Scanning Force Microscopy (SFM)

And Atomic Force Microscopy (AFM)

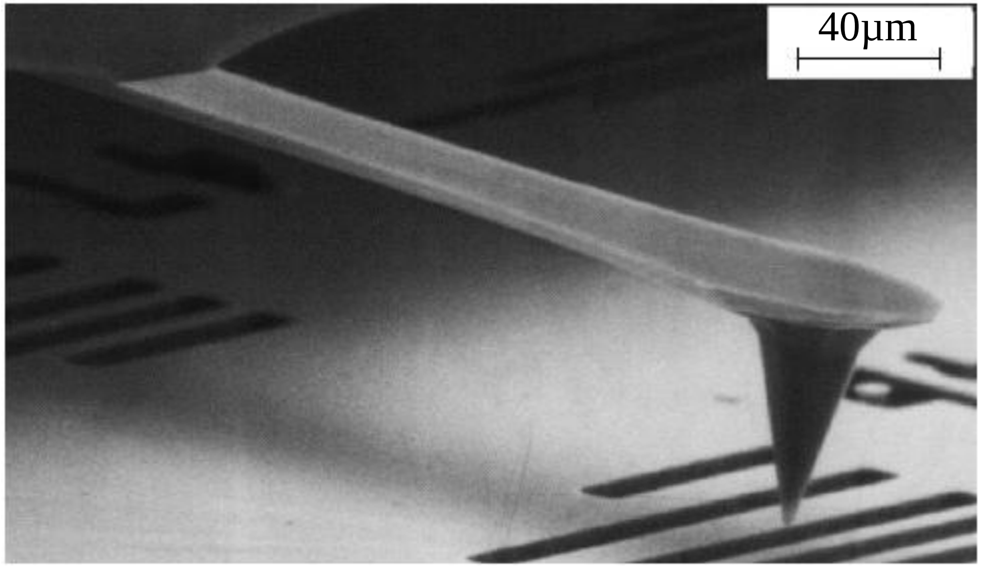
Force Sensors – Cantilevers

There are some simple criteria to be considered, when cantilevers are fabricated:

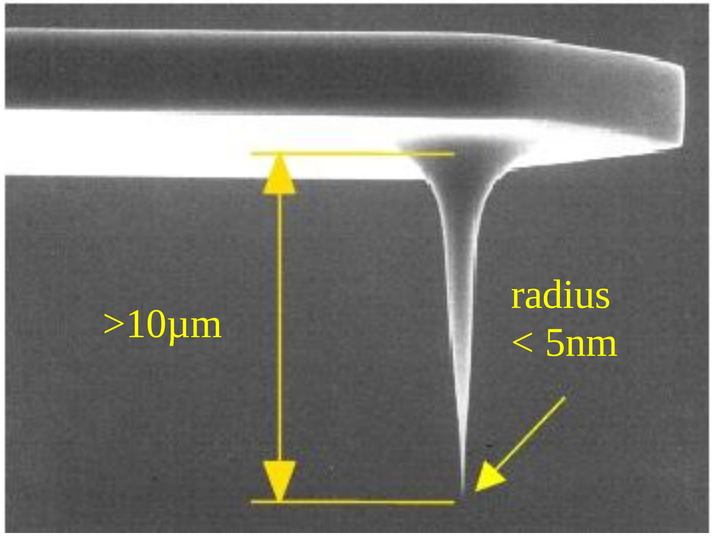
- resonance frequency f_R > 100Hz (building vibrations), > 10 kHz (sound waves)
- high force sensitivity requires low spring constants (MFM:, 0.1 N/m, mRFM: 0.001 N/m)
- atomic resolution requires spring constant to be in range of atomic spring constants > 10N/m
- thermal vibrations of the cantilever < 0.1nm, i.e. k > 0.4 N/m at 300K

It can be shown that only cantilevers of dimensions in the micrometer range fulfill these design criteria. Generally, higher resonance frequencies require smaller cantilevers.

