# Atomic force microscopy

KOBE UNIVERSITY

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http://www.edu.kobe-u.ac.jp/sci-onishi/index-C.html

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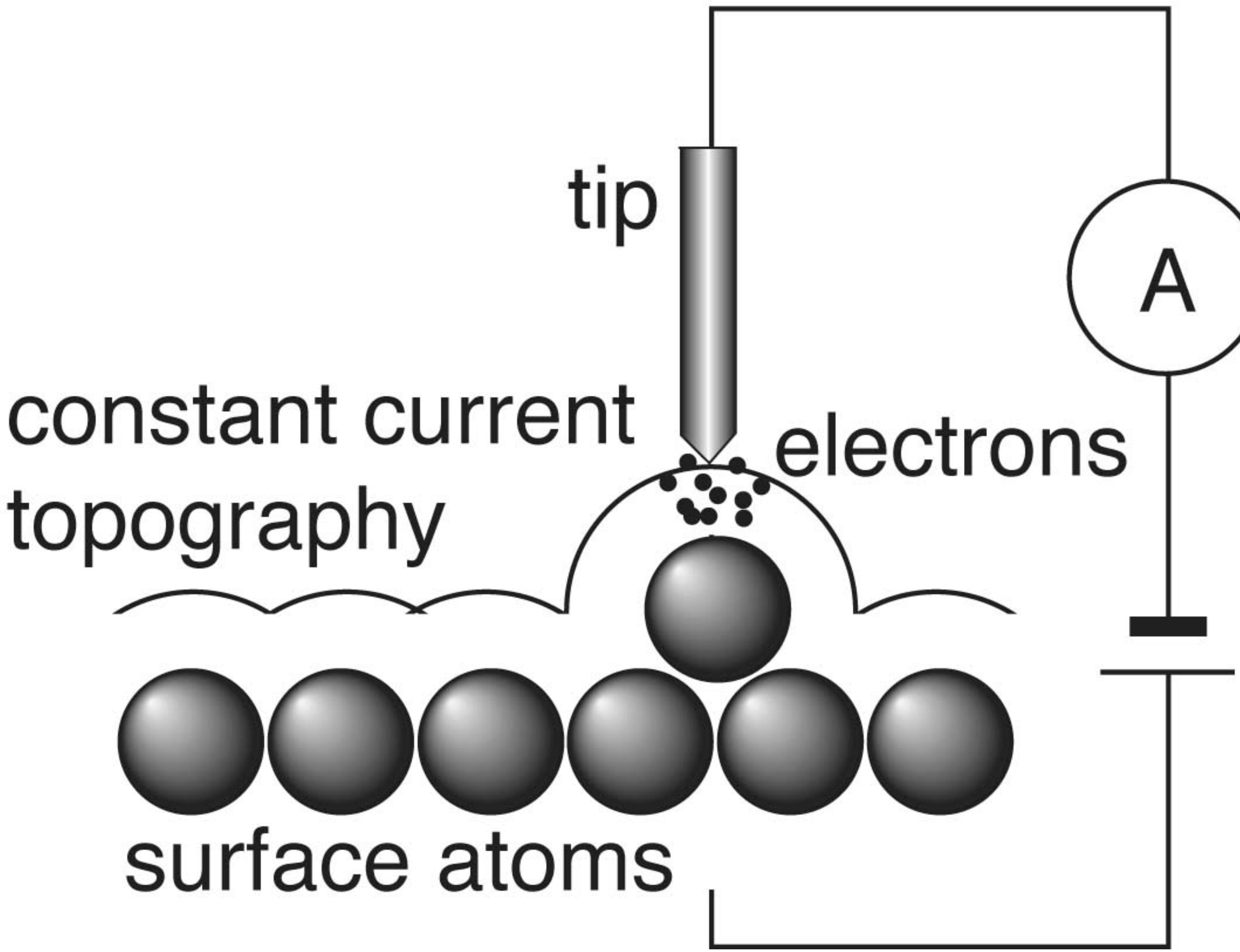
# Graduation in March

# Questions

- What is atomic force microscopy?
- How is it similar to and different from scanning tunneling microscopy?

# Scanning Tunneling Microscope (STM)




electron tunneling from/to the metal tip sensitive to tip-surface gap distance

# Nobel prize in 1986

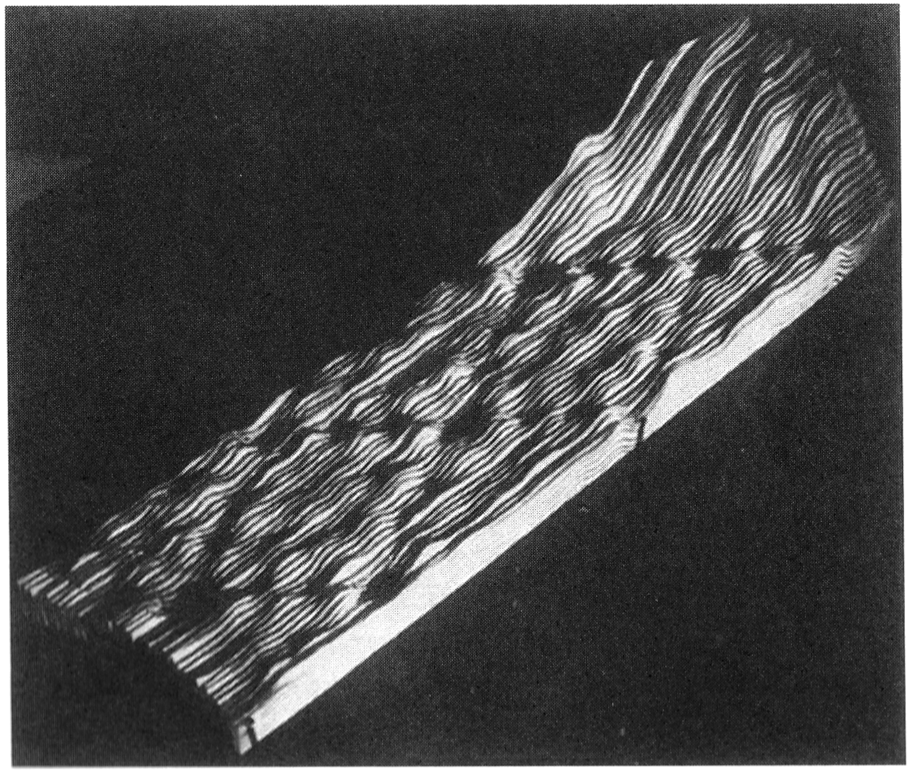


図 4.1　Si(111)7×7 表面の STM 像．STM の発明者 Binnig と Rohrer による最初のイメージ．（G. Binnig *et al.*, *Phys. Rev. Lett.*, **50**(1983), 120）

