Femtosecond laser micromachining

Ultrafast and Ultrasmall: Part I
2008 ITRI Femtosecond Laser International Forum
Tainan, Taiwan, 14 October 2008

Outline

- femtosecond laser micromachining
- femtosecond laser doping
- nonlinear optics at the nanoscale

Femtosecond laser micromachining

Ultrafast and Ultrasmall: Part I
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Rafael Gattass


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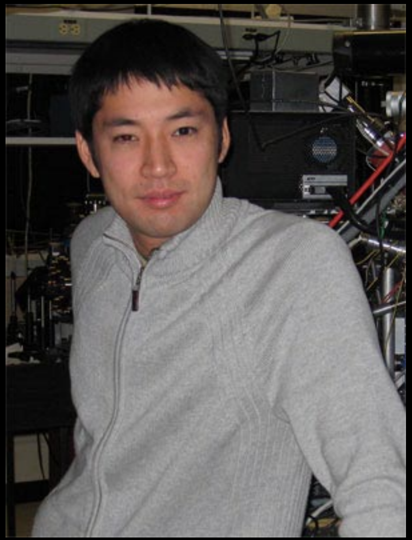

Masanao Kamata

and also....

Iva Maxwell
San Chung
Eli Glezer
Chris Schaffer
Nozomi Nishimura
Jonathan Ashcom
Jeremy Hwang
Nan Shen
Dr. André Brodeur
Dr. Sanjoy Kumar
Dr. Limin Tong
Dr. Prissana Thamboon

Prof. Igor Khruschev (Aston University)
Prof. Denise Krol (UC Davis)
Dr. Yossi Chay (Sagitta, Inc.)
Dr. S.K. Sundaram (PNNL)
Prof. Minoru Obara (Keio University)
Prof. Don Ingber (Harvard Medical School)
Prof. Aravi Samuel (Harvard)

My message

fs micromachining: great technique for manipulating matter

Introduction

Introduction

Breakdown threshold and plasma formation in femtosecond laser–solid interaction

D. von der Linde and H. Schüler

Institut für Laser- und Plasmaphysik, Universität Essen, D-45117 Essen, Germany

Received March 6, 1995; revised manuscript received June 15, 1995

Combining femtosecond pump–probe techniques with optical microscopy, we have studied laser-induced optical breakdown in optically transparent solids with high temporal and spatial resolution. The threshold of plasma formation has been determined from measurements of the changes of the optical reflectivity associated with the developing plasma. It is shown that plasma generation occurs at the surface. We have observed a remarkable resistance to optical breakdown and material damage in the interaction of femtosecond laser pulses with bulk optical materials.

1. INTRODUCTION

The interaction of intense femtosecond laser pulses with solids offers the possibility of producing a new class of plasmas having approximately solid-state density and spatial density scale lengths much smaller than the wavelength of light. These high-density plasmas with extremely sharp density gradients are currently of great interest, particularly from the point of view of generating bright, ultrashort x-ray pulses. To produce such a plasma, the laser pulse should rise from the intensity level corresponding to the threshold of plasma formation to the peak value in a time much shorter than the time scale of plasma expansion. Thus the specification of the tol-

One of the key points in the research of Bloembergen and his co-workers was the use of very tightly focused laser beams, which allowed them to reach the breakdown threshold of the materials while staying well below the critical power of self-focusing. Self-focusing is one of the major problems in the measurement of bulk breakdown thresholds. In a more recent review Soileau *et al.*[5] carefully examined the role of self-focusing in experiments measuring laser-induced breakdown of bulk dielectric materials. They concluded that the breakdown and damage thresholds are also strongly influenced by extrinsic effects.

Thus far, the issue of breakdown thresholds in femtosecond laser–solid interaction has barely been touched. Very recently, Du *et al.*[6] carried out laser-induced breakdown experiments on fused silica with pulses ranging in duration from 7 ns to as low as 150 fs. They reported an interesting dependence of the fluence threshold on pulse duration, particularly a pronounced increase of the threshold with decreasing pulse duration below 10 ps.

Introduction

"… clear evidence that no bulk plasmas…

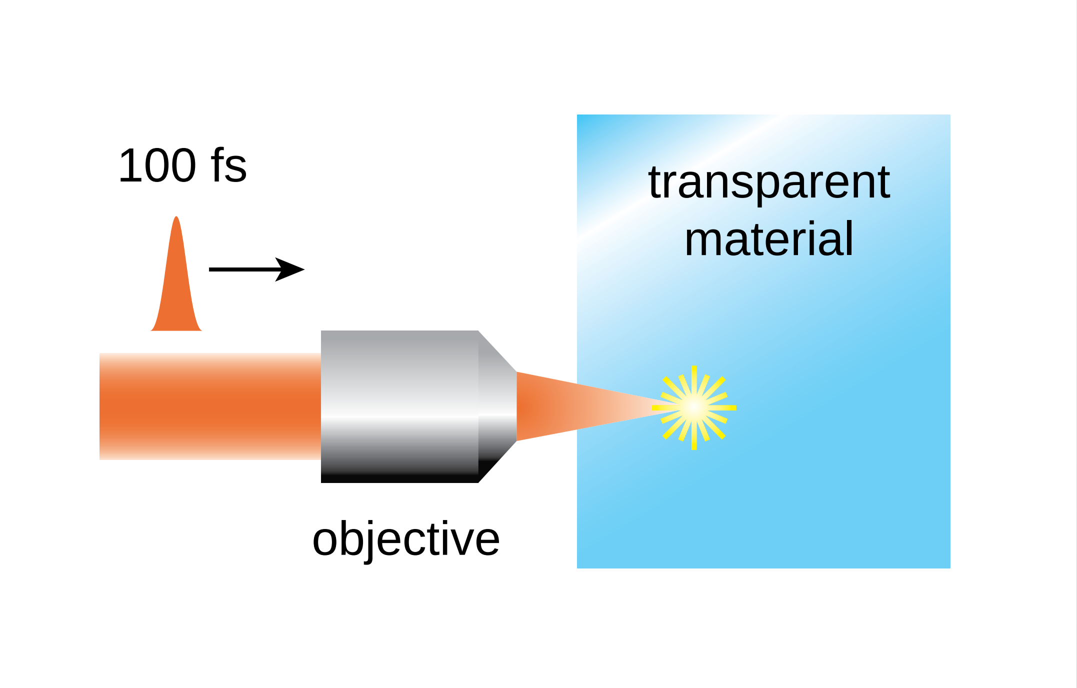
[and] … no bulk damage could be produced

with femtosecond laser pulses"

von der Linde, *et al*., *J. Opt. Soc. Am*. B **13**, 216 (1996)

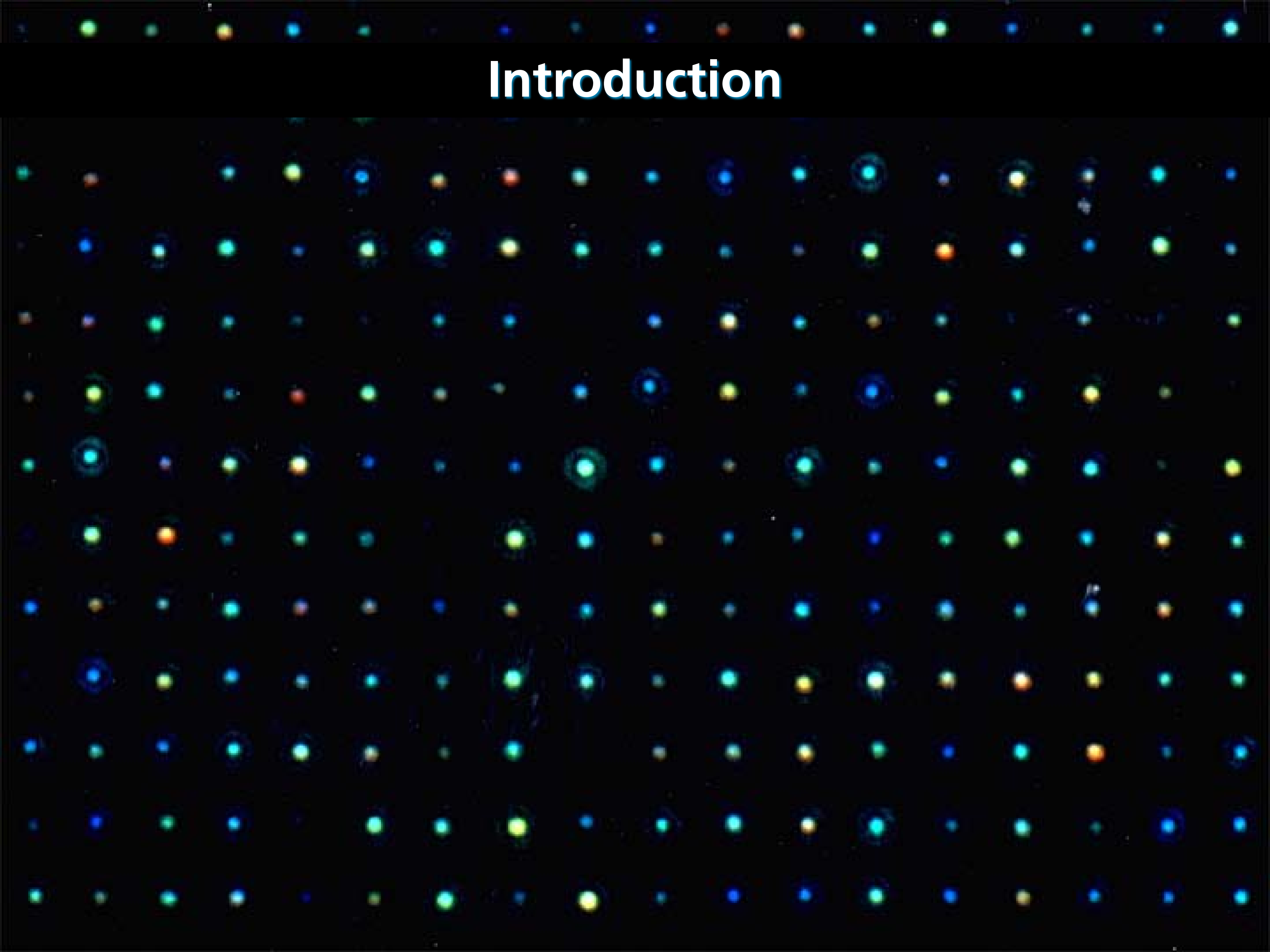
Introduction

focus laser beam inside material



Opt. Lett. **21**, 2023 (1996)

Introduction

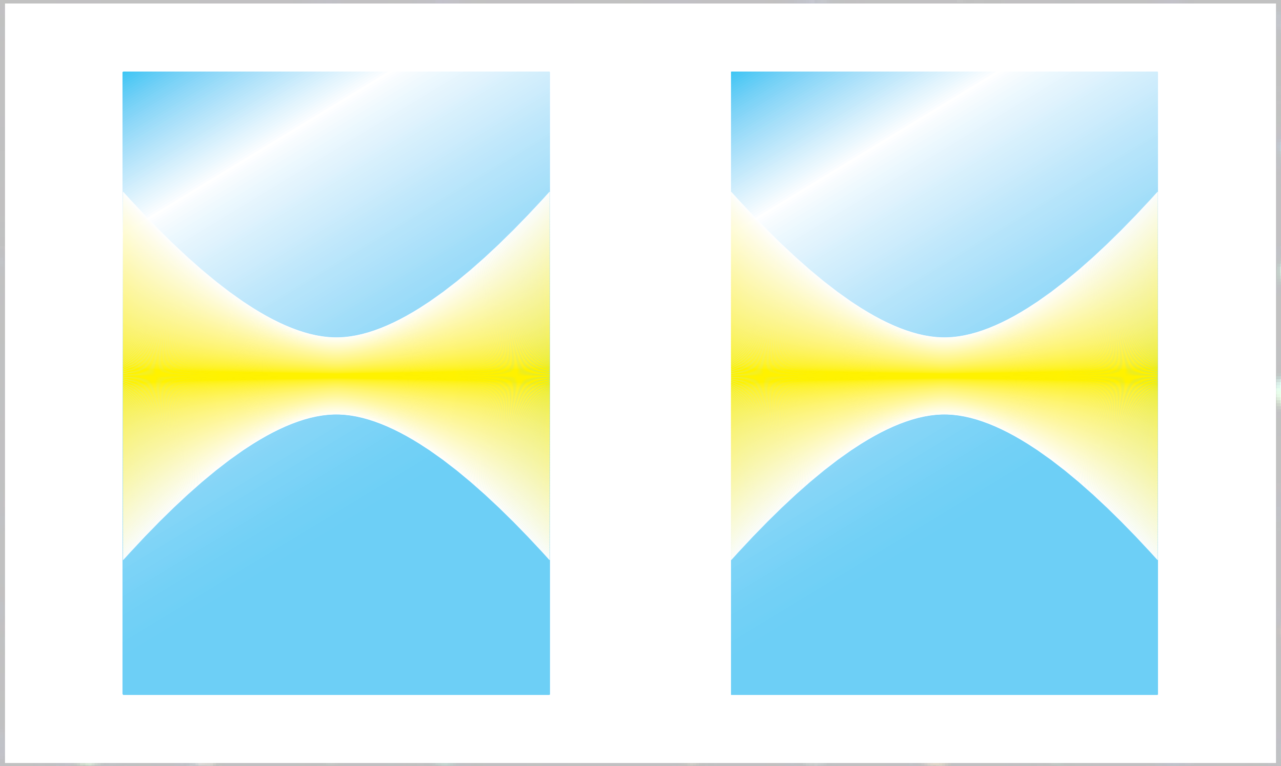


Introduction

photon energy < bandgap $\longrightarrow$ nonlinear interaction

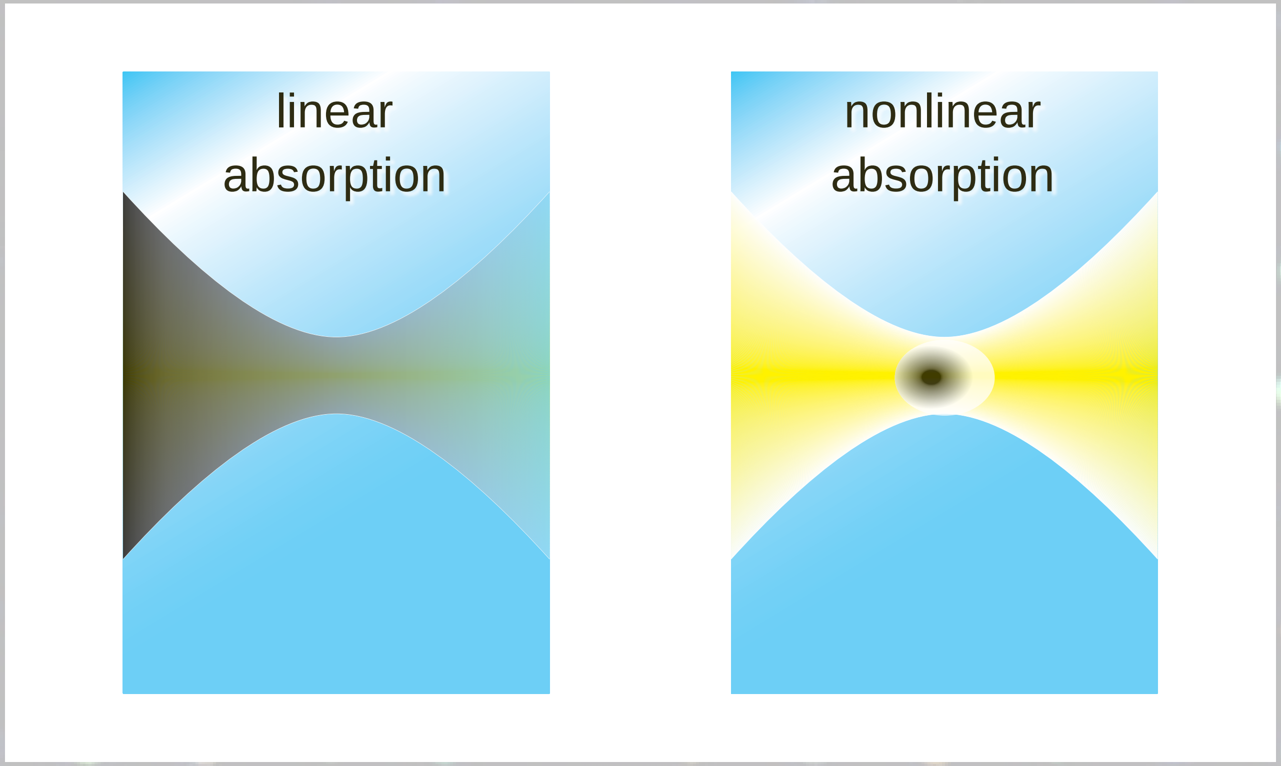
Introduction

nonlinear interaction provides bulk confinement



Introduction

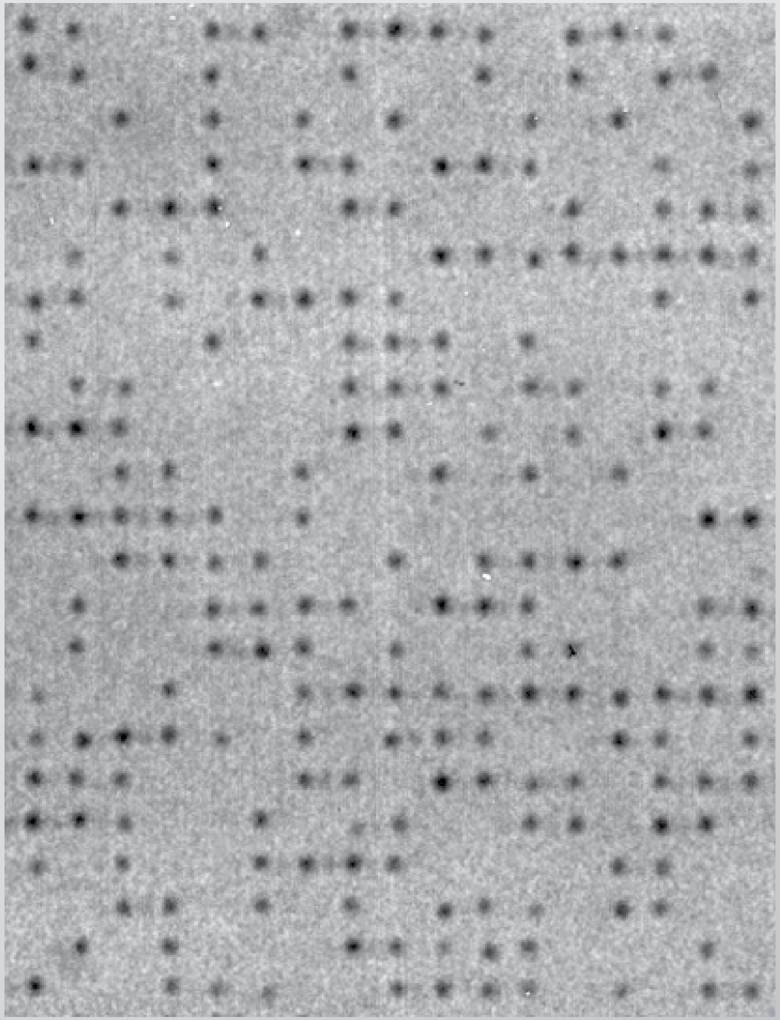
nonlinear interaction provides bulk confinement



Femtosecond micromachining

Some applications:

