Magnetic Force Microscopy

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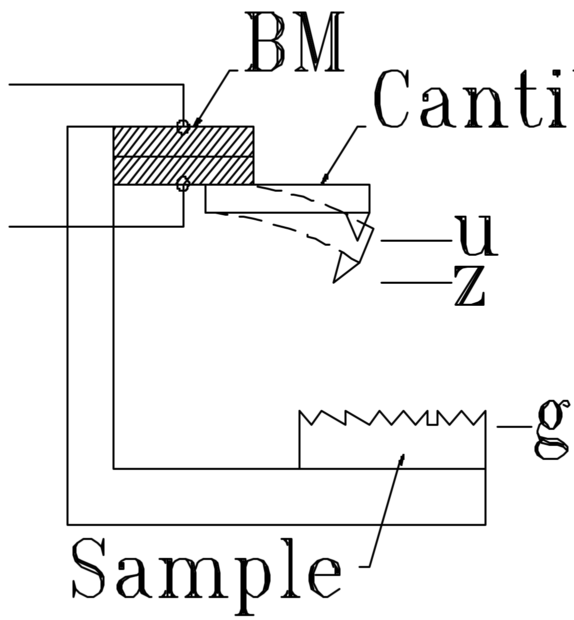
Development of MFM

- **Noncontact mode**
  - ✧weak interaction
    - ✓magnetic, electric and attr. VdW force
  - ✧resonance frequency shift: $\Delta w_0 \sim w_0 (F' / 2k)$.
    - ✓amplitude change
    - ✓lock-in technique
  - ✧tip-sample spacing dependence
- **Principle of noncontact mode**



✧One dimentional harmonic osicillator

$$F(z) = F_0 + F_1(z_0)z$$

$$m \frac{\partial^2 z}{\partial t^2} + g \frac{\partial z}{\partial t} + k(z - u) = F(z)$$

The positions of the bimorph and the lever

$$u = u_0 + a\exp(iwt)$$
$$z = z_0 + z$$ respectively.

then

$$m\frac{\partial^2 z}{\partial t^2} + g\frac{\partial z}{\partial t} + k[z - a\exp(iwt)] = F'z$$

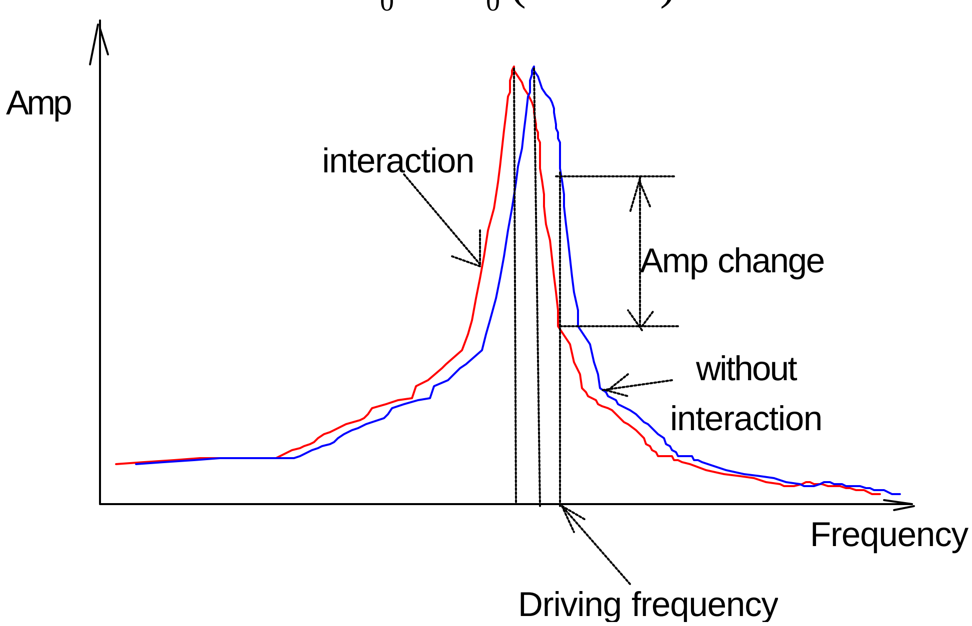
The amplitude of vibration is given by

$$A_b(w, F') = \left(\frac{ak\exp(iq)}{k' - w^2 m + iwg}\right)$$

where $k' = k - F'$

The motion of the lever is now influenced by the force derivative(resonance frequency shift).

$$\Delta w_0 \sim w_0(F'/2k).$$



At the frequency with maximum sensitivity,

$$\omega_m \cong \omega_0'\left(1+\frac{1}{2\sqrt{2}Q}\right)$$

The amplitude change is given by

$$\Delta A = \left(\frac{2A_0 Q}{3\sqrt{3}k}\right) F'$$

- contrast mechanism of MFM

✧point dipole model

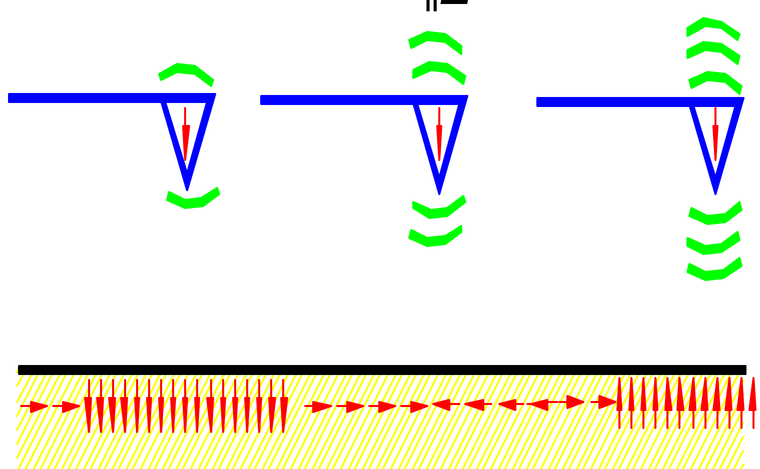
$$\vec{F} = \nabla(\vec{m}\cdot\vec{H})$$