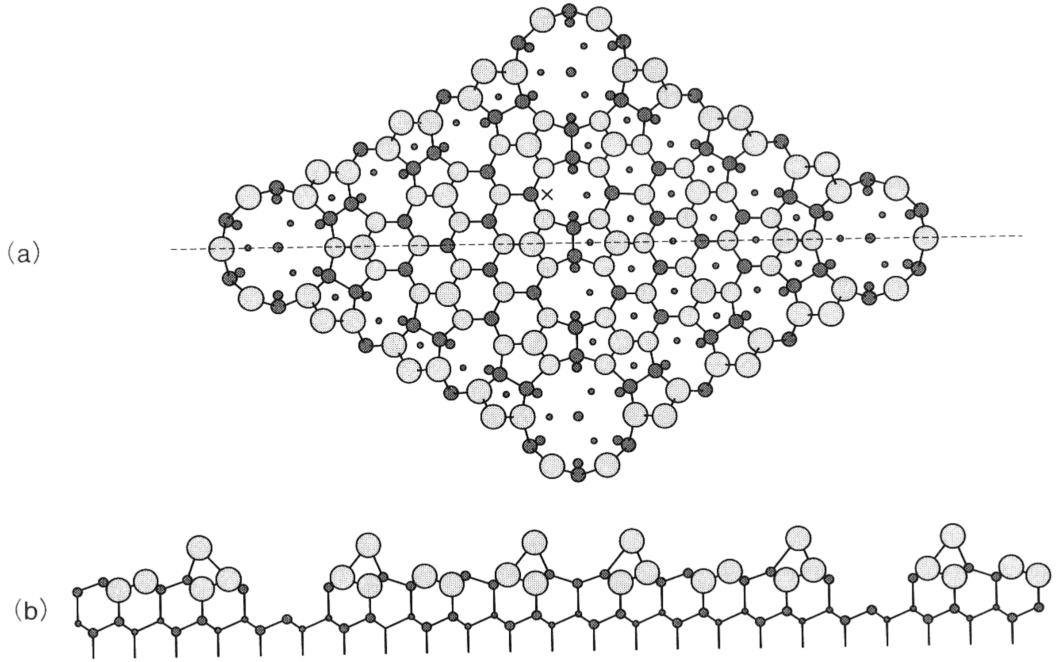
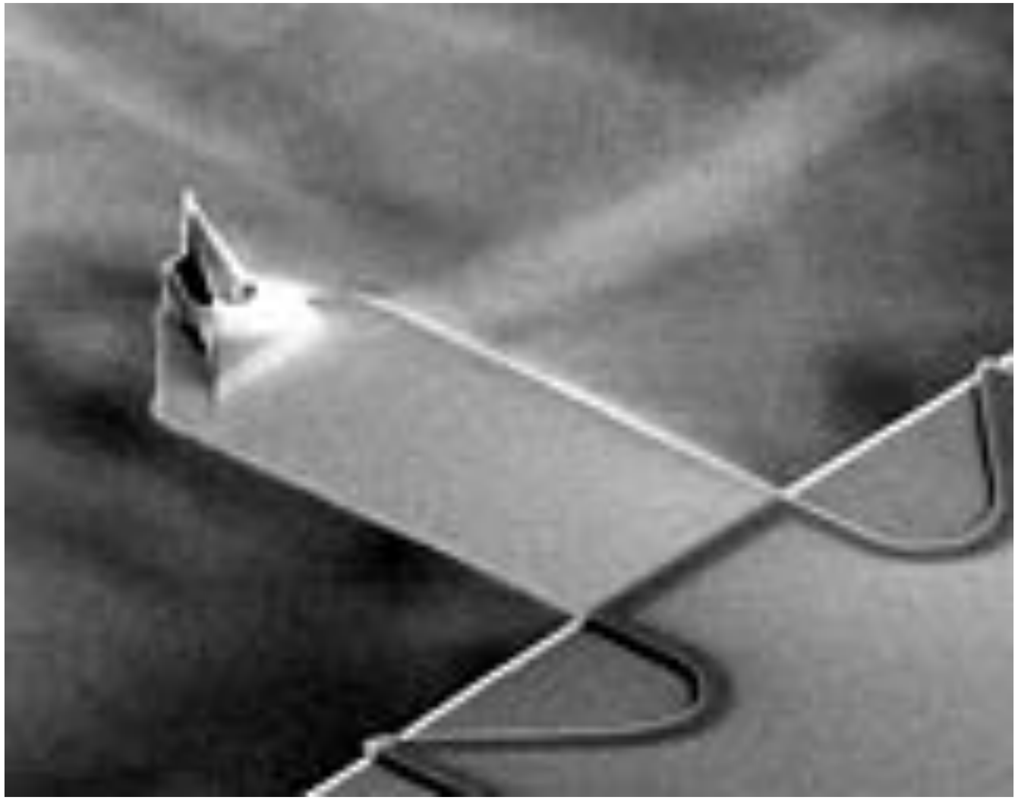
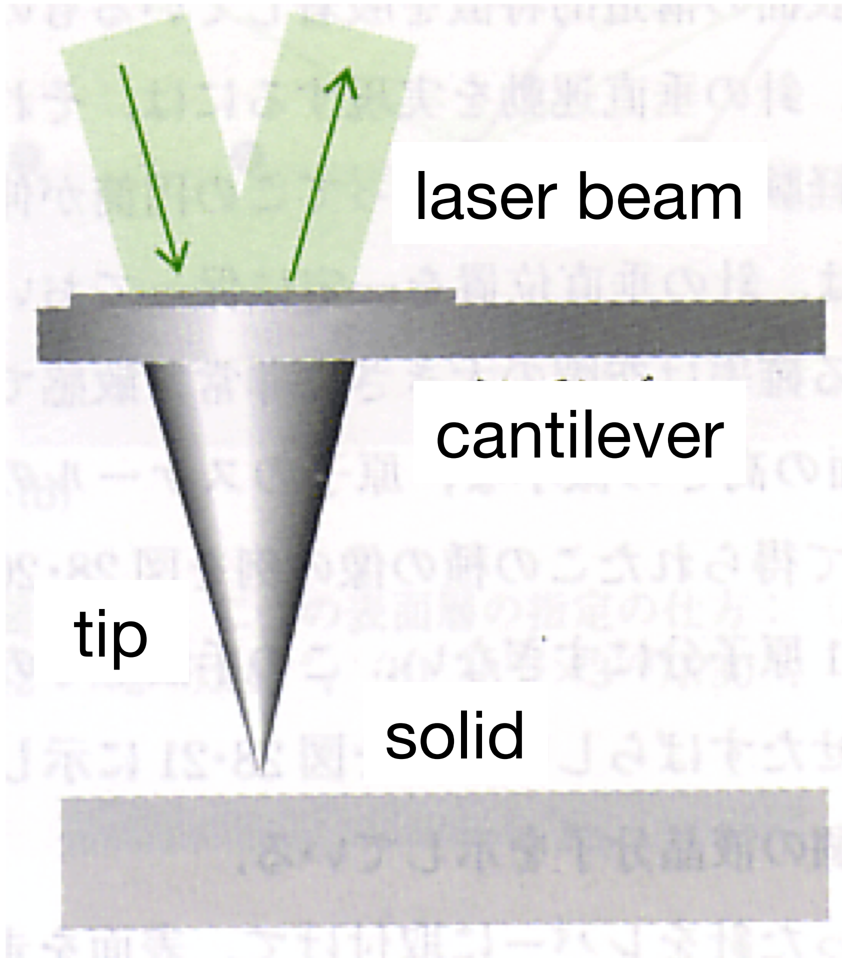



**図 4.2**　Si(111) 7×7 再配列構造．高柳らによる dimer adatom stacking-fault(DAS)モデル．(a)上面からの眺め．(b)側面からの眺め．（K. Takayanagi *et al.*, *Surf. Sci.*, **164**(1985), 367.）

# Atomic Force Microscope (AFM)

for insulator object





# Tip in contact

a cantilever, plate spring, with a tip at its free end

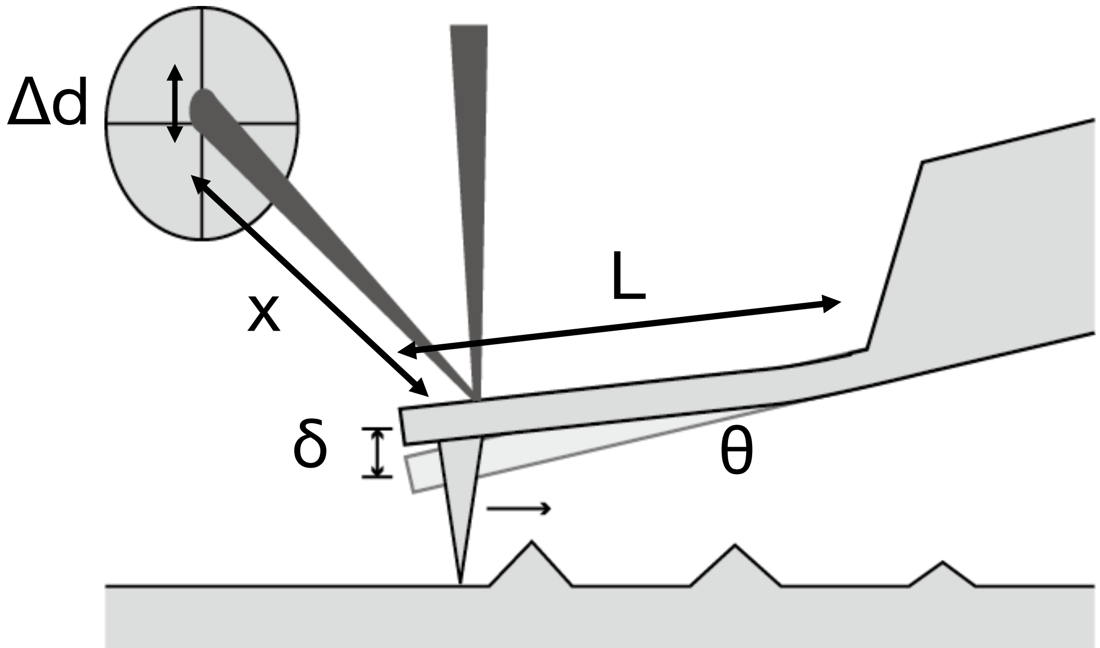
cantilever deflection, $\theta = \delta / L$

