Development of Phase Locked Oscillator in UHV

Dynamic Force Microscopy and its application to the Tip-Sample Interaction on the VC(100)

09 – 03 – 99

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Understanding non-contact regime

**Conventional non-contact**
Ambient condition (Amplitude change $\Delta A$)
Non-destructive
no atomic resolution
Probes physical interactions ($A \ll D$)

**Tapping**
Ambient condition (tap. amp. $\Delta A$ or phase $\Delta \phi$)
No atomic resolution
Destructive
Probes physical interactions ($A \gg D$)

**UHV non-contact**
resonance frequency shift $\Delta f$
Non-destructive
True atomic resolution (point defects)
Probes physical + chemical (local) interactions ($A \approx D$)
Amplitude: 20nm – 60nm
Bias
- Allows the tip-sample gap to be very small in a controllable way (long range electrostatic force)
- Eliminates the contact potential

Tip:
- conducting tip (compatible with STM)
- electrostatic force

Sample:
- reactive sample (strong chemical interaction)

Ex) samples that have exhibited atomic resolution by FM non-contact mode (published): Si(111), InP(110), TiO2(110), InAs(110), alkalihalides

We need the circuits for:

- Electrostatic modulation
  $\Rightarrow$ Bias optimization in UHV NC-AFM
  ($\omega$ component vs. bias curve)
  $\Rightarrow$ Imaging of contact potential difference in UHV or ambient condition

- Oscillation amplitude measurement (rms-to-dc converter)
  $\Rightarrow$ Vibration amplitude control in UHV NC-AFM
  $\Rightarrow$ Tapping mode operation in ambient condition
FB BW = $\omega_0/2Q = 0.5$ Hz
@ $\omega_0 = 50$ kHz, Q = 50000 in UHV

**Drawback of Slope Detection**

Oscillator (Positive Feedback): Phase Shifter

Tip-sample system determines the oscillation frequency

FB BW: Characteristics of demodulator (100Hz-1kHz)

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Damping --> AGC

Phase Shifter

Amp

Detector

FM Demodulator

FM Feedback

Topography
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Phase Locked Loop

\[ H(s) \equiv \frac{\theta_o(s)}{\theta_i(s)} = \frac{G(s)}{1 + G(s)} = \frac{Ks + K\omega_2}{s^3/\omega_3 + s^2 + Ks + K\omega_2} \]

\( \omega_2 \) : 3dB cutoff of Loop Filter

\( \omega_3 \) : Op Amp Bandwidth

\( K = K_d K_h K_o \) : Overall Amplification

Bandwidth of PLL
\[ F_c = \frac{1}{2} \frac{\partial C}{\partial z} V_{ac}^2 (1 - \cos 2\omega t) \]
STM Combined AFM

Tip Characterization -> Current

Sample Characterization -> STM

Sample Characterization

STM
Simple FM Oscillator

Phase Locked Oscillator
Phase Locked Loop Transfer Function

\[ H(j\omega) = j\omega_n (2\zeta - \omega_n / K_o K_d) + \omega_n^2 - \omega^2 + 2j\zeta \omega_n \omega + \omega_n^2 \]

\[ \omega_n = \sqrt{\frac{K_o K_d}{\tau_1 + \tau_2}} \]

\[ \zeta = \frac{1}{2} \sqrt{\frac{K_o K_d}{\tau_1 + \tau_2} \left( \tau_2 + \frac{1}{K_o K_d} \right)} \]
Experimental Setup

\[ F_z(z) = \frac{1}{4} \frac{\partial C(z)}{\partial z} V_m^2 (1 - \cos(2\Omega t)) \]
**Characterization of Phase Locked Oscillator**

- Bandwidth (frequency at which 0.707 times ($f_{3dB}$) the input relative to the zero-frequency gain) of PLO $\approx 340$ Hz $\Rightarrow$ Practical scanning speed

- Bandwidth of PLL is nearly the same value with that of PLO

- Natural frequency $\omega_n = 2\pi \times 360$ rad/sec

- Damping constant $\zeta = 1.02$. 

![Graph showing transfer function and frequency response of PLO and PLL](image)
Δf-distance curve on the cleaned VC(100)

- noise level \((\Delta f)_{\text{rms}} \sim 5 \text{Hz} \) for Omicron system
- noise level \((\Delta f)_{\text{rms}} \leq 1 \text{Hz} \) for PLL demodulator
  cf) atomic corrugation \sim 2-3 \text{Hz}

- noise level \((\Delta f)_{\text{rms}} \leq 1 \text{Hz} \) for PLL demodulator
- well-defined value of the measured Δf-d in repulsive tapping regime
Indirect Extraction of Interaction Force and Interaction Energy from $\Delta f$-$d$ Curve.


\[ F_{\text{int}}(\xi, \lambda) = \frac{2k}{f_0} \frac{a^{3/2}}{\sqrt{2}} \int_{-\infty}^{\infty} \frac{d\zeta}{\sqrt{\zeta^2 - \xi^2}} \Delta f(\zeta, \lambda) d\xi \]

\[ U_{\text{int}}(\xi, \lambda) = \frac{2k}{f_0} \frac{a^{3/2}}{\sqrt{2}} \int_{-\infty}^{\infty} \frac{d\xi}{\sqrt{\xi^2 - \zeta^2}} \Delta f(\zeta, \lambda) d\zeta \]

- Numerical calculation with MathCad
- Interaction Force $\sim 0.1 \text{nN}$ near surface (cf. Si-Si $\sim 10 \text{nN}$)
- Interaction Energy $\sim 1.2 \text{eV}$ (cf. Si-Si $\sim 20-30 \text{eV}$)

⇒ Interaction of Si-Vc is less reactive than that of Si-Si tip-sample system
Summary

- Design and Construction of PLO
- Measured the bandwidth of PLO using electrostatic force modulation is over 340Hz, which is practical scanning speed to get an image.
- $\Delta f$-d curve was measured on a cleaned VC(100) surface with this system and compared the result with that of conventional one.
- $\Delta f$-distance curve was used to extract the interaction force and energy between tip and sample based on recently proposed model by Dürig.
- Capacitance measurement.

Conclusion

- The PLO method is an extremely effective way to excite sensors coherently with constant excitation voltage in the tapping regime.
- A Method for In-situ Characterization of Tip-shape Using Electrostatic Force Modulation

Next Step

- Direct heating system
  $\Rightarrow$ Atomic Resolution of Si(111)