m : magnetic moment of the tip

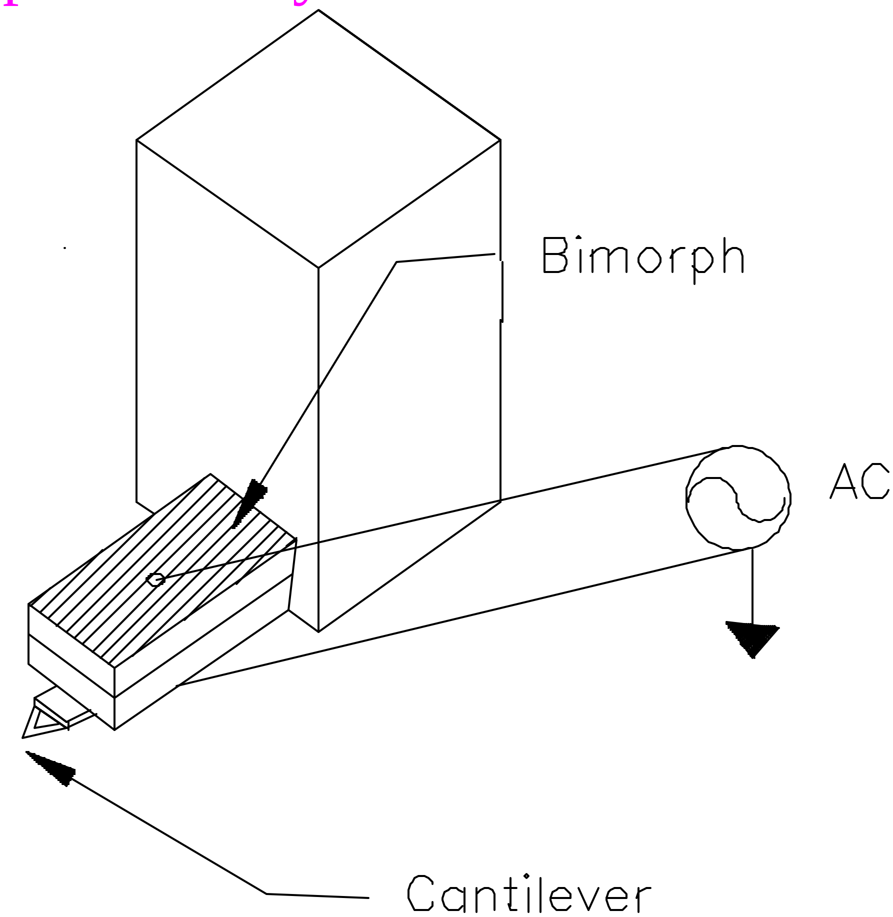
H : stray field from sample

$$F' = \frac{\partial(\vec{F}\cdot\hat{z})}{\partial z} = m_x \frac{\partial^2 H_x}{\partial z^2} + m_y \frac{\partial^2 H_y}{\partial z^2} + m_z \frac{\partial^2 H_z}{\partial z^2}$$

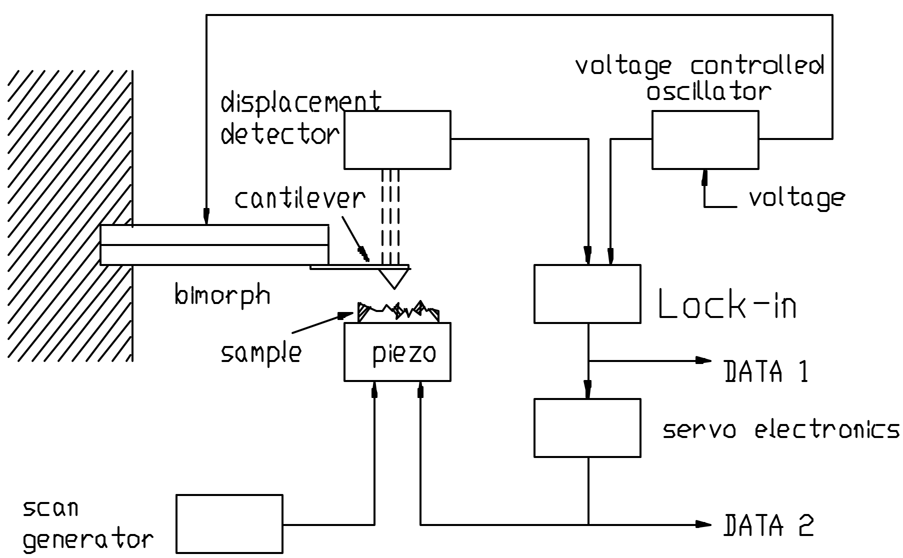
for $\vec{m} = m_z\hat{z}$, $F' = m_z \dfrac{\partial^2 H_z}{\partial z^2}$



