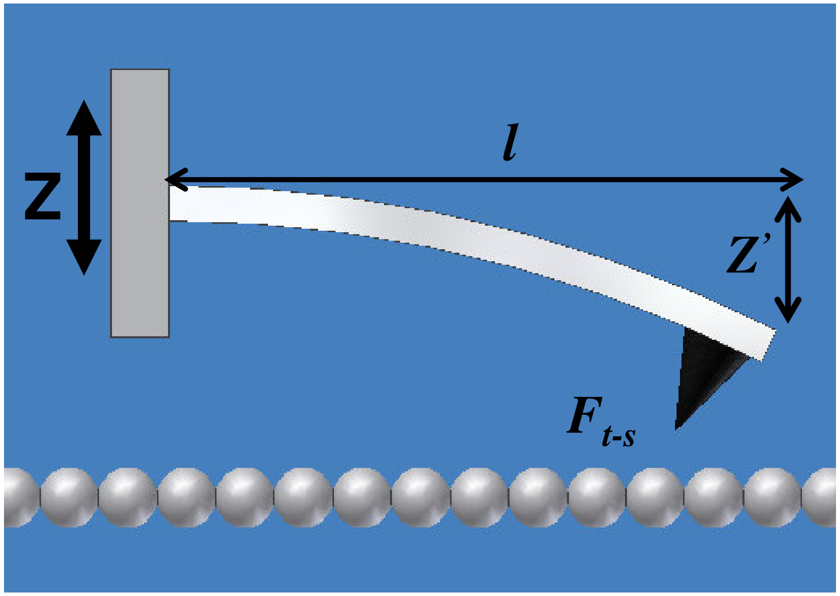
Tuning Fork
FM-AFM

AFM-Fundamental Concepts



Atomic Force Microscopy (AFM)

- Tip-surface interaction ($F_{t\text{-}s}$) causes deflection of cantilever
- Measure deflection (z')
  - STM
  - Optically
  - Self sensing
    - Piezoelectric
    - Piezoresistive
- Deflection proportional to tip-surface force (beam equation)

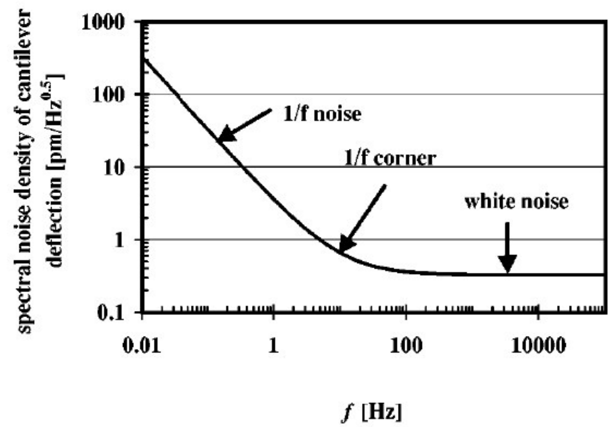
$$z' = -\frac{l^3}{3EI} F_{t-s}$$

- Scan across surface while adjusting Z

AFM-Classification

- Static
    - Measure deflection
    - Shown earlier
- Dynamic
    - Deliberately oscillate cantilever
    - Measure changes to amplitude, frequency, and/or phase caused by tip-sample interaction
  - Amplitude Modulation (AM)
    - Maintain driving frequency and driving amplitude
    - Measure cantilever amplitude changes
  - Frequency Modulation (FM)
    - Actively maintain cantilever amplitude
    - Measure cantilever frequency shift

Why FM-AFM?



- Static
  - *1/f* noise
  - Scan rate versus force sensitivity
    - Small k for high sensitivity
    - Large k for higher scan rate (bandwidth)

$$k = 3\frac{EI}{l^3} \Rightarrow z' = \left(\frac{1}{k}\right)F_{t-s}$$

$$f_0 = \frac{1}{2\pi}\sqrt{\frac{k}{m_{eff}}} \quad need\ f_0 >> (BW)$$

- Dynamic
  - Shift away from dc
  - AM-AFM
    - Slow transient decay
  - FM-AFM
    - Rapid change in natural frequency

$$\tau_{AM} \approx 2Q / f_0$$

$$\tau_{FM} \approx 1 / f_0$$

However, all offer atomic resolution

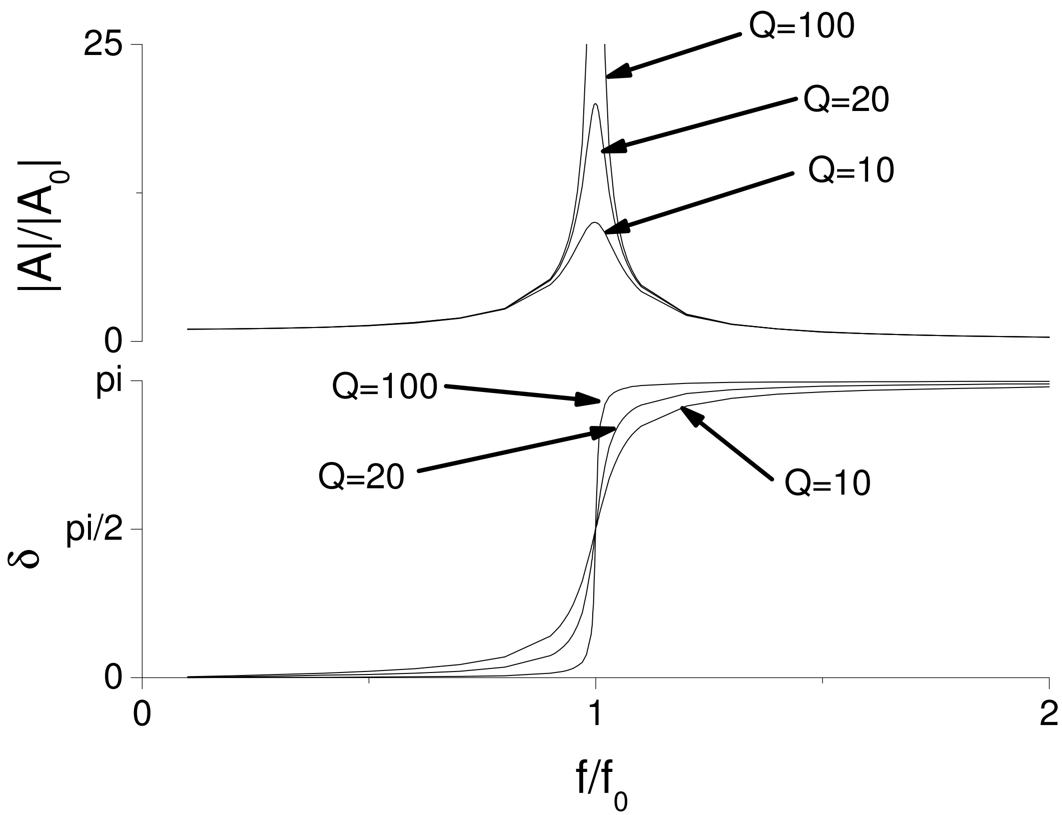
Cantilever Model

- Consider cantilever as damped, harmonic oscillator with sinusoidal driving force
- Phase, δ, is difference between driving force and resultant cantilever oscillation

