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A tuning fork force microscope

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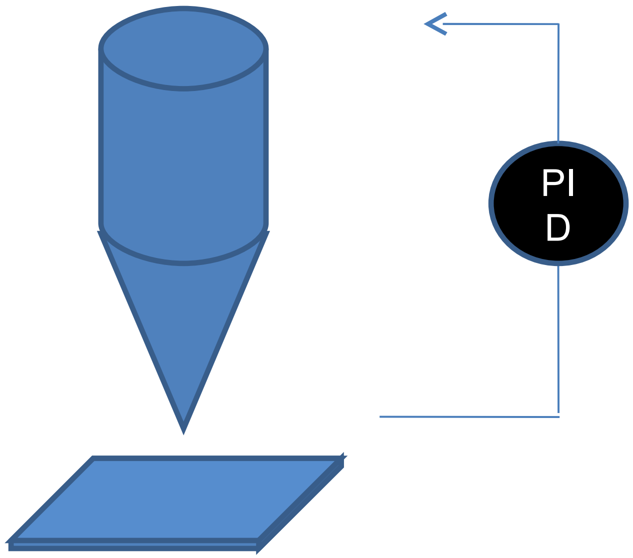
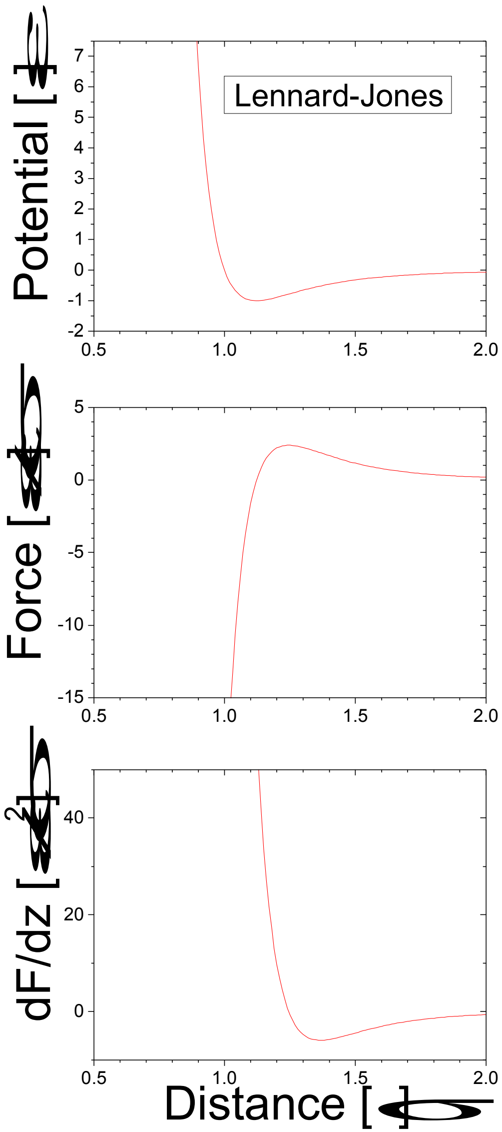
Scanning Probe Microscopy

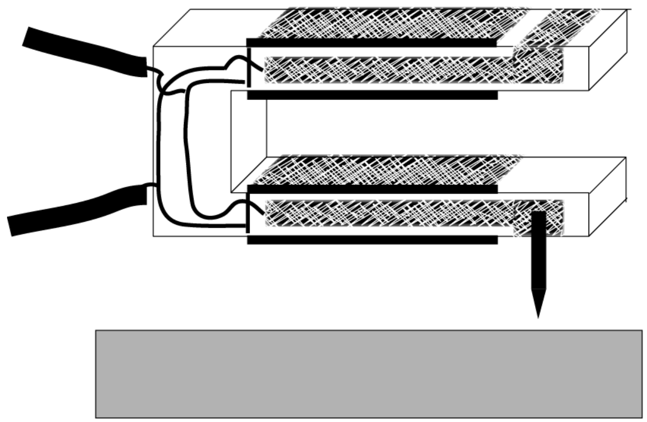


Measures a quantity F that is fed into a PID. This determines the difference to a desired value and changes the position of the tip accordingly, using an actuator.

Quantity	Instrument
Current	STM
Force	AFM
Magnetic Force	MFM
Workfunction	KPM
Force Gradient	??? (TF AFM)

The interaction potential





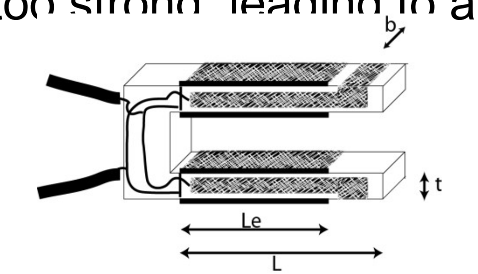
$$\kappa_{tot} = \kappa + \kappa_{tip-sample}$$

$$m_{tot} = m_{eff} + m_{tip}$$

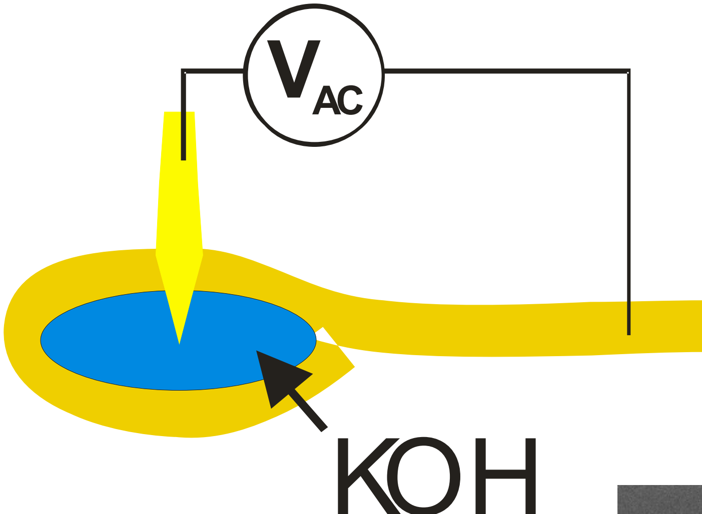
Large κ leads to a relatively insensitive tuning fork

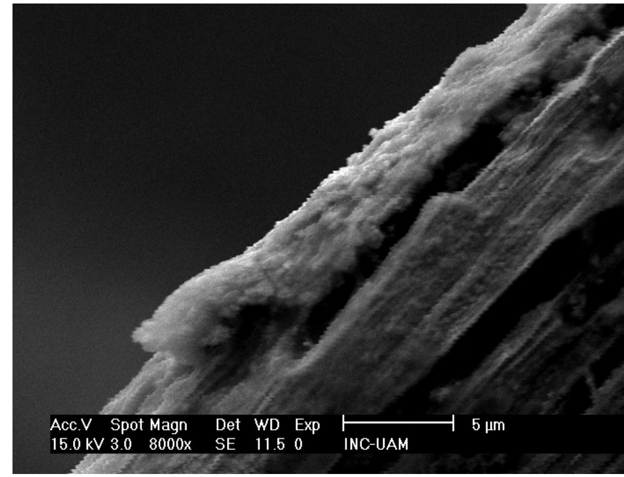
Small κ makes the surface too strong, leading to a "snapping" of the tip

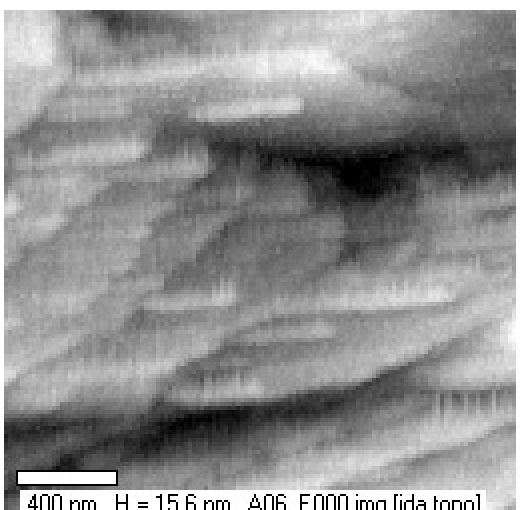
$$\kappa = \frac{1}{4} Yb \left(\frac{t}{L} \right)^3 \approx 2 \text{ kNm}^{-1}$$

