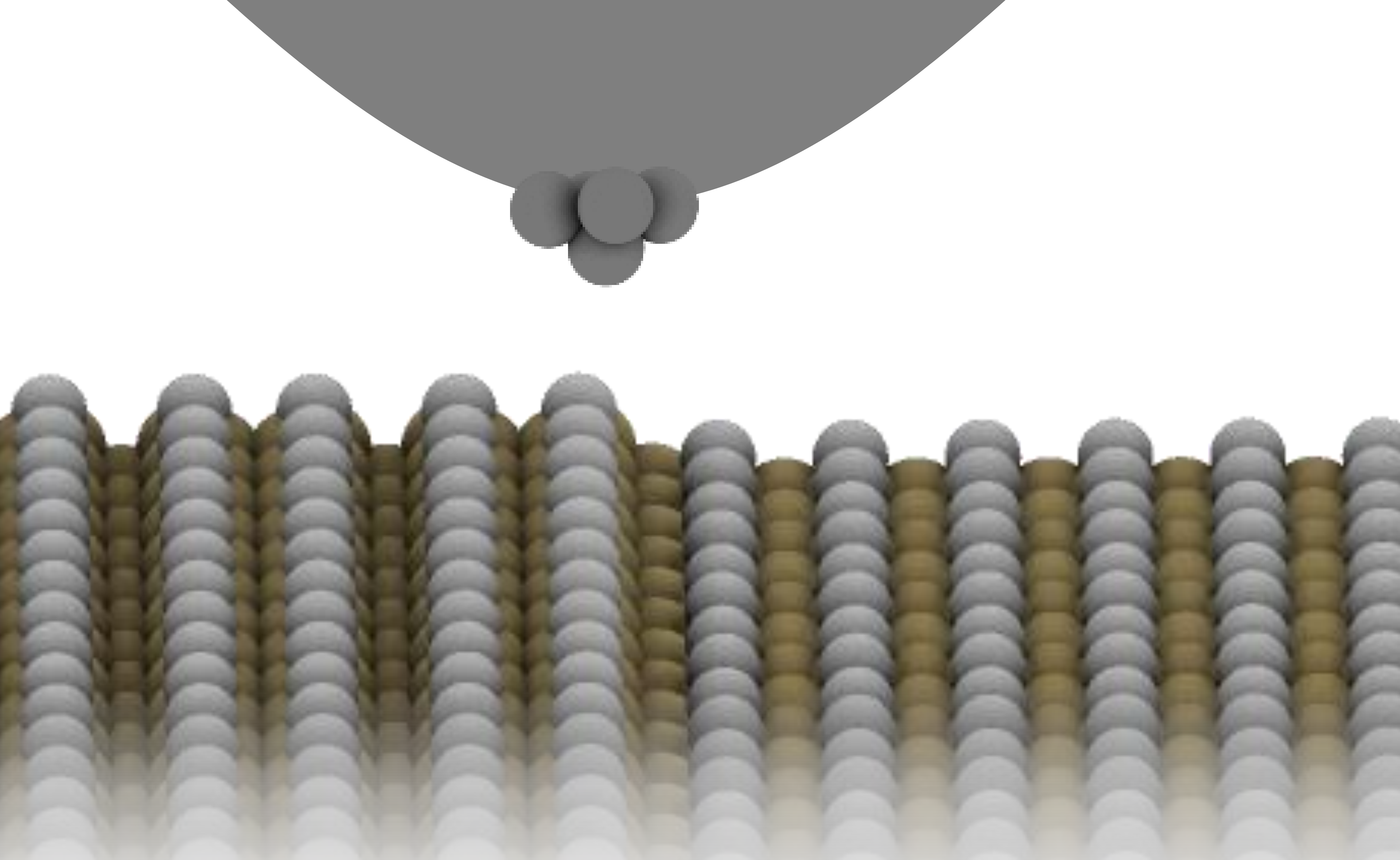
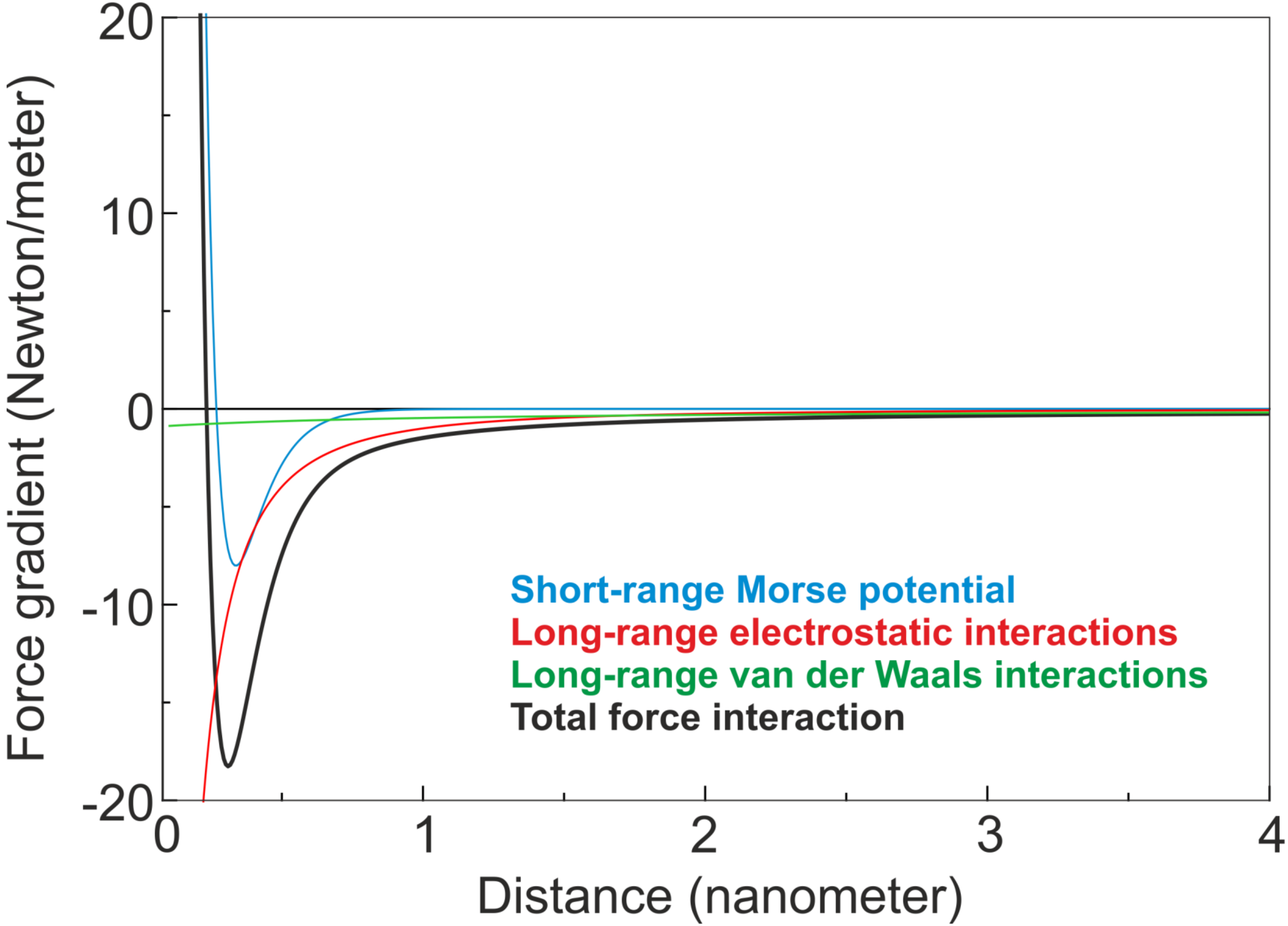


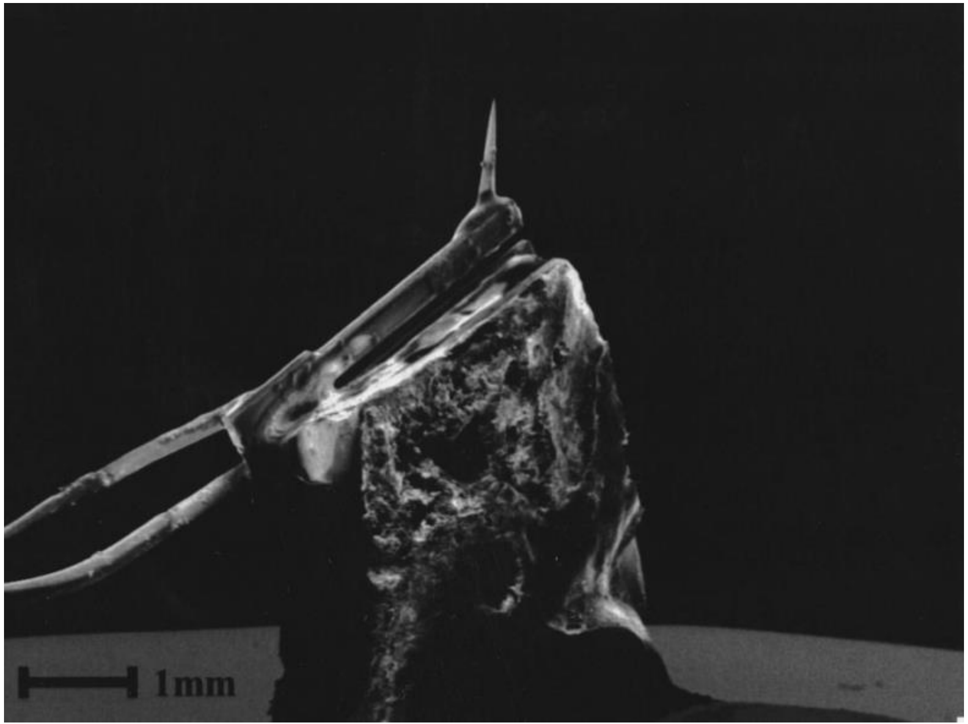
Want to probe interaction that is dominated by the apex atom of the tip and the closest surface atom



Short-range Morse potential
Long-range electrostatic interactions
Long-range van der Waals interactions
Total force interaction
Force gradient (Newton/meter)
20
10
0
-10
-20
0
1
2
3
4
Distance (nanometer)

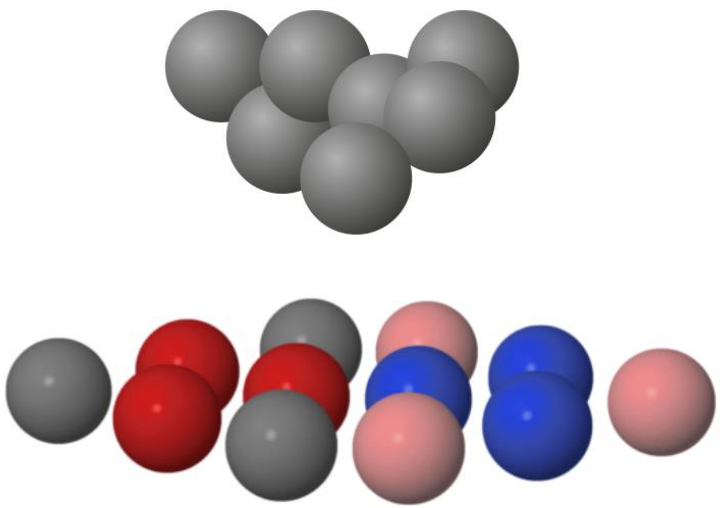
Inspiration for the qPlus

- Measure frequency
- Oscillate with small amplitudes
- Cantilever stiff enough to prevent *snap-to-contact*

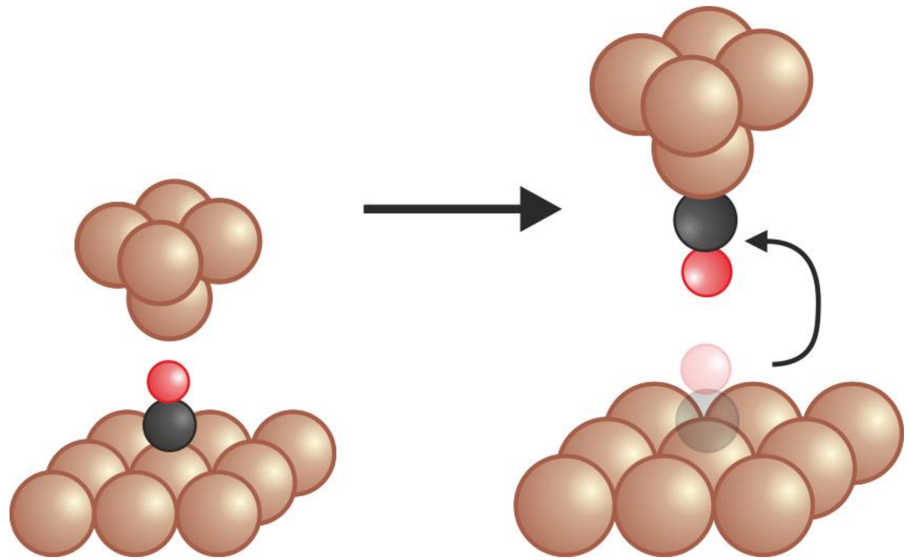


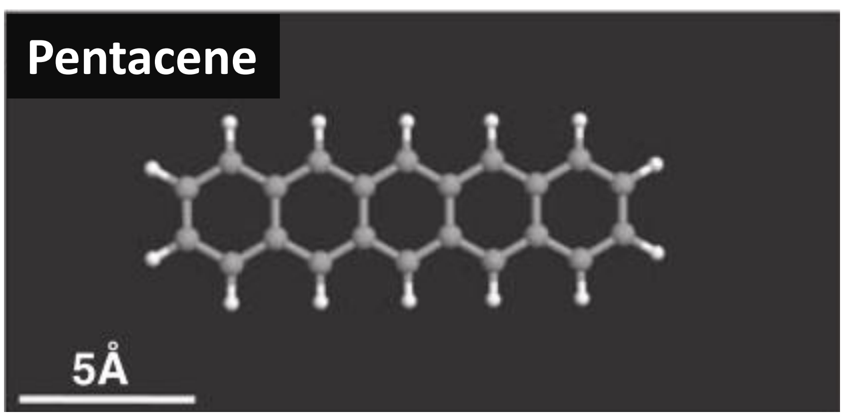
F.J. Giessibl, Appl. Phys. Lett. **73**, 3956 (1998)

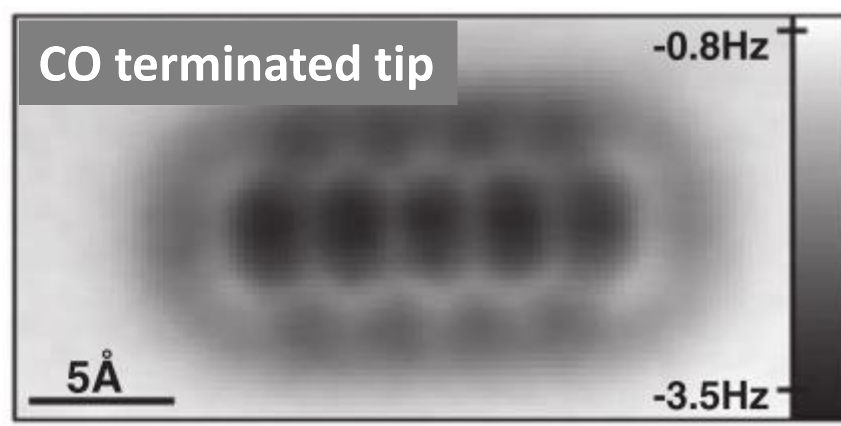
How do “we” “normally” do AFM?



