

ME597/PHYS57000
Fall Semester 2009
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).

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).

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

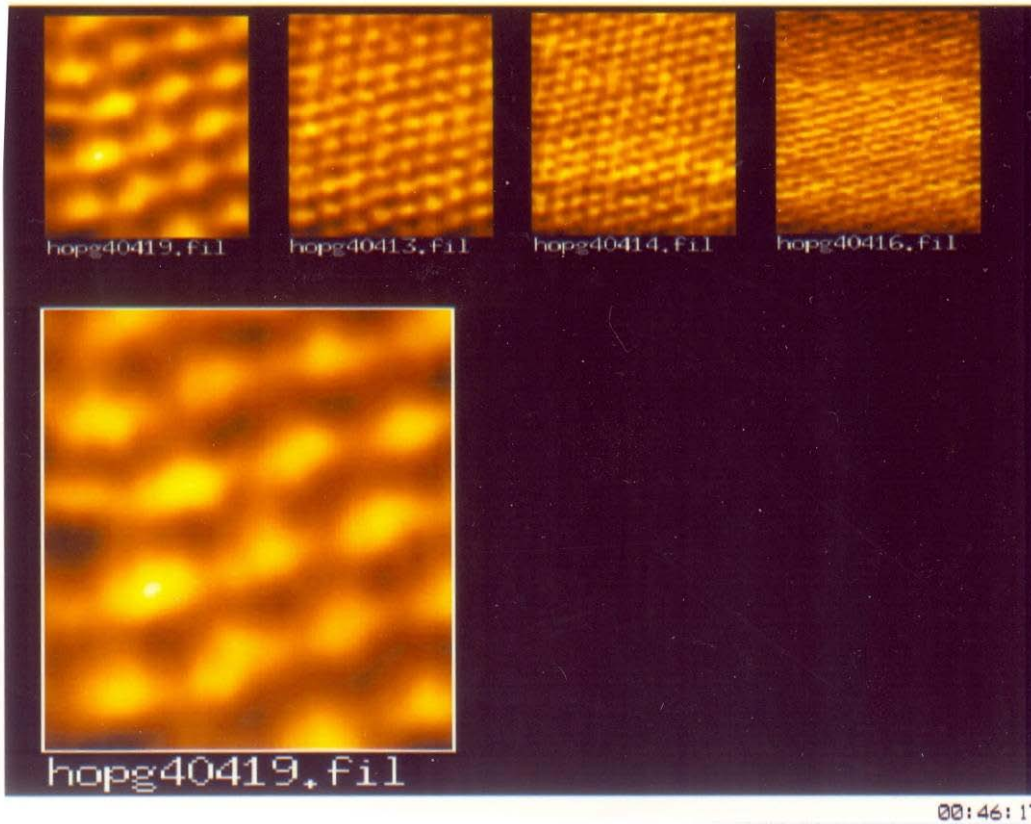
First International Workshop on Noncontact AFM – 1998 – Proceedings published in *Appl. Surf. Sci.* 140, 243-456 (1999).

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

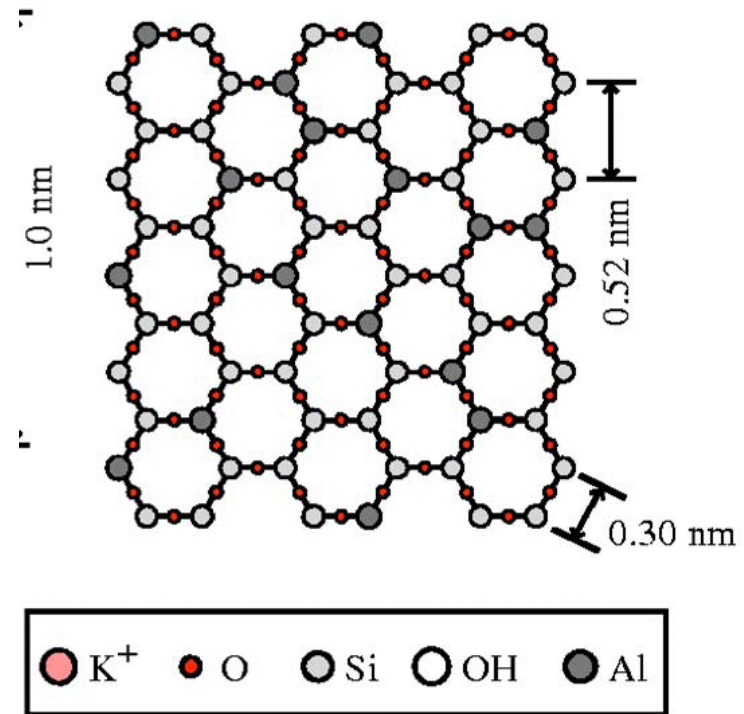
1995

Atomic periodicity using contact mode AFM (constant applied force)

Contact AFM image of freshly
cleaved mica



Mica



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

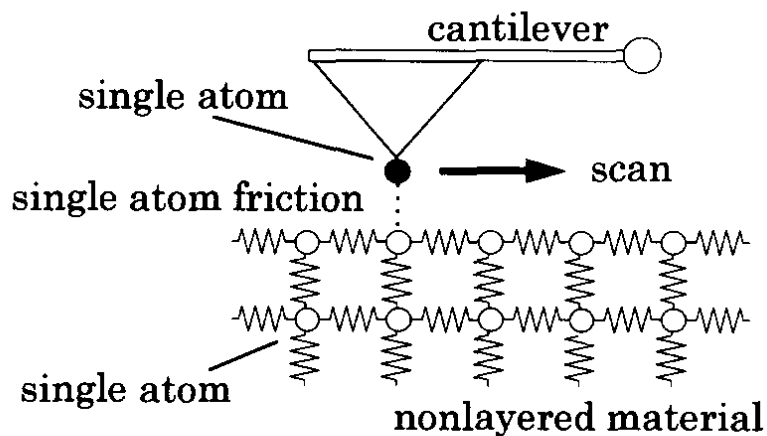
T. Fukuma, et al., Appl. Phys. Lett.
87, 034101 (2005).

Issues

- Large contact force required!
- Finite contact radius, r_c could be ~ 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?

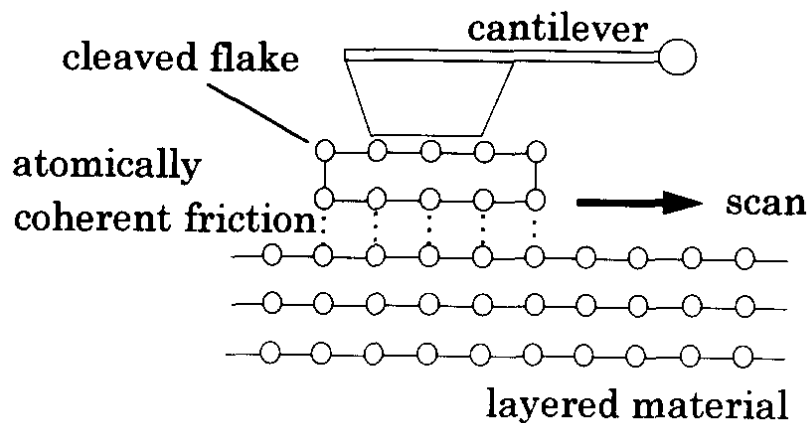
Stick-Slip friction maps

(a)



