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 ΔA)
Non-destructive
no atomic resolution
Probes physical interactions ($A << D$)

Tapping

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

UHV non-contact

resonance frequency shift Δf
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), TiO_2(110), InAs(110), alkalihalides

We need the circuits for:

- Electrostatic modulation
  ⇒Bias optimization in UHV NC-AFM
  (ω component vs. bias curve)
  ⇒imaging of contact potential difference in UHV or ambient condition

- Oscillation amplitude measurement (rms-to-dc converter)
  ⇒Vibration amplitude control in UHV NC-AFM
  ⇒Tapping mode operation in ambient condition

Drawback of Slope Detection

FB BW = $\omega_0/2Q$ = 0.5 Hz

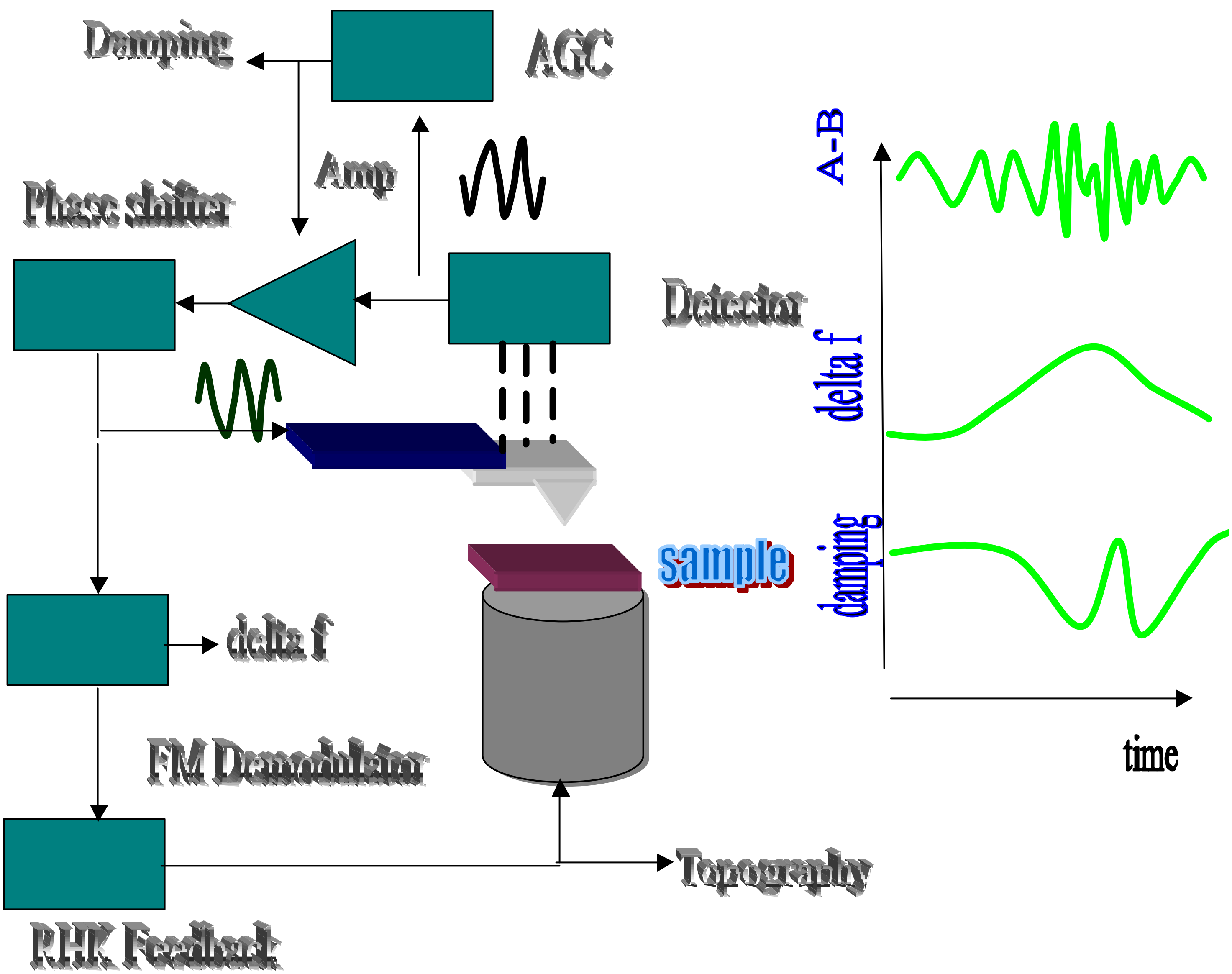
@ ω_0= 50 kHz , Q =50000 in UHV

FM Detection

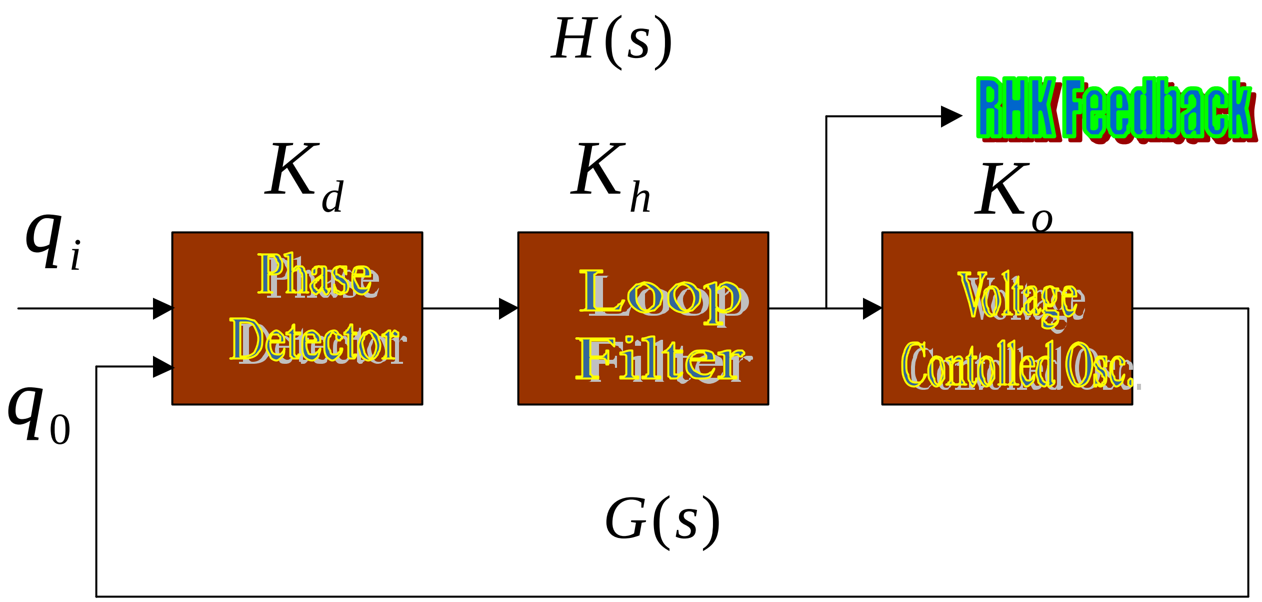
Oscillator(Positive Feedback): Phase Shifter