- data storage
- waveguides
- microfluidics

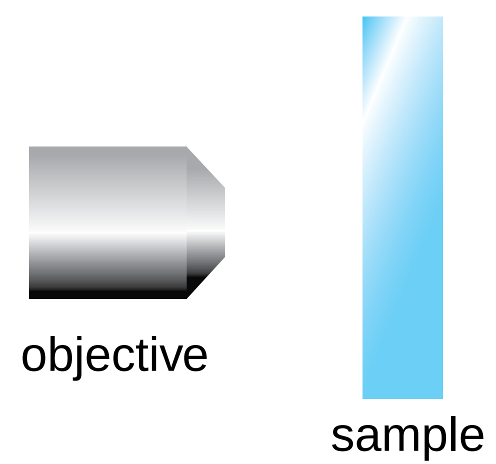


Outline

- femtosecond micromachining
- low-energy machining
- applications

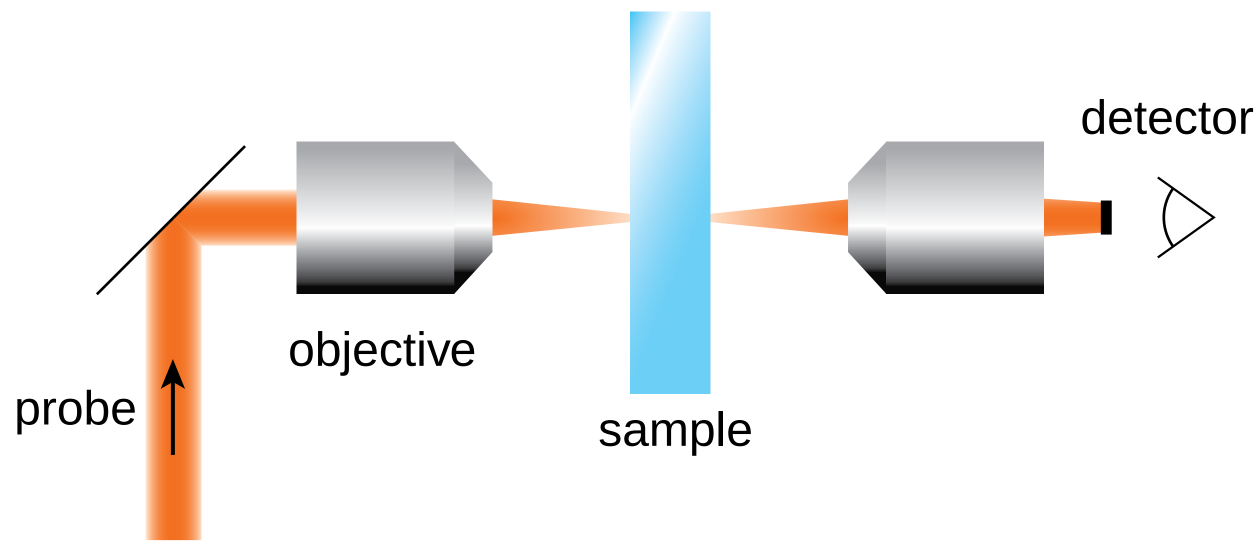
Femtosecond micromachining

Dark-field scattering



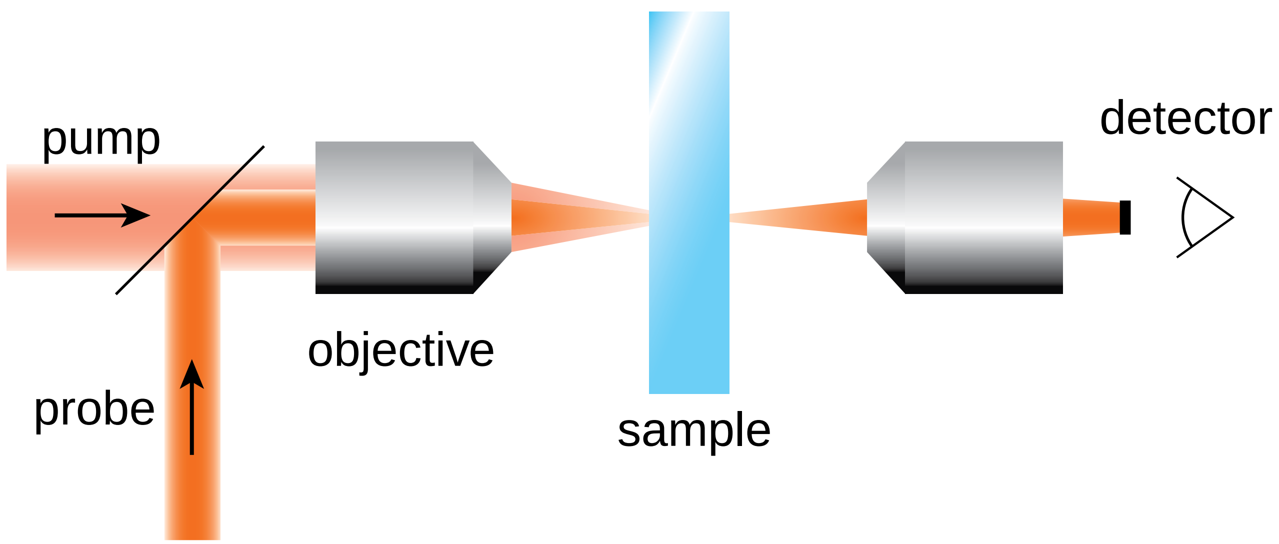
Femtosecond micromachining

block probe beam…



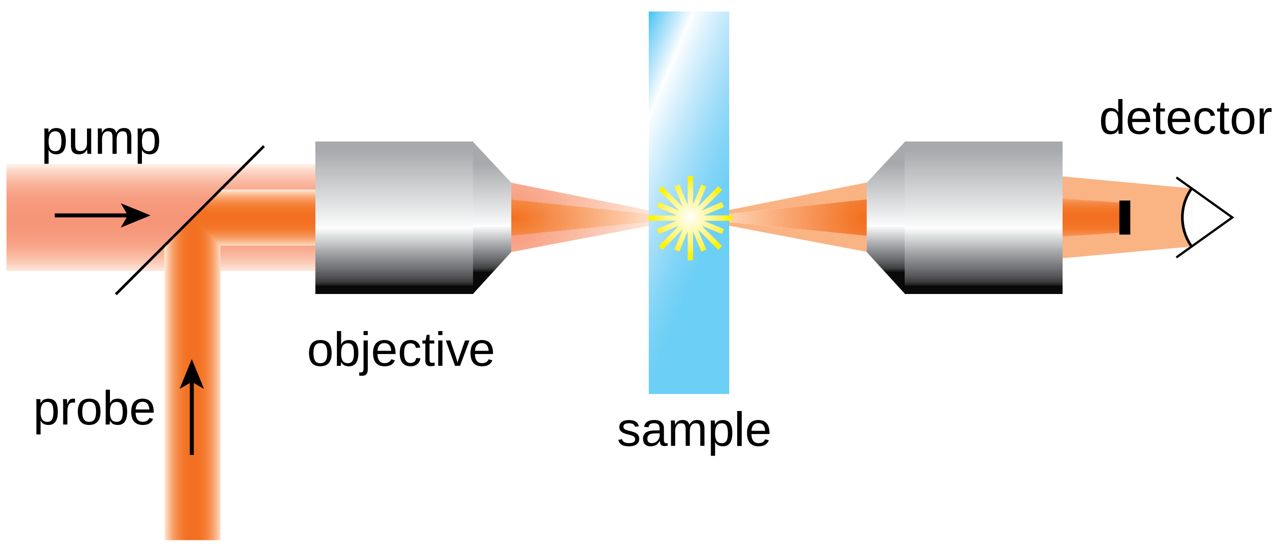
Femtosecond micromachining

… bring in pump beam…



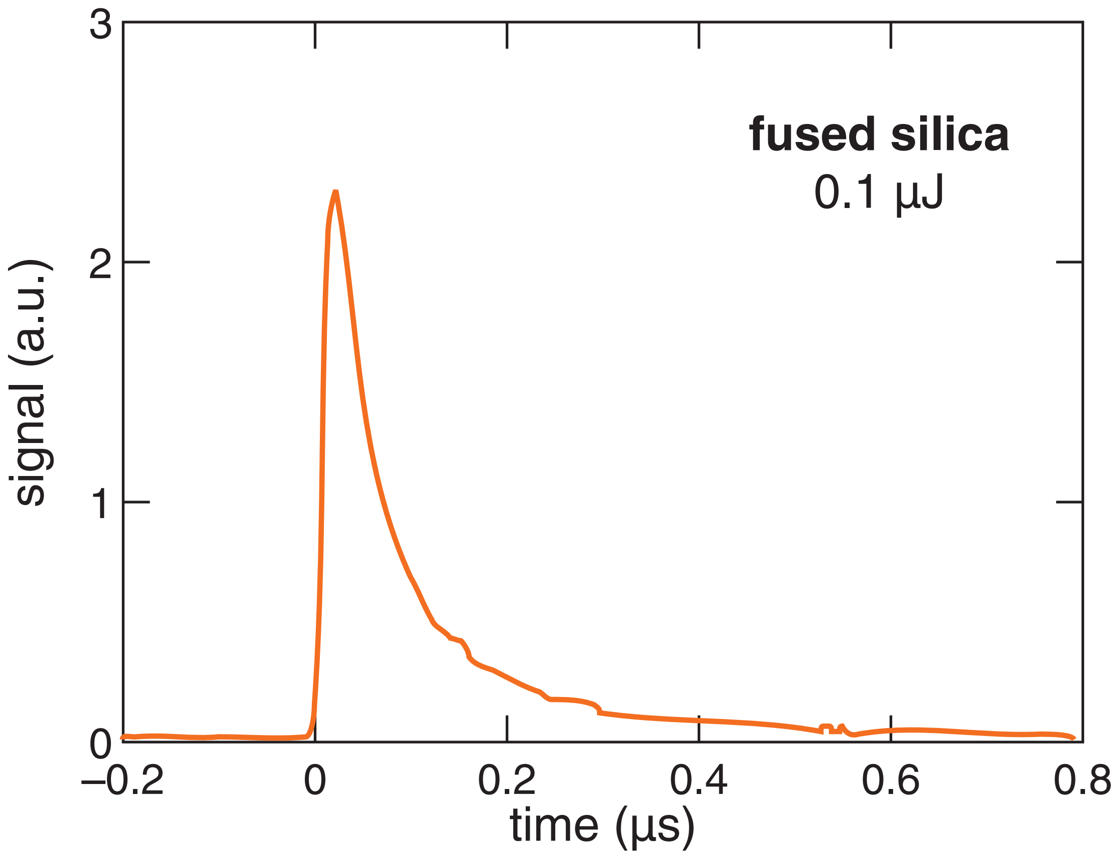
Femtosecond micromachining

… damage scatters probe beam



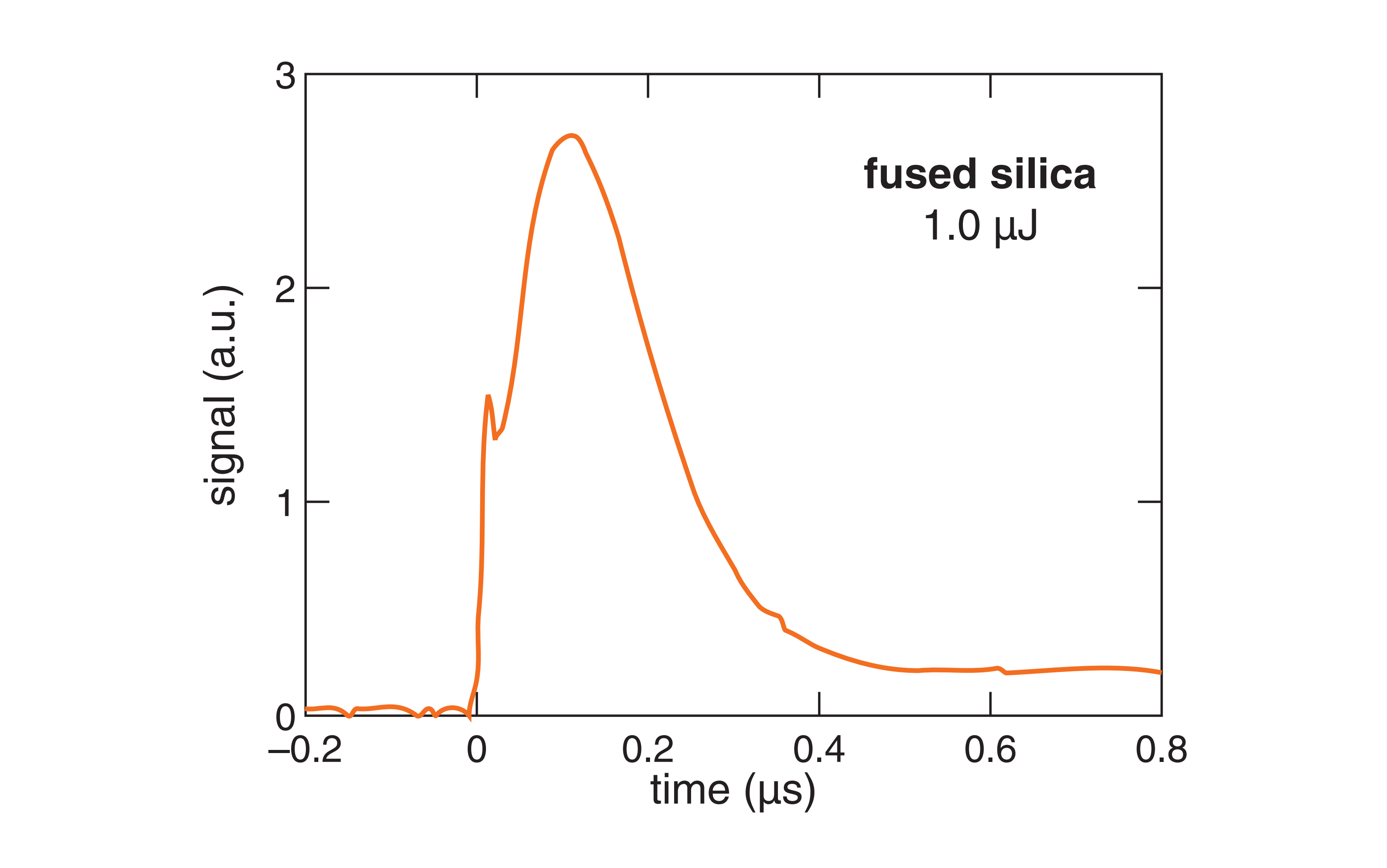
Femtosecond micromachining

scattered signal



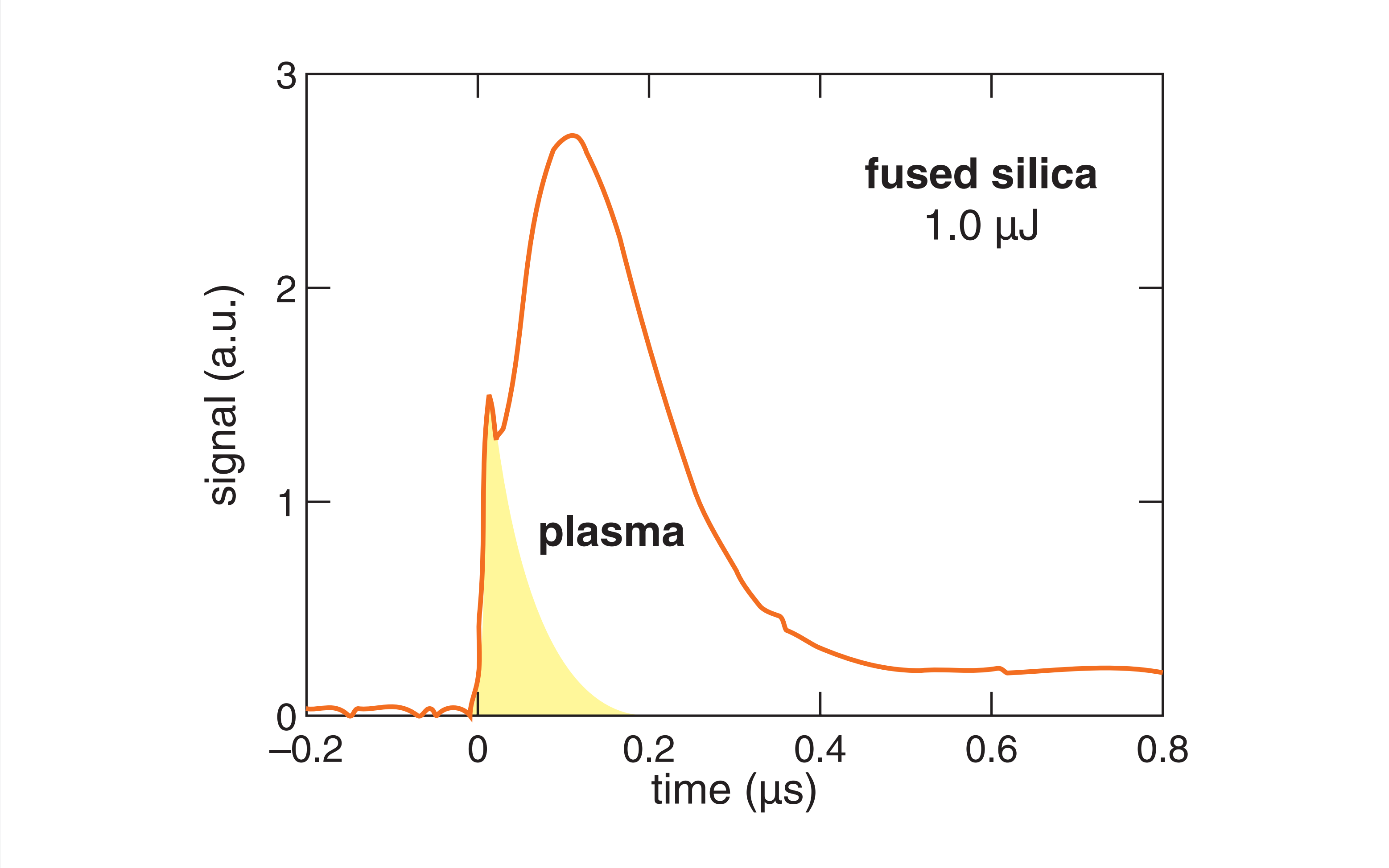
Femtosecond micromachining

scattered signal



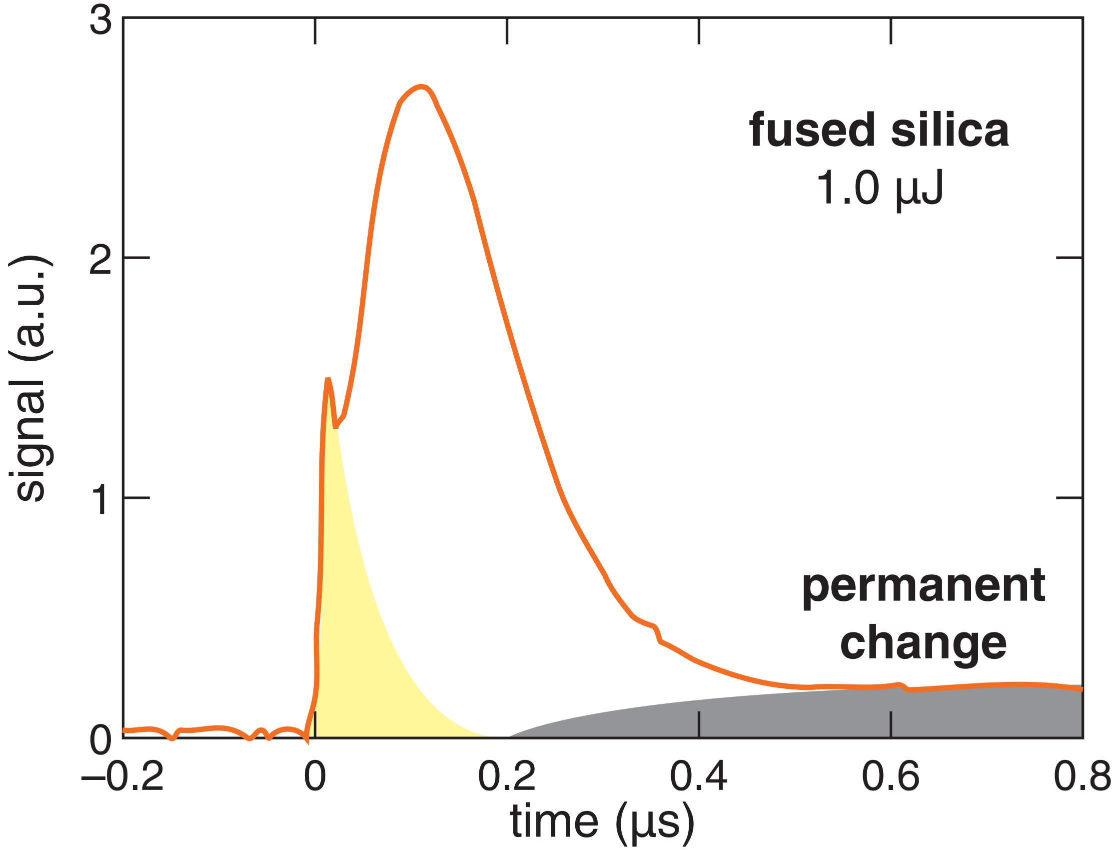
Femtosecond micromachining

scattered signal



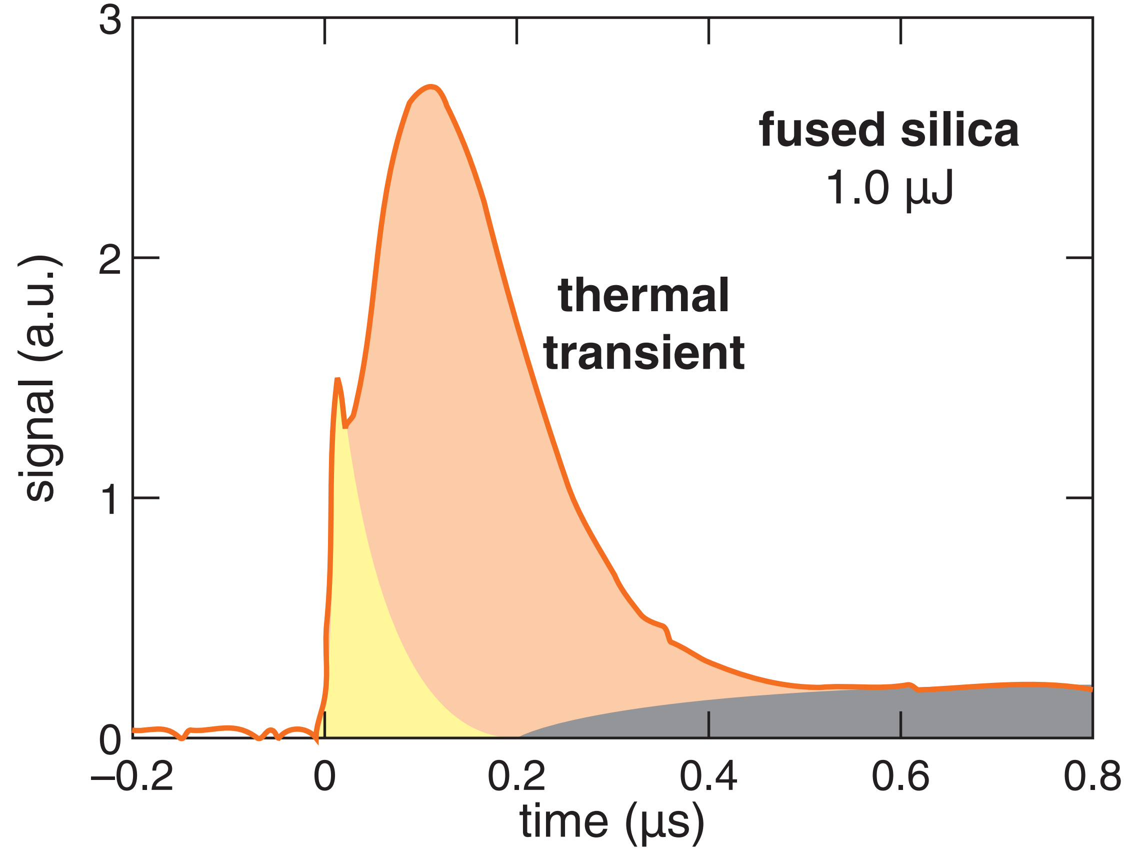
Femtosecond micromachining

scattered signal



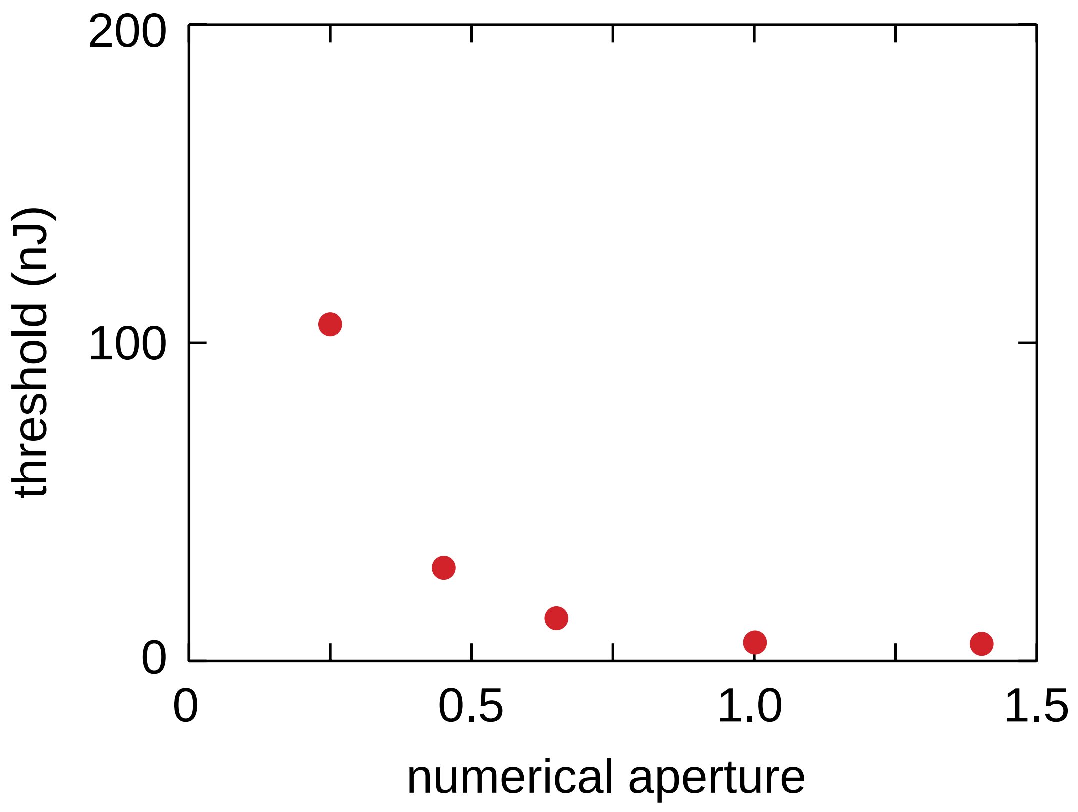
Femtosecond micromachining

scattered signal



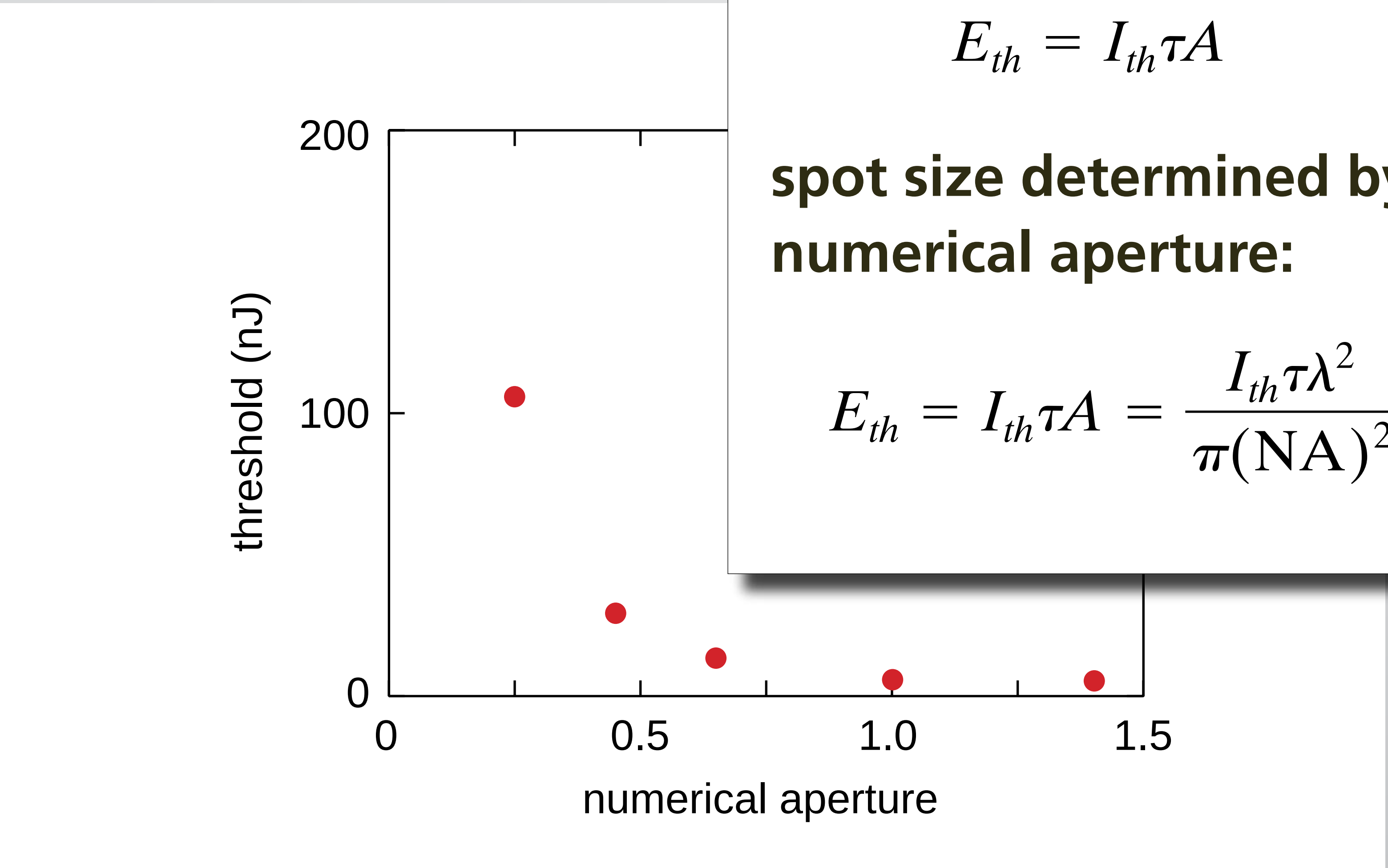
Femtosecond micromachining

vary numerical aperture



Femtosecond micromachining

vary numeric



intensity threshold:

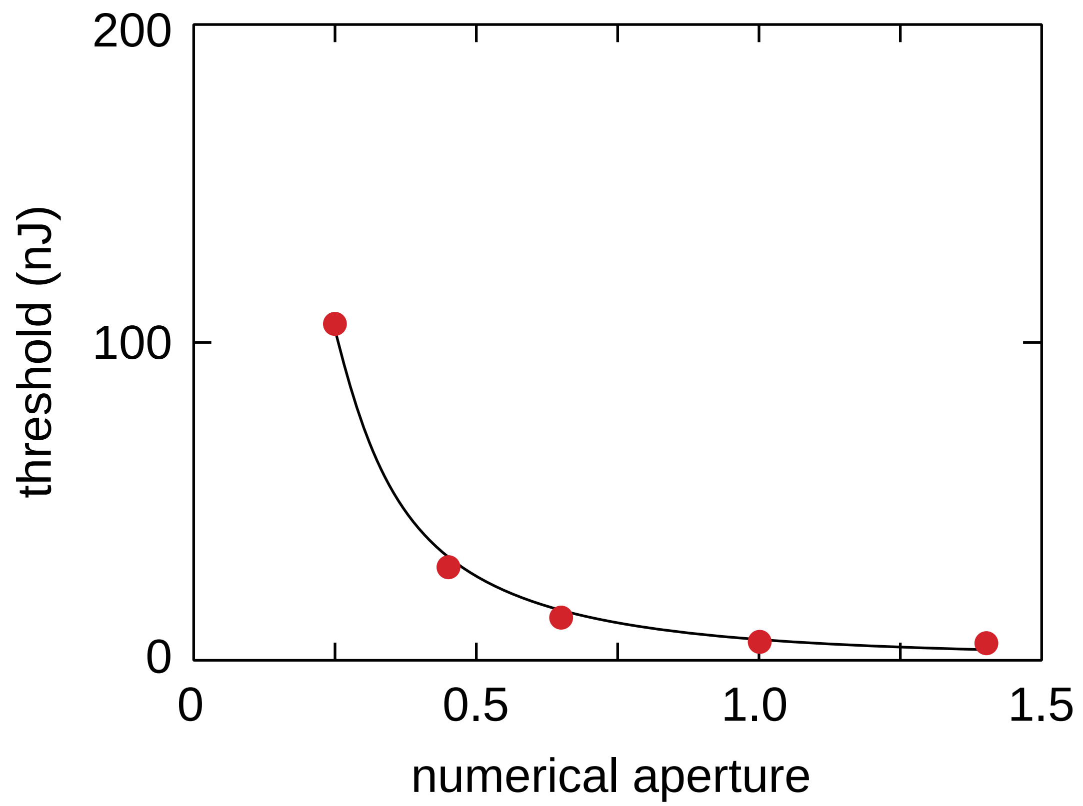
$$E_{th} = I_{th} \tau A$$

spot size determined by numerical aperture:

$$E_{th} = I_{th} \tau A = \frac{I_{th} \tau \lambda^2}{\pi (\mathrm{NA})^2}$$

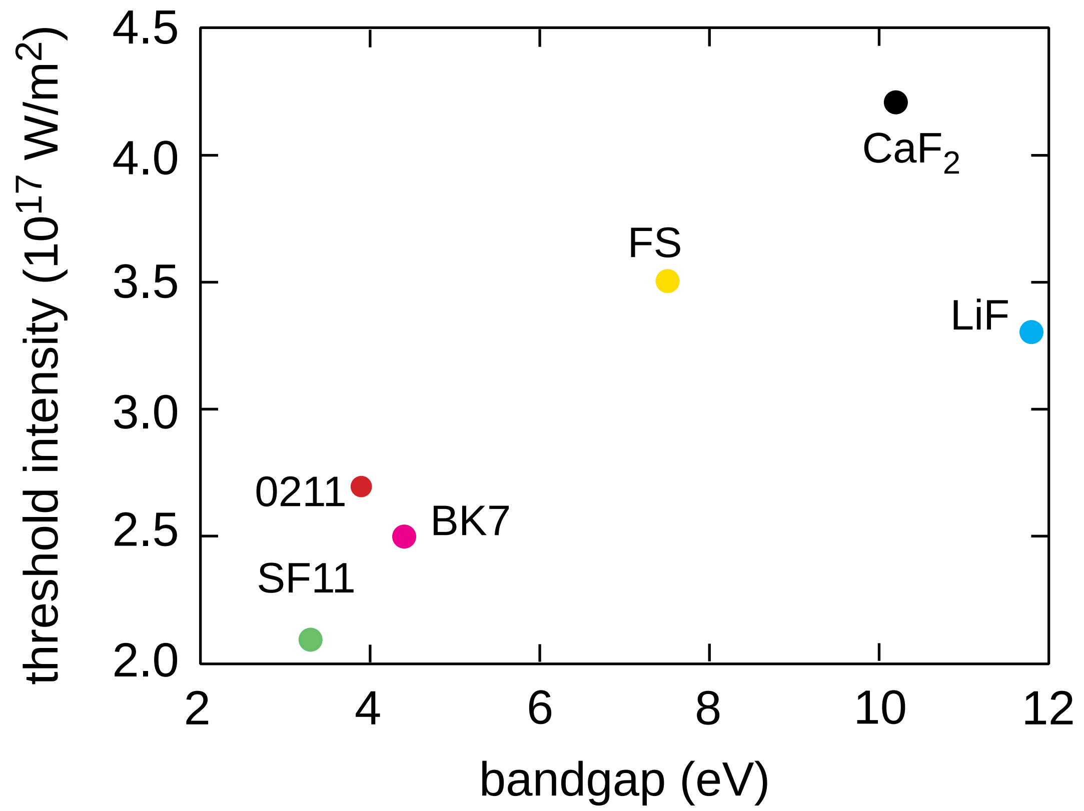
Femtosecond micromachining

fit gives threshold intensity: I_{th} = 2.5 x 10^{17} W/m^{2}



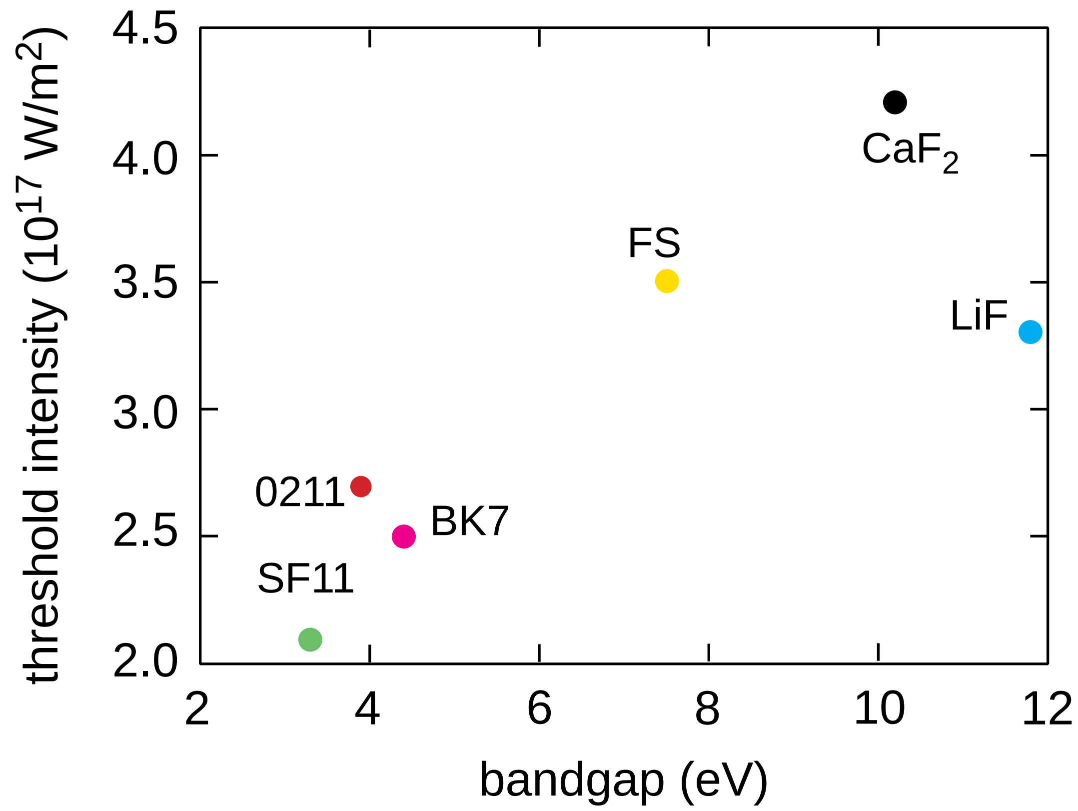
Femtosecond micromachining

vary material…



Femtosecond micromachining

…threshold varies with band gap (but not much!)



