Micromachining with fs-pulses

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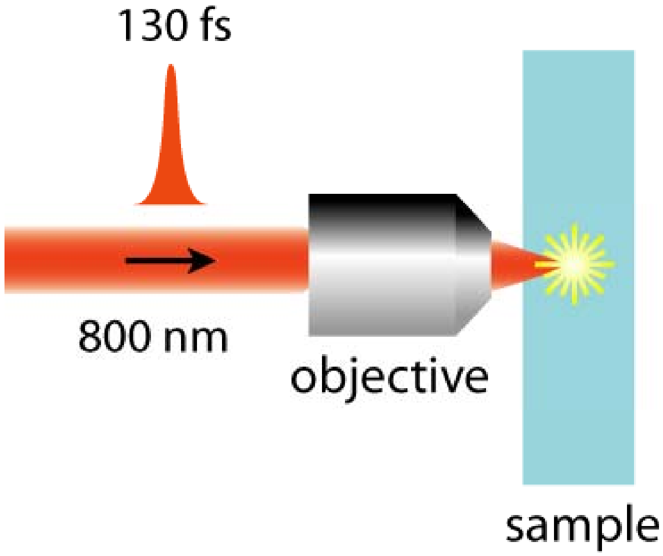
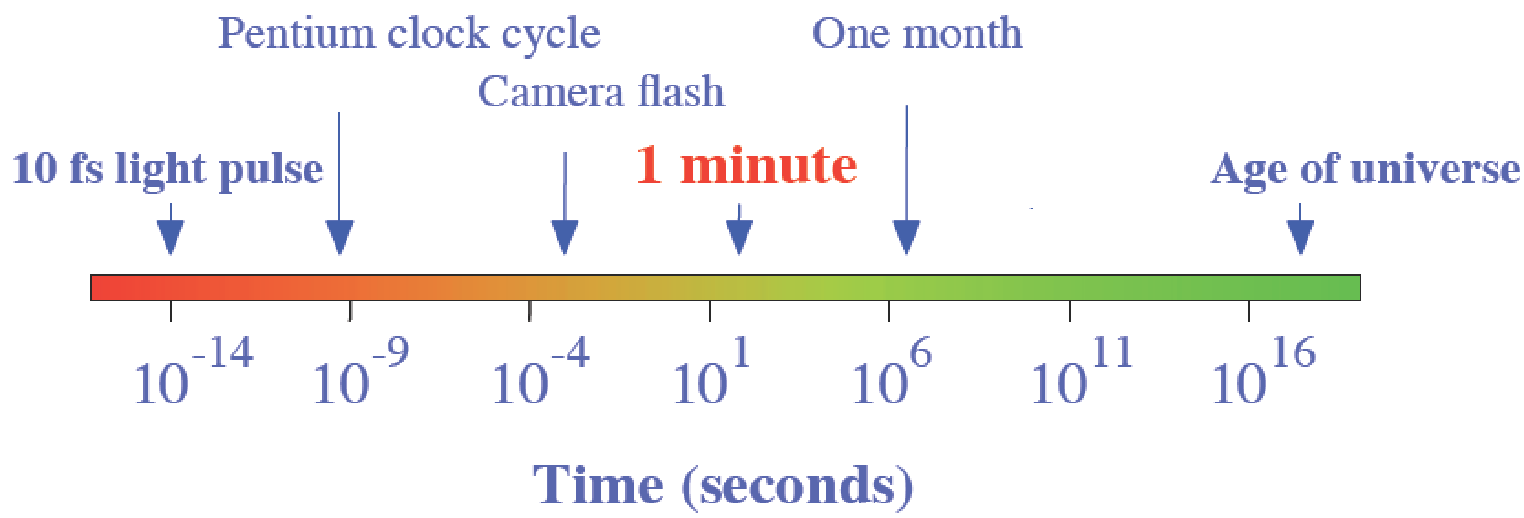
Microfabrication

Microfabricate and microstructure materials using fs-laser and nonlinear optical processes



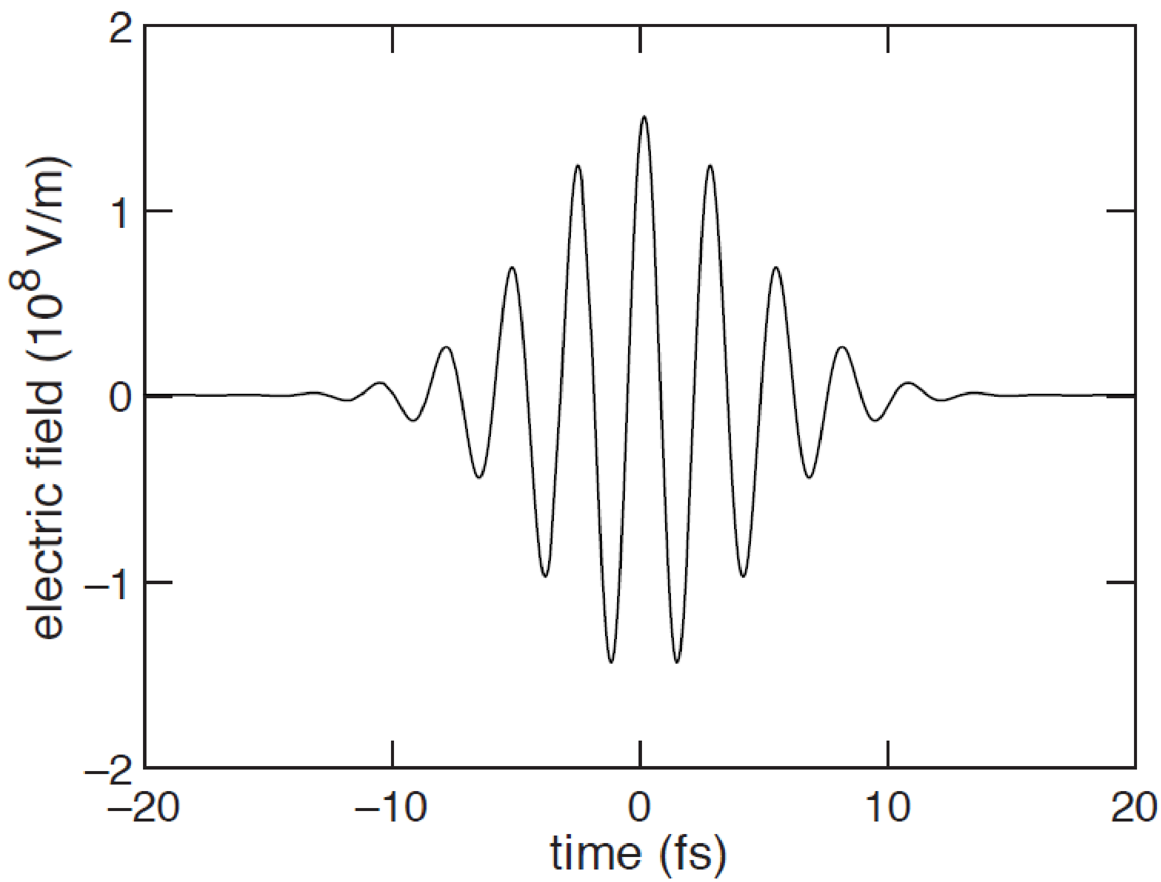
Microfabrication

1 fs = 10^{-15} s



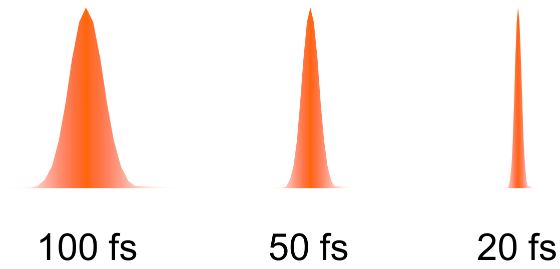
introduction

how short is a femtosecond pulse ?



Microfabrication

Ti:Sapphire lasers



Very intense light

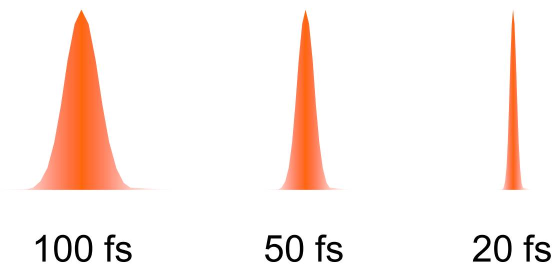
Laser intensities ~ 100 GW/cm²

$1 \times 10^{11} W/cm^2$

Laser pointer: $1\ mW/cm^2$ ($1 \times 10^{-3}\ W/\ cm^2$)

fs-laser micromachining

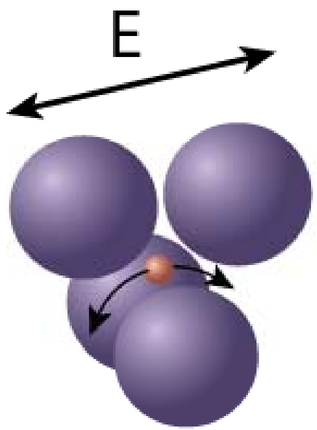
Ti:Sapphire lasers



Very intense light

Nonlinear Optical Phenomena

Nonlinear Optics



anharmonic oscillator

high light intensity

$E_{rad.} \sim E_{inter.}$

nonlinear polarization response

$$P = \varepsilon_0 \left(\chi^{(1)} E + \chi^{(2)} E^2 + \chi^{(3)} E^3 + \ldots \right)$$

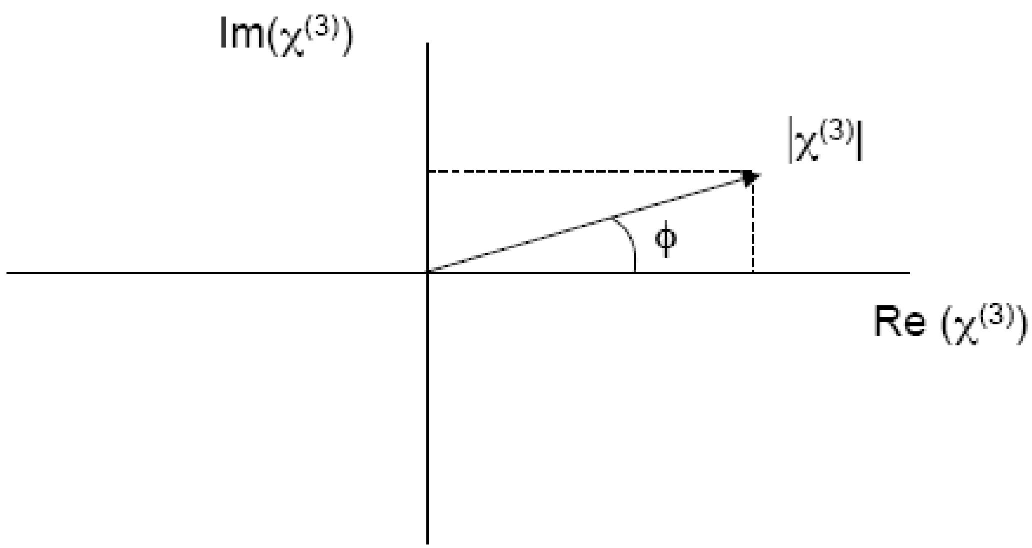
Nonlinear Optics

$\chi^{(3)}$ is a complex quantity

$$\chi^{(3)} = \mathrm{Re}\,(\chi^{(3)}) + i\,\mathrm{Im}(\chi^{(3)})$$

Related to intensity dependent refractive index

Related to two-photon absorption



Nonlinear Optics

Third order processes: $\chi^{(3)}$

Refractive process:

$$n = n_0 + n_2 I$$

- self-phase modulation
- lens-like effect

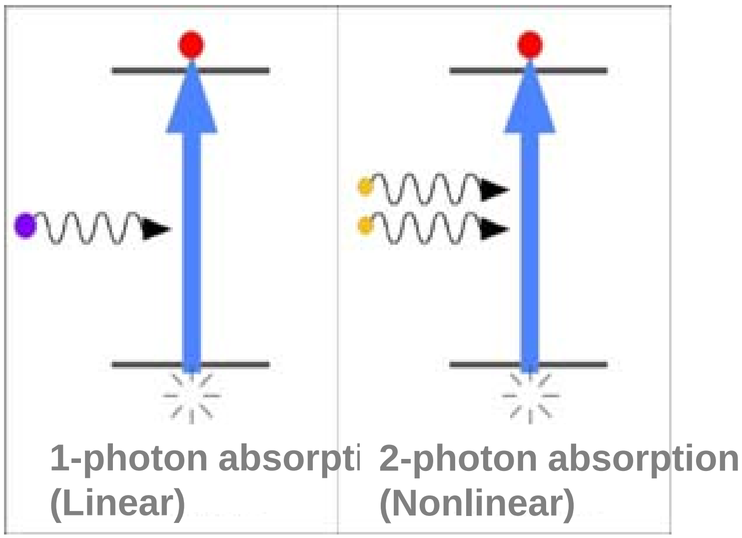
Absorptive process:

$$\alpha = \alpha_0 + \beta I$$

- nonlinear absorption
- two-photon absorption

Two-photon absorption

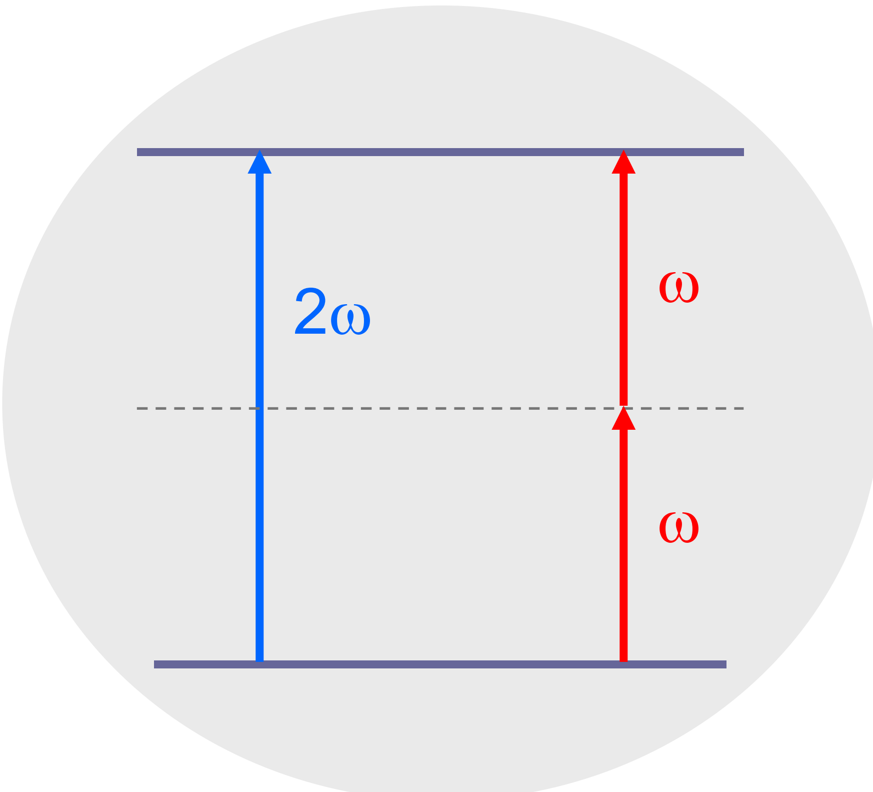
Phenomenon does not described for the Classical Physics and does not observed until the development of the Laser.



Theoretical model: Maria Göppert-Mayer, 1931

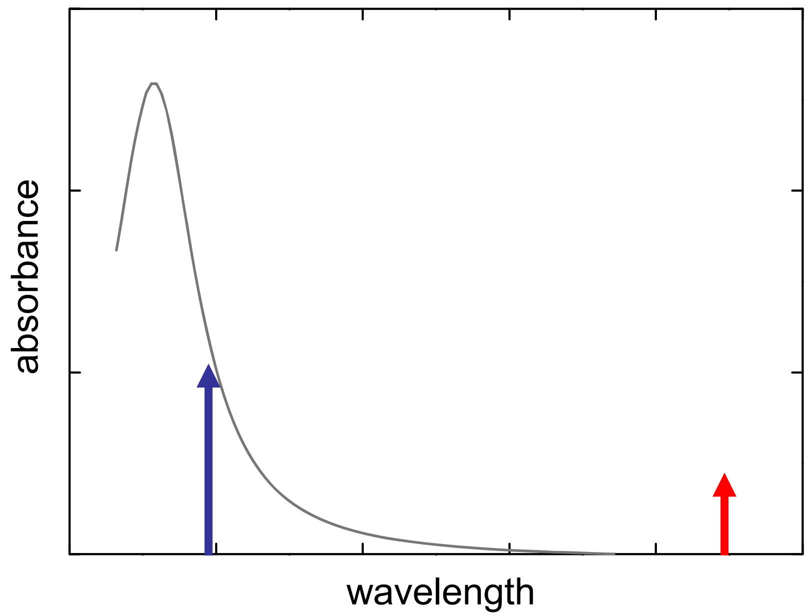
Two photons from an intense laser light beam are simultaneously absorbed in the same “quantum act”, leading the molecule to some excited state with energy equivalent to the absorbed two photons.

Two-photon absorption



$$\alpha = \alpha_0 + \beta I$$

Third order processes $\chi^{(3)}$



fs-laser microfabrication

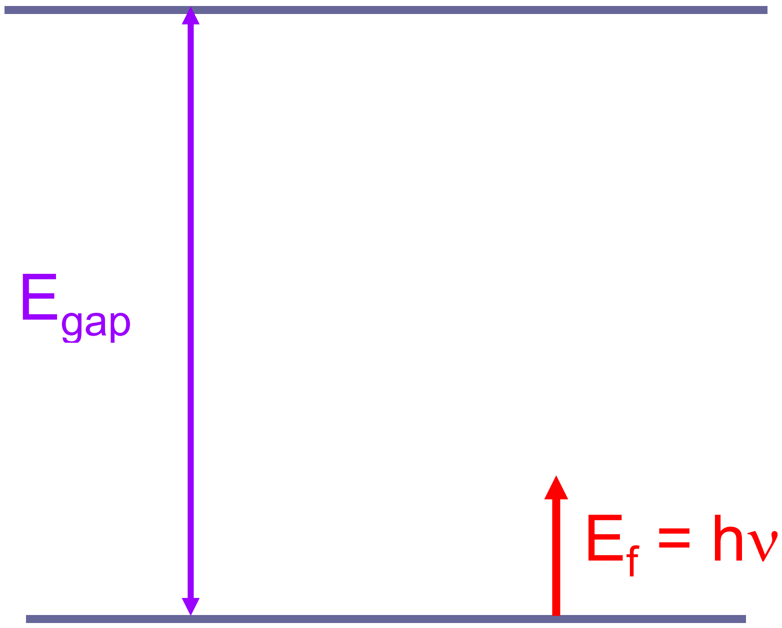
photon energy < bandgap

↓

nonlinear interaction

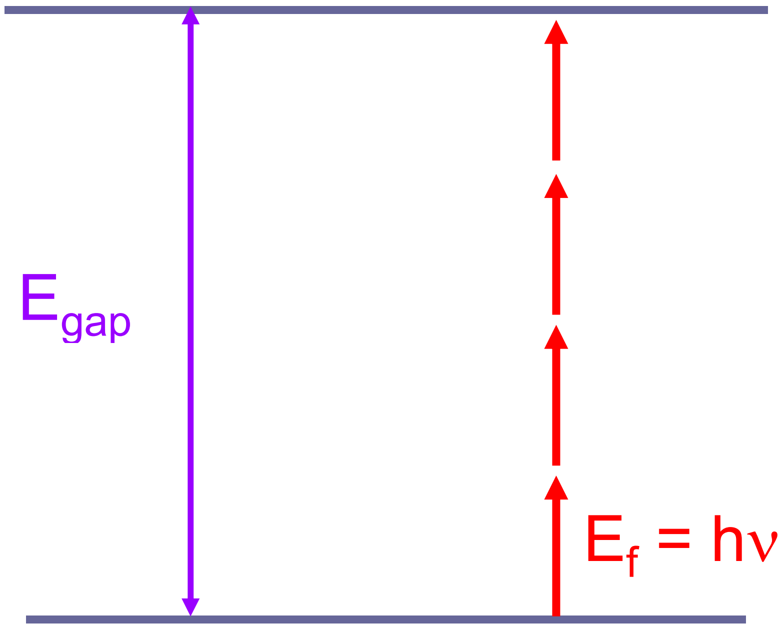
fs-laser microfabrication

nonlinear interaction



fs-laser microfabrication

nonlinear interaction



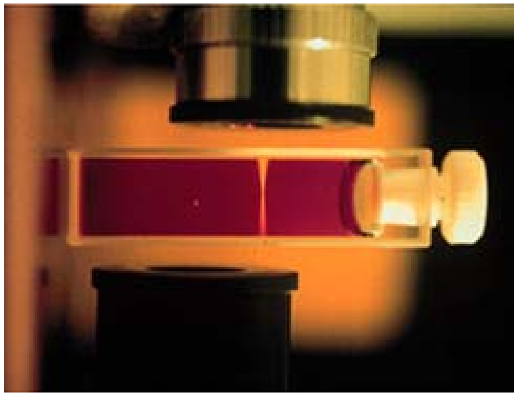
multiphoton absorption

multiphoton absorption

nonlinear interaction

spatial confinement of excitation

two-photon absorption

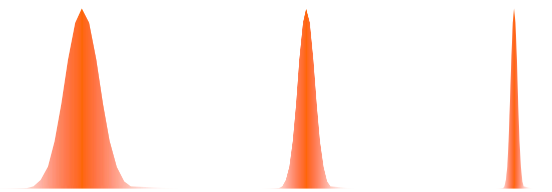


$$\alpha = \alpha_0 + \beta I$$
$$R \propto I^2$$

feature exploited for microfabrication

femtosecond pulses

Ti:Sapphire lasers



100 fs 50 fs 20 fs

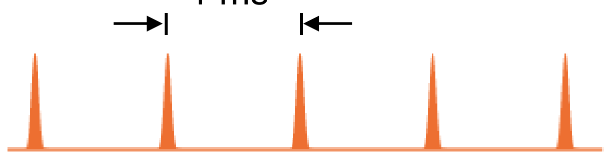
1 fs = 10^{-15} s

Repetition rate

Energy

1 ms

1 KHz

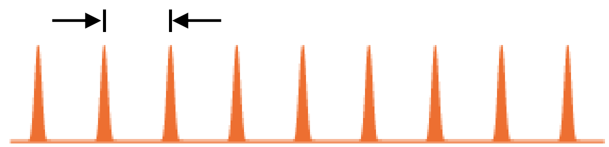


mJ

100 fs

12 ns

86 MHz



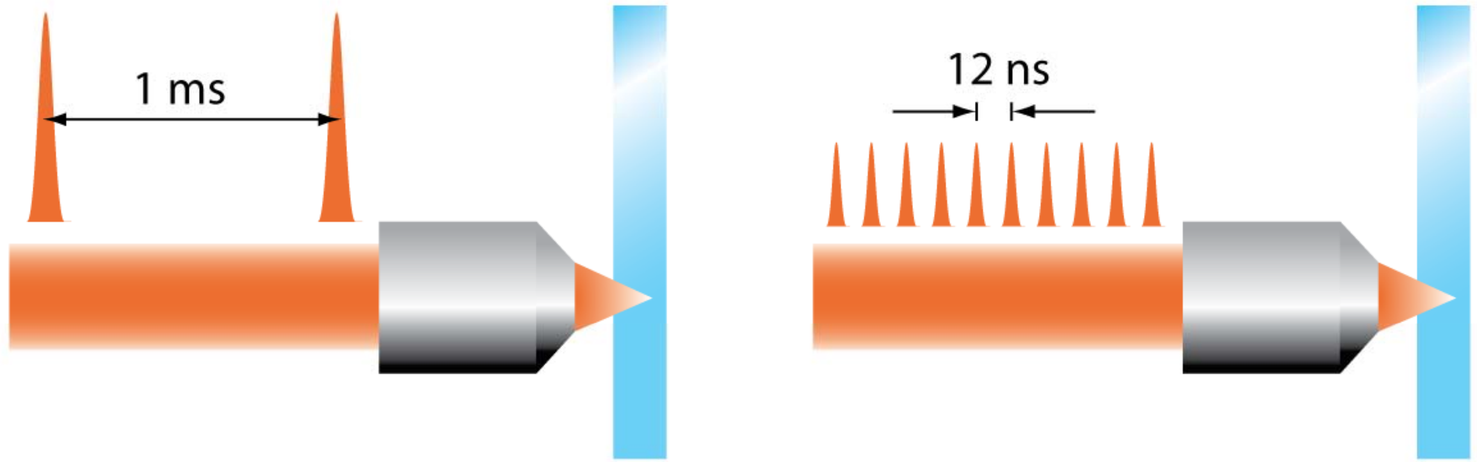
nJ

100 fs

fs-micromachining

amplified laser

oscillator



heat diffusion time: $t_{diff} \sim 1\ \mu s$

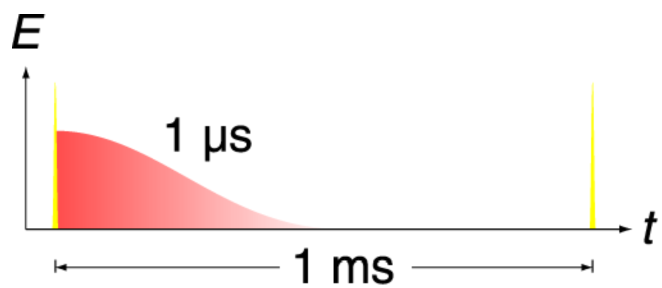
fs-micromachining

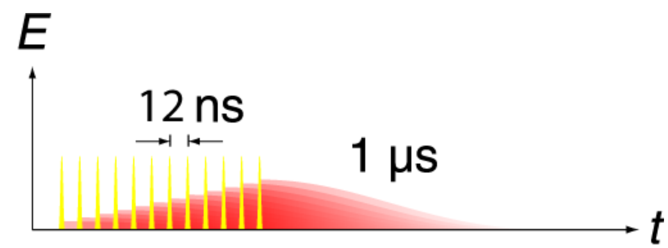
amplified laser

oscillator

low repetition laser

high repetition laser





repetitive

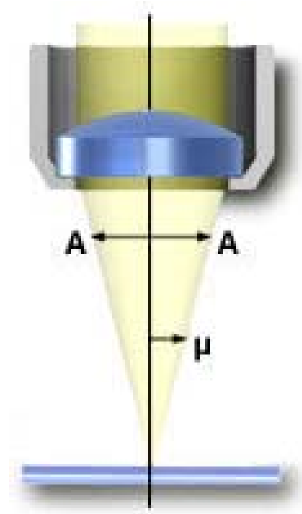
cumulative

fs-micromachining

high repetition rate micromaching

- material's change cause by accumulative effects
- spherical structuring region
- structured region exceeds the focal volume

