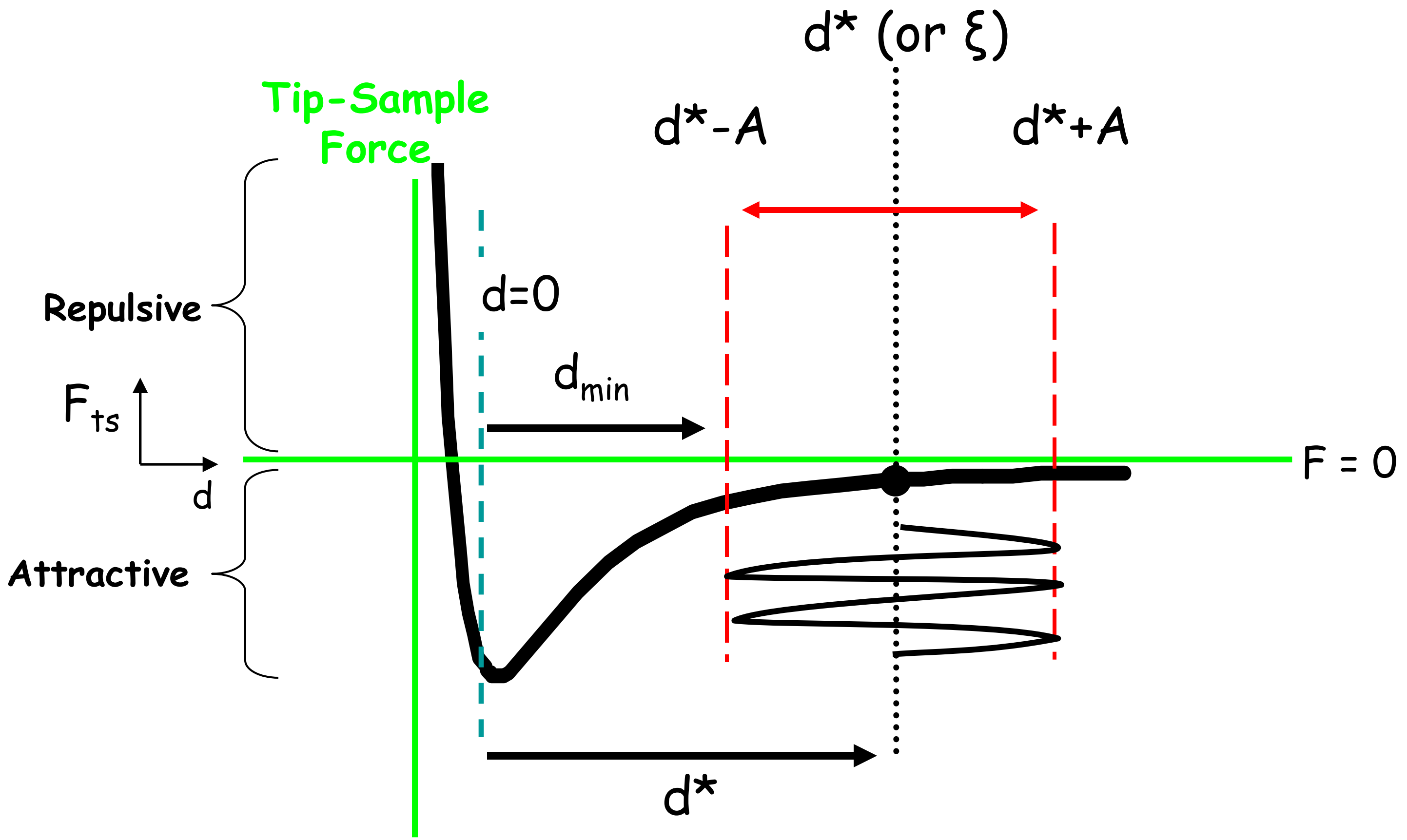
ME597/PHYS57000
Fall Semester 2009
Lecture 22

Frequency Modulated AFM
- Experimental Details -

Suggested Reading: F. Giessibl, Rev. Mod. Phys. **75**, 949 (2003)

Last Lecture

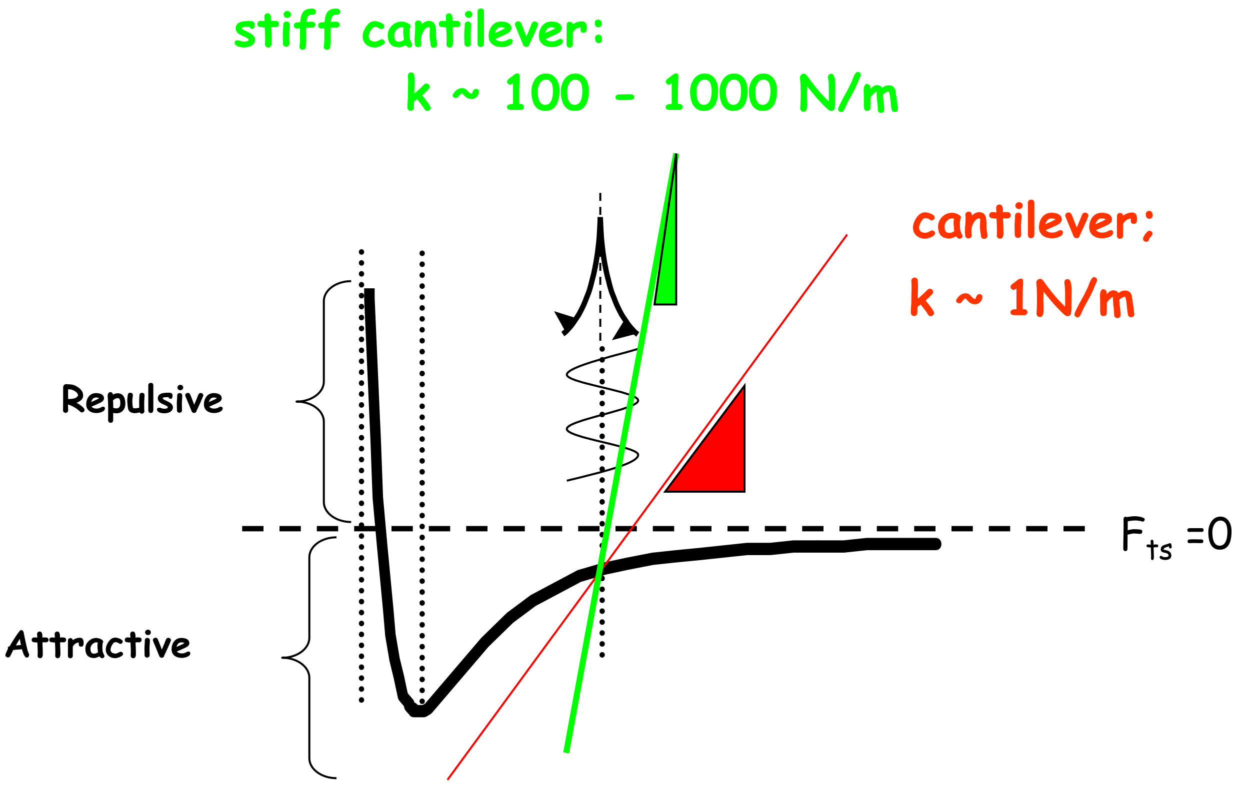


$$F_{ts}(d_{\min}) = 2k_c \int_{d_{\min}}^{\infty} \left\{ \left[1 + \frac{\sqrt{A}}{8\sqrt{\pi(\xi - d_{\min})}}\right] \Omega(\xi) - \frac{A^{3/2}}{\sqrt{2\,(\xi - d_{\min})}} \frac{d\Omega(\xi)}{d\xi} \right\} d\xi$$