$$\ddot{x} + 2\beta\dot{x} + \omega_0^2 x = A_{drive}\cos(\omega t)$$

$$|A| = \frac{|A_{drive}|}{\sqrt{(1 - f_{drive}^2 / f_0^2) + f_{drive}^2 / (f_0^2 Q)}}$$

$$\delta = \tan^{-1}\left(\frac{f_{drive}}{Qf_0(1 - f_{drive}^2 / f_0^2)}\right)$$



Tip-Surface Interaction

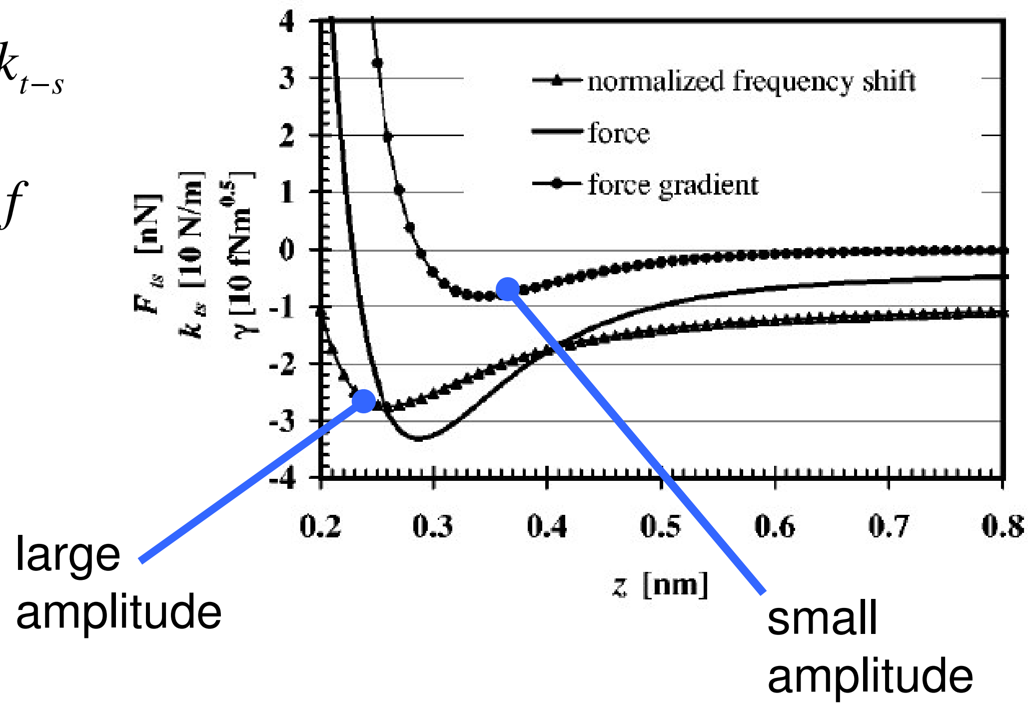
- Cause of tip-sample force, F_{ts},
  - Van der Waal
  - Chemical
  - Electrostatic
- Force between tip and sample causes a change in the natural frequency

$$k_{t-s} = -\partial F_{t-s} / \partial z \rightarrow k^* = k + k_{t-s}$$

$$f = \frac{1}{2\pi}\sqrt{\frac{k^*}{m_{eff}}} \rightarrow f = f_0 + \Delta f$$

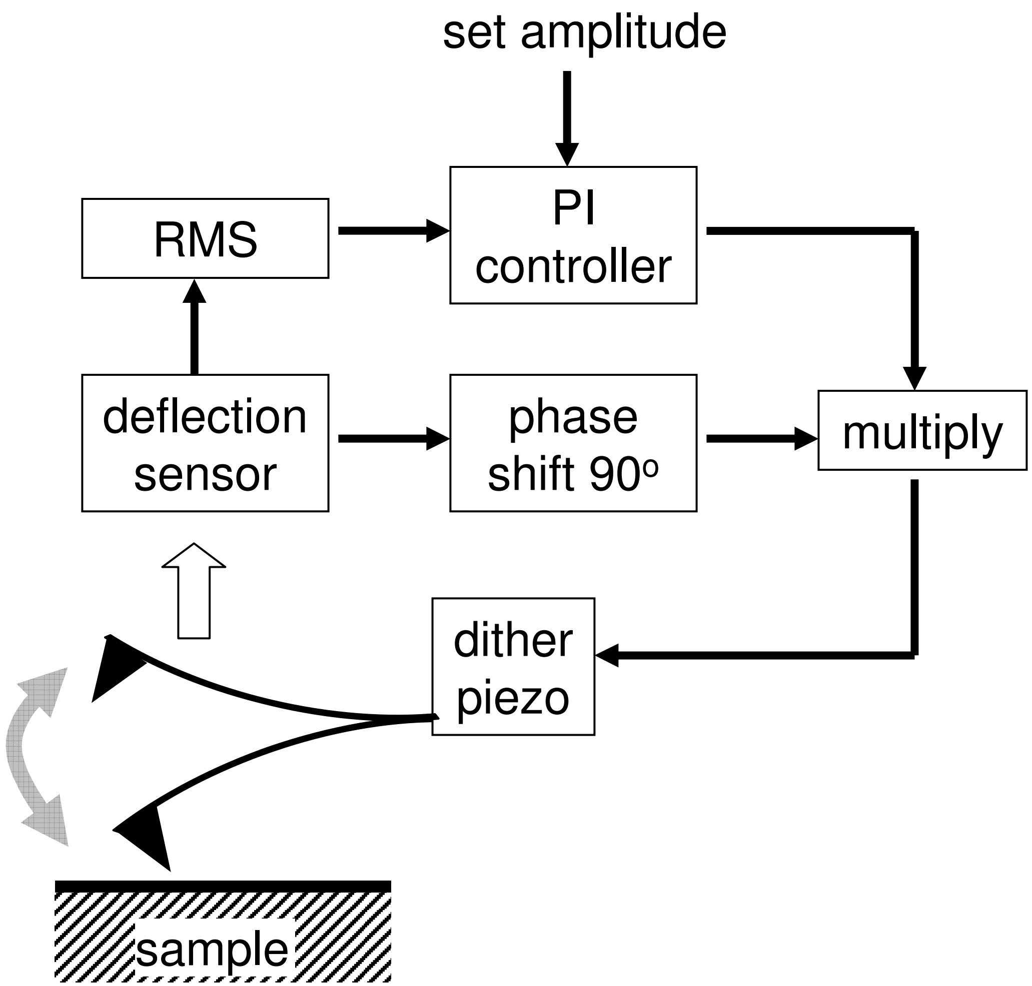
$$\Delta f = -\frac{f_0}{kA^2}\langle F_{t-s} q' \rangle$$