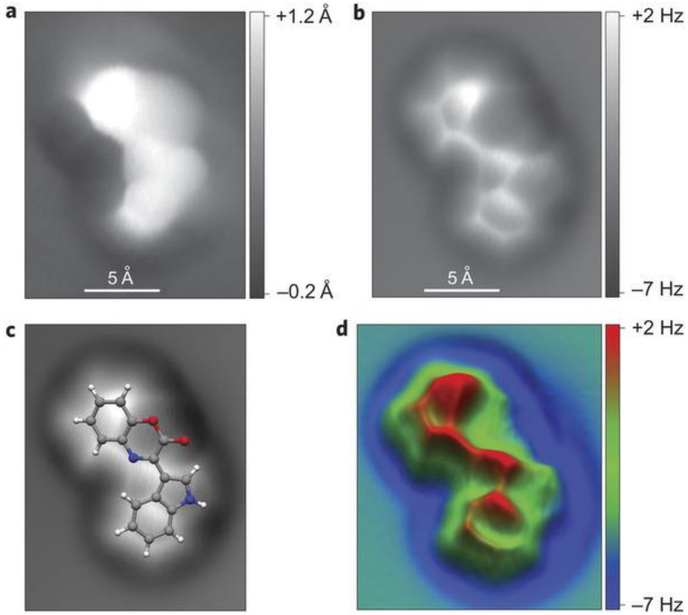
- Approach tip to surface
- Poke, pulse and pray
- Achieve atomic resolution and scan







Gross, Mohn, Moll, Liljeroth and Meyer, Science, **325**, 1110 (2009)



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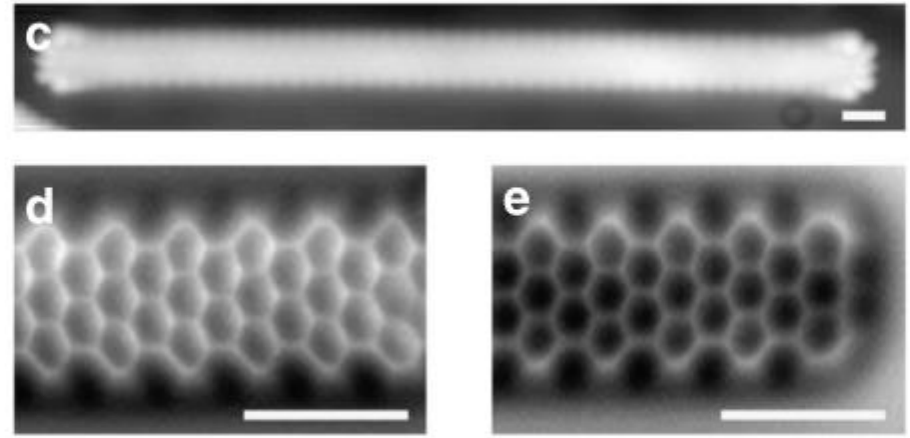

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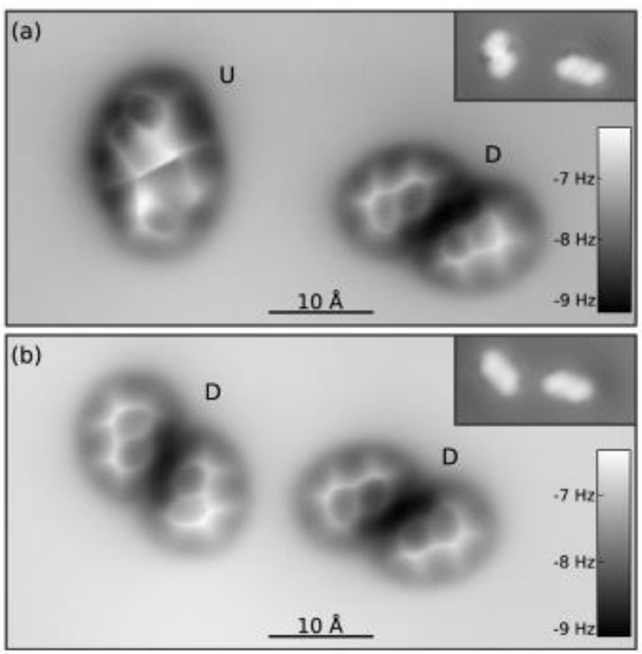
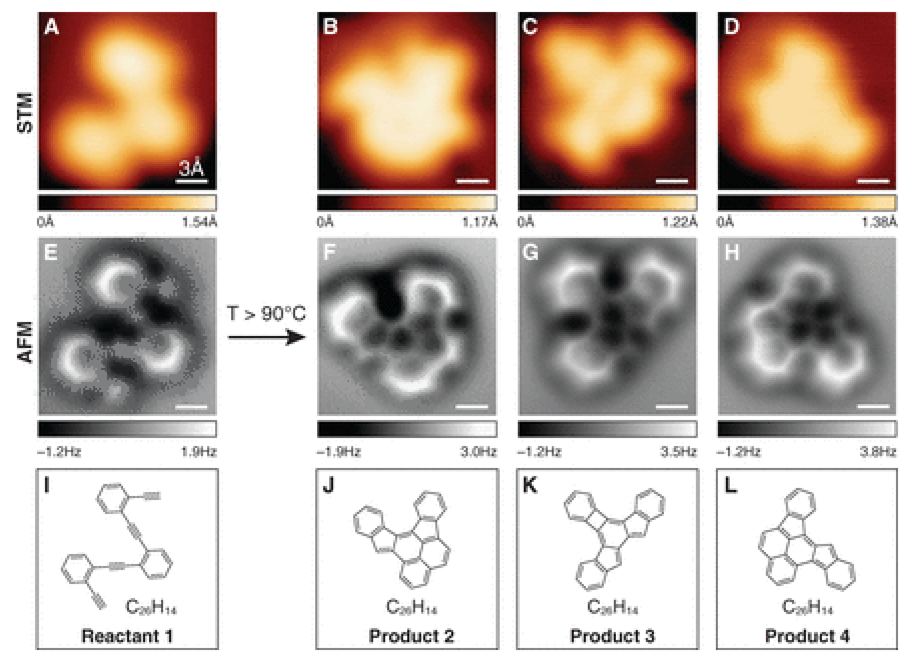
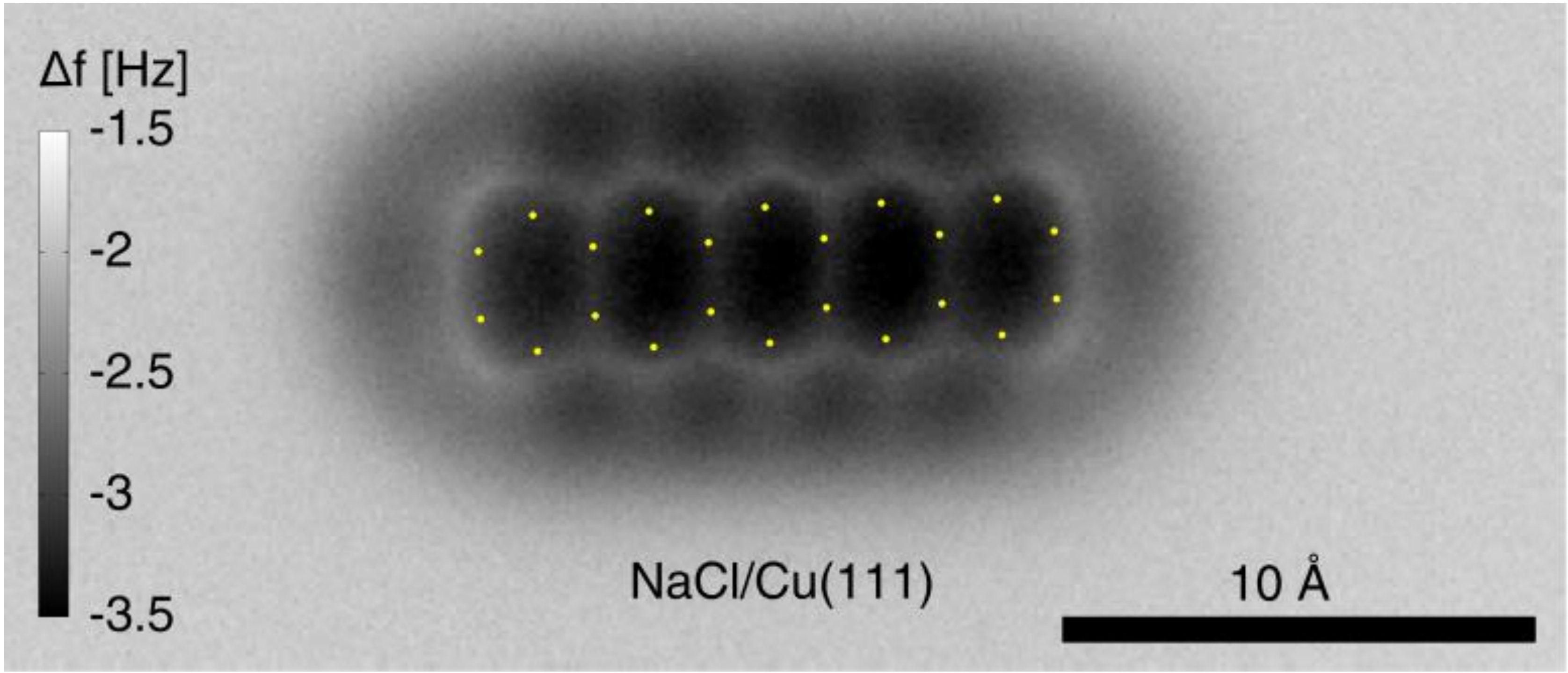


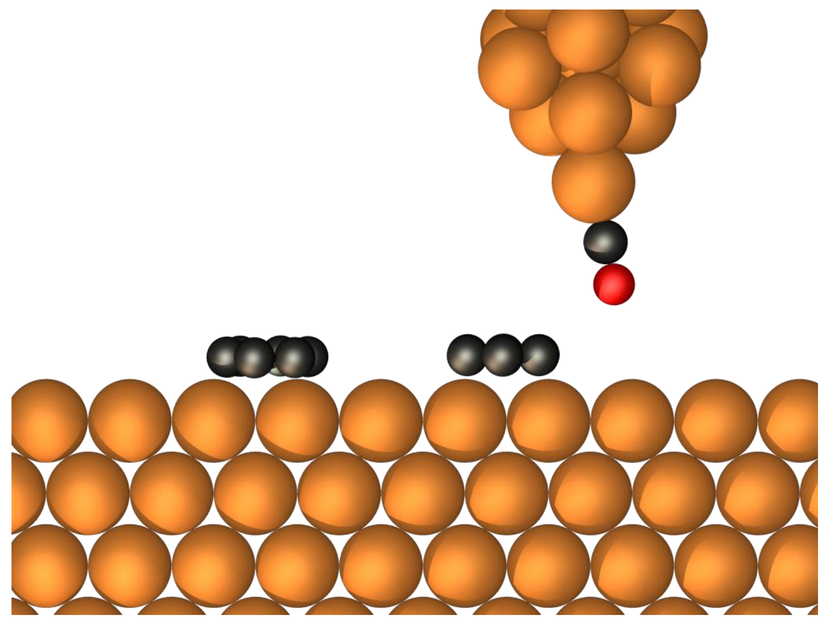
Pavlicek et al, Phys Rev Lett, **108**, 086101 (2012)



De Oteyza et al, Science, **340**, 1434 (2013)



Neu et al, Phys Rev B, **89**, 205407 (2014)



PRL 106, 046104 (2011) PHYSICAL REVIEW LETTERS week ending 28 JANUARY 2011

Quantitative Atomic Force Microscopy with Carbon Monoxide Terminated Tips

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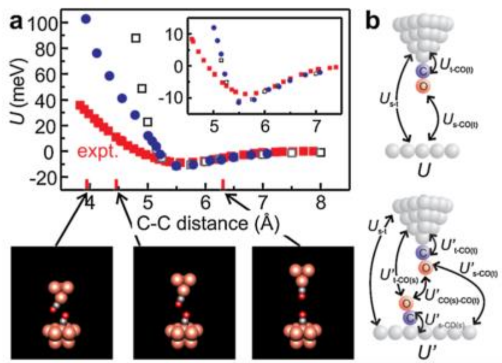

general and occur in all noncontact AFM experiments employing molecule-terminated tips.

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[1] G. Binnig *et al.*, Phys. Rev. Lett. **50**, 120 (1983).
[2] M. F. Crommie, C. P. Lutz, and D. M. Eigler, Science **262**, 218 (1993).