deflection of relrected laser beam, $2\theta$

shift of laser spot on a , $\Delta d = 2\theta x$

$\delta$=1 nm, L=100 μm, x=5 cm then $\Delta d$ =1 μm

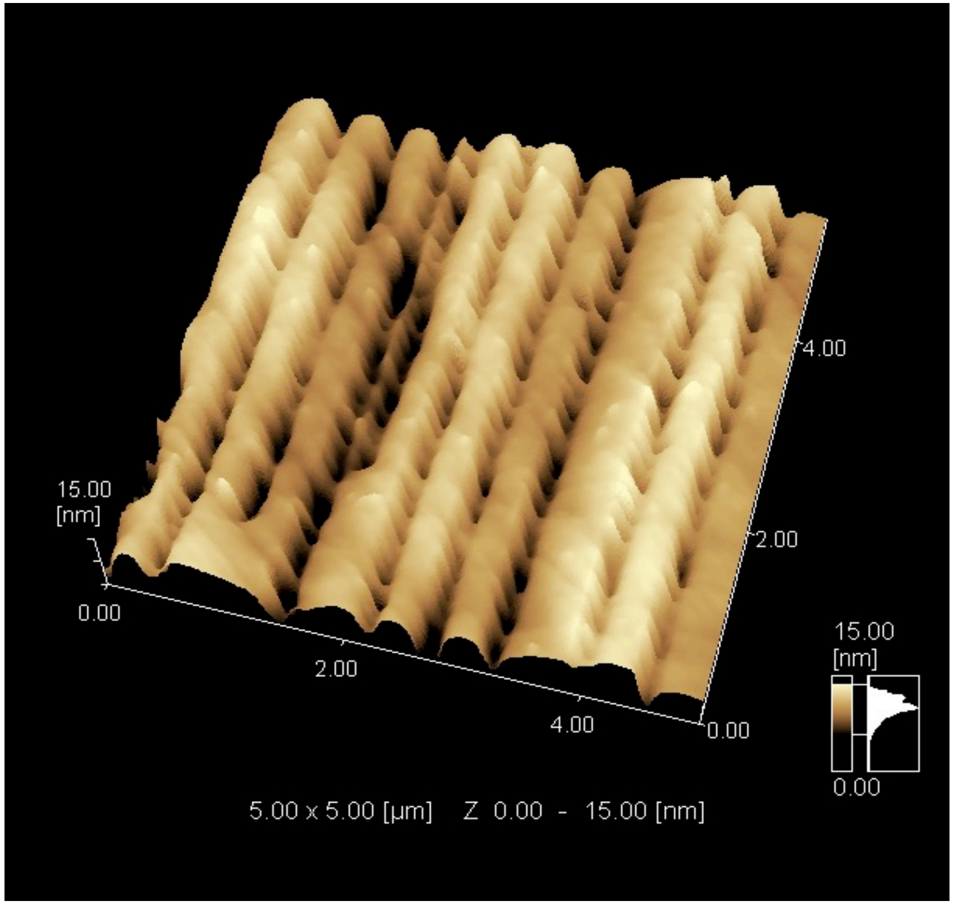
cantilever spring constant k = 10 N $m^{-1}$, 10 nN force on the tip



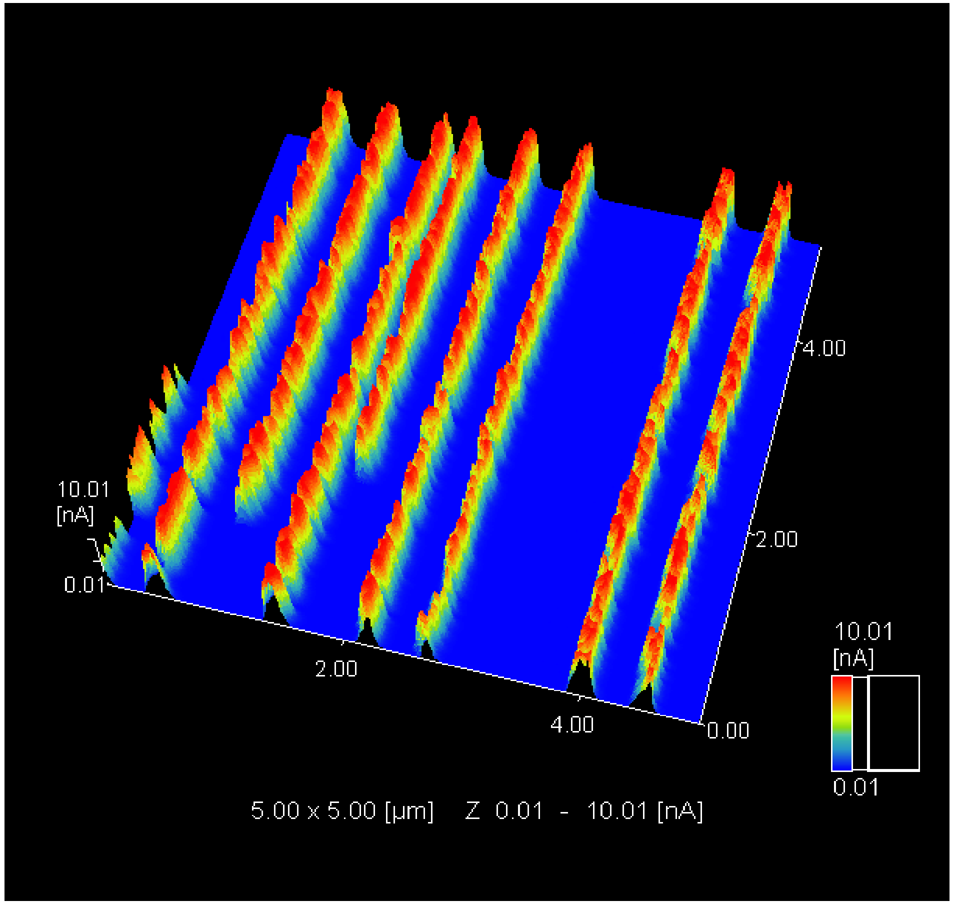
# Scans in contact

## electric circuits

### topography




### electric conductivity

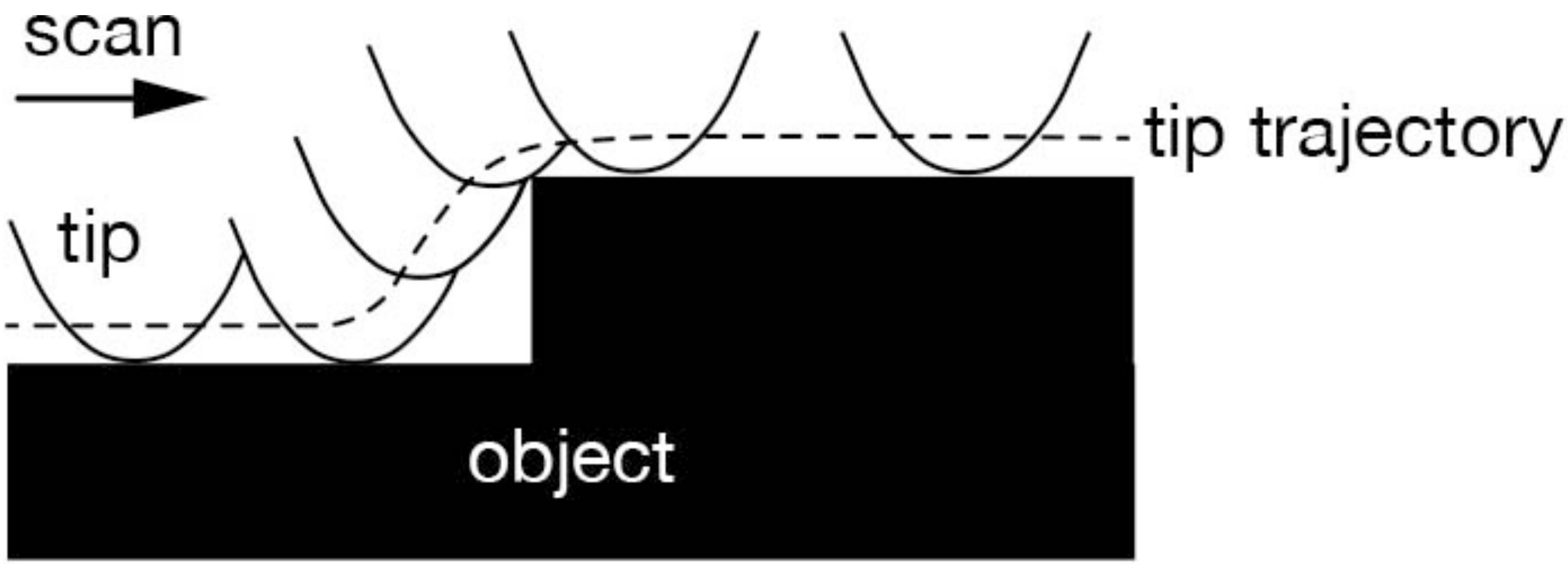


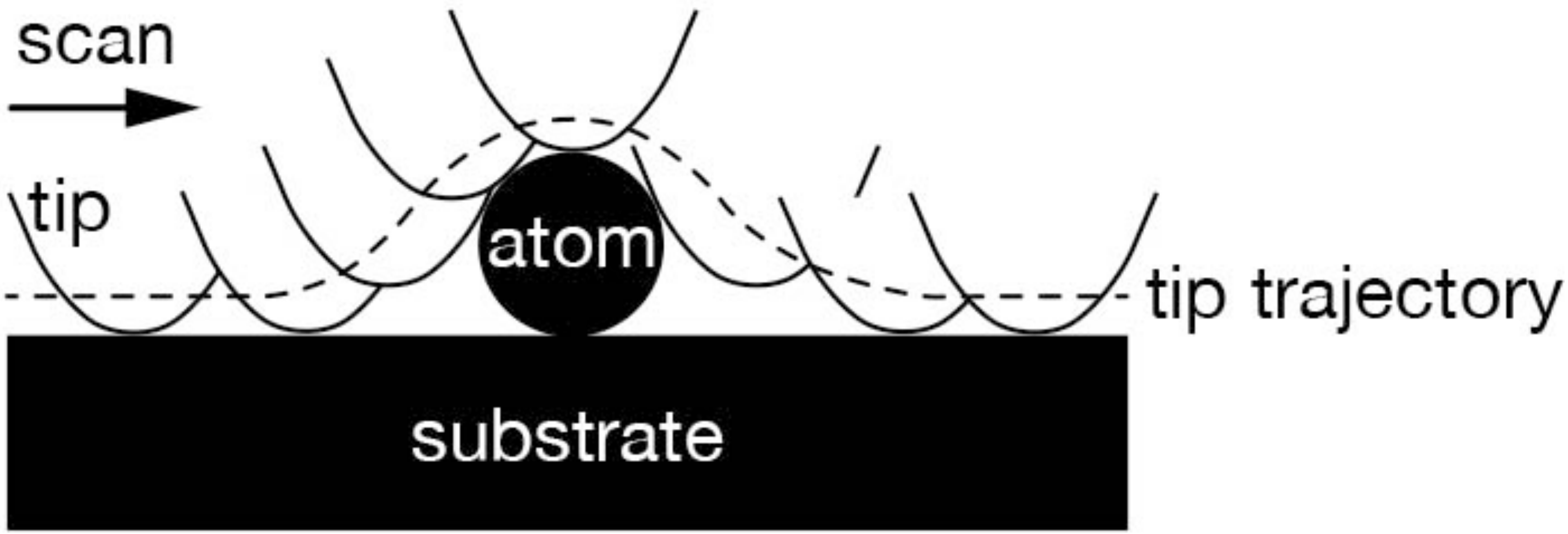

courtesy by Shimadzu Co.

