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SMR: 1643/3

**WINTER COLLEGE ON OPTICS ON OPTICS AND  
PHOTONICS IN NANOSCIENCE AND NANOTECHNOLOGY**

( 7 - 18 February 2005)

***“Optical spectroscopy at the nanoscale”***

presented by:

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# Optical spectroscopy at the nanoscale - physical concepts

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motivation: „chemical nanoscope“

microscope principle for attaining 10 nm resolution

microwave, visible and mid-infrared realisations

applications in

materials sciences

polymers

semiconductors

biology



# Optical spectroscopy at the nanoscale - physical concepts

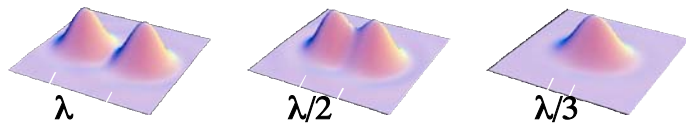
**I overview of SNOM**

**II s-SNOM basics**

**III s-SNOM spectroscopy**



## Why near fields?



because **far-field diffraction limits the optical resolution to  $\lambda/2$**   
**far fields** are propagating waves far away ( $\gg \lambda$ ) from an object/source

### near fields

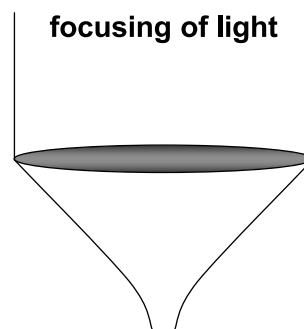
- decay evanescently, i.e. they are non propagating
- are bound to matter (they „stick“ to the object)
- are strongly localized ( $\ll \lambda$ )

**exploiting near-fields allows optics at the nanometer scale**

## Abbe limit (1873)

**numerical aperture**  
 $NA = n \cdot \sin \alpha$

**in air:**  $NA \leq 1$   
 $d_{\min} \geq \lambda/2$

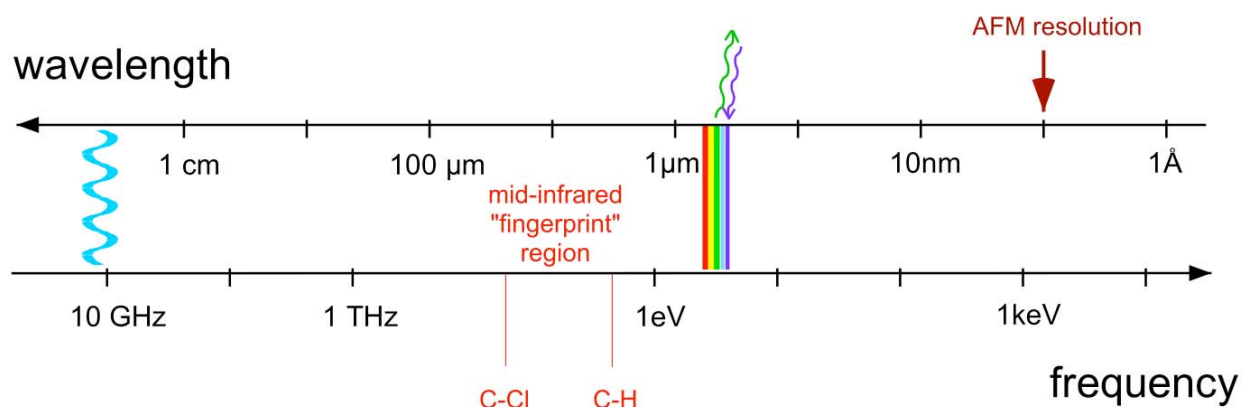


but .... many interesting objects are much smaller than  $\lambda$ :

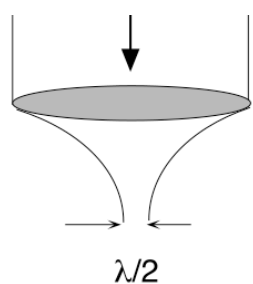
- nanoparticles
- quantum dots
- single molecules
- biological structures

optical-spectroscopic analysis **at the nanoscale** should be fascinating

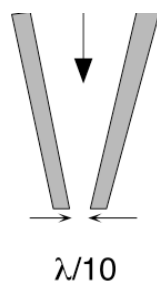
## Greatly sub-wavelength resolution?



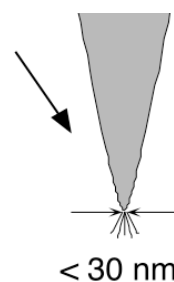
## Photon focusing concepts



**classical**  
diffraction-limited



**aperture SNOM**  
aperture-limited

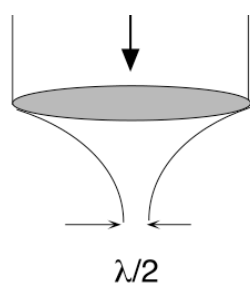


**scattering SNOM**  
tip-limited

## History of SNOM

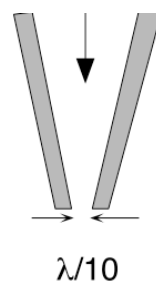
- 1928 Proposal by Synge on subwavelength resolution by **aperture** scanning
- 1972 First realization of Synge's idea by Ash and Nicols using microwaves; resolution  $\lambda/60$
- 1982 Scanning Tunneling Microscope (STM) by Binnig and Rohrer
- 1984 Near-field **aperture** SNOM, independently by Lewis and Pohl
- 1985 **Scattering** probe proposed by Wessel
- 1986 Atomic Force Microscope (AFM) by Binnig, Quate and Gerber
- 1991 Betzig et al. metal coated tapered fiber tip **aperture**
- 1995 Zenhausern, Martin, Wickramasinghe 7 Angström optical resolution ! ? by light **scattering** from an AFM tip

## Optical microscope concepts



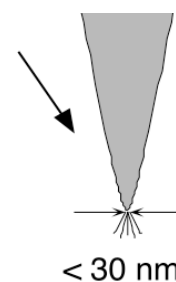
**classical**  
diffraction-limited

free-space



**aperture SNOM**  
aperture-limited

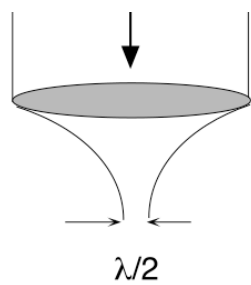
guided



**scattering SNOM**  
tip-limited

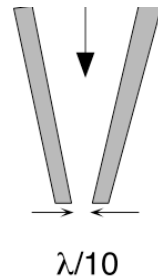
confined

## Historic roots of microscopy concepts



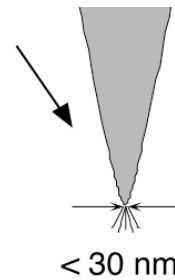
**classical**  
diffraction-limited

**light**  
≈1600? Galileo



**aperture SNOM**  
aperture-limited

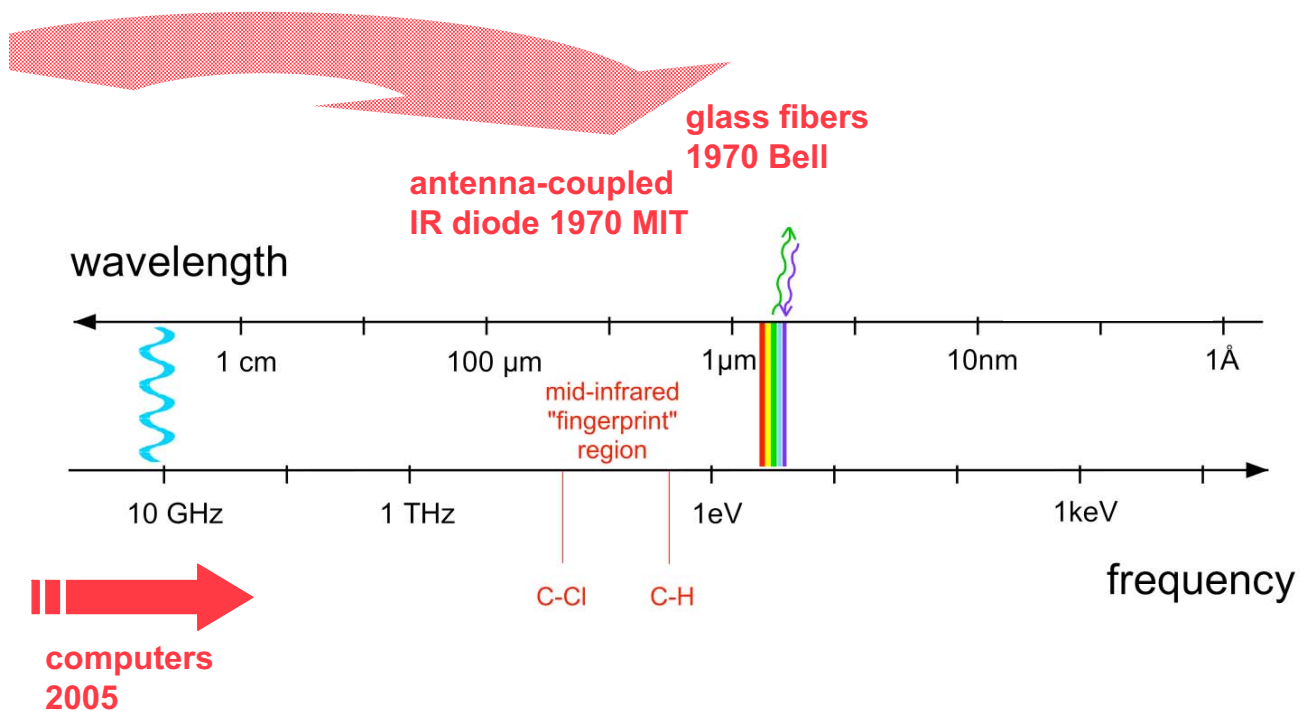
**microwaves**  
≈1940 GB, MIT



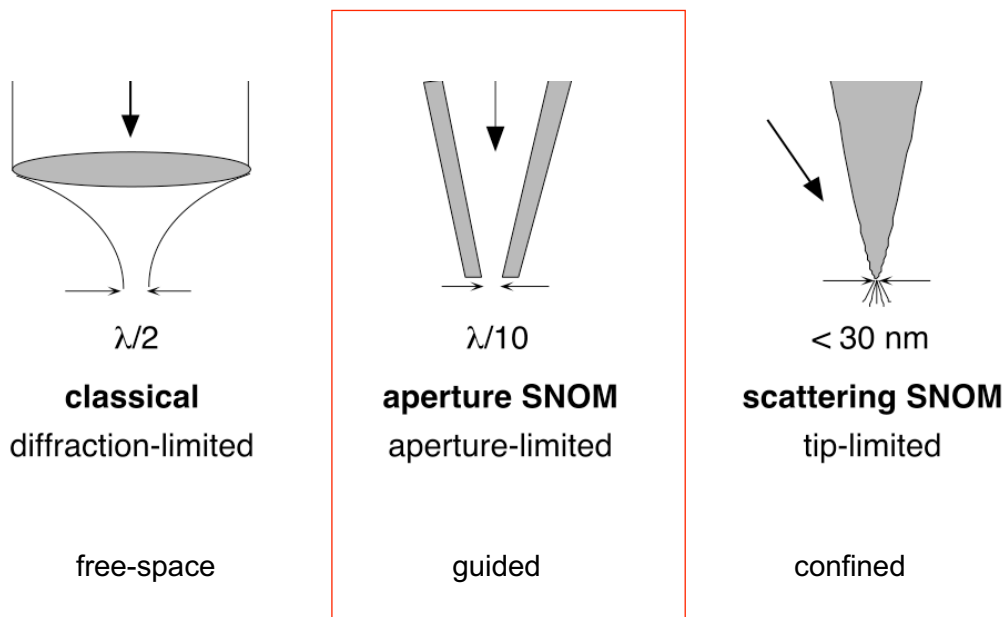
**scattering SNOM**  
tip-limited

**electronics**  
≈1950 Bell

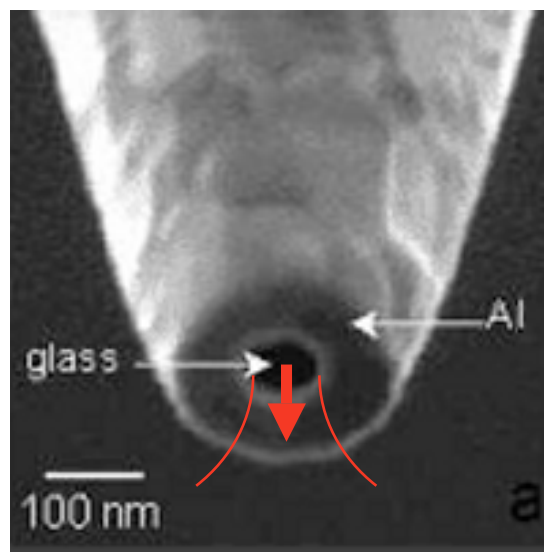
## Electronics concepts push optics



## Aperture SNOM basics



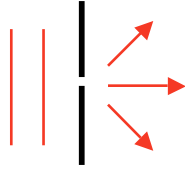
## Aperture probe for visible light



## Theory of optical fields in the aperture

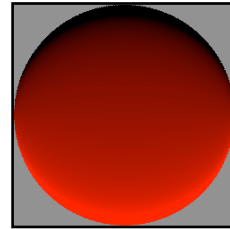
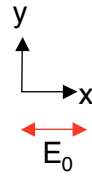
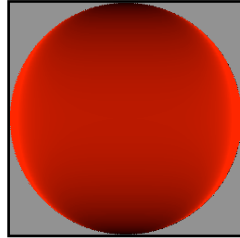
infinitely thin screen  
with infinite conductivity

hole of diameter  $2a \ll \lambda$



1944 Bethe

1950/54 Bouwkamp



$$\frac{E_x}{E_0} = -\frac{8ik}{3\pi} \left( \sqrt{a^2 - r^2} + \frac{r^2}{2\sqrt{a^2 - r^2}} \cos^2 \varphi \right)$$

$$\frac{H_x}{H_0} = 0$$

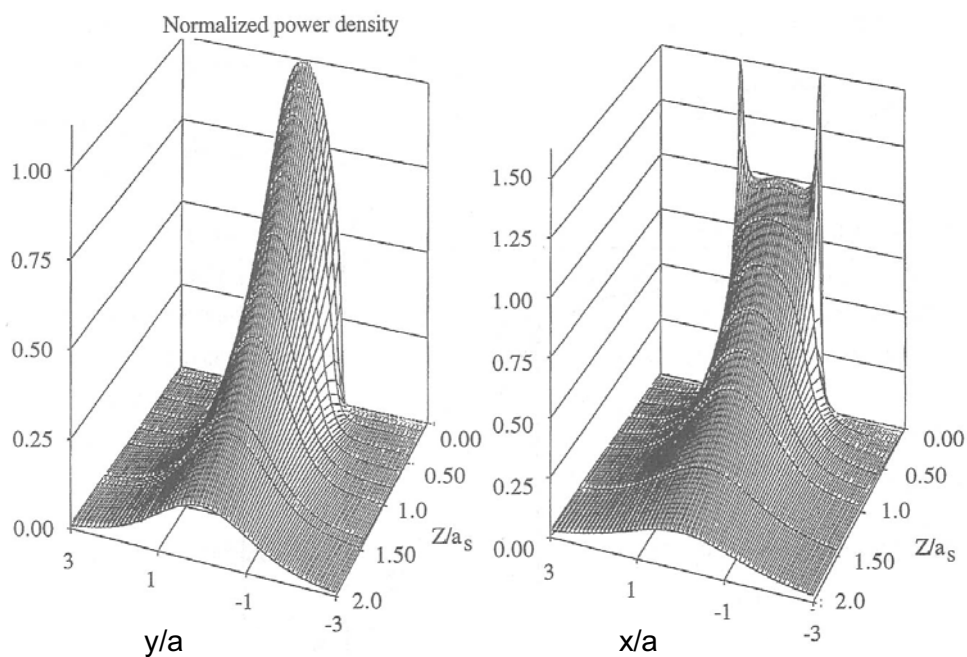
$$\frac{E_y}{E_0} = -\frac{8ik}{3\pi} \left( \frac{r^2}{2\sqrt{a^2 - r^2}} \cos \varphi \sin \varphi \right)$$

$$\frac{H_y}{H_0} = 1$$

$$\frac{E_z}{E_0} = 0$$

$$\frac{H_z}{H_0} = -\frac{4}{\pi} \frac{r}{\sqrt{a^2 - r^2}} \sin \varphi$$

## Light intensity decays outside the aperture





## Propagation away from aperture

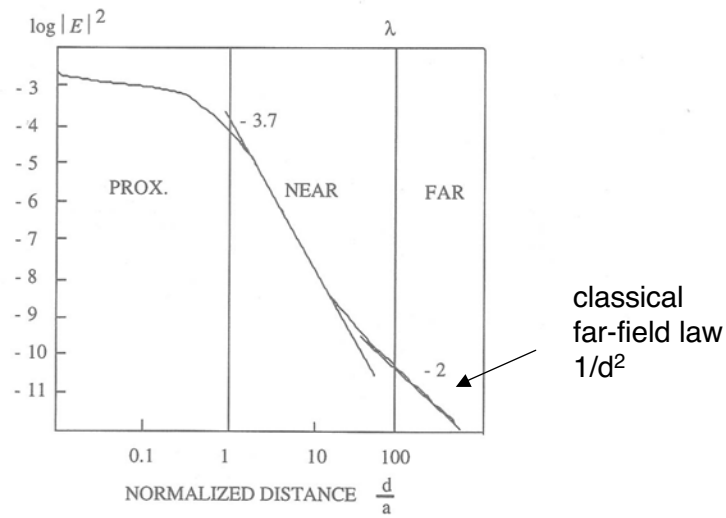
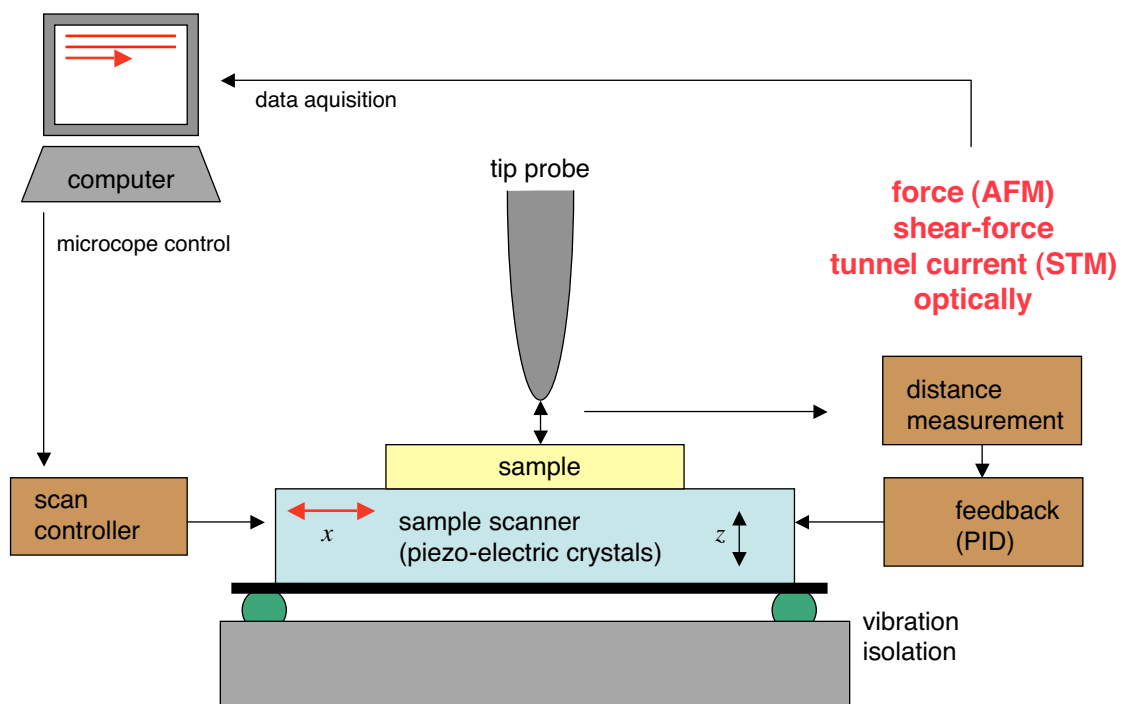
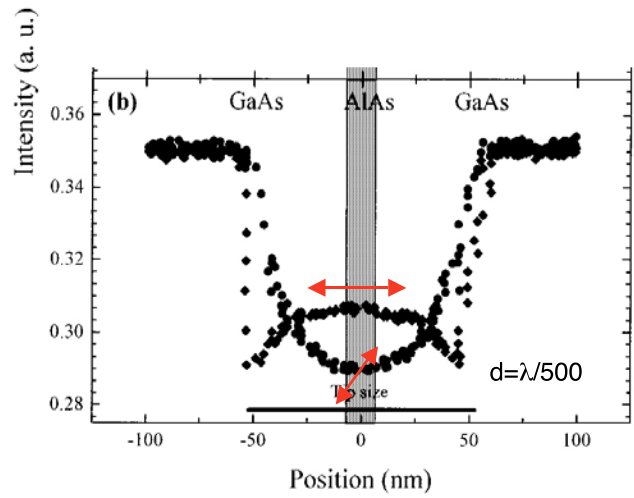
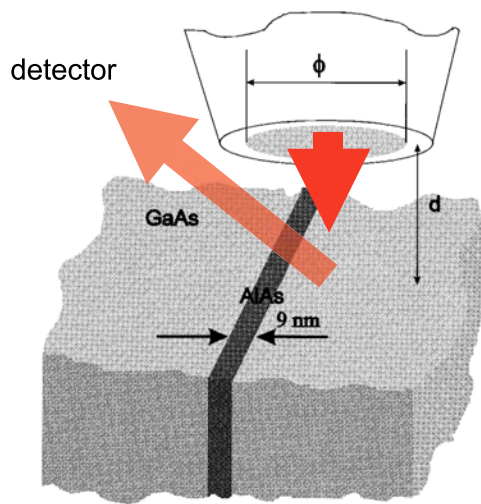


Fig.1.3.10 Calculated on-axis transmitted energy density vs normalized distance from the center of the hole of radius taken as  $a = \lambda/100$ . After Dürig<sup>41</sup>.