REPORTS

Bond-Order Discrimination by Atomic Force Microscopy

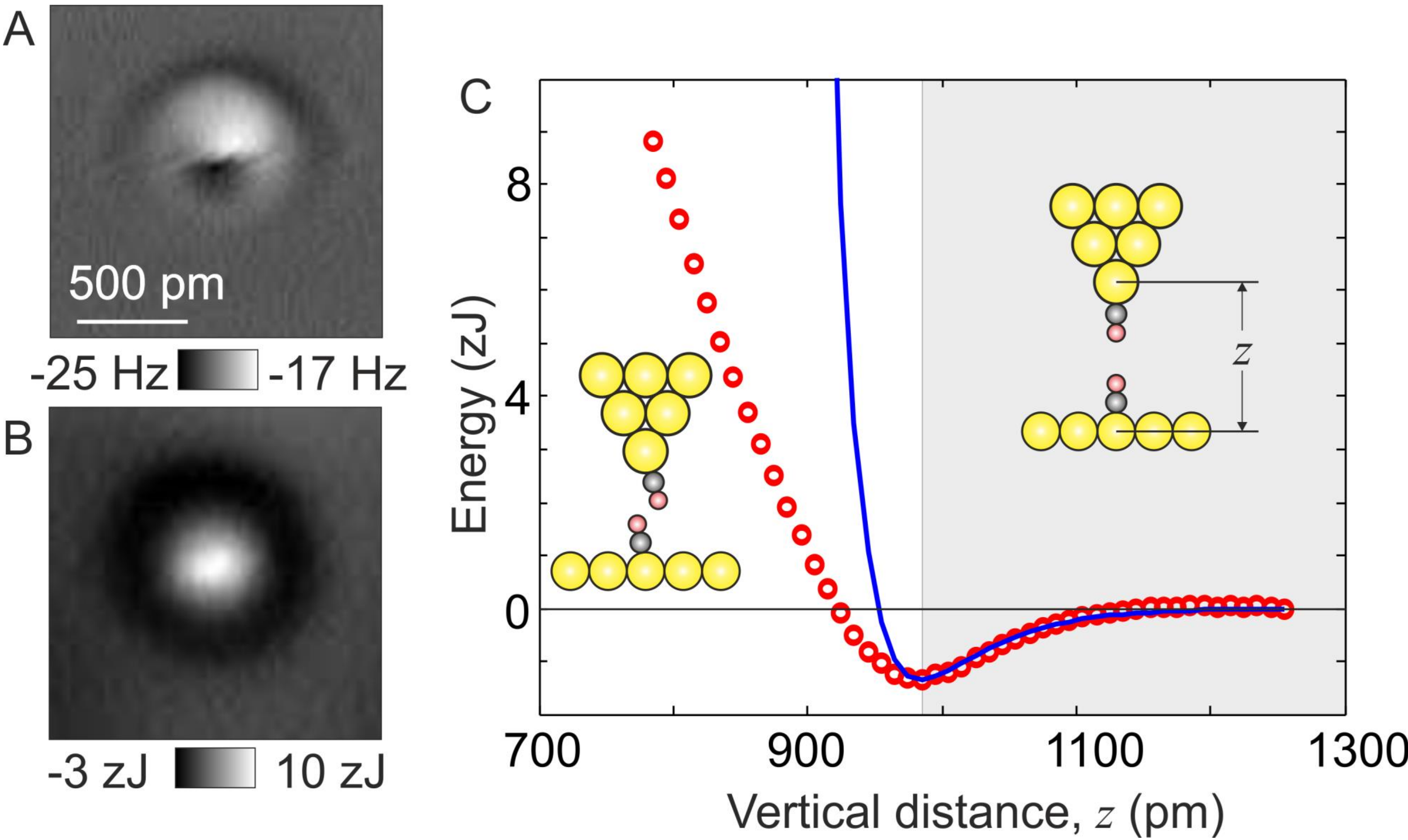
Leo Gross,[1*] Fabian Mohn,[1] Nikolaj Moll,[1] Bruno Schuler,[1] Alejandro Criado,[2] Enrique Guitián,[2] Diego Peña,[2] André Gourdon,[3] Gerhard Meyer[1]

scanning probe microscopy offers the possibility of studying single bonds in individual molecules.

Recently, rapid progress has been reported in the field of noncontact atomic force microscopy (NC-AFM), including the chemical identification of individual surface atoms (*7*), atomic resolution of carbon nanotubes (*8*), C_{60} (*9*), and planar organic molecules (*10*). For molecules, not only the

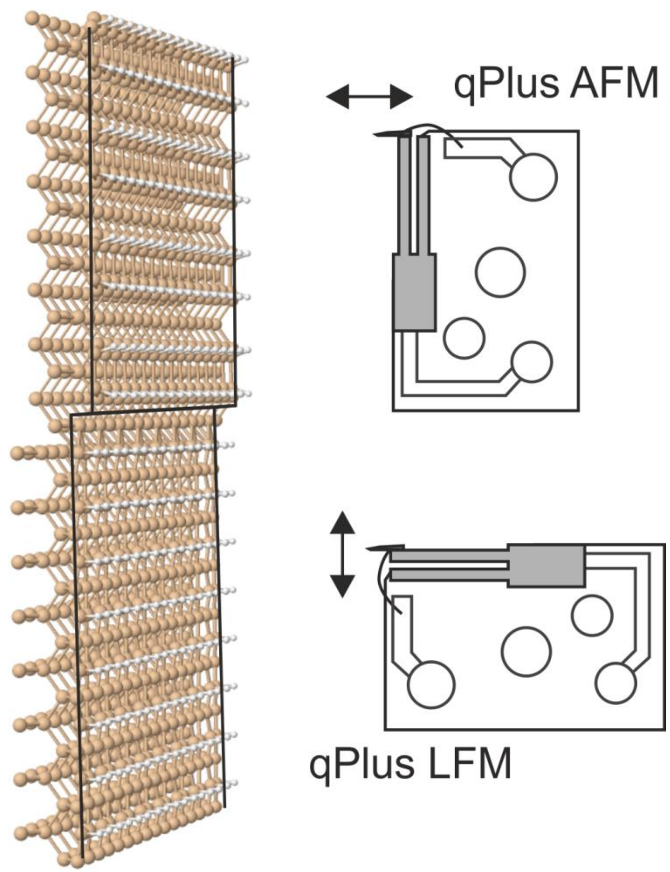
Calculation of the resulting forces upon lateral displacement of the O atom at the Cu_2CO tip yielded a calculated lateral spring constant of $k_{Cu2} = 0.5$ N/m. We also explored tips with CO attached to a Cu_3, a Cu_5, and a Cu_{14} cluster, which resulted in lateral spring constants of $k_{Cu3} = 1.0$ N/m, $k_{Cu5} = 1.3$ N/m, and $k_{Cu14} = 0.3$ N/m, respectively. For an Au_5 cluster we obtained $k_{Au5} = 1.6$ N/m. Note that for all these tips, in contrast to the Cu_2 tip, the lateral spring constants also depend on the azimuthal direction due the broken cylindrical symmetry. The results compare reasonably well with the

Normal AFM



A
500 pm
-25 Hz
-17 Hz
B
-3 zJ
10 zJ
C
Energy (zJ)
8
4
0
700
900
1100
1300
Vertical distance, z (pm)
z

Directly measure the lateral forces: Lateral Force Microscopy (LFM)



Giessibl et al, Proc Nat Acad Sci, **99**, 12006 (2002)
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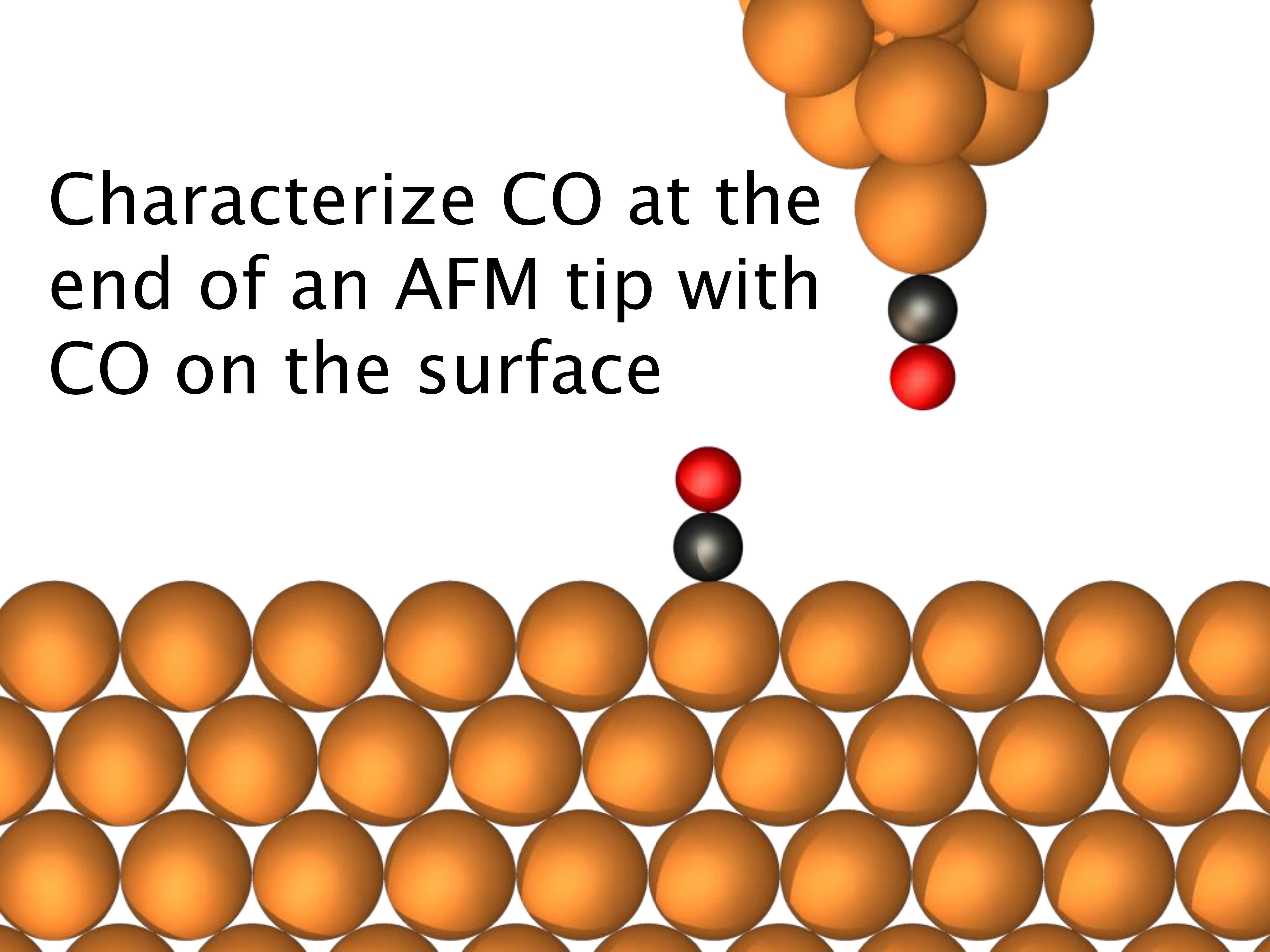
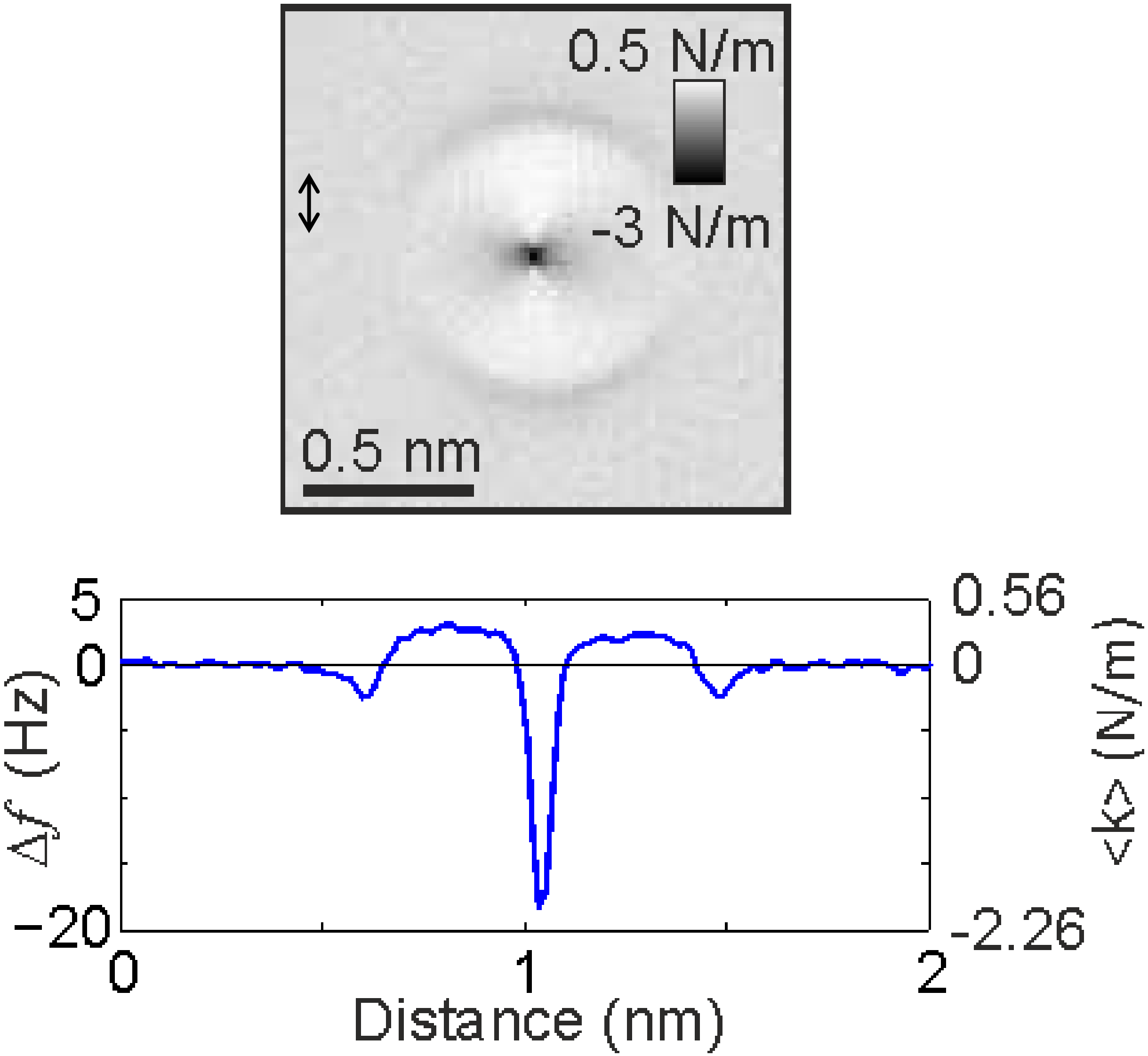
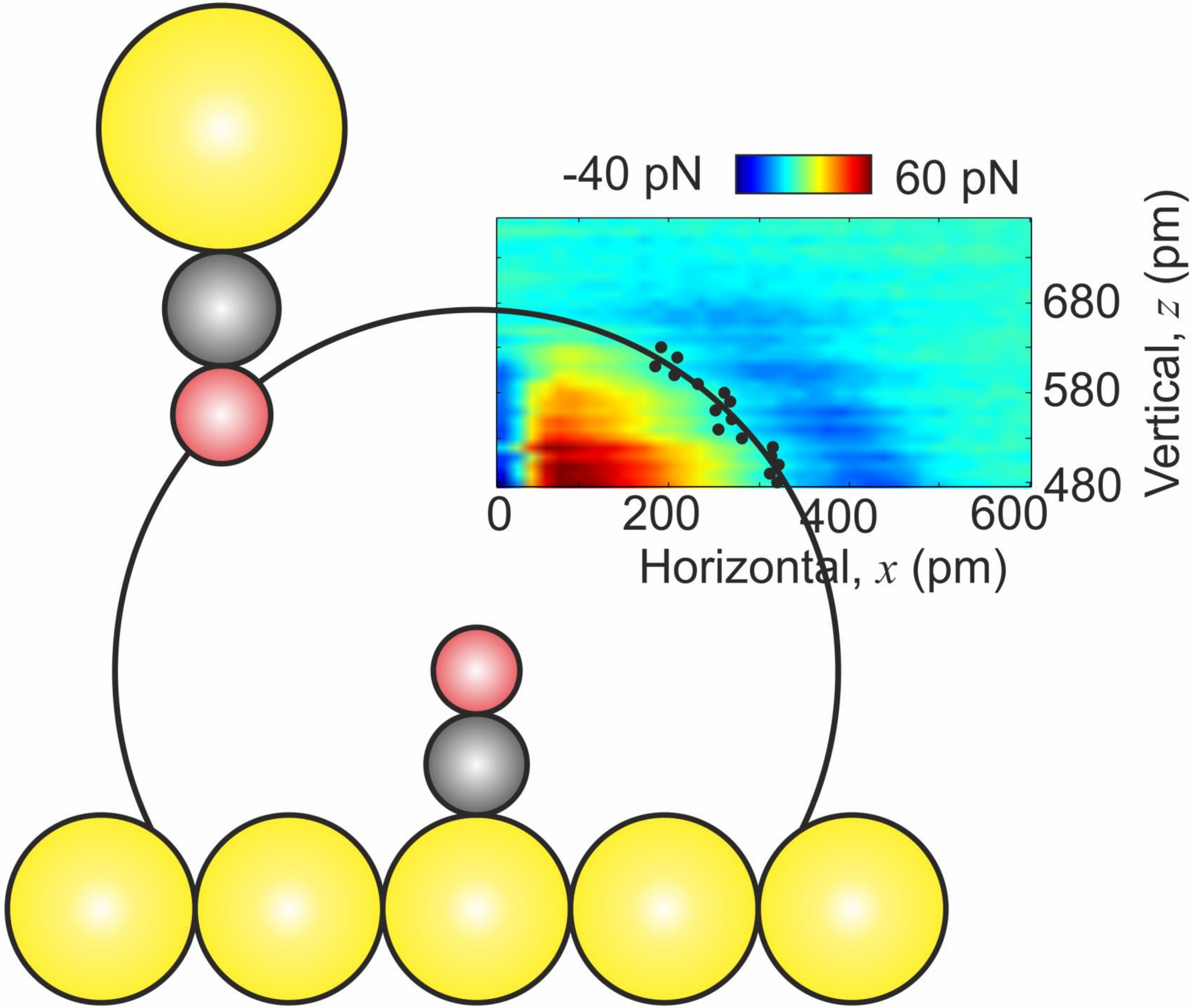
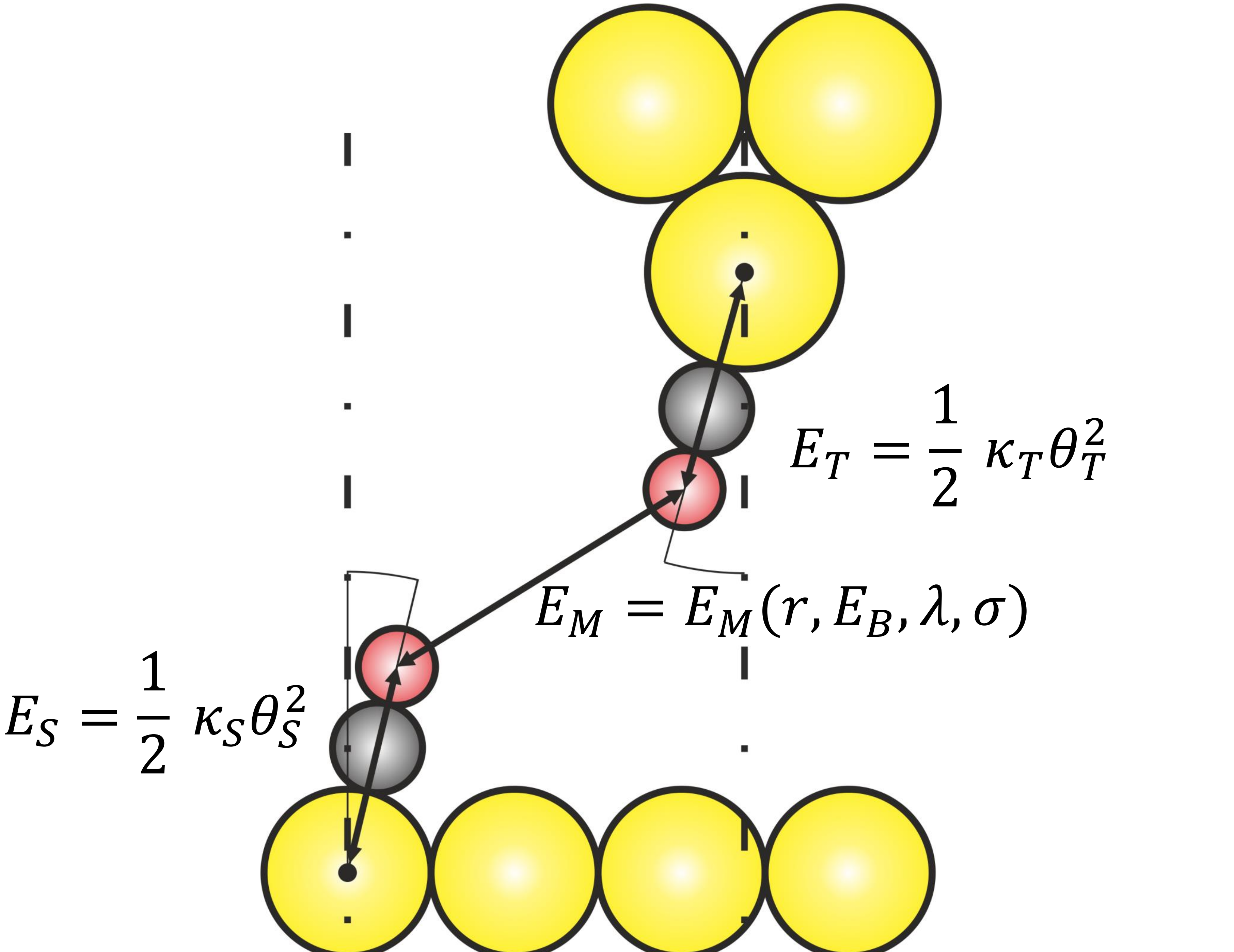
Characterize CO at the end of an AFM tip with CO on the surface