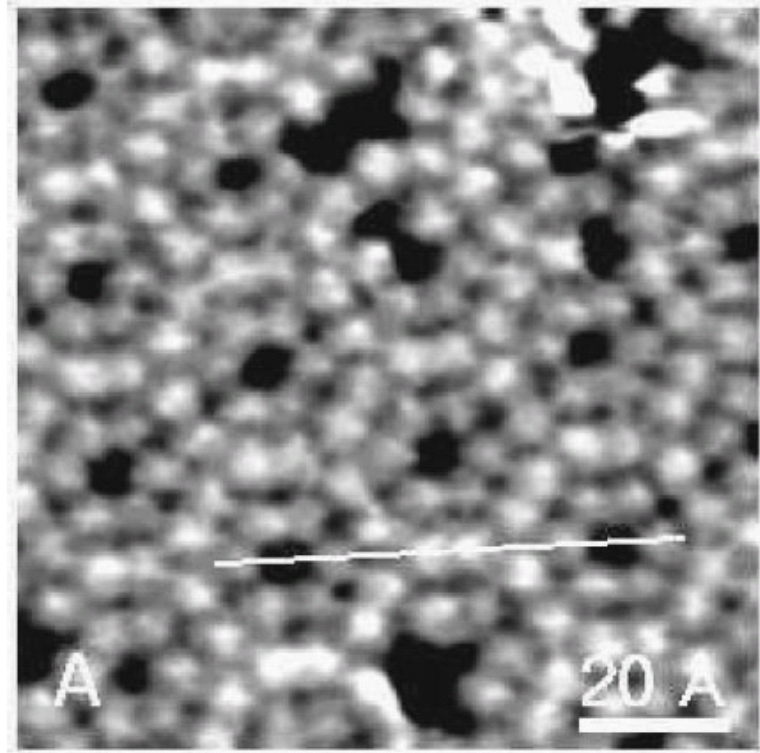
Stick-Slip Model Spatially quantized adhesion with a "jump" to next sticking point. Atomic periodicity results, but only a fraction of the unit cell is "imaged".

(b)



Seeing atoms with AM-AFM (constant amplitude)

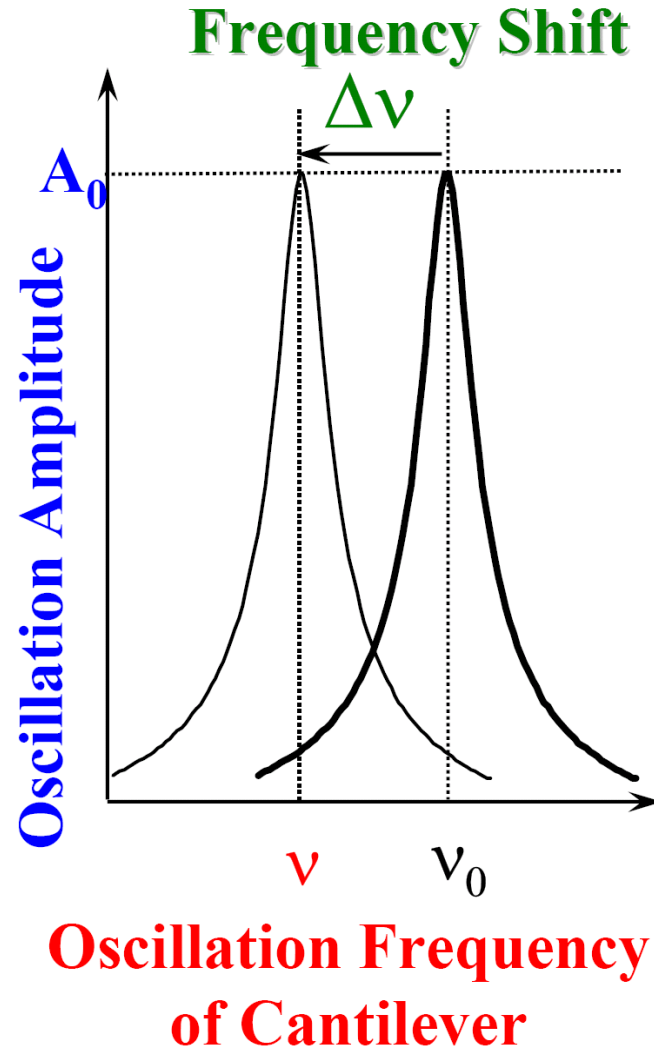
Atomic resolution Si(111)



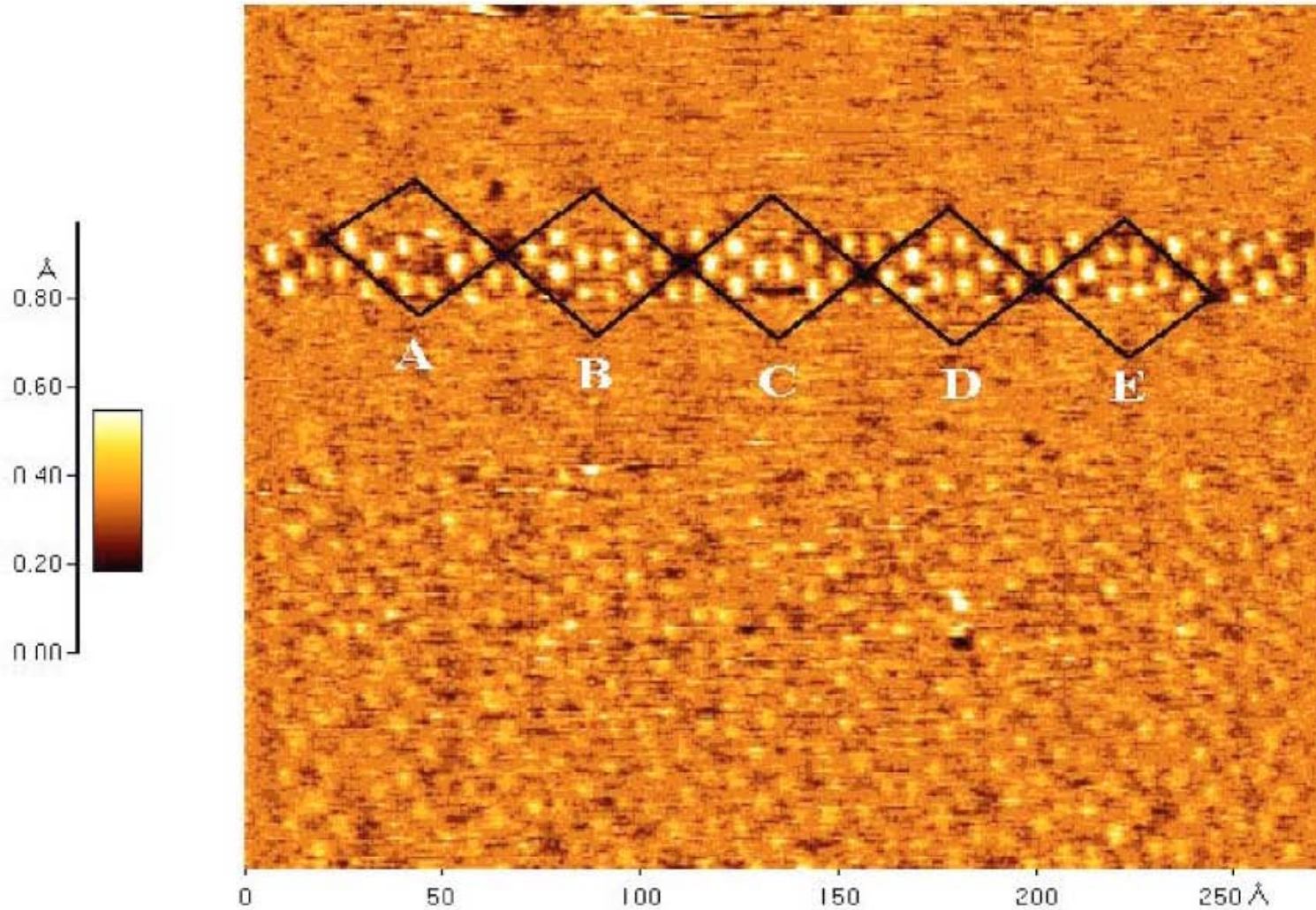
$k=60$ N/m; $f_o=16.4$ kHz; $Q=550$; $A_o=0.8$ nm

(not many reports! Why?)

