Breaking the diffraction limit: Analysis of diode lasers by nearfield scanning optical microscopy (NSOM)

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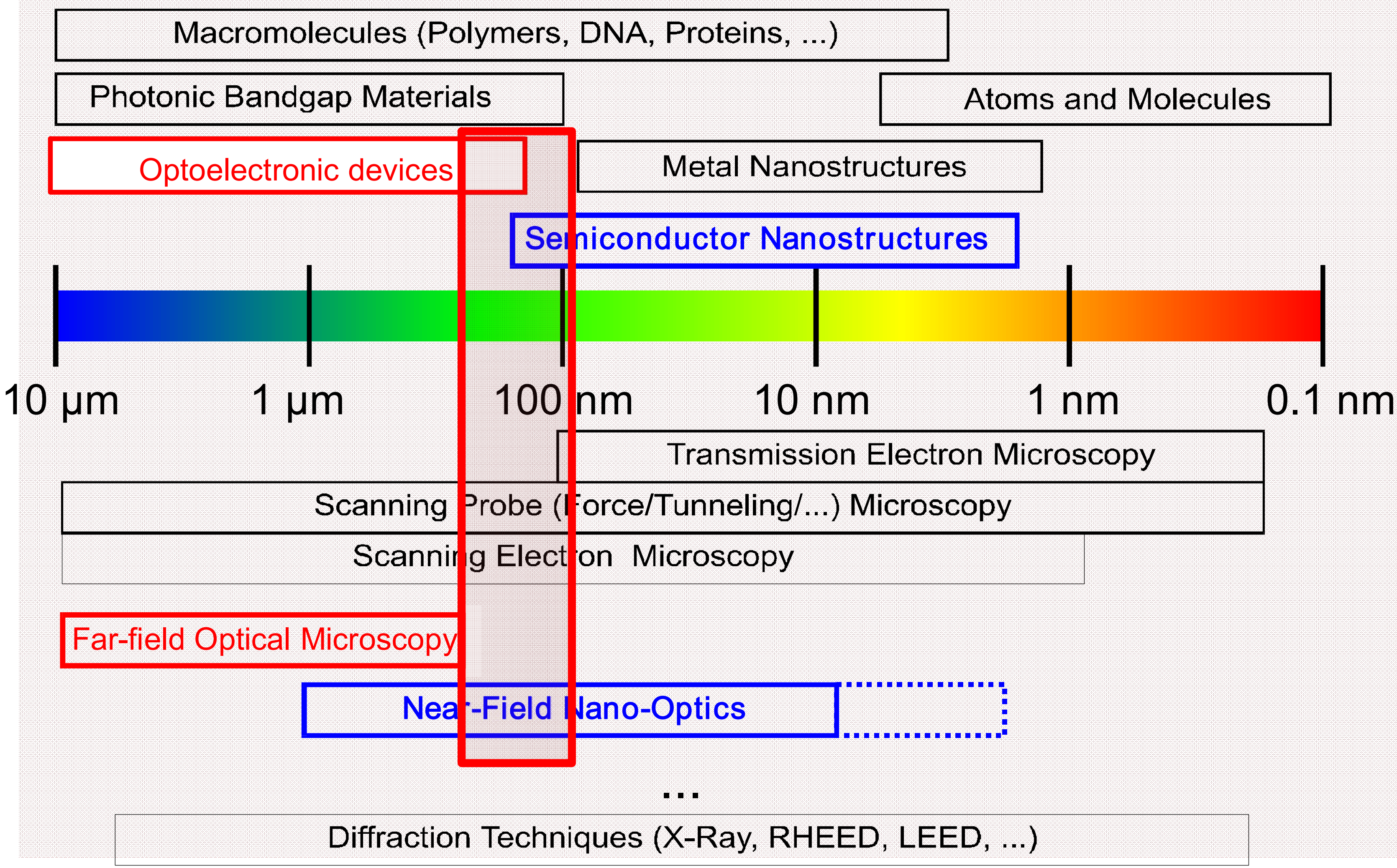
Outline

1. Introduction
   NSOM = Nearfield Scanning Optical Microscopy
   Principles and opportunities
   Spatial resolution
2. Methodology
   Laser emission, spontaneous emission and PL
3. NOBIC = Nearfield Optical Beam Induced Current
4. Experimental setups and equipment
5. Analysis of waveguides and determination of mode profiles
6. VCSEL
7. Surface recombination velocity at facets
8. Defect creation during device operation
9. Summary
10. Acknowledgement

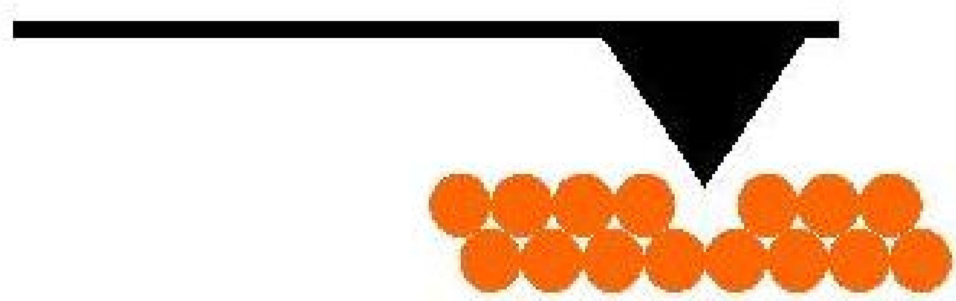
Introduction

Nanostructures and Nanoanalytical Tools



Introduction

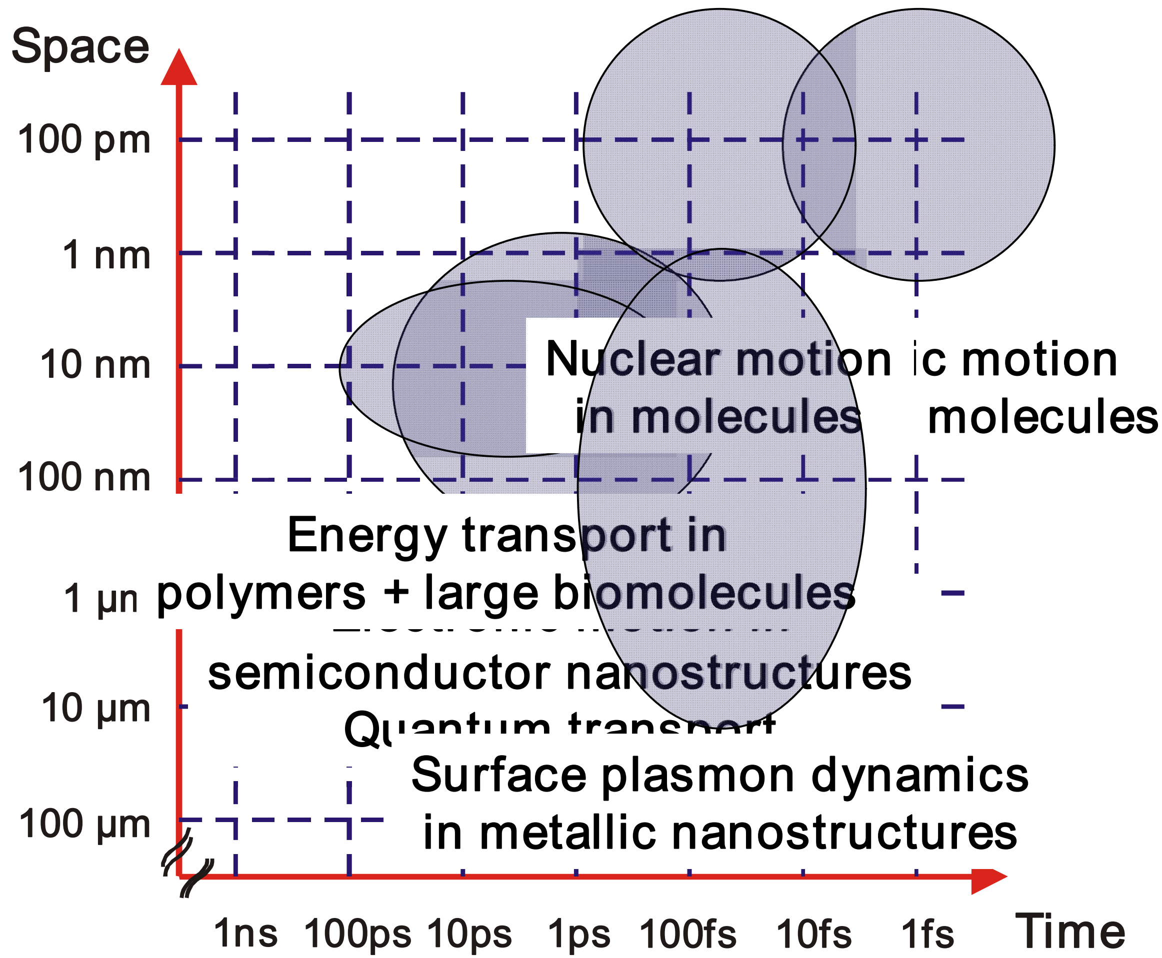
Scanning probe microscopy



Compare: If 1 atom had the size of an orange, the cantilever would be 100 km long

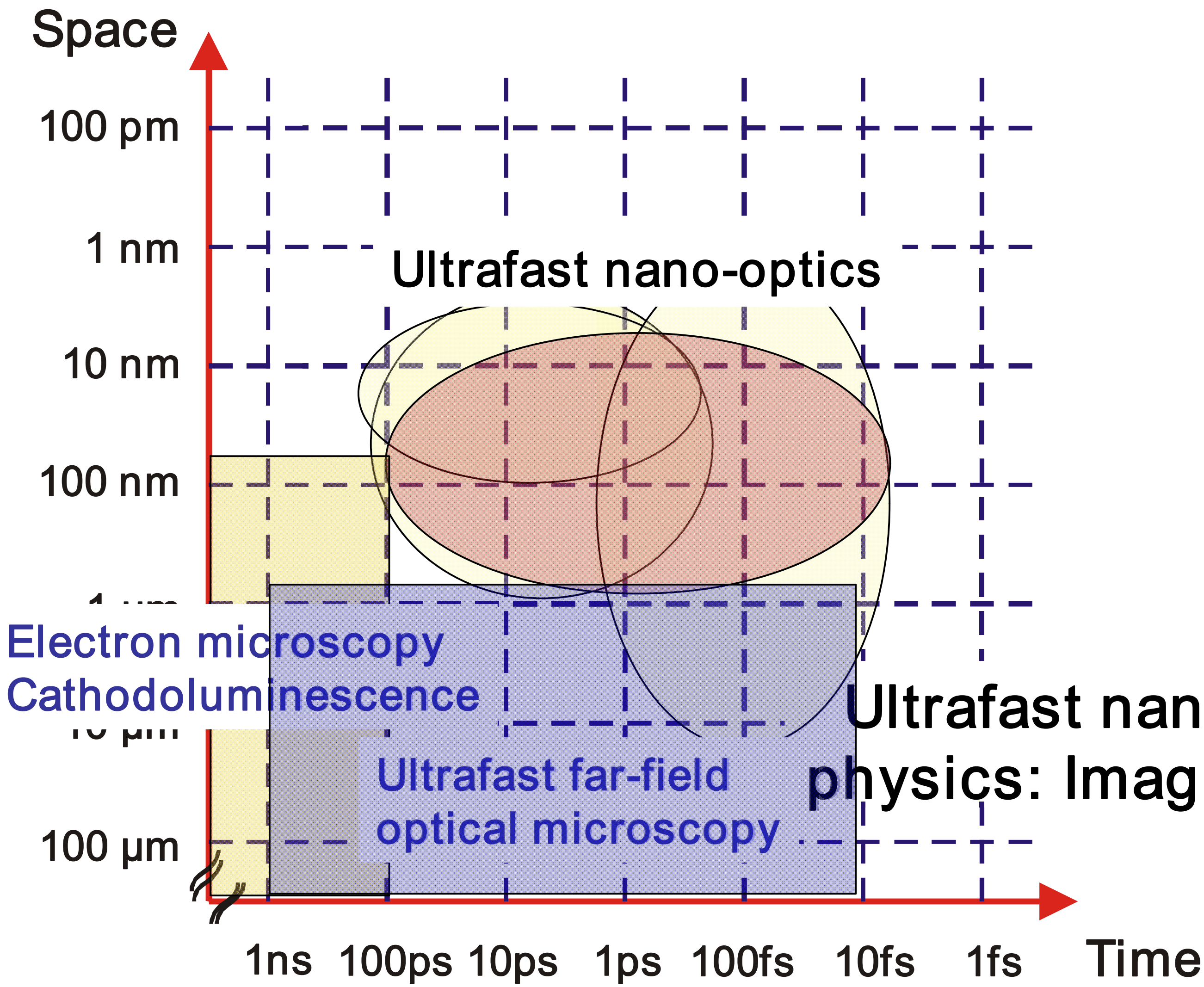
Disc players for atoms

Introduction



Physical phenomena happen on ultrashort length and time scales

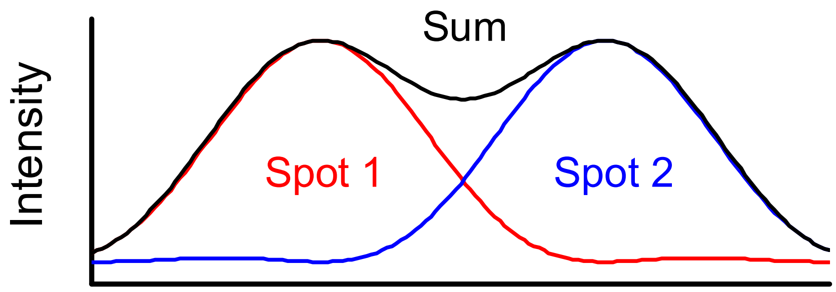
Introduction

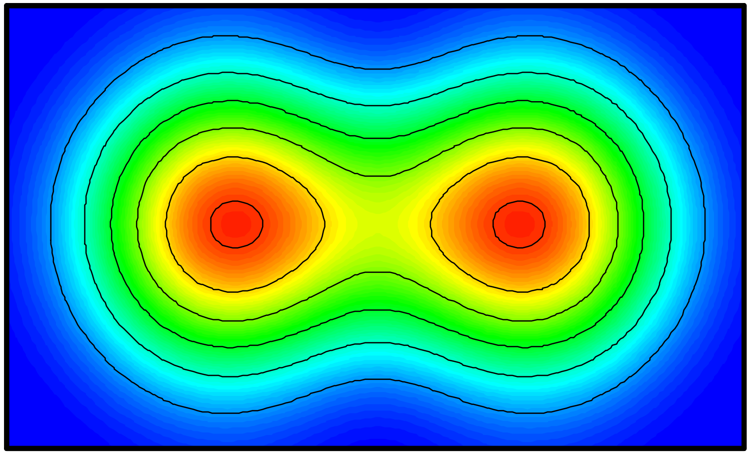


Ultrafast nano-scale physics: Imaging tools

Introduction

Rayleigh limit: $\Delta x \approx 0.61 \lambda / N.A.$

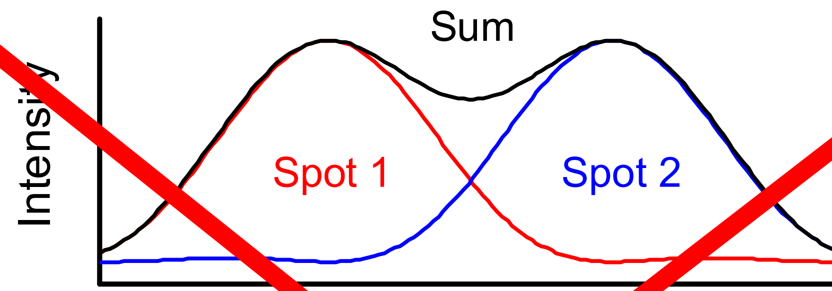


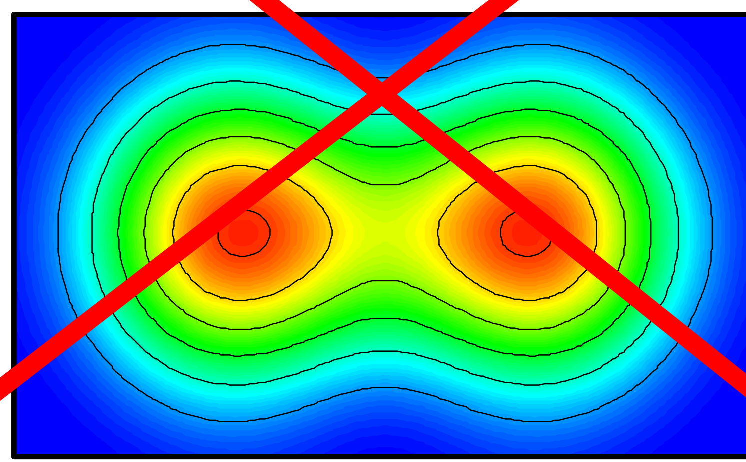


The resolution in optical microscopy is limited by the wavelength of light

Introduction

Rayleigh limit: $\Delta x \approx 0.61 \lambda / N.A.$

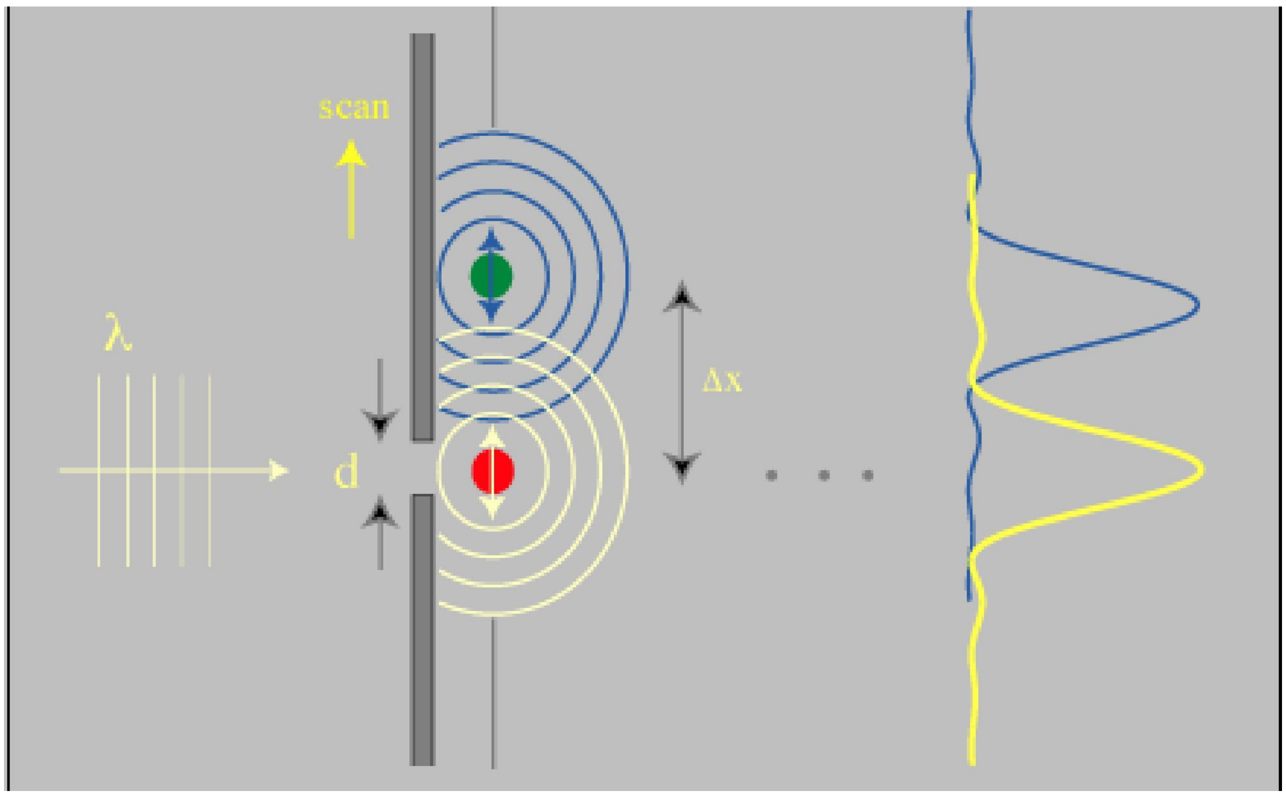




The resolution in optical microscopy is limited by the wavelength of light

Breaking the resolution limit in microscopy

Near-field scanning optical microscopy



Diffraction-unlimited resolution

Introduction

Spatial resolution in near-field microscopy

Electromagnetic-field distribution: superposition of monochromatic plane waves:

$$E = E_0 \exp(i\vec{k}_0\vec{r})\exp(-i\omega t) \quad = E_0 \exp(i(k_x x + k_y y)\exp(ik_z z)\exp(-i\omega t)$$

$$k_0 = \left|\vec{k}_0\right| = \sqrt{k_x{}^2 + k_y{}^2 + k_z{}^2}$$

for given k_x, k_y: two solutions:

(a) propagating waves: $k_{lat} = \sqrt{k_x{}^2 + k_y{}^2} < k_0$ $\quad k_z$ *real.*

(b) evanescent waves: $k_{lat} = \sqrt{k_x{}^2 + k_y{}^2} > k_0$ $\quad k_z$ *imaginary.*

Consequence: Intensity of evanescent waves decreases exponentially with increasing z

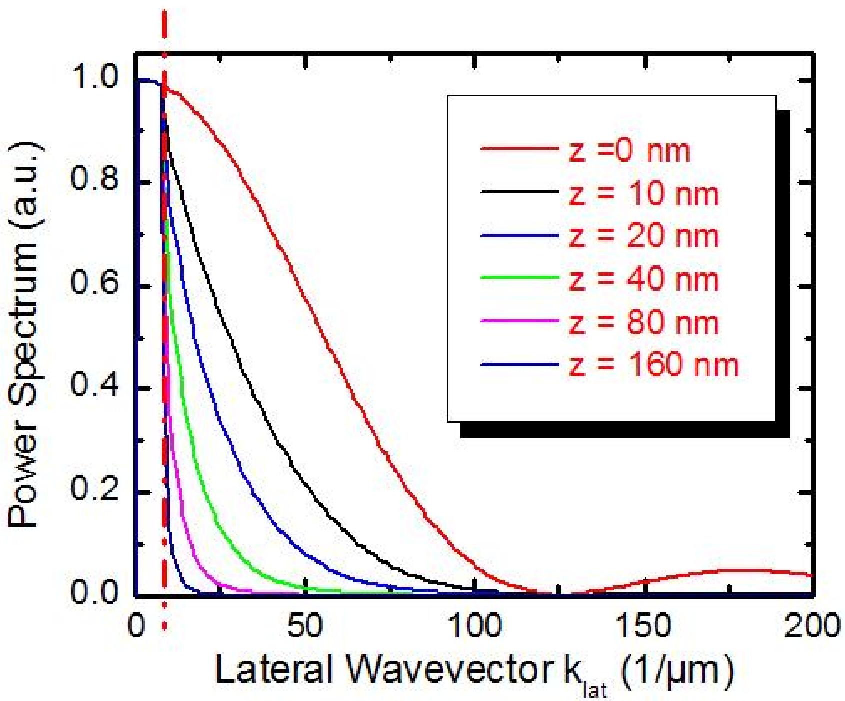
How to get optical super-resolution ?: $\Delta k_x \Delta x \geq 1$

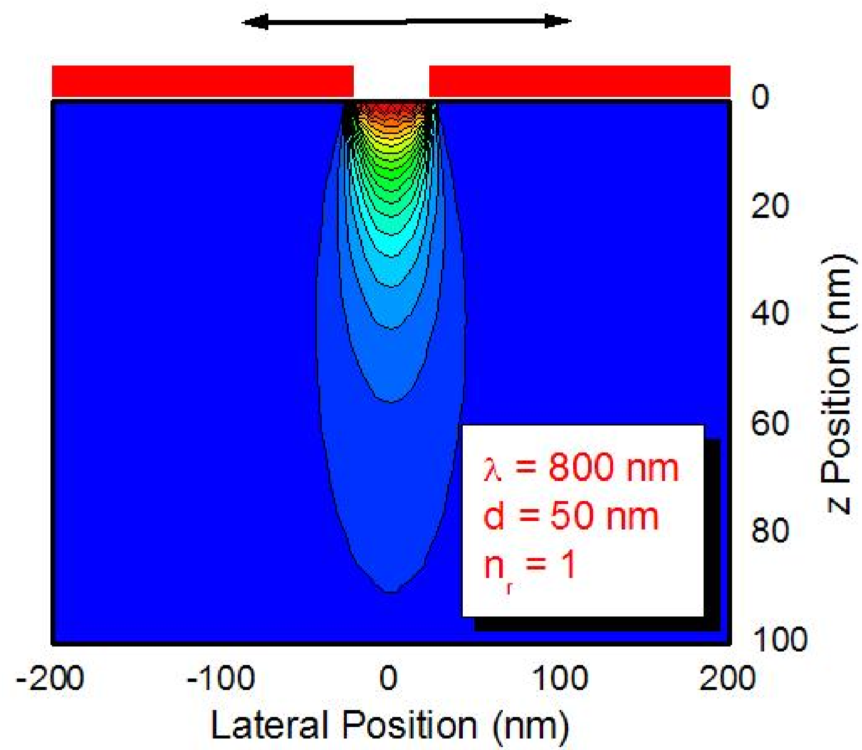
Use evanescent modes!