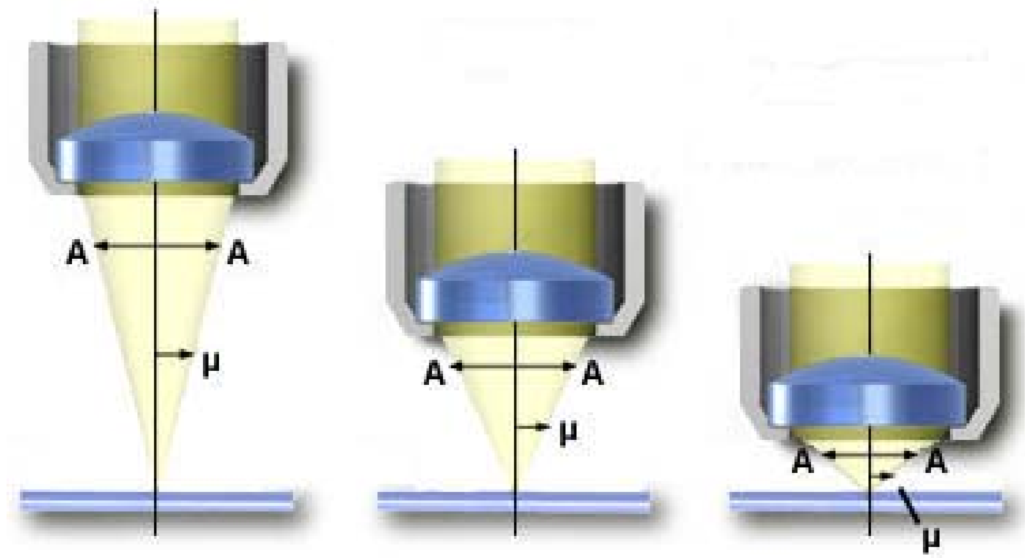
fs-micromachining: focusing



The angle μ is one-half the angular aperture A

$$NA = n \sin \mu$$

fs-micromachining: focusing



NA = 0.12

$\mu = 7^o$

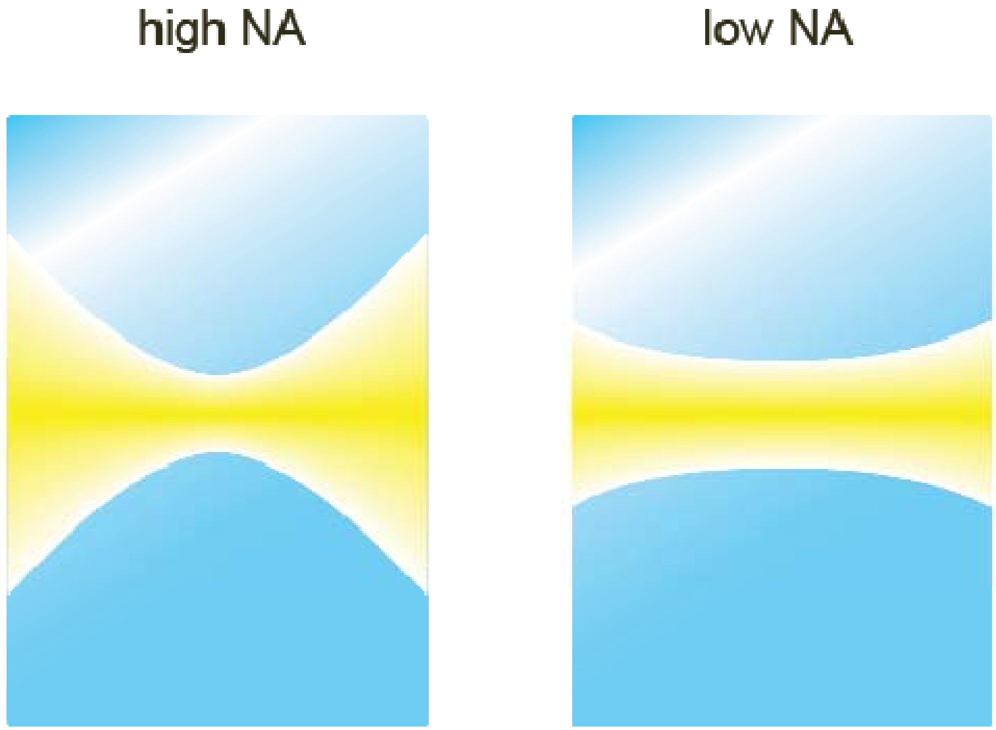
NA = 0.34

$\mu = 20^o$

NA = 0.87

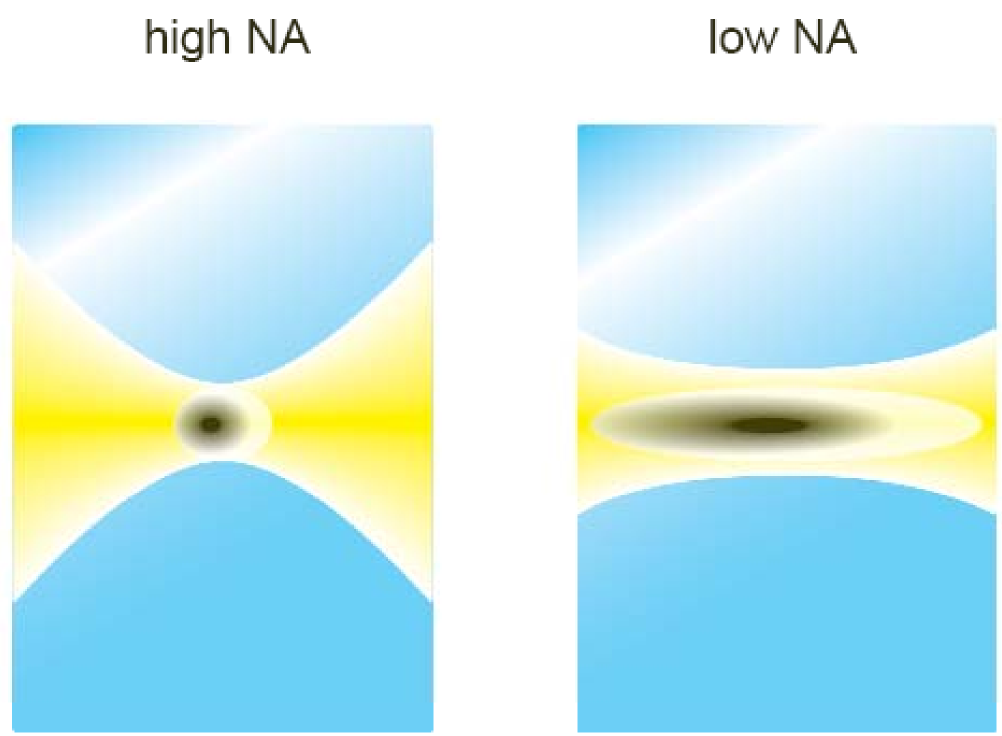
$\mu = 60^o$

what is the difference ?



$$w_0 = \frac{\lambda}{\pi NA}\sqrt{1 - NA^2}$$

very different confocal lenght/interaction length



fs-micromachining

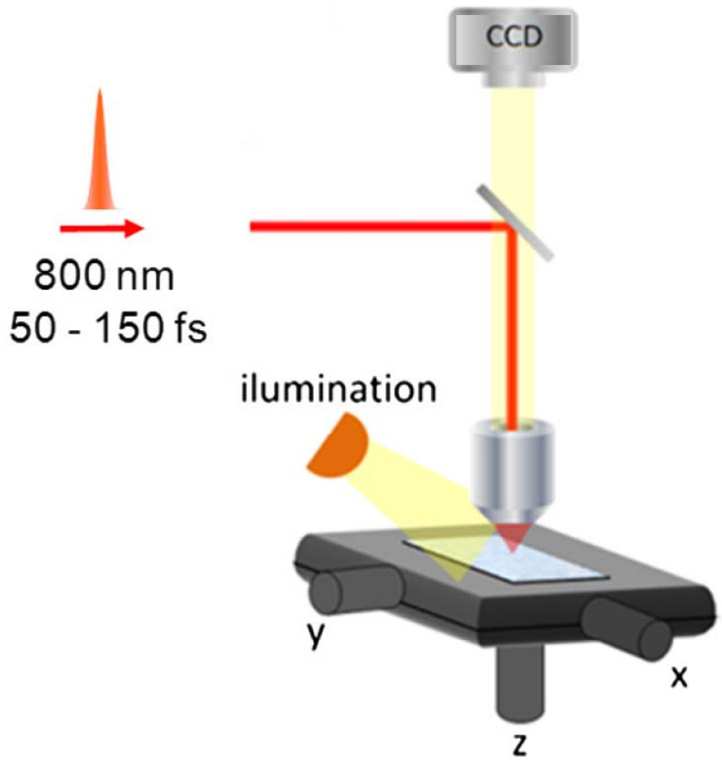
microfabrication can be controlled by

- objective NA
- number of pulses – scanning speed
- pulse energy

two main techniques

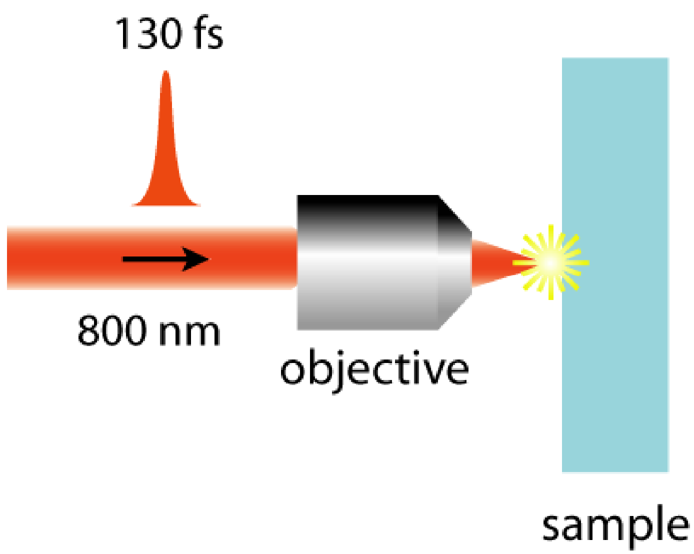
- fs-laser micromachining/microstructuring
- microfabrication via two-photon polymerization

fs-laser microstructuring experimental setup



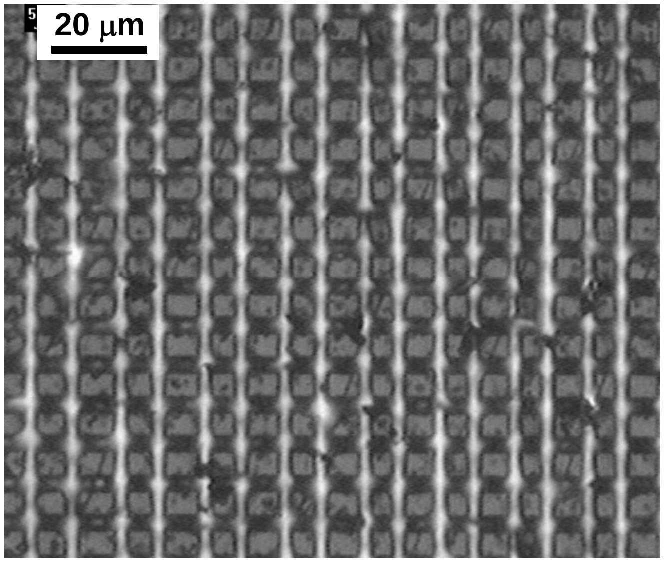
fs-laser micromachining

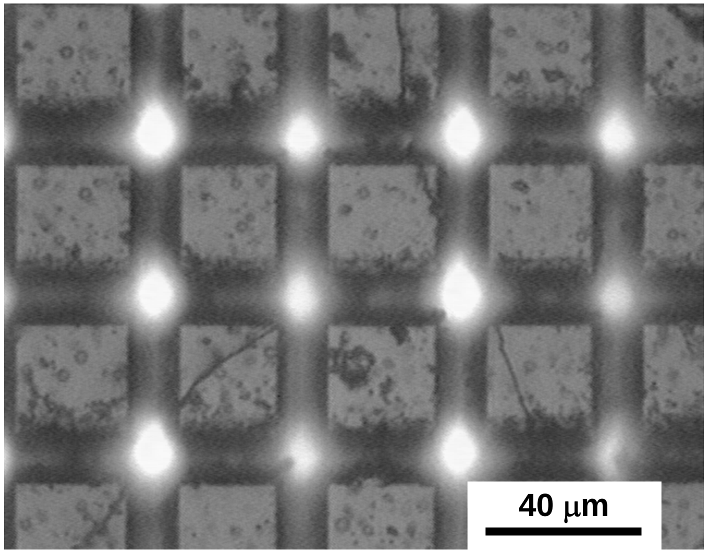
Surface



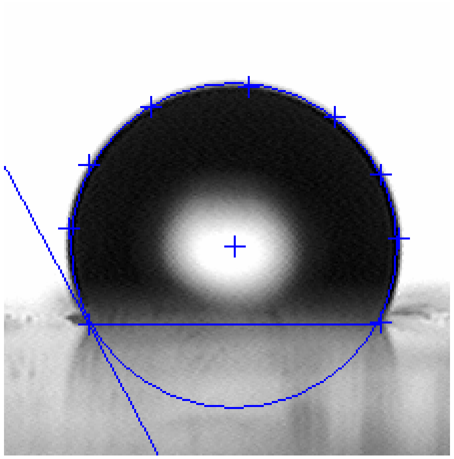
laser microfabrication: super hydrophobic surface

examples of fabricated surfaces



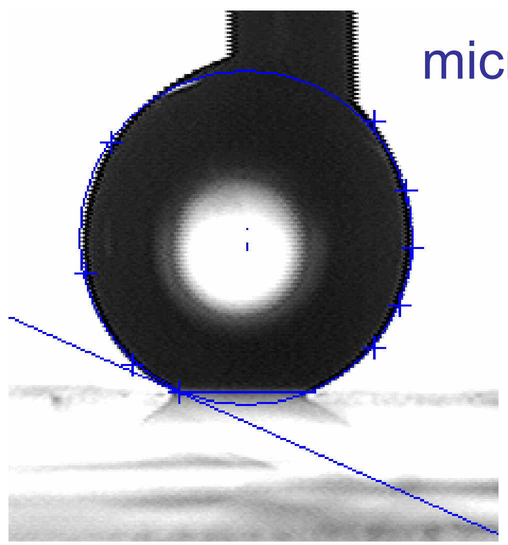


microstructuring polymer



flat surface

θ = 118º

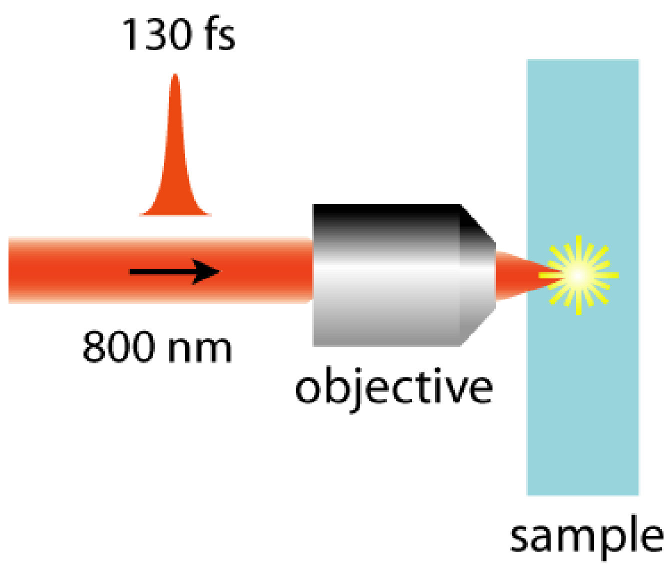


microstructured surface

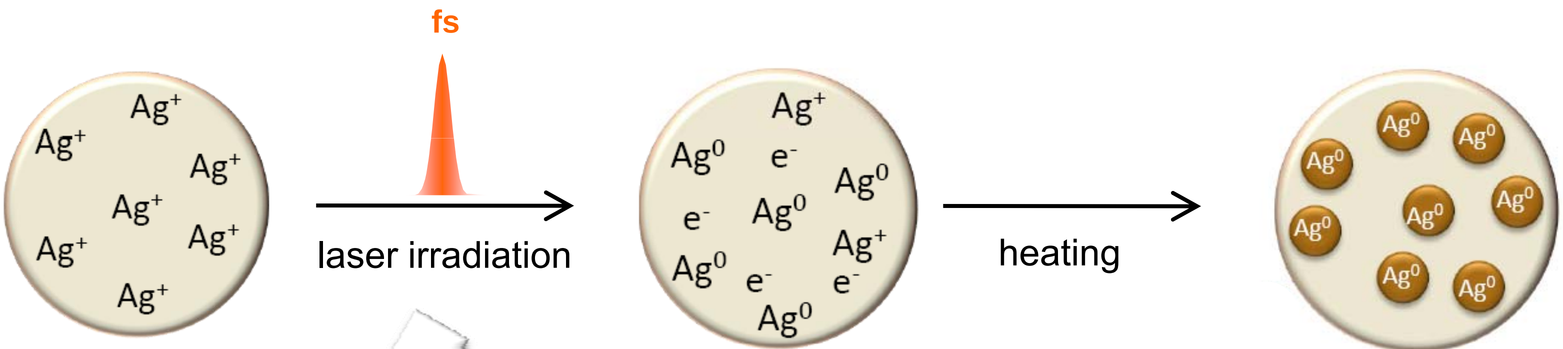
θ = 160º

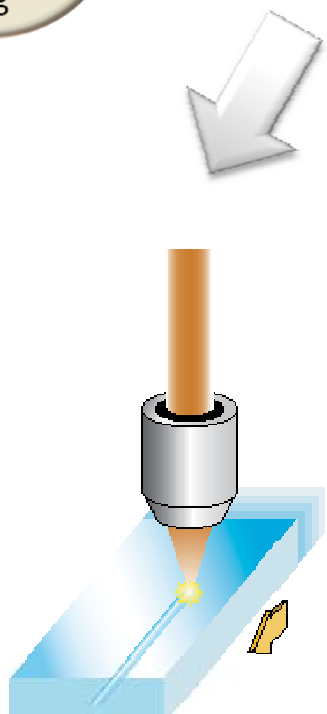
fs-laser micromachining

Volume



Generation of Ag nanoparticles





Ag nanoparticles are generated only in the irradiated area due to the **fs-laser induced photoreduction**

Free electron generation

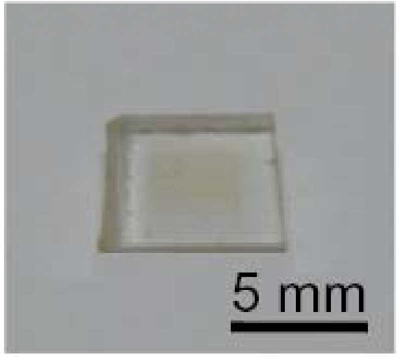
Photoreduction reaction

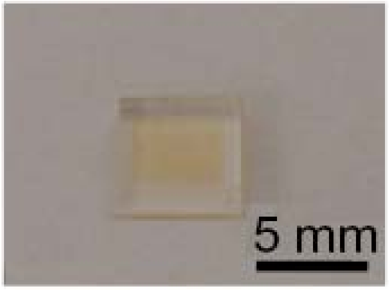
$Ag^+ + e^- \rightarrow Ag^0$

Generation of Ag nanoparticles

Silver doped barium borate glass (Ag:BBO)

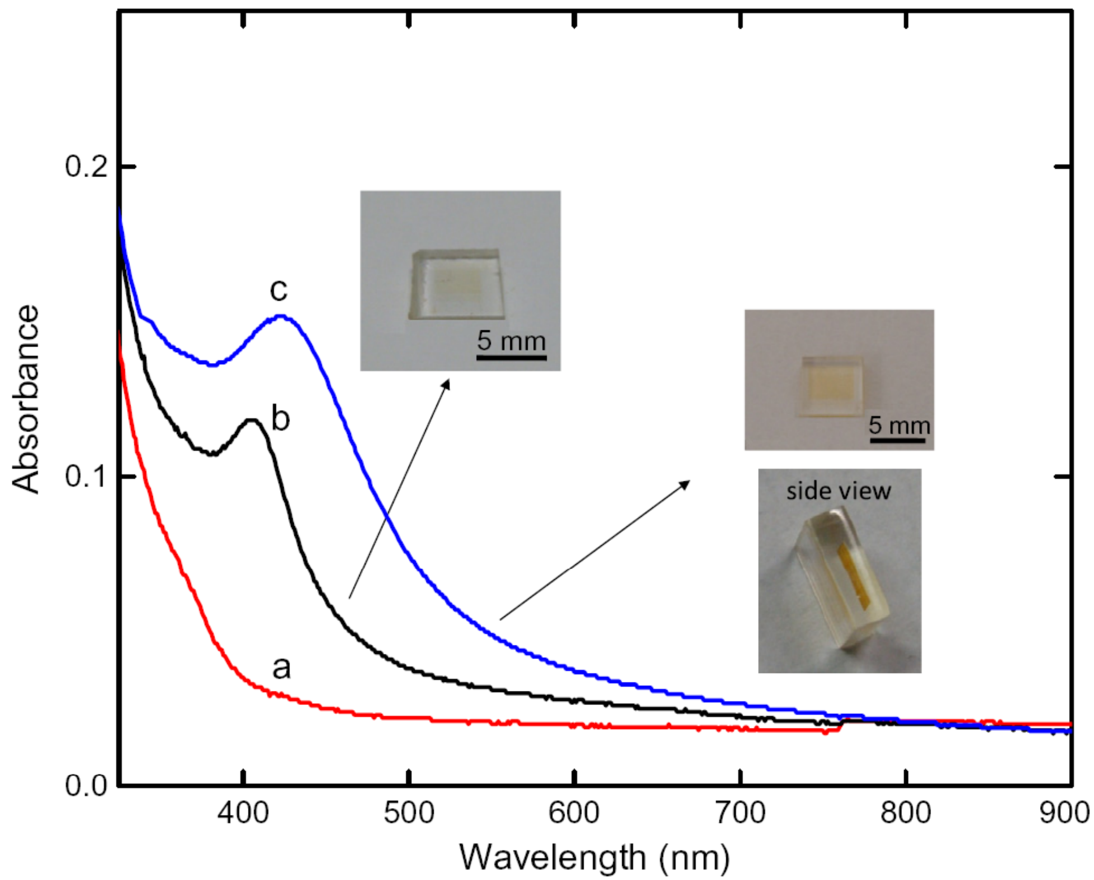
Sample after irradiation with the amplified fs-laser (1 kHz) and subsequent thermal treatment at 400 C for 1 h





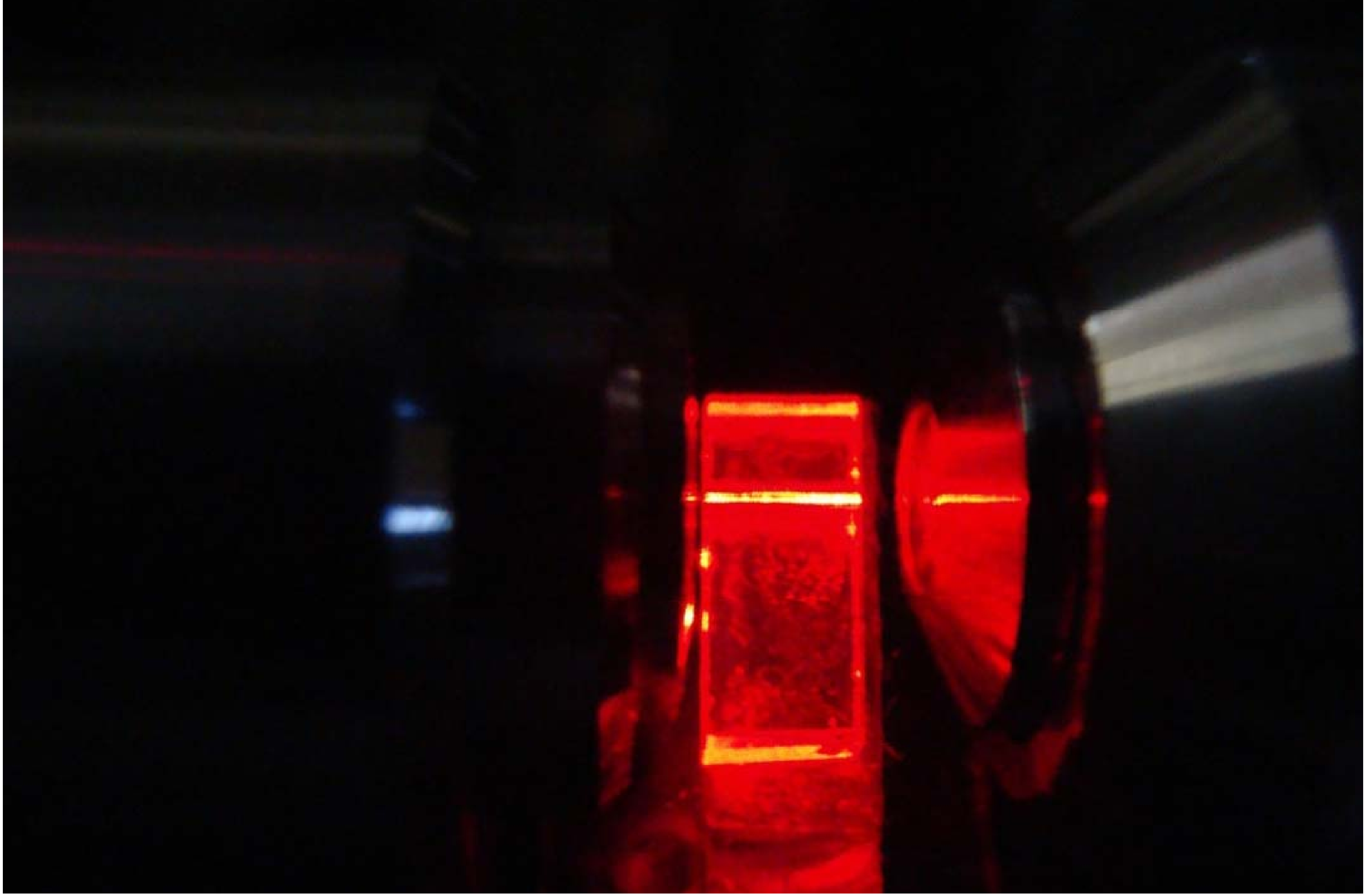
Sample after irradiation with the 5 MHz fs-laser

Generation of Ag nanoparticles



Absorption spectrum of the Ag:BBO sample as prepared (a), after irradiation with the 5 MHz fs-laser (b) and after irradiation with the amplified fs-laser (1 kHz) and subsequent thermal treatment.

fs-laser waveguides fabrication



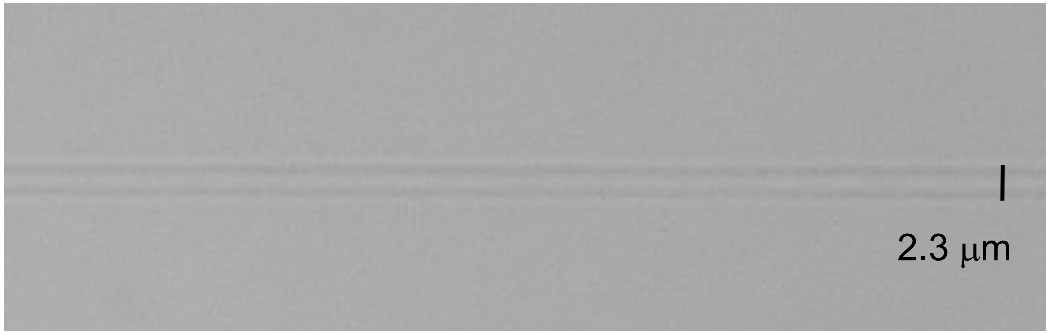
Waveguides fabrication

Sample:

Ag:P7W3

Tungsten lead pyrophosphate glass - ($70Pb_2P_2O_7$-$30WO_3$):1AgCl (%mol)

Waveguides fabricated using the 5-MHz laser system (50 fs) with 37 nJ/pulse and v = 10 µm/s