→ tip-sample sytem determines the oscillation frequency

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



Phase Locked Loop



$$H(s) \equiv \frac{q_0(s)}{q_i(s)} = \frac{G(s)}{1+G(s)} = \frac{Ks + Kw_2}{s^3/w_3 + s^2 + Ks + Kw_2}$$

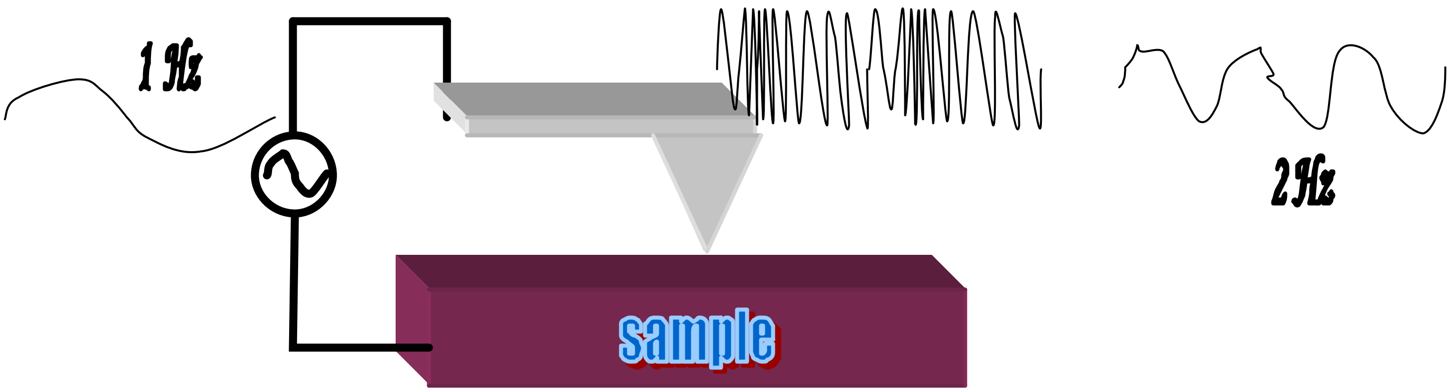
w_2 : 3dB cutoff of Loop Filter

w_3 : Op Amp Bandwidth

$K = K_d K_h K_o$: Overall Amplication

