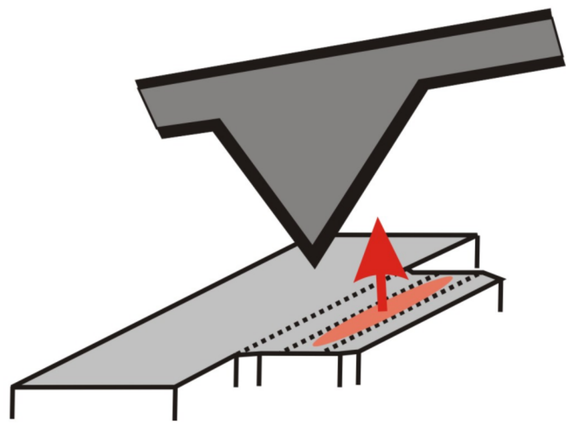
Journée thématique couplage champ proche – photonique
Lille, Institut Pasteur, 11 octobre 2016

AFM probe heated by absorbing laser radiation, What can we expect for the study of IR lasers?



Richard Arinero, Alexei Baranov

and Ioffe Institute, St Petersbourg

in the frame of LIA ILNACS

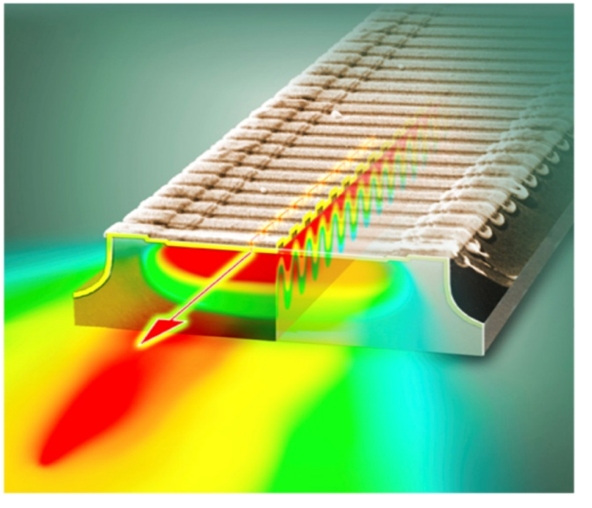
NANOMIR → **World leader in III-Sb technologies (GaSb, InAs, AlSb, InSb…)**

effective band gaps particularly well suited to the mid-infrared (**mid-IR~2 – 12 µm**) → **III-Sb IR Lasers**

Many applications

- **Gas analysis** (pollution or process monitoring, physics of gases, of the atmosphere,…),
- **Medical applications** (surgery, diagnosis,..),
- **Free-space communications**
- **Security- and defense-related applications** (detection of toxic or explosive species,…)

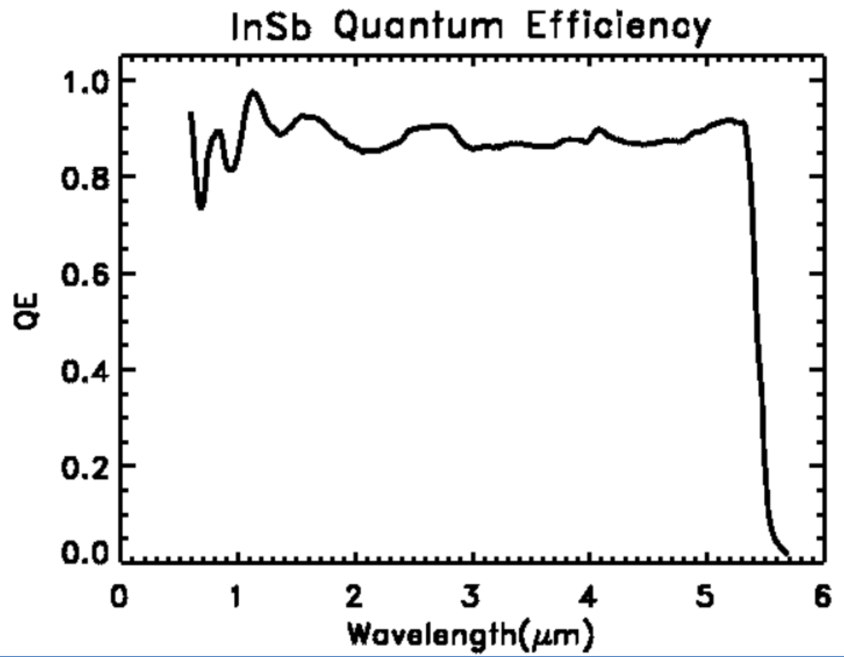
An actual task is to investigate the <u>local complex spatial mode structure</u> and <u>the power of light</u> emerging from the <u>active zone</u>, which sometimes requires <u>high spatial resolution</u>.



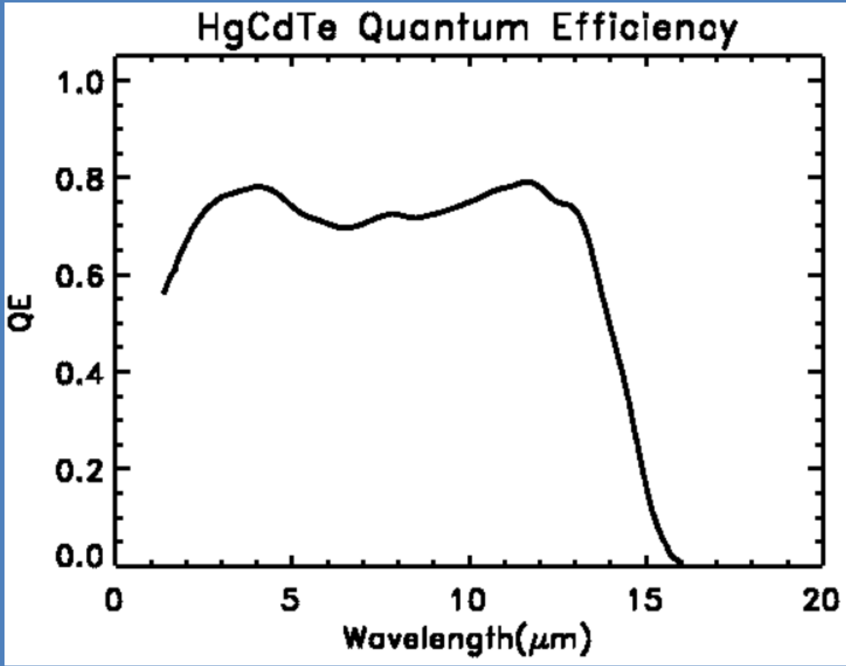
Actual Detectors

InSb: high sensitivity up to λ = 5 μm

Possible coupling with optical fibered probes (as in "classical" scanning near-field optical microcopy (SNOM)) to collect the near-field light

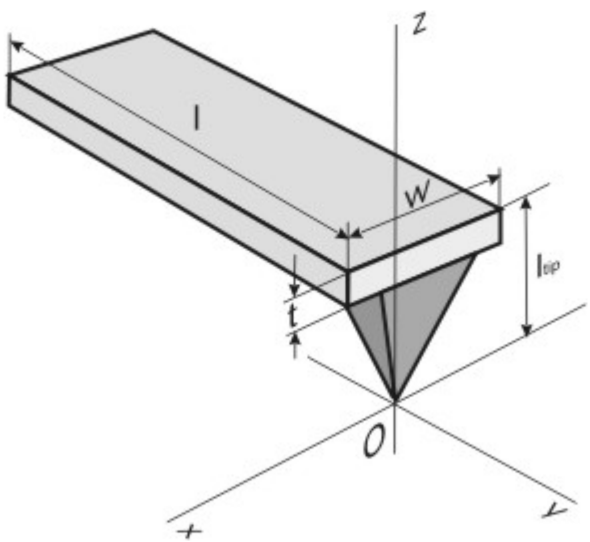


Between 5 and 12 μm: MCT detectors



Beyond 12 μm actual detectors performances become too poor to be used for SNOM of the lasers emitting in this range and suitable optical fibers are not available

AFM Probe: a thermal sensor?



t - thickness, w - width, l – length and the Young modulus (E) of the cantilever

Si or Si_3N_4

Possible coating on reflector and/or tip side (Al, Au, PtIr, Cr, W_2C…)

When heated by ΔT, the <u>linear dimensions and Young modulus</u> of the cantilever change:

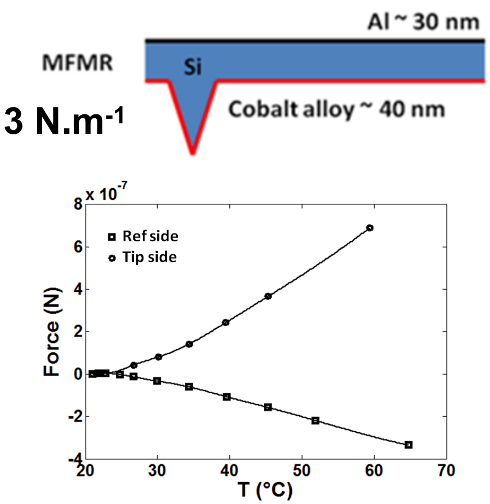
$$\Delta l/l = \Delta w/w = \Delta t/t = \alpha\Delta T$$