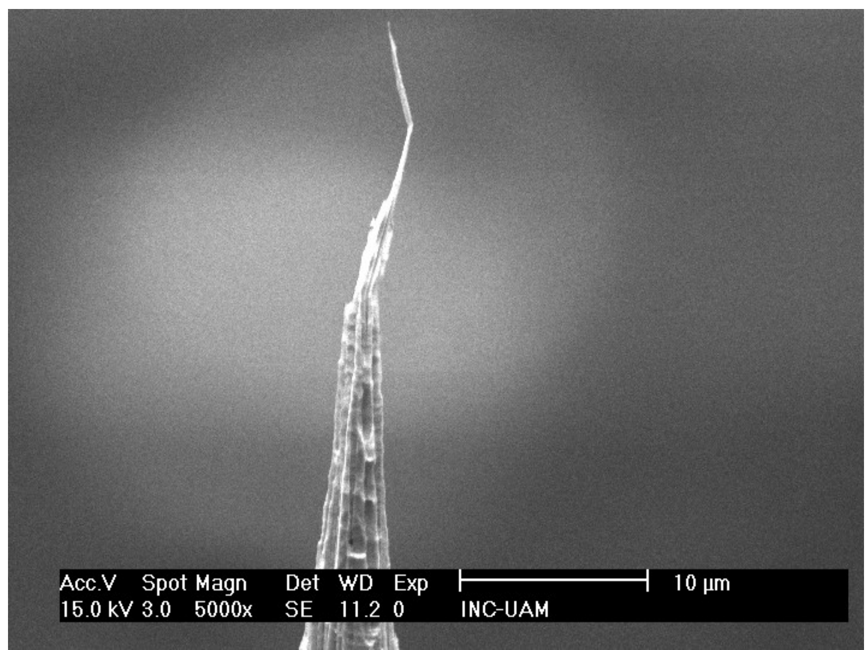


Etching commercial wire in KOH

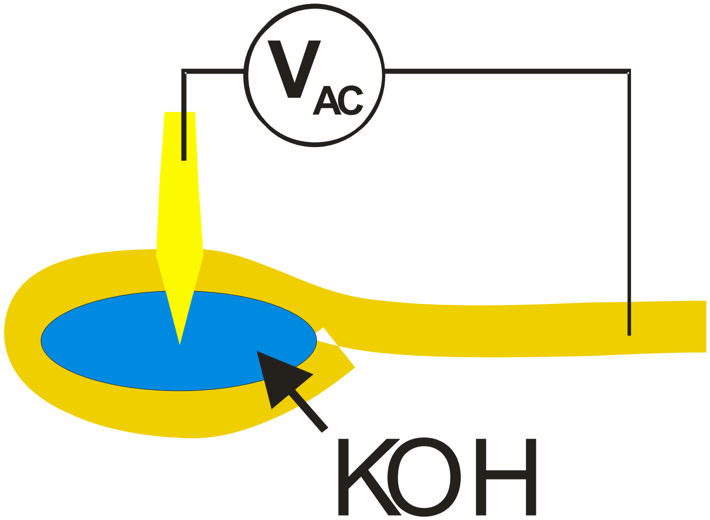


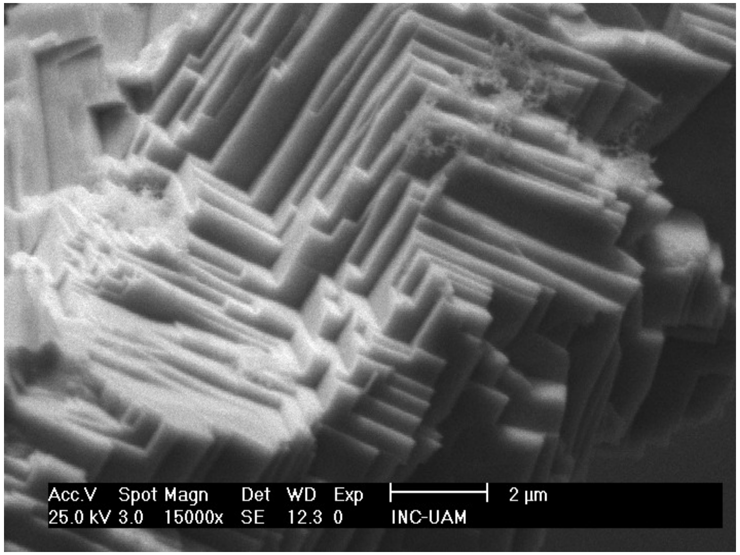


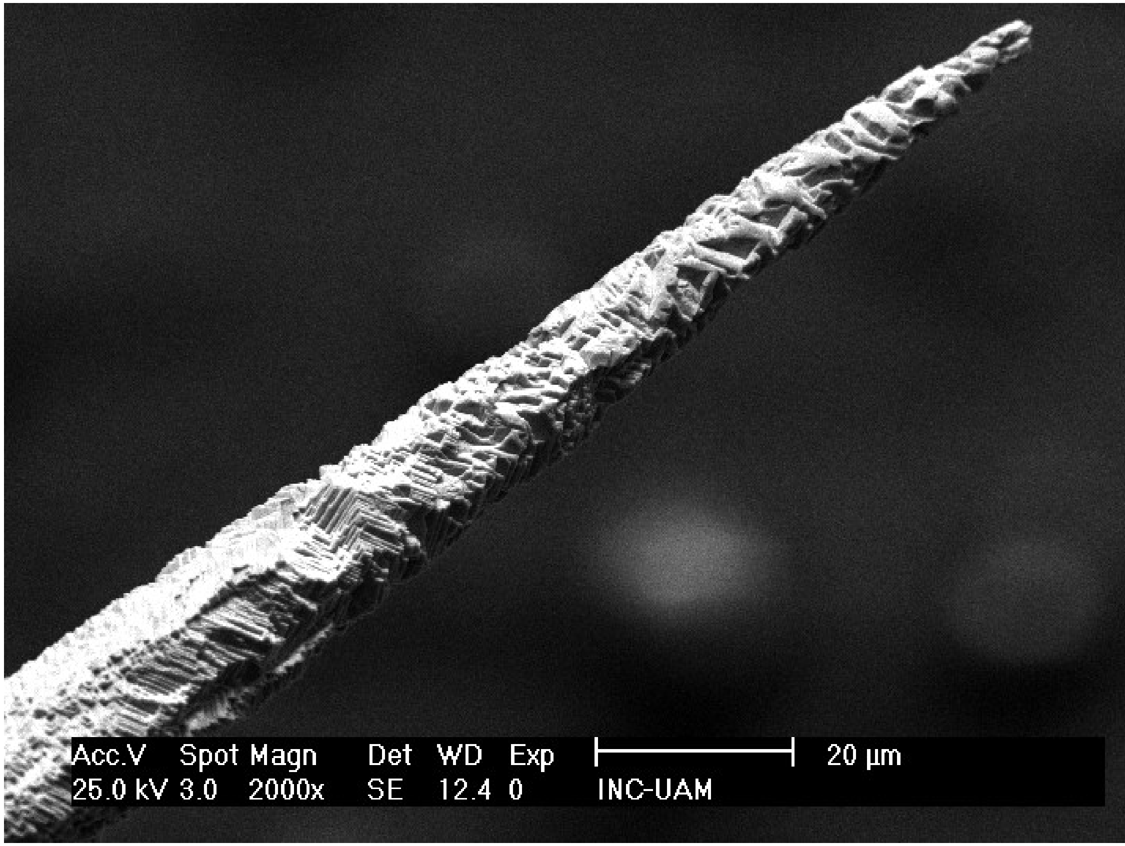




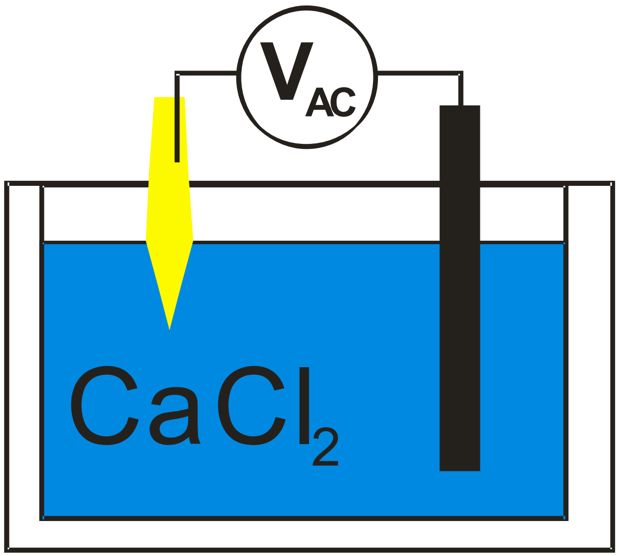
Etching annealed wire in KOH

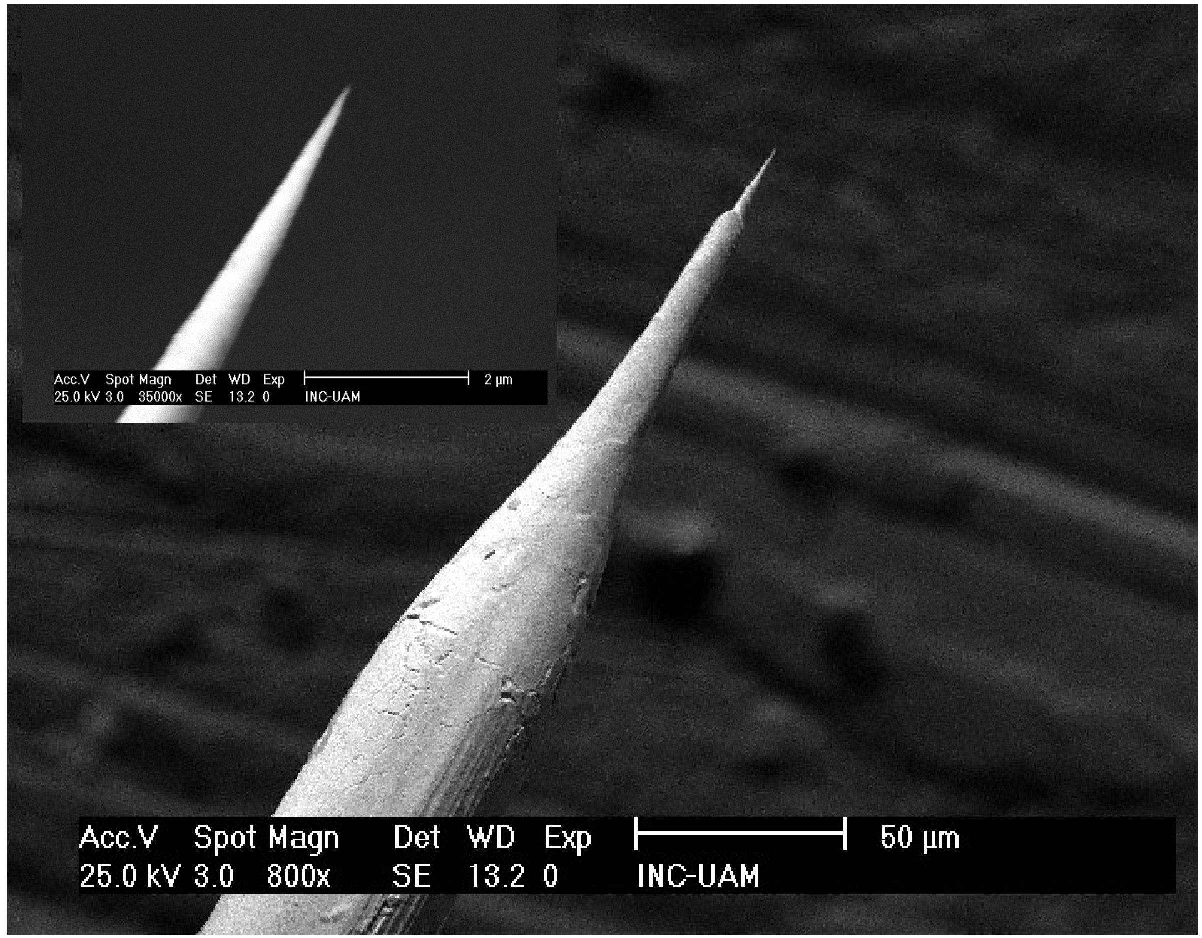




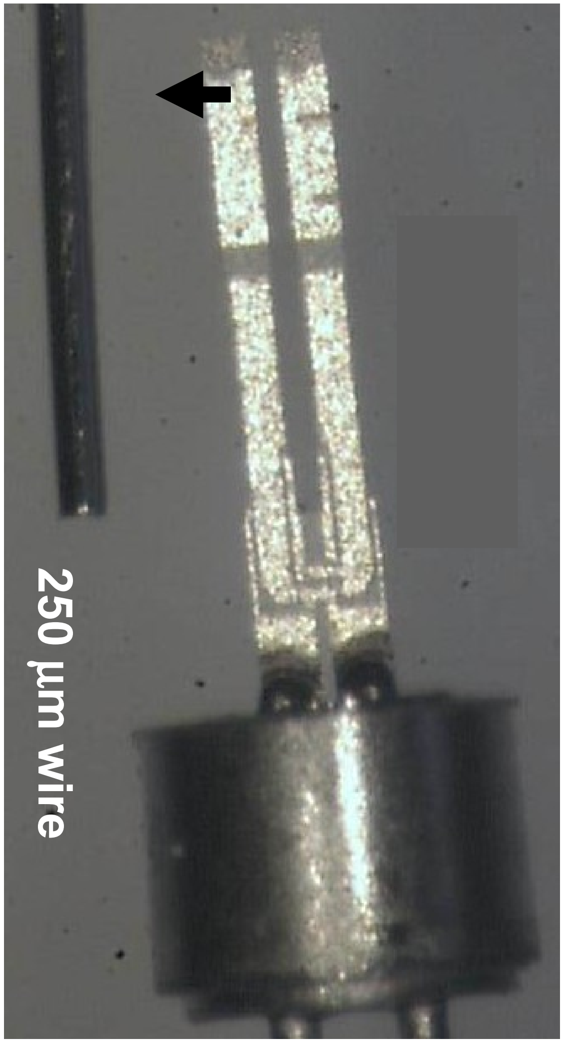


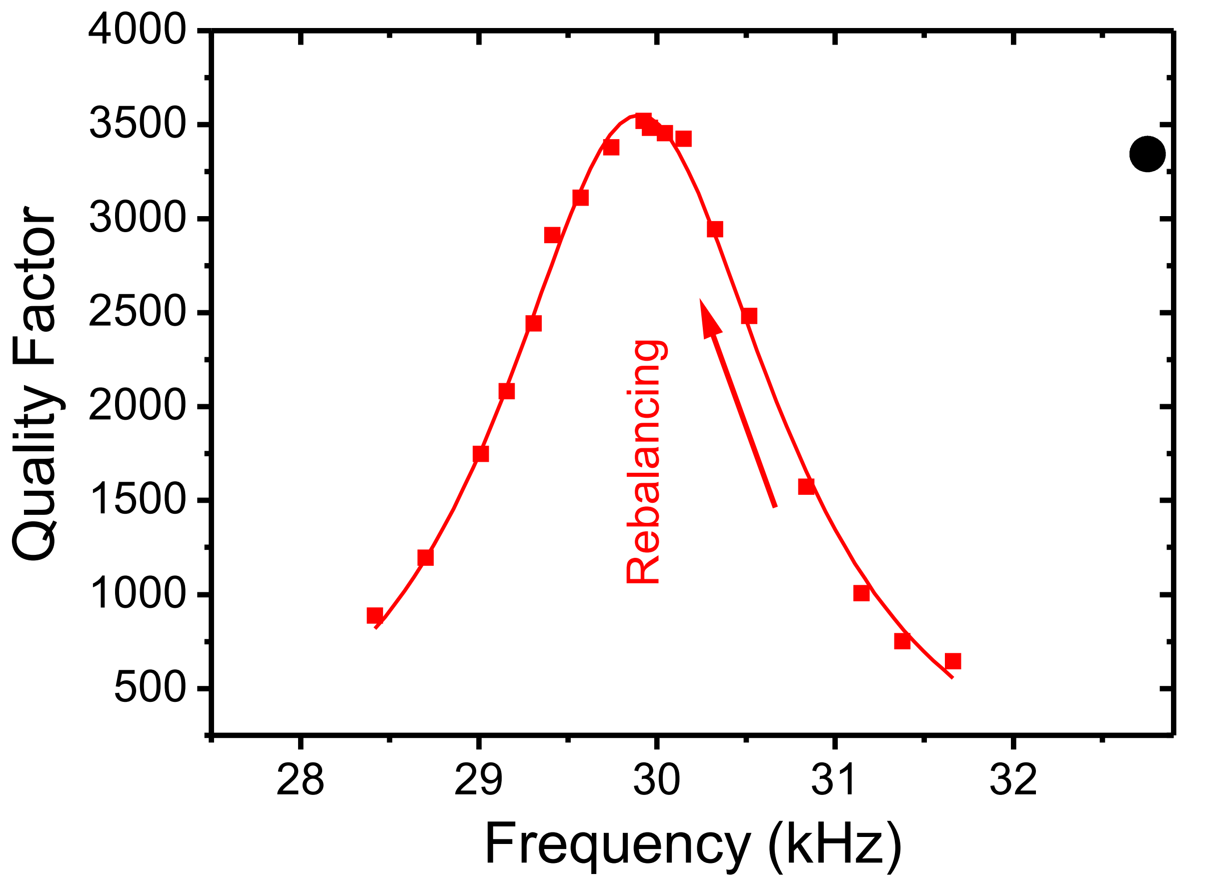
The annealed wire in $CaCl_2$





Equilibration of the Prongs

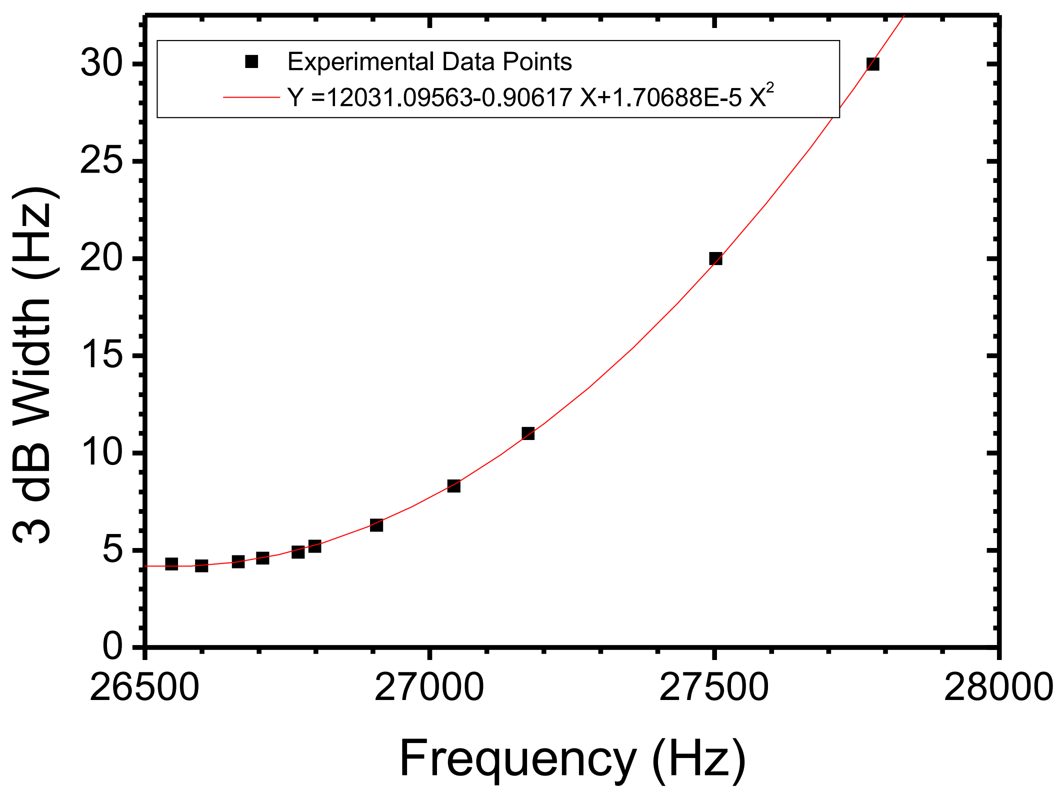