● bimorph driven system

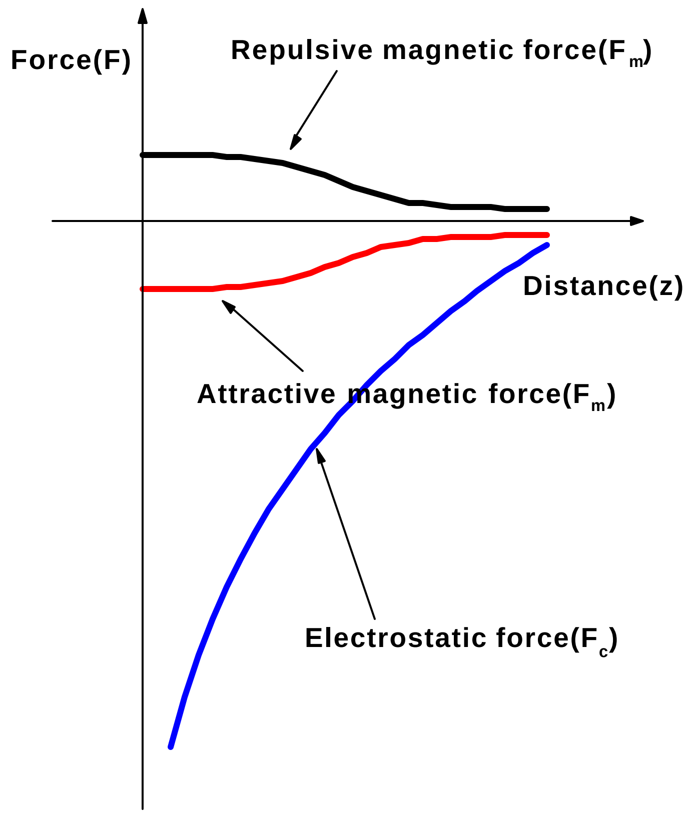


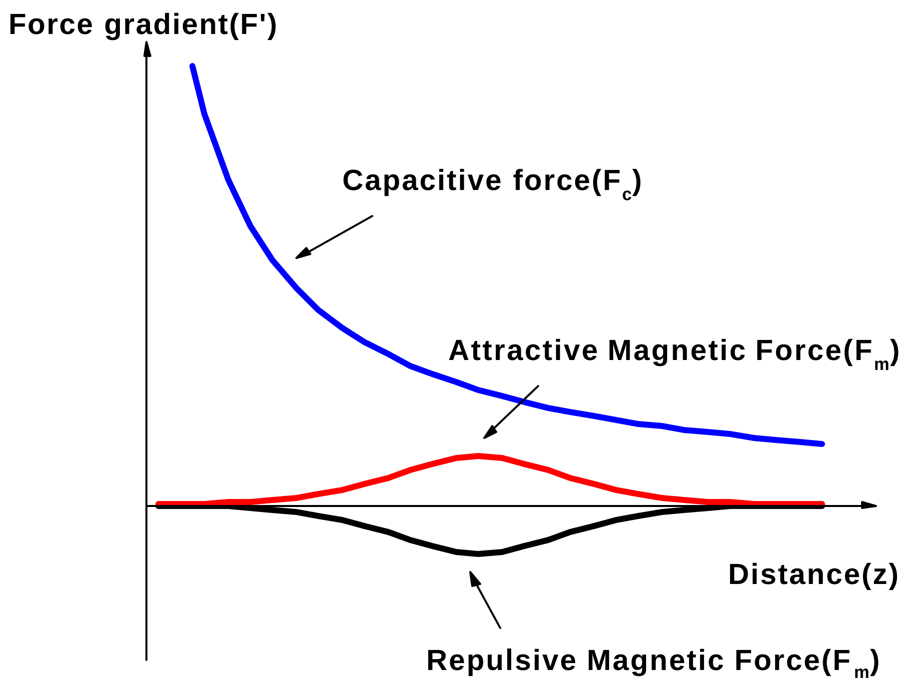
● feedback in MFM



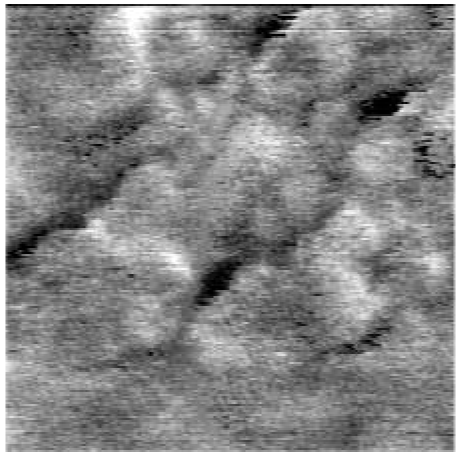
- operating condition
  - ✧oscillation freq:$\omega \sim \omega_0$
    - ✓resonance frequency shift
  - ✧tip-sample distance:10-100nm
    - ✓long range magnetic interaction
  - ✧bias between tip and sample: 0V-10V
    - ✓electrostatic force
- servo force
  - ✧attractive or repusive magnetic force
    - ✓tip crash due to polarity change
    - ✓need of servo force for feedback
  - ✧addition of overall attractive force
    - ✓control of the spacing between tip and sample
    - ✓additional electrostatic force
  - ✧ $$\Delta A = \left(\frac{2A_0 Q}{3\sqrt{3}k} \right) \Delta \left(F_m' + F_c' \right)$$
  - ✧under feedback: $\Delta A = 0$
    - ✓ $$\Delta z = \left[\frac{\Delta F_m'}{\partial F_{servo}' / \partial z} \right]_{z = z_0}$$

