Review of NSOM Microscopy for Materials

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Outline :

Introduction : concept of near-field scanning optical microscopy (NSOM)

A. Aperture NSOM

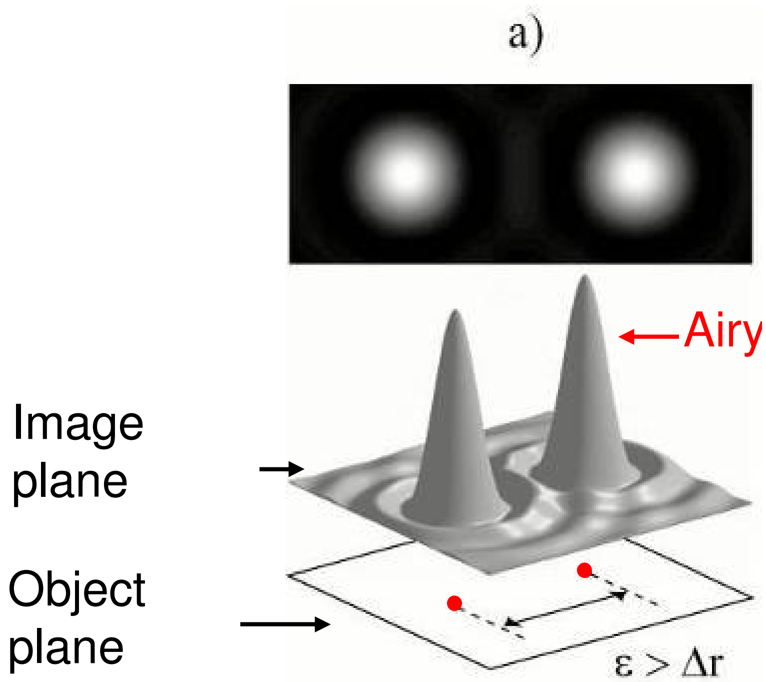
B. Scattering type NSOM

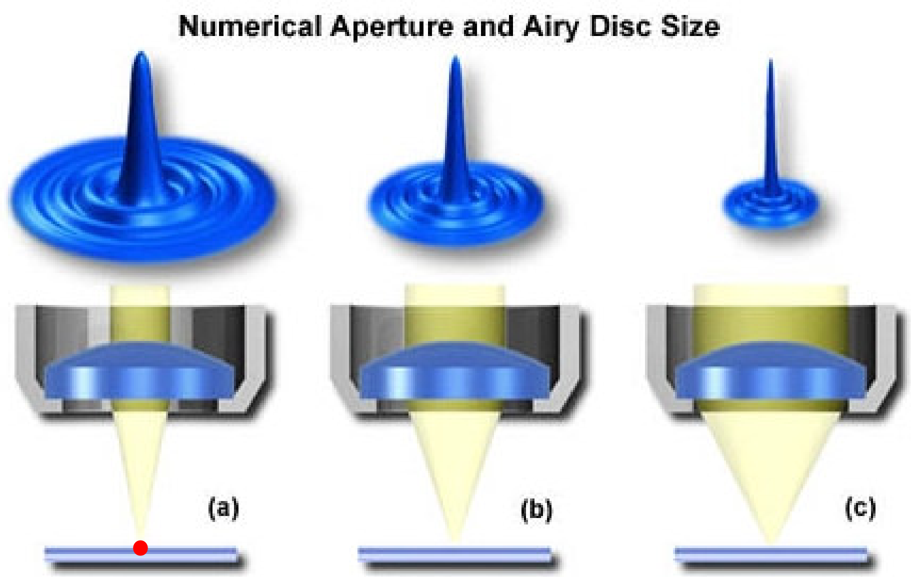
C. Thermal Radiation Scanning Tunnelling Microscope

D. NSOM with active fluorescent nano object

Far-field optical microscopy

• **Resolution limit** :





ref : http://www.olympusmicro.com/

Numerical aperture : NA=$n \sin\theta$

Rayleigh criterion :

$$\Delta r = \frac{0.6 \cdot \lambda}{n \sin\theta}$$

Example :

λ~0.5 µm (visible)

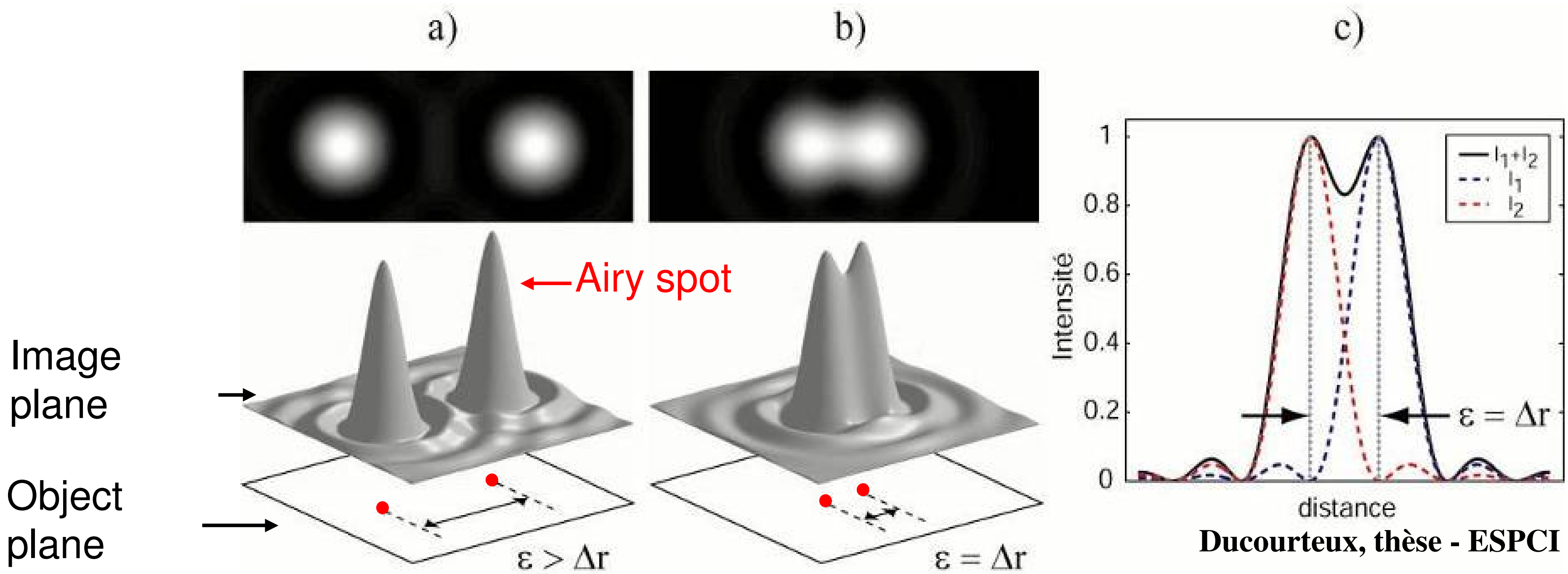
n = 1

$\sin\ \theta = 0.95$

$\Delta r \approx 320$ nm

Far-field optical microscopy

- **Resolution limit :**



Ducourteux, thèse - ESPCI

Numerical aperture : NA=n sinθ

Rayleigh criterion : $$\Delta r = \frac{0.6 \cdot \lambda}{n \sin \theta}$$

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sin θ = 0.95

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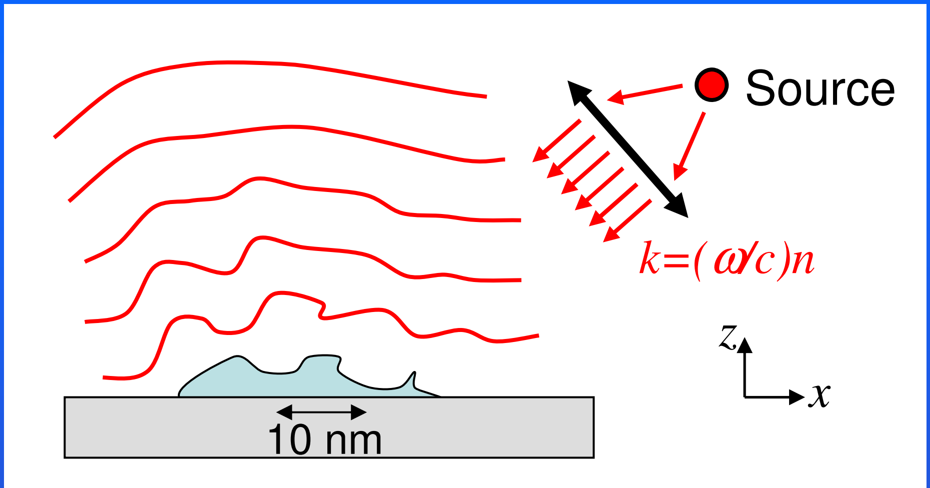
Near-field :definition



$$\mathbf{E}(x,y,z)=\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\hat{\mathbf{E}}(k_x,k_y;0)\,e^{i[k_x x+k_y y+k_z z]}dk_x dk_y$$

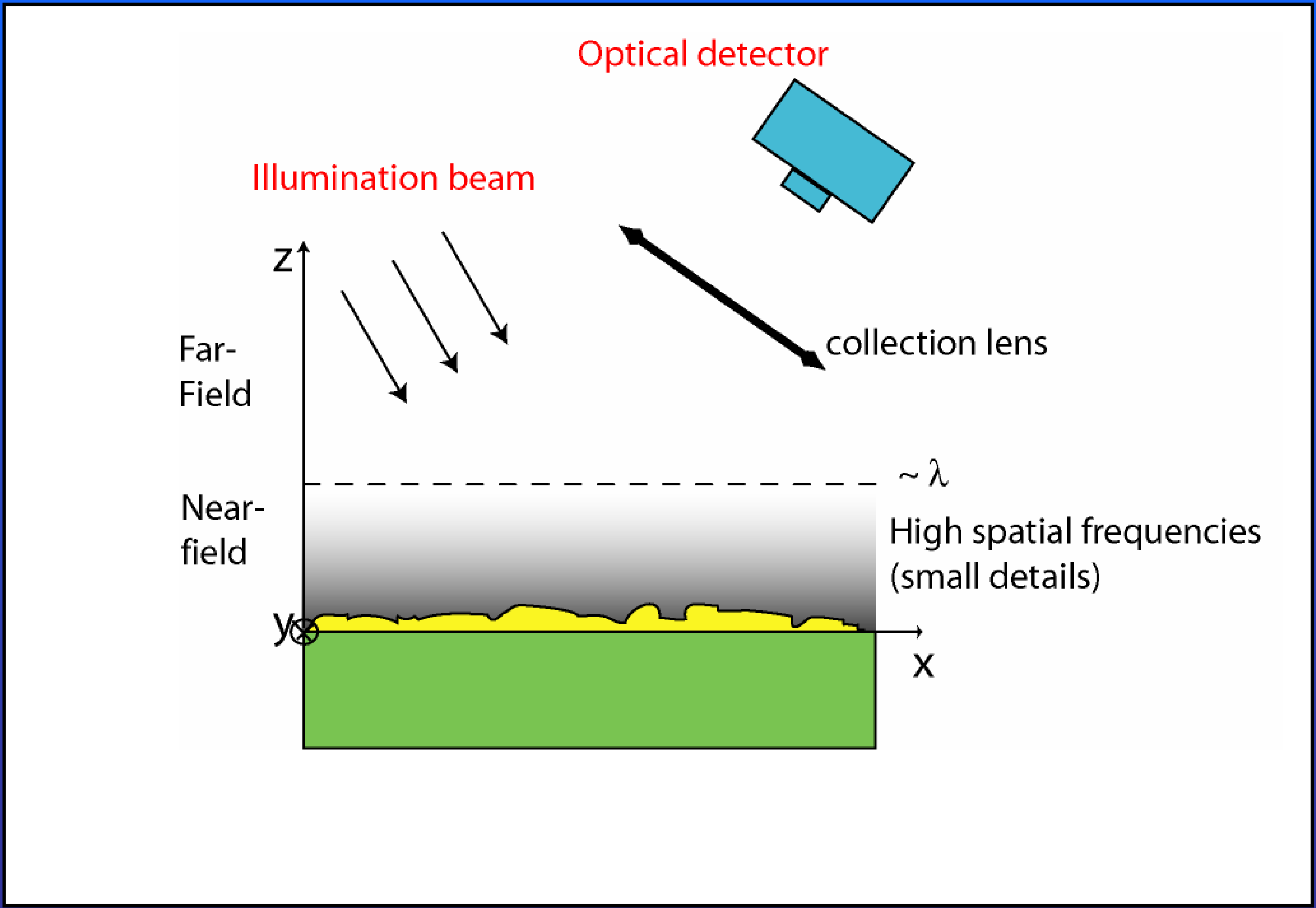
Spatial Fourier transform

$$k_z=\sqrt{\left(k^2-k_x^{\ 2}-k_y^{\ 2}\right)} \quad \text{with } \mathrm{Im}\{k_z\}\geq 0$$