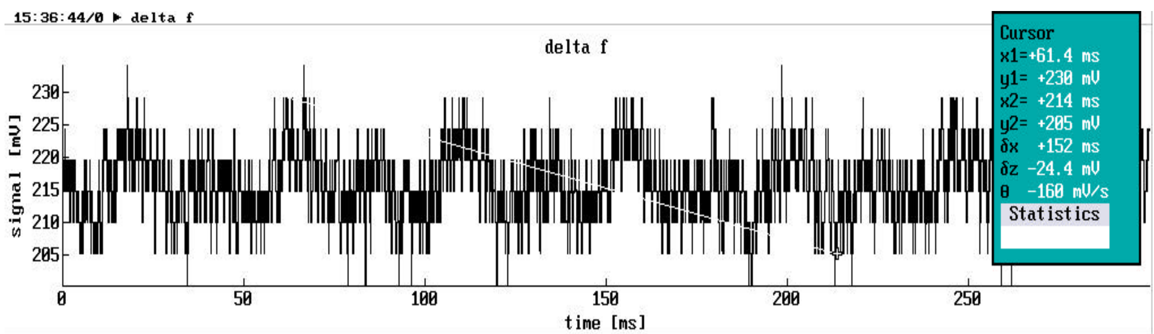
Bandwidth of PLL

Test Signal → Frequency Modulation → Demodulation

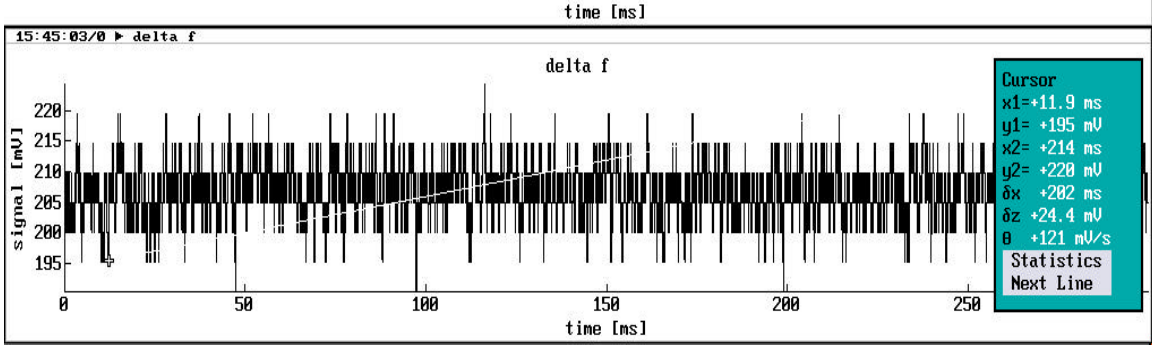


$$F_c = \frac{1}{2}\frac{\partial C}{\partial z} V_{ac}{}^2 (1 - \cos 2wt)$$

Vac=0



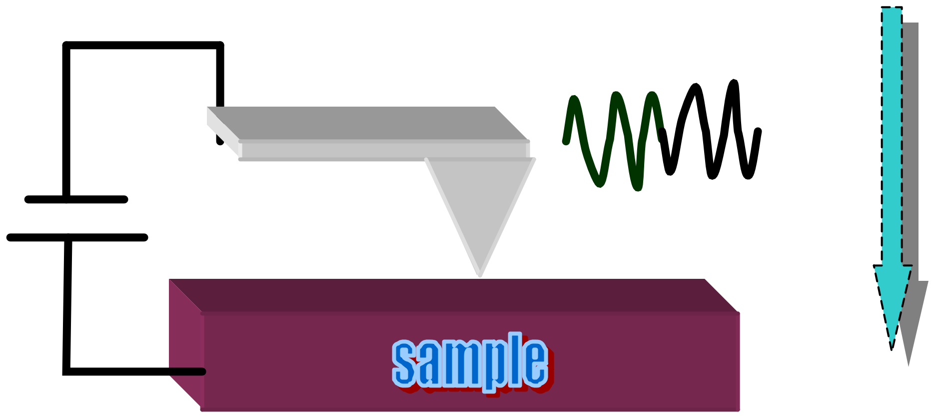
Vac=0



Noise Level of Omicron Demodulator → ~5 Hz

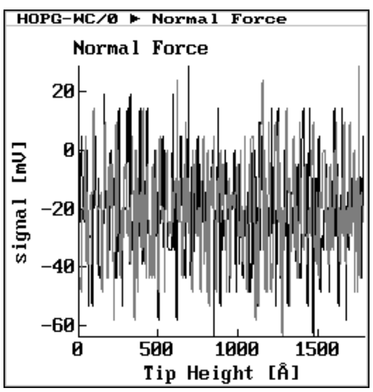
Atomic Resolution → Noise 1 Hz

STM Combined AFM