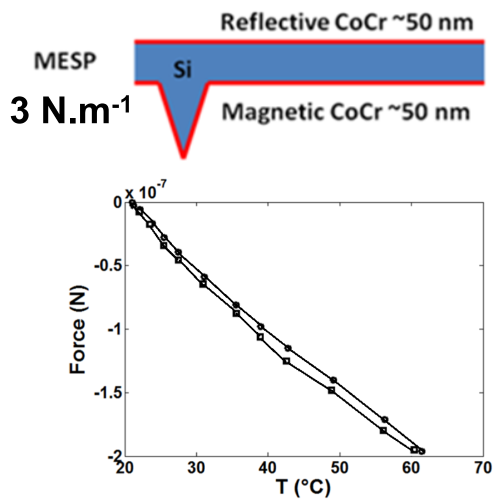
α: Thermal expansion coefficient

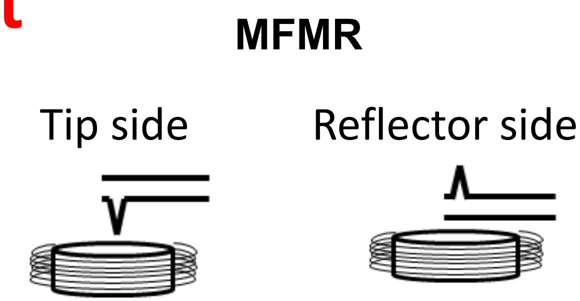
$$\Delta E/E = \beta\Delta T$$

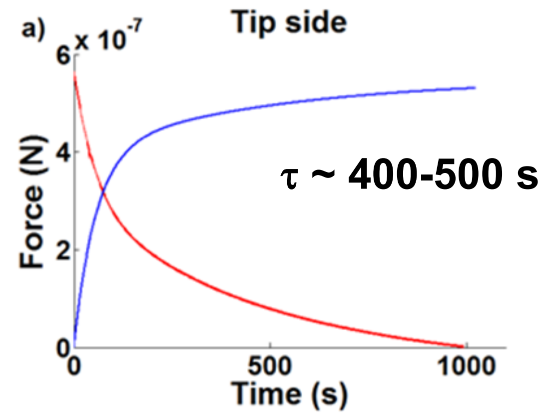
β: Young modulus temperature coefficient

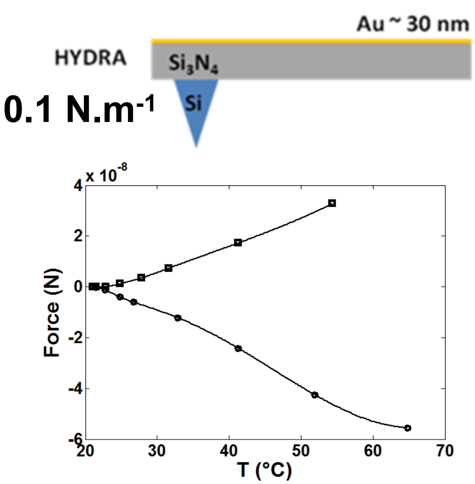
1. Bilayer or multilayer thermal effect

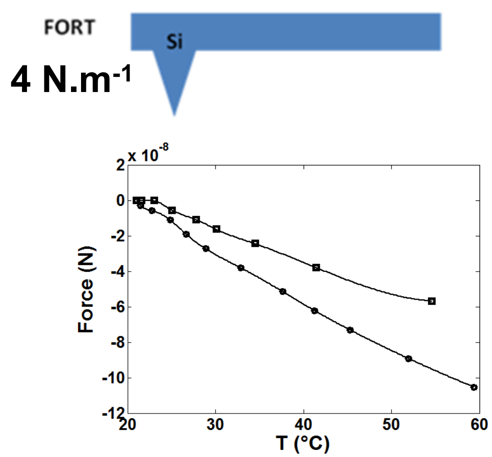


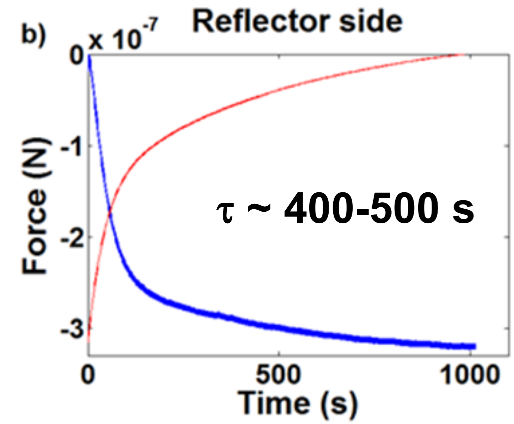






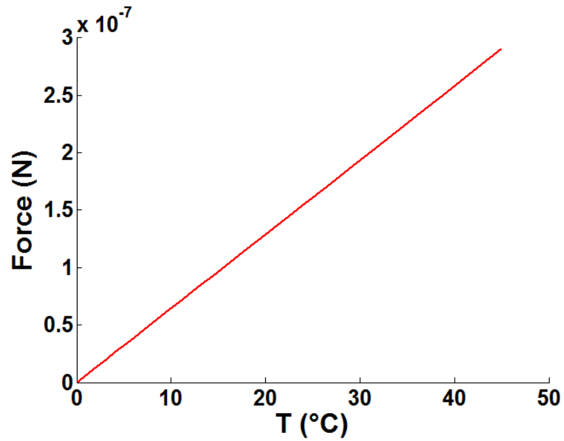






I = 2.5 A, B = 10 mT → T_{max}= 45 °C

Stoney 1909
P. Roy Soc London Vol 82

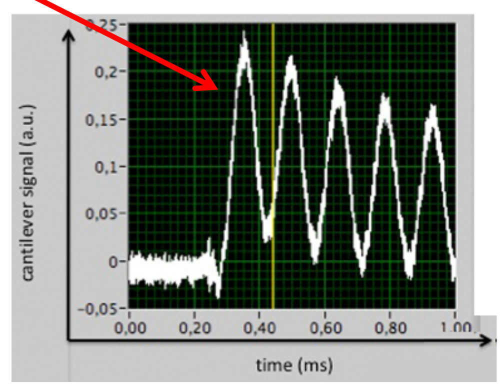


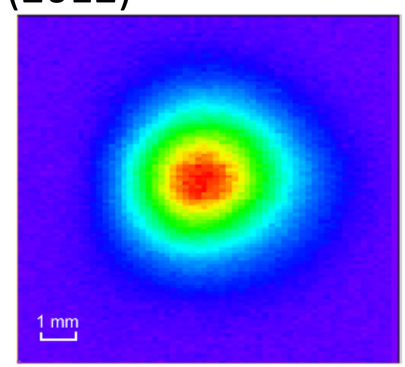
Sensitivity ~ few pN/mK
Low temperature variation difficult to detect with standard AFM in static mode

Each macropulse excites the resonance of the cantilever

Tunable free- electron laser (FEL)

Ortega et al APL 101 (2012)





λ in the far-IR to THz domain
Possible graphite layer on tip side to enhance Light absoption

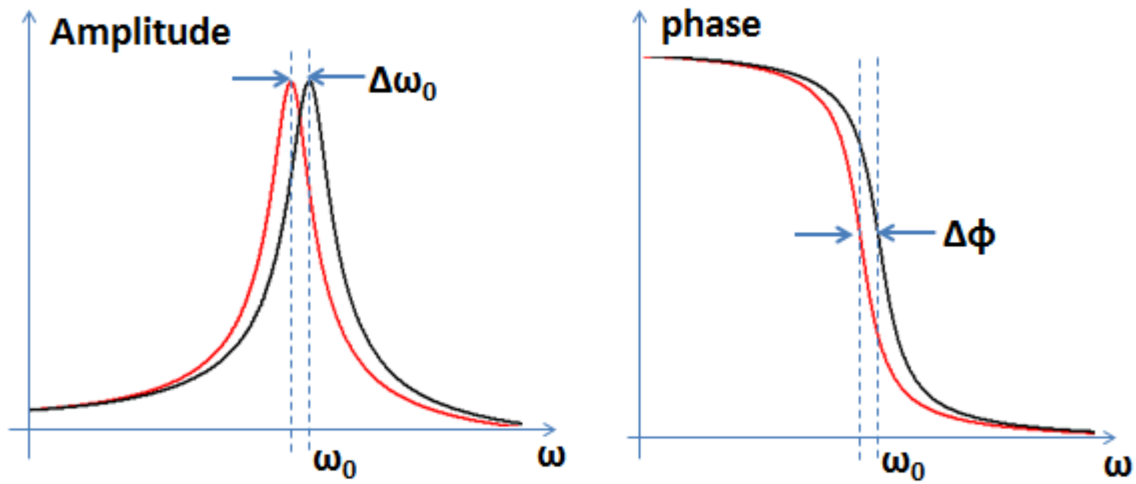
pulses 5 ps long in macropulse trains of 8 µs at 25Hz and cover the range of 4–150 µm

Beam profile at λ = 37 µm using the cantilever. RMS size is approximately 2mm

2. Modification of dynamic response

$$\omega_0 = \sqrt{\frac{k}{m_{eff}}} \qquad k = \frac{t^3}{l^3} wE$$

Temperature dependence



$$\frac{\Delta\omega_0}{\omega_0} = \frac{1}{2}\left(3\frac{\Delta t}{t} - 3\frac{\Delta l}{l} + \frac{\Delta w}{w} + \frac{\Delta E}{E}\right) = \frac{1}{2}\left(\cancel{\alpha\Delta T} + \beta\Delta T\right)$$