$$\gamma \equiv \frac{kA^{3/2}}{f_0} \Delta f$$

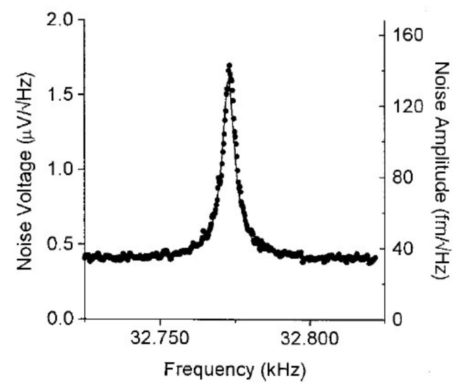


Experimental Set-Up

Mechanical Excitation



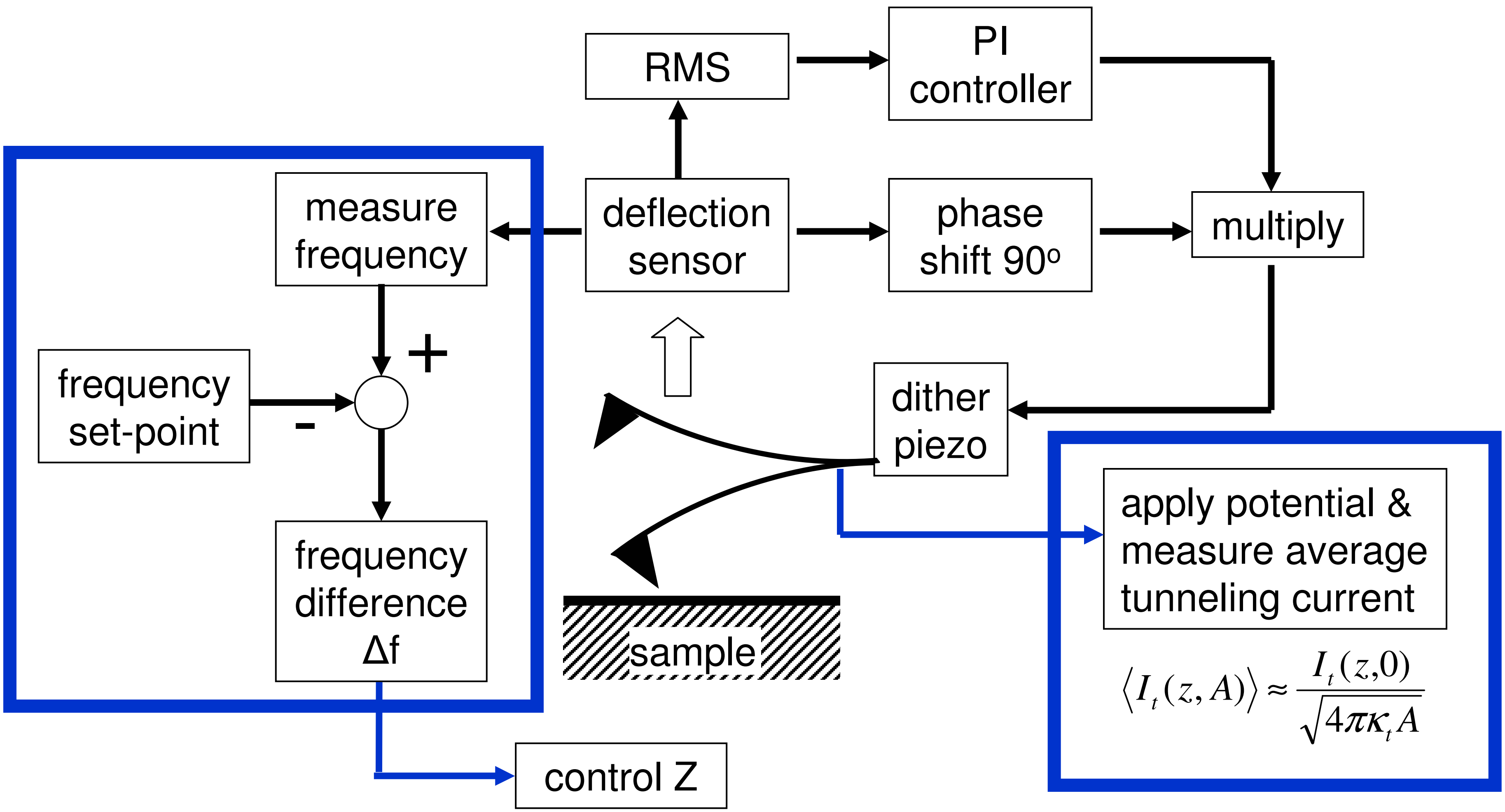
But what gets it started?