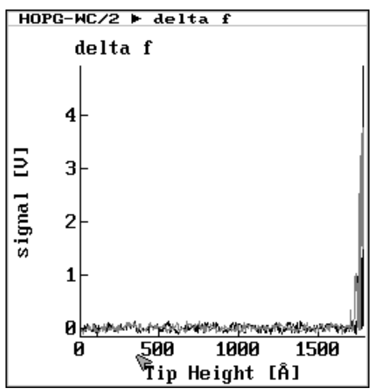


Tip Characterization → Current

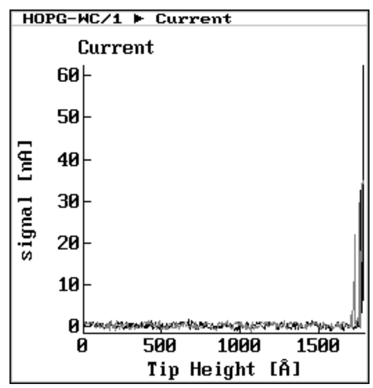
A-B



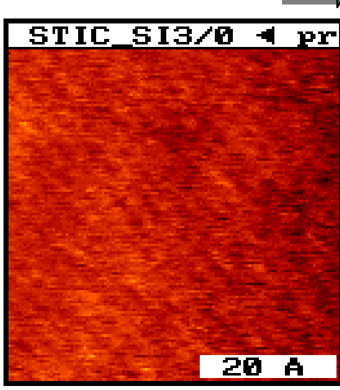
delta f

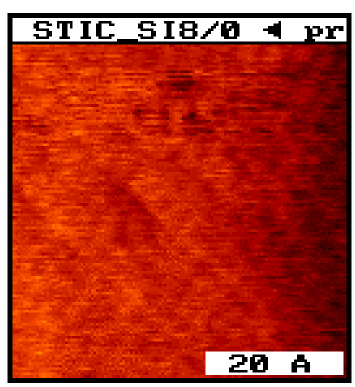


Current



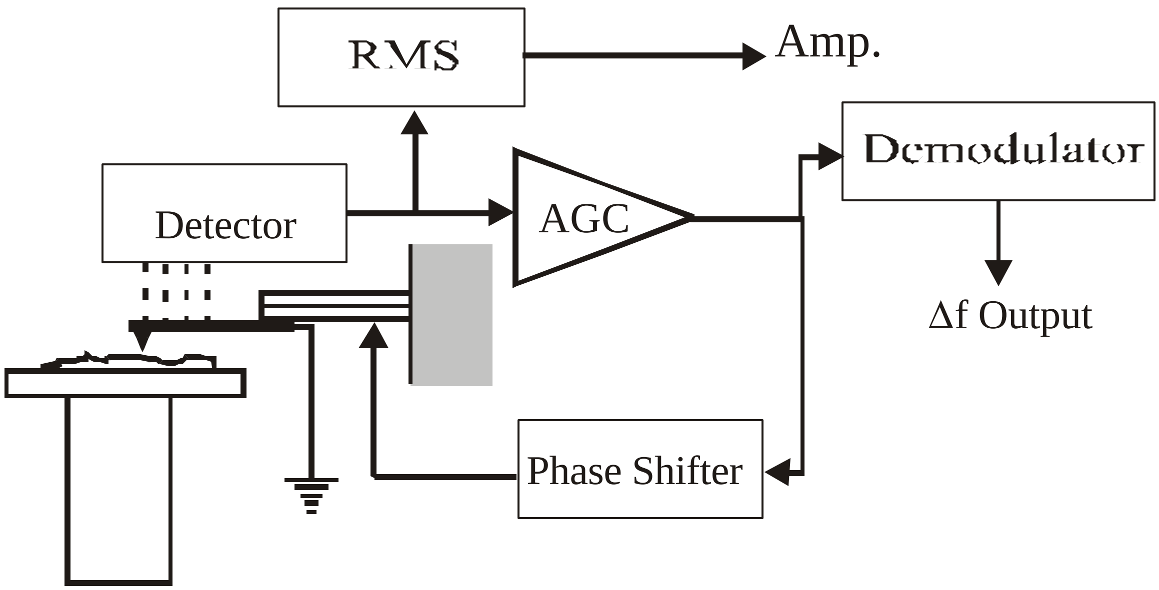
Sample Characterization → STM



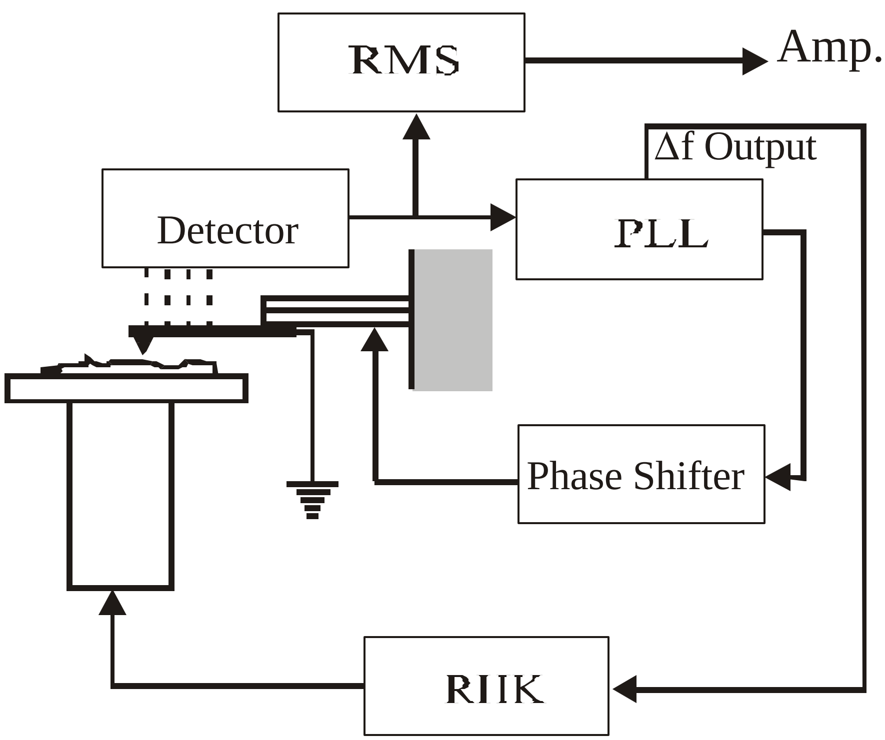


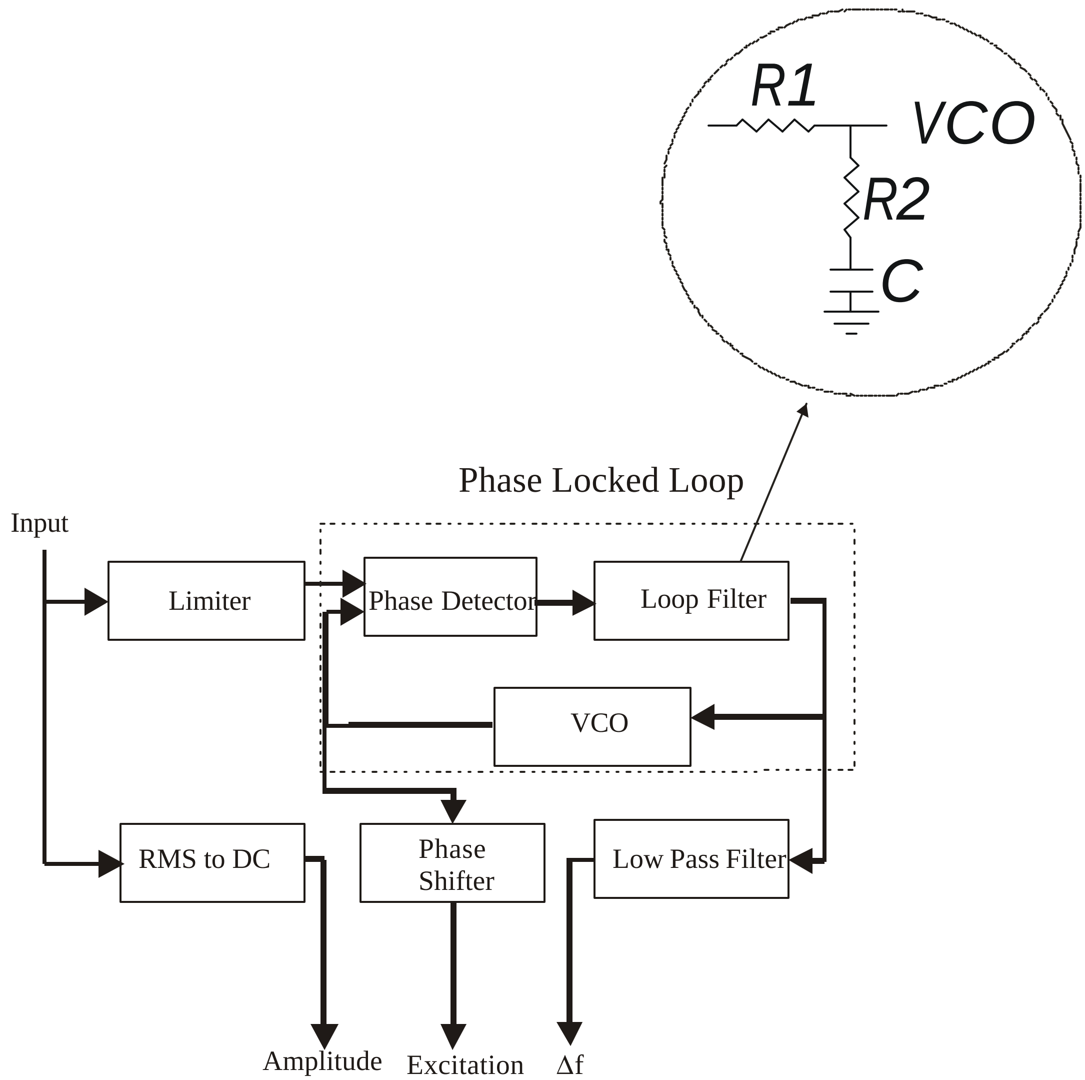
TiC(100)