Si : $\alpha \sim 10^{-6}\,K^{-1} \ll \beta \sim 10^{-4}\,K^{-1}$

Negative frequency or phase shift

$$\frac{\Delta\omega_0}{\omega_0} \approx -0.3\times 10^{-4}\,\Delta T \qquad \Delta\phi \approx 2Q\frac{\Delta\omega_0}{\omega_0} \qquad \Delta\phi_{\min} \approx 0.1^\circ$$

Under vacuum (~ 10^{-6} mbar) : Q = 20000

$$\Rightarrow \quad \Delta T(\min) \approx 1.5mK$$

Temperature equalization time versus scan velocity

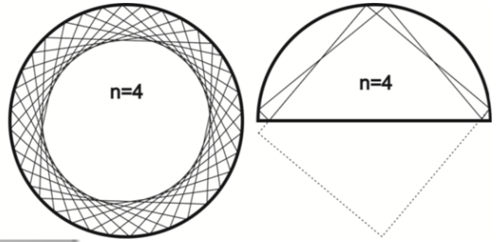
$$\tau = L^2/\chi$$

Thermal diffusivity of Si $\chi = 0.9cm^2/s$

T(time between 2 pixels) =
Time to scan one line/number
of measurement points per line

$$\tau \approx 0.45ms \quad << \quad T = {1s}/{256} \approx 4ms$$

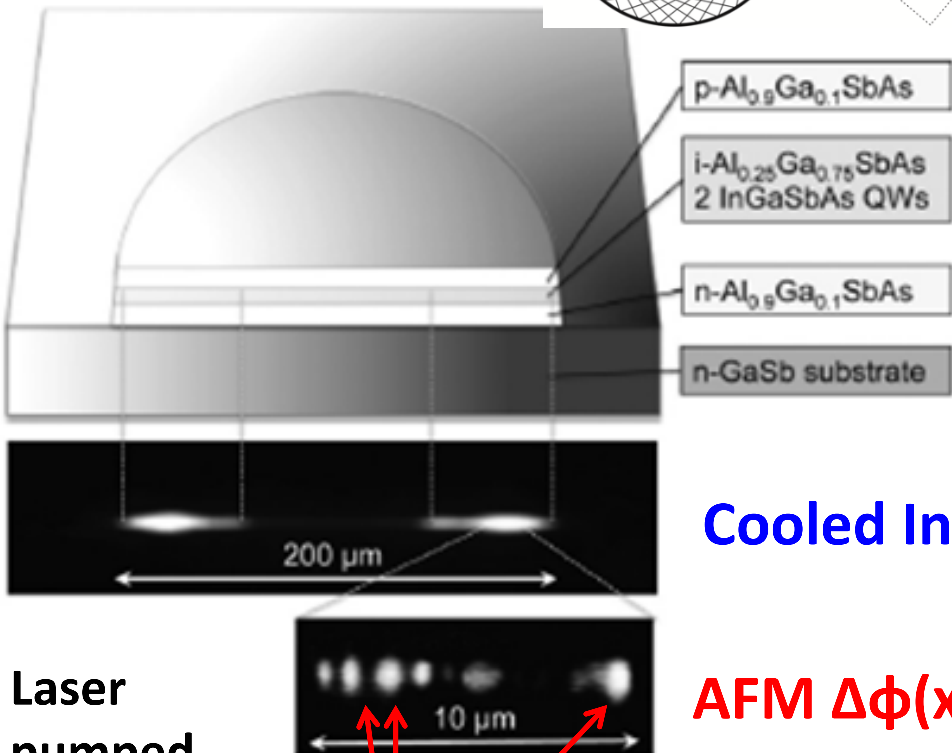
Laser WGM
(Whispering Gallery Modes)



λ =2.15 µm

I_{th} = 40 mA

P = 0.5 mW



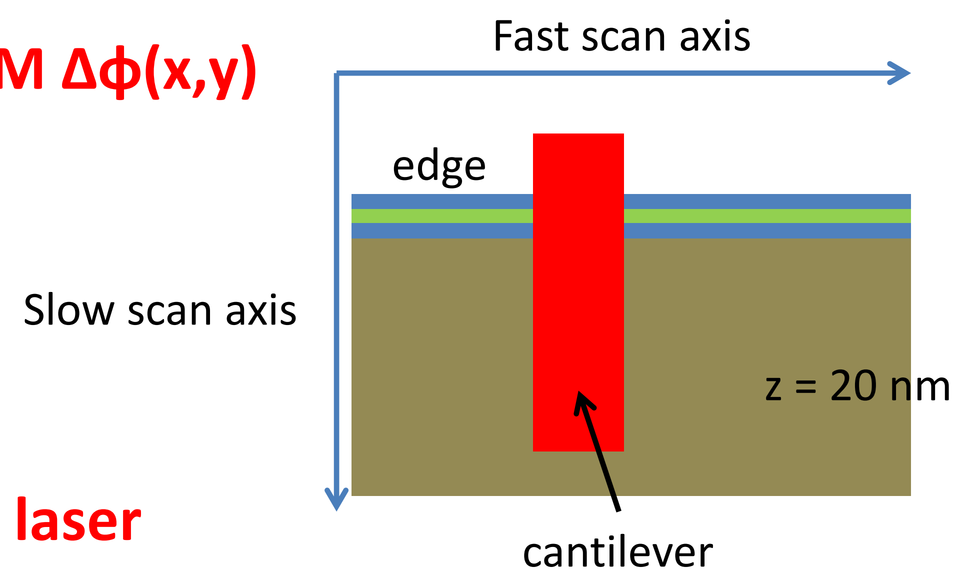
Active zone width 0.7 µm

AM-AFM under vacuum using second resonance

Cooled InSb IR camera

Laser pumped at 65 mA

AFM $\Delta\phi(x,y)$



Bright spots located in the waveguide = optical modes of WGM laser

Estimation of absorbed power and temperature increase

Maximum absorbed power (if the probe interacts with all the optical power)

$$P_{abs} = P\left(1 - e^{-\alpha h}\right) \approx 0.03mW$$

α = 100 cm^{-1} absorption coefficient of IR-radiation by free electrons in silicon

h = 15 µm tip height

Absorbed energy in one point = Pabs ×(recepting surface/emitting surface) ×time at each point

$$Q \approx 2nJ \qquad \sim 0.4 \times 0.4 \mu m^2 \qquad \sim 5 \times 1 \mu m^2 \qquad 4ms$$

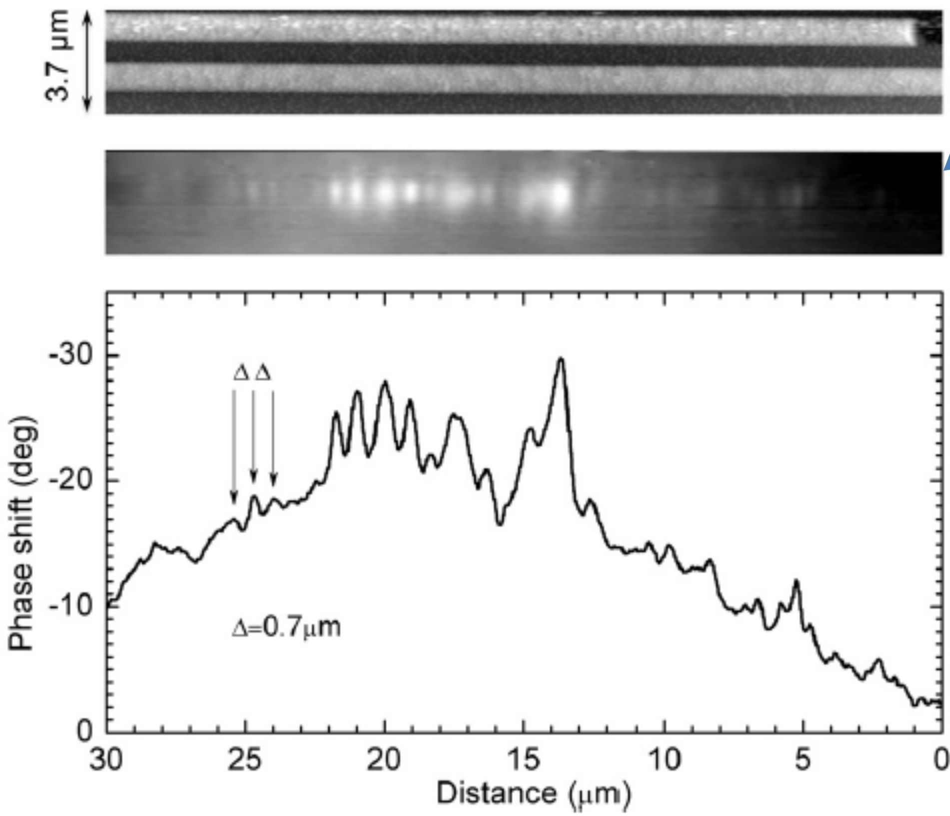
(= spatial Resolution)