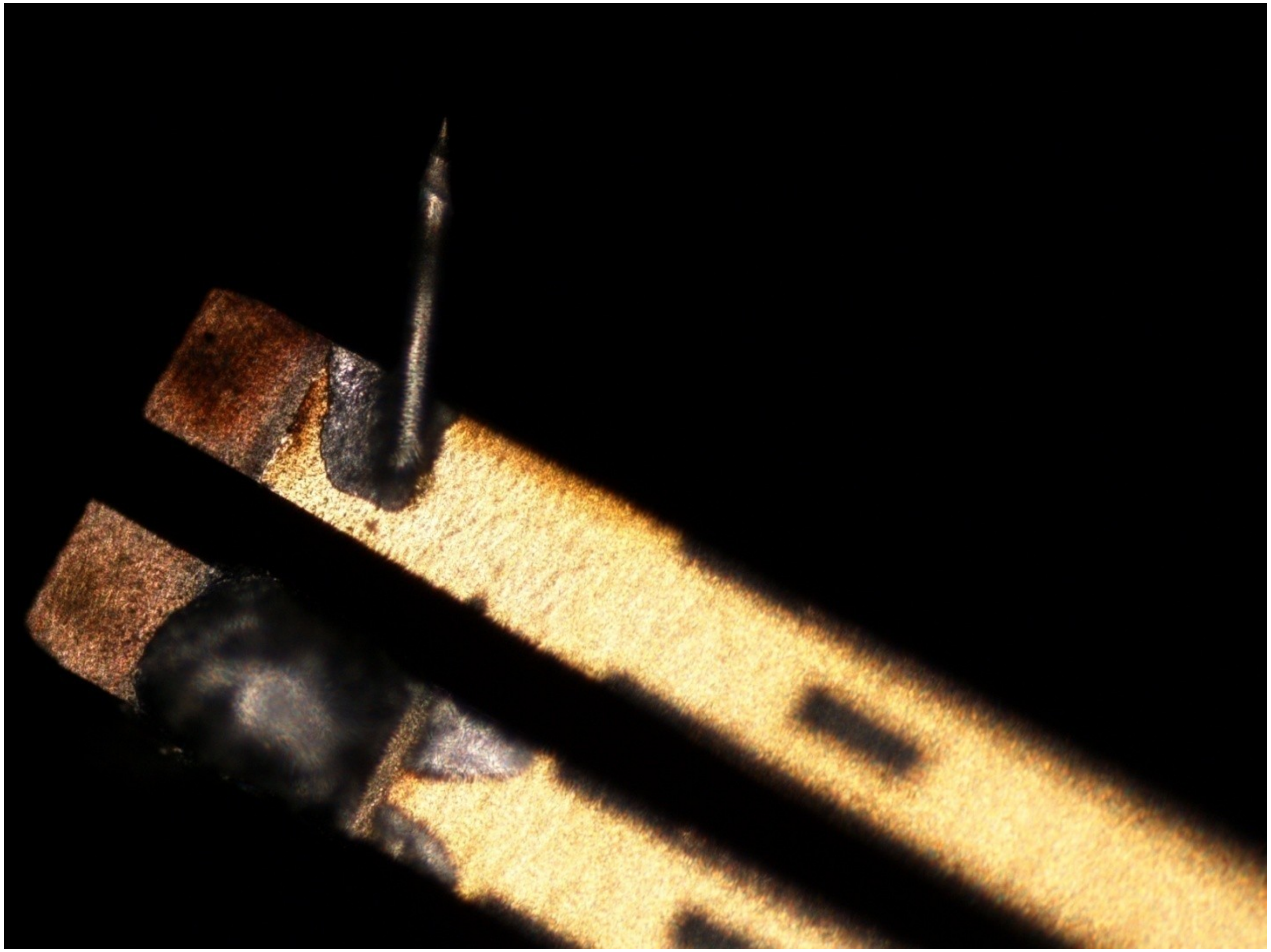
Precise Compensation

f_0 (Hz)	Δf (Hz)	Q (*1000)	Expected f_{00} (Hz)
27778	30	0.9	-
27502	20	1.4	-
27173	11.0	2.5	26405
27041.9	8.3	3.6	26406
26906.2	6.3	4.3	26465
26797.9	5.2	5.2	26502
26768.6	4.9	5.5	26506
26706.6	4.6	5.8	26520
26663.6	4.4	6.1	26529
26599.1	4.2	6.3	26535
26547.0	4.3	6.2	26545

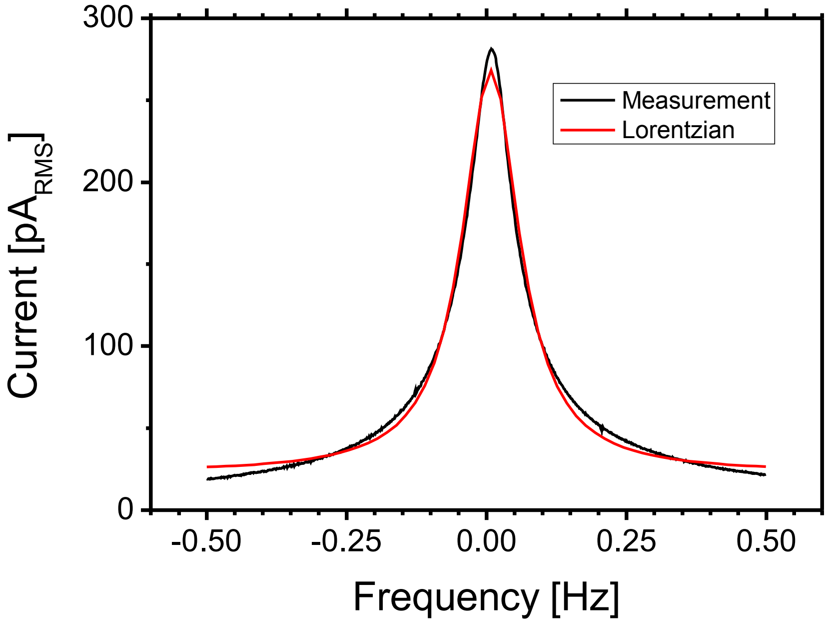
Compensation of the mass by solder paste of which each particle of approx. 50 µm diameter changes the frequency by 10 Hz