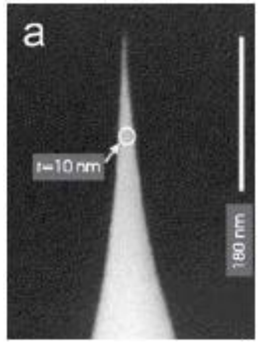
single crystalline silicon cantilevers



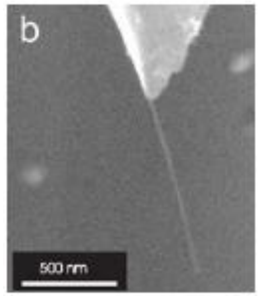
high-aspect ratio tips



ultrasharp tip

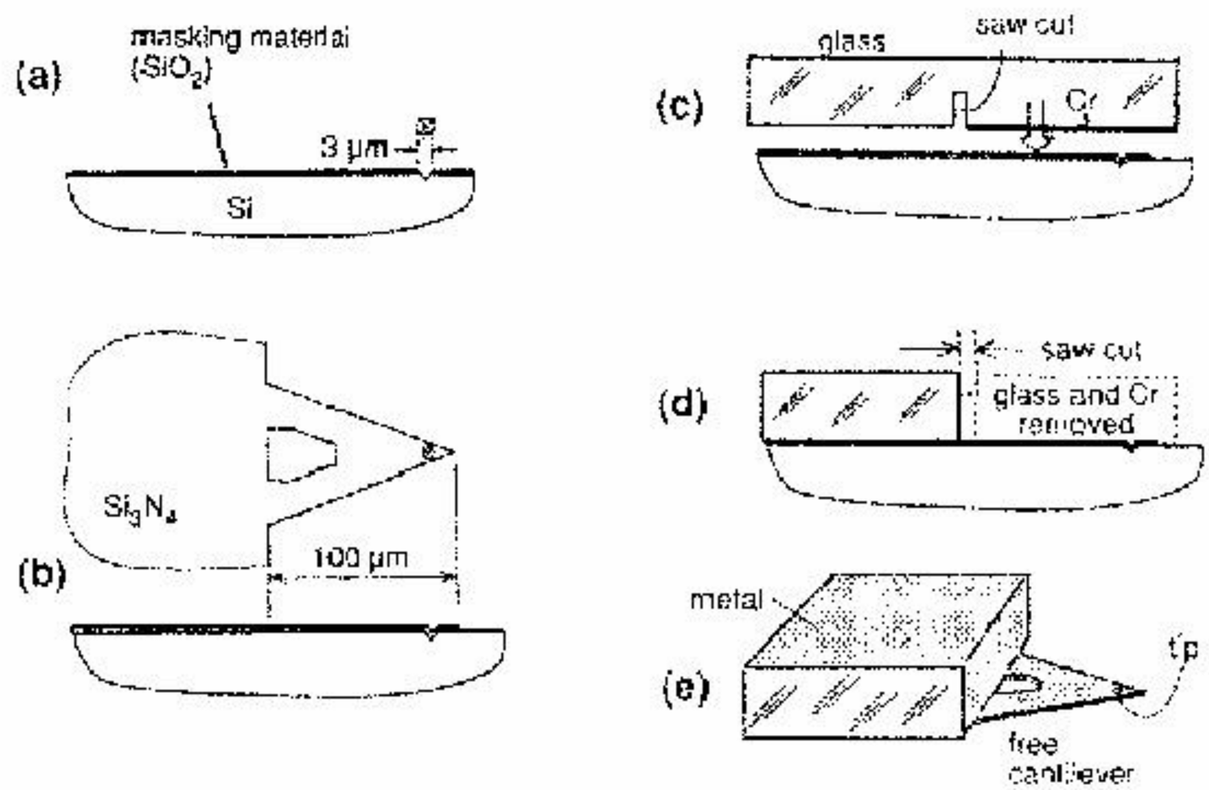


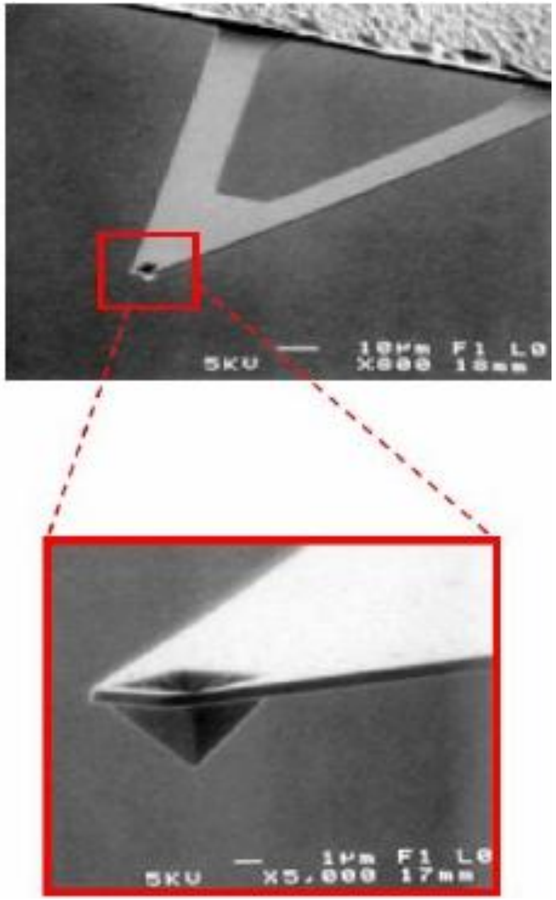
nanotube tip

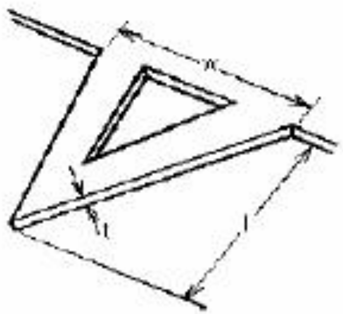


force constant: 0.01 – 100 N/m
resonance frequency: 5 – 500 kHz

Microfabrication of Si_3N_4 - Cantilevers



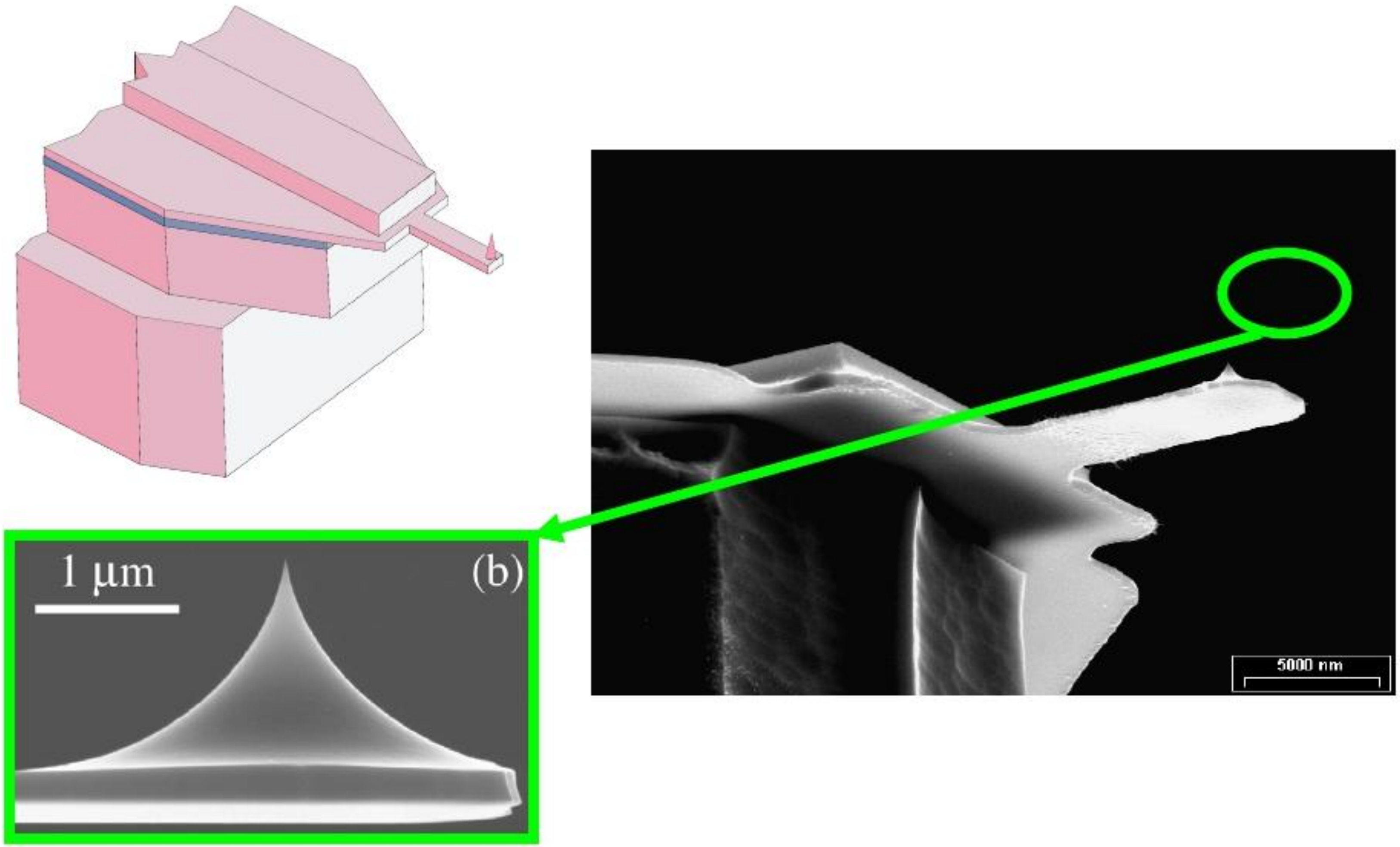




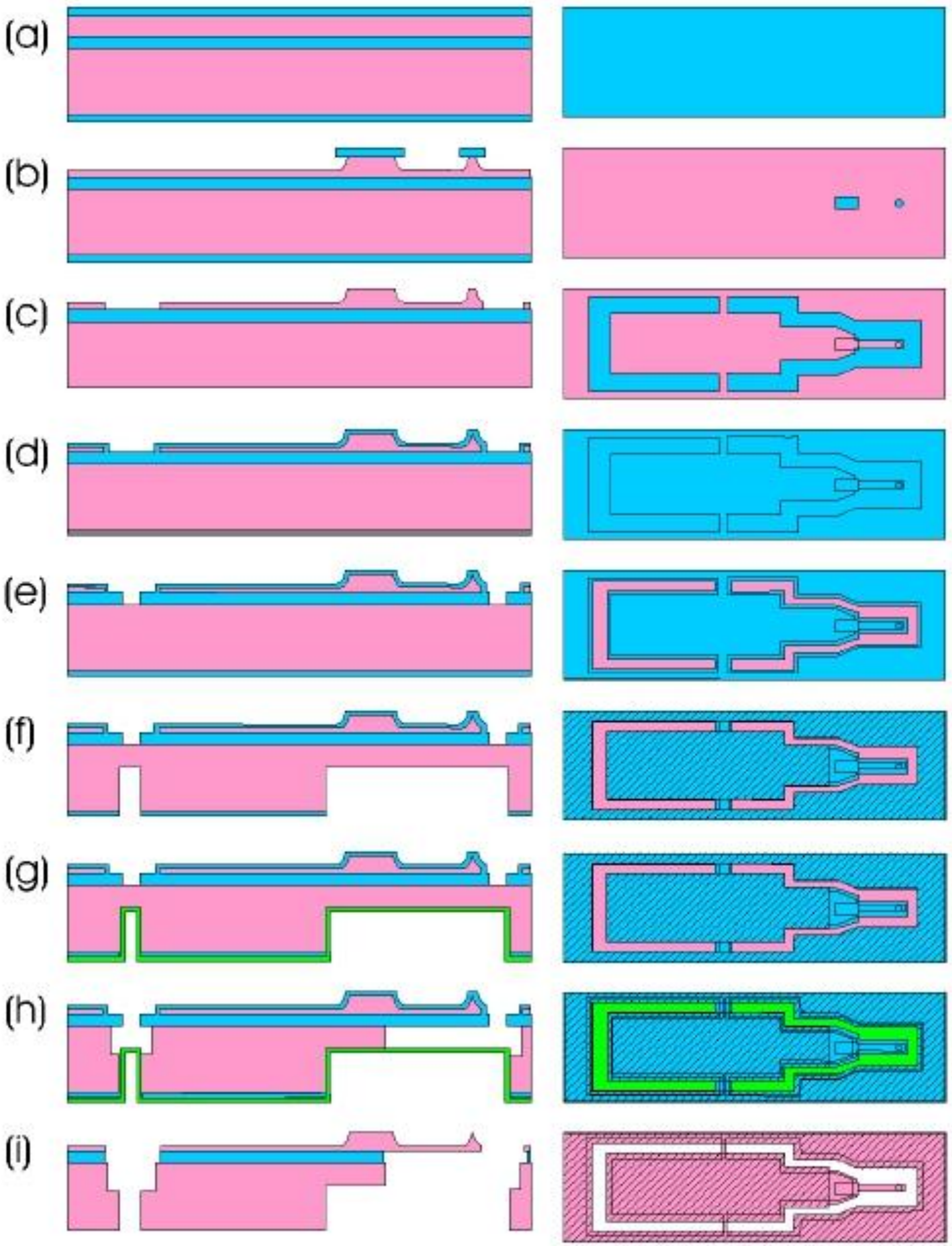
Cantilevers sizes range:
from 100 to 200µm in length (l),
10 to 40 µm in width (w), and
0.3 to 2µm in thickness (t)