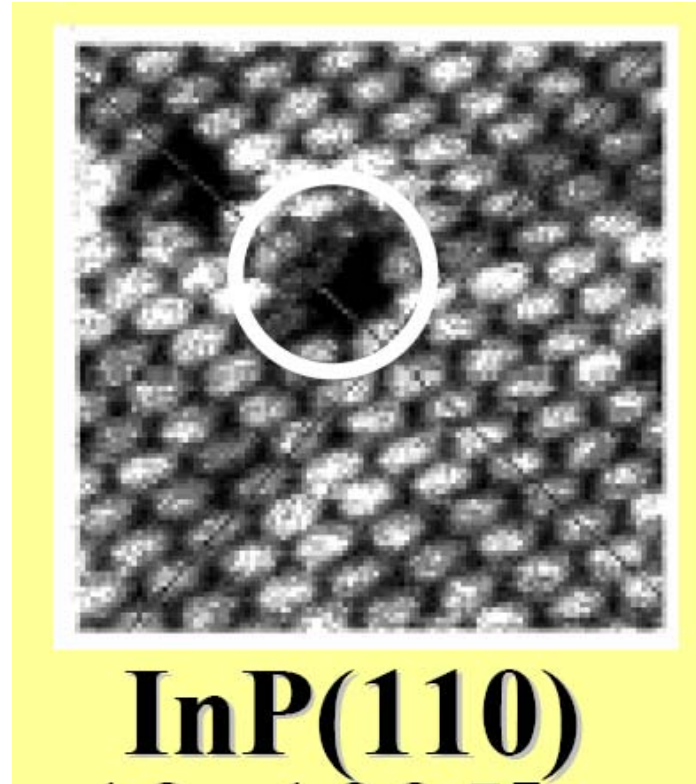
Seeing atoms with FM-AFM (constant frequency)



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



Atomic Point Defects - FM-AFM

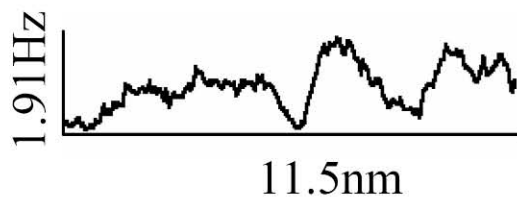
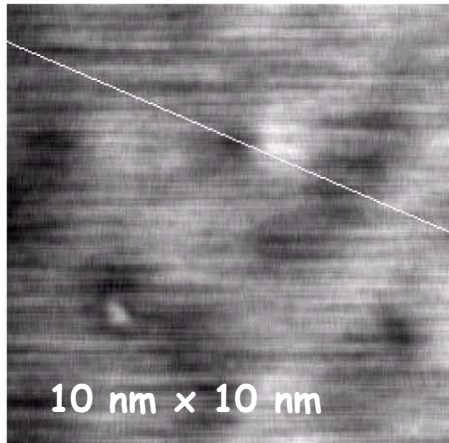


H. Ueyamam, M. Ohta, Y. Sugawara, and S. Morita, Jpn. J. Appl. Phys. 34, L1086 (1995).

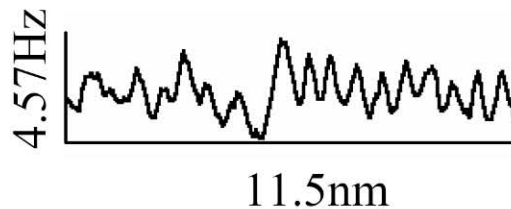
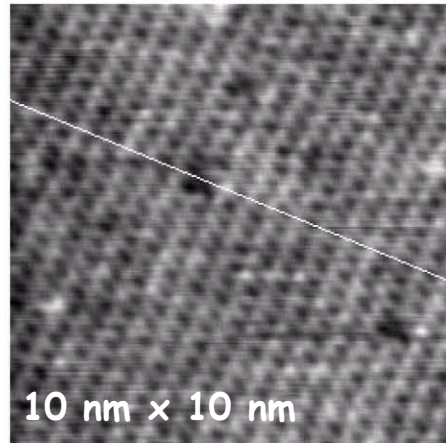
Obtaining Atomic Resolution with FM-AFM

Cleaved p-doped-GaAs(001) in UHV

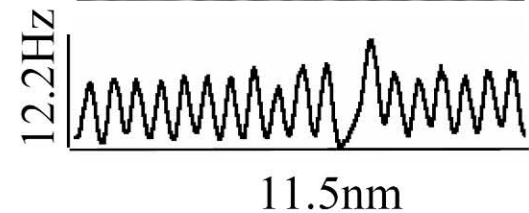
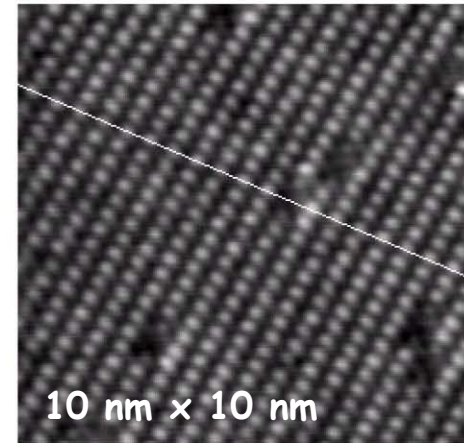
$d_{\min}=0.4 \text{ nm}; \Delta f=-31 \text{ Hz}$