Simple FM Oscillator



Phase Locked Oscillator



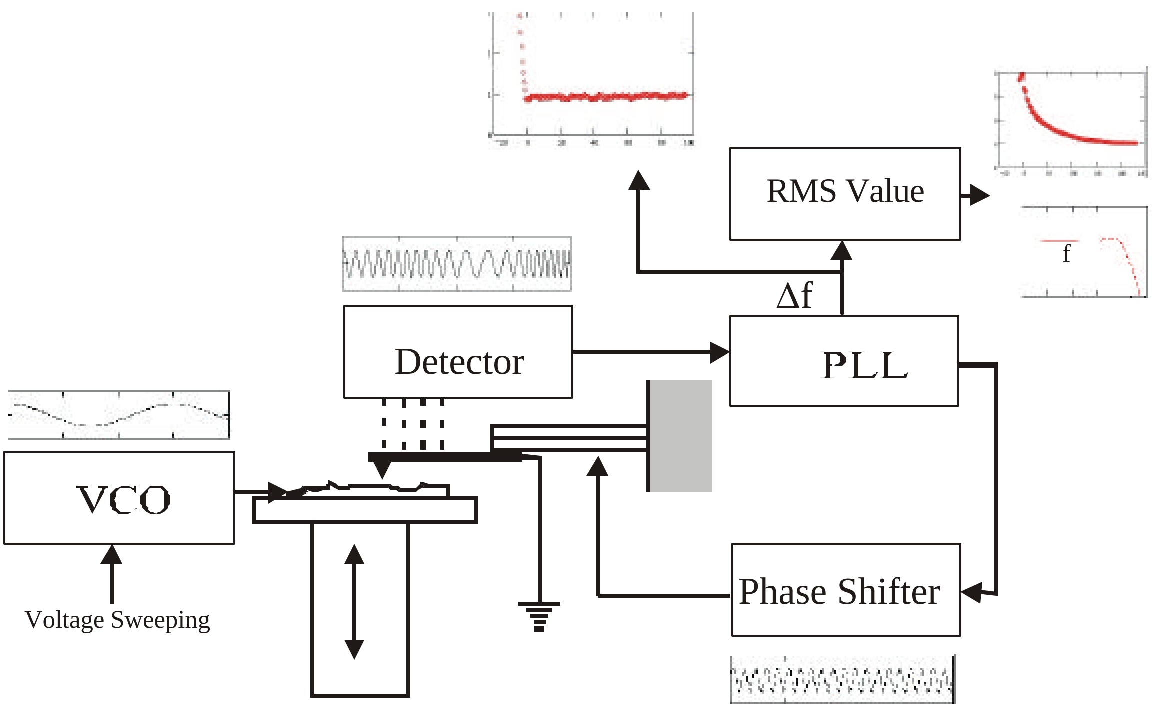


Phase Locked Loop Transfer Function

$$H(j\omega) = \frac{j\omega\omega_n(2\varsigma - \omega_n / K_o K_d) + \omega_n^2}{-\omega^2 + 2j\varsigma\omega_n\omega + \omega_n^2}$$

$$\omega_n = \sqrt{\frac{K_o K_d}{\tau_1 + \tau_2}} \qquad \zeta = \frac{1}{2}\sqrt{\frac{K_o K_d}{\tau_1 + \tau_2}}\left(\tau_2 + \frac{1}{K_o K_d}\right)$$

Experimental Setup



$$F_c(z) = \frac{1}{4}\frac{\partial C(z)}{\partial z} V_{ac}^2 (1 - \cos(2\Omega \cdot t))$$

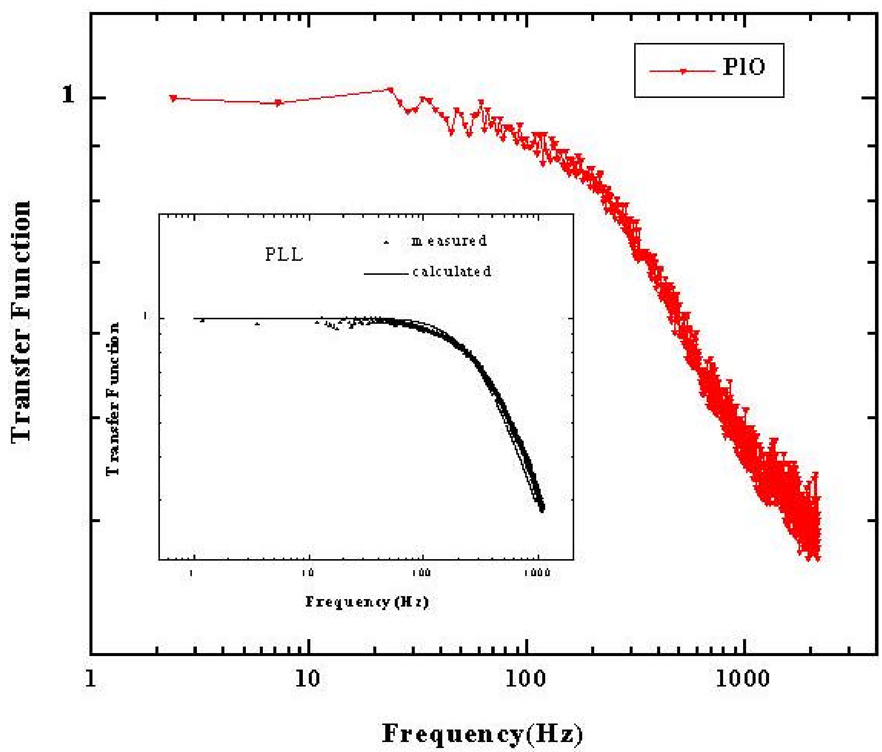
Characterization of Phase Locked Oscillator