Ultrasmall Cantilevers

Small cantilever as such are relatively easy to fabricate (IBM “Millipede” Experience)
l < 30µm, *w* < 5µm, and *t* < 250 nm; but the cantilever anchoring structure is not straightforward



Dry Etch Fabrication Process



Si wafer

Tip and backbone etching by RIE

Defining cantilever by RIE

Thermal oxidation

Front trench etched by RIE

Back trench etching by DRIE

Sputter aluminium etch stop

Anisotropic DRIE and isotropic RIE

Wet etching

Mechanical Properties of Cantilevers

flexural spring constant

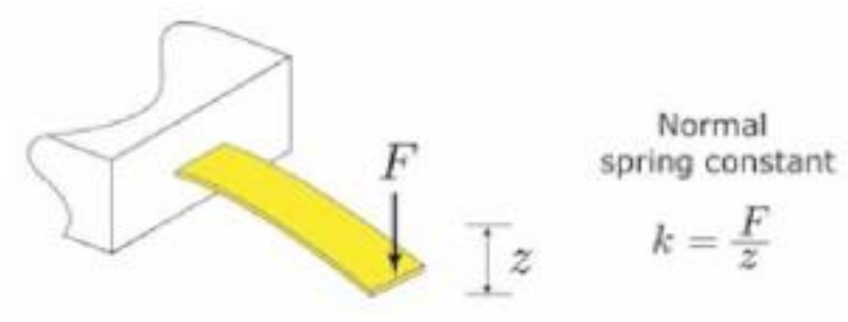


Fig. 1: Schematic illustration of the normal spring constant.