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

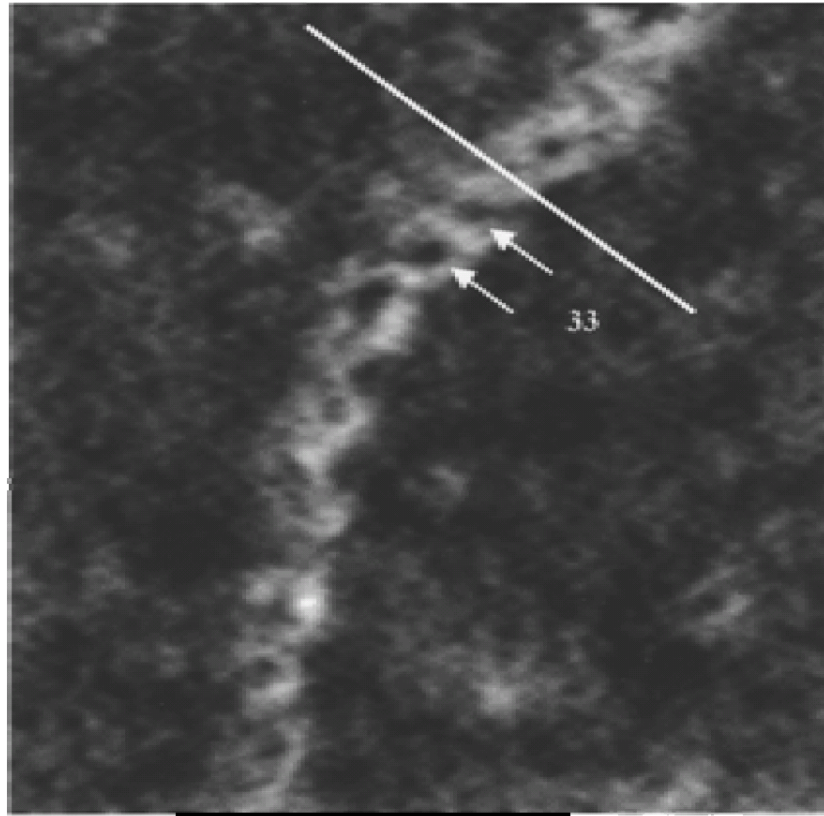


$d_{\min}=0.08 \text{ nm}; \Delta f=-70 \text{ Hz}$



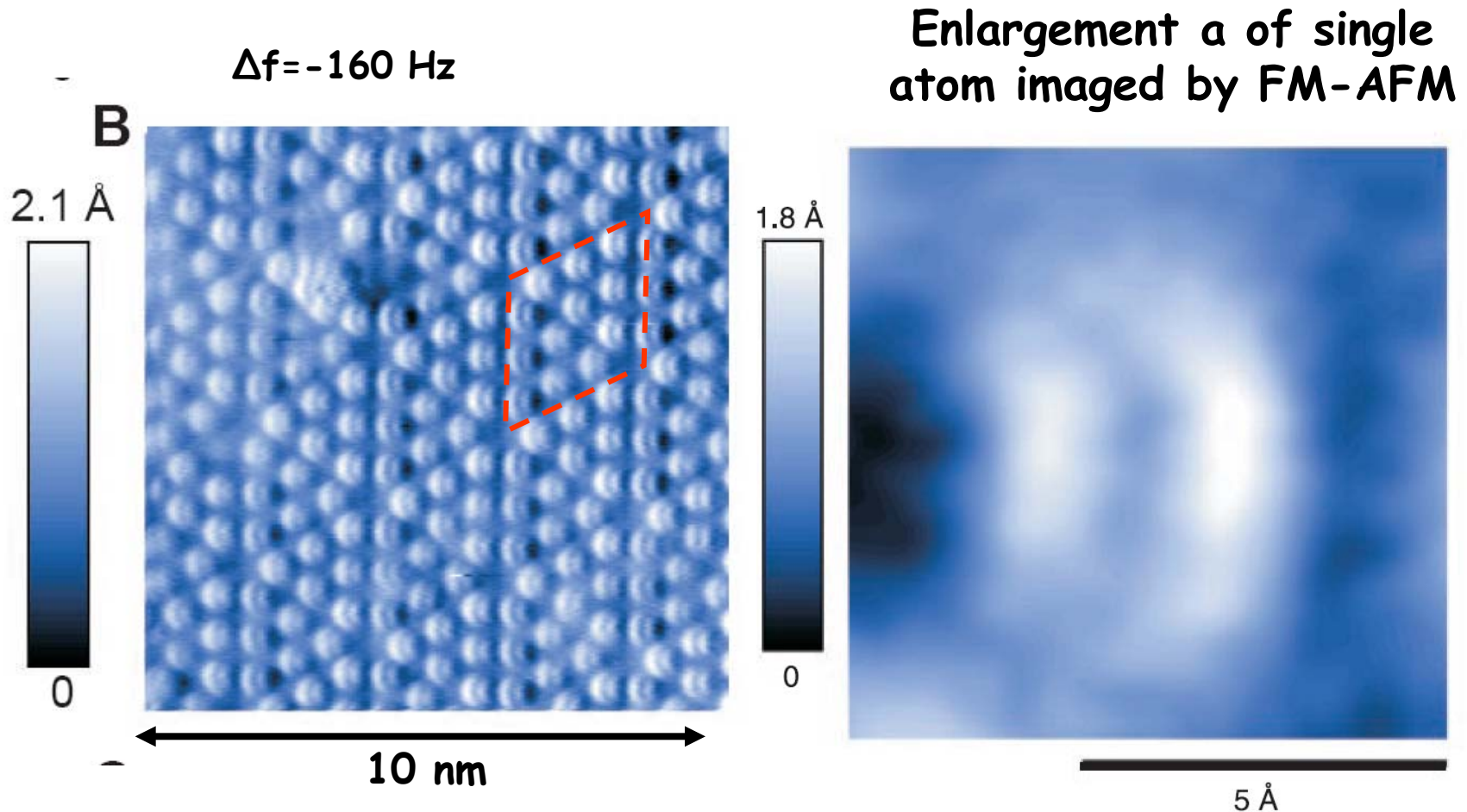
$k = 35 \text{ N/m}; f_0 = 150 \text{ kHz}; A_0=9 \text{ nm}; Q=38,000$

Imaging DNA with FM-AFM



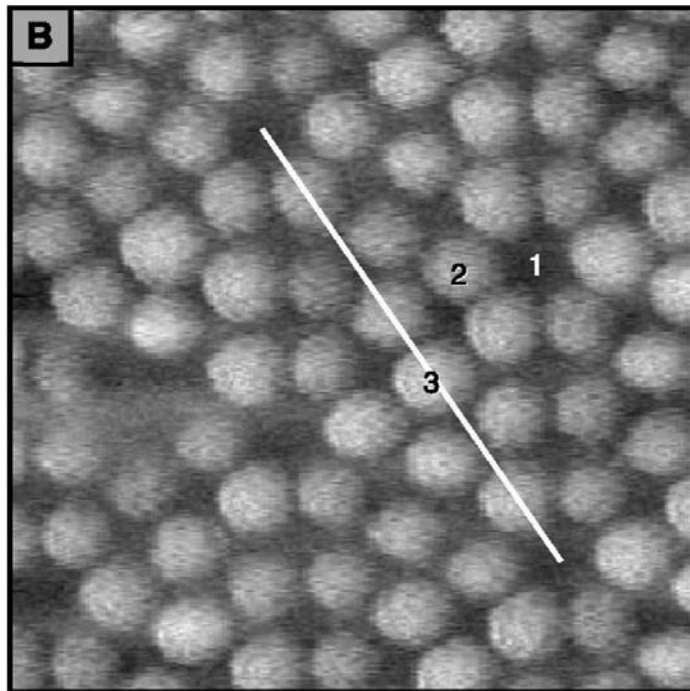
T. Uchihashi, M. Tanigawa, M. Ashino, Y. Sugawara, K. Yokoyama, S. Morita, and M. Ishikawa, *Langmuir* 16, 1349 (2000).

Sub-atomic resolution?

