

ME597/PHYS57000  
Fall Semester 2010  
Lecture 23

FM-AFM Selected Results  
Achieving Atomic Resolution  
with AFM

# Seeing atoms with AFMs

Image of graphite using contact-mode AFM: G. Binnig, Ch. Gerber, E. Stoll, T.R. Albrecht, and C.F. Quate, *Europhys. Lett.* 3, 181 (1987).

Frequency modulation (FM) method – high Q, large amplitude: T.R. Albrecht, P. Grutter, D. Horne, D. Rugar, *J. Appl. Phys.* 69, 668 (1991).

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Si(111)-(7x7) using noncontact AFM: F.J. Giessibl, *Science* 267, 68 (1995).

Si(111)-(7x7) using noncontact AFM: S. Kitamura and M. Iwatsuki, *Jpn. J. Appl. Phys.* 34, L145 (1995)

Atomic point defects in cleaved InP(110): H. Ueyamam, M. Ohta, Y. Sugawara, and S. Morita, *Jpn. J. Appl. Phys.* 34, L1086 (1995)

Defect motion of atomic point defects in cleaved InP(110): Y. Sugawara, M. Ohta, H. Ueyamam and S. Morita, *Science* 270, 1647 (1995).

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Si(111)-(7x7) using noncontact AFM: R. Luthi, et al., *Z. Phys. B* 100, 165 (1996).

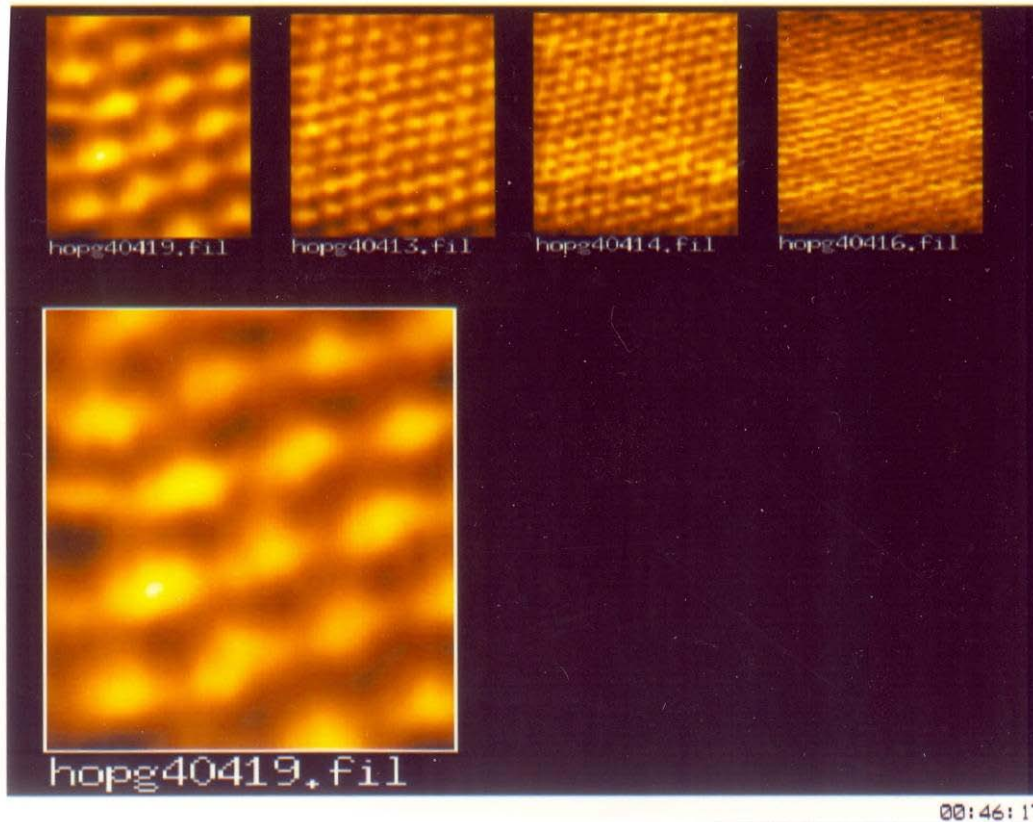
First International Workshop on Noncontact AFM – 1998 – Proceedings published in *Appl. Surf. Sci.* 140, 243-456 (1999).

*Non-contact Atomic Force Microscopy*, Eds. S. Morita, R. Wiesendanger and E. Meyer, Springer (2002).

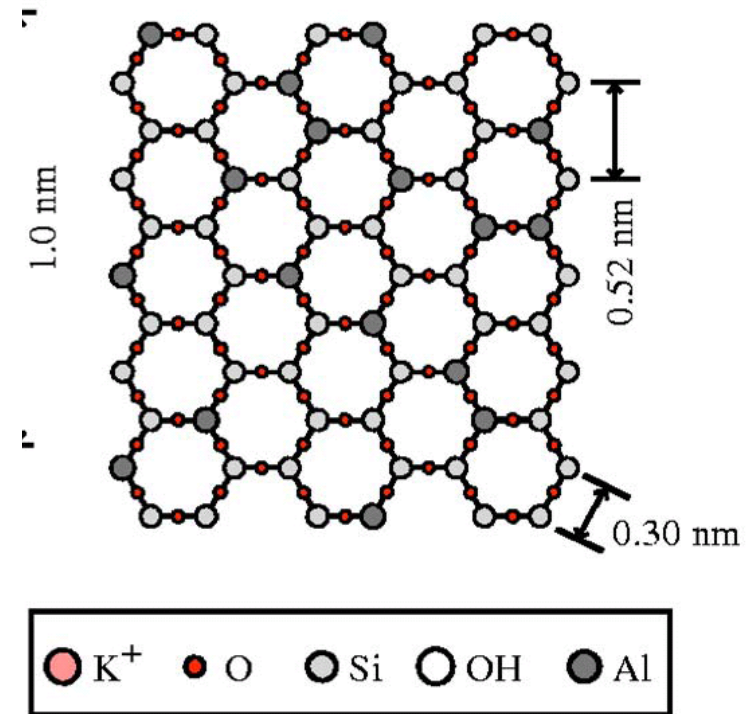
1995

# Atomic periodicity using contact mode AFM (constant applied force)

Contact AFM image of freshly  
cleaved mica



Mica



D. Schaefer, PhD thesis, Purdue University (1993)

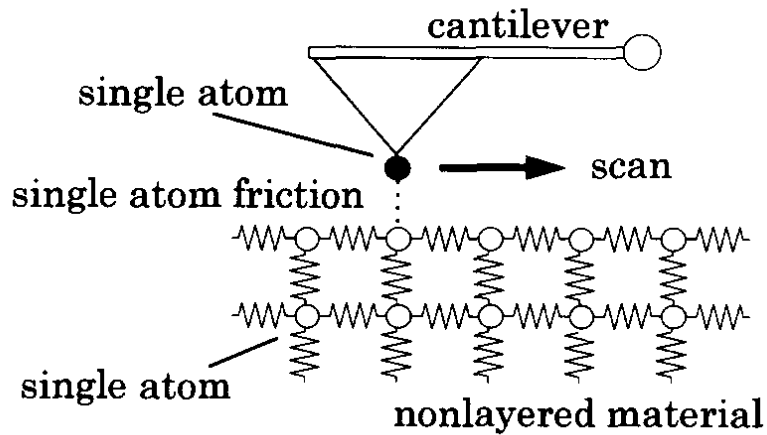
T. Fukuma, et al., Appl. Phys. Lett.  
87, 034101 (2005).

## Issues

- Large contact force required!
- Finite contact radius,  $r_c$  could be  $\sim 2$  nm
- $\pi r_c^2 / a_0^2 \gg 1$
- Large normal force  $\rightarrow$  high friction
- Coupling between lateral and normal force?
- Feedback loops are never perfect
- No defects?