E : elasticity module for Si = 1.69×10^{11} N/m^2

w, l : cantilever width, length can be measured from SEM or optical microscopy images

t : cantilever thickness, difficult to determine exactly

thickness from measured resonance and length

$$t = \frac{2 \cdot \sqrt{12}\pi}{1.875^2} \sqrt{\frac{\rho}{E}} f \cdot l^2$$

$$t = 7.23 \times 10^{-4} \mathrm{s/m} \cdot f \cdot l^2$$

f : cantilever resonance frequency

ρ : density for Si = 2330 kg/m3

torsional spring constant

$$k_T = \frac{G \cdot w \cdot t^3}{3 \cdot h^2 \cdot l}$$

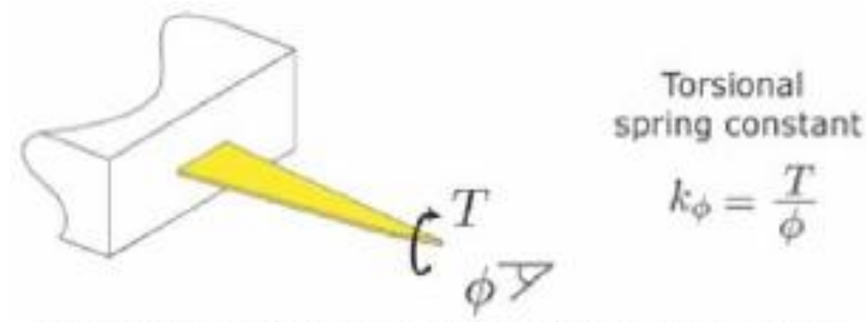


Fig. 2: Schematic illustration of the torsional spring constant.

Driven Damped Oscillator

Forces:

$$F_{net} = \underbrace{F_s}_{\substack{\text{restoring}\\ \text{elastic force}}} + \underbrace{F_f}_{\substack{\text{dissipative}\\ \text{friction force}}} + \underbrace{F_d}_{\substack{\text{driving}\\ \text{force}}}$$

Equation of motion:

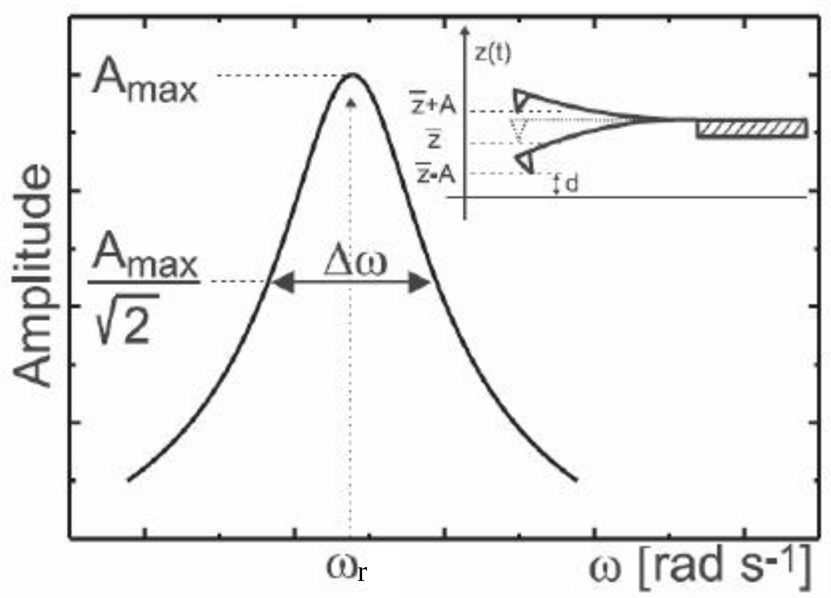
$$m\ddot{x} + b\dot{x} + kx = F_0 \cos(\omega t + \theta_0)$$

General Solution:

$$x(t) = x_h(t) + x_i(t) = \underbrace{A_h \exp(-\gamma t)\cos(\omega_1 t + \phi_h)}_{\text{transient term}} + \underbrace{\frac{F_0 / m}{\sqrt{\left(\omega_0{}^2 - \omega^2\right)^2 + 4\gamma^2\omega^2}}\cos(\omega t - \phi)}_{\text{steady state term}}$$

with: $\phi = \tan^{-1} \dfrac{2\gamma\omega}{\omega_0{}^2 - \omega^2}$

Amplitude Resonance



$$kA_{exc}\cos(\omega t) = \frac{k}{{\omega_0}^2}\ddot{z}(t) + \frac{k}{\omega_0 Q}\dot{z}(t) + kz(t)$$

$$z(t) = \overline{z} + Asin(\omega t)$$

$$Q = A_{max}/A_{exc} = \omega_r/2\Delta\omega$$

The amplitude of the particular solution reaches maximum when the driving force is equal to