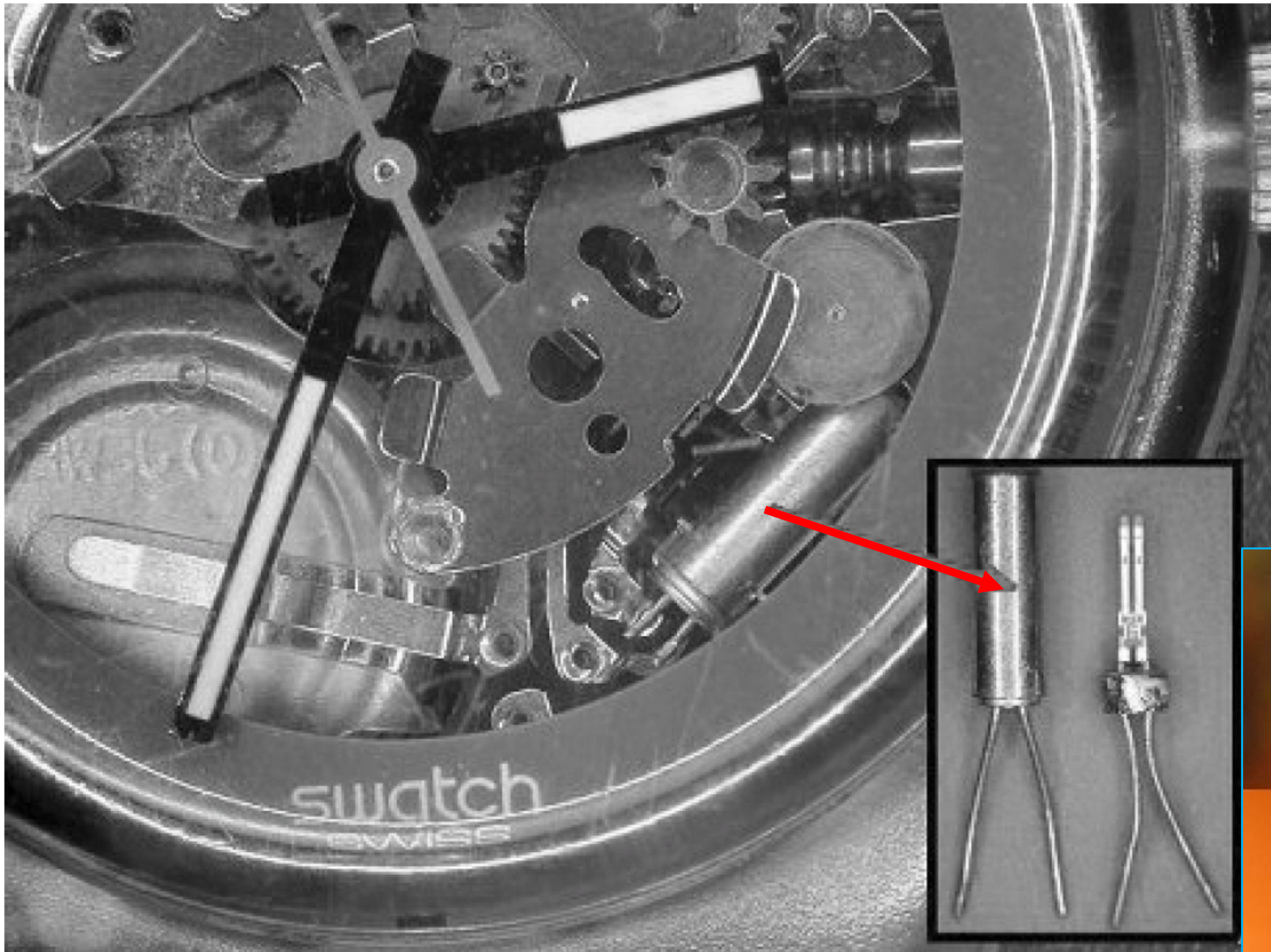
where $\Omega(\xi) \equiv \dfrac{\Delta f(\xi)}{f_o}$ $\qquad \xi \Leftrightarrow d^*$

What is Required?

- High stability
- Must measure small frequency shifts accurately
- Large spring constant to eliminate jump to contact

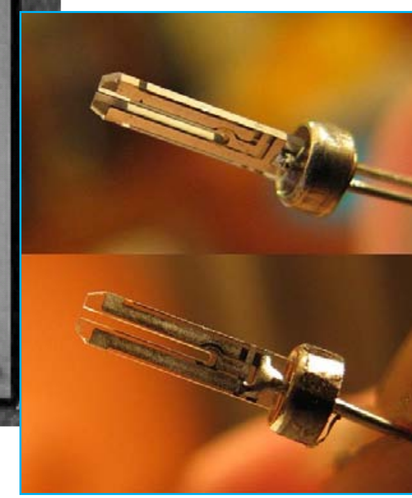


New Idea: Tuning Forks



Bulova
Accutron: 1960

Cost:
~0.25 USD



Source: wikipedia

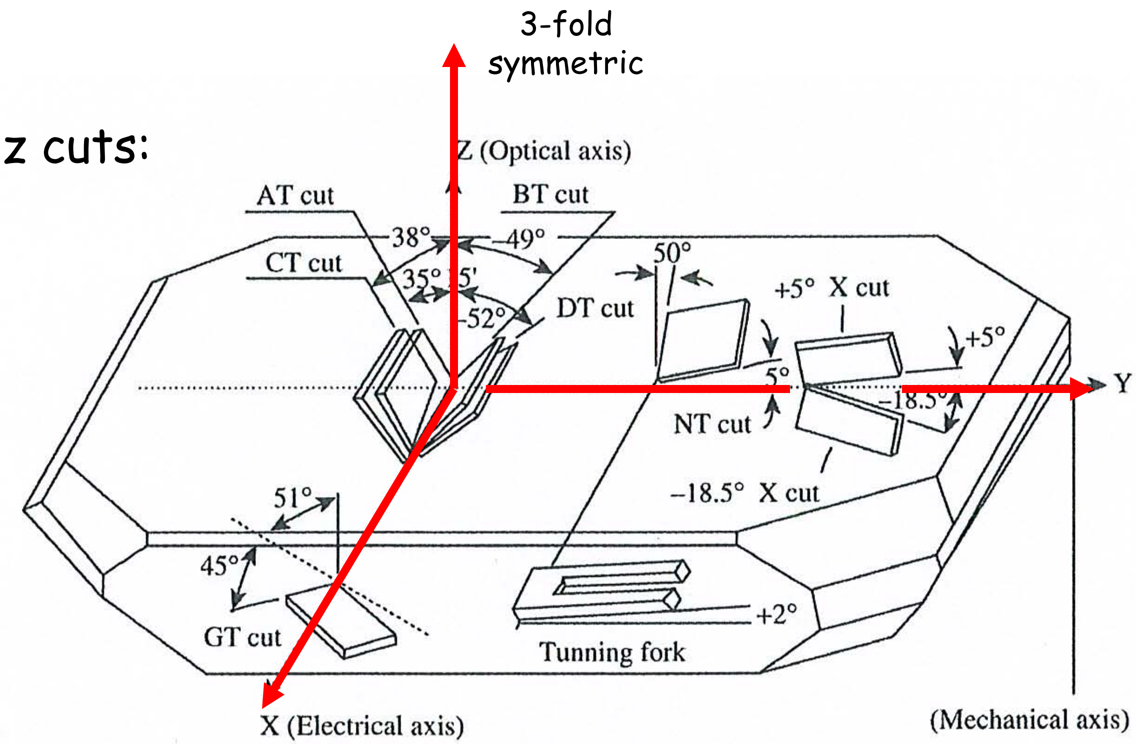
$$f_o = 2^N; \quad N = \text{integer}$$

$$f_o = 2^{15} = 32,768.0000\ Hz$$

Quartz: a piezoelectric material

(highly anisotropic crystalline SiO_2)

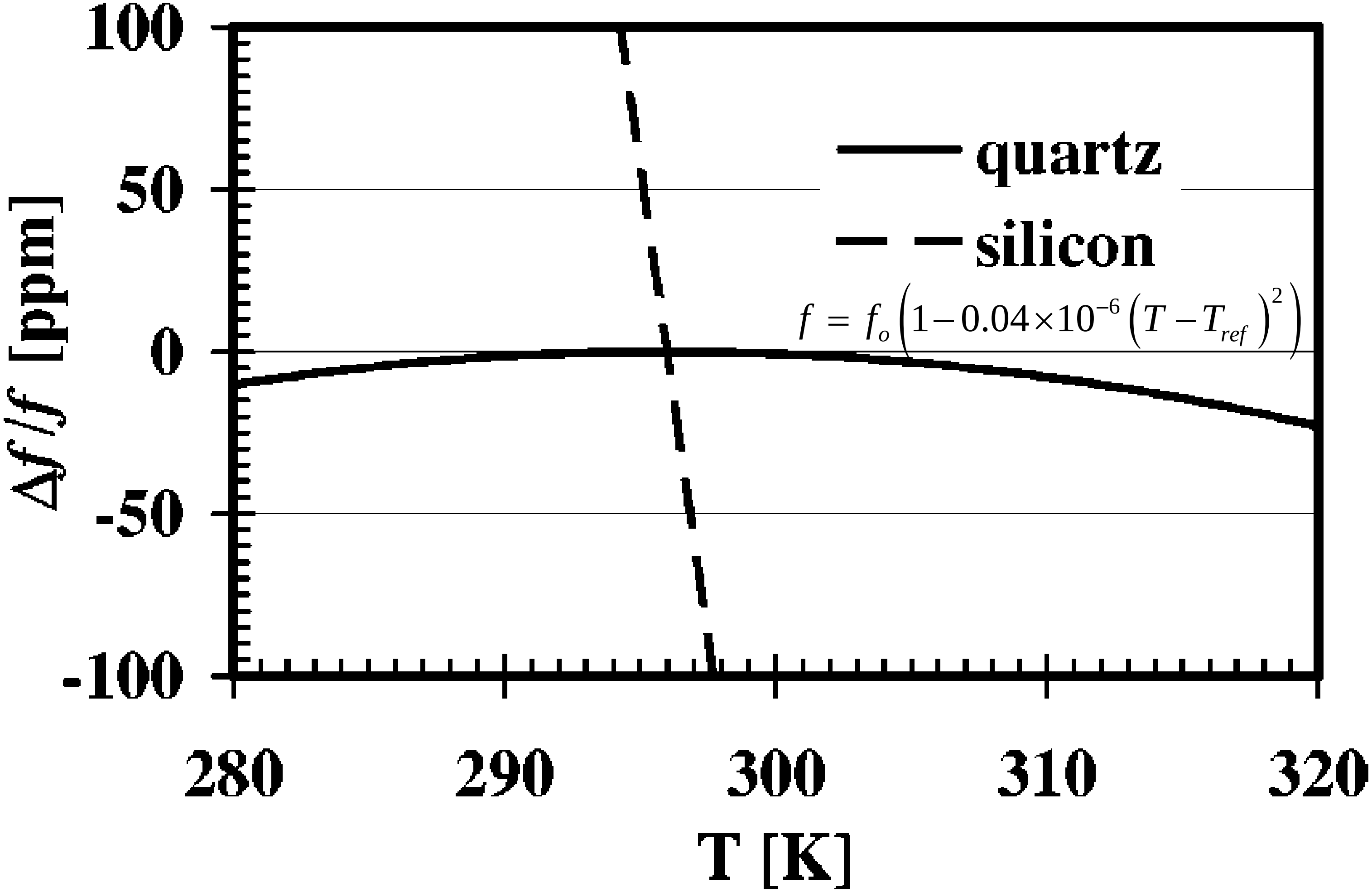
Standard quartz cuts:



Mechanical stress develops electric potential

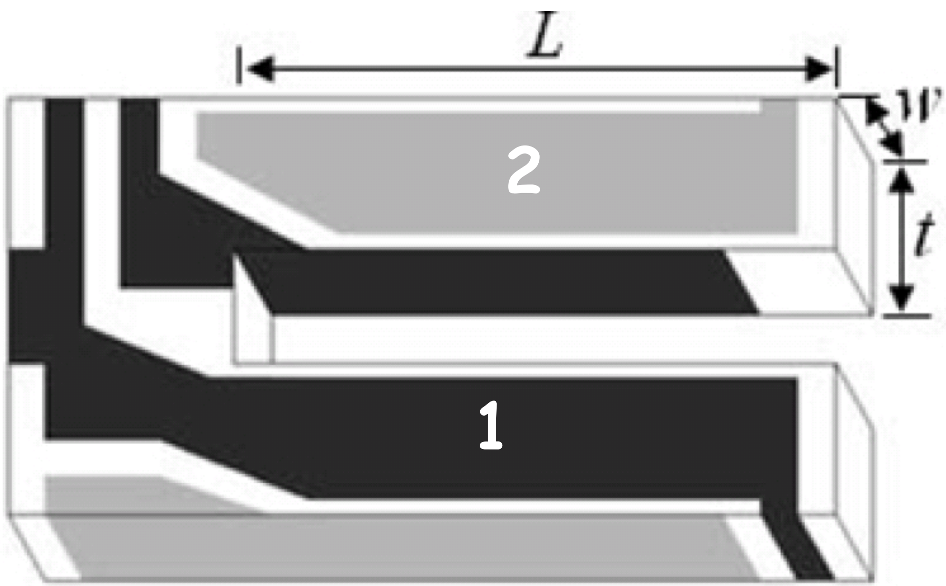
Introduction to Scanning Tunneling Microscopy, C. Julian Chen, Oxford University Press (2008).

Thermal stability of quartz compared to Si

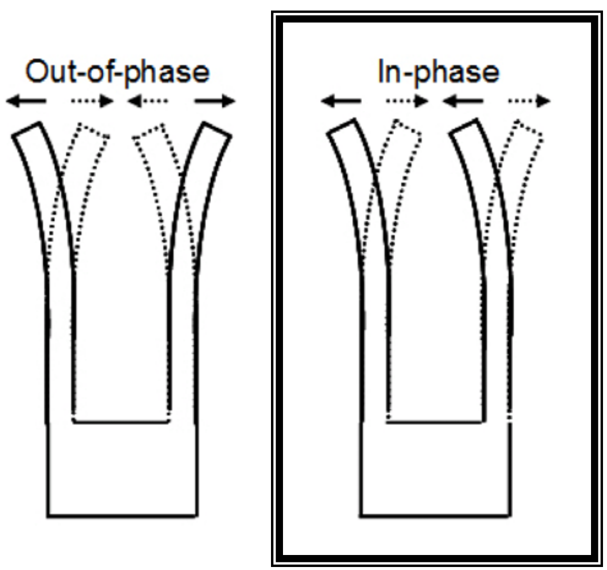


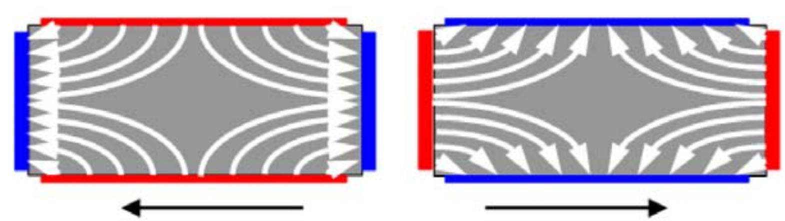
F. Giessibl, Rev. Mod. Phys. **75**, 949 (2003)