# No atomic resolution with a tip in contact

Why?

# Single-atom apex required



# Dilemma

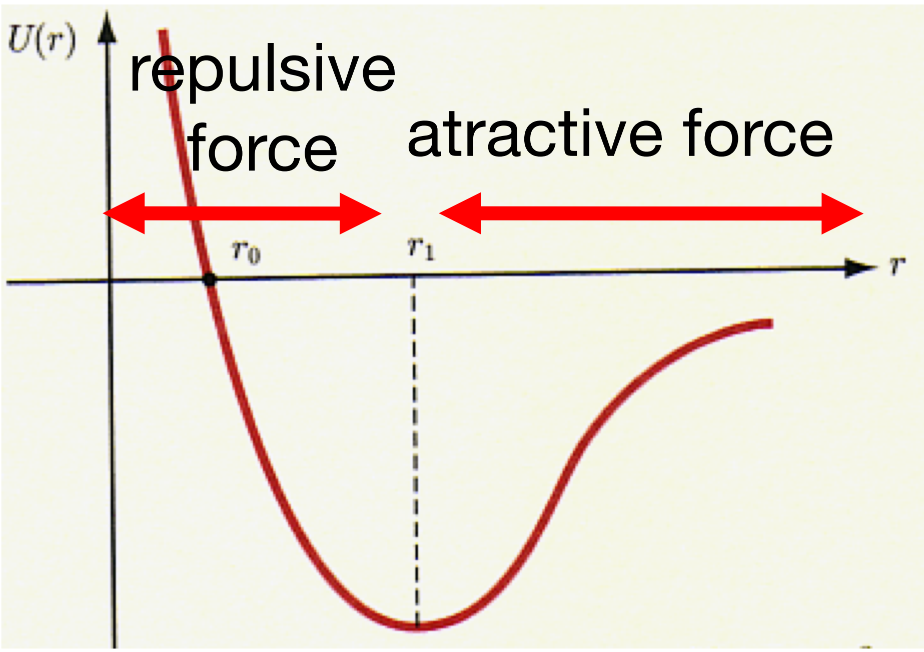
tip pulled by van der Waals force

hard cantilever required not to be in contact

vs

weak tip-surface force should be detected

soft cantilever required




Lennard-Jones potential

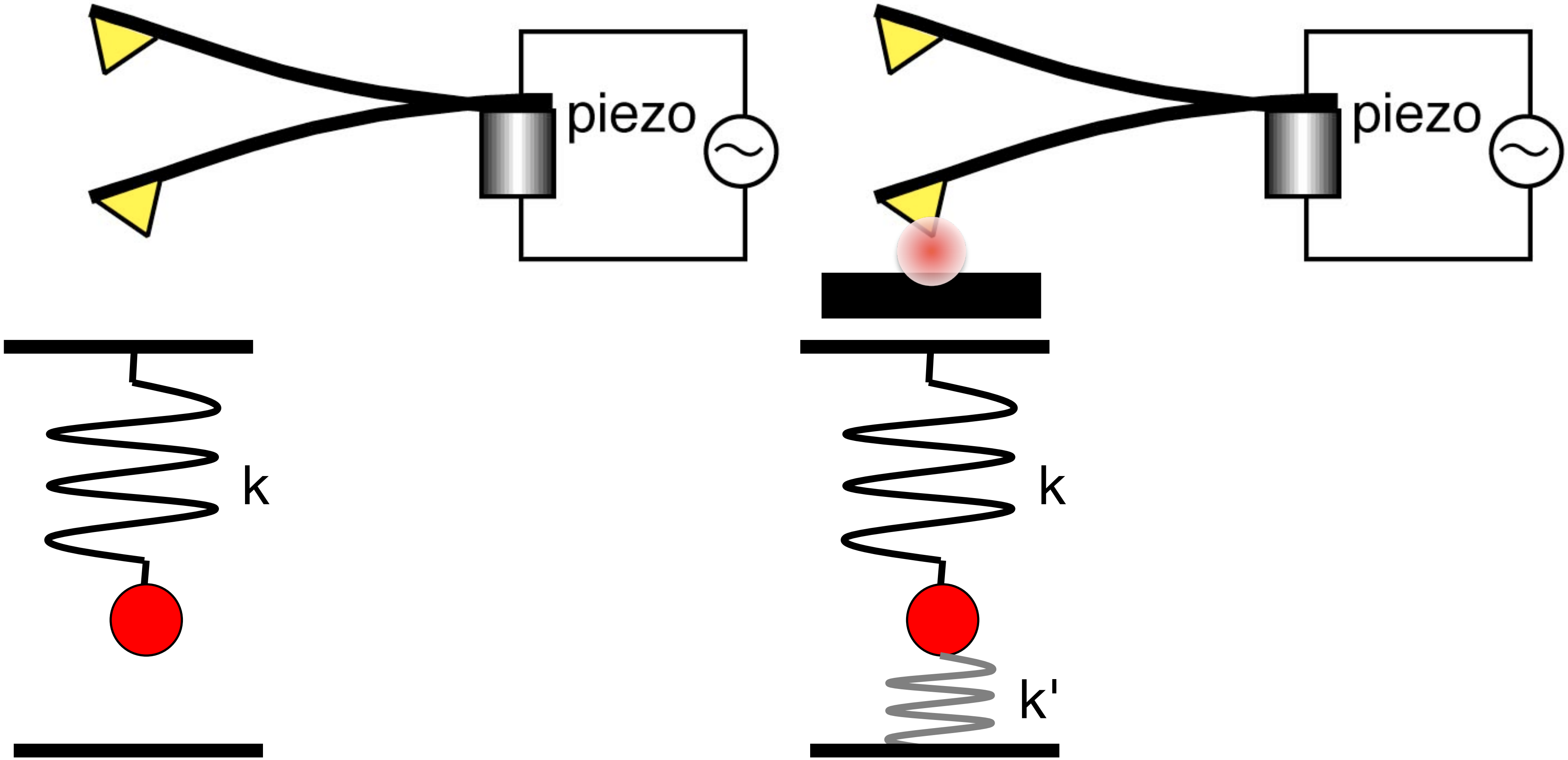
$U(r) = U_0 \{ (r_0/r)^{12} - (r_0/r)^6 \}$