$$\frac{1}{2}k\left\langle z_{th}^{2}\right\rangle = \frac{1}{2}k_{b}T$$

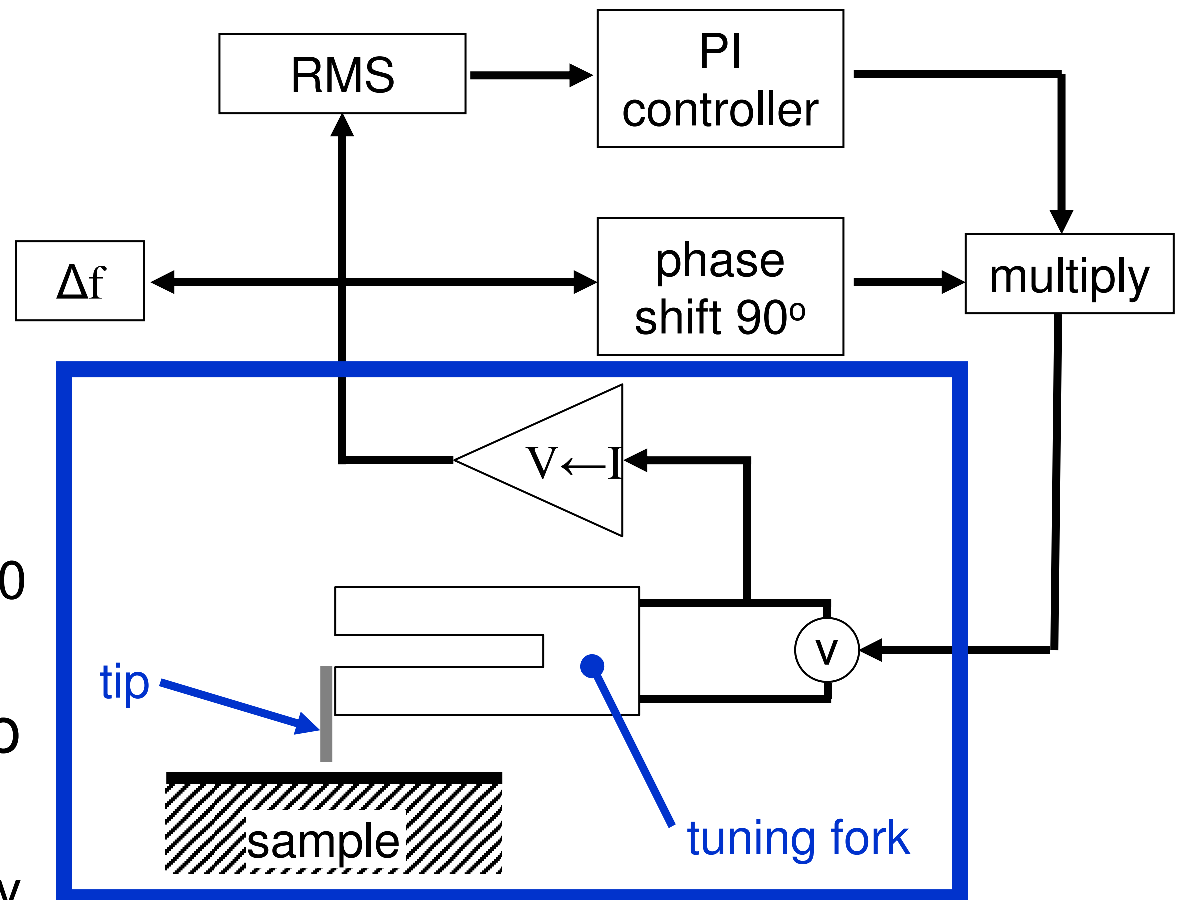
Experimental Set-Up

Mechanical Excitation



Experimental Set-Up

Tuning Fork & Electrical Excitation



EE eliminates:

- dither piezo
- deflection sensor

TF enhances:

- Q from ~100→ ~10,000 (S/N increases)

Quartz vs. other piezo

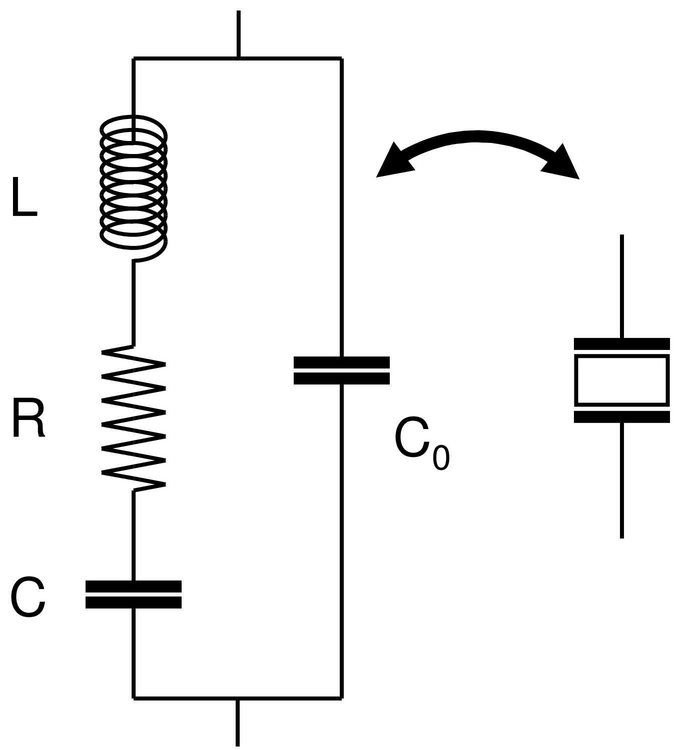
- Low dissipation
- High-frequency stability