Femtosecond micromachining

what prevents damage at low NA?

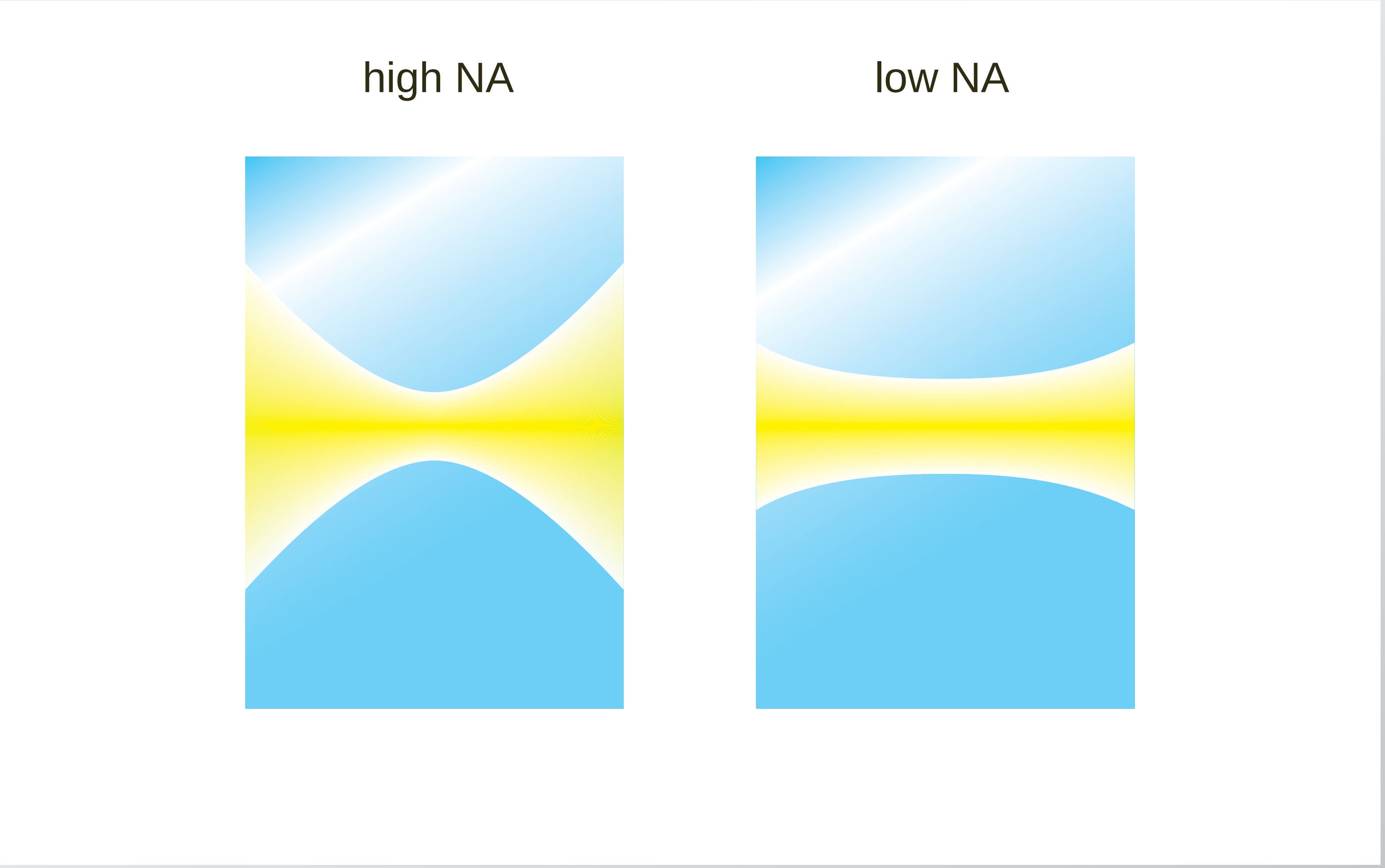
Femtosecond micromachining

Competing nonlinear effects:

- multiphoton absorption
- supercontinuum generation
- self-focusing

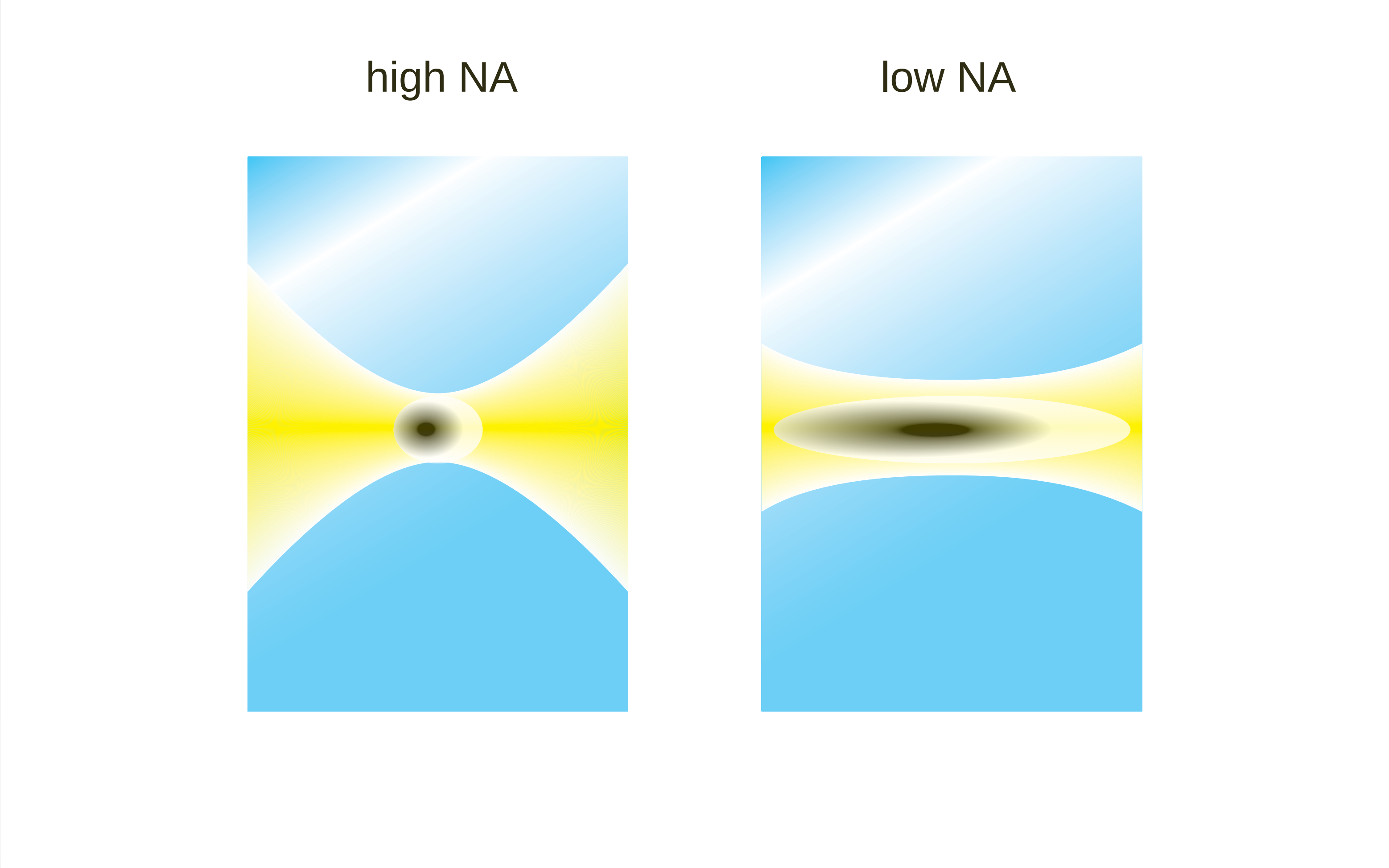
Femtosecond micromachining

why the difference?



Femtosecond micromachining

very different confocal length/interaction length

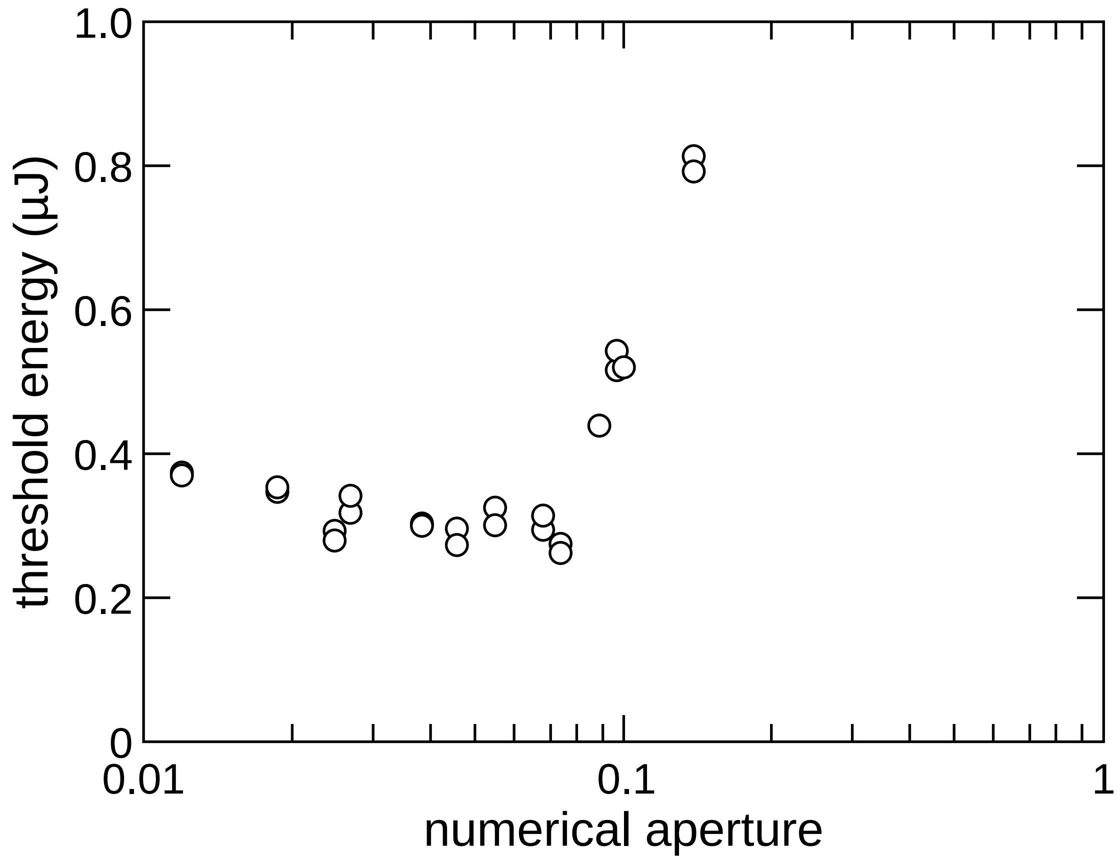


Femtosecond micromachining

high NA: interaction length too short for self-focusing

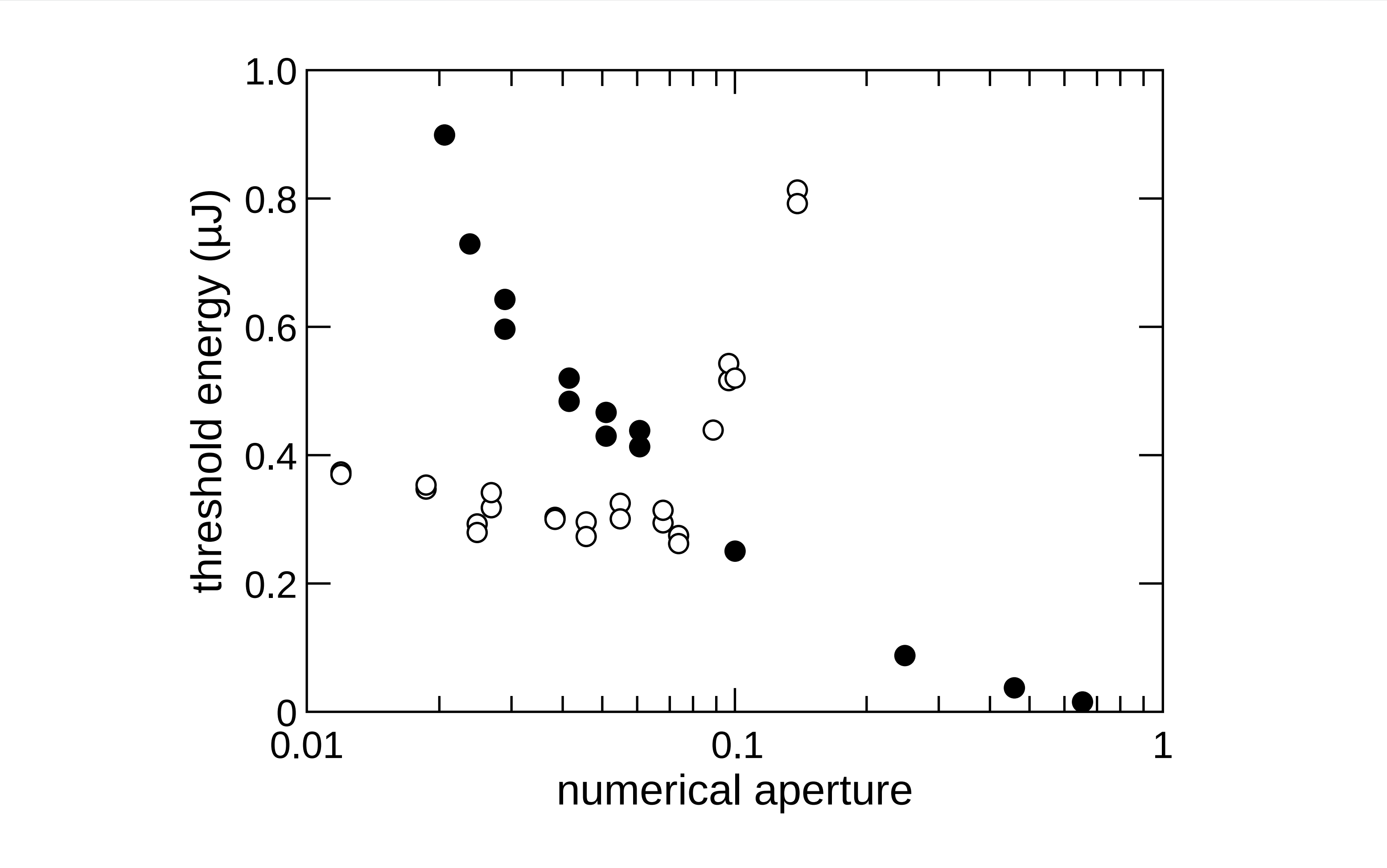
Femtosecond micromachining

threshold for supercontinuum generation



Femtosecond micromachining

threshold for damage



Femtosecond micromachining

Points to keep in mind:

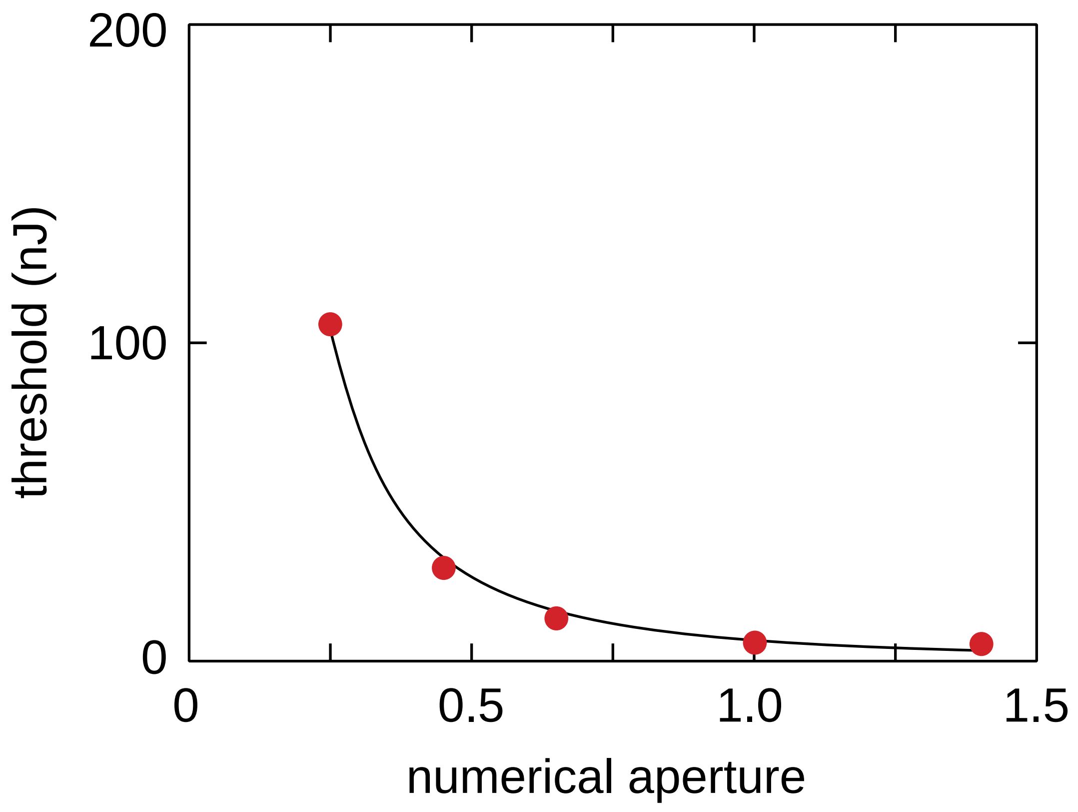
- threshold critically dependent on NA
- surprisingly little material dependence
- avalanche ionization important

Outline

- femtosecond micromachining
- low-energy machining
- applications

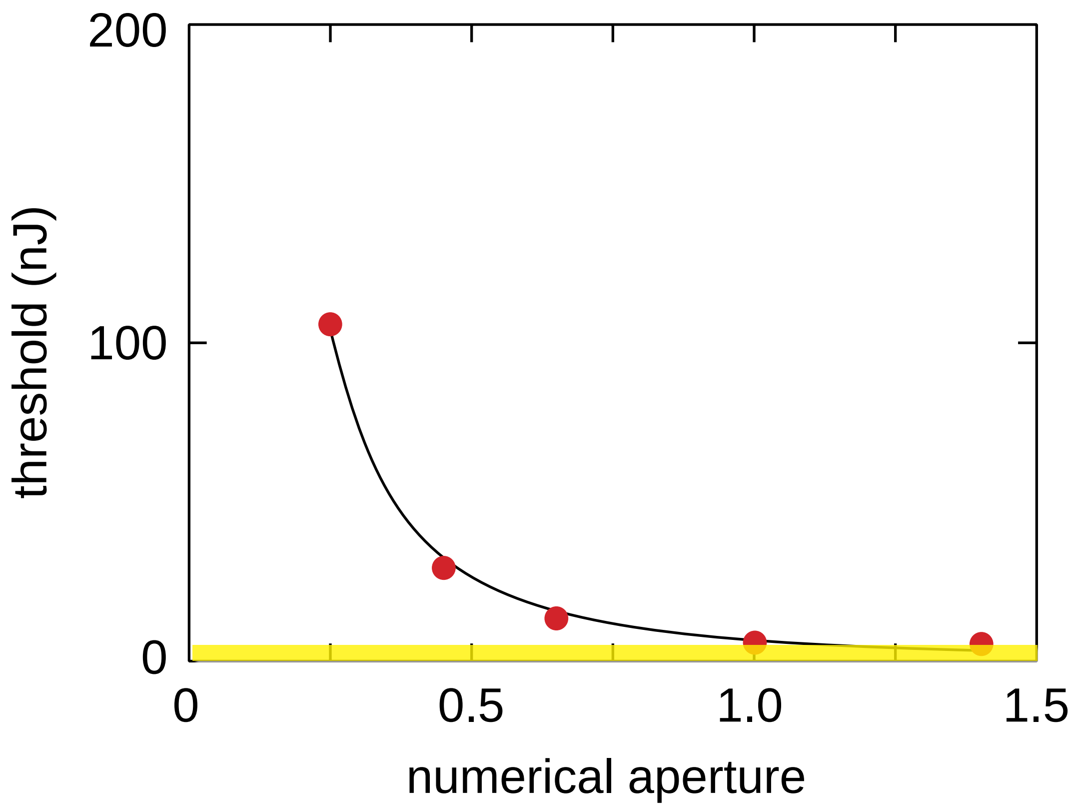
Low-energy machining

threshold decreases with increasing numerical aperture



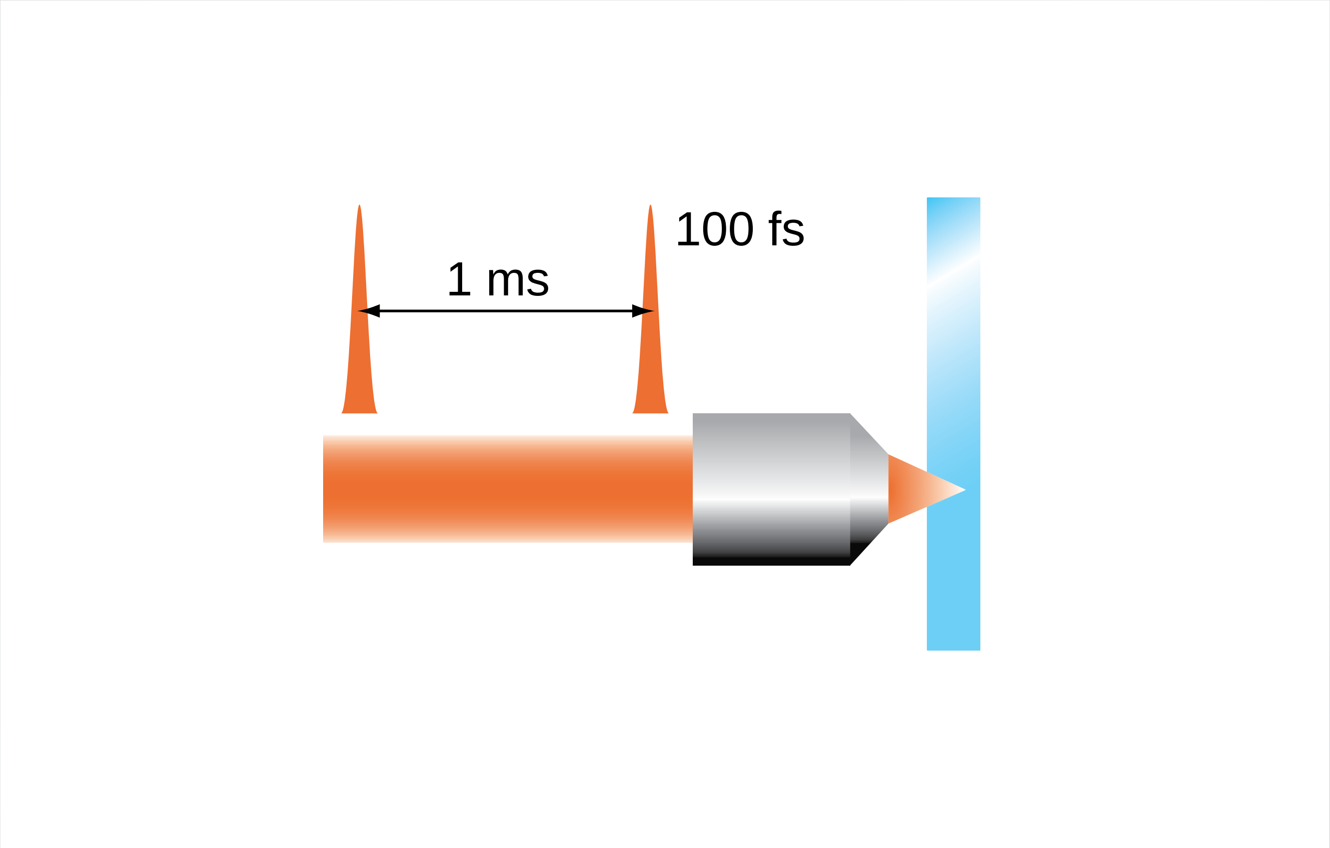
Low-energy machining

less than 10 nJ at high numerical aperture!