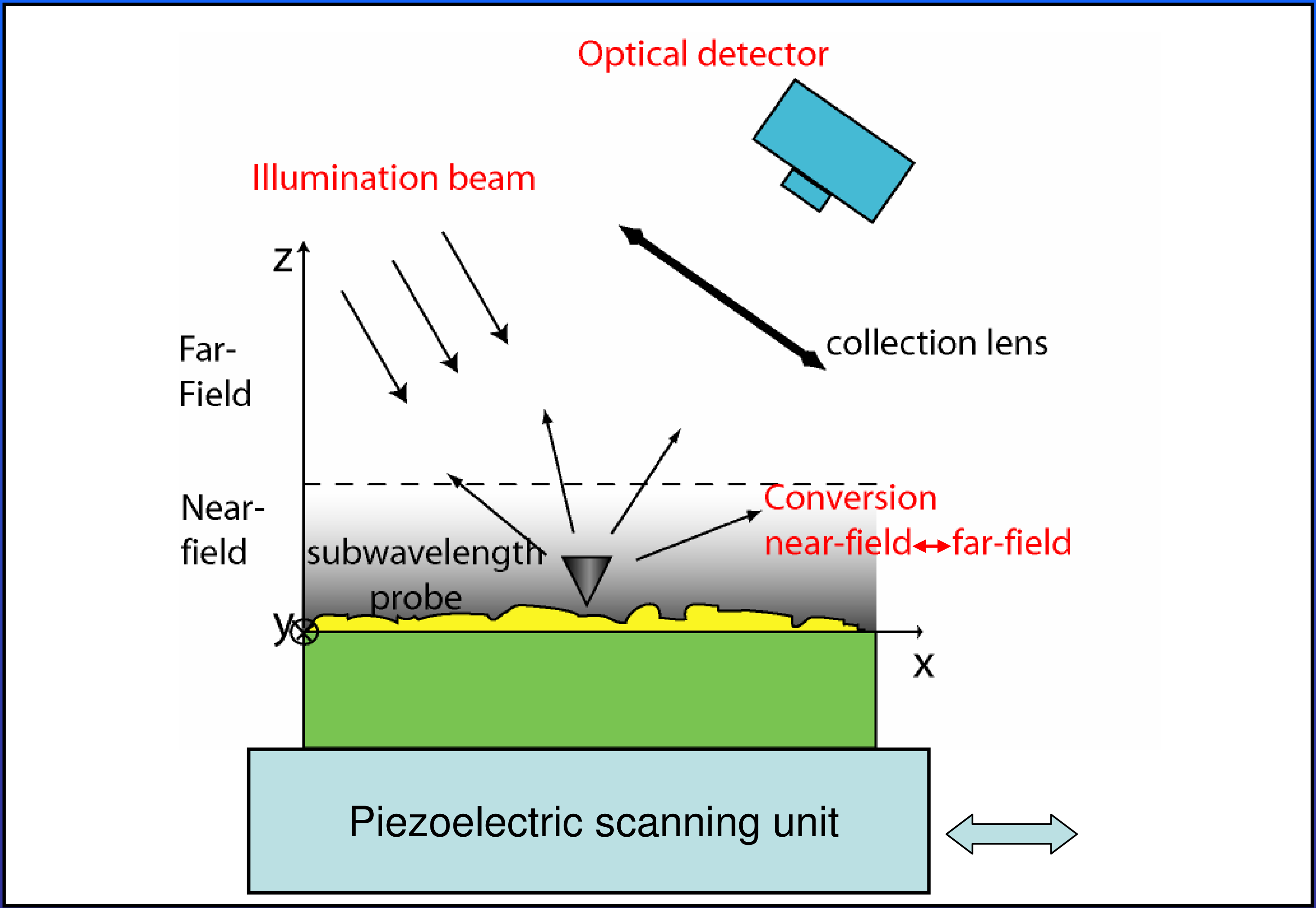
Plane waves :	$e^{i[k_x x+k_y y]}\,e^{ikz}$,	$k_x^{\ 2}+k_y^{\ 2}\leq k^2$	Low spatial frequencies
Evanescent waves :	$e^{i[k_x x+k_y y]}\,e^{-k_z z}$,	$k_x^{\ 2}+k_y^{\ 2}>k^2$	High spatial frequencies

Distance is a low-pass filter !

Near-field scanning optical microscopy NSOM : principle

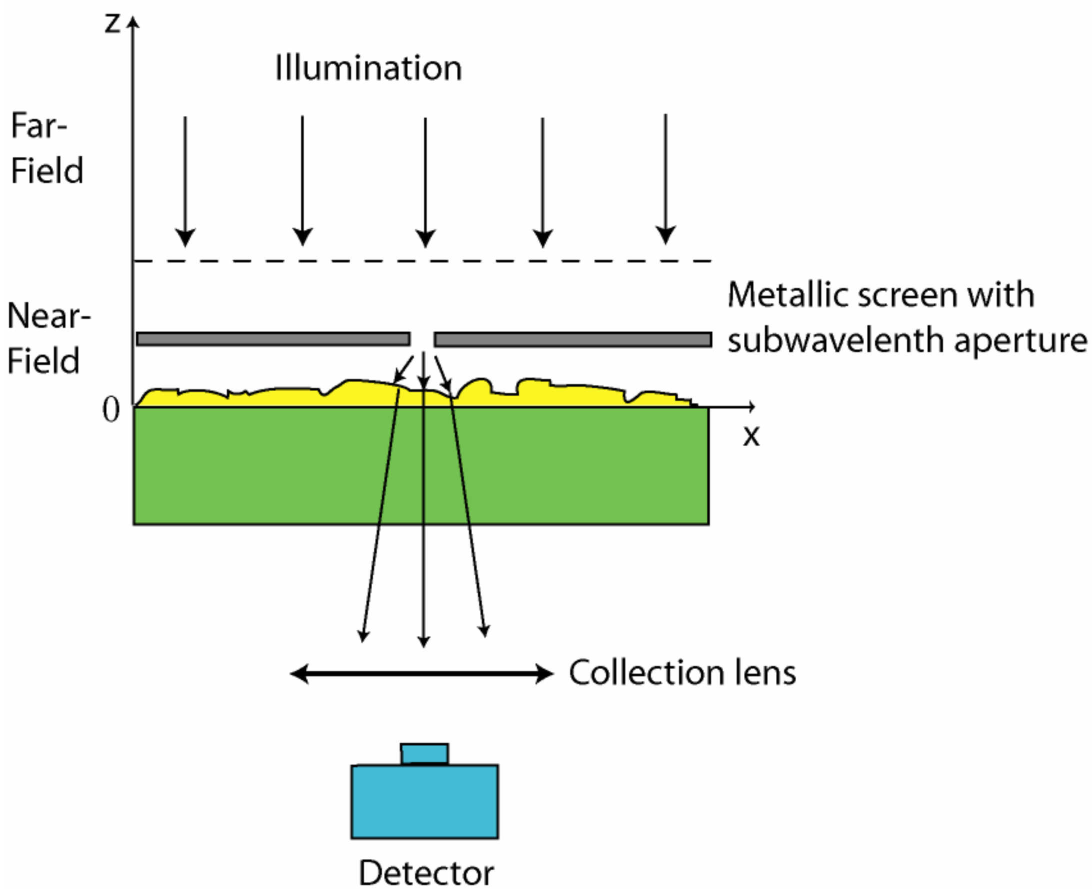


Near-field scanning optical microscopy NSOM : principle



A. Aperture NSOM

Synge's idea (1928) "to illuminate the sample through a subwavelength hole"

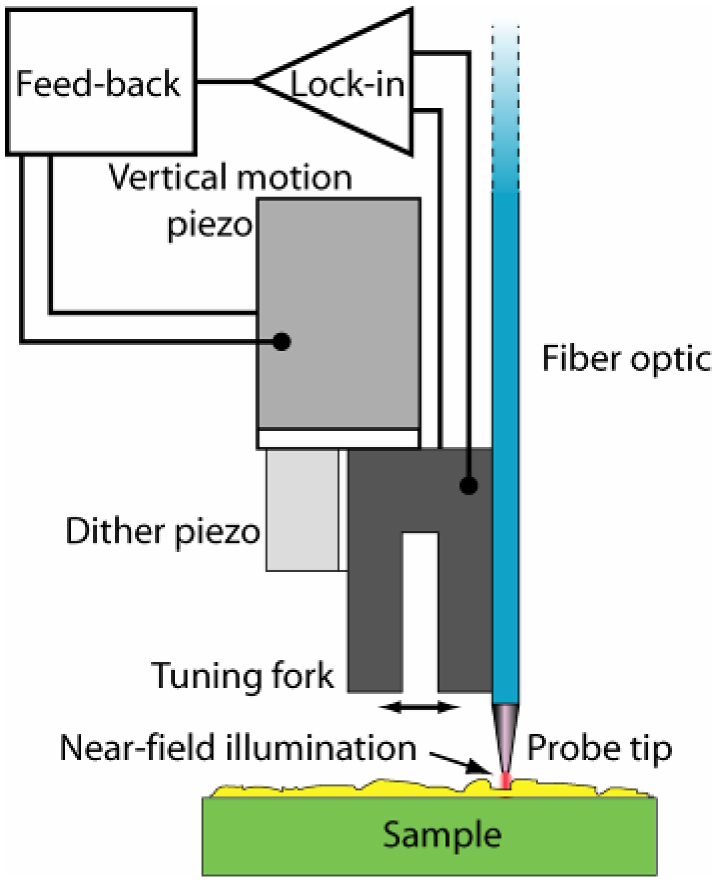


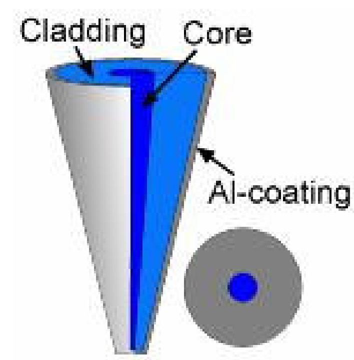
Synge, Phylos. Mag. **6**, 356 (1928)

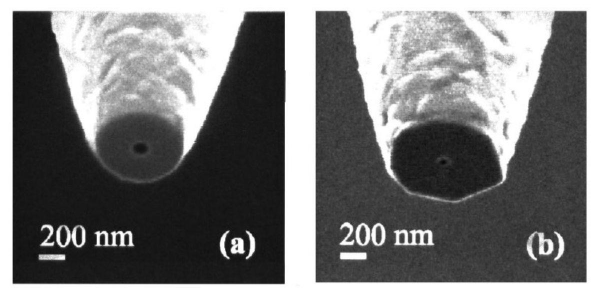
A. Aperture NSOM

Practical realization : D. W. Pohl (1984) - Appl. Phys. Lett. **44**, 651 (1984)

Subwavelength hole on an AFM scanning unit



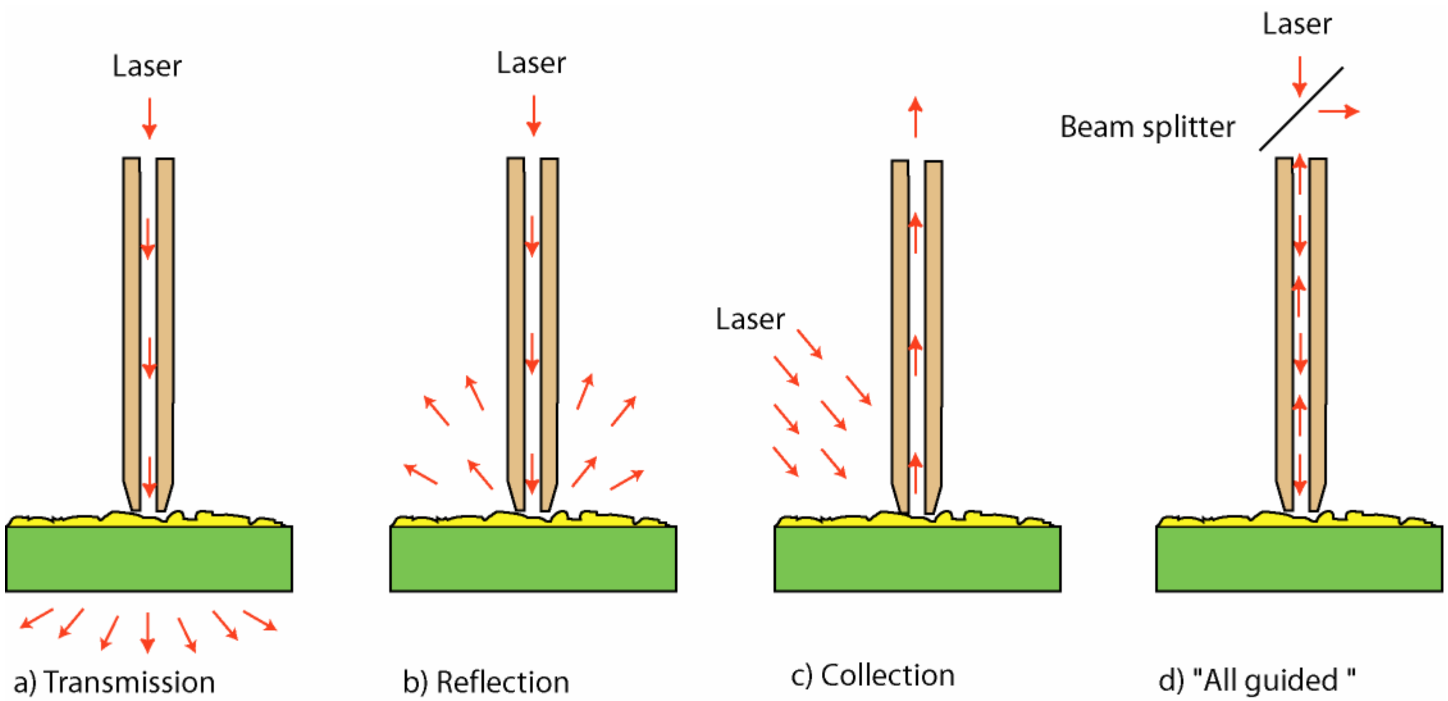




J. A. Veerman, et al.
Appl. Phys. Lett. **72**, 3115 (1998).

A. Aperture NSOM

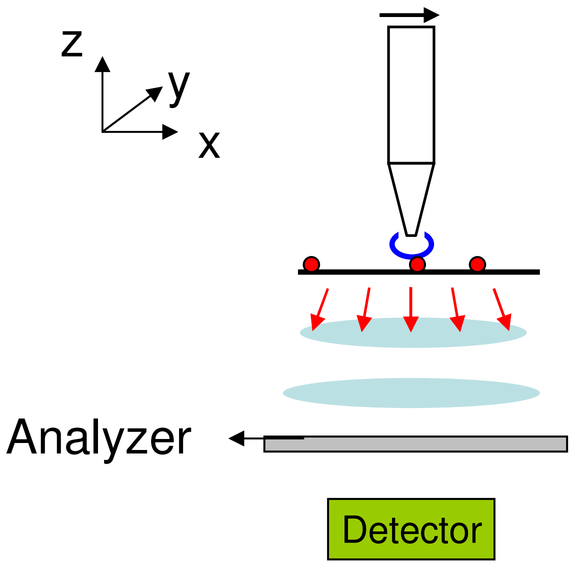
Different operating modes



A. Aperture NSOM

Applications : luminescence

• Single fluorescent molecules :



J.A. Veerman, et al., J. Microsc. **194**, 477 (1999)

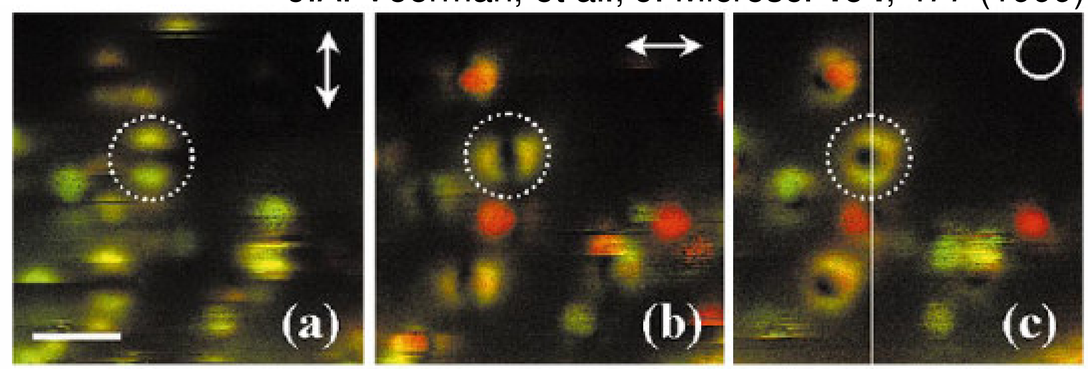
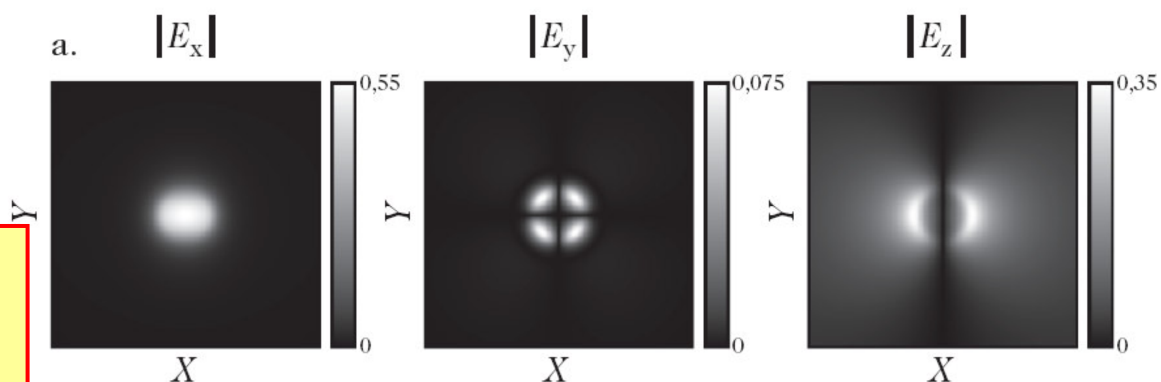


Image : 1.2 x1.2 µm

Organic molecule : DiIC18

➡ Molecule dipole // z

Field distribution around fiber tip aperture (incident polarization // x) →



Possibility to know dipole orientation from image symmetry.