Experimental Set-Up

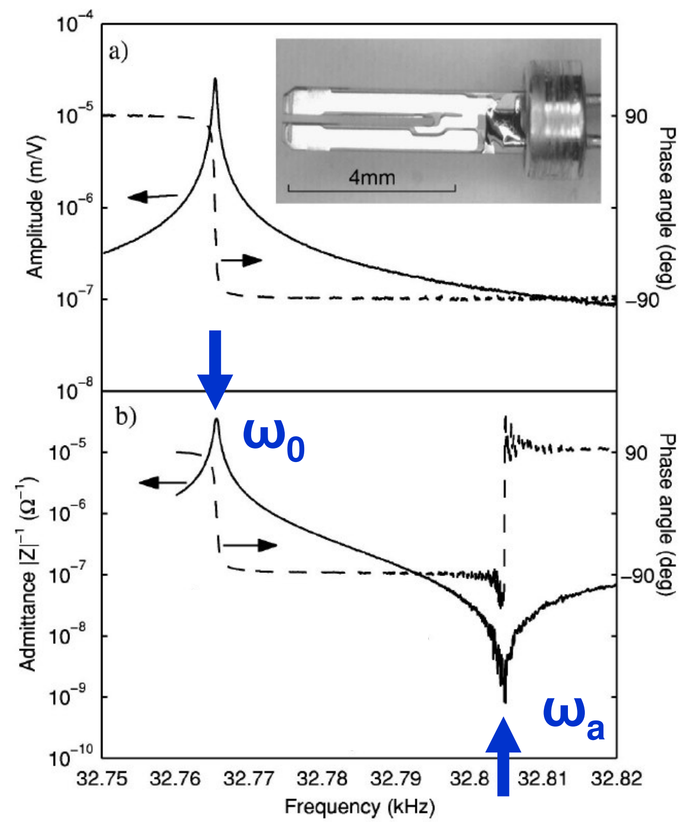
Electrical Excitation

equivalent circuit

tuning fork



L=8.1e3H, R=27kΩ, C=2.9fF, C_0=1.2pF

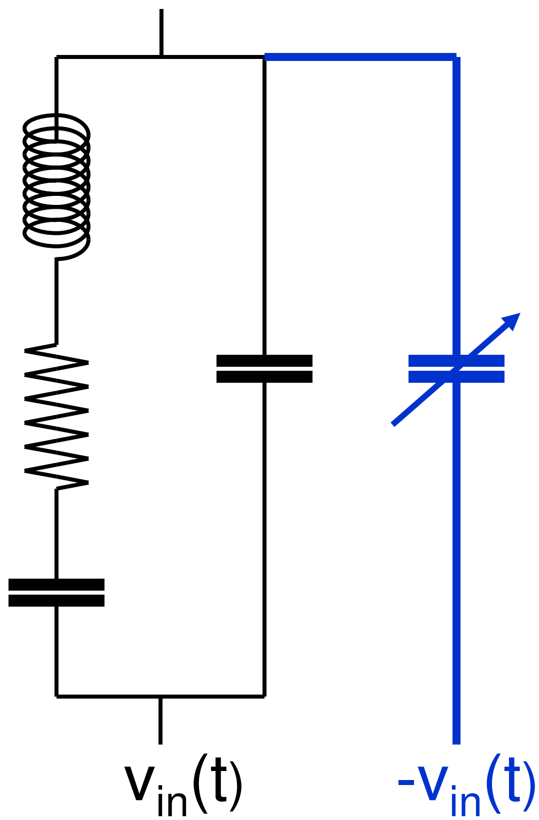


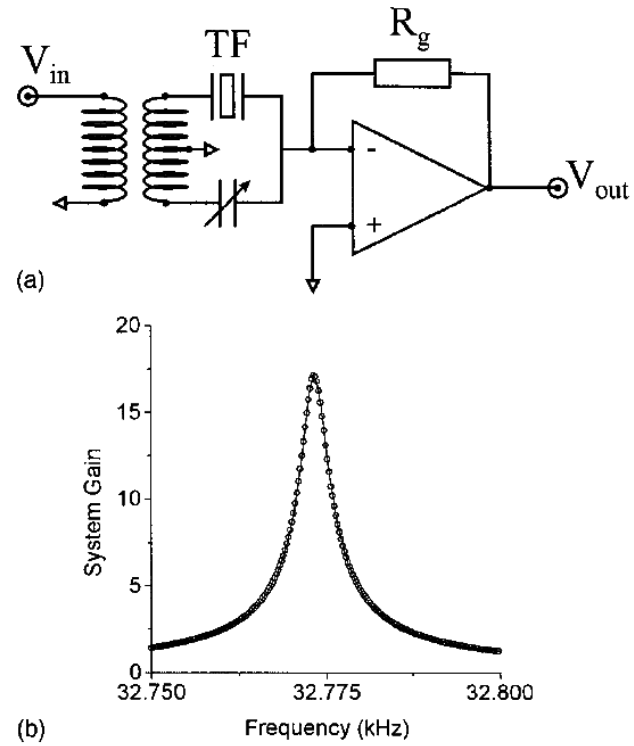
$$\omega_0 = 1/\sqrt{LC}$$

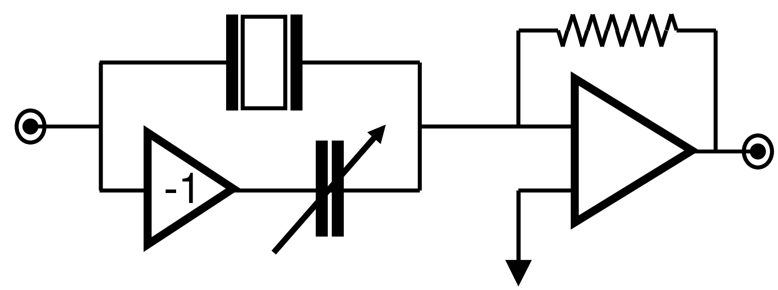
$$\omega_a = \omega_0\sqrt{1 + C/C_0}$$