✓data 2: contours of constant force gradient

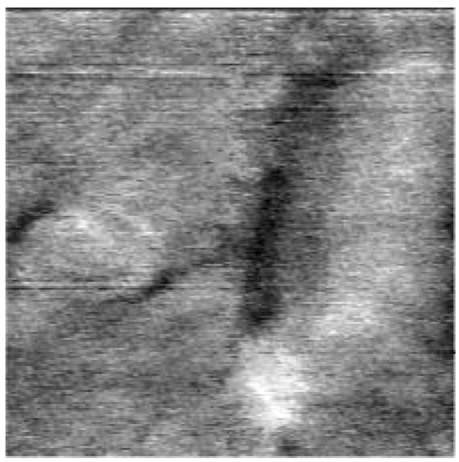




- Co-Pd multilayer film
  - ✧sample preparation
    - ✓total thickness is about 300A
    - ✓(4.0Co+13.2Pd)17 layer
    - ✓glass substrate
  - ✧image
    - ✓earth's magnetic field
    - ✓observation of natural magnetic domain



(1.8μm× 1.8μm)



(1.8μm× 1.8μm)

Summary

- MFM using resonnce frequency shift was constructed.
- The contrast mechanism of MFM was discussed by using one dimensional harmonic oscillator model.
- The role of electrostatic force as servo force under feedback was discussed.

● MFM was applied for the observation of magnetic domain of the magnetic multilayer films