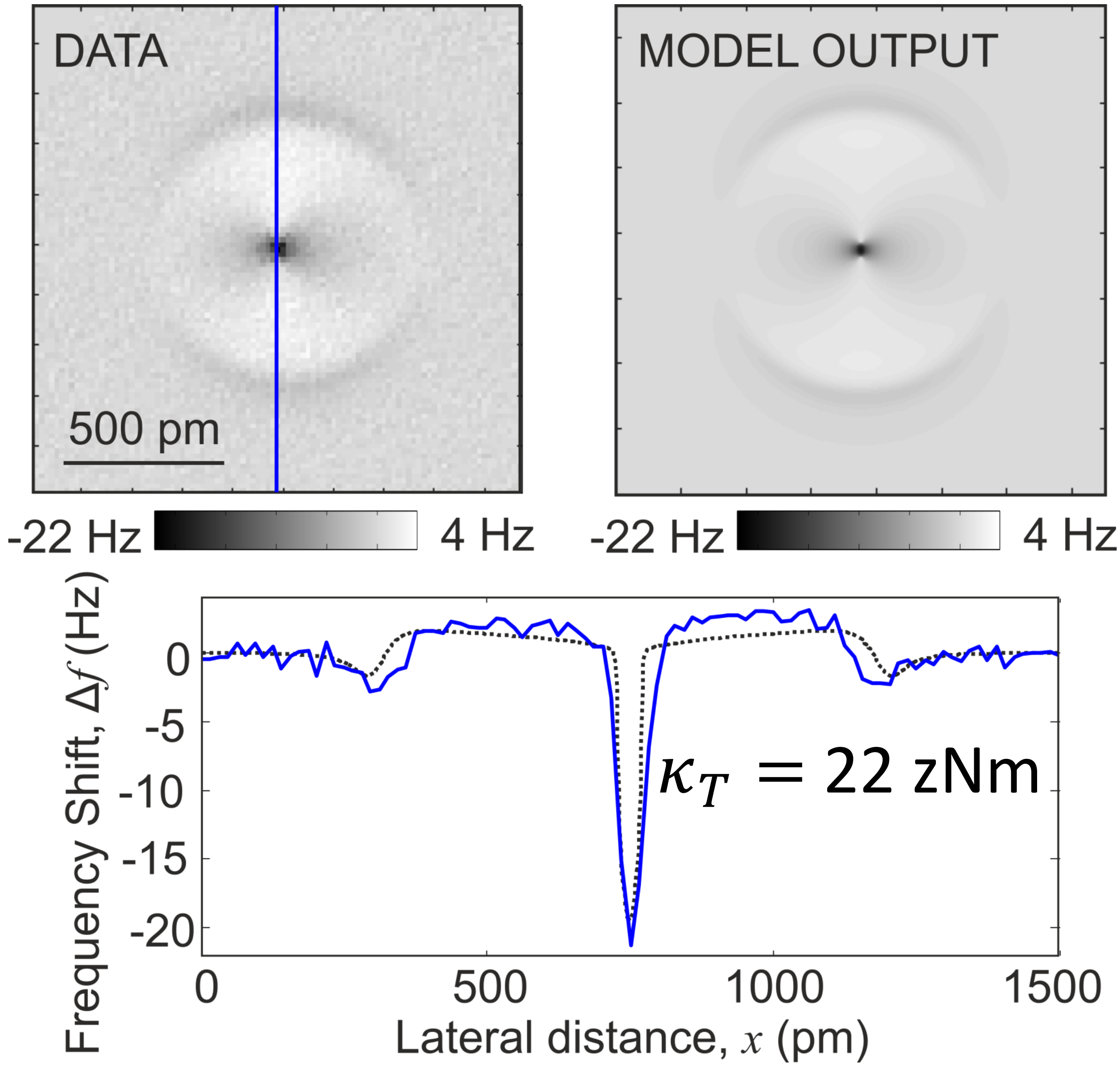
Lateral force microscopy data




-40 pN
60 pN
680
580
480
Vertical, z (pm)
0
200
400
600
Horizontal, x (pm)



$E_T = \frac{1}{2}\ \kappa_T \theta_T^2$
$E_M = E_M(r, E_B, \lambda, \sigma)$
$E_S = \frac{1}{2}\ \kappa_S \theta_S^2$



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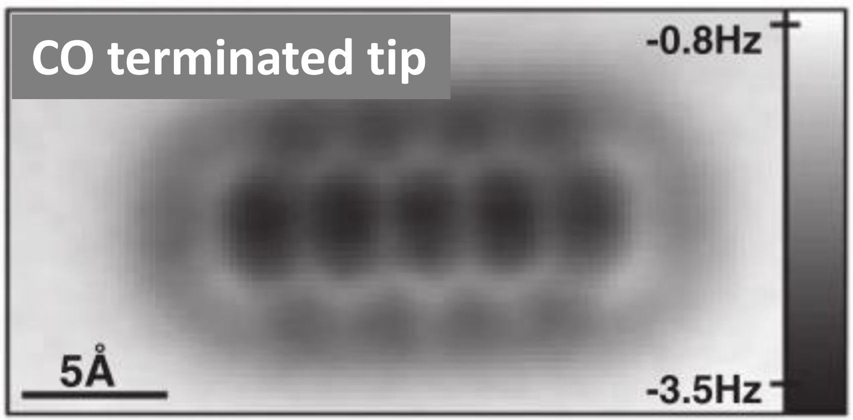
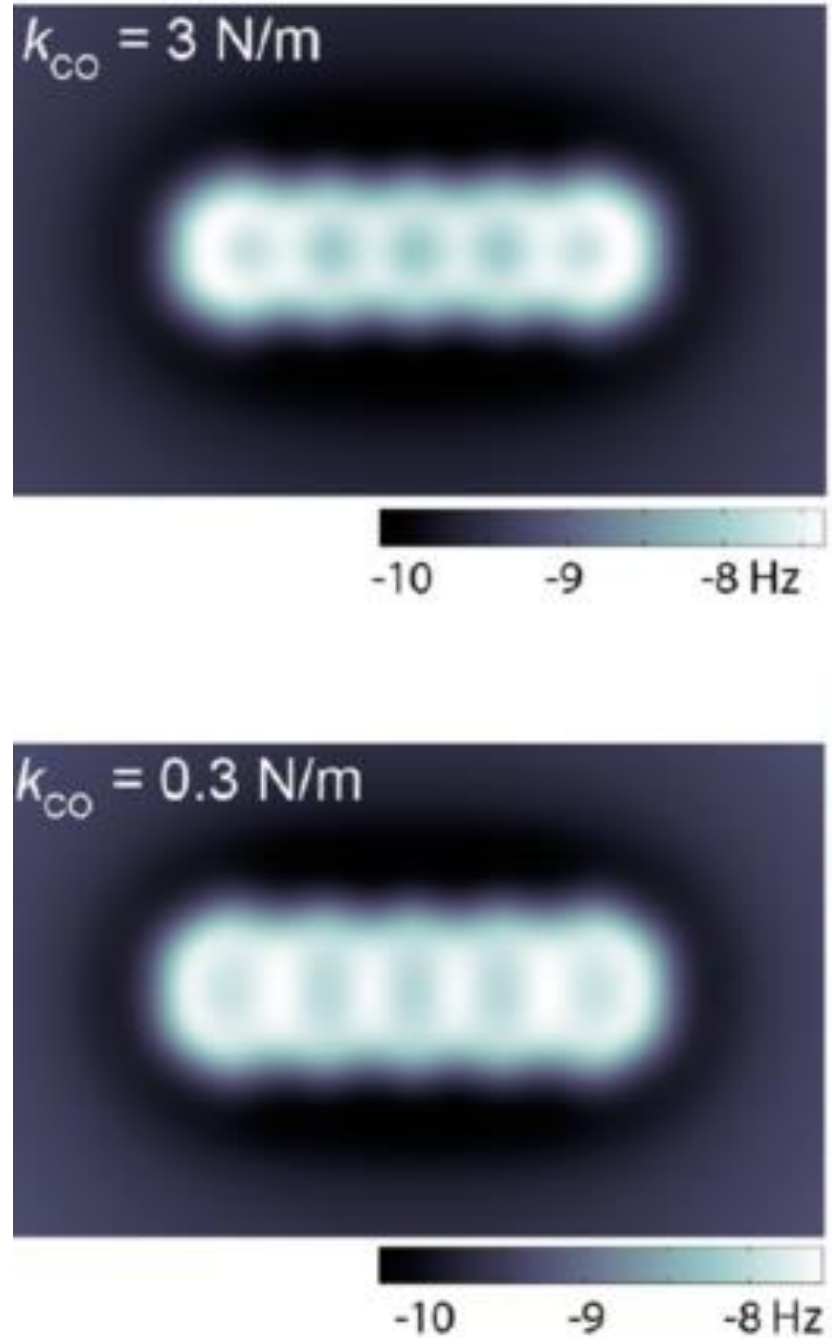
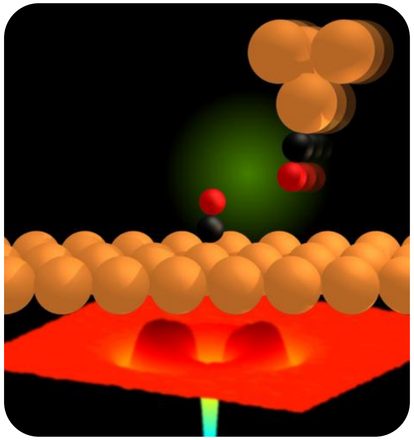