## Scanning tip microscope principle



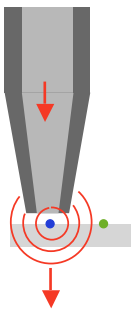
## Aperture SNOM performance



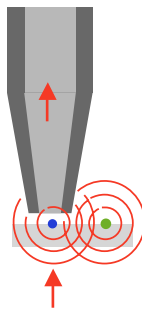
Appl. Phys. Lett. **70**, 1932, (1997)  
R.S. Decca, H.D. Drew, and K.L. Empson

## Aperture SNOM operation modes

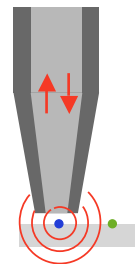
Illumination  
in transmission



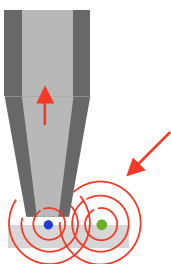
Collection  
in transmission



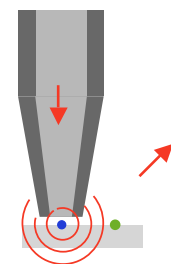
Illumination and collection  
in reflection



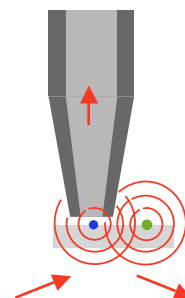
Collection in  
oblique reflection



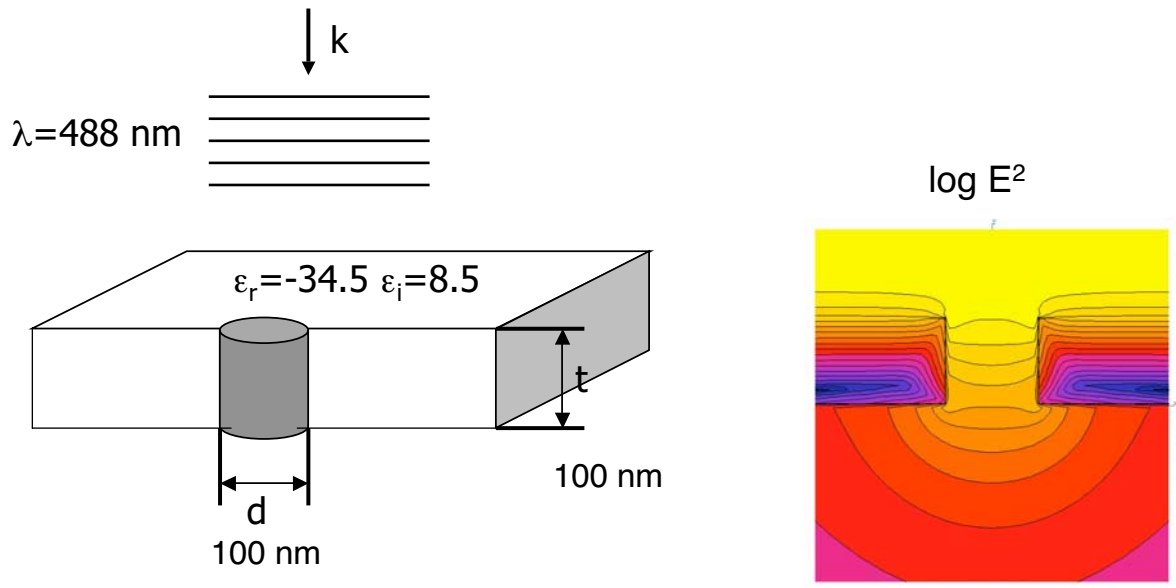
Illumination in  
oblique reflection



Collection in  
TIR illumination



## Thick metal screen - multiple multipole calculation

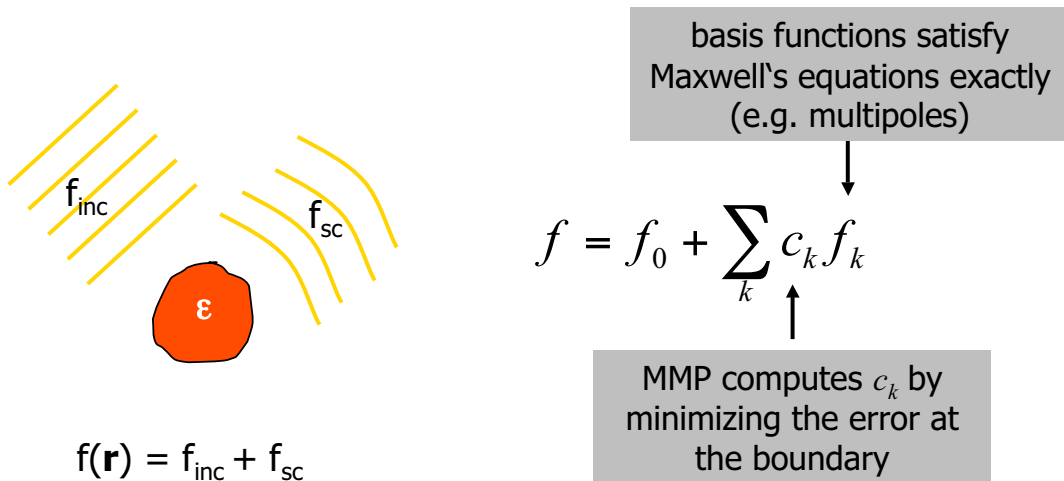


J. Renger (Dresden)

## MMP concept

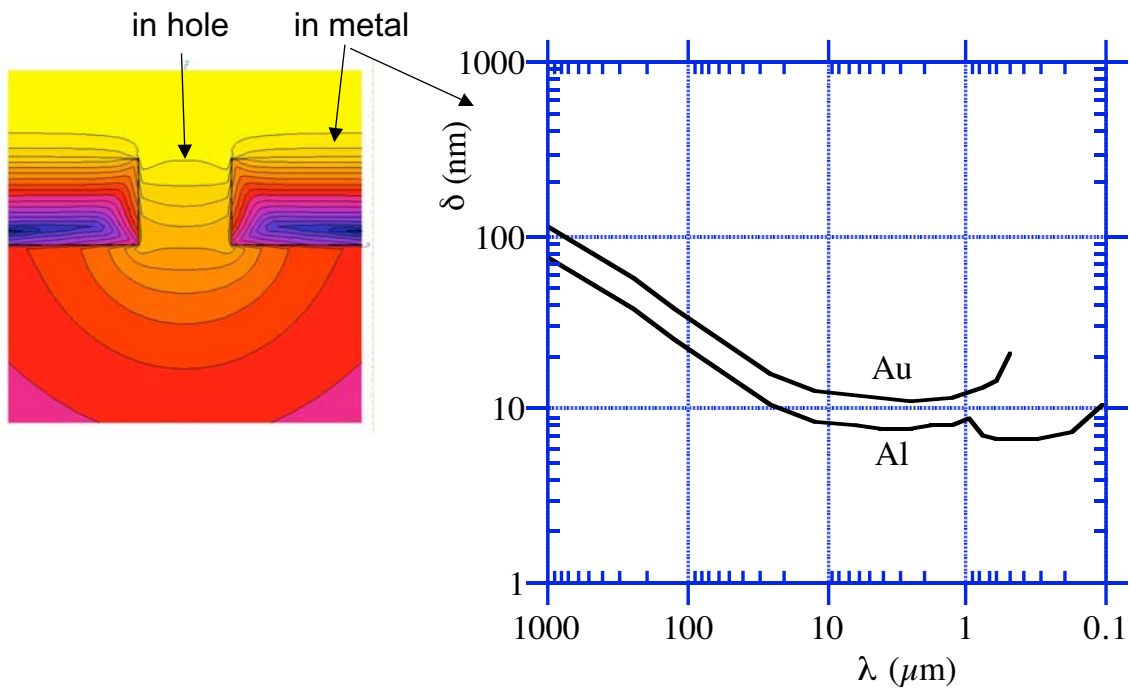
numerical methods in electrodynamics, e.g.

- domain methods: Finite-Difference Time-Domain (FDTD)
- boundary methods: Multiple Multipole Method<sup>1</sup> (MMP)



[1] C. Hafner, *The Generalized Multiple Multipole Technique for Computational Electromagnetics* (Artech, Boston, 1990).

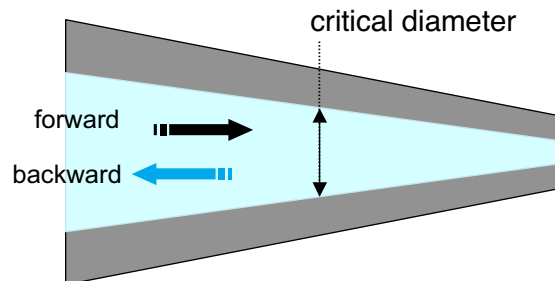
## Finite penetration depth



## Evanescent transmission by mode ansatz

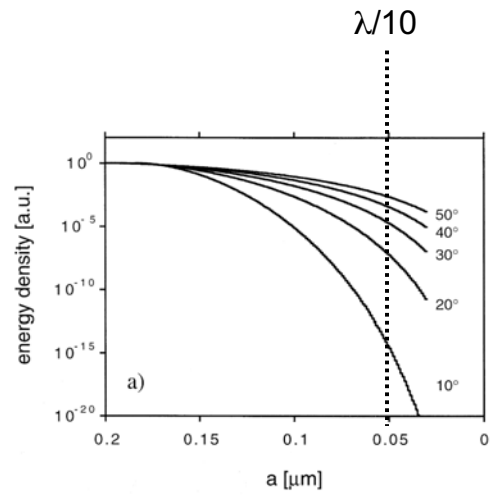
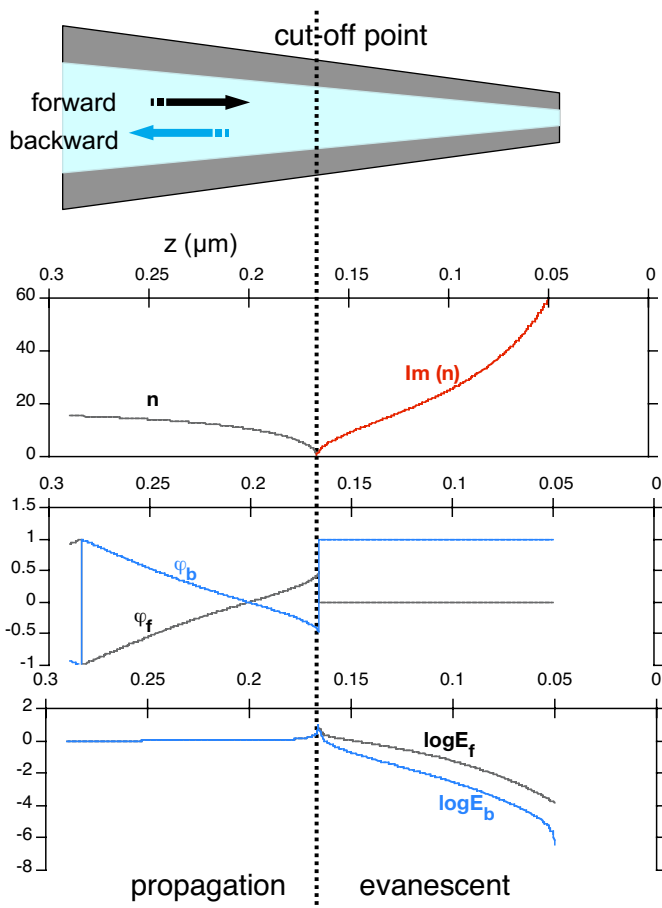
B. Knoll and F. Keilmann, Opt. Commun. **162**, 177 (1999)

$$\omega > \sqrt{n^2 + m^2} \frac{\pi c}{a\sqrt{\epsilon}} = \omega_c(n, m) \quad \text{no propagation if } a < \lambda/2$$

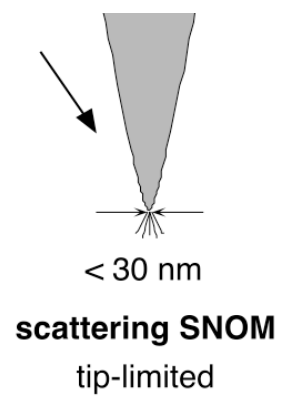
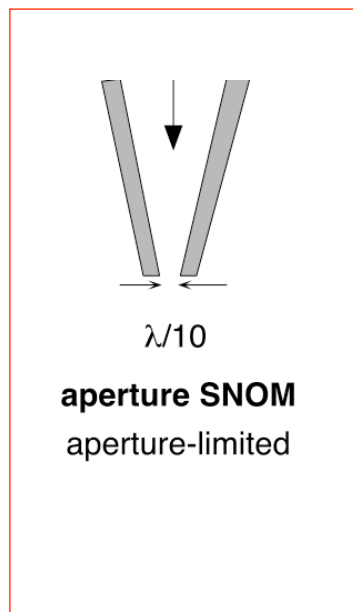
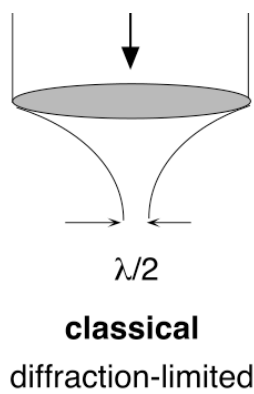


$$\frac{dE_f}{dz} = ik(z)E_f - \frac{1}{a} \frac{da}{dz} E_f - \frac{1}{2k(z)} \frac{dk(z)}{dz} (E_f - E_b)$$

$$\frac{dE_b}{dz} = -ik(z)E_b - \frac{1}{a} \frac{da}{dz} E_b - \frac{1}{2k(z)} \frac{dk(z)}{dz} (E_b - E_f)$$



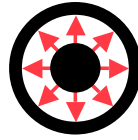
## Aperture SNOM limit: $\lambda/10$



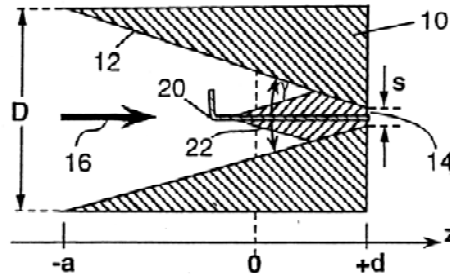
## Coaxial taper for aperture SNOM ?



hollow guide has cutoff



coaxial guide has **no cutoff**



**United States Patent** [18]  
Keilmann

[11] Patent Number: **4,994,818**  
[45] Date of Patent: Feb. 19, 1991

[54] SCANNING TIP FOR OPTICAL RADIATION

OTHER PUBLICATIONS

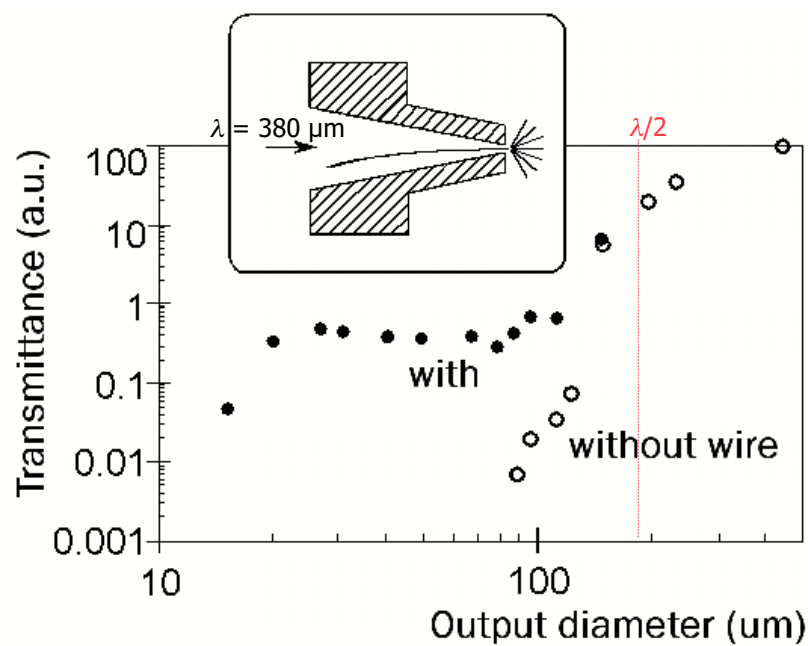
[75] Inventor: Fritz Keilmann, Stuttgart, Fed. Rep. of Germany

E. A. Ash et al., Nature vol. 237, Jun 30, 1972, pp. 510-512.  
Optical Stethoscopy: Image Recording with Resolution, D. W. Pohl, W. Denk and M. Lantz-Apr. 1, 1984, pp. 651-653.

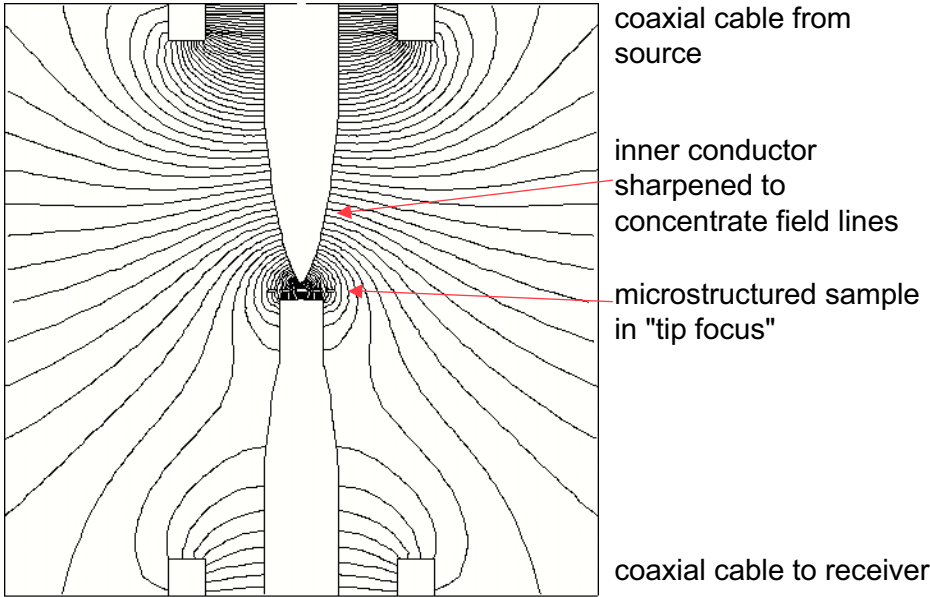
[73] Assignee: Max Planck-Gesellschaft zur Foerderung der Wissenschaften e.V., Fed. Rep. of Germany