Low-energy machining

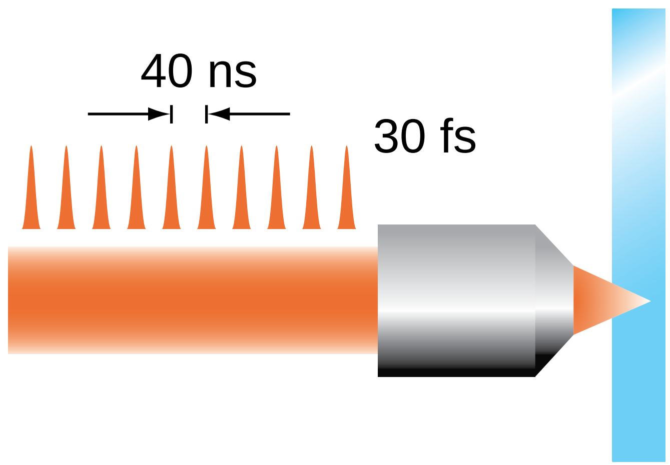
amplified laser: 1 kHz, 1 mJ



heat diffusion time: $\tau_{diff} \approx 1\ \mu s$

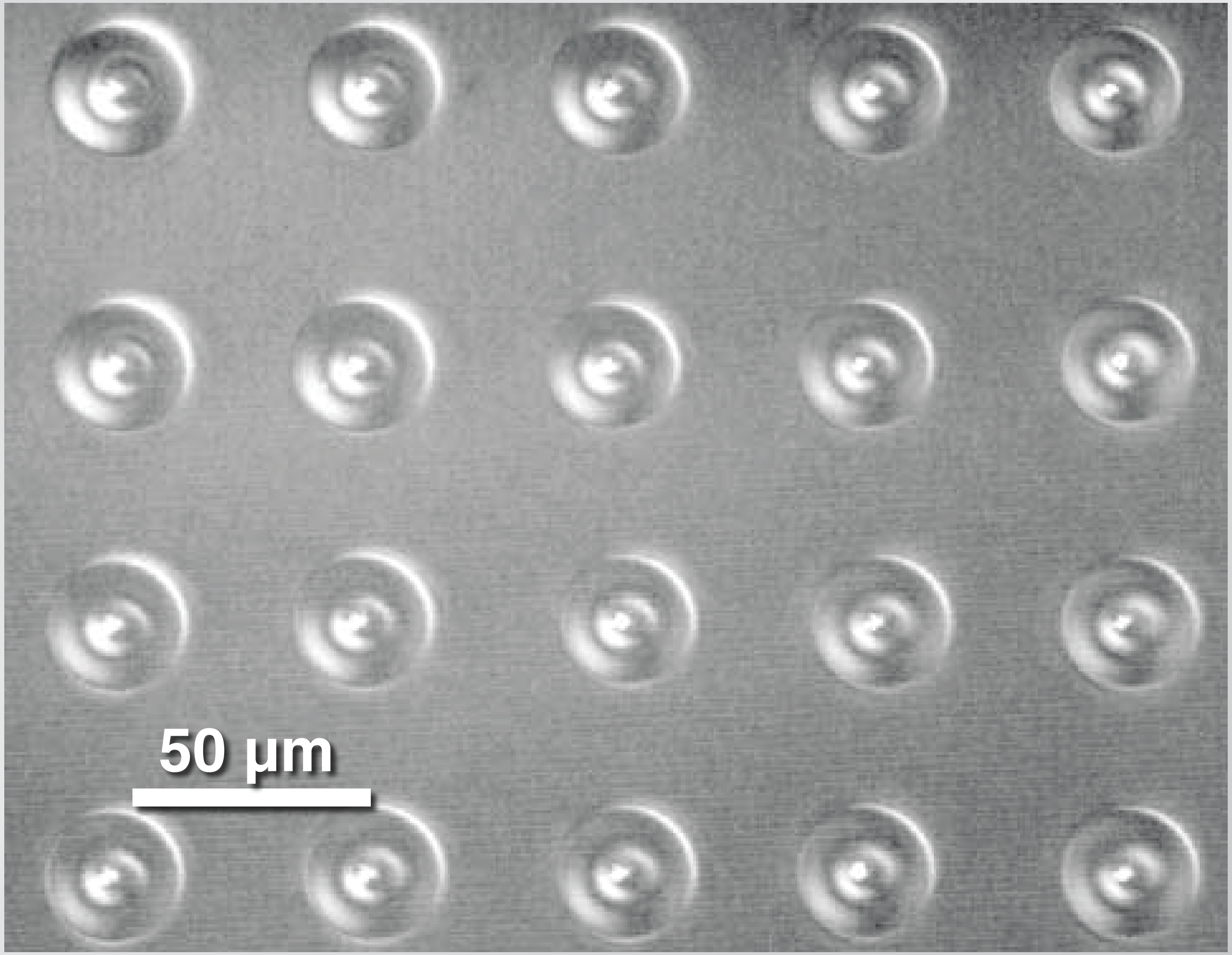
Low-energy machining

long cavity oscillator: 25 MHz, 25 nJ



heat diffusion time: $\tau_{diff} \approx 1\ \mu s$

Low-energy machining



Low-energy machining

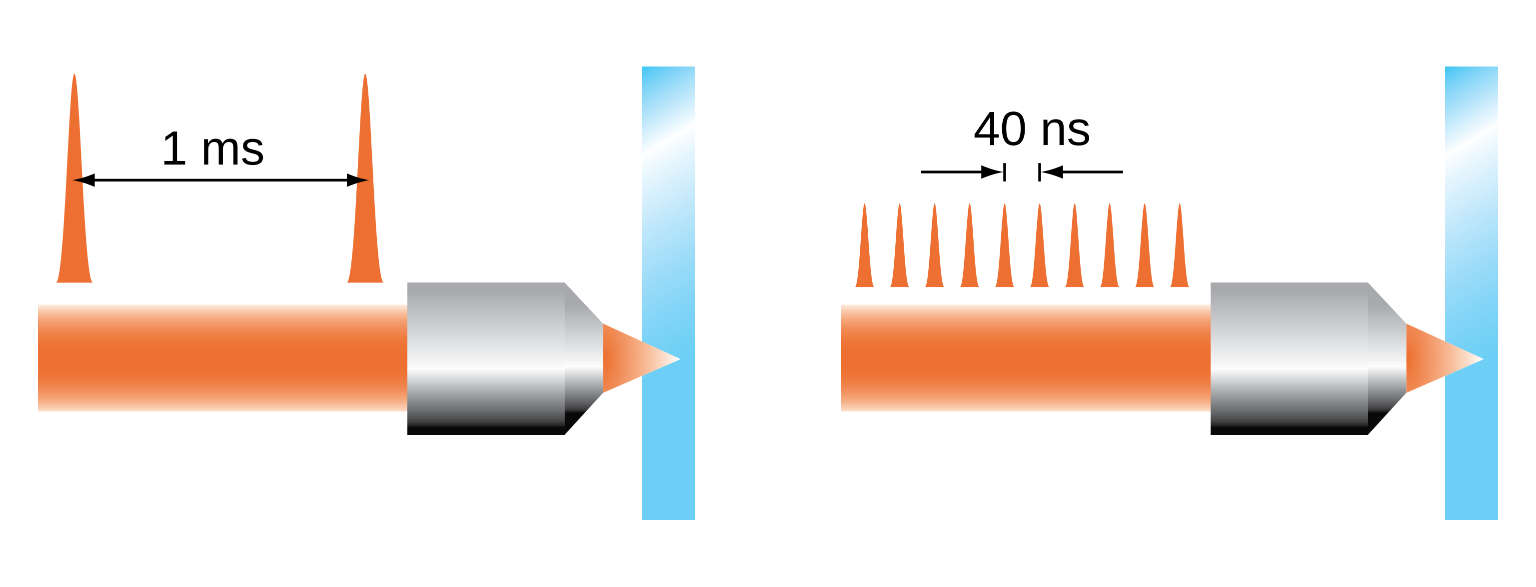
High repetition-rate micromachining:

- structural changes exceed focal volume
- spherical structures
- density change caused by melting

Low-energy machining

amplified laser

oscillator

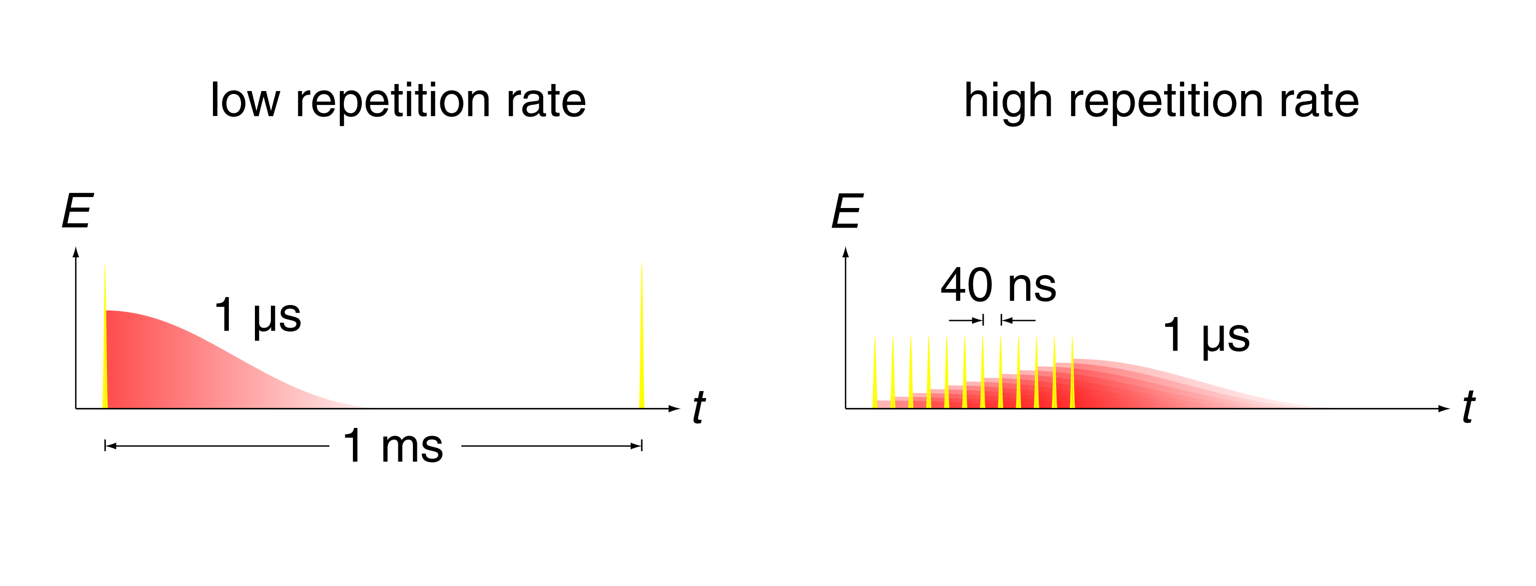


repetitive

cumulative

Low-energy machining

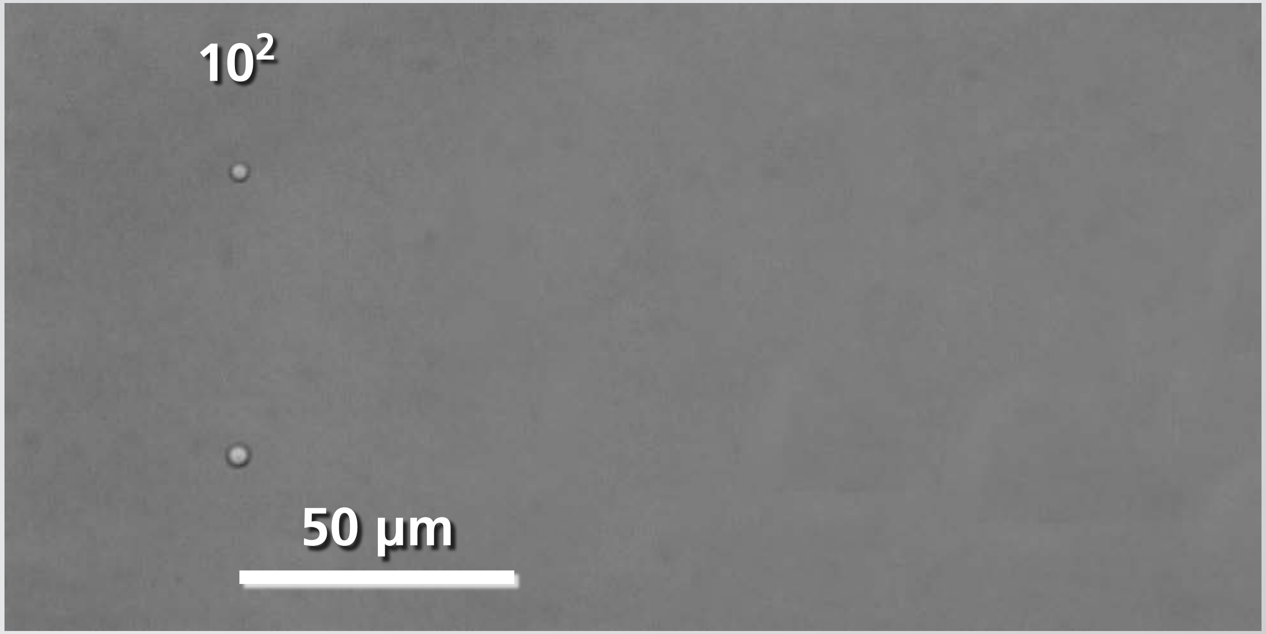
amplified laser | **oscillator**



repetitive | **cumulative**

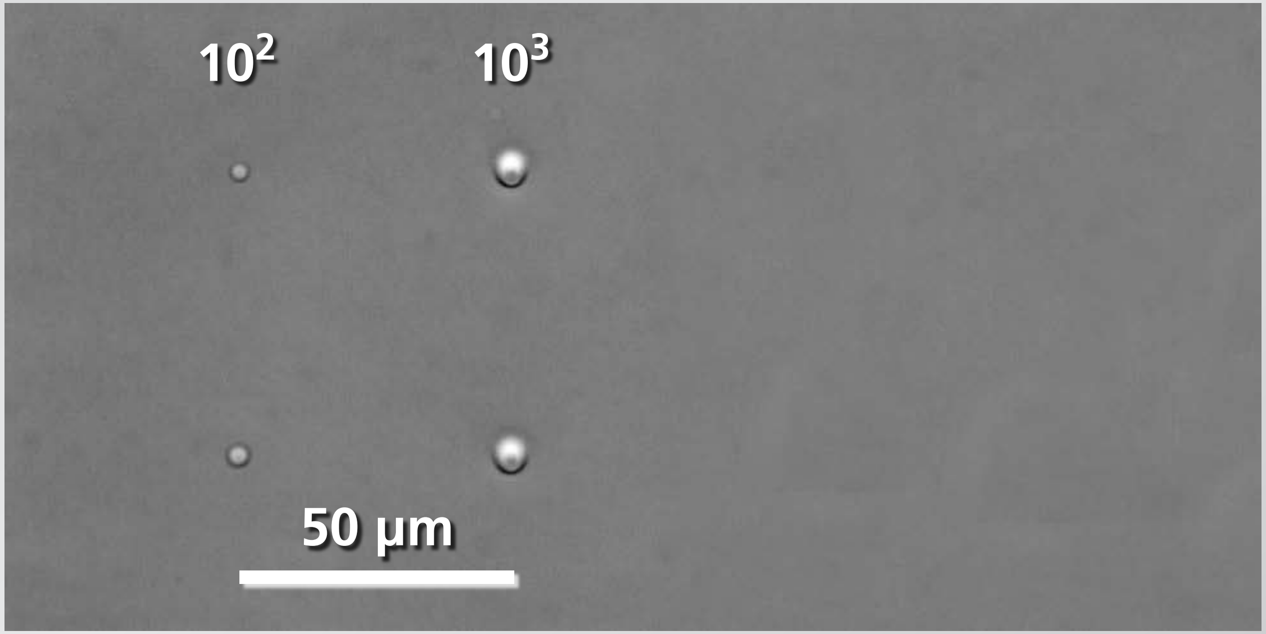
Low-energy machining

the longer the irradiation…



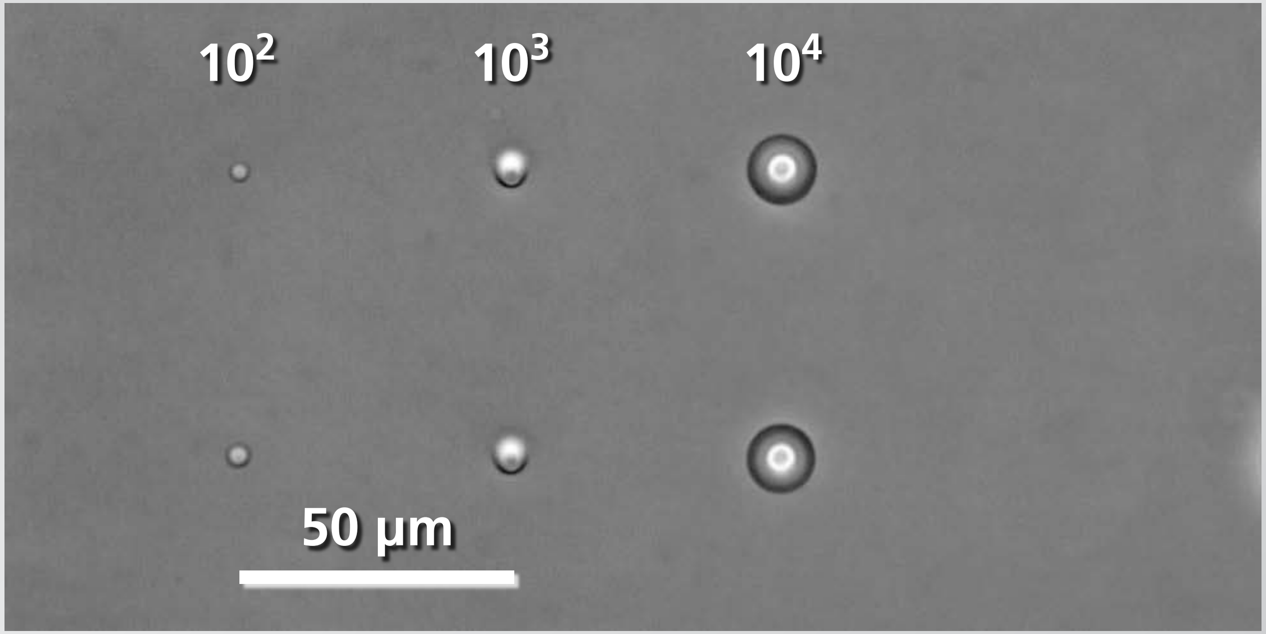
Low-energy machining

the longer the irradiation…



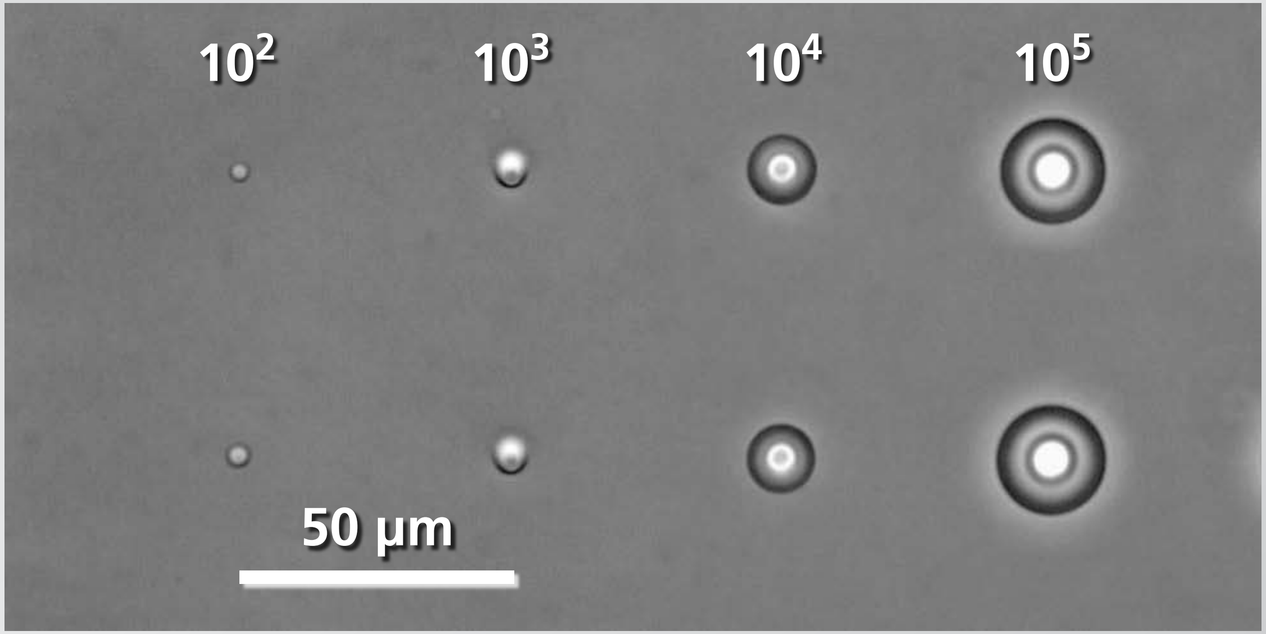
Low-energy machining

the longer the irradiation…



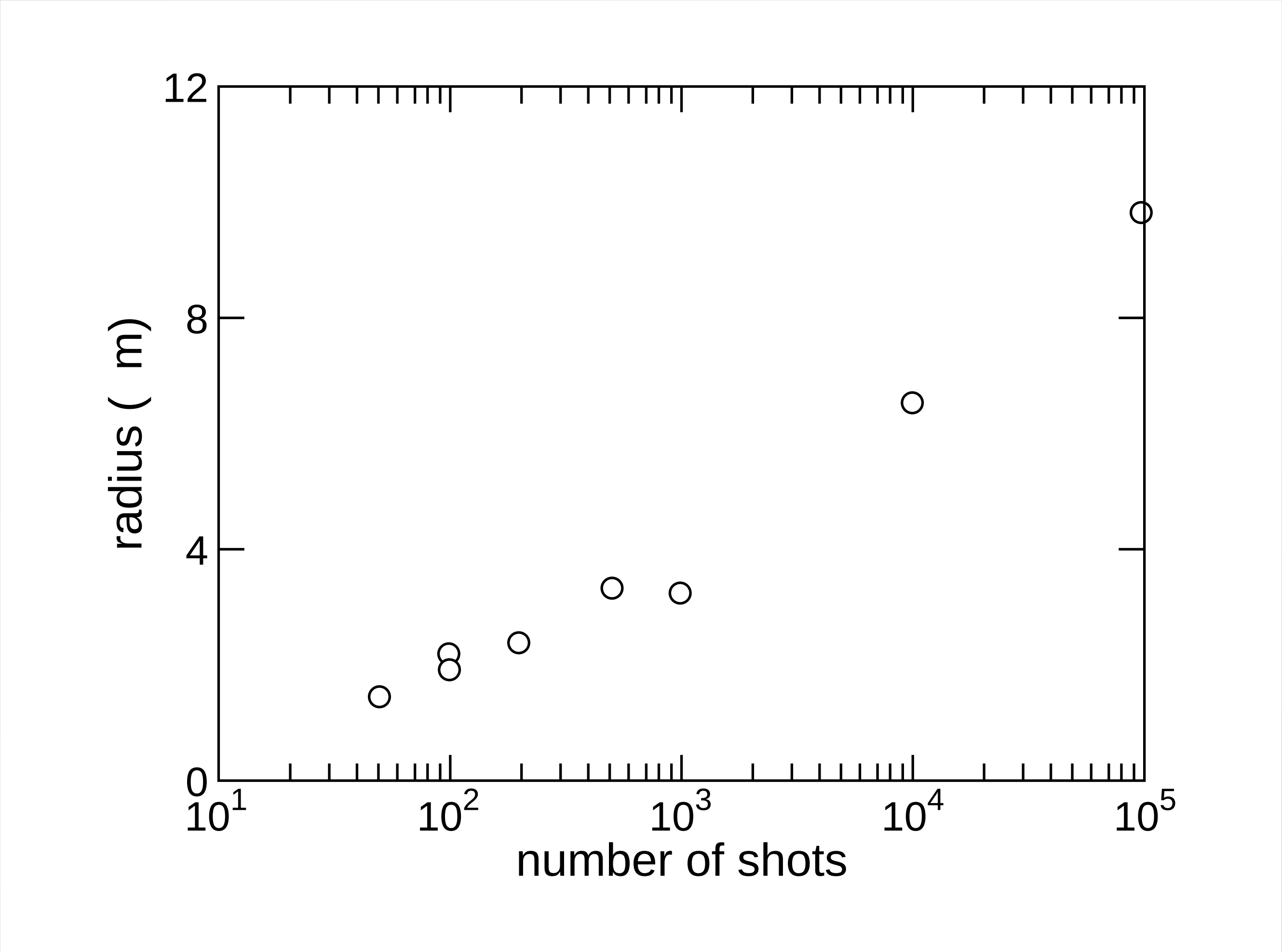
Low-energy machining

the longer the irradiation…



… the larger the radius

Low-energy machining



Low-energy machining

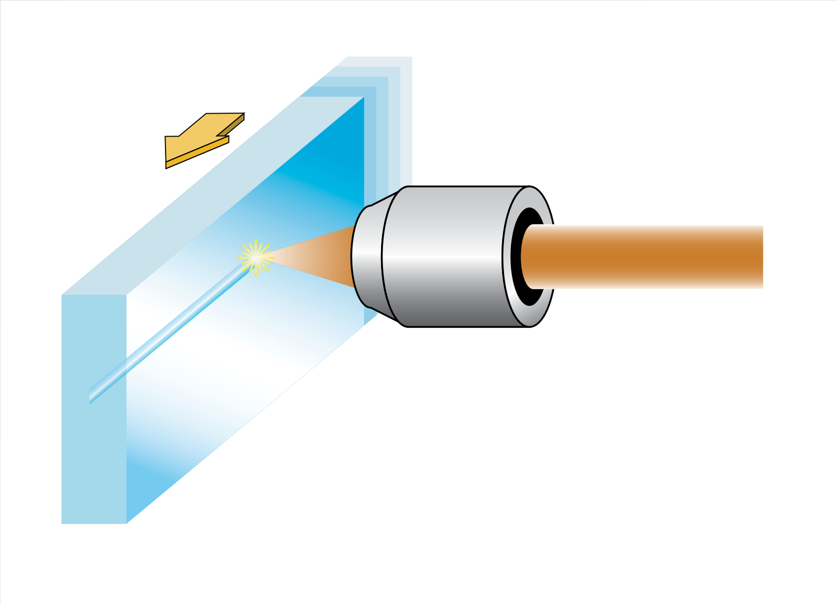
at high-rep rate: internal “point-source of heat”

Outline

- femtosecond micromachining
- low-energy machining
- applications

Low-energy machining

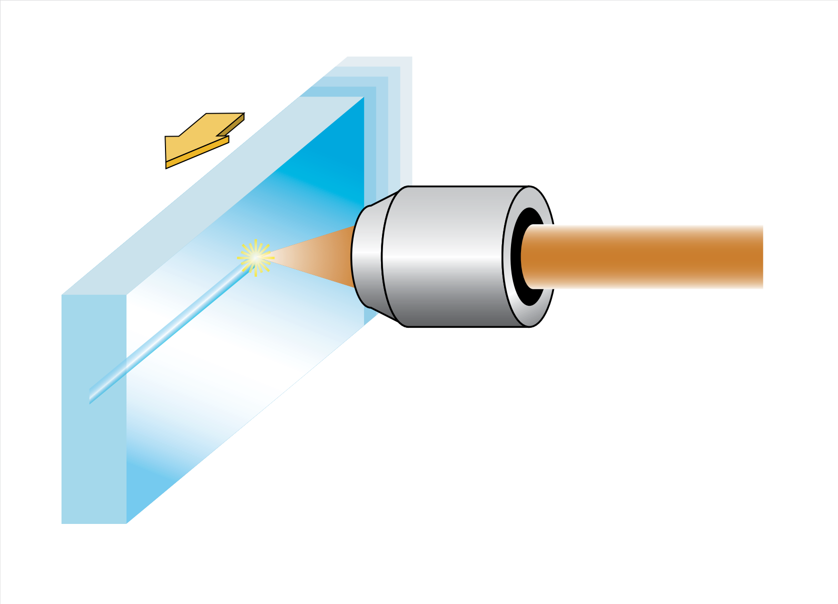
waveguide micromachining

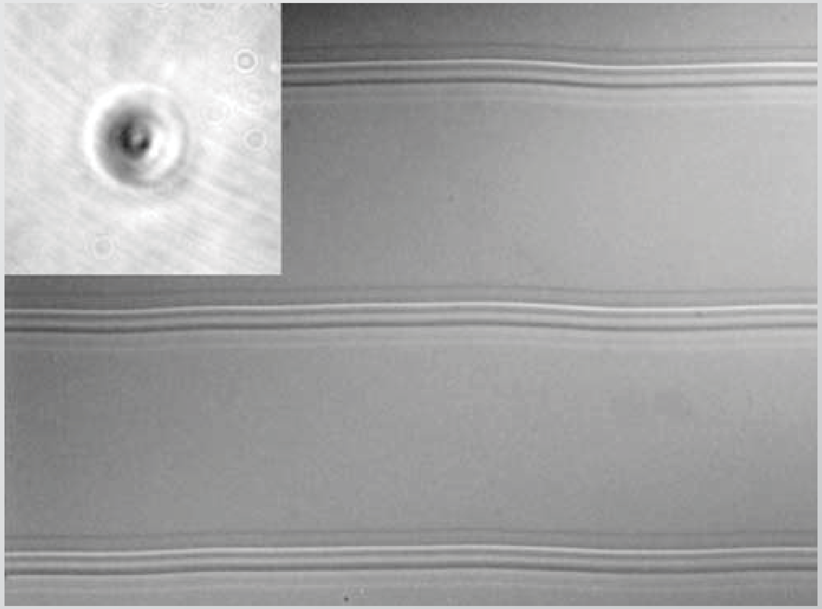


Opt. Lett. **26**, 93 (2001)