MFM using Electrostatic Force Modulation

● drawback of bimorph driven system

✧indirect modulation

✧uncontrolled vertical deflection

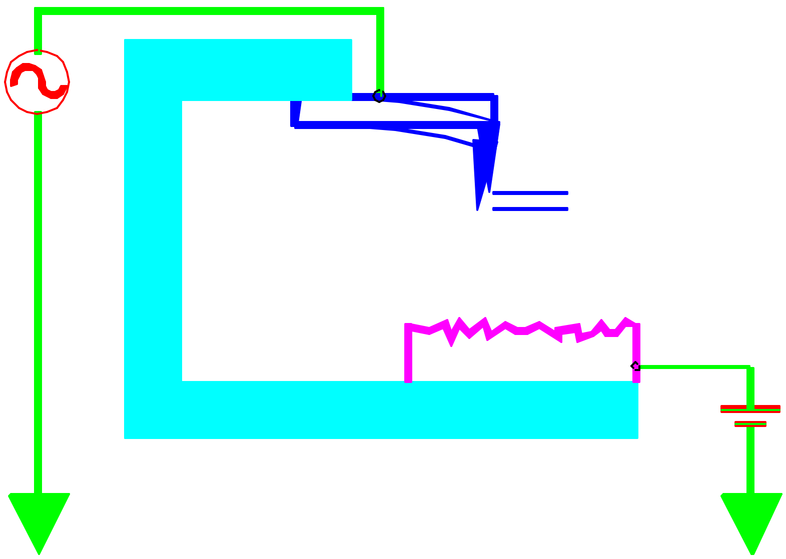
⇒unstable feedback

✧complex amplitude vs. frequency

⇒restriction in op. frequency range

- electrostatic force modulation

✧direct modulation

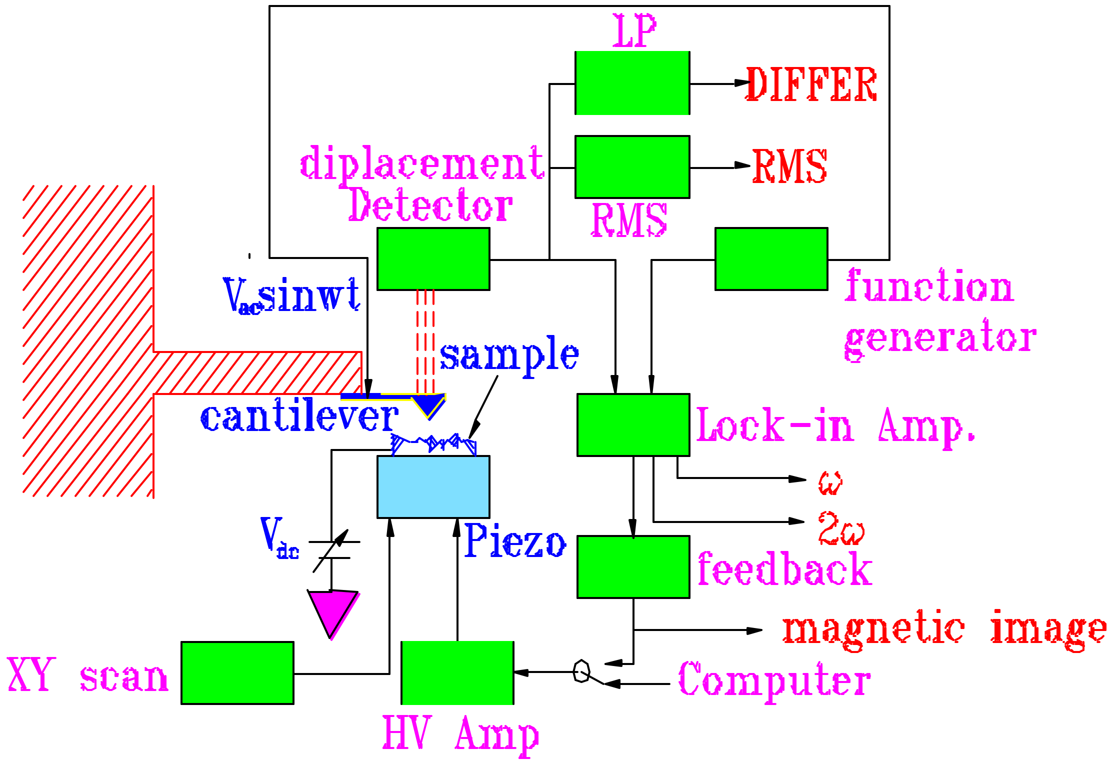


✧ac voltage between tip and sample : $V = V_{ac} \sin \omega t$

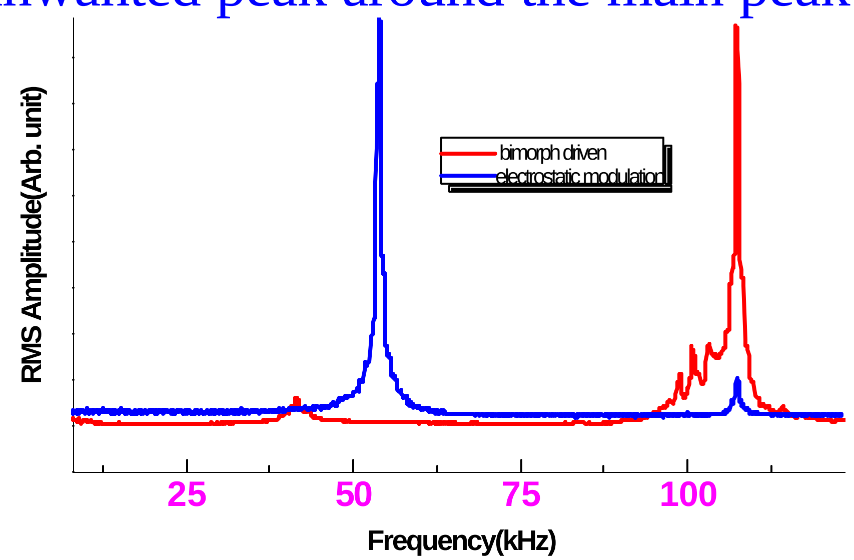
✧driving force: $f_c = \frac{1}{4} V_{ac}^2 \frac{\partial C}{\partial z}(1 - \cos 2\omega t)$

✧ $m \frac{\partial^2 z}{\partial t^2} + g \frac{\partial z}{\partial t} + k(z - u_0) = F_m + F_c + F_{vdW}$

- block schematics



- rms amplitude-frequencycurve
  - ✧electrostatic modulation system
    - ✓well-defined amp.-freq. spectrum
  - ✧bimorph driven system
    - ✓unwanted peak around the main peak



- 2ω component

$$m\frac{\partial^2 z}{\partial t^2}+\gamma\frac{\partial z}{\partial t}+k(z-u_0)=F_m+F_{vdW}+\frac{1}{4}V_{ac}^2\frac{\partial C}{\partial z}(1-\cos 2\omega t)$$

Near average position z_0,

$$z=z_0+z^{(1)}+\ldots$$

then

$$z_{2\omega}^{(1)}=-\frac{\Phi(z_0)\sin(2\omega t+\varphi^{(1)})}{\sqrt{(\omega_0'^2-4\omega^2)^2+16(\gamma\omega)^2}},\ \varphi^{(1)}=\arctan\frac{\omega_0'^2-4\omega^2}{4\gamma\omega}$$

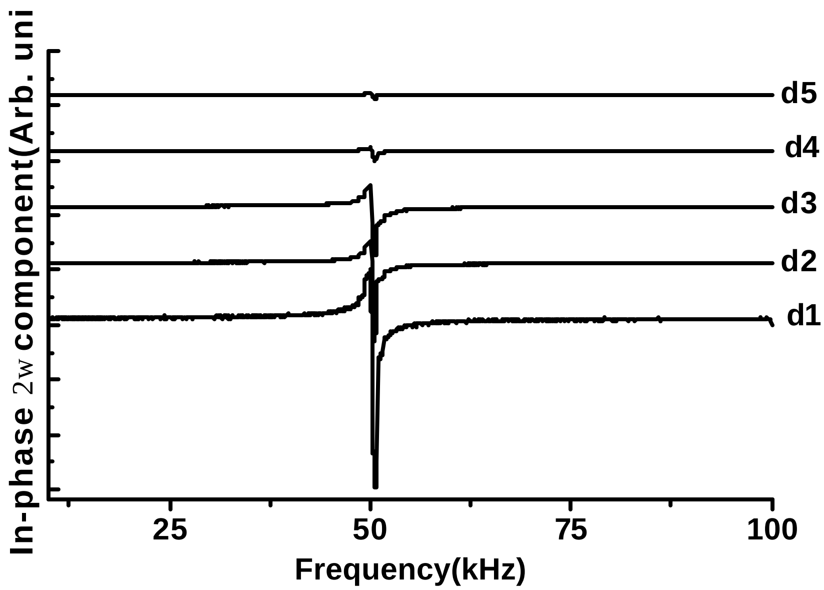
where

$$\omega_0^2=\frac{k}{m},\ \gamma=2b/m,\ \Phi(z_0)=\frac{1}{4}\frac{\partial C_{tip}(z_0)}{m\partial z}V_{ac}^2,\ \omega_0'^2=\frac{k}{m}-\frac{F_m'(z_0)}{m}-\Phi^{(1)}(z_0)$$