Electrode Geometry Selects Vibrational Mode

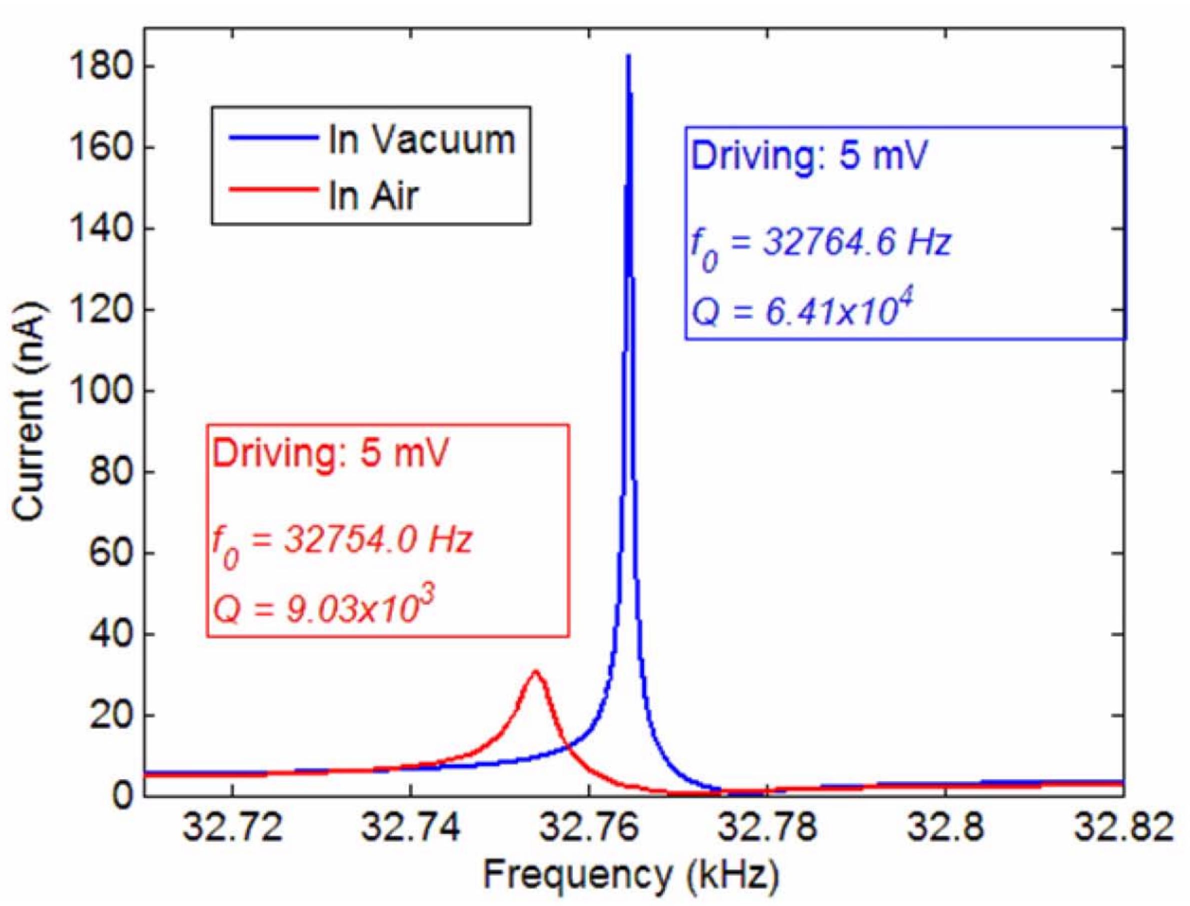


$$V_{12} = V_o \sin(\omega t)$$



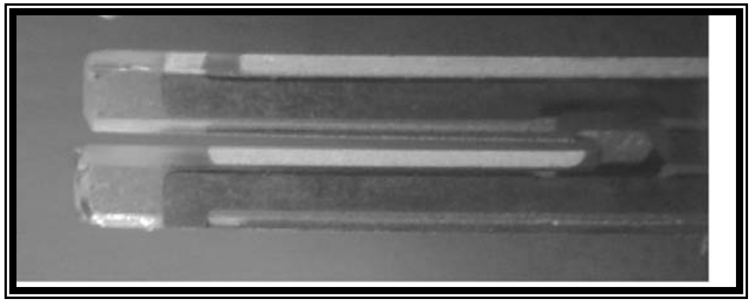


Vibration Spectrum



Y. Qin, PhD thesis, Purdue University (2007).

Raltron Model R26 Tuning Fork

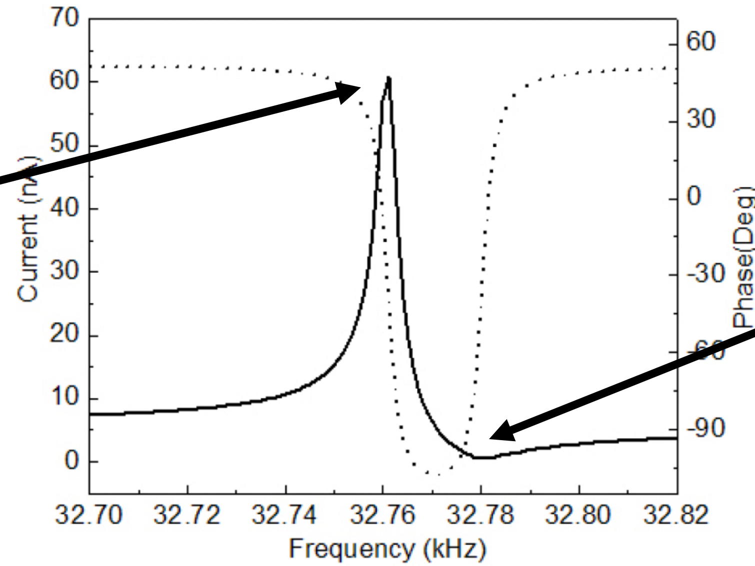


Length (mm)	3.20 ± 0.01	Effective mass (kg)	2.72×10^{-7}
Thickness (mm)	0.40 ± 0.01	Spring constant (kN/m)	12.7
Width (mm)	0.33 ± 0.01	Resonance (kHz)	34.39
Density (kg/m^3)	2.65×10^3	Young's Modulus(Pa)	7.87×10^{10}

Y. Qin, PhD thesis, Purdue University (2007).

Understanding the Resonance

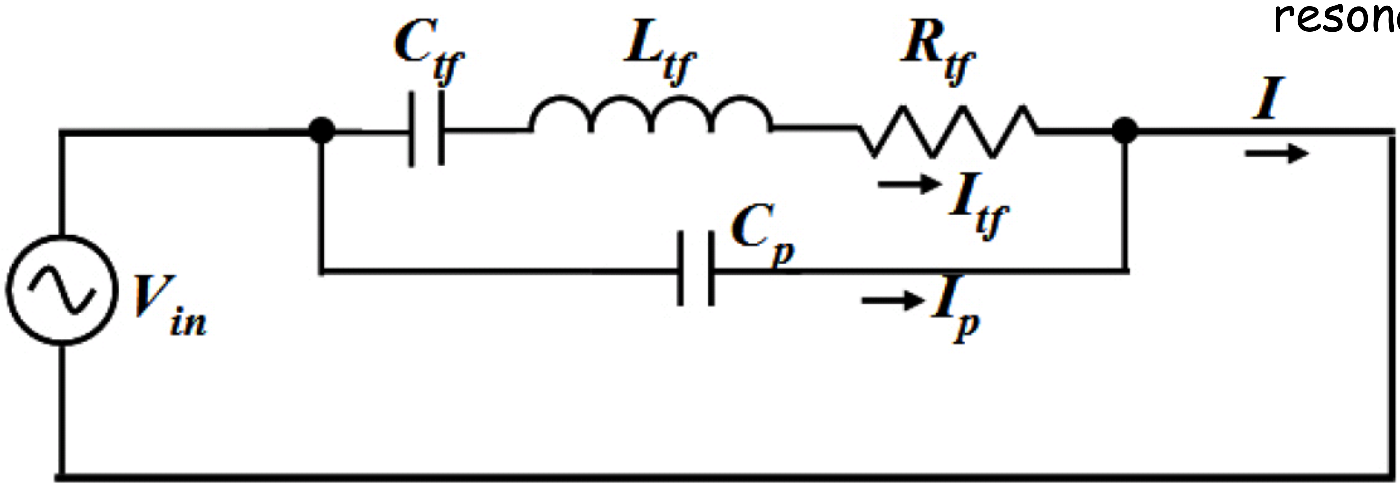
Resonance:
Minimum impedance



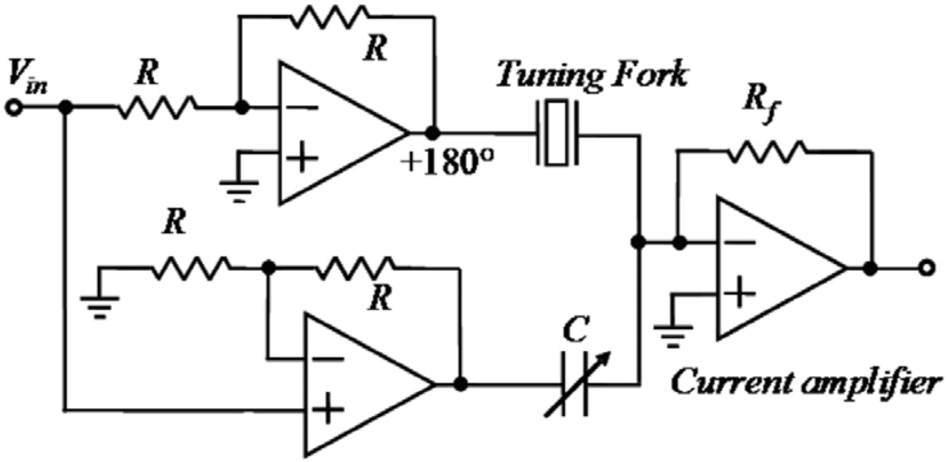
Anti-resonance:
Maximum impedance

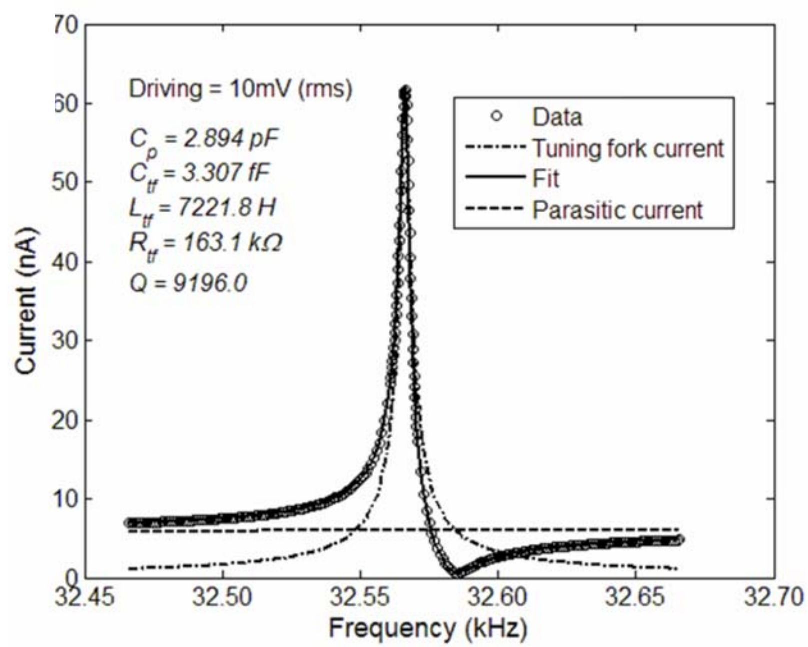
Relative phase of branch currents important in both resonance and anti-resonance

Equivalent Circuit



Eliminating the Parasitic Capacitance





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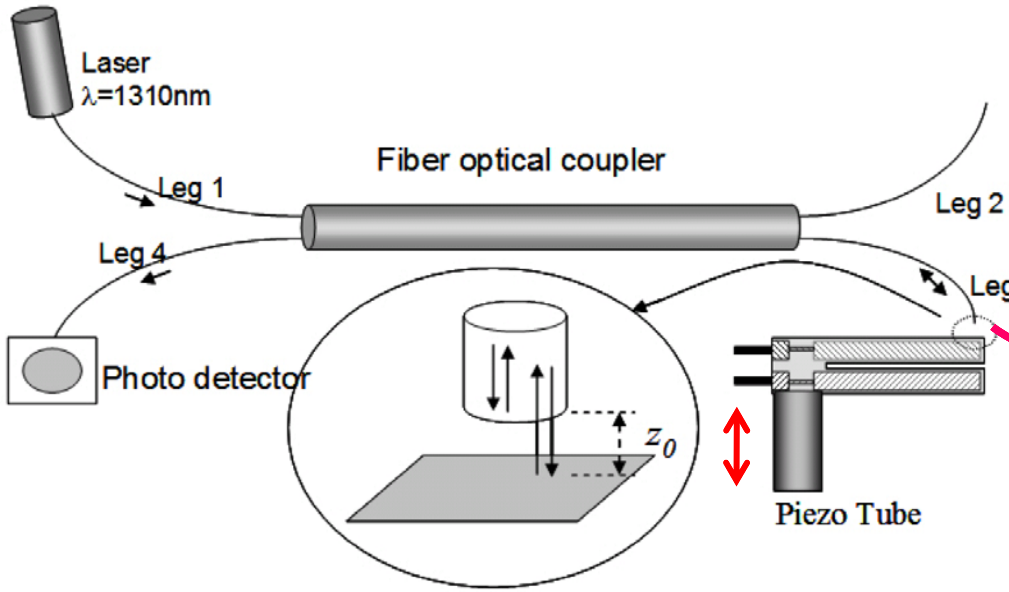
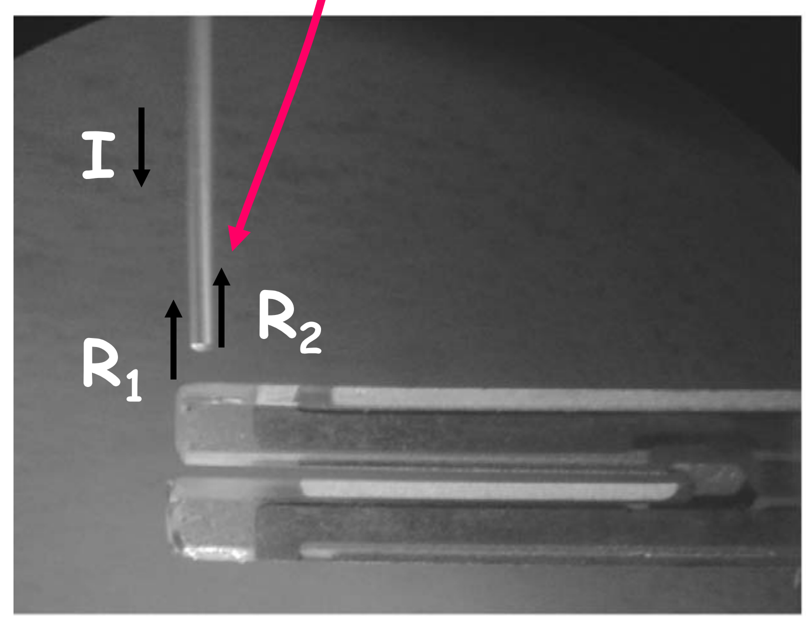
Calibrating the Amplitude of Oscillation