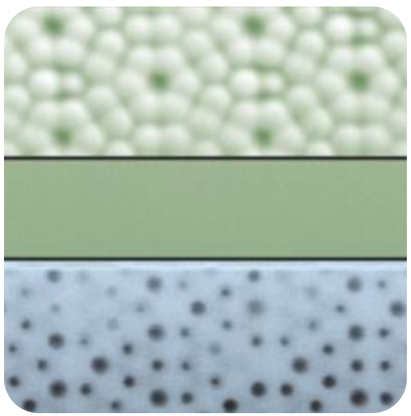
Gross et al, Science, **325**, 1110 (2009)



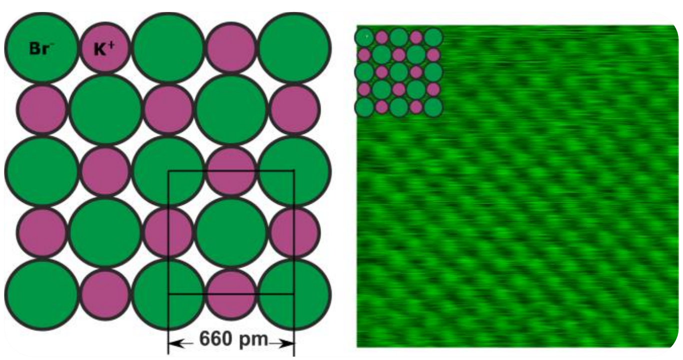
Boneschanscher et al, ACS Nano, **8**, 2006 (2014)



Using lateral force microscopy to probe molecular stiffness



Using simultaneous force and current measurements to investigate a phantom force

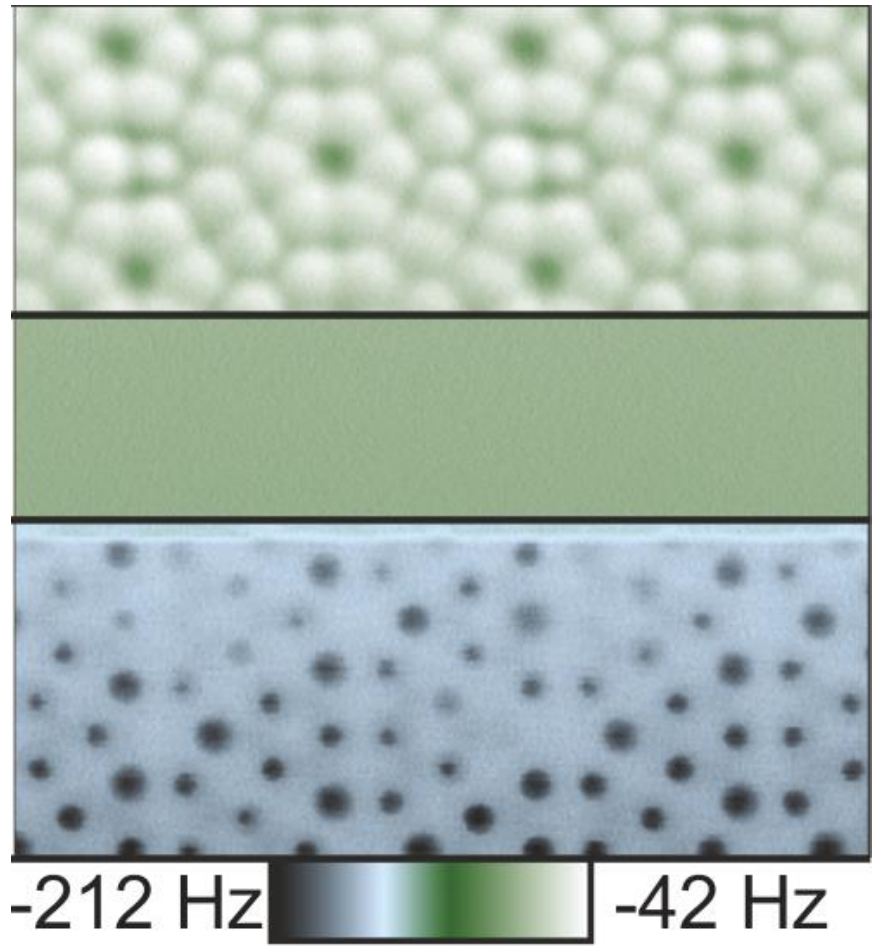


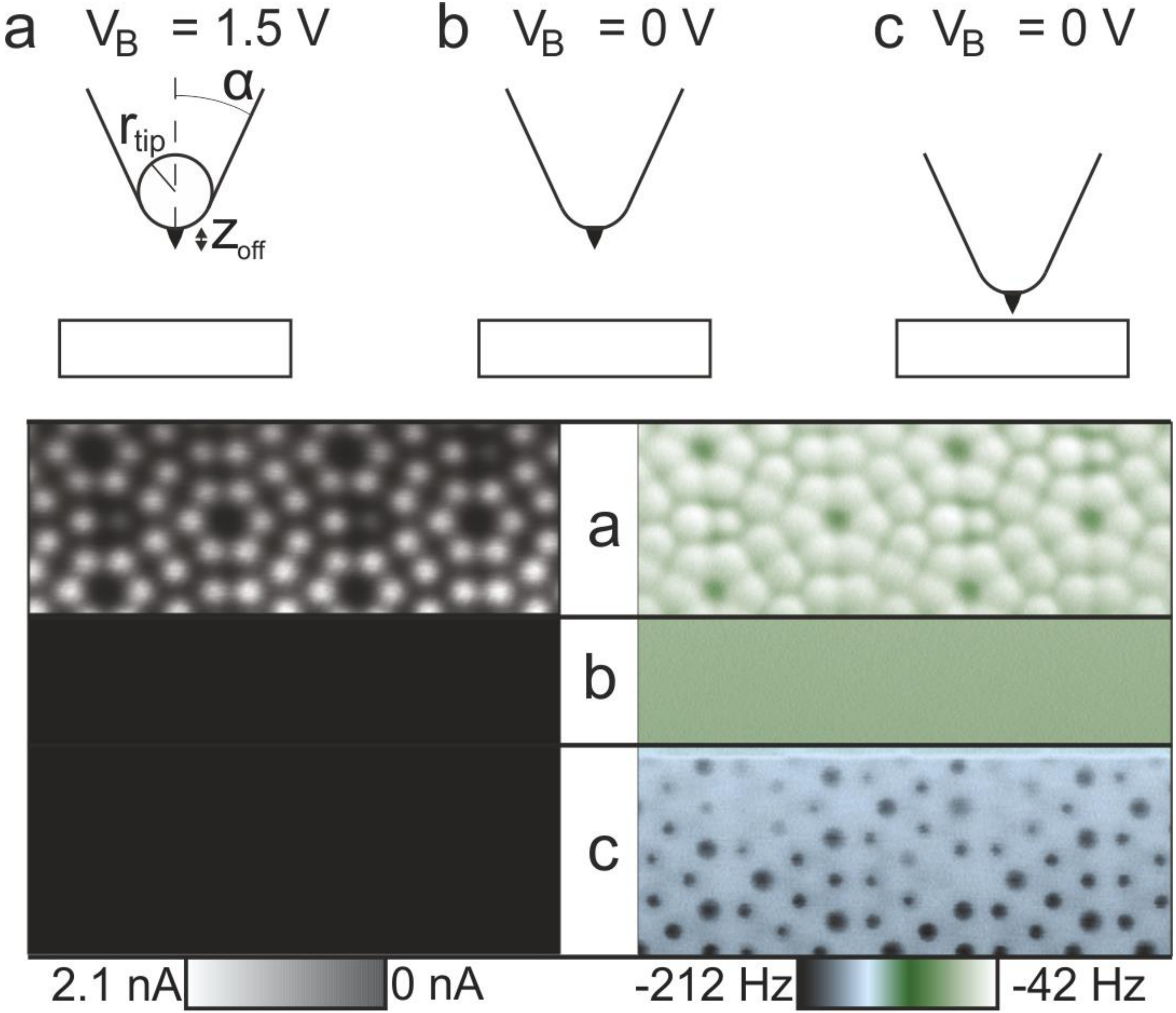
Taking UHV know-how and moving to ambient

…a phantom force?

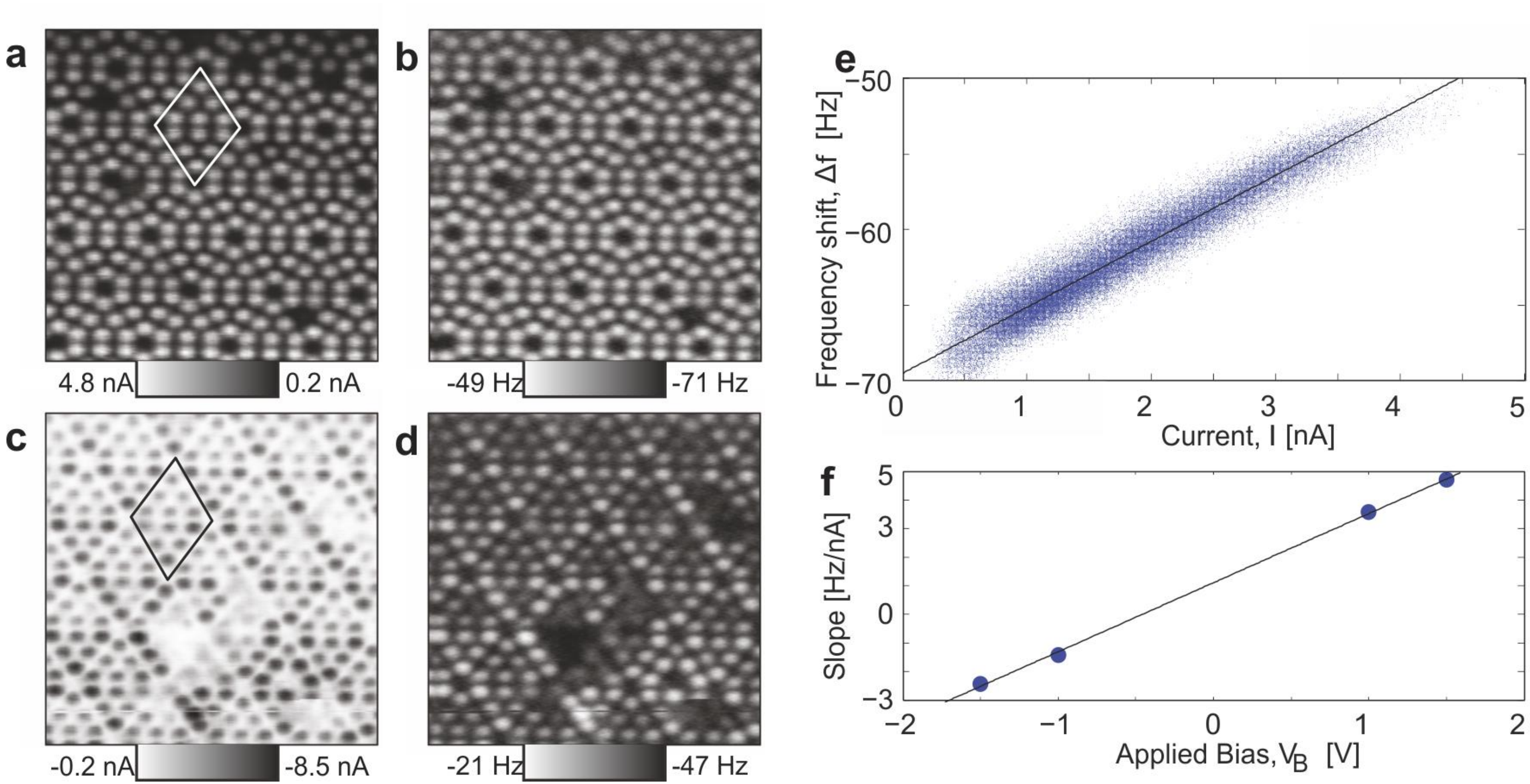
AFM data of silicon taken with an applied bias