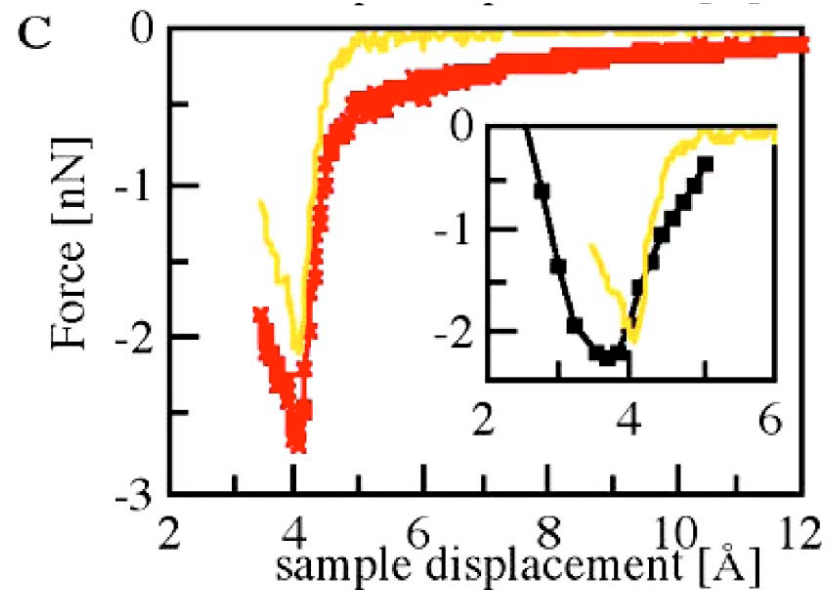
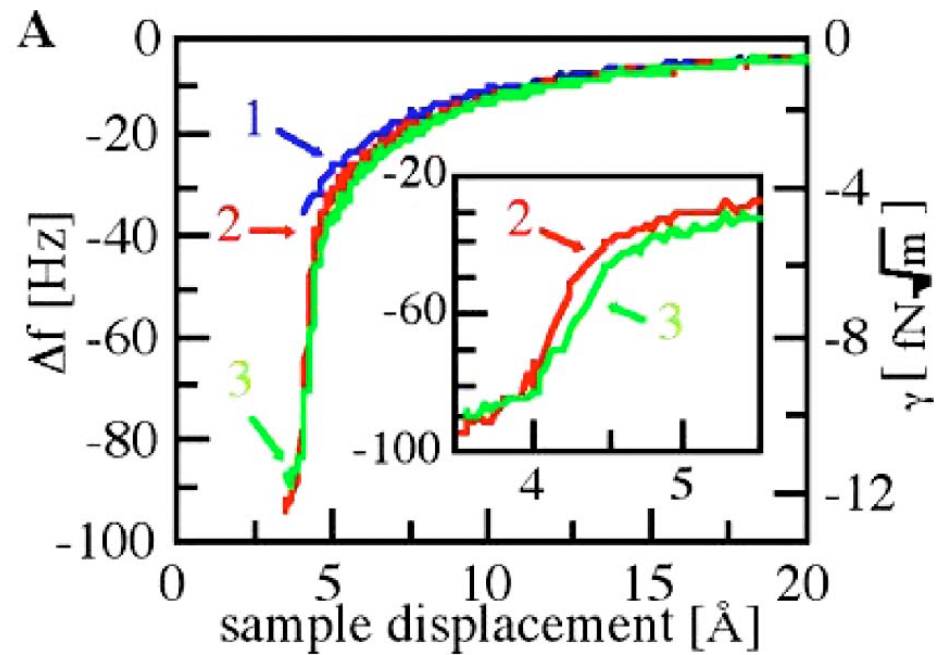


Crescents are interpreted as images of two atomic orbitals of the front atom of the tip

Force Spectroscopy



Si(111)-(7x7)



2D Binary Alloys

PERIODIC TABLE OF THE ELEMENTS

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

RELATIVE ATOMIC MASS (1)

GROUP IUPAC

GROUP CAS

ATOMIC NUMBER

SYMBOL

ELEMENT NAME

■ Metal ■ Semimetal ■ Nonmetal
1 Alkali metal 16 Chalcogens element
2 Alkaline earth metal 17 Halogens element
10 Transition metals 18 Noble gas
14 Lanthanide
15 Actinide

STANDARD STATE (25 °C; 101 kPa)

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

PERIOD	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	
GROUP	IA	IIA											IIIA	IVA	VA	VIA	VIIA	VIIIA	
1	1 1.0079 H HYDROGEN																		2 4.0026 He HELIUM
2	3 6.941 Li LITHIUM	4 9.0122 Be BERYLLIUM											5 10.811 B BORON	6 12.011 C CARBON	7 14.007 N NITROGEN	8 15.999 O OXYGEN	9 18.998 F FLUORINE	10 20.180 Ne NEON	
3	11 22.990 Na SODIUM	12 24.305 Mg MAGNESIUM											13 26.982 Al ALUMINIUM	14 28.086 Si SILICON	15 30.974 P PHOSPHORUS	16 32.065 S SULPHUR	17 35.453 Cl CHLORINE	18 39.948 Ar ARGON	
4	19 39.098 K POTASSIUM	20 40.078 Ca CALCIUM	21 44.956 Sc SCANDIUM	22 47.867 Ti TITANIUM	23 50.942 V VANADIUM	24 51.996 Cr CHROMIUM	25 54.938 Mn MANGANESE	26 55.845 Fe IRON	27 58.933 Co COBALT	28 58.693 Ni NICKEL	29 63.546 Cu COPPER	30 65.39 Zn ZINC	31 69.723 Ga GALLIUM	32 72.64 Ge GERMANIUM	33 74.922 As ARSENIC	34 78.96 Se SELENIUM	35 79.904 Br BROMINE	36 83.80 Kr KRYPTON	
5	37 85.468 Rb RUBIDIUM	38 87.62 Sr STRONTIUM	39 88.906 Y YTRIUM	40 91.224 Zr ZIRCONIUM	41 92.906 Nb NIOBIUM	42 95.94 Mo MOLYBDENUM	43 (98) Tc TECHNETIUM	44 101.07 Ru RUTHENIUM	45 102.91 Rh RHODIUM	46 106.42 Pd PALLADIUM	47 107.87 Ag SILVER	48 112.41 Cd CADMIUM	49 114.82 In INDIUM	50 118.71 Sn TIN	51 121.76 Sb ANTIMONY	52 127.60 Te TELLURIUM	53 126.90 I IODINE	54 131.29 Xe XENON	
6	55 132.91 Cs CAESIUM	56 137.33 Ba BARIUM	57-71 La-Lu Lanthanide	72 178.49 Hf HAFNIUM	73 180.95 Ta TANTALUM	74 183.84 W TUNGSTEN	75 186.21 Re RHENIUM	76 190.23 Os OSMIUM	77 192.22 Ir IRIDIUM	78 195.08 Pt PLATINUM	79 196.97 Au GOLD	80 200.59 Hg MERCURY	81 204.38 Tl THALLIUM	82 207.2 Pb LEAD	83 208.98 Bi BISMUTH	84 (209) Po POLONIUM	85 (210) At ASTATINE	86 (222) Rn RADON	
7	87 (223) Fr FRANCIUM	88 (226) Ra RADIUM	89-103 Ac-Lr Actinide	104 (261) Rf RUTHERFORDIUM	105 (262) Db DUBNIUM	106 (266) Sg SEABORGIUM	107 (264) Bh BOHRIUM	108 (277) Hs HASSIUM	109 (268) Mt MEITNERIUM	110 (281) Uun UNUNNIUM	111 (272) Uuu UNUNUNIUM	112 (285) Uub UNUNBIUM	114 (289) Uuq UNUNQUADIUM						

(1) Pure Appl. Chem., 73, No. 4, 667-683 (2001)

Relative atomic mass is shown with five significant figures. For elements having no stable nuclides, the value enclosed in brackets indicates the mass number of the longest-lived isotope of the element.

However three such elements (Th, Pa, and U) do have a characteristic terrestrial isotopic composition, and for these an atomic weight is tabulated.