Infrared fiber optic interferometer



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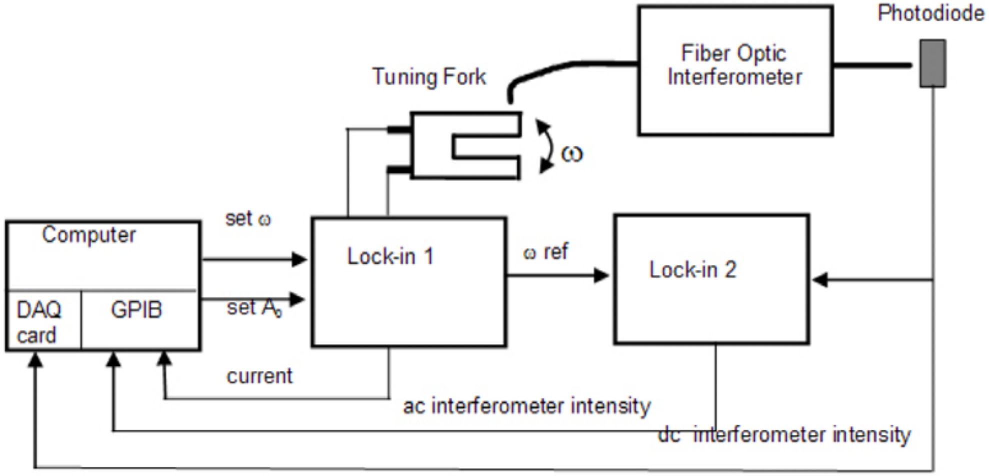
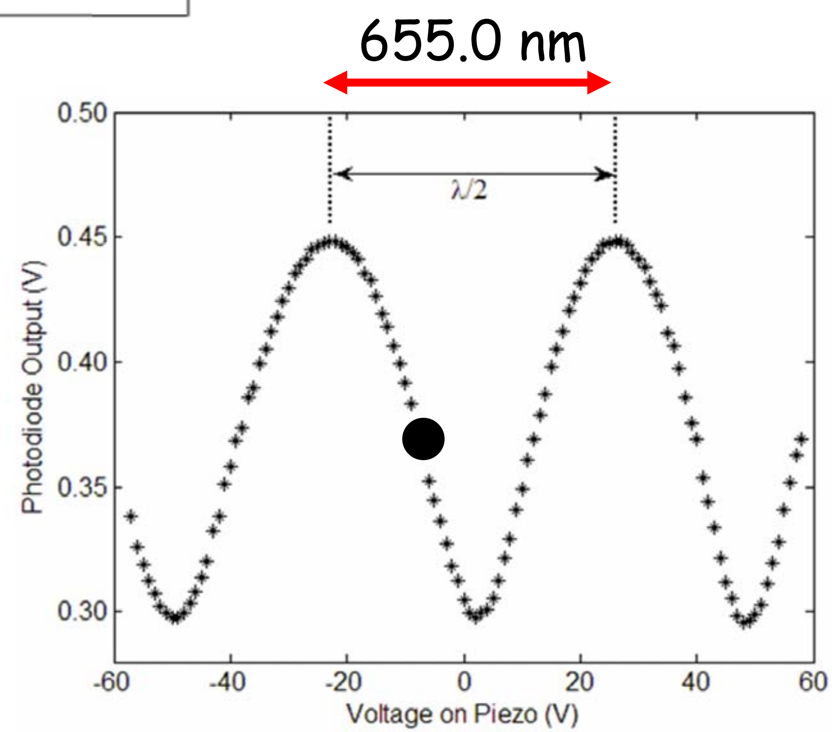
Typical calibration
(determining A_o vs. applied driving voltage)





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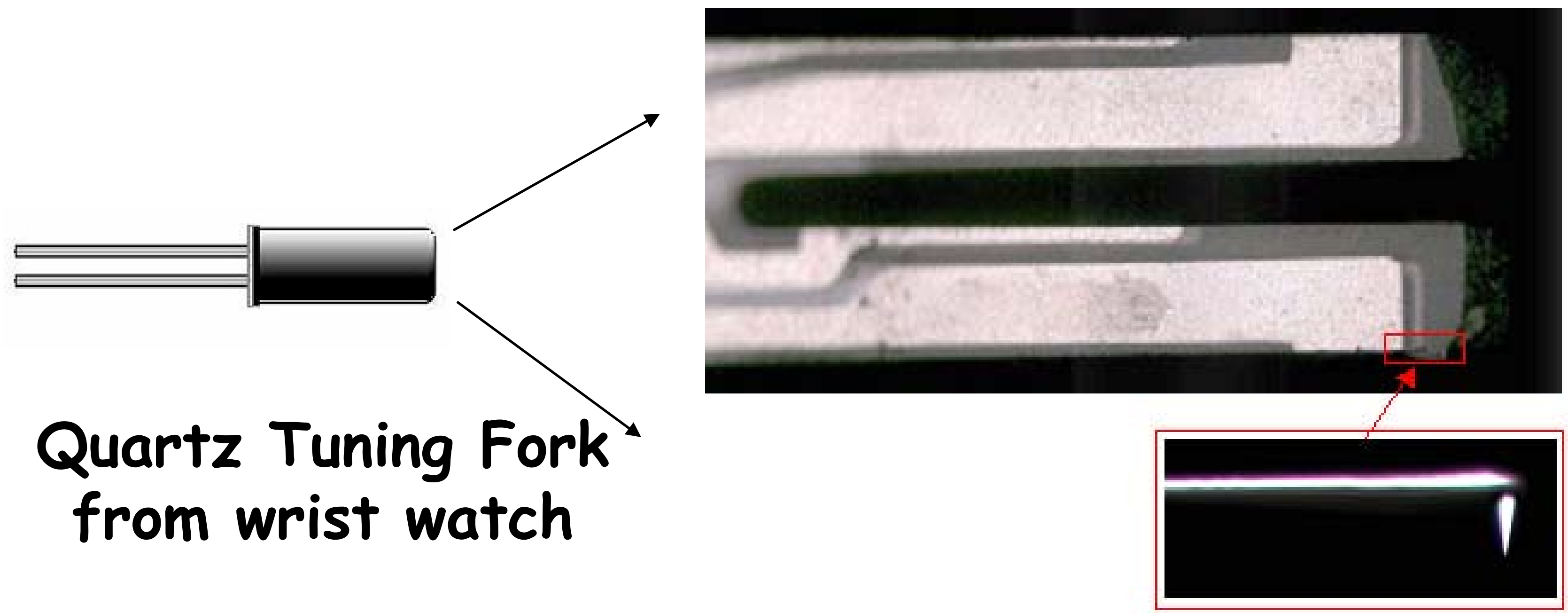
Mounting a Tip: Tuning Fork AFM