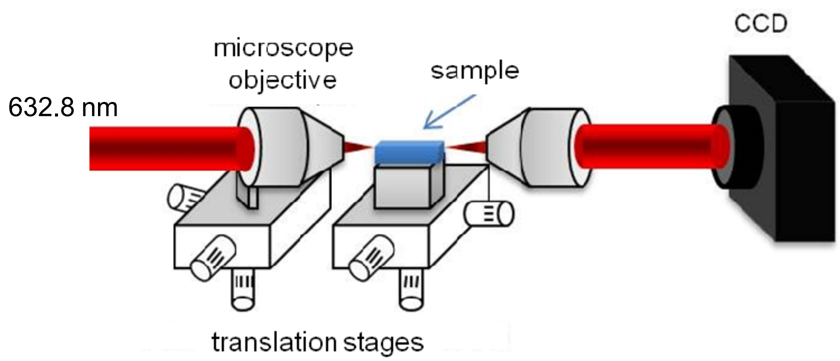


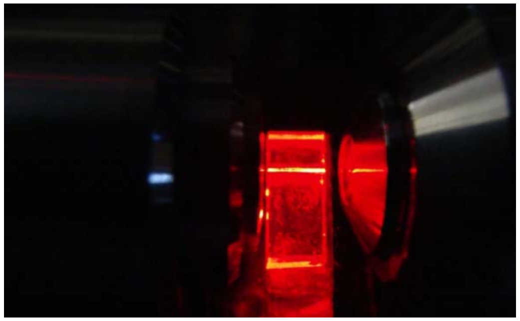
Top view

Cross-section view

Waveguides fabrication

Coupling light into the waveguides





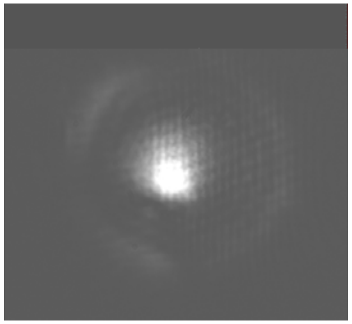
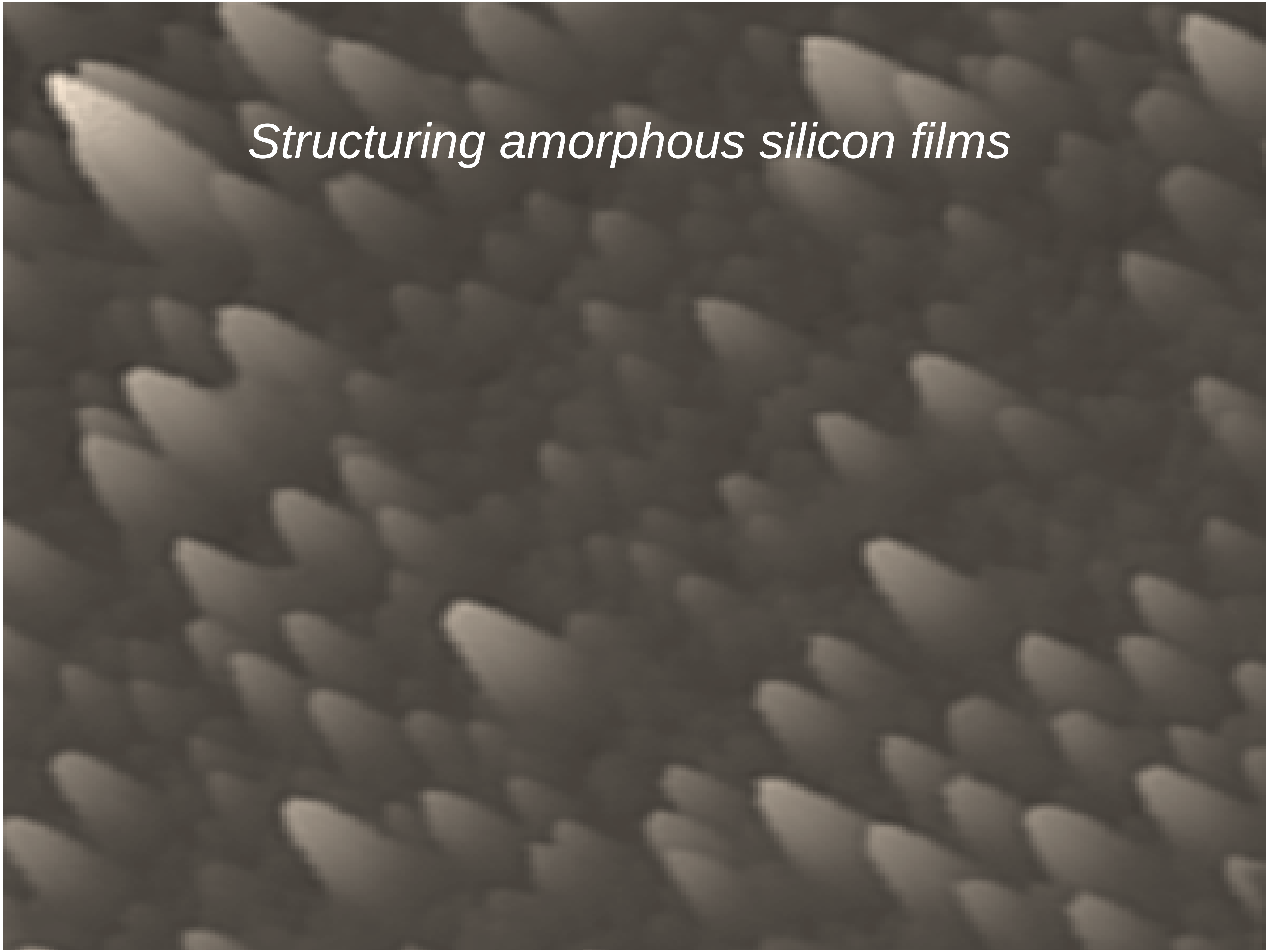


image of the waveguide output

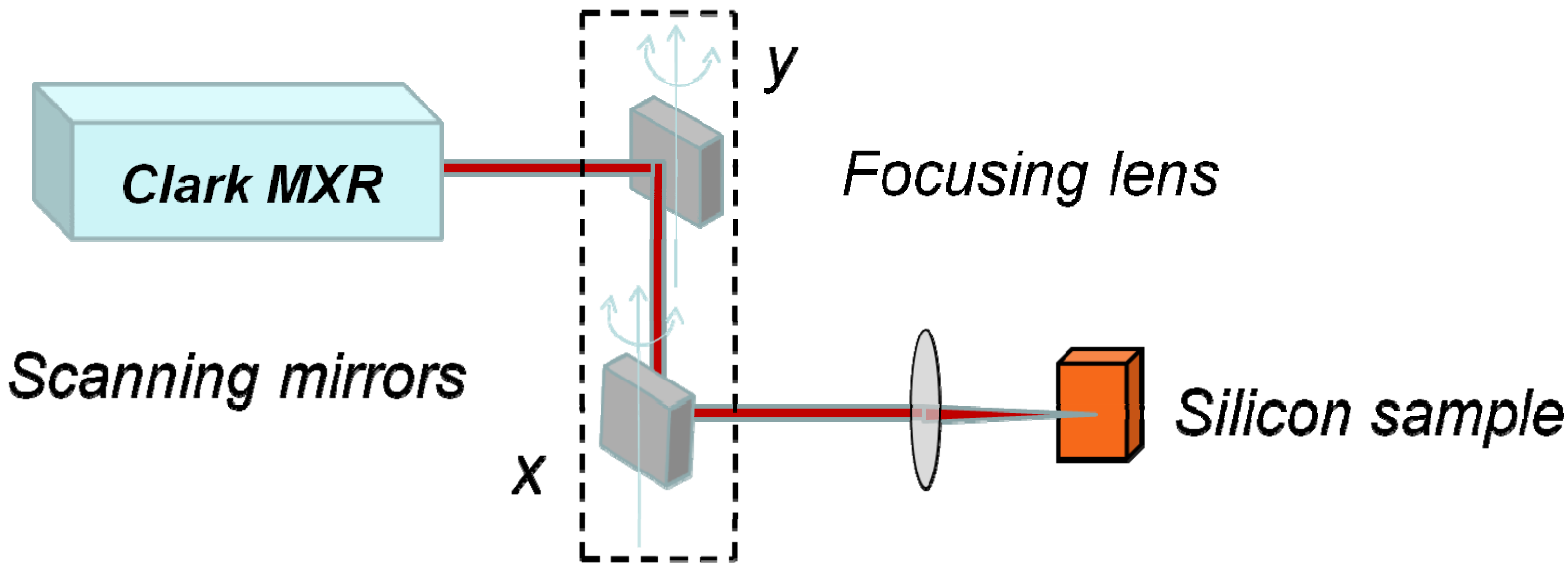
measured waveguide loss L = 1.3 dB/mm

Structuring amorphous silicon films



structuring amorphous Si surface

Experimental setup uses a pair of scanning mirrors

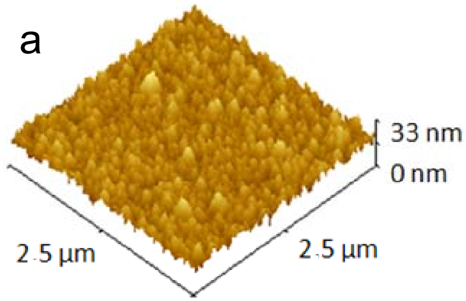


150 fs, 775 nm, 1 KHz, v = 5 mm/s, f= 20 cm

structuring amorphous Si surface

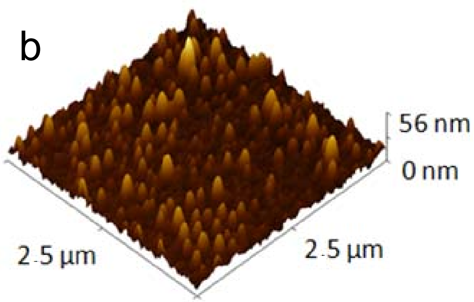
AFM micrographs of aSi microstructures at different laser intensities

a



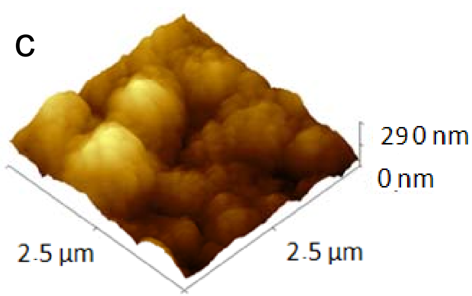
before irradiation

b



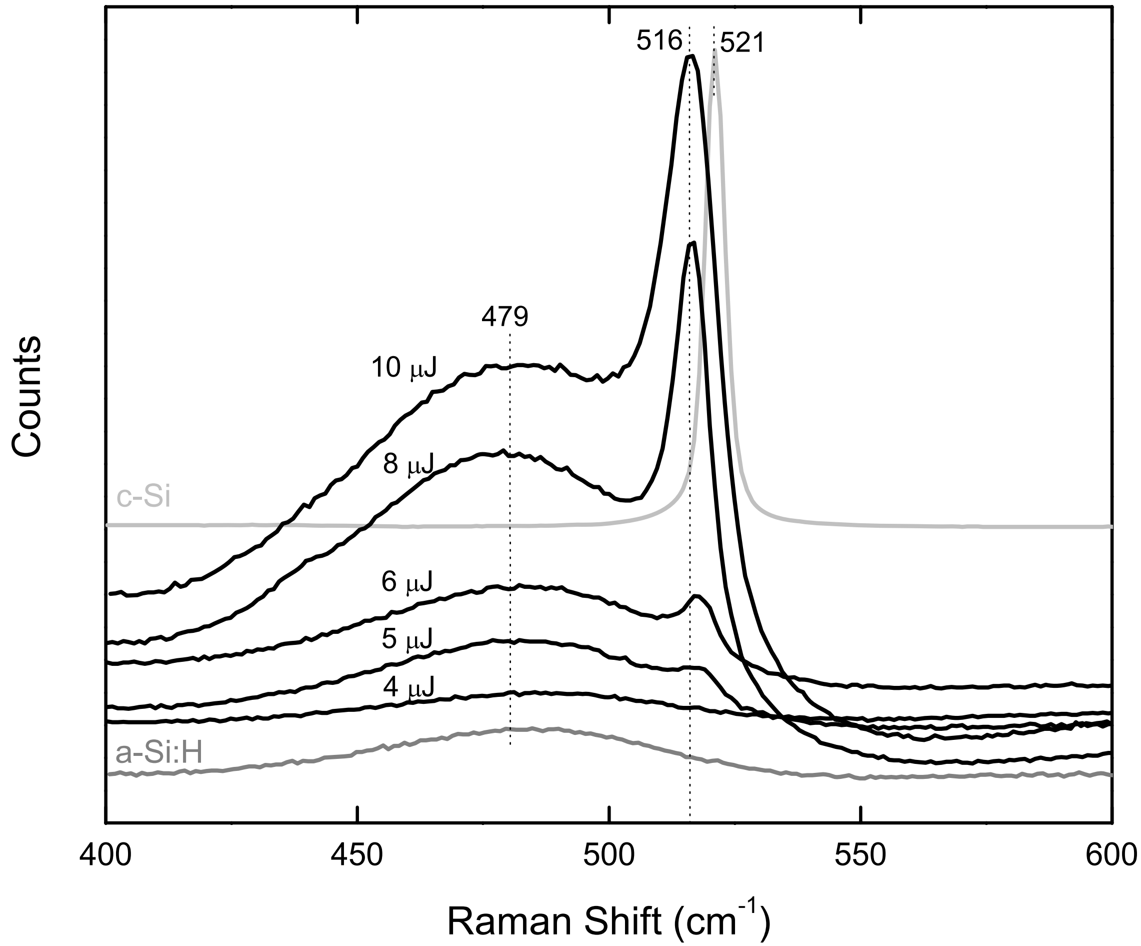
E = 5 µJ/pulse

c



E = 8 µJ/pulse

structuring amorphous Si surface



Micro-Raman analysis reveals the crystallization of the aSi upon fs-laser irradiation

structuring amorphous Si surface

The crystalline volume fraction

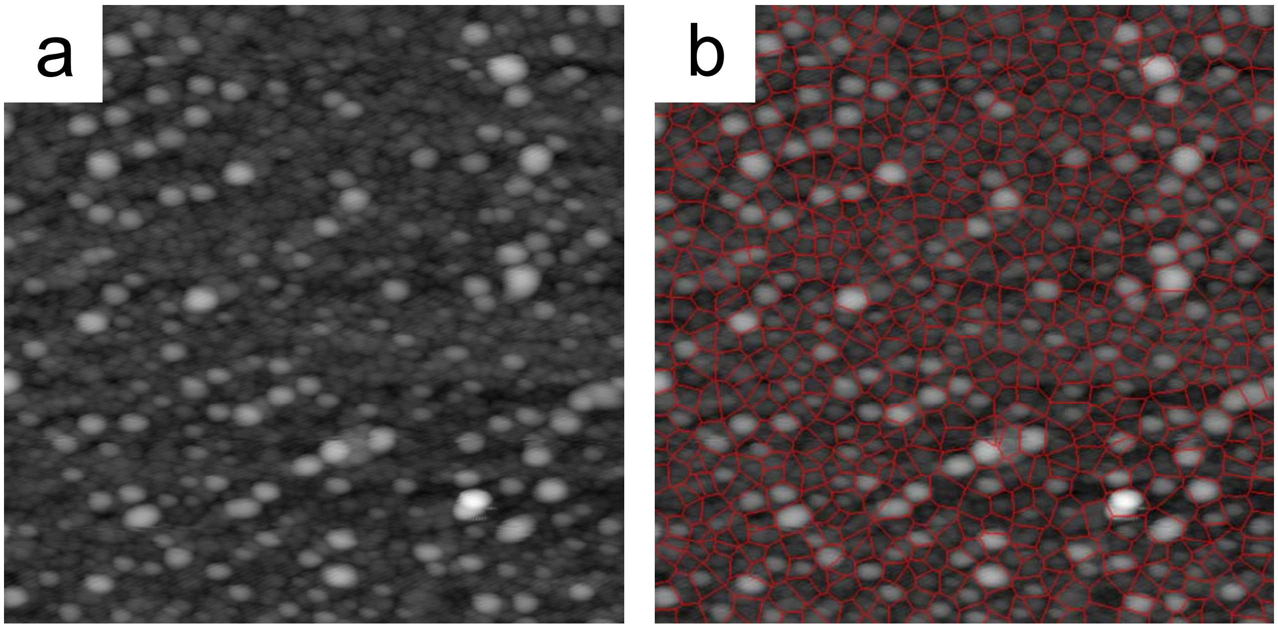
$$X_c = I_{cp} / (I_{cp} - \sigma I_{ap})$$

in which I_{cp} and I_{ap} are the intensities of the crystalline peak and at the center of the amorphous band

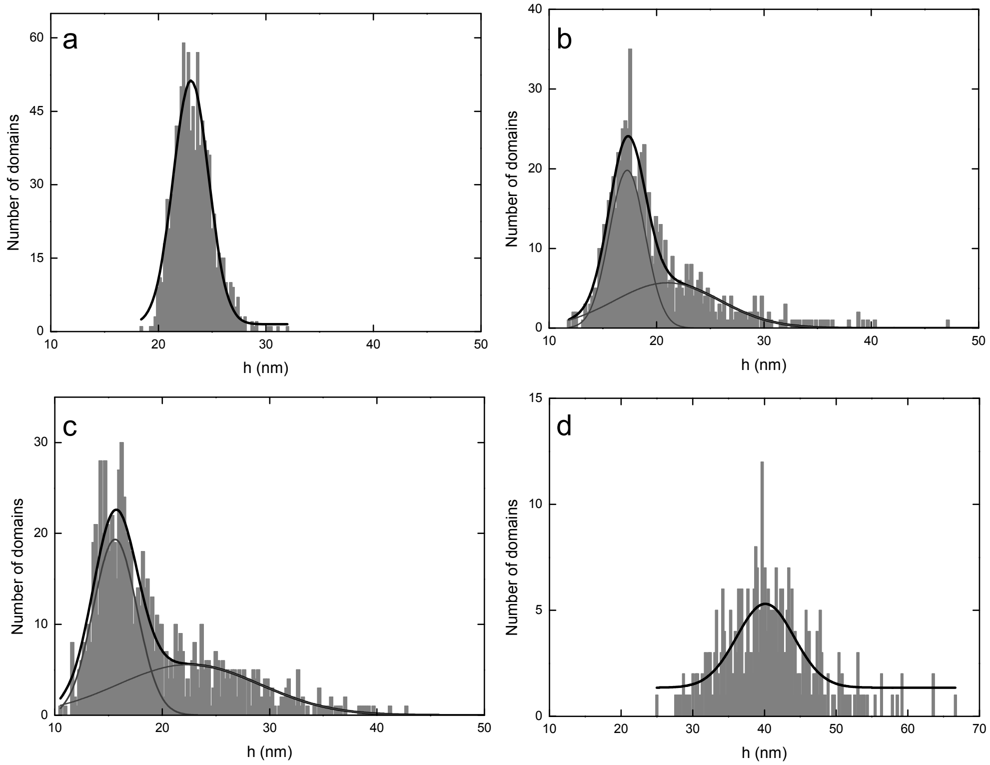
Pulse energy (μJ)	X_c **(%)**	**Raman peak (cm^{-1})**	**Nanocrystal diameter (nm)**
4	0	-	-
5	43	519	9
6	48	518	6
8	62	517	5
10	73	516	4

structuring amorphous Si surface

AFM image of a a-Si:H sample irradiated with 5 μJ (a) and its corresponding segmentation obtained using the Voroni´s diagram method (b).

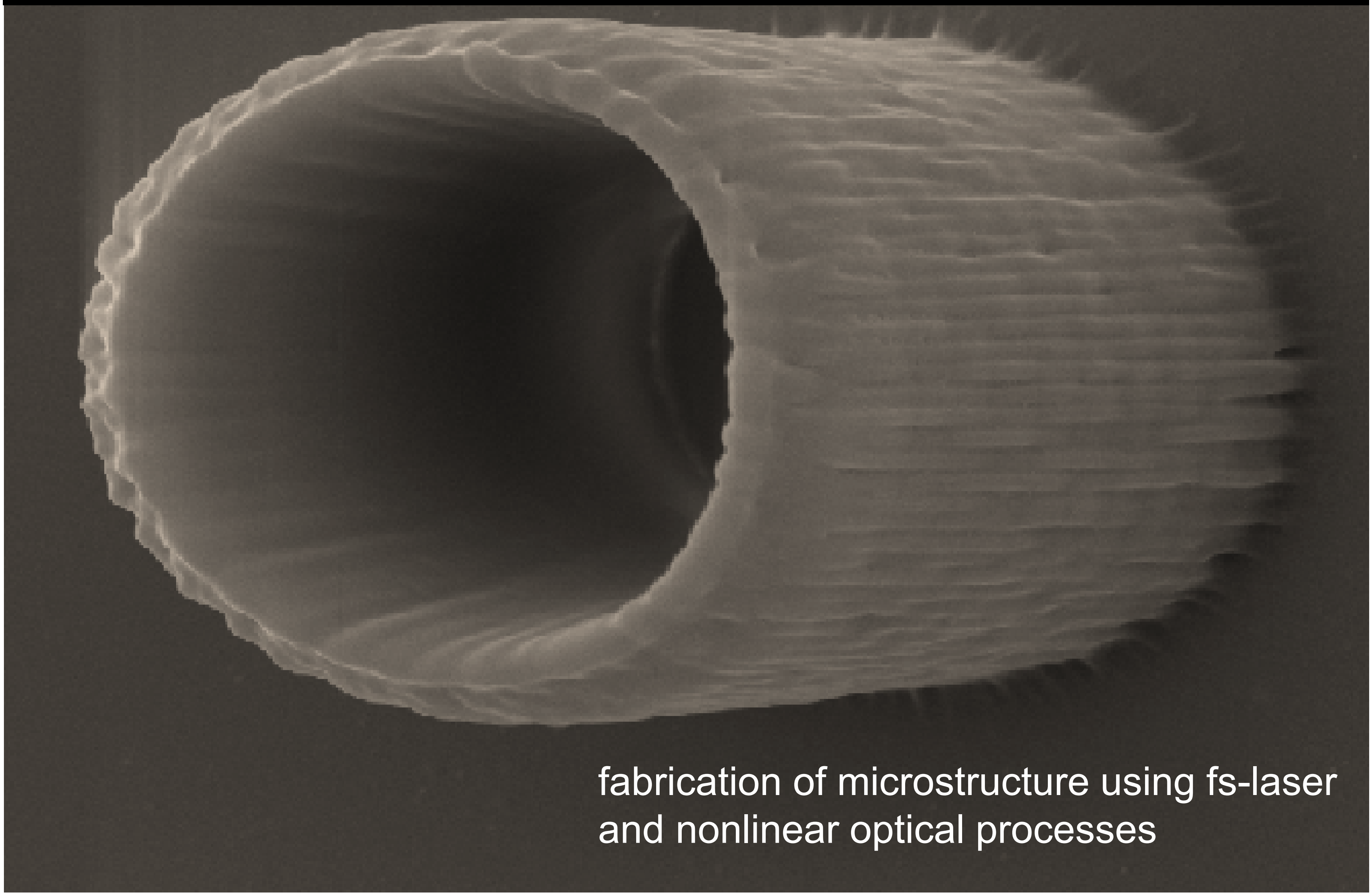


structuring amorphous Si surface



Height histograms of the domains on the sample surface
(a) before laser irradiation
(b) E = 4 μJ
(c) E = 5 μJ
(d) E = 6 μJ

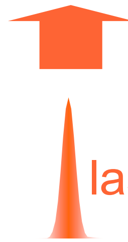
fs-laser microfabrication



fabrication of microstructure using fs-laser
and nonlinear optical processes

Two-photon polymerization

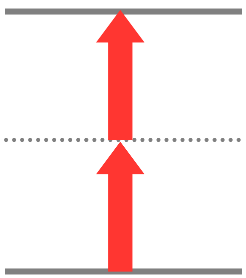
Monomer + Photoinitiator → Polymer



laser pulse

100 fs

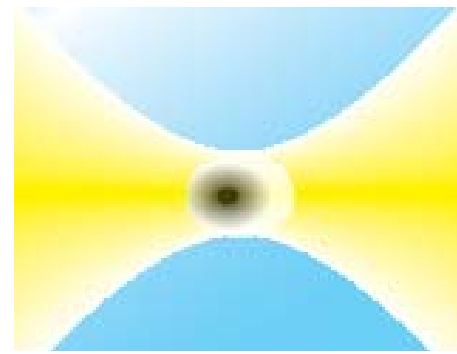
Photoinitiator is excited by ***two-photon absorption***

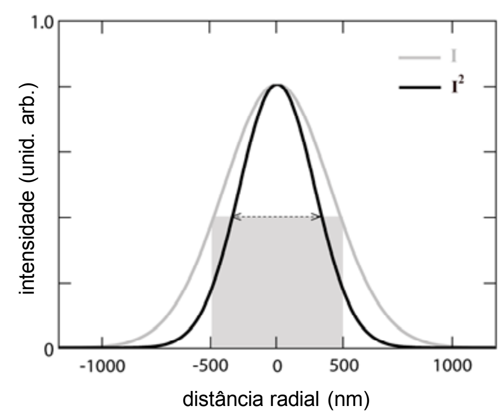


$$R \propto I^2$$

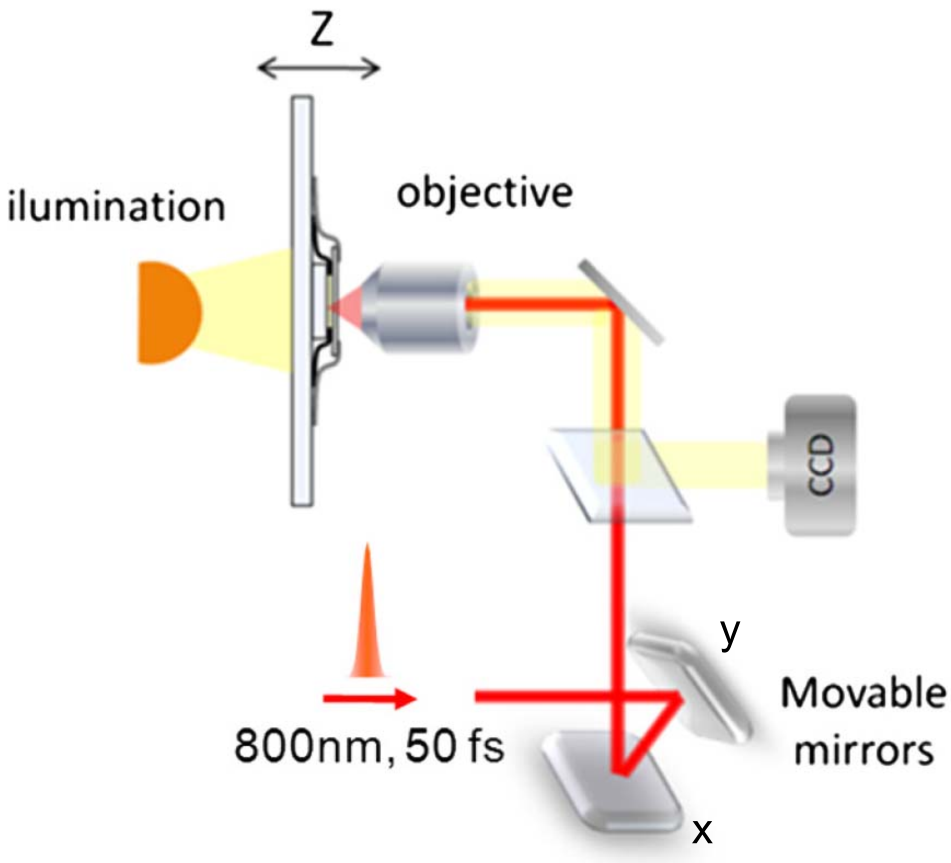
The polymerization is confined to the focal volume.