Introduction

Diffraction by 1-dimensinal slit (Kirchhoff Approximation)

Monochromatic plane wave ($k_0 = 2\pi n_r/\lambda$ - λ = 800 nm) incident on slit (width d = 50 nm)



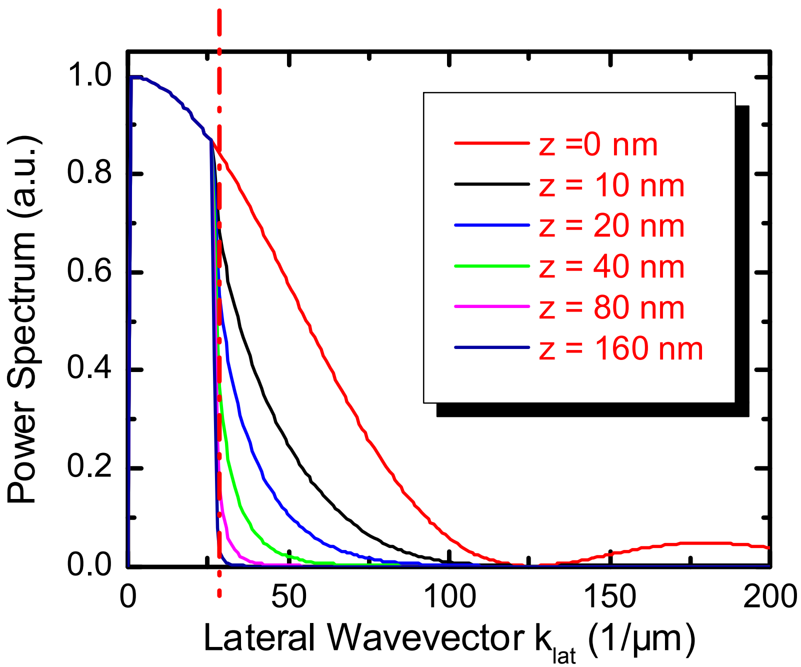


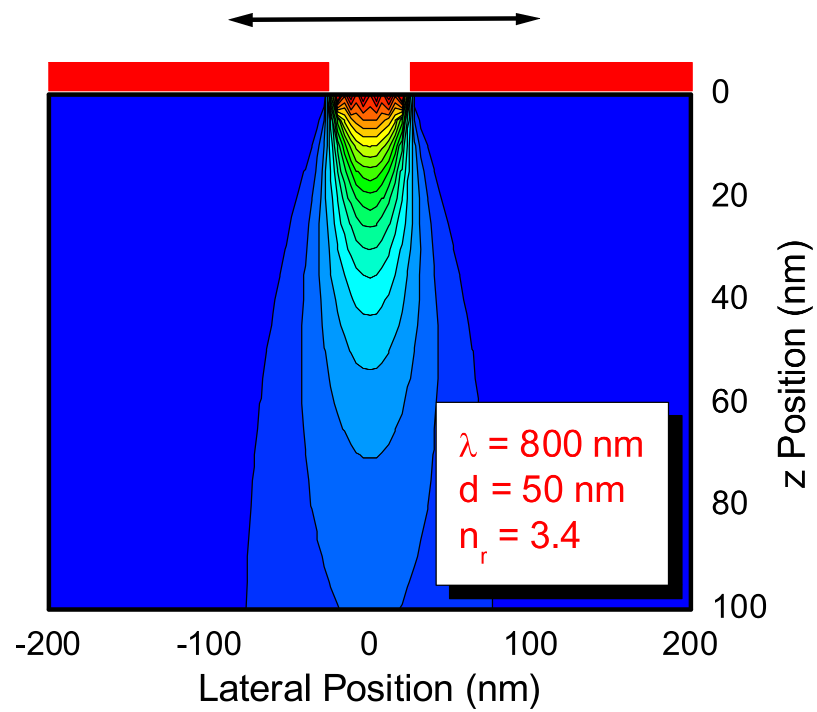
Evanescent waves: $k_{lat} > k_0 = 2\pi n_r/\lambda$ - $k_z^2 = (k_0^2 - k_{lat}^2) < 0$ - k_z imaginary

Propagating waves: $k_{lat} < k_0 = 2\pi n_r/\lambda$ - $k_z^2 = (k_0^2 - k_{lat}^2) > 0$ - k_z real

Diffraction by 1-dimensinal slit (Kirchhoff Approximation)

Monochromatic plane wave ($k_0 = 2\pi n_r/\lambda$ - λ = 800 nm) incident on slit (width d = 50 nm)



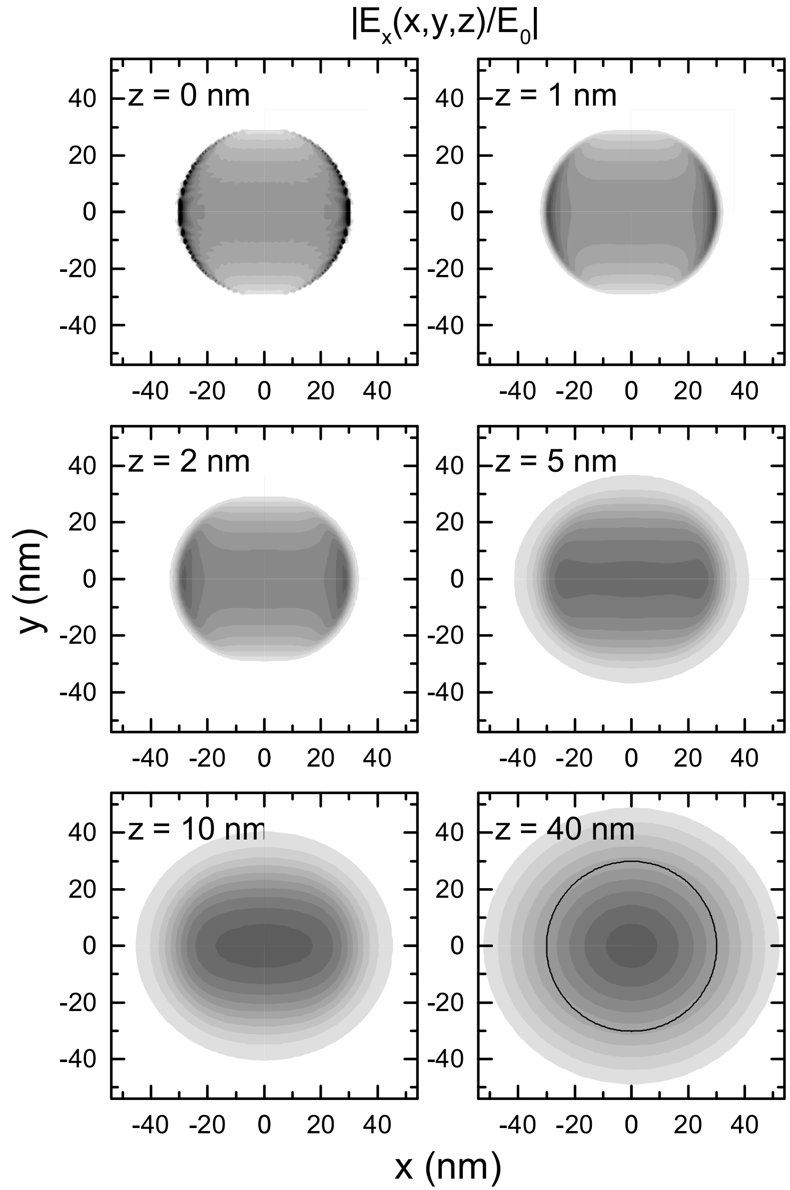


Evanescent waves: $k_{lat} > k_0 = 2\pi n_r/\lambda$ - $k_z^2 = (k_0^2 - k_{lat}^2) < 0$ - k_z imaginary

Propagating waves: $k_{lat} < k_0 = 2\pi n_r/\lambda$ - $k_z^2 = (k_0^2 - k_{lat}^2) > 0$ - k_z real

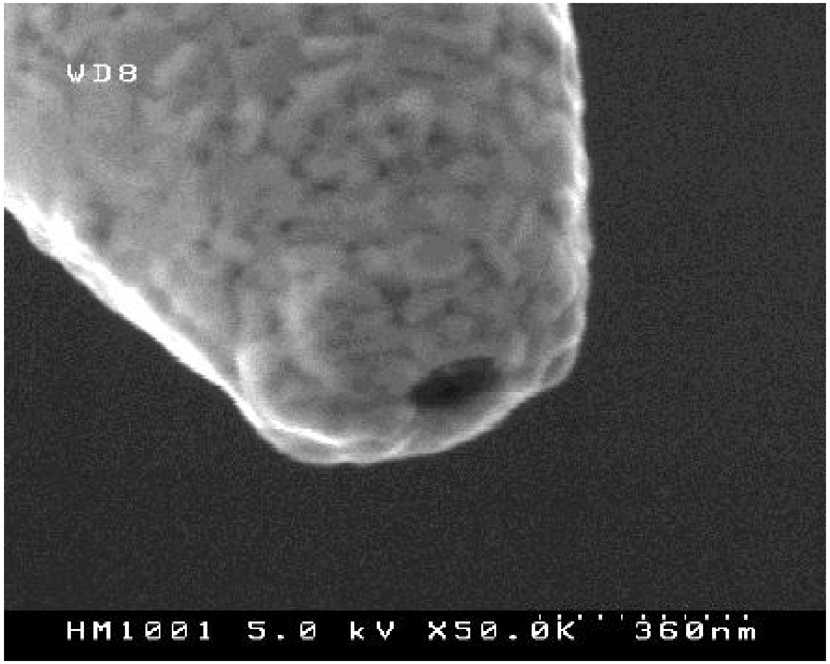
Introduction

Two-dimensional field distribution $E_x(x,y)$ behind a r=30 nm aperture in a perfect metal film



Introduction

Aperture-based near-field microscopy



\+ excellent rejection of propagating waves

\- low transmission efficiency (10^{-4} - 10^{-3} for 100 nm apertures)

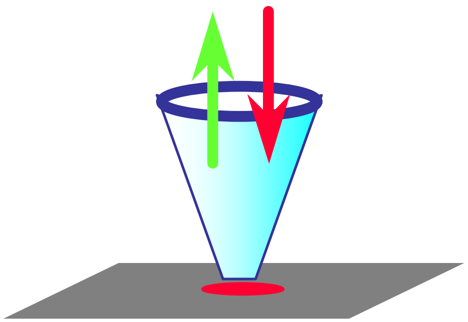
Introduction

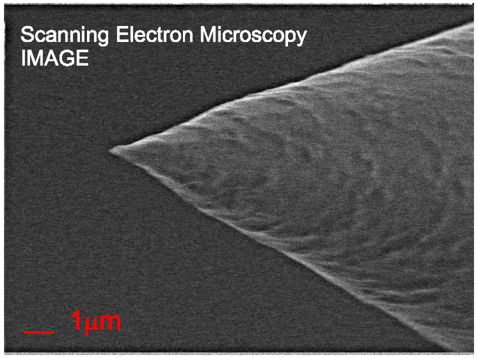
Aperture-based near-field microscopy

Introduction

Near-field Reflectance Spectroscopy with Uncoated Fiber Probes

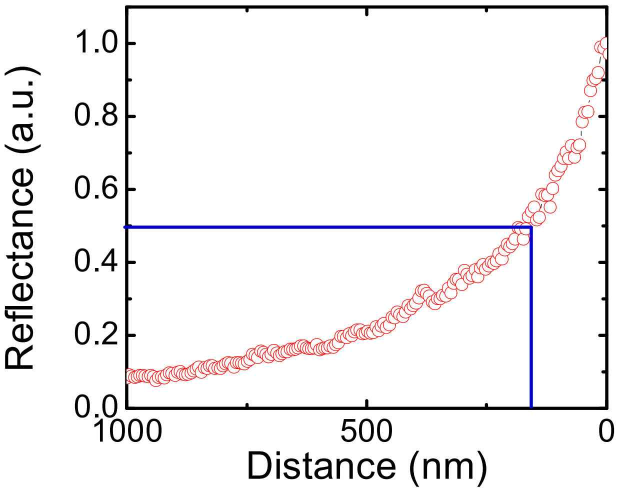
Illumination/Collection Mode





Transmission efficiency close to 1
Extremely high collection efficiency

Sensitive probing of near-field reflectance



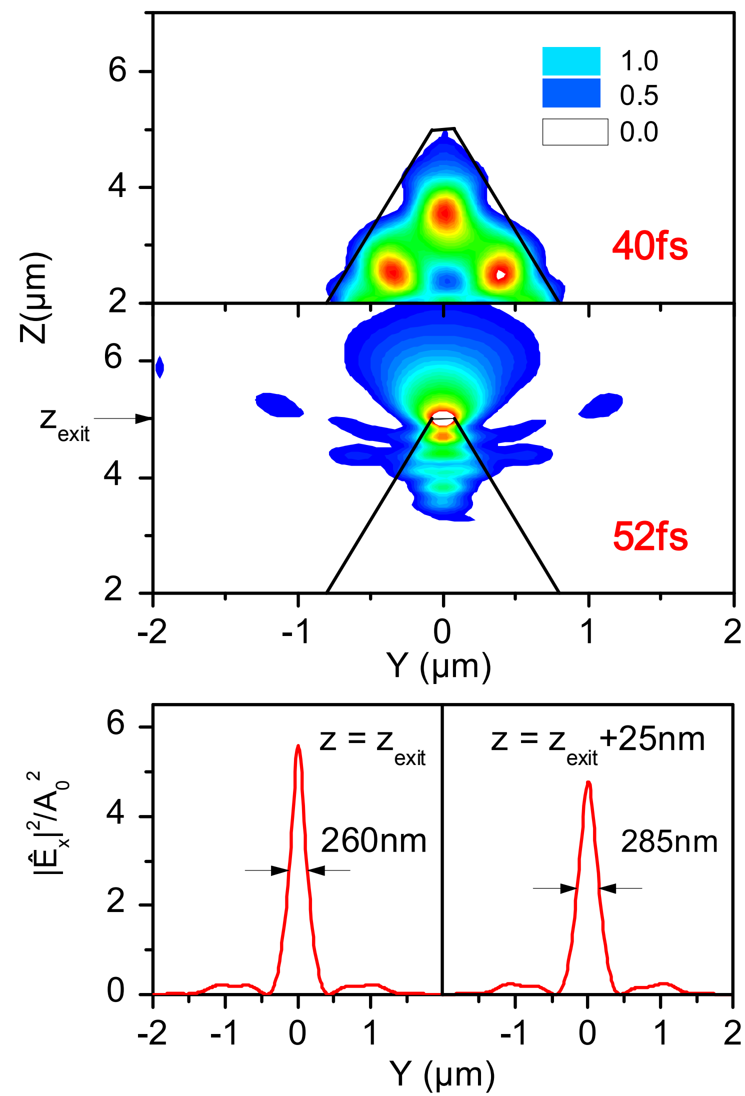
Resolution down to λ/5 (150 nm)

Experiment: F. Intonti et al, PRL **87**, 076801 (2001), PRB **63**, 075313 (2001)
Theory: R. Müller and C. Lienau, Appl. Phys. Lett. **76**, 3367 (2000).

Introduction

Pulse propagation through uncoated fiber probes

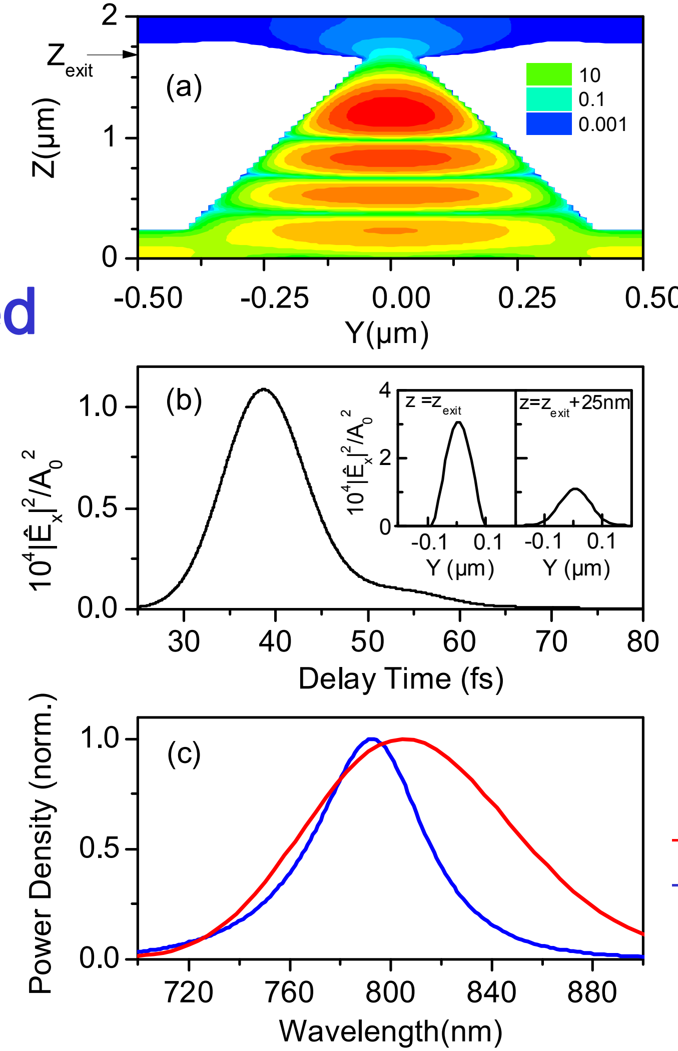
2D modelling
color-code
represents
$|E|^2 A_0^2$



R. Müller Appl. Phys. Lett. 76, 3367 (2000)
and J. Microscopy 202, 339 (2001).

Introduction

Pulse propagation through metal-coated fiber probes



2D modelling
color-code represents
$|E|^2 A_0^2$

$|E|^2 A_0^2$ of a
10 fs Gaussian pulse
at the 100 nm aperture

input pulse
output pulse

R. Müller and C. Lienau
Appl. Phys. Lett. 76, 3367 (2000)
J. Microscopy 202, 339 (2001).

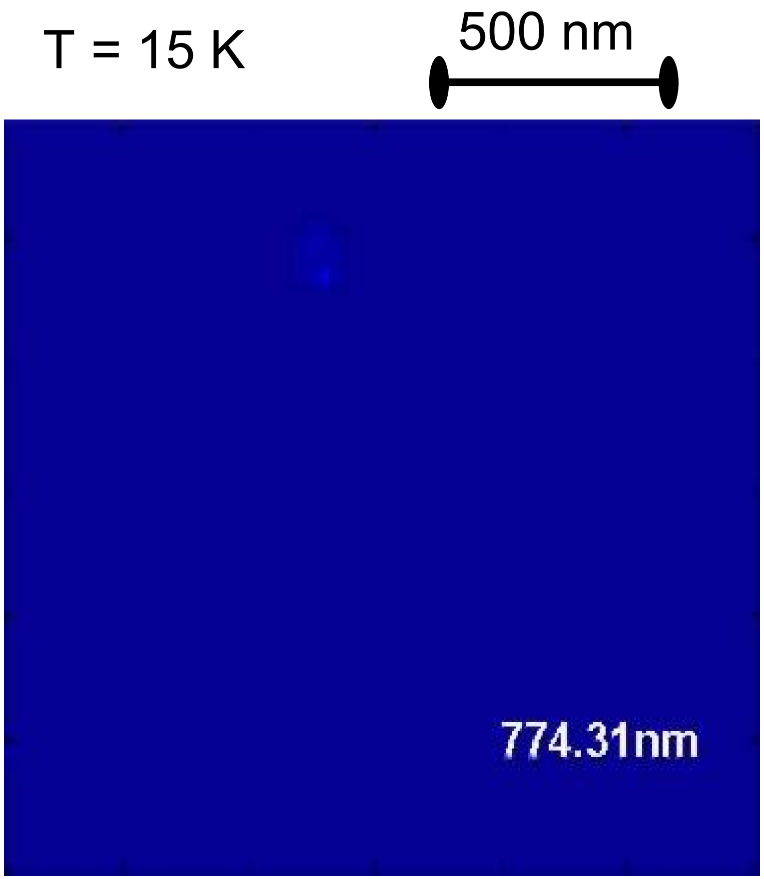
Introduction

Application: Raman spectroscopy of Carbon Nanotubes

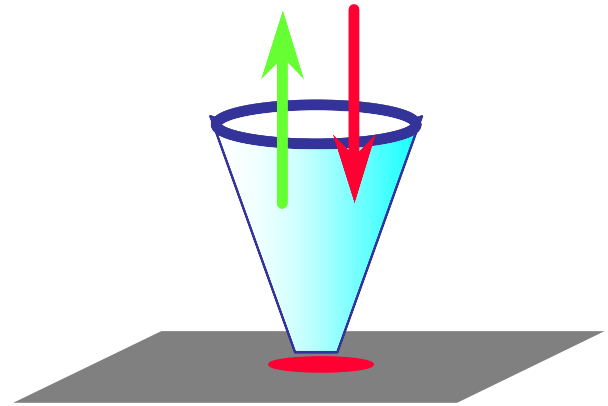
A. Hartschuh et al., Phys. Rev. Lett. (2003)

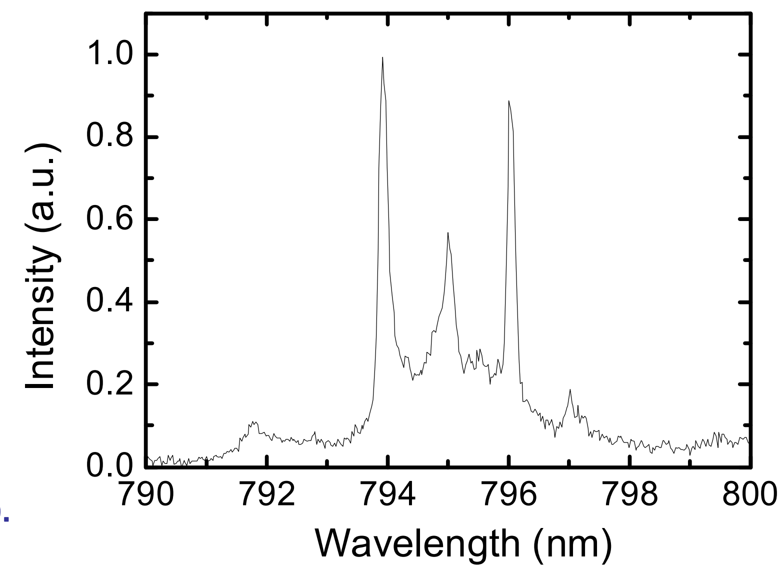
Introduction

Nanophotoluminescence of single localized excitons



F. Intonti et al., Phys. Rev. Lett. 87, 076801 (2001).





Introduction

Apertureless Near-field Scanning Optical Microscopy

+ Strong field enhancement (10 x) at ultrasharp metal tips
+ Spatial resolution limited by radius of curvature of the tip
+ Spatial resolution down to 10 nm (and beyond?)