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

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

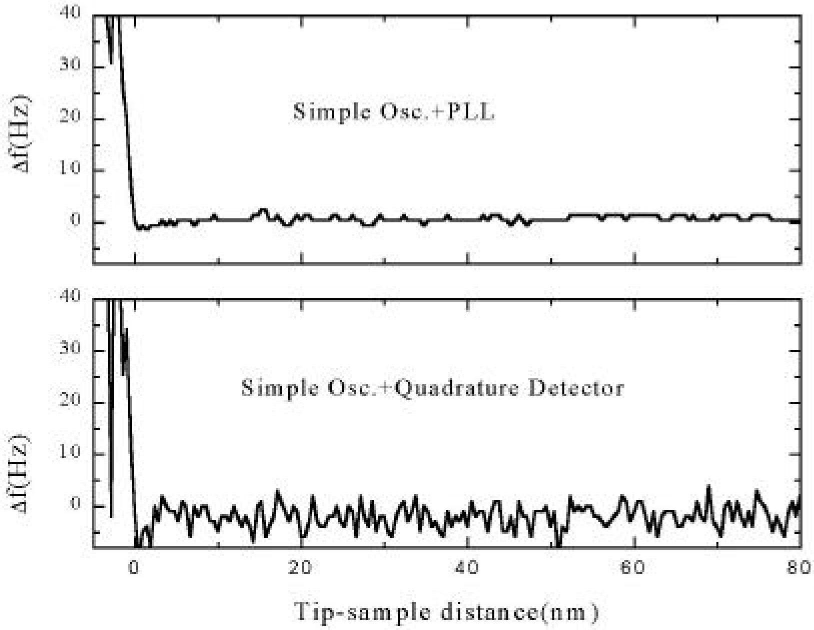
-Natural frequency w_n=2p×360rad/sec

-Damping constant z=1.02.

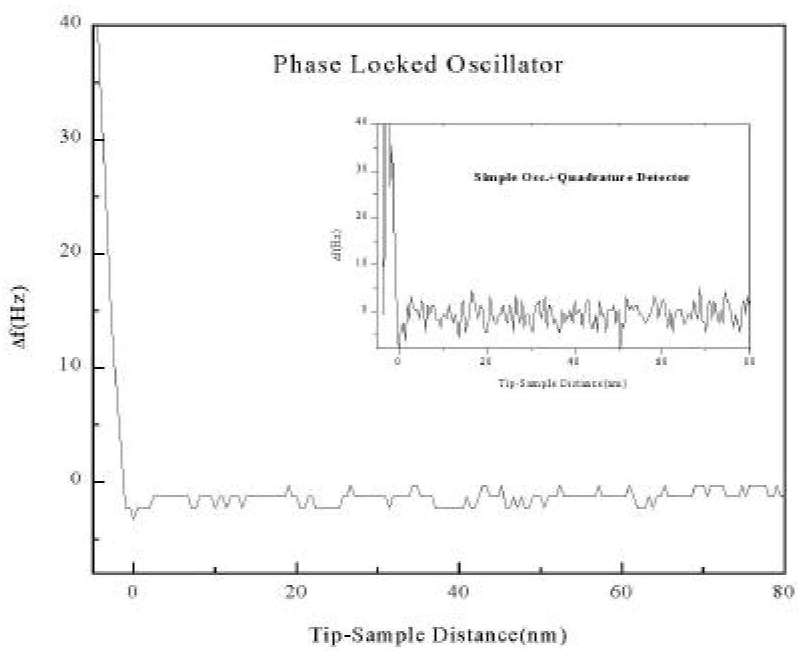


Δf-distance curve on the cleaned VC(100)

-noise level **(Df)rms ~ 5Hz for Omicron system**
-noise level (Df)$_{rms}$ £ 1Hz for PLL demodulator
cf)atomic corrugation ~2-3*Hz*



- **noise level (Df)$_{rms}$ £ 1Hz for PLL demodulator**
- **well-defined value of the measured Df-d in repulsive tapping regime**



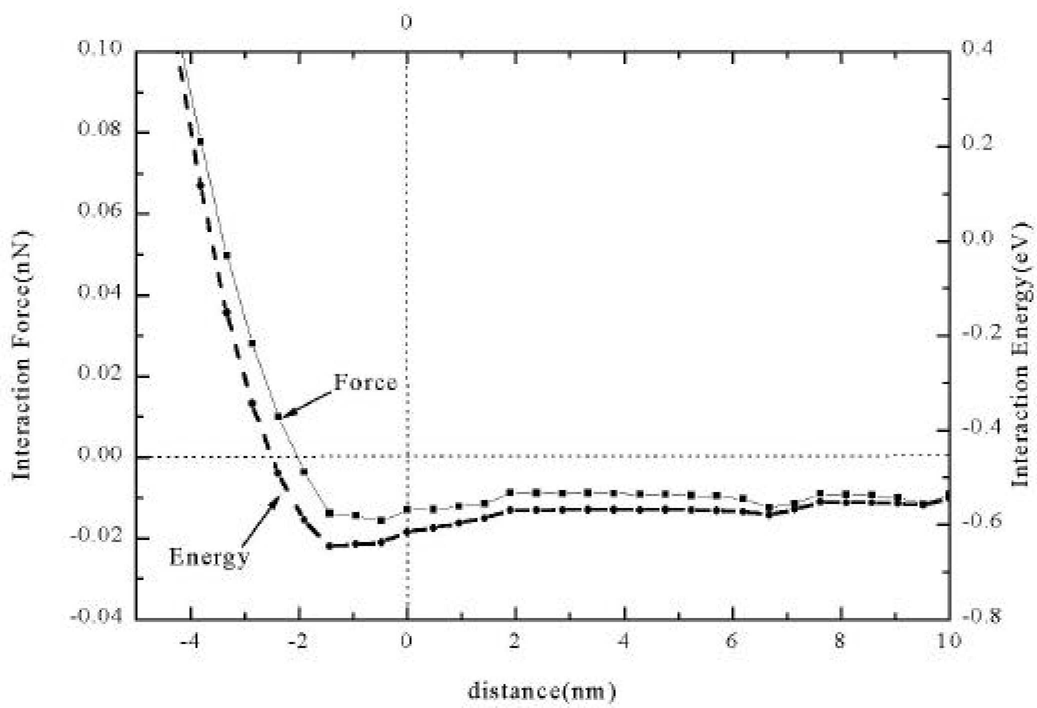
Indirect Extraction of Interaction Force and Interaction Energy from Df-d Curve.

