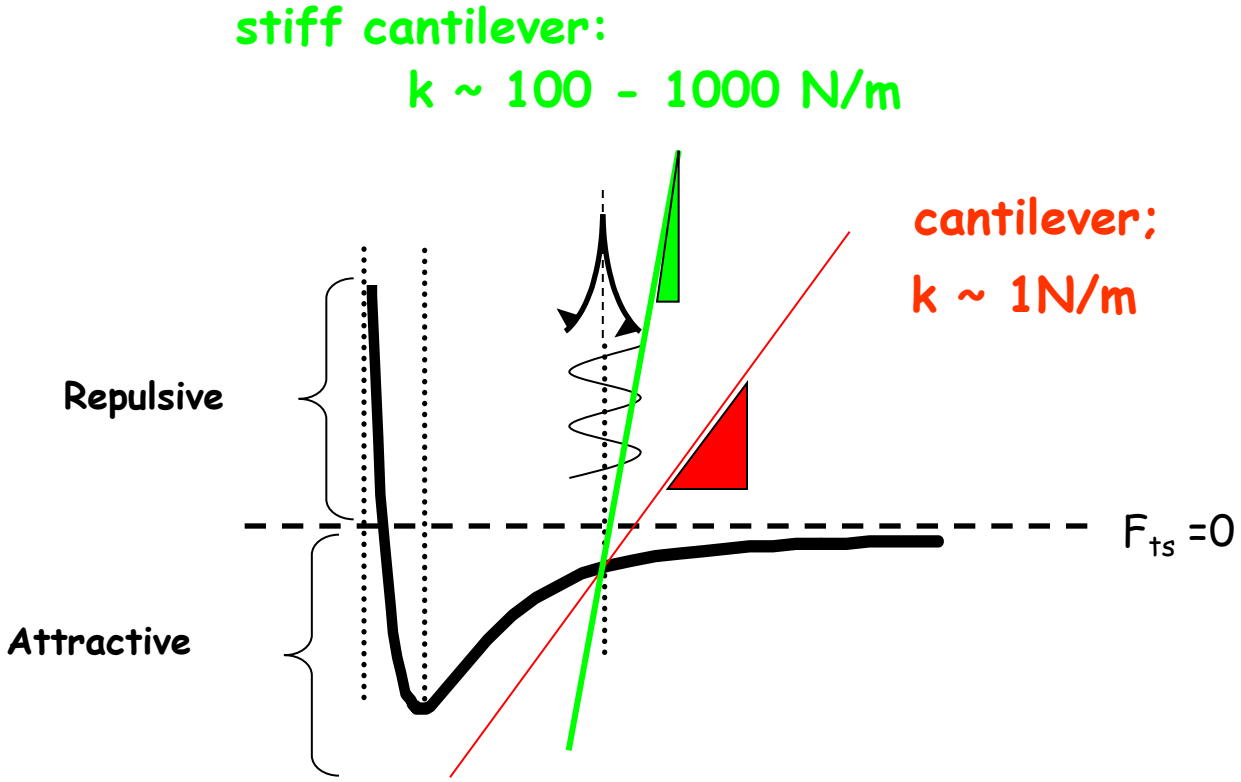
# ME597/PHYS57000
# Fall Semester 2009
# Lecture 22

## Frequency Modulated AFM
## - Experimental Details -

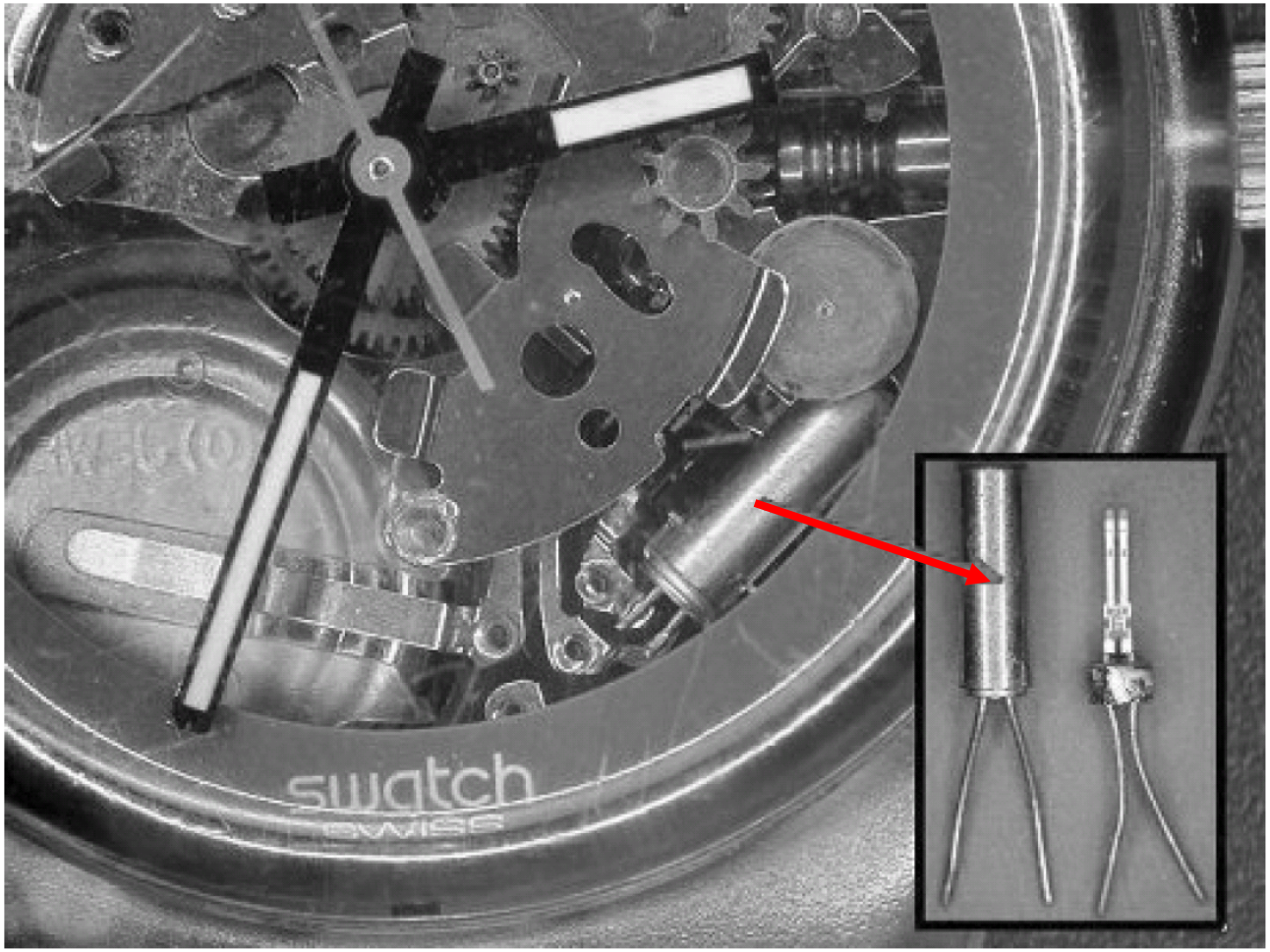
Suggested Reading: F. Giessibl, Rev. Mod. Phys. **75**, 949 (2003)

# What is Required?

- High stability
- Measure small frequency shifts accurately
- Large spring constant