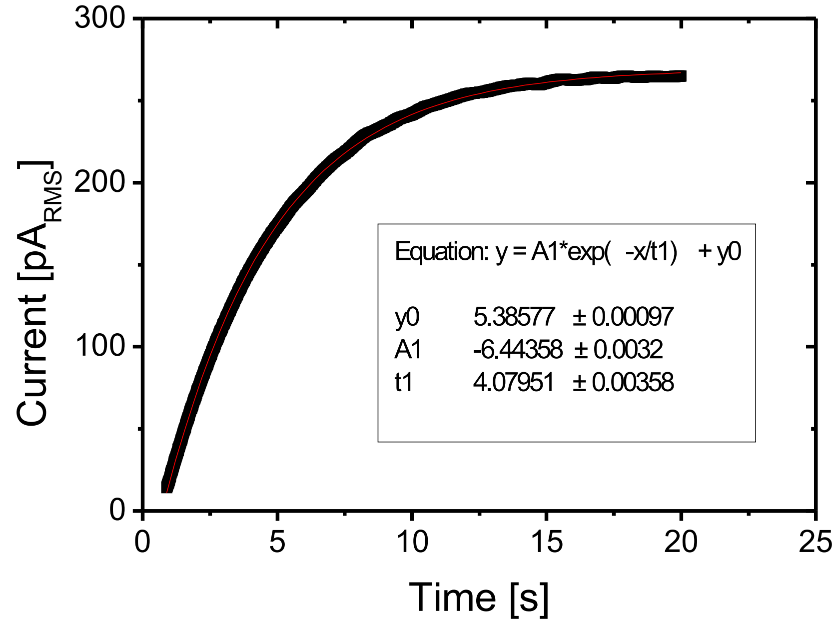


The final candidate



The Tuning Fork at low T





Q=(360±5)*10^3

Q=(363±1)*10^3

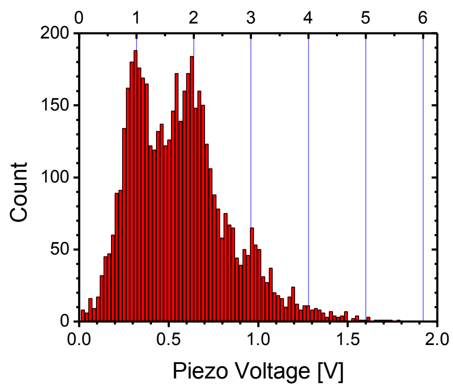
$$R=\frac{V}{I}=\frac{5\cdot 10^{-6}}{2\sqrt{2}*267\cdot 10^{-12}}=6.62\ \mathrm{k}\,\Omega$$

$$L=\frac{RQ}{\omega}=\frac{6.62\cdot 10^{3}*363\cdot 10^{3}}{2\pi*27502.60}=13.8\ \mathrm{kH}$$

$$C=\frac{1}{L\omega^{2}}=2.43\ \mathrm{fF}$$

Calibration

From DC



0.78±0.06 nm/V_{DC}

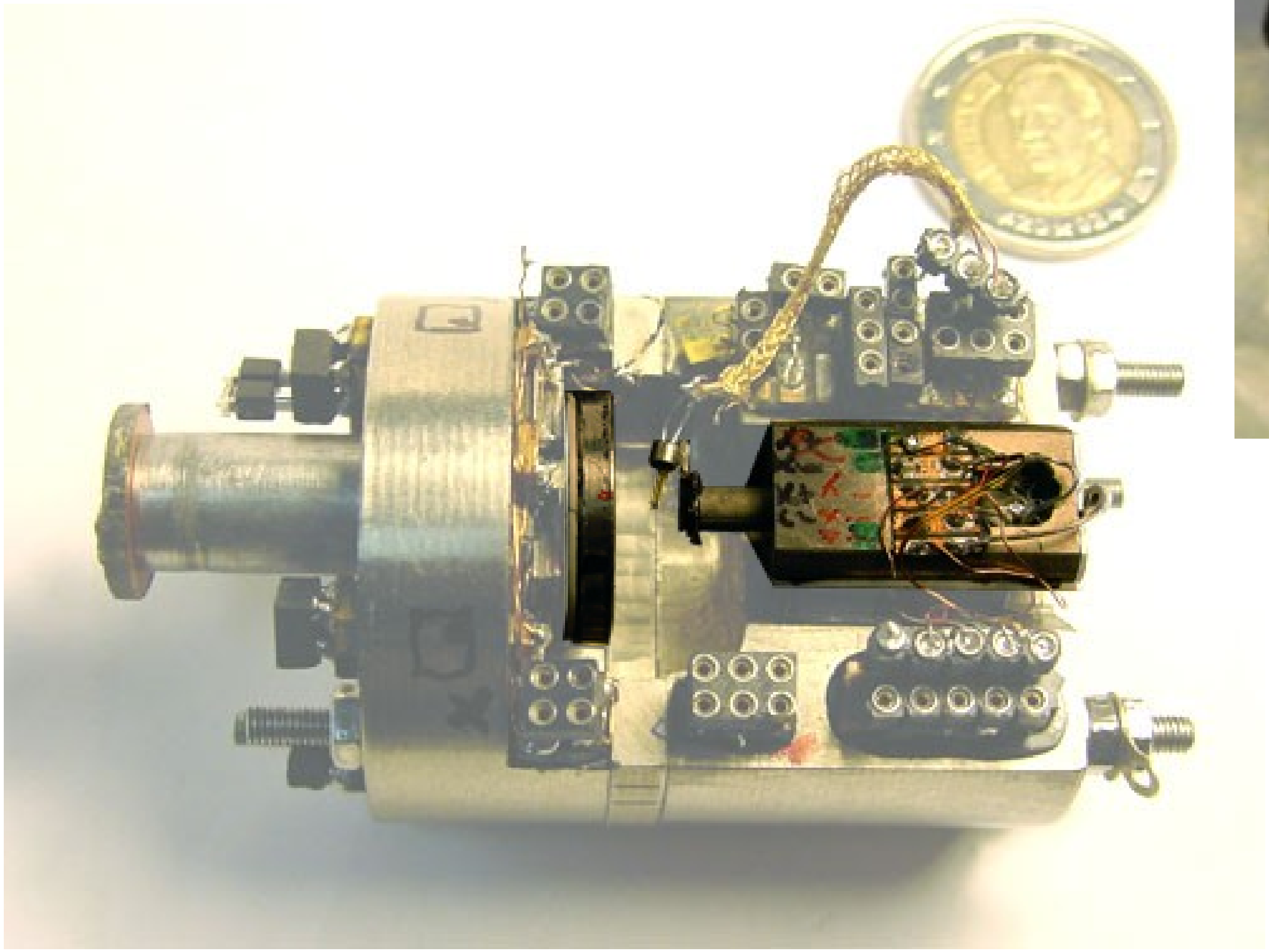
$$\frac{A}{V_{AC}} = Q\frac{\Delta z}{V_{DC}}$$