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3. NOBIC = Nearfield Optical Beam Induced Current
4. Experimental setups and equipment
5. Analysis of waveguides and determination of mode profiles
6. VCSEL
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Analysis of laser emission

RW laser

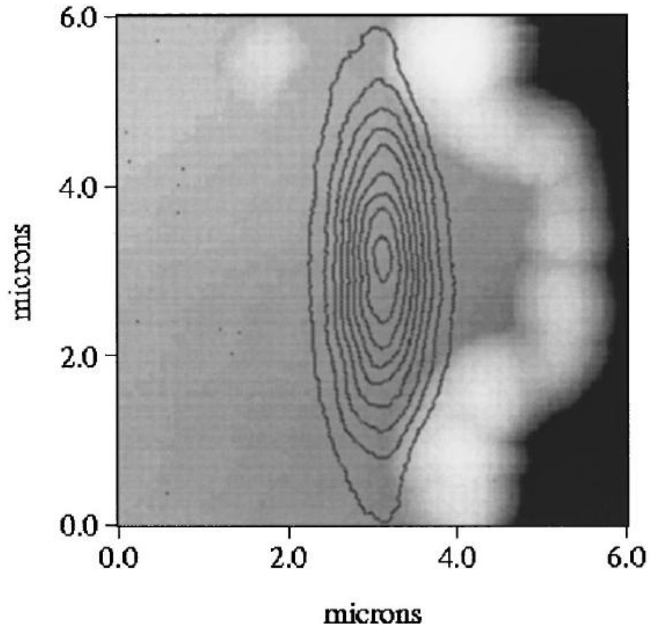


FIG. 1. Near-field collection mode image of the GRINSCH laser diode emission intensity (constant intensity contours) superimposed on the topographical shear-force image (greyscale). The metal contact on top of the mesa slightly protrudes over the facet of the device, yielding the brighter topographic regions.

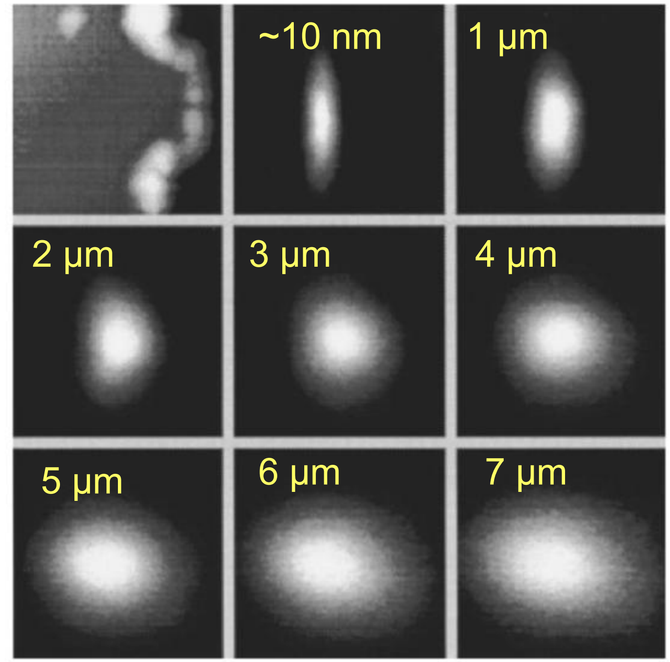
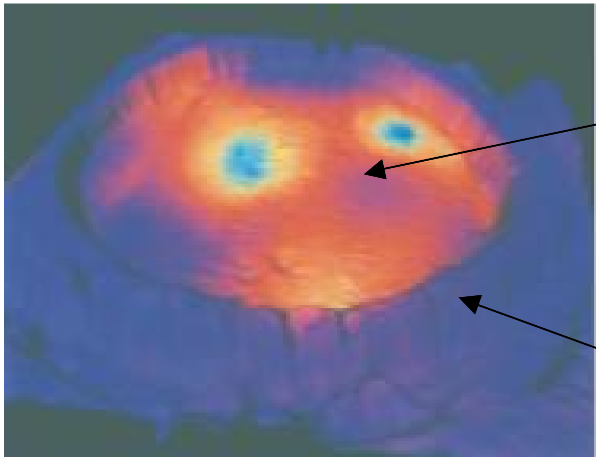


FIG. 3. Images of the beam propagation from the near field to 7 μm from the laser diode taken in 1 μm steps. The top left image is the topography to provide the physical orientation for the laser emission images given in left to right sequence. All images are 6×6 μm. The greyscale for each image is chosen to maximize contrast.

W. D. Herzog, M. S. Ünlü, B. B. Goldberg, G. H. Rhodes, and C. Harder, *Appl. Phys. Lett.* **65** 688 (1997).

Analysis of laser emission

VCSEL

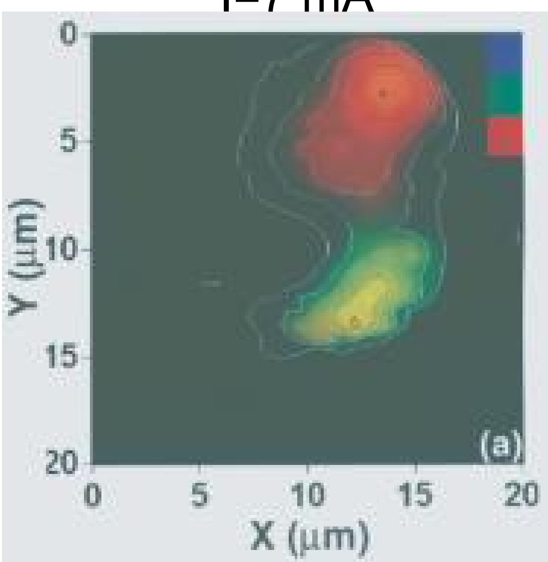


Emission intensity (color)

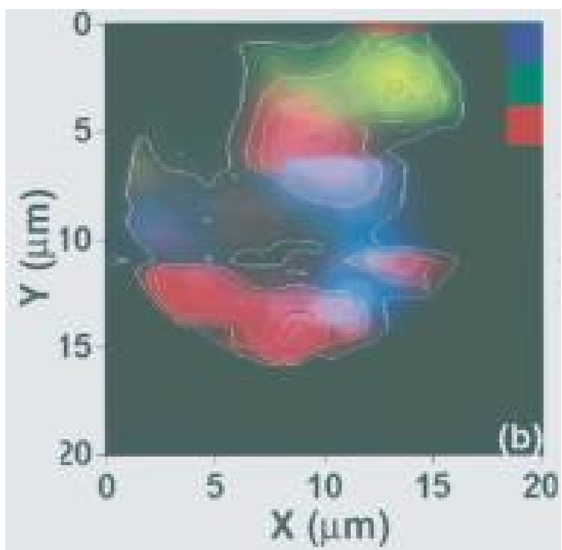
VCSEL aperture (blue)

Van der Rhodes et al.
Appl. Phys. Lett. **72**,1811 (1998)

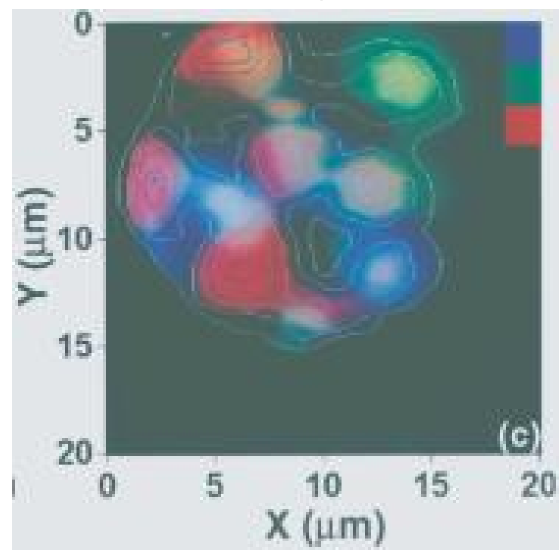
I=7 mA



I=10 mA



I=15 mA



Analysis of laser emission

Such work at devices is extremely useful,

1. if confocal microscopy fails

if not, you waste your resources

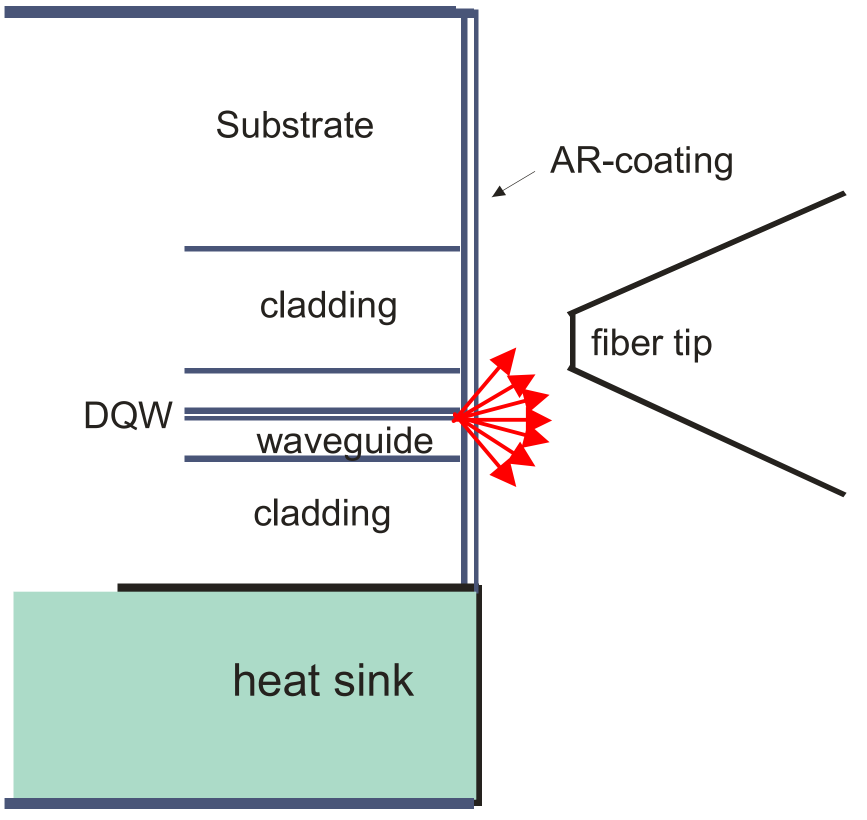
2. if the fiber tip does not influence the emission

unfortunately, this is the case when investigating lasing devices

These statements hold in general for the application of NSOM !

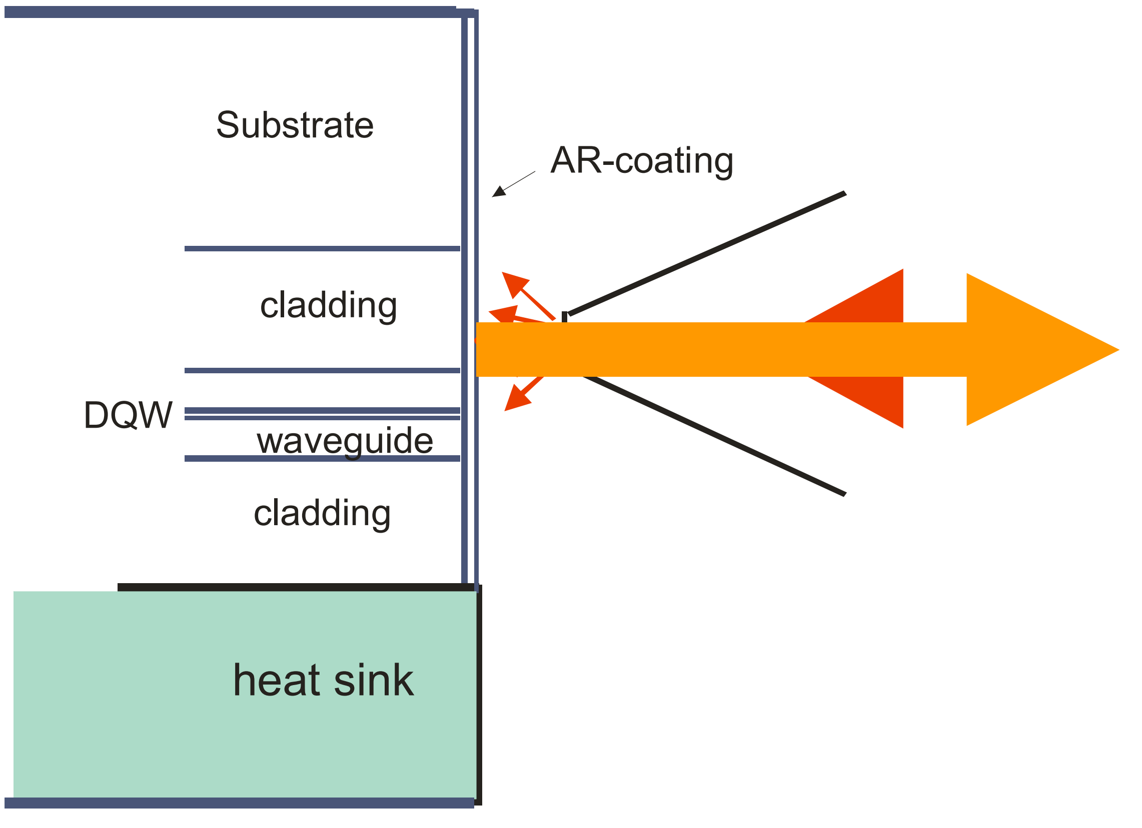
What is better?

- Spontaneous emission



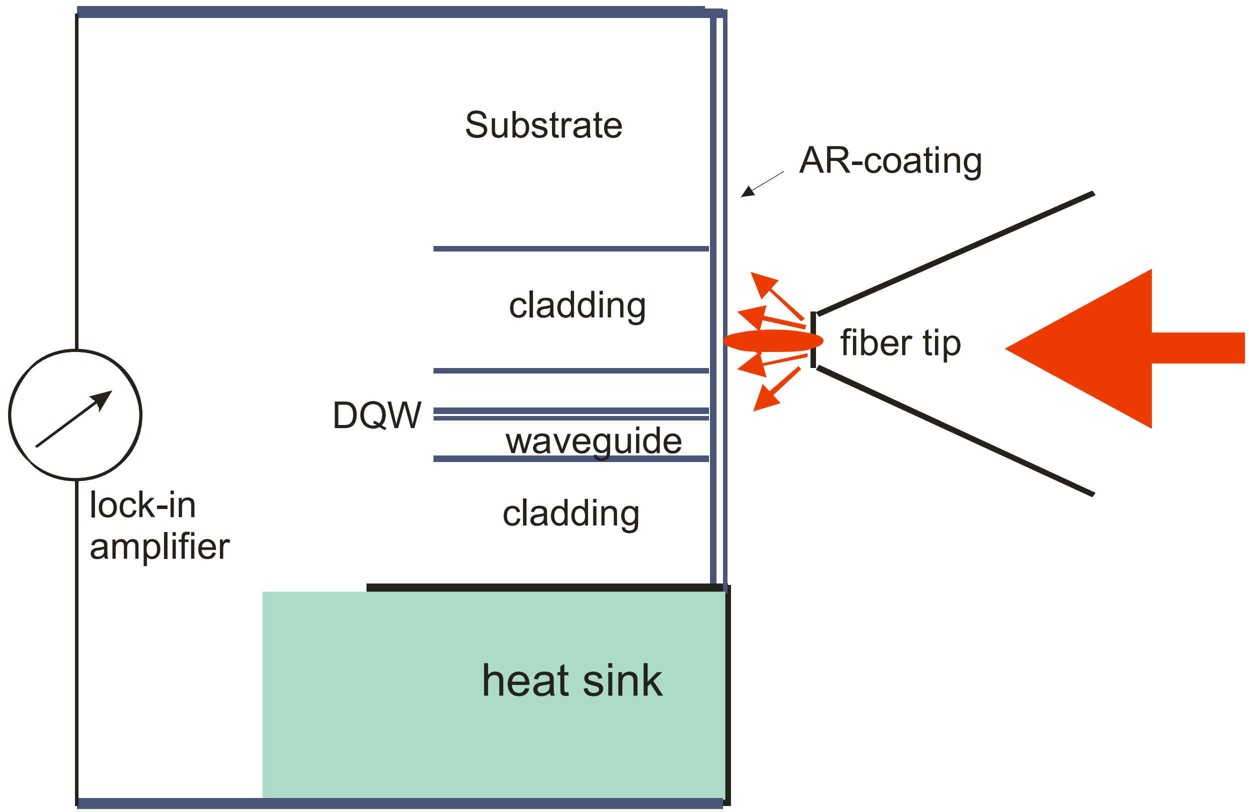
What is better?

- Spontaneous emission
- Photoluminescence



What is better?

- Spontaneous emission
- Photoluminescence
- Absorption (Photocurrent) NOBIC

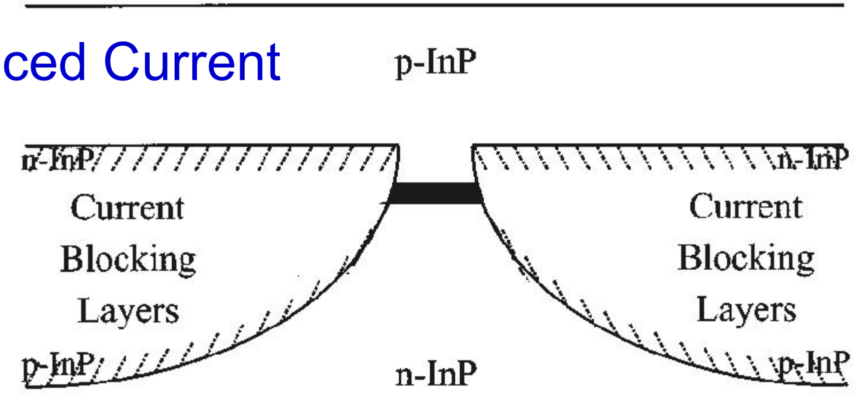


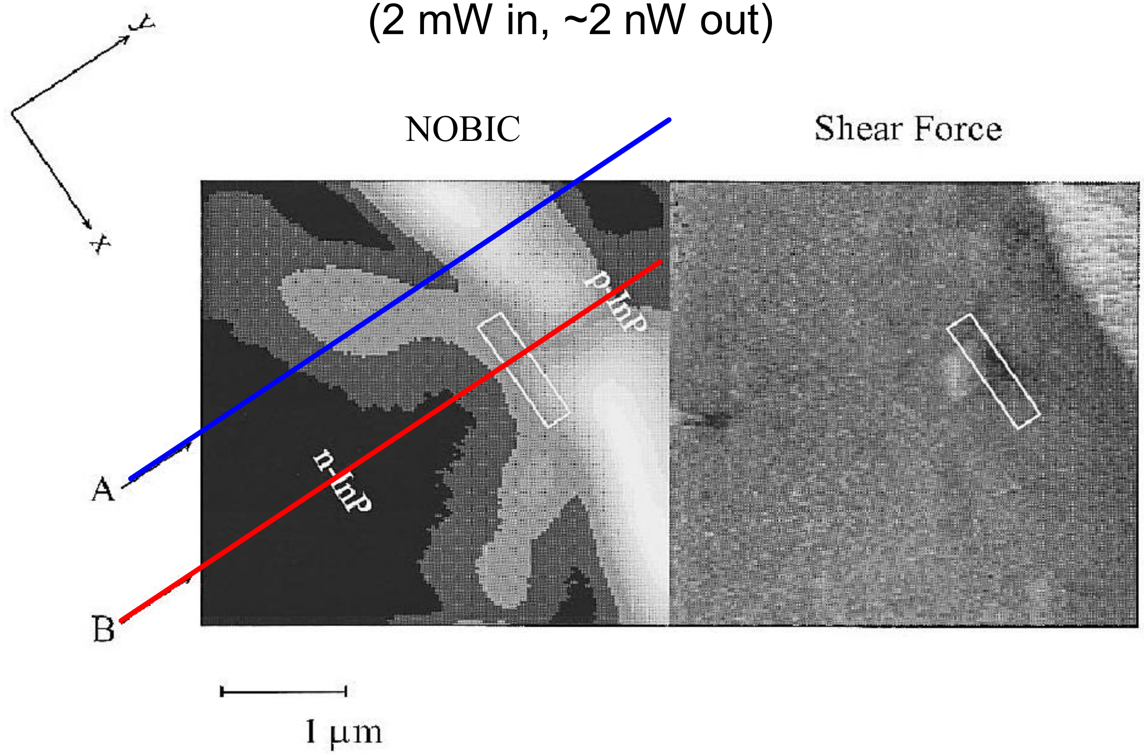
NOBIC

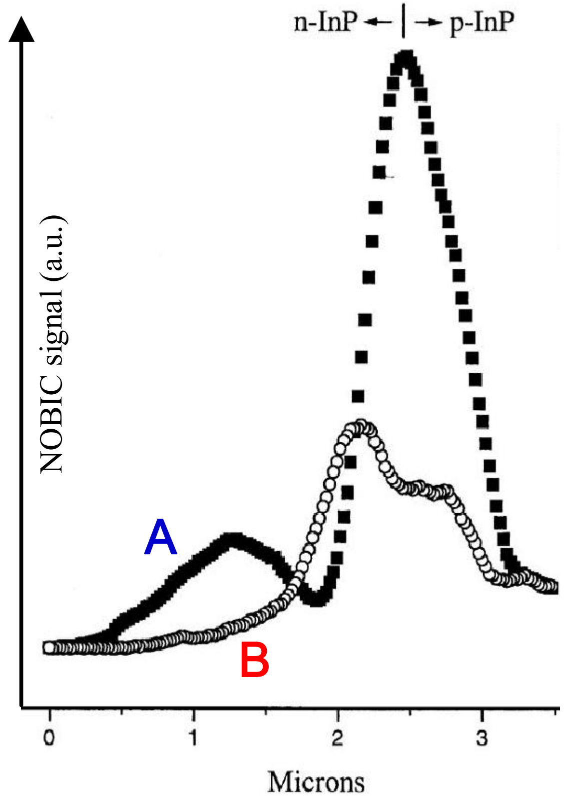
NOBIC = Nearfield Optical Beam Induced Current