$$Q = m_c c_{si} \Delta T$$

$$m_c \approx 40ng$$

$$\Delta T_{\max} = 60mK$$

Same WGM laser pumped at 45 mA



radial distribution of the lasing WG mode in the plane of cleavage

+

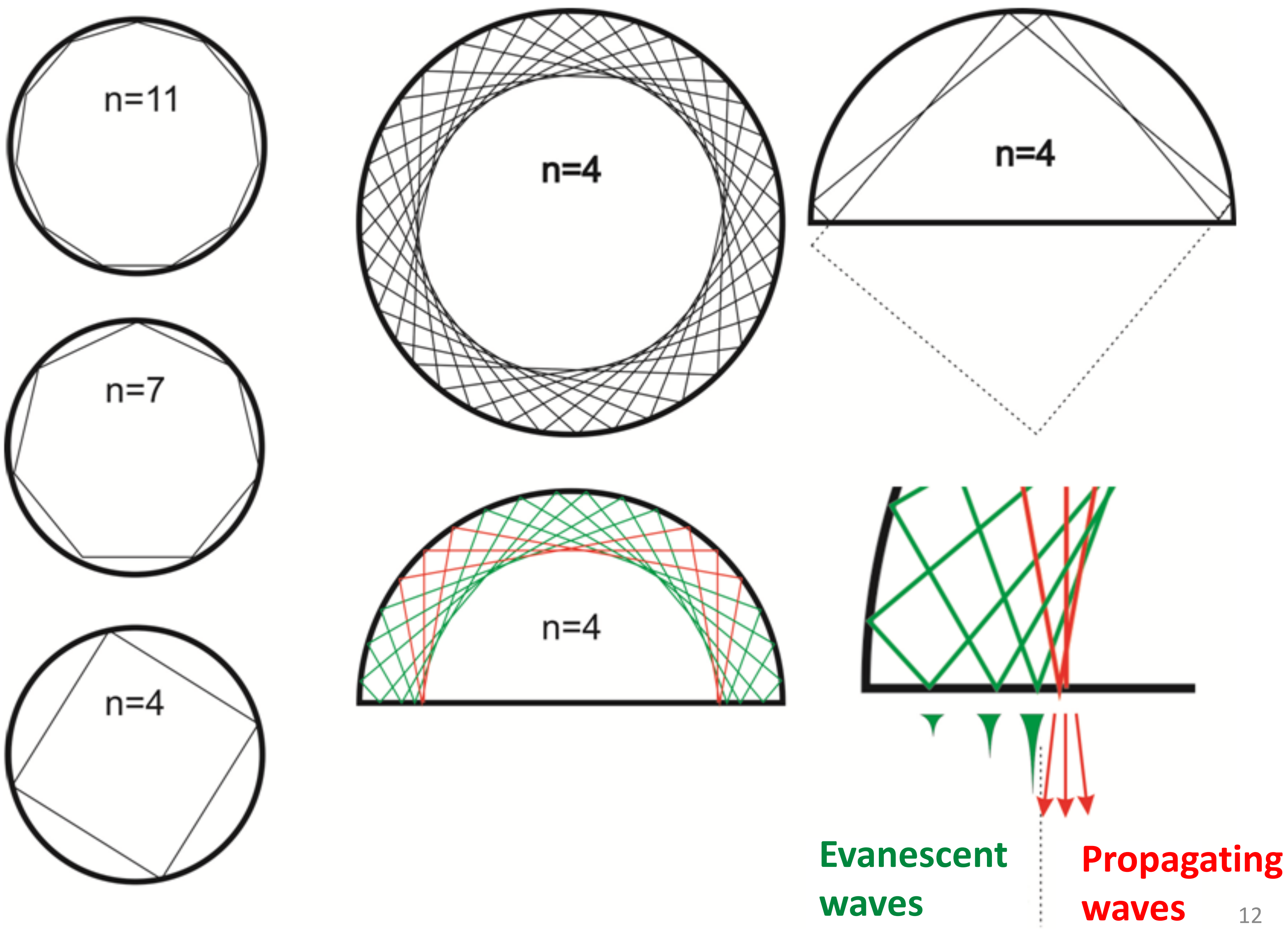
emission pattern modulated by a series of weak equidistant lines

Δ = 0.7 µm
= wavelength inside the waveguide
(effective refractive Index ≈ 3.5)

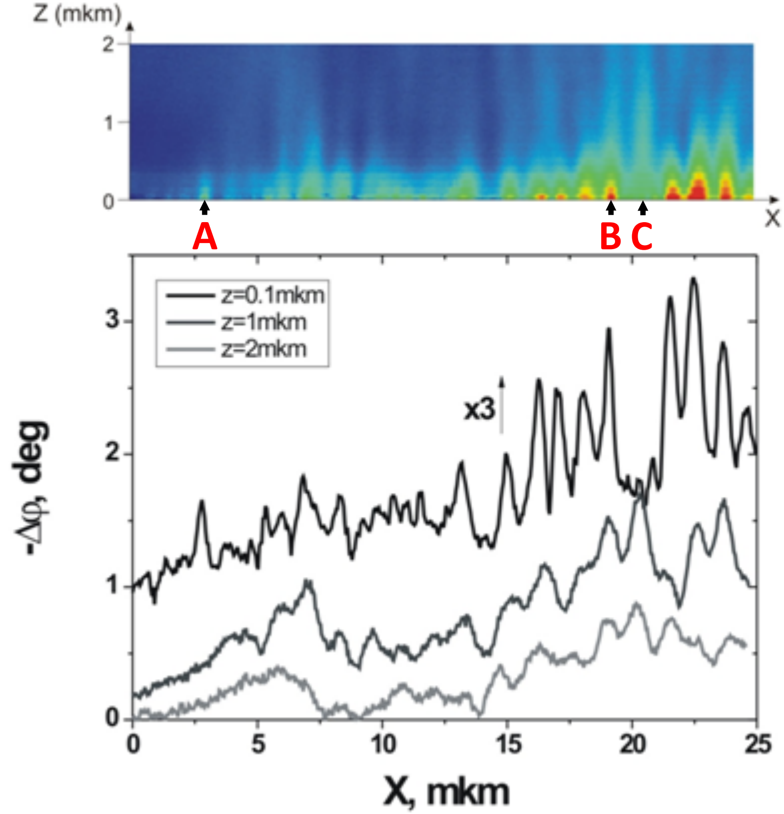
Spatial resolution ~0.3-0.4 µm !

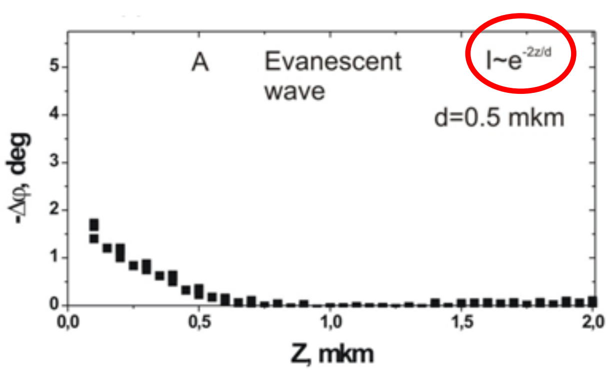
Much lower than tip dimensions !