Editor: Aditya Vardhan (advvar@netlinx.com)

LANTHANIDE

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

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

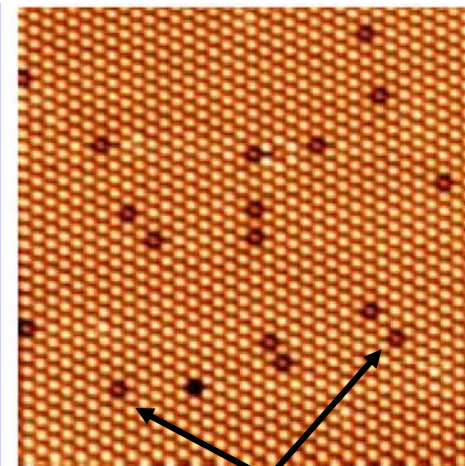
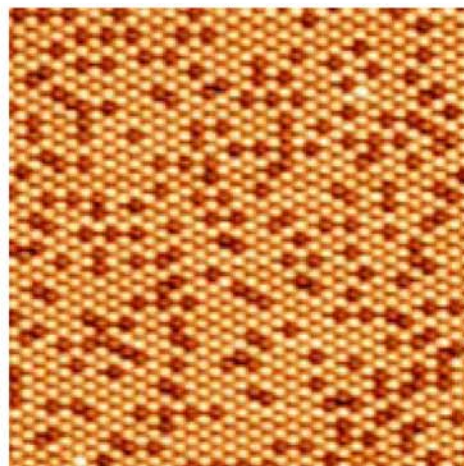
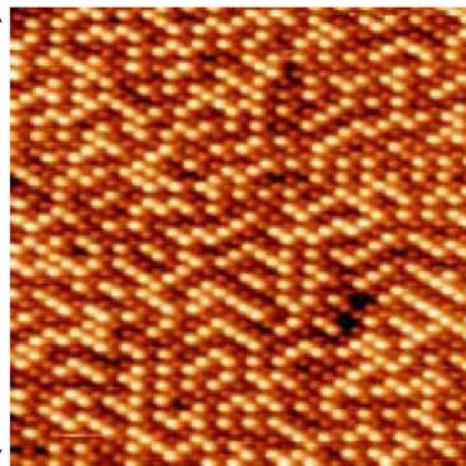
Sn - 1/4 ML

Sn - 1/3 ML

50% Sn; 50% Si

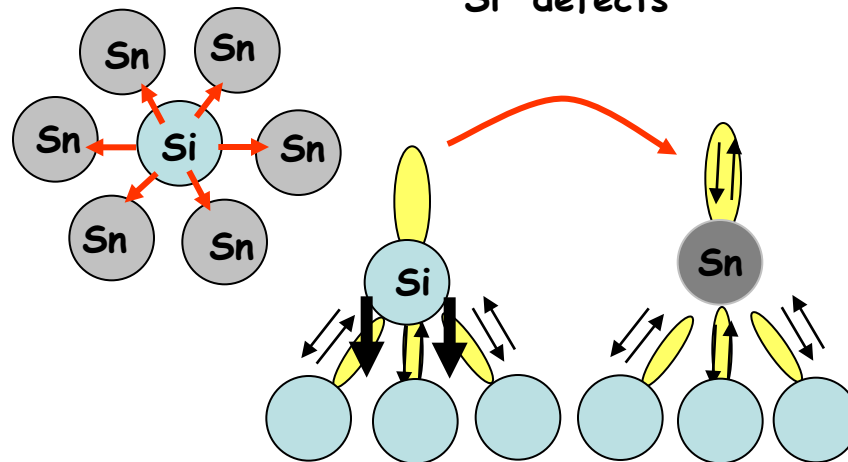
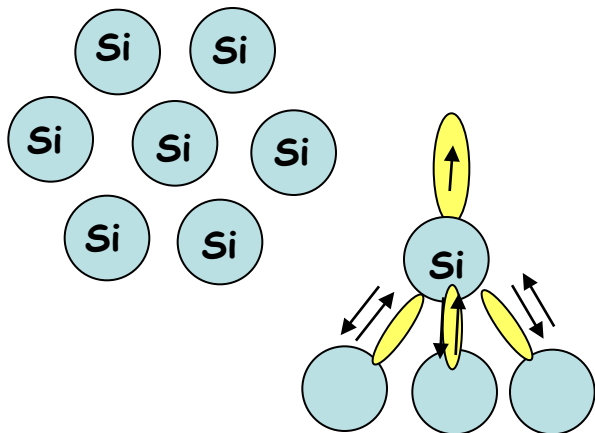
75% Sn; 25% Si

99% Sn; 1% Si

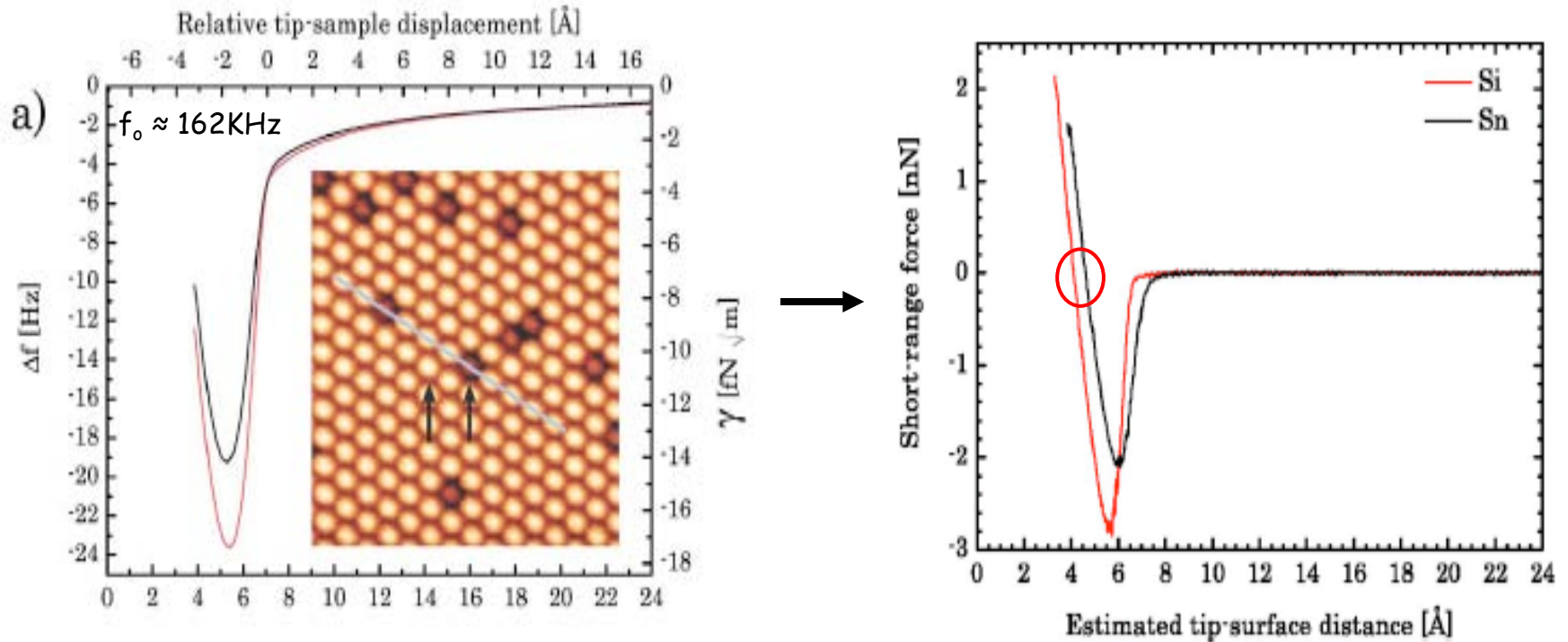


20 nm x 20 nm; 1ML on Si(111)= 7.84×10^{14} atoms/cm²

Si "defects"