pulling force strength

proportional to $r^{-5}$

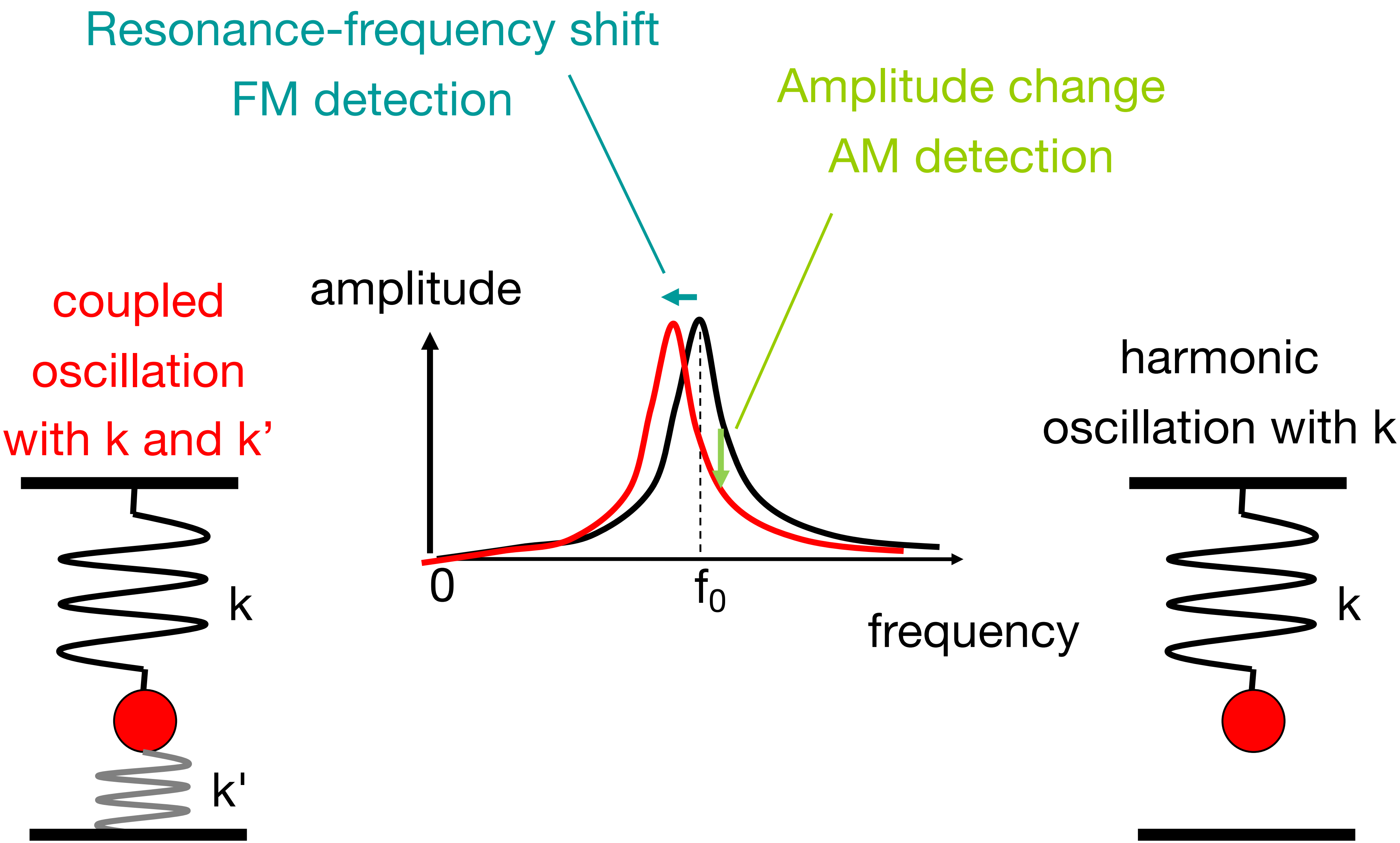
# Dynamic AFM

harmonic oscillation coupled oscillation




oscillation sensitive to tip-surface force gradient even with a hard cantilever

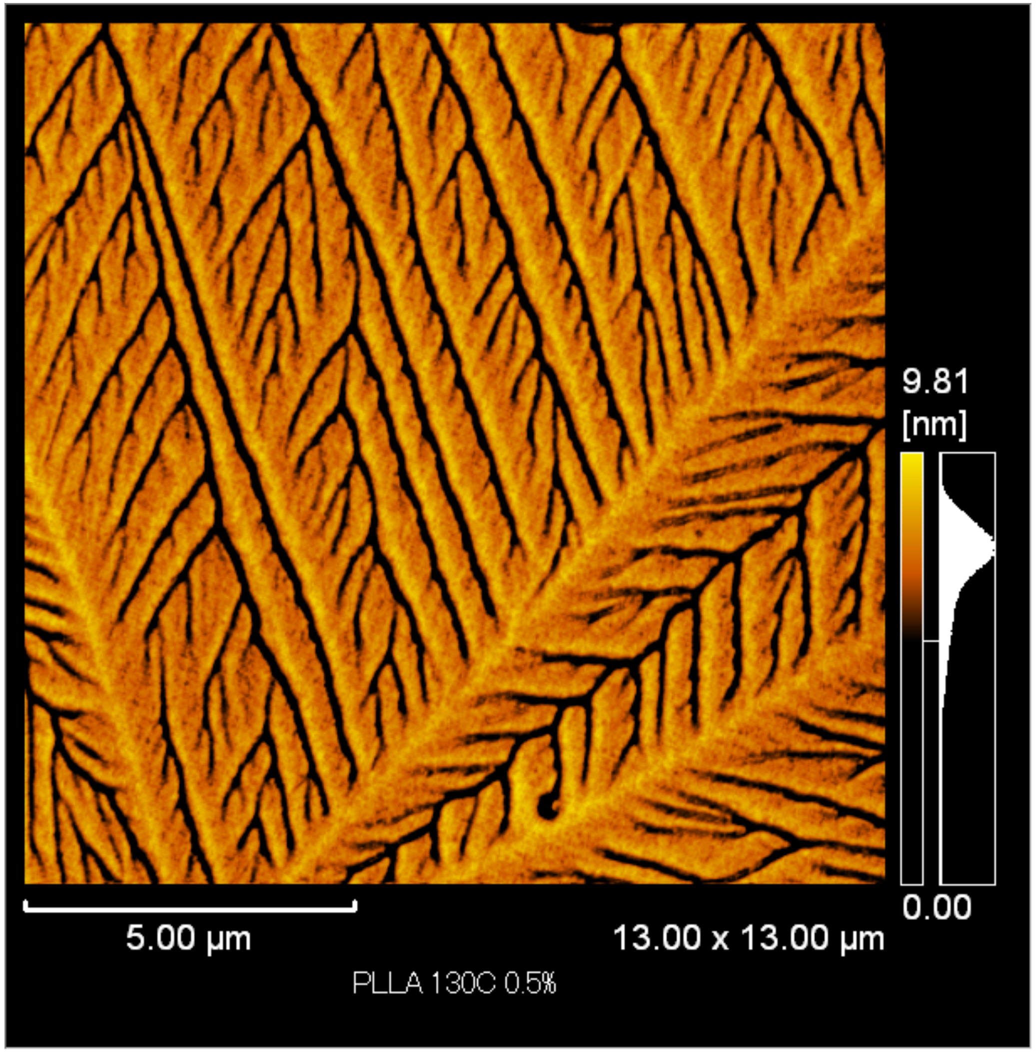
# AM vs FM



Resonance-frequency shift
FM detection
Amplitude change
AM detection
coupled
oscillation
with k and k’
amplitude
0
f0
frequency
harmonic
oscillation with k
k
k'
k

# Scans in AM detection

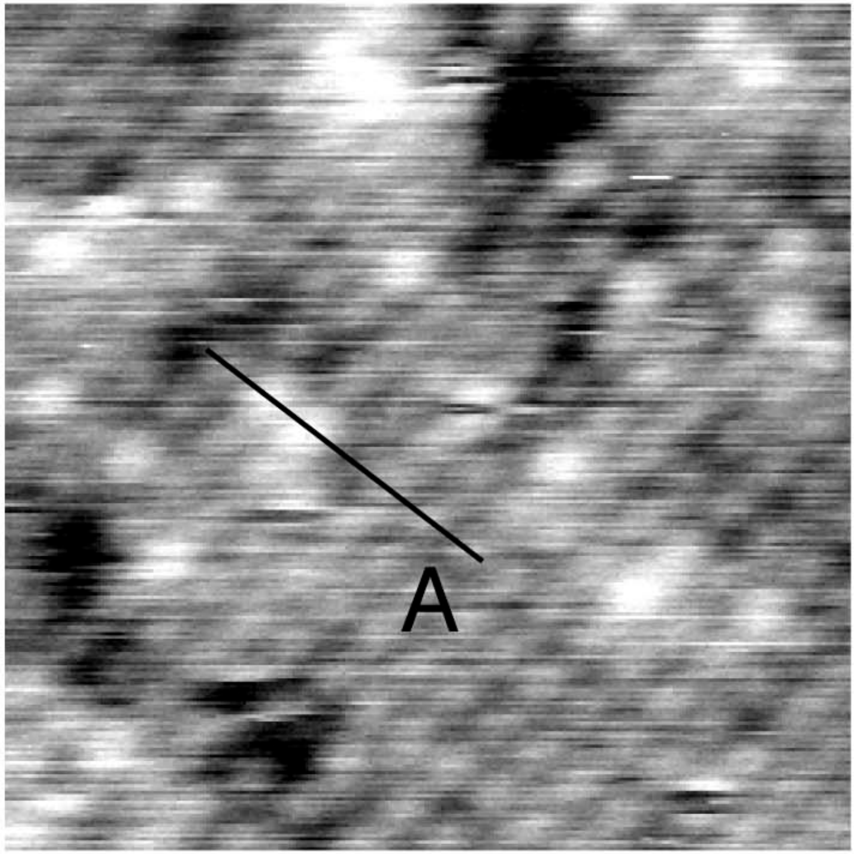
*L*-poly-lactate



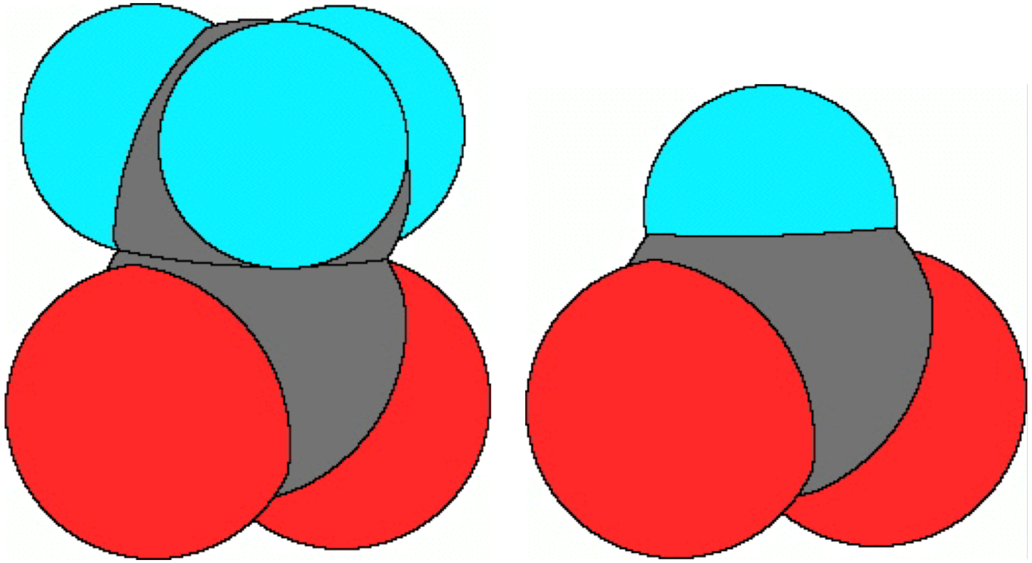

courtesy by 清華大学, 化学工程系, 謝続明 and Shimadzu Co.