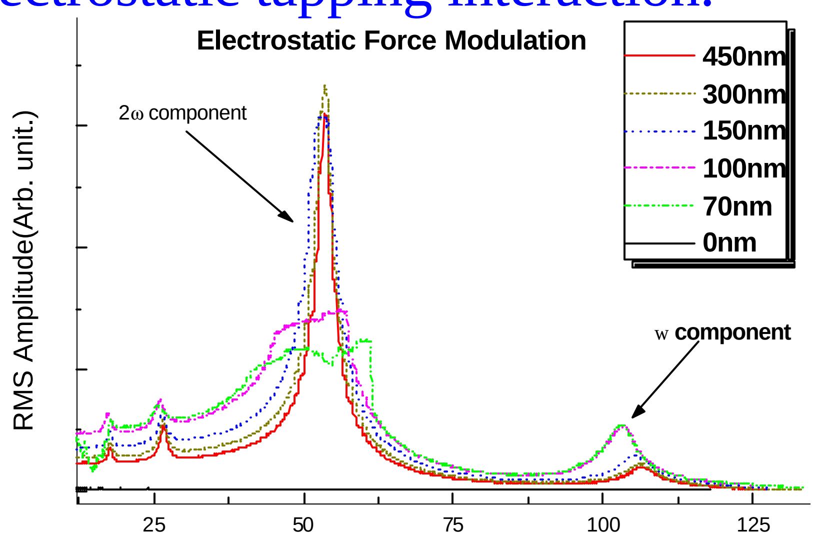
In-phase output $$X_{2\omega}=-\frac{4\Phi(z_0)\gamma\omega}{(4\omega^2-\omega_0'^2)^2+16(\gamma\omega)^2}$$

In-quadrature output $$Y_{2\omega}=\frac{\Phi(z_0)(4\omega^2-\omega_0'^2)}{(4\omega^2-\omega_0'^2)^2+16(\gamma\omega)^2}$$

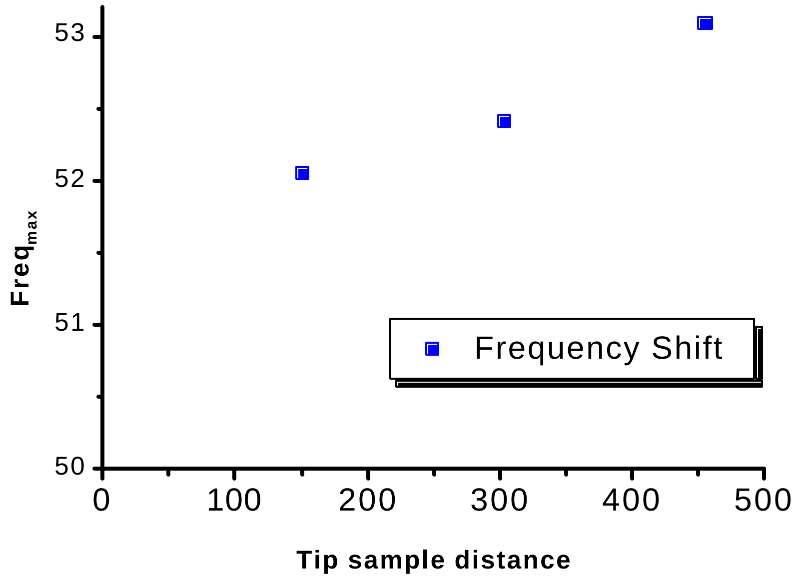
- in-phase component for different distances
  - ✓ d5=20μm, d4 =10μm, d3=5μm, d2=2μm, d1=1μm.



- rms amplitude-frequency curve
  - ✧various tip-sample distances:
  - ✧subharmonic peaks
    - ✓ $m\frac{\partial^2 z}{\partial t^2}+\gamma\frac{\partial z}{\partial t}+k(z-u)=F_m+F_c+F_{vdw}+F_{rep}$
    - ✓nonlinear characteristics of capacitance
  - ✧truncated peaked near 100nm
    - ✓electrostatic tapping interaction.



✧resonance frequency in noncontact regime

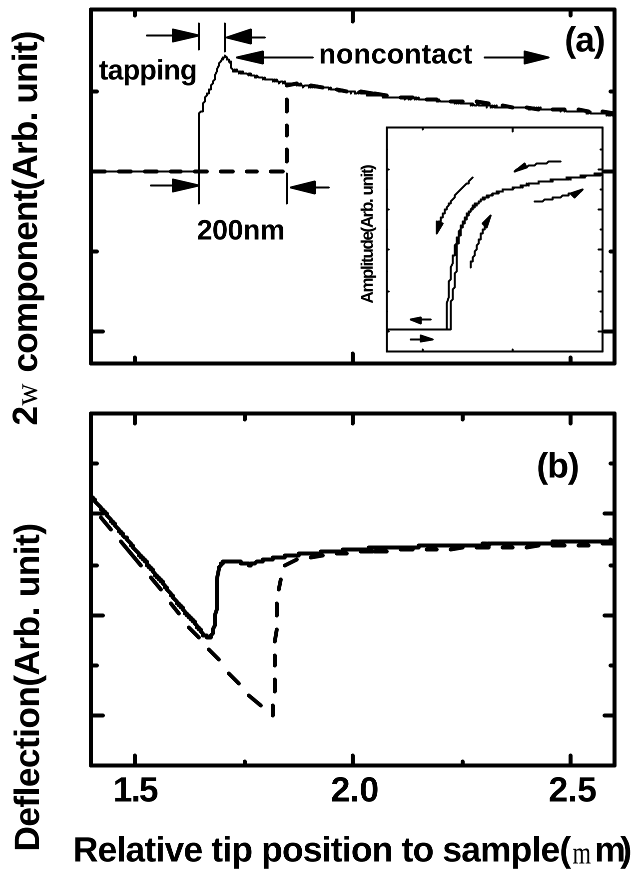


2ω Amplitude-Distance Curve

✧cantilever :*Co* coating(*~40nm*), *k=2.1N/m*, f_{res}=*65kHz*

✧V_{ac}=*14V*, *fop*=*33.43kHz*

✧sample: *CoCr* thin film(*t ~ 300nm*)