$$\omega = \omega_r = \sqrt{{\omega_0}^2 - 2\gamma^2}$$

On resonance, the phase shift

$$\phi = \frac{\pi}{2}$$

Far below resonance

$\omega \ll \omega_r, \quad \phi \to 0$

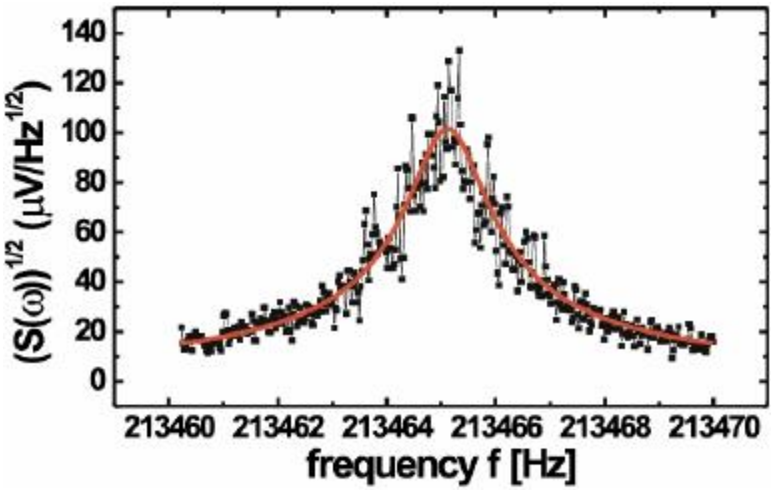
Far above resonance

$\omega \gg \omega_r, \quad \phi \to \pi$

Thermal Noise of Cantilevers

Mean square amplitude of thermally driven cantilever

$$\langle x^2(\nu)\rangle = \frac{2k_BT}{\omega_k Qk}\cdot\frac{\Delta\nu}{\left\{\left[1-\left(\frac{\nu}{\nu_k}\right)^2\right]^2+\left(\frac{\nu}{\nu_k Q}\right)^2\right\}}$$



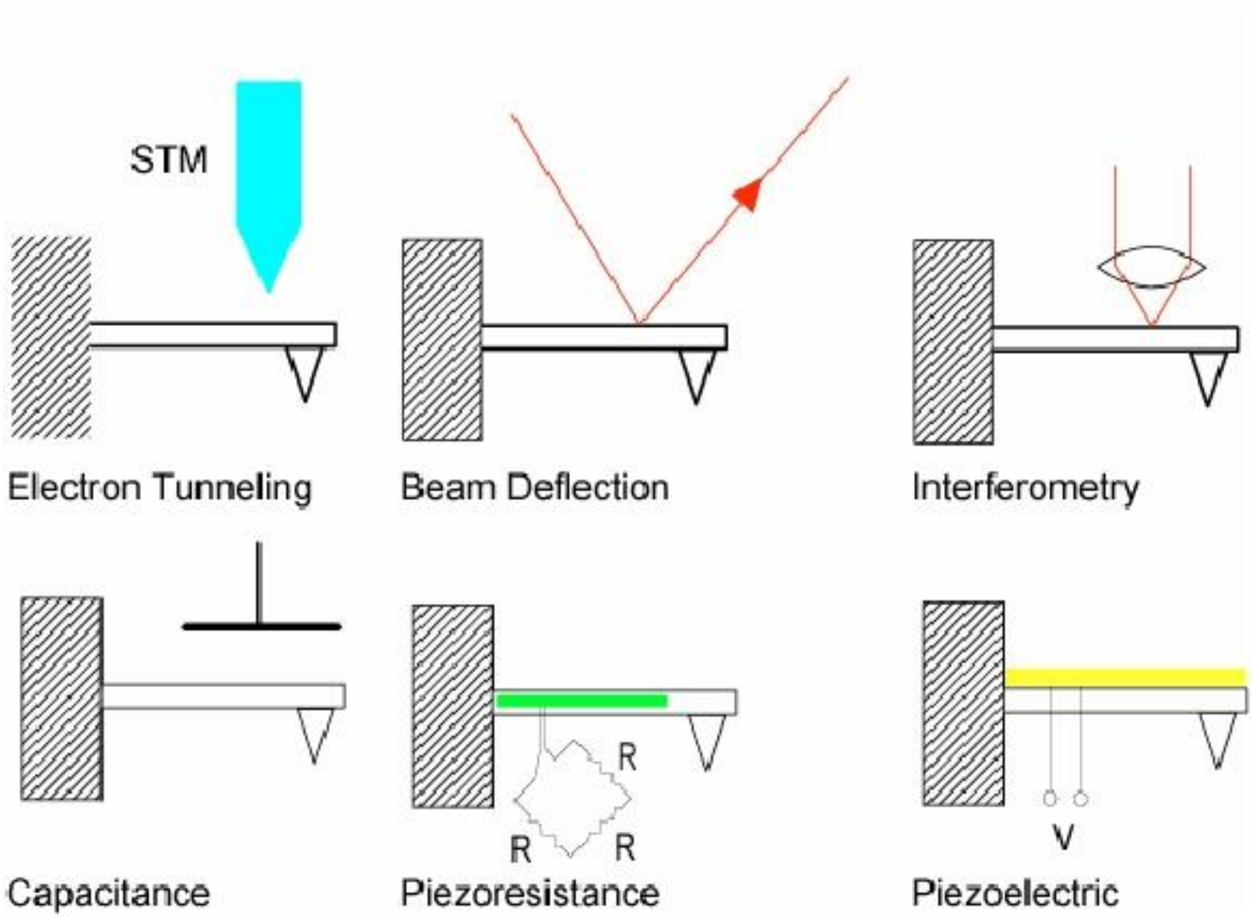
can be used to calibrate the cantilever's force constant: $k = \frac{1}{\pi Q}\frac{k_BT}{\langle x^2(\nu_k)\rangle}\frac{\Delta\nu}{\nu_k}$

Minimum measurable force gradient due to thermal noise of cantilever

$$\left.\frac{\partial}{\partial z}F_z\right|_{min,rms} = \frac{1}{A_{rms}}\cdot\sqrt{\frac{4k_bTBc_L}{2\pi f_0 Q}}$$