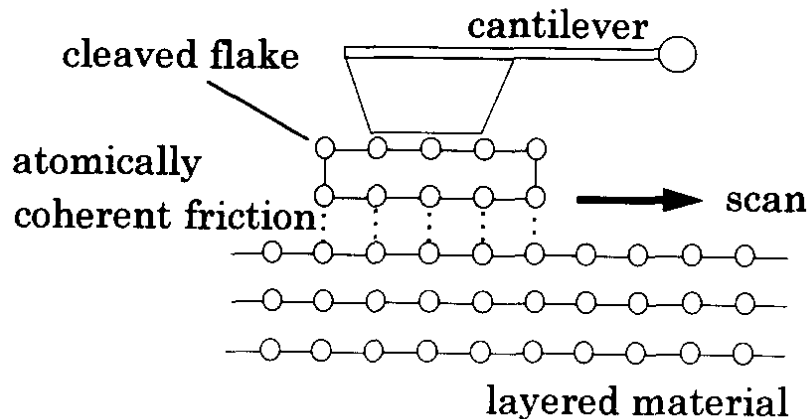
# Stick-Slip friction maps

(a)



**Stick-Slip Model**  
Spatially quantized adhesion with a "jump" to next sticking point. Atomic periodicity results, but only a fraction of the unit cell is "imaged".

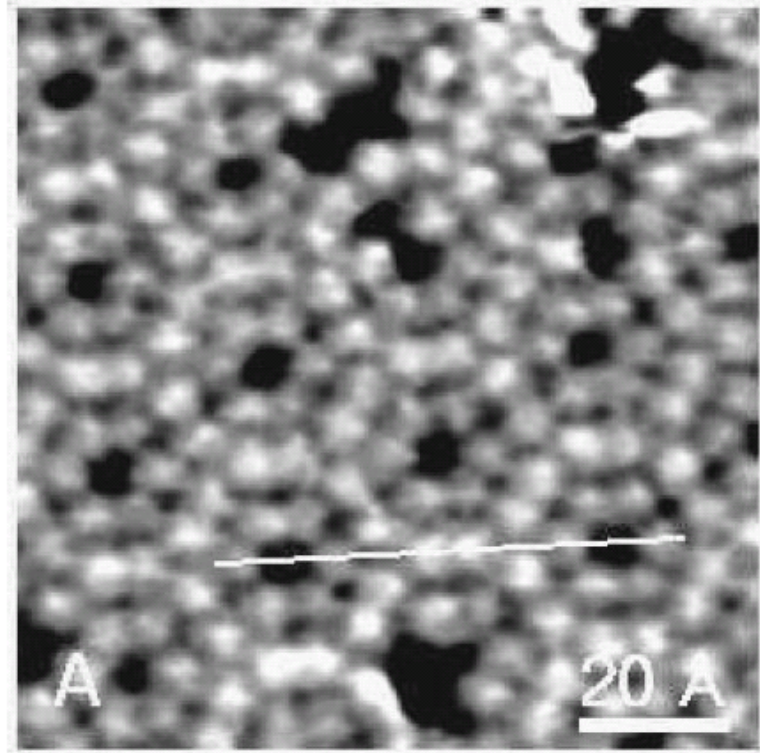
(b)



Explains why you never see defects

# Seeing atoms with AM-AFM (constant amplitude)

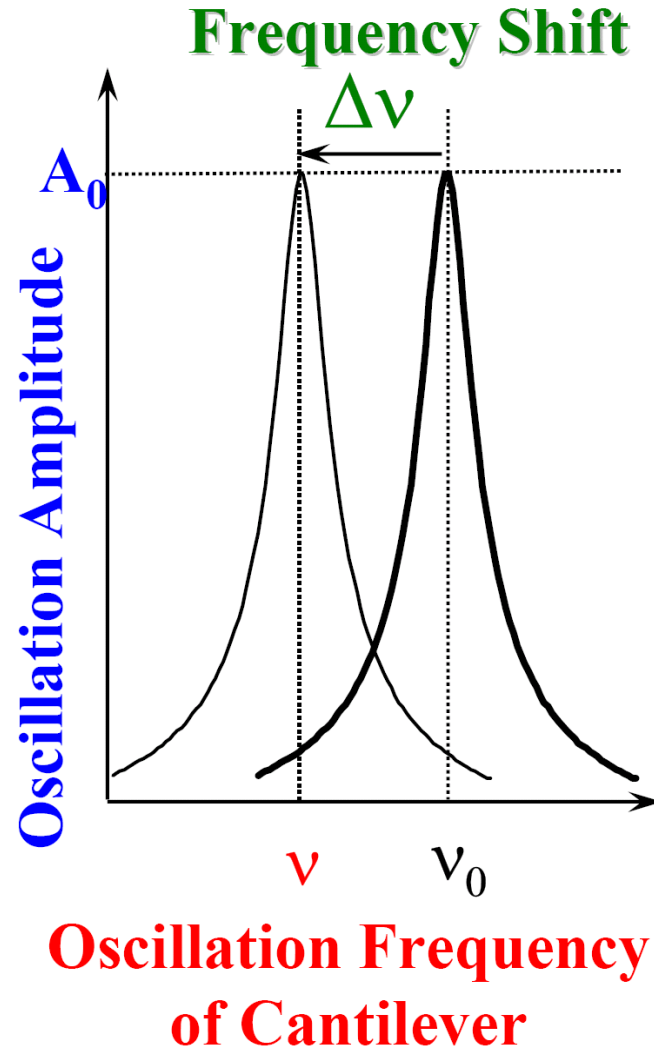
Atomic resolution Si(111)



$k=60$  N/m;  $f_0=16.4$  kHz;  $Q=550$ ;  $A_0=0.8$  nm

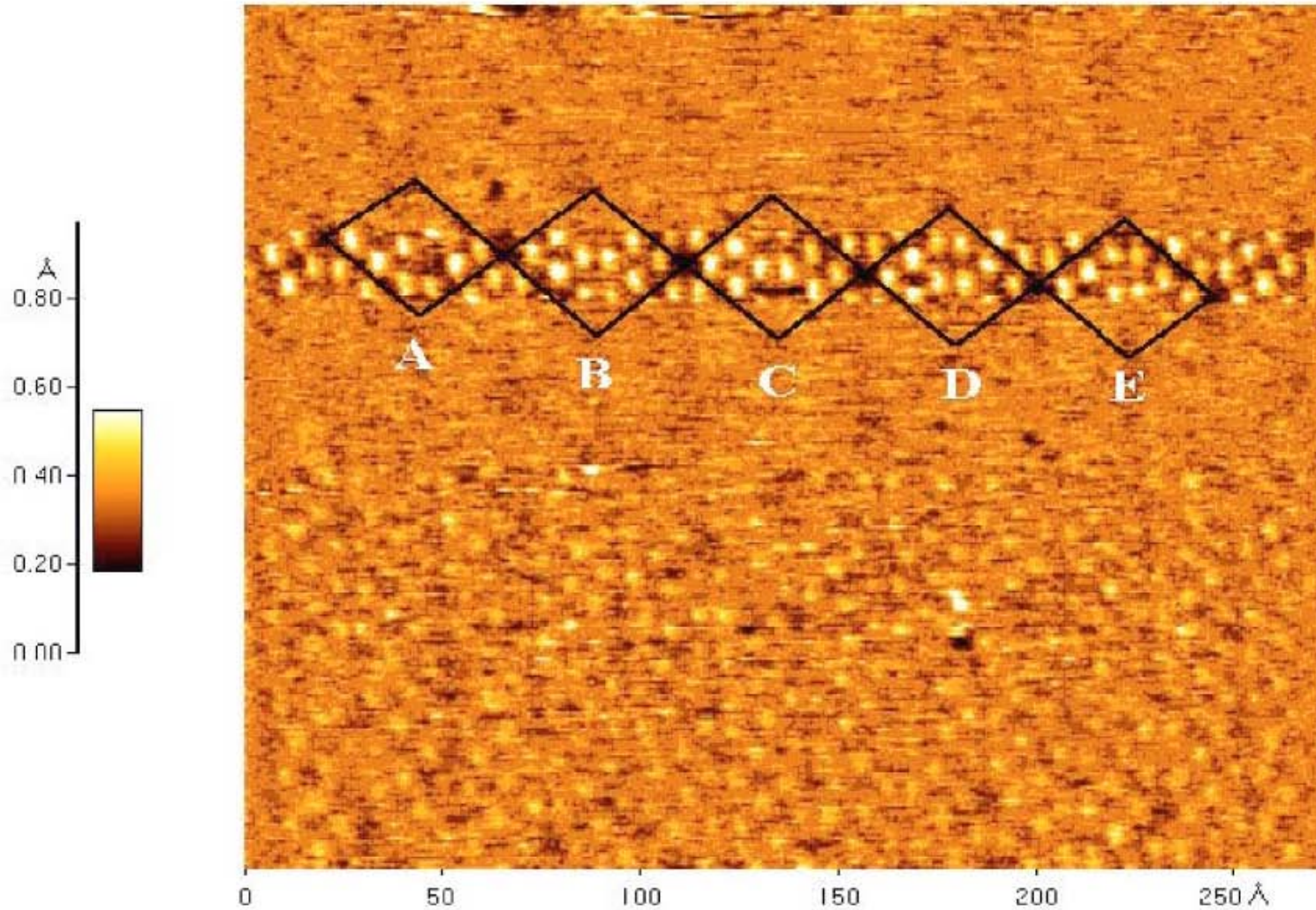
(not many reports! Why?)