Buratto et al. (AT&T Bell Lab.)
Appl. Phys. Lett. 65, 2654 (1994)

Excitation at 633 nm
(2 mW in, ~2 nW out)







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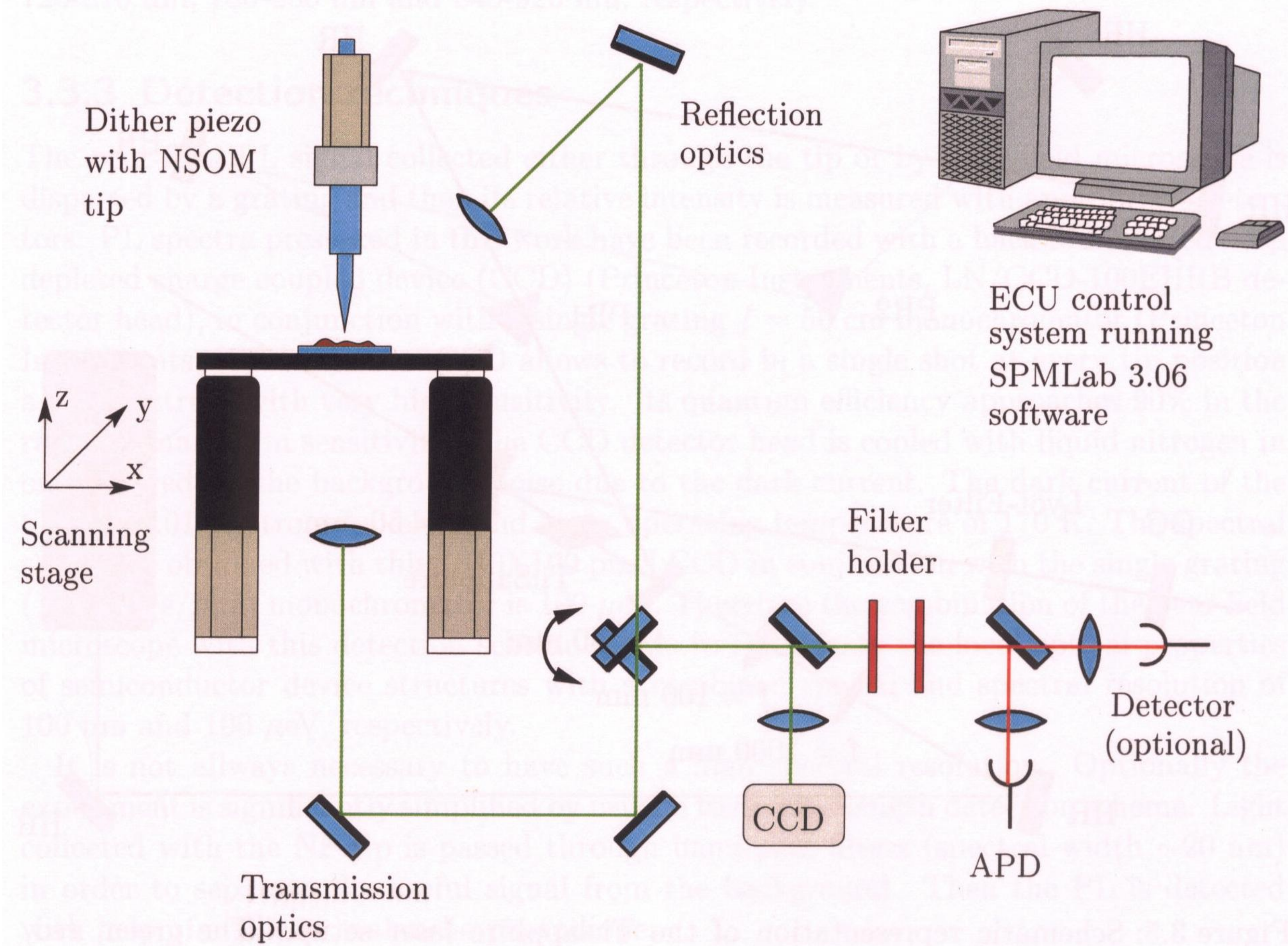
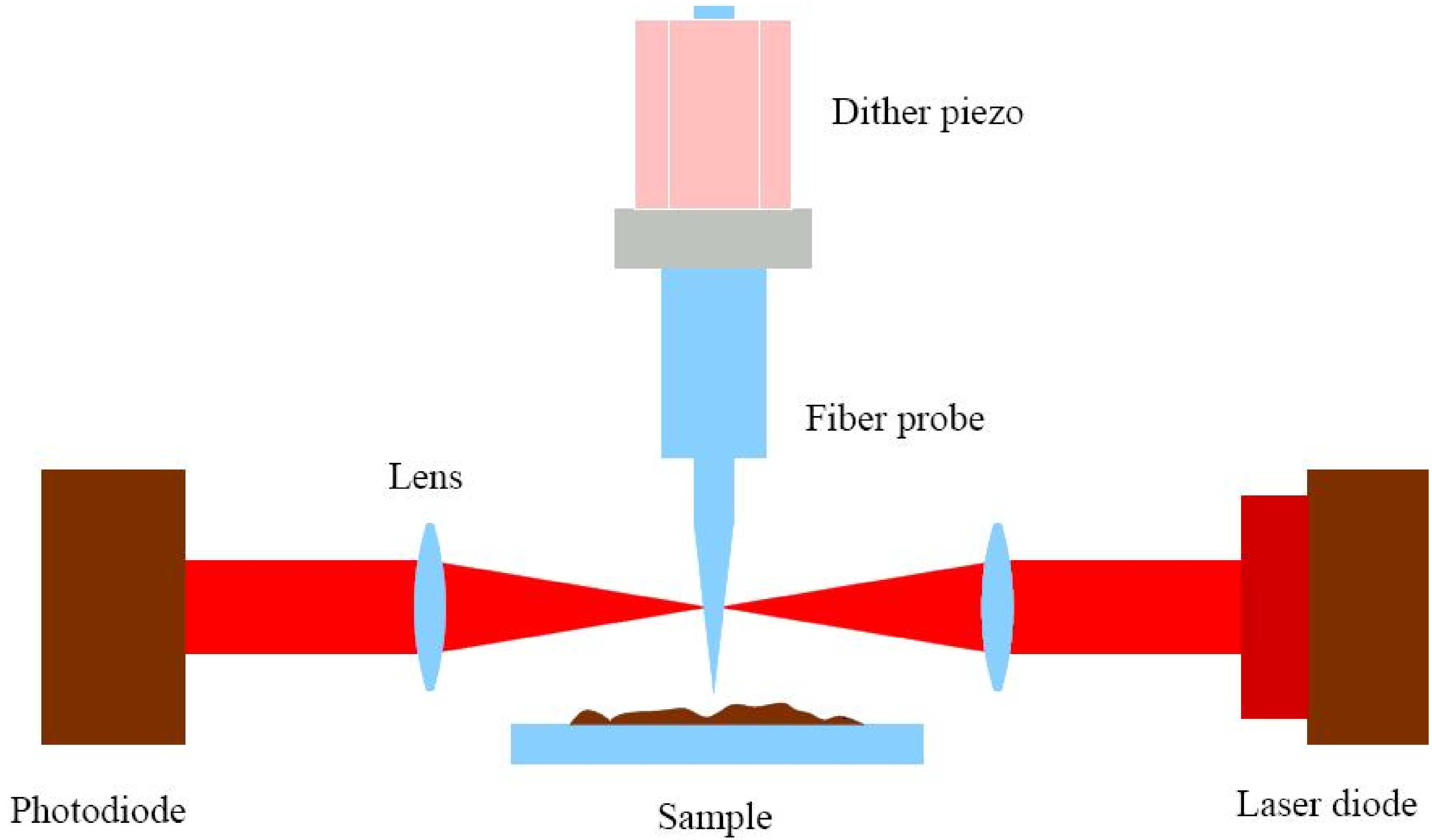
Experimental setups and equipment



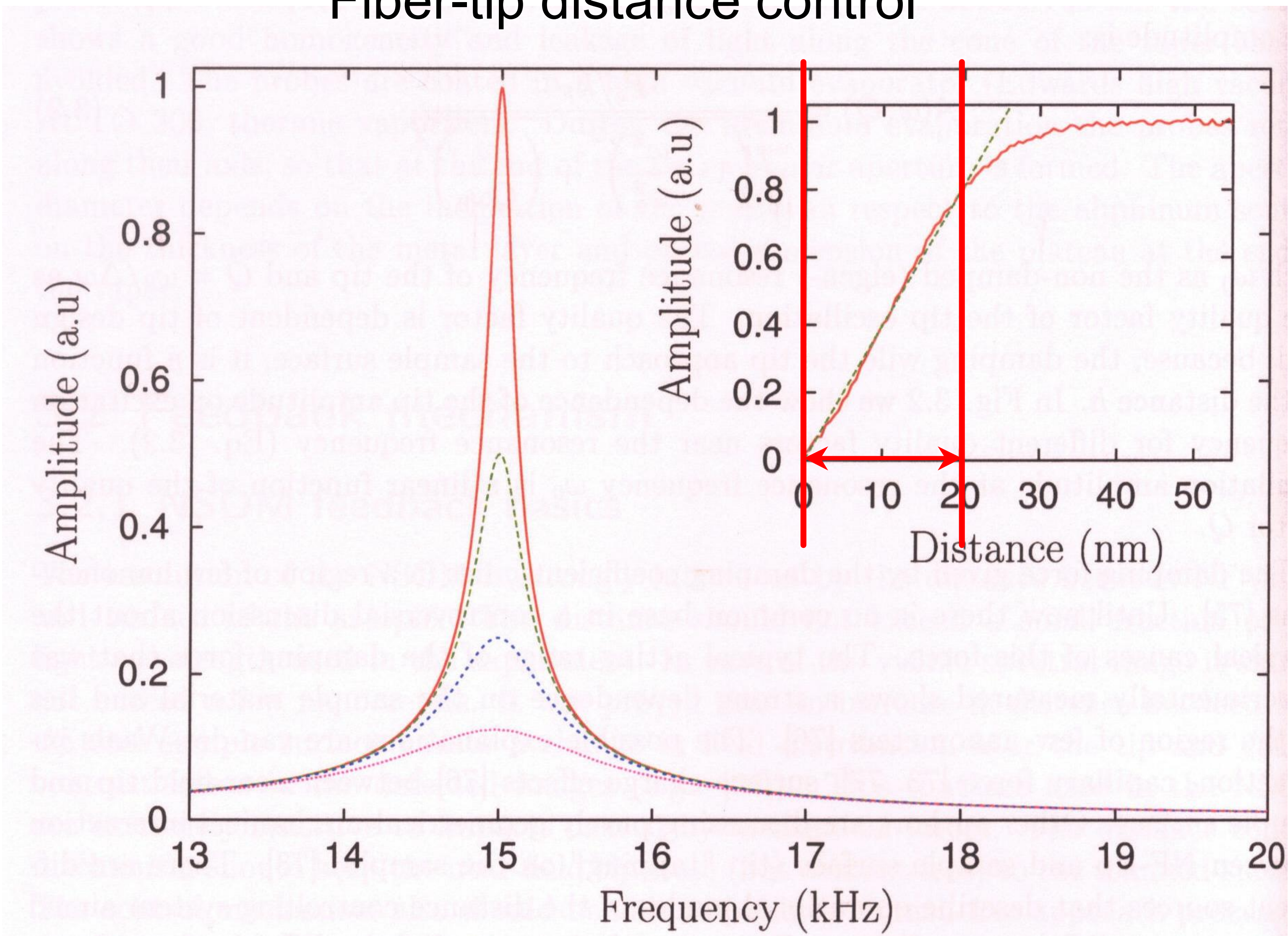
Experimental setups and equipment

Fiber-tip distance control



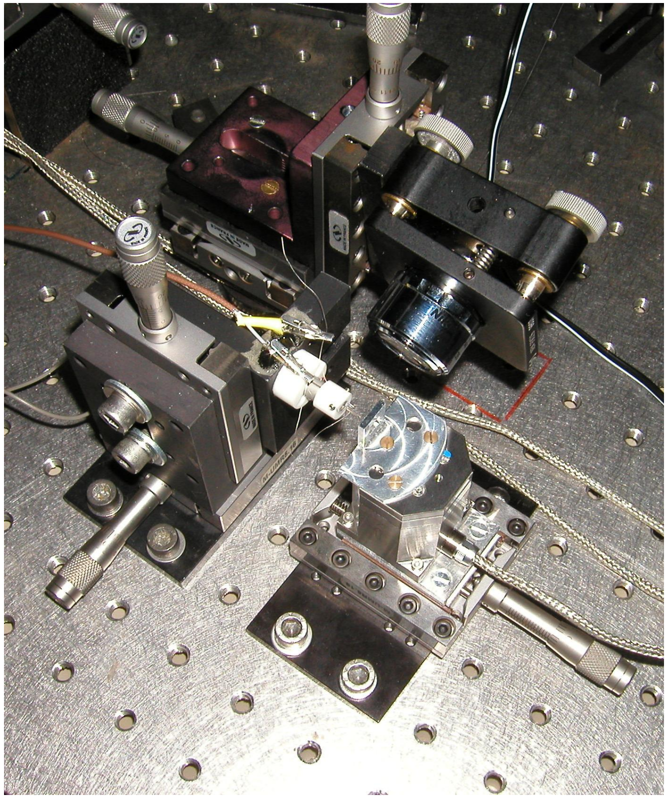
Experimental setups and equipment

Fiber-tip distance control



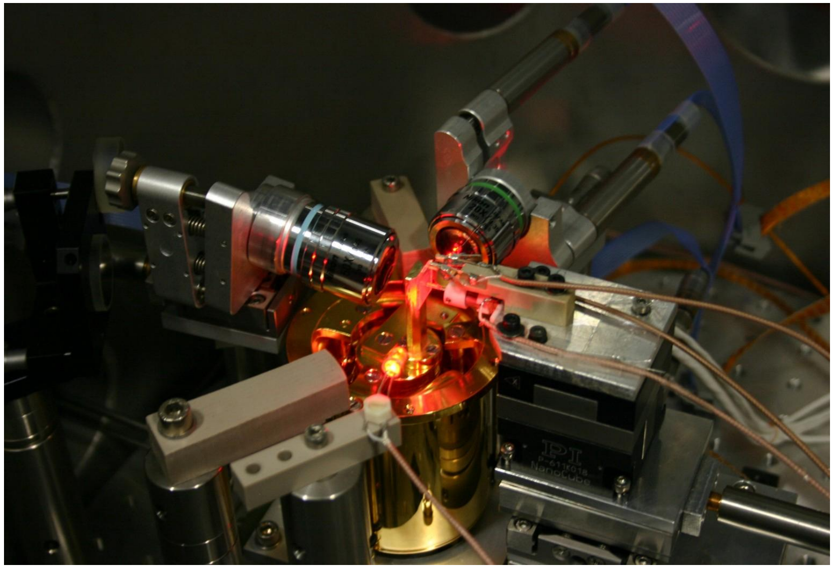
Experimental setups and equipment

Home-built Scanning Near-field Optical Microscopes



G. Behme et al., Rev. Sci. Instrum. **68**, 3458 (1997)

Set-up with cryostat for Measurements at 10 - 300 Kelvin

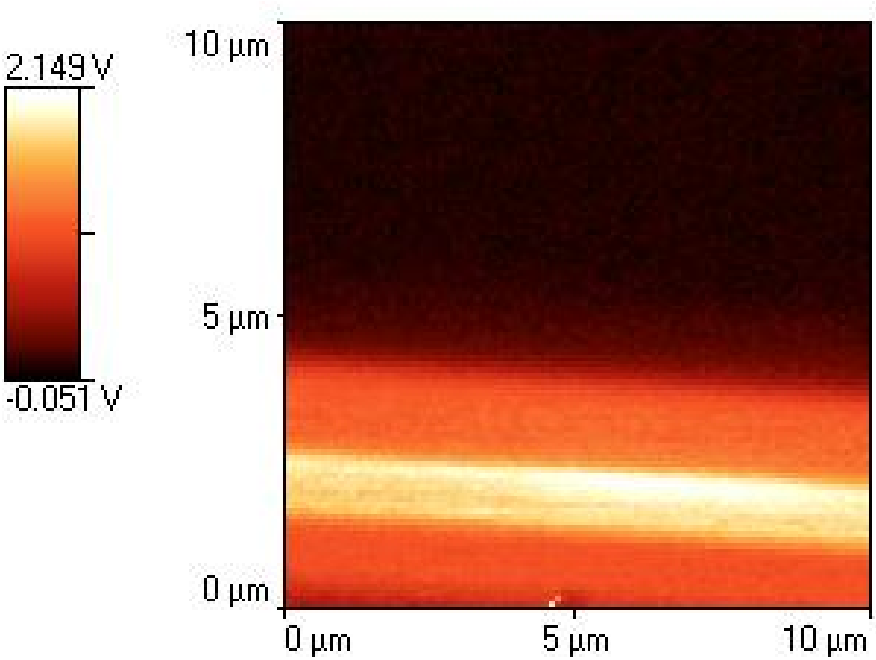


"Customers:"
Uni Magdeburg, D
KTH Stockholm, Sweden
Forschungszentrum Jülich, D
University of Arkansas, USA

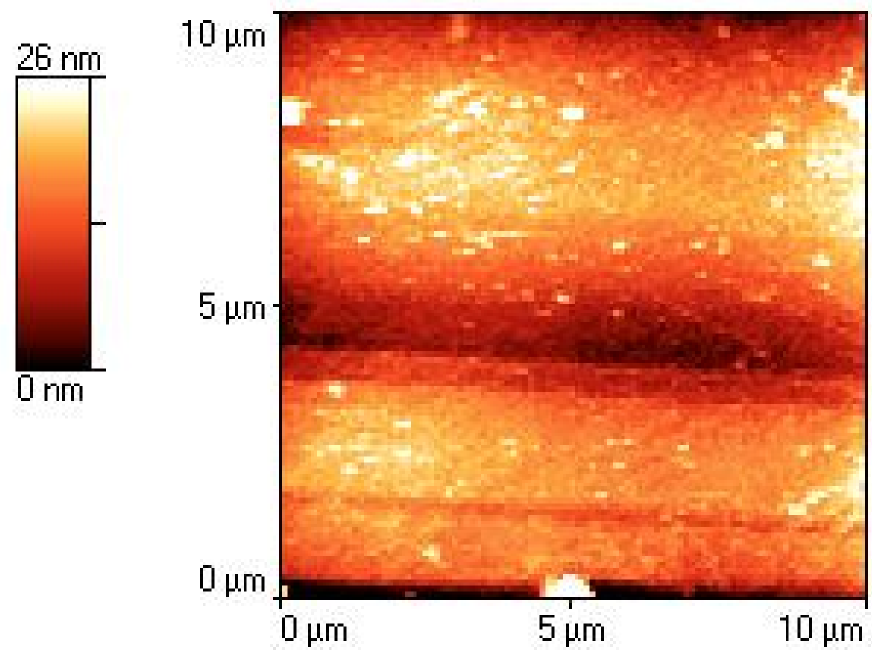
Experimental setups and equipment

NSOM data

PC-signal (R)



topography



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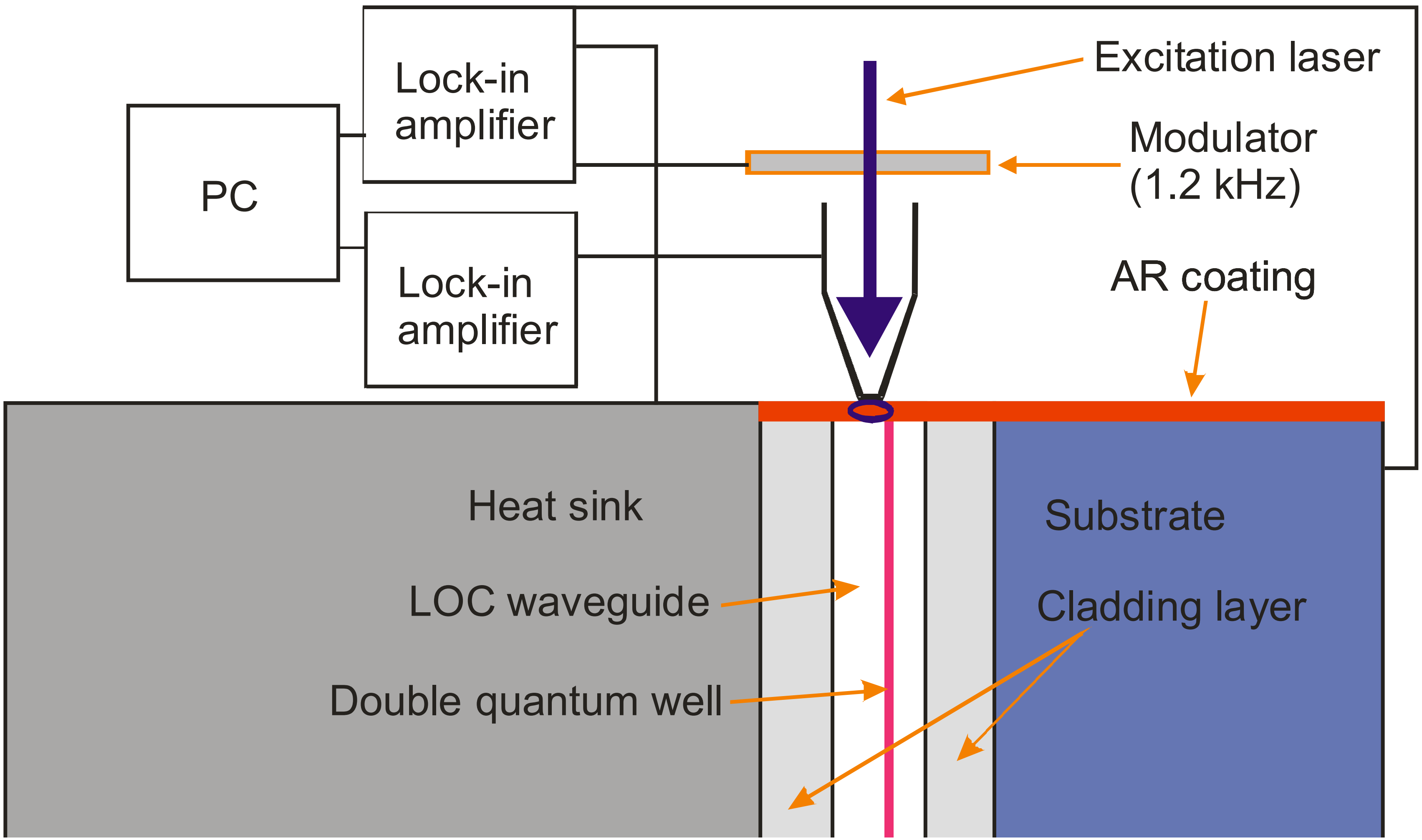
Analysis of waveguides