Low-energy machining

waveguide micromachining

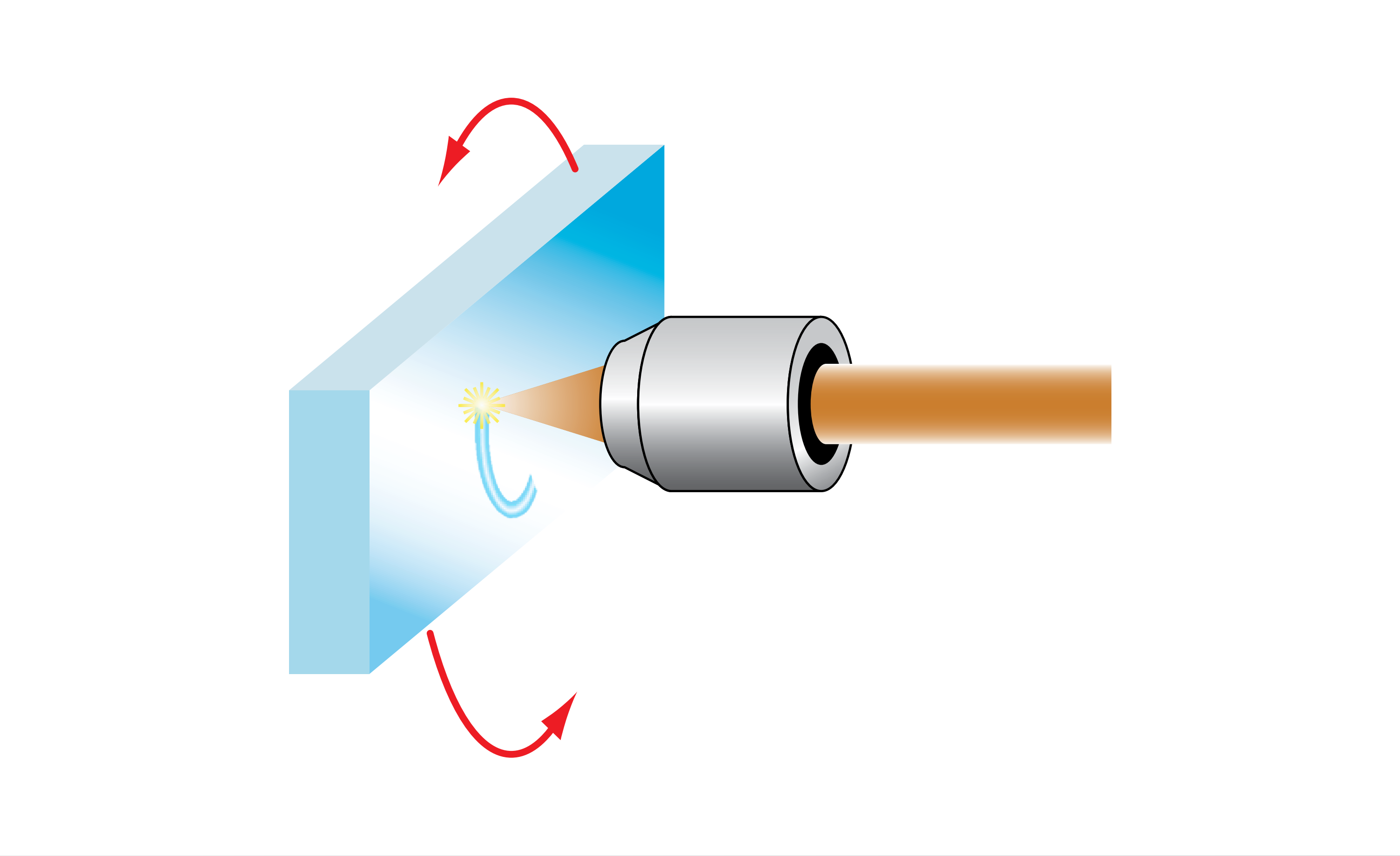




Opt. Lett. **26**, 93 (2001)

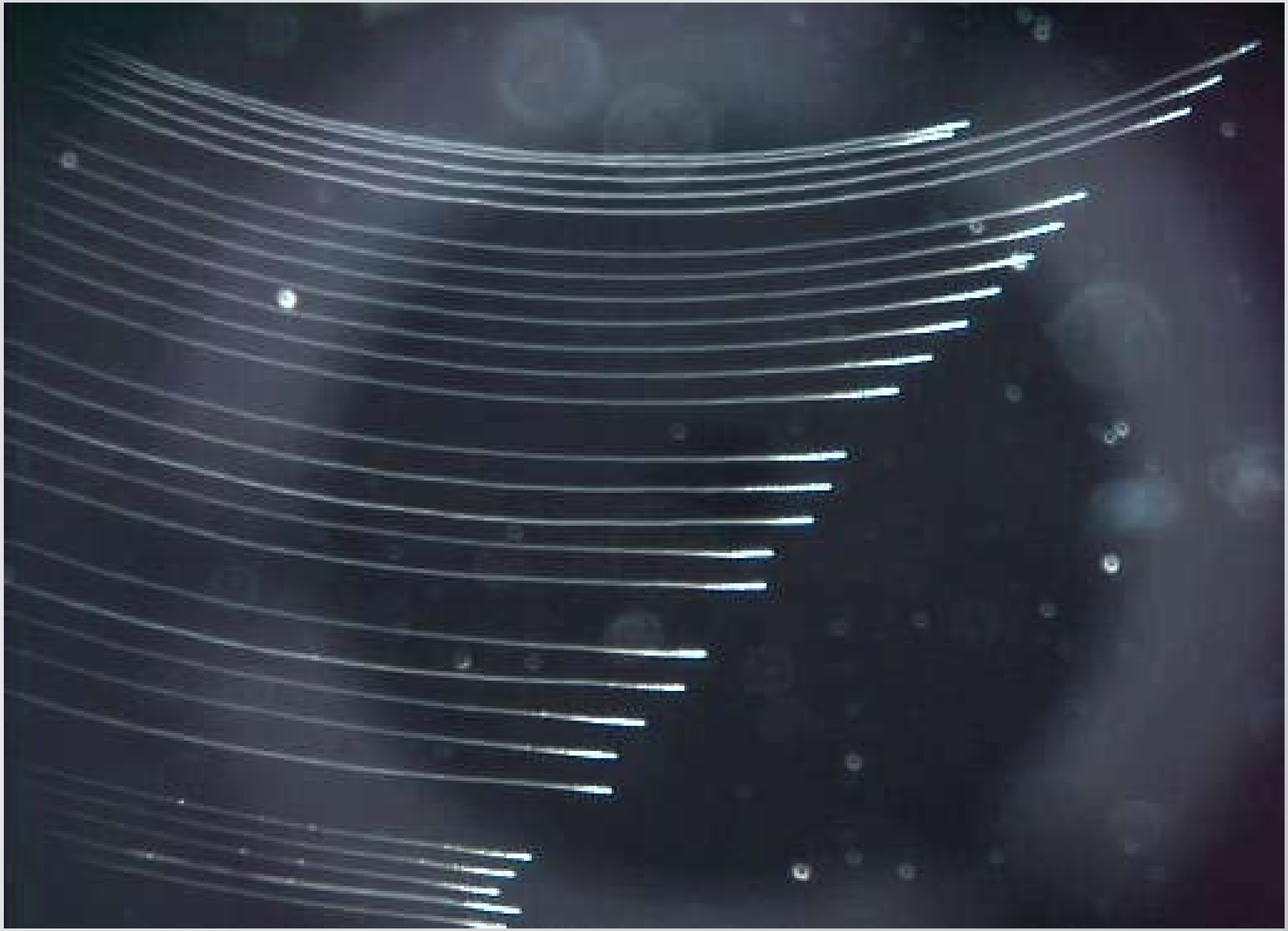
Applications

curved waveguides



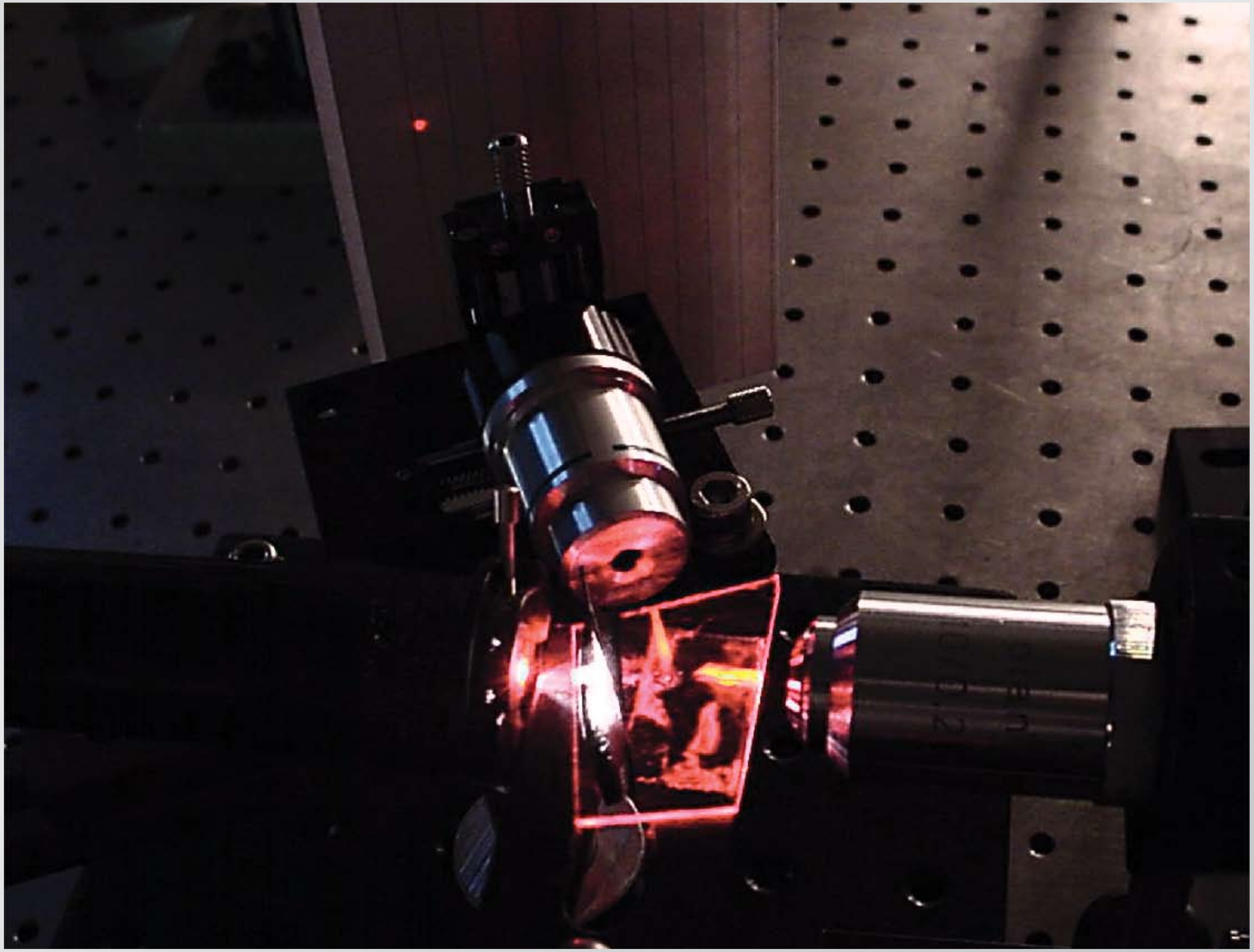
Applications

curved waveguides



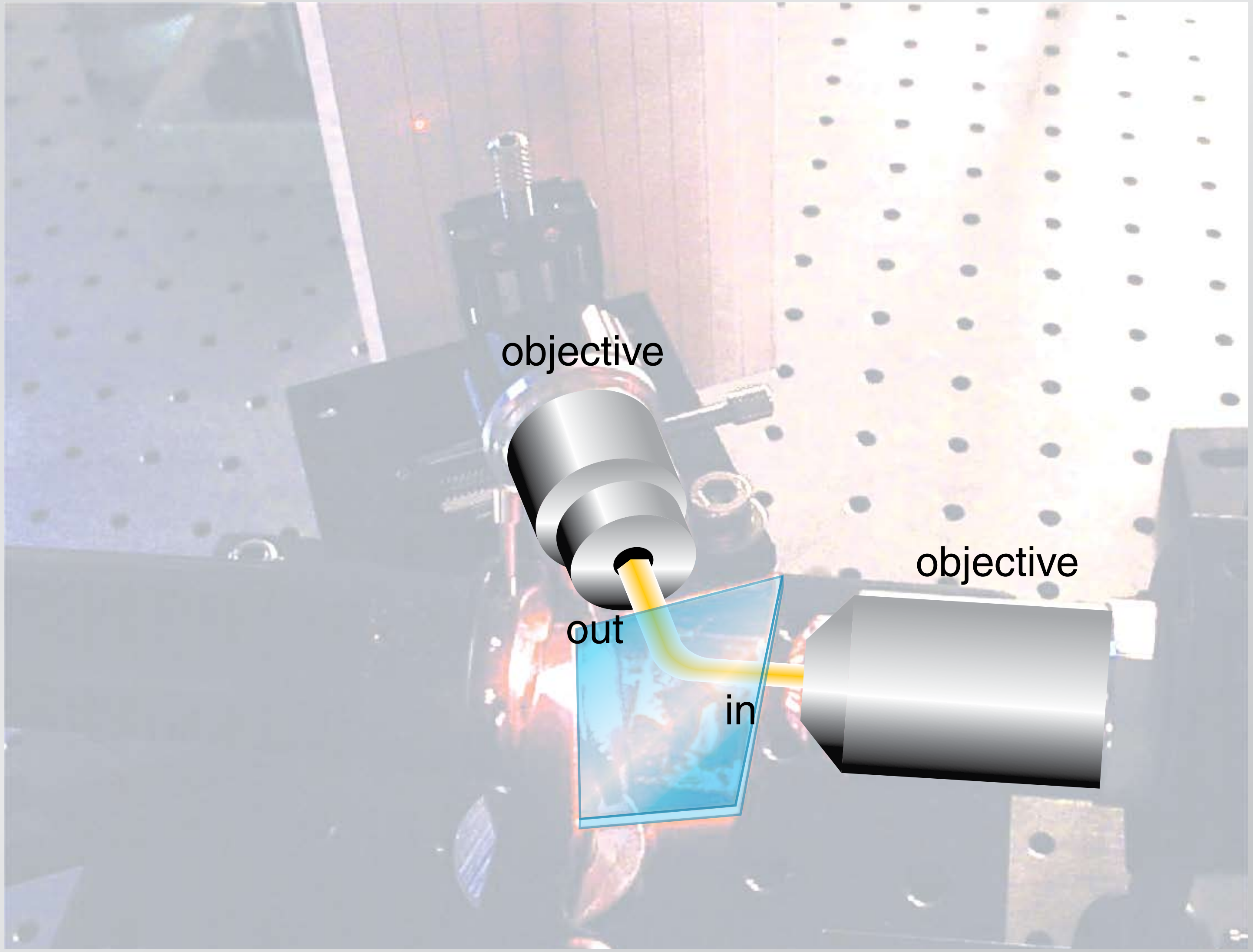
Applications

curved waveguides



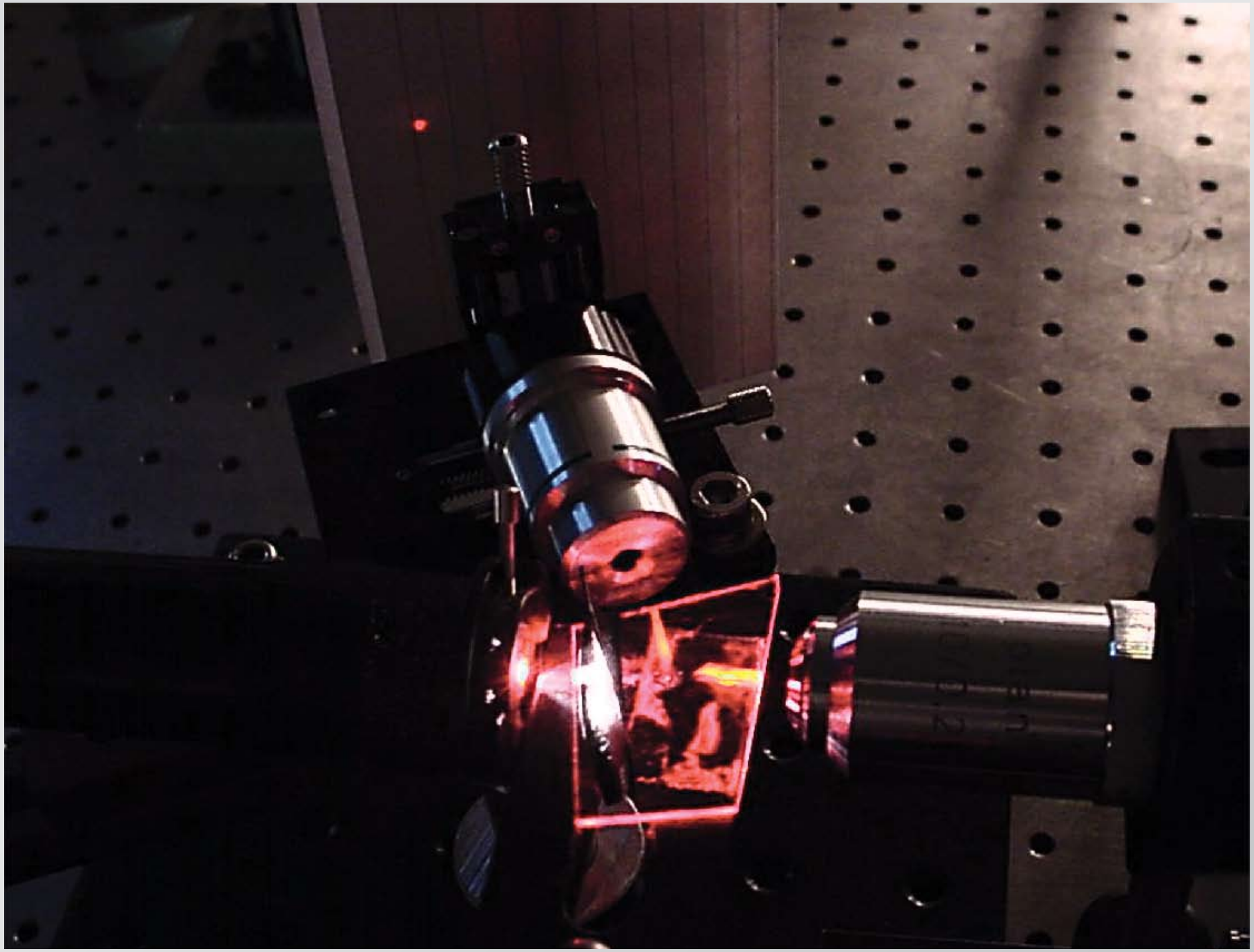
Applications

curved waveguides



Applications

curved waveguides



Applications

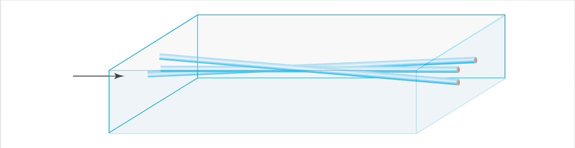
photonic fabrication techniques

	fs micromachining	other
loss (dB/cm)	< 3	0.1–3
bending radius	36 mm	30–40 mm
Δn	2×10^{-3}	10^{-4} – 0.5
3D integration	Y	N

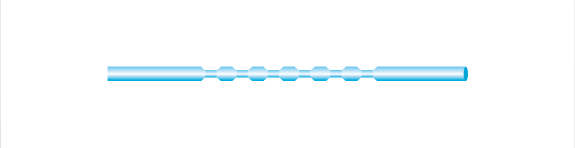
Applications

photonic devices

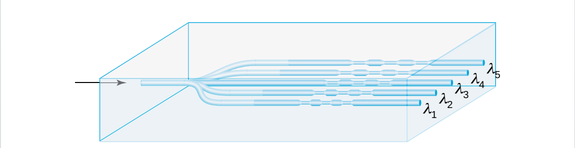
3D splitter



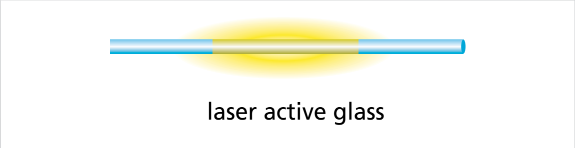
Bragg grating



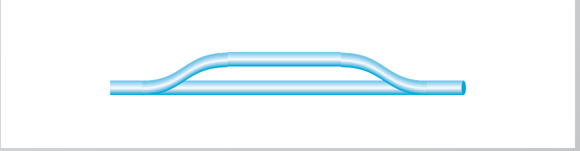
demultiplexer



amplifier



interferometer



Applications

all-optical sensor

Appl. Phys. Lett. **87**, 051106 (2005)

Applications

all-optical sensor

Appl. Phys. Lett. **87**, 051106 (2005)

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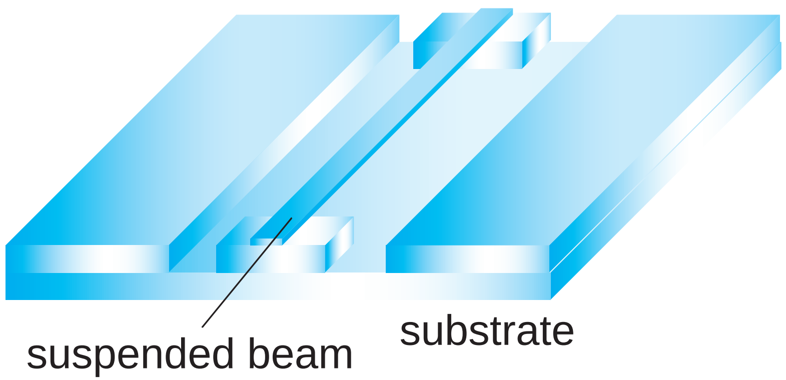
all-optical sensor



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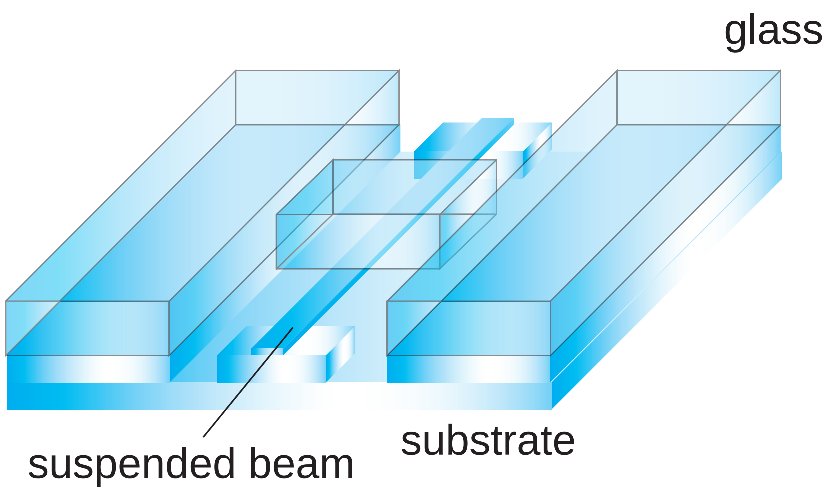
Applications

all-optical sensor



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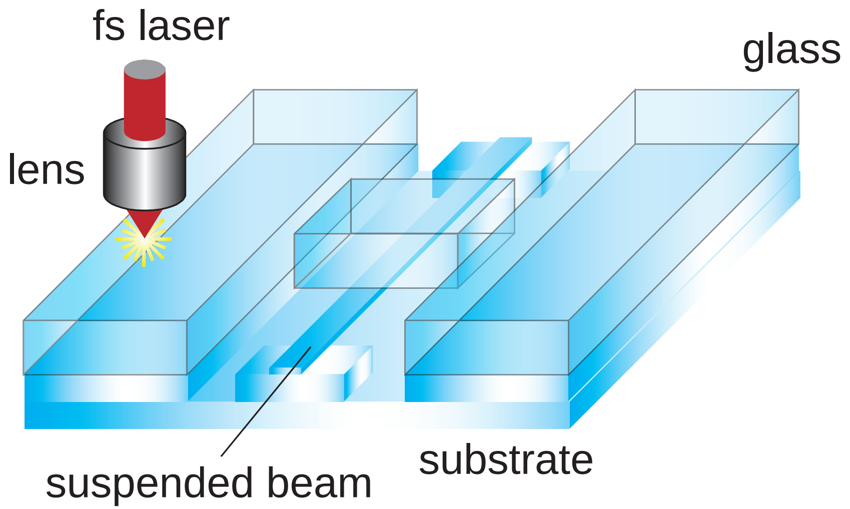
Applications

all-optical sensor



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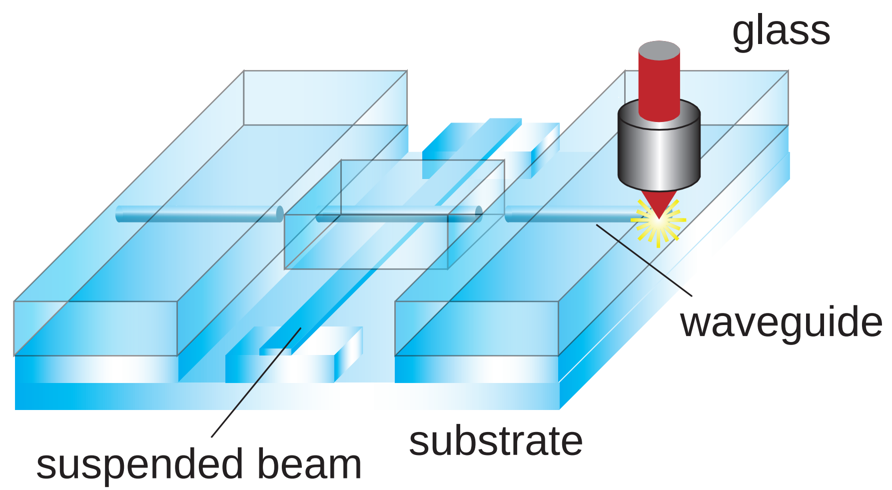
Applications

all-optical sensor



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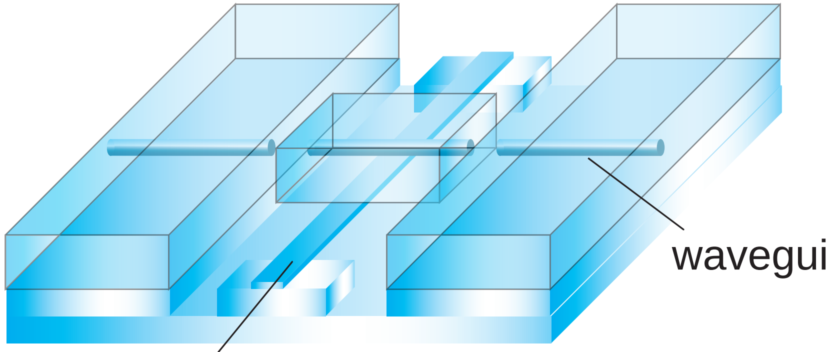
Applications

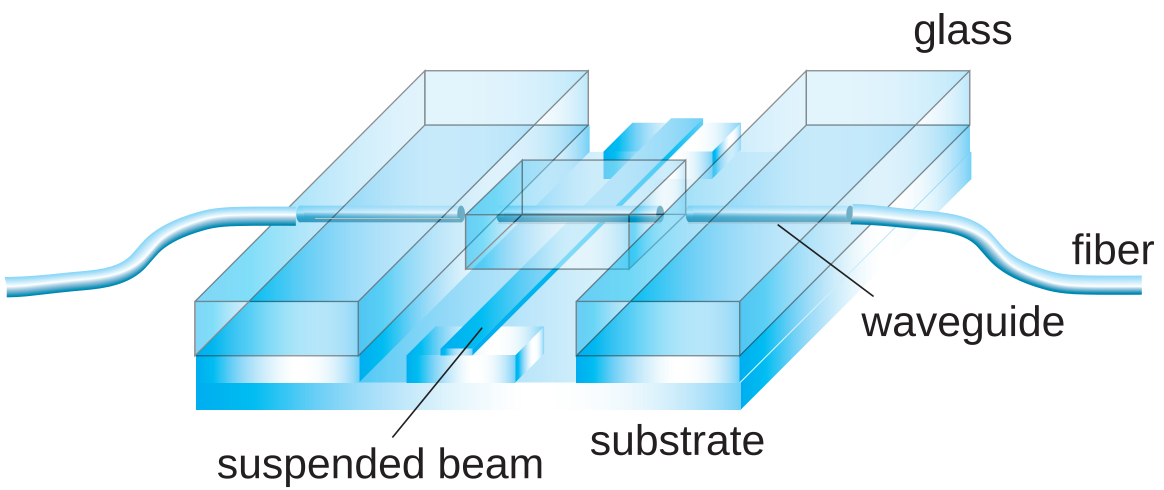
all-optical sensor



Appl. Phys. Lett. **87**, 051106 (2005)