k ≅ 1000 N/m

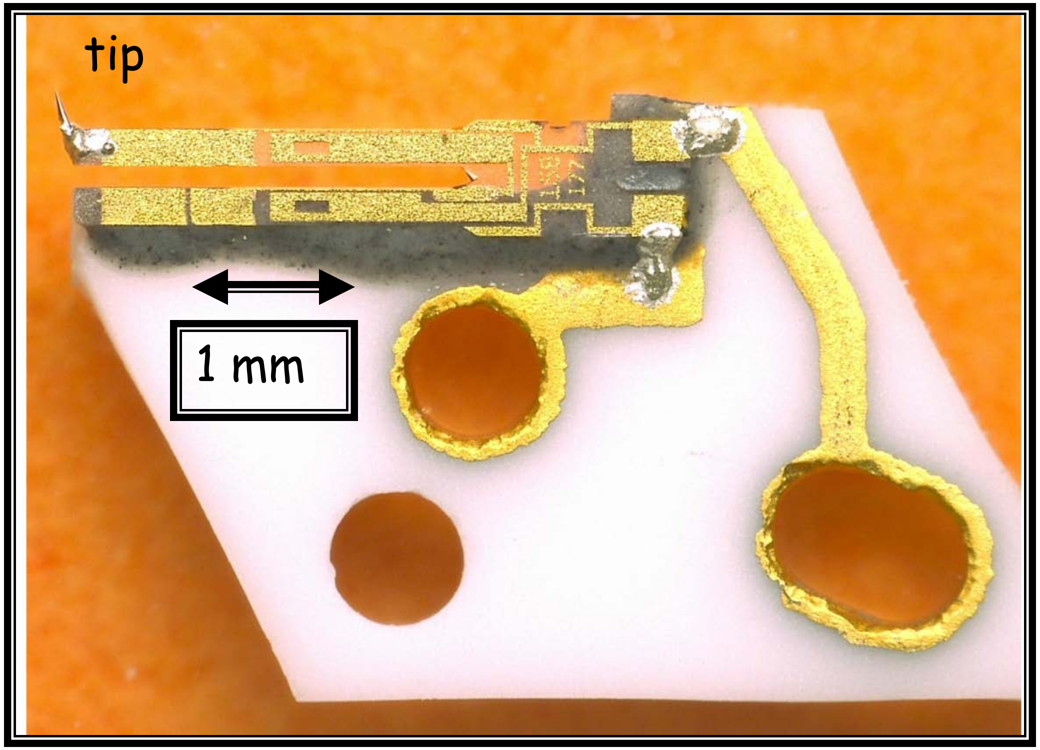


Quartz Tuning Fork from wrist watch

Q in vacuum ≅ 45,000
Q in air ≅ 9,000

Y. Qin, PhD thesis, Purdue University

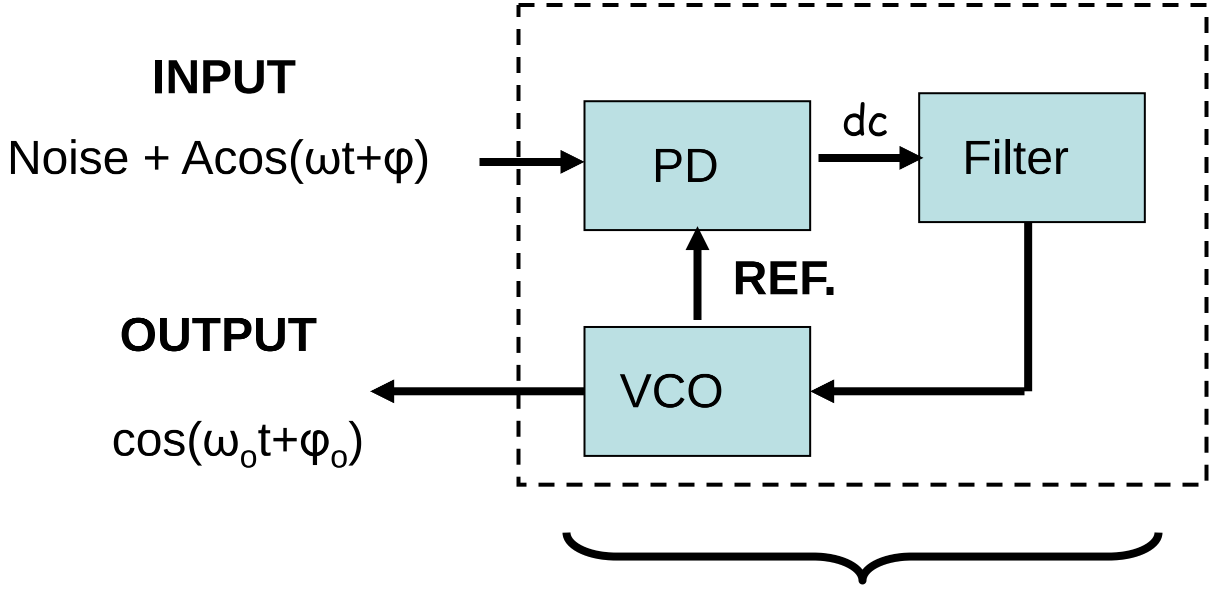
Commercially available Q-plus sensor



courtesy, F. Giessibl

Intro to Phase Locked Loops (PLLs)

Phase-Locked Loops (PLLs) track the frequency of an input "noisy" sinusoidal signal that is known to have a variable frequency.



The PLL consists of three components:

- Phase Detector (PD)
- Loop filter
- Voltage-Controlled Oscillator (VCO)

PLL Notes:

PLL

It is assumed that the frequency change of the input signal is not too large.

It is assumed that the approximate frequency range of the input signal is roughly known.

The PD estimates the phase difference between an input (noisy) signal and a clean signal (reference) produced by the VCO. The PD circuit generates a **dc** voltage proportional to the phase difference between these two signals.

The loop filter "smoothes" the **dc** voltage produced by the PD.

The VCO accepts the smoothed **dc** voltage and generates a signal with a frequency that is continuously adjusted by the **dc** voltage. This is accomplished by modifying the frequency of an internal oscillator (no noise) until a match to the frequency of the input signal is achieved.

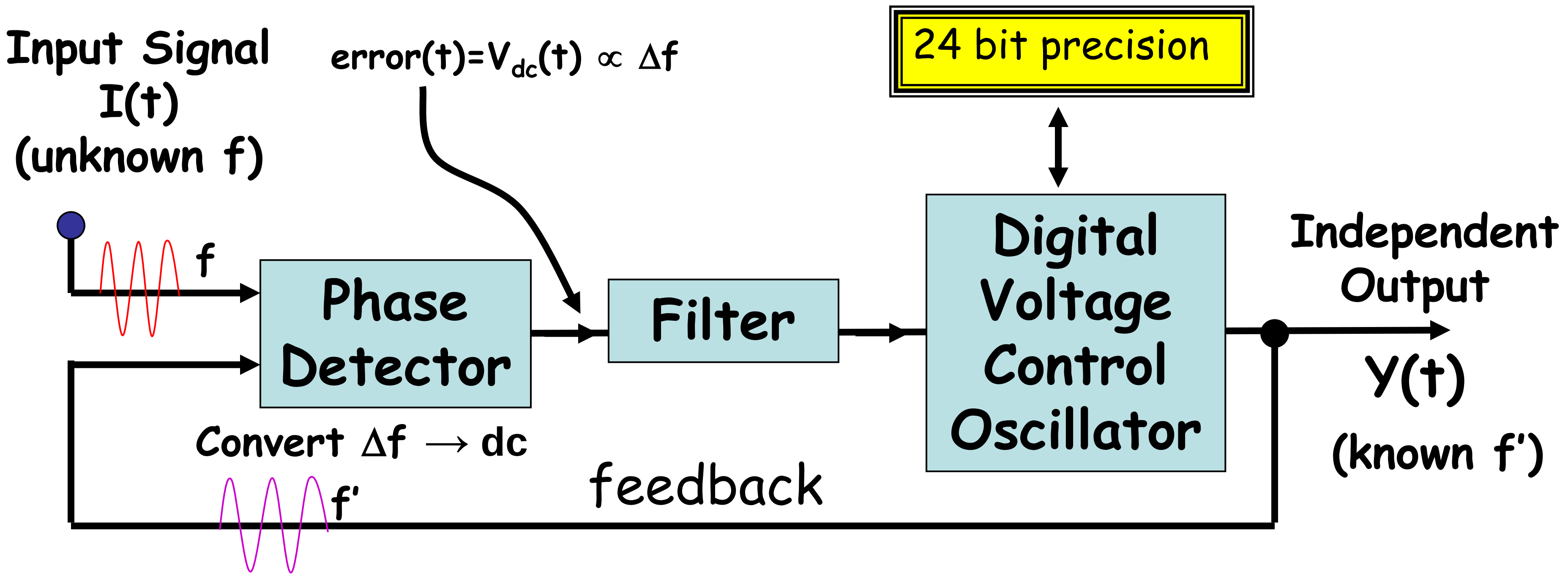
When a match occurs, the **dc** voltage produced by the filter goes to **zero** and the known output (ω_o, φ_o) is said to match the input (ω, φ).

The PLL-design goal is to select an appropriate loop filter that produces an acceptable transient and steady-state response of the closed-loop system

The "bandwidth" of a PLL is the frequency at which the PLL begins to lose "lock" with the reference signal.