"Les nouvelles microscopies" Belin (2006)- images L. Aigouy

A. Aperture NSOM

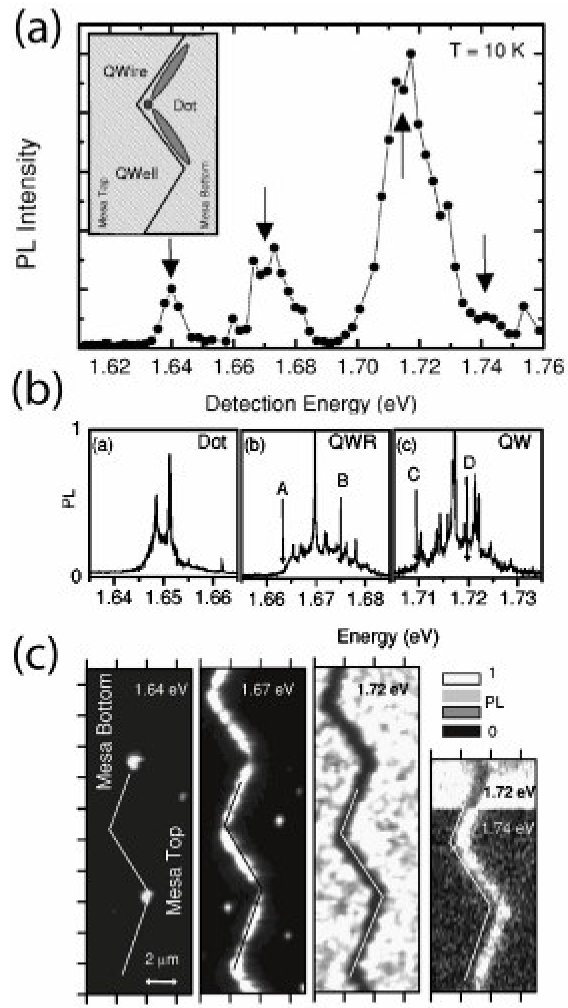
Applications : luminescence

• Luminescence in quantum heterostructures :

Global luminescence spectrum

Local spectra

Energy resolved imaging



V. Emiliani, et al., Phys. Rev. B **64**, 155316 (2001).

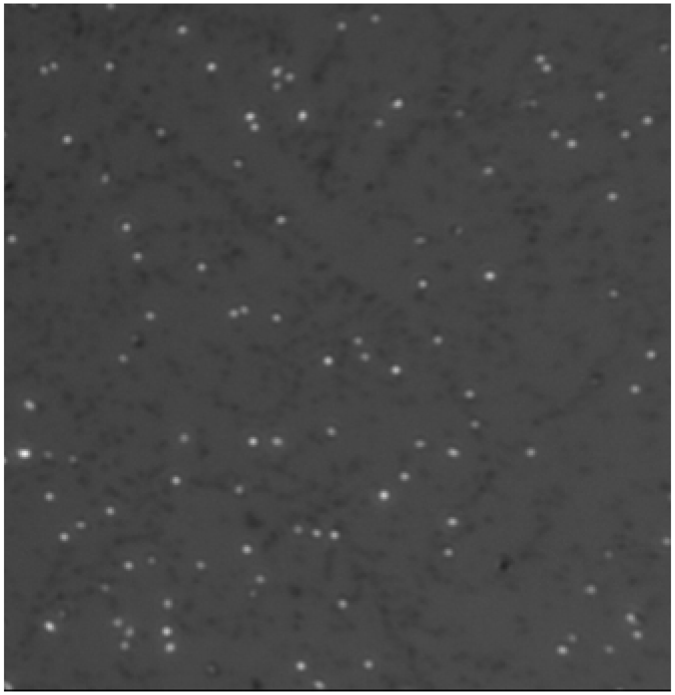
B. Scattering type NSOM

s-NSOM : Principle

• Light scattering by subwavelength objects :

Classical (far field) microscopy image

Image size:
35 µm x 35 µm



Gold beads (ϕ ~ 50 nm)
Visible illumination (λ ~ 500 nm)

Each nano particle = dipole

Dipole moment $\mathbf{p} = \varepsilon_m \alpha \mathbf{E_0}$

Scattering cross section $C_{scat}(\omega) = \frac{k^4}{6\pi}|\alpha|^2$

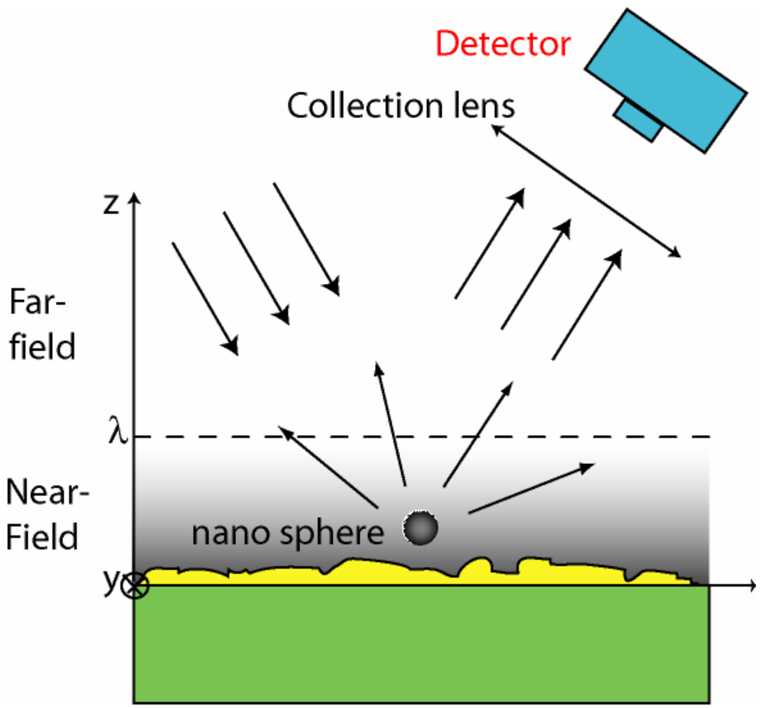
Scattered intensity $I \propto C_{scat} E_0^{\ 2}$

B. Scattering type NSOM

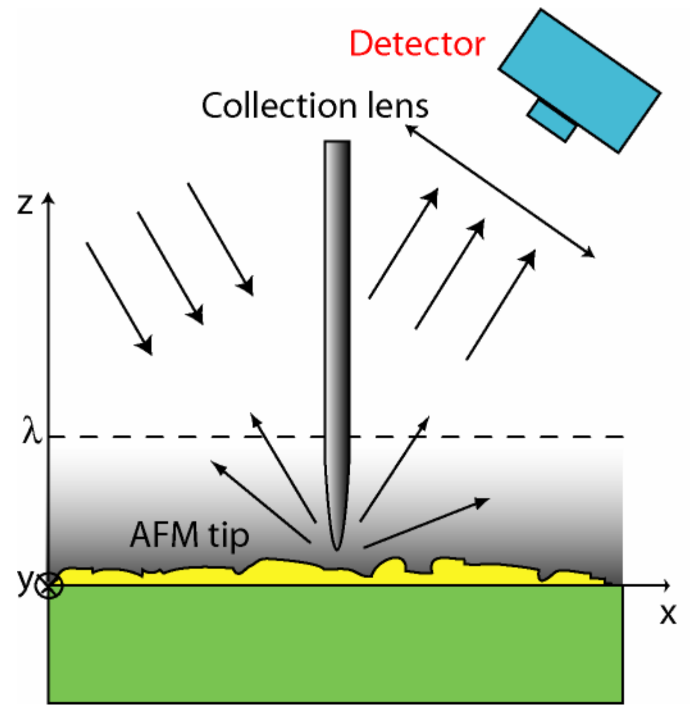
s-NSOM : Principle

• Controlled displacement of a single subwavelength scatterer

Idea :



In practice :

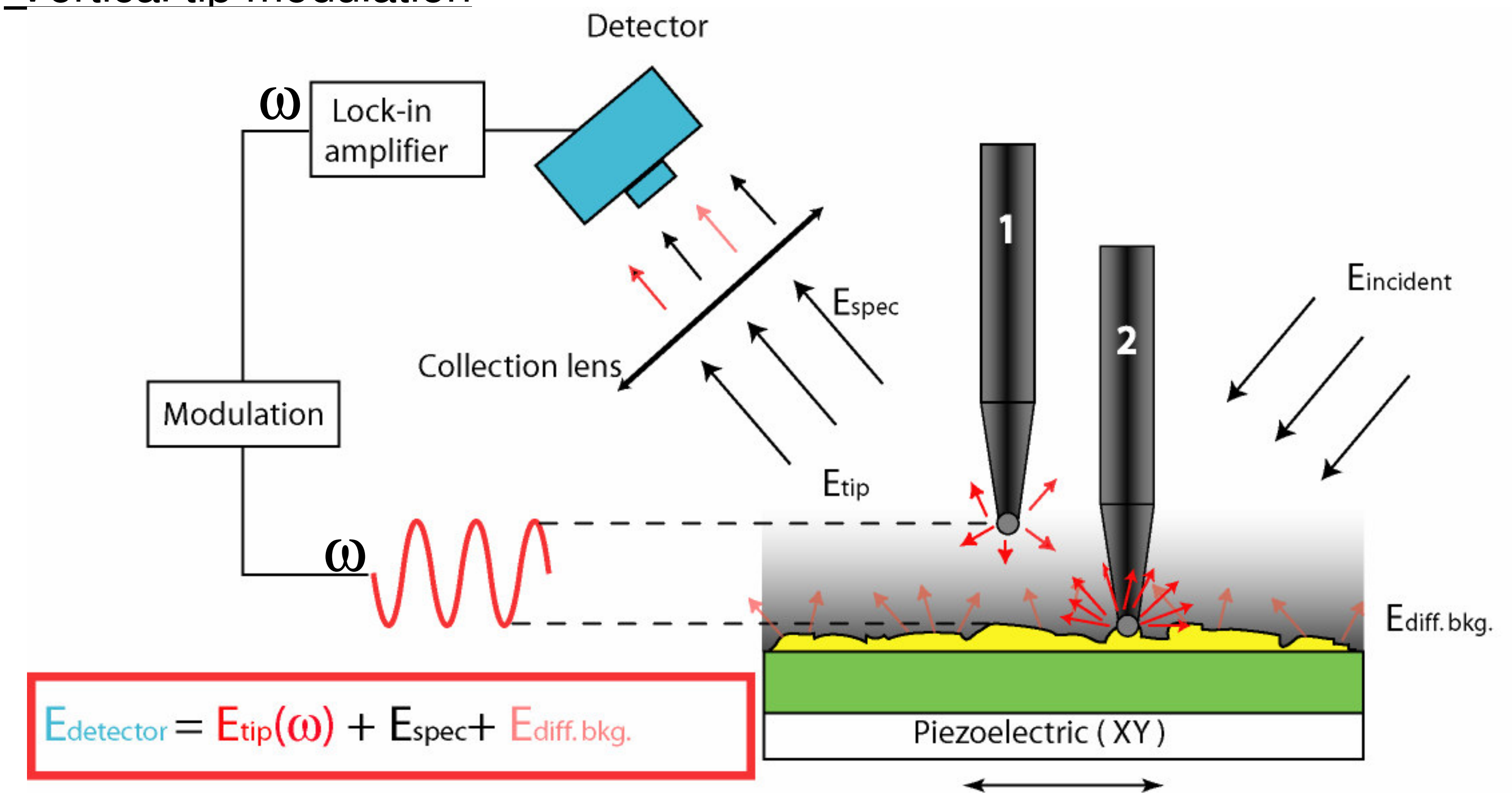


Recording of scattered signal vs. AFM tip position → Near-field optical image with resolution ~ ϕ