# Scans in FM detection

$10 \times 10\ nm^2$




vacuum



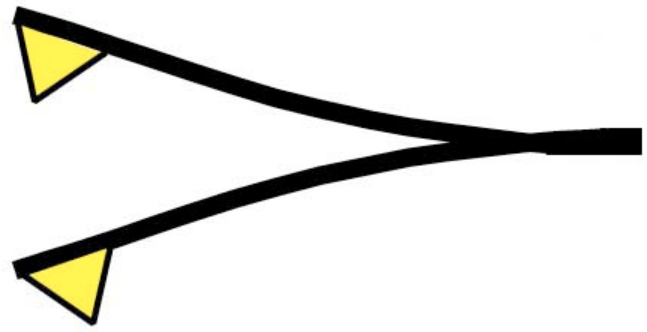
$f_0$: 300 kHz, $\Delta f$: -147 Hz, A: 8 nm

A. Sasahara, H. Uetsuka, H. Onishi, J. Phys. Chem. B 105 (2001) 1.

JSPM4500, JEOL

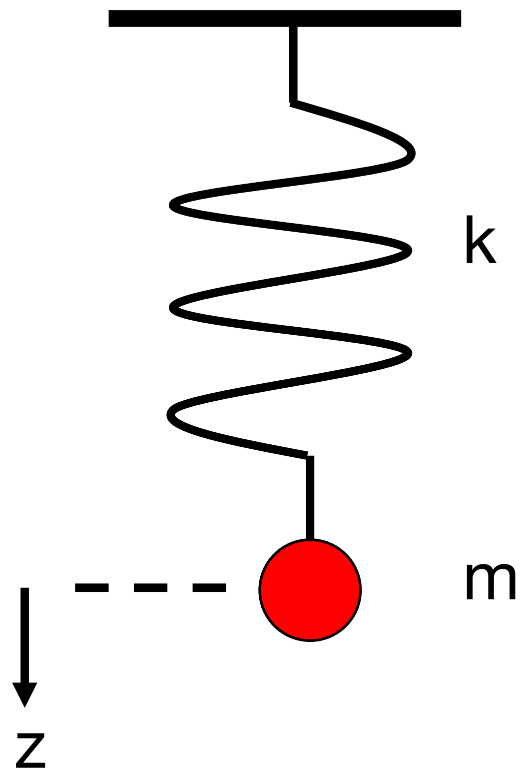
# Harmonic oscillation

$$m\,(d^2z\,/\,dt^2) = -k\,z$$



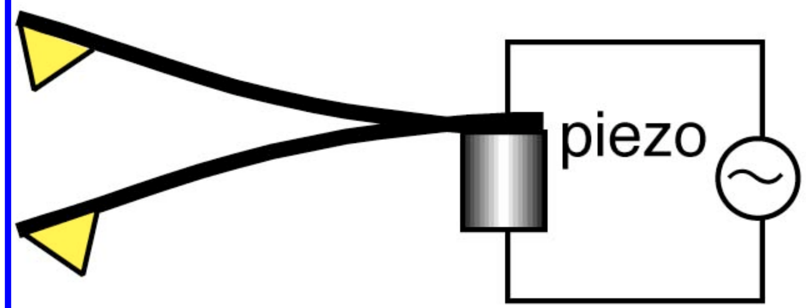
$$z = (z_0\,e^{i\theta})\,e^{i\omega_0 t}$$

$$\omega_0{}^2 = k/m$$



# Forced oscillation with no friction

$$m\ (d^2z\ /\ dt^2) = -k\ z + Fe^{i\omega t}$$

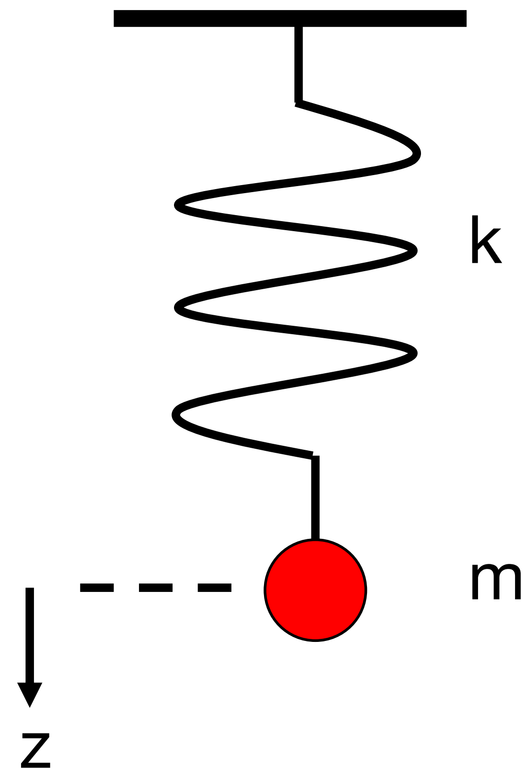



practice

Assume $z = (z_0\ e^{i\theta})\ e^{i\omega t}$.

Determine $z_0$ and $\theta$

as a function of $\omega$.



# Forced oscillation with no friction

$z = (z_0\, e^{i\theta})\, e^{i\omega t}$

$m\, (d^2z\, /\, dt^2) = -m\omega^2 z_0 e^{i\theta}\, e^{i\omega t}$

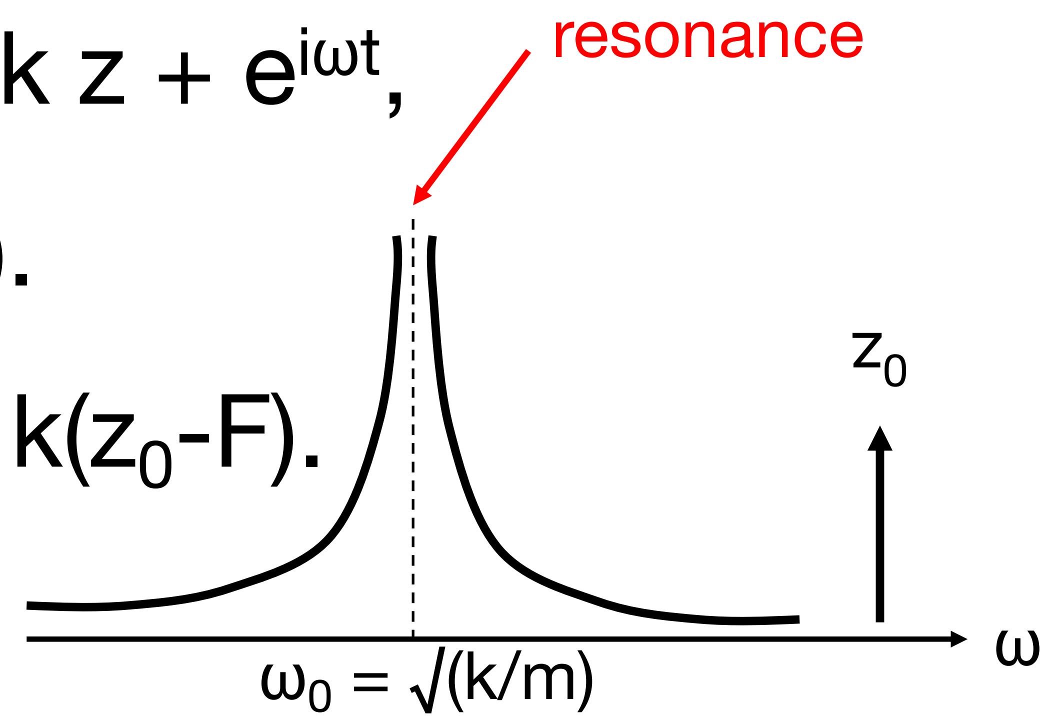
$-k\, z + Fe^{i\omega t} = -k\, (z_0\, e^{i\theta} - F)\, e^{i\omega t}$

To be $m(d^2z\, /\, dt^2) = -k\, z + e^{i\omega t}$,

$m\omega^2 z_0 e^{i\theta} = k\, (z_0\, e^{i\theta} - F)$.