High spatial resolution





Two-photon polymerization setup



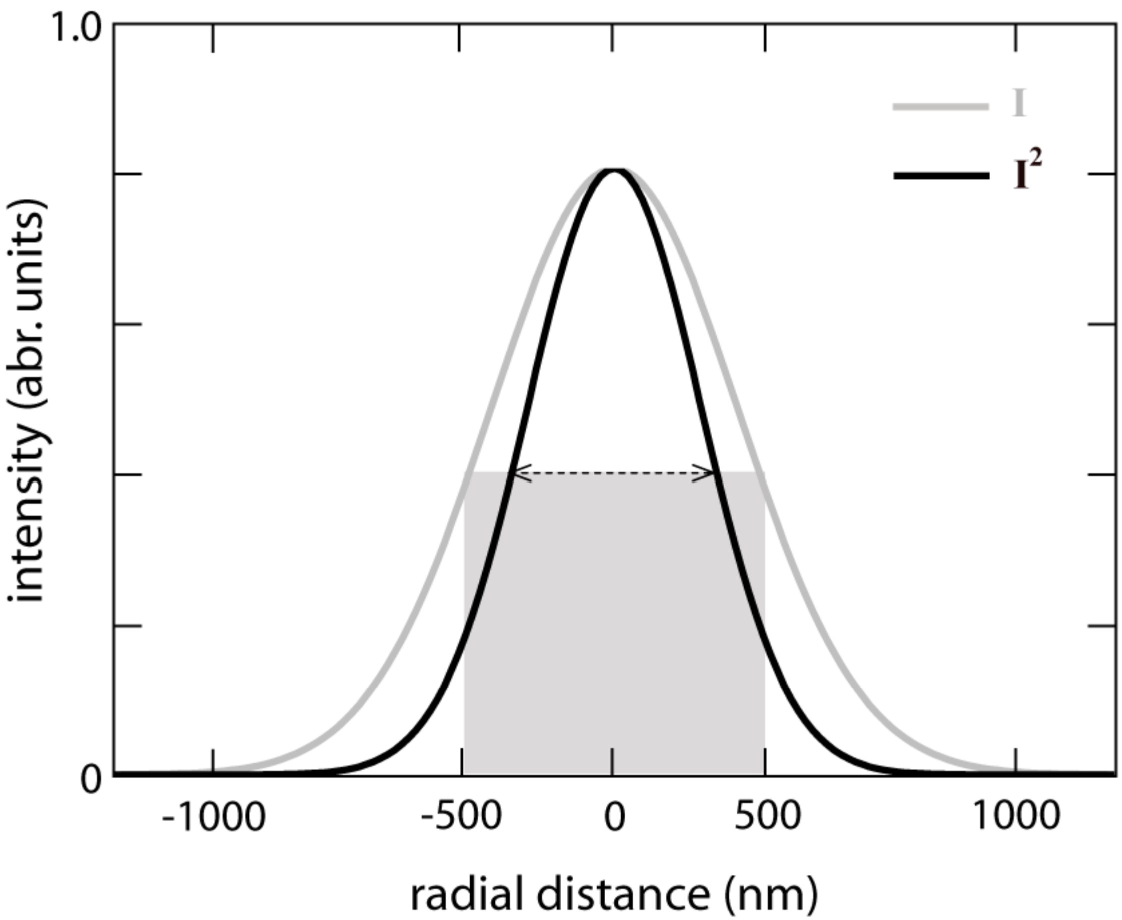
Ti:sapphire laser oscillator

- 50 fs
- 800 nm
- 80 MHz
- 20 mW

Objective

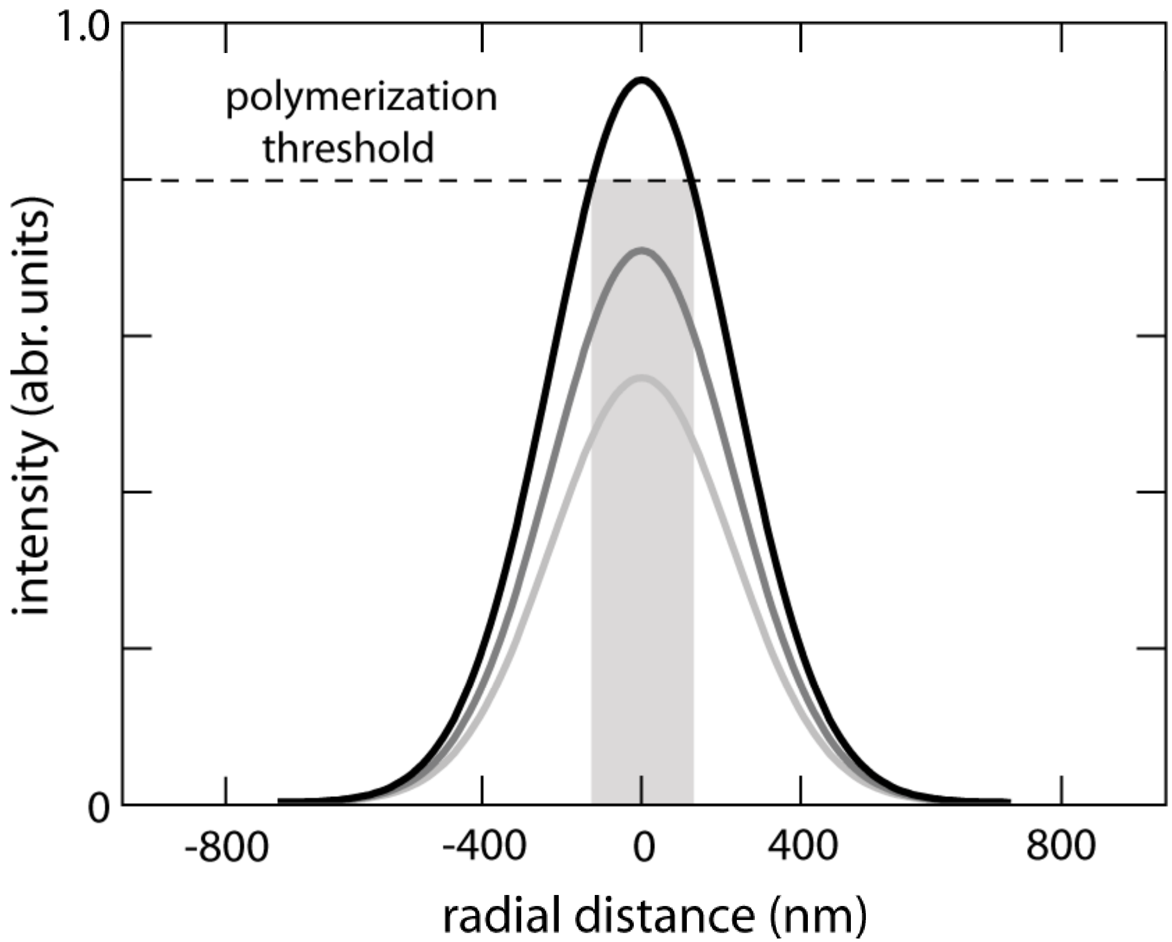
40 x
0.65 NA

Two-photon polymerization



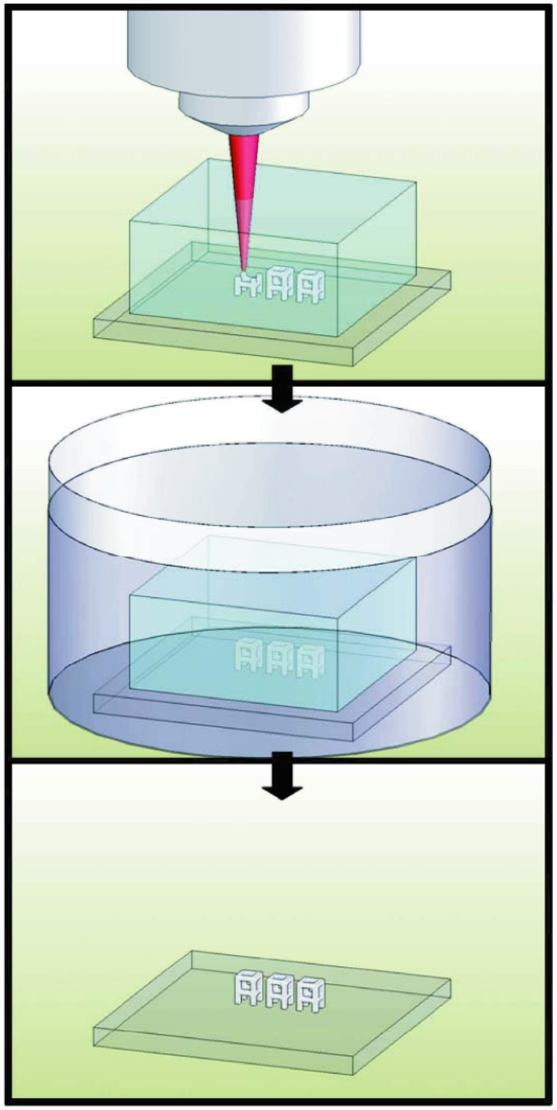
bellow the diffraction limit

Two-photon polymerization



even higher spatial resolution

Two-photon polymerization

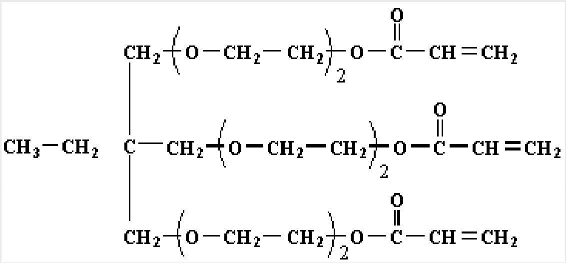


After the fabrication, the sample is immersed in ethanol to wash away any unsolidified resin and then dried

Resin preparation

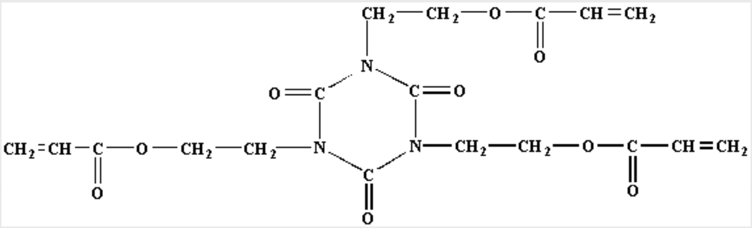
Monomers

Monomer A



reduces the shrinkage upon polymerization

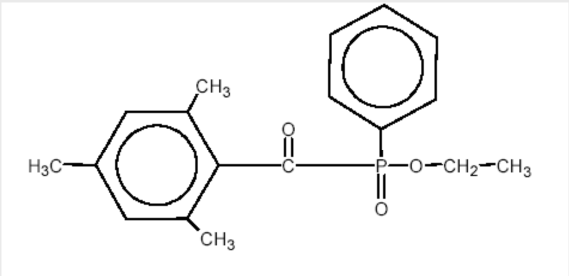
Monomer B



gives hardness to the polymeric structure

Photoinitiator

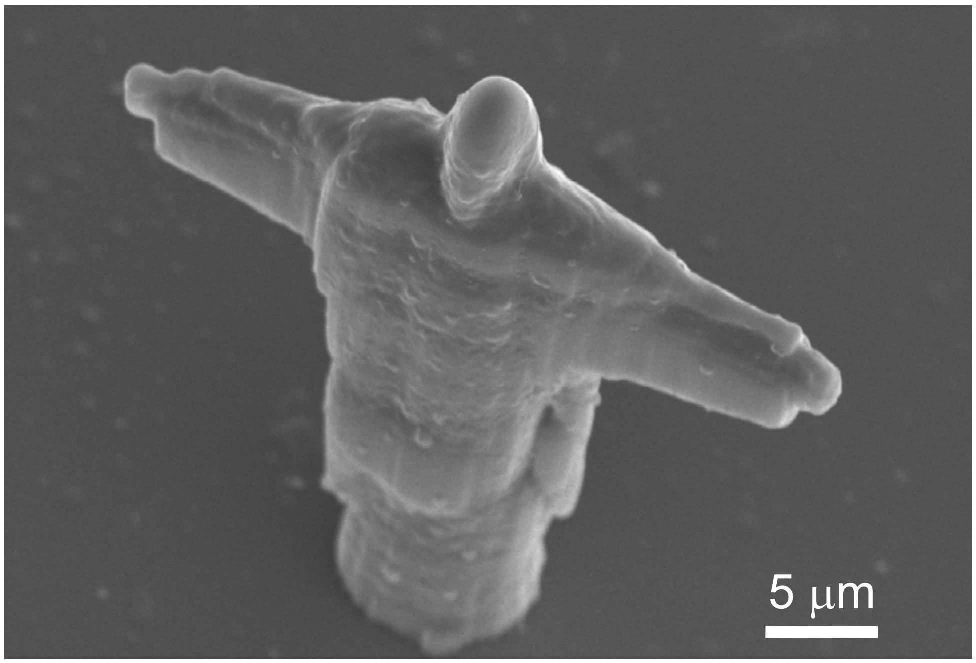
Lucirin TPO-L



Appl. Phys. A, 90, 633–636 (2008)

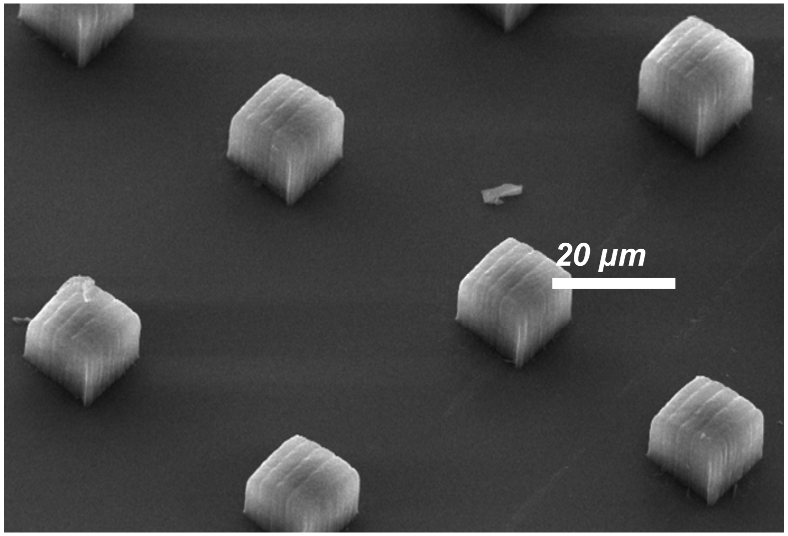
two-photon polymerization

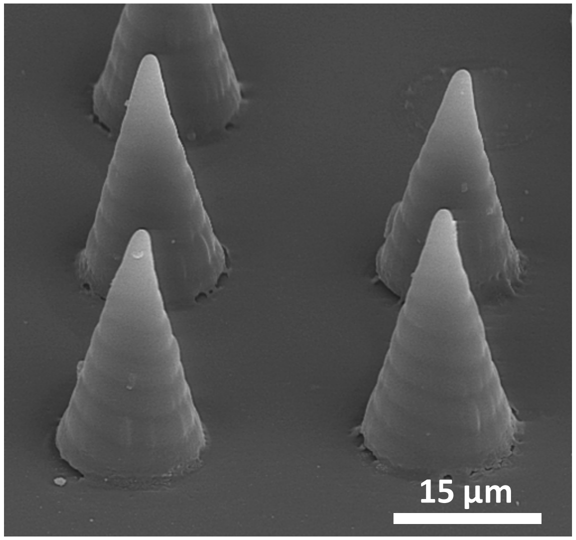
Microstructure fabricated by two-photon polymerization

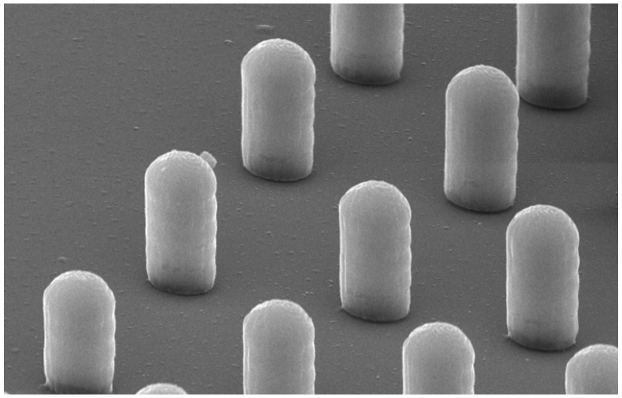


Two-photon polymerization

Microstructures fabricated by two-photon polymerization

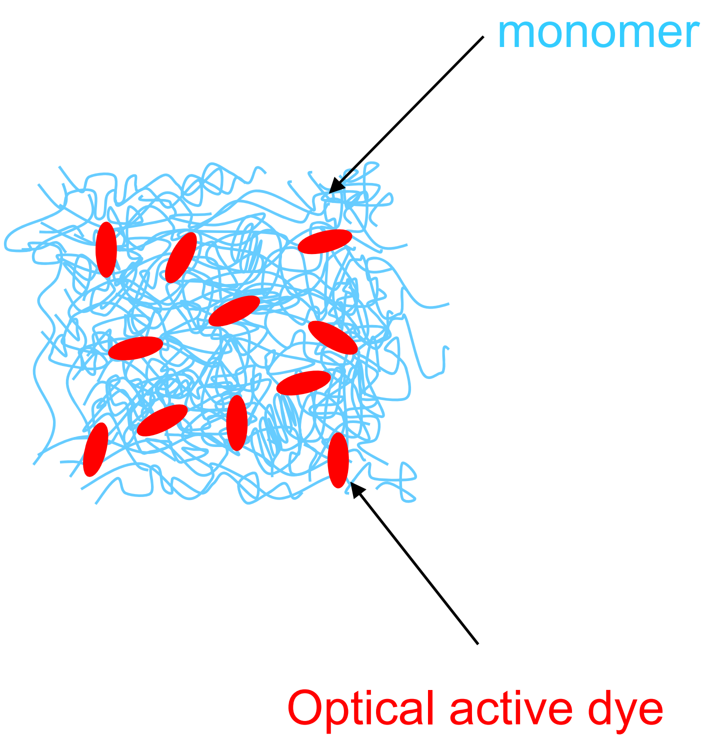


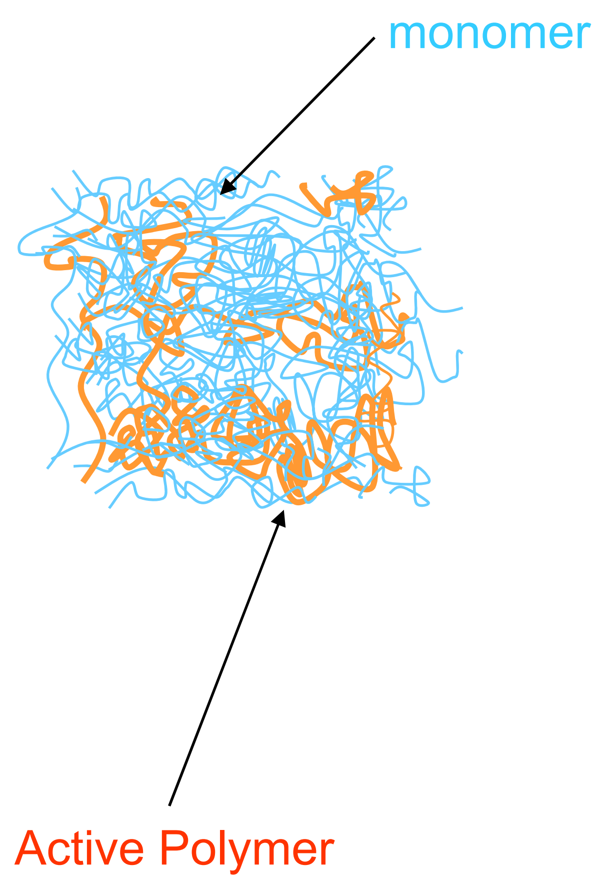




Doping microstructures

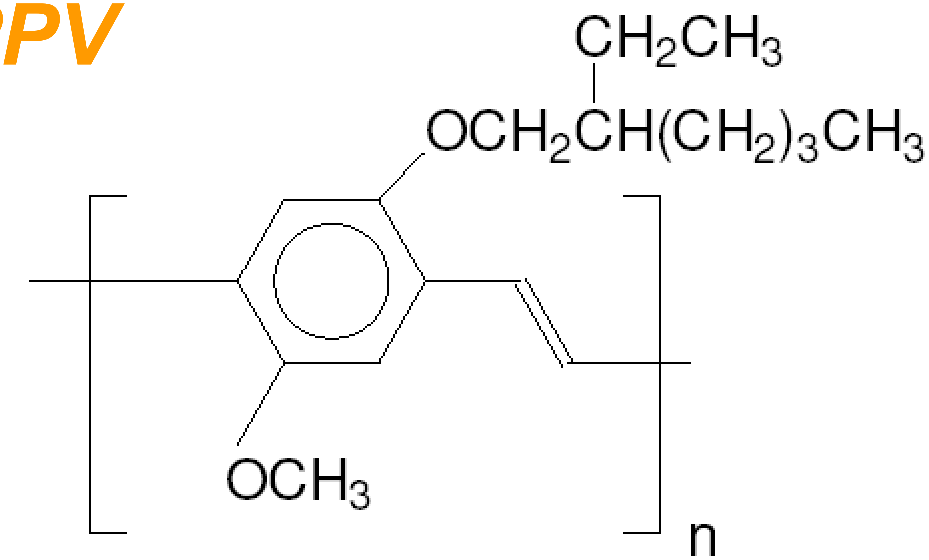
Microstructures containing active compounds





Microstructure containing MEH-PPV

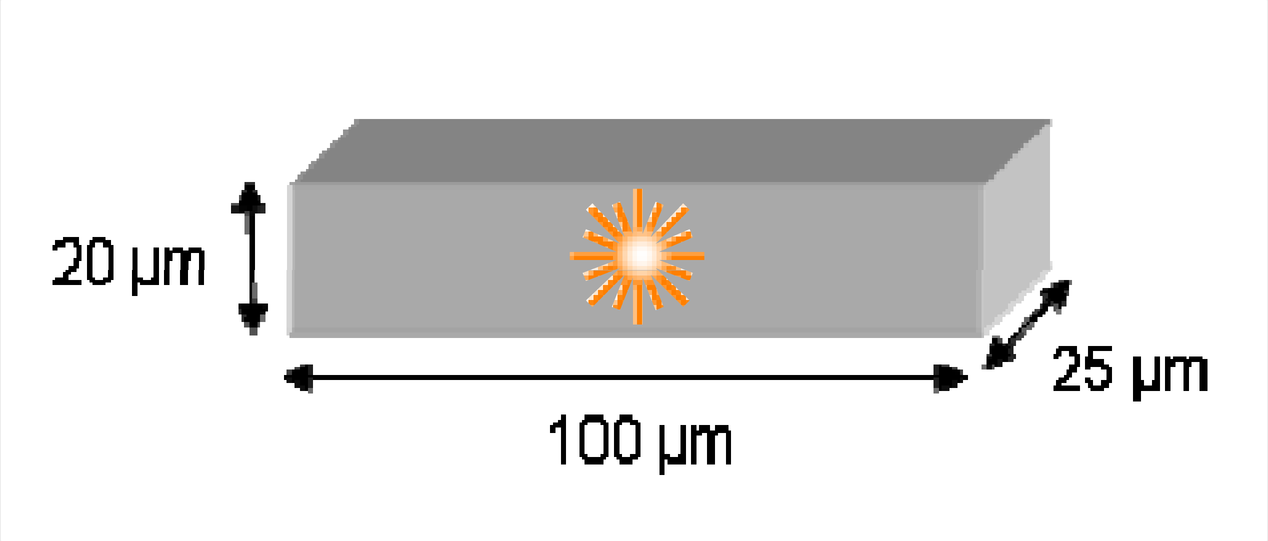
MEH-PPV



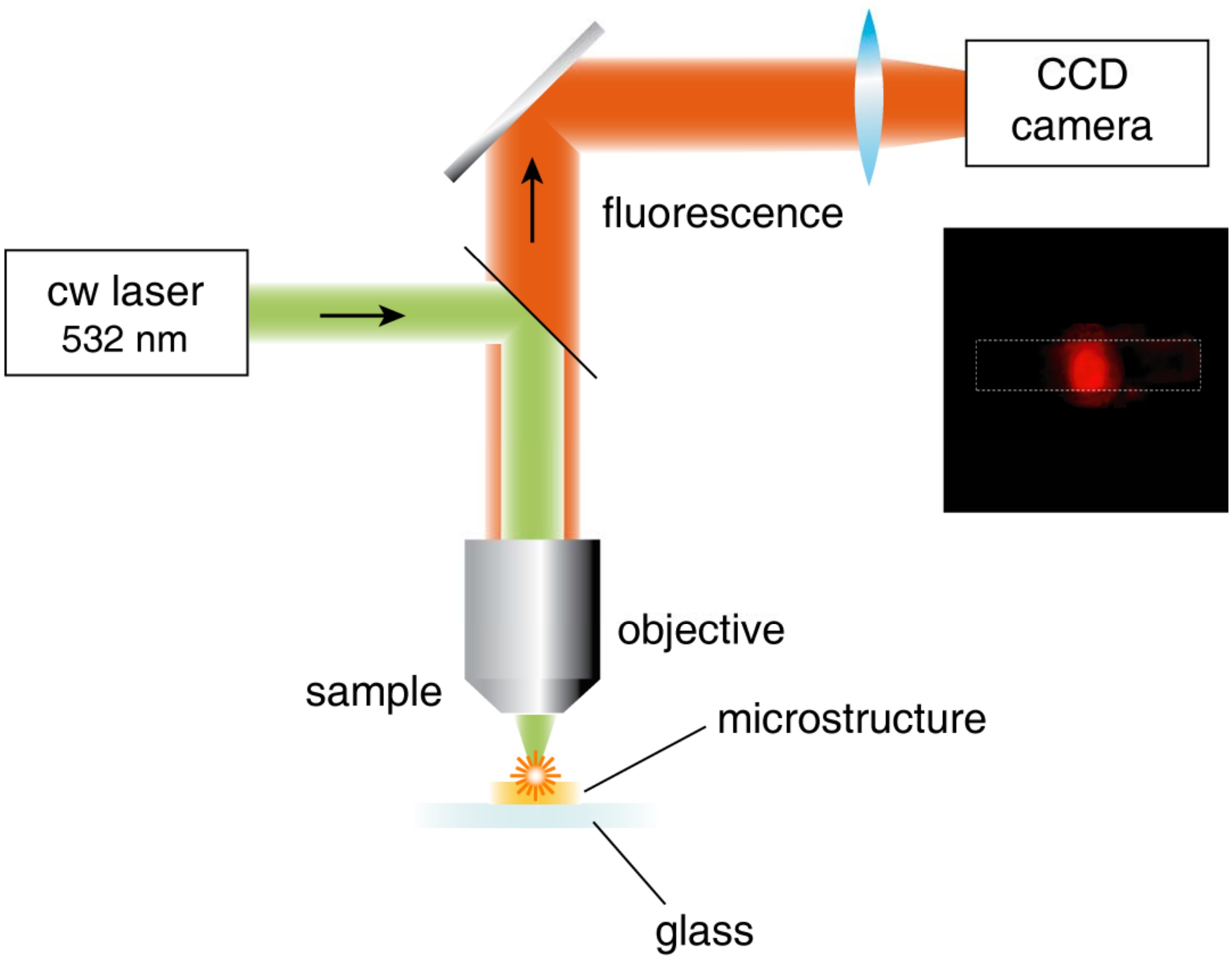
- Fluorescence
- Electro Luminescent
- Conductive

Microstructure containing MEH-PPV

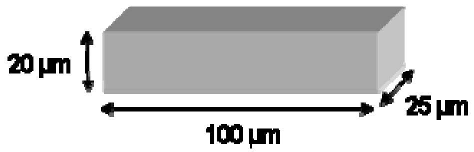
Do we have waveguiding in the microstructure ?

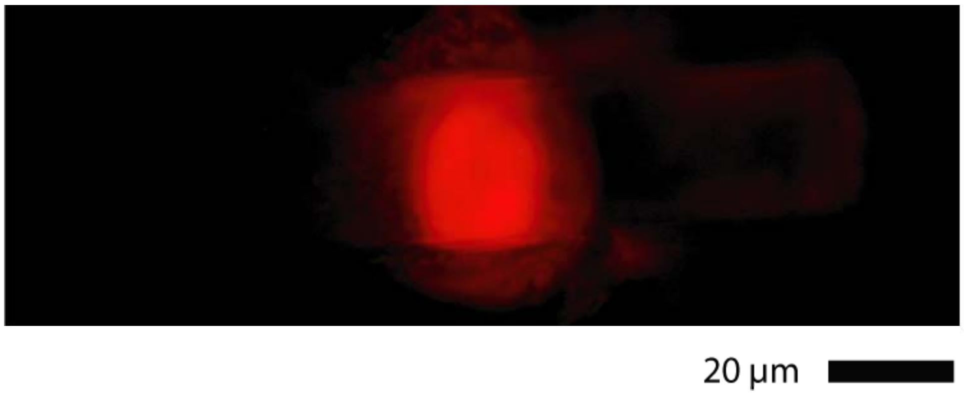


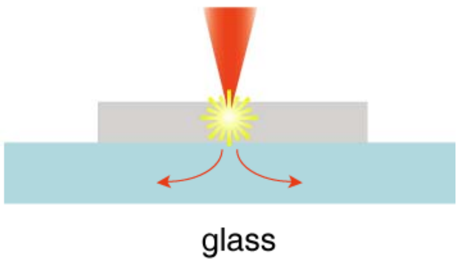
Microstructure containing MEH-PPV



Microstructure containing MEH-PPV

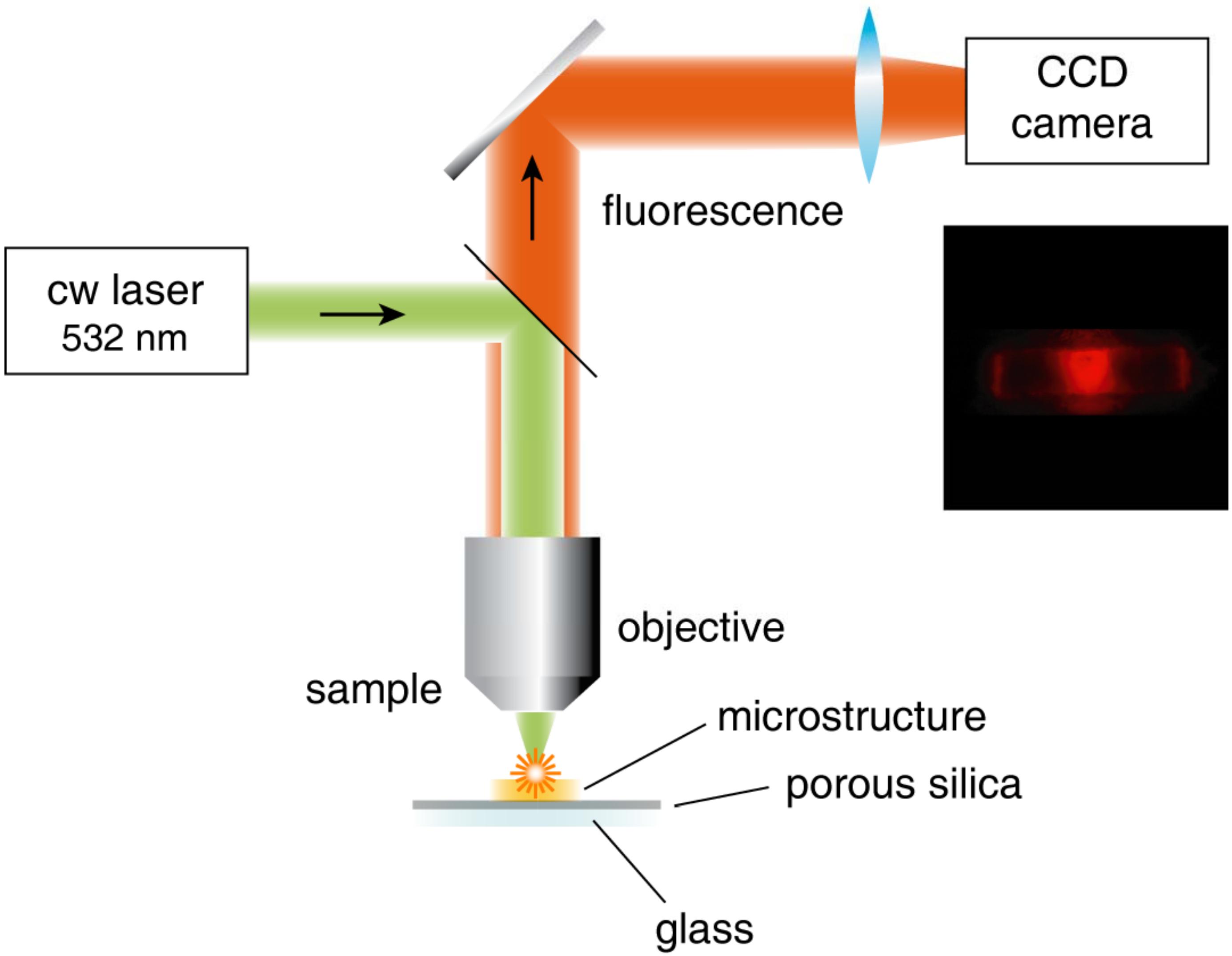




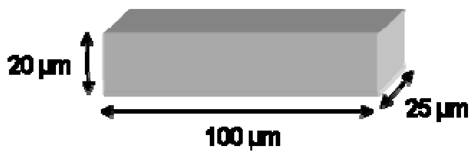


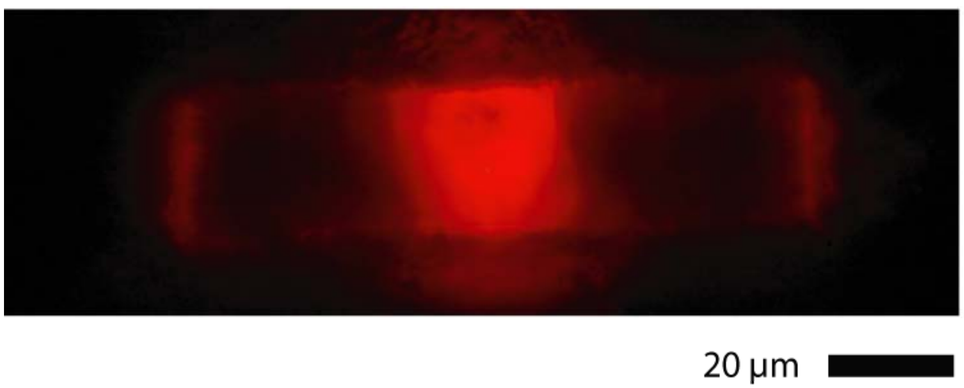
Appl. Phys. Lett., 95 1133091-3 (2009)