U. Dürig, Appl. Phys. Lett, 75, 435(1999)

$$F_{\text{int}}(x\lambda) = \frac{2k}{f_0}\frac{a^{3/2}}{\sqrt{2}\lambda^{1/2}}\int_z^{\infty}\frac{\frac{d}{dV}\Delta f(z\lambda)}{\sqrt{z-x}}dz$$

$$U_{\text{int}}(x\lambda) = \frac{2k}{f_0}\frac{a^{3/2}\lambda^{1/2}}{\sqrt{2}}\int_z^{\infty}\frac{\Delta f(z\lambda)}{\sqrt{z-x}}dz$$

-Numerical calculation with MathCad
-Interaction Force ~0.1nN near surface(cf. Si-Si ~ 10nN)
-Interaction Energy ~1.2eV(cf. Si-Si ~20-30eV)



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

Summary

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

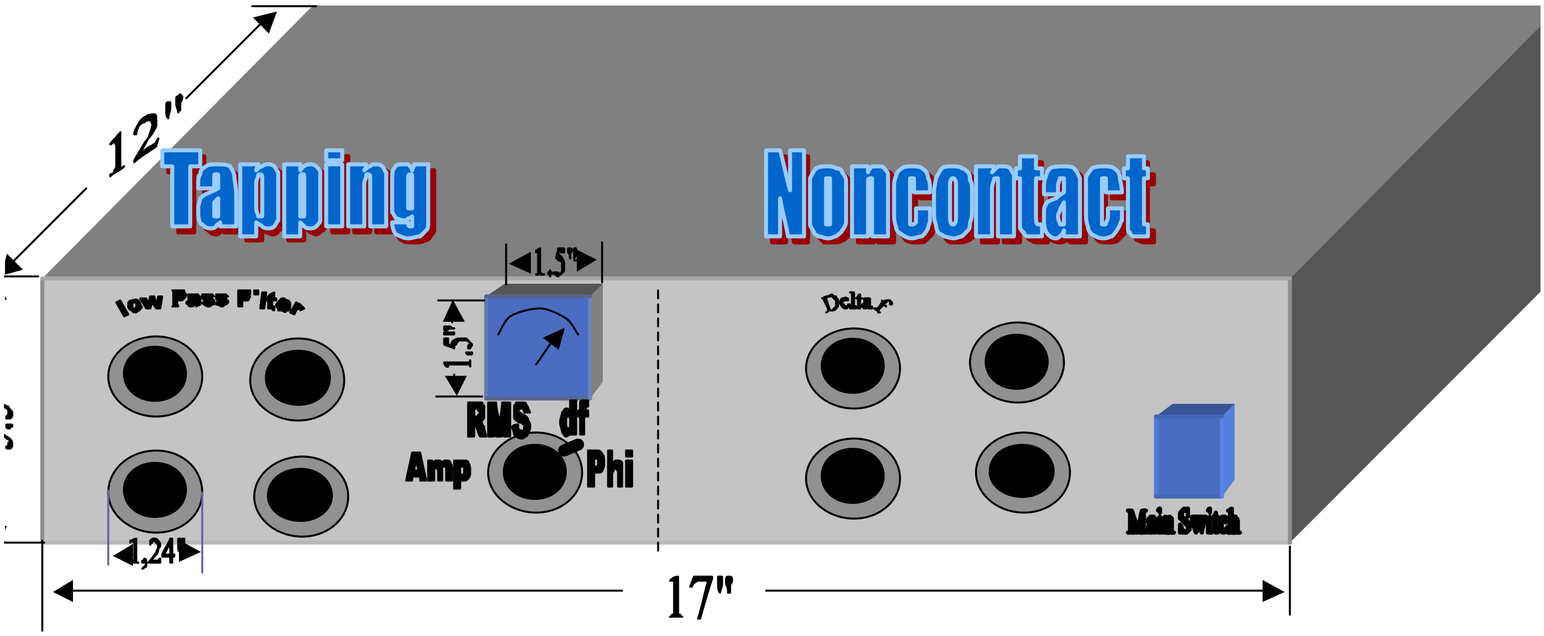
Conclusion

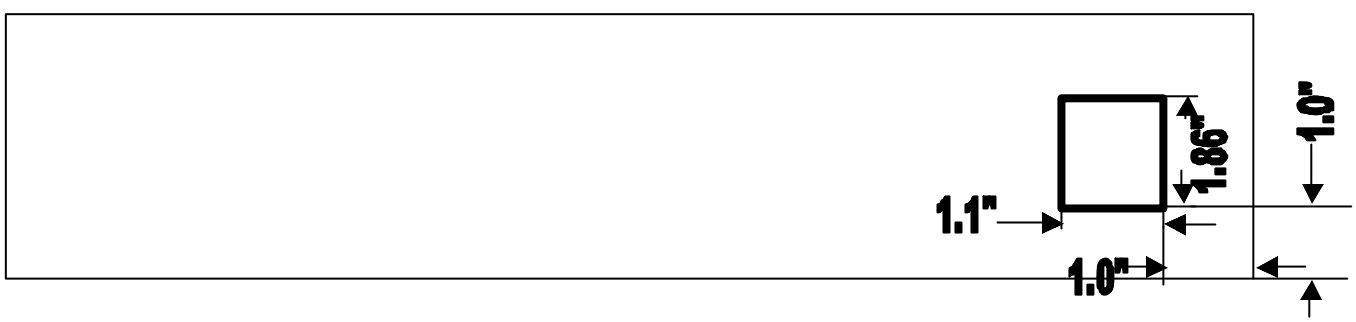
- The PLO method is an extremely effective way to excite sensors coherently with constant excitation voltage in the tapping regime.
- ***A Method for In-situ Characterization of Tip-shape Using Electrostatic Force Modulation***