Setup



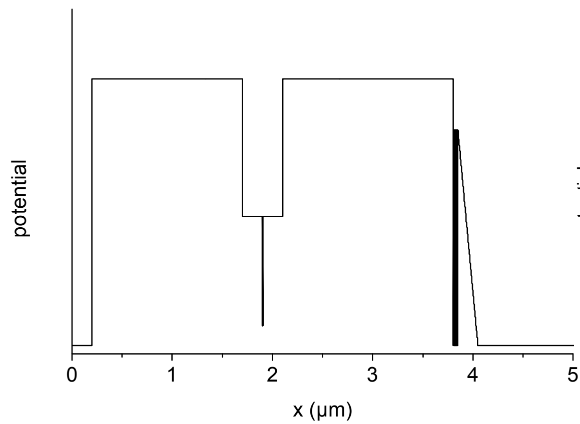
Analysis of waveguides

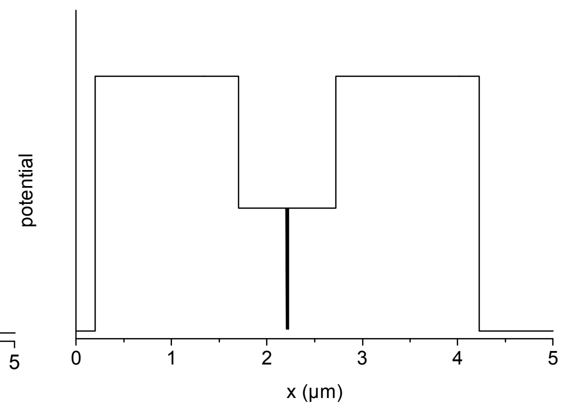
Results obtained at single symmetric and asymmetric waveguides

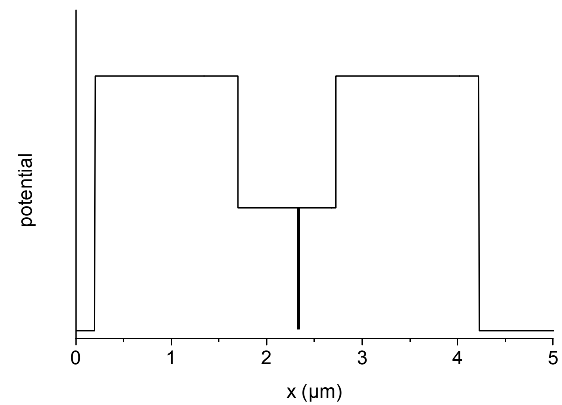
Step INdex
SIN

Large Optical Cavity
LOC symmetric waveguide

Large Optical Cavity
LOC asymmetric waveguide



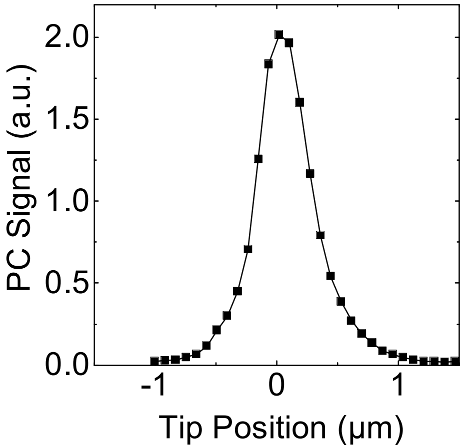


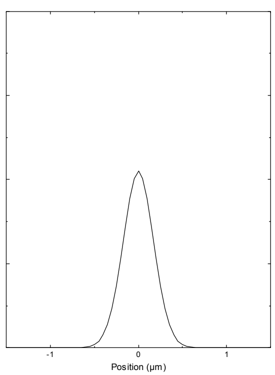


resonant NSOM Photocurrent (Absorption)

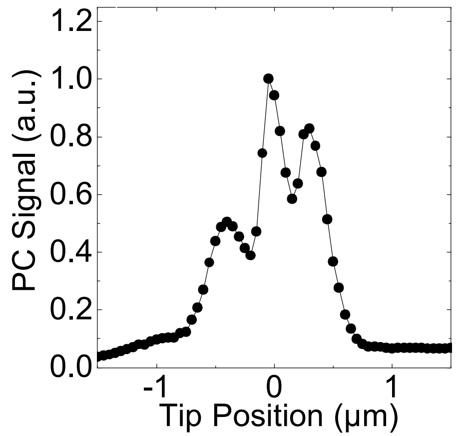
Analysis of waveguides

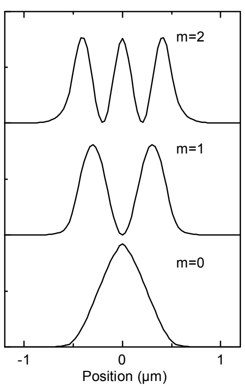
Step INdex
SIN



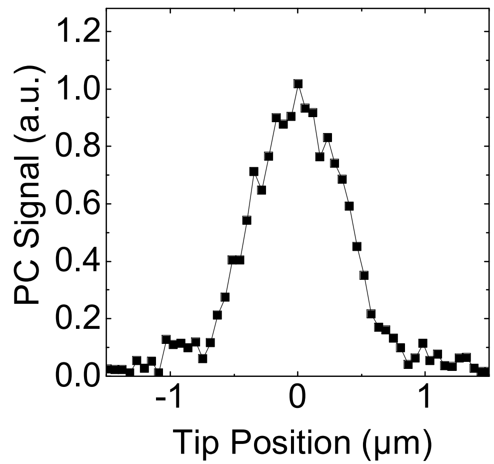


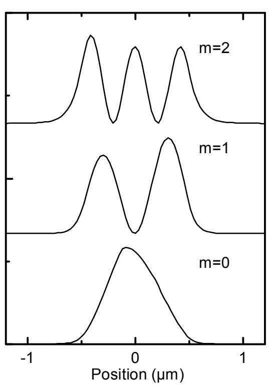
Large Optical Cavity
LOC symmetric waveguide





Large Optical Cavity
LOC asymmetric waveguide





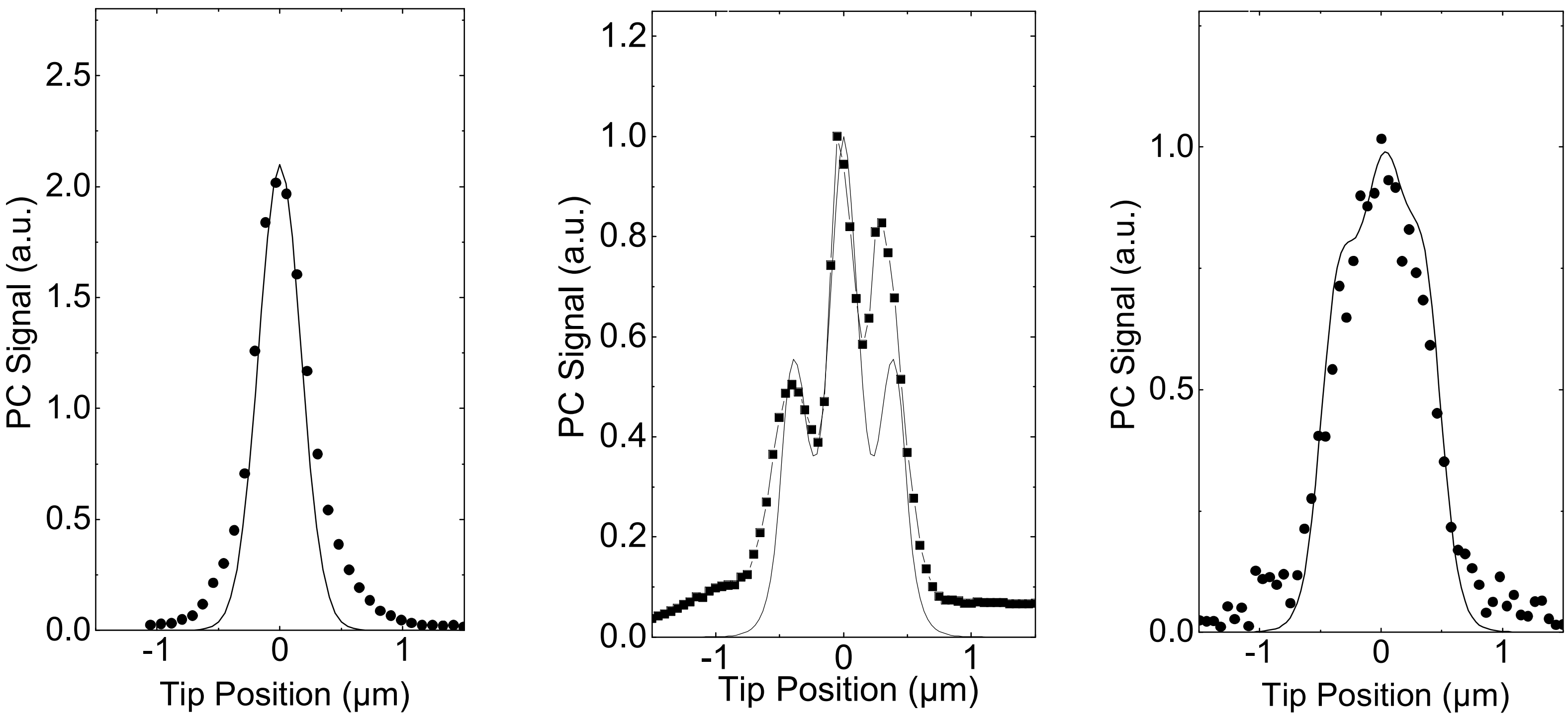
Analysis of waveguides

Comparison of the guided modes in a waveguide and the wavefunctions in a quantum well

Field	$\Psi(\mathbf{r},t) = \Psi(\mathbf{r})\,\mathrm{e}^{i\omega t}$ Wave function in Bloch form	$\mathbf{H}(\mathbf{r},t) = \mathbf{H}(\mathbf{r})\,\mathrm{e}^{i\omega t}$ Harmonic modes in Bloch form
Eigenvalue problem	$H\Psi = E\Psi$	$\mathbf{\Theta H} = (\omega/c)^2\mathbf{H}$
Hermitian operator	$H = \frac{-\hbar^2\nabla^2}{2m} + V(\mathbf{r})$	$\mathbf{\Theta} = \nabla \times \left(\frac{1}{\varepsilon(\mathbf{r})}\nabla \times\right)$
Periodicity of the system	$V(\mathbf{r}) = V(\mathbf{r}+\mathbf{R})$ Periodic potential for all lattice vectors $\mathbf{R}$	$\varepsilon(\mathbf{r}) = \varepsilon(\mathbf{r}+\mathbf{R})$ Periodic dielectric for all lattice vectors $\mathbf{R}$
Variational theorem	$E_{var} = \frac{<\Psi\|H\|\Psi>}{<\Psi\|\Psi>}$ is minimized when Ψ is an eigenstate of H	$E_{var} = \frac{(\mathbf{H},\mathbf{\Theta H})}{(\mathbf{H},\mathbf{H})}$ is minimized when $\mathbf{H}$ is normal mode of $\mathbf{\Theta}$

Analysis of waveguides

Step INdex SIN	Large Optical Cavity LOC symmetric waveguide	Large Optical Cavity LOC asymmetric waveguide

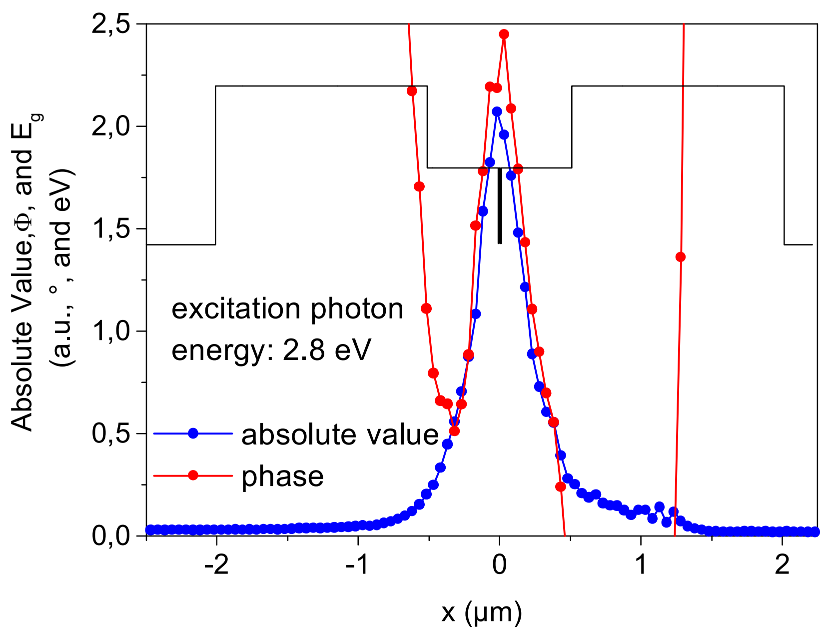


- NSOM Photocurrent reveals mode structure of waveguides
- asymmetric waveguides have a specific NSOM Photocurrent signature

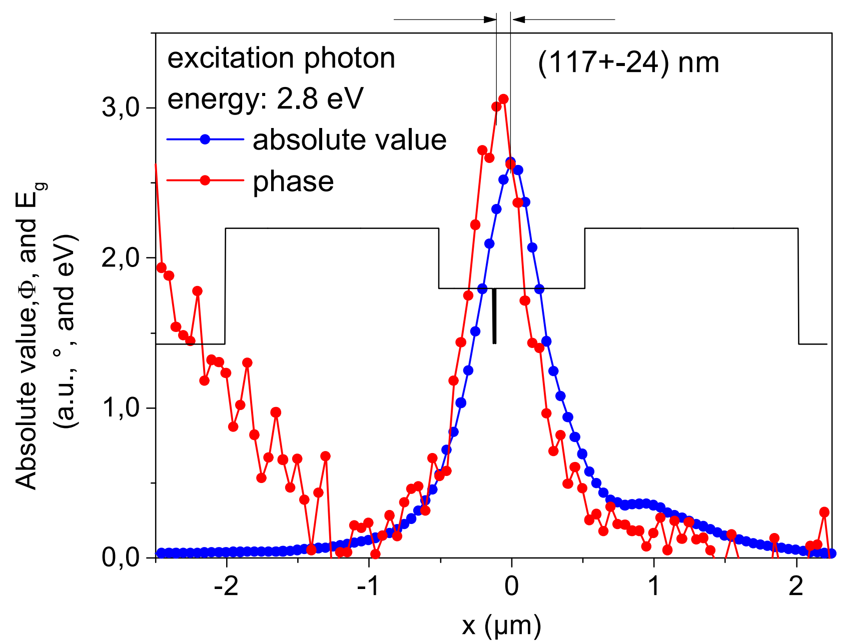
Analysis of waveguides

NOBIC contrast from the photocurrent phase for non-resonant (surface) excitation

NOBIC line scans from the symmetric LOC structure



NOBIC line scans from the asymmetric LOC structure



Analysis of waveguides

Single waveguides

- Resonant excitation (coupling into the waveguide modes)
- NOBIC reveals mode structure of waveguides
- asymmetric waveguides have a specific NOBIC signature
- Non-resonant excitation (pure carrier-pair creation)
- detection of the QW within the waveguide

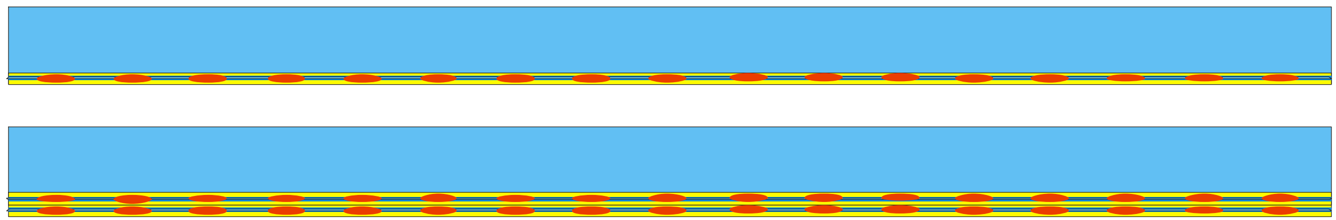
T. Guenther et al.
„Near-Field Photocurrent Imaging of the Optical Mode Profiles of Semiconductor Laser Diodes“
Appl. Phys. Lett. **78** 1463-1465 (2001).

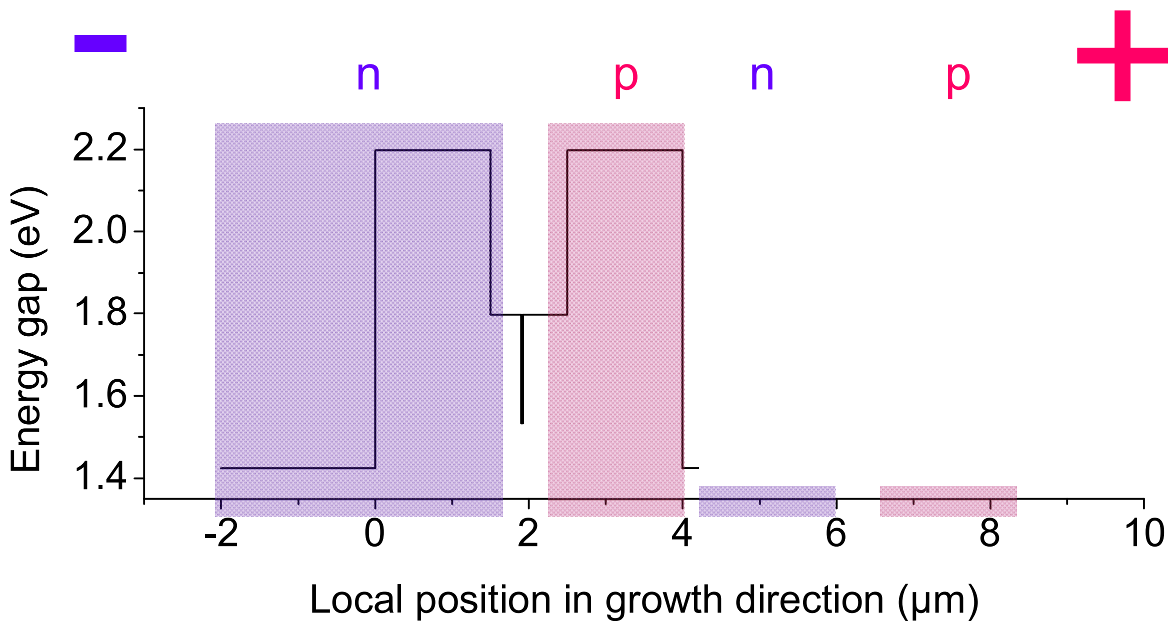
Analysis of waveguides

Nanostacks® - interband cascade diode laser

'regular' high-power diode laser array

Nanostack®





J. P. van der Ziel and W. T. Tsang, *Appl. Phys. Lett.* **41**, 499-501 (1982).

J. Ch. Garcia, E. Rosencher, Ph. Collot, N. Laurent, J. L. Guyaux, B. Vinter, and J. Nagle, *Appl. Phys. Lett.* **71**, 3752-3754 (1997).

S. G. Patterson, G. S. Petrich, R. J. Ram, and L. A. Kolodziejski, Electron Lett. 35, 395 (1999).

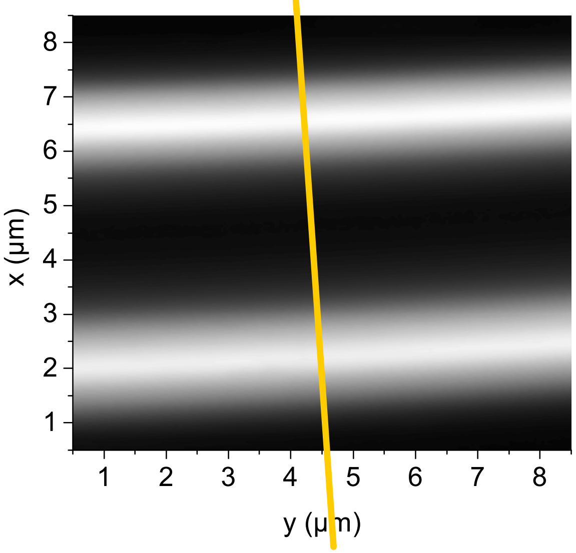
C. Hanke, L. Korte, B. D. Acklin, M. Behringer, G. Herrmann, J. Luft, B. De Odorico, M. Marchiano, J. Wilhelmi, *Proc. SPIE* **3947**, 50-57(2000).