So, $\theta = 0$ and $m\omega^2 z_0 = k(z_0 - F)$.

$\therefore\, z_0 = F\, /\, (k - m\omega^2)$

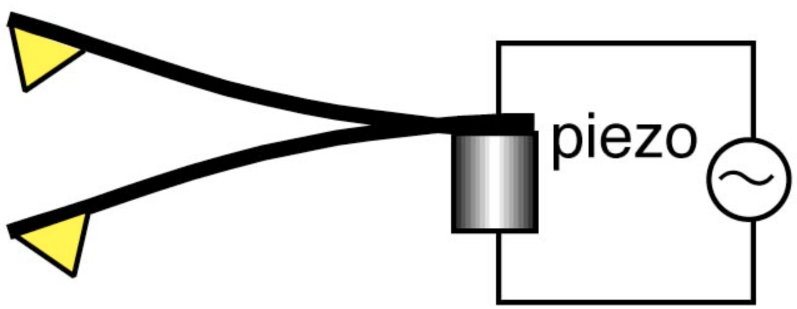


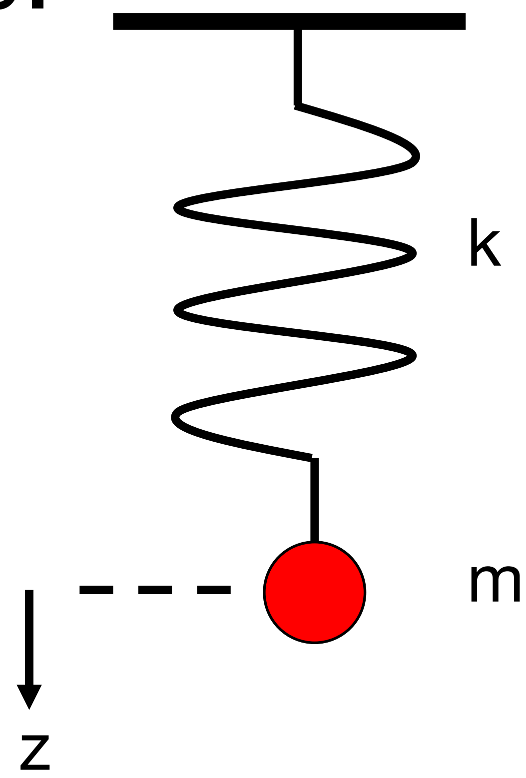
# Forced oscillation with friction

$$m\,(d^2z\,/\,dt^2) = -k\,z\;{\color{red}-\gamma\,dz/dt} + Fe^{i\omega t}$$

Assume $z=(z_0\,e^{i\theta})\,e^{i\omega t}$.

Determine $z_0$ and $\theta$.



# Forced oscillation with friction

$z = (z_0\, e^{i\theta})\, e^{i\omega t}$

$m\,(d^2z\,/\,dt^2) = -m\omega^2 z_0 e^{i\theta}\, e^{i\omega t}$

$-kz\, -\gamma dz/dt + Fe^{i\omega t} = -k\,(z_0 e^{i\theta} + \gamma z_0 e^{i\omega} - F)\, e^{i\omega t}$

To be $m(d^2z/dt^2) = -kz - \gamma dz/dt + Fe^{i\omega t}$ ,

$m\omega^2 z_0 e^{i\theta} = k(z_0 e^{i\theta} + \gamma z_0 e^{i\omega} - F)$.

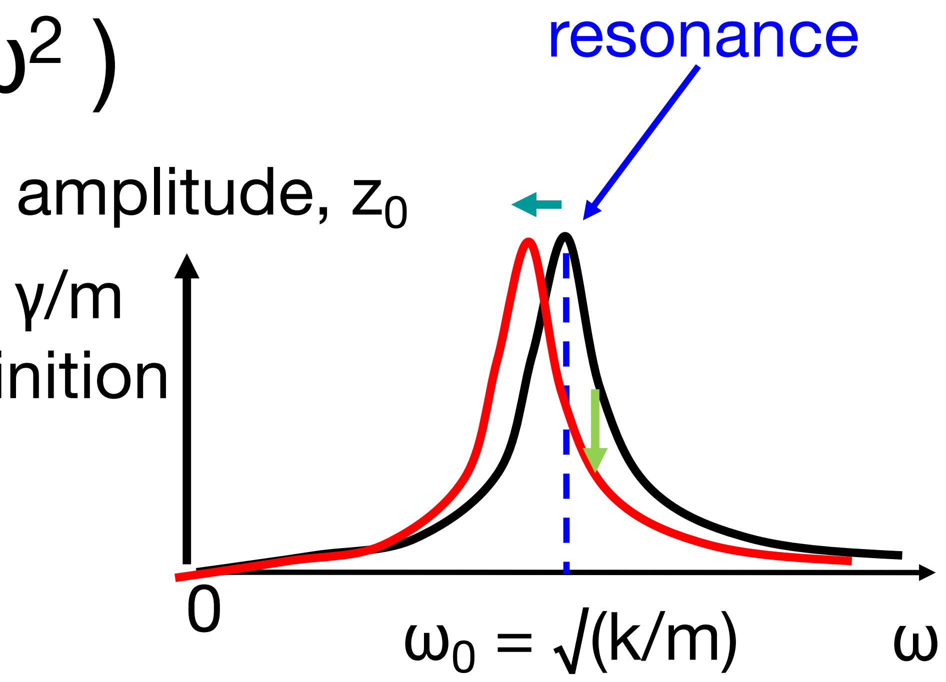
# Forced oscillation with friction

$$m\omega^2 z_0 e^{i\theta} = k(z_0 e^{i\theta} + \gamma z_0 e^{i\omega} - F)$$

$$z_0 = F / ( (k-m\omega^2)^2 + (\gamma\omega)^2 )^{1/2}$$

and

$$\tan\theta = -\gamma\omega / ( k-m\omega^2 )$$




full width at halh maximum of $z_0^2 = \gamma/m$

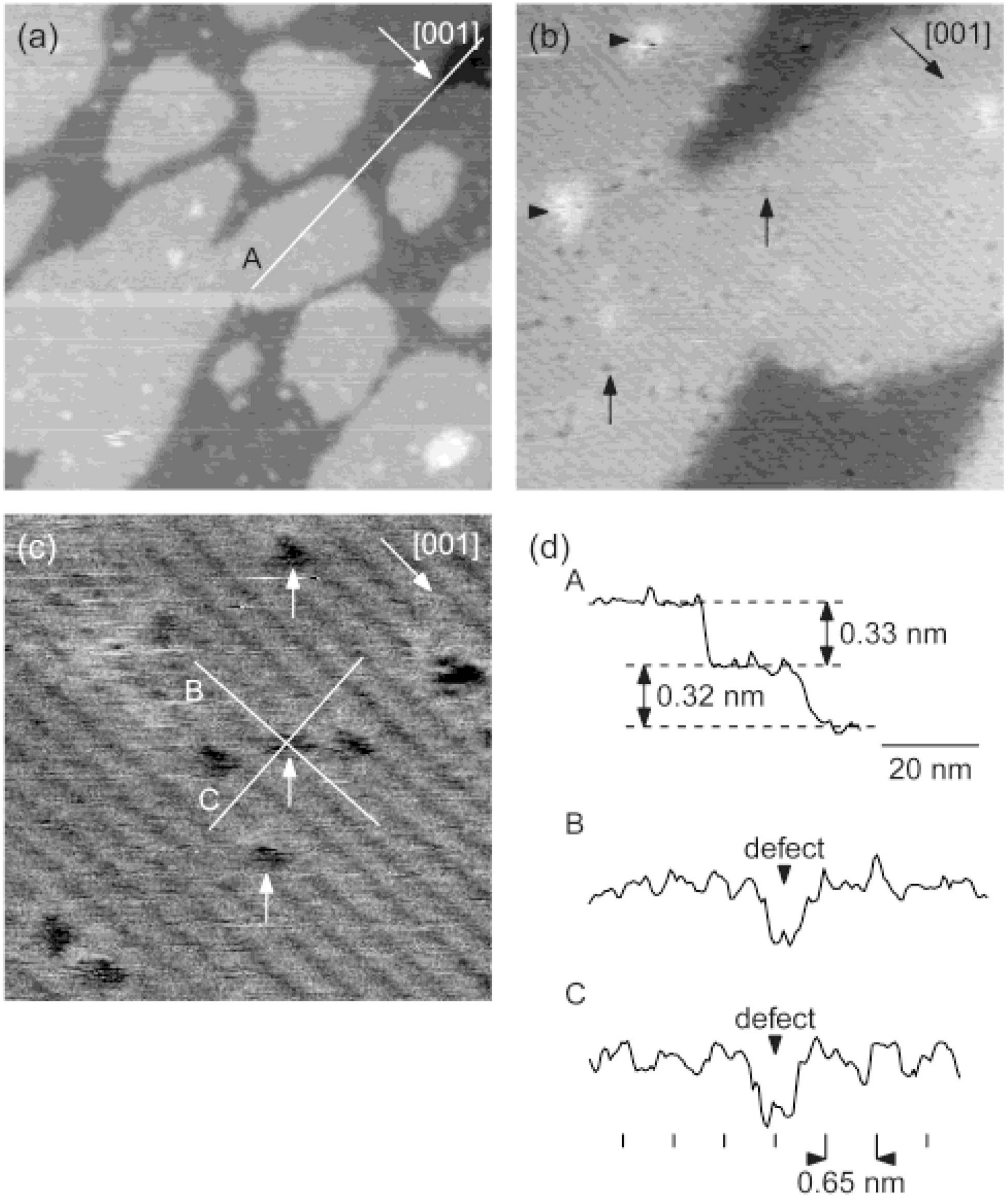
quality factor $Q = \omega_0$ / fwhm by definition