Experimental Set-Up

Electrical Excitation

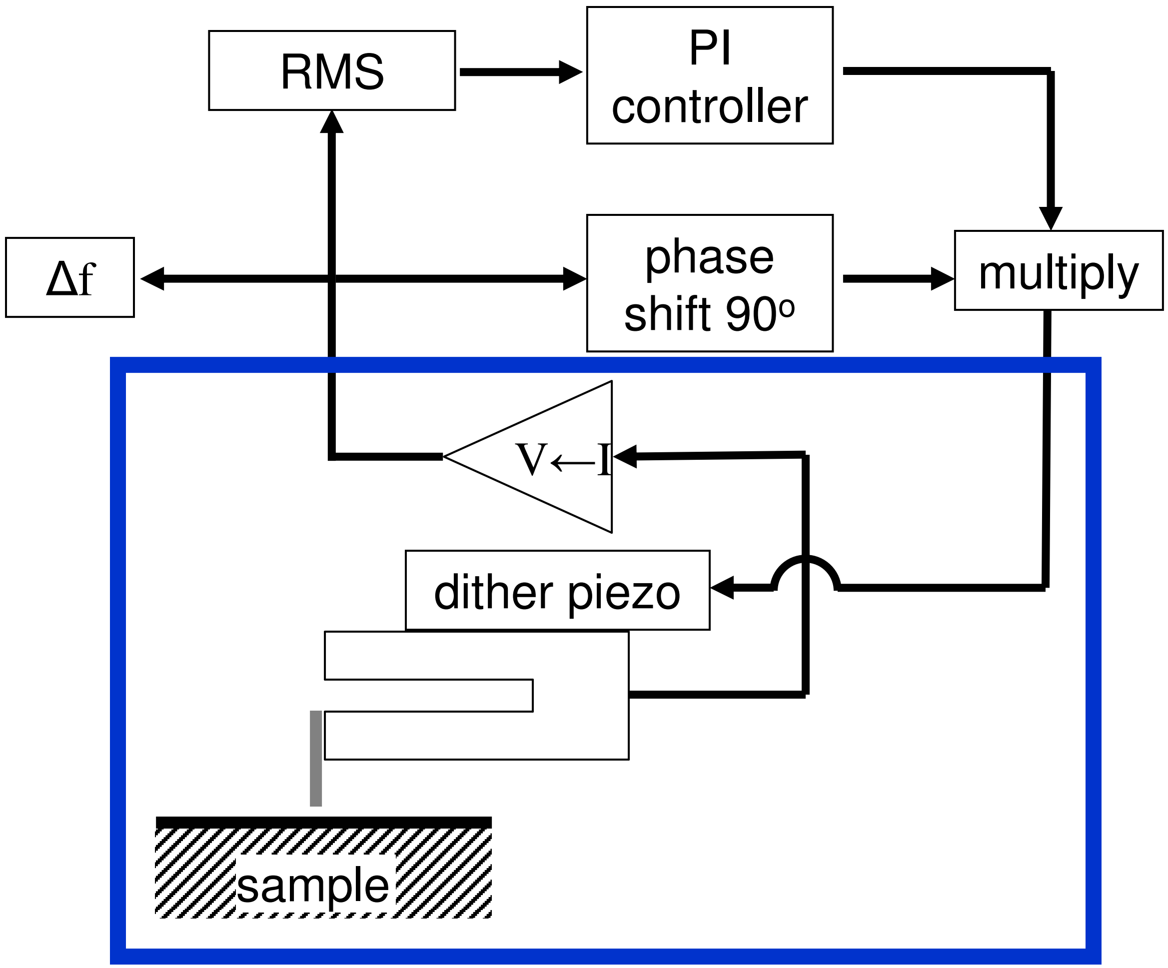






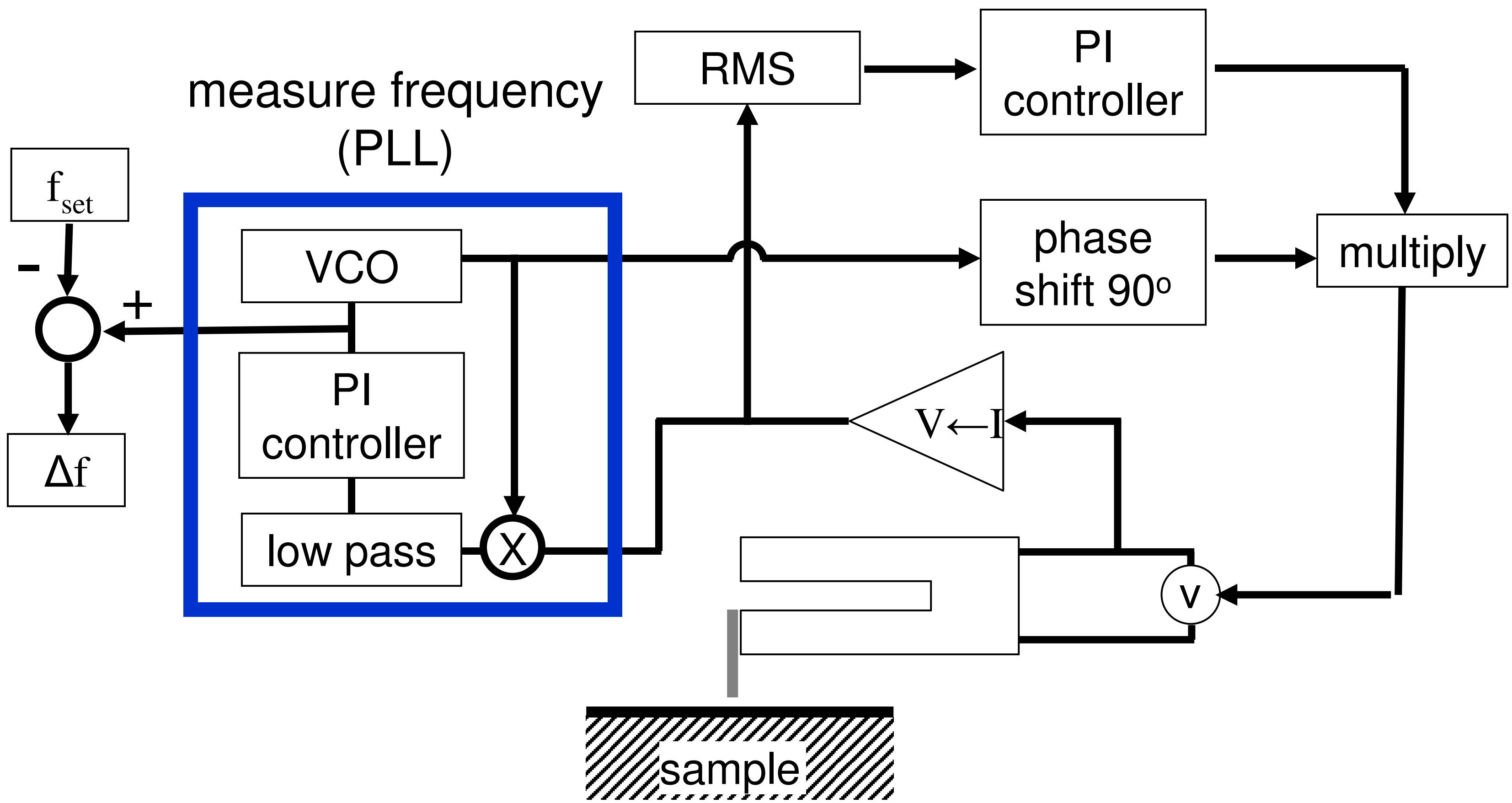
Experimental Set-Up

Tuning Fork & Mechanical Excitation



Experimental Set-Up

Electrical Excitation-Variation

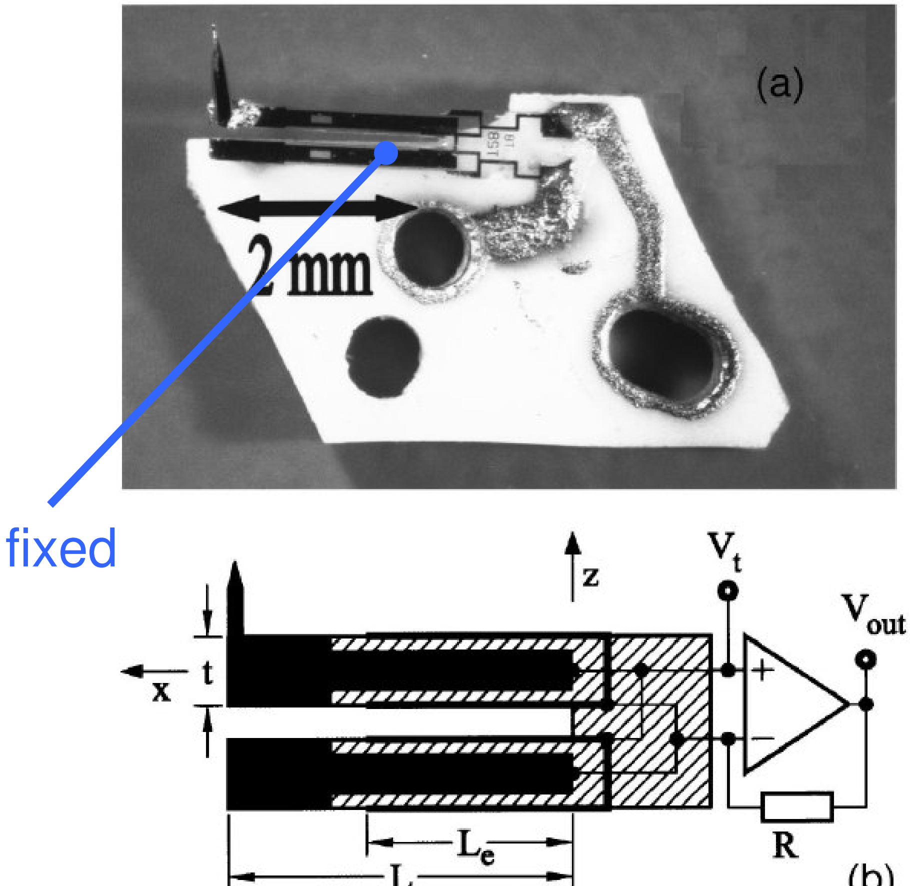


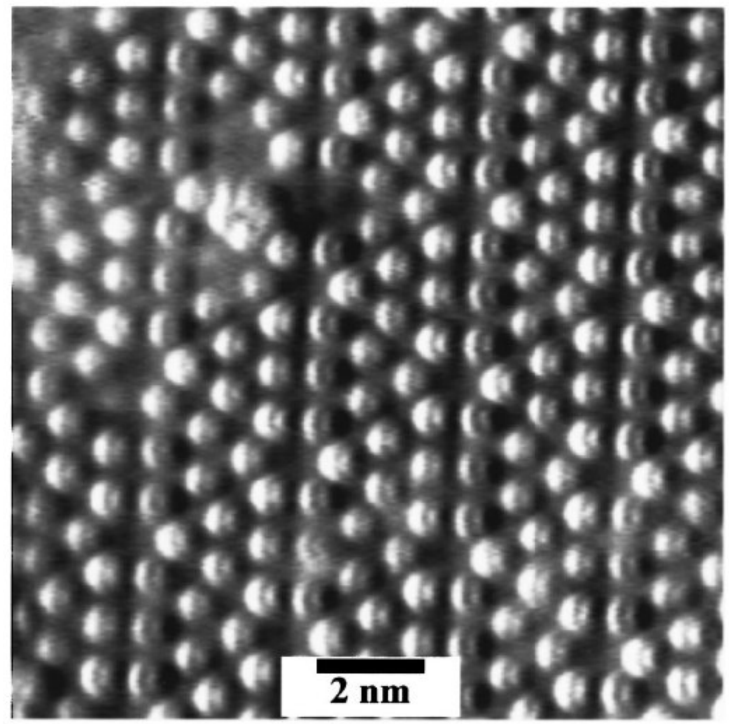
Tuning Fork