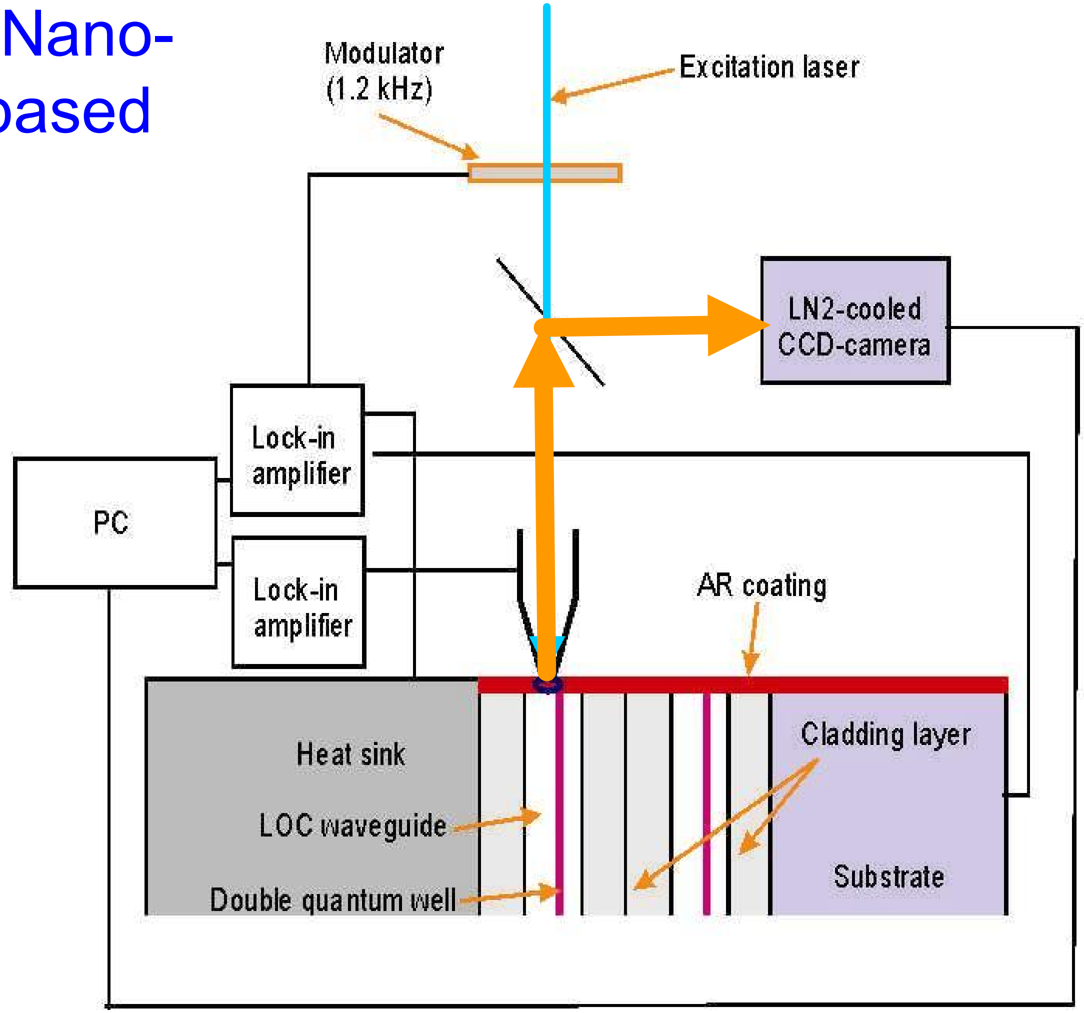
http://www.osram-os.com/news/news_power.html

Analysis of waveguides

Detailed analysis of Nano-stacks® by NSOM-based spectroscopy

- Photoluminescence
- Photocurrent (Absorption)
- Device emission

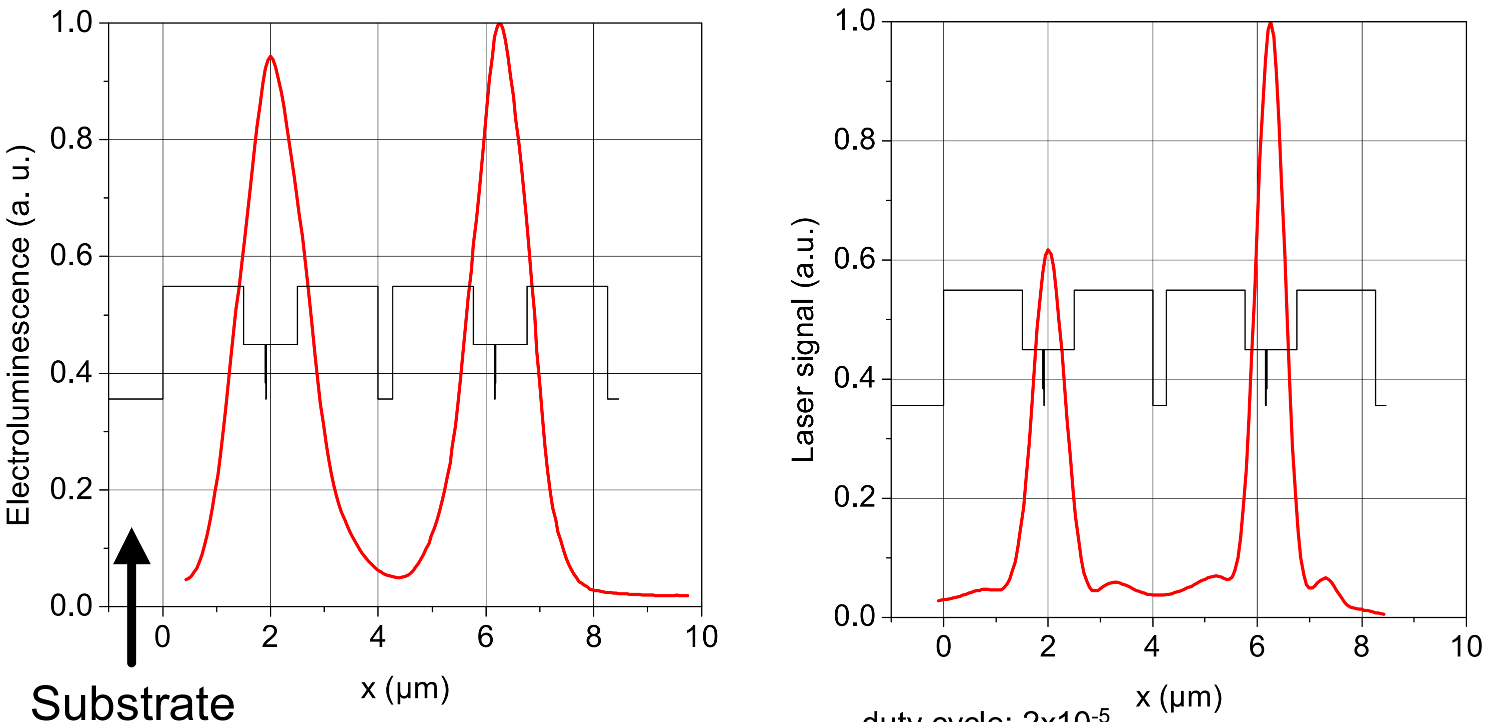




Analysis of waveguides

Results from Nanostacks® with two vertically stacked asymmetric waveguides

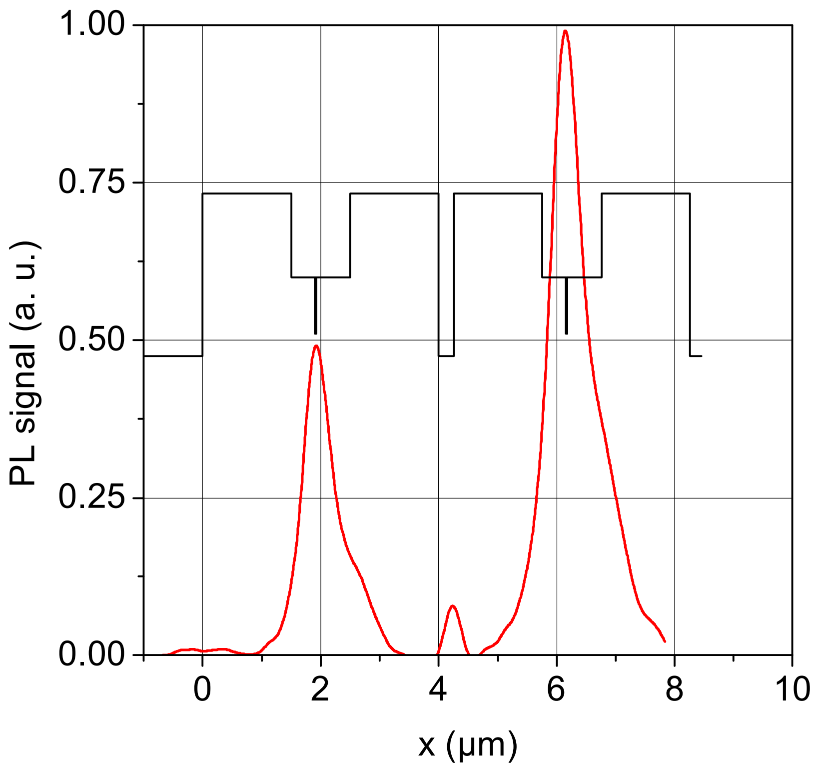
NSOM Device Emission



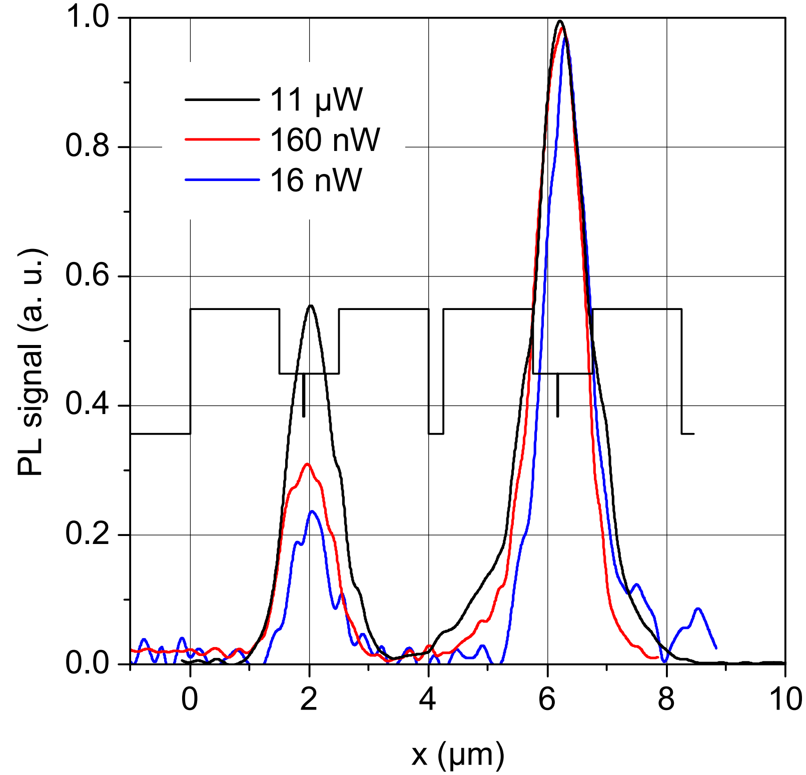
duty cycle: $2x10^{-5}$
no thermal load

Analysis of waveguides

NSOM PL Emission



excitation photon energy: 2.8 eV
detection photon energy: 1.5 eV

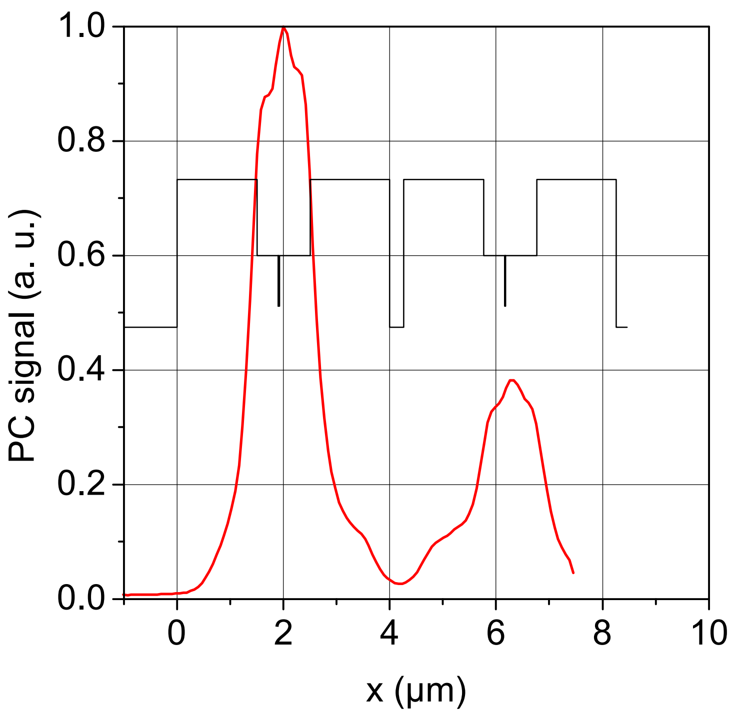


excitation photon energy: 1.69 eV
detection photon energy: 1.5 eV

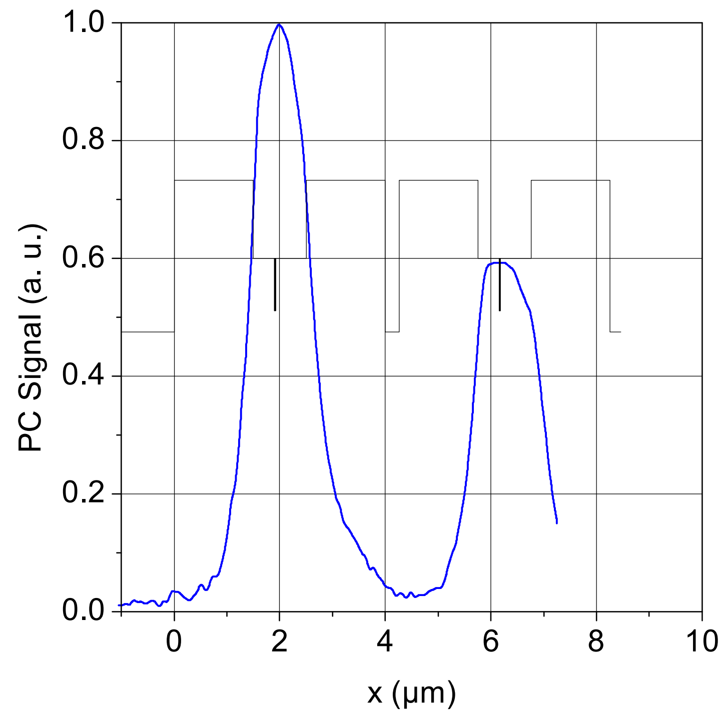
PL-signal ~ δn

Analysis of waveguides

resonant and non-resonant NSOM Photocurrent (Absorption)



excitation photon energy: 1.69 eV

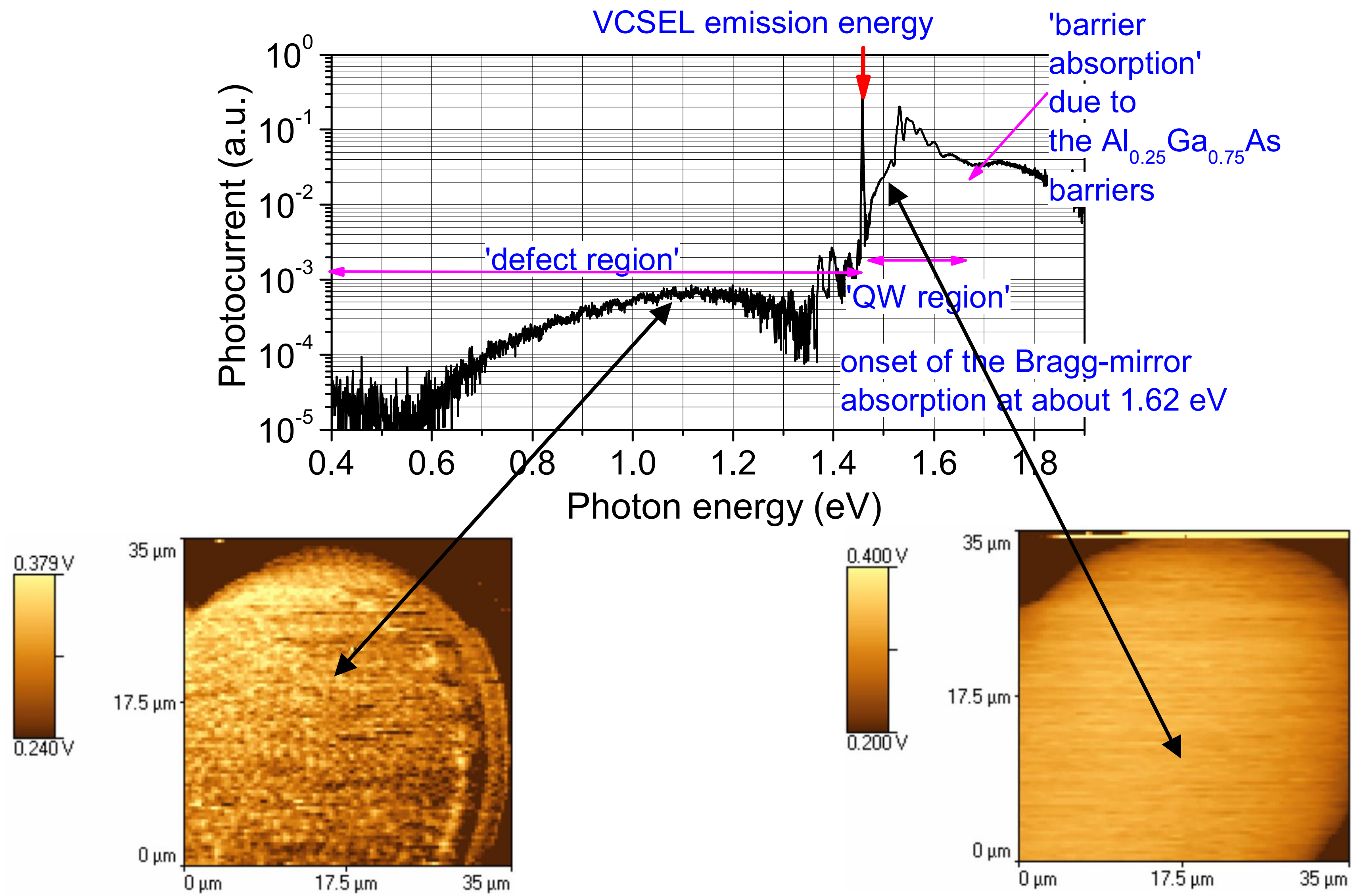


excitation photon energy: 2.8 eV

Photocurrent-signal ~ δn×grad(V)

V. Malyarchuk et al. "Uniformity tests of individual segments of interband cascade diode laser nanostacks®" *J. Appl. Phys.* **92**, 2729-2733 (2002).

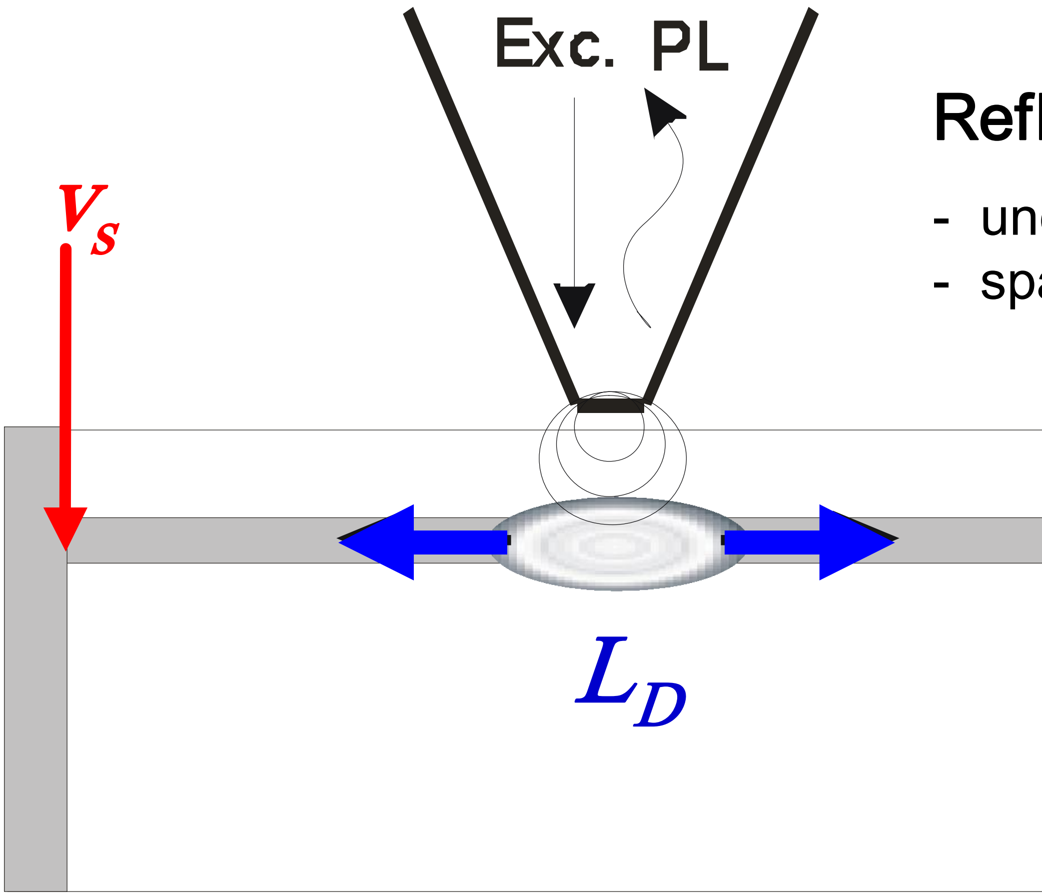
NOBIC at VCSELS



Outline

1. Introduction
   NSOM = Nearfield Scanning Optical Microscopy
   Principles and opportunities
   Spatial resolution
2. Methodology
   Laser emission, spontaneous emission and PL
3. NOBIC = Nearfield Optical Beam Induced Current
4. Experimental setups and equipment
5. Analysis of waveguides and determination of mode profiles
6. VCSEL
7. **Surface recombination velocity at facets**
8. Defect creation during device operation
9. Summary
10. Acknowledgement

Surface Recombination Velocity



Reflection PL experiment

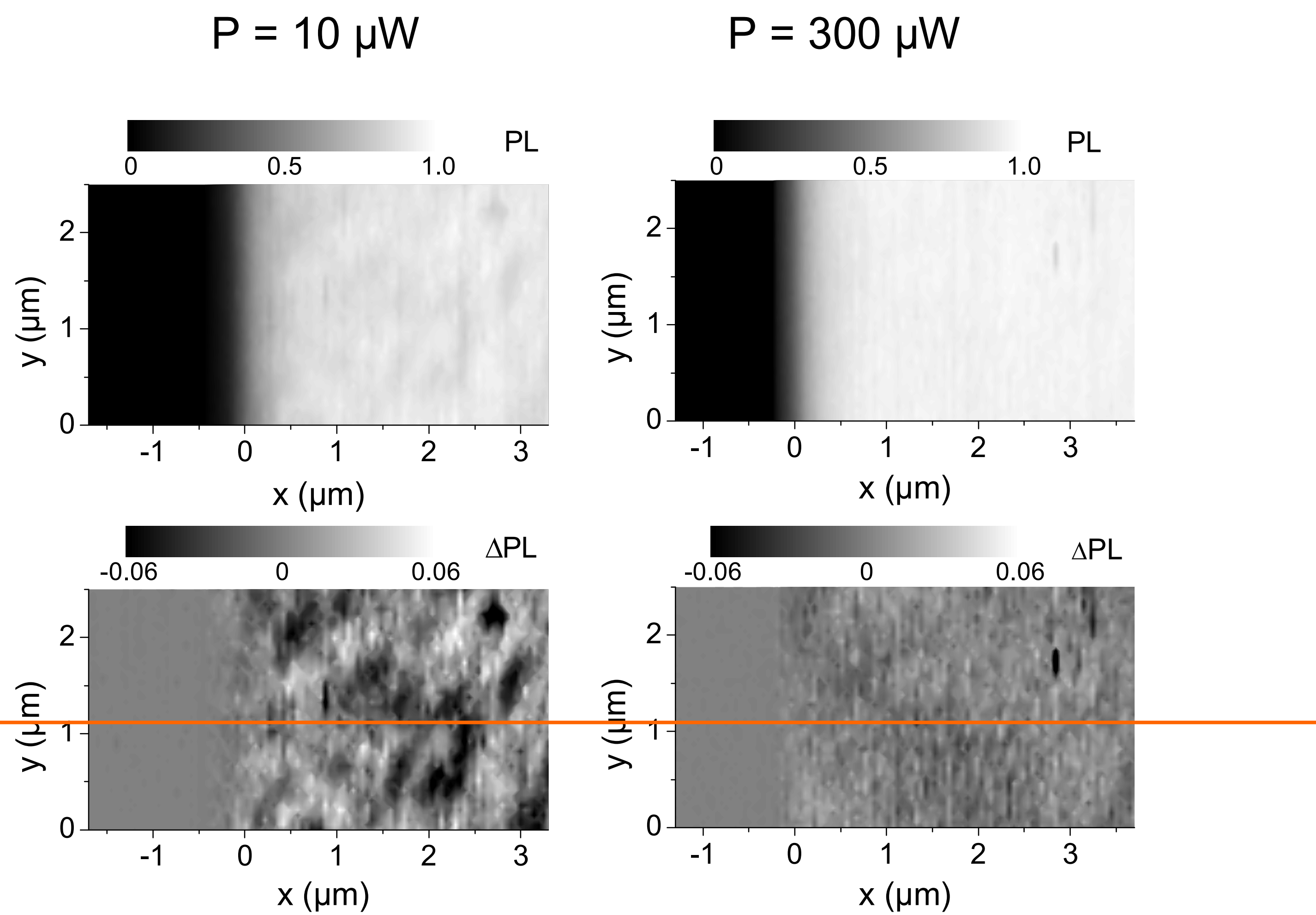
- uncoated fiber tip
- spatial resolution: 150 nm