B. Scattering type NSOM

s-NSOM : Principle

• Vertical tip modulation



- To extract $E_{tip}(\omega)$ from the background

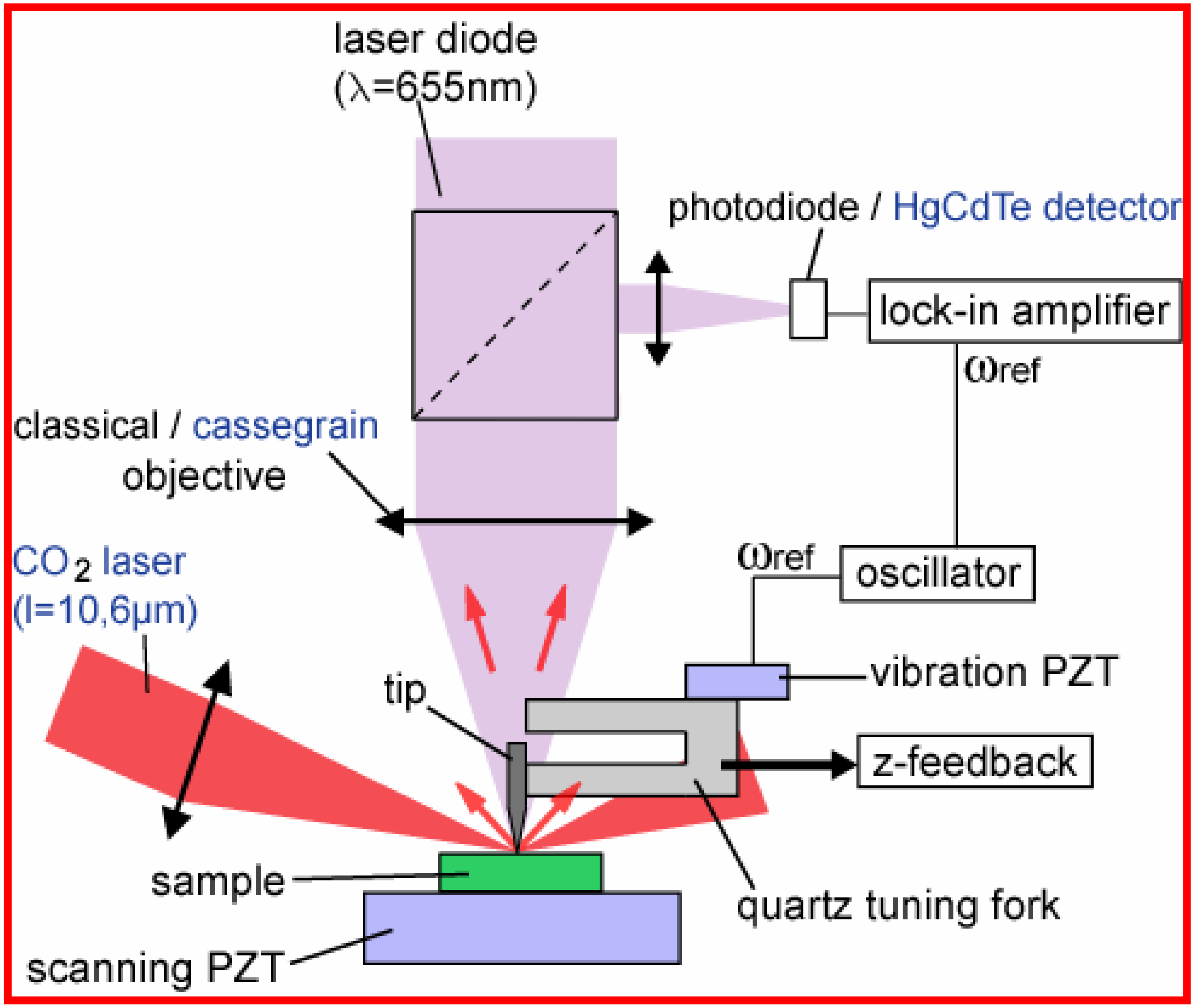
- Surface topography (AFM, « tapping » mode)

B. Scattering type NSOM

Example of s-NSOM design

Two modes :

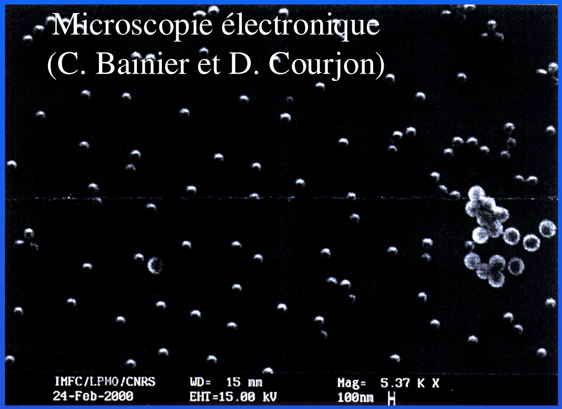
- Visible : λ=655 nm
- Infrared : λ=10.6 μm



Y. De Wilde, F. Formanek, L. Aigouy, Rev. Sci. Instrum. **74**, 3889 (2003)

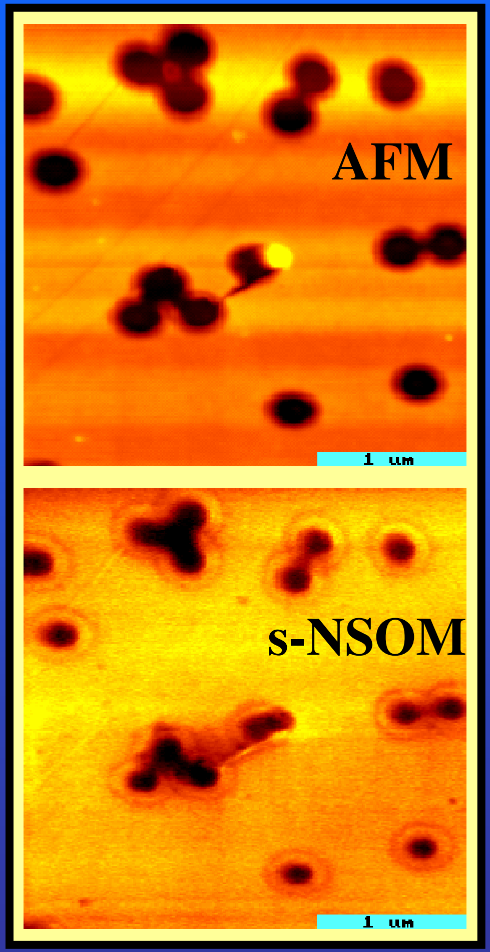
s-NSOM with visible or infrared laser illumination : experimental results

SUBWAVELENGTH HOLES (ϕ=200nm) : INFRARED imaging

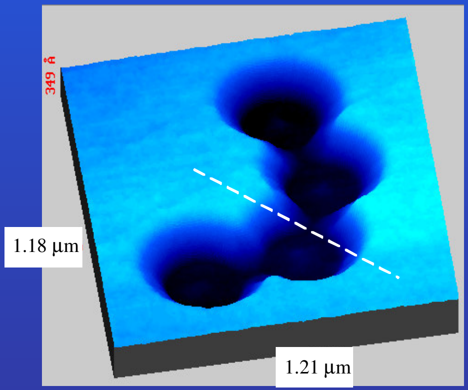


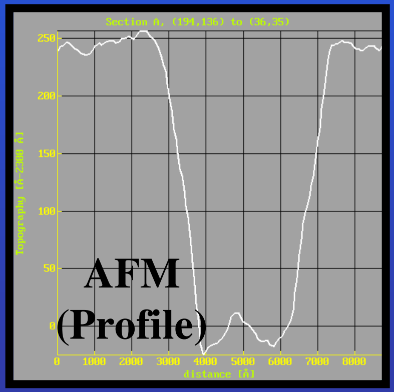
Formanek, De Wilde, Aigouy, J. Appl. Phys. 93, 9548 (2003)

GDR Optique de champ proche Appl. Optics 42, 691 (2003)



AFM (topography)





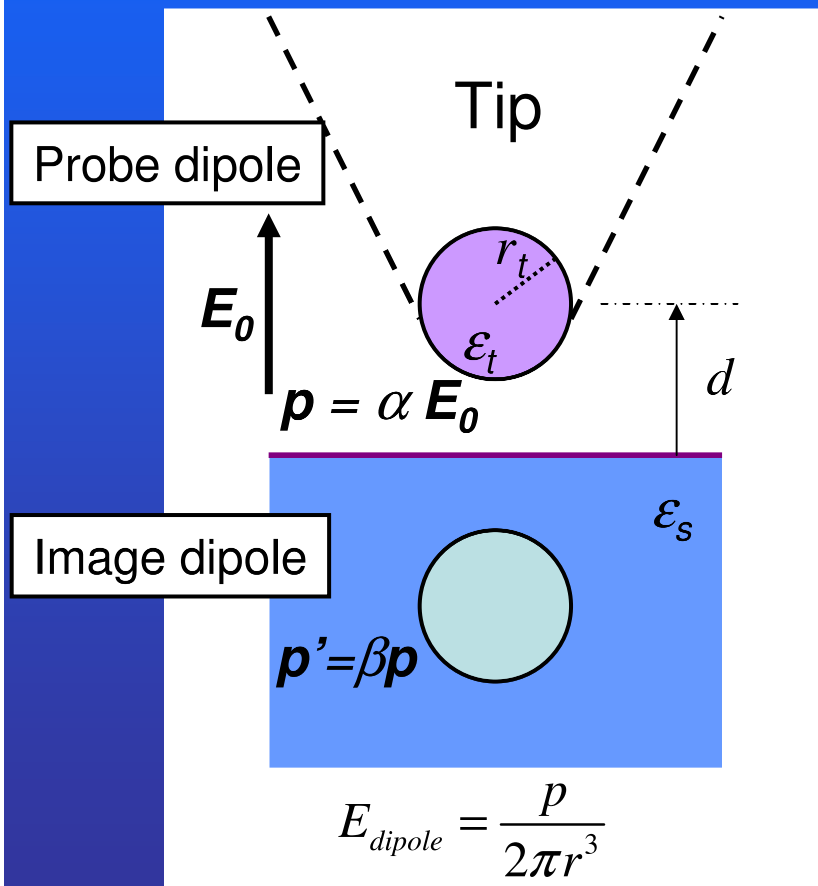
SNOM (3µmx3µm)

Infrared illumination λ=10,6 µm

Optical resolution ~ 30 - 50 nm
~ λ/200

s-NSOM: Relation to materials dielectric functions

The optical signal is due to scattering of the coupled probe dipole – image dipole system



Scattering cross section

$$C_{scat}(\omega) = \frac{k^4}{6\pi}\left|\alpha^{eff}\right|^2$$

Effective polarizability

$$\alpha^{eff} = \frac{\alpha(1+\beta)}{1-\frac{\alpha\beta}{16\pi d^3}}$$

$$E = E_0 + E_{image}$$

Sphere dipole

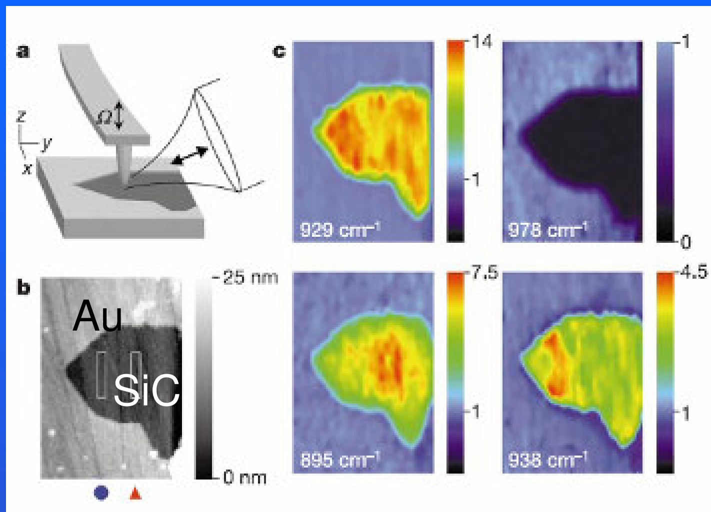
$$\alpha = 4\pi r_t^3 \frac{\varepsilon_t - 1}{\varepsilon_t + 2}$$

Image dipole

$$\beta = \frac{\varepsilon_s - 1}{\varepsilon_s + 1}$$

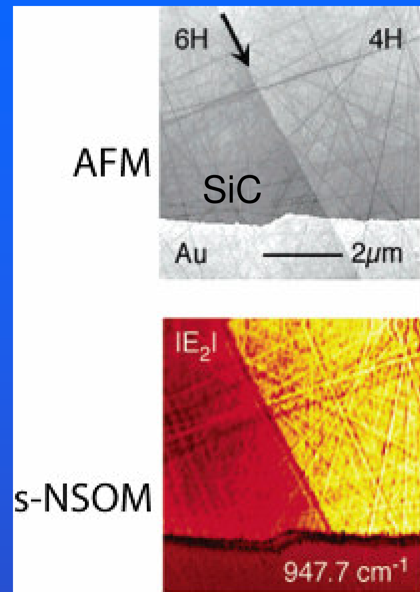
B. Knoll and F. Keilmann, Opt. Comm. **182**, 321 (2000).

Relation to materials properties (IR, $\lambda \sim 10\mu m$)



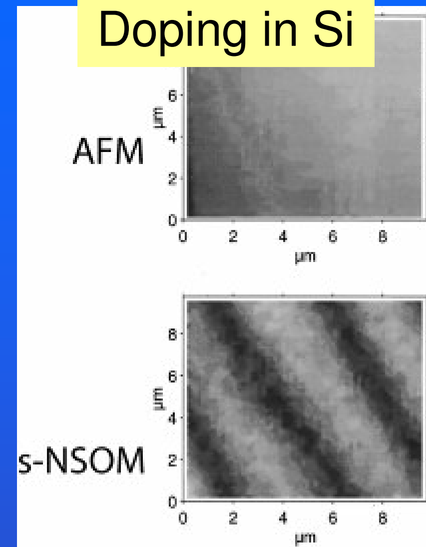
R. Hillenbrand et al. , Nature **418**, 159 (2002)

Phonon-polariton→resonance in α_{eff}



A. Huber, et al., Nanolett. **6**, 774 (2006).

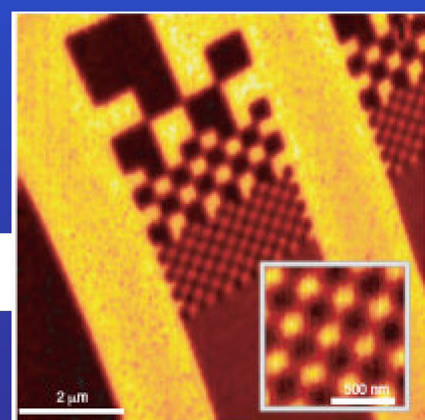
Doping in Si



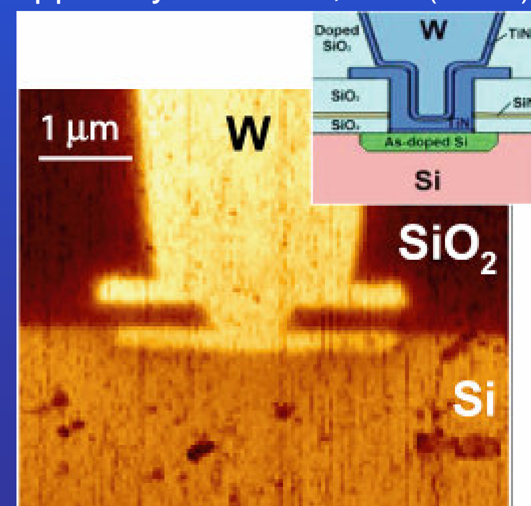
A. Lahrech, et al., Appl. Phys. Lett. **71**, 575 (1997).