Primary Examiner—Rolf Hille  
Assistant Examiner—Hanshanh 1

## Coaxial taper in the far infrared

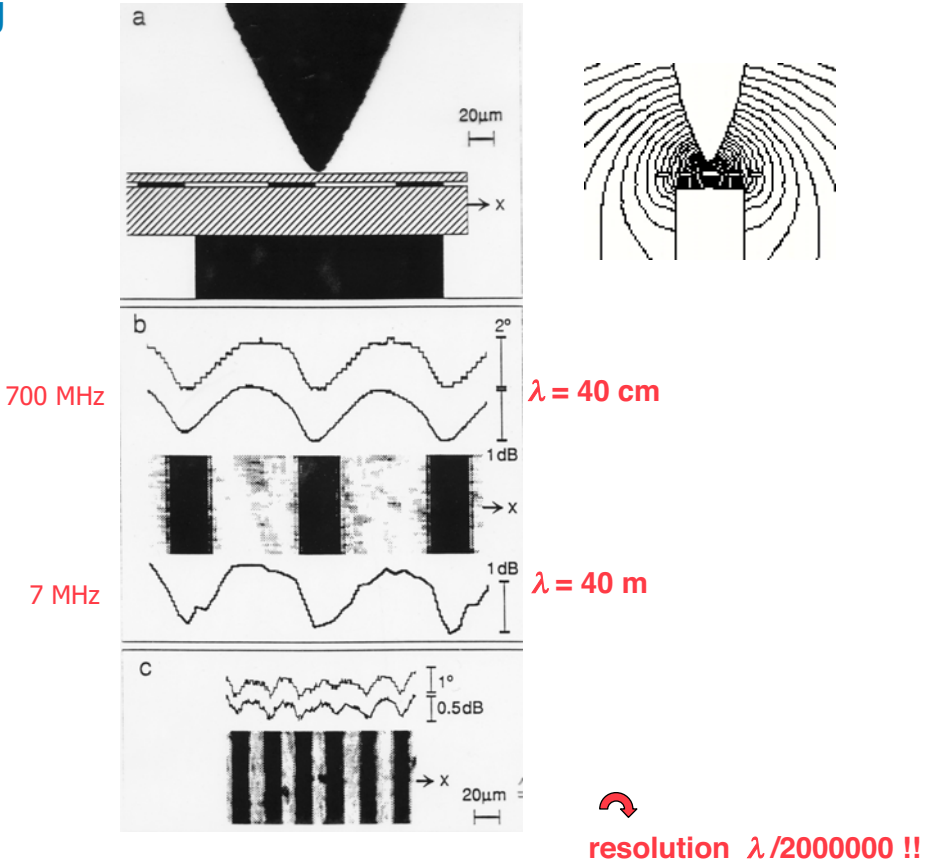


# Radiowave microscope

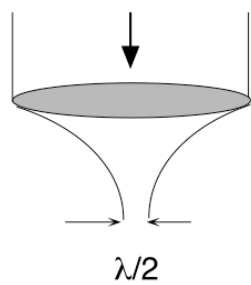


F. Keilmann, D.v.d. Weide, J. Eickelkamp, R. Merz, and U. Stöckle, Opt. Comm. **129**, 15 (1996)

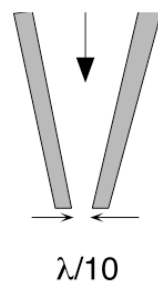
# Radioimaging



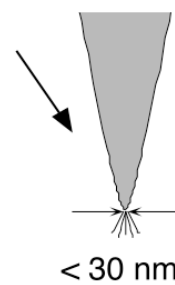
# Microscope principles use different interaction concepts



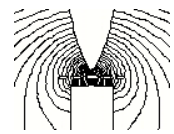
**classical**  
diffraction-limited  
free-space



**aperture SNOM**  
aperture-limited  
guided



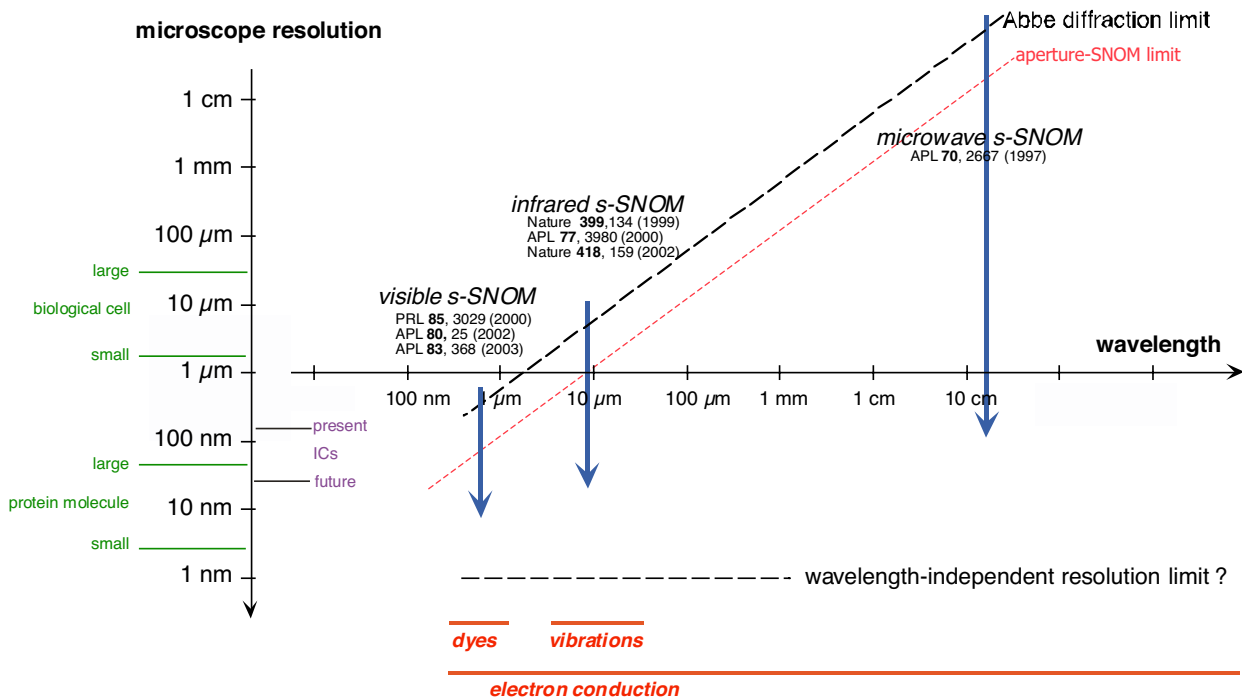
**scattering SNOM**  
tip-limited  
confined



**transverse polarisation**  
**travelling wave**

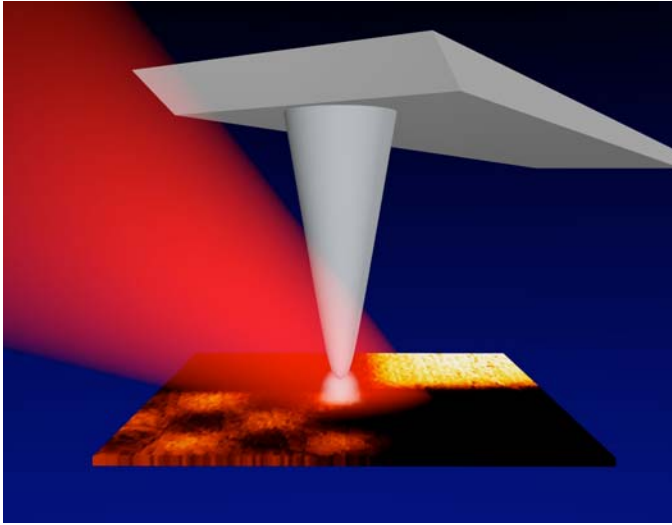
**longitudinal polarisation**  
**electrostatic field**

# Apertureless near-field microscopy chances



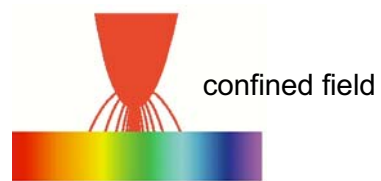


## „Apertureless“ or s-SNOM

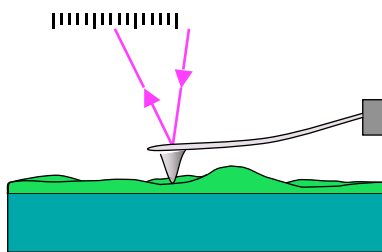


a cantilevered  
metal tip  
serves as antenna

near field with  
 $\approx 20$  nm spot size  
probes surface

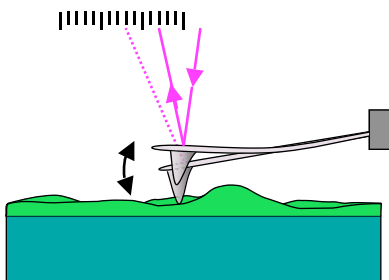


## Cantilever height measured by laser reflection



feedback to keep cantilever  
bending constant

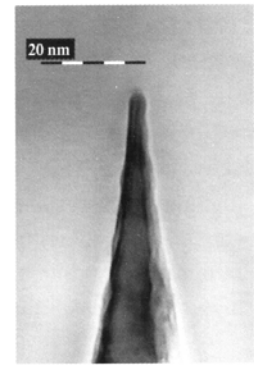
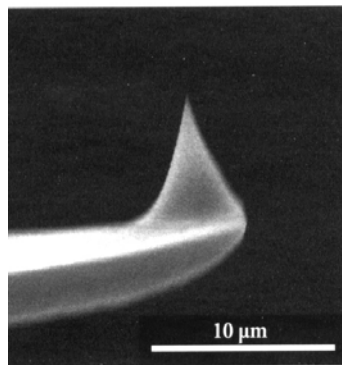
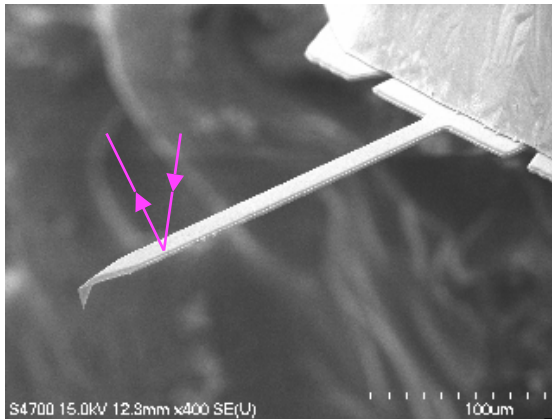
yields AFM topography



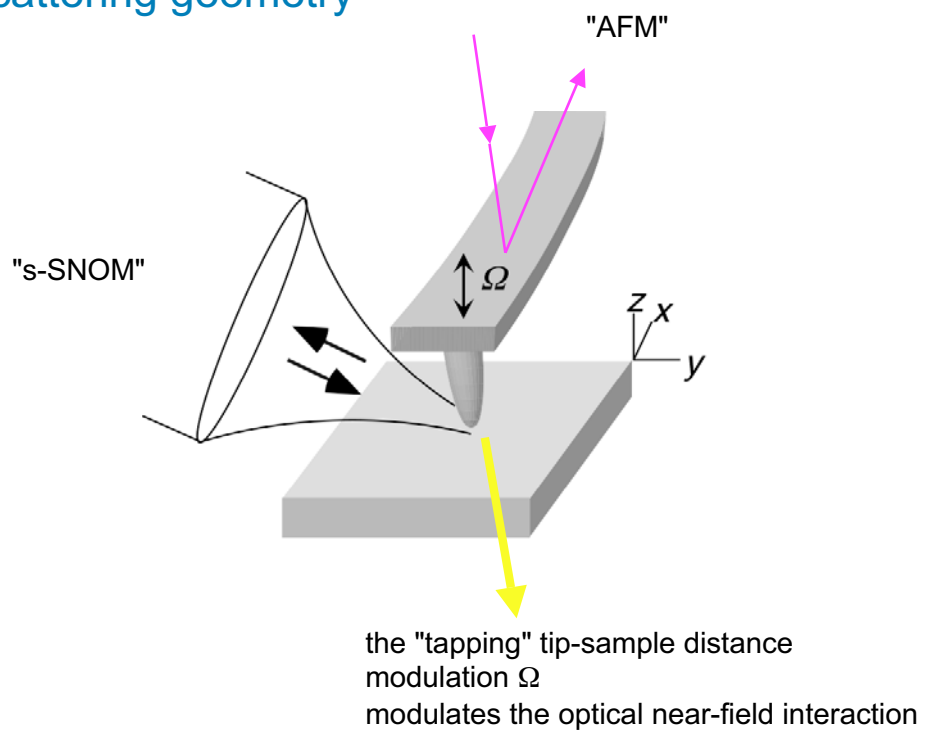
tapping oscillation

allows fast tip-sample  
distance modulation

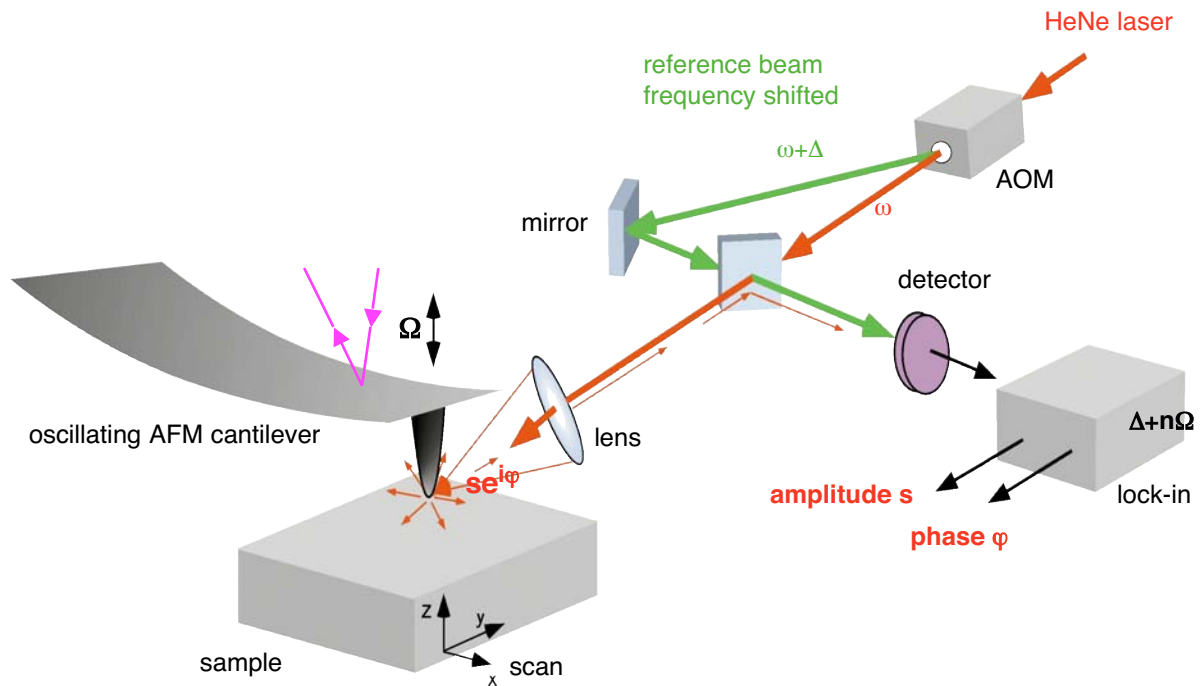
## Commercial Si cantilever tips



## Backscattering geometry

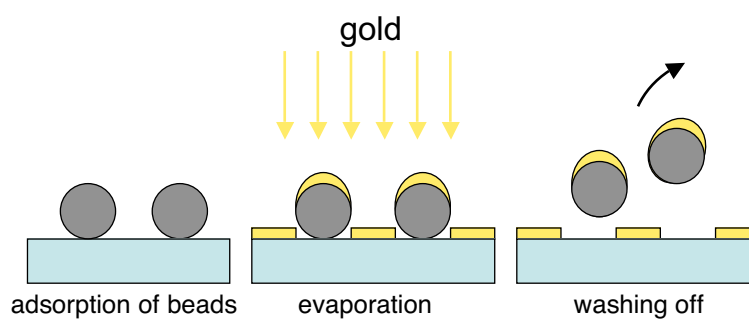


## s-SNOM with heterodyne detection of backscattering

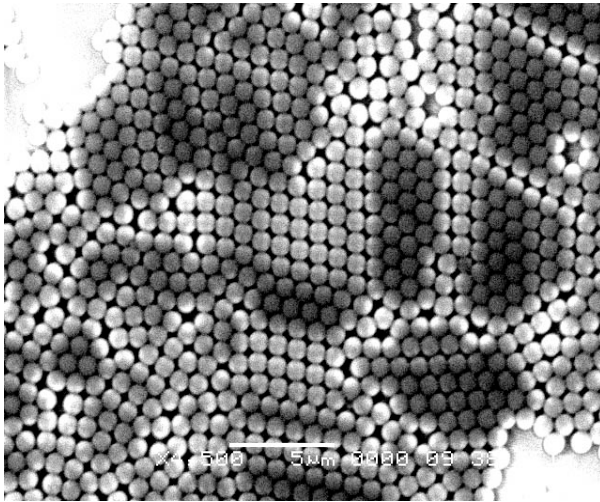


R. Hillenbrand, F. Keilmann, Phys. Rev. Lett. **80**, 3029 (2000)

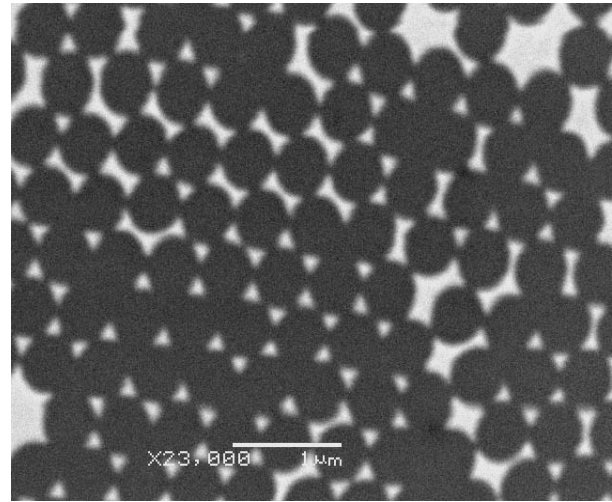
## Test sample by colloidal lithography



## Test sample Au on Si

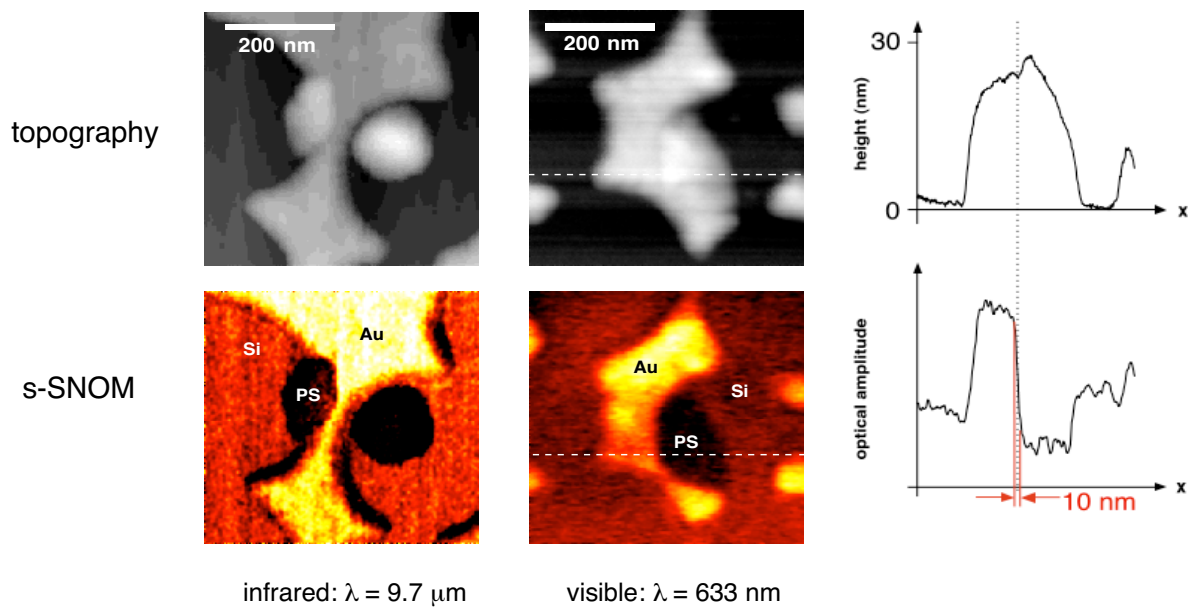


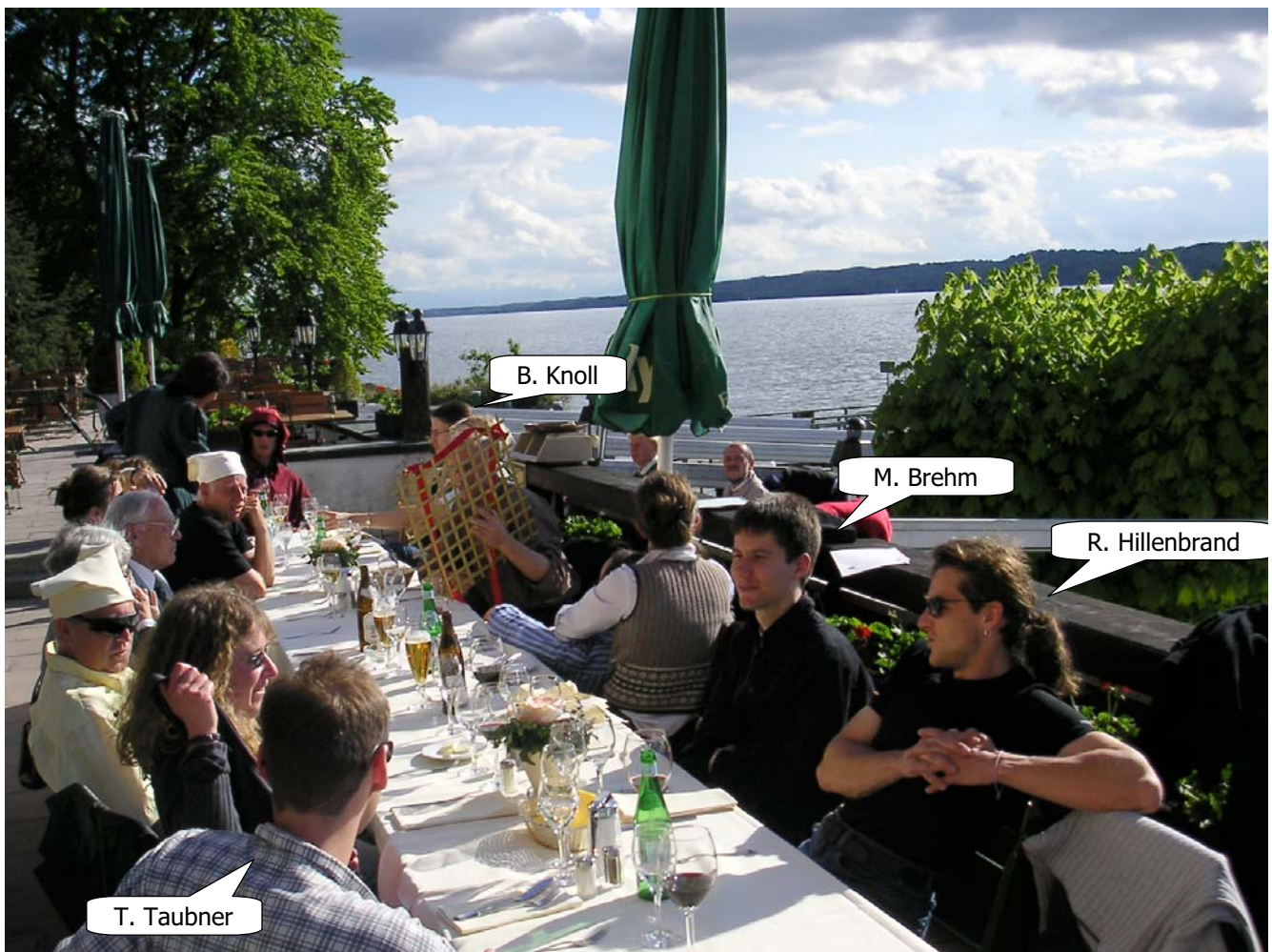
SEM image of self-assembled monolayer of polystyrene (PS) beads