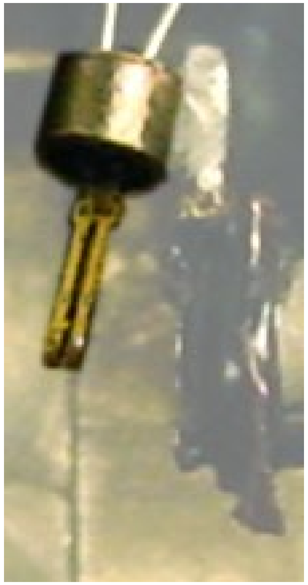
1.85±0.15 nm/nA_{AC}

$$Q = \frac{\kappa A^2}{\pi V_{AC} I_{AC} / \omega_{00}}$$

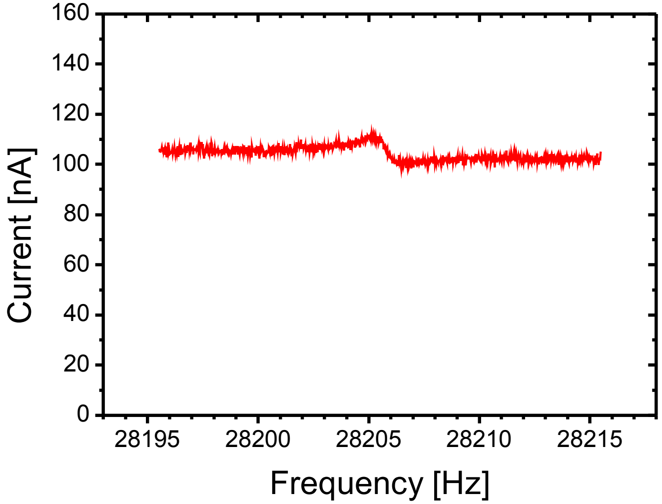
κ = 2.8±0.2 kN/m

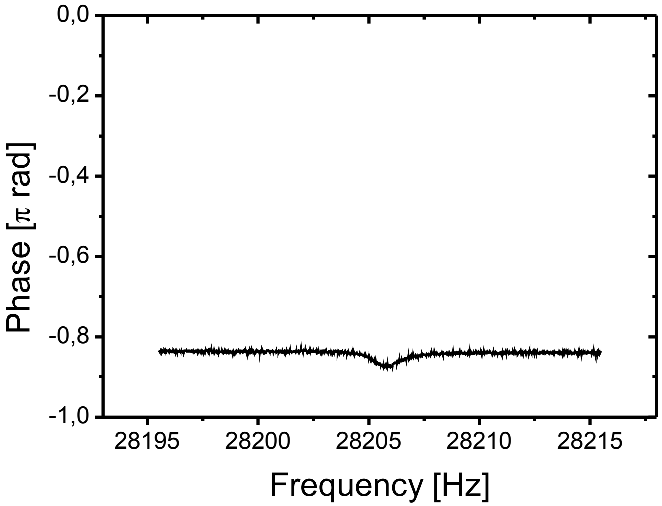
The Microscope

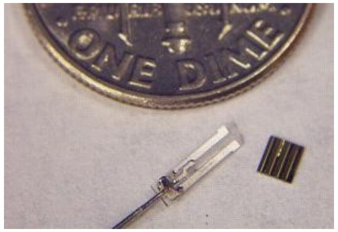




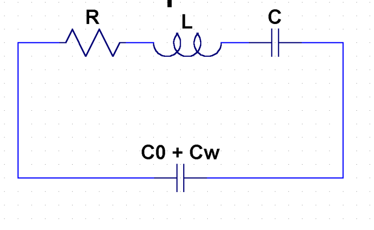
Electrical Compensation

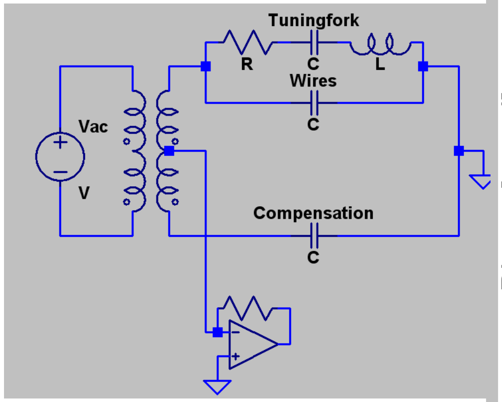


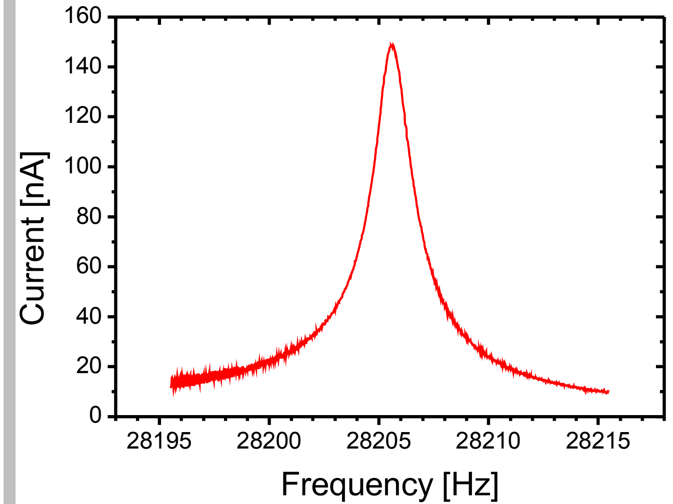


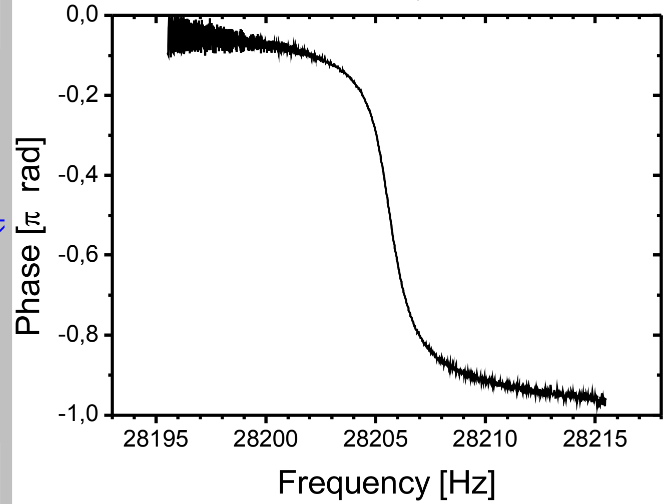


equals

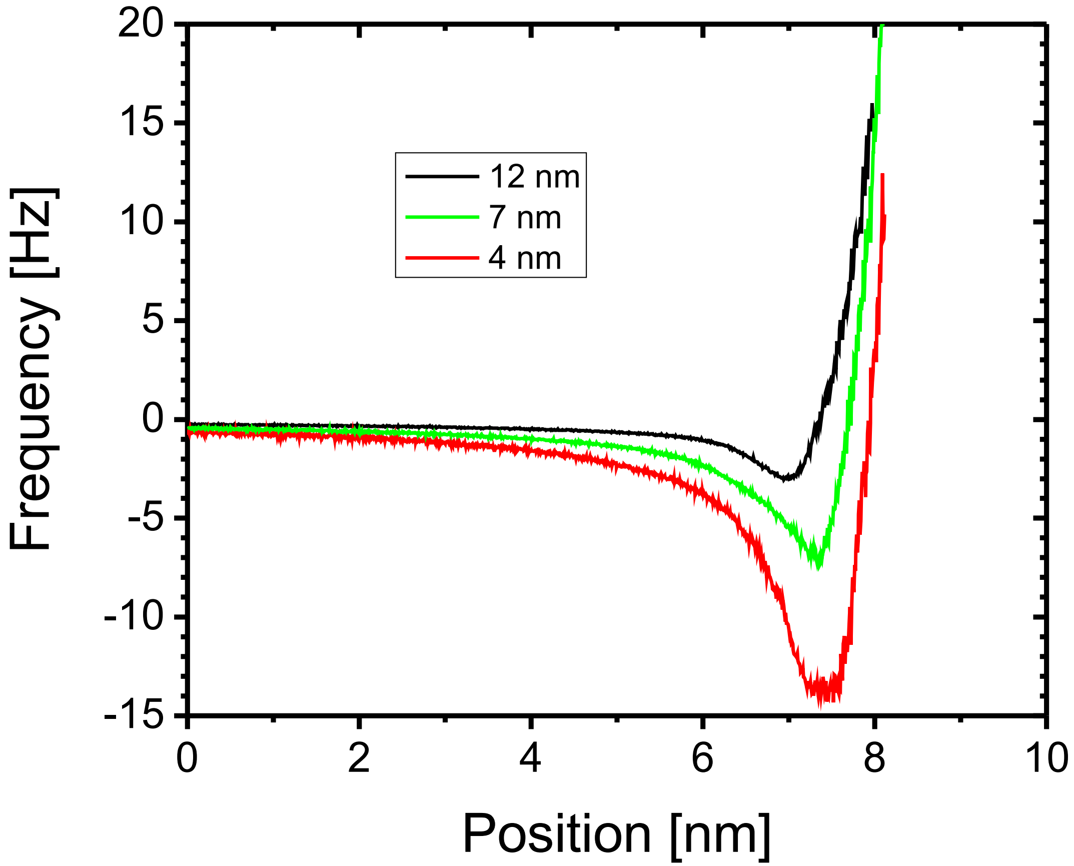








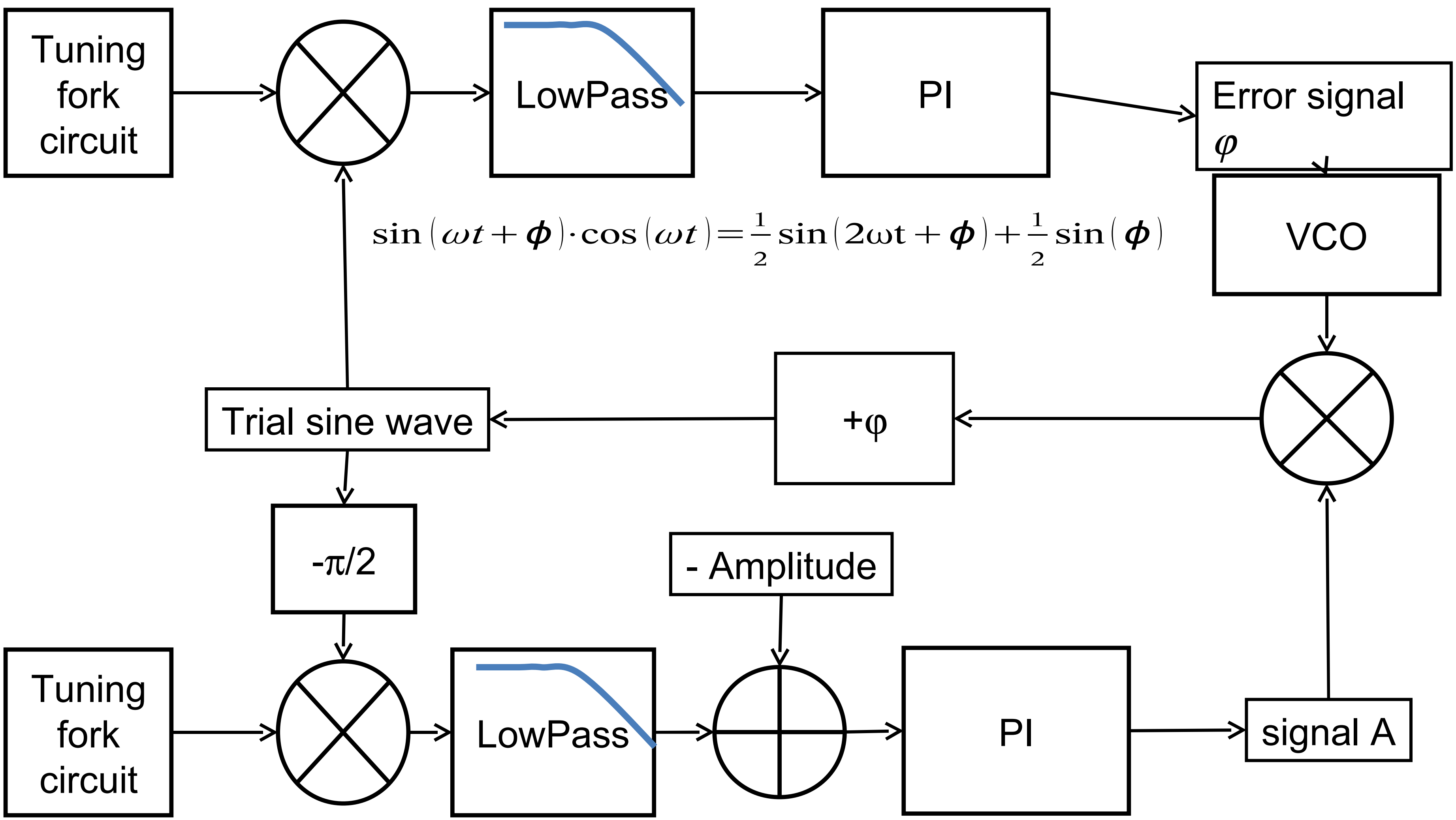
Need PLL



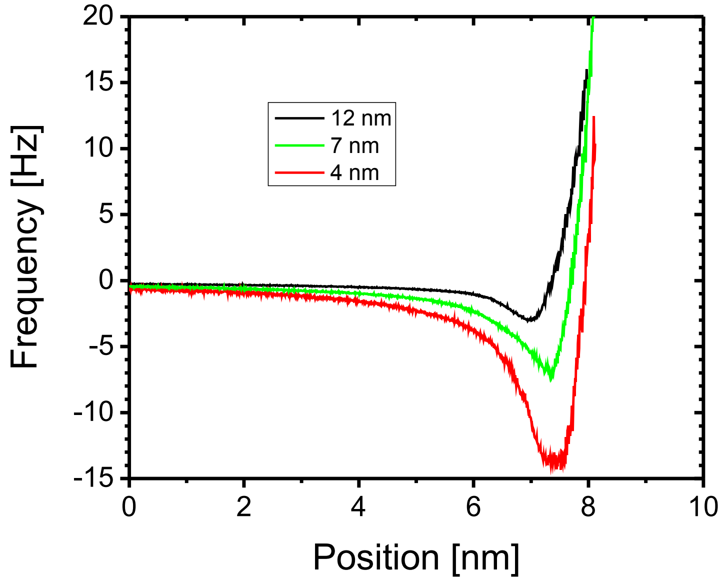
The observed change in resonance frequency with distance can be of the order of 10 Hz. Our resonance had a width of 0.2 Hz, making constant frequency excitation impossible.

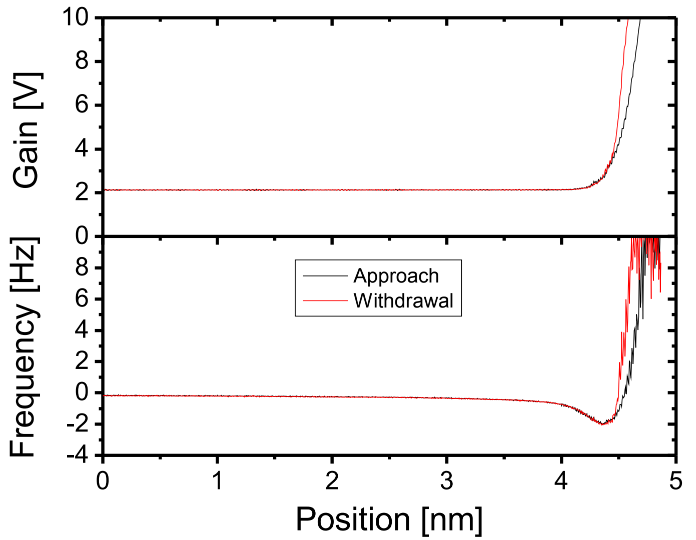
We thus need to excite at the resonance → We have need of a phase locked loop (PLL)

The PLL circuit



Problems with course approach





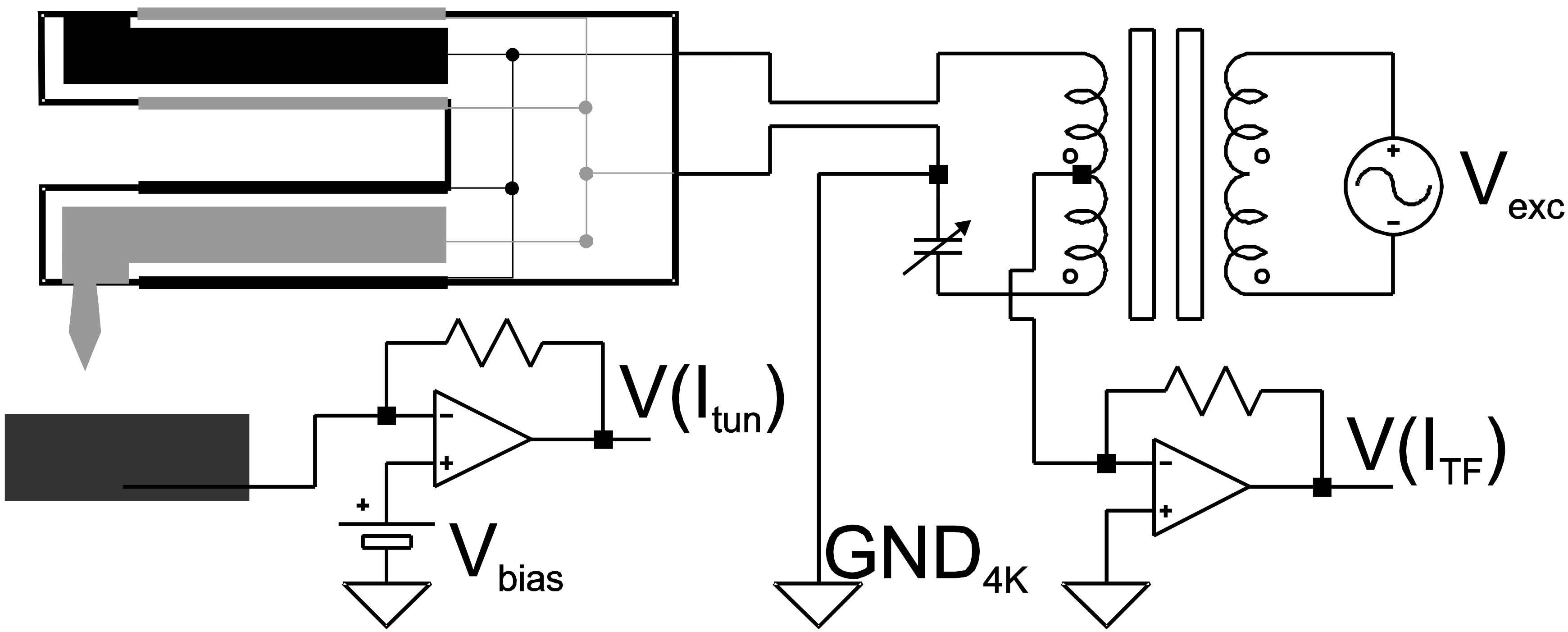
•At low amplitudes the frequency signal responds sooner to the presence of the surface, but the electrical signal is smaller.