# New Idea: Tuning Forks



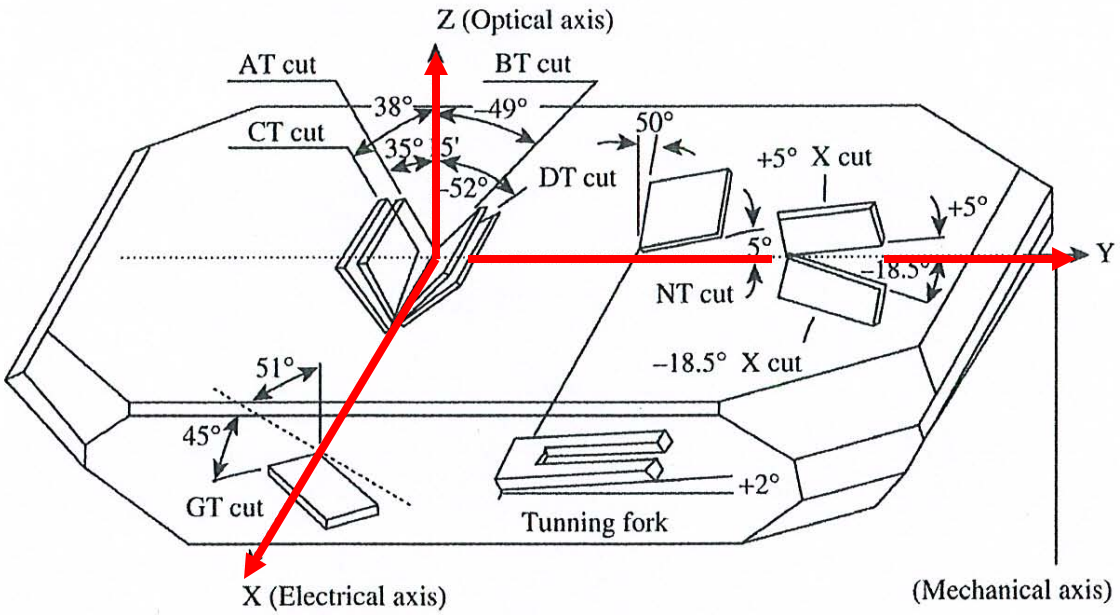

Cost:

~0.25 USD

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

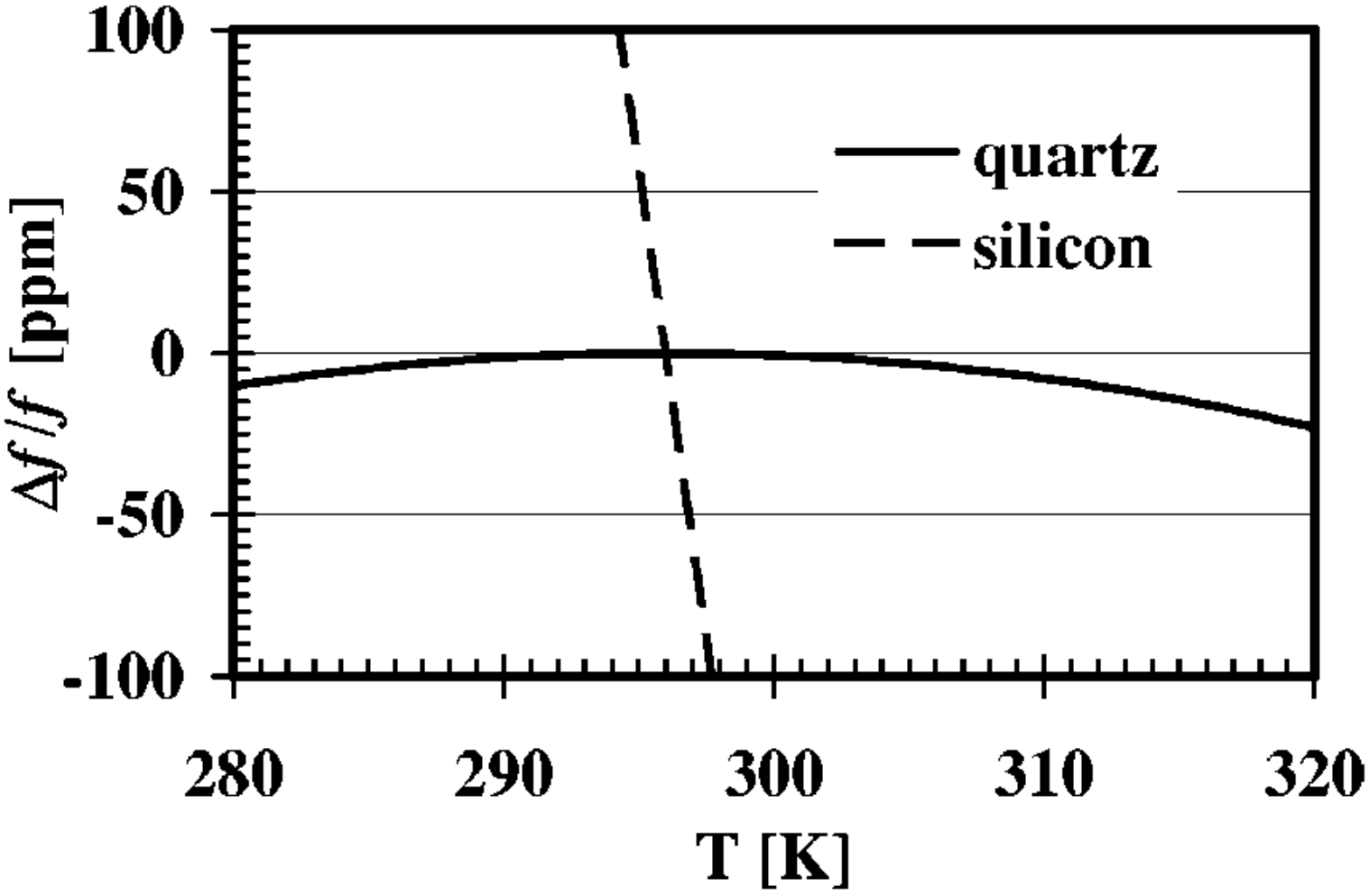
$$f_o = 2^{15} = 32,768.0000\ Hz$$

# Quartz: a piezoelectric material



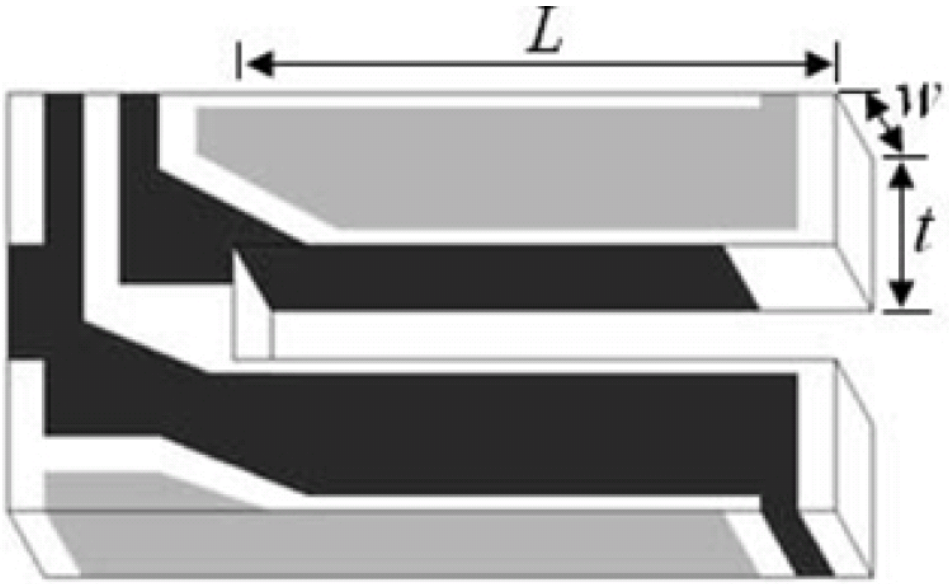

*Introduction to Scanning Tunneling Microscopy*, C. Julian Chen, Oxford University Press (2008).