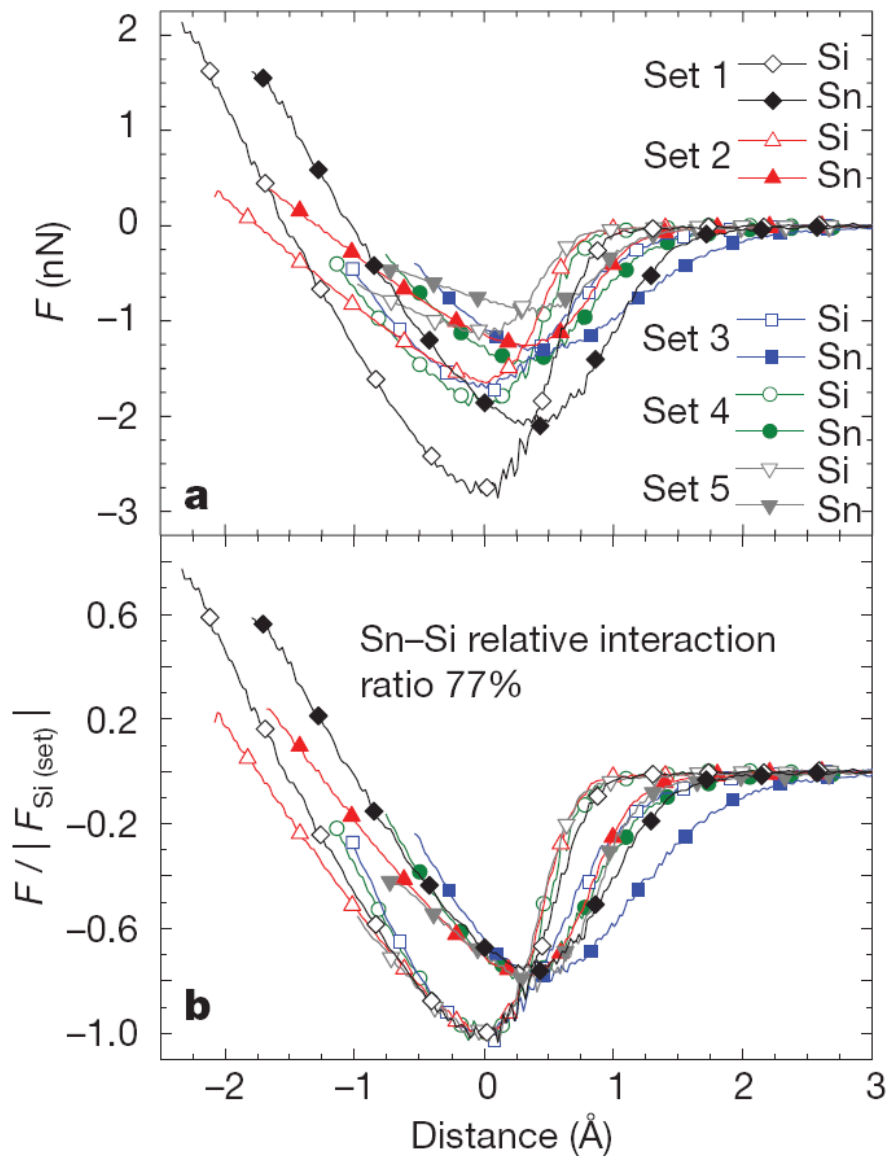
Measuring the Interaction Force



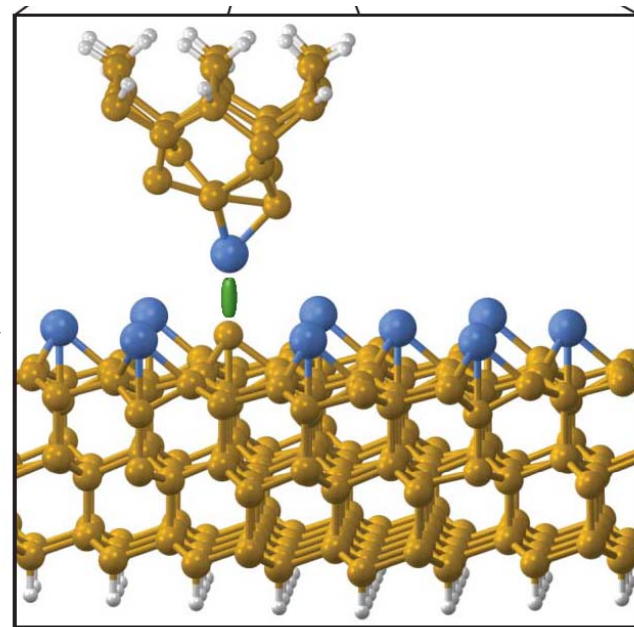
Y. Sugimoto, et al., Phys Rev. B73, 205329 (2006).

Atomic Fingerprints

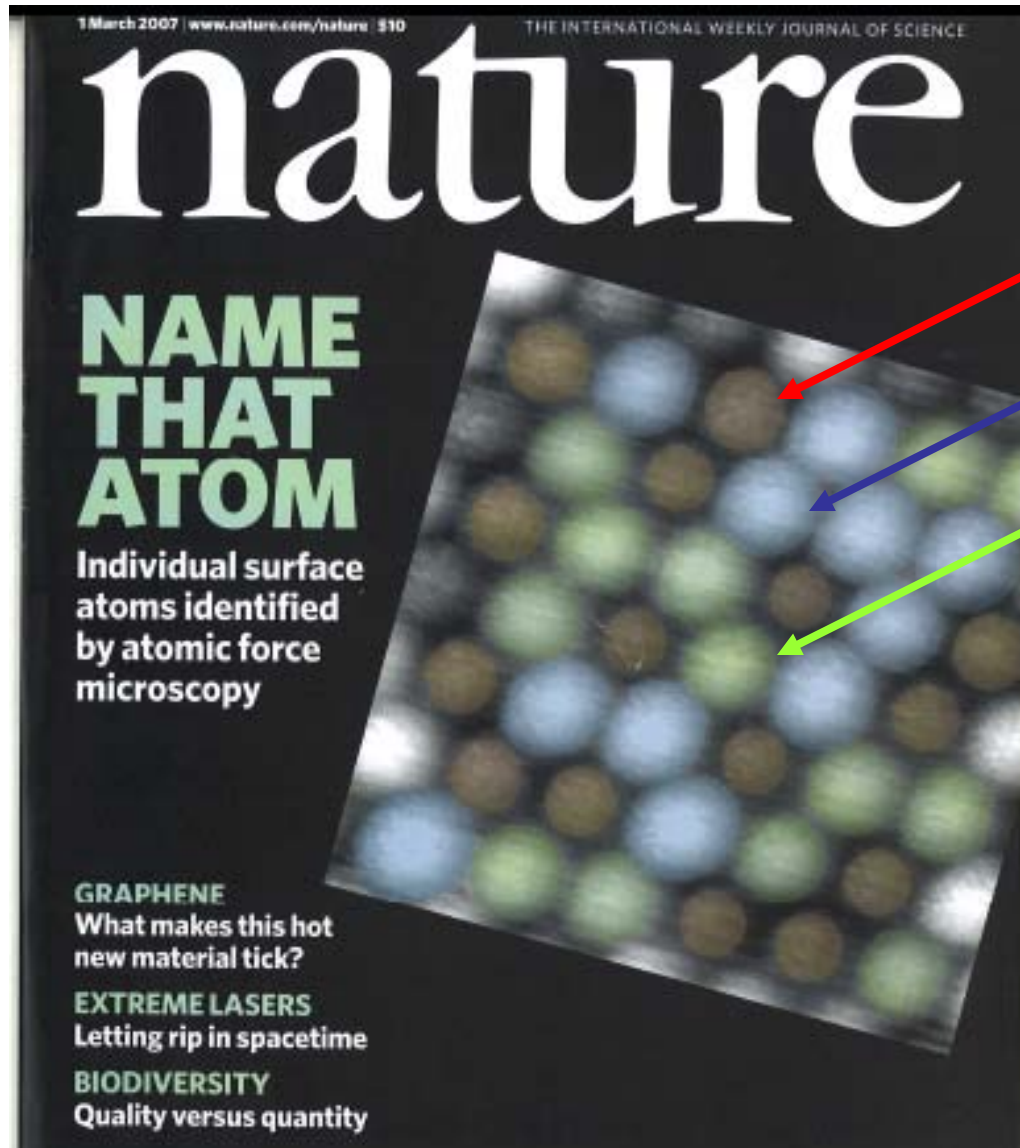
Tip-to-tip variability



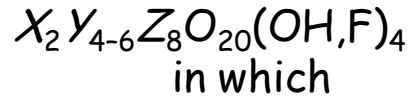
Precise tip structure?