# Seeing atoms with FM-AFM (constant frequency)



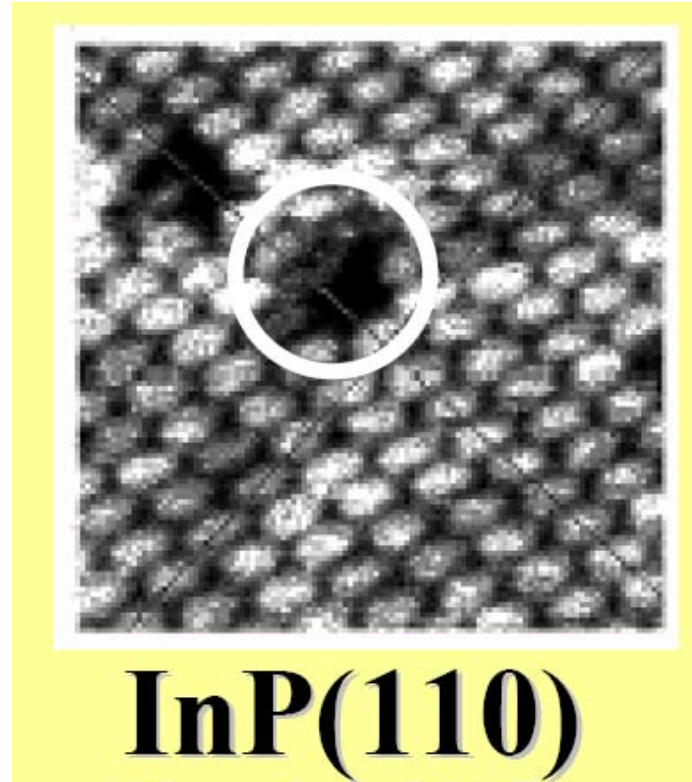


# Atomically resolved FM-AFM Image of Si(111)-(7x7)





# Atomic Point Defects - FM-AFM

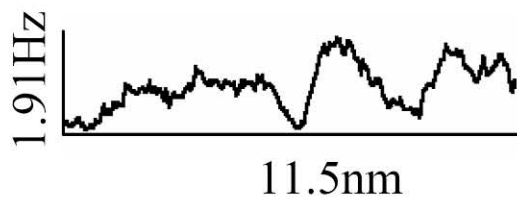
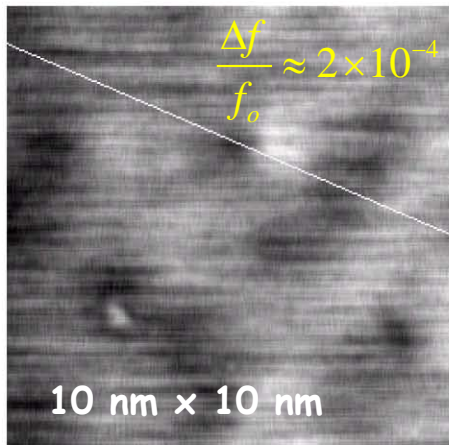


H. Ueyamam, M. Ohta, Y. Sugawara, and S. Morita, Jpn. J. Appl. Phys. 34, L1086 (1995).

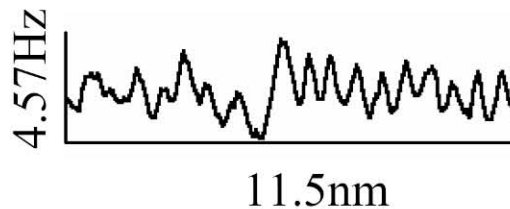
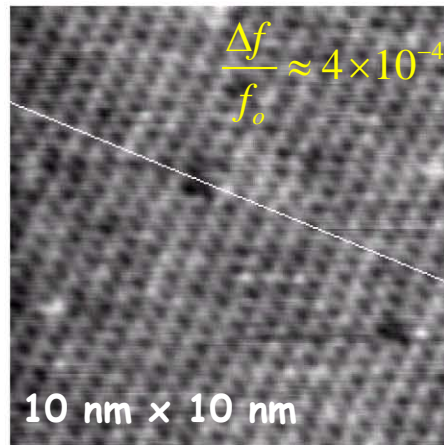
# Obtaining Atomic Resolution with FM-AFM

Cleaved p-doped-GaAs(001) in UHV

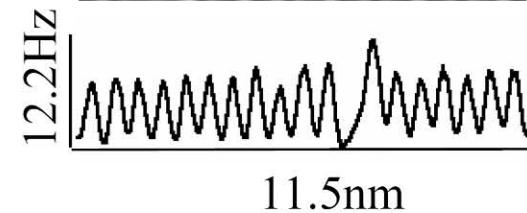
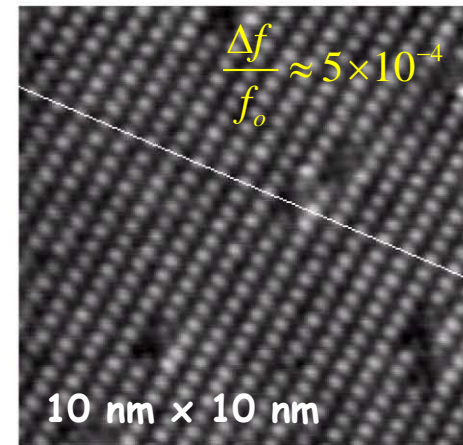
$d_{\min}=0.4 \text{ nm}; \Delta f=-31 \text{ Hz}$