Amorphous vs. crystalline SiC

N. Ocelic and R. Hillenbrand Nature Mater. **3**, 606 (2004).

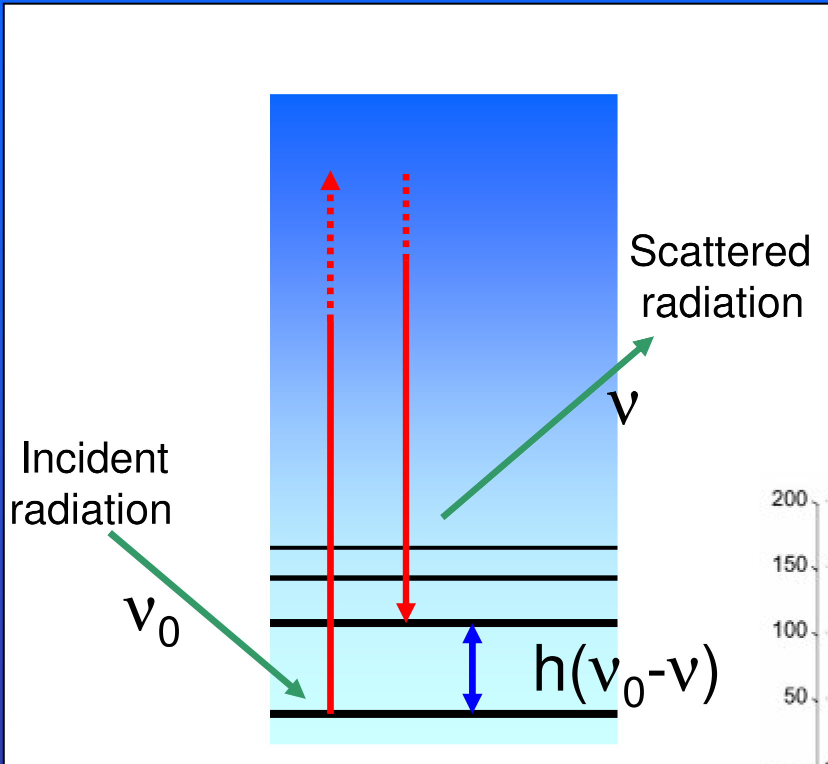


Crystal structure



R. Hillenbrand, et al.
Collaboration with Infineon (J. Wittborn)
(Presented at NFO9 - to be published)

s-NSOM : Nano Raman spectroscopy

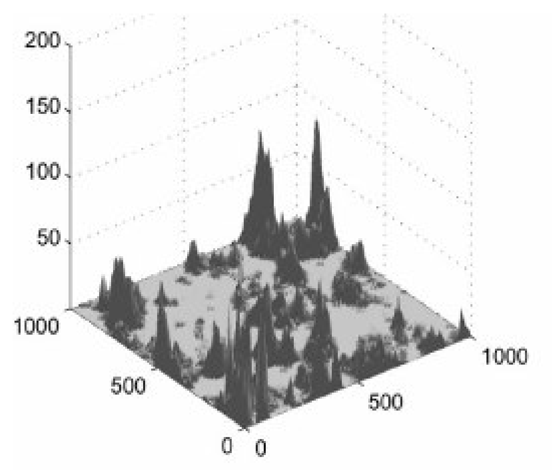


Material identification via
the energy of molecular vibrations

Typical molecule :

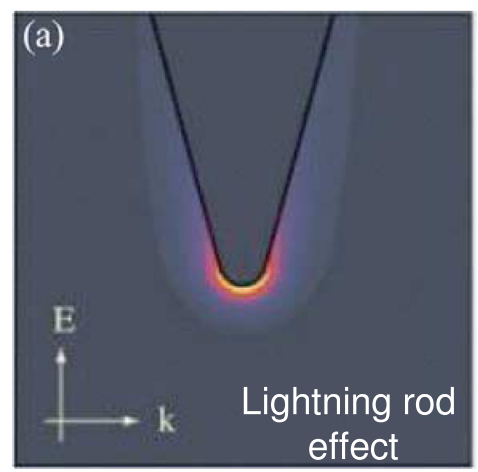
$C_{scat} \sim 10^{-30}\ cm^2$

• Solution : local field enhancement



SERS

Ducourtieux et al.,
Phys. Rev. B **64**, 165403 (2001).

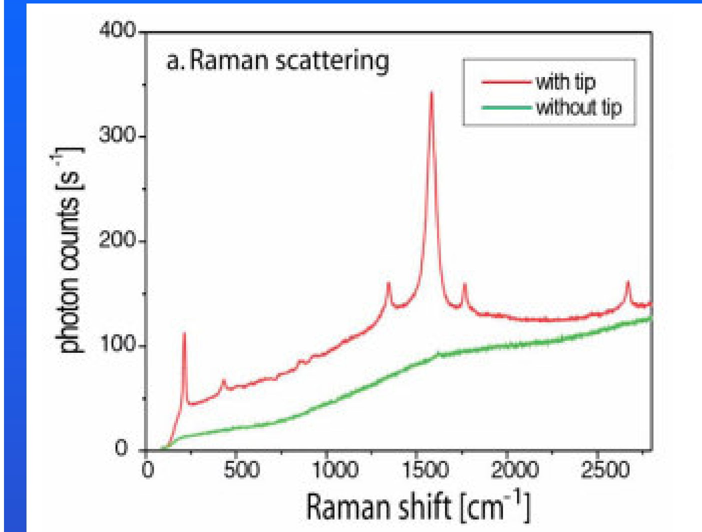


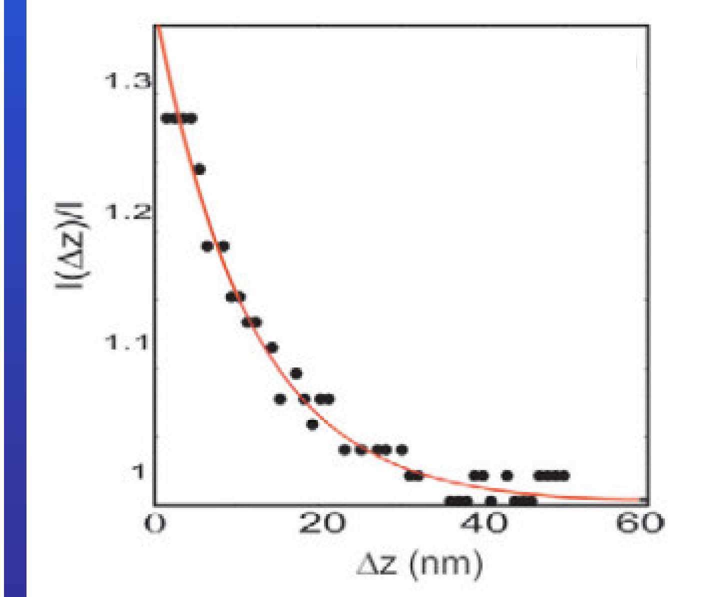
TERS

Anderson et al.,
Materials Today (2005).

s-NSOM : Nano Raman spectroscopy

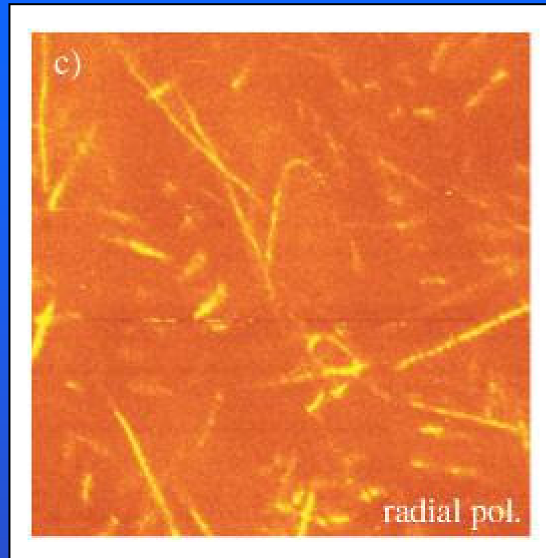
TERS on Carbon nanotubes





H. Qian, et al.,

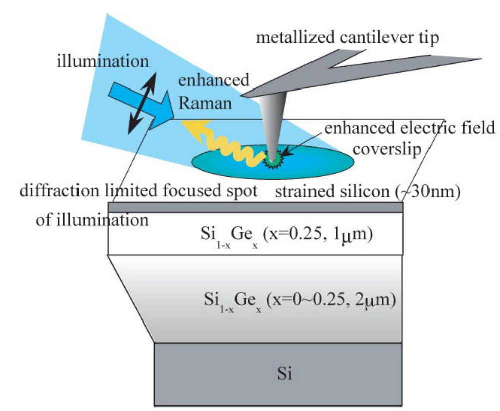
Phys. Stat. Sol. (b) **243**, 3146 (2006).

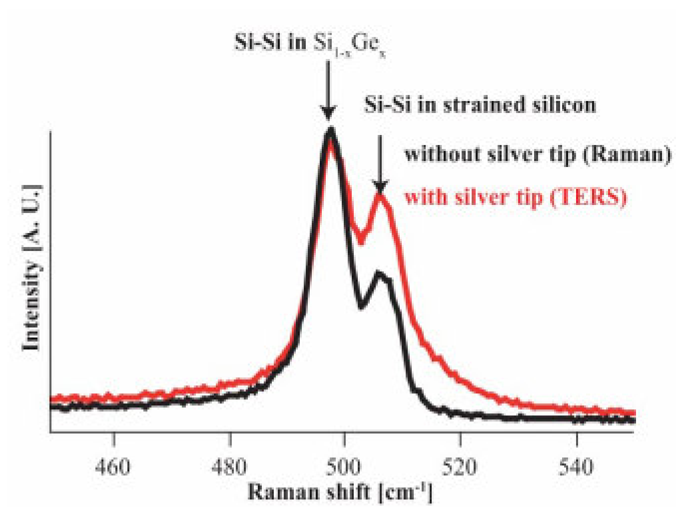


Nano Raman Imaging

N. Anderson J. Opt. A: Pure Appl. Opt. **8** , S227 (2006).

TERS on strained silicon





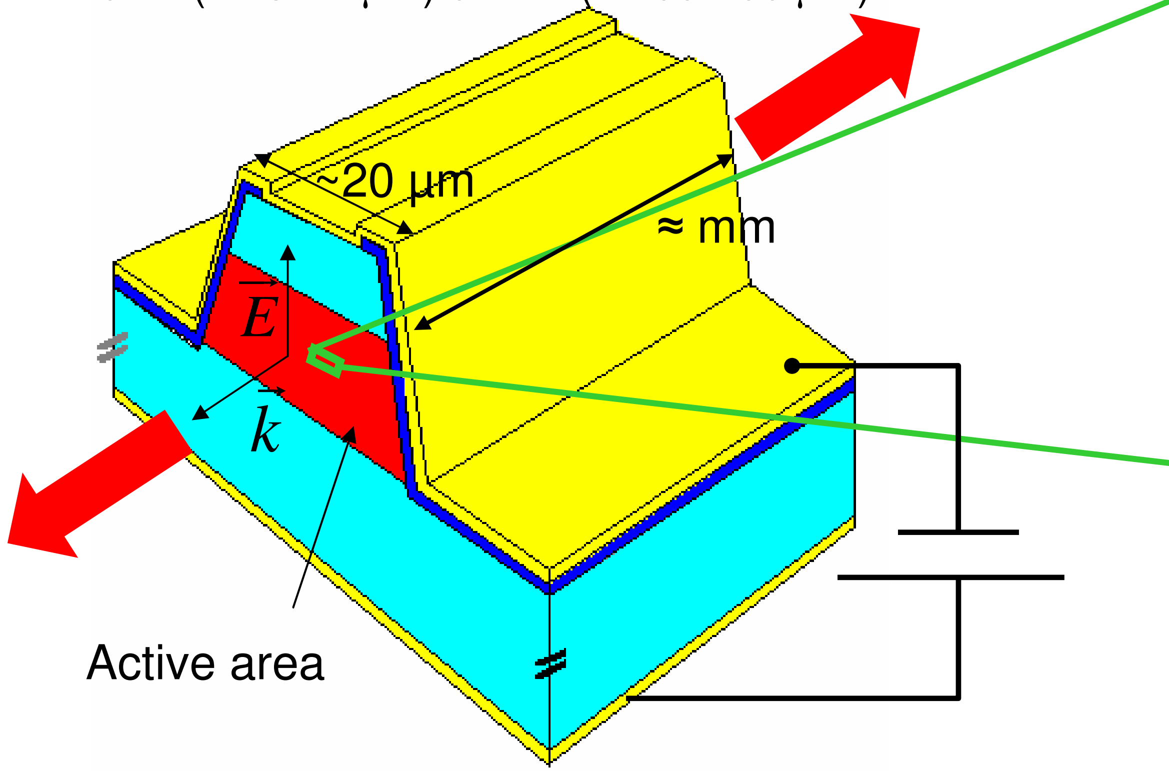
N. Hayazawa, et al., SPIE Newsroom 10.1117/2.1200611.0426

s-NSOM-Imaging working semiconducting devices

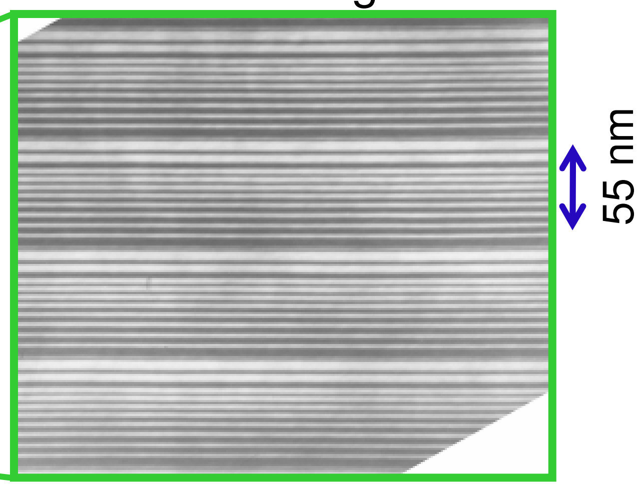
Quantum cascade lasers

InGaAs/AlInAs, GaAs/AlGaAs, InAs/AlSb…

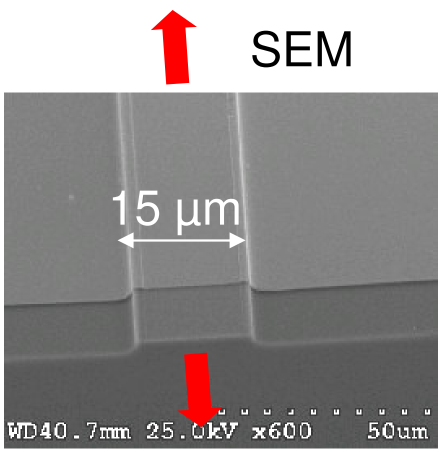
λ: mid-IR (λ≈ 3-24 µm) & THz (λ≈ 60-200 µm)