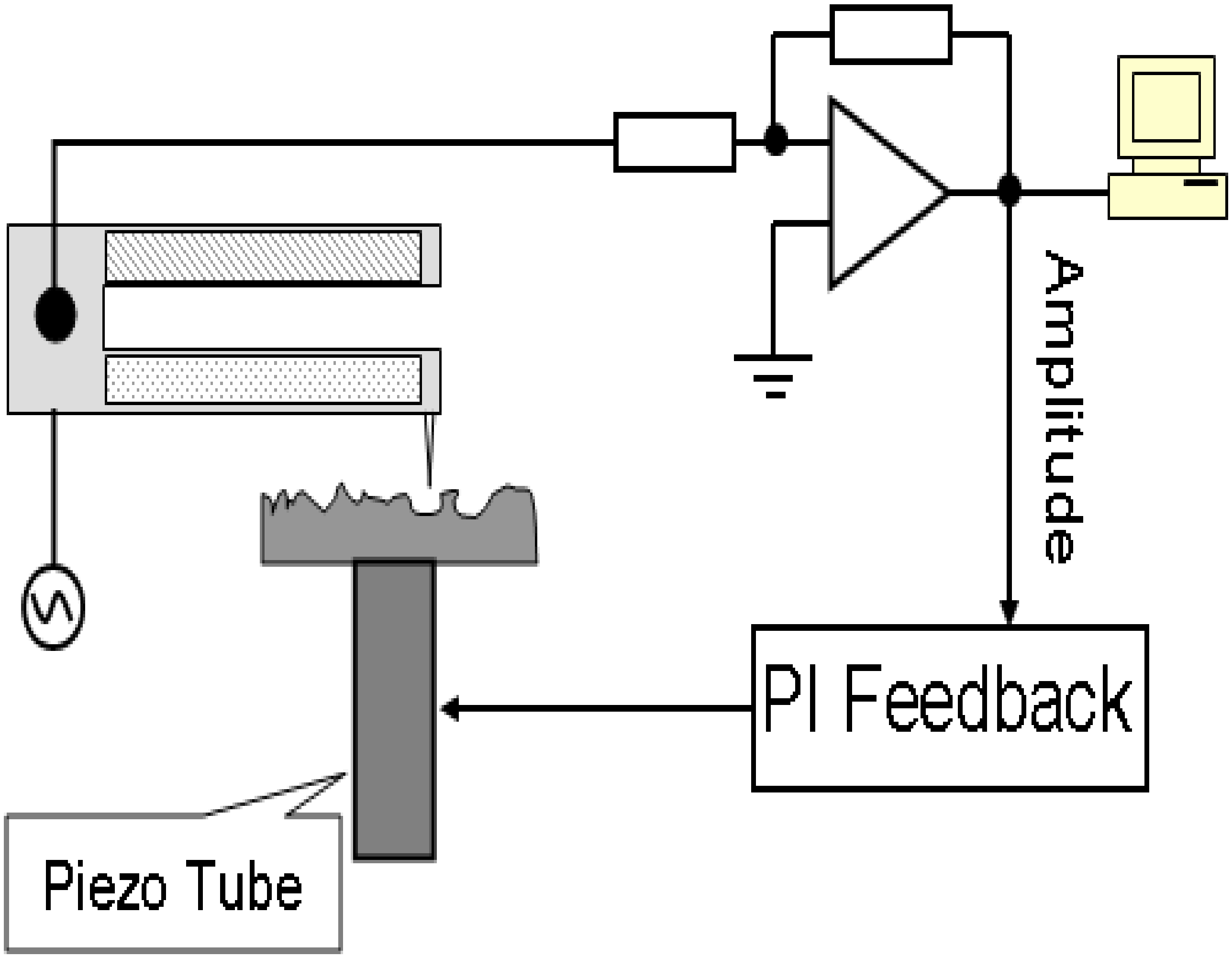
Principle of Digital Phase-Lock Loops (PLL)

TASK: Instantly track and measure frequency of an input signal I(t) with high accuracy



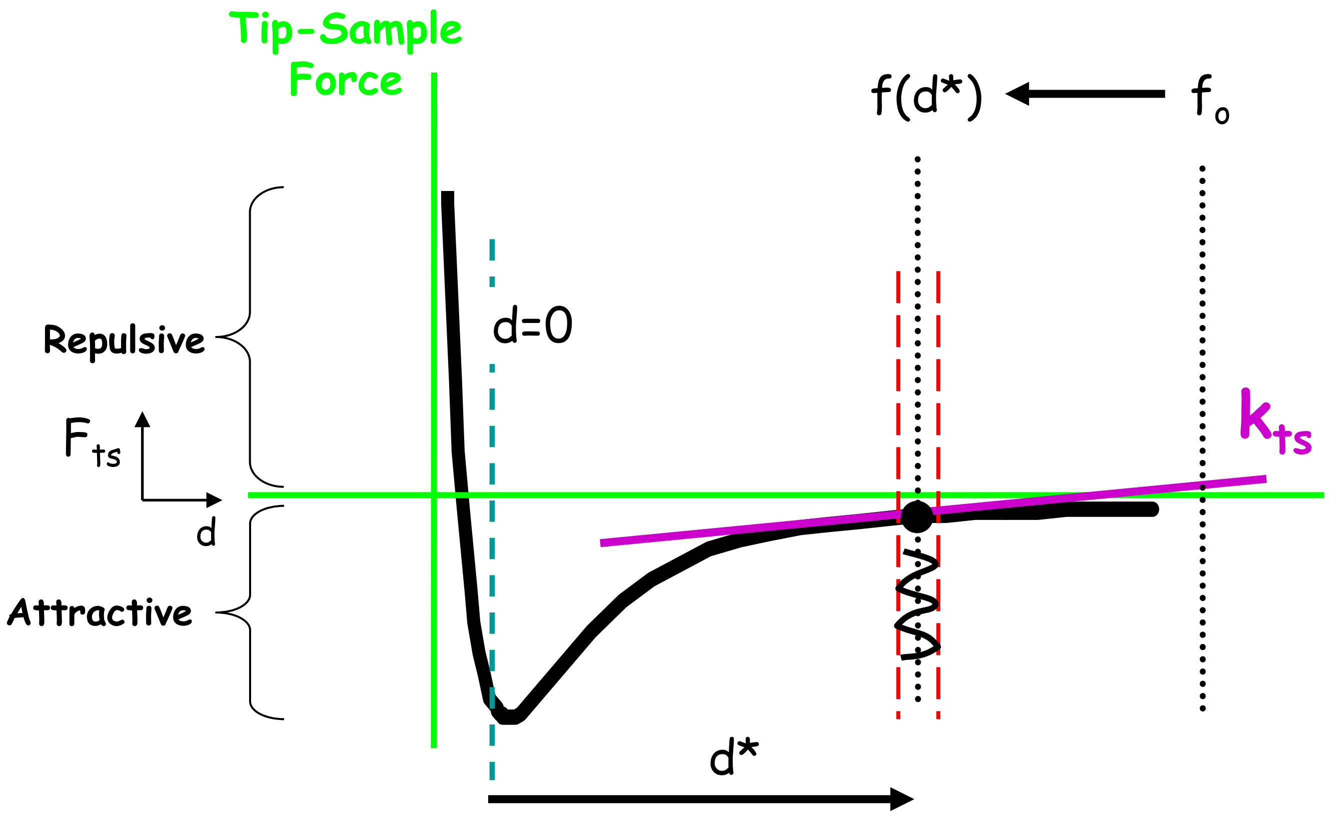
- Negative feedback!
- Goal is to make $\Delta f = f - f' = 0$