SEM image after Au evaporation and dissolving the beads

## Material-dependent, $\lambda$ -independent near-field contrast



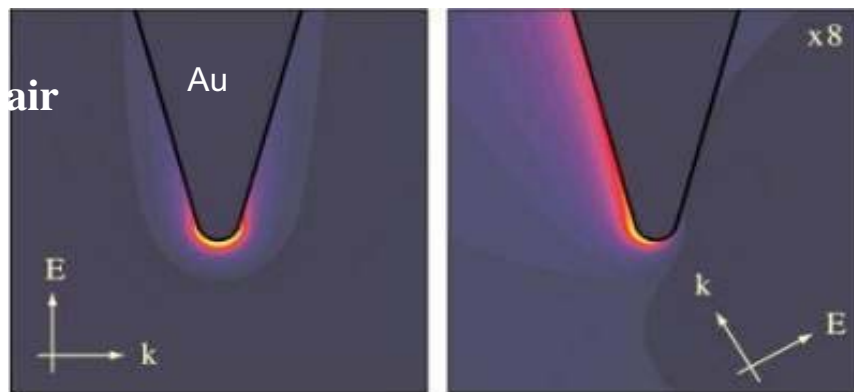


## s-SNOM issues and challenges

- Resolution was ultimate goal -> advantage over aperture-SNOM
- to explain the contrast, physical theory
- But: Artefacts by topography (tip-sample distance changes) and background scattered light (lots of „doubtful“ images!)
- Modulation techniques are necessary
- Field enhancement is there, but how big is it really?
- **tip-enhanced** microscopies evolve, such as probing Raman-scattered light, Rayleigh-scattered light (VIS, IR and THz, microwave), fluorescence, second-harmonic-generation, writing with tip-enhanced fields

## Tip focusing

incident light becomes enhanced, on a highly confined spot



<http://www.optics.rochester.edu:8080/workgroups/novotny/>

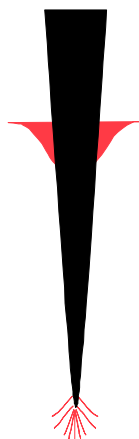
such narrow confinement prerequisite for s-SNOM  
physical concepts: antenna, surface waves

how does this spot interact with the sample  
analytic theory

## Surface waves

Maxwell equations allow solutions of bound waves on  
"conductive" surfaces (i.e. negative  $\epsilon$ )

metal	surface plasmon polariton
dielectric	surface phonon polariton
	surface exciton polariton



a Sommerfeld wave = a wire plasmon  
travels along a metal wire;  
can it "focus" at the tip?

any connections?

an electrostatic field is intensified at a metal tip  
(lightning rod effect)

## Surface plasmon polaritons

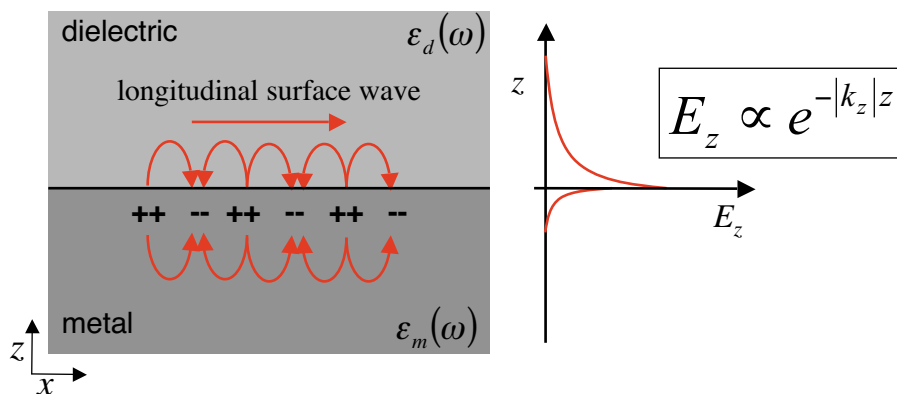
Radiative surface plasmons are coupled with propagating EM waves

Nonradiative surface plasmons do not couple with propagating EM waves

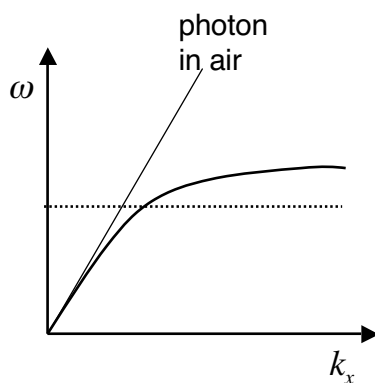
On perfectly flat surfaces SPPs are always nonradiative!

Mixed transversal and longitudinal EM field

In contrast to TIR the plasmon field on both sides of the interface are evanescent



## Surface plasmon polariton dispersion



for a given  $\omega$ :  $k$  of photon in air  $<$   $k$  of SPP



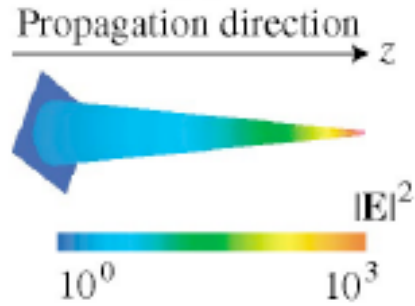
no excitation of SPP is possible

(on flat surface;  
remedy: grating or prism coupling)



a Sommerfeld wave = a wire plasmon  
travels along a metal wire;  
can it "focus" at the tip?

Stockman theory: yes! PRL 93, 137404 (2004)



how to launch the surface wave?

## Antenna



a device to catch the wind



a device to catch radio

optimal length:  
 $L = \lambda/4$

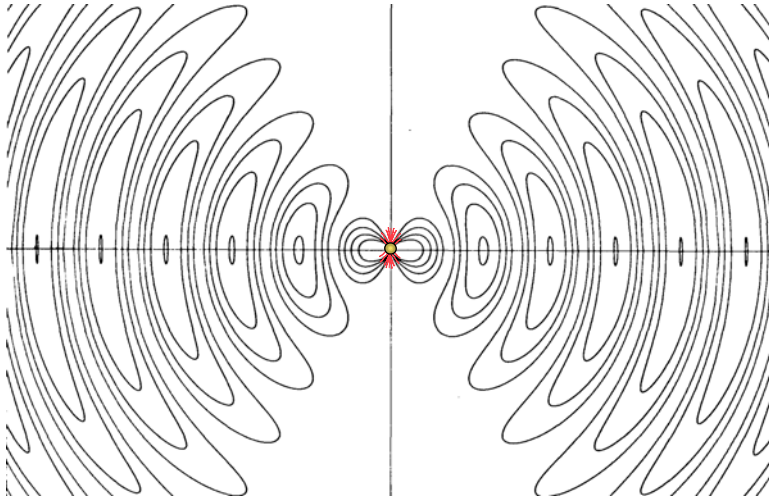
absorption  
cross section:  
 $L^2$

⇒ generally, a device to **couple** electromagnetic energy  
from one mode into another:

- Gaussian beam
- fiber guide
- hollow metal guide
- coaxial guide
- surface wave
- 2dim
- 1dim
- 0dim



## Molecular/atomic dipole emitter/absorber

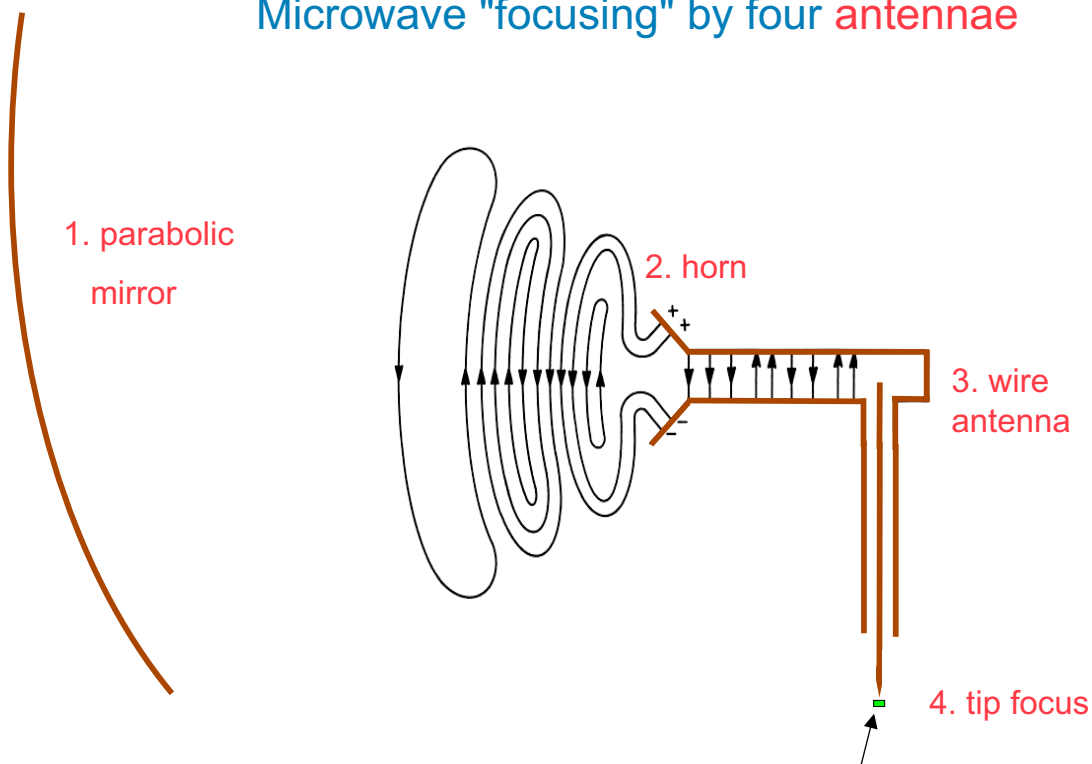


has very bad  
antenna efficiency:

even if the absorption cross section were unusually large  
e.g.,  $10^{-14} \text{ cm}^2 = 1 \text{ nm}^2$

the antenna efficiency, at  $\lambda=400 \text{ nm}$ , is still only  
 $(1 \text{ nm} / 100 \text{ nm})^2 = 10^{-4}$

## Microwave "focusing" by four antennae



at  $\lambda = 10 \text{ cm}$  overall efficiency to reach  $1 \mu\text{m}$  transistor/diode  $>50\%$  !!!!

## Antenna lobes in the infrared

Evenson APL 17, 8 (1970)

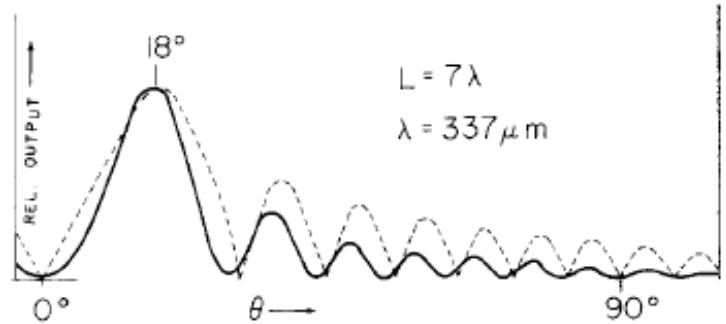
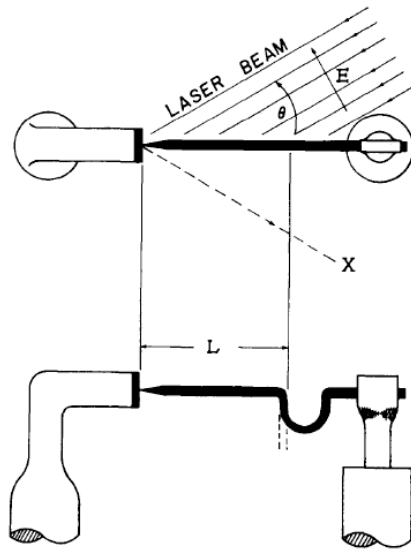


FIG. 2. Portion of the antenna pattern of a whisker seven wavelengths long. Solid curve, experimental; dashed curve, theoretical.

## Efficiency obtained with infrared antenna,

Völcker, Krieger, Walther, J.Vac.Sci.Tech.B 12 2129 (1994)

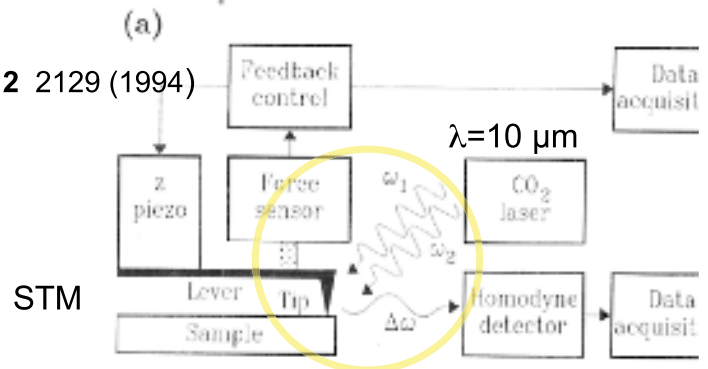
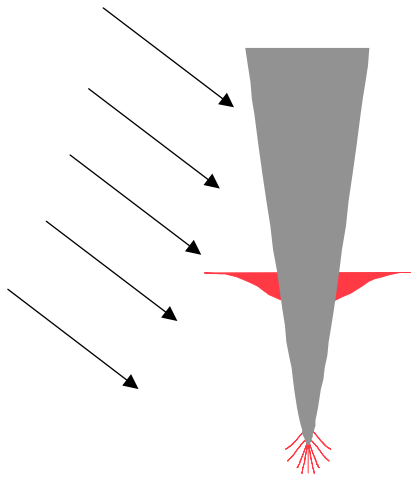


TABLE I. Power conversion in the tip-sample junction.

Applied laser power	$P_{\omega_1}^l + P_{\omega_2}^l$	30 mW	0
Power received by the tip	$P_{\omega_1}^a + P_{\omega_2}^a$	730 $\mu$ W	1.6
Power at $\omega$ in the gap	$P_{\omega_1}^g + P_{\omega_2}^g$	41 nW	5.8
Power at $\Delta\omega$ in the gap	$P_{\Delta\omega}^g$	130 pW	8.3
Total power emitted at $\Delta\omega$	$P_{\Delta\omega}^t$	640 aW	10.7
Detected power at $\Delta\omega$	$P_{\Delta\omega}^d$	200 aW	11.2

<sup>a</sup>Experimental value.

## What we learn: two steps

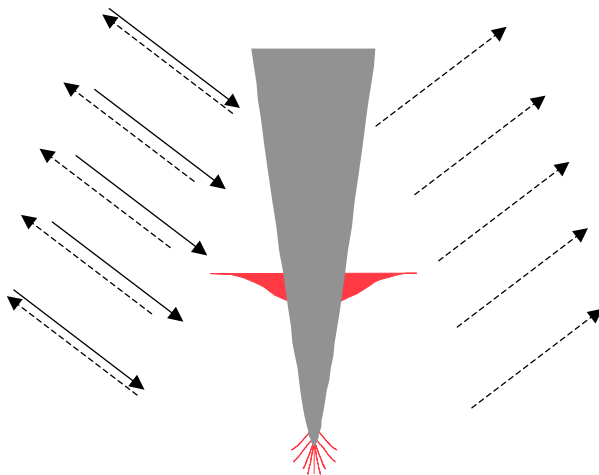


in order to **create** a strong near field at the solid tip

1. light from the free-space has to be intercepted by an antenna, i.e., by a structure longer than the immediate apex region

2. currents or surface waves distributed along the antenna should exit the apex region

## Three more

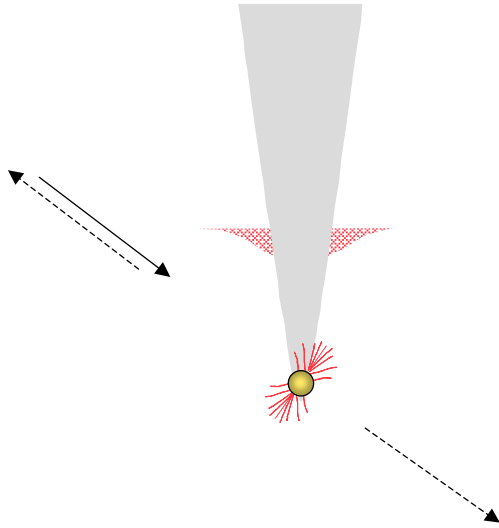


3. to **interact** with the sample

4. to excite currents or surface waves distributed along the antenna

5. to emit a free-space beam

## Is antenna needed?



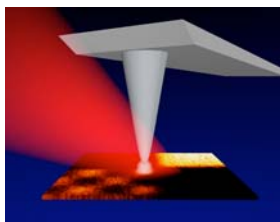
if the tip were replaced by a very small particle

confined near fields also occur

but possibly much weaker

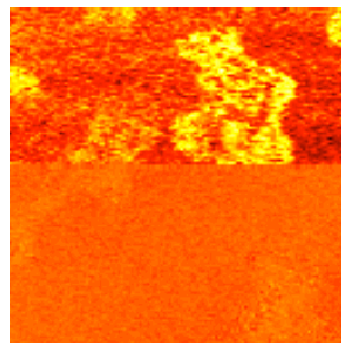
(exception: dielectric resonance  
e.g. from particle plasmon)

## Polarization test at $\lambda=10\mu\text{m}$

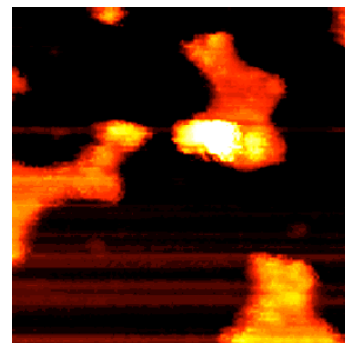


p-polarization

s-polarization



infrared

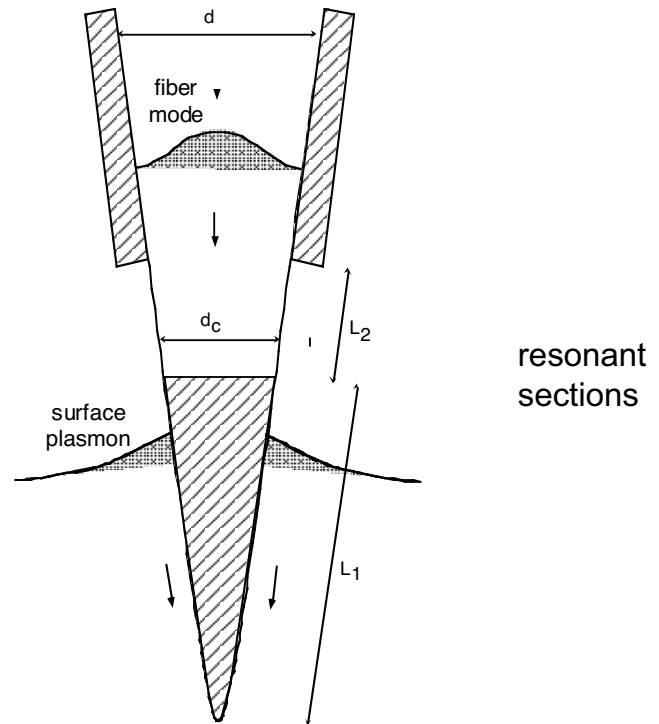


topography

## Tip-on-aperture

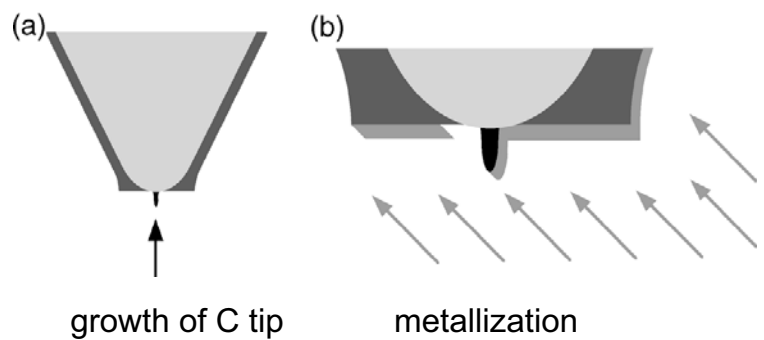
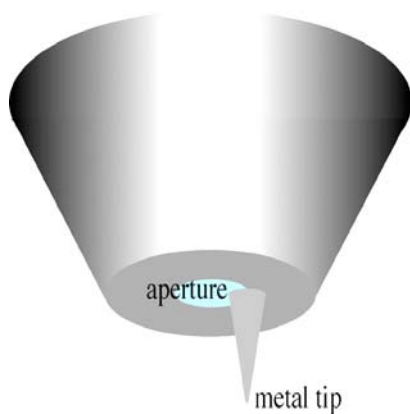
aperture SNOM  
is used...