$$A \cdot \sin(\omega t + \phi) \cdot \cos(\omega t) =$$
$$\frac{1}{2} A \sin(2\omega t + \phi) + \frac{1}{2} A \sin(\phi)$$

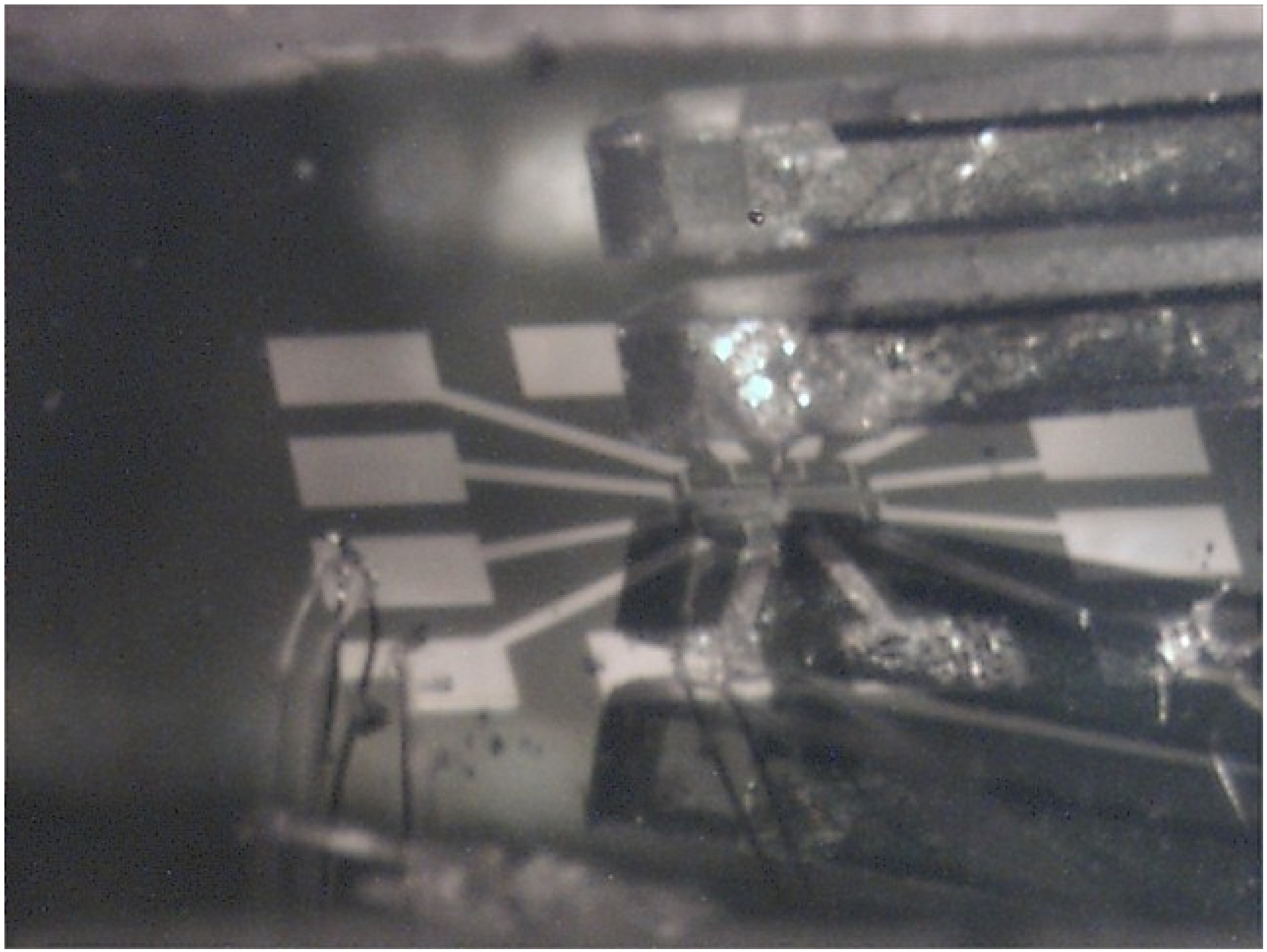
•Since the error signal in phase and amplitude are coupled these PIDs will have a lot of cross-talk.

•Although frequency appears the logical choice, amplitude is far more reliable for high Q tuning forks.

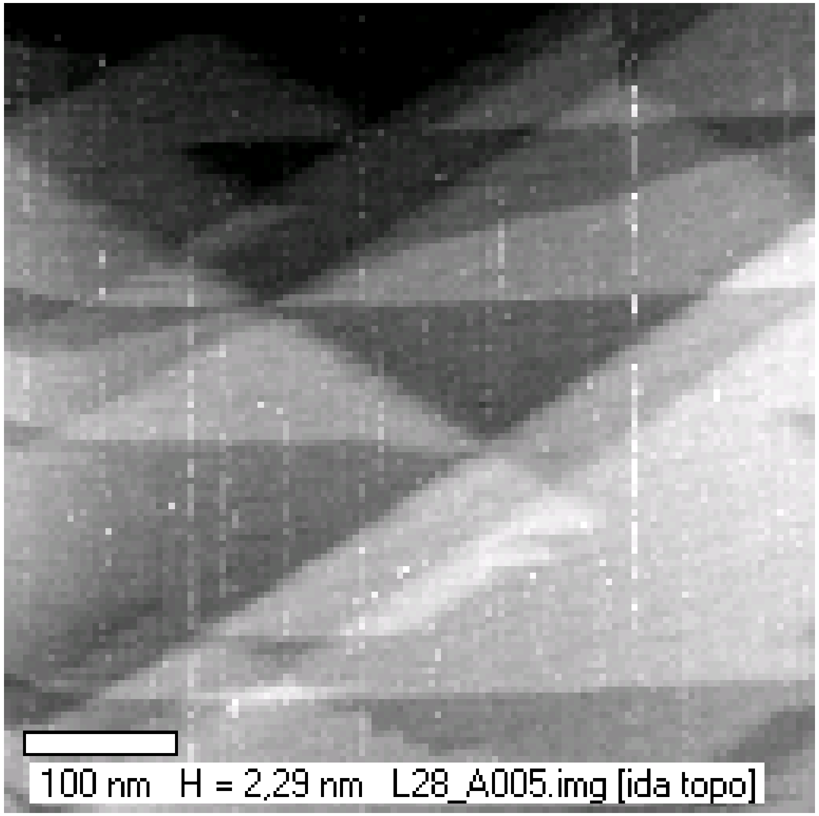
Combined AFM STM

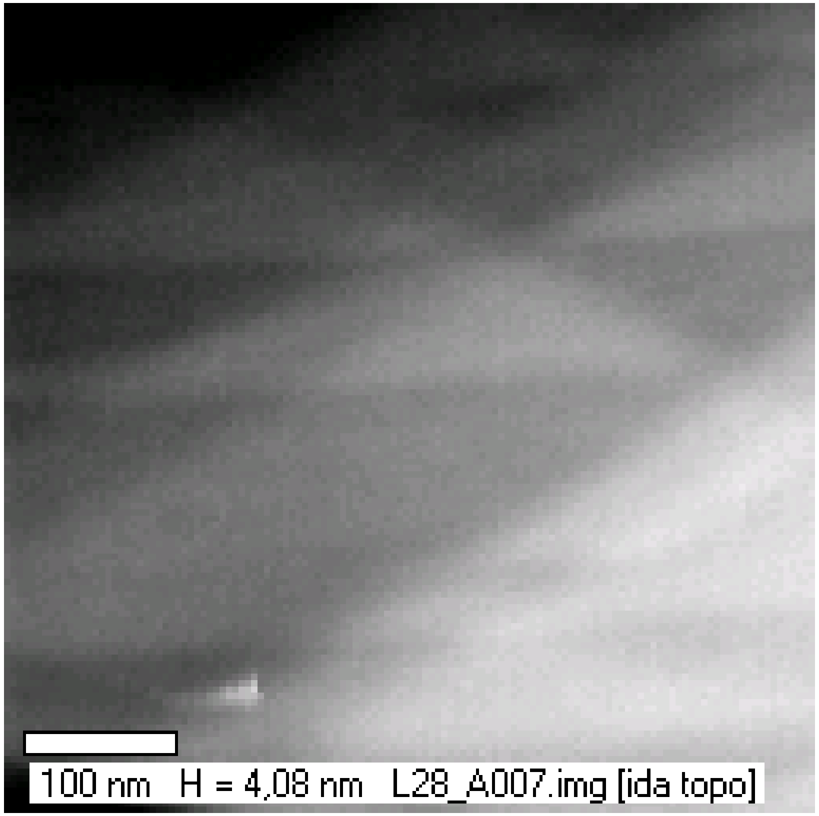


The scanning



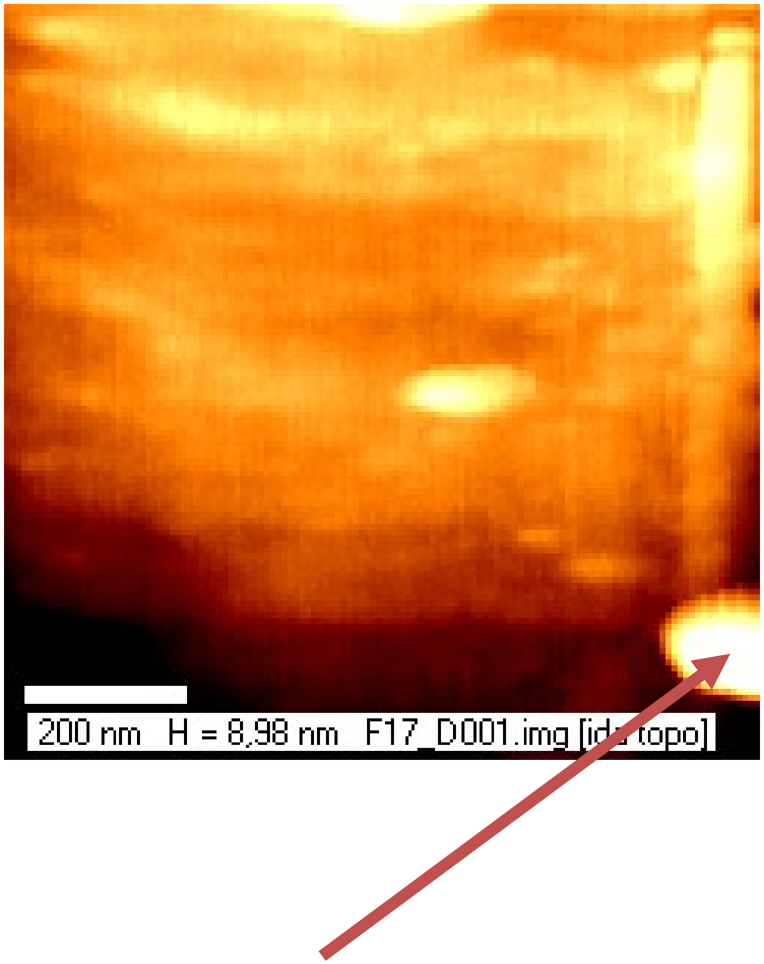
STM vs AFM on Au(111)