appears very different to data without a bias

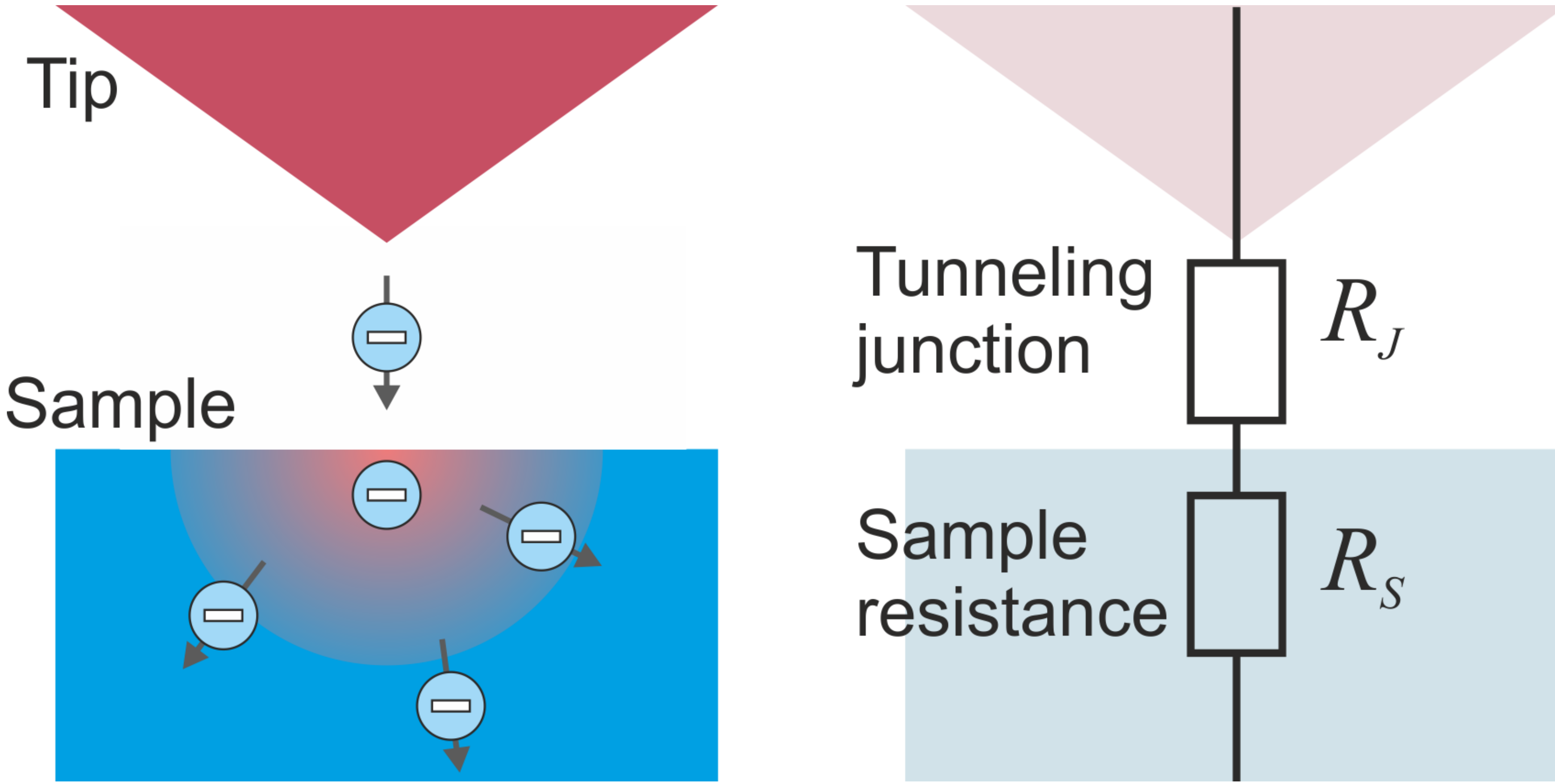




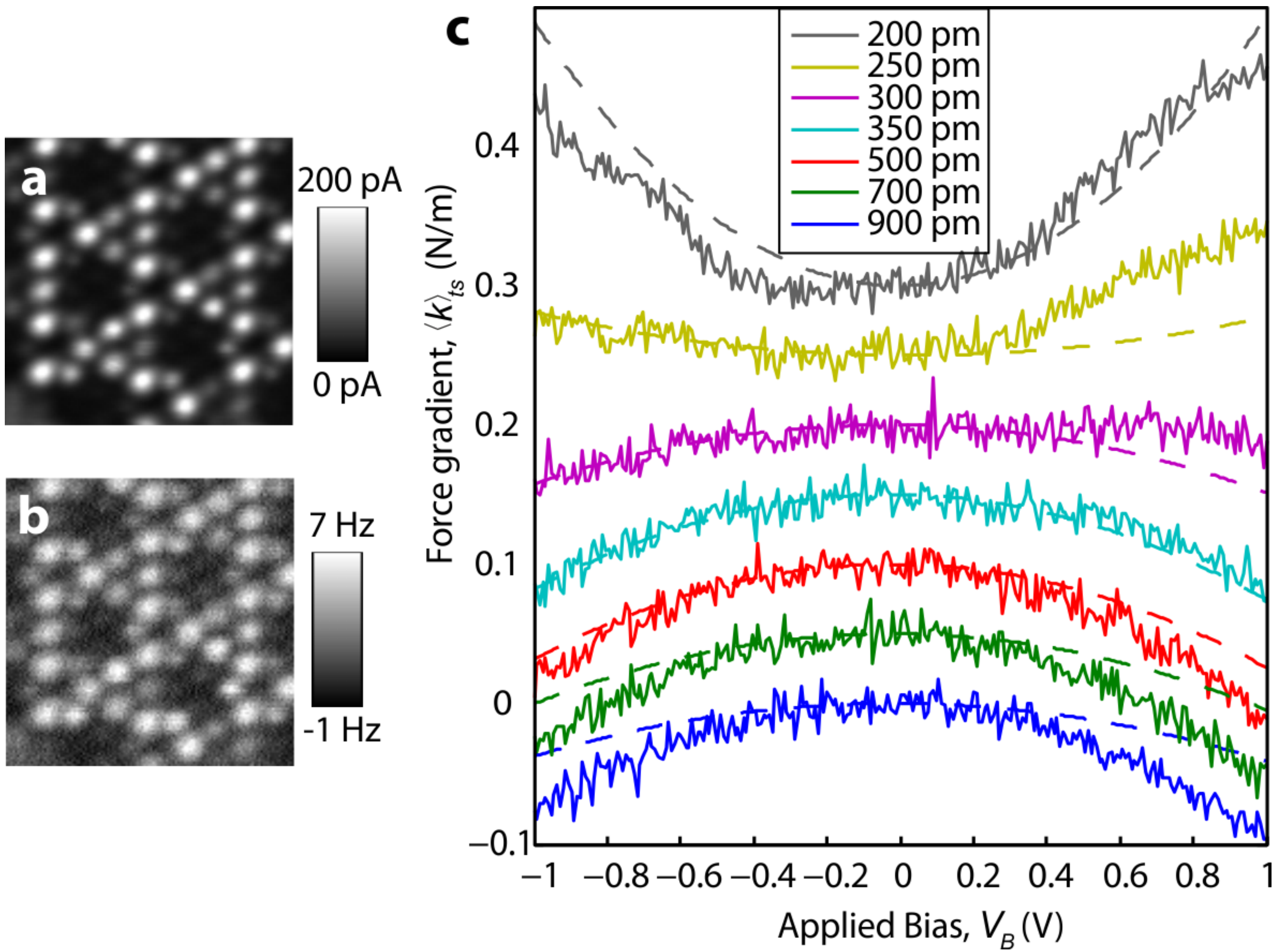
Weymouth et al, Phys Rev Lett **106**, 226801 (2011)



Weymouth et al, Phys Rev Lett **106**, 226801 (2011)



Forthcoming: NC-AFM Vol. 3, Ed. S. Morita, Springer, 2015



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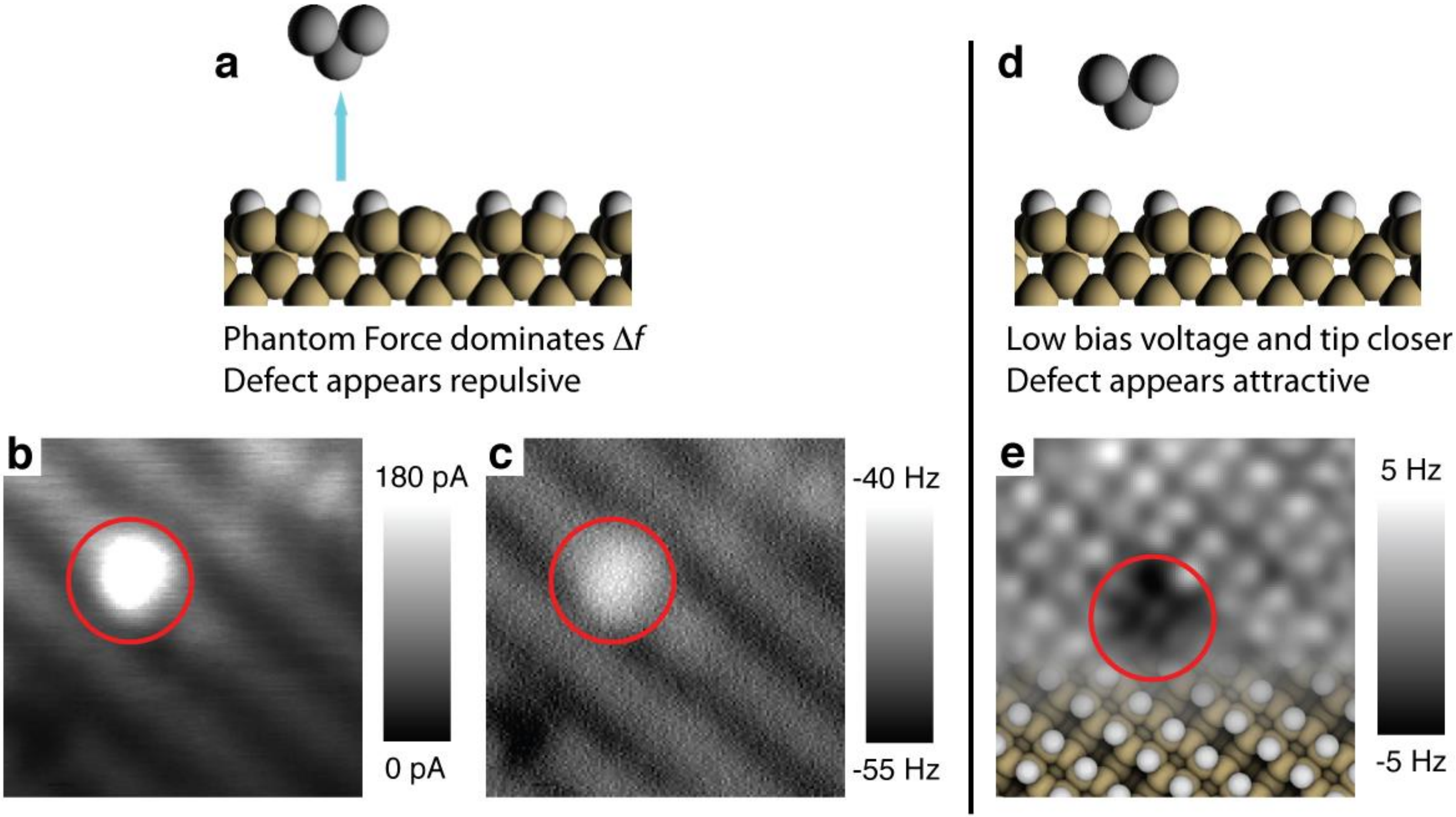
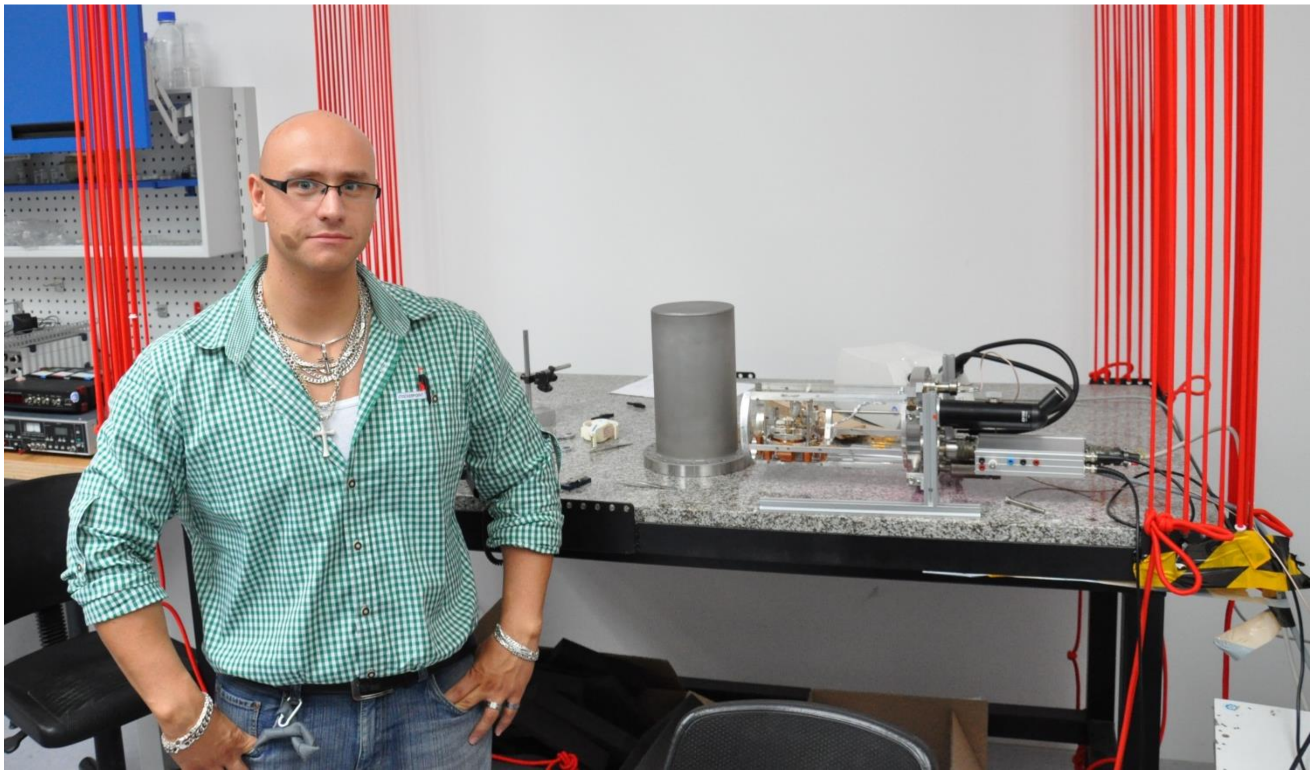