V. Malyarchuk, J. W. Tomm, V. Talalaev, Ch. Lienau,
F. Rinner, and M. Baeumler *Appl. Phys. Lett.* **81** 346 (2002).

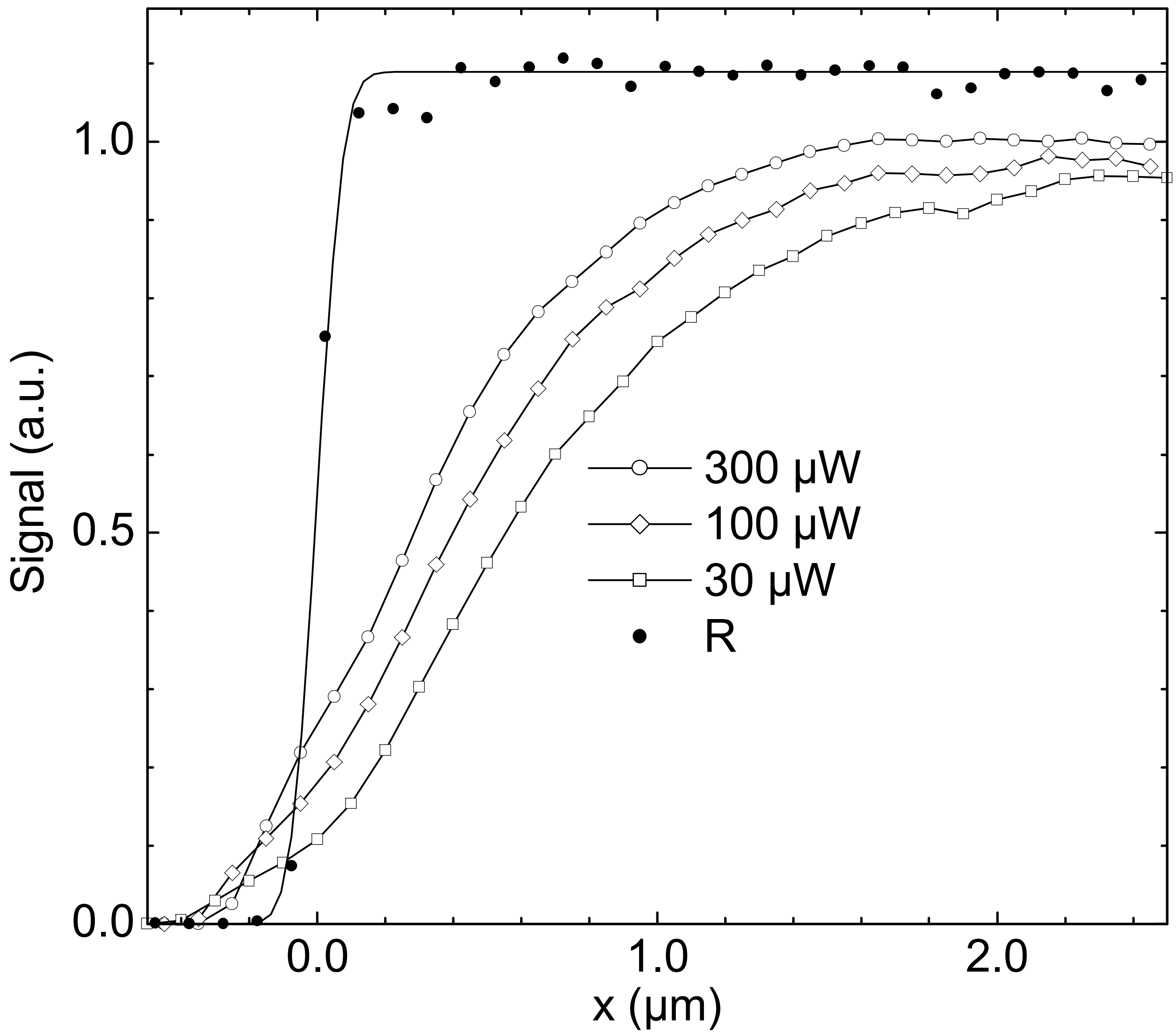
Surface Recombination Velocity

QW PL collected through the fiber and detected by a single photon counting system

Line-leveled images



Surface Recombination Velocity



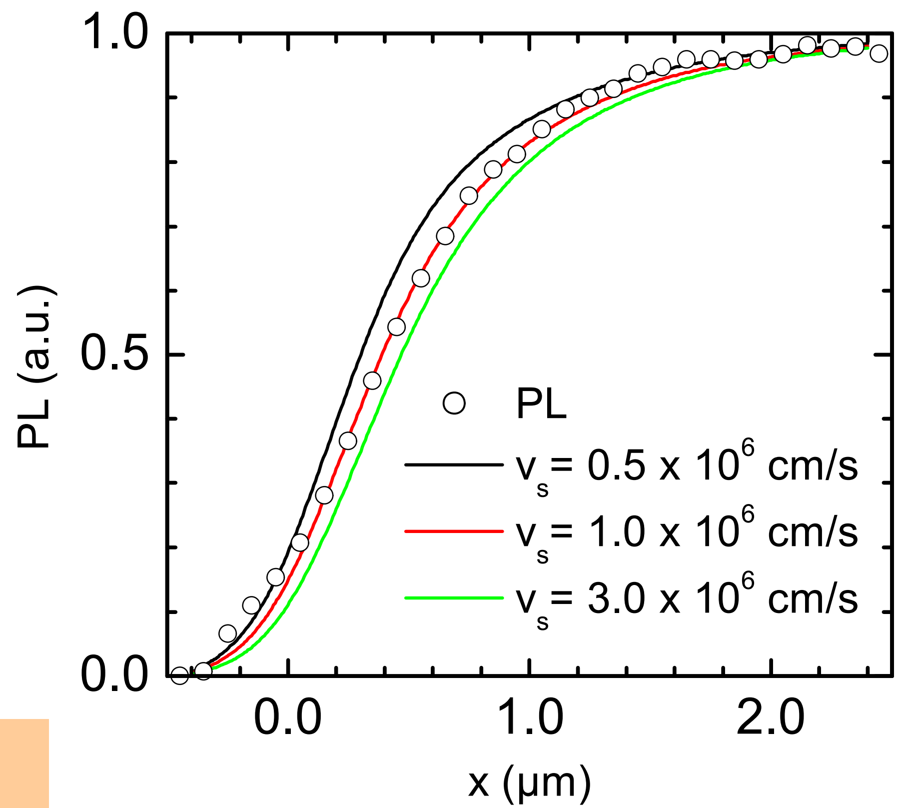
Surface Recombination Velocity

$$D\left(\frac{\partial^2}{\partial x^2}+\frac{\partial^2}{\partial y^2}\right)n-\frac{n}{\tau_{rec}}+n_a g(x_0,y_0)=0$$

$$L_D=\sqrt{D\tau_{rec}}$$

$$g(x_0,y_0)=\frac{1}{\sqrt{2\pi}\sigma}e^{-\frac{(x-x_0)^2+(y-y_0)^2}{2\sigma^2}}$$

$$x=0: \quad D\left.\frac{\partial n}{\partial x}\right|_{x=0}=\mathrm{v}_s\cdot n$$

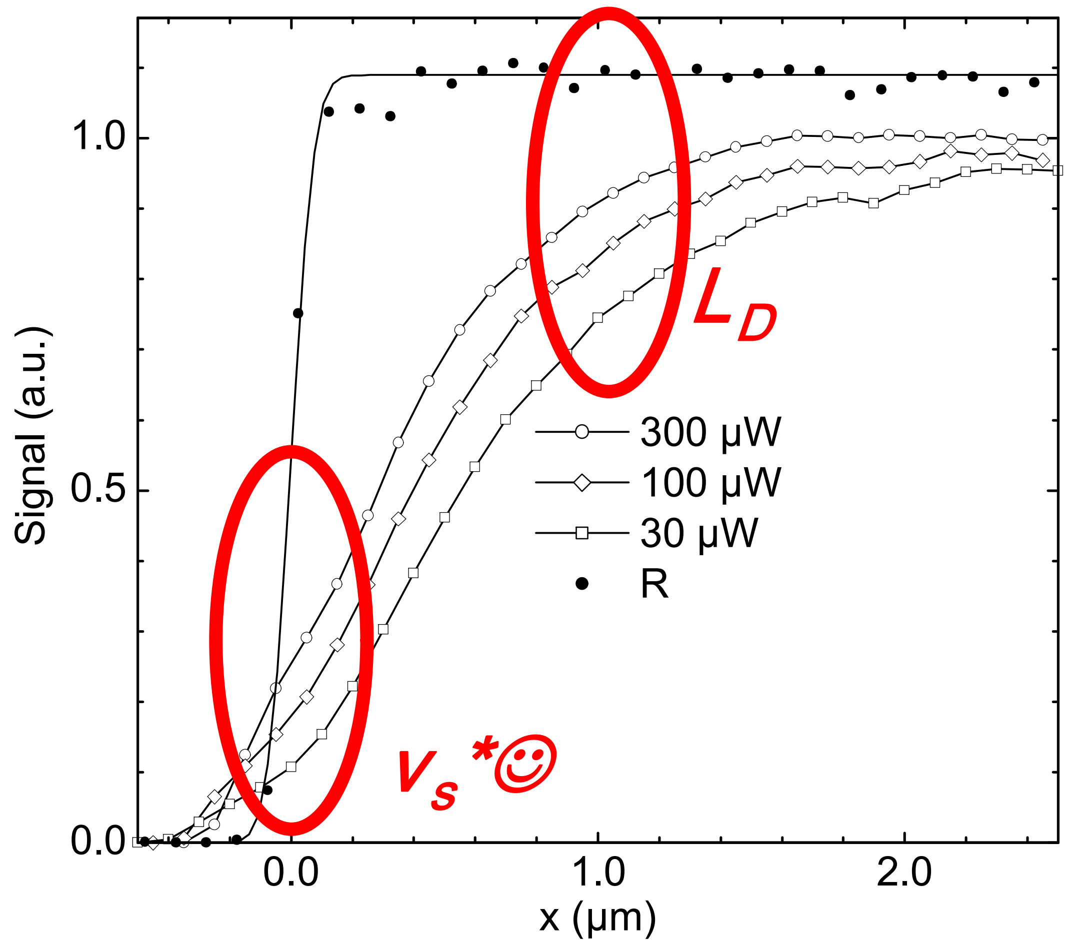


diffusion length L_D and the product $(\mathrm{v}_s\cdot\tau_{rec})$ can be deduced

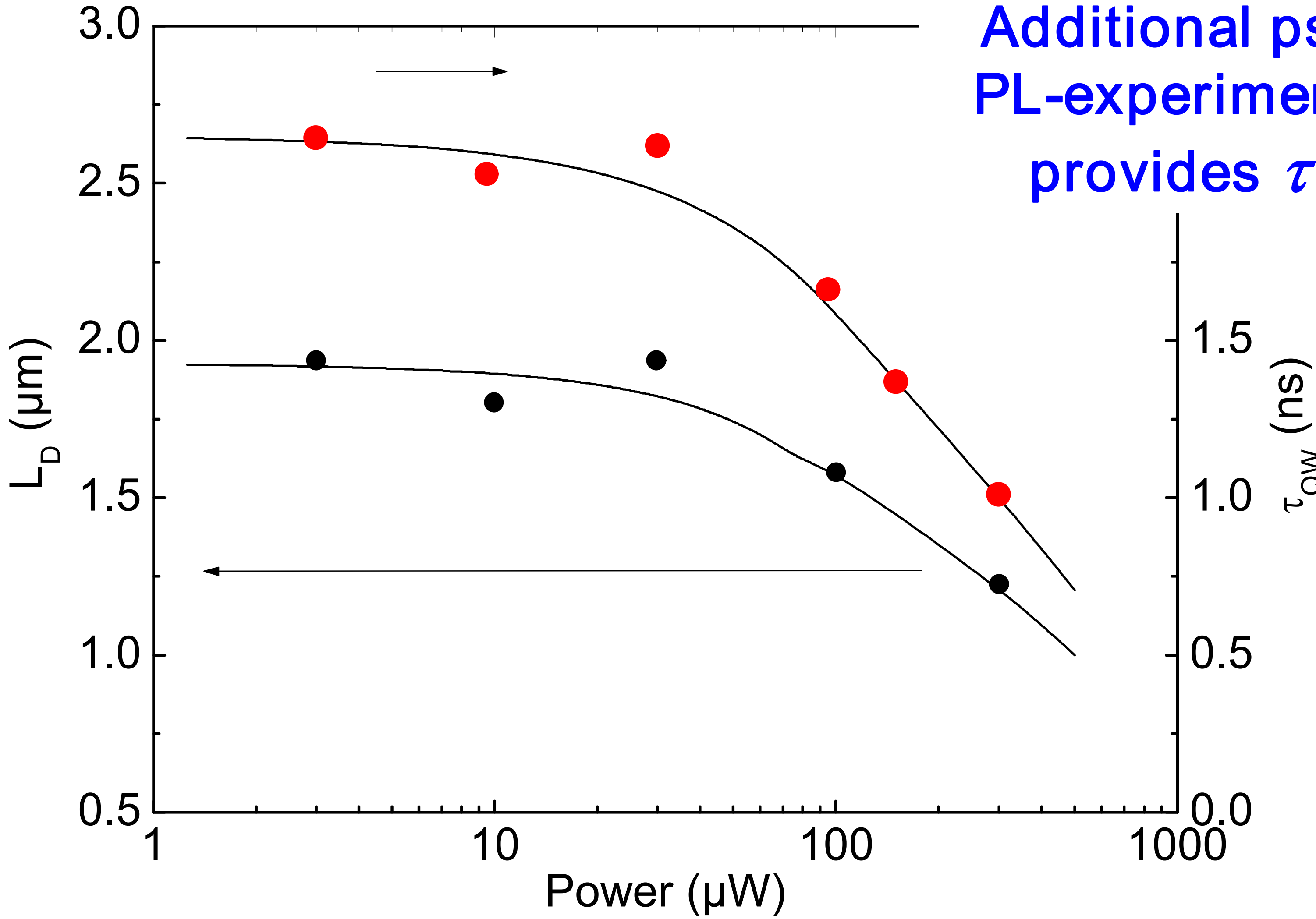
Example calculated for:

D = 15 cm^2/s τ = 1.7 ns

Surface Recombination Velocity

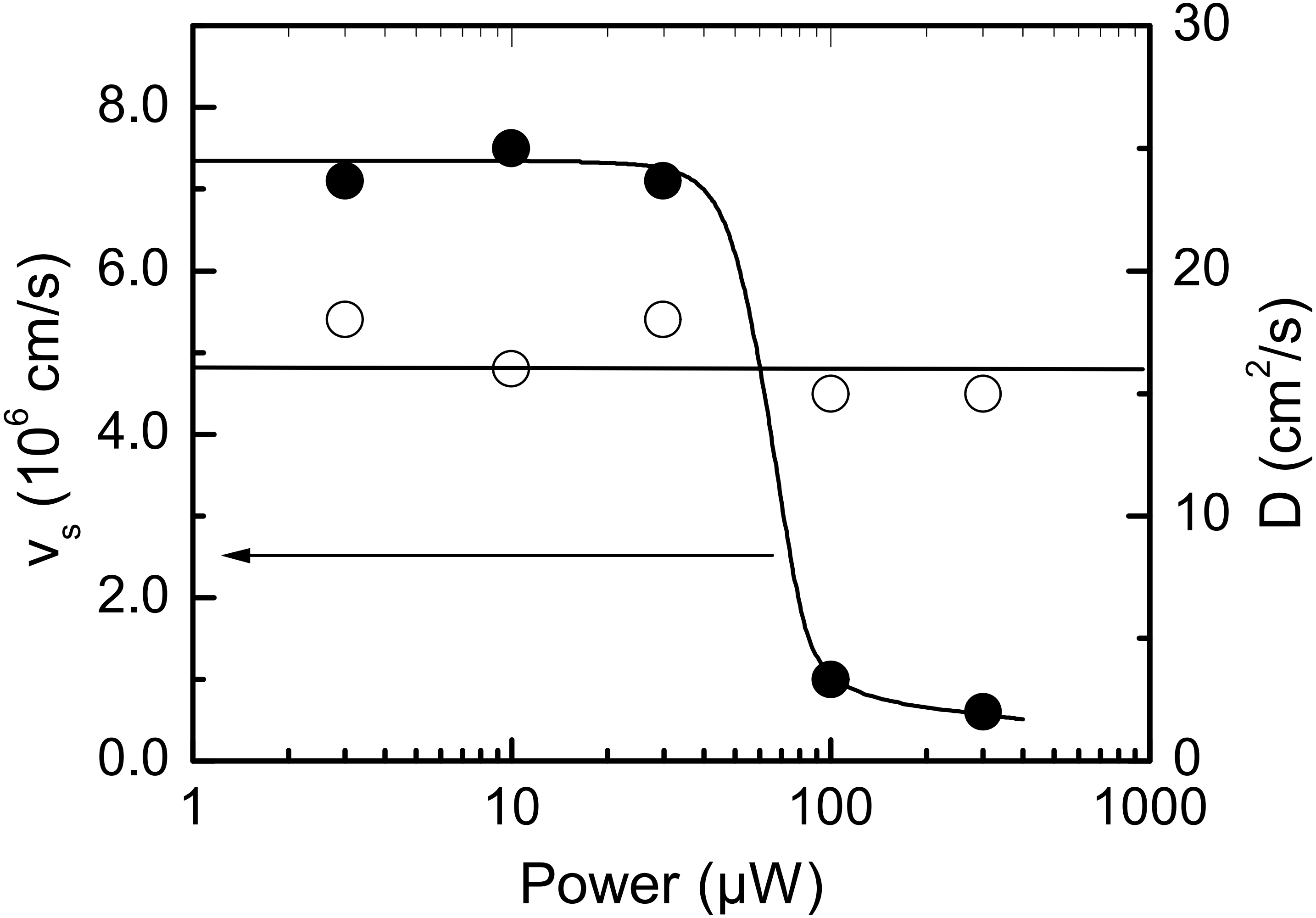


Surface Recombination Velocity



Additional ps-PL-experiment provides τ

Surface Recombination Velocity



V. Malyarchuk, J. W. Tomm, V. Talalaev, Ch. Lienau, F. Rinner, and M.Baeumler *Appl. Phys. Lett.* **81** 346 (2002).

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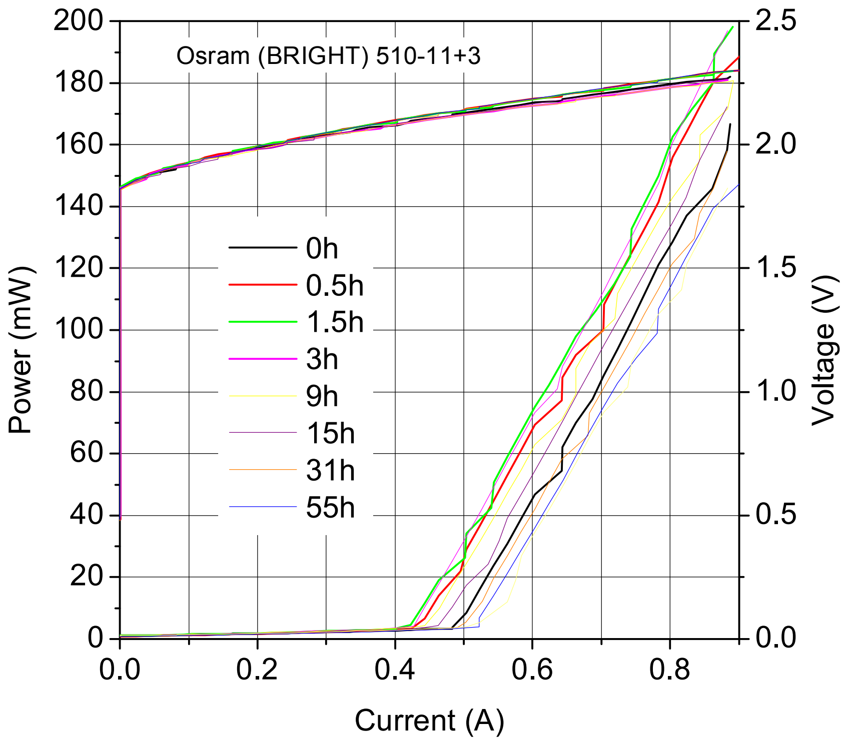
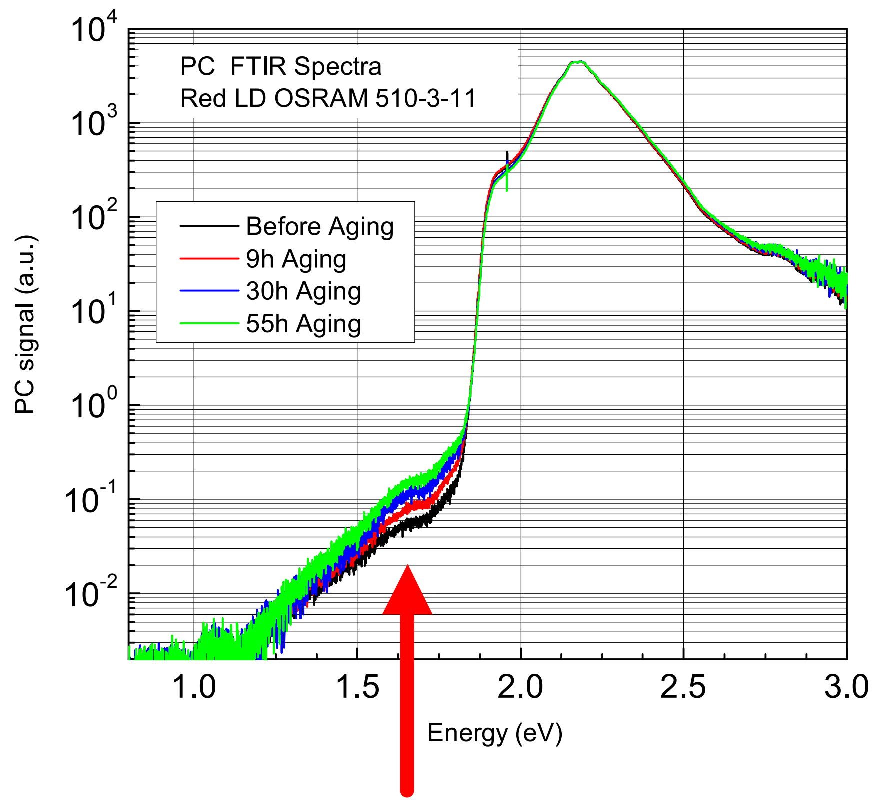
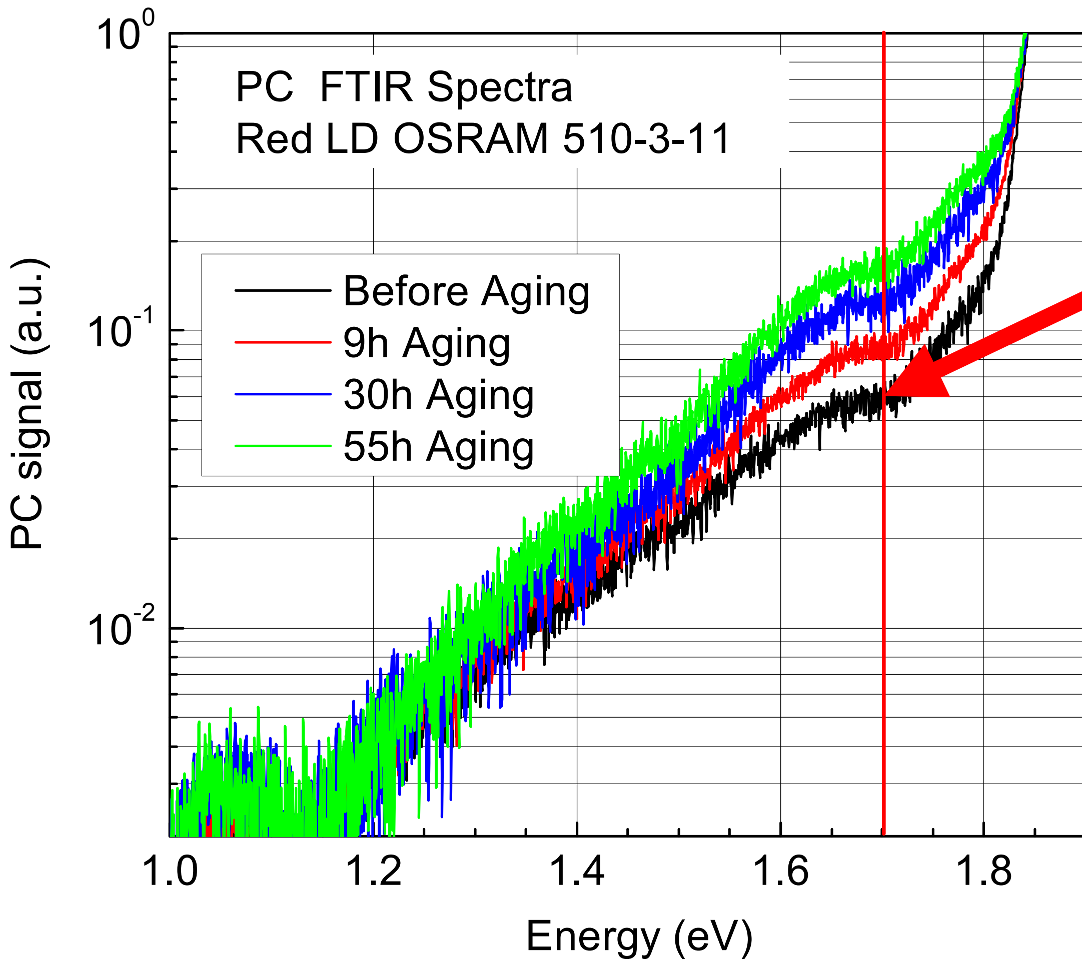
Defect creation during device operation

Result from the BRIGHT project





Defect creation during device operation



Defect-to-Band-Transitions?