Tuning Fork AFM



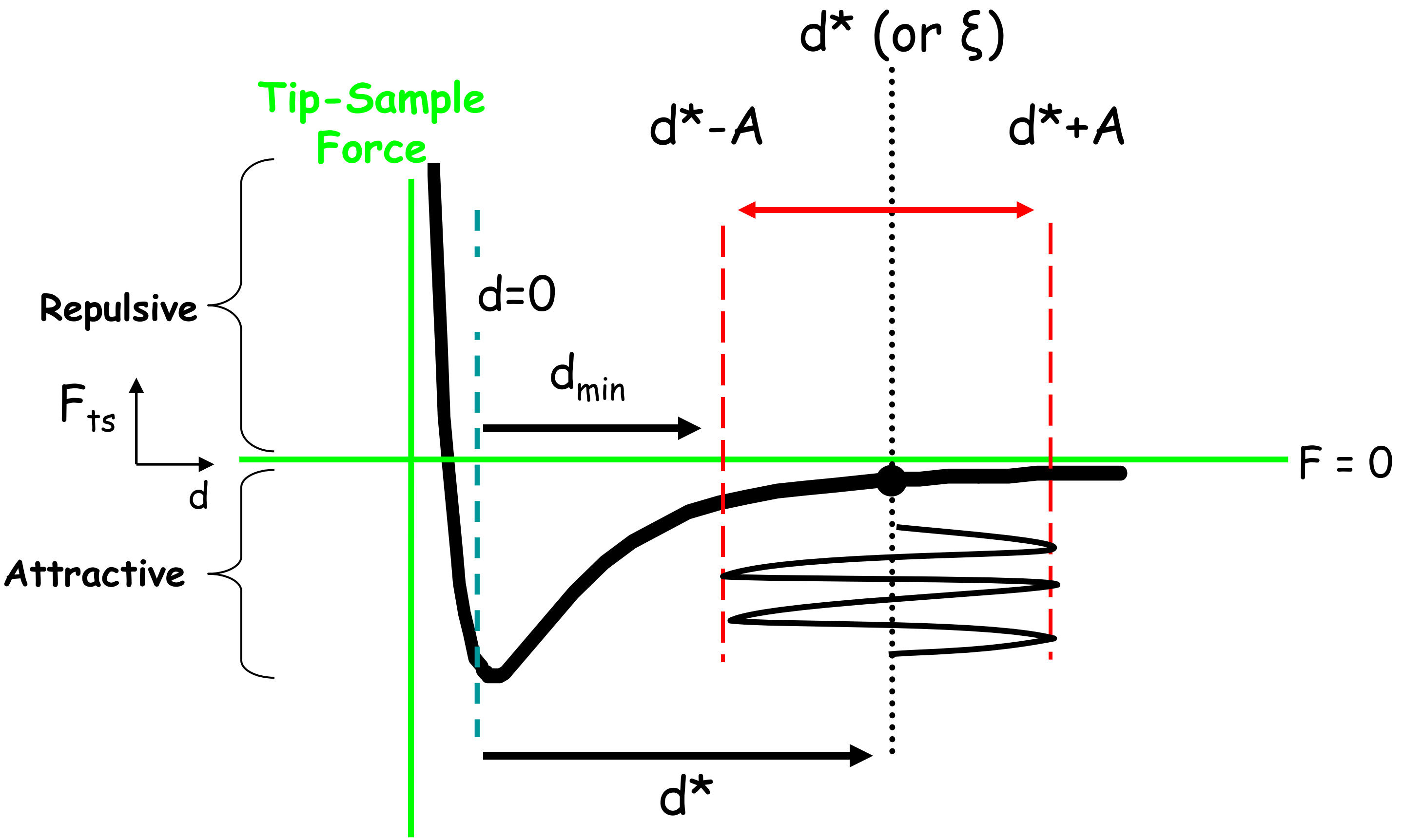
No laser required to measure deflection

FM-AFM
Constant Frequency Images



Scan while keeping ω(d*) and Q constant

FM-AFM Force Spectroscopy



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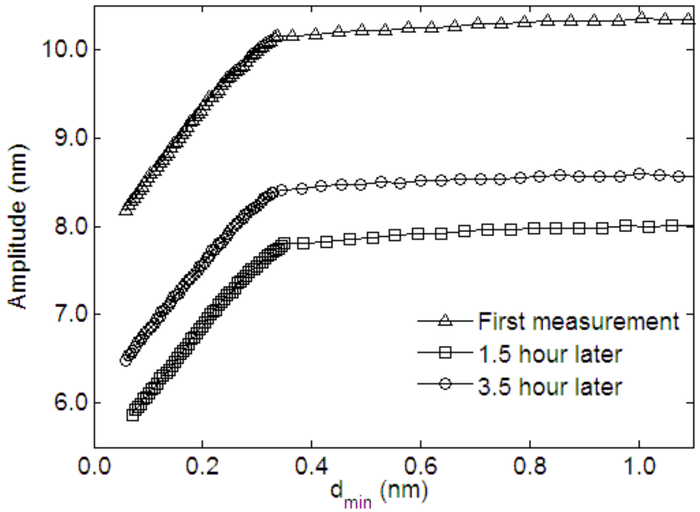
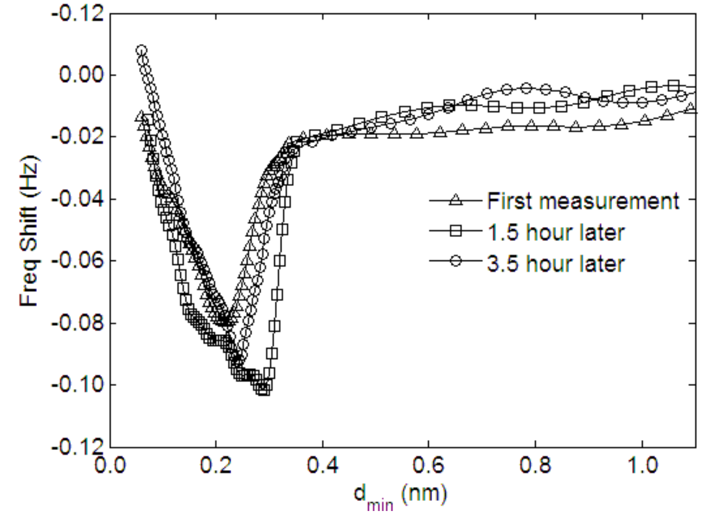
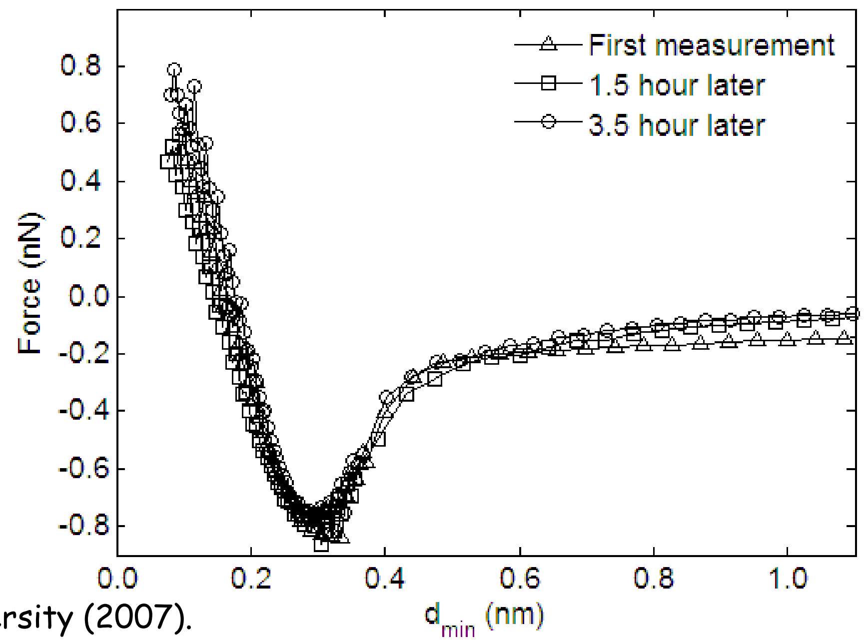
where $\Omega(\xi) \equiv \dfrac{\Delta f(\xi)}{f_o}$ $\qquad \xi \Leftrightarrow d^*$

FM-AFM Force Spectroscopy

W tip – HOPG substrate

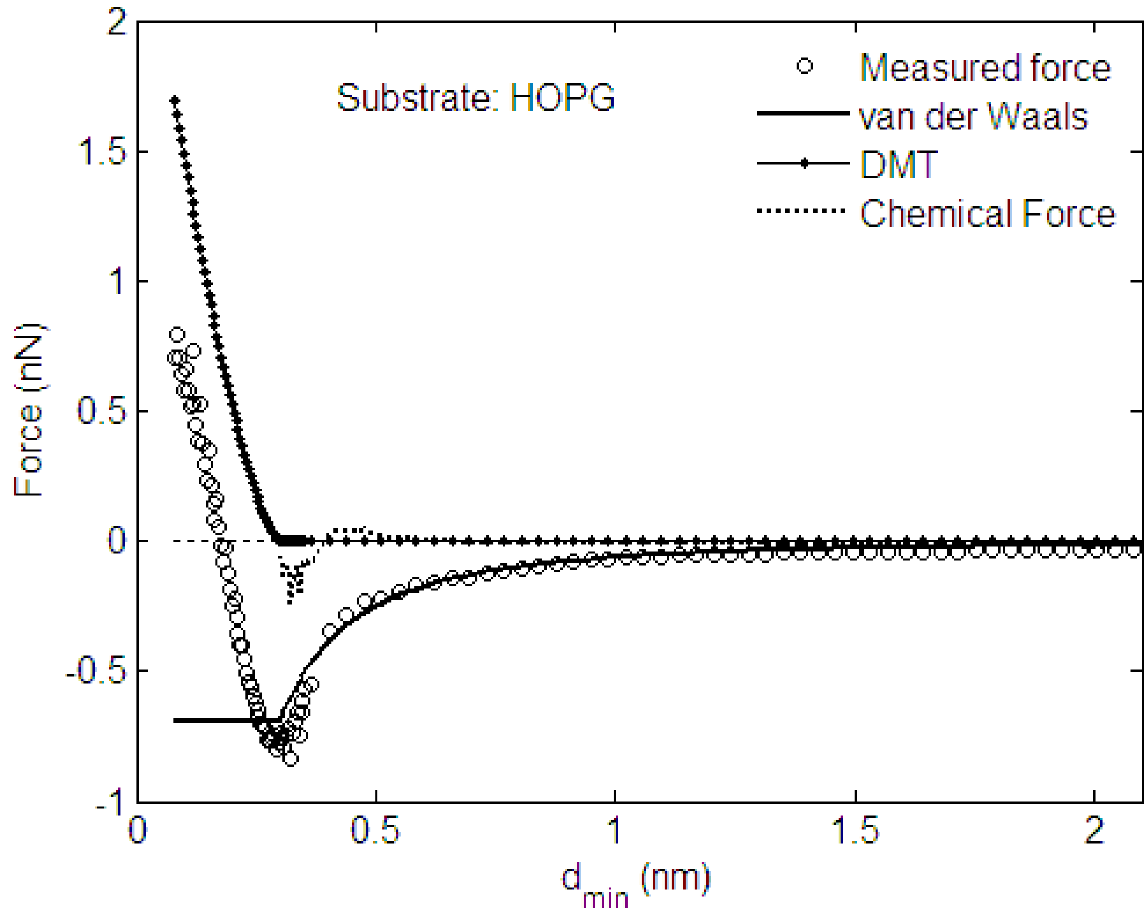






Y. Qin, PhD thesis, Purdue University (2007).

Fit to data



FIT: a_o=0.3 nm, H=3.3×10^{-19} J, E*=11.6 GPa, R_{eff} =1.13 nm

Y. Qin, PhD thesis, Purdue University (2007).