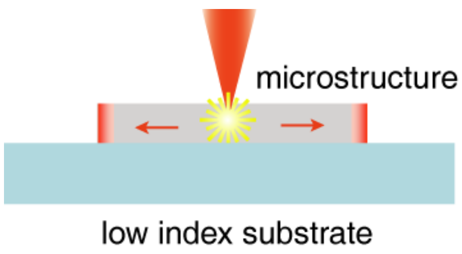
Microstructure containing MEH-PPV



Microstructure containing MEH-PPV



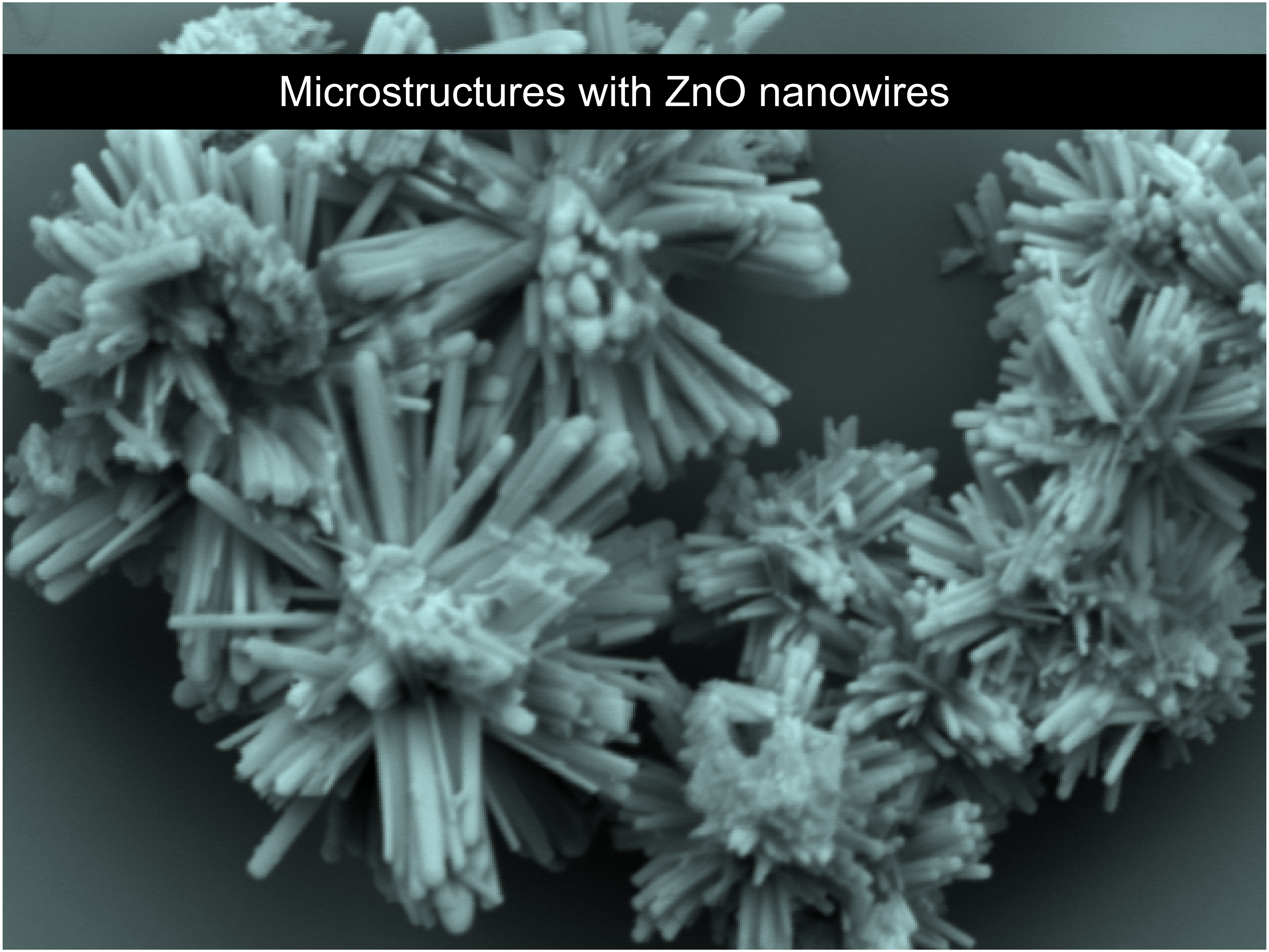




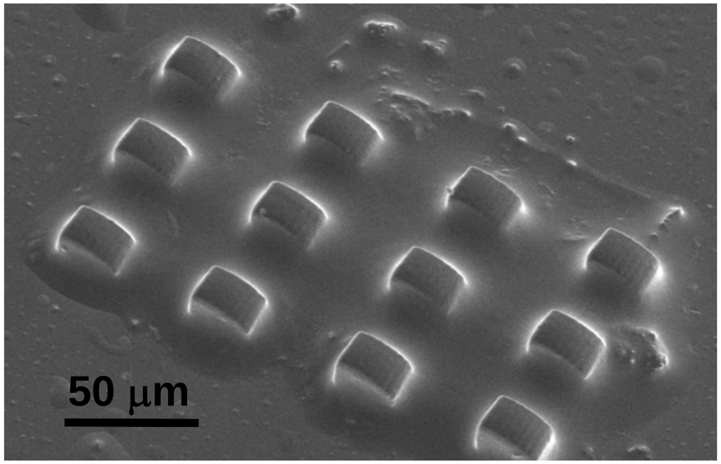
waveguiding of the microstructure fabricated on porous silica substrate (*n*= 1.185)

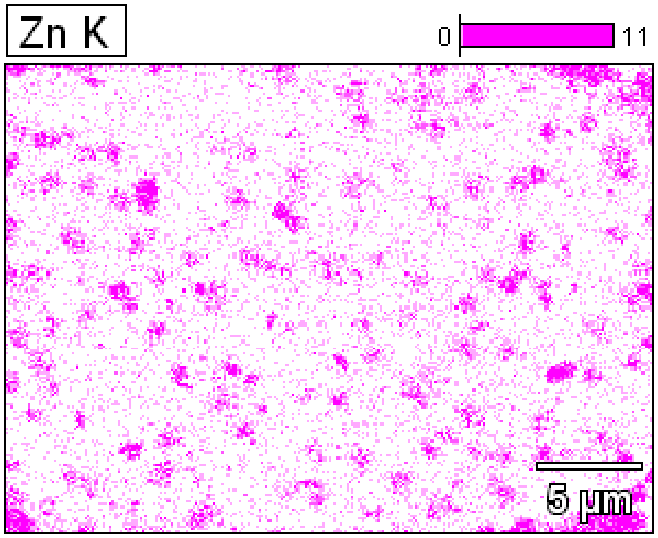
Applications: micro-laser; fluorescent microstructures; conductive microstructures

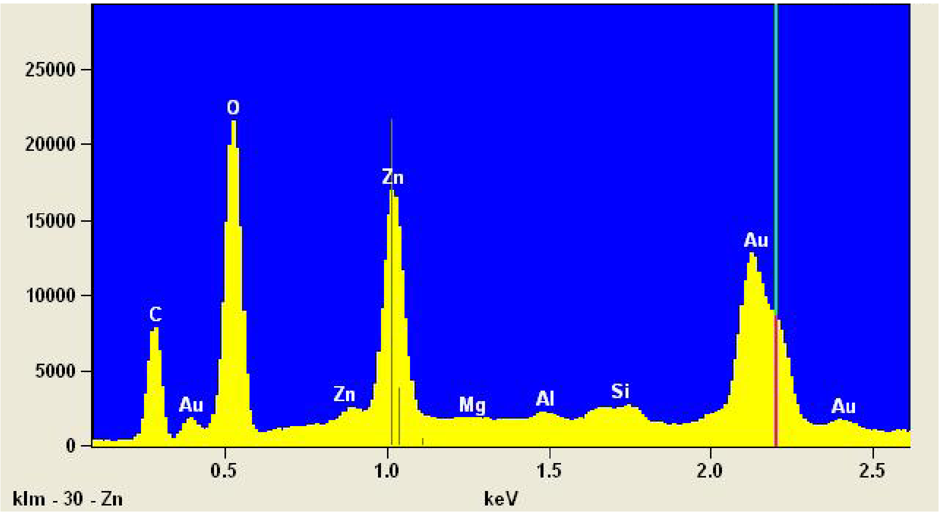
Microstructures with ZnO nanowires



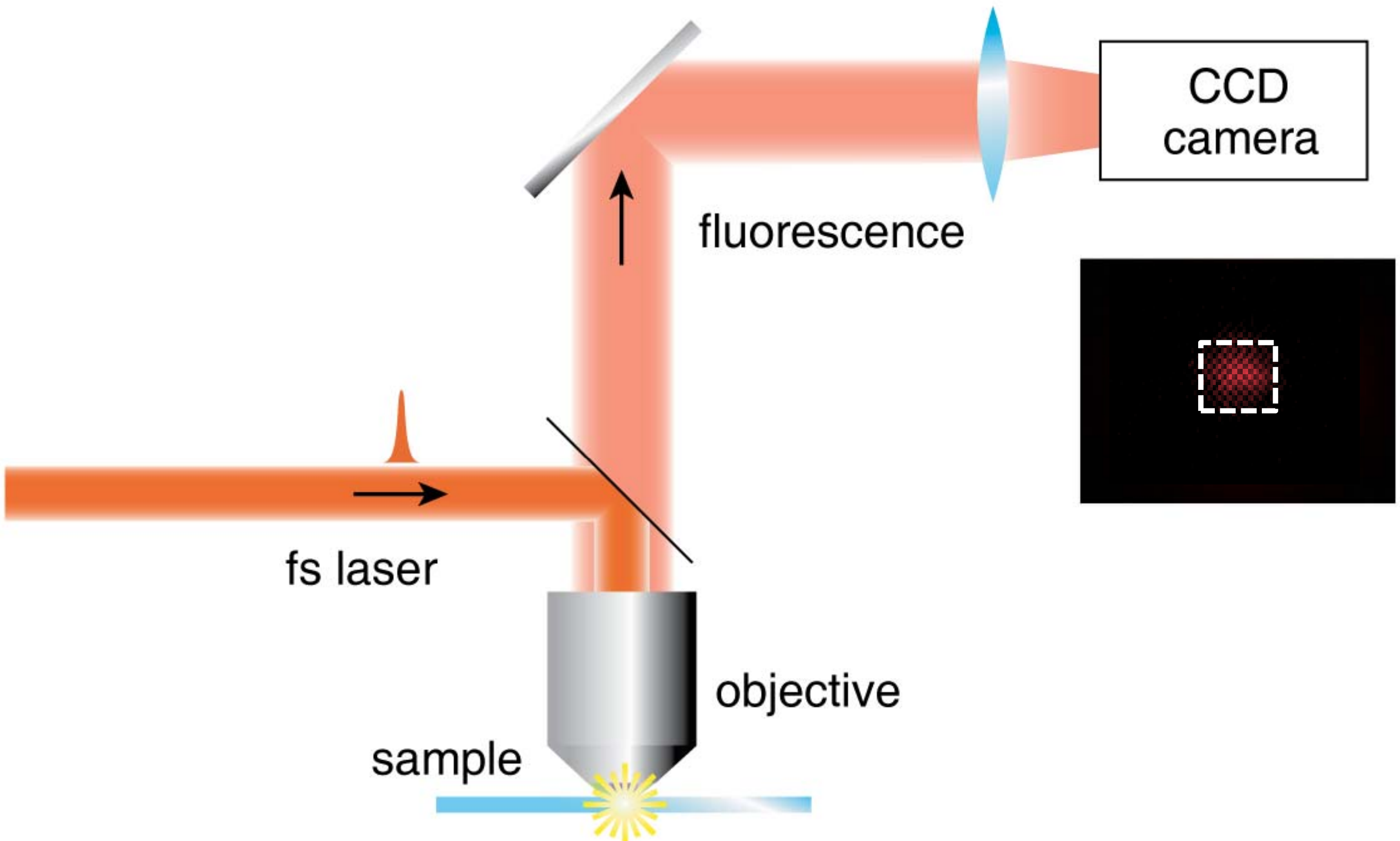
Microstructures with ZnO nanowires



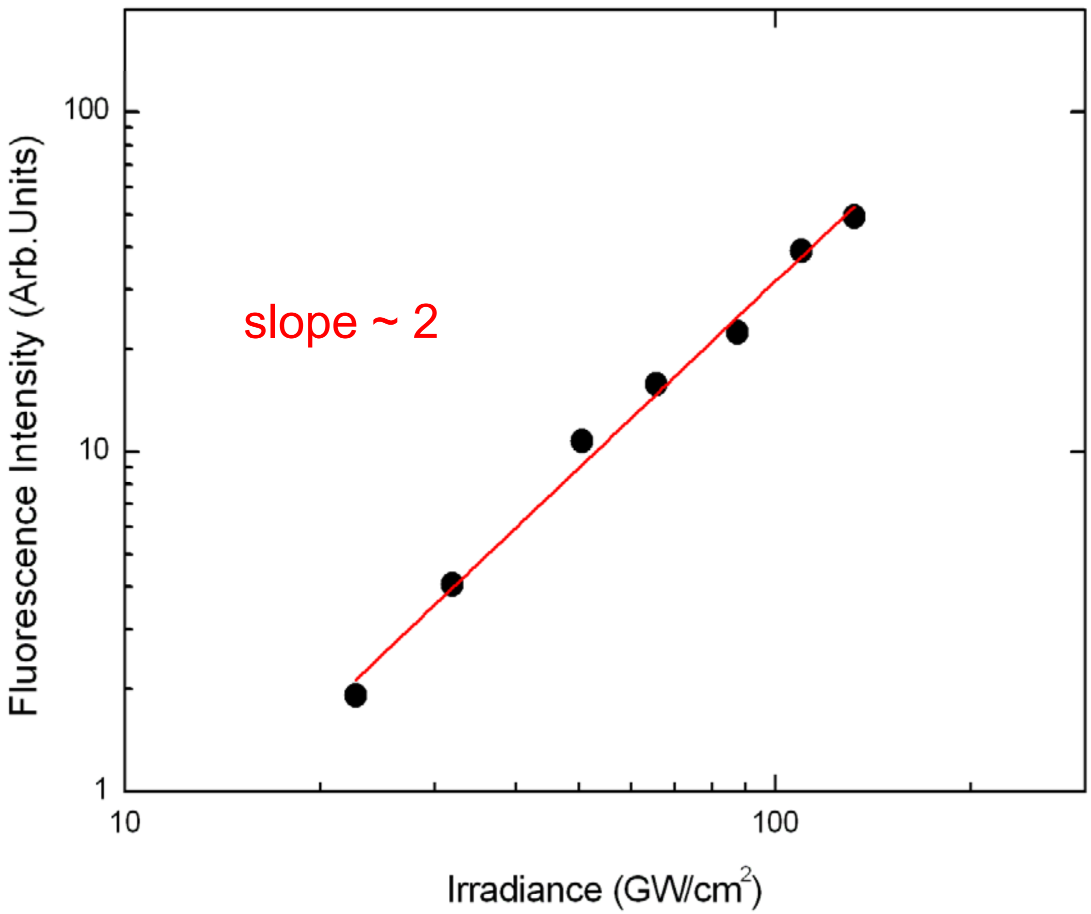




Microstructures with ZnO nanowires

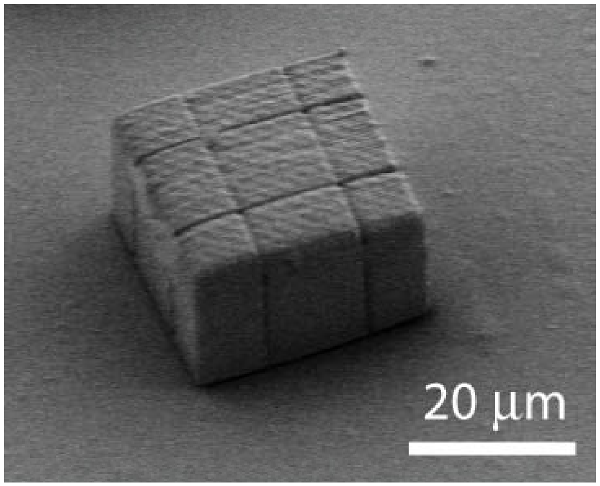


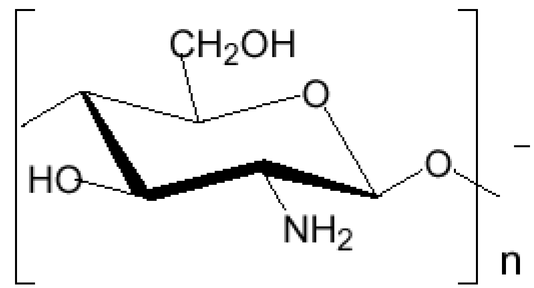
Microstructures with ZnO nanowires

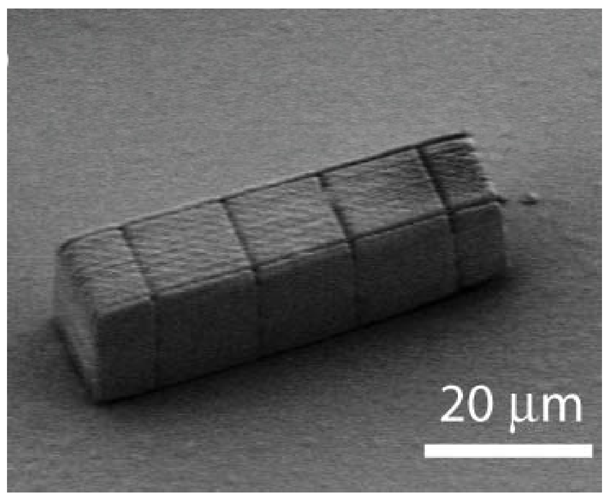


Doping microstructures

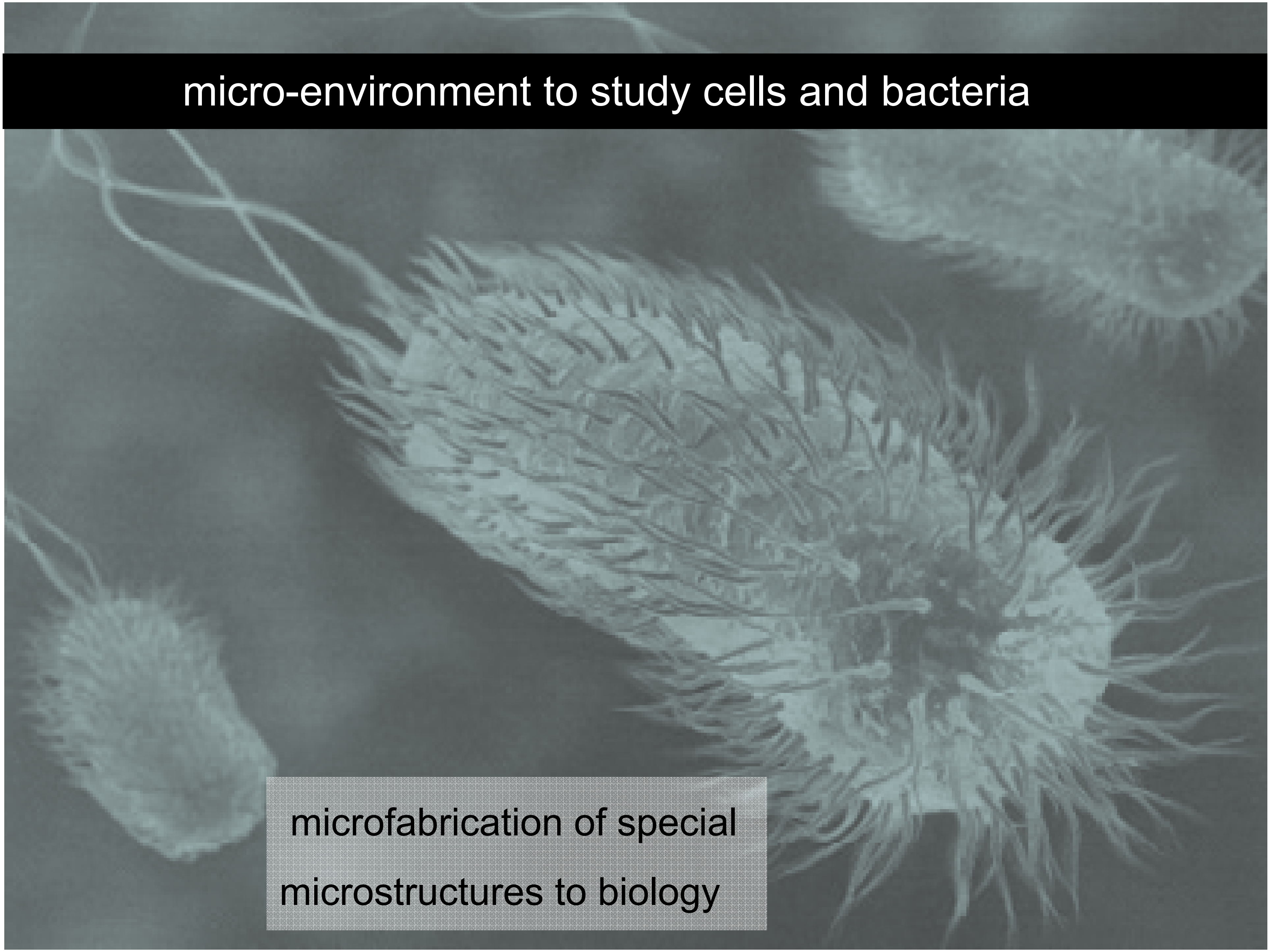
- microstructures containing biopolymer - chitosan







micro-environment to study cells and bacteria

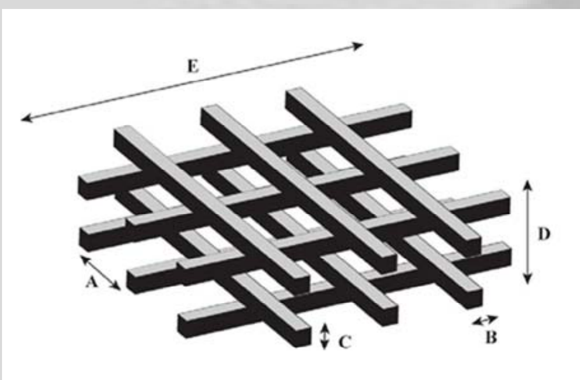


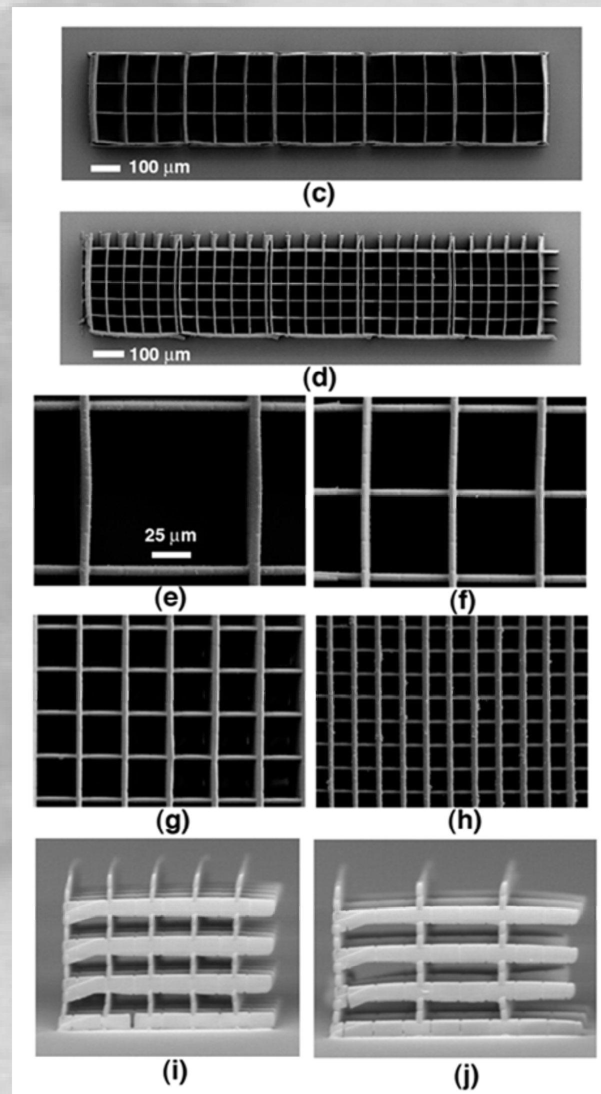
microfabrication of special microstructures to biology