$d_{\min}=0.1 \text{ nm}; \Delta f=-62 \text{ Hz}$

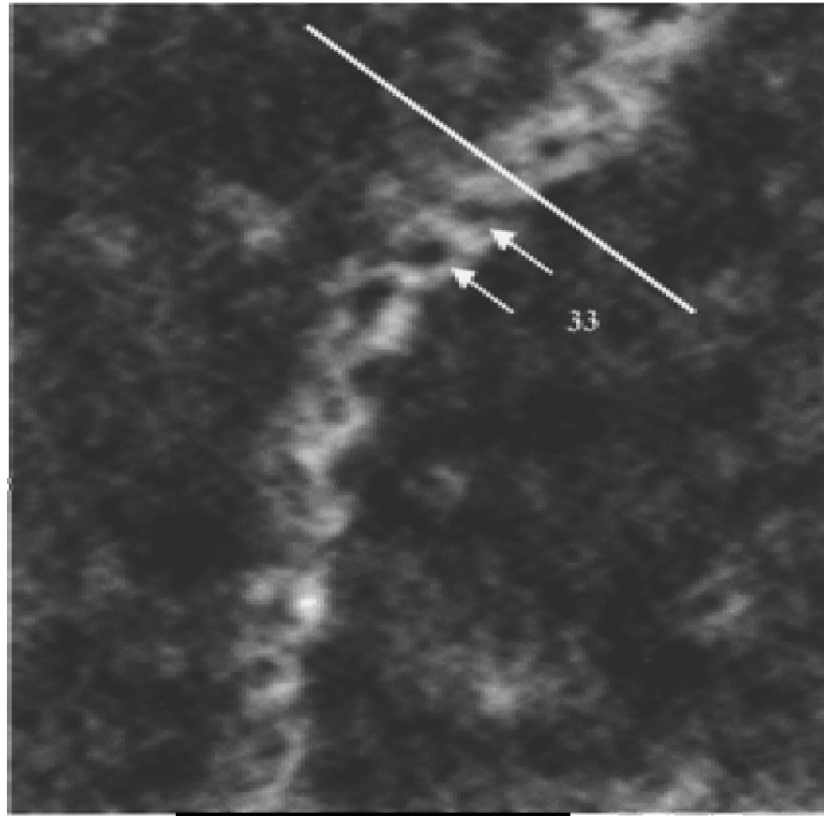


$d_{\min}=0.08 \text{ nm}; \Delta f=-70 \text{ Hz}$



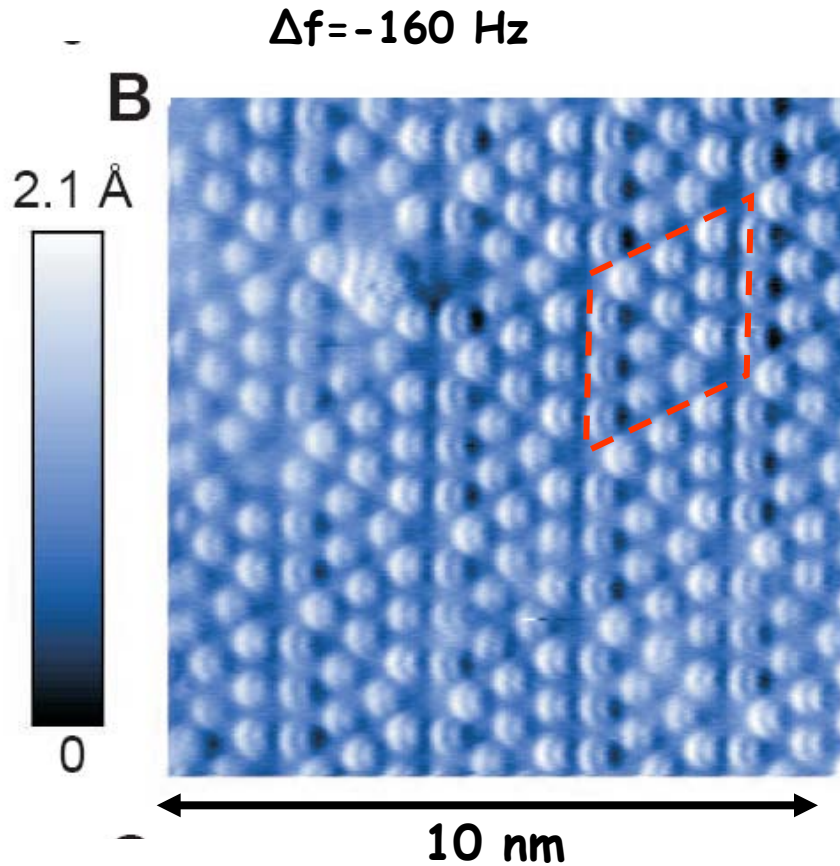
$k = 35 \text{ N/m}; f_0 = 150 \text{ kHz}; A_0=9 \text{ nm}; Q=38,000$

# Imaging DNA with FM-AFM

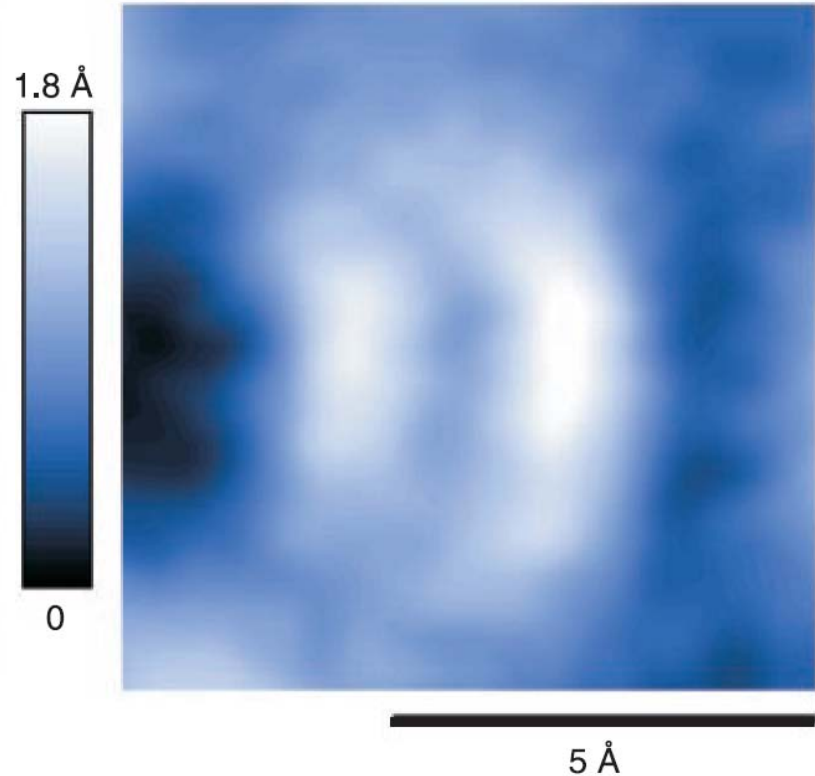


T. Uchihashi, M. Tanigawa, M. Ashino, Y. Sugawara, K. Yokoyama, S. Morita, and M. Ishikawa, *Langmuir* 16, 1349 (2000).

# Sub-atomic resolution? (W tip)



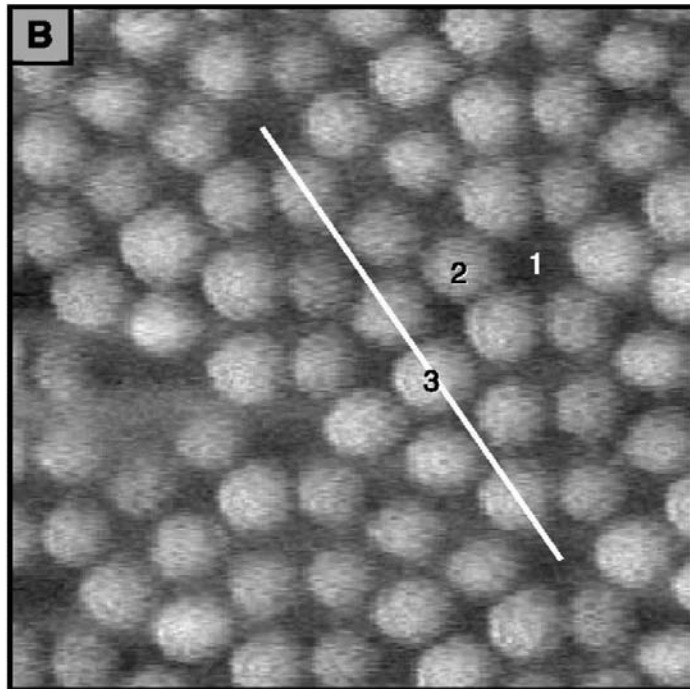
Enlargement of a single atom imaged by FM-AFM