Applications

all-optical sensor



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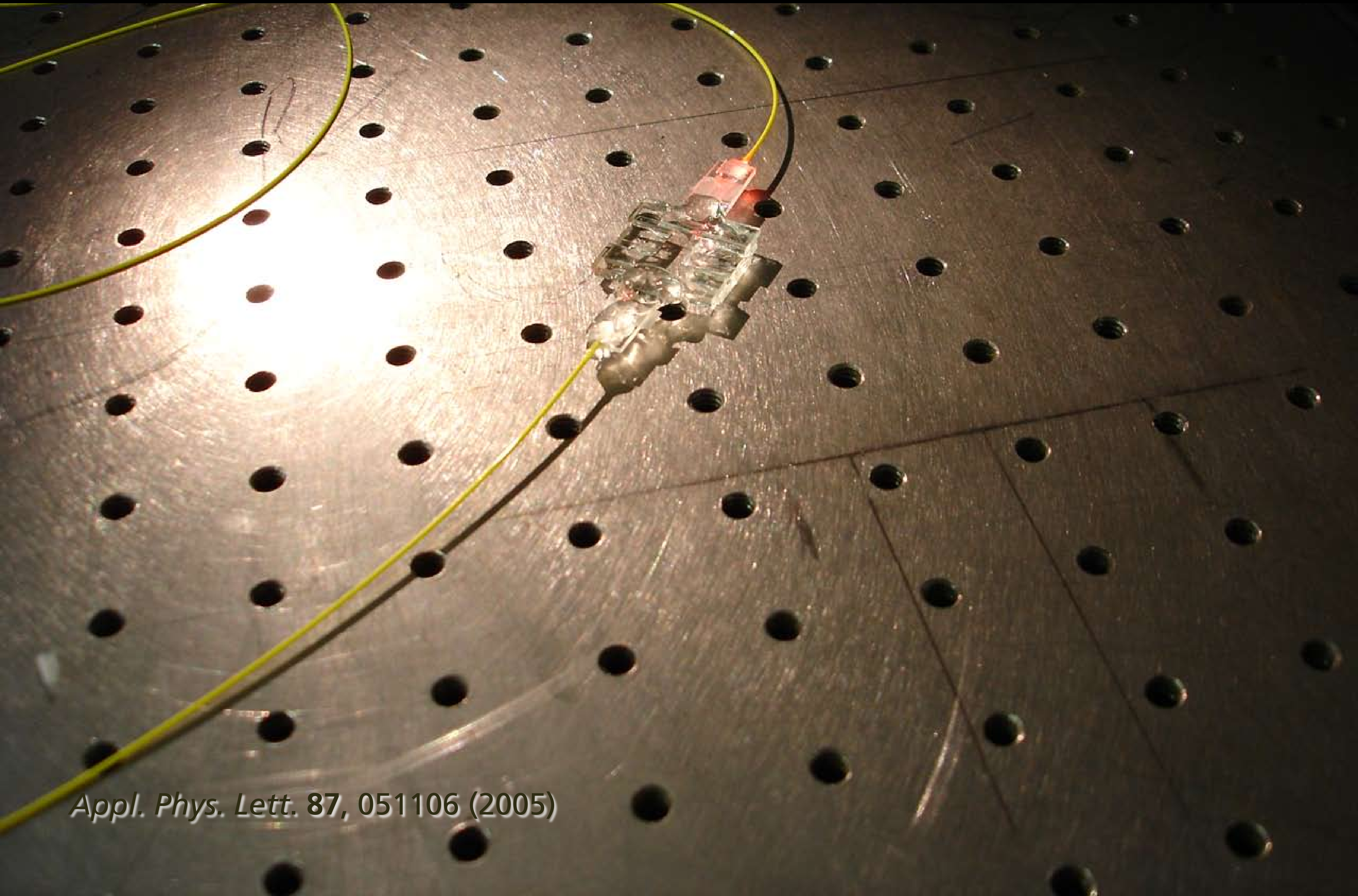
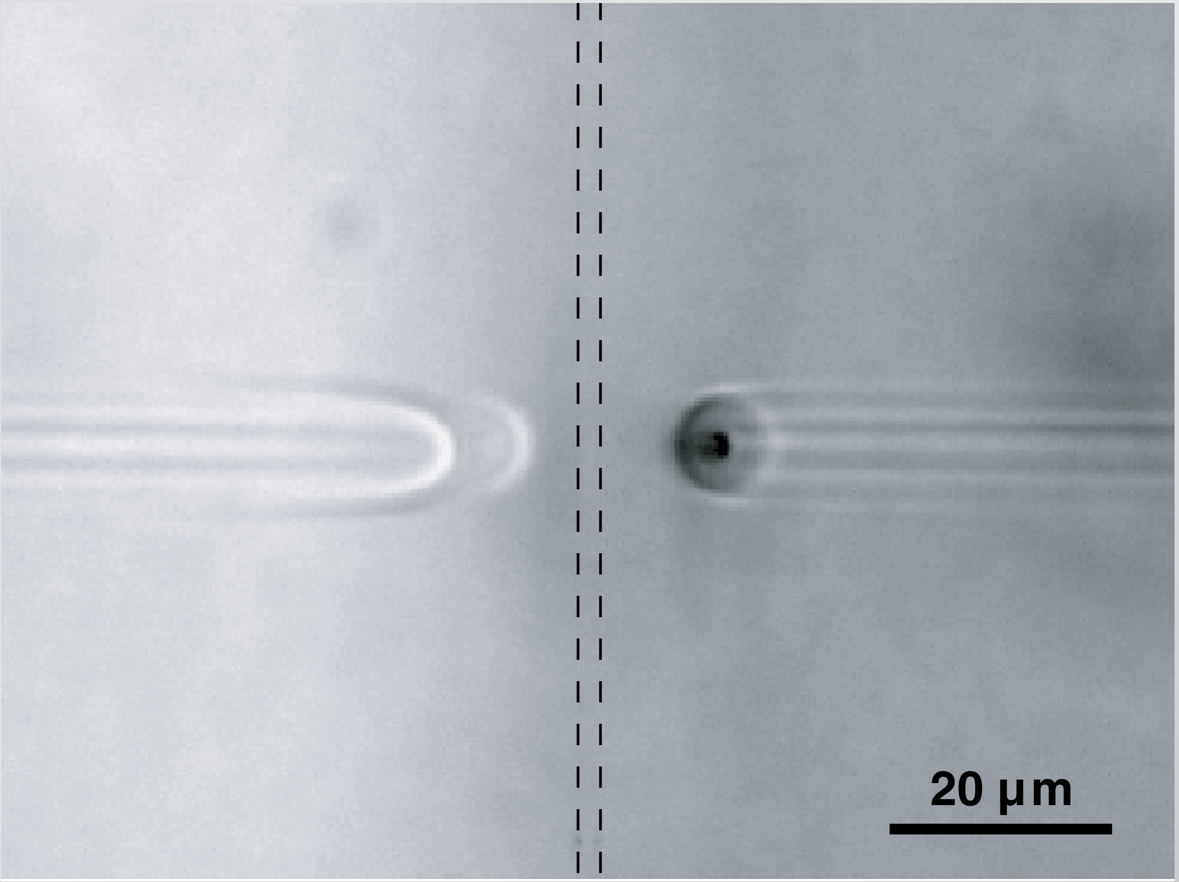
Applications



Appl. Phys. Lett. **87**, 051106 (2005)

Applications

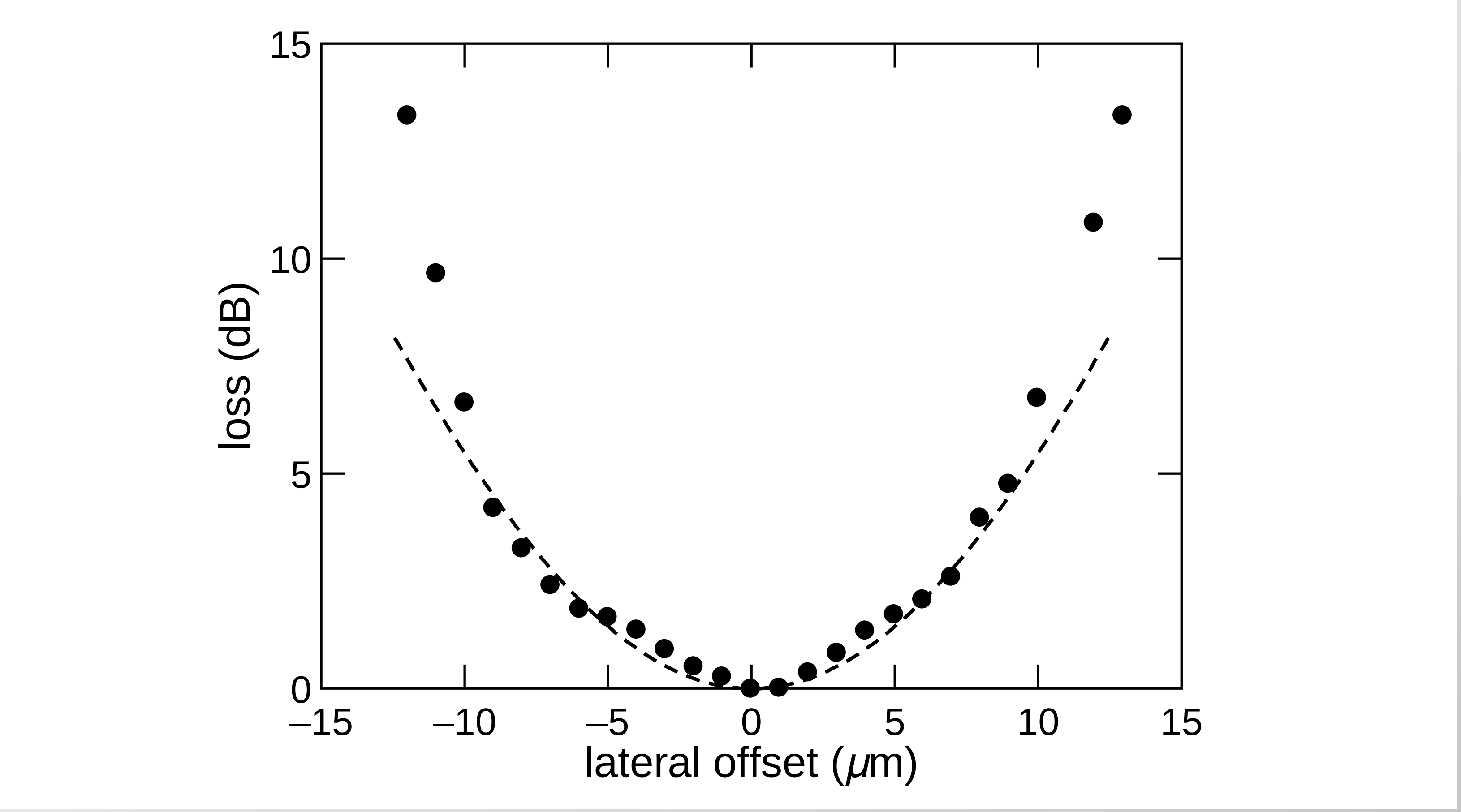
sensor gap



Appl. Phys. Lett. **87**, 051106 (2005)

Applications

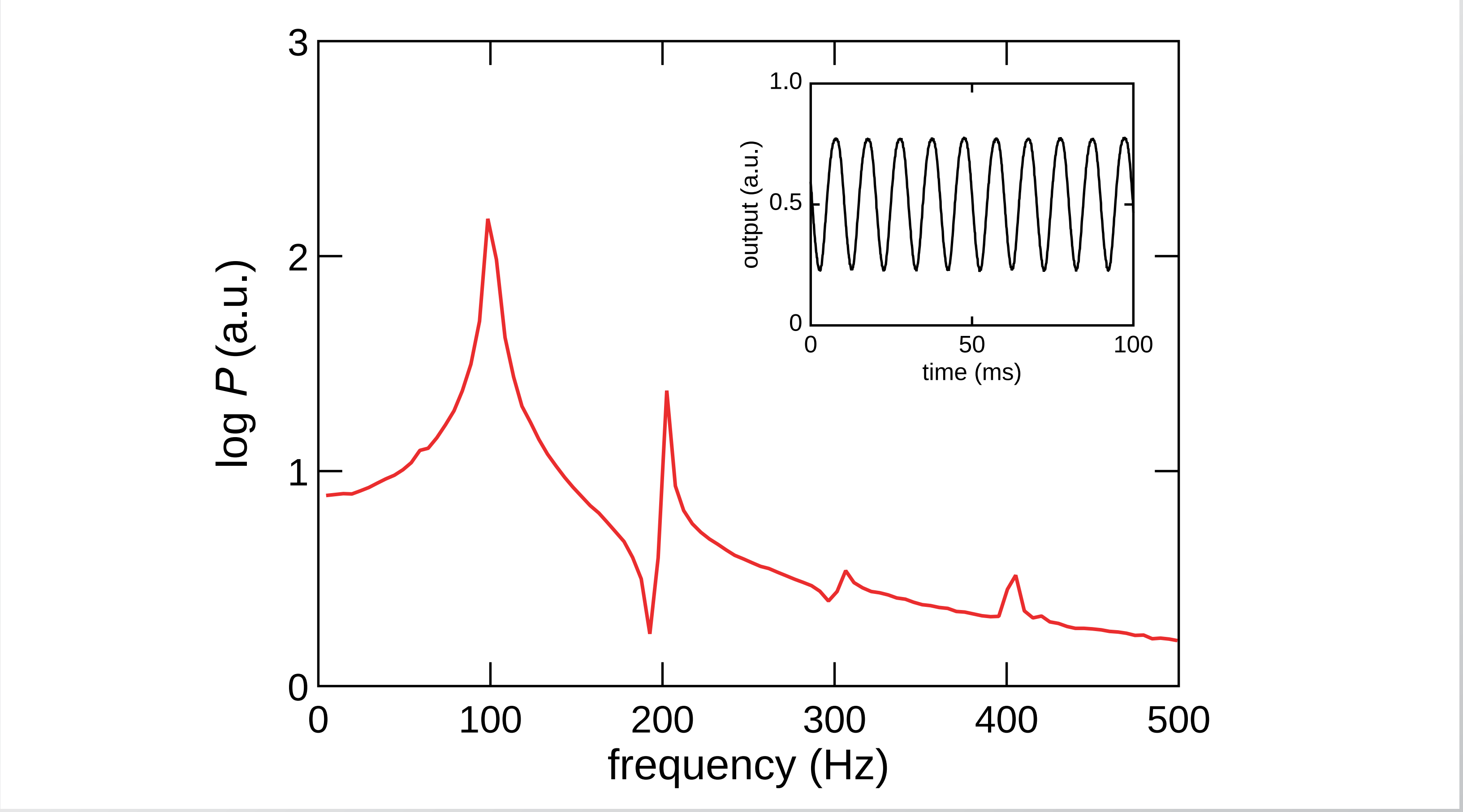
calibration



Appl. Phys. Lett. **87**, 051106 (2005)

Applications

sensor response to 100 Hz acoustic wave



Appl. Phys. Lett. **87**, 051106 (2005)

Applications

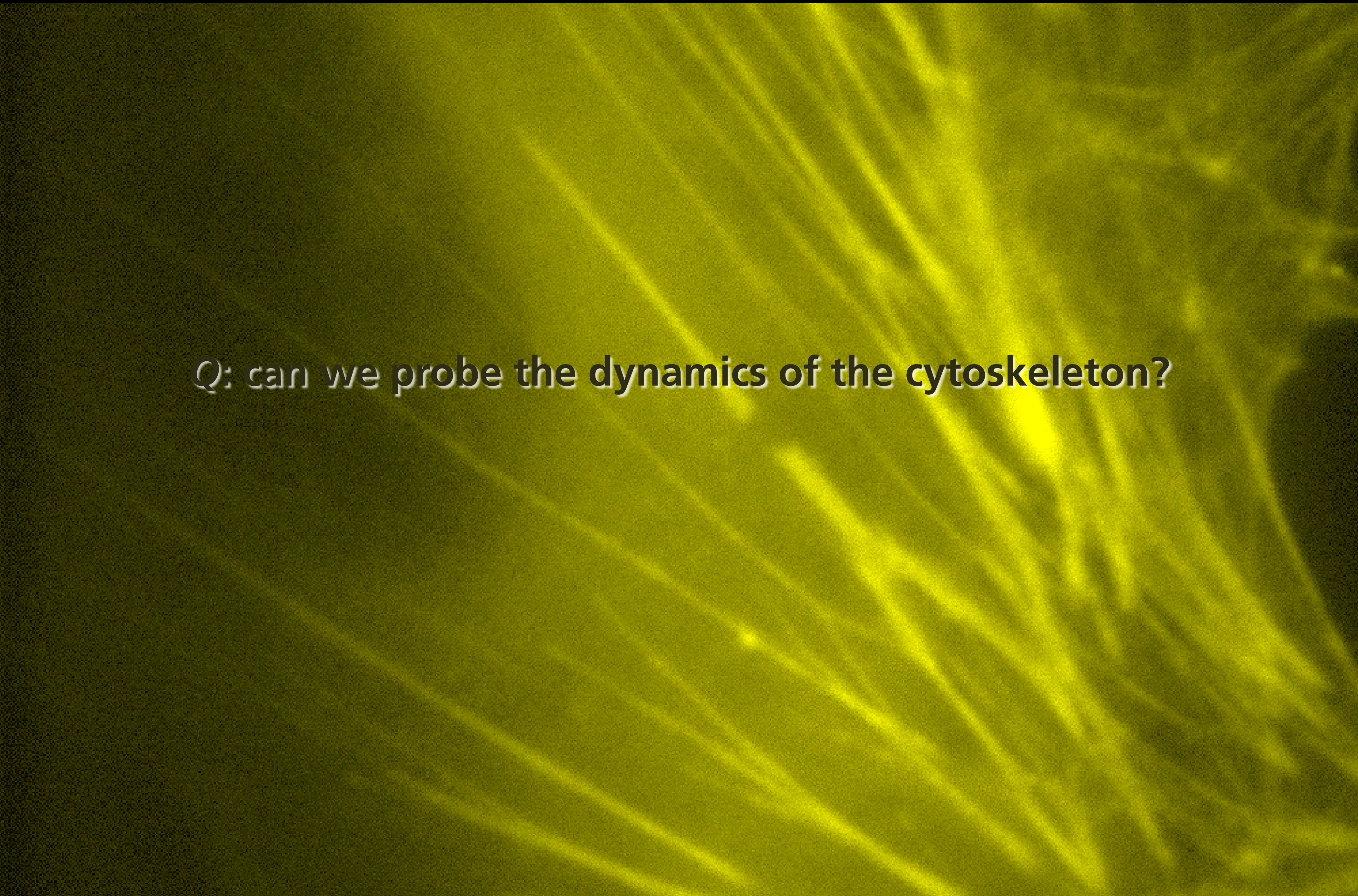
ideal tool for ablating (living) tissue

Applications

- standard biochemical tools: species selective
- fs laser “nanosurgery”: site specific

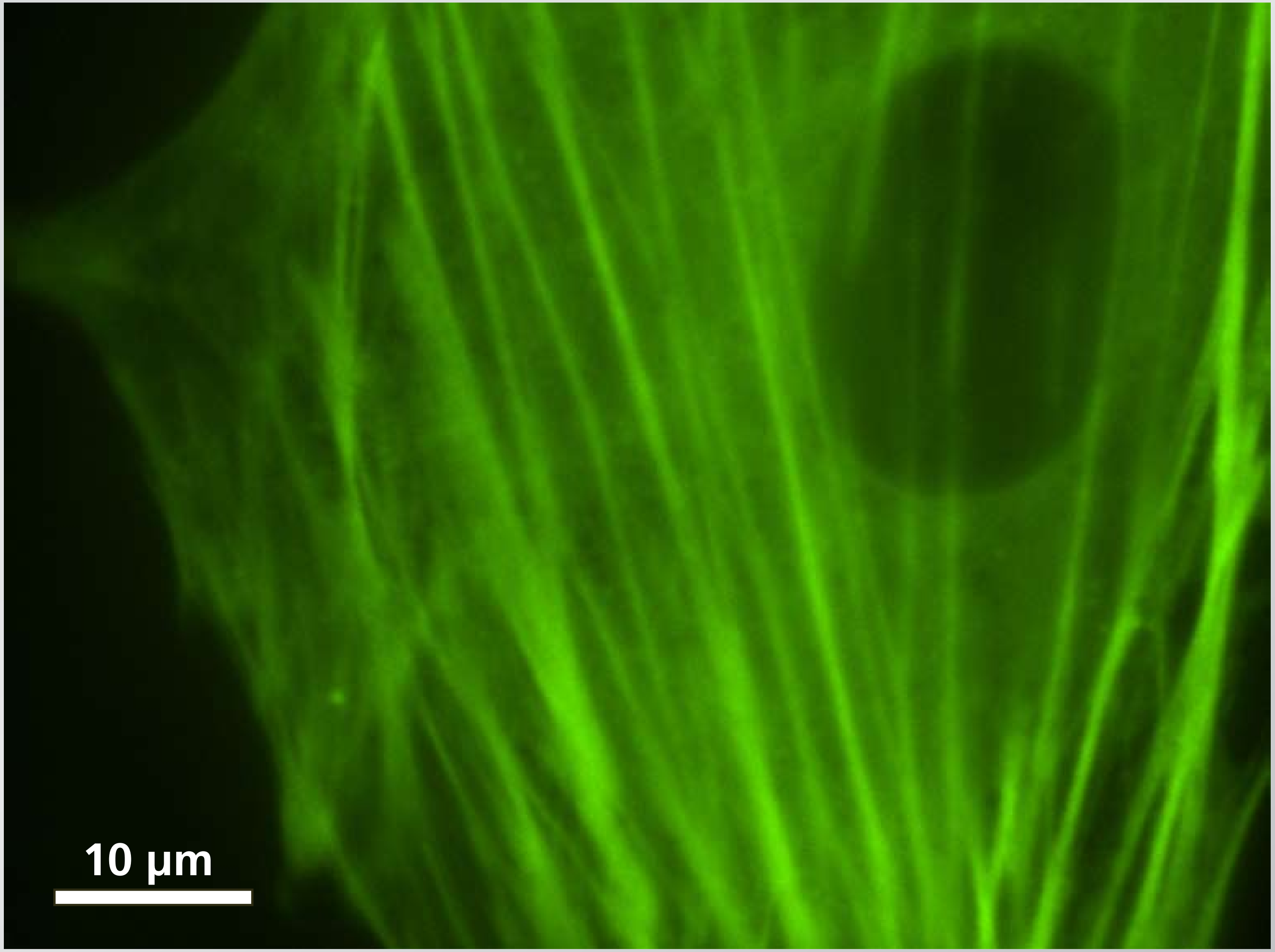
Applications

Q: can we probe the dynamics of the cytoskeleton?