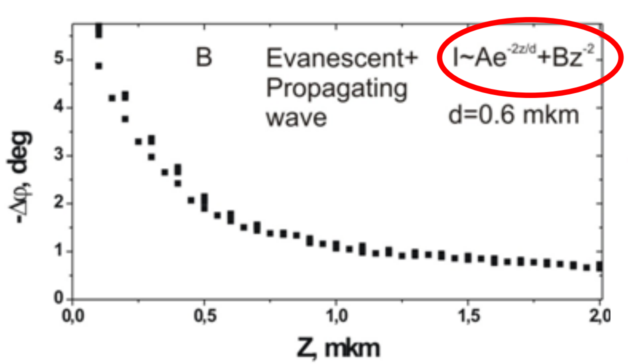
Evanescent and propagating waves

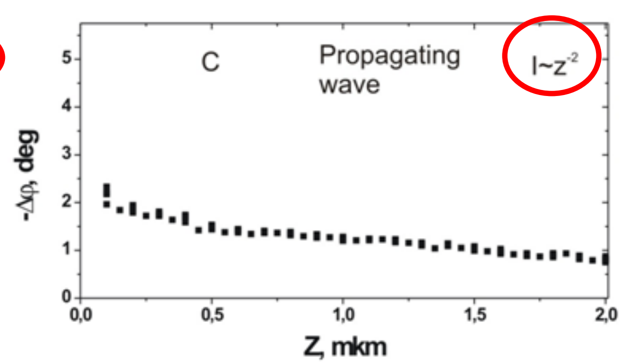


Evanescent and propagating waves



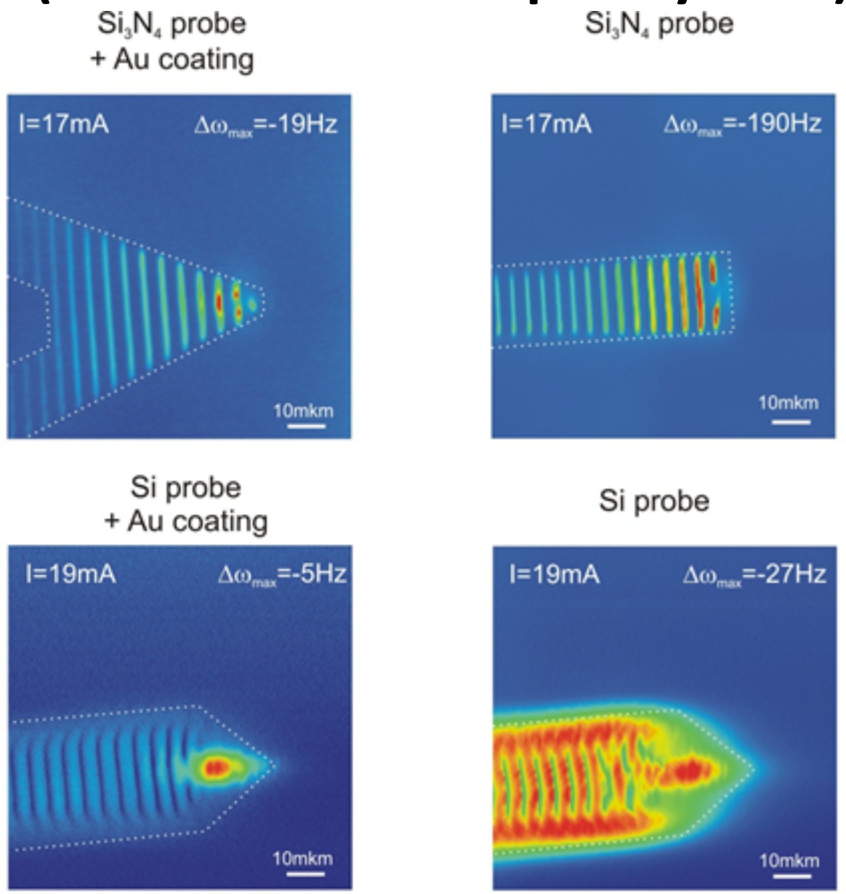


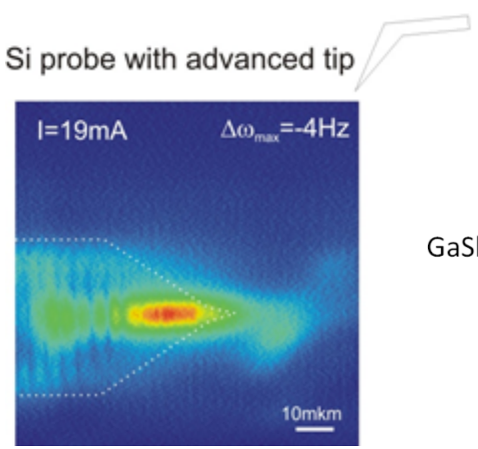


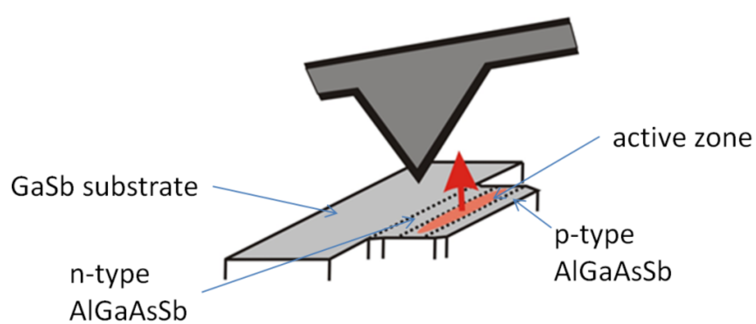


LIFS (Laser induced frequency shift)

z = 2µm







« Ridge » GaSb-based diode lasers emitting at 2.1 µm

I = 16.5 mA

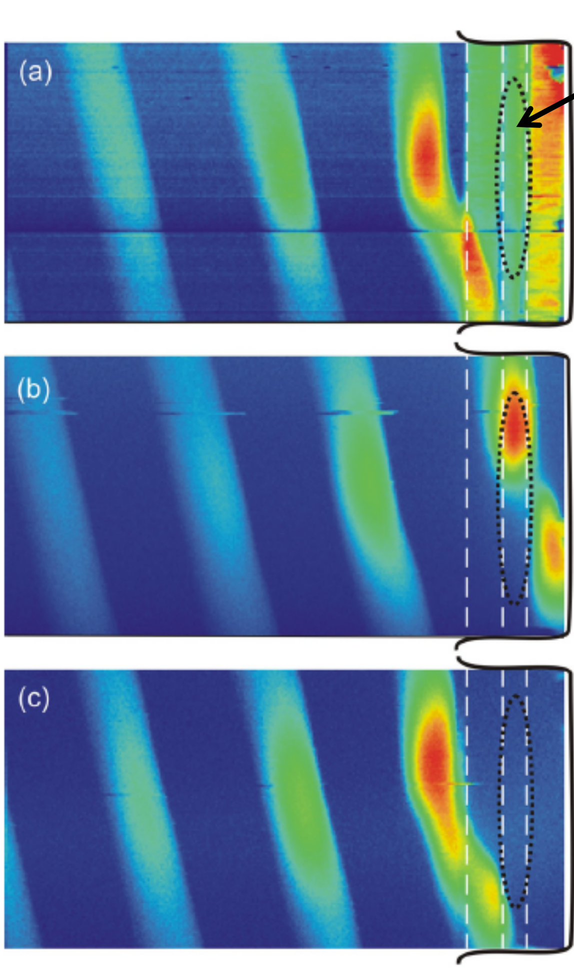
P = 1 mW

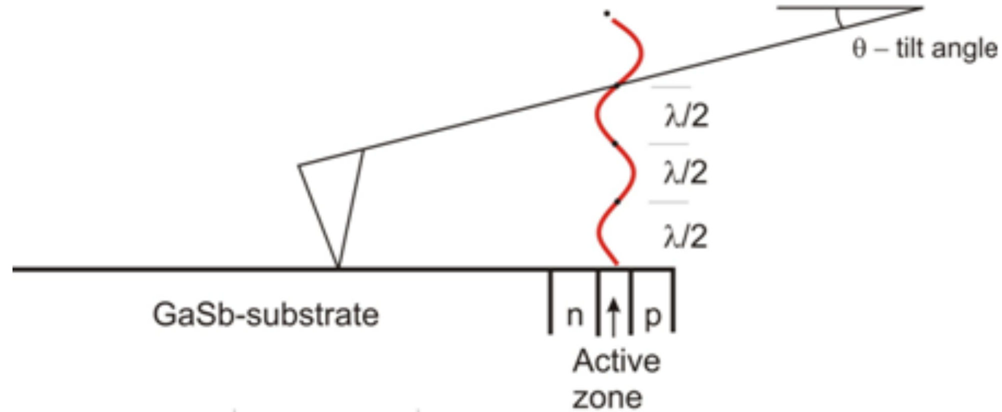
The 0.8 µm-thick active region of the devices contained two GaInSbAs/GaAlSbAs quantum wells

Periodic lines Δ ~ 4.5 µm

Interferences?

LIFS images





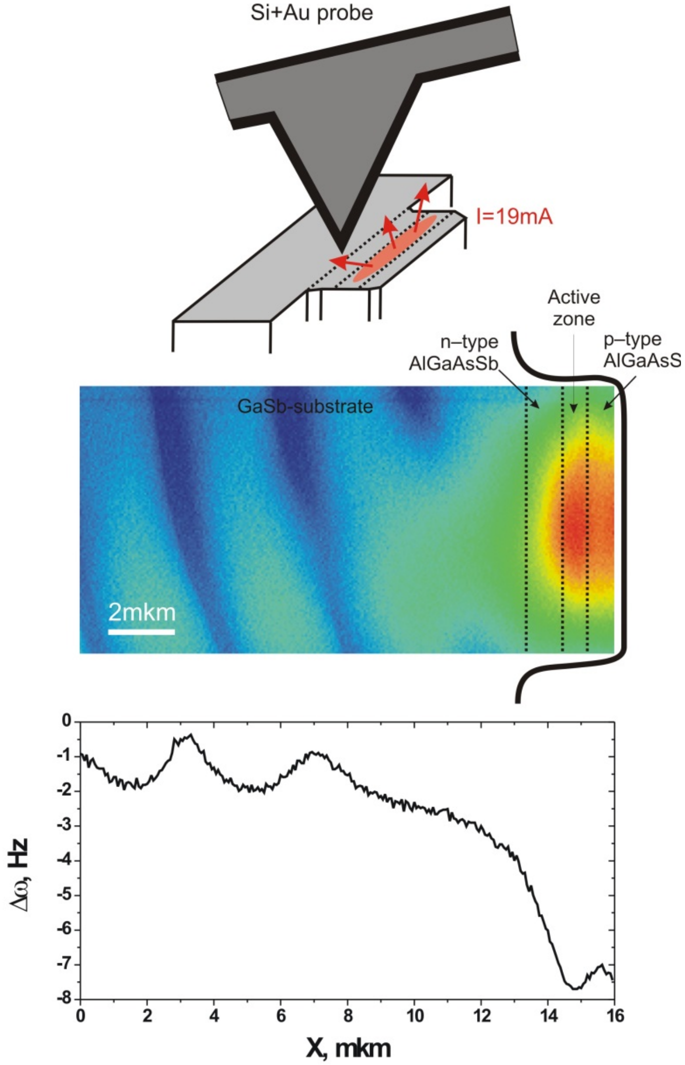
Probe	Period	Angle
Si ATEC	4.4mkm	13°
Si	4.4mkm	13°
Si+Au	4.4mkm	13°
Si_3N_4	4.1mkm	14°
Si_3N_4+Au	4.8mkm	12°