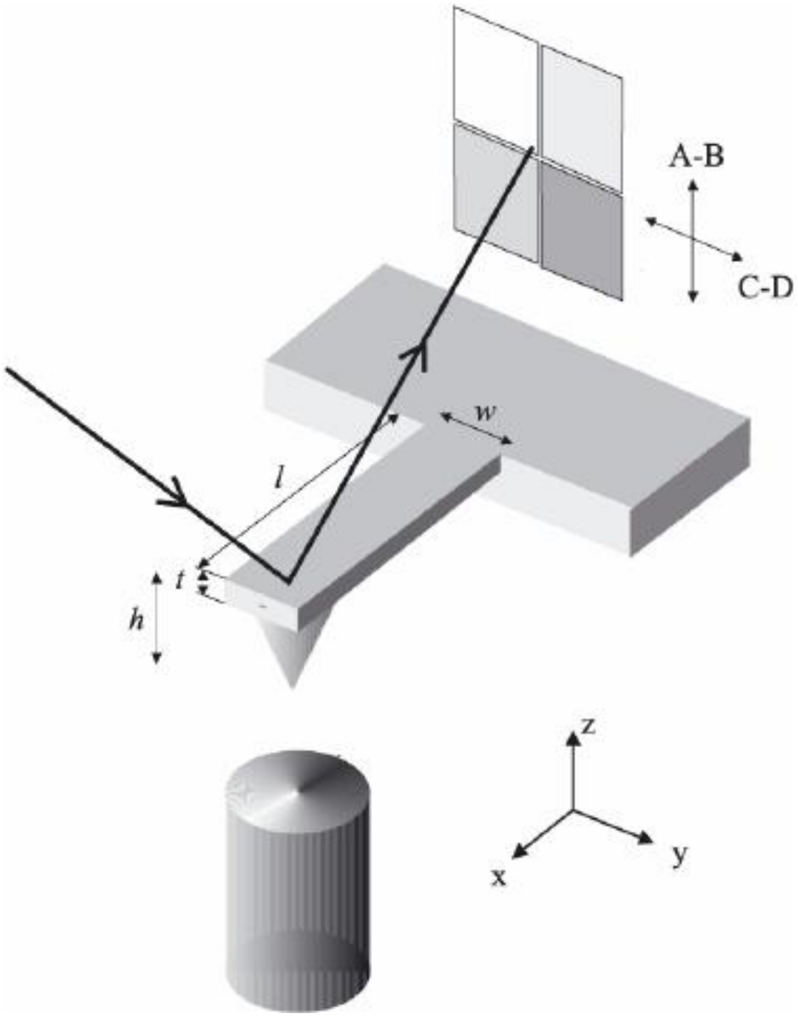
with A_{rms}: rms-amplitude of driven cantilever, T: temperature, B: measurement bandwith, cL: cantilever force constant, k_b = 1.381 x10^{-23} Boltzmann constant.

Deflection Sensors



Electron Tunneling:	original concept, potentially sensitive, practically problematic
Beam Deflection:	most widely used, robust, high sensitivity, not directly quantitative, requires calibration
Interferometry:	best sensitivity, quantitative, uses limited space, complicated
Capacitance:	sensor can be microfabricated, strong force from sensor, limited sensitivity
Piezoresistance:	ideal for microfabrication & integration, limited sensitivity, heating of cantilever
Piezoelectric:	mostly quartz tuning forks, good for true atomic resolution, limited sensitivity

Beam Deflection Sensor



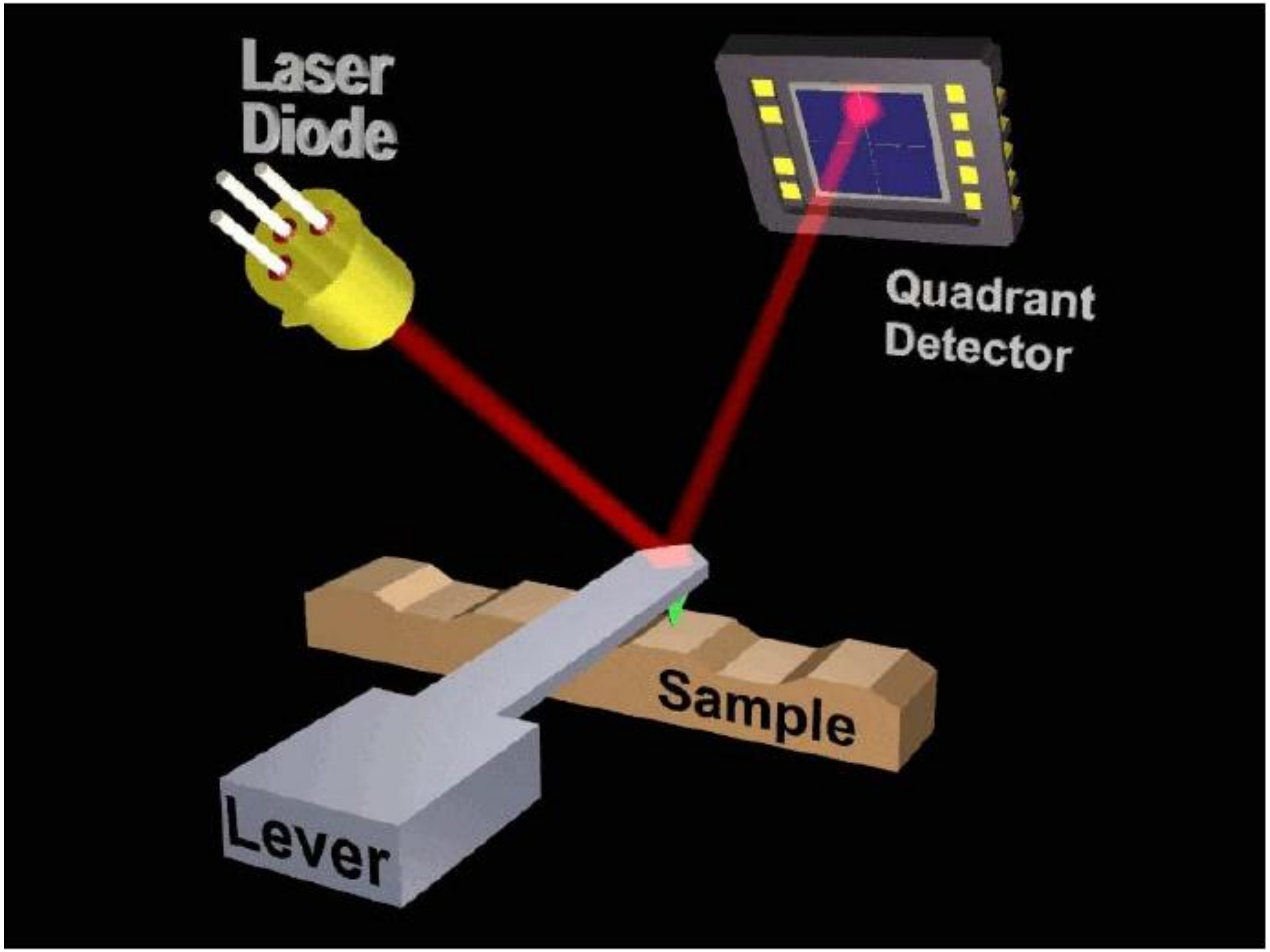
Basics
- most widely used sensor.
- adjustment of Laser or Super-LED beam to the cantilever (2 directions)
- adjustment of 4Q-diode to reflected beam, e.g.
  - mostly one rotatable mirror (up-down)
  - linear 4Q-diode (left-right)

Advantages
- vertical & lateral deflection
- easy to use
- robust
- cheap

Disadvantages
- not intrisically quantitative, requires calibration
- requires large volume
- large area photodiodes -> fmax < 2MHz

A laser beam is reflected off the rear side of the cantilever. Angular deflections of the laser beam are measured with a position sensitive detector (4-quadrant photo diode). The A-B-signal is proportional to the normal force and the C-D-signal is proportional to the torsional force.