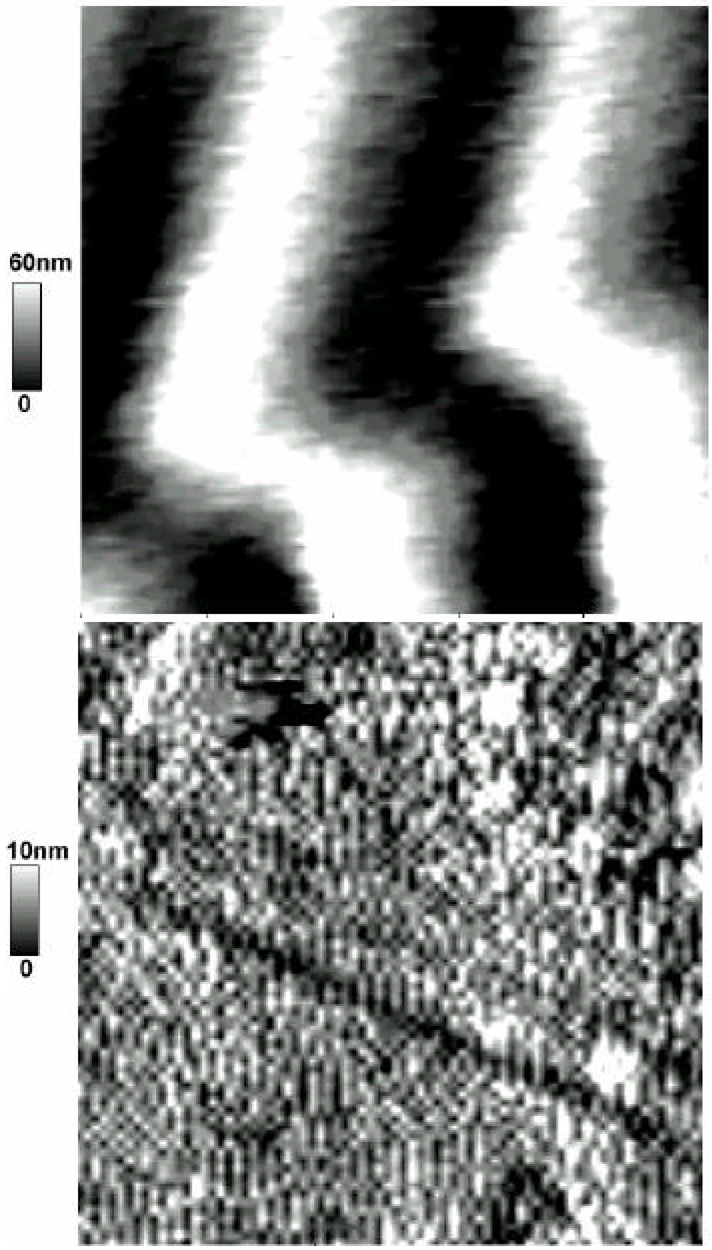


✧good amplitude vs. frequency curve(***cf.bimorph***)
✧long range electrostatic capacitive modulation
⇒*stable imaging condition*
✧2ω increases as tip approaches surface(***cf. inset***)
⇒*high signal to noise ratio*

Results

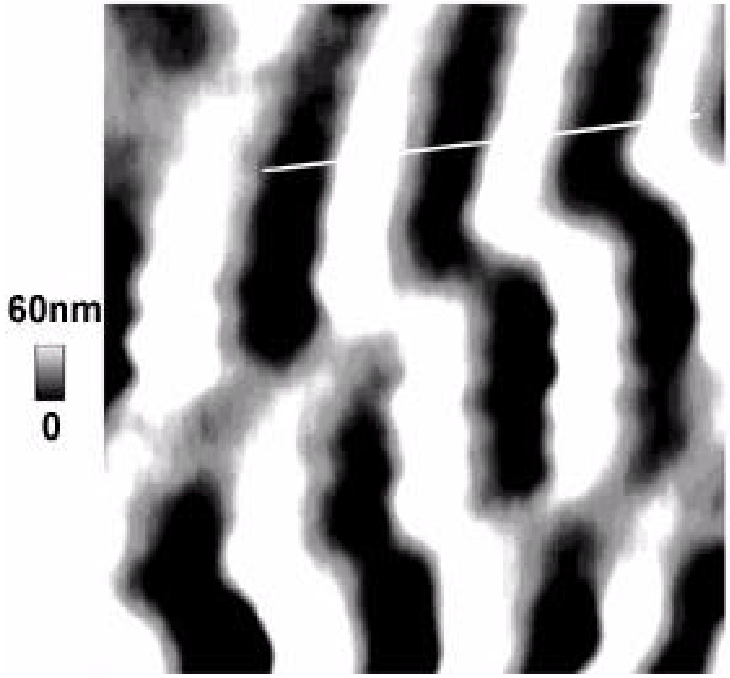
✧noncontact regime(*vibration~80nm*)
⇒*labyrinthine domain(period 4.5~5mm)*
✧tapping regime(*vibration~85nm, d~90nm*)