3D cell migration

- 3D cell migration studies in micro-scaffolds

SEM of the scaffolds





110 µm pore size

52 µm pore size

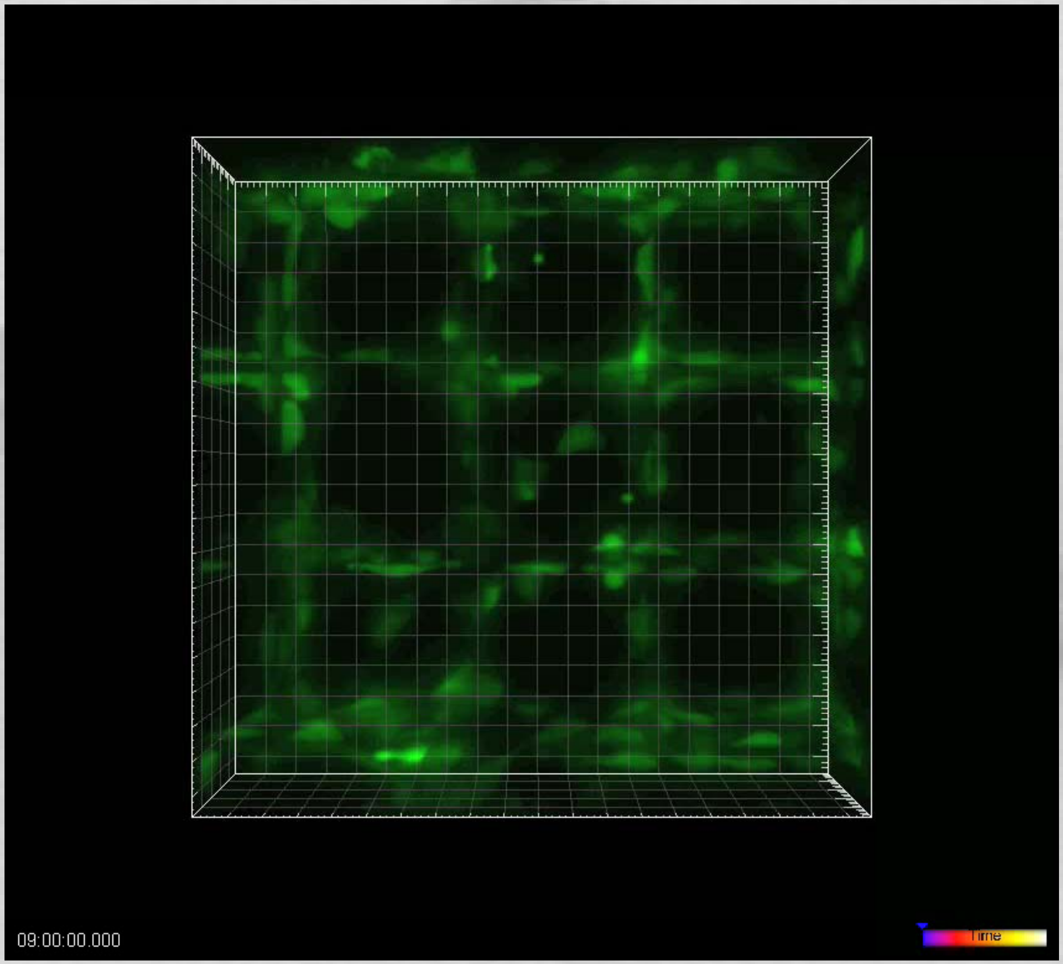
Top view

110, 52, 25, 12 µm pore size

Side view

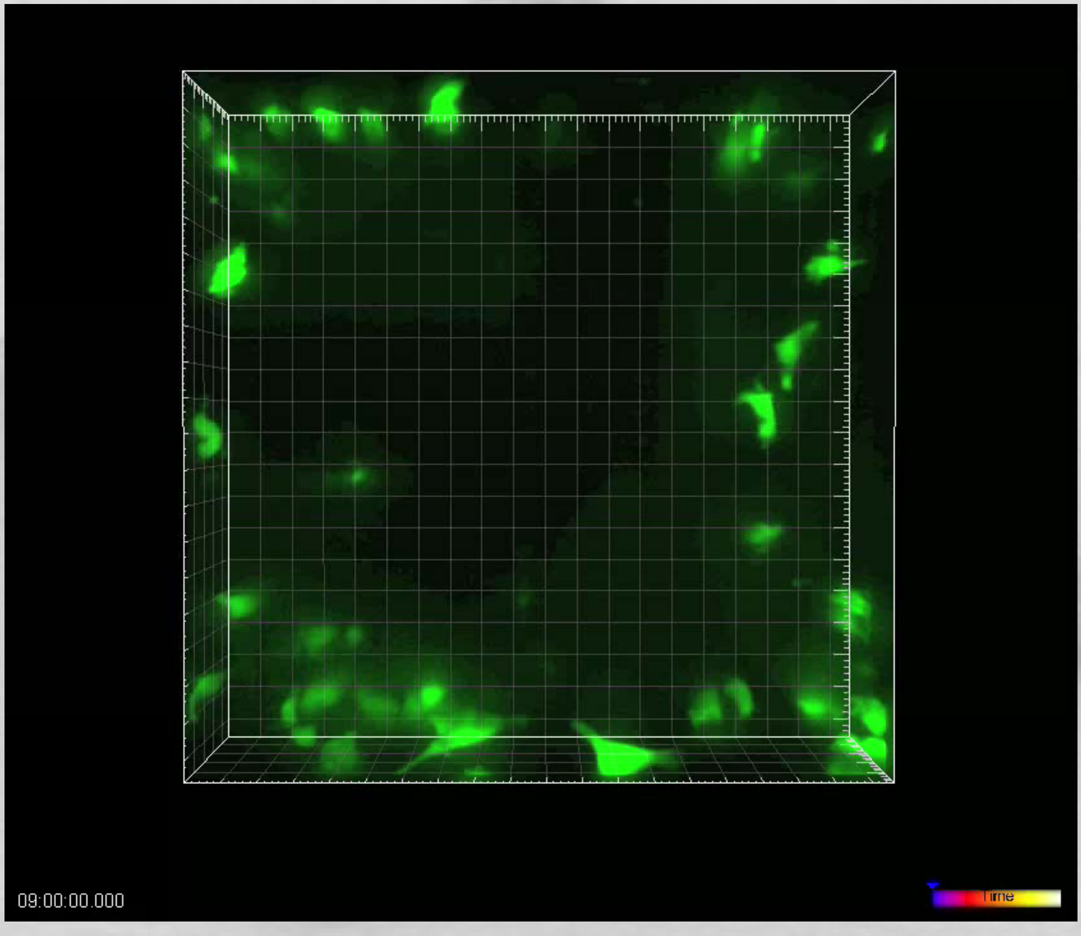
25, 52 µm pore size

3D cell migration



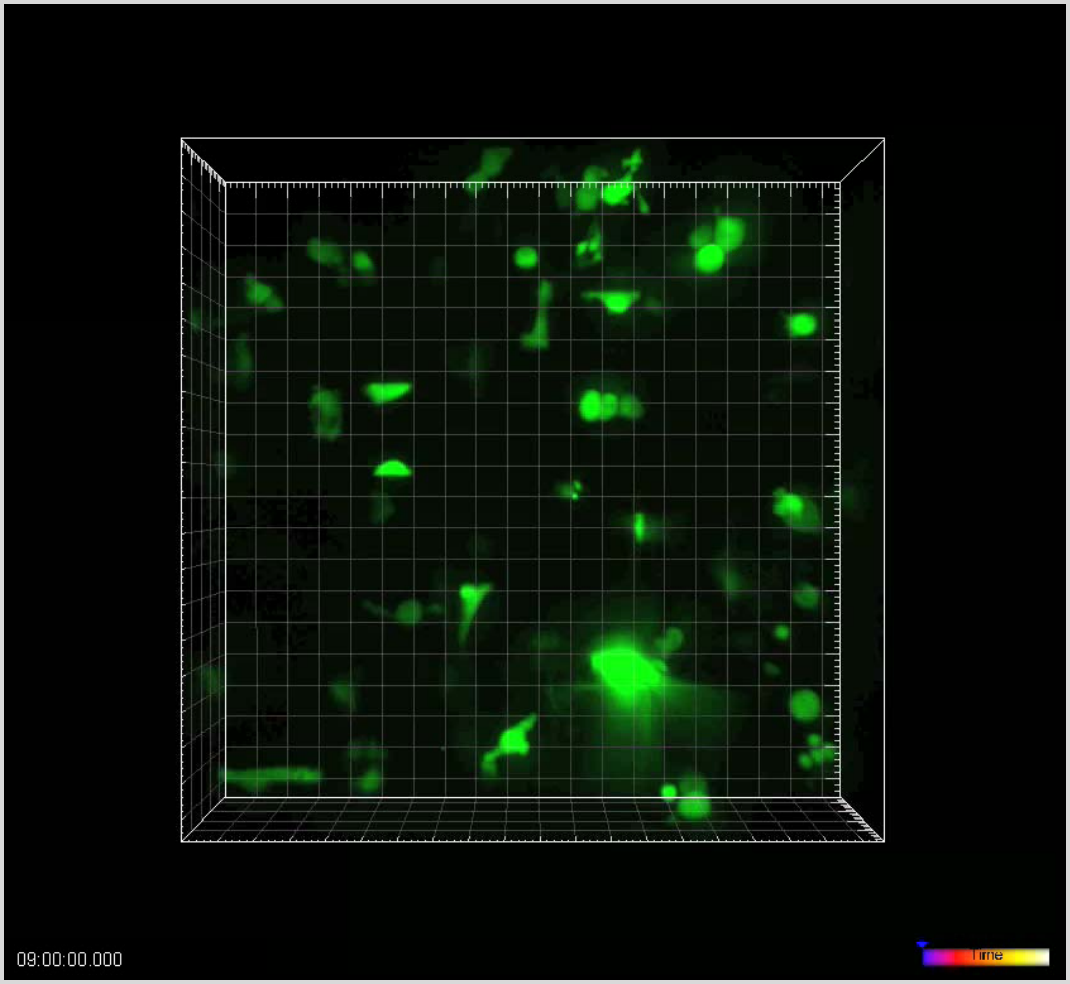
110 μm pore size

3D cell migration



12 µm pore size

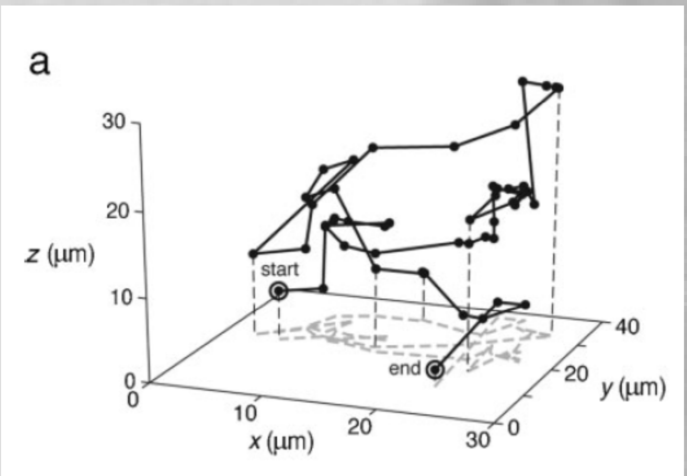
3D cell migration

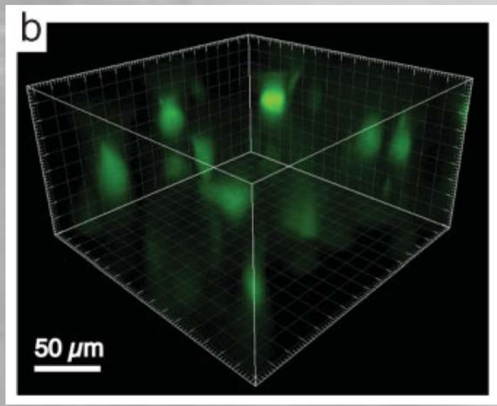


52 μm pore size

3D cell migration

- 3D cell migration studies in micro-scaffolds



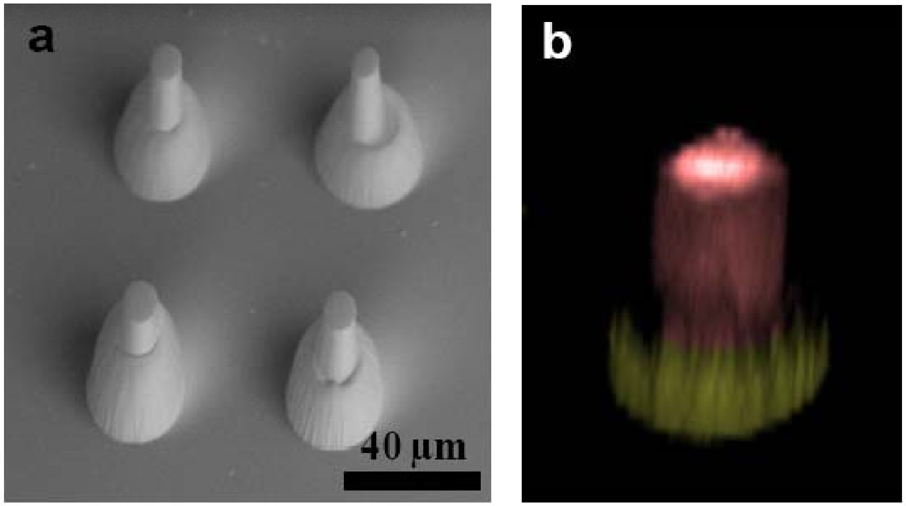


Advanced Materials, 20, 4494-4498 (2008)

Guiding bacterial growth in a micro-environment

to study bacterial growth it was needed to develop
double doped microstructures

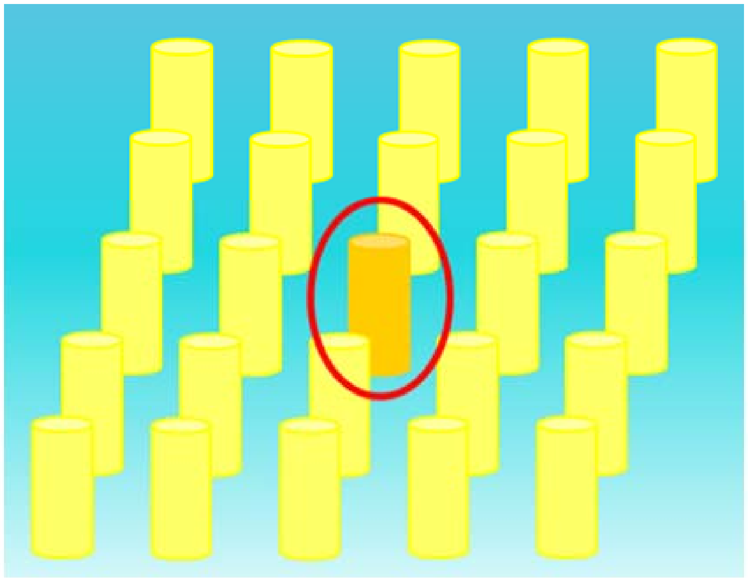
microstructure containing Fluorescein and Rhodamine

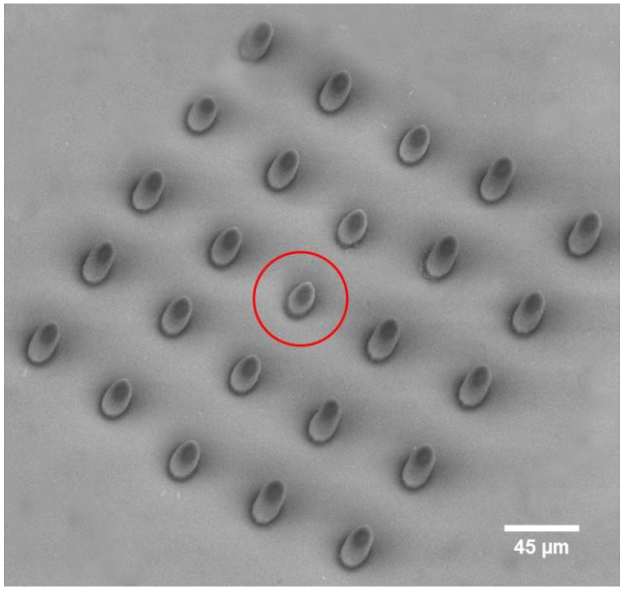


(a) SEM of a double-doped microstructure (top view).
(b) Confocal fluorescent microscopy image of the same microstructure.

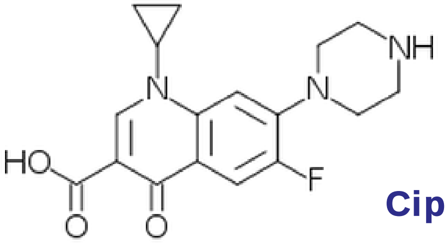
Guiding bacterial growth in a micro-environment

Study the development of E. coli in micro-environments:





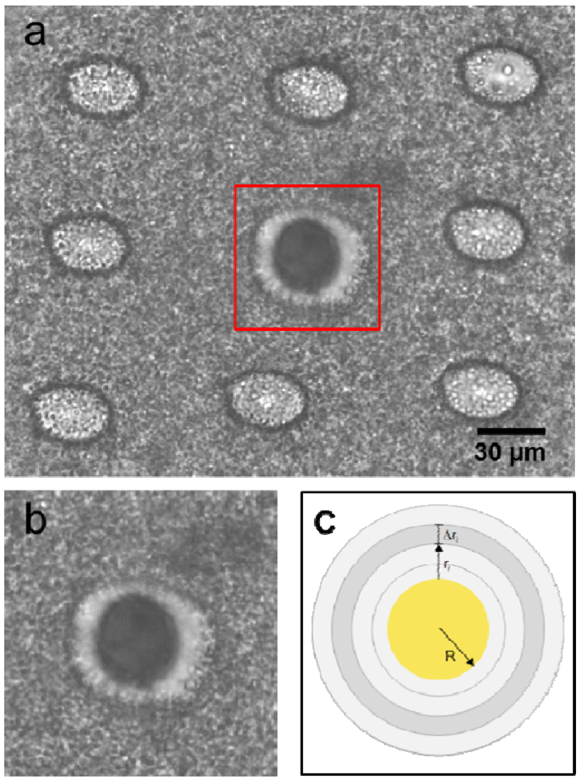
micro-environment in which the central structure contains antibiotic.



Ciprofloxacin

Guiding bacterial growth in a micro-environment

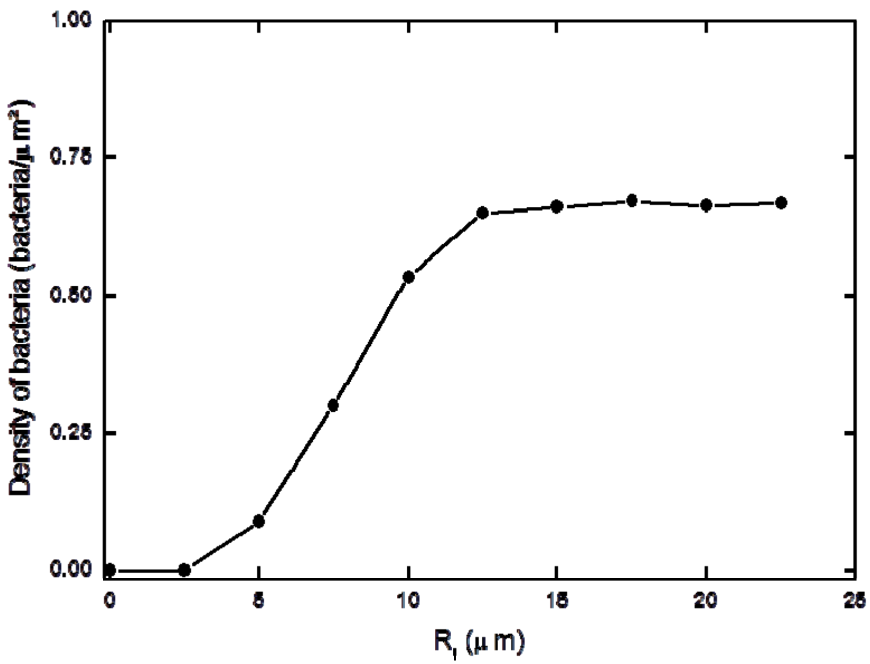
Study the development of E. coli in micro-environments:



after 3 hours, we observed that a small region around the doped structure does not show bacterial growth.

such inhibition zone was analyzed by determining the bacterial density in concentric rings

Guiding bacterial growth in a micro-environment



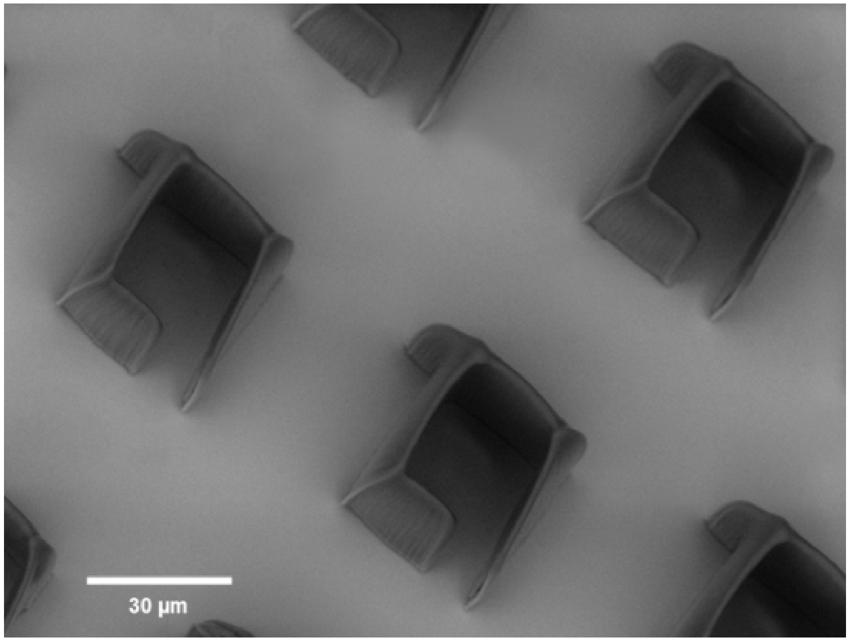
the density of bacteria grows monotonically with r_i

saturating when r_i reaches approximately 12 μm in about 0.7 bacteria/μm^2

the inhibition zone has a maximum range of approximately 10 μm, being more effective as one gets closer to the microstructure impregnated with ciprofloxacin

Guiding bacterial growth in a micro-environment

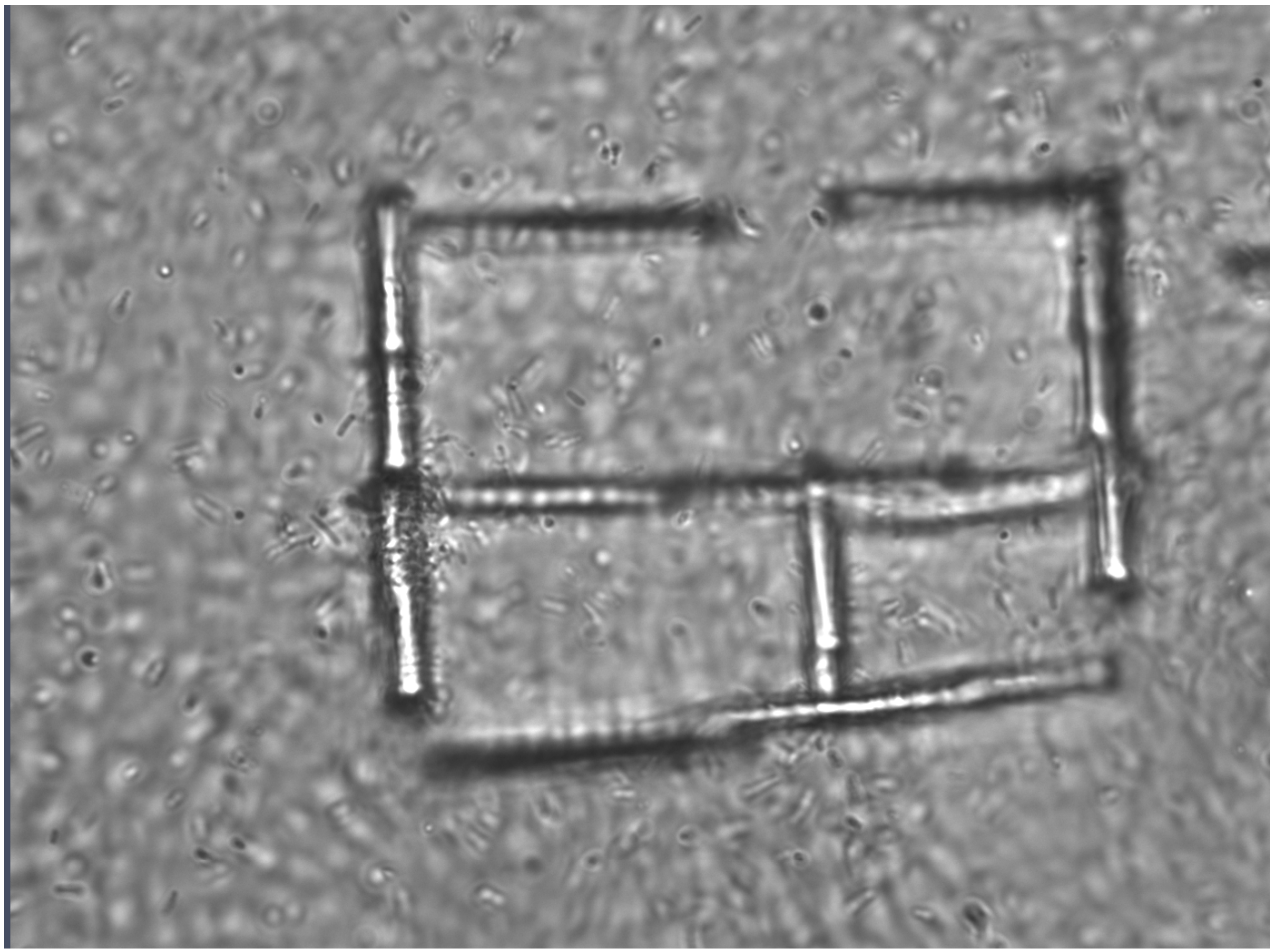
Bacteria microtraps



using micro-environments to study the dynamics of bacterial migration

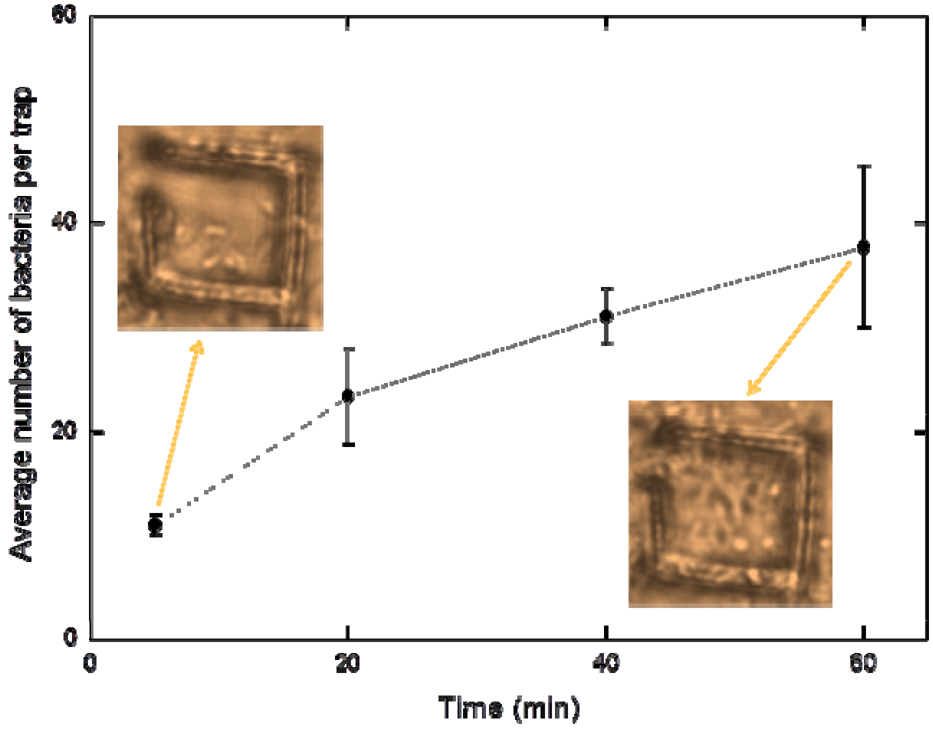
Guiding bacterial growth in a micro-environment

Bacteria microtraps



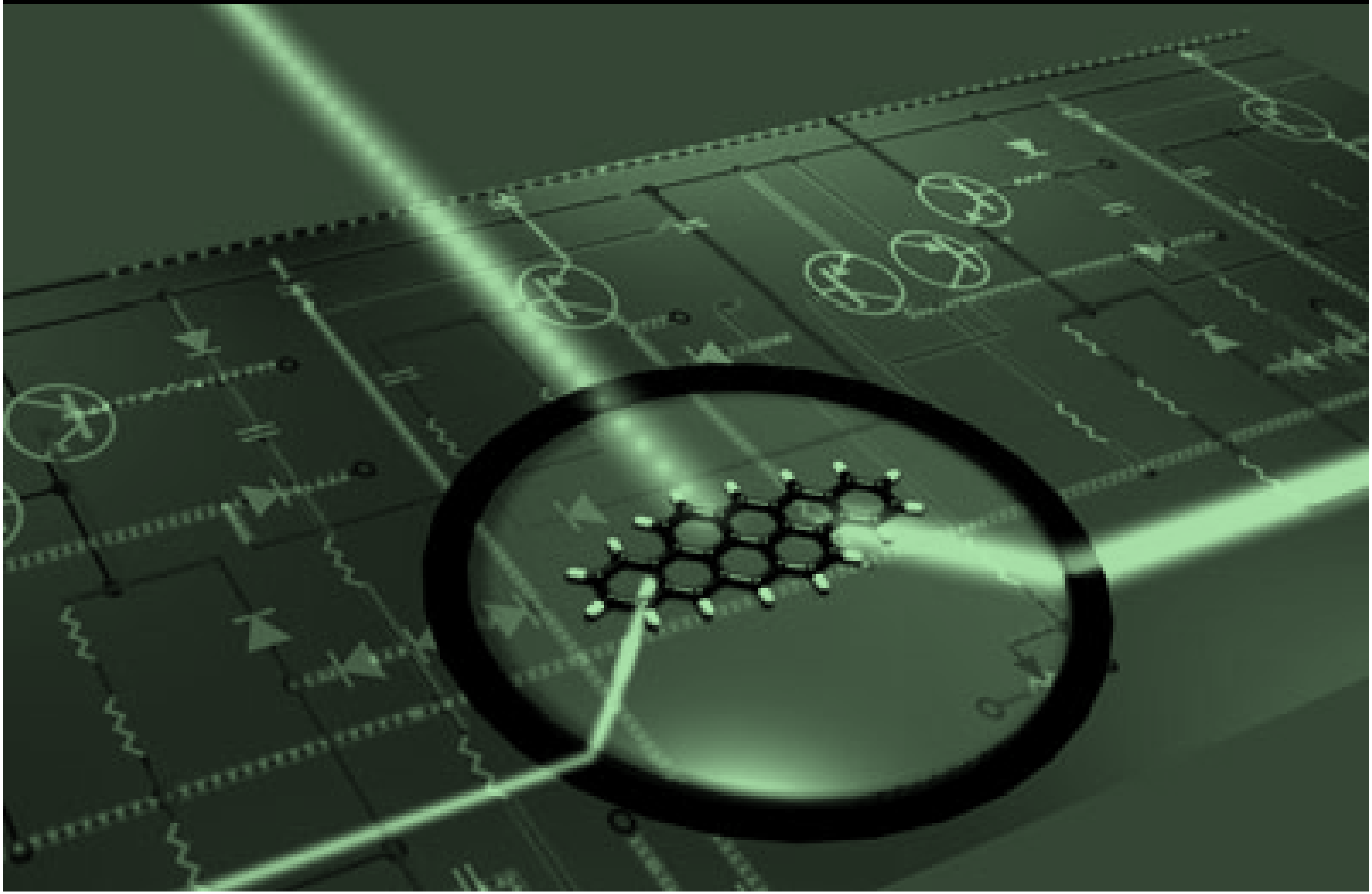
Guiding bacterial growth in a micro-environment