Chemical Identification



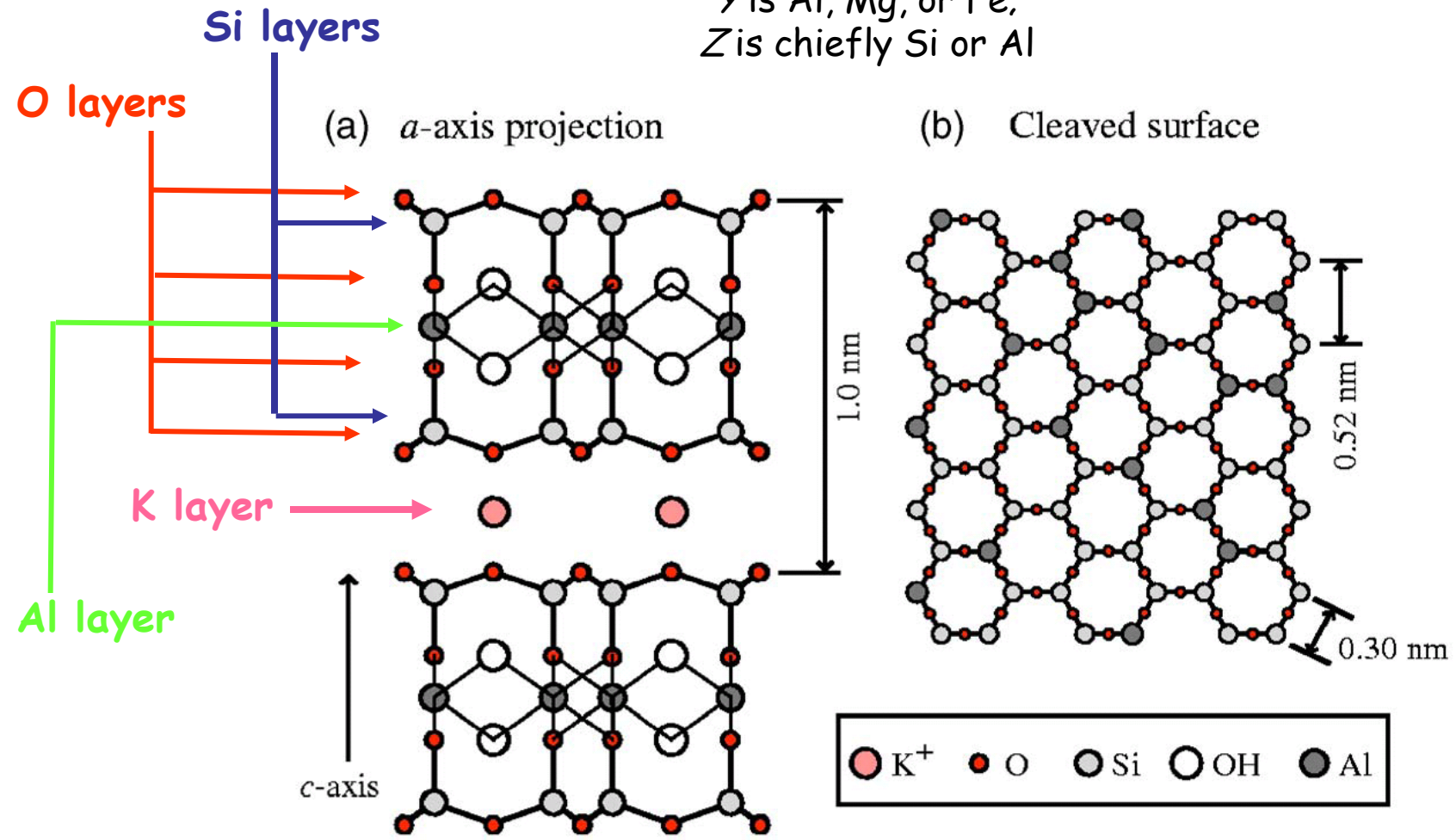
Mica Crystallographic Structure



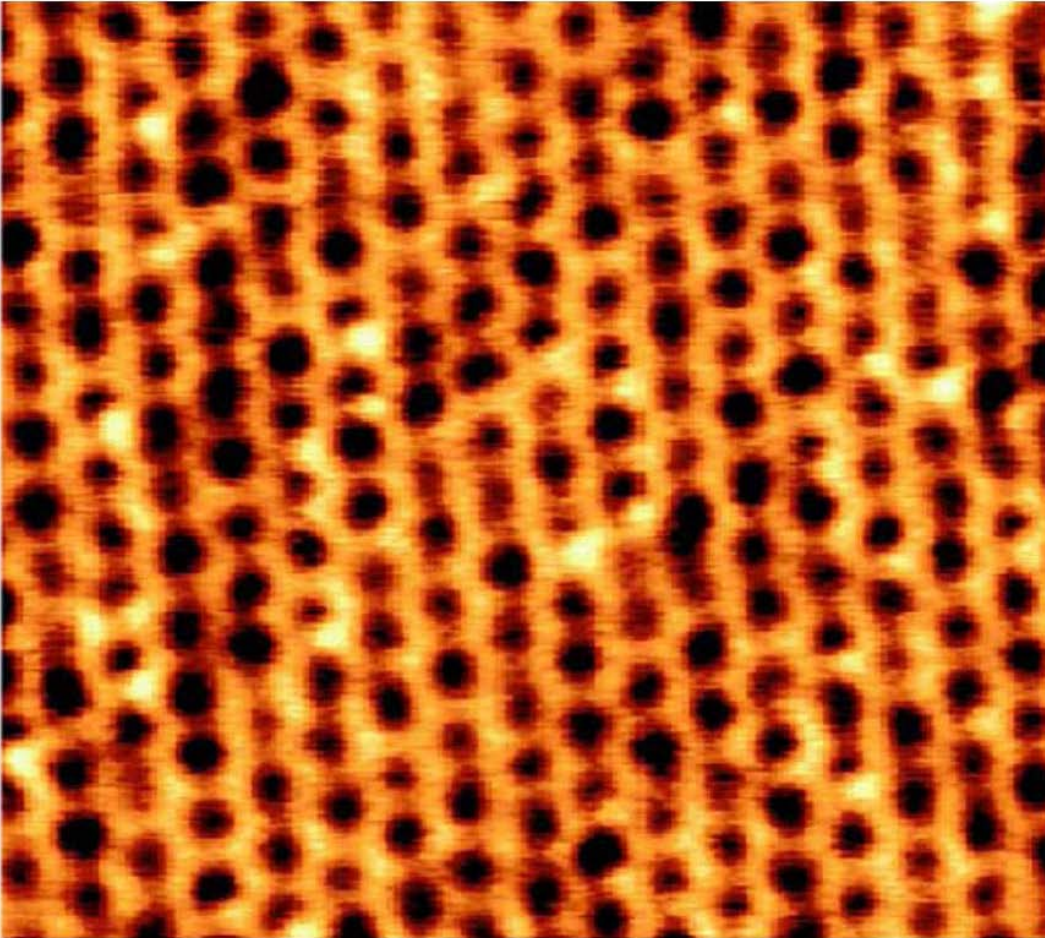
X is K, Na, or Ca;

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

$Q = 20-30$