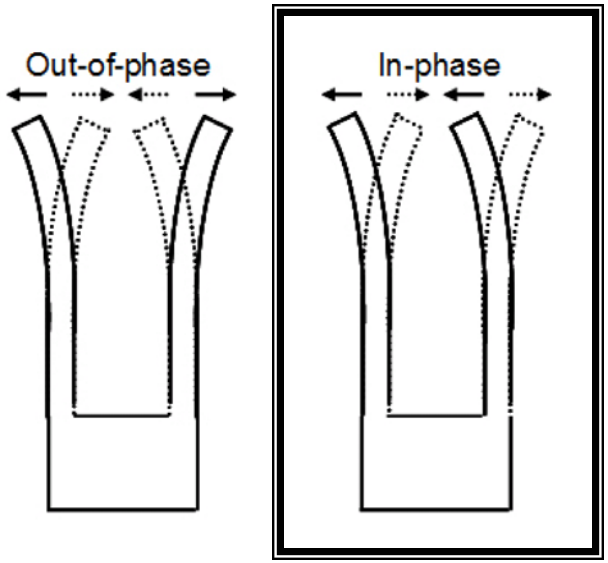
# Thermal stability of quartz compared to Si

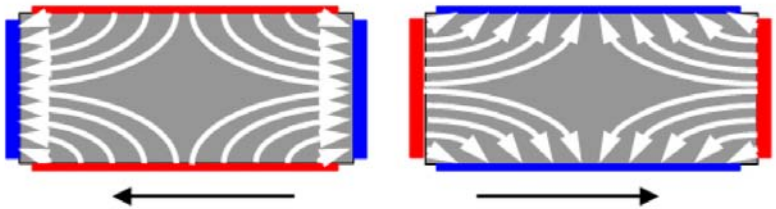



F. Giessibl, Rev. Mod. Phys. **75**, 949 (2003)

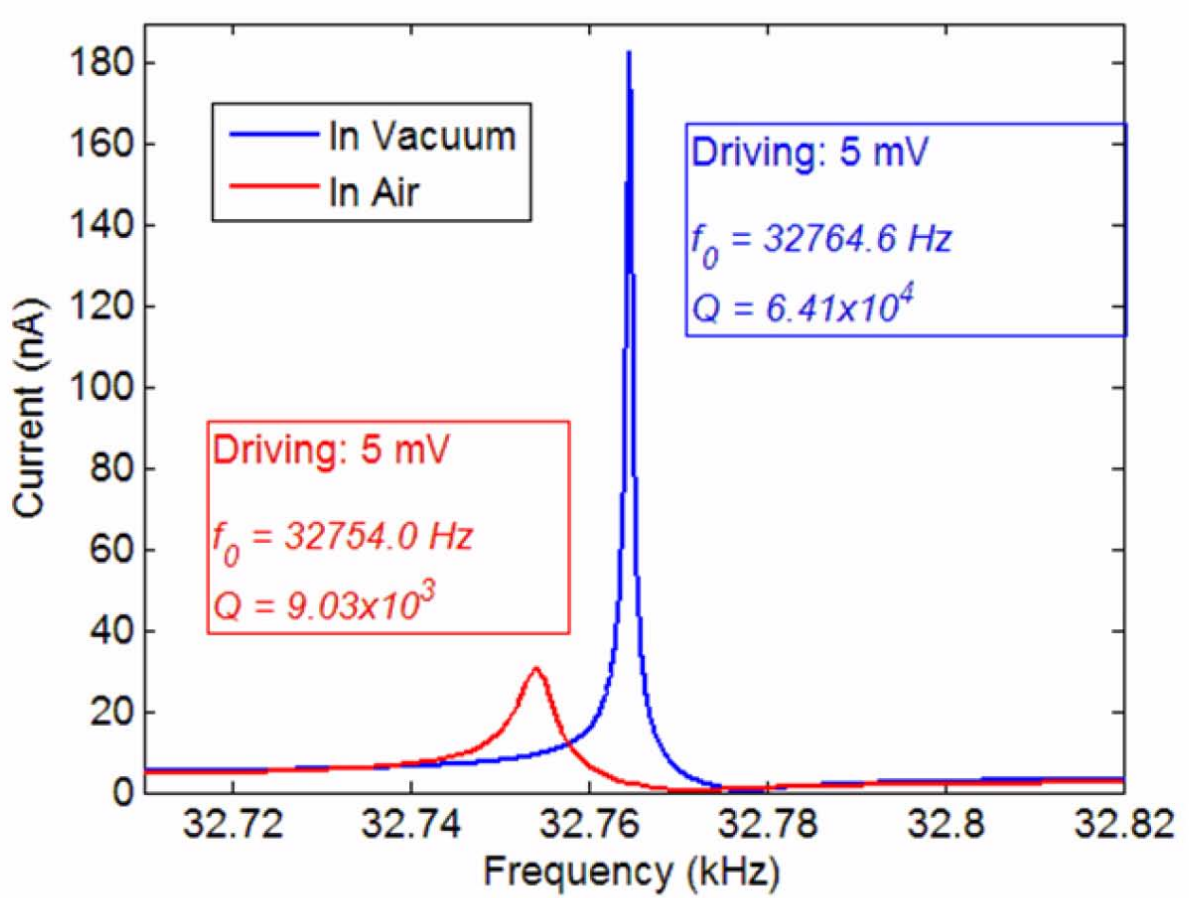
# Electrode Geometry Selects Vibrational Mode