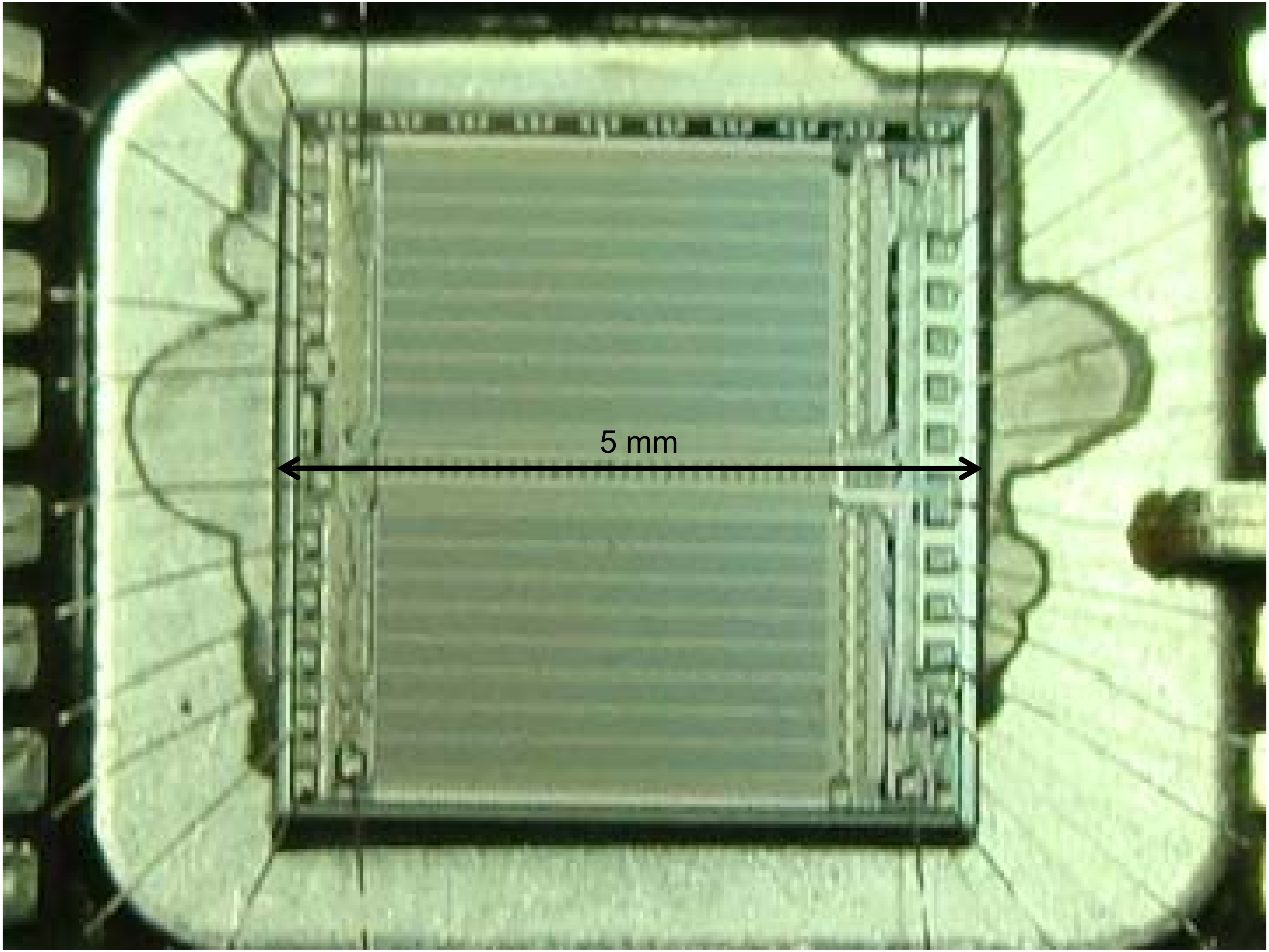
Bacteria microtraps

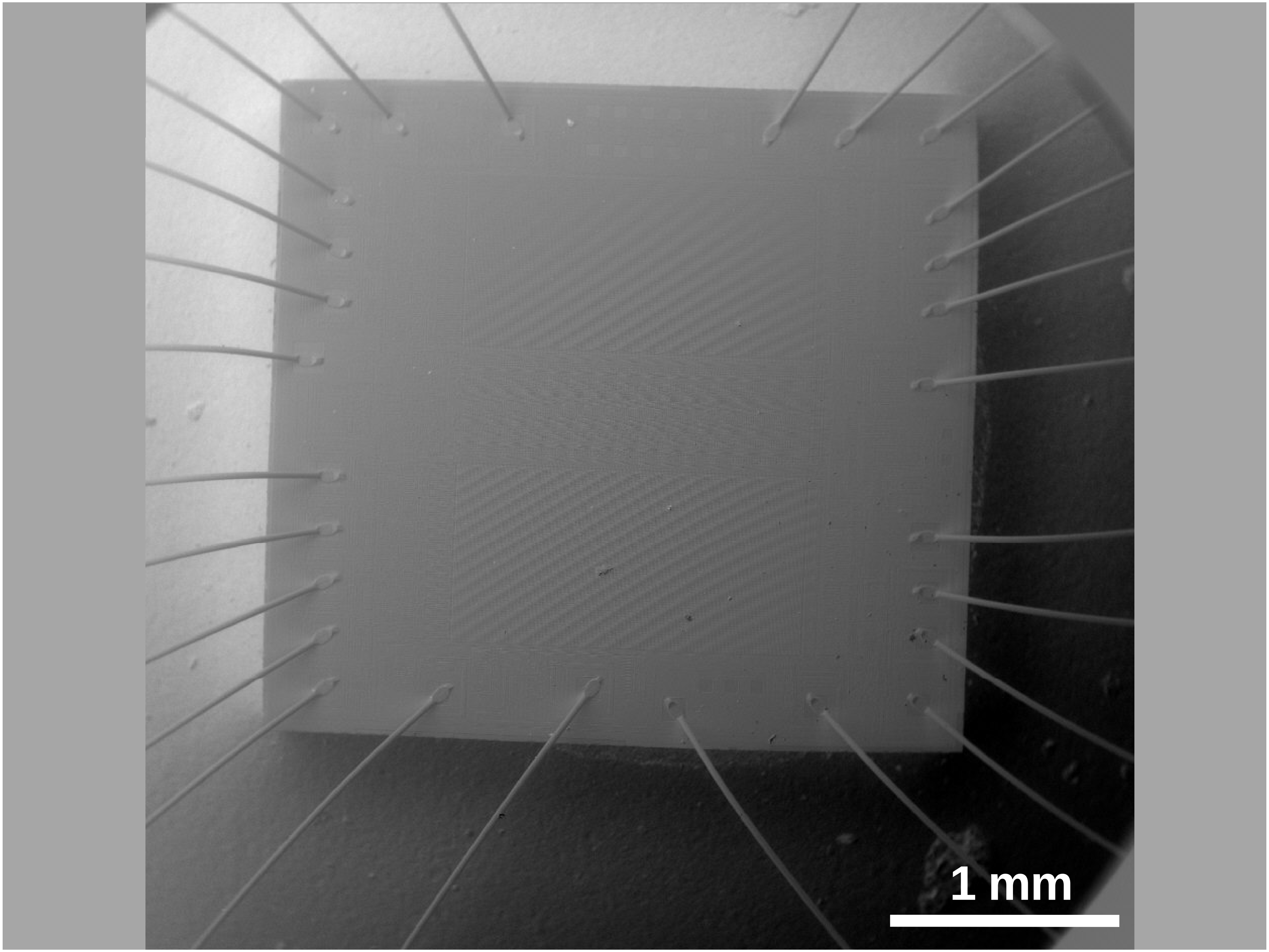


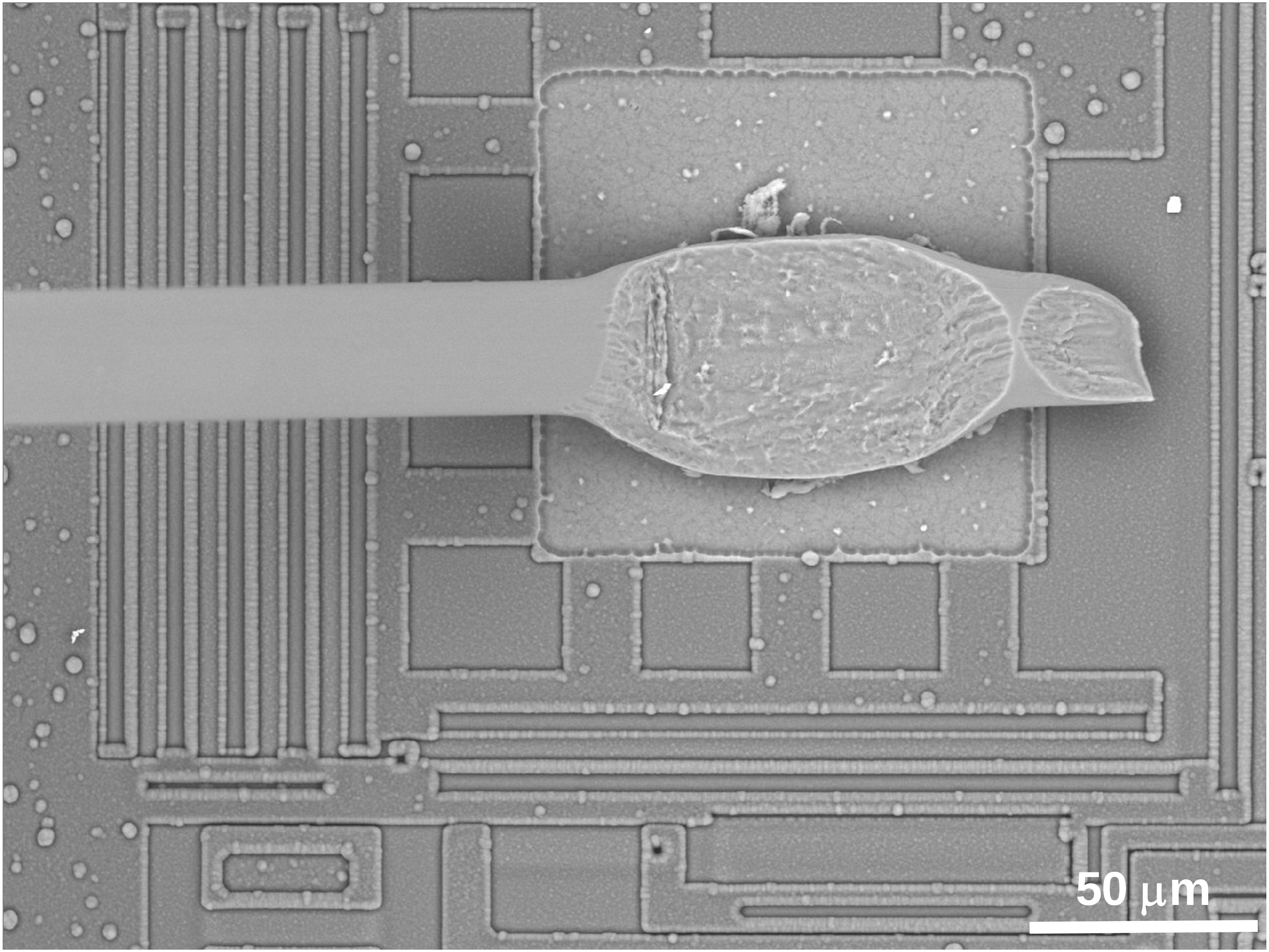
using micro-environments to study the dynamics of bacterial migration

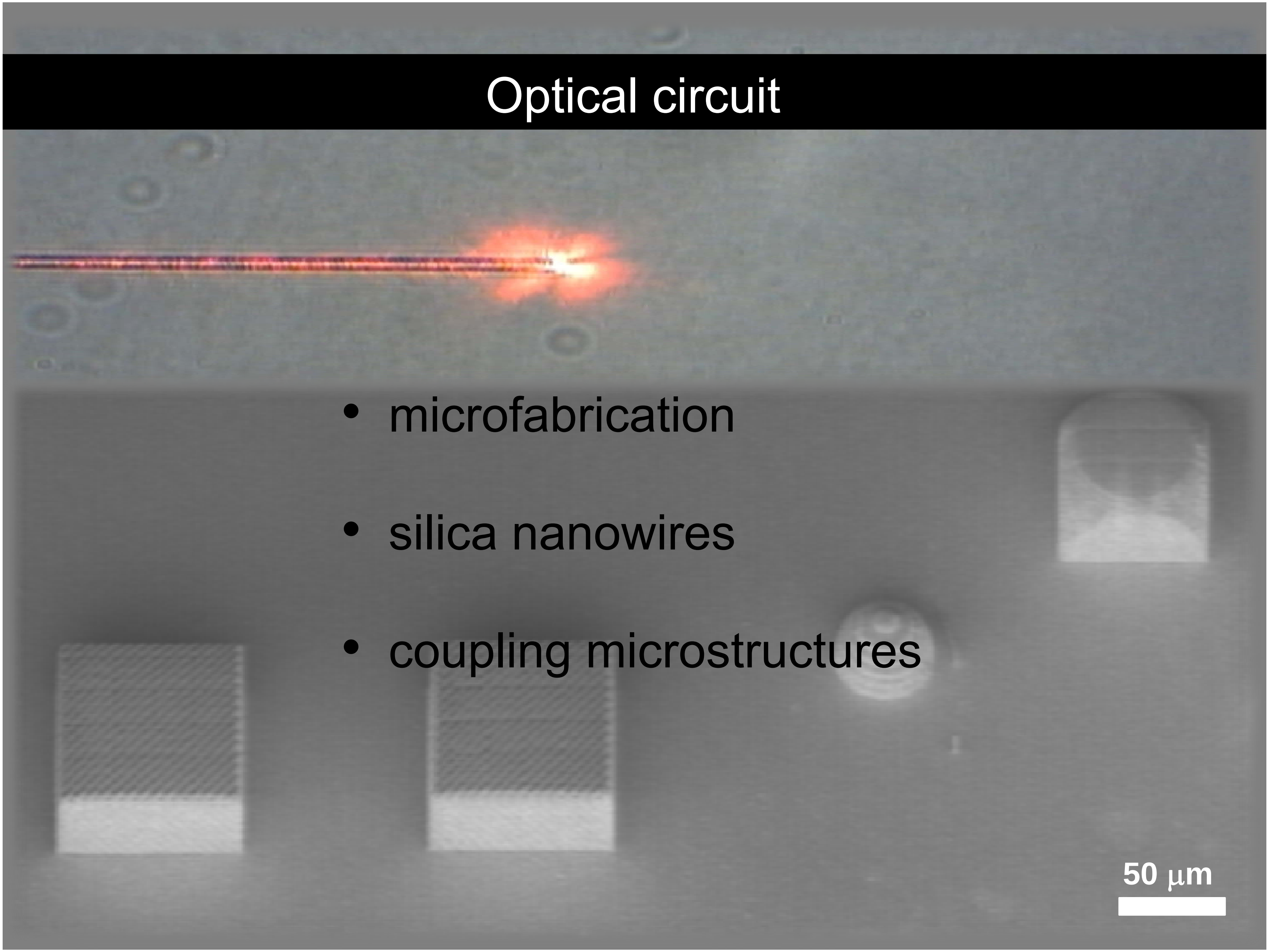
Optical circuit




5 mm

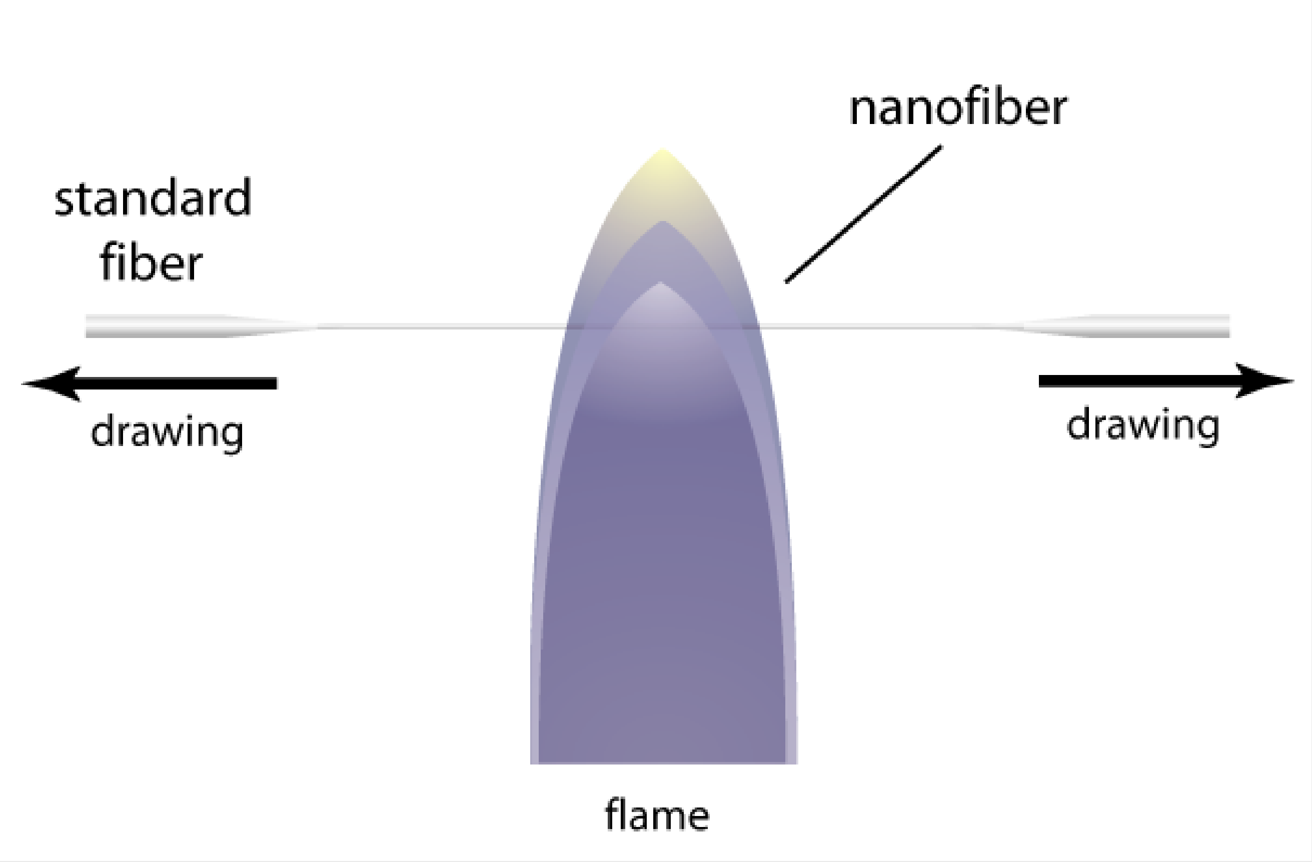

1 mm


50 μm

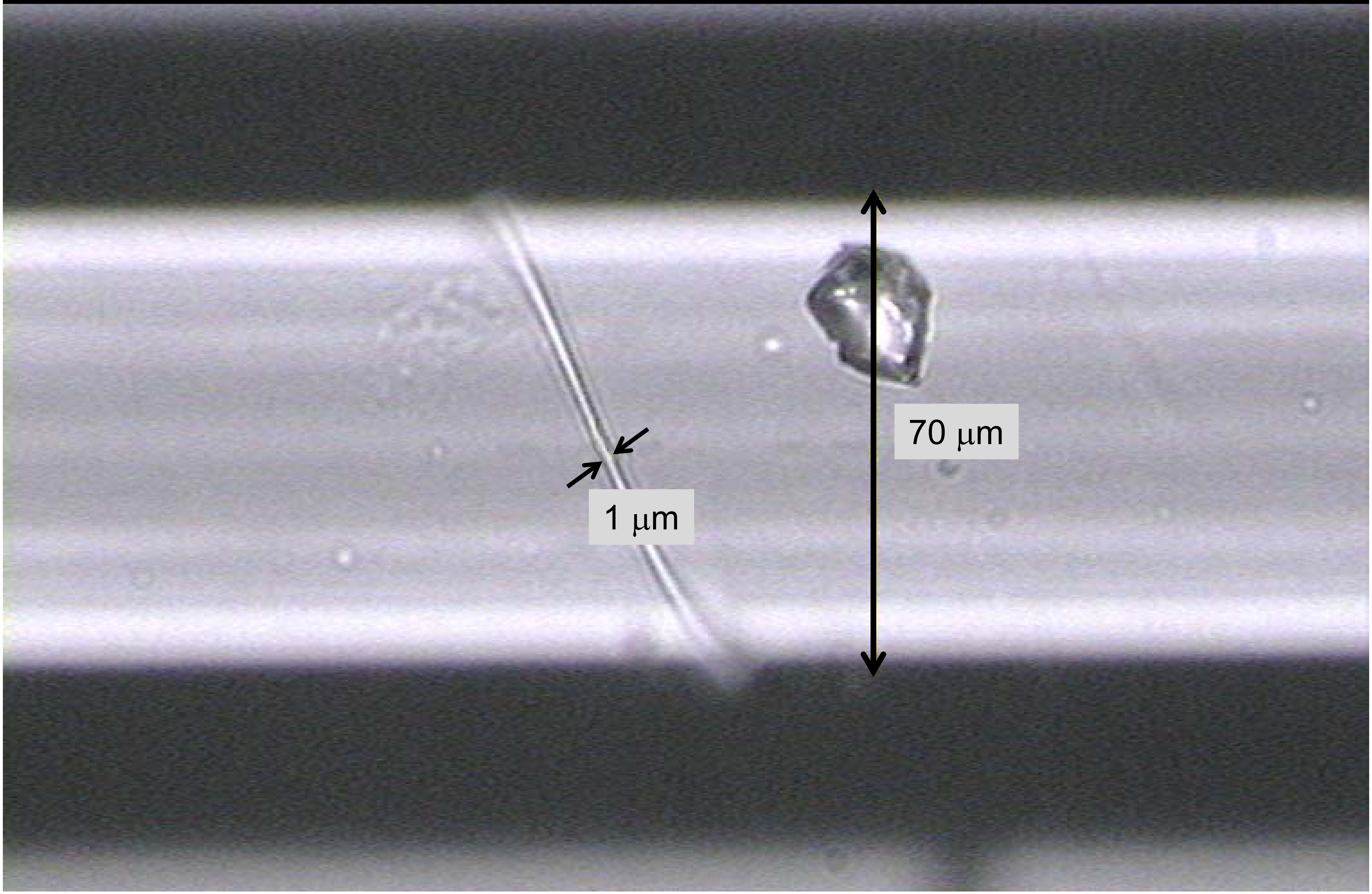

Optical circuit
• microfabrication
• silica nanowires
• coupling microstructures
50 μm