Mechanical vs. Electrical

- Mechanical
  - simpler electronics
  - marginally improved S/N
- Electrical
  - no dither piezo
  - eliminate one gluing step

Mechanical Excitation

Atomic Resolution





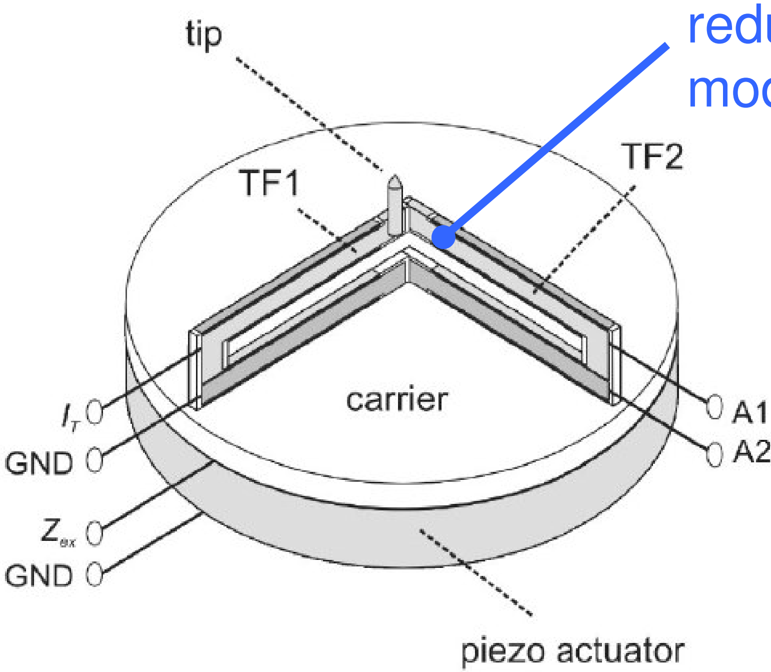
Si(111)-(7x7)

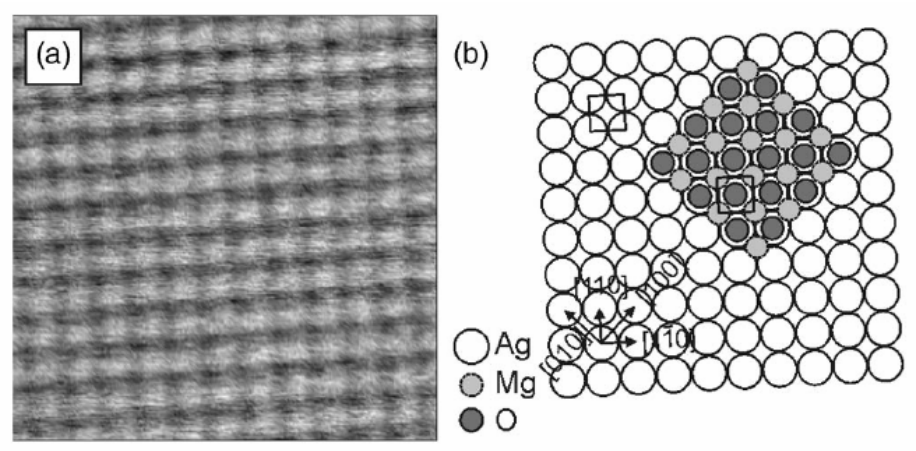
Giessibl FJ APPLIED PHYSICS LETTERS 76 (11): 1470-1472 MAR 13 2000