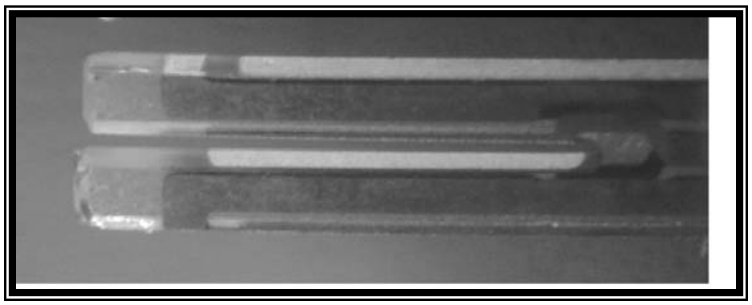



# Vibration Spectrum




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

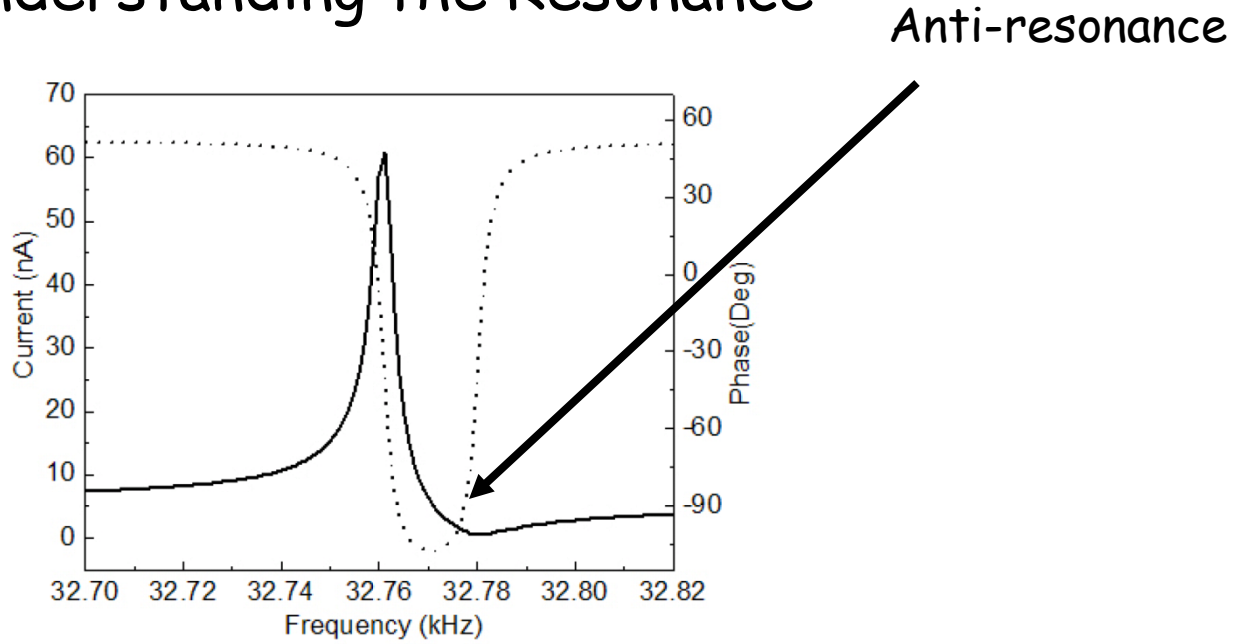
# Raltron Model R26 Tuning Fork



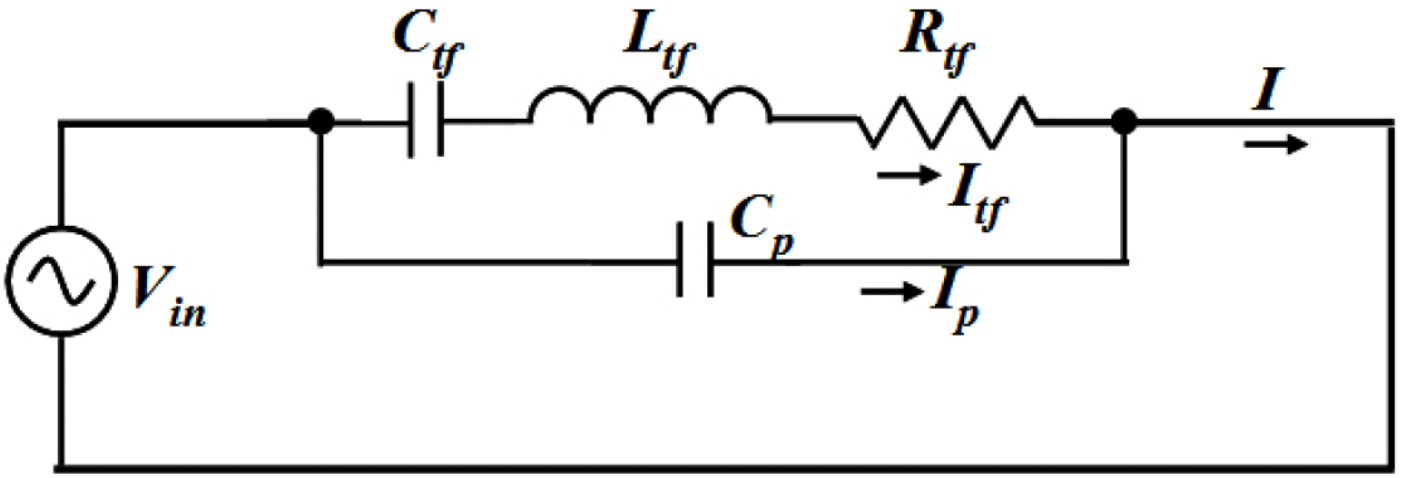
| | | | |
|---|---|---|---|
| Length (mm) | $3.20 \pm 0.01$ | Effective mass (kg) | $2.72 \times 10^{-7}$ |
| Thickness (mm) | $0.40 \pm 0.01$ | Spring constant (kN/m) | 12.7 |
| Width (mm) | $0.33 \pm 0.01$ | Resonance (kHz) | 34.39 |
| Density (kg/m$^3$) | $2.65 \times 10^3$ | Young's Modulus(Pa) |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