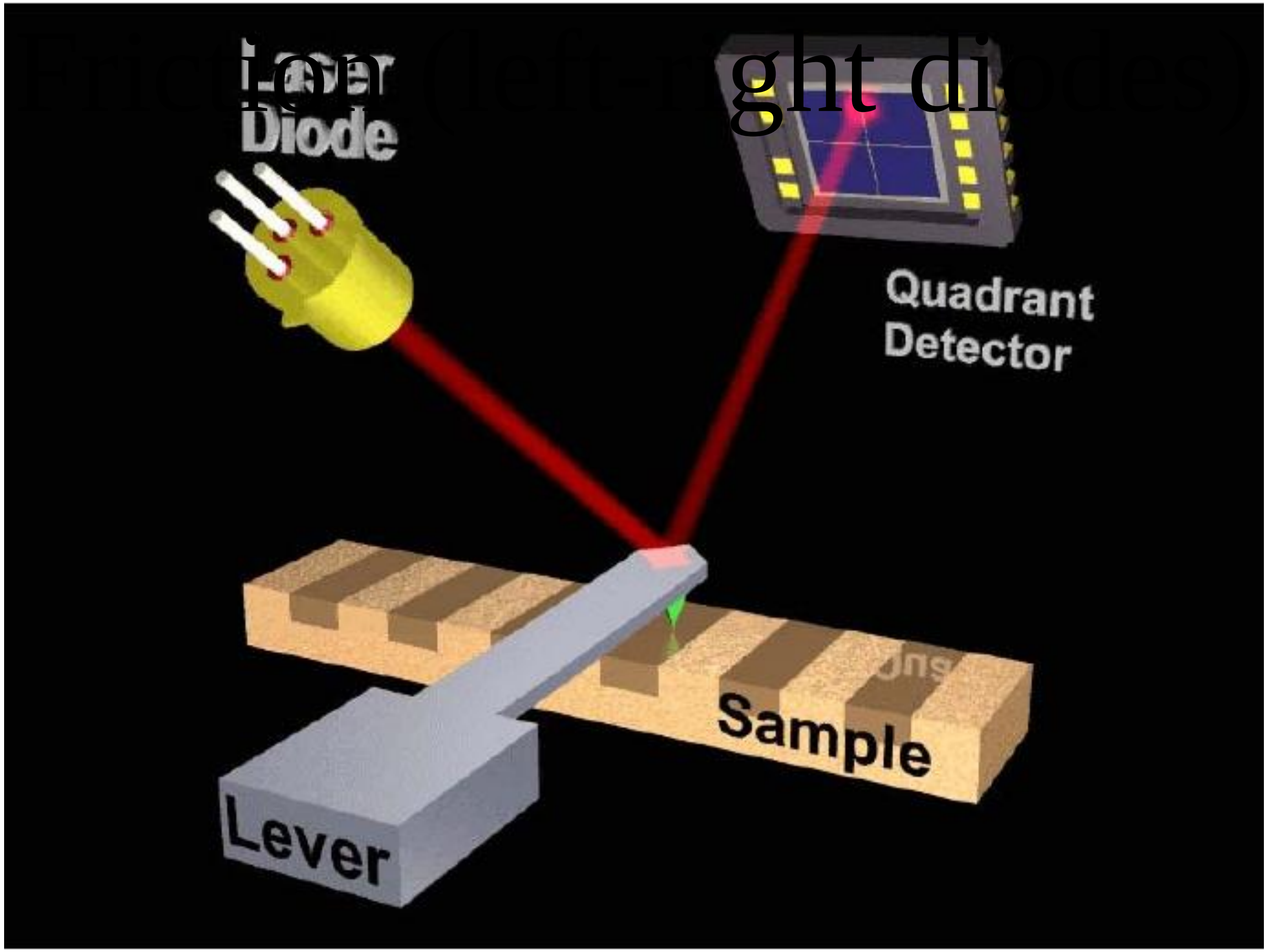
Topography Measurement



Animation: H. R. Hidber, NCCR on Nanoscale Science University of Basel

A laser beam is reflected off the rear side of the cantilever. Angular deflections of the laser beam are measured with a position sensitive detector (4-quadrant photo diode). The A-B-signal is proportional to the normal force or topography and the C-D-signal is proportional to the torsional force.

Friction Measurement



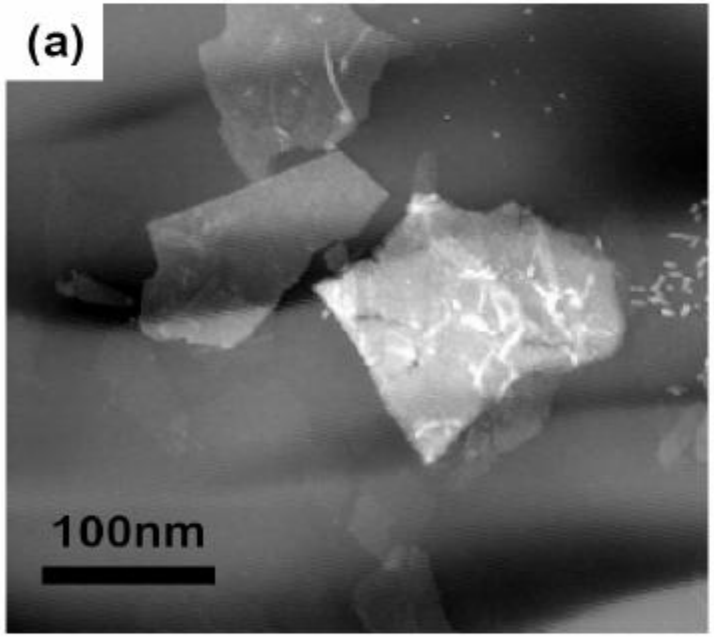
Animation: H.-R. Hidber, NCCR on Nanoscale Science University of Basel

A laser beam is reflected off the rear side of the cantilever. Angular deflections of the laser beam are measured with a position sensitive detector (4-quadrant photo diode). The A-B-signal is proportional to the normal force or topography and the C-D-signal is proportional to the torsional force or friction.