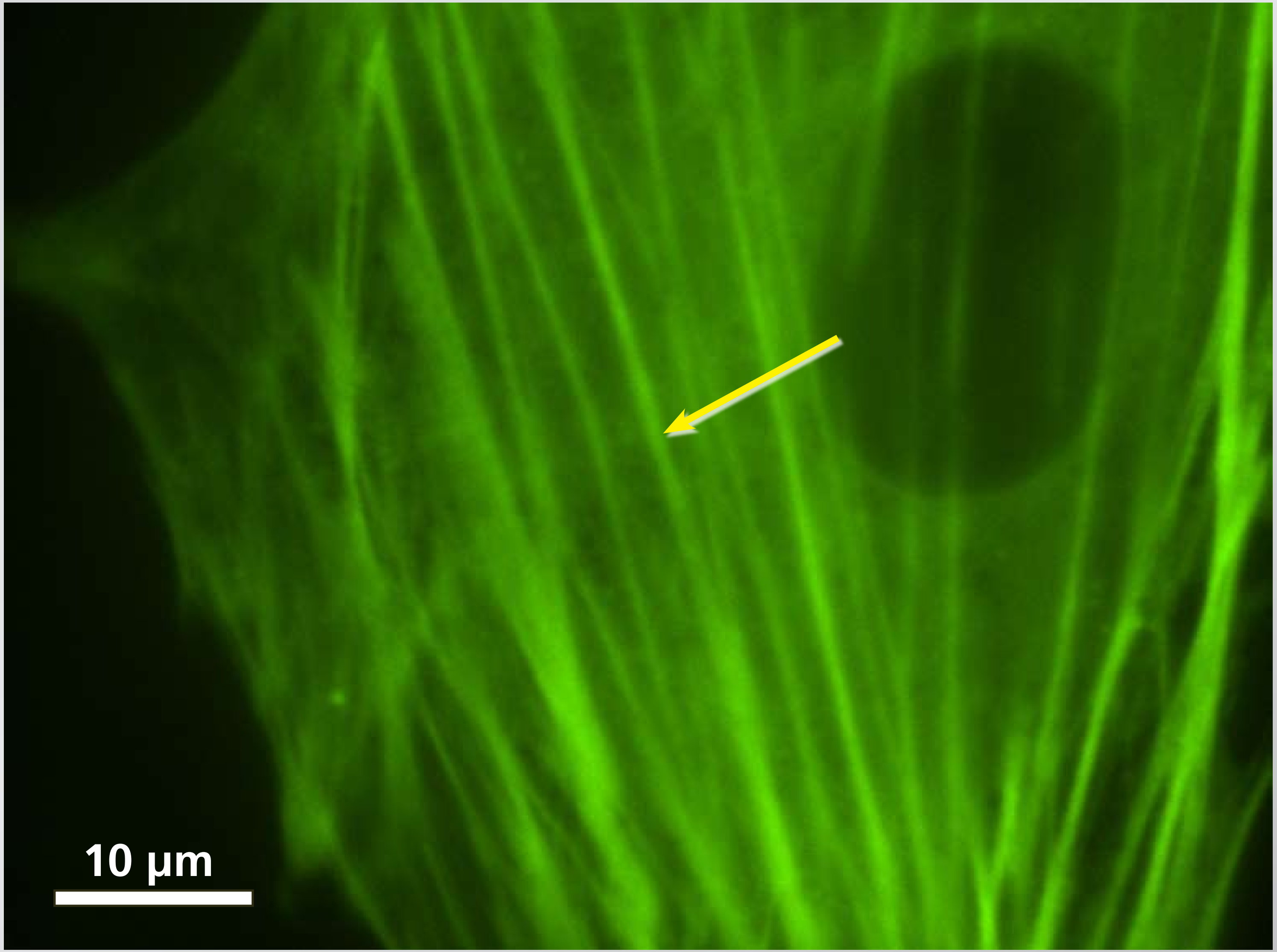
Applications

actin fiber network of a live cell



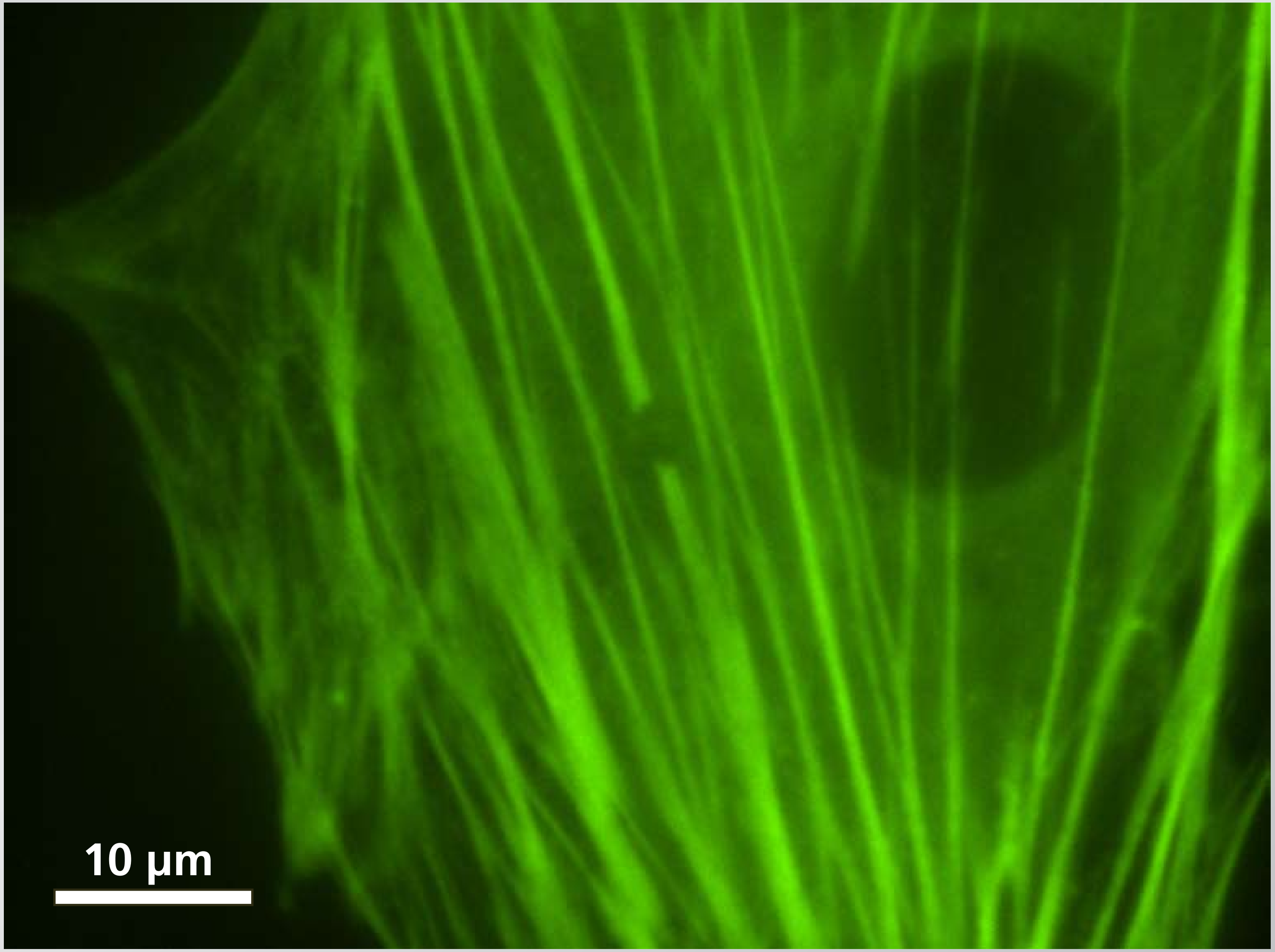
Applications

cut a single fiber bundle



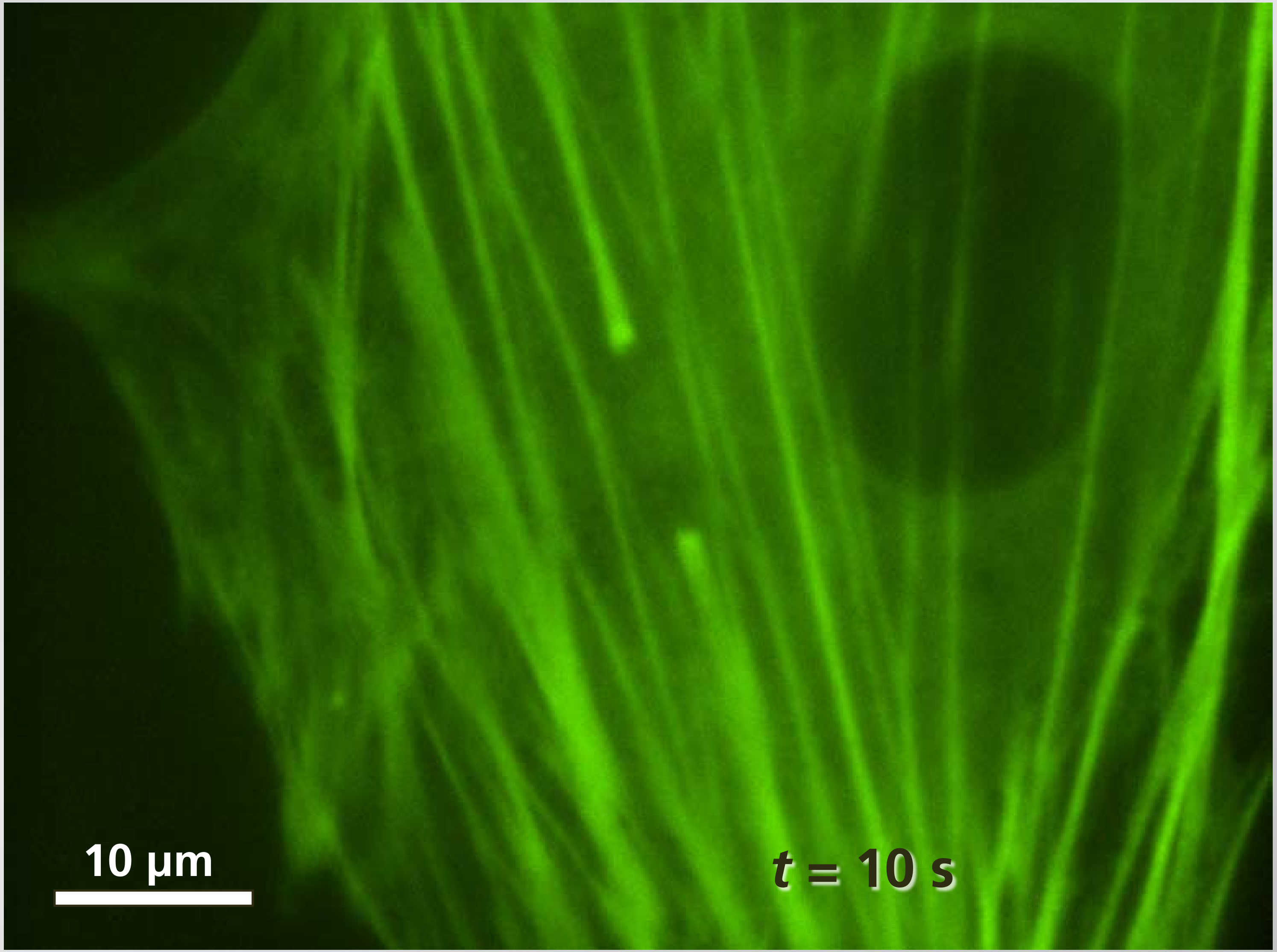
Applications

cut a single fiber bundle



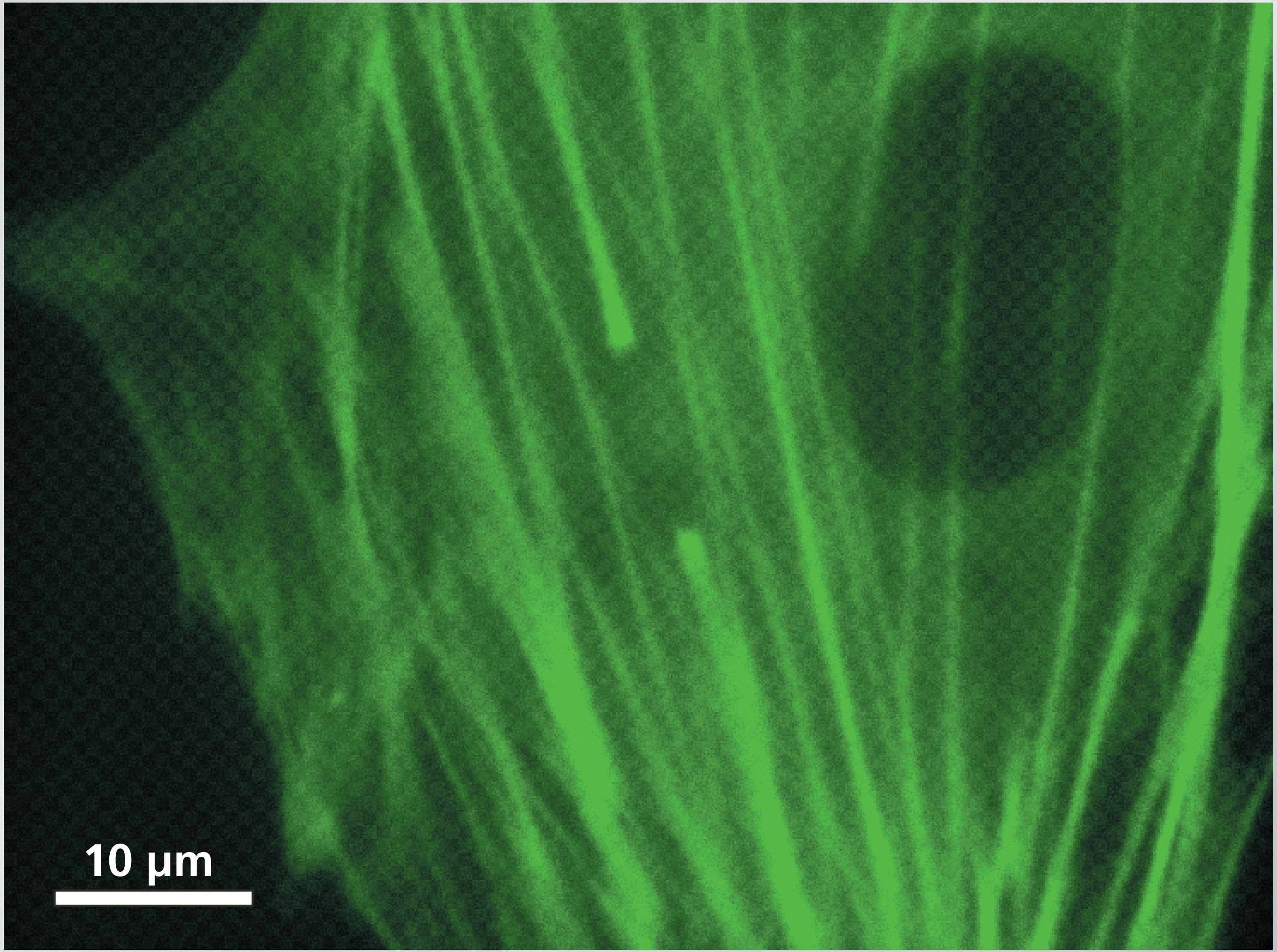
Applications

gap widens with time



Applications

dynamics provides information on *in vivo* mechanics



Summary

great tool for

- “wiring light”
- micromanipulating the machinery of life

Summary

- important parameters: focusing, energy, repetition rate
- nearly material independent
- two regimes: low and high repetition rate
- high-repetition rate (thermal) machining fast, convenient

Summary

- important parameters: focusing, energy, repetition rate
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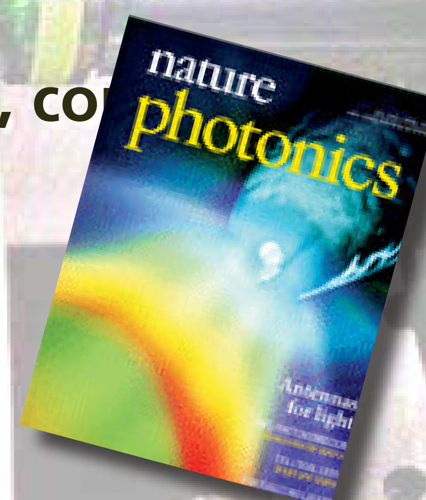
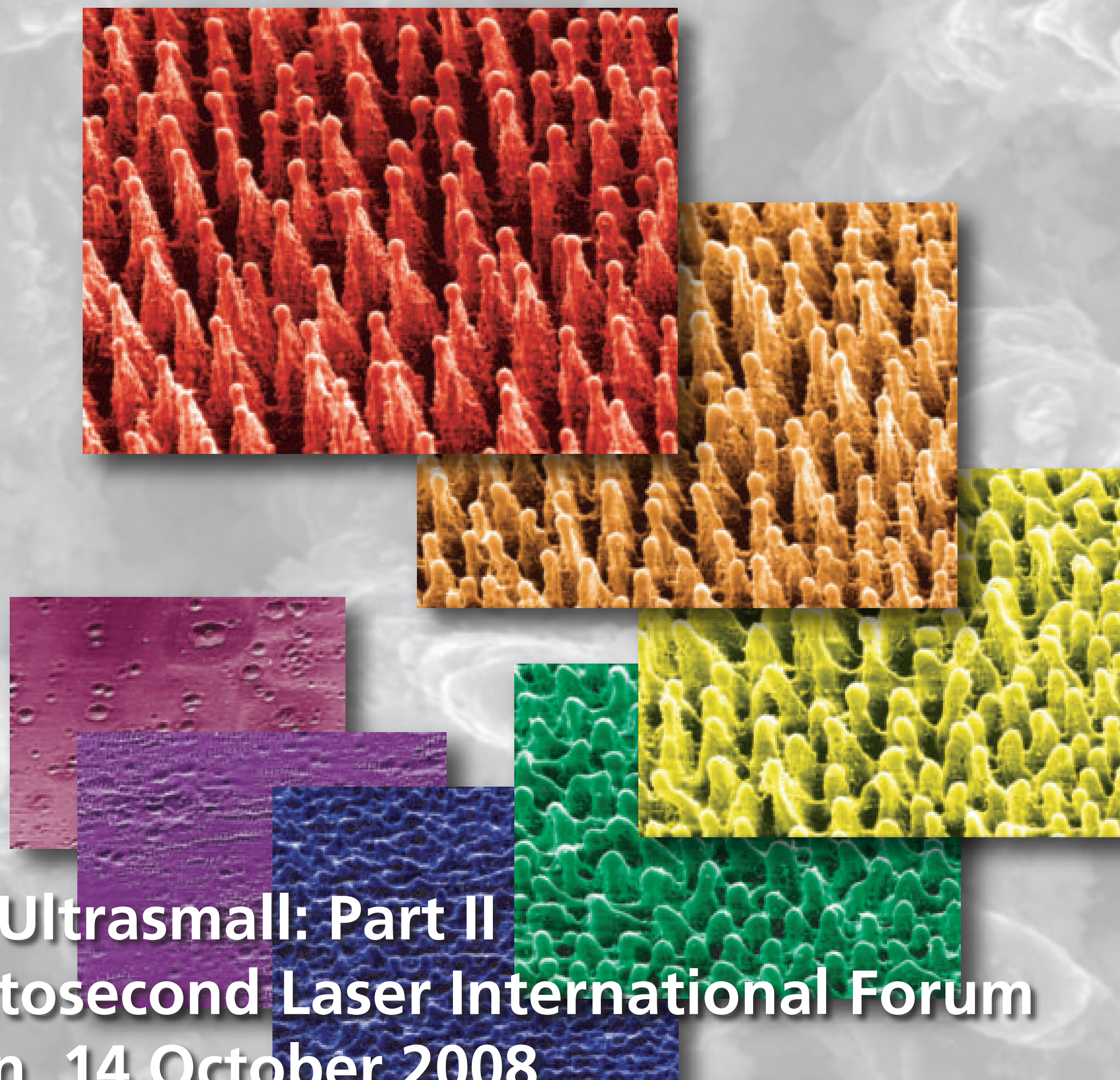


Nature Photonics **2**, 219 (2008)

Femtosecond laser doping



Ultrafast and Ultrasmall: Part II
2008 ITRI Femtosecond Laser International Forum
Tainan, Taiwan, 14 October 2008


Eric Mazur


Mark Winkler


Eric Diebold


Brian Tull

and also....

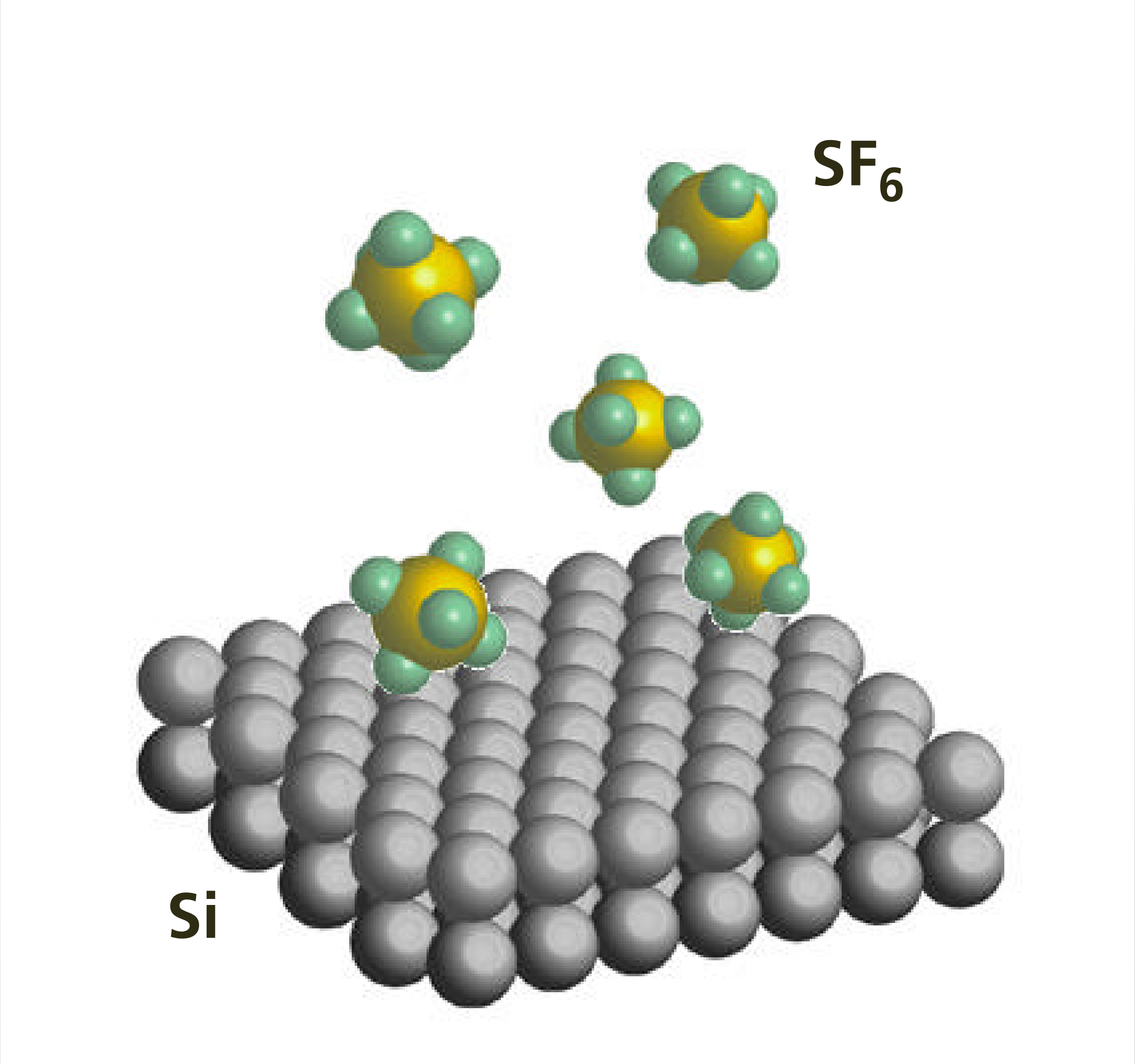
Dr. Jim Carey
Dr. Tsing-Hua Her
Dr. Shrenik Deliwala
Dr. Richard Finlay
Dr. Michael Sheehy
Dr. Jeffrey Warrander
Dr. Claudia Wu
Dr. Rebecca Younkin
Prof. Catherine Crouch
Prof. Mengyan Shen

Dr. John Chervinsky
Dr. Joshua Levinson

Dr. François Génin (LLNL)
Dr. Richard Farrell
Dr. Arieh Karger (RMD)
Dr. Richard Meyers (RMD)

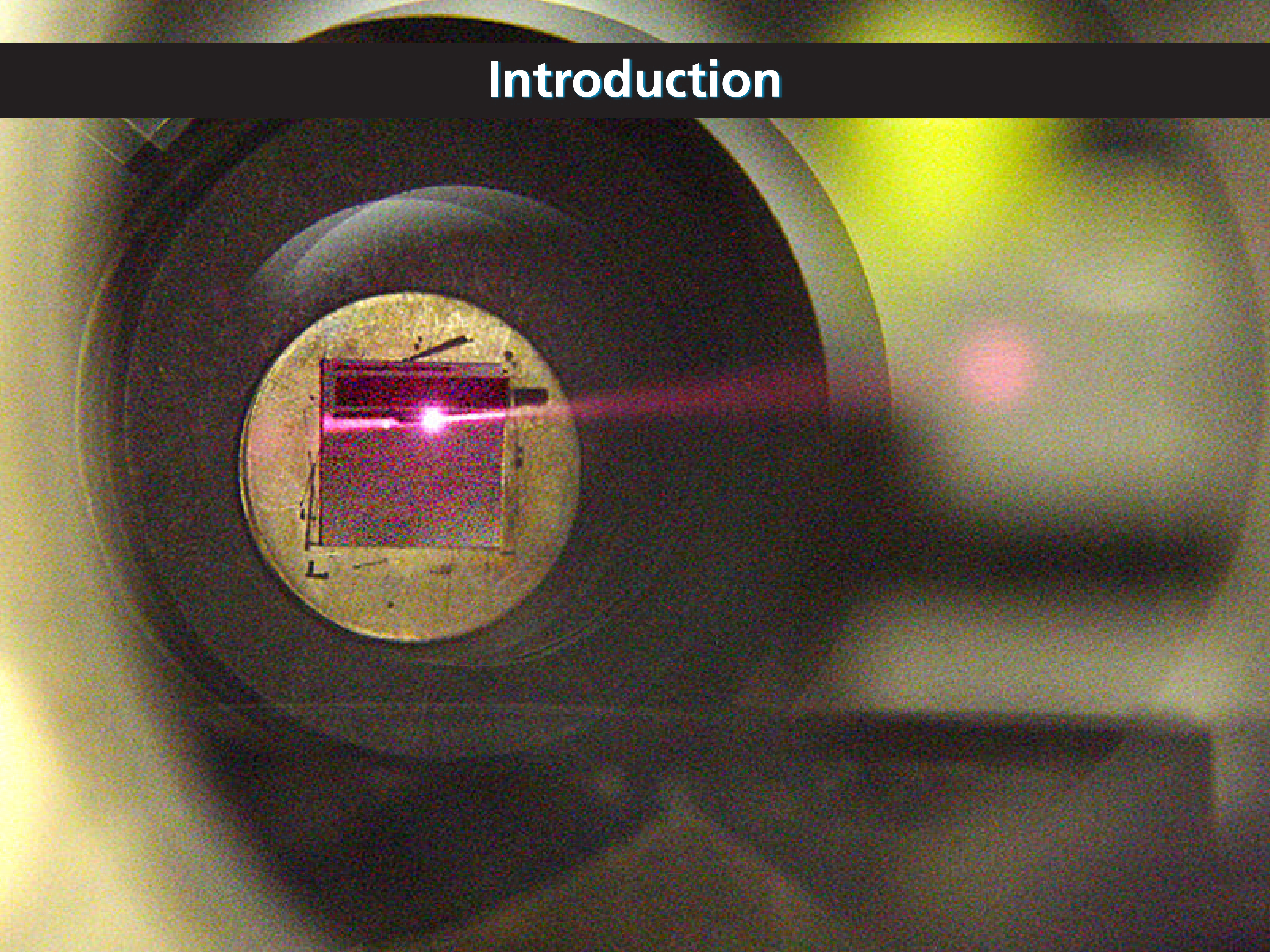
Prof. Michael Aziz
Prof. Cynthia Friend
Prof. Li Zhao (Fudan)