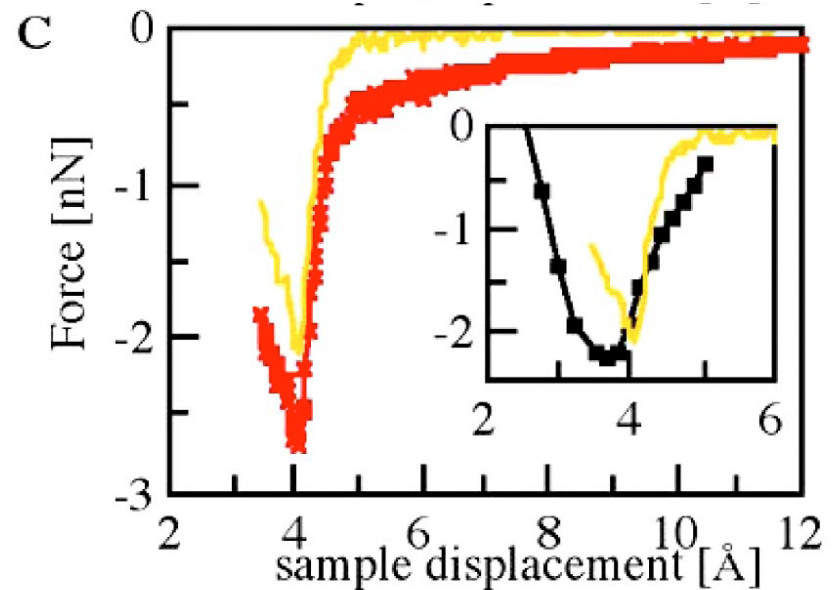
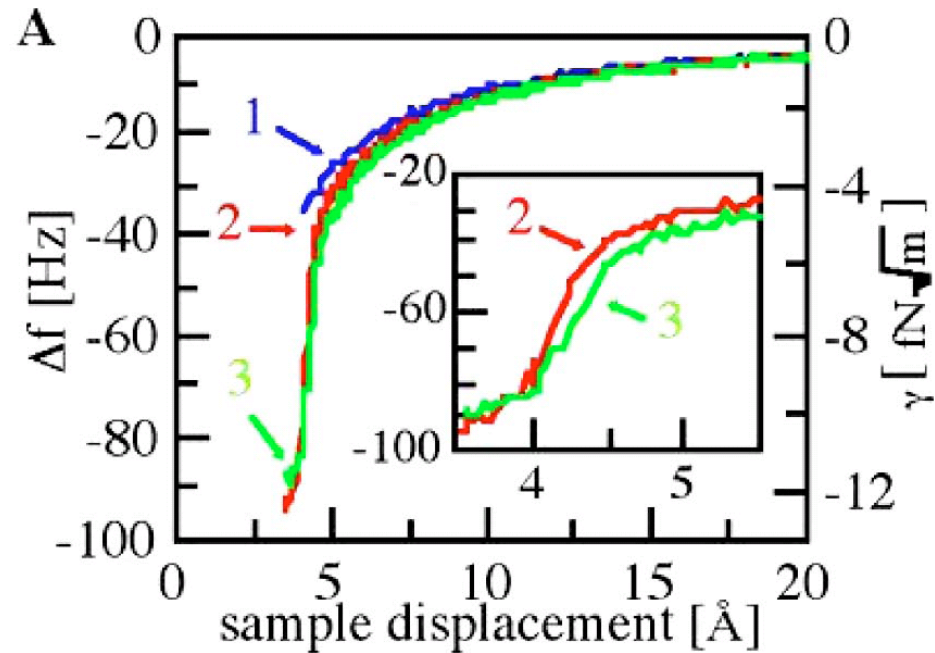
Crescents are interpreted as images of two atomic orbitals of the front atom of the tip



# Force Spectroscopy



**Si(111)-(7x7)**



# 2D Binary Alloys

## PERIODIC TABLE OF THE ELEMENTS

<http://www.ktf-split.hr/periodni/en/>

Legend:

- Metal
- Semimetal
- Nonmetal
- 1 Alkali metal
- 2 Alkaline earth metal
- 3-10 Transition metals
- L Lanthanide
- A Actinide
- 16 Chalcogens element
- 17 Halogens element
- 18 Noble gas

STANDARD STATE (25 °C; 101 kPa)

- Ne - gas
- Fe - solid
- Ga - liquid
- Tc - synthetic

PERIOD	GROUP I A		GROUP II A		GROUP III B										GROUP IV B										GROUP V B										GROUP VI B										GROUP VII A										GROUP VIII A																																																																																																													
1	1 1.0079 <b>H</b> HYDROGEN		2 4 9.0122 <b>Li</b> LITHIUM		3 5 10.811 <b>B</b> BORON																																																				18 2 4.0026 <b>He</b> HELIUM																																																																																																											
2	3 6.941 <b>Li</b> LITHIUM		4 9.0122 <b>Be</b> BERYLLIUM																																																														9 18.998 <b>F</b> FLUORINE										10 20.180 <b>Ne</b> NEON																																																																																									
3	11 22.990 <b>Na</b> SODIUM		12 24.305 <b>Mg</b> MAGNESIUM																																																																								17 35.453 <b>Cl</b> CHLORINE										18 39.948 <b>Ar</b> ARGON																																																																															
4	19 39.098 <b>K</b> POTASSIUM		20 40.078 <b>Ca</b> CALCIUM																																																																																		33 74.922 <b>As</b> ARSENIC										34 78.96 <b>Se</b> SELENIUM										35 79.904 <b>Br</b> BROMINE										36 83.80 <b>Kr</b> KRYPTON																																																	
5	37 85.468 <b>Rb</b> RUBIDIUM		38 87.62 <b>Sr</b> STRONTIUM																																																																																																						49 114.82 <b>In</b> INDIUM										50 118.71 <b>Sn</b> TIN										51 121.76 <b>Sb</b> ANTIMONY										52 127.60 <b>Te</b> TELLURIUM										53 126.90 <b>I</b> IODINE										54 131.29 <b>Xe</b> XENON									
6	55 132.91 <b>Cs</b> CAESIUM		56 137.33 <b>Ba</b> BARIUM		57-71 <b>La-Lu</b> Lanthanide										72 178.49 <b>Hf</b> HAFNIUM										73 180.95 <b>Ta</b> TANTALUM										74 183.84 <b>W</b> TUNGSTEN										75 186.21 <b>Re</b> RHENIUM										76 190.23 <b>Os</b> OSMIUM										77 192.22 <b>Ir</b> IRIDIUM										78 195.08 <b>Pt</b> PLATINUM										79 196.97 <b>Au</b> GOLD										80 200.59 <b>Hg</b> MERCURY										81 204.38 <b>Tl</b> THALLIUM										82 207.2 <b>Pb</b> LEAD										83 208.98 <b>Bi</b> BISMUTH										84 (209) <b>Po</b> POLONIUM										85 (210) <b>At</b> ASTATINE										86 (222) <b>Rn</b> RADON									
7	87 (223) <b>Fr</b> FRANCIUM		88 (226) <b>Ra</b> RADIUM		89-103 <b>Ac-Lr</b> Actinide										104 (261) <b>Rf</b> RUTHERFORDIUM										105 (262) <b>Db</b> DUBNIUM										106 (266) <b>Sg</b> SEABORGIUM										107 (264) <b>Bh</b> BOHRIUM										108 (277) <b>Hs</b> HASSIUM										109 (268) <b>Mt</b> MEITNERIUM										110 (281) <b>Uun</b> UNUNNIUM										111 (272) <b>Uuu</b> UNUNUNIUM										112 (285) <b>Uub</b> UNUNBIUM										114 (289) <b>Uuq</b> UNUNQUADIUM																																																											

**LANTHANIDE**

57 138.91 <b>La</b> LANTHANUM	58 140.12 <b>Ce</b> CERIUM	59 140.91 <b>Pr</b> PRASEODYMIUM	60 144.24 <b>Nd</b> NEODYMIUM	61 (145) <b>Pm</b> PROMETHIUM	62 150.36 <b>Sm</b> SAMARIUM	63 151.96 <b>Eu</b> EUROPIUM	64 157.25 <b>Gd</b> GADOLINIUM	65 158.93 <b>Tb</b> TERBIUM	66 162.50 <b>Dy</b> DYSPROSIUM	67 164.93 <b>Ho</b> HOLMIUM	68 167.26 <b>Er</b> ERBIUM	69 168.93 <b>Tm</b> THULIUM	70 173.04 <b>Yb</b> YTTERIUM	71 174.97 <b>Lu</b> LUTETIUM
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**ACTINIDE**