Forthcoming: NC-AFM Vol. 3, Ed. S. Morita, Springer, 2015

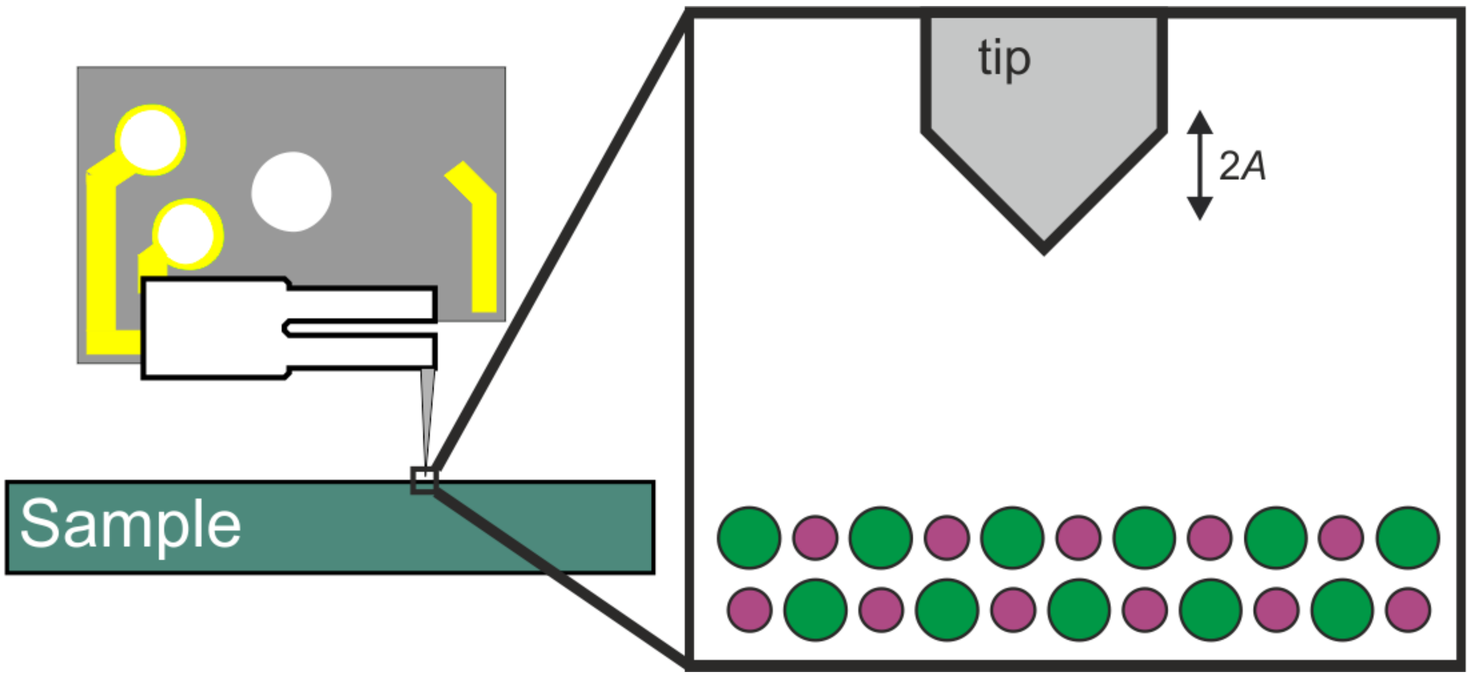
Taking UHV know-how and moving to ambient environments



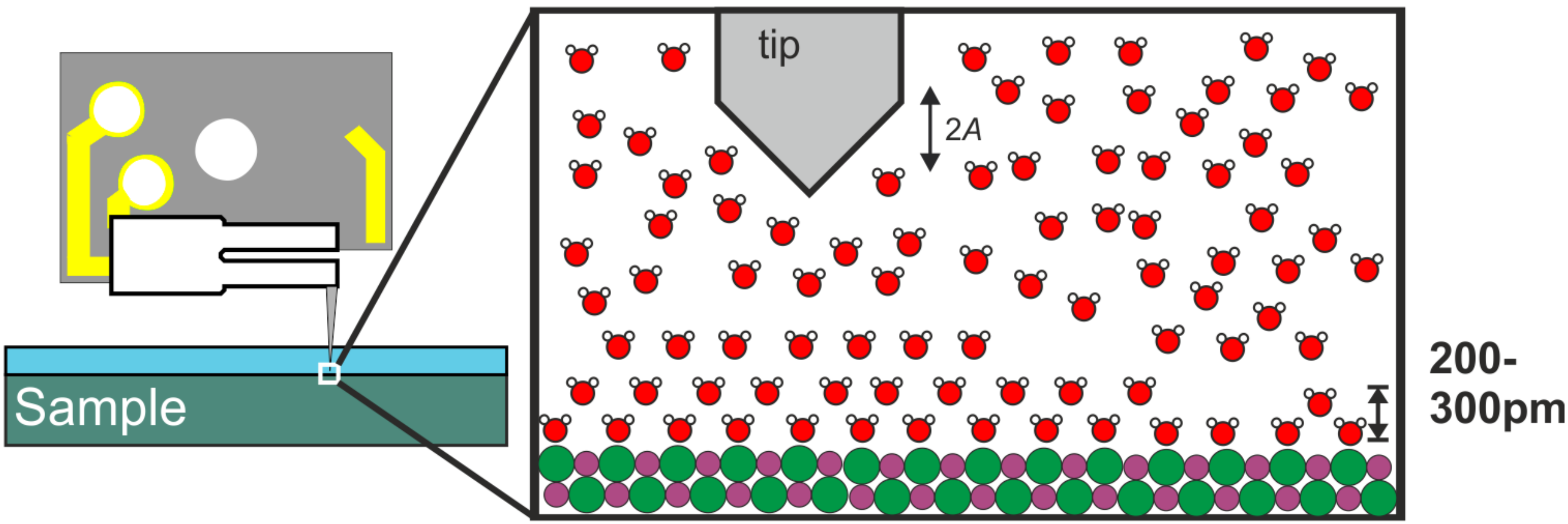
D. Wastl

Wastl, Weymouth, Giessibl. Phys. Rev. B, **87**, 245415 (2013)
Wastl, Weymouth, Giessibl. ACS Nano, **8**, 5233 (2014)