=10,000 in vacuum

= 500 in air

= 10 in water

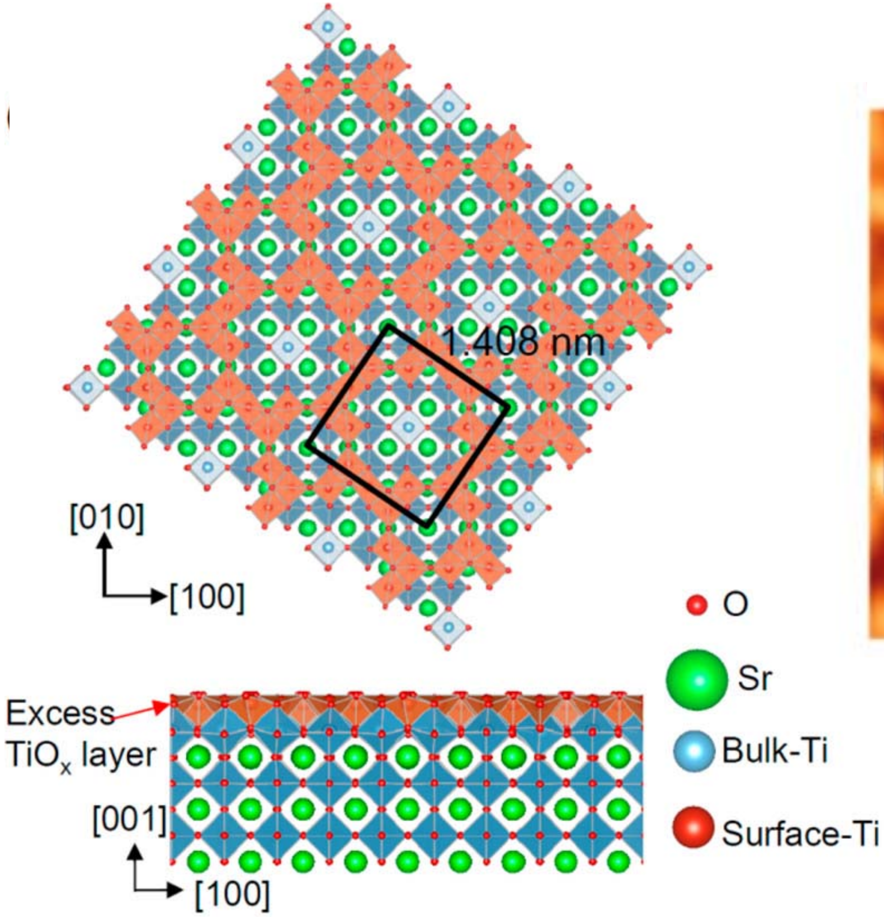
# $TiO_2$ in 1 atm $N_2$



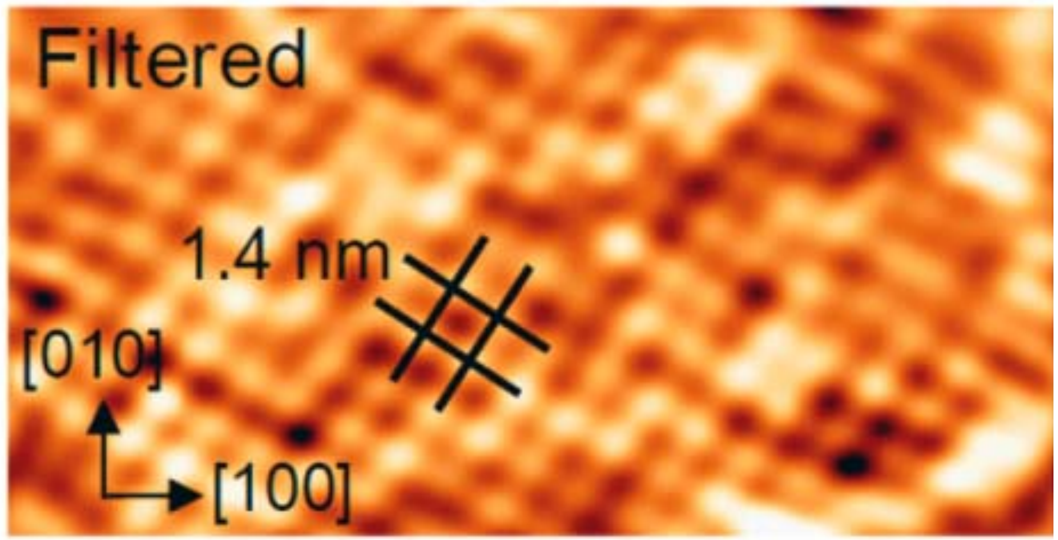

Q = 500

Sasahara et. al., J. Phys. Chem. B108 (2004) 15735.

# $SrTiO_3$(100) in water




(√13 x √13) reconstruction



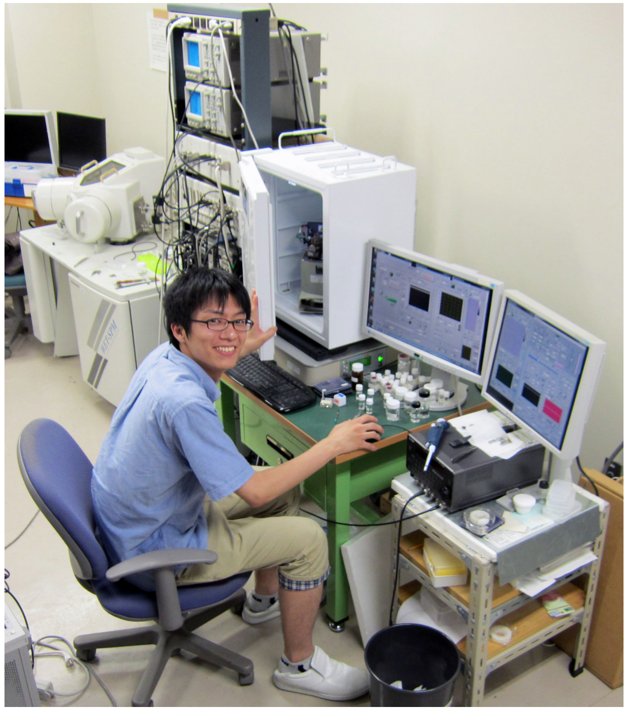

AFM topography
in a KCl solution (50 mM)

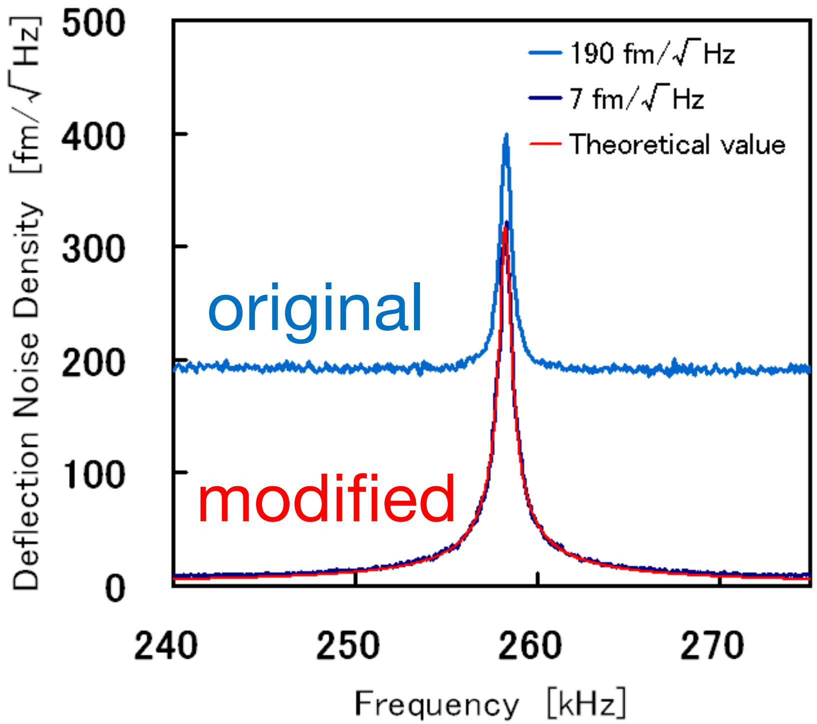
Seiji Kawasaki et al., J. Phys. Chem. C 121 (2017) 2268.

# FM-AFM in low-Q environments

## $10^4$ in vacuum, 300 in air, 10 in water

T. Fukuma et al., Rev. Sci. Instrum. 76 (2005) 053704.






Shimadzu, SPM-8100FM, in developing

10 pN force sensitivity

SHIMADZU

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