89 (227) <b>Ac</b> ACTINIUM	90 232.04 <b>Th</b> THORIUM	91 231.04 <b>Pa</b> PROTACTINIUM	92 238.03 <b>U</b> URANIUM	93 (237) <b>Np</b> NEPTUNIUM	94 (244) <b>Pu</b> PLUTONIUM	95 (243) <b>Am</b> AMERICIUM	96 (247) <b>Cm</b> CURIUM	97 (247) <b>Bk</b> BERKELIUM	98 (251) <b>Cf</b> CALIFORNIUM	99 (252) <b>Es</b> EINSTEINIUM	100 (257) <b>Fm</b> FERMIUM	101 (258) <b>Md</b> MENDELEVIUM	102 (259) <b>No</b> NOBELIUM	103 (262) <b>Lr</b> LAWRENCIUM
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Editor: Aditya Vardhan (advvar@netlinx.com)

Intense interest because i) new surface structures and ii) possibility of tailoring the electronic properties of a surface



# Increasing Sn coverage on Si(111) substrate

Sn - 1/6 ML

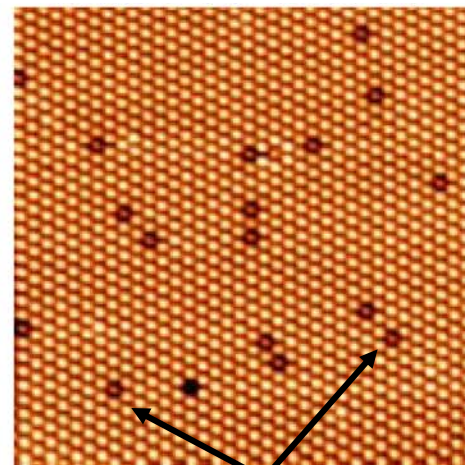
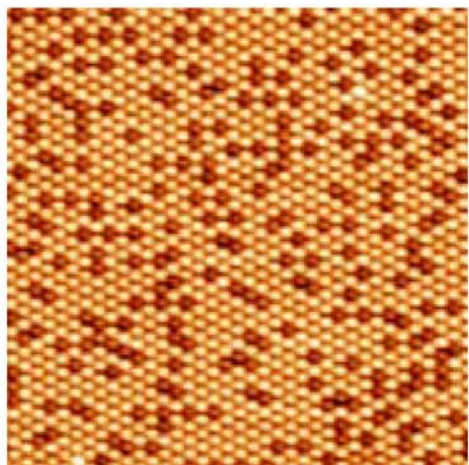
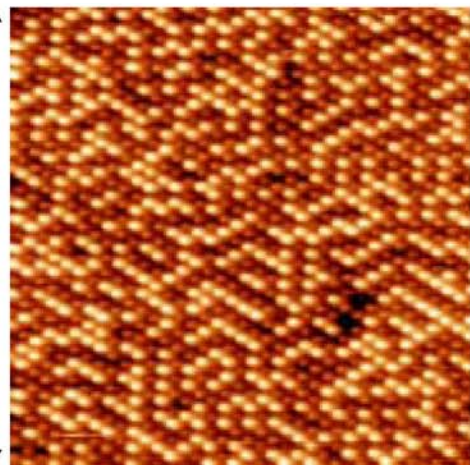
Sn - 1/4 ML

Sn - 1/3 ML

50% Sn; 50% Si

75% Sn; 25% Si

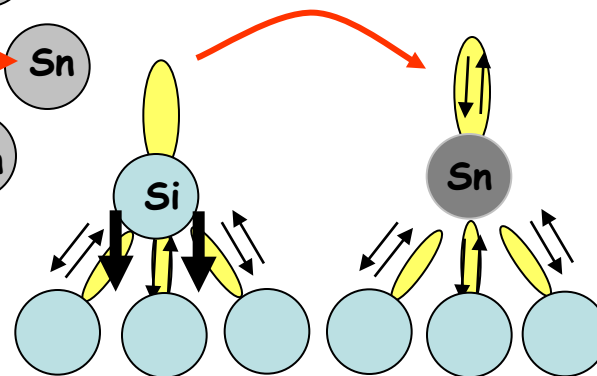
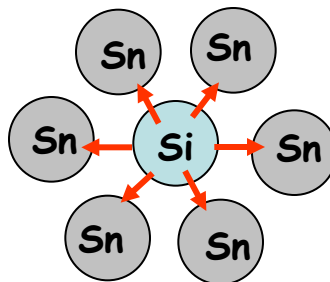
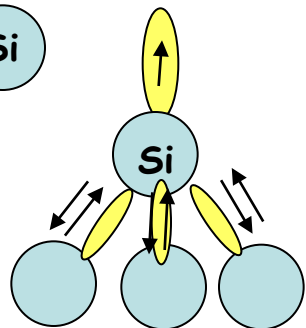
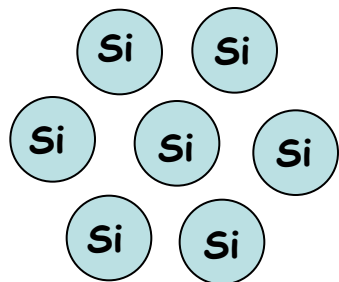
99% Sn; 1% Si



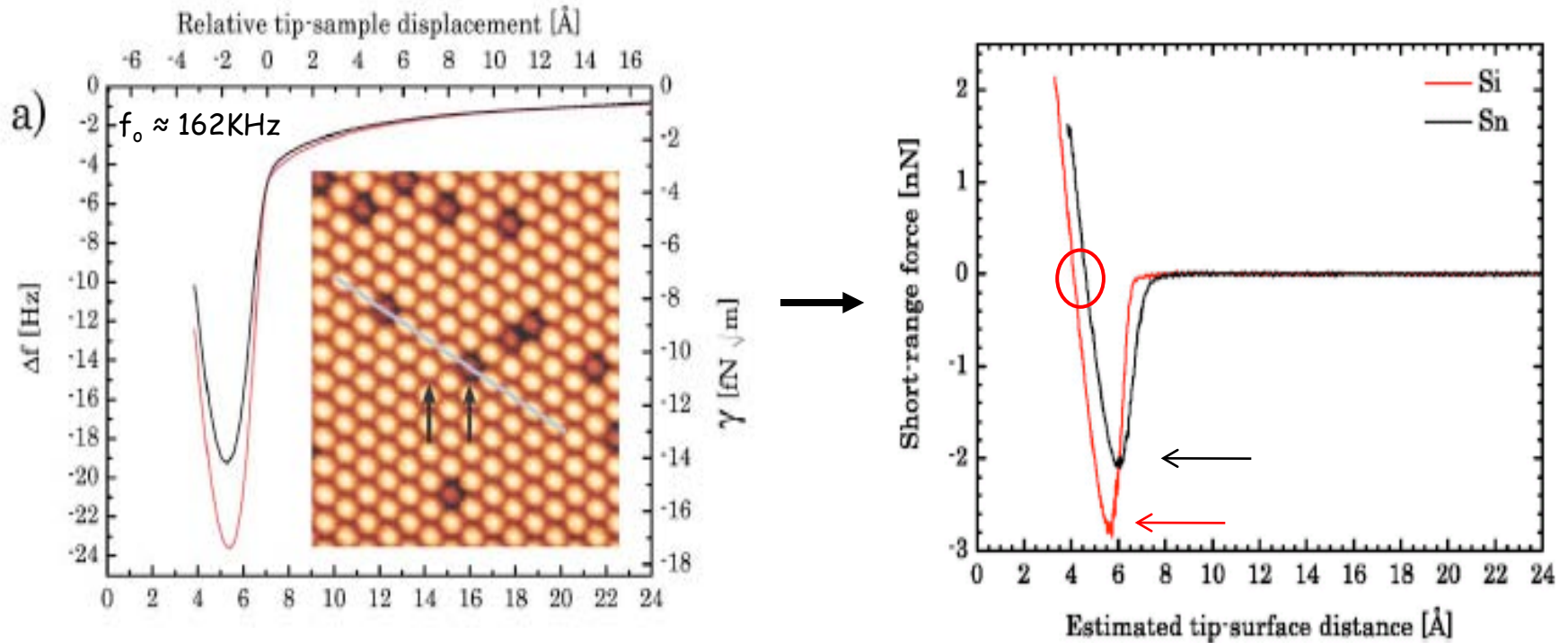
$a_{\text{Sn}} \sim 3a_{\text{Si}}$

20 nm x 20 nm; 1ML on Si(111) =  $7.84 \times 10^{14}$  atoms/cm<sup>2</sup>

Si "defects"