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

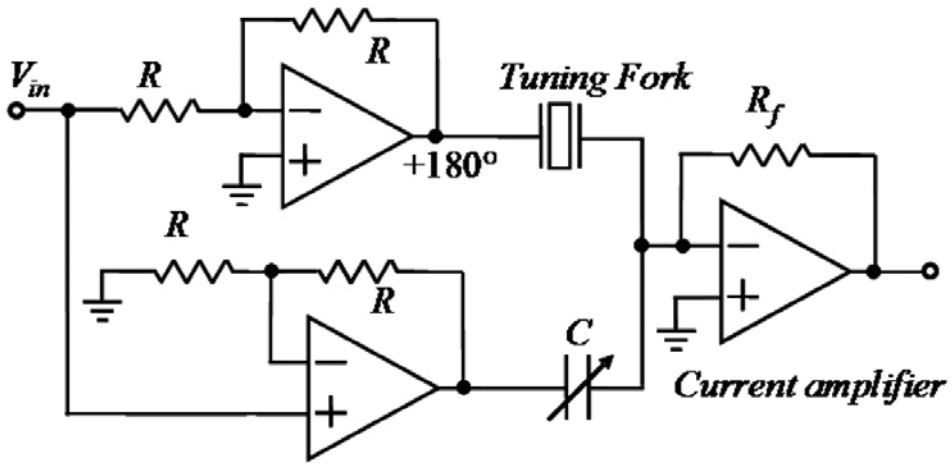
# Understanding the Resonance

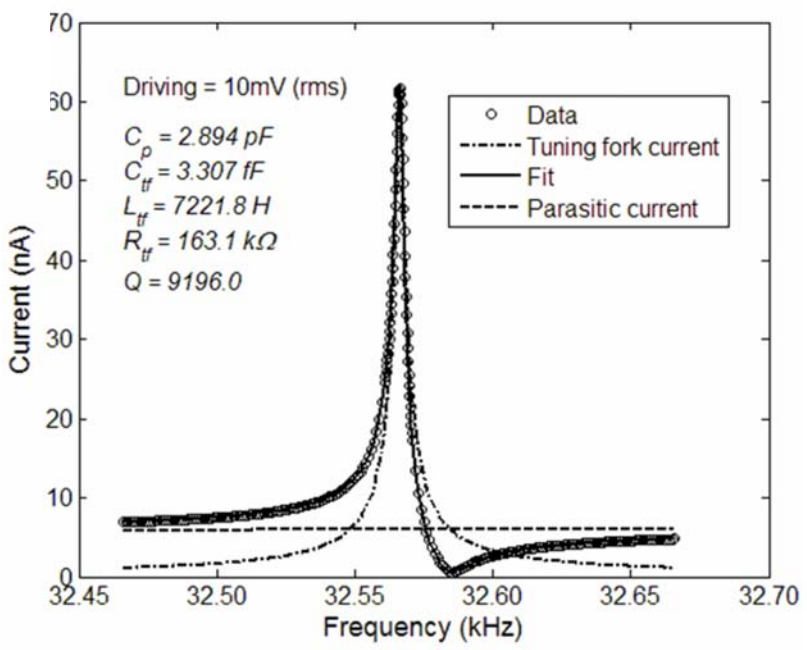



# Equivalent Circuit



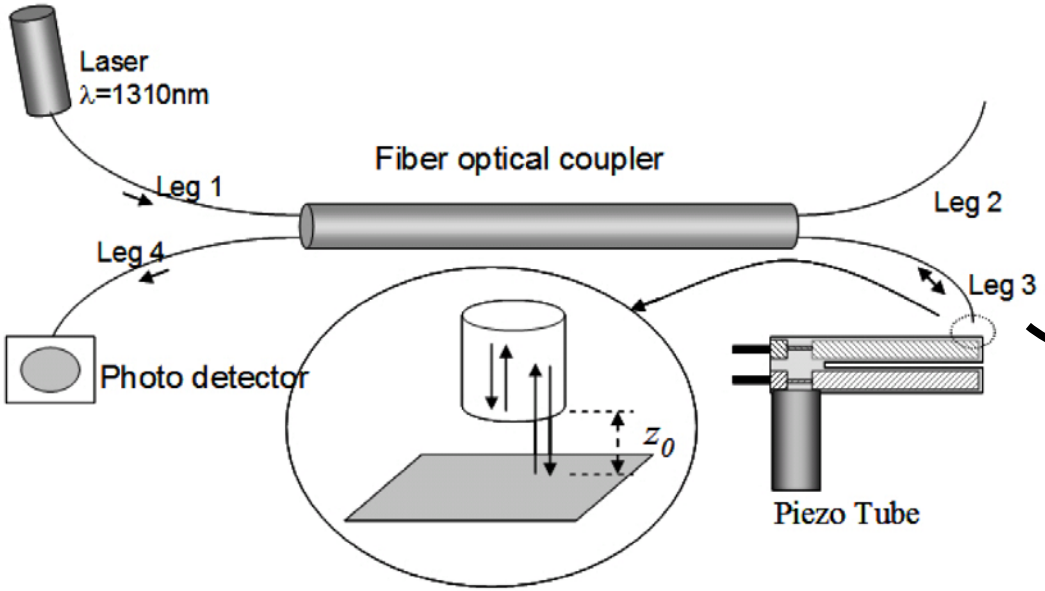
# Eliminating the Parasitic Capacitance



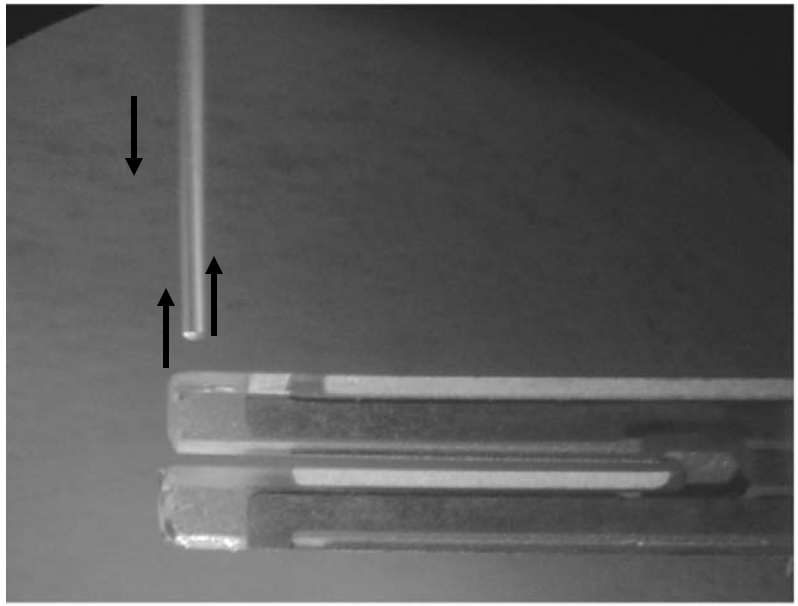




Y. Qin, PhD thesis, Purdue University (2007).

# Calibrating the Amplitude of Oscillation

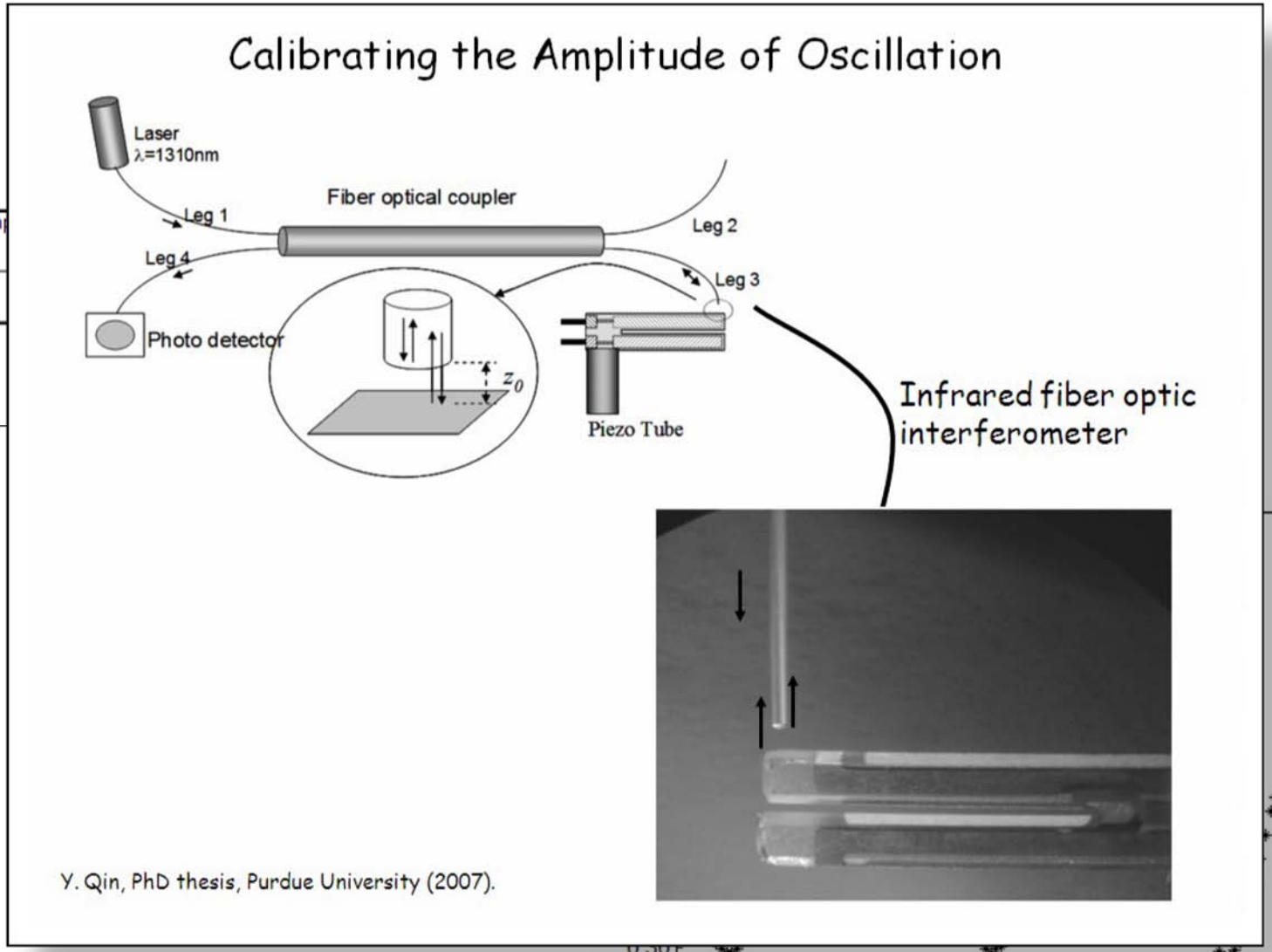



Infrared fiber optic interferometer



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