TEM image



SEM

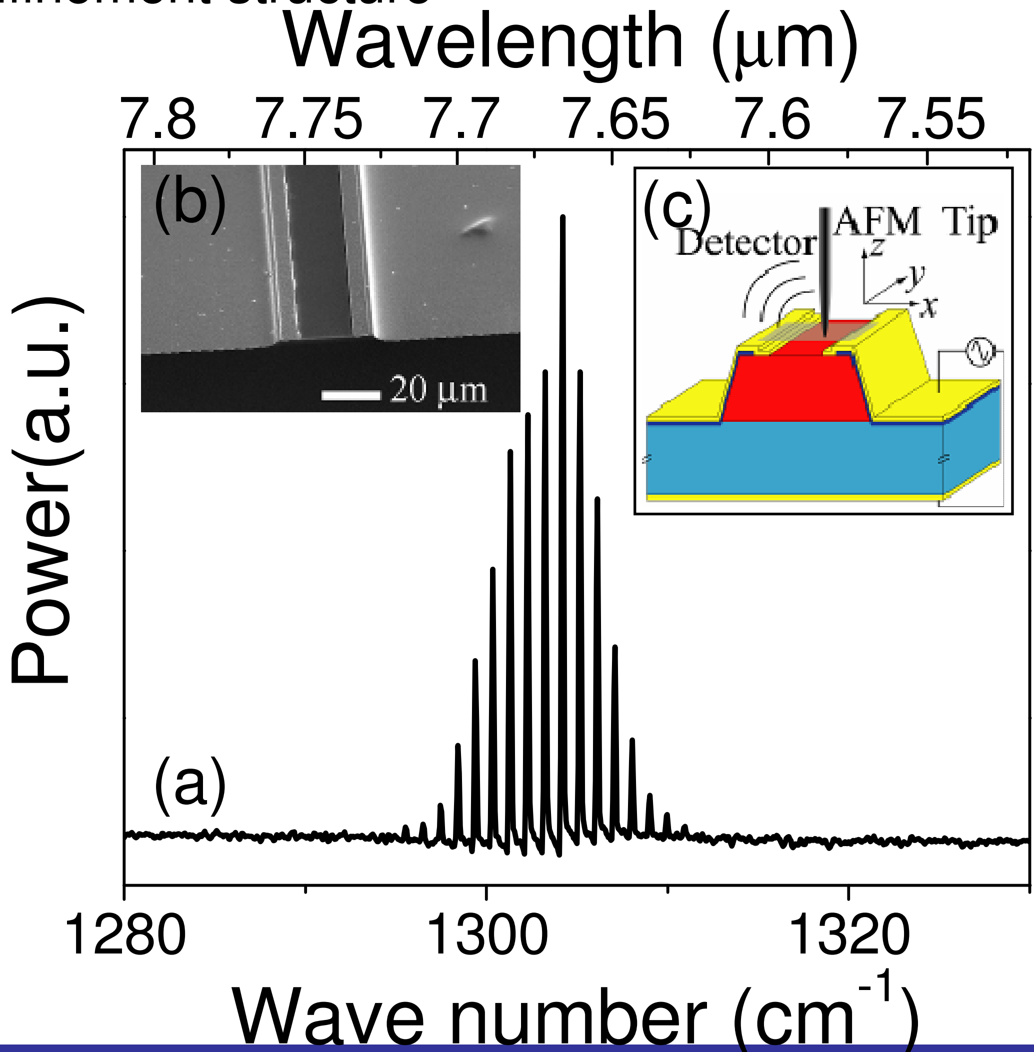


R. Colombelli (Institut Electronique Fondamentale, Orsay,FR)
V. Moreau - M. Bahriz (PhD students)
L. Wilson, A. Krysa (University of Sheffield,UK)
Y. De Wilde (ESPCI, Paris,FR)
P.-A. Lemoine (PhD student)

s-NSOM-Imaging working semiconducting devices

Quantum cascade lasers

Air confinement structure



$$\lambda = 7.78\ \mu m$$

$$n_{eff} = 3.4$$

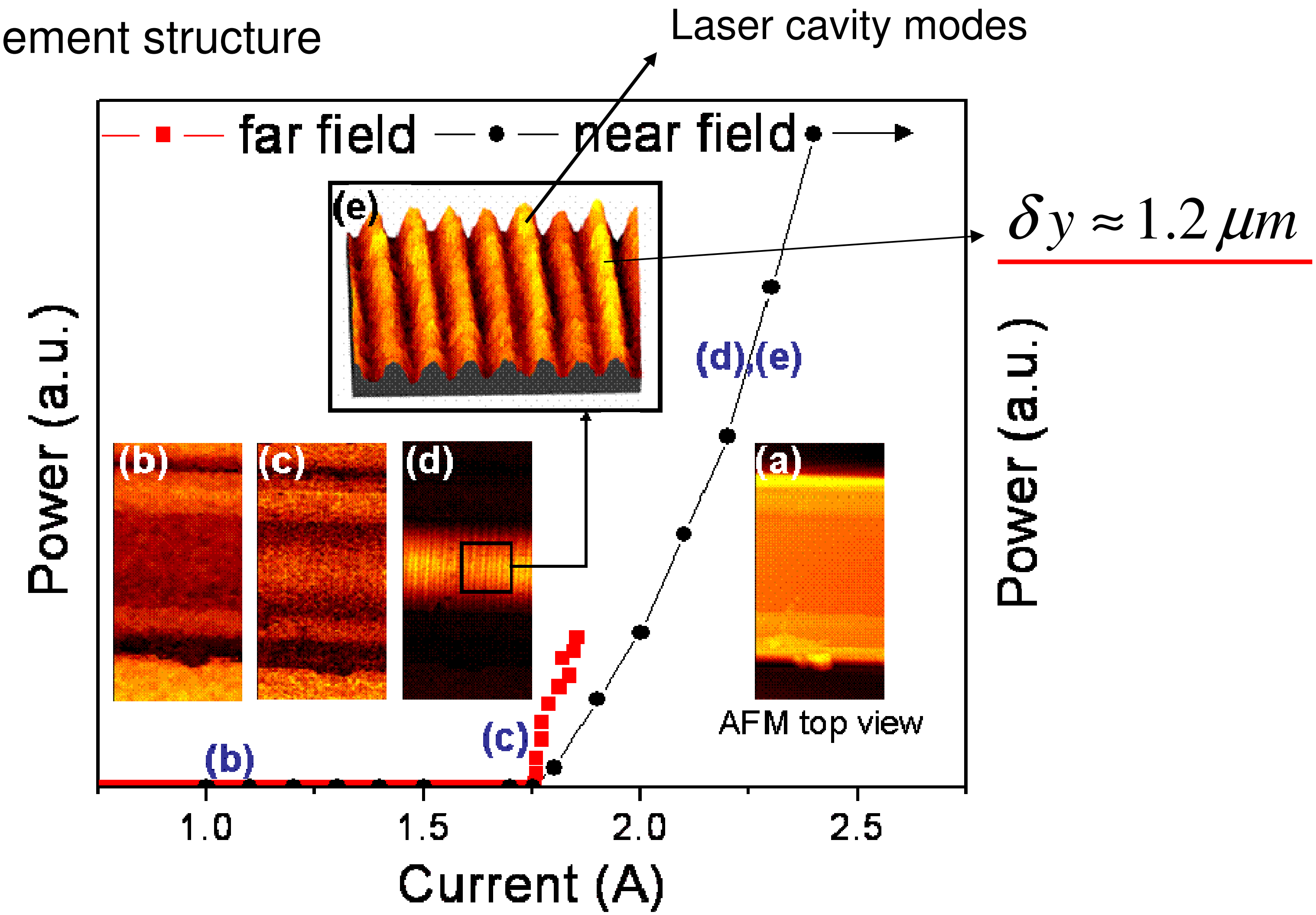
Laser cavity modes

$$\delta y = \frac{\lambda}{2n_{eff}} = 1.14\ \mu m$$

s-NSOM-Imaging working semiconducting devices

Quantum cascade lasers

Air confinement structure

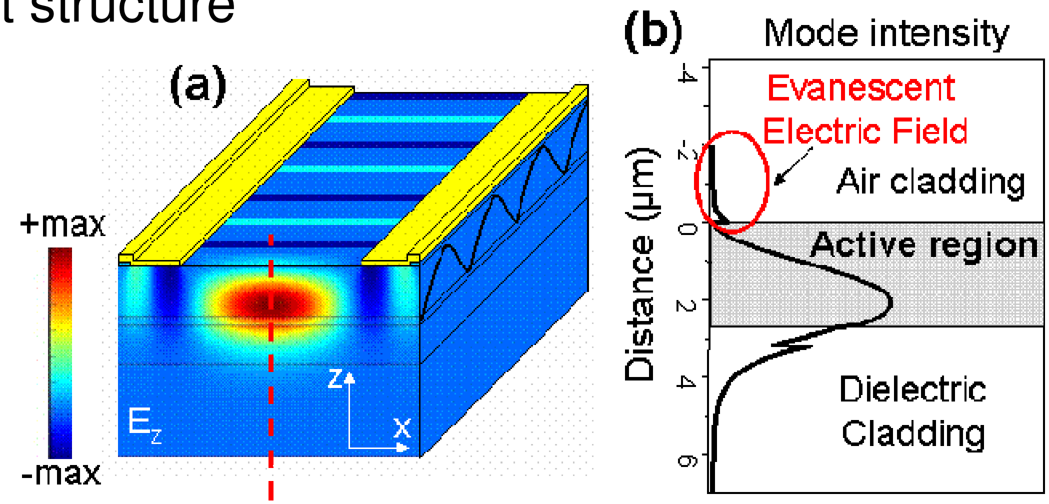


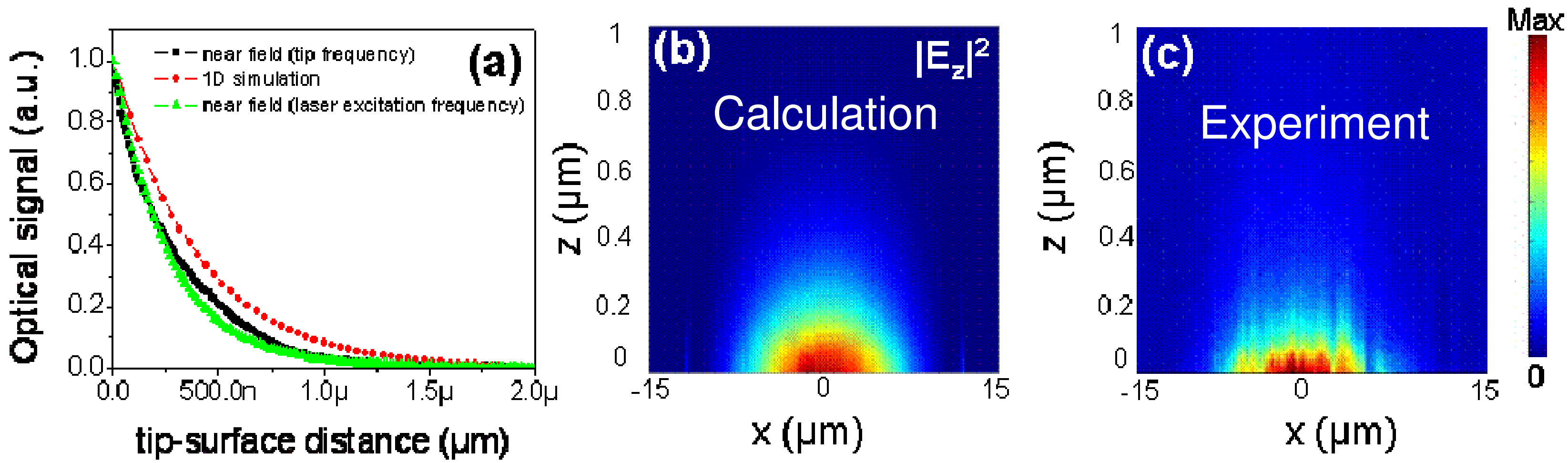
V. Moreau, P.-A. Lemoine, et al. , Appl. Phys. Lett. (2007)

s-NSOM-Imaging working semiconducting devices

Quantum cascade lasers

Air confinement structure





V. Moreau, P.-A. Lemoine, et al. , Appl. Phys. Lett. (2007)

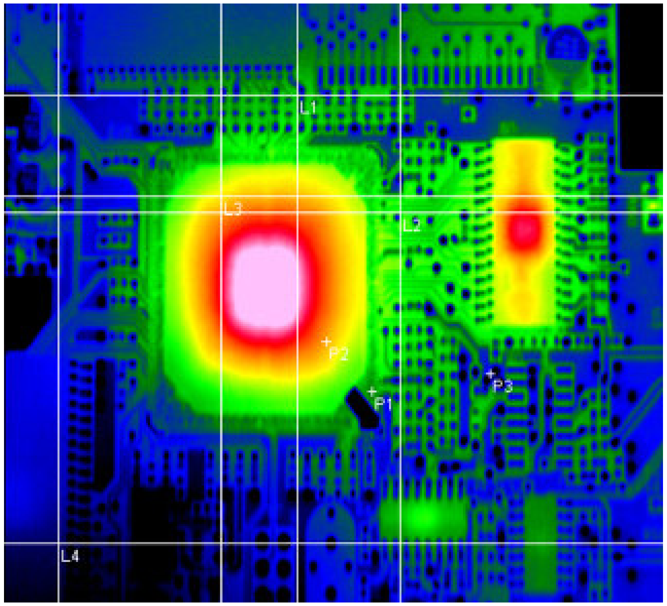
C. Thermal radiation scanning tunnelling microscope

TRSTM

Infrared night vision camera

http://cis.jhu.edu

Far-field thermal infrared microscope



www.infrared1.com

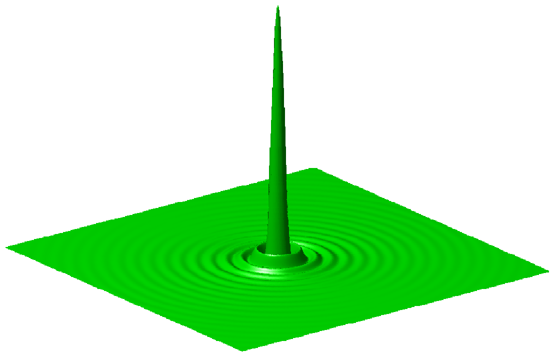
Resolution ~ 5 μm

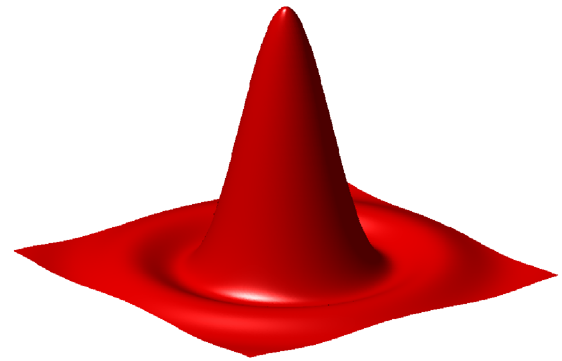
Gray body : Spectrum $G(\lambda,T) = \Sigma_m(\lambda)\, B(\lambda,T)$