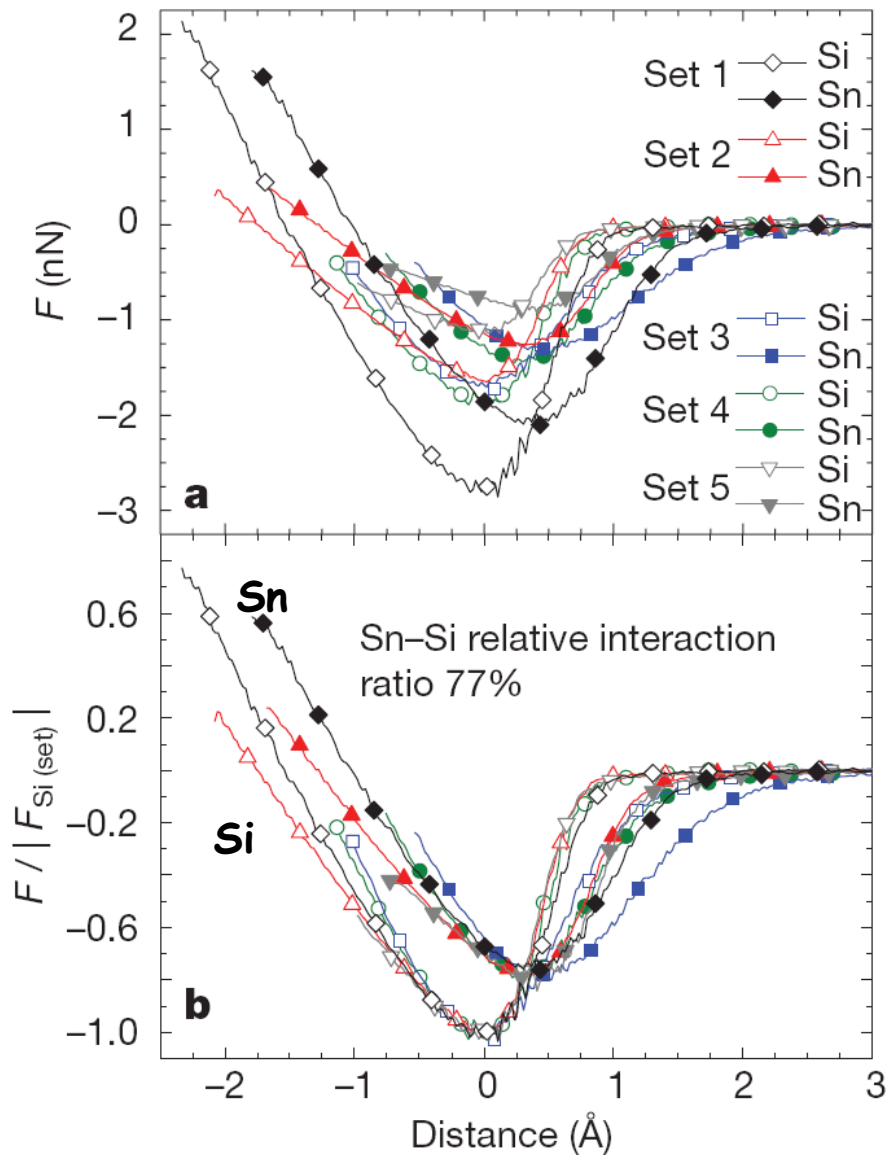


# Measuring the Interaction Force

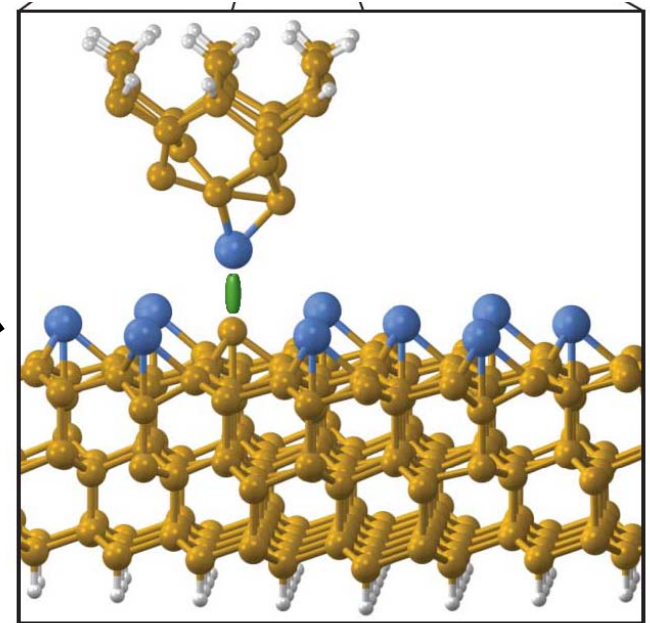


# Atomic Fingerprints: Sn-Si

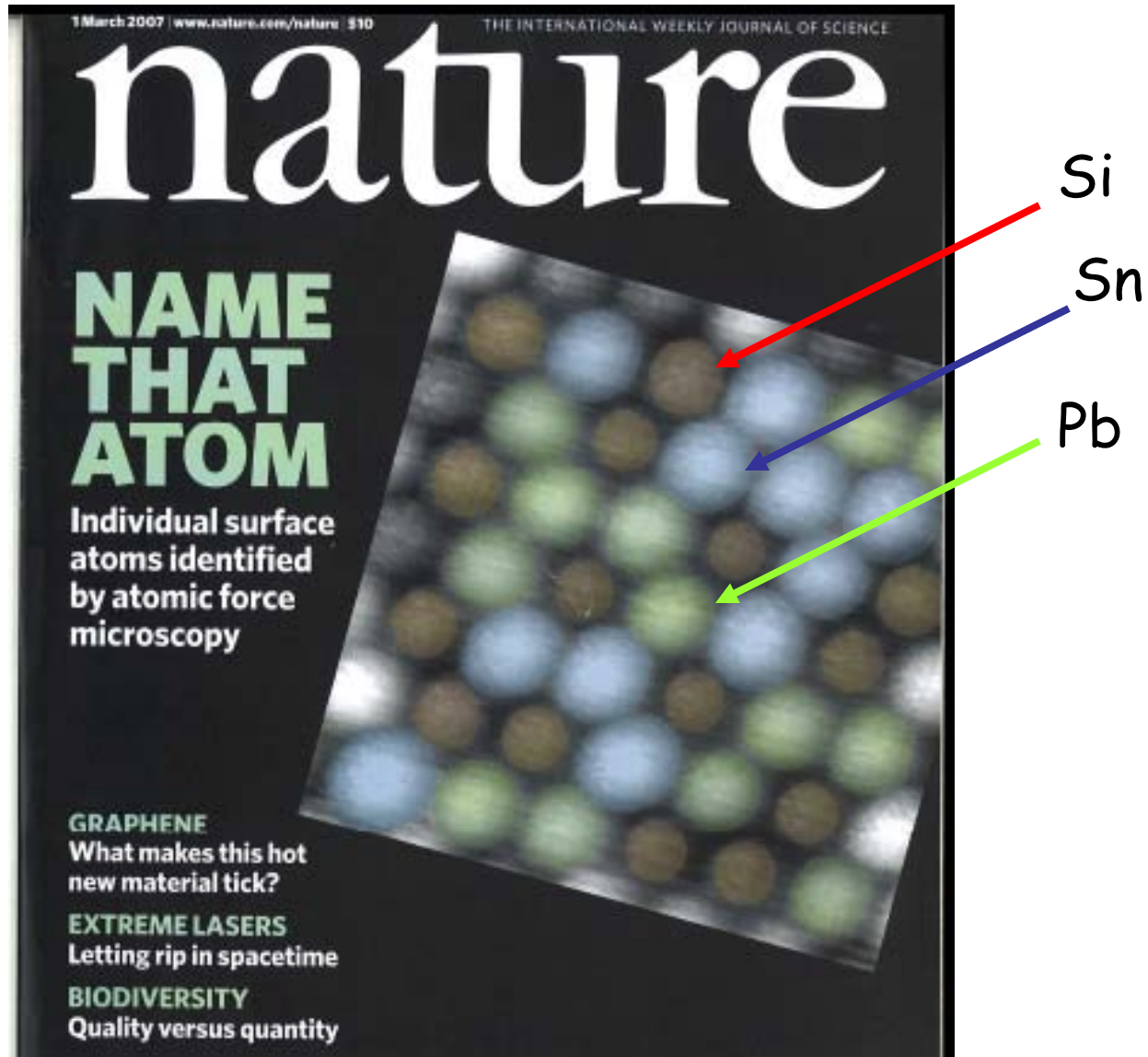
## Tip-to-tip variability



## Precise tip structure?

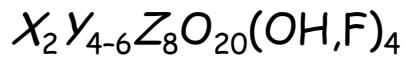