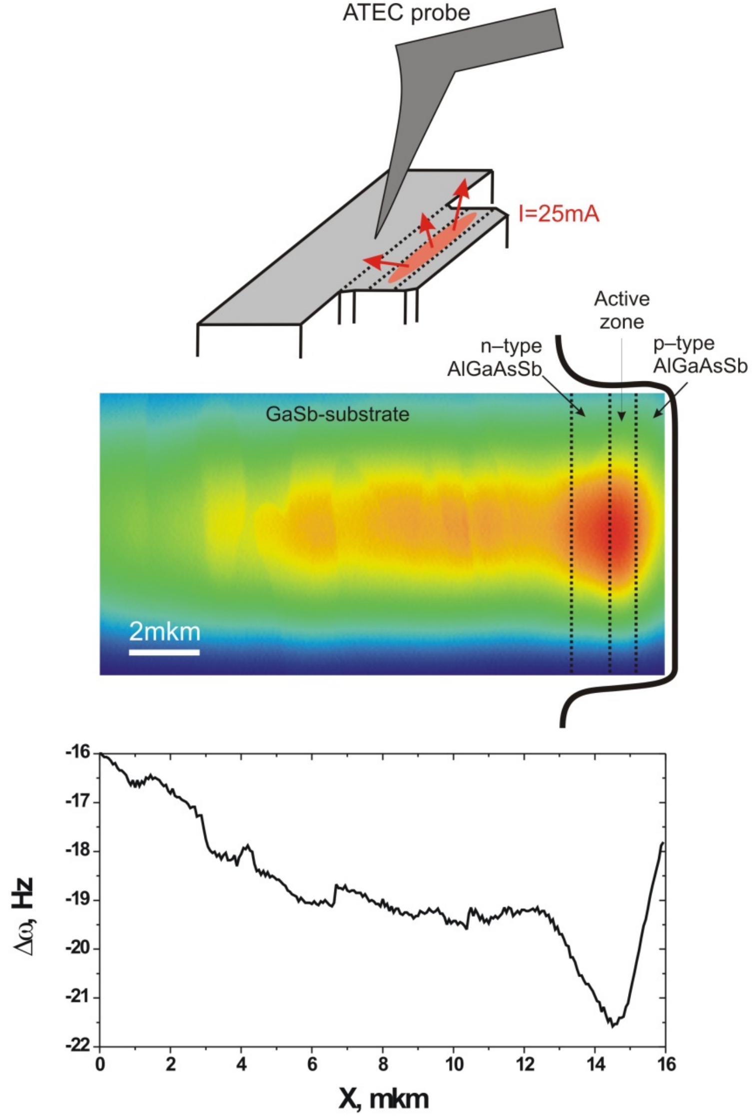
$$\lambda/2 = \Delta * \tan\theta$$

With an increase of Δz =λ/2 lines are shifted by one period

Analysis of LIFS intensity

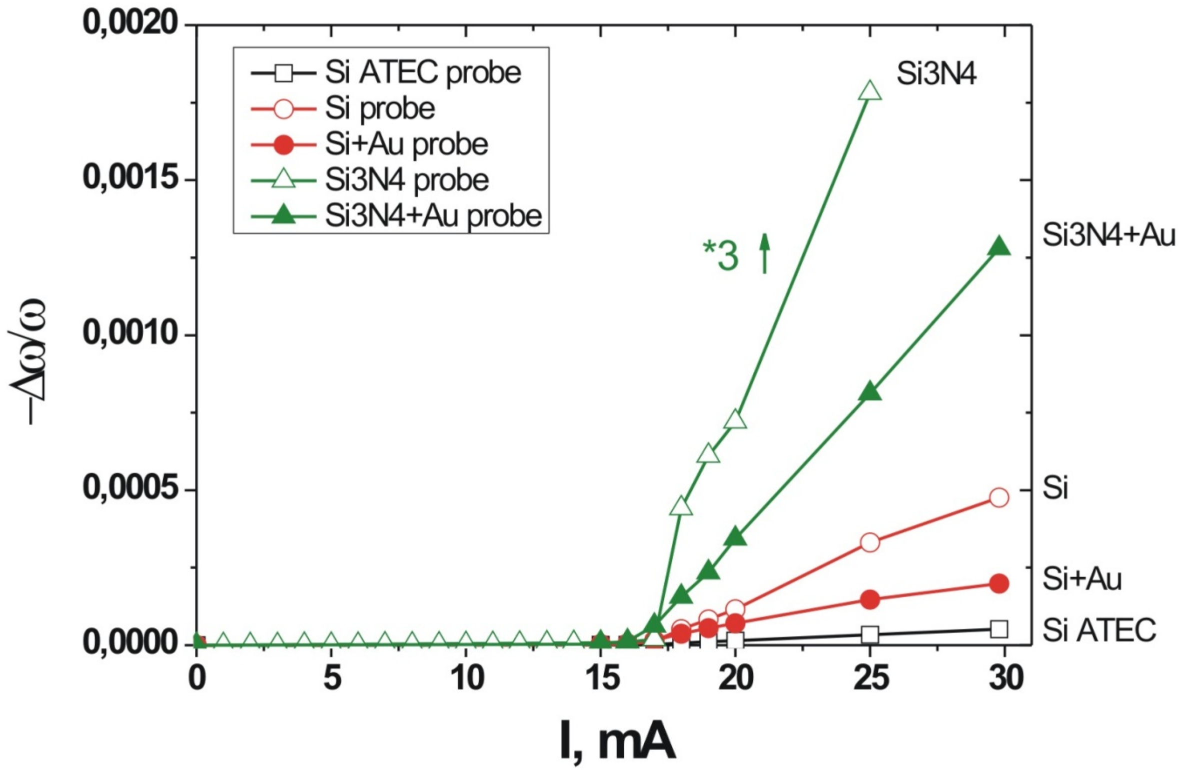
z = 2µm





Analysis of LIFS intensity

z = 2µm



1. **Au coating on tip side reduces the detected signal (reflection of radiation)**
2. **Signal is mainly due to absorption in the bulk and the top layer (the radiation absorption by silicon is weak at 2.1 µm and Si_3N_4 is transparent)**
3. **Signal is stronger with Si_3N_4 than Si : Why ?**

Sensitivity

Thermal conduction: Fourier's law in permanent regime

$$\frac{\Delta f_0}{f_0} = \frac{1}{2}\beta\Delta T$$

$$\lambda S \Delta T / L = Pk$$

The rate of heat flow is proportional to the temperature variation

P : laser power
S : cantilever cross section
k : part of absorbed power by the cantilever
λ : thermal conductivity

$$\Phi = \frac{\Delta T}{R_{th}}$$

$$R_{th} = \frac{L}{\lambda S}$$

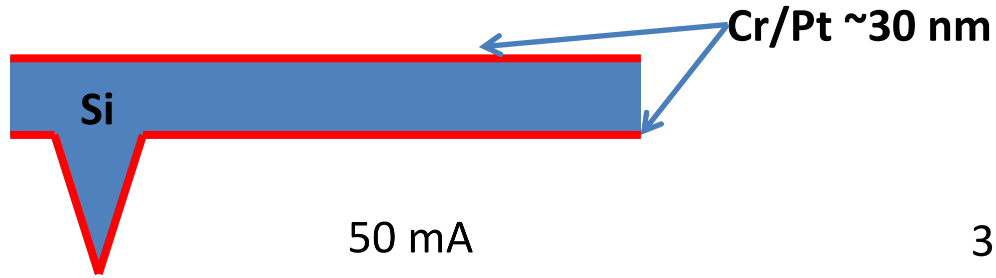
$$\boxed{Sensitivity = \frac{\Delta f_0 / f_0}{P} = \frac{\beta}{2\lambda}\frac{L}{S}k}$$

λ_{Si} = 130 W/(m.K)

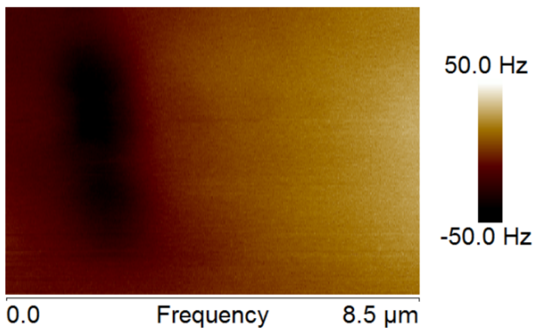
λ_{Si3N4} = 30 W/(m.K)

High sensitivity of Si_3N_4 probes is mainly due to the poor heat spreading because of the thermal conductivity and the small cross section of the cantilever.