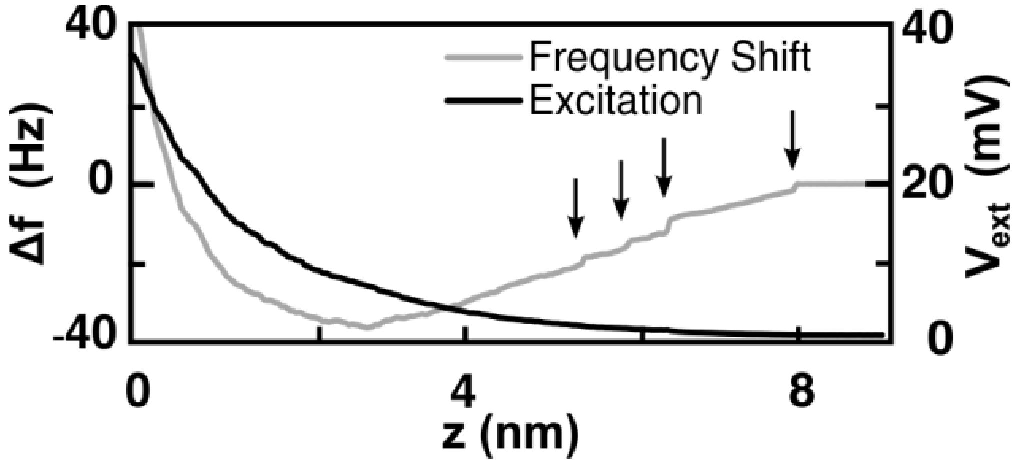
Vacuum conditions



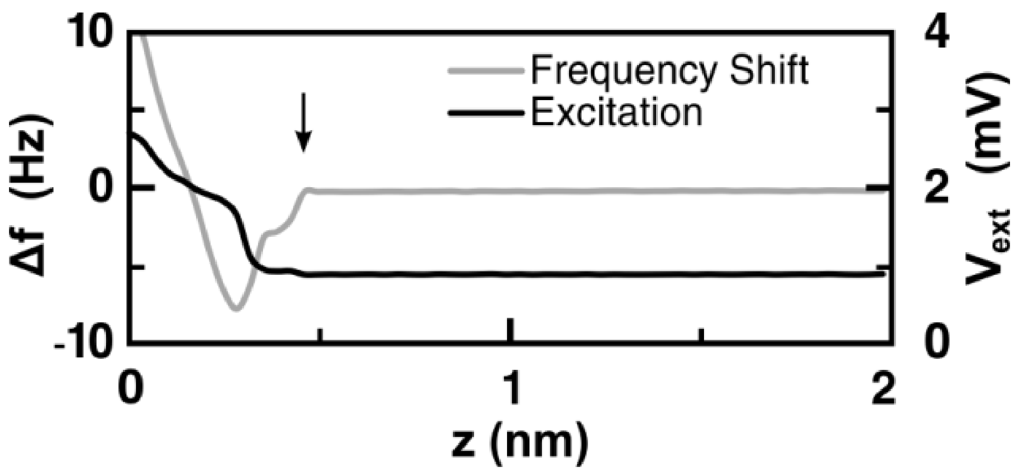
Ambient conditions



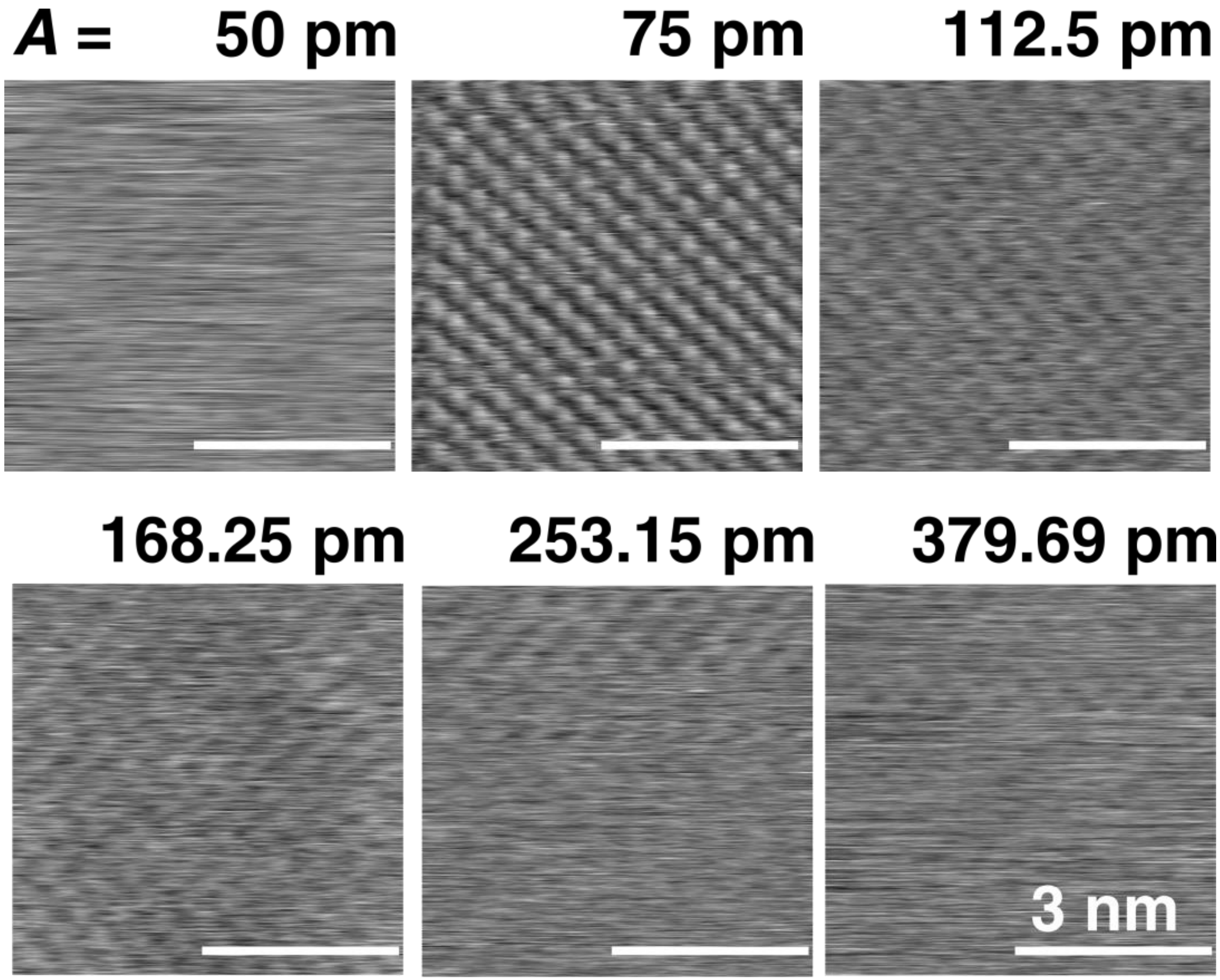
Comparing wet…



…and dry surfaces

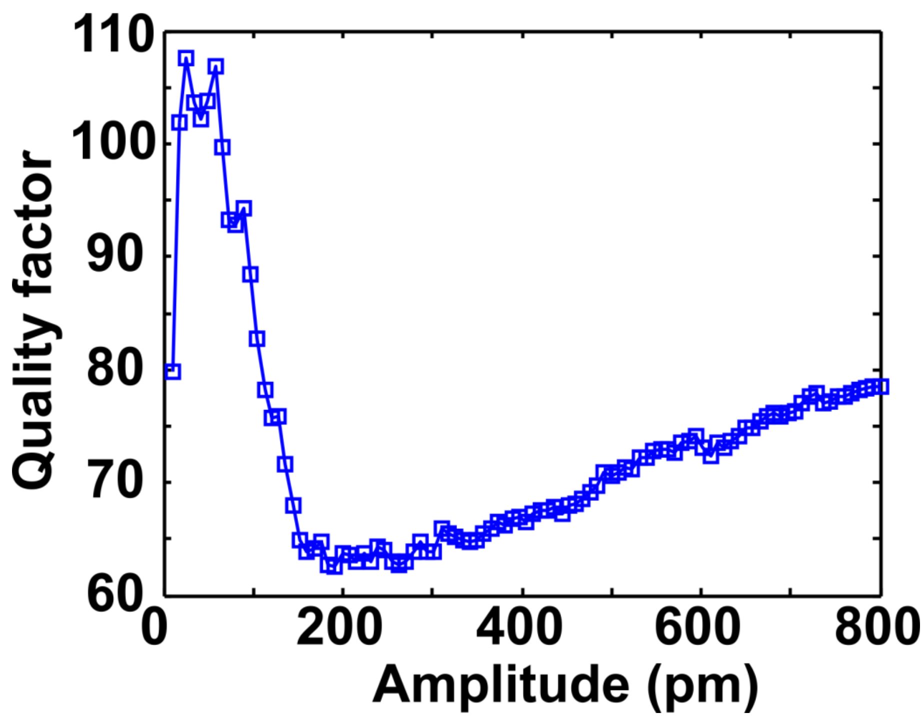


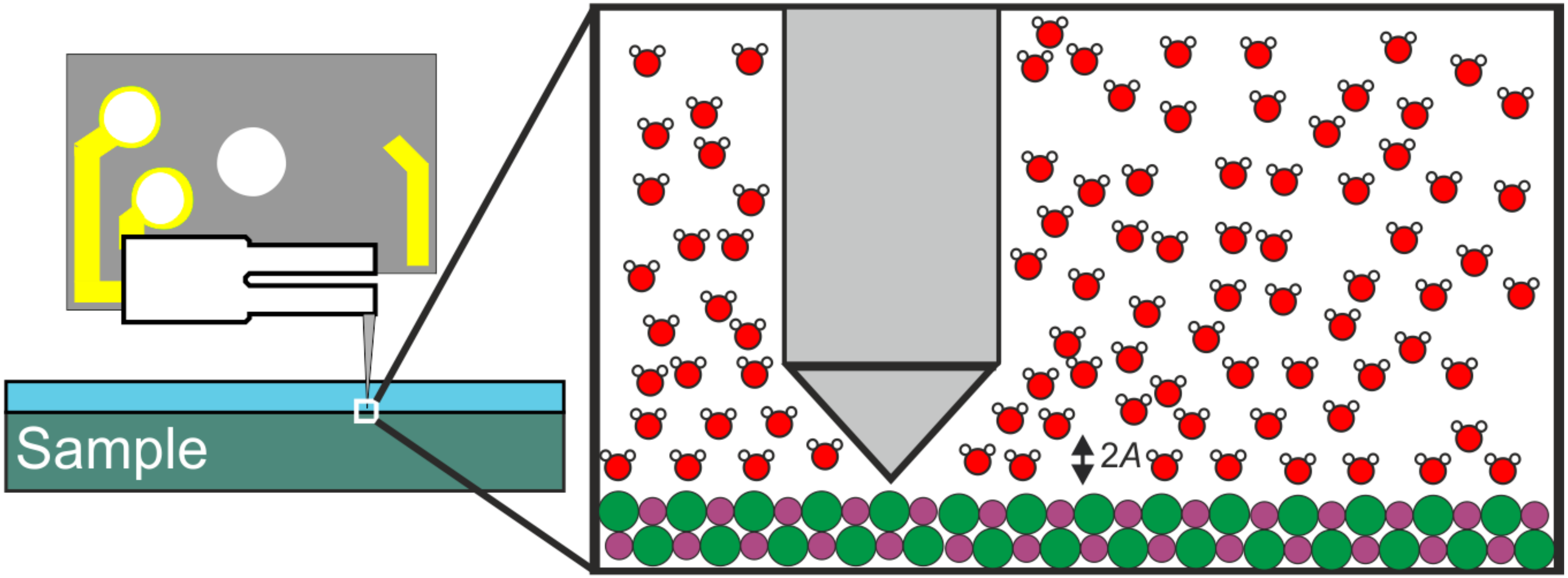
Strong effect of A on images

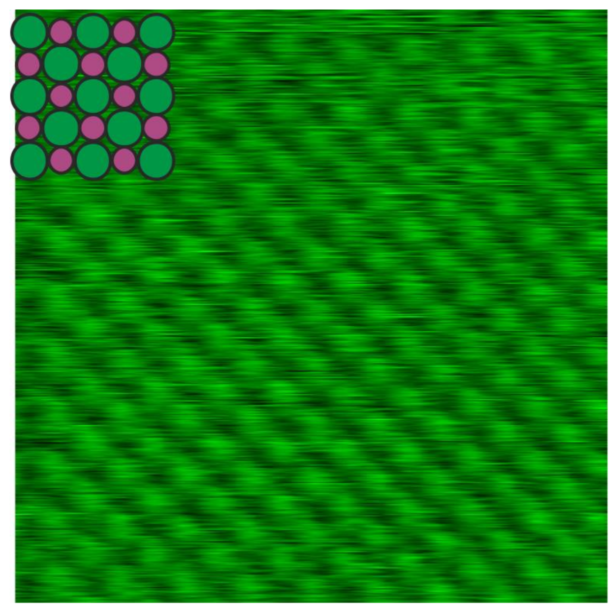


Calculate effective quality factor

$$Q = 2\pi \frac{\text{Energy stored}}{\text{Energy loss}} = 2\pi \frac{\frac{1}{2}kA^2}{E_{loss}}$$

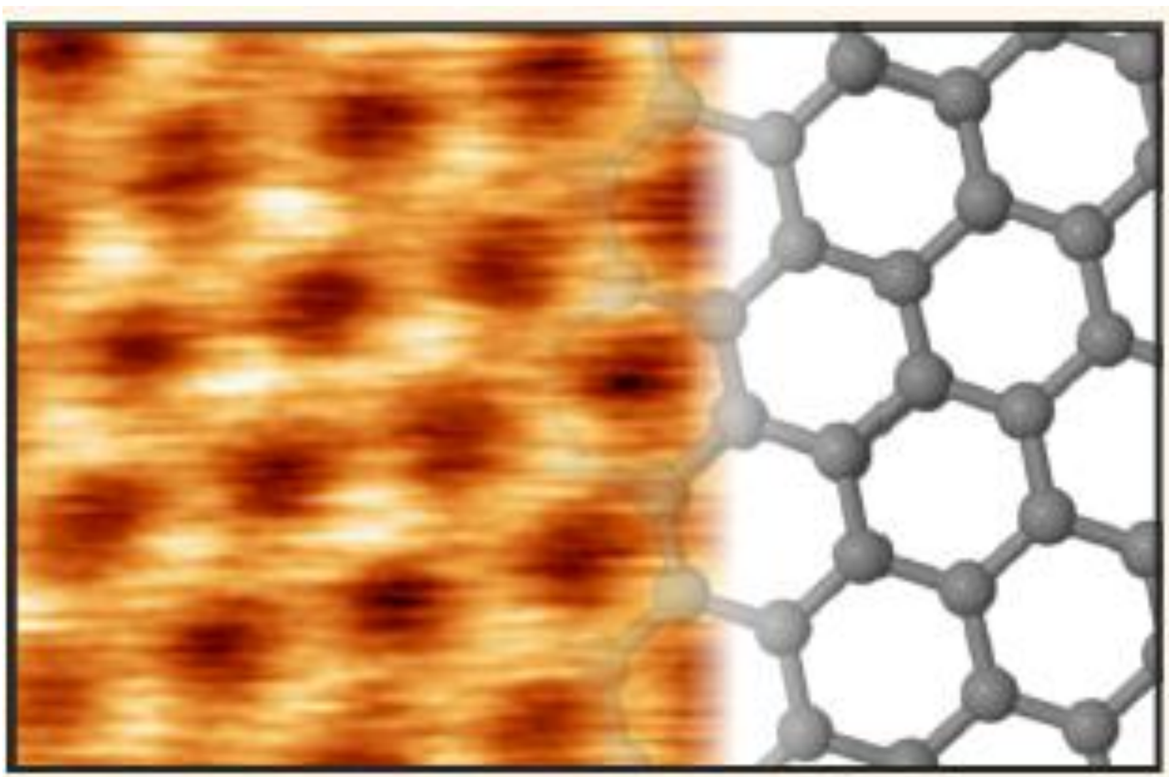




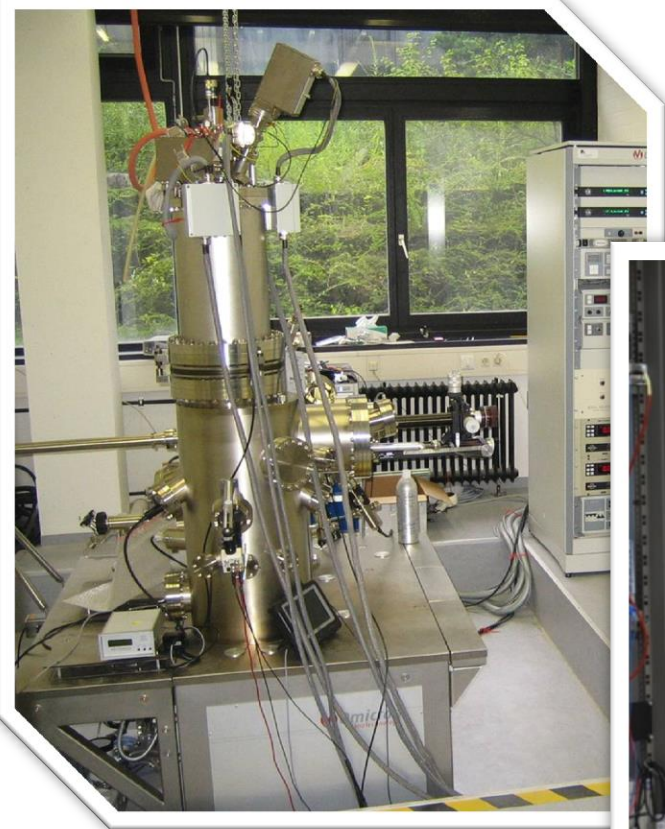


Wastl, et al. Phys. Rev. B, **87**, 245415 (2013)

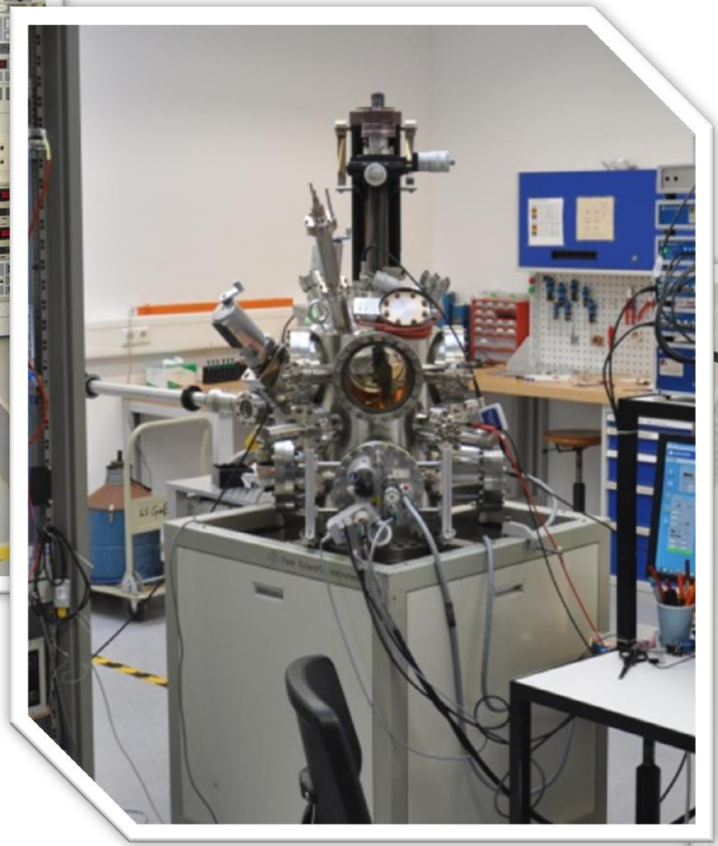
Applied to graphitic surfaces: graphene and graphite



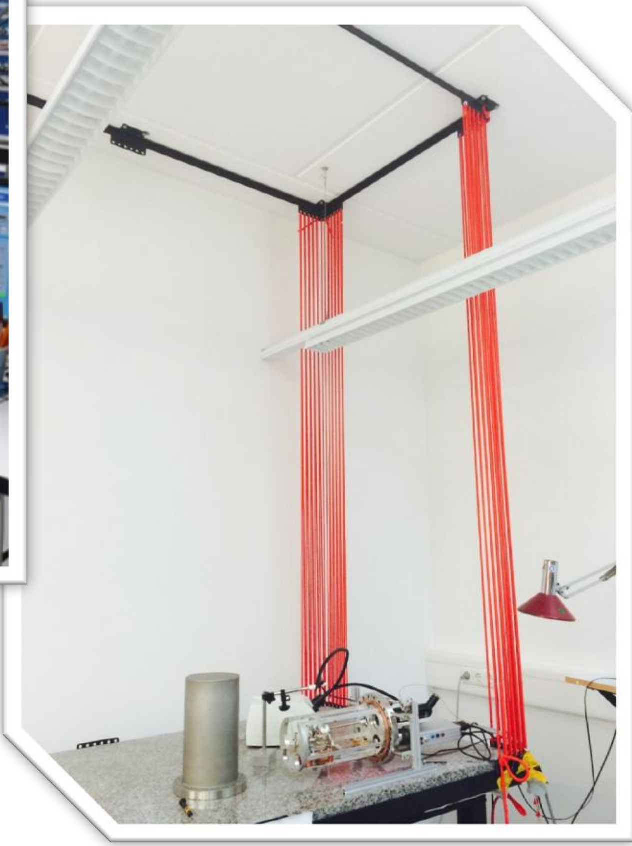
Wastl, et al. ACS Nano, **8**, 5233 (2014)



4.4 K
UHV



room temperature
UHV



ambient

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