Detection of thermal radiation emitted by the object itself

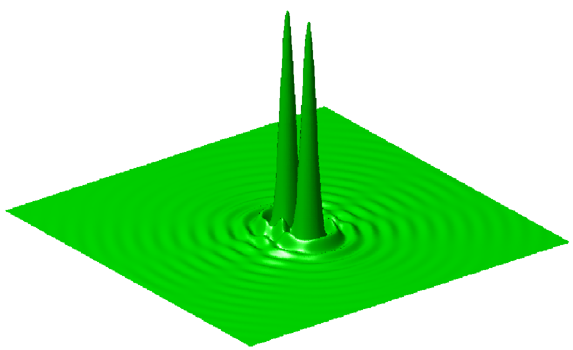
Far-field thermal infrared microscope

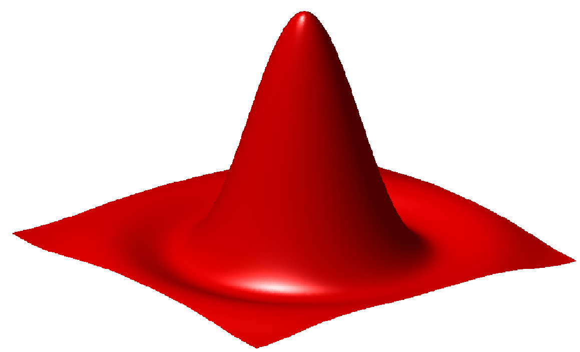
<u>Image of a point</u> : 550 nm (green)   4 μm (Infrared)





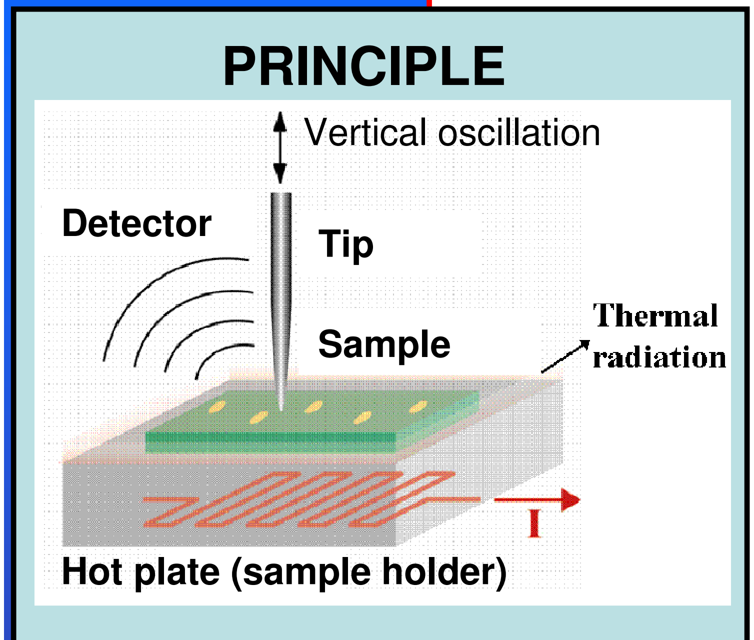
<u>Two points</u> 600 nm apart :

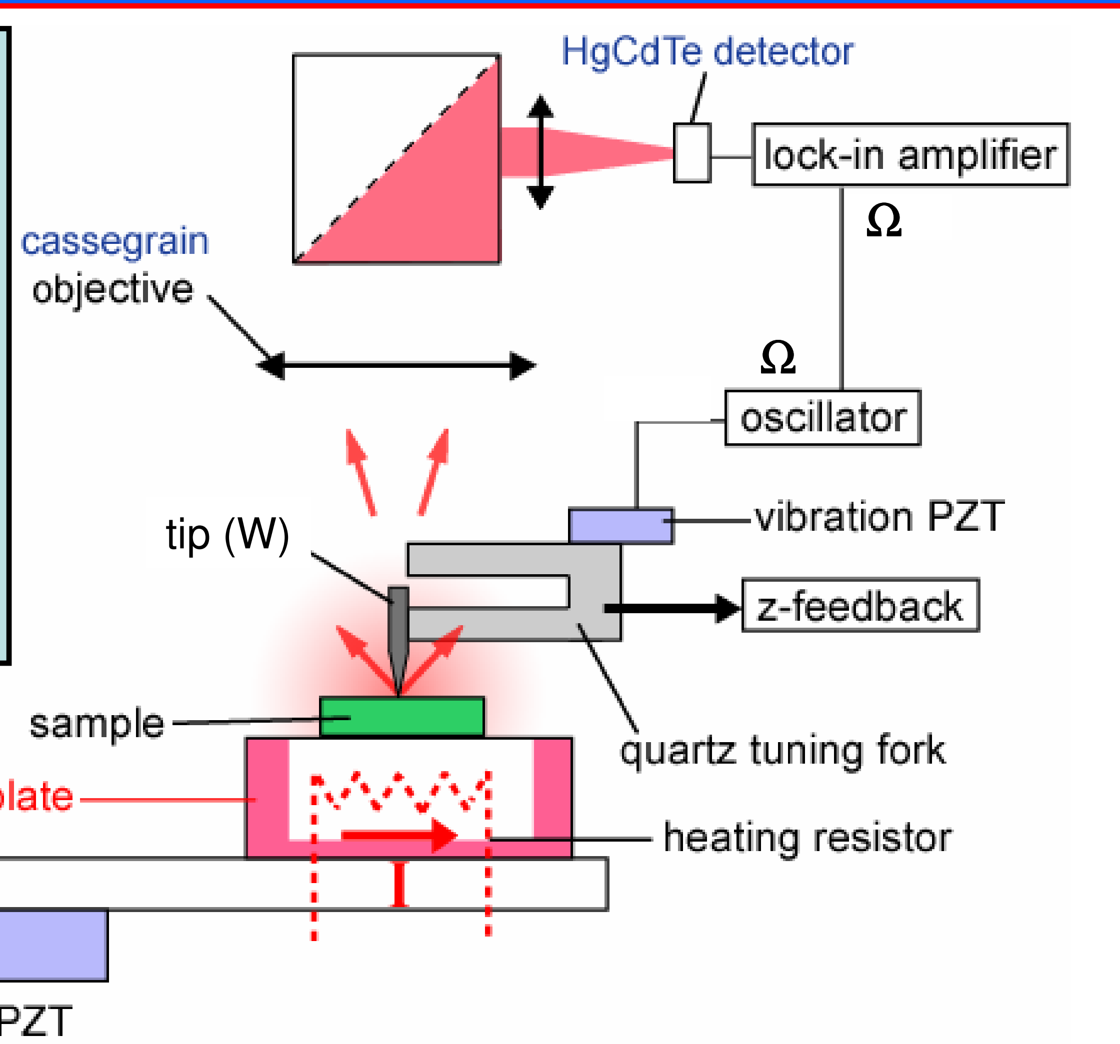




Resolution limit ~ $\lambda/2$

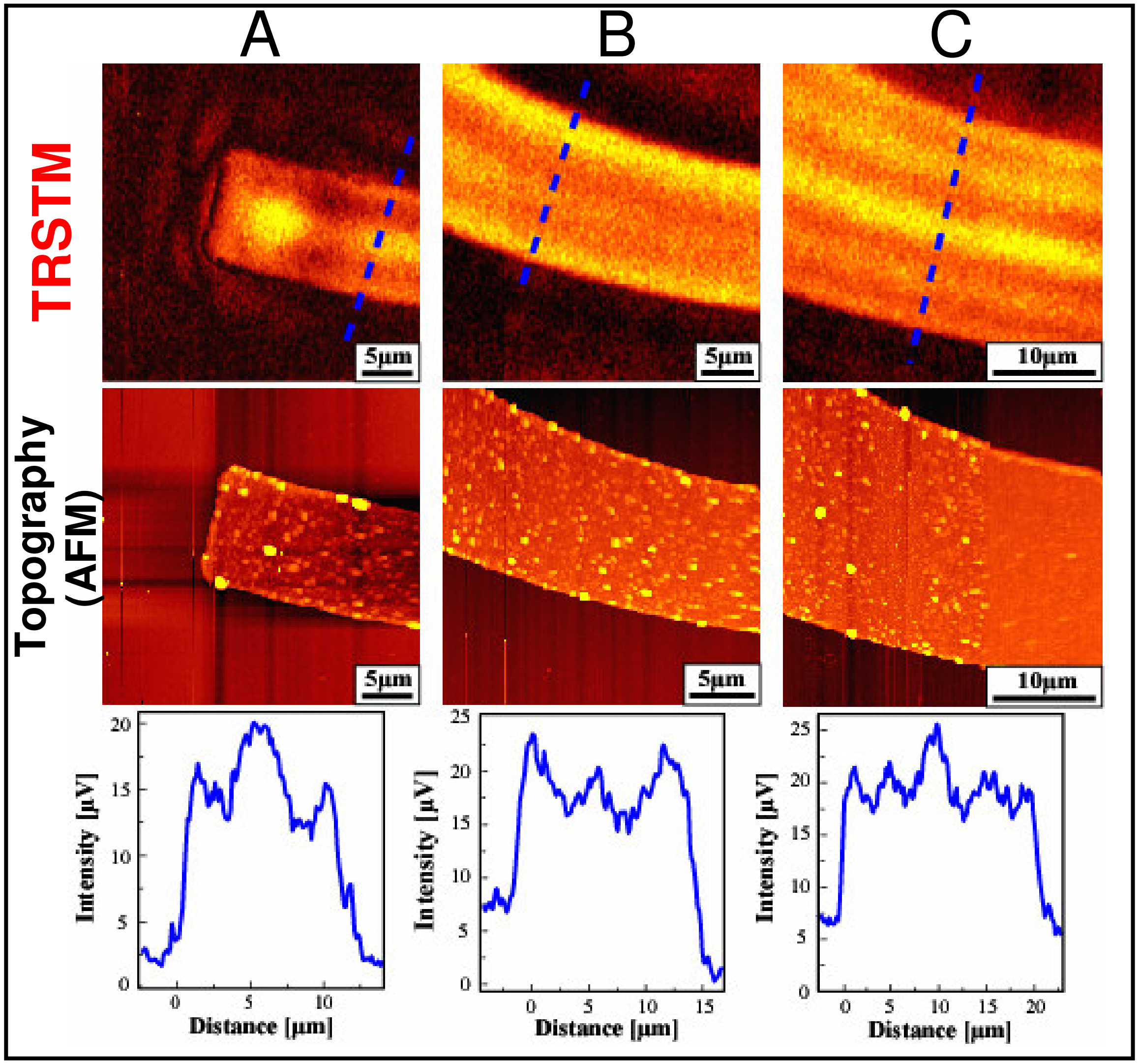
Near-field detection of thermal radiation : TRSTM (Thermal Radiation STM)



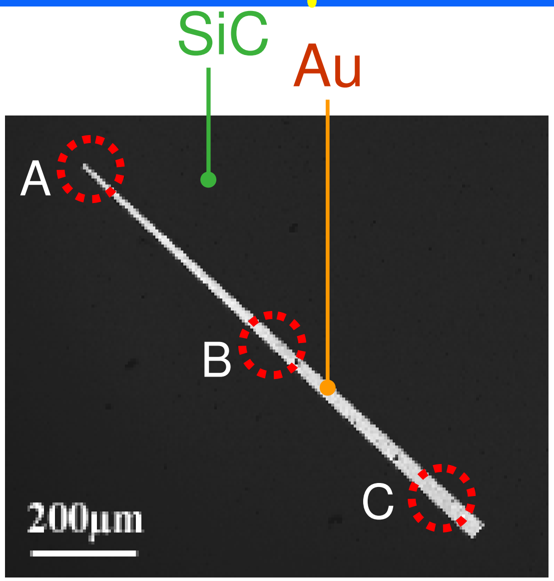


- Apertureless SNOM without any external source.
- Scattering of near-field thermal radiation at the surface at T≠0.

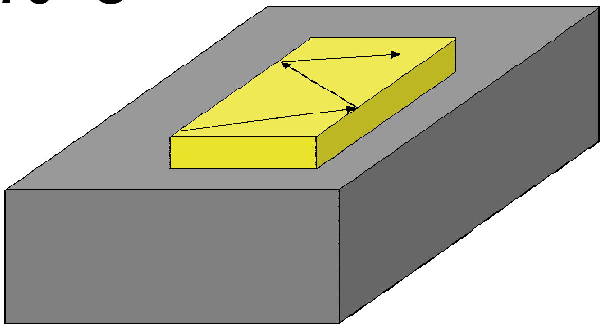
Energy selection : TRSTM images with filter at λ = 10.9 μm



De Wilde, Formanek, Carminati, Gralak, Lemoine, Mulet, Joulain, Chen, Greffet, Nature **444**, 740 (2006).