# Chemical Identification





# Mica Crystallographic Structure

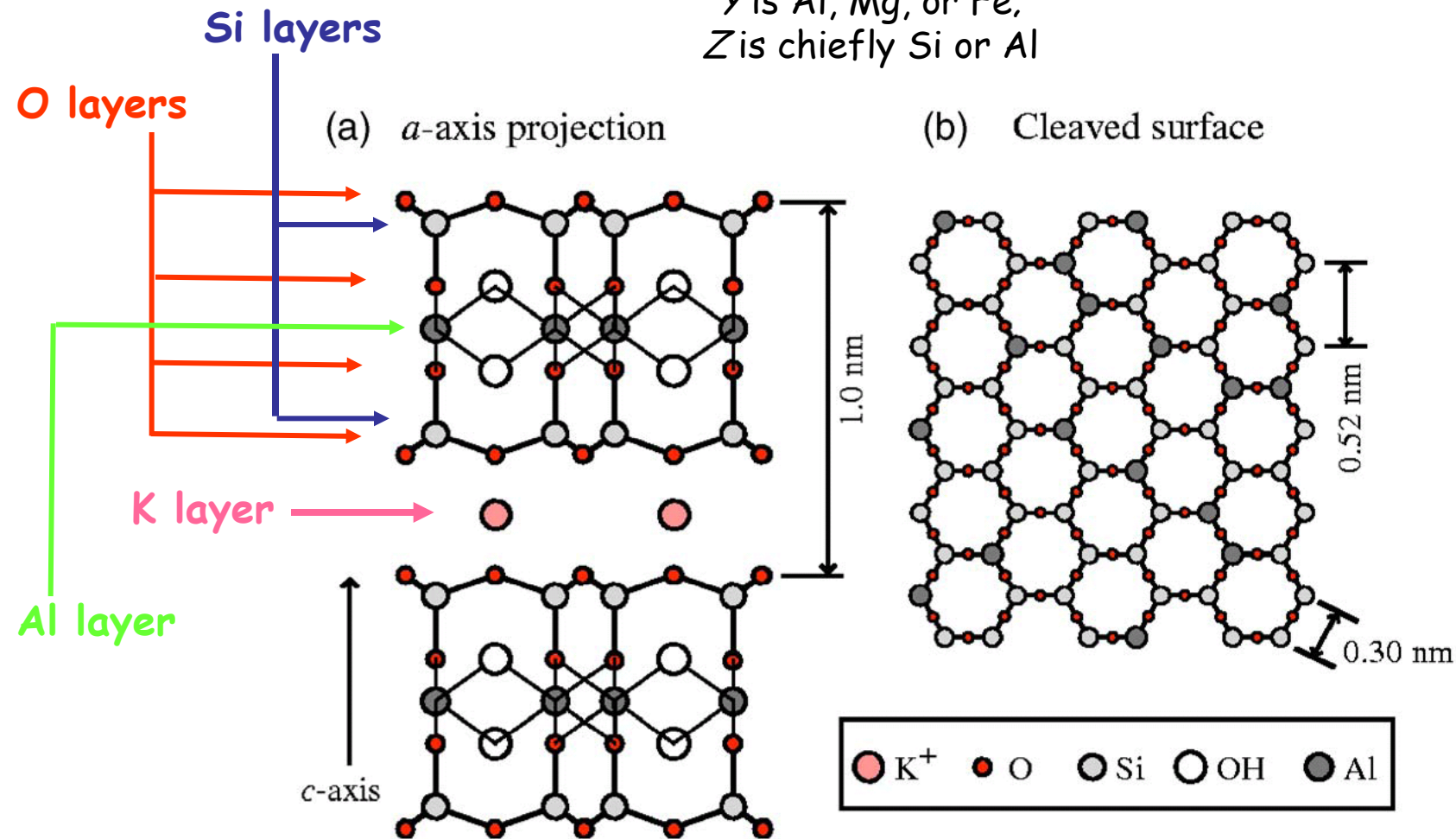


in which

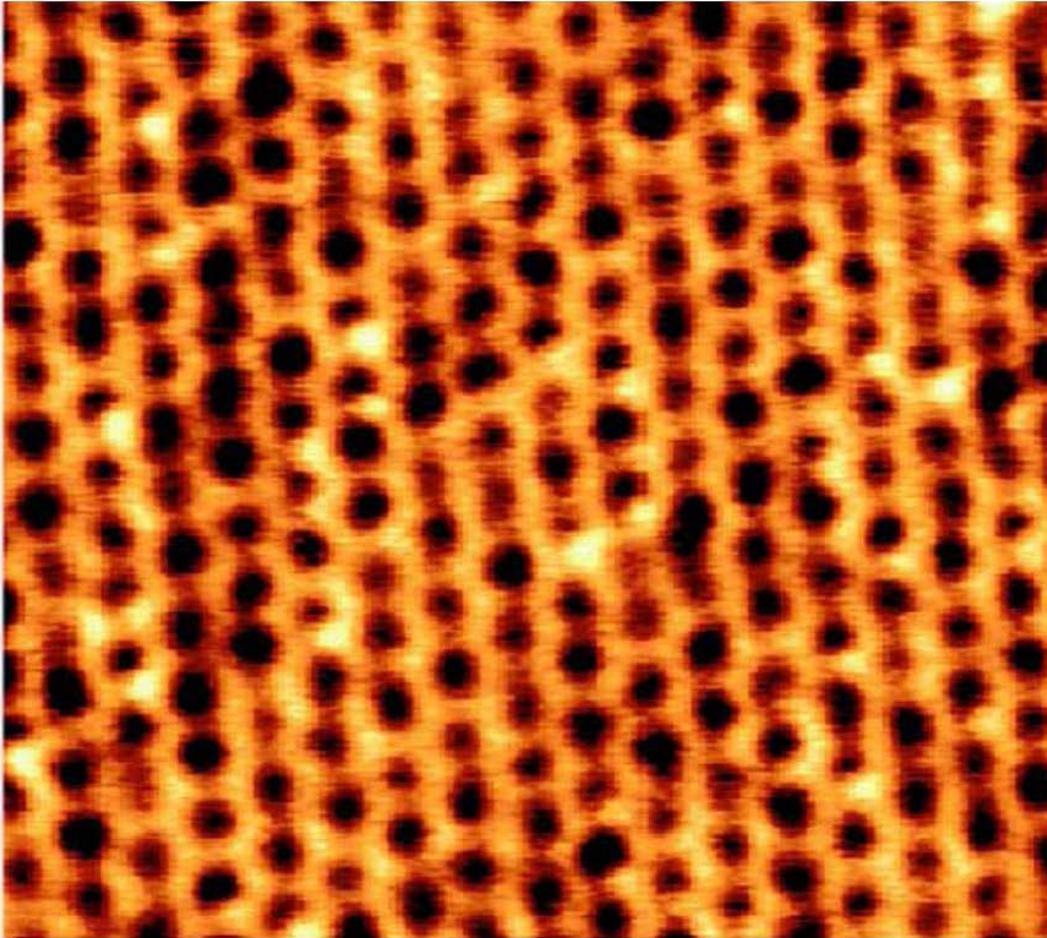
X is K, Na, or Ca;

Y is Al, Mg, or Fe;

Z is chiefly Si or Al



# Mica under Water



$A_0 = 0.16-0.33 \text{ nm}$

Vertical resolution 2-6 pm

Lateral resolution 300 pm

$Q = 20-30$