...to illuminate  
solid tip



F. Keilmann, R. Guckenberger  
Patent DE 19522546 (1995)

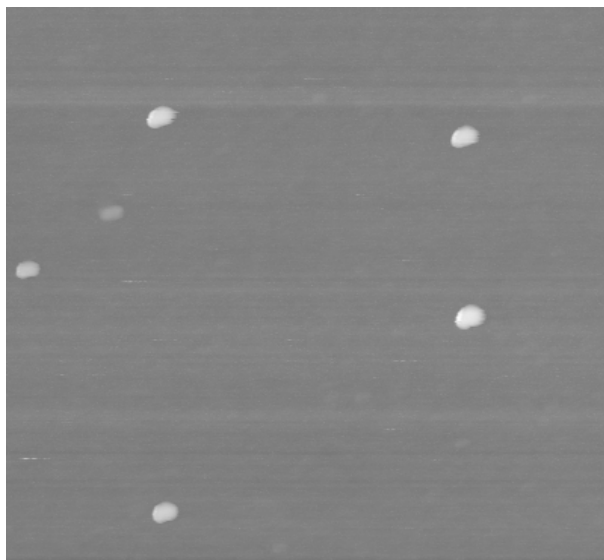
## Tip-on-aperture experimental



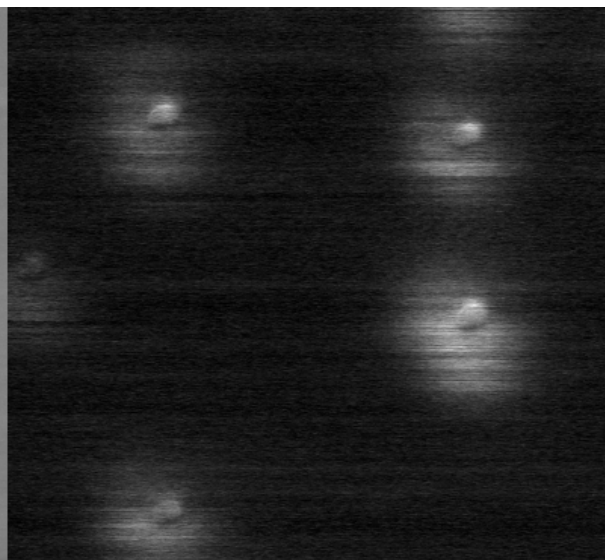
H.G. Frey, A. Kriele, F. Keilmann, and R. Guckenberger, APL **81**, 5030 (2002)

## Fluorescent beads

topography

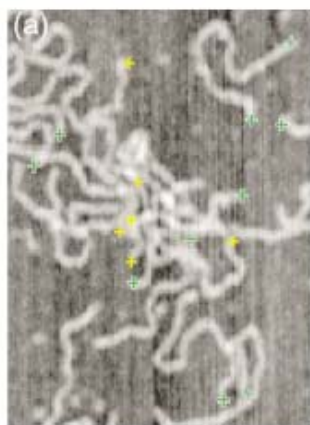


fluorescence

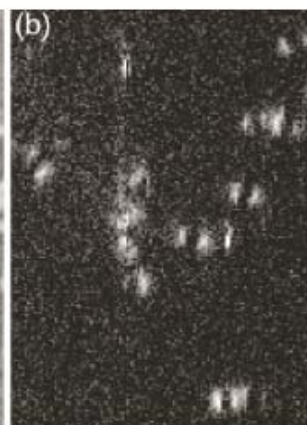


## DNA with single dye molecules

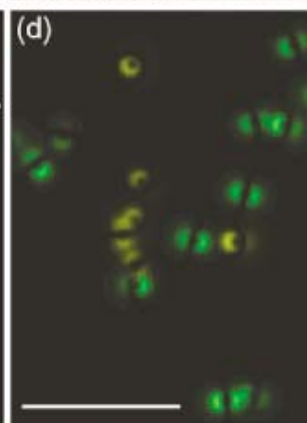
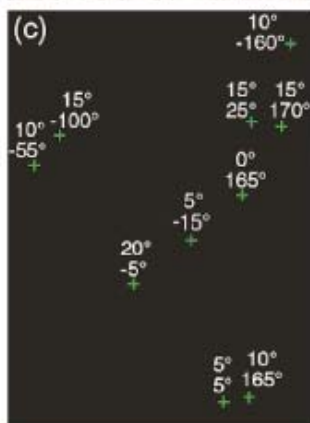
topography



fluorescence

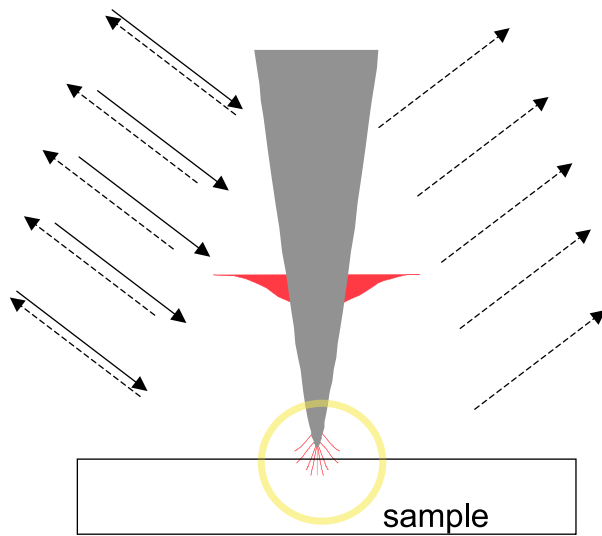


modelling of  
fluorescence



Guckenberger et al.  
PRL Nov. 2004

## How can one understand step 3. near-field interaction ?

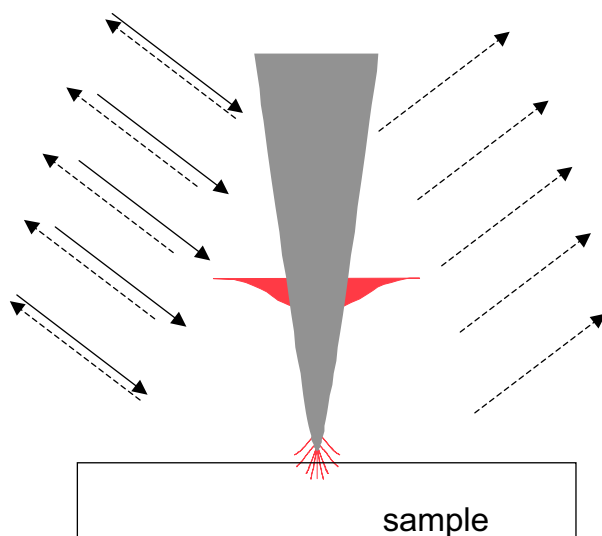


3. to **interact** with the sample

4. to excite currents or surface waves distributed along the antenna

5. to emit a free-space beam

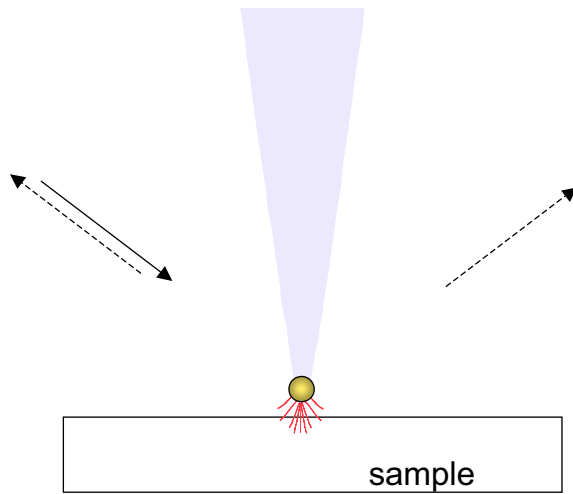
## Only apex counts



idea:

near-field **shape** does not depend on long shaft

## Point dipole theory



to model the near-field interaction

we approximate the tip by a small sphere

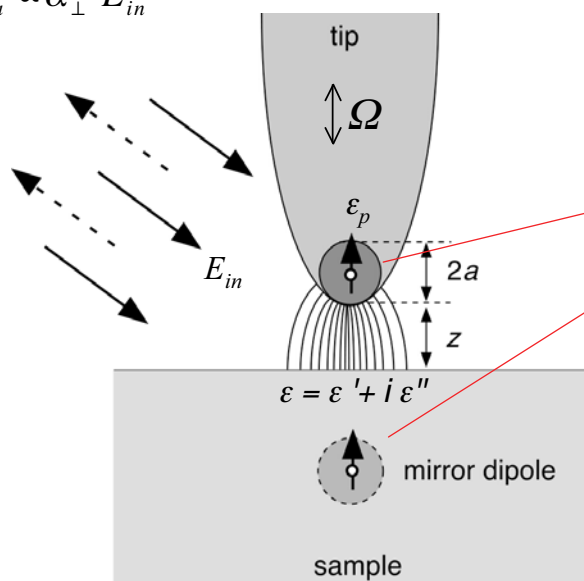
but retain z-orientation of near field due to tip shaft

calculate dipole moment of point dipole in sphere center

## Near-field interaction between point dipole and sample

measured far-field:

$$E_{sca} \propto \alpha_{\perp}^{eff} E_{in}$$



treated by combining the scattering from two dipoles

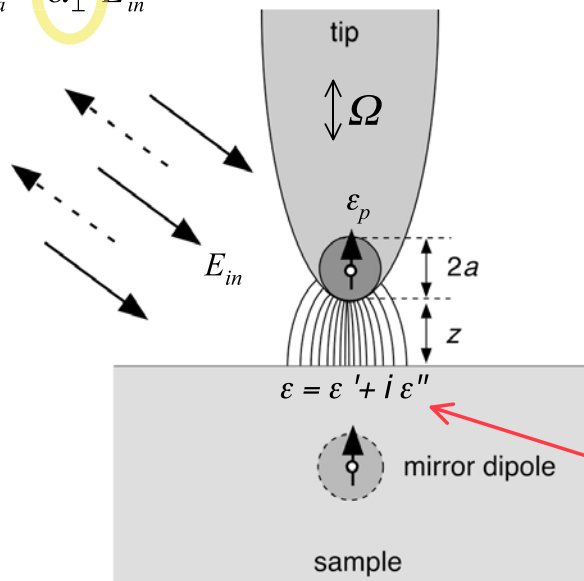
point dipole in tip apex interacting with mirror dipole in the sample



## Near-field interaction measures $\epsilon = \epsilon' + i\epsilon''$ of sample

measured far-field:

$$E_{sca} \propto \alpha_{\perp}^{eff} E_{in}$$



polarizability of tip dipole:

$$\alpha = 4\pi a^3 \frac{(\epsilon_p - 1)}{(\epsilon_p + 2)}$$

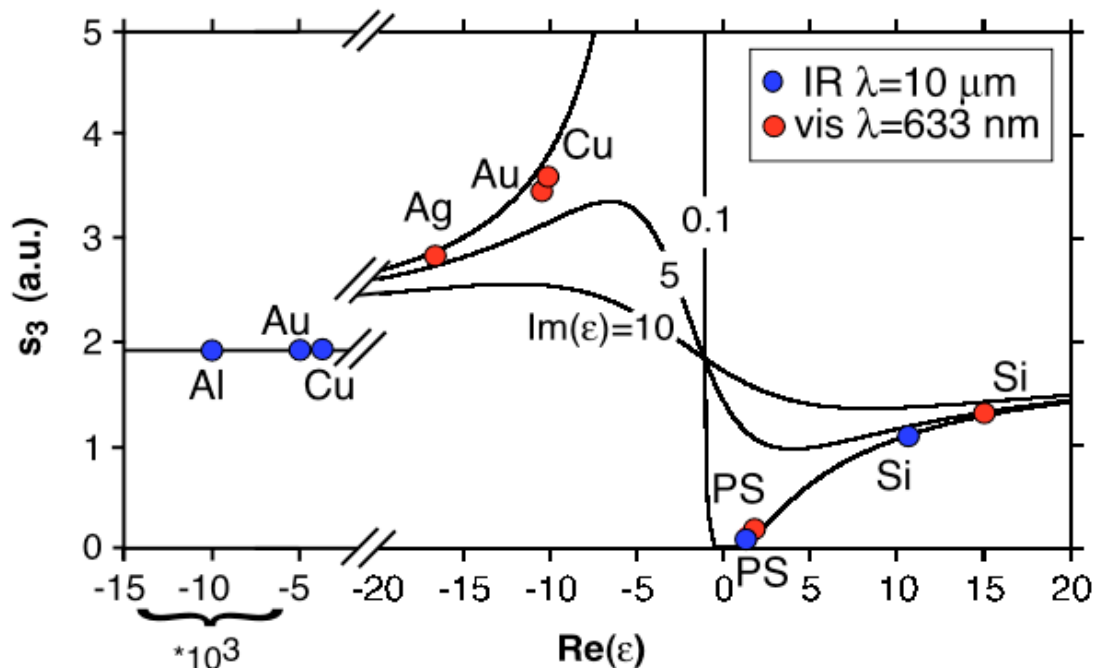
effective polarizability of tip and sample:

$$\alpha_{\perp}^{eff} = \frac{\alpha(1 + \beta)}{1 - \frac{\alpha\beta}{16\pi(z + a)^3}}$$

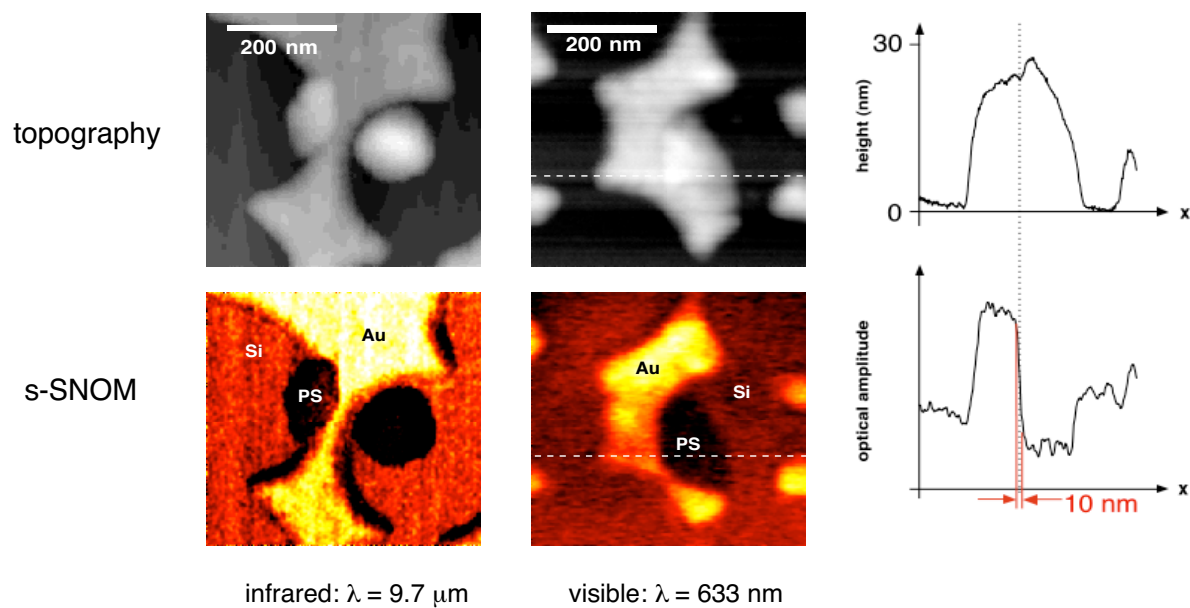
with  $\beta = \frac{(\epsilon - 1)}{(\epsilon + 1)}$

complex  $\epsilon$  determines scattering amplitude and phase

## Predicted scattering amplitude from point d. model



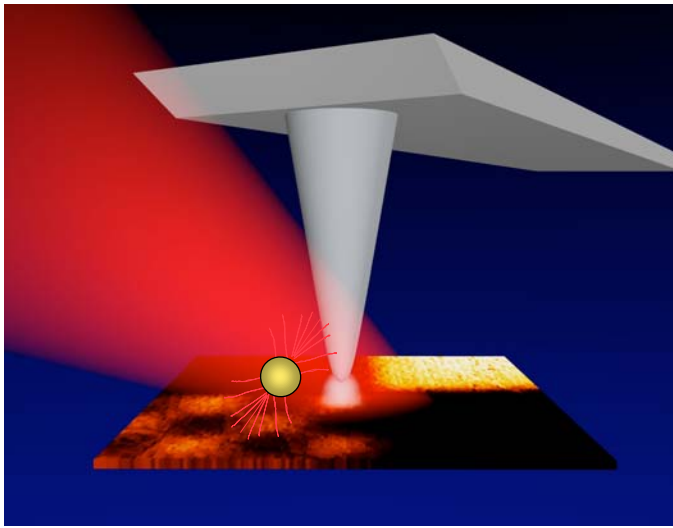
## Material-dependent, $\lambda$ -independent near-field contrast



T. Taubner, R. Hillenbrand, F. Keilmann, *J. Microscopy* **210**, 311 (2003)

break

## „Apertureless“ or s-SNOM



a cantilevered  
metal tip  
serves as antenna

near field with  
 $\approx 20$  nm spot size  
probes surface



## Dielectric resonance of a small particle

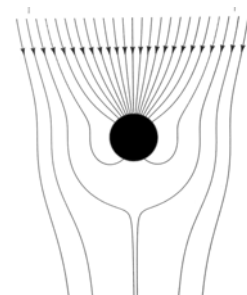
small particles can become optically resonant

condition  $\epsilon' = -2$ ,  $\epsilon''$  small

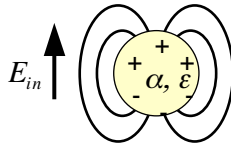
(dielectric antenna)

consequences

- enhanced near field
- enhanced Raman scattering
- enhanced nonlinear conversion