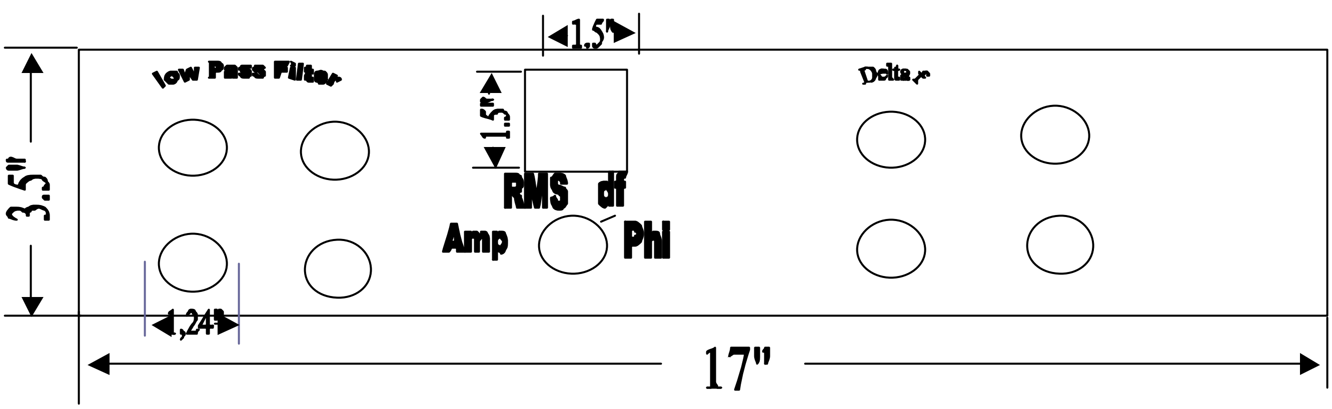
Next Step

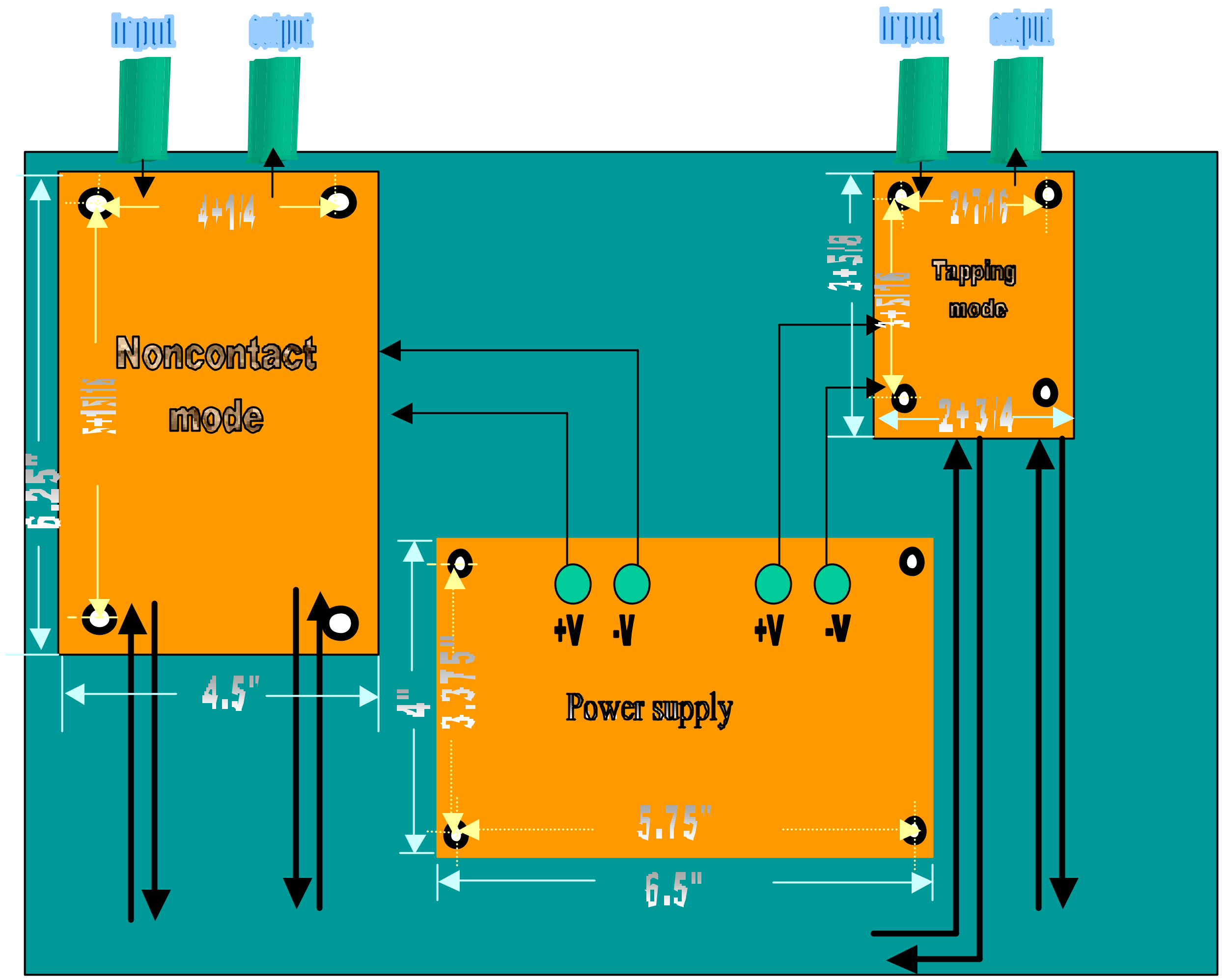
- Direct heating system

$\Rightarrow$Atomic Resolution of Si(111)


12"
Tapping
Noncontact
1.5"
low Pass Filter
1.5"
RMS
df
Amp
Phi
Delta
Main Switch
1,24"
17"


1.86"
1.0"
1.1"
1.0"


1.5"
3.5"
low Pass Filter
1.5"
Delta
RMS
df
Amp
Phi
1,24"
17"


input
output
input
output
4+1/4
Noncontact
mode
5+15/16
6.25"
4.5"
2+7/16
3+5/8
Tapping
mode
2+3/4
+V
-V
+V
-V
4"
3.375"
Power supply
5.75"
6.5"