⇒*elongated grains(~300nm´600nm)*

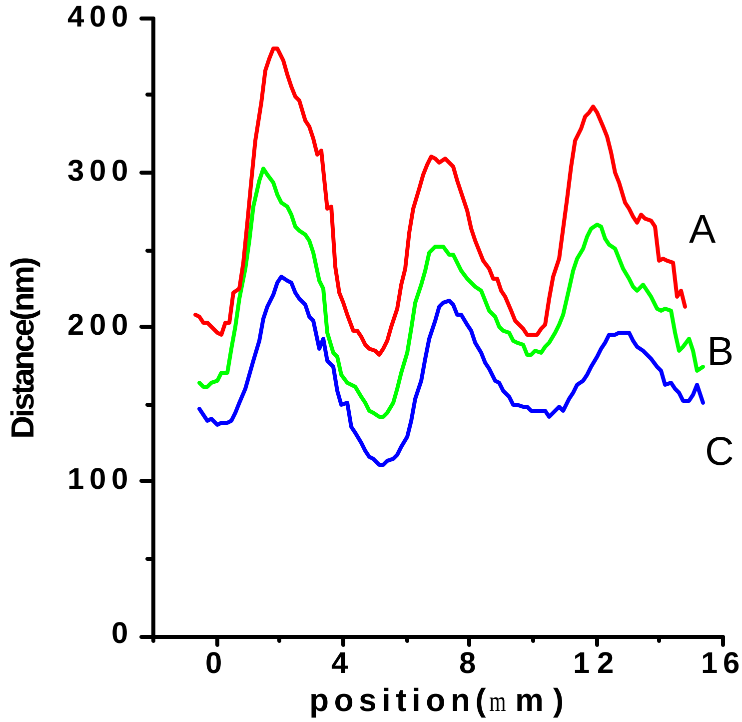


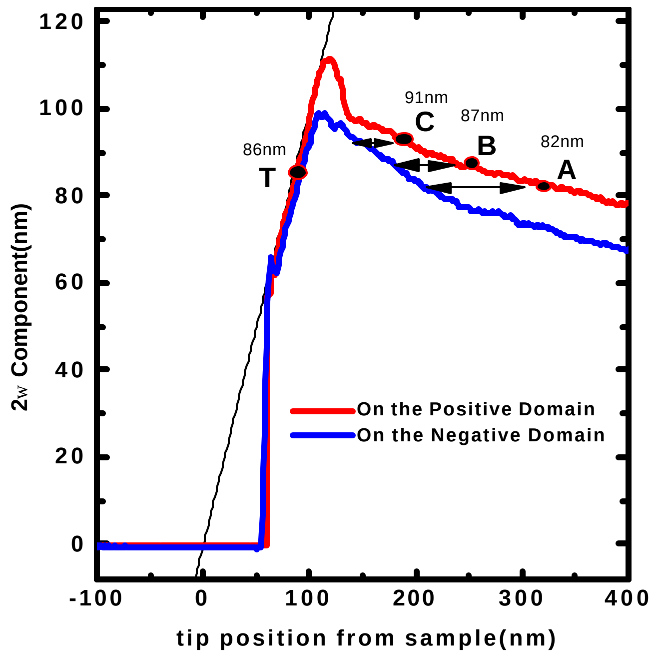
(10µm×10µm)

- ✧noncontact regime(*vibration amp.~80nm*)
- ✧contrast increase for larger distance

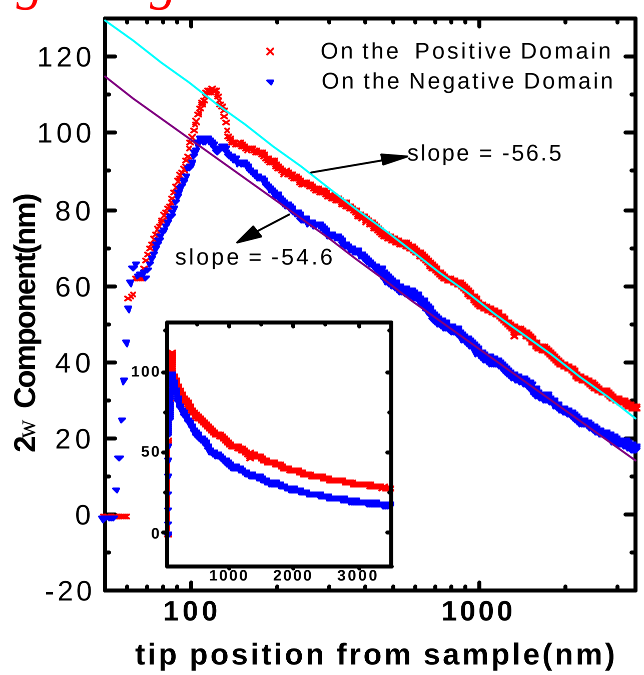


(20μm×20μm)





⇒long range magnetic interaction



✧ $\frac{\partial C(z_0)}{\partial z} \approx a \ln(D / z_0)$

⇒conical tip model

⇒electrostatic long range order interaction

⇒stable feedback condition

Summary

- ✧development of MFM using electroststic force modulation
- ✧good amplitude vs. frequency curve(***cf. bimorph***)
- ✧long range electrostatic capacitive modulation

  ⇒*stable imaging condition*
- ✧increase of 2ω as tip approaches surface

  ⇒*high signal to noise ratio*
- ✧*conical tip model* in the noncontact regime
- ✧*labyrinthine domain(period 4.5~5mm)* on CoCr thin film
- ✧*elongated grains(~300nm´600nm)*
- ✧promising tool for studying magnetic sample