## Examples

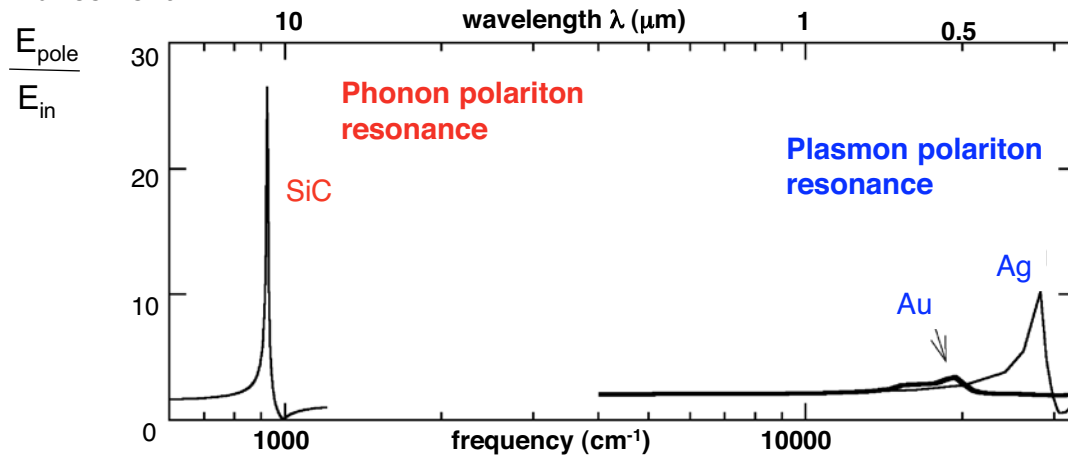


$$\alpha = 4\pi a^3 \frac{\epsilon - 1}{\epsilon + 2}$$

resonance at  
 $\epsilon = -2$

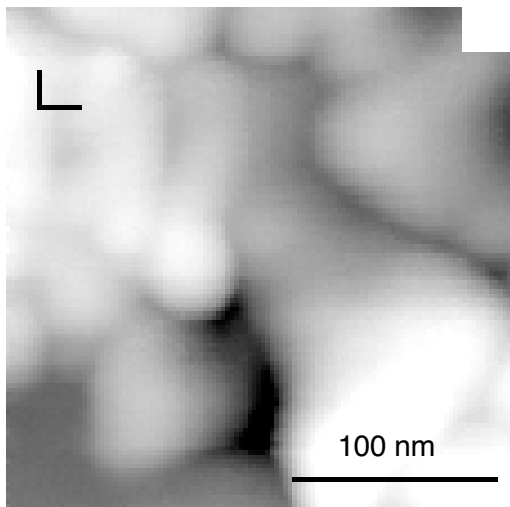


### Field enhancement

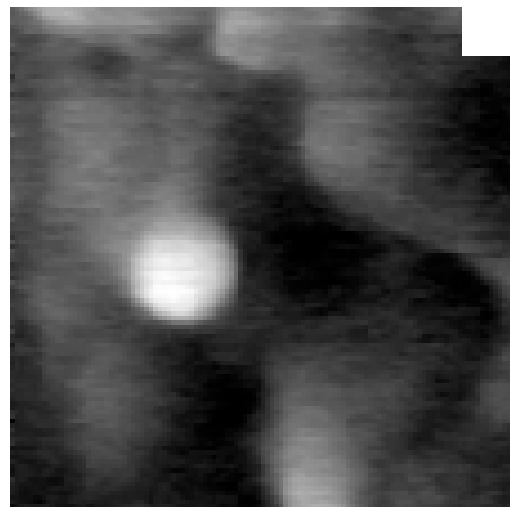


## Example

$\lambda = 633 \text{ nm}$

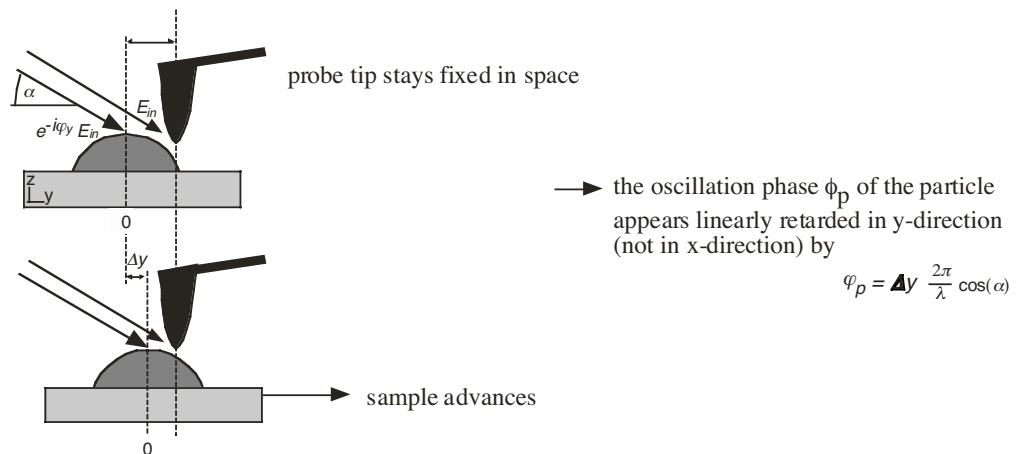
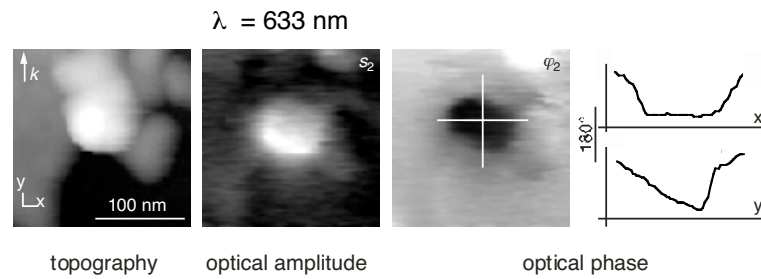


topography

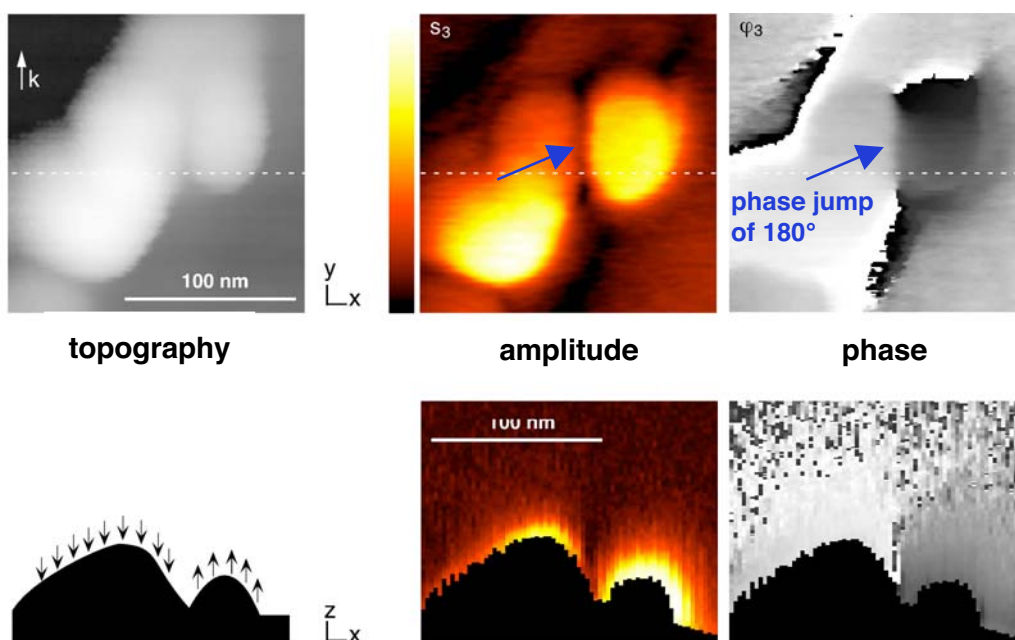


optical amplitude

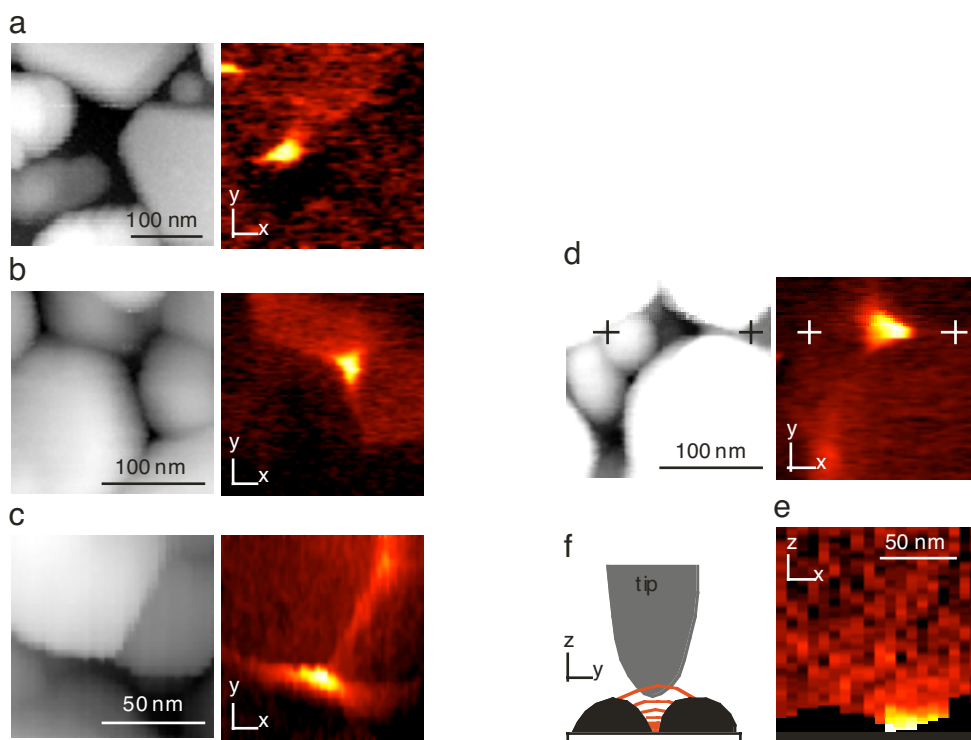
## Phase gradient in scan direction



## Particle with quadrupolar mode



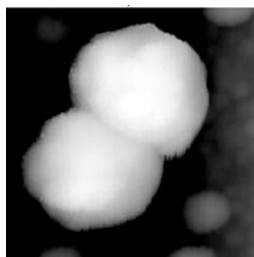
## Highly localized fields in gaps



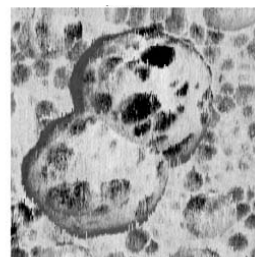
## Gap field in Ag dimer

sample from H. Xu and M. Käll (Göteborg)

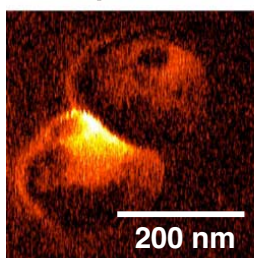
topography



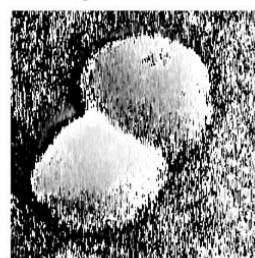
mechanical phase



amplitude



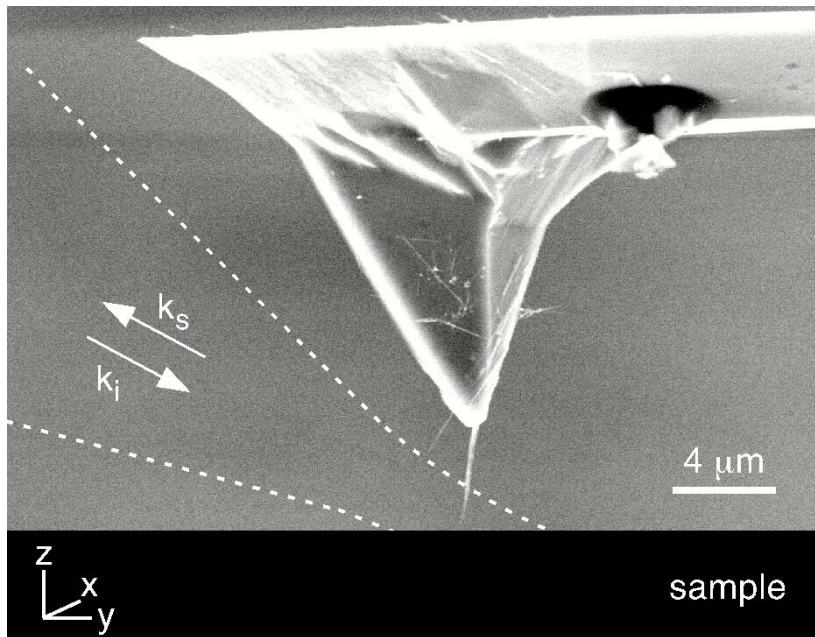
phase



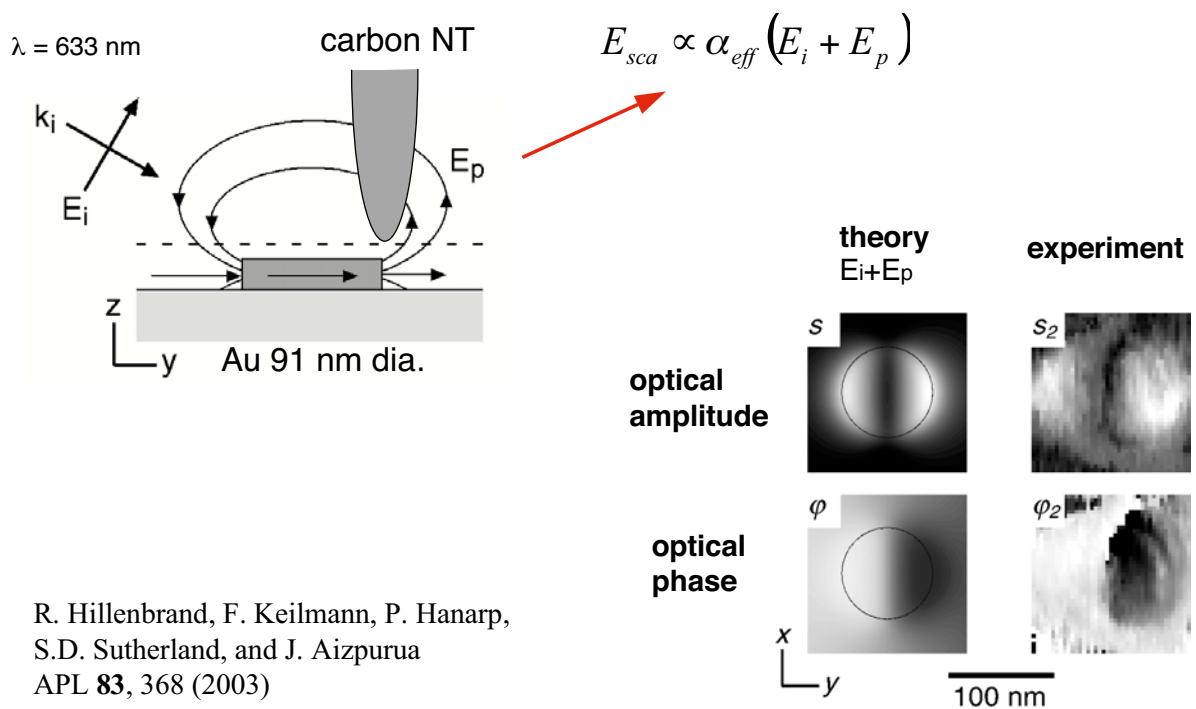
s-SNOM at  $\lambda=633\text{nm}$

# Quantitative study using carbon nanotube bundle as tip

supplied by npoint

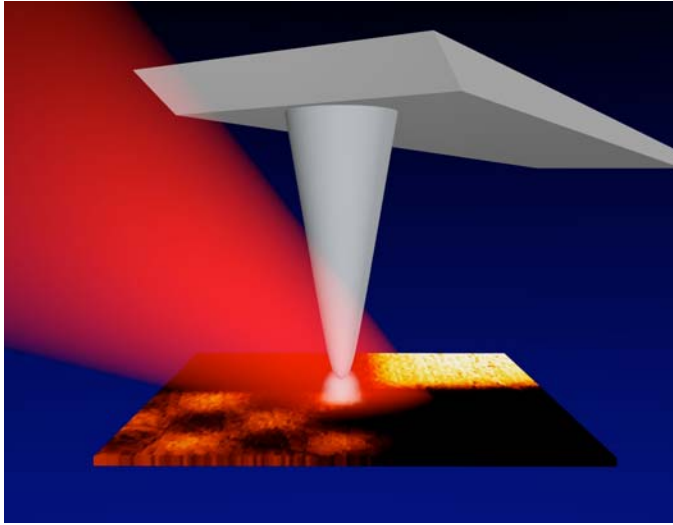


## Imaging enhanced near field of tailor-made Au disk



R. Hillenbrand, F. Keilmann, P. Hanarp,  
S.D. Sutherland, and J. Aizpurua  
APL **83**, 368 (2003)

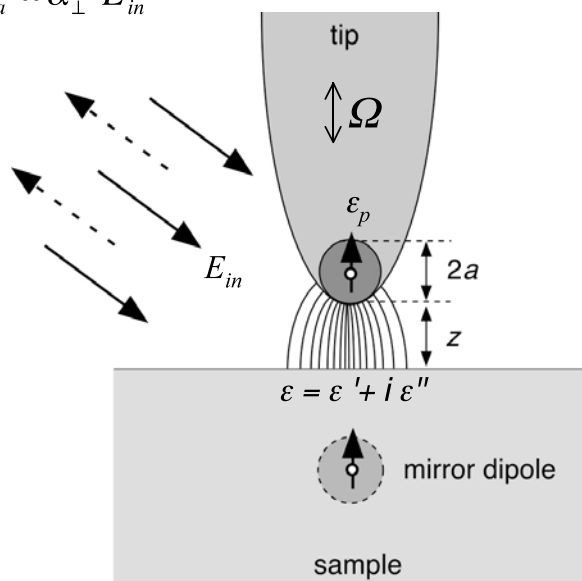
## back to local spectroscopic probing



## Near-field interaction is nonlinear in z

measured far-field:

$$E_{sca} \propto \alpha_{\perp}^{eff} E_{in}$$



polarizability  
of tip dipole:

$$\alpha = 4\pi a^3 \frac{(\epsilon_p - 1)}{(\epsilon_p + 2)}$$

effective polarizability  
of tip and sample:

$$\alpha_{\perp}^{eff} = \frac{\alpha(1 + \beta)}{1 - \frac{\alpha\beta}{16\pi(z + a)^3}}$$

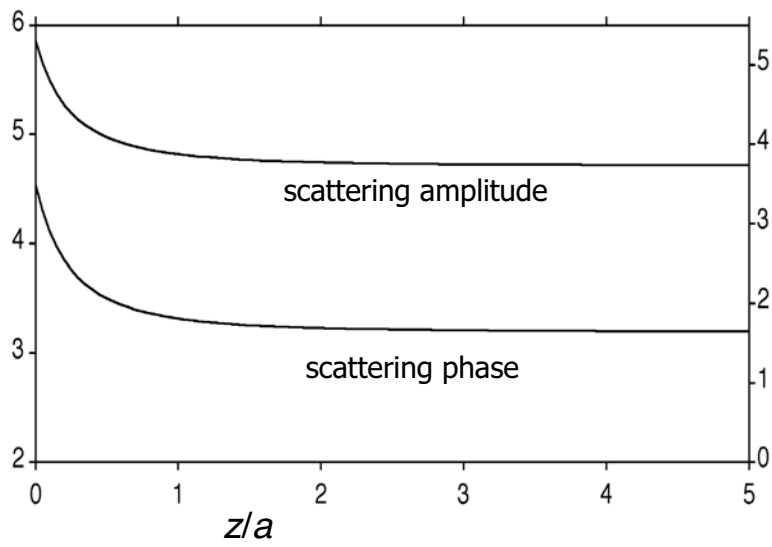
with

$$\beta = \frac{(\epsilon - 1)}{(\epsilon + 1)}$$

nonlinear  
characteristic

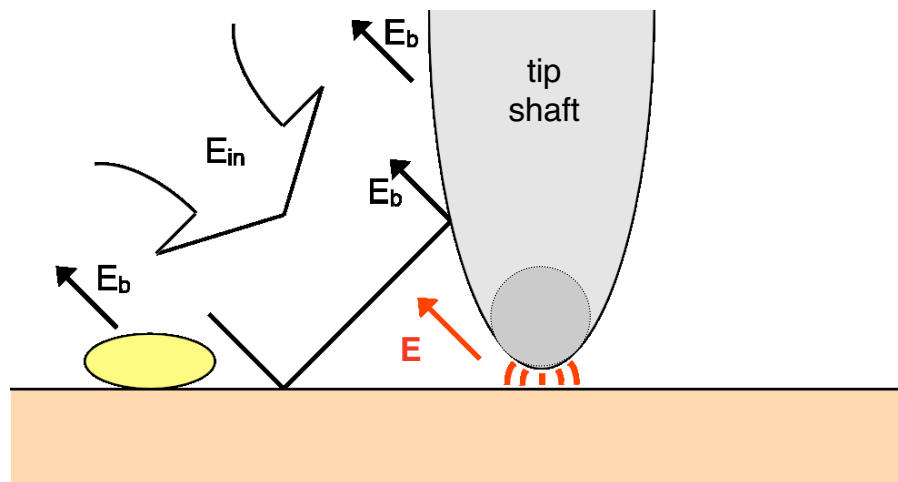


## Approach from point dipole theory



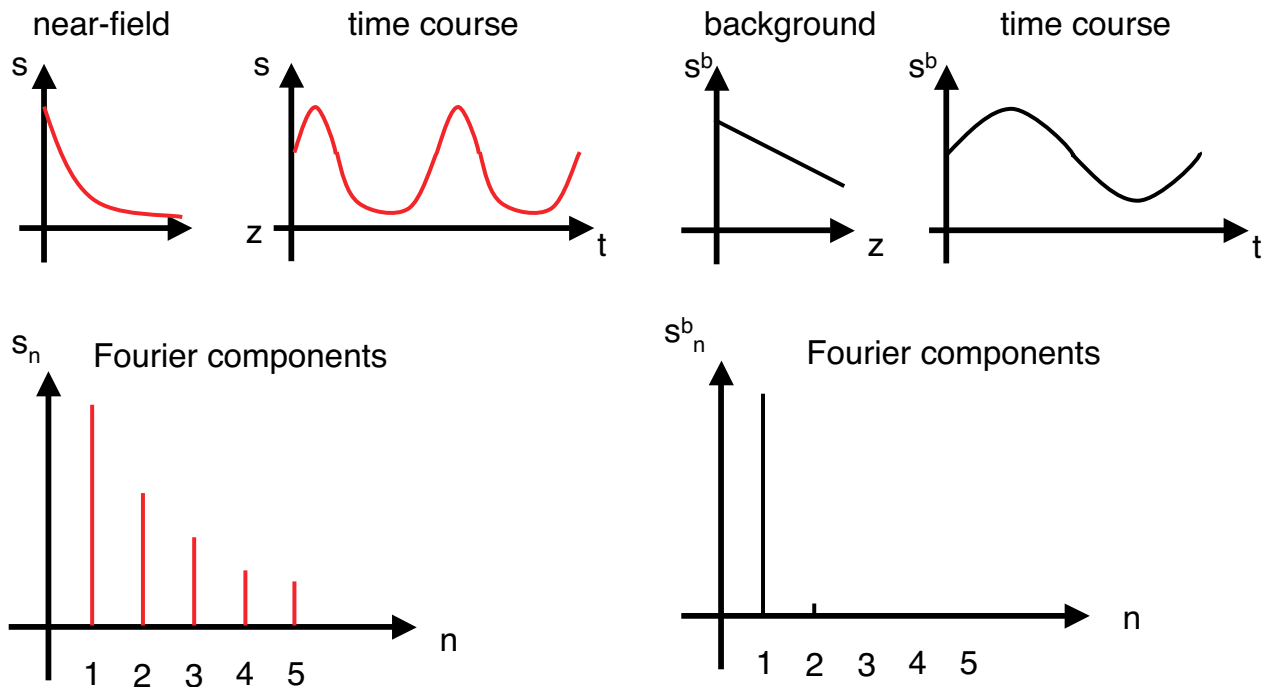
...allows suppression  
of background scattering:


## Disturbing scattering "background"



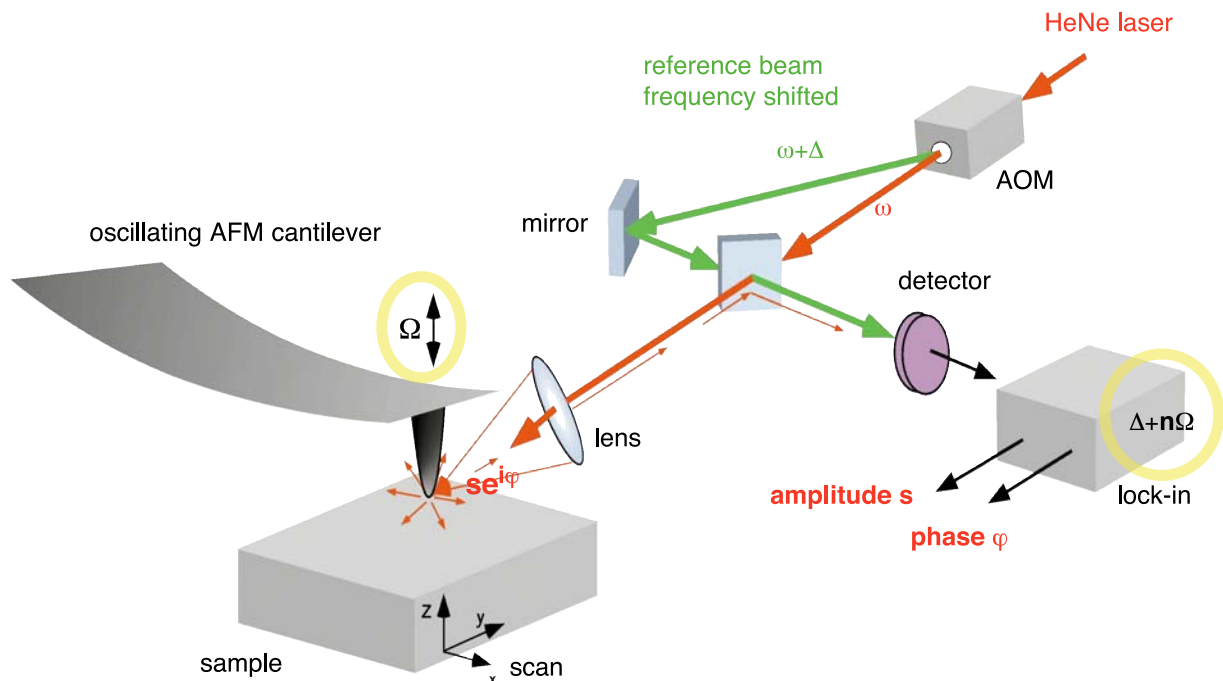
$E_b$  : background scattered light       $E$  : scattered light from near-field interaction

## Fourier components in scattered intensity

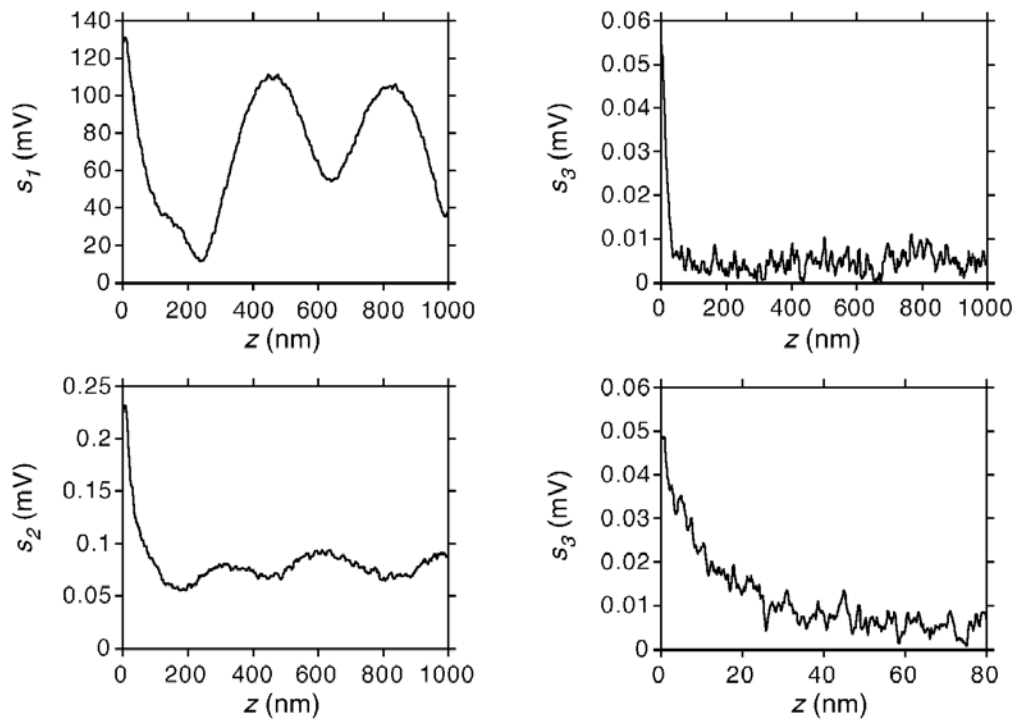


 if  $n$  is chosen high enough then:  $s_n > s_n^b$   
 Near-field amplitude dominates over background amplitude

## s-SNOM with heterodyne detection of backscattering



## Approach curves at $n\Omega$ demodulation



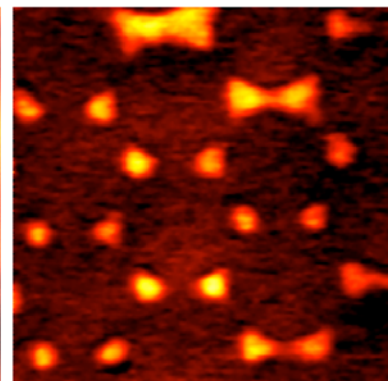
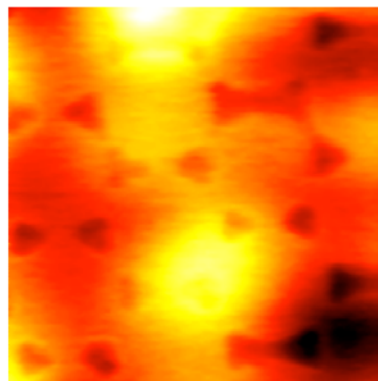
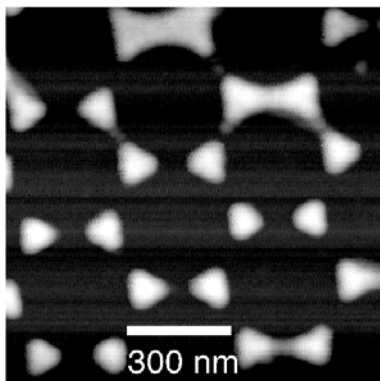
## Example of background suppression

Au islands on Si

topography

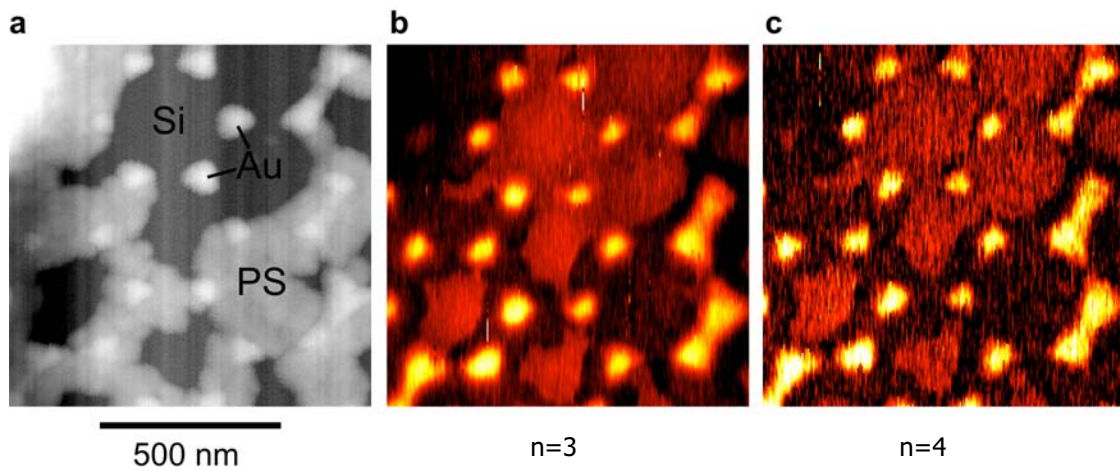
$s_1$

$s_3$



## Stable contrasts

Au islands on Si, partly covered with PS film



contrast not affected by choice of  $n$

## Broken tip

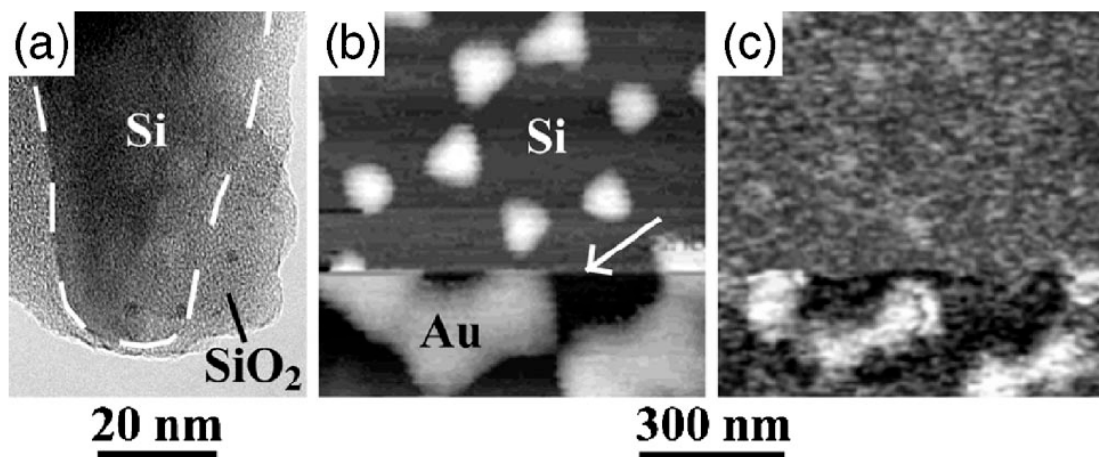


FIG. 4. *s*-SNOM with a crashed Si tip. (a) TEM image of a typical Si tip crashed during probing. (b) Topography and (c) simultaneously acquired near-field optical image taken at demodulation order  $n=3$ . The tip crash is marked by an arrow.

$\lambda = 633 \text{ nm}$

## Inhibiting oxide

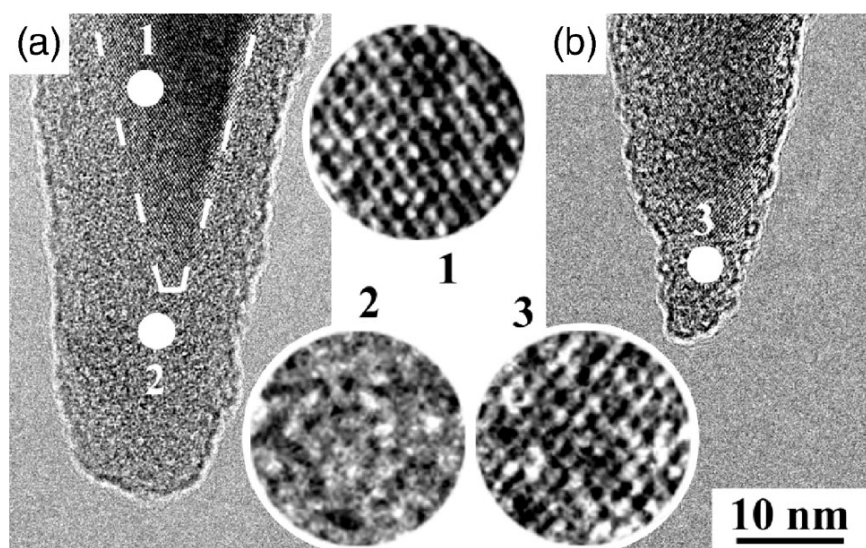


FIG. 3. TEM image of the tip apex of a typical (a) off-the-shelf Si probe and (b) Si probe etched in buffered HF. The insets 1–3 are scaled-up images of the probe's atomic structure in the white areas marked in (a) and (b).

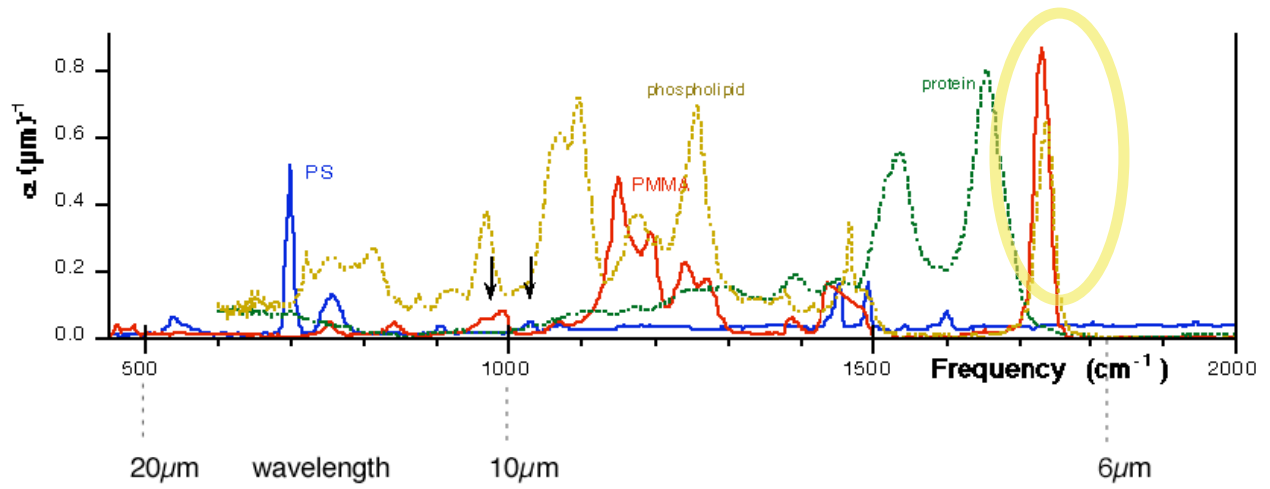


Application in polymers

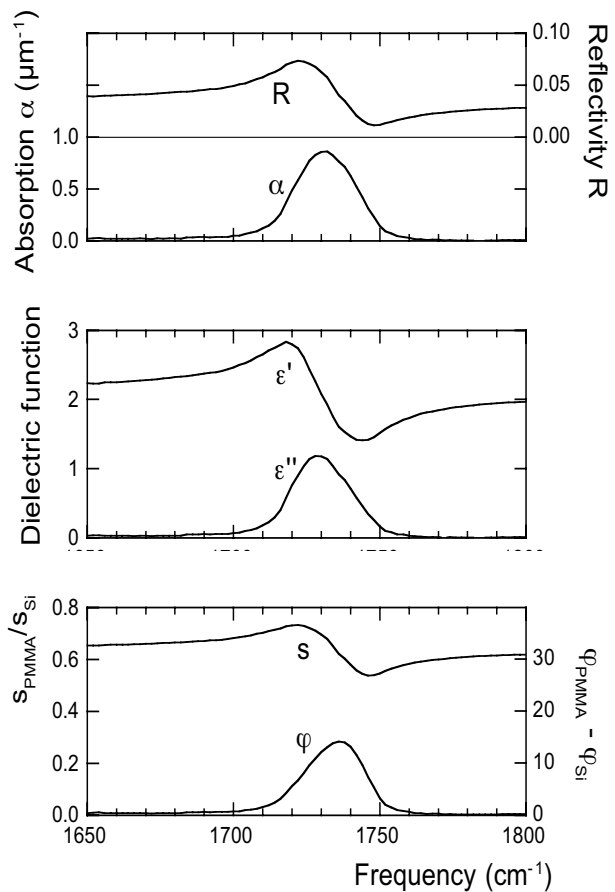
## Typical Vibrational Absorption Spectra

measured ellipsometrically

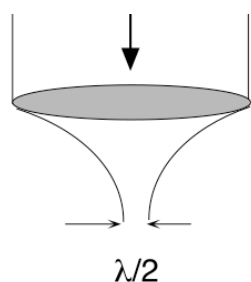
recalculated for  $\alpha$  - absorption coefficient



Predicted near-field response of a molecular oscillator (data of PMMA)

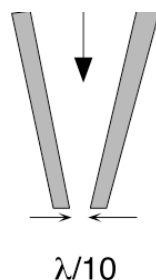


## Microscope principles use different interaction concepts



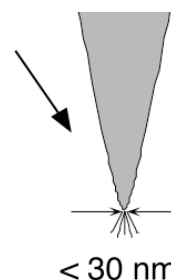
**classical**  
diffraction-limited

free-space



**aperture SNOM**  
aperture-limited

guided



**scattering SNOM**  
tip-limited

confined

**transverse waves**

**longitudinal field**

## Pairs of optics observables

*to determine  $n + ik$  unambiguously*

$\alpha$  absorption coefficient

Transmission spectrometer

R reflectivity

Reflection spectrometer

R reflectivity

$\varphi$  phase of reflection

Interferometer

$R_p / R_s$  reflectivity ratio

$\varphi_p - \varphi_s$  reflection phase difference

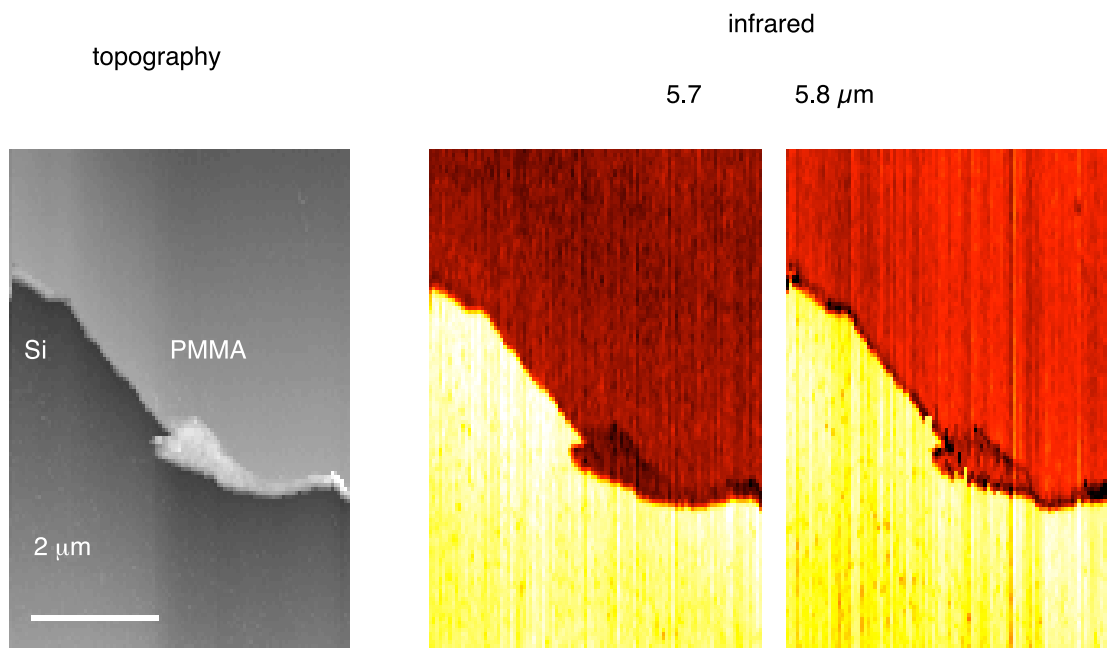
Ellipsometer

$s / s_{ref}$  scattering amplitude

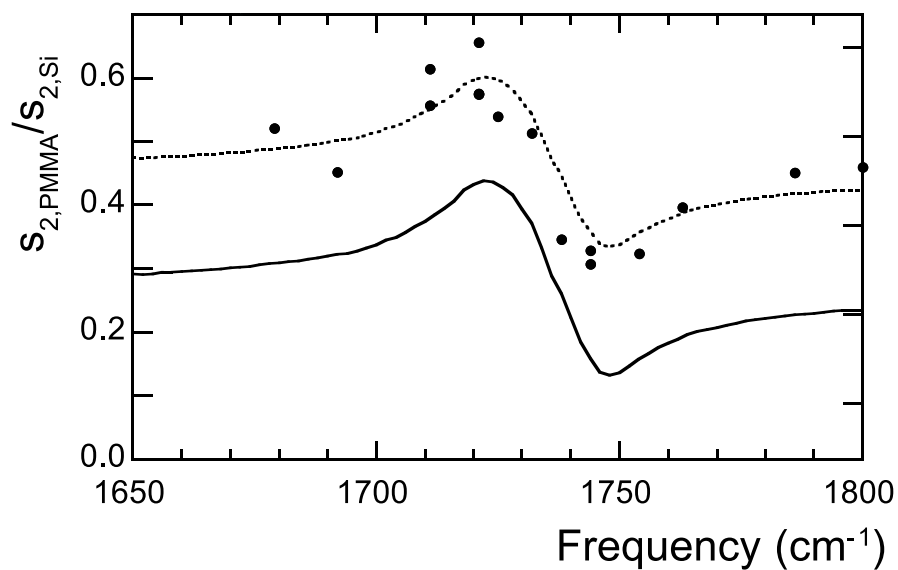
$\varphi - \varphi_{ref}$  scattering phase

scattering near-field microscope (s-SNOM)