Silica nanowires

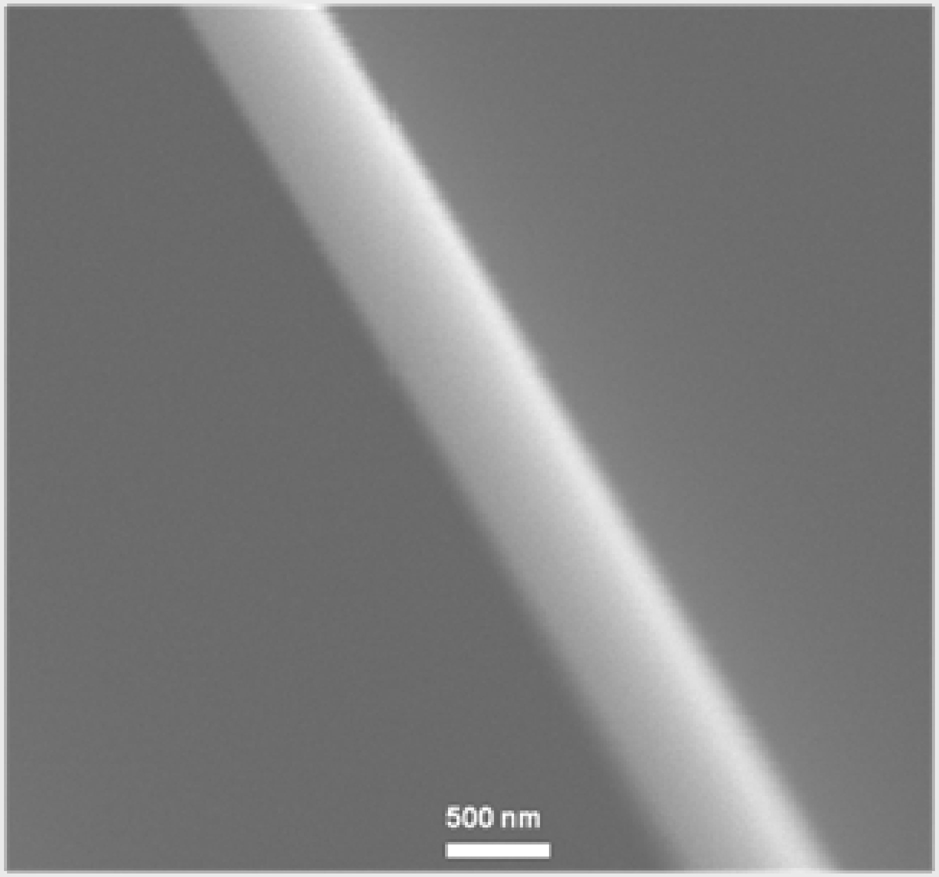
nanowires fabrication process



Silica nanowires

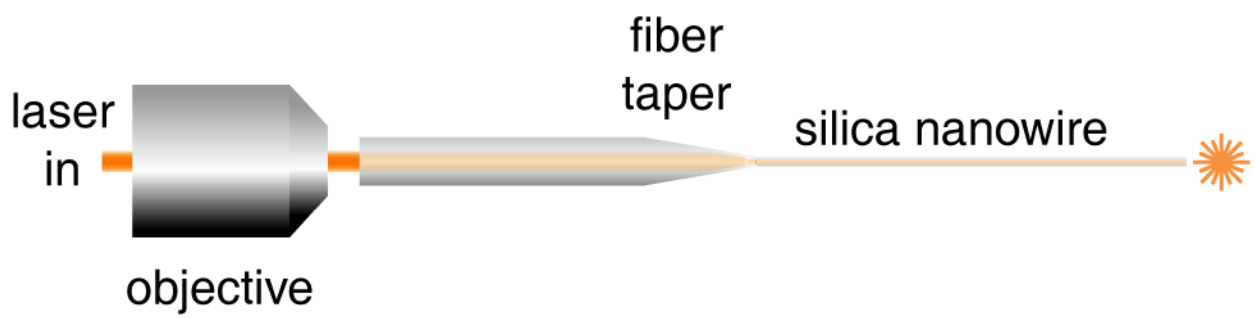


Silica nanowires



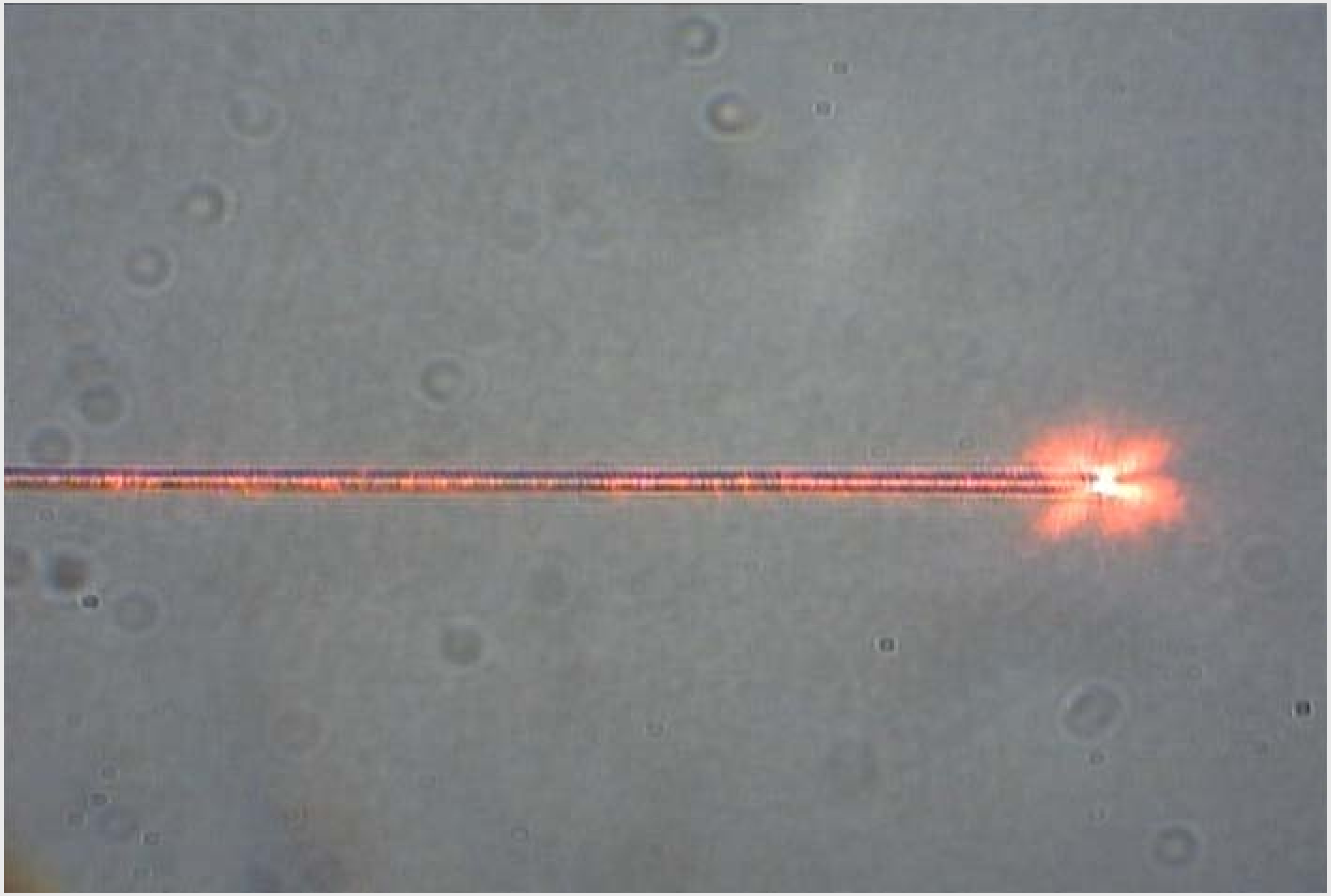
Silica nanowires

coupling light into nanowires



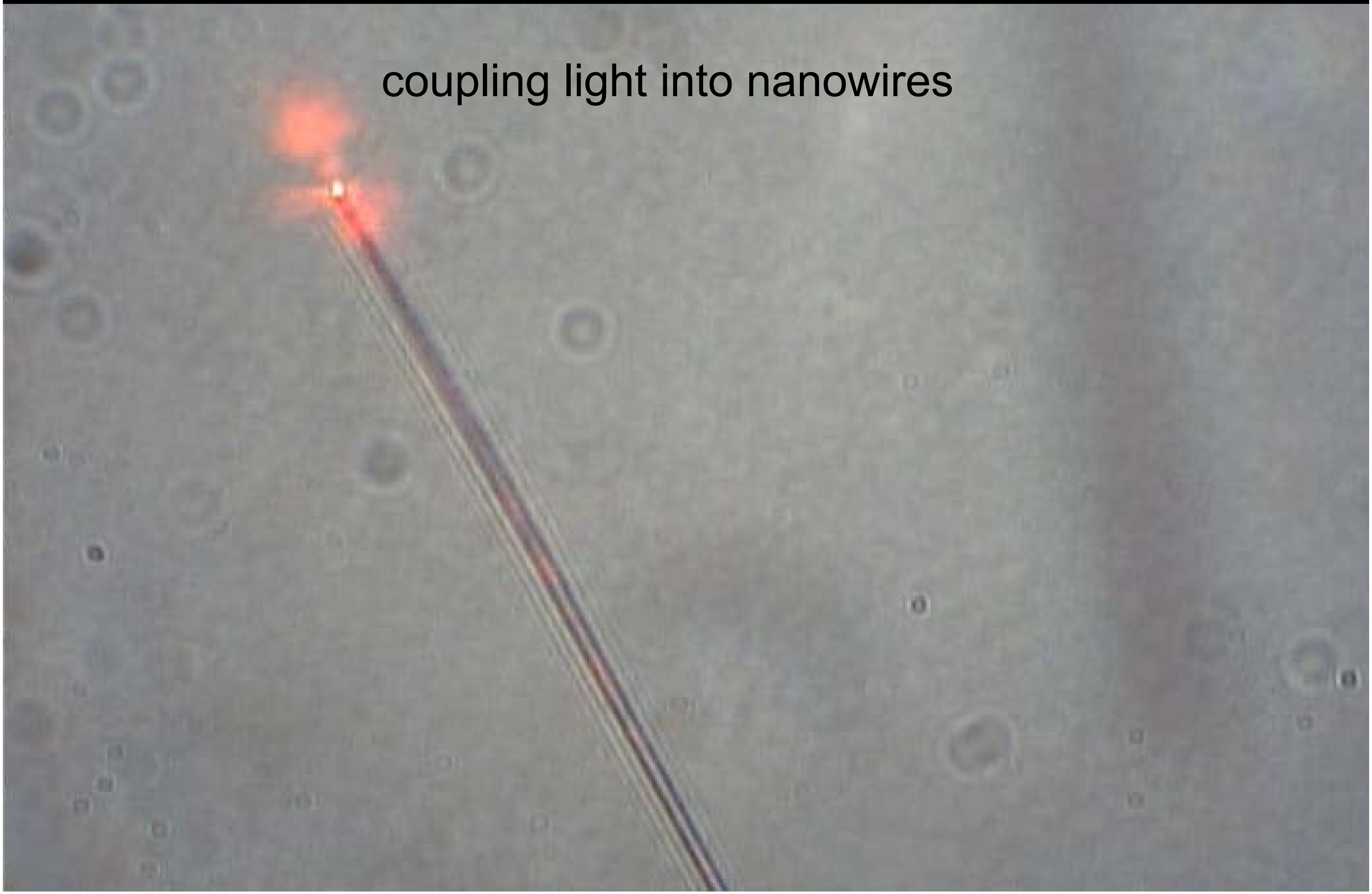
Silica nanowires

coupling light into nanowires



Silica nanowires

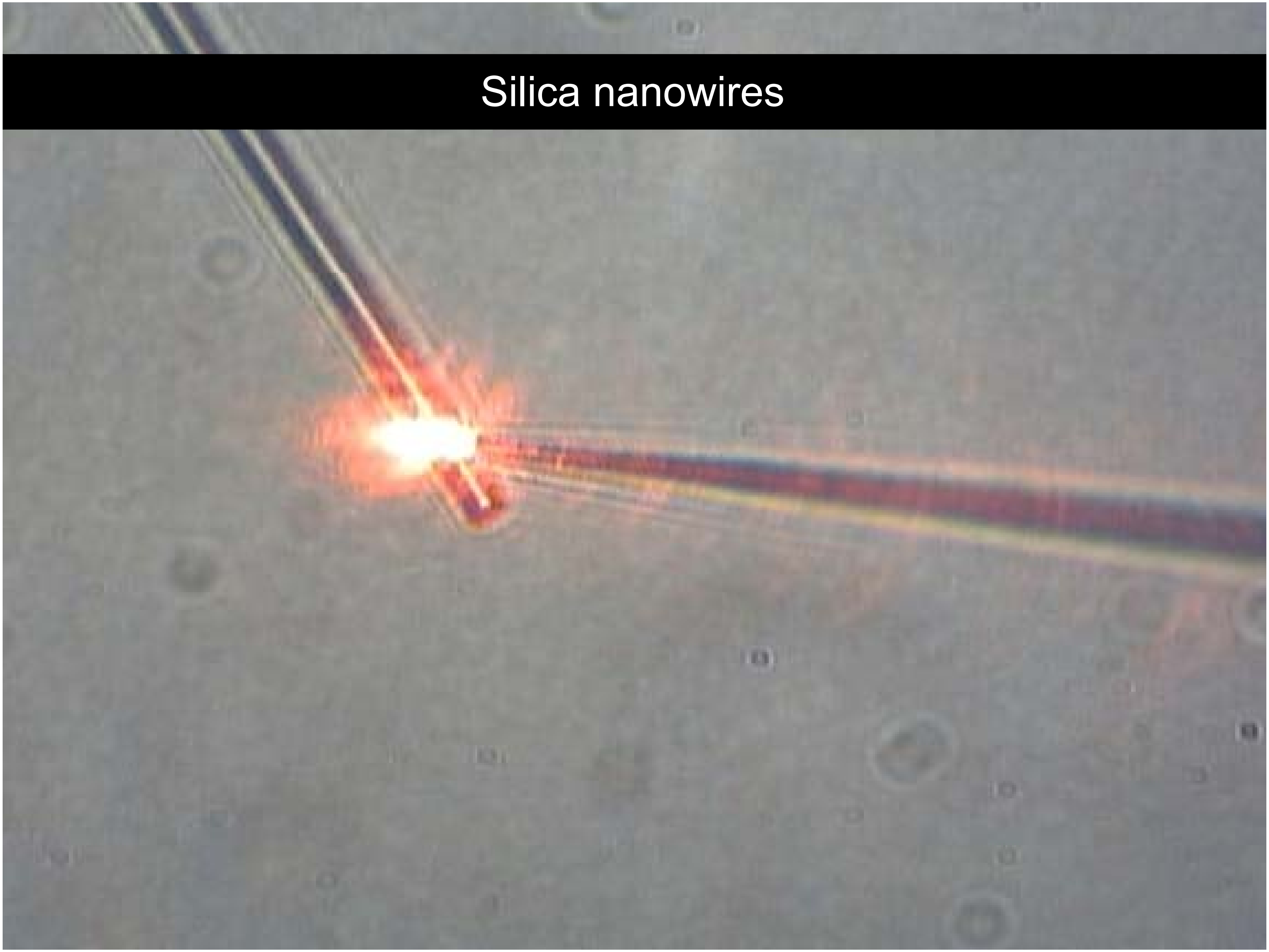
coupling light into nanowires



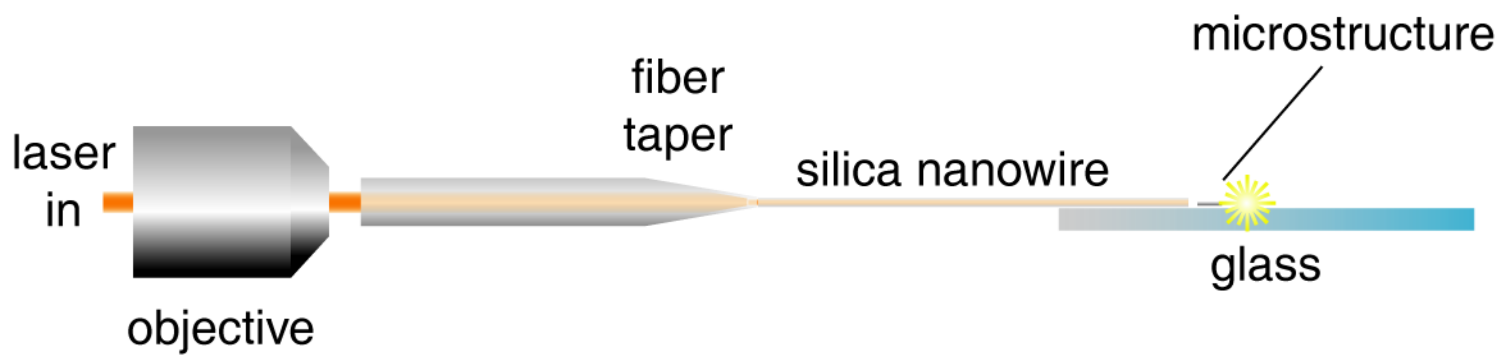
Silica nanowires

Manipulating the nanowires

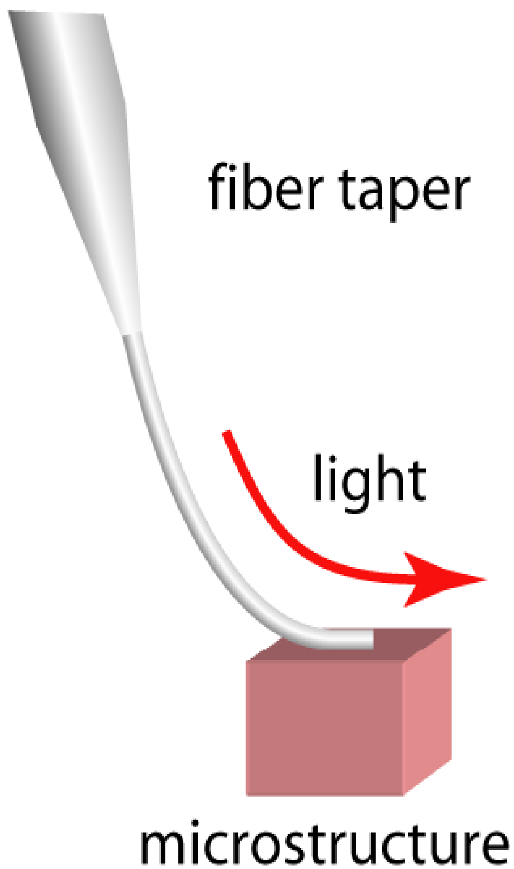
Silica nanowires



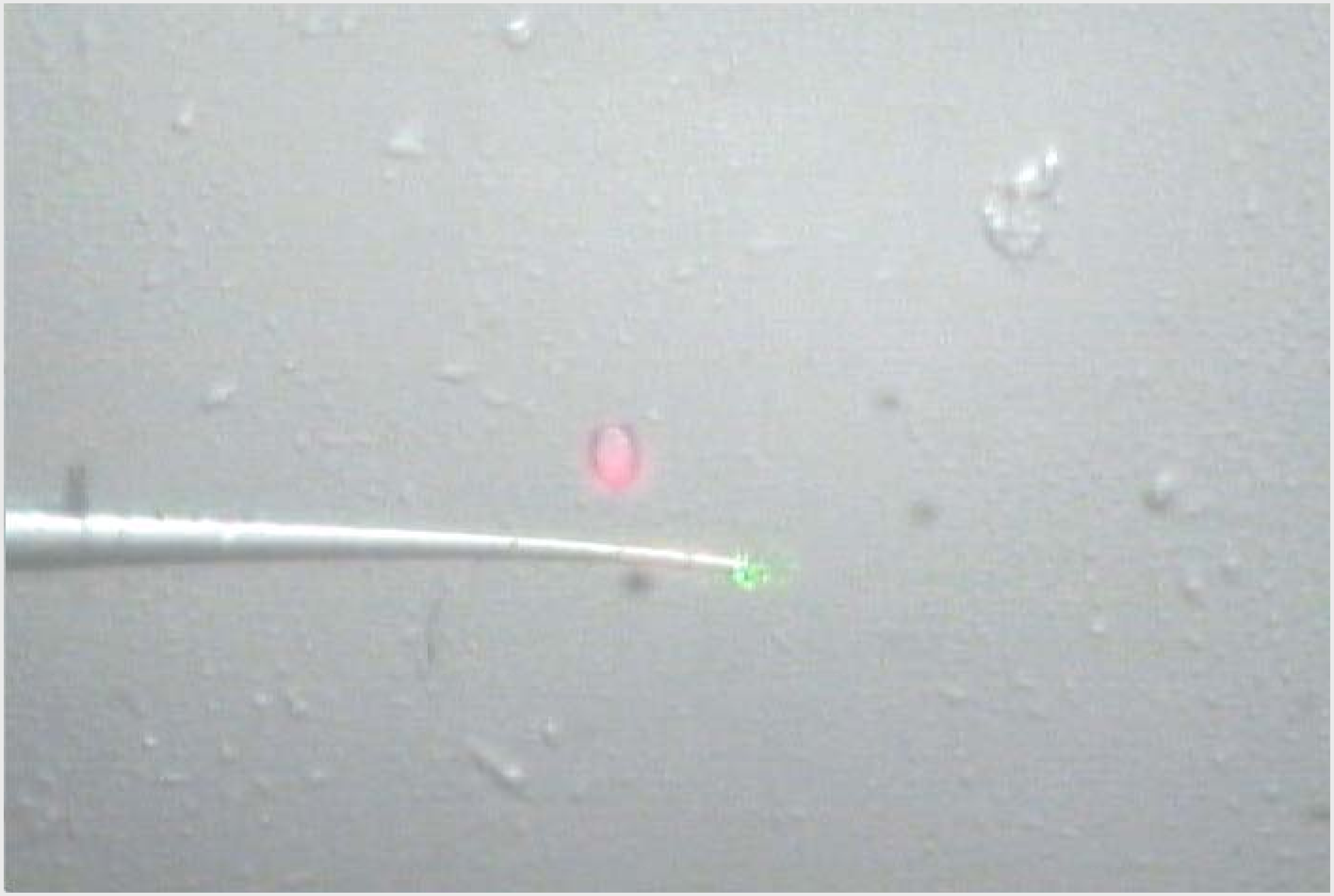
Coupling microstructures



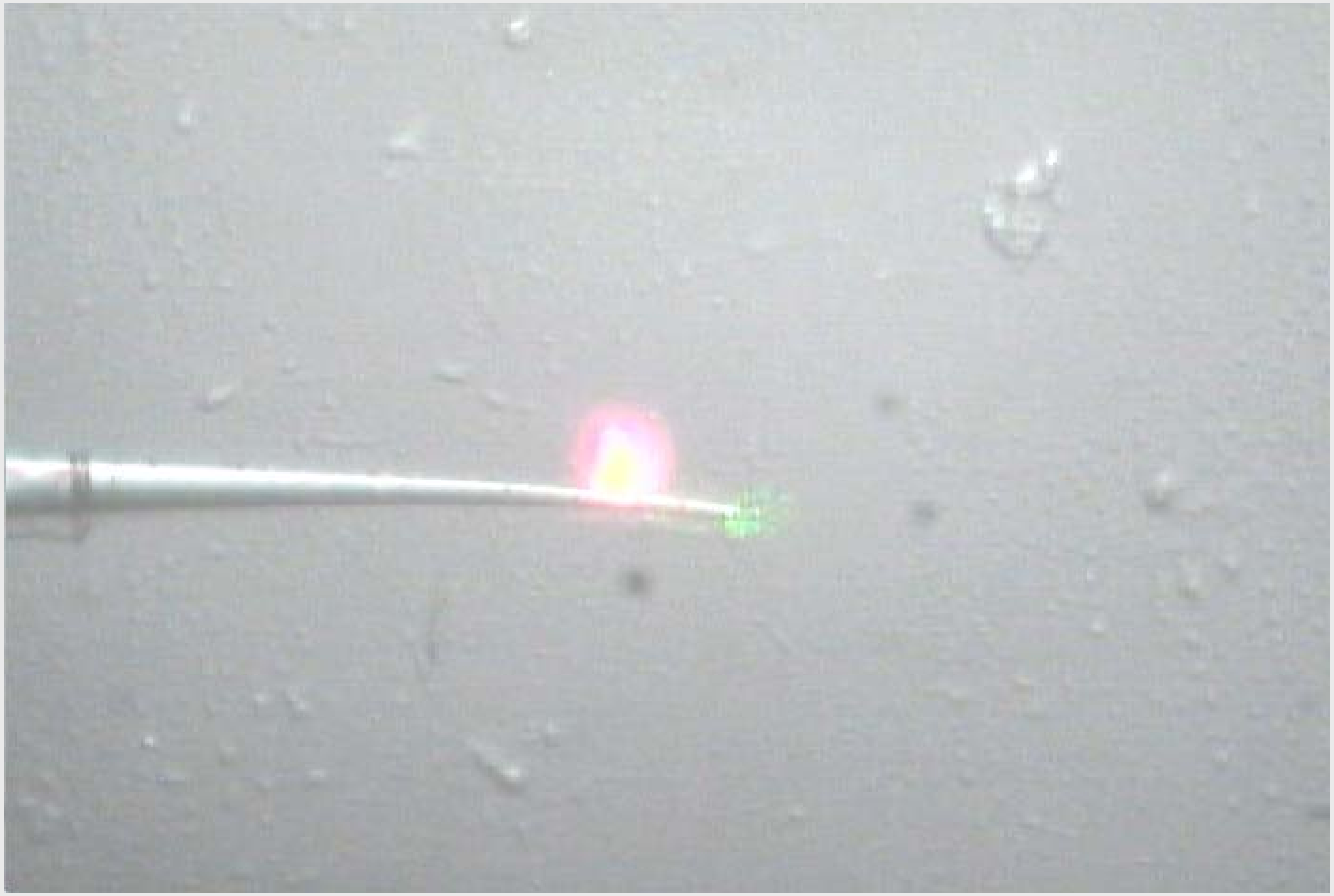
Coupling microstructures



Coupling microstructures



Coupling microstructures



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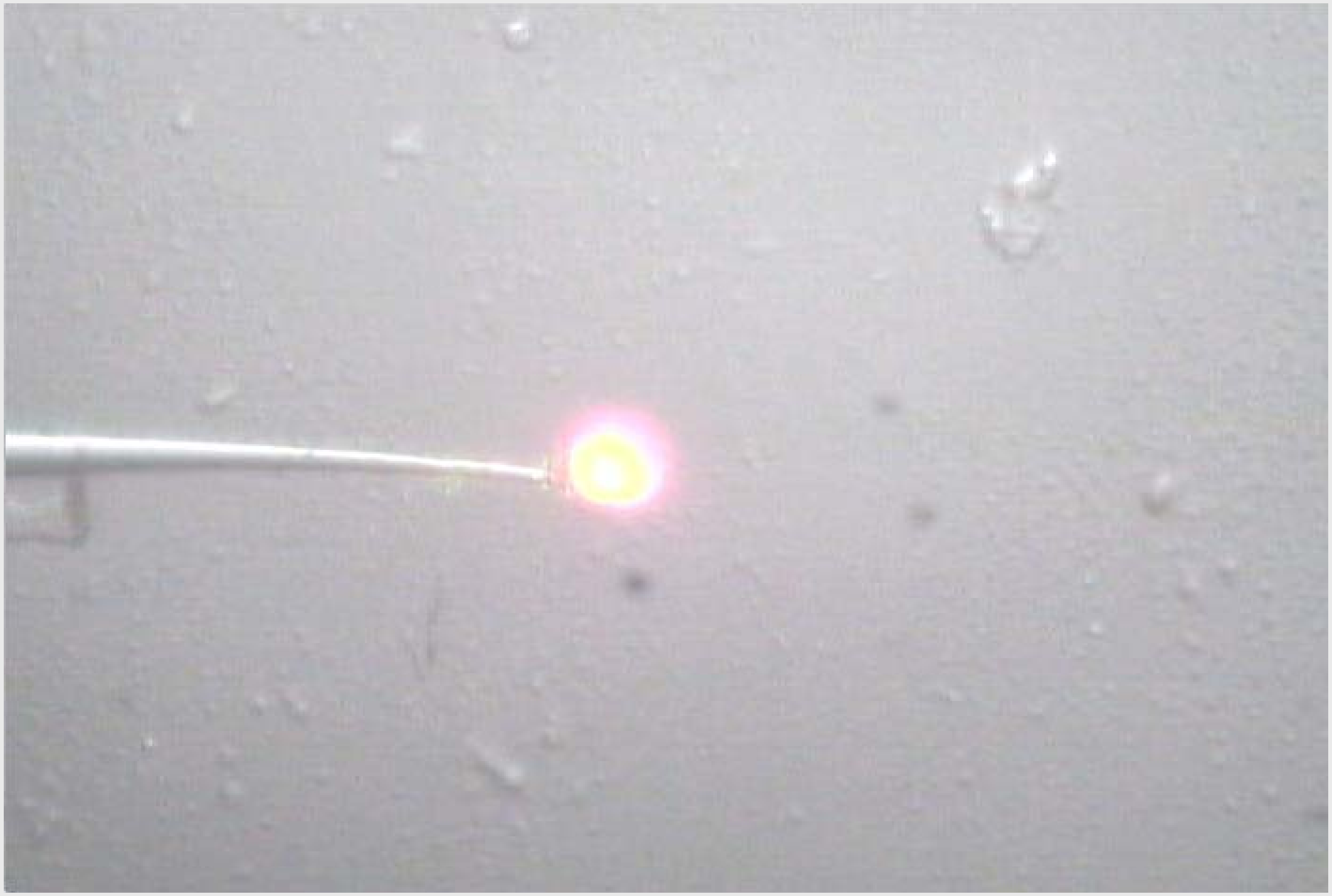

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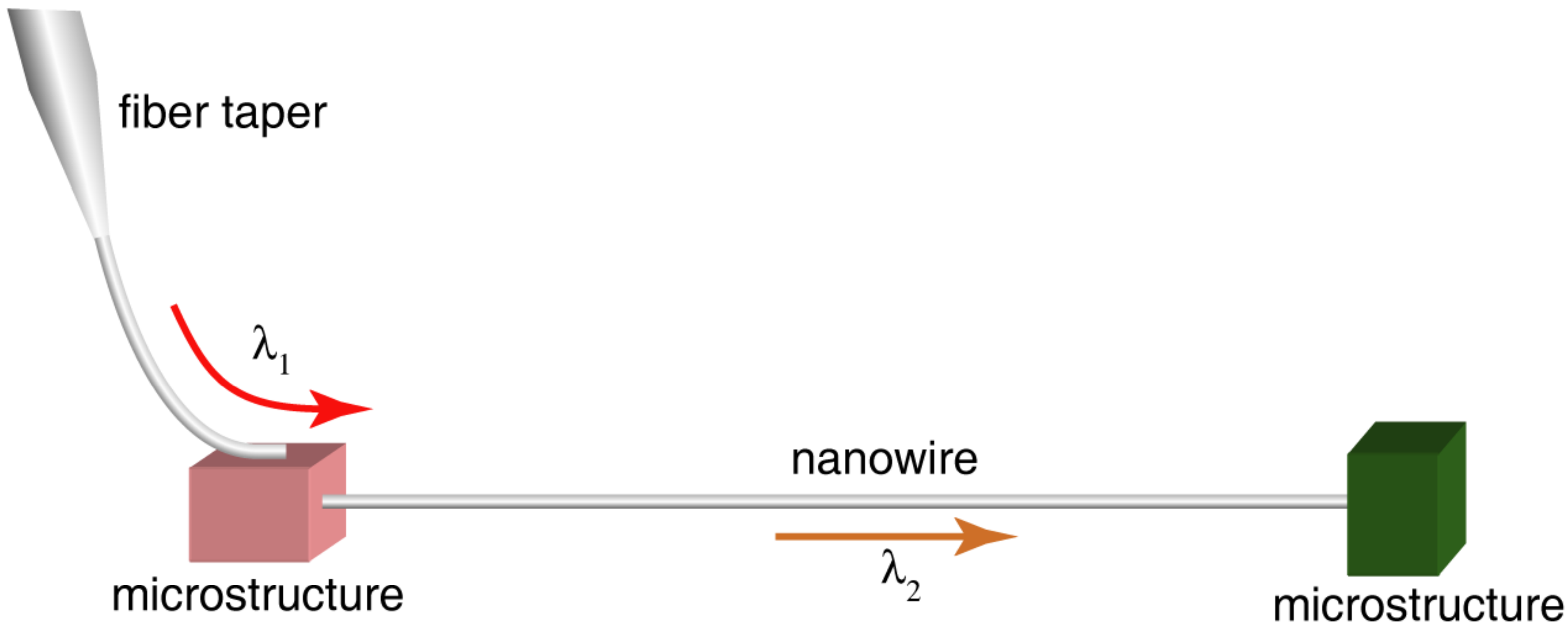
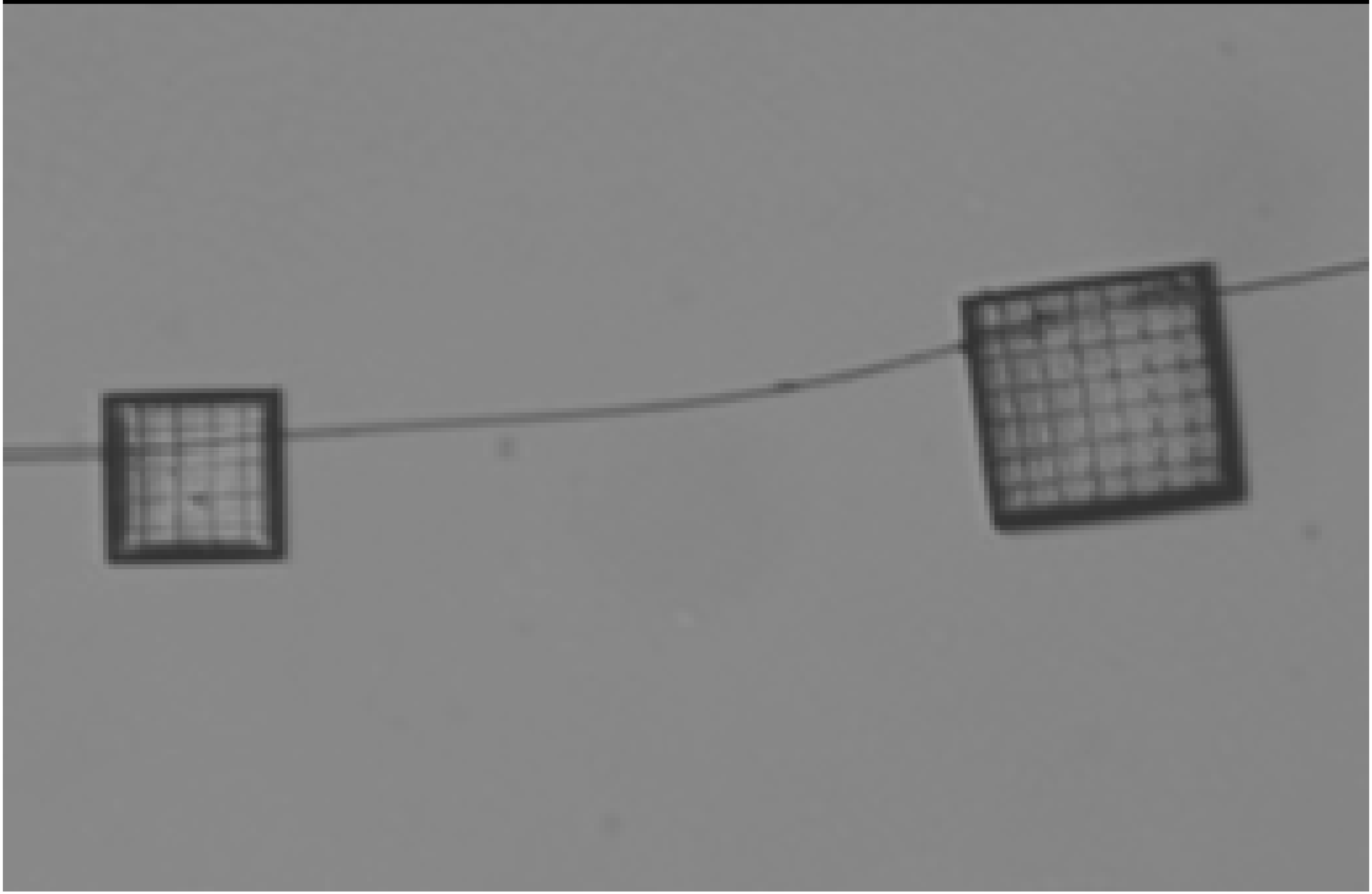


Coupling microstructures



Acknowledgments

Team

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Ruben Fonseca
Renato Martins
Paulo H. D. Ferreira

FAPESP

CNPq

CAPES

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