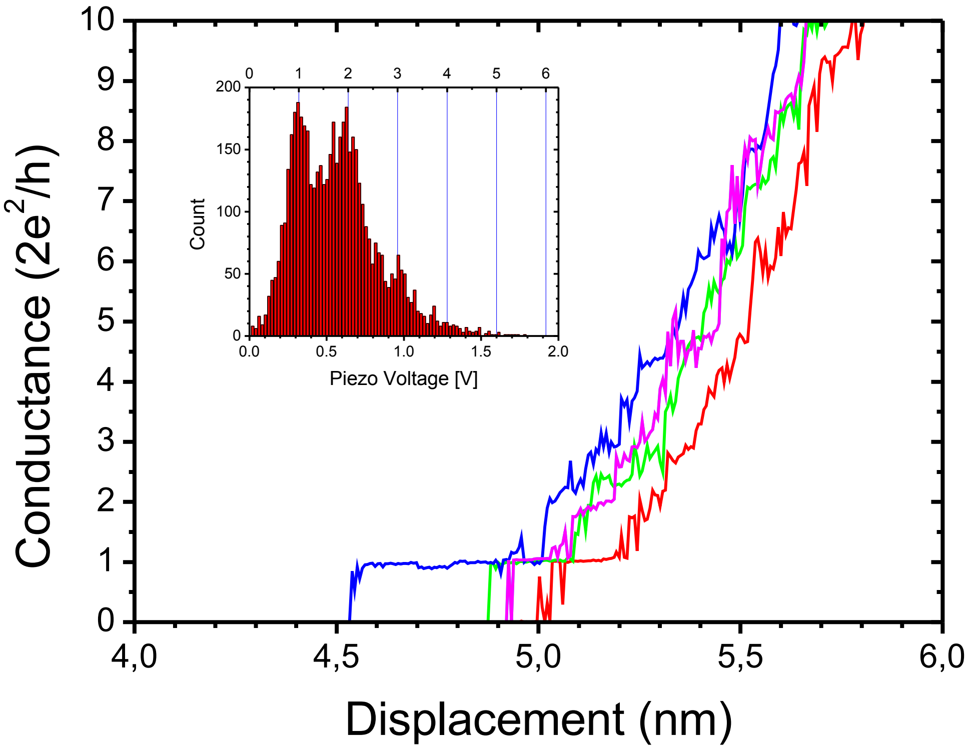




Clean touch on Au(111)

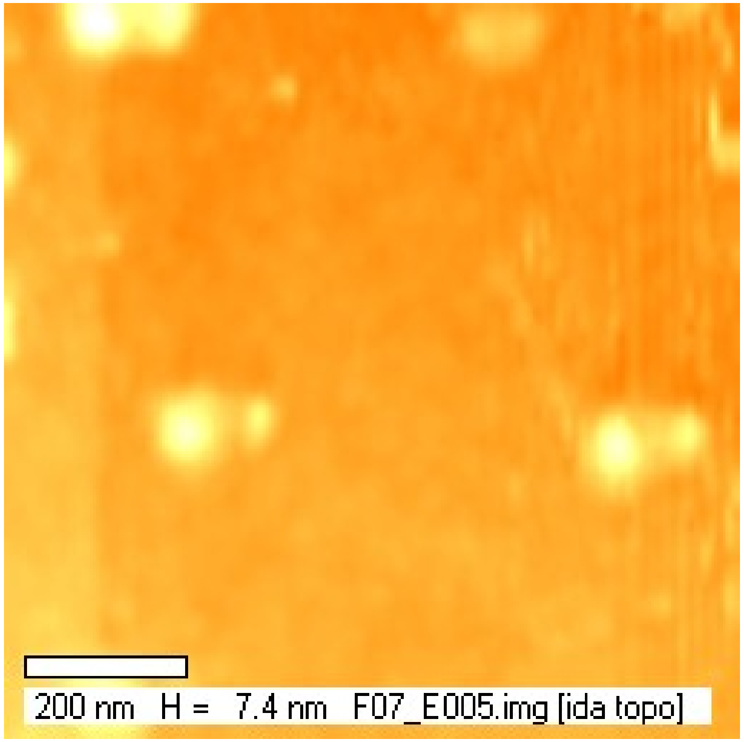
FM-AFM



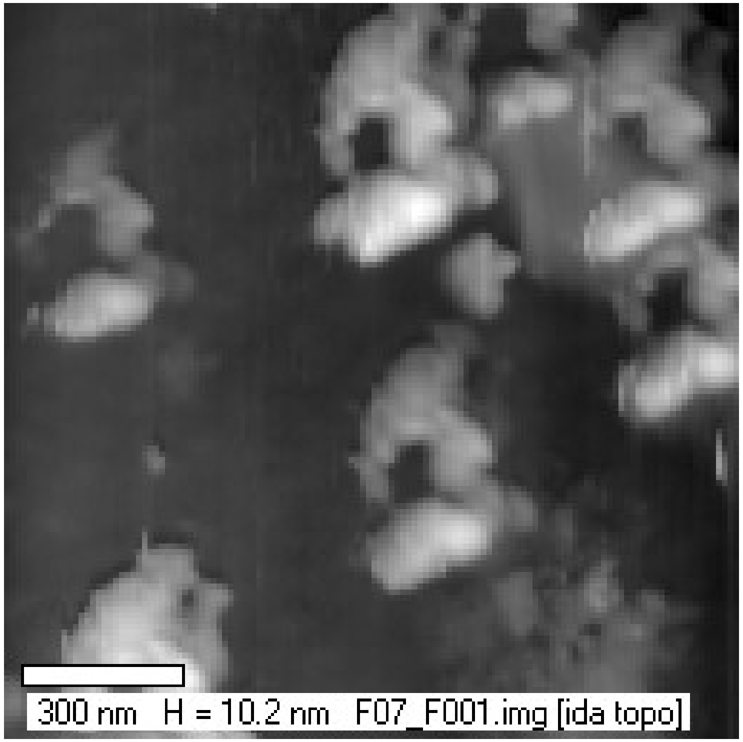


4K

Imaging Au clusters on Glass



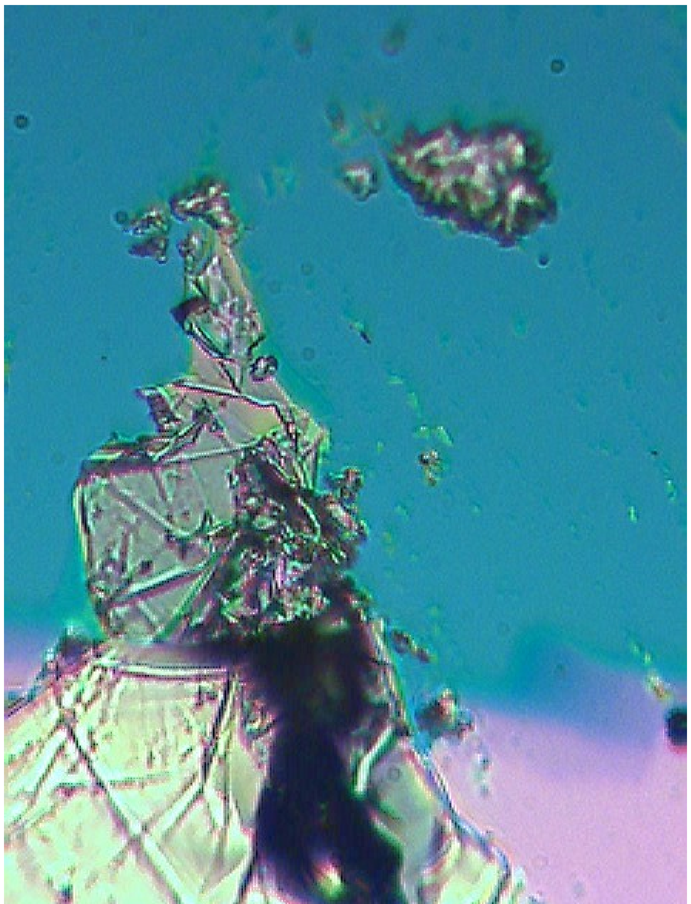
$$\kappa_{tip-sample} = 0.41 \pm 0.03 \text{ N/m}$$

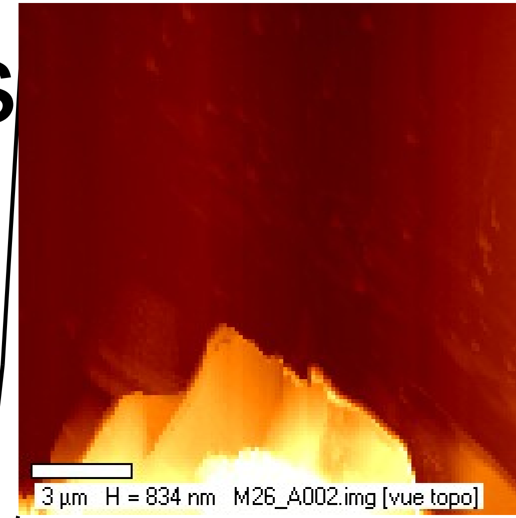


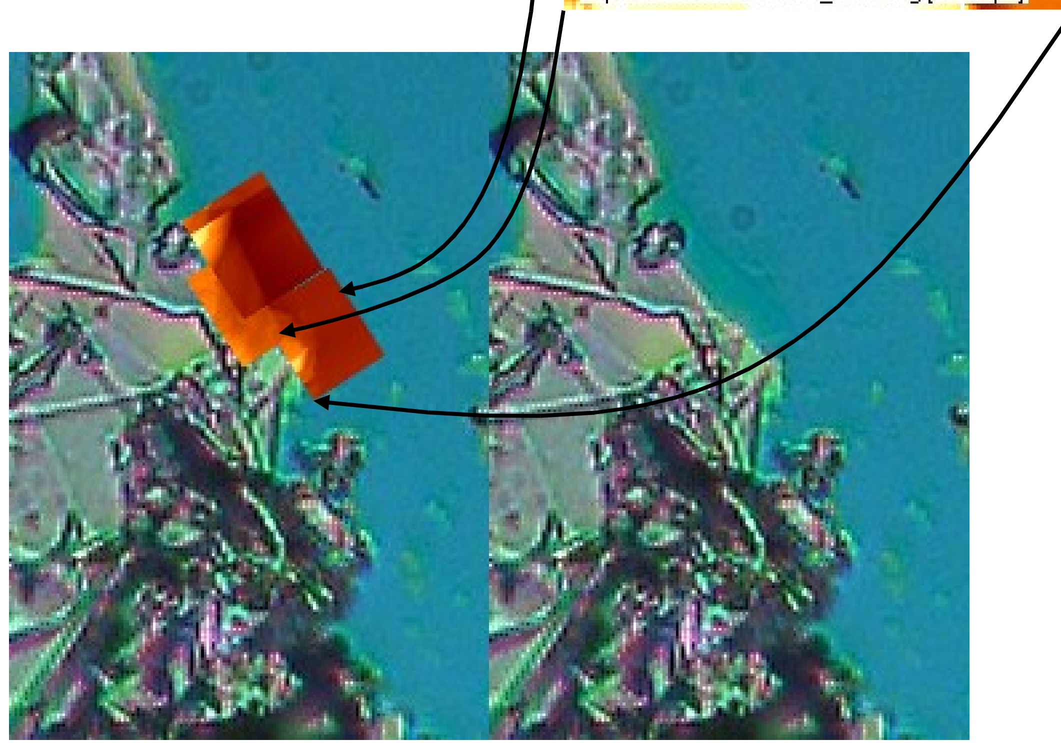
After extra indentation (bent tip)