## s-SNOM of 50 nm PMMA on Si



## Resulting near-field spectrum

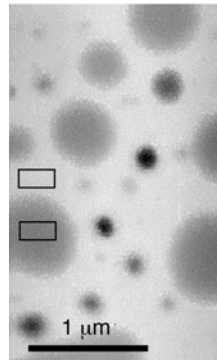
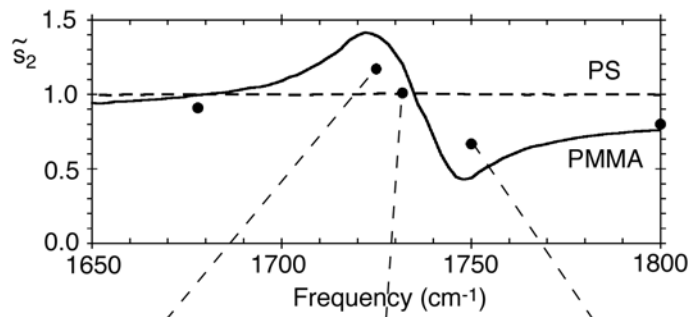


T. Taubner, R. Hillenbrand, and F. Keilmann, *Nanoscale polymer identification by spectral signature in scattering infrared near-field microscopy*, APL **85**, 5064 (2004)

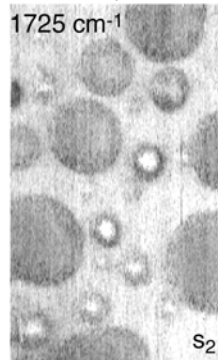


## Polymer blend

70 nm thick film  
PS/PMMA 20/80



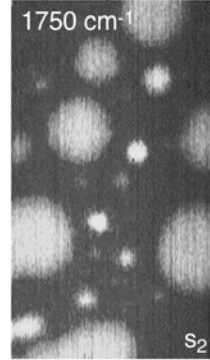
topography



IR:1725  $\text{cm}^{-1}$

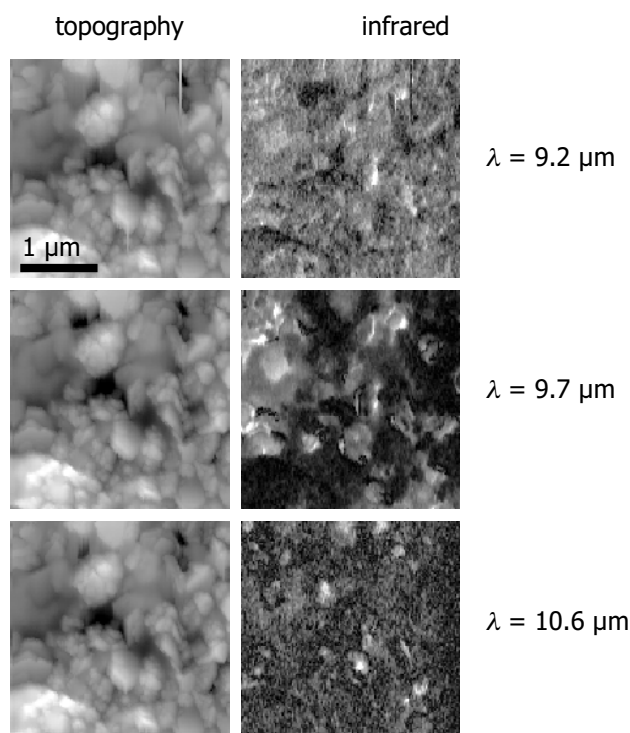


1732  $\text{cm}^{-1}$



1750  $\text{cm}^{-1}$

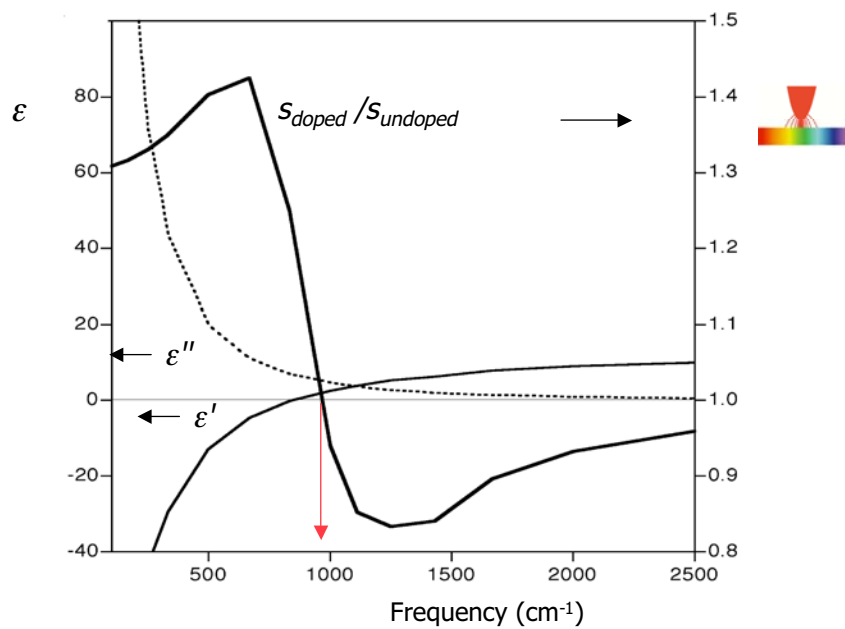
## Infrared s-SNOM of industrial paper coating



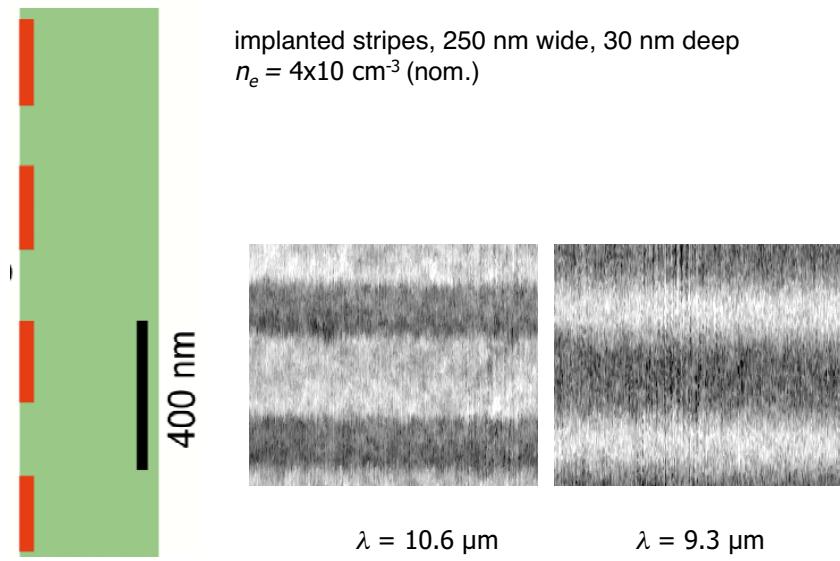
## Application in nanoelectronics

### Free carrier mapping in Si

Drude model of free carrier response  
 $\epsilon(\omega) = -\omega_p^2 / (\omega^2 + i\omega\tau^{-1})$  where  $\omega_p^2 = n_e e^2 / \pi c^2 m^*$   
 $n_e = 4 \times 10^{18} \text{ cm}^{-3}$

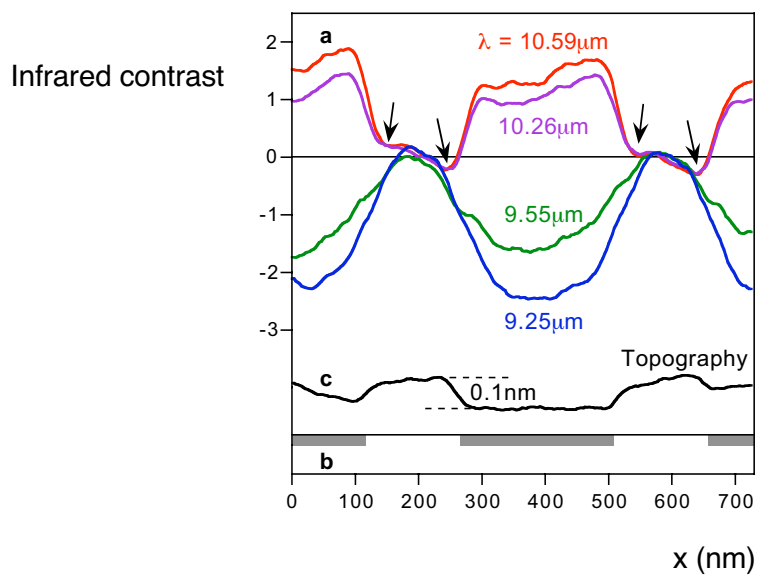


## Imaging subsurface electrons

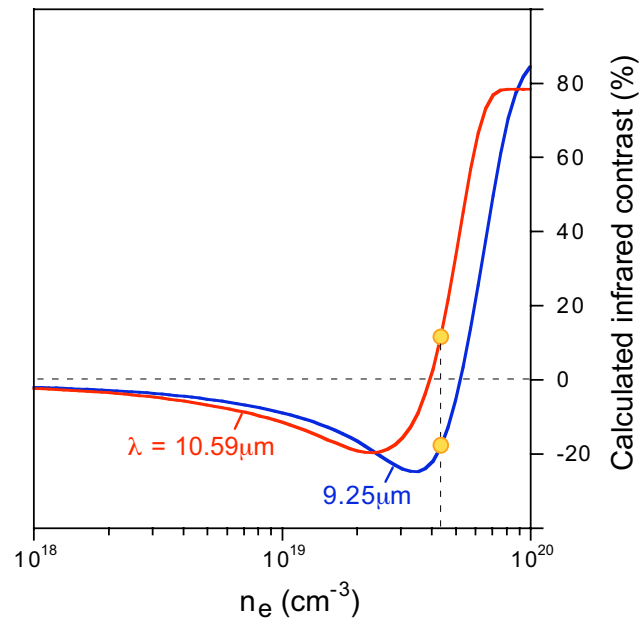


B. Knoll and F. Keilmann, *Infrared conductivity mapping for nanoelectronics*, APL 77, 3980 (2000)

## Free carrier contrast of doped Si

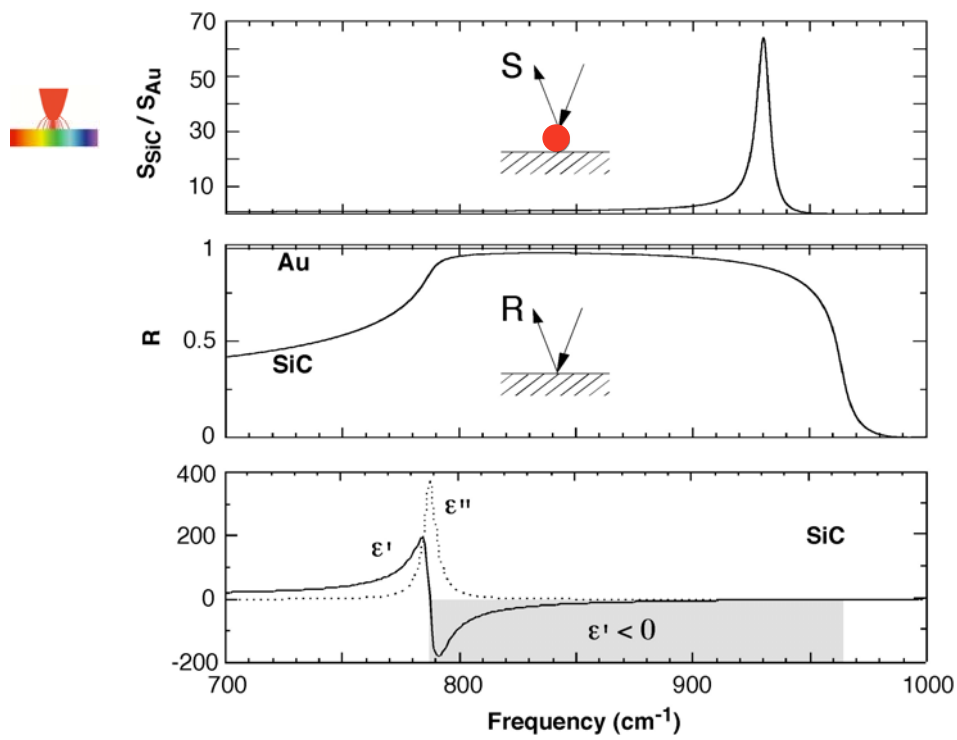


## Determination of carrier density

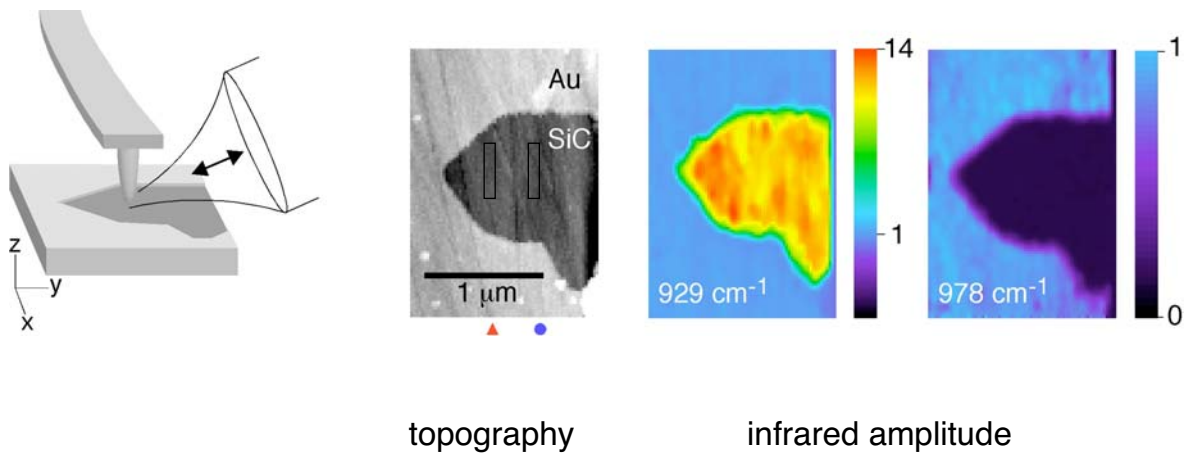


Application in crystal quality assessment

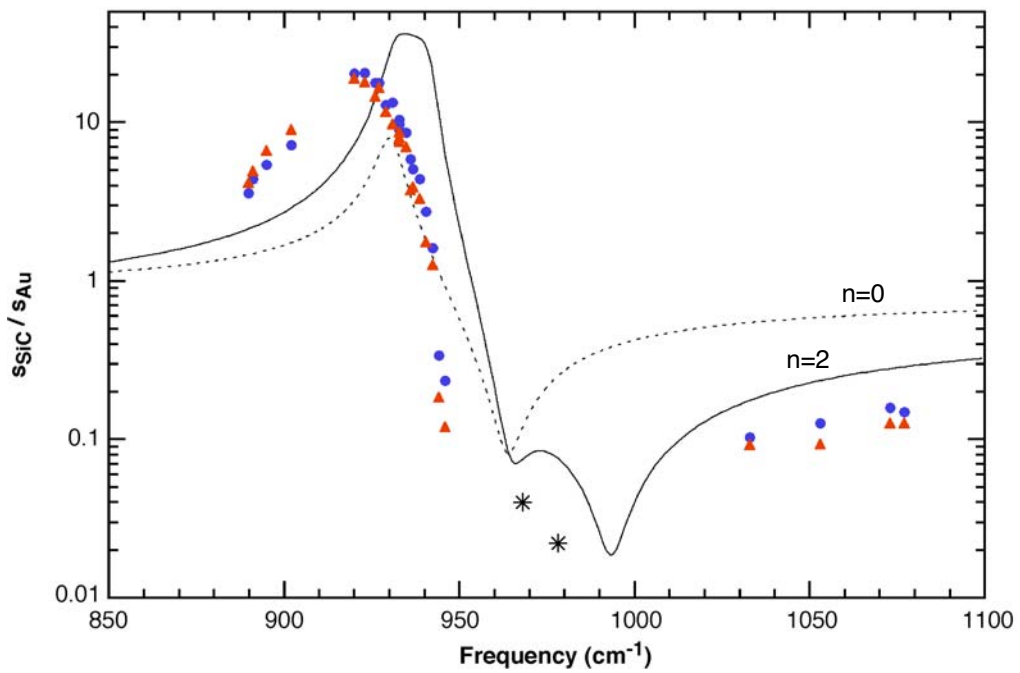
## Predicted s-SNOM response of phonon oscillator



## s-SNOM imaging of partly Au-covered SiC



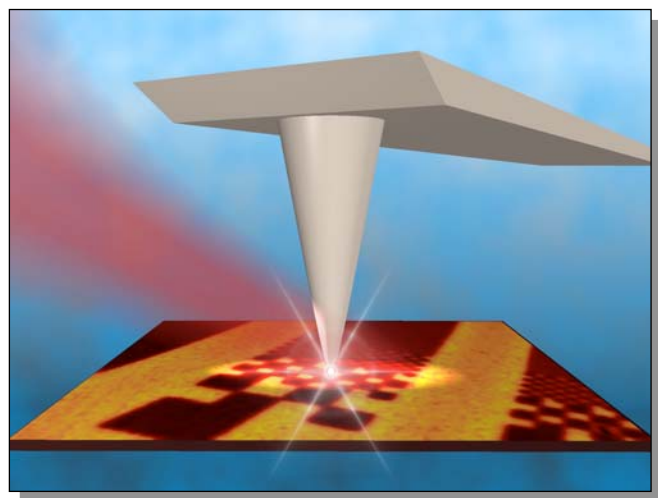
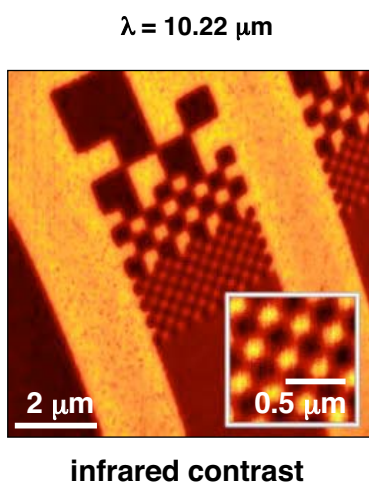
## Verification of phonon resonance



R. Hillenbrand, T. Taubner, F. Keilmann, *Nature* **418**, 159 (2002)

## Nanoscale tailoring of surface phonon polaritons

by transforming crystalline to amorphous SiC by focused ion beam (FIB)



➔  **durable, longterm, high-density IR-ROM**

N. Ocelic, R. Hillenbrand, *Nature Materials* **3**, 606-609 (2004)

# Summary

- \* nanoscopic field concentration at metal tip



brings spectroscopic power to the nanosciences

- \* Infrared s-SNOM chances

- \* same  $<10$  nm resolution as in visible
- \* but better antenna efficiency
- \* opportunities to highlight specific contrasts
  - rotational
  - vibrational
  - low-energy electronic
  - superconductivity
  - cyclotron resonance...