# Typical calibration
## ($A_0$ vs. applied driving voltage)





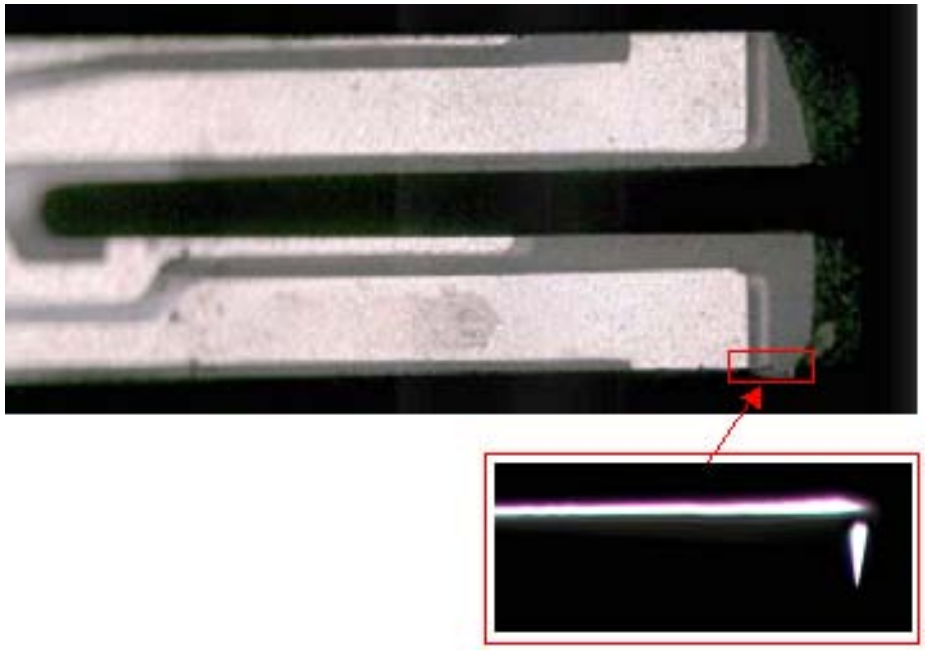


Y. Qin, PhD thesis, Purdue University (2007).

# Mounting a Tip: Tuning Fork AFM

$k \cong 1000$ N/m

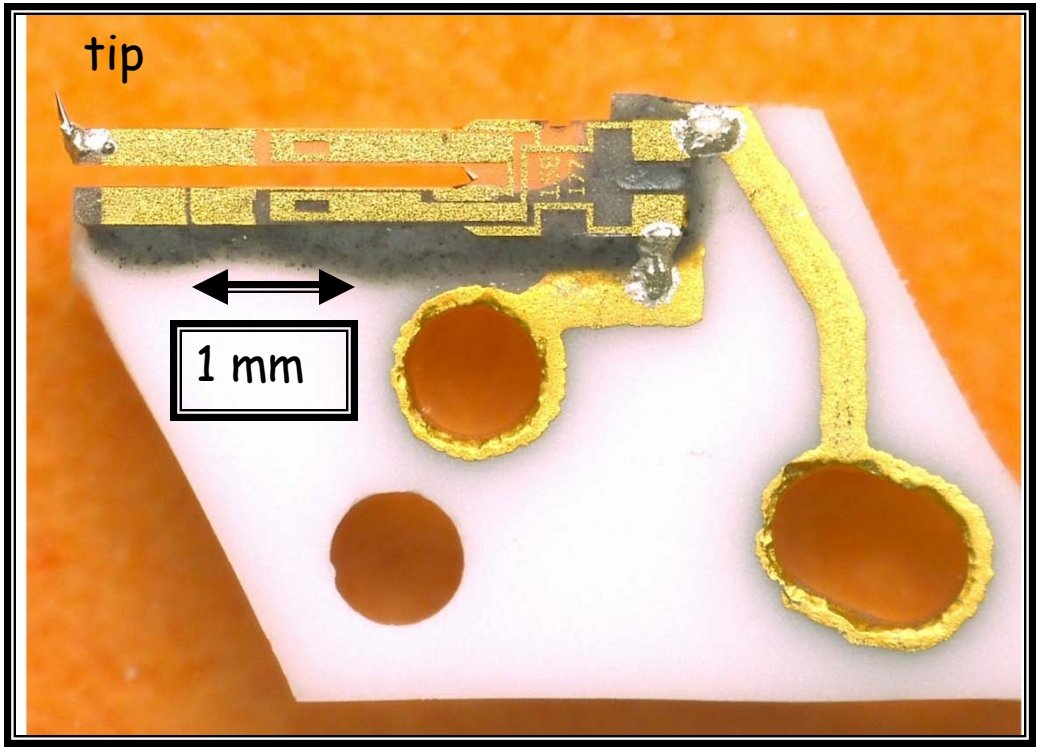
Quartz Tuning Fork
from wrist watch



Q in vacuum ≅ 45,000
Q in air ≅ 9,000

Y. Qin, PhD thesis, Purdue University

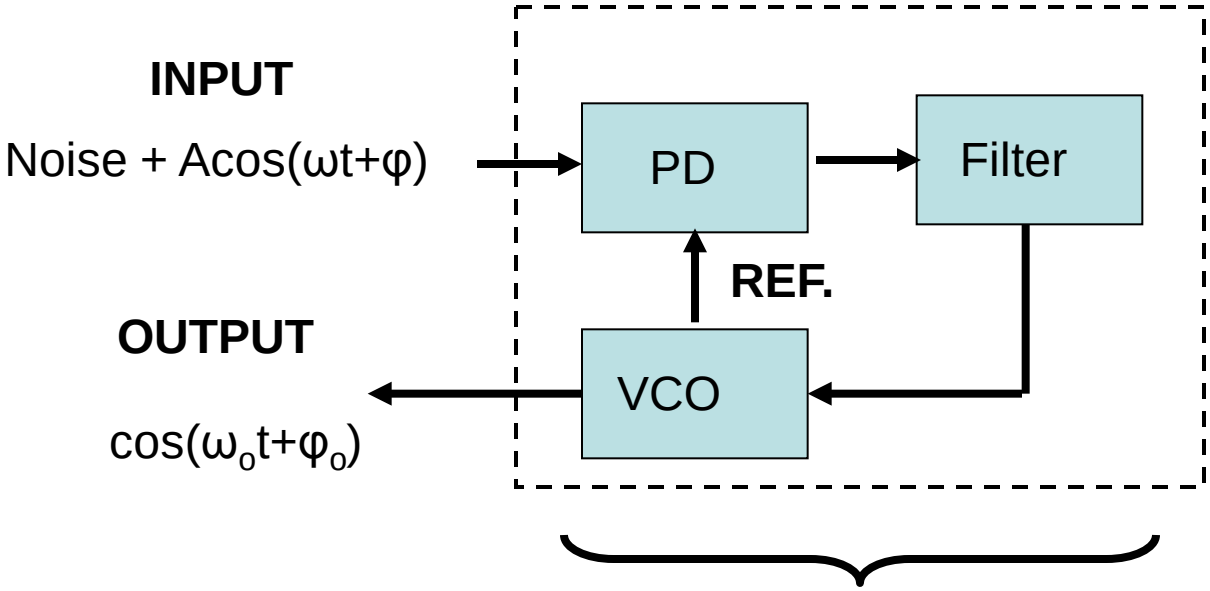
# Commercially available Q-plus sensor




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.

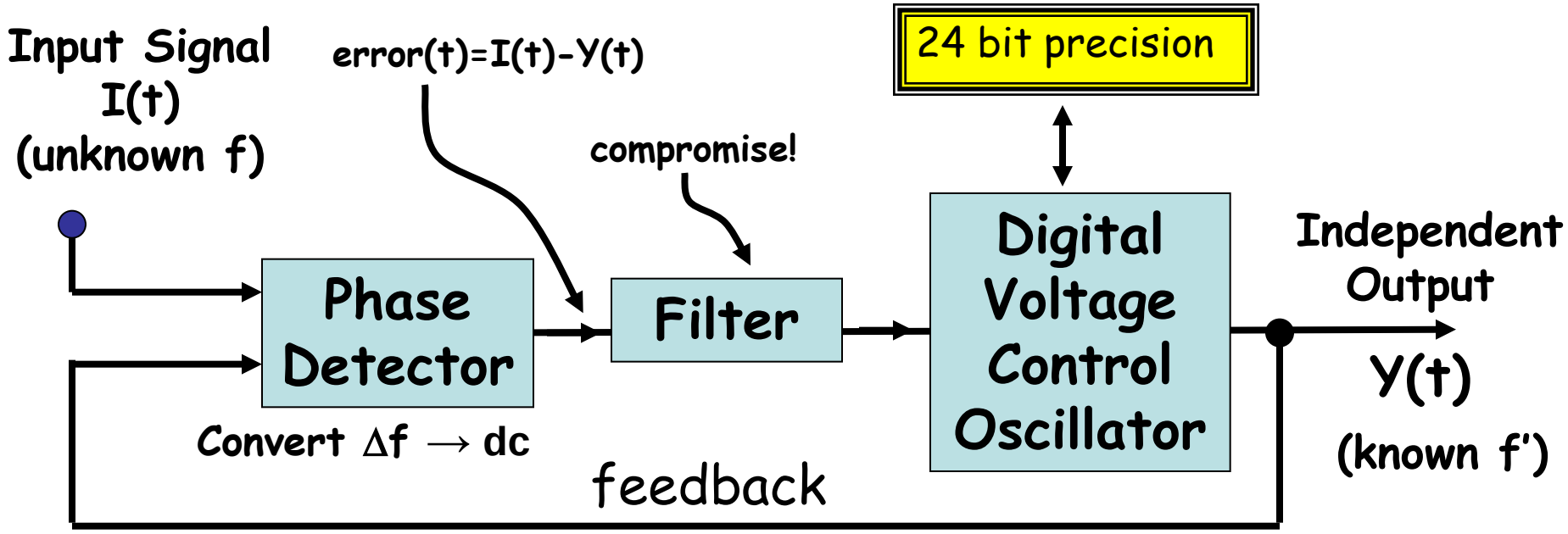



The PLL consists of three components:

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

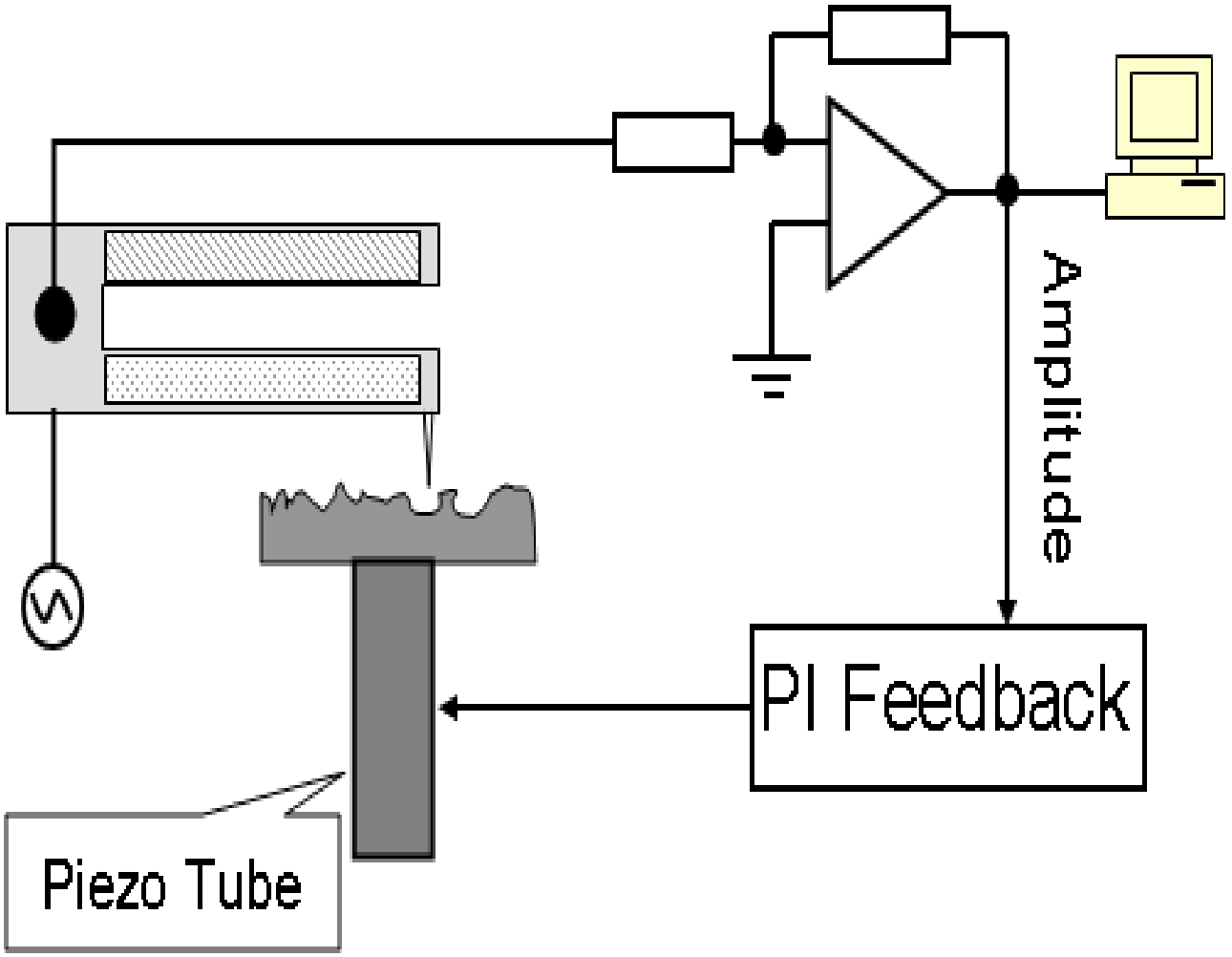
# Principle of Digital Phase-Lock Loops (PLL)