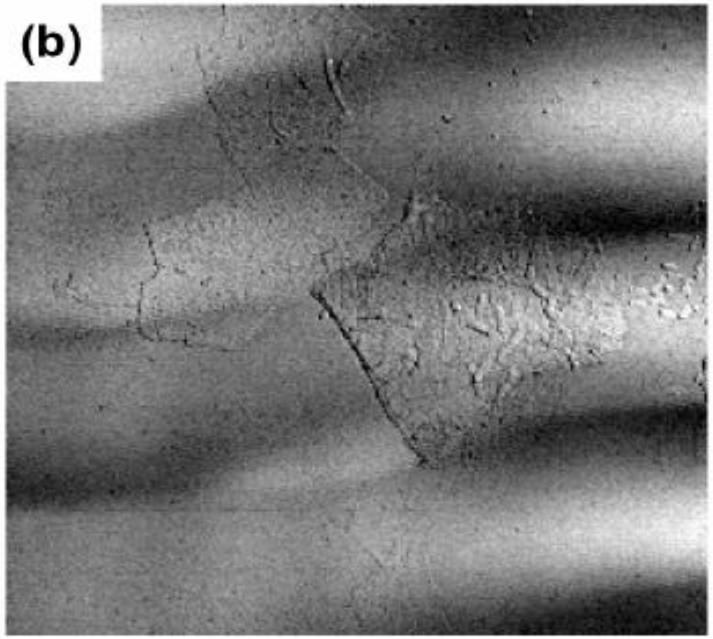
Attention: Artifacts on flat Samples

Due to the bad focus (> 30μm) the laser beam also hits the sample. The beams reflected from the sample and from the cantilever interfer. Image distortions (wave-like features) become visible in this image of MoS_2-platelets on mica. The distance between the interference maxima, $d_{max} = \lambda/\sin\theta$ is related to the wavelength of the laser source, λ (typically about 620 nm), where the angle of incidence of the laser beam relative to the sample surface, θ, is taken into account.

Topography Image

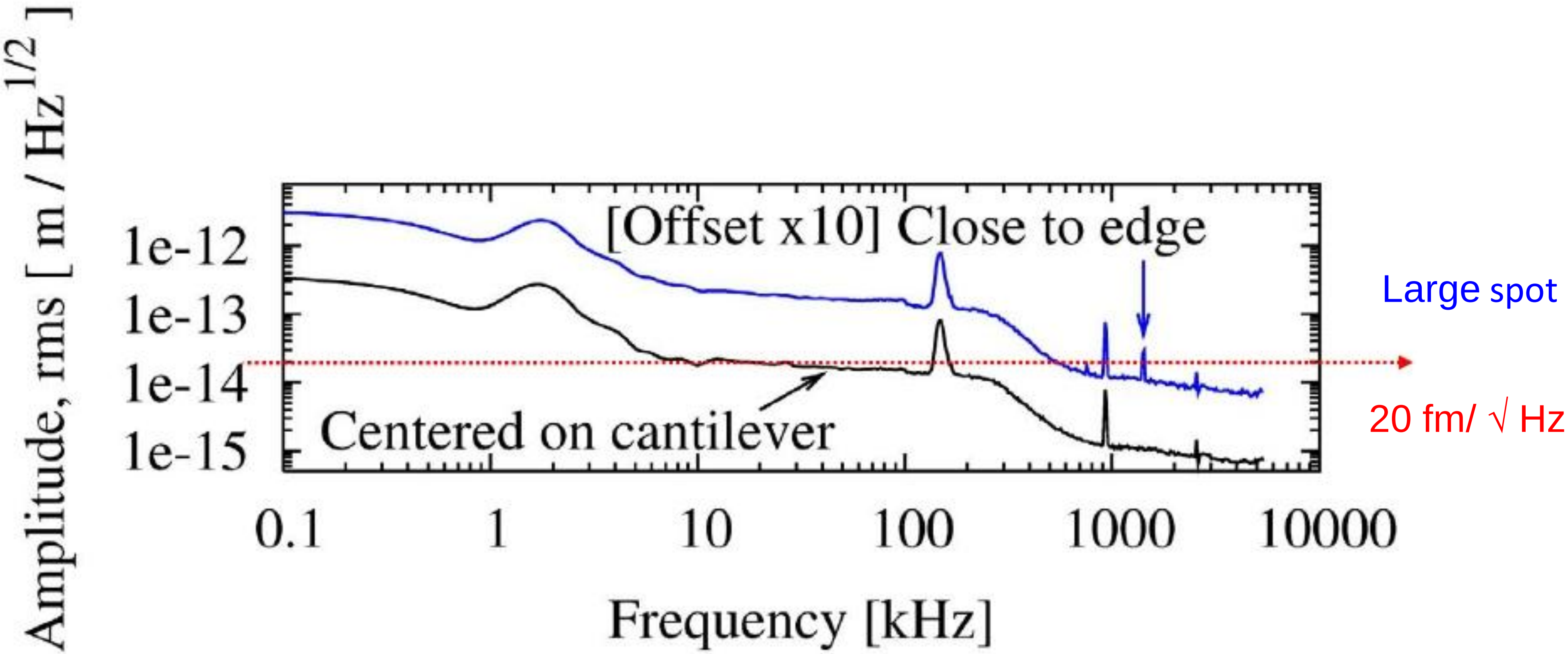


Friction Force Image



The problem can be avoided by an improved optics or by power light emitting diodes which have a broader spectrum and small coherence length.

Noise Limit measured on Conventional Cantilever



Oral *et al*., Rev. Sci. Instrum. 74, 3656 (2003): ~ 40 fm/√Hz, with fiber interferometer and 5-axis alignment
Fukuma *et al*., NC-AFM conference (Sept. 2004): ~ 20 fm/√Hz, with optimized beam deflection