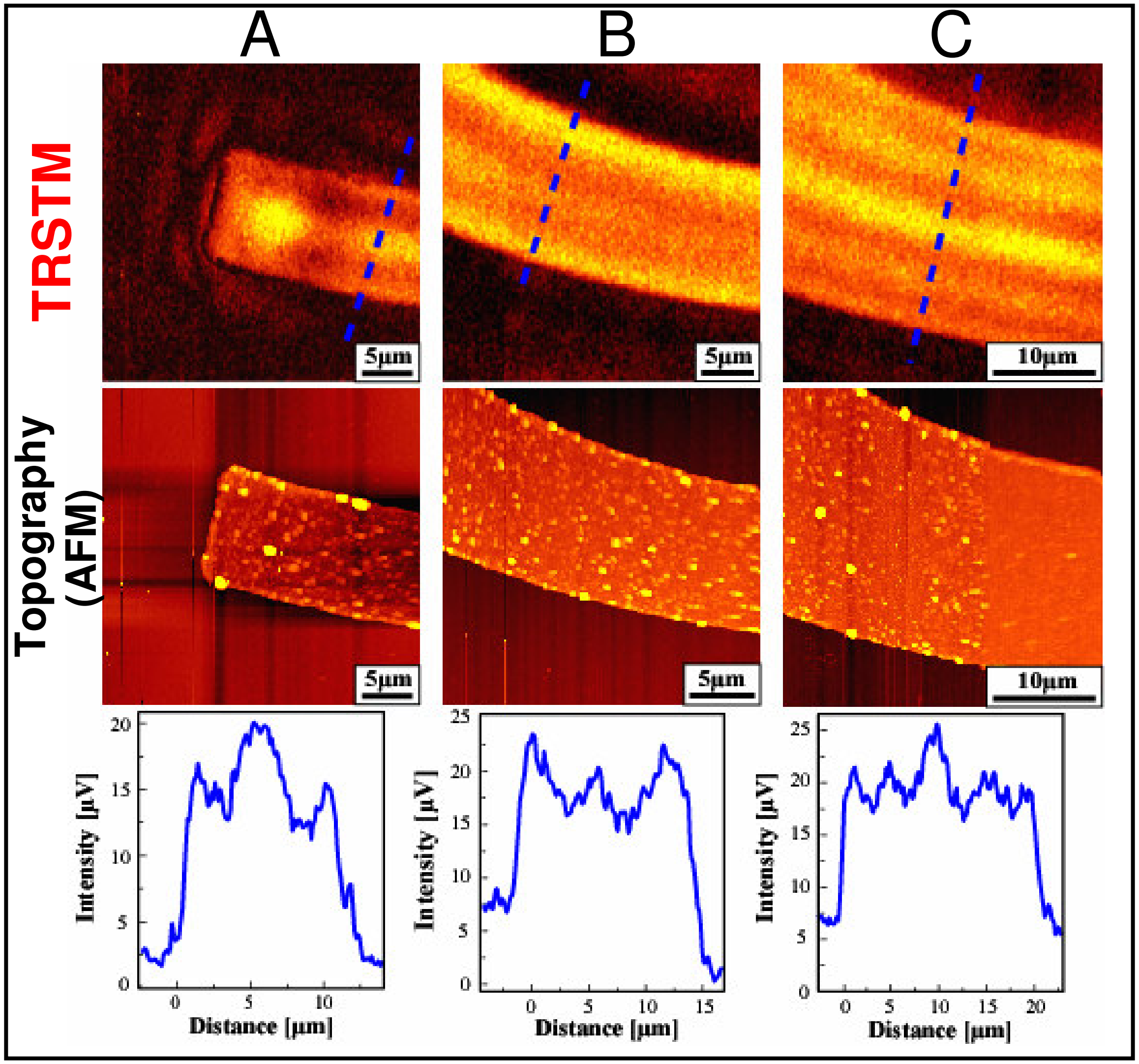


T=170 ℃



Fringes
coherence in near-field
thermal radiation

Energy selection :
TRSTM images with filter at λ = 10.9 μm

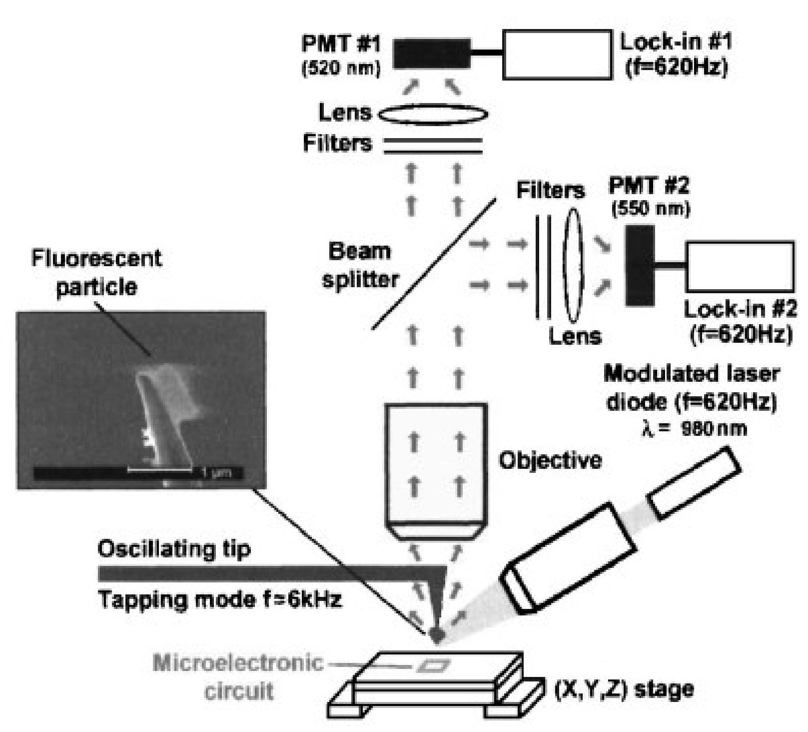


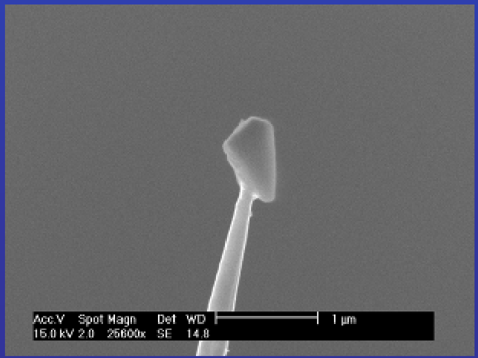
De Wilde, Formanek, Carminati, Gralak, Lemoine,
Mulet, Joulain, Chen, Greffet, Nature **444**, 740 (2006).

<u>Prospect for metrology</u> :

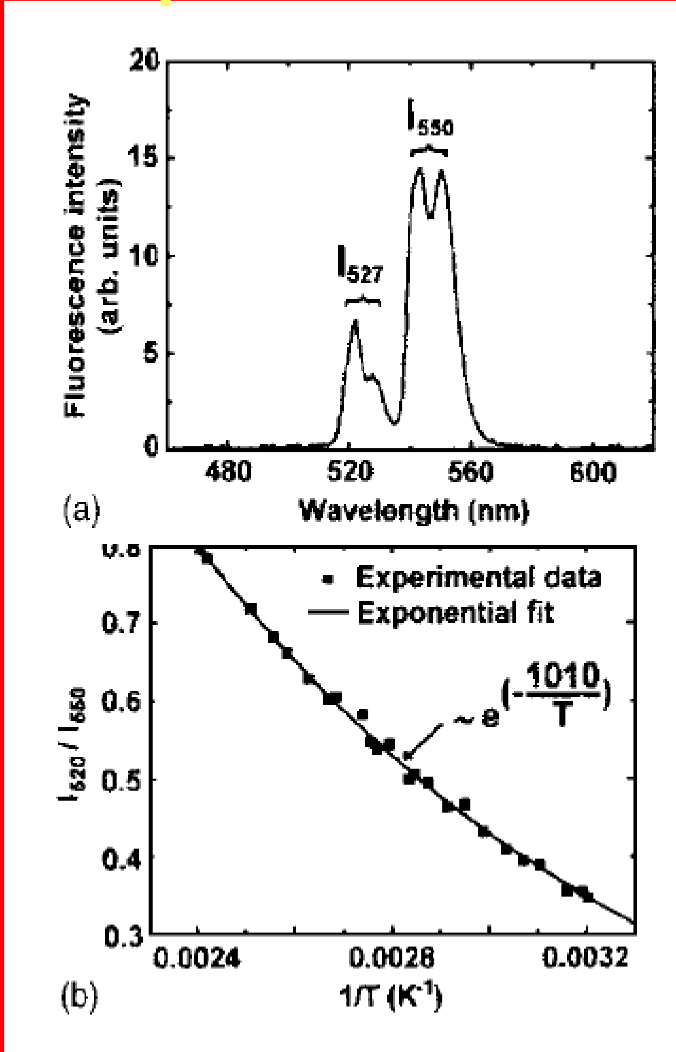
- The spectrum of TRSTM signal is specific to each material.
- To use the TRSTM as a local temperature sensor

D. Active fluorescent probes



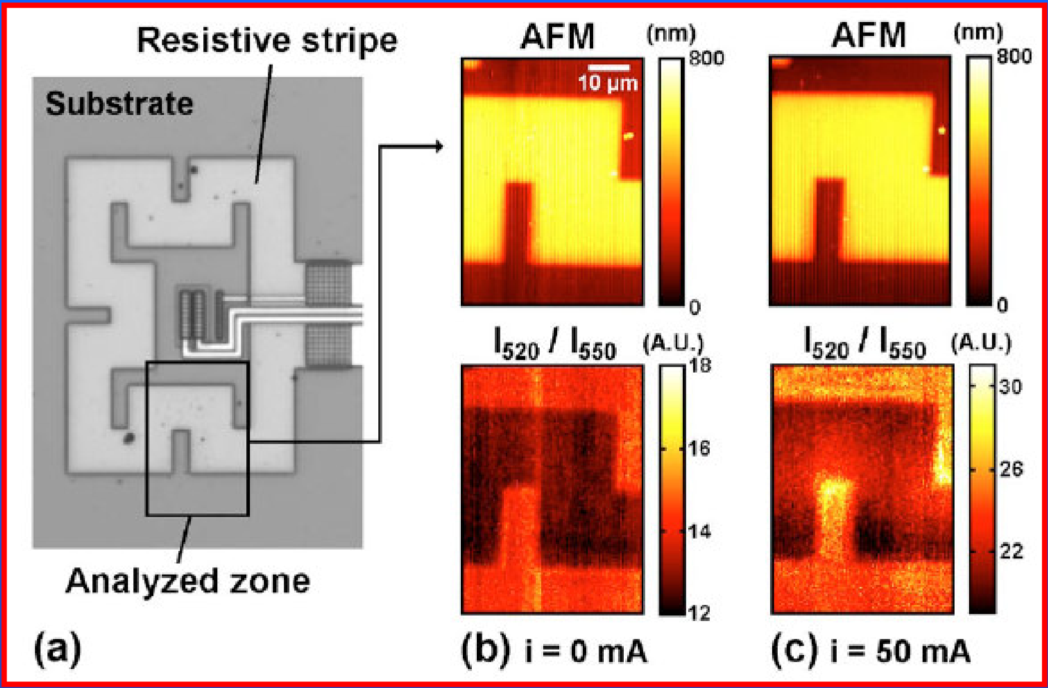


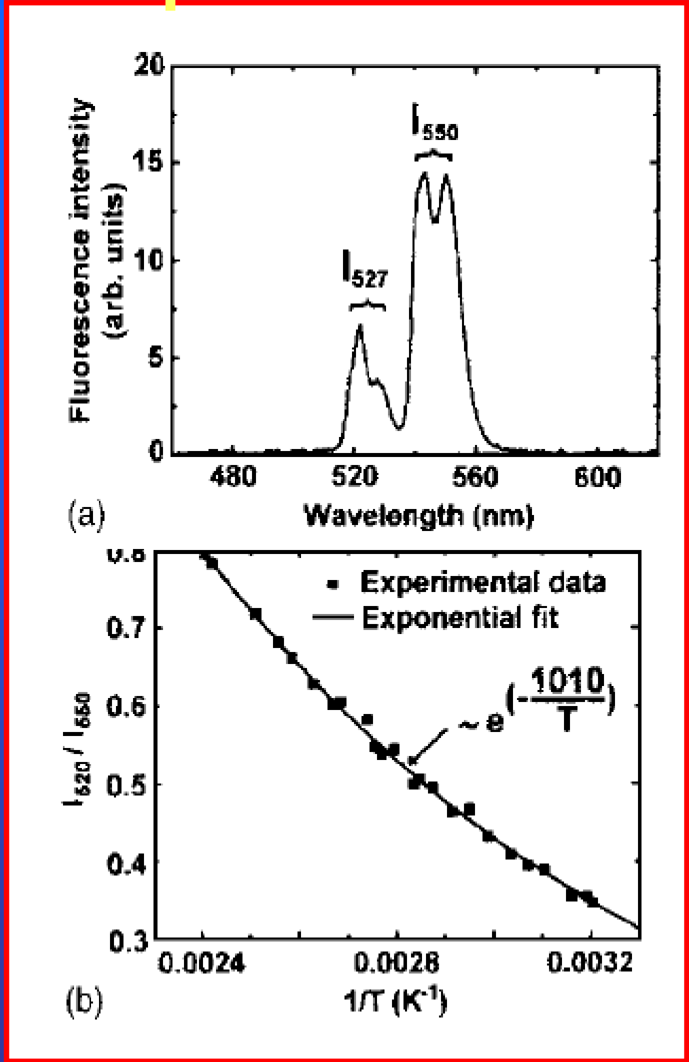
L. Aigouy, et al.
Appl. Phys. Lett. **87**, 184105 (2005).

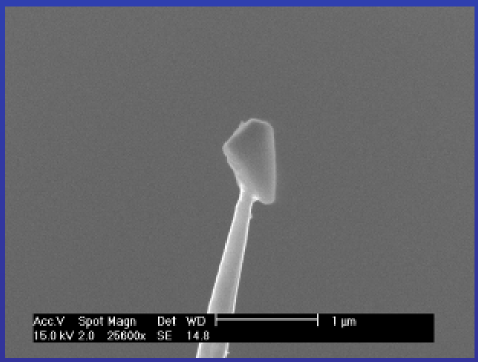


Principle : to use a fluorescent nano object at the extremity of an AFM tip as a local temperature sensor

D. Active fluorescent probes







L. Aigouy, et al.
Appl. Phys. Lett. **87**, 184105 (2005).

Principle : to use a fluorescent nano object at the extremity of an AFM tip as a local temperature sensor

Conclusions :

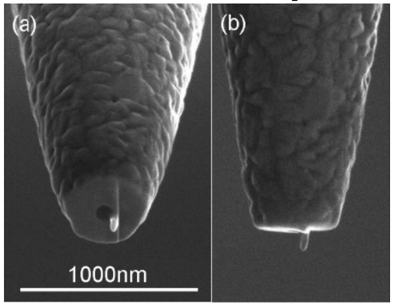
NSOM microscopy is an active field of research to achieve optical material characterization

Most far-field methods are nowadays accessible in the near-field: luminescence, Raman scattering, Infrared imaging, thermal emission…

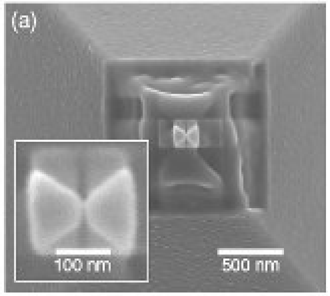
A large variety of NSOM types have been developed : Aperture-probe, scattering type-NSOM, TRSTM,active probes.

Current trend :

To use new concepts such as optical nano antenna to improve the NSOM efficiency.



T.H. Taminiau, et al., Nanolett. **7**,.28 (2007).



J. N. Farahani, et al., Phys. Rev. Lett. **95**, 017402 (2005)