Mechanical Excitation

Atomic Resolution

reduce parallel & torsion modes



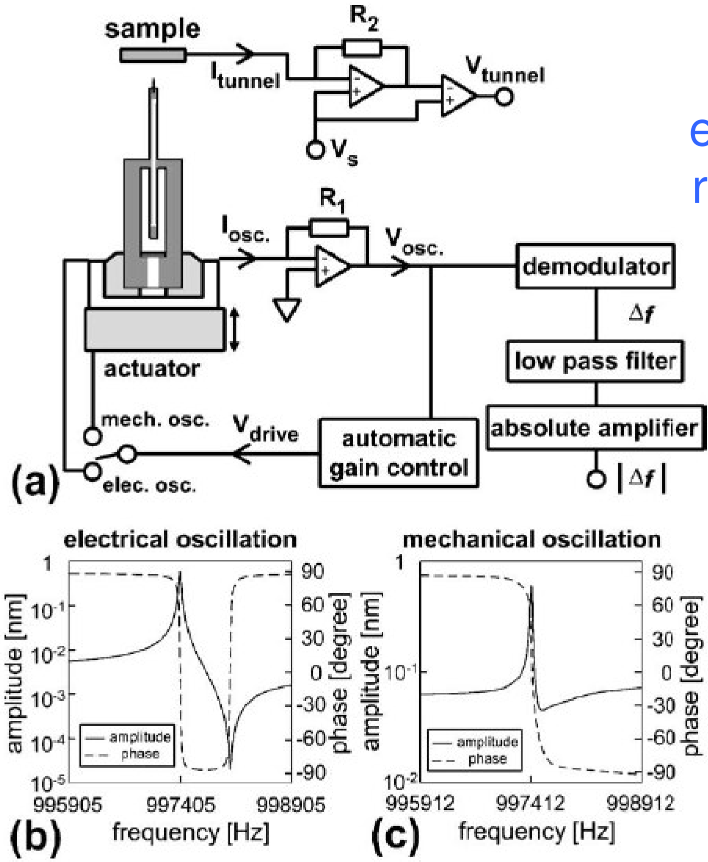


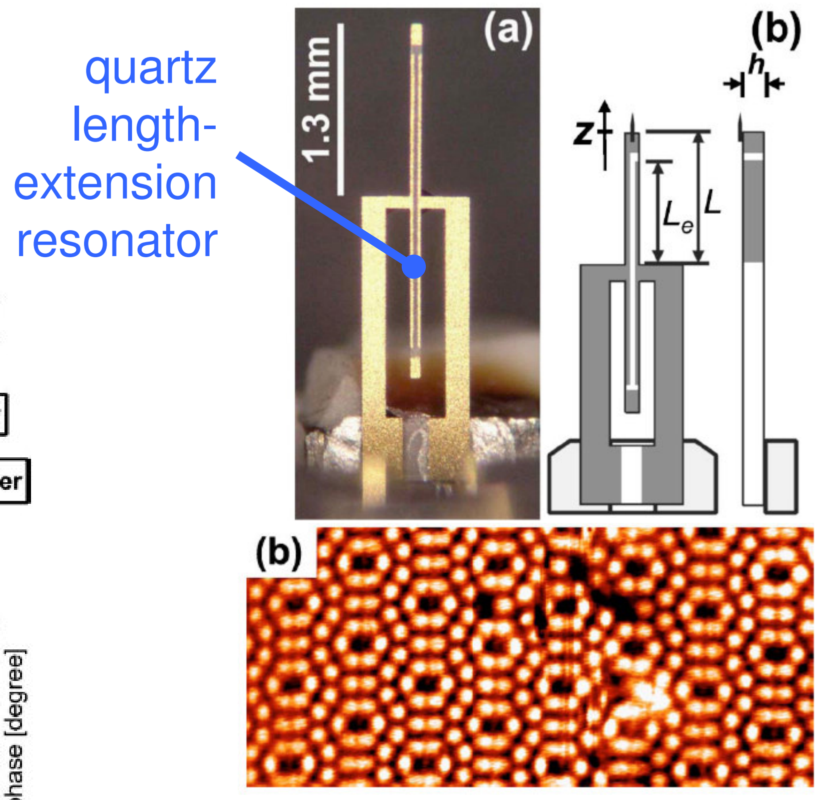
MgO on Ag(001)

Heyde M, Sterrer M, Rust HP, et al. APPLIED PHYSICS LETTERS 87, 083104 2005

Electrical Excitation

Atomic Resolution





Si(111)-(7x7)

An TS, Eguchi T, Akiyama K, et al. APPLIED PHYSICS LETTERS 87, 133114 2005

References

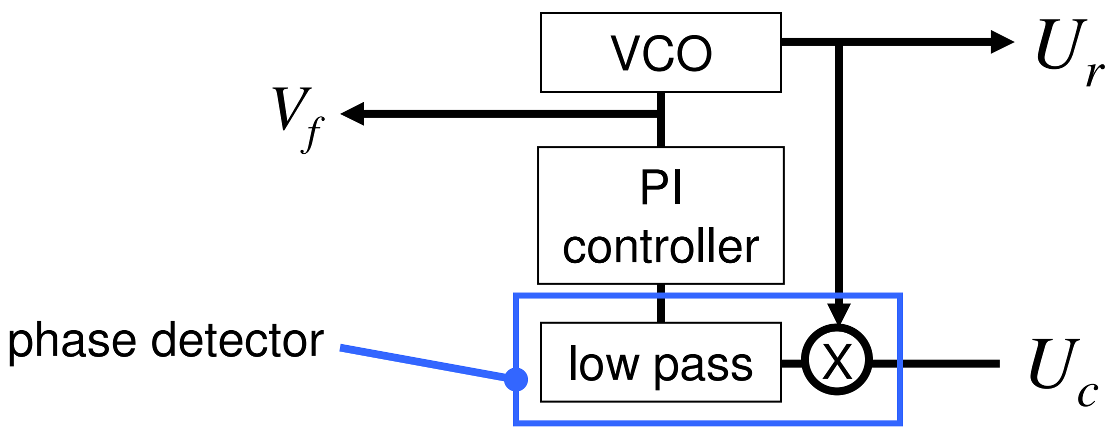
Giessibl, F.J. Rev. Mod. Phys., Vol. 75, No. 3, July 2003

Rychen, J., *et al.*, Rev. Sci. Instrum., Vol. 71, No. 4, April 2000

Loppacher, Ch., *et al.*, Appl. Phys. A 66, S215-218 (1998)

Phase Locked Loop

Details



$$U_c = \hat{U}_c \sin(\omega_c t + \varphi_c)\,; \quad U_r = \hat{U}_r \cos(\omega_r t + \varphi_r)$$

$$U_c U_r = \frac{\hat{U}_c \hat{U}_r}{2}\left[\sin((\omega_c - \omega_r)t + (\varphi_c - \varphi_r)) + \sin((\omega_c + \omega_r)t + (\varphi_c + \varphi_r))\right]$$

$$\text{locked PLL} \Rightarrow \omega_c - \omega_r = 0 \,\&\, \text{low - pass filter}$$

$$U_c U_r \cong \frac{\hat{U}_c \hat{U}_r}{2} \sin(\varphi_c - \varphi_r) \cong K_d \Delta\varphi$$