Hybrid samples

"Graphene" on Silicon Oxide





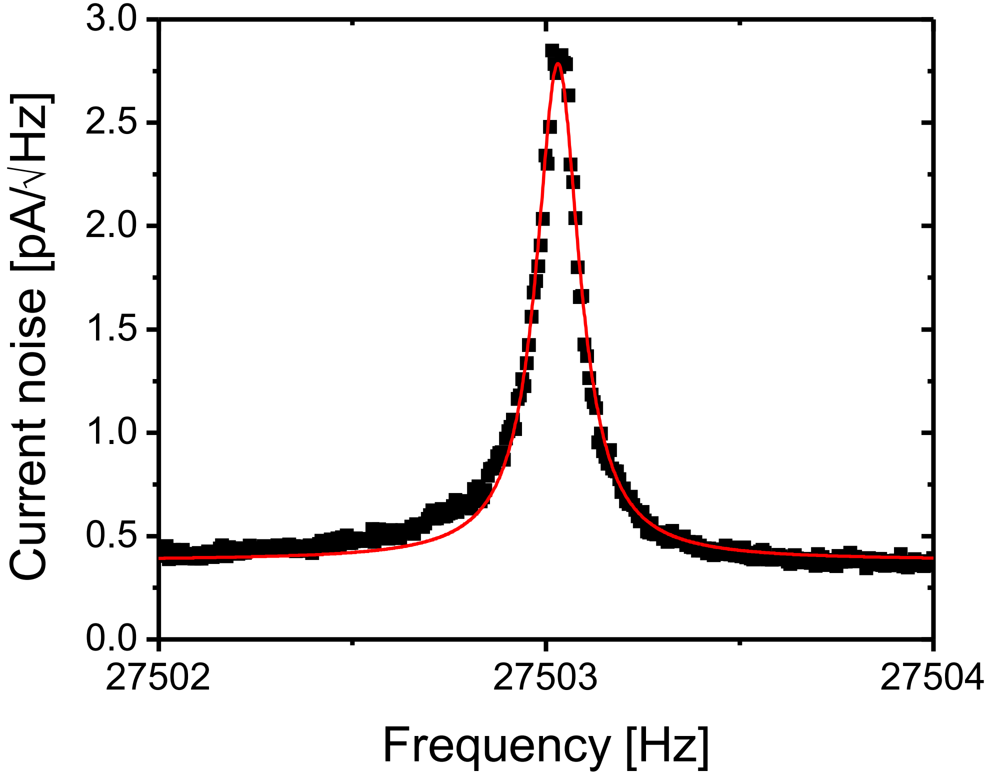


The Tuning Fork AFM

- Is hybrid
- Is non-violent
- Is cool
- Is sharp
- Sees colors

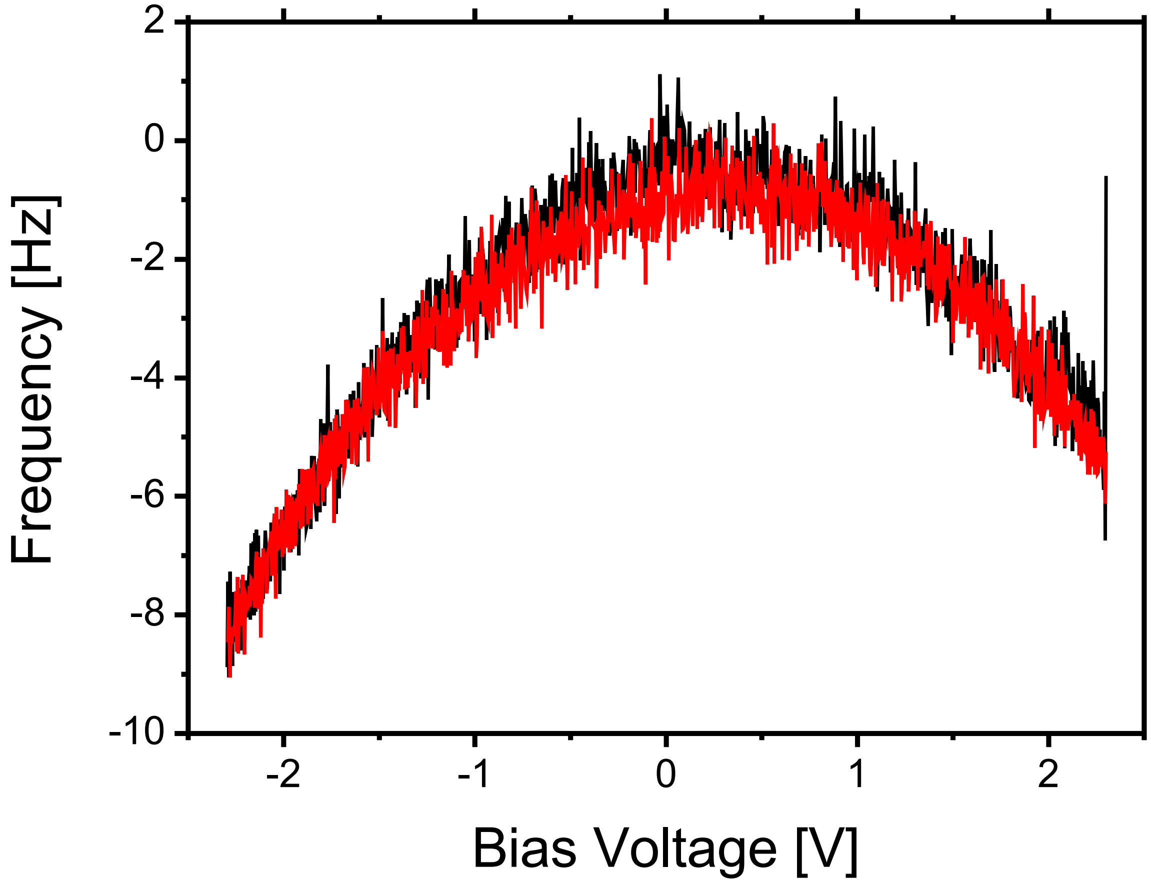
•Can measure both conductive and non-conductive surfaces
•Is a non-contact technique and therefore does not destroy the substrate
•Does not need any adjustments for low temperature use
•Has vertical resolution sub-nm, horizontal 10’s of nm.
•In combination with a bulk tip readily usable for spectroscopy.

Noise behavior understood

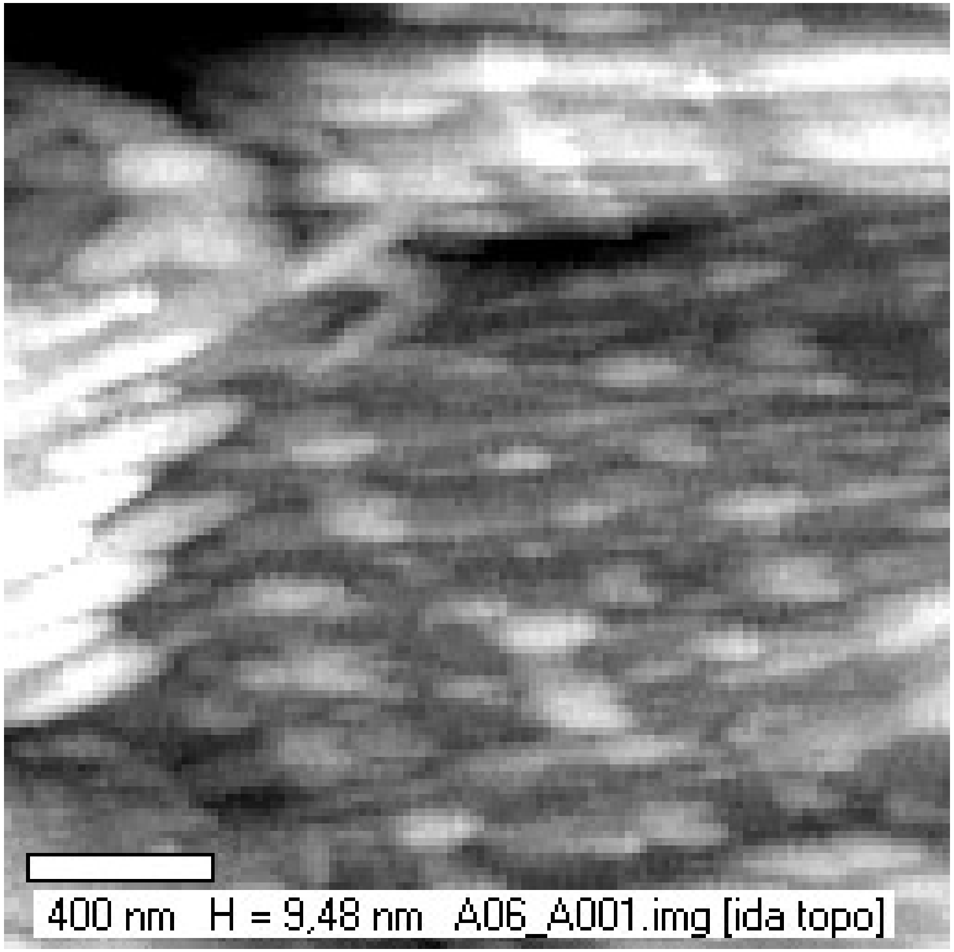


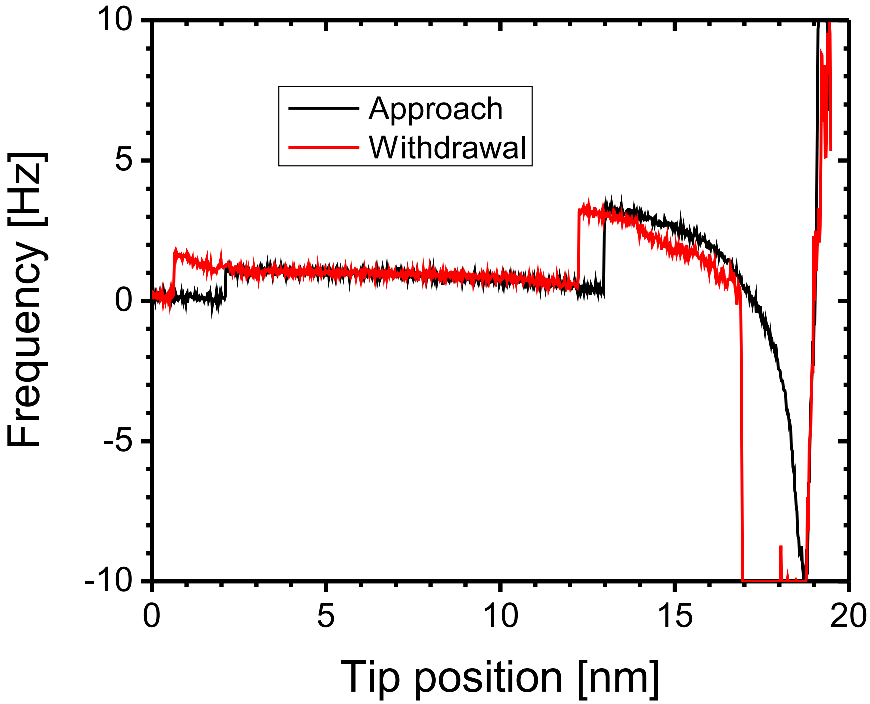
@ 4.2 K
Thermal noise measured by taking the average of 200 FFT-spectra each of $16.7 * 10^6$ data points. (one night)

Kelvin effect



Double tips


400 nm H = 9,48 nm A06_A001.img [ida topo]


Approach
Withdrawal
Frequency [Hz]
Tip position [nm]
10
5
0
-5
-10
0
5
10
15
20