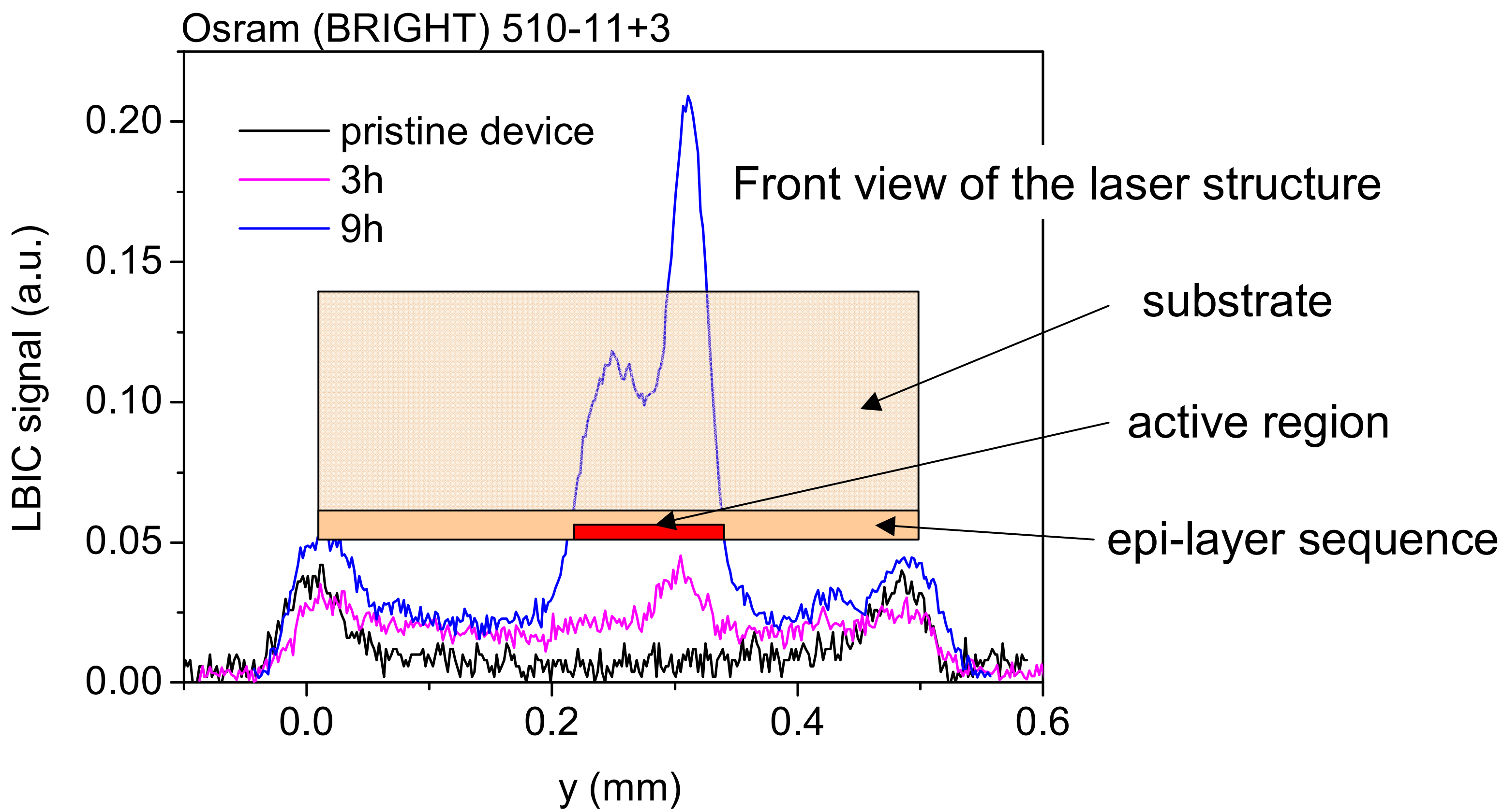
At 1.7 eV (730 nm), there is a threefold increase of the signal within 55 h of aging.

Where are the 'defects' located?

Active region???

Defect creation during device operation

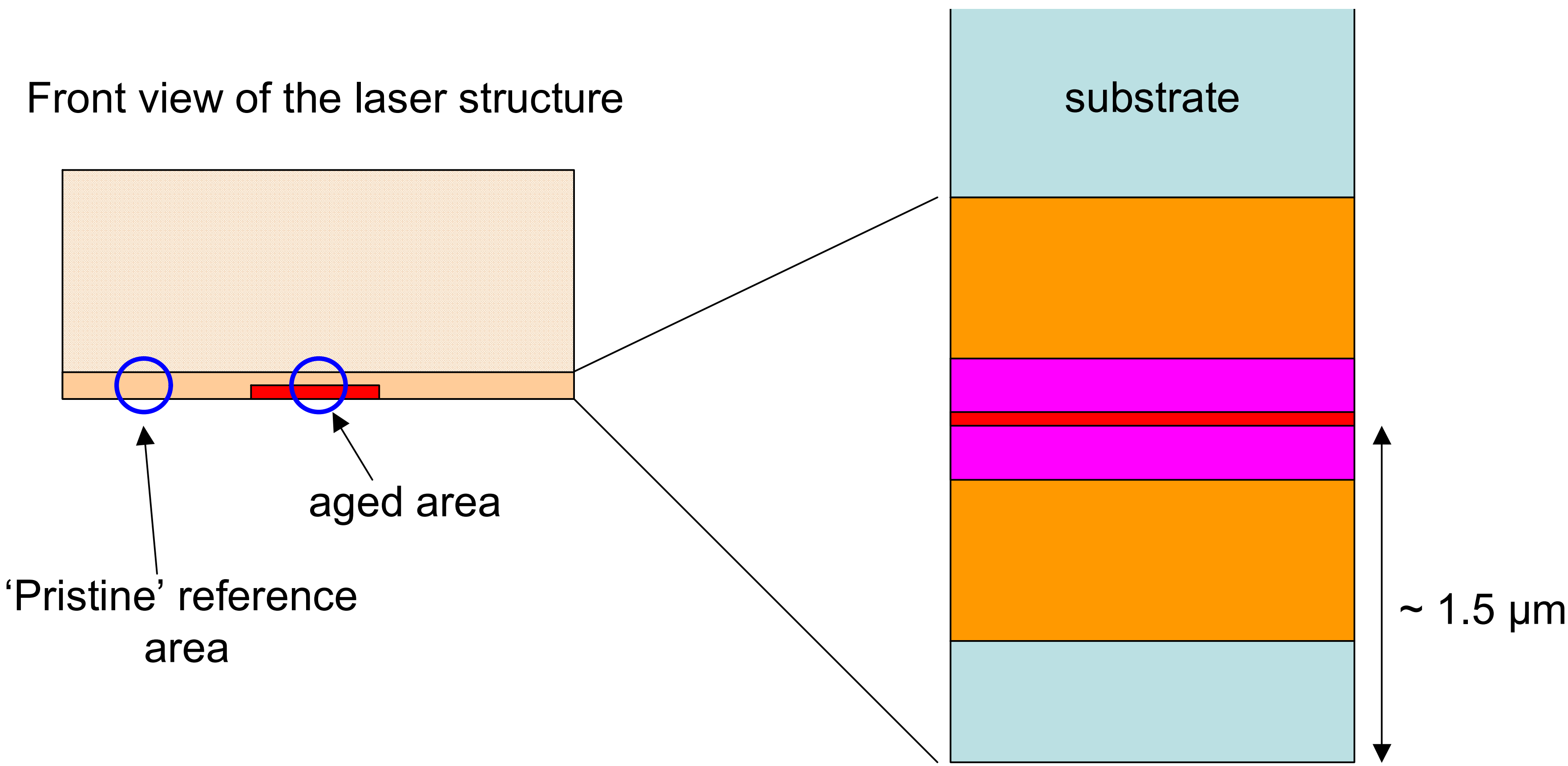
1. Laterally, i.e., where along the device…



LBIC (Laser Beam Induced Current) excited resonantly to the defects reveals them to be underneath the metalized emitter stripe.

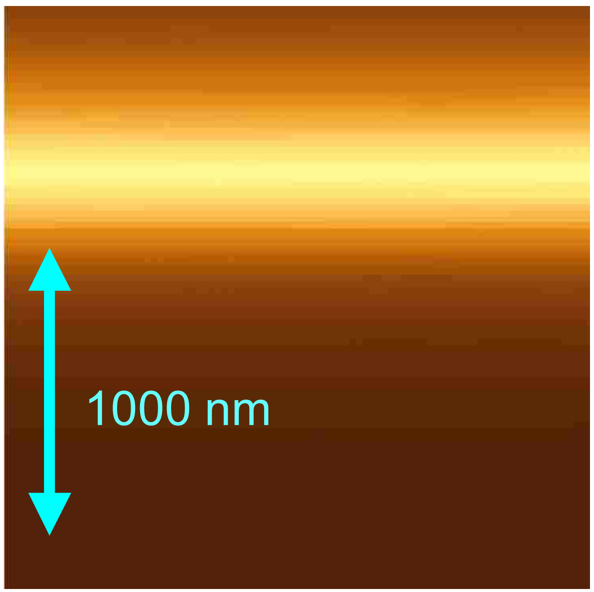
Defect creation during device operation

2. Vertically, i.e., where along the layer sequence …

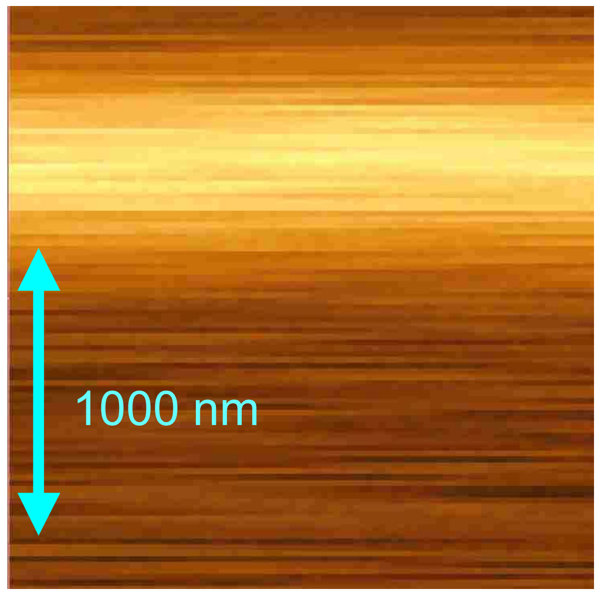


Defect creation during device operation

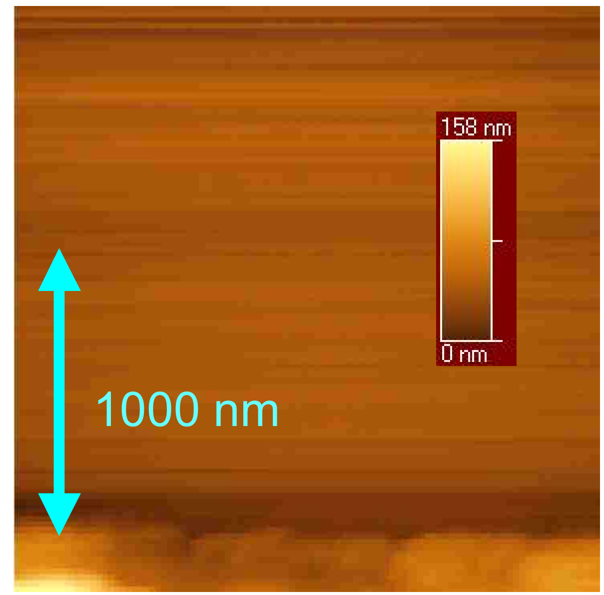
NOBIC-Data:
(Nearfield Optical Beam Induced Current)



633 nm



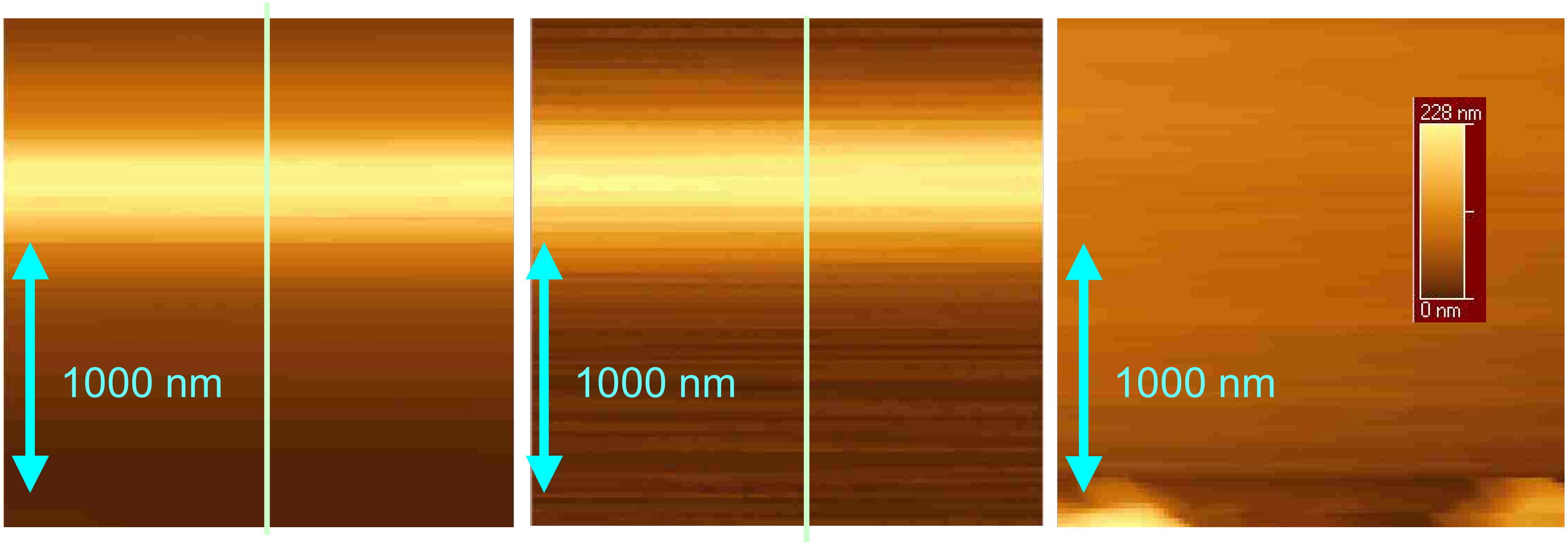
730 nm



topography

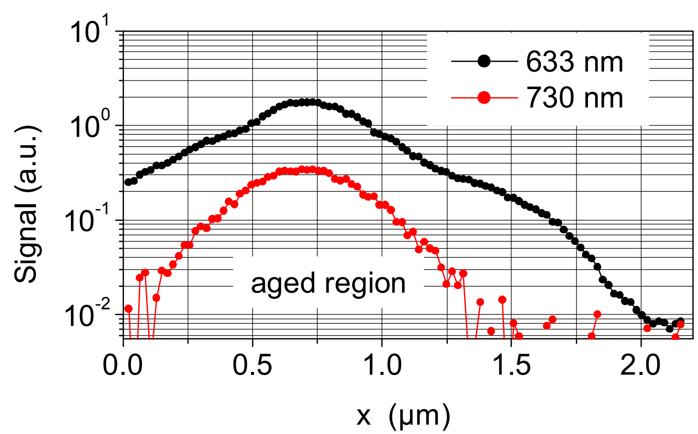
pristine device region

Defect creation during device operation

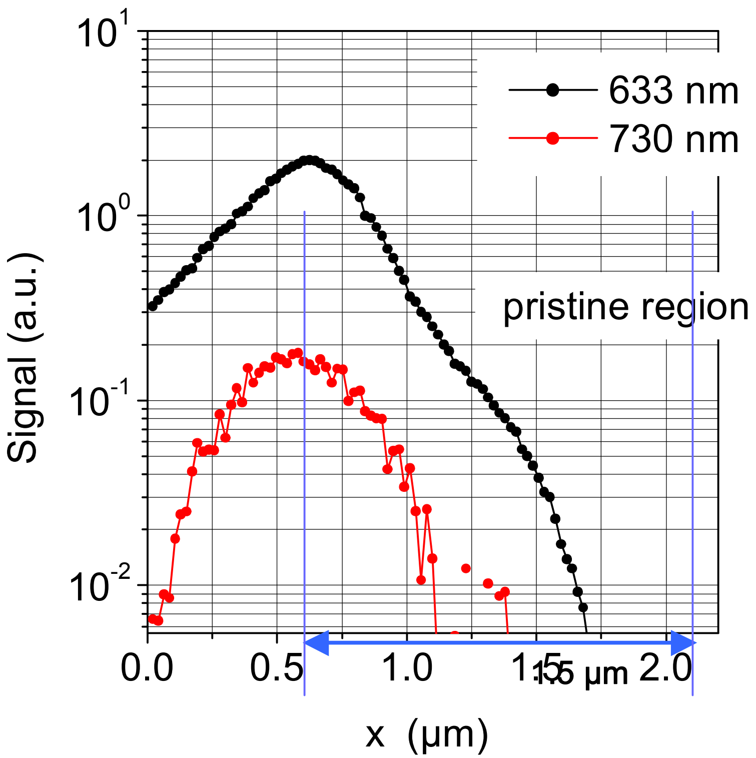


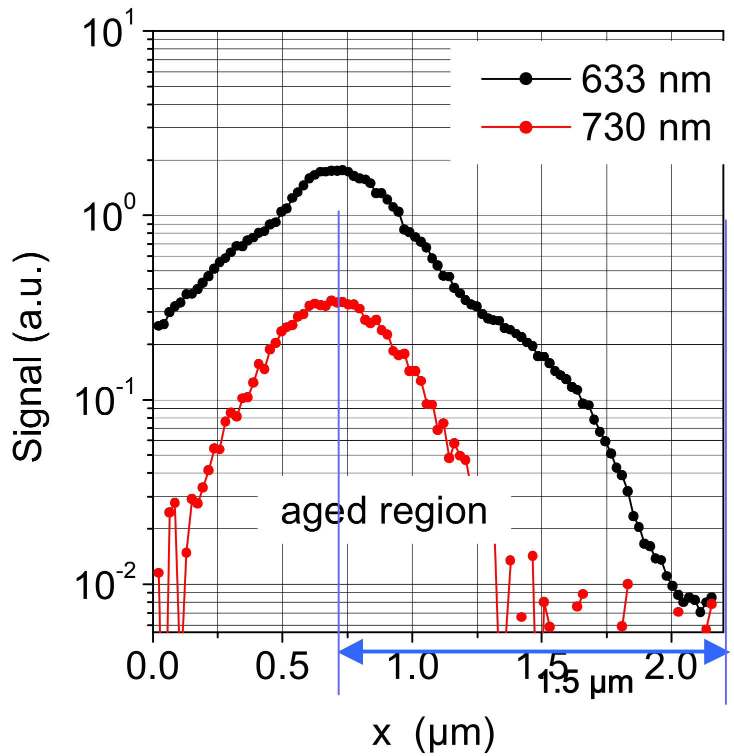
633 nm | 730 nm | topography

aged device region



Defect creation during device operation





There is a threefold increase of the 730 nm- signal with respect to the 633 nm-signal 1.5 µm away from the active region (towards the heat sink), there is no photosensitivity.

The creation of deep levels takes place at a location that allows interaction with the laser emission.

There are additional 3 sets of data couples from different regions, which confirm the result.

Claus Ropers et al. *Appl. Phys. Lett.* **88**, 133513 (2006).

Summary

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- Spatial resolution

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NOBIC = Nearfield Optical Beam Induced Current

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VCSEL

Surface recombination velocity at facets

Defect creation during device operation

NSOM is extremely useful if you need a spatial resolution beyond the diffraction limit.

NOBIC allows optical analysis at devices along growth direction.

Acknowledgement

- Christoph Lienau
- Alexander Richter, Tobias Günther, Viktor Malyarchuk, Roland Müller, Claus Ropers, Thomas Elsässer
- Martin Behringer, Johannes Luft, Peter Brick, Norbert Linder, Bernd Mayer, Martin Müller, Sönke Tautz, Wolfgang Schmid, Götz Erbert, Jürgen Sebastian, Siegfried Gramlich, Eberhard Richter, Heiko Kissel, Frank Brunner, Markus Weyers, Günter Tränkle