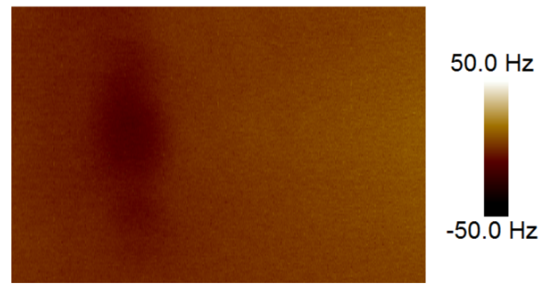
Absorption vs scattering

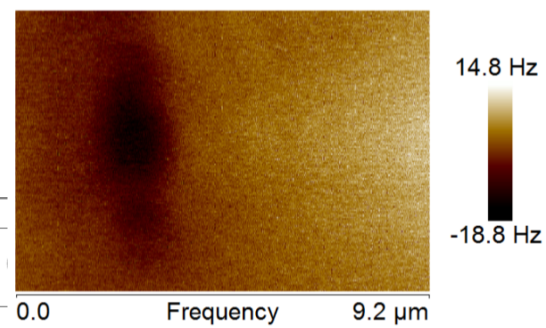


82 mA

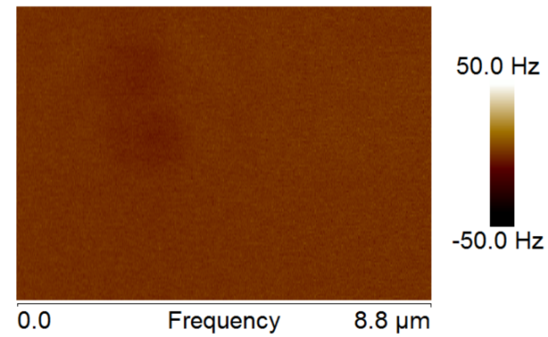


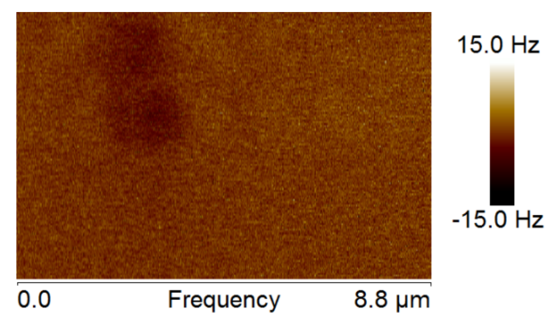
50 mA

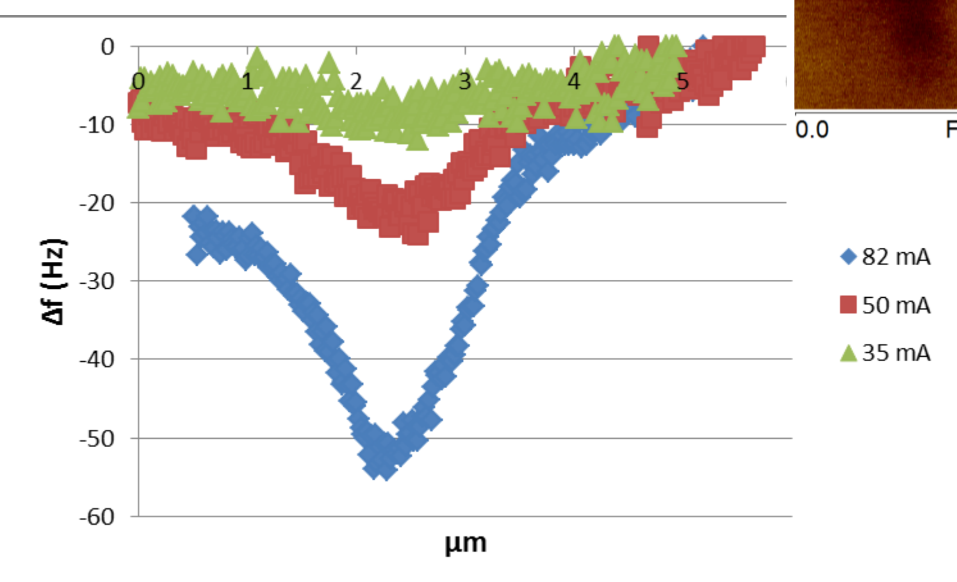




35 mA

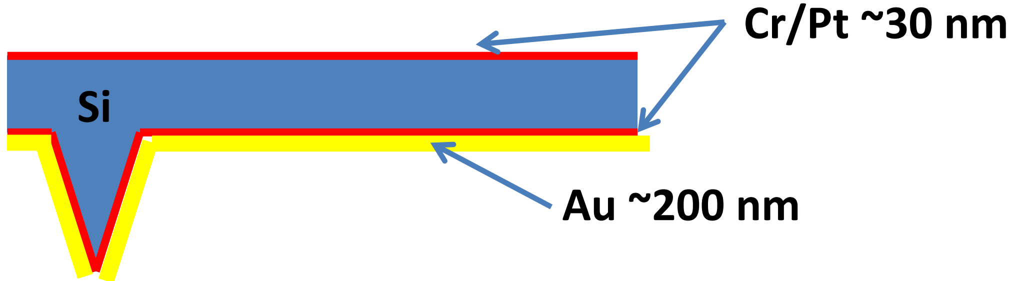


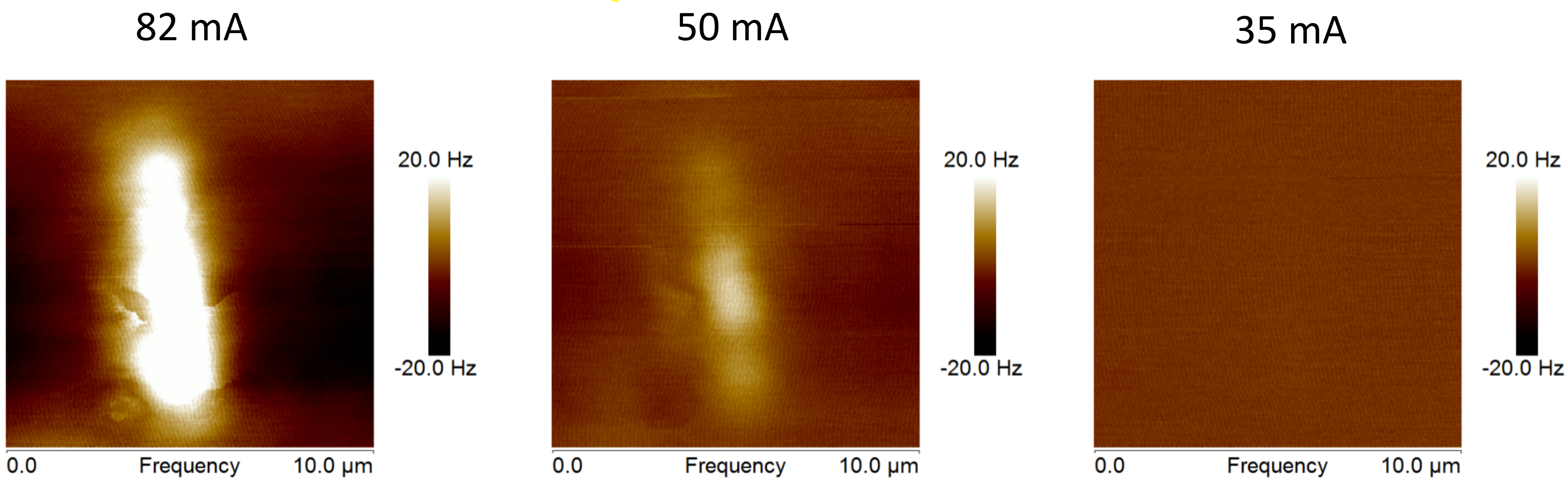


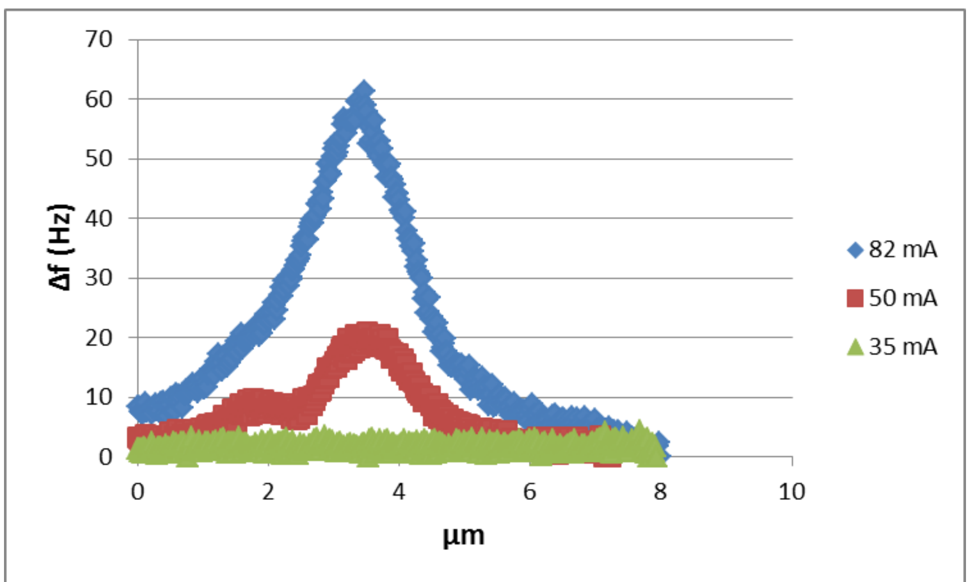


z = 1 µm

Absorption vs scattering







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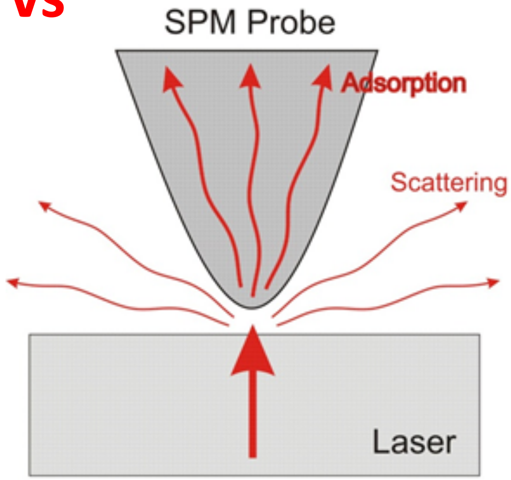
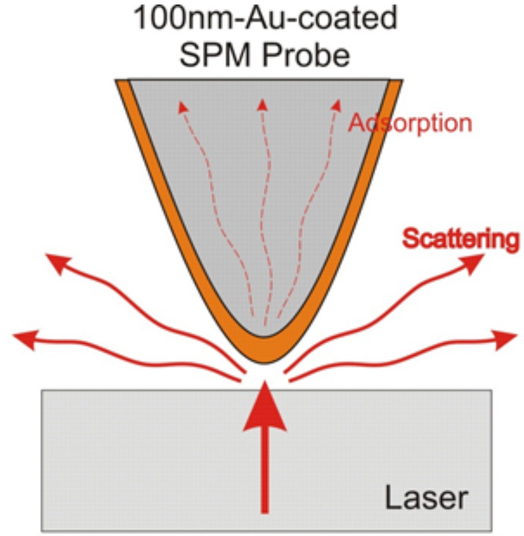