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



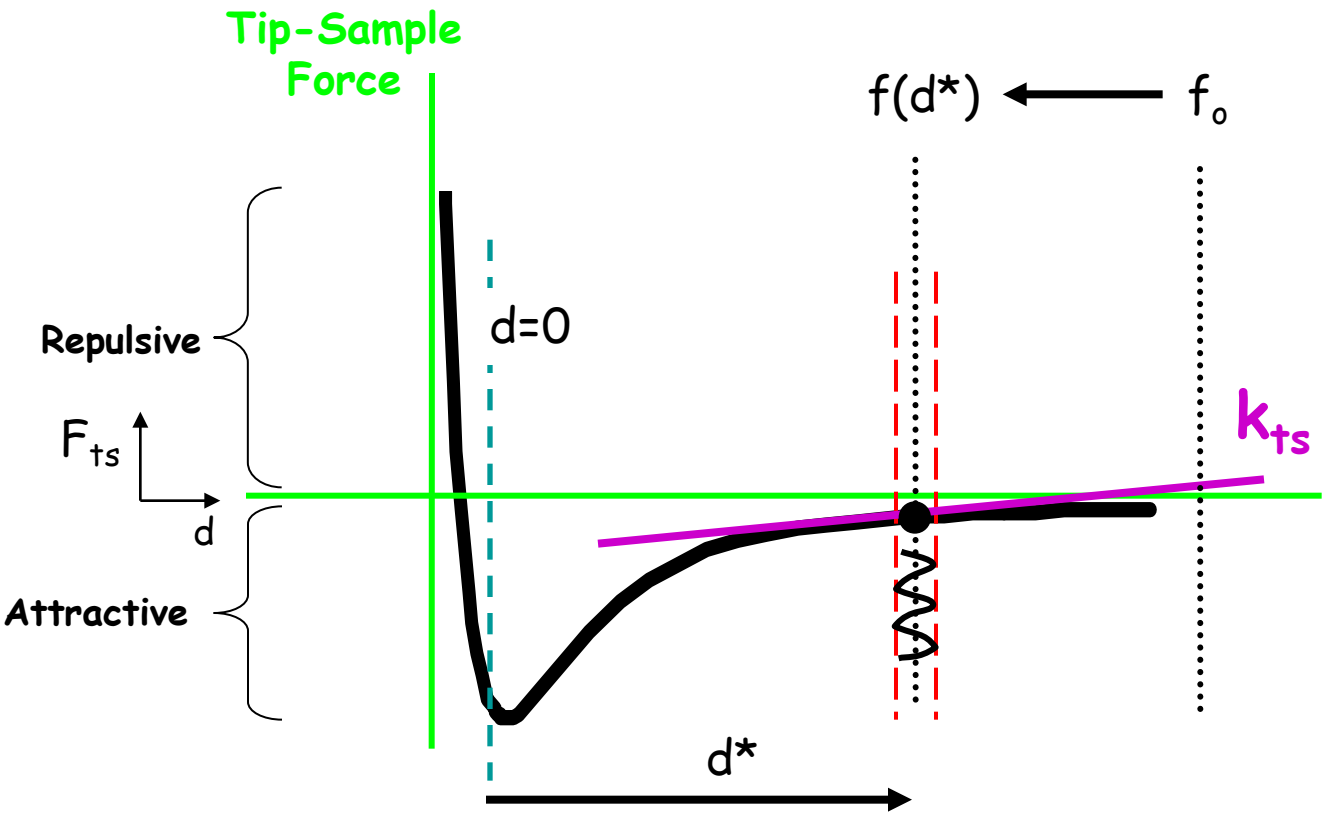

- Negative feedback!
- Goal is to make $\Delta f = f - f' = 0$

# Tuning Fork AFM



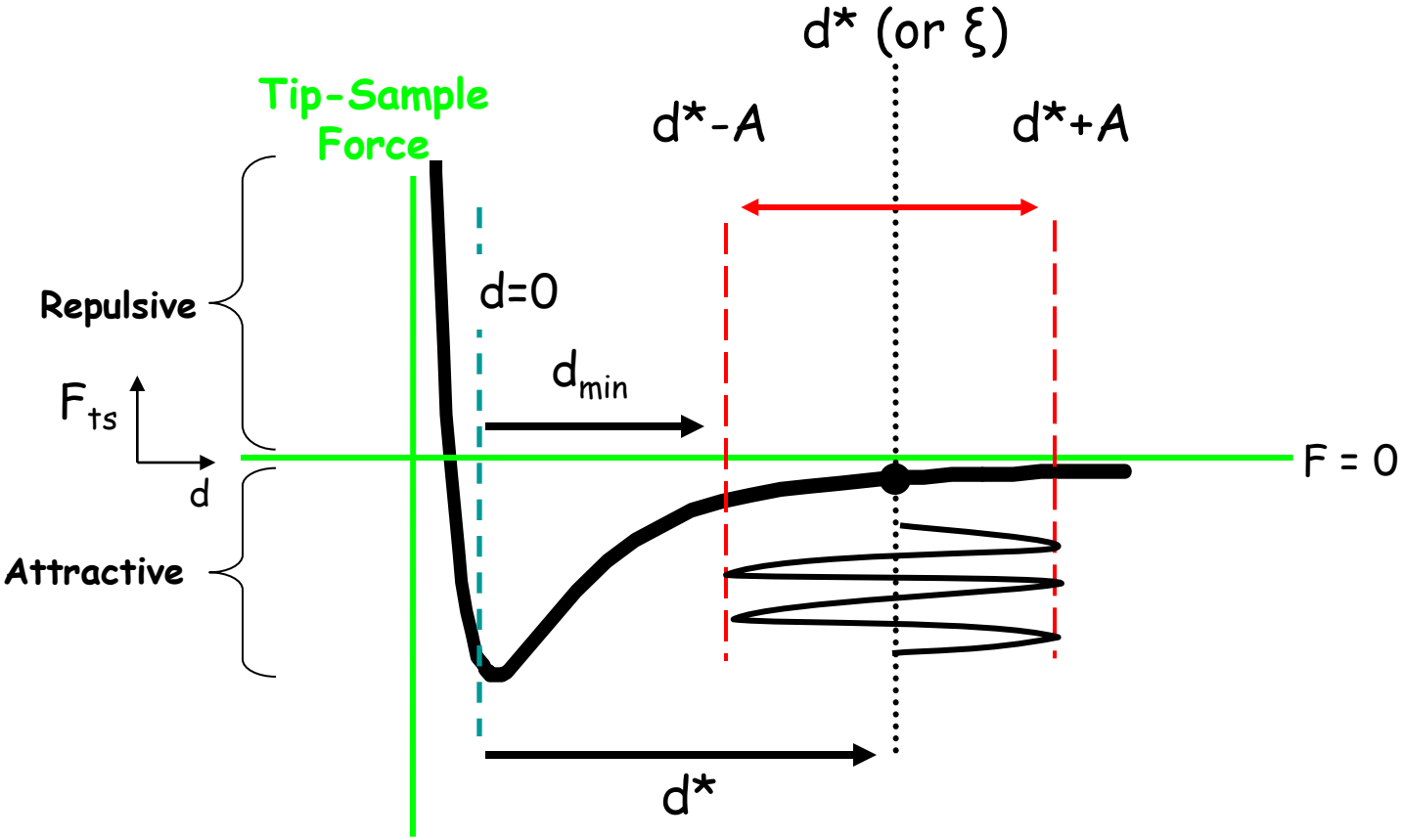

No laser required to measure deflection

# FM-AFM
# Constant Frequency Images




Scan while keeping ω(d*) and Q constant

# FM-AFM Force Spectroscopy

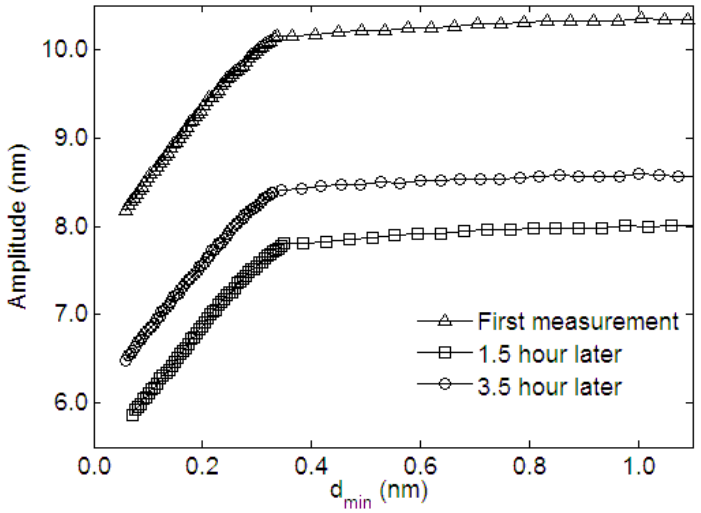


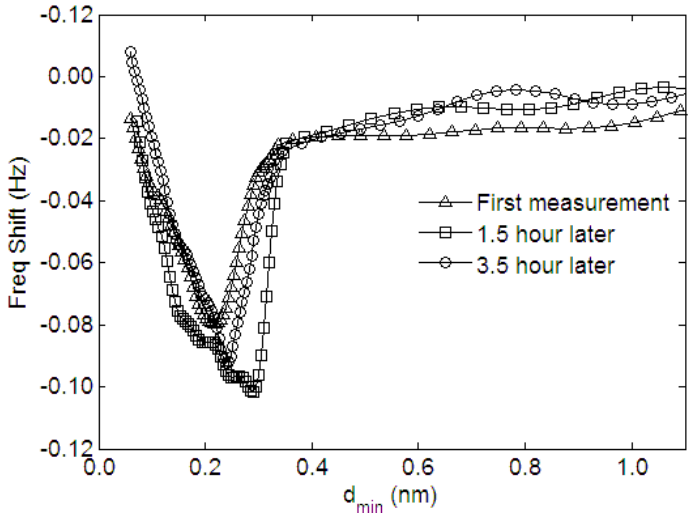

$$F_{ts}(d_{\min}) = 2k_c \int_{d_{\min}}^{\infty} \left\{ \left[ 1 + \frac{\sqrt{A}}{8\sqrt{\pi(\xi - d_{\min})}} \right] \Omega(\xi) - \frac{A^{3/2}}{\sqrt{2}\,(\xi - d_{\min})} \frac{d\Omega(\xi)}{d\xi} \right\} d\xi$$

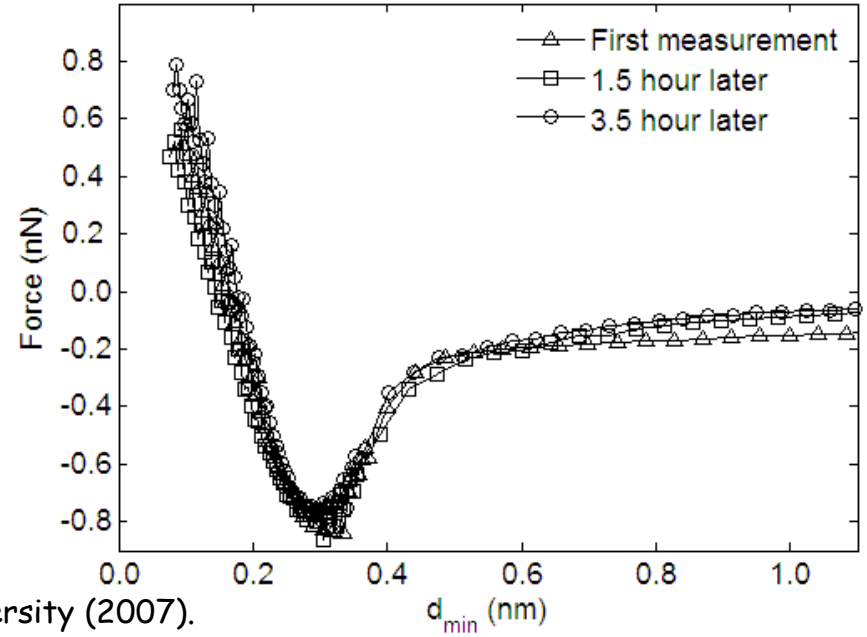
where $\Omega(\xi) \equiv \dfrac{\Delta f(\xi)}{f_o}$ $\qquad \xi \Leftrightarrow d^*$

# FM-AFM Force Spectroscopy

## W tip – HOPG substrate

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