Adsorption

Heating

Negative Frequency shift

Scattering

$F_{scattering}$

$$m\ddot{z} + \gamma\dot{z} + kz = F_{sc0} + \frac{dF_{sc}}{dz} z$$

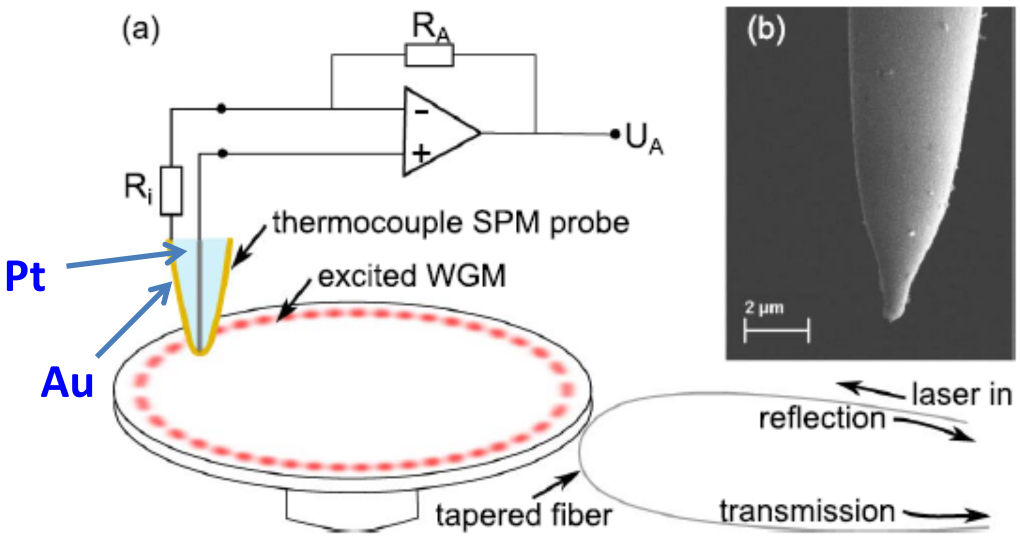
$$\omega = \sqrt{\frac{k - dF_{sc} / dz}{m}}$$

$$\frac{dF_{sc}}{dz} < 0$$

Positive Frequency shift !

Other techniques

March 1, 2014 / Vol. 39, No. 5 / OPTICS LETTERS, Klein et al, Abbe Center of Photonics, Jena, Germany



Highly sensitive mode mapping of whispering-gallery modes by <u>scanning thermocouple-probe microscopy</u>

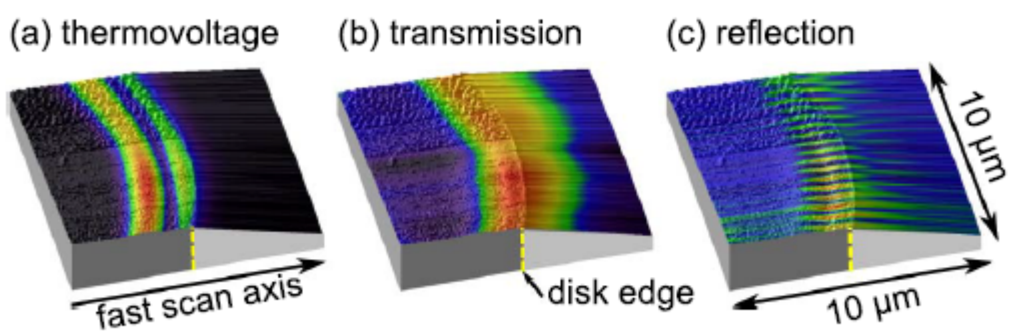


Fig. 3. (a) Thermovoltage map of a WGM with two radial maxima, overlaid on the topographic image. (b),(c) Synchronously measured (b) transmission and (c) reflection through the excitation taper.

λ =1550 nm

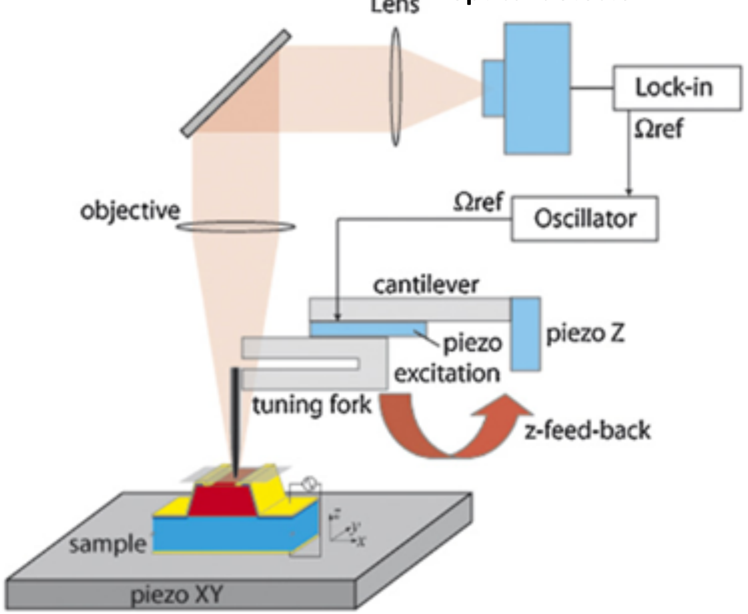
Apertureless Scannning Near Field Microscopy (aSNOM)

P.-A. Lemoine et al. / Materials Science and Engineering B 149 (2008) 270–274

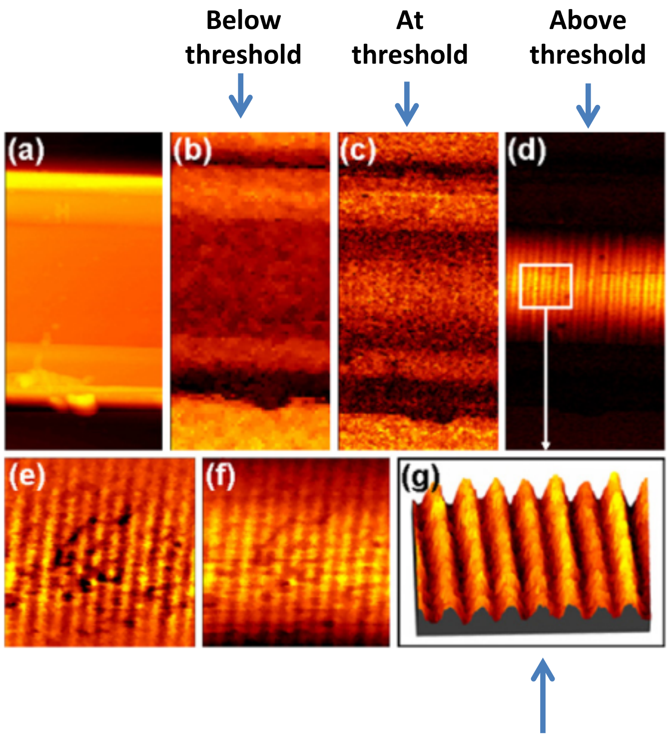
Conventional SNOM: based on the use of optical fiber coupled to a probe with sub-wavelength aperture

Fibers not adapted to wavelengths > 5 µm

aSNOM (or sSNOM: scattering SNOM): scattering of the near-field by the AFM tip Apex



QCL at 7.7 µm



Standing wave interfringe of about 1.25 µm

Perspectives

InAs/AlSb quantum cascade lasers operating in the far infrared (near 20 µm)

Wavelengths within the 4th atmospheric transparency windows, which would allow, for example, extending the spectroscopy application domain.

➡ **Actual task: work at ambient temperature and continuous regime**

Studies at both low temperature ~80-140 K (pulsed regime) and ambient temperature (continuous regime)

Characterization of other kind of IR lasers (Vecsels…)

Improvement of IR absoption: graphene?, InSb?, InGaAs? Grown by MBE on tip side…

Improvement of spatial resolution: metal or III-V layer deposition or growth on tip side excluding tip apex

Correction of tilt angle in order to control light interference with cantilever