Introduction

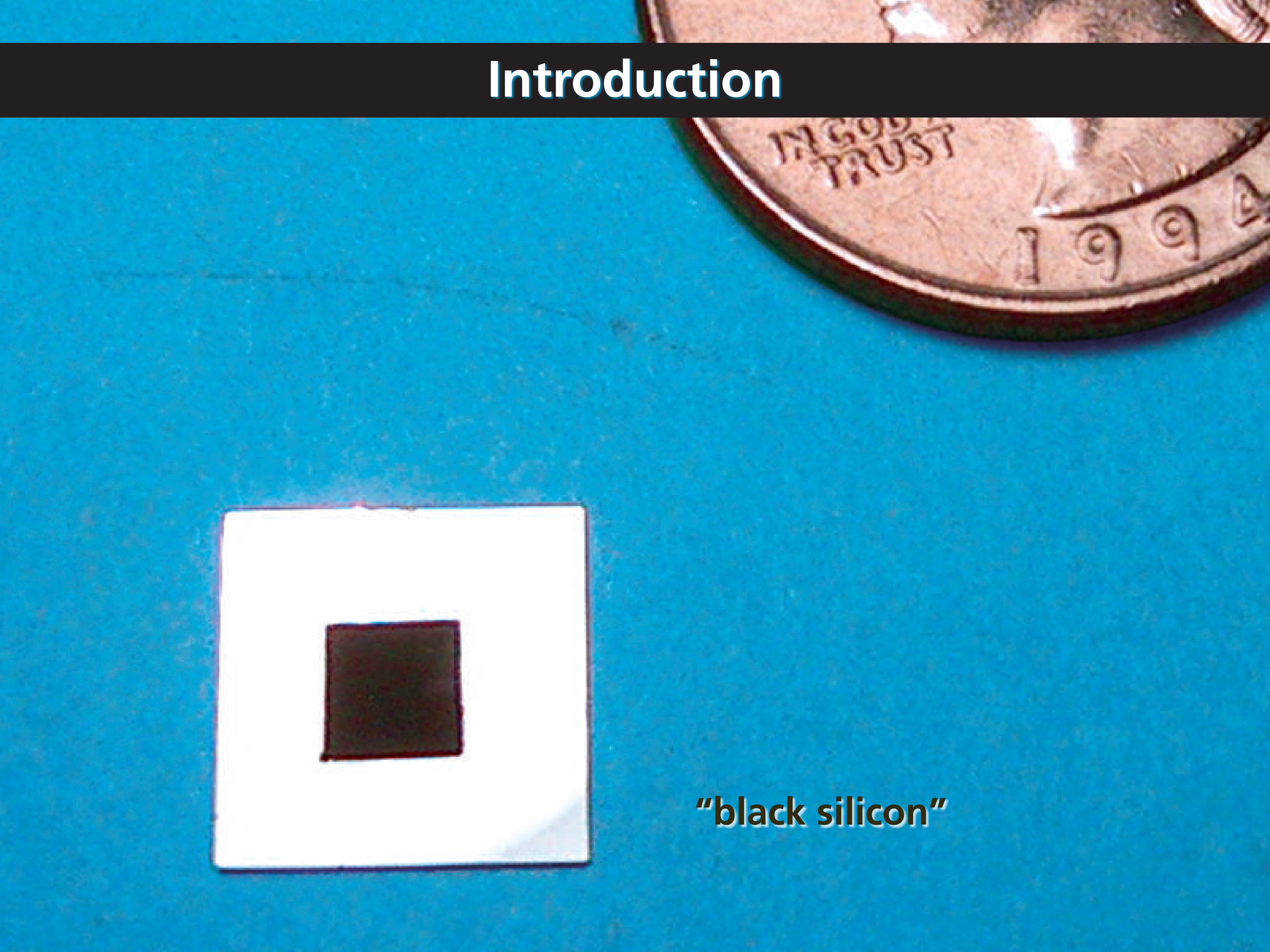


irradiate with 100-fs 10 kJ/m^2 pulses

Introduction

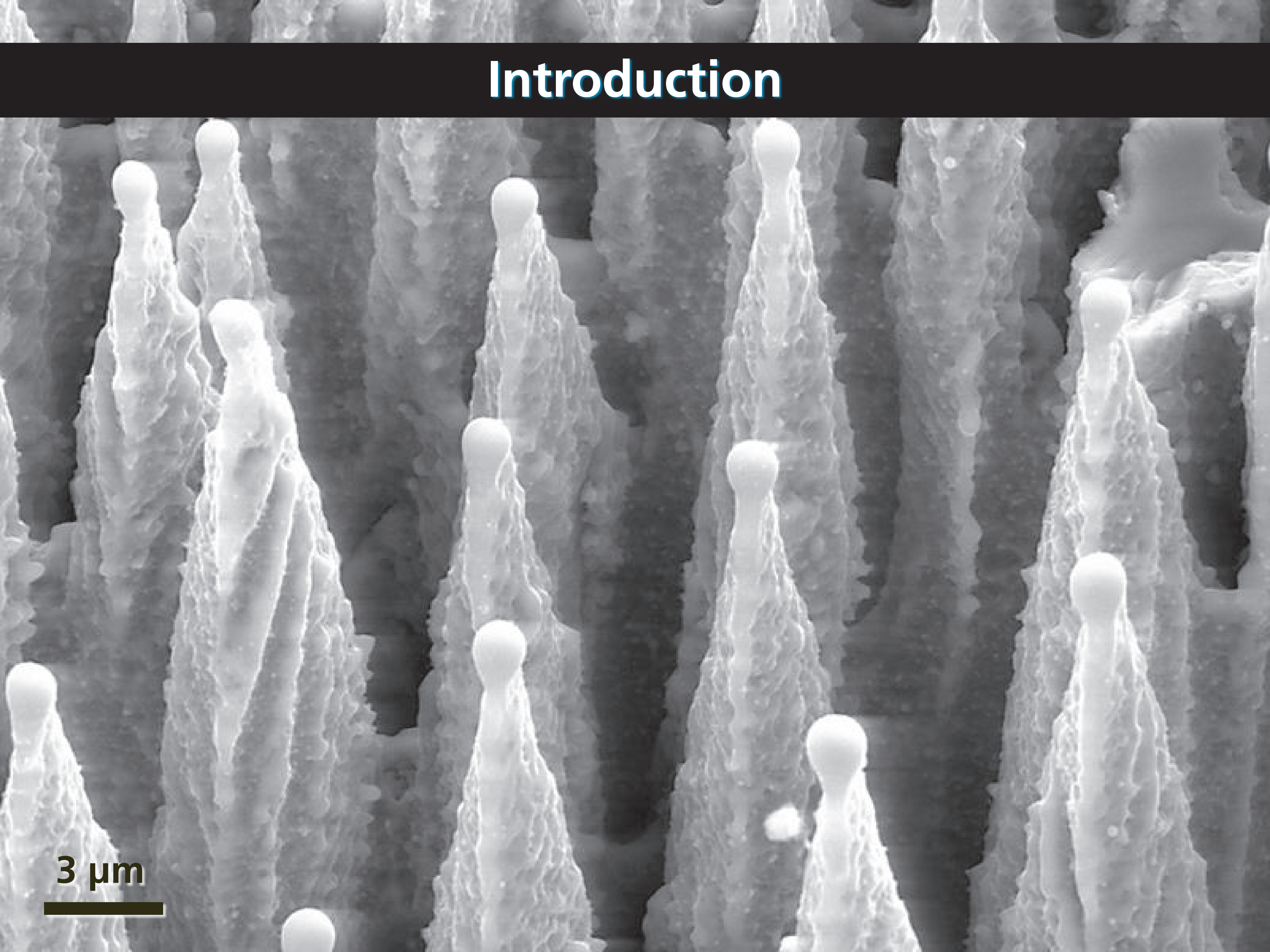


Introduction



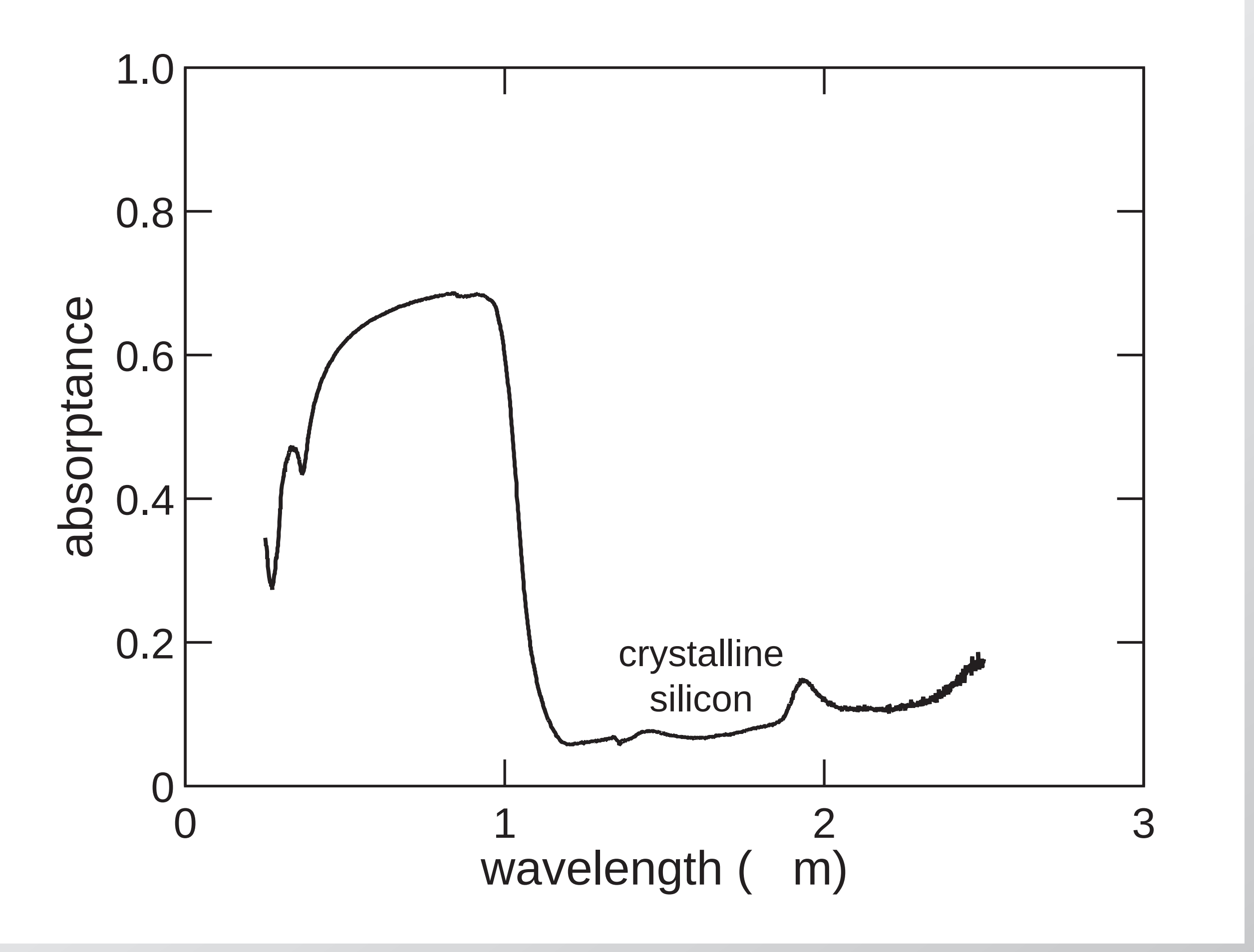
“black silicon”

Introduction



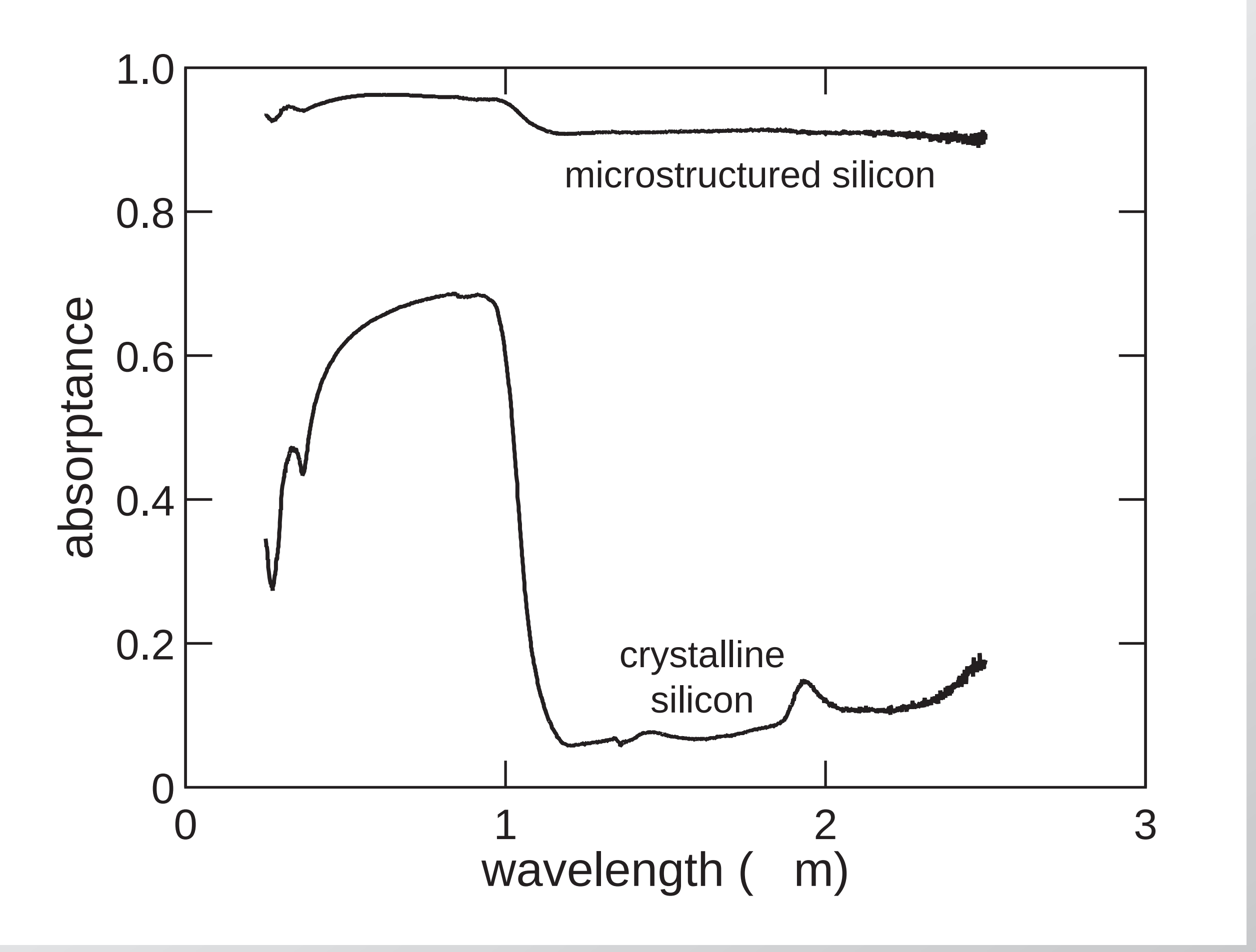
Introduction

absorptance (1 – *R* – *T*)

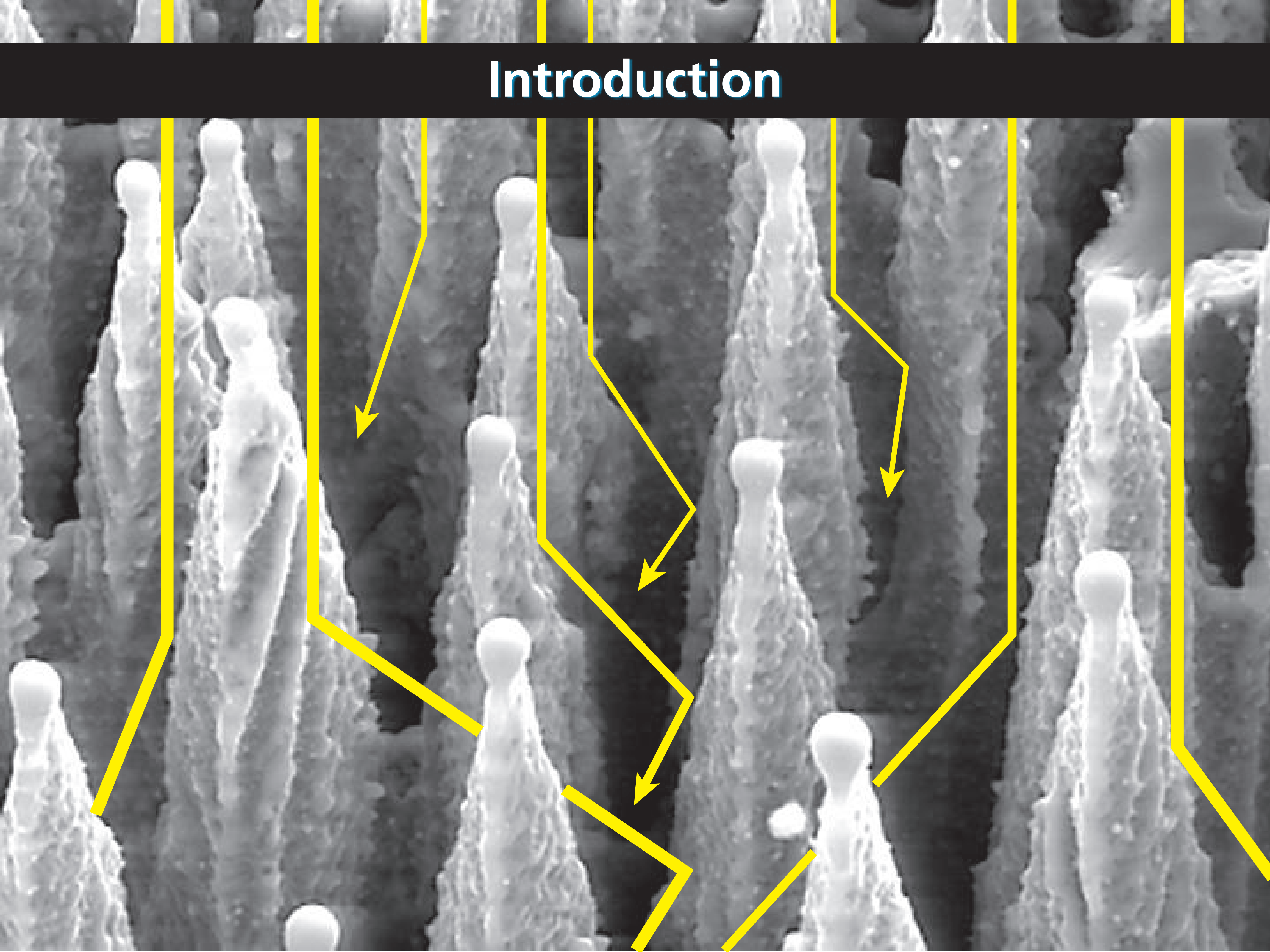


Introduction

absorptance (1 – *R* – *T*)

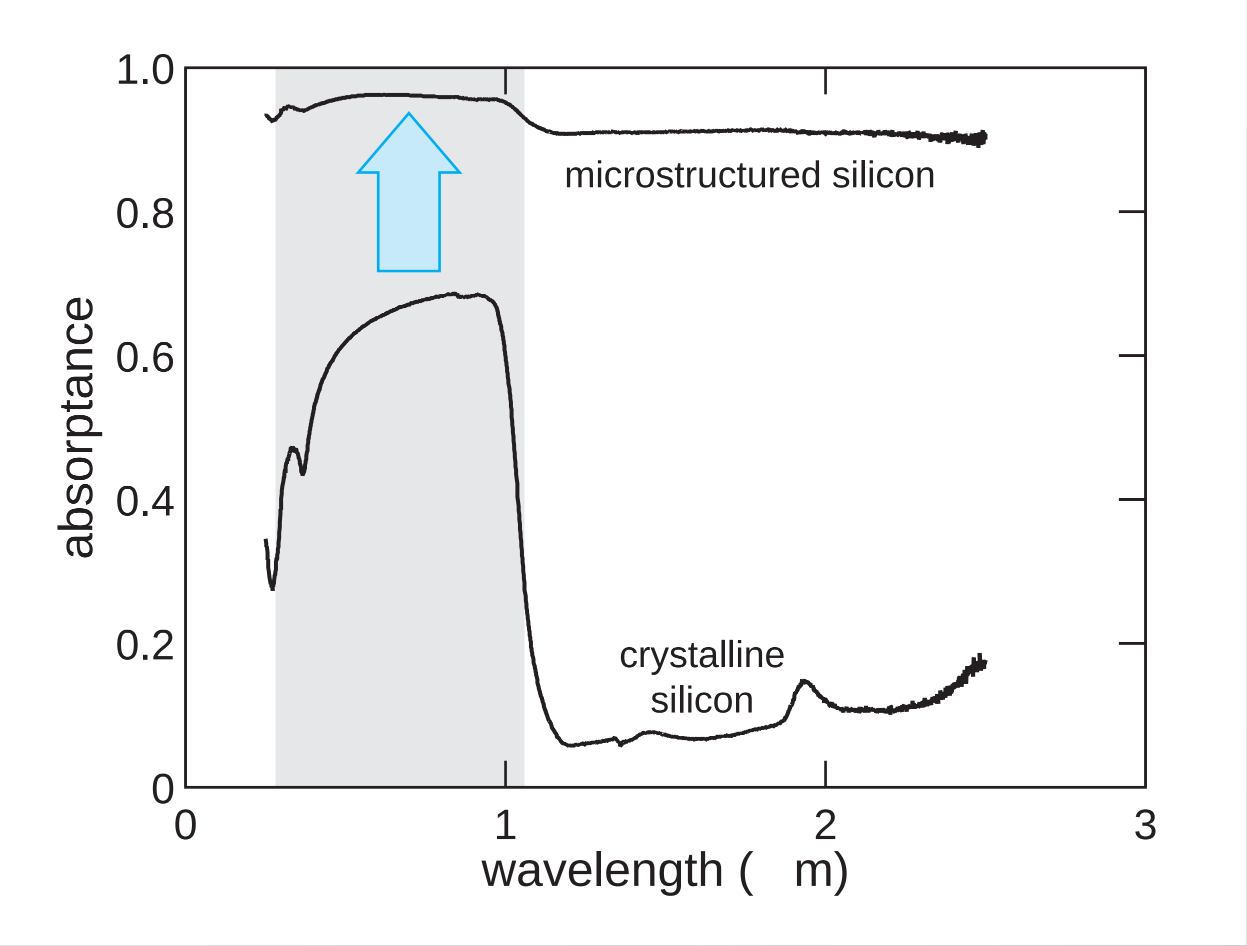


Introduction



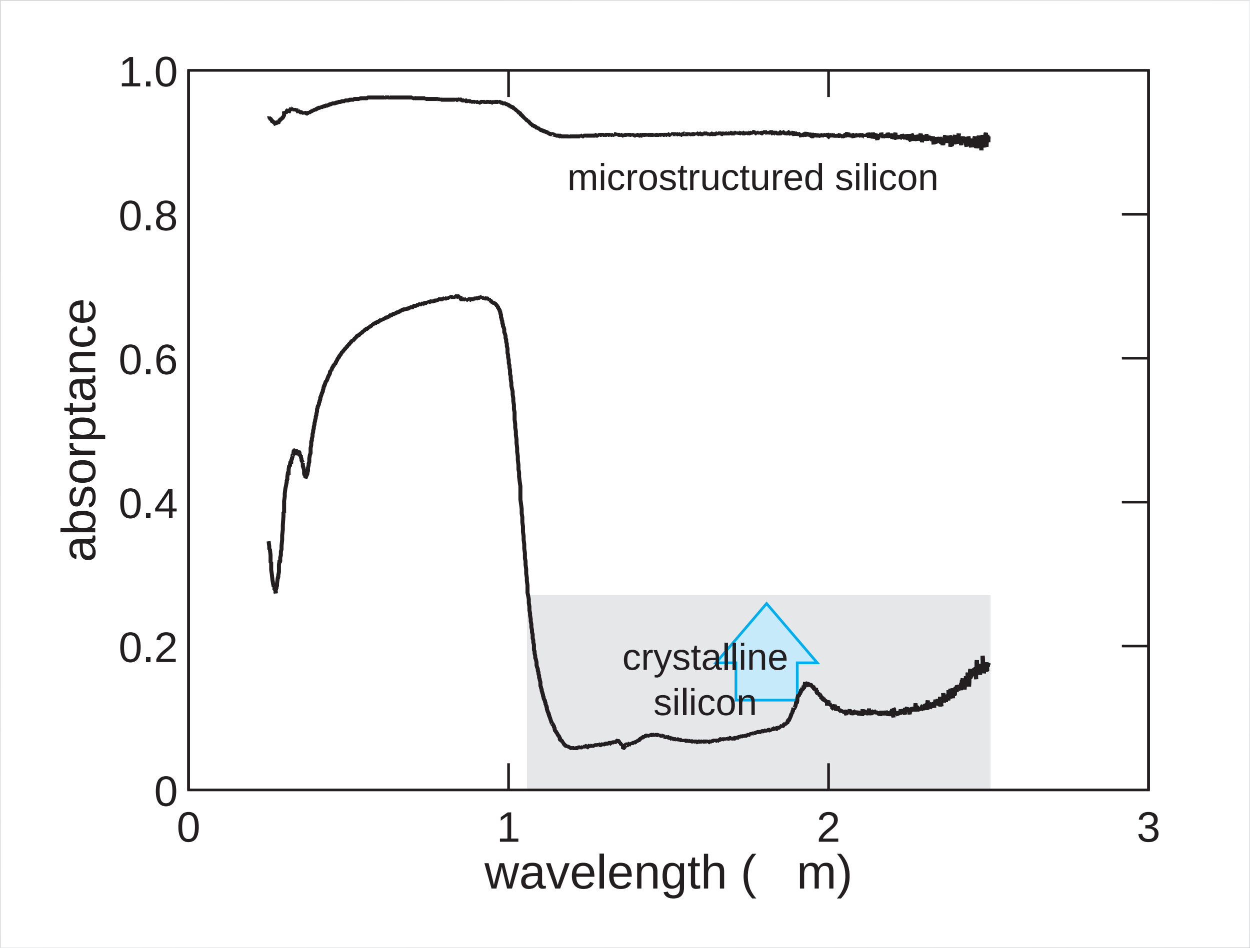
Introduction

multiple reflections enhance absorption



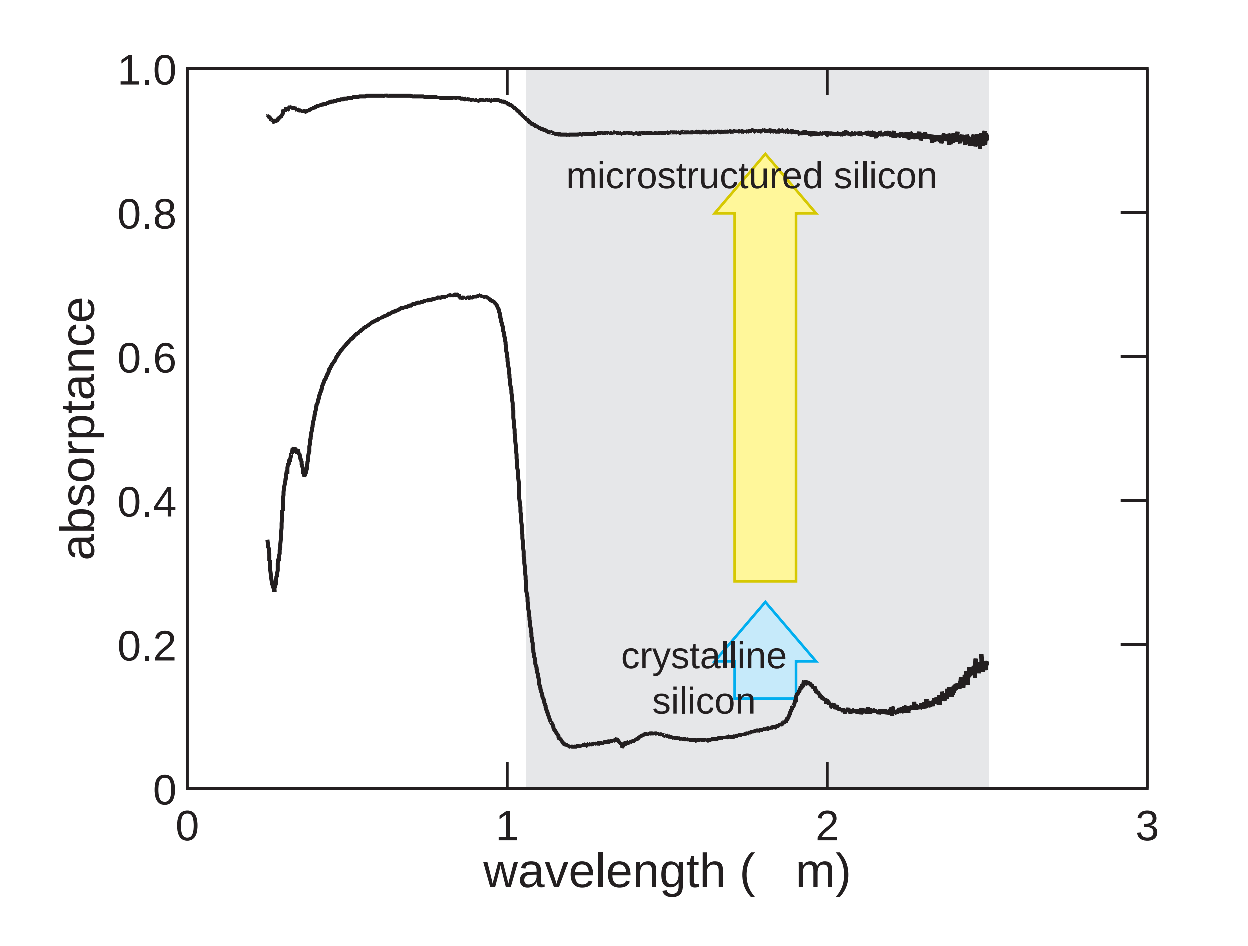
Introduction

multiple reflections enhance absorption



Introduction

electronic band structure changes



Introduction

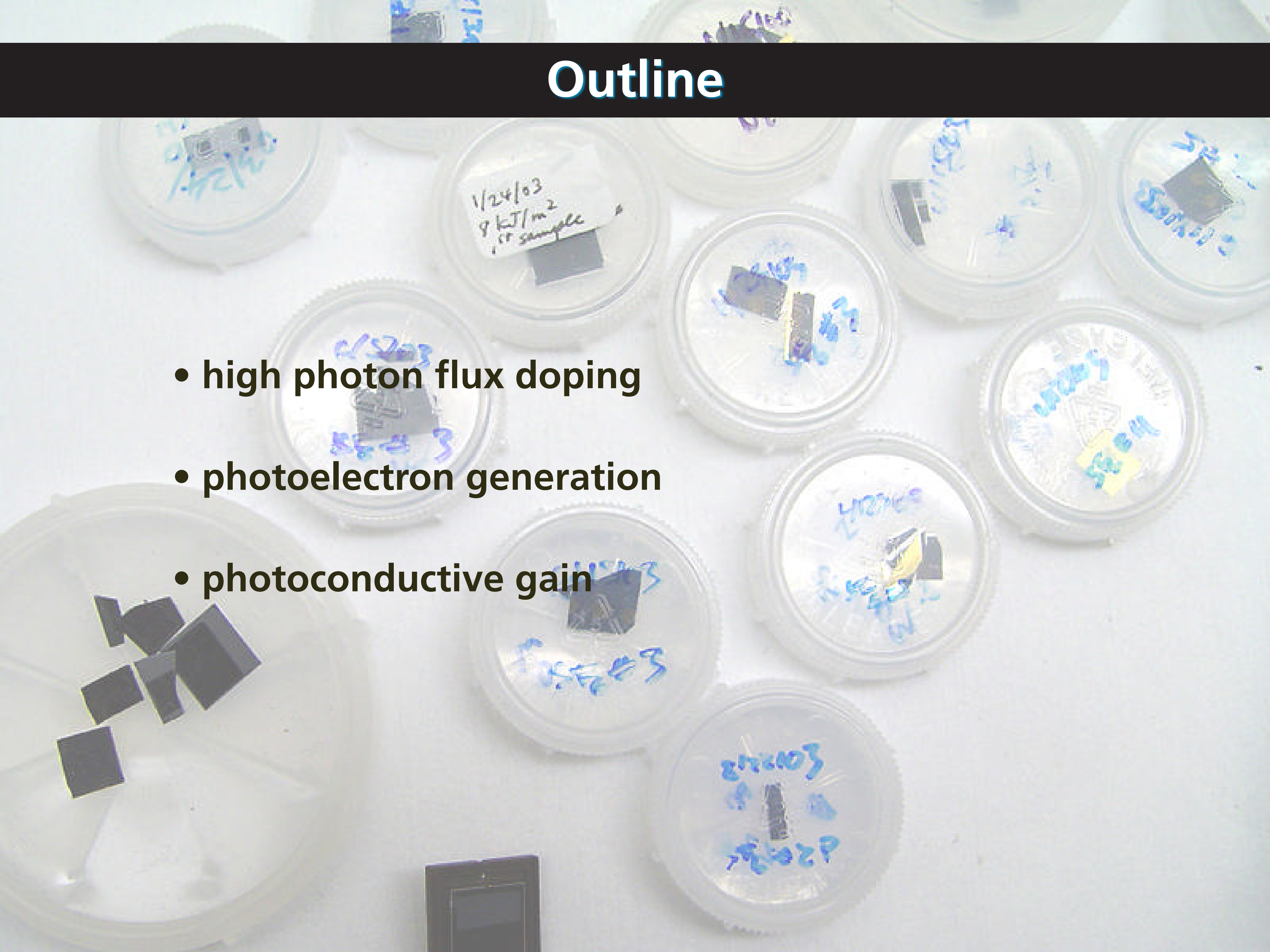
band structure changes: defects and/or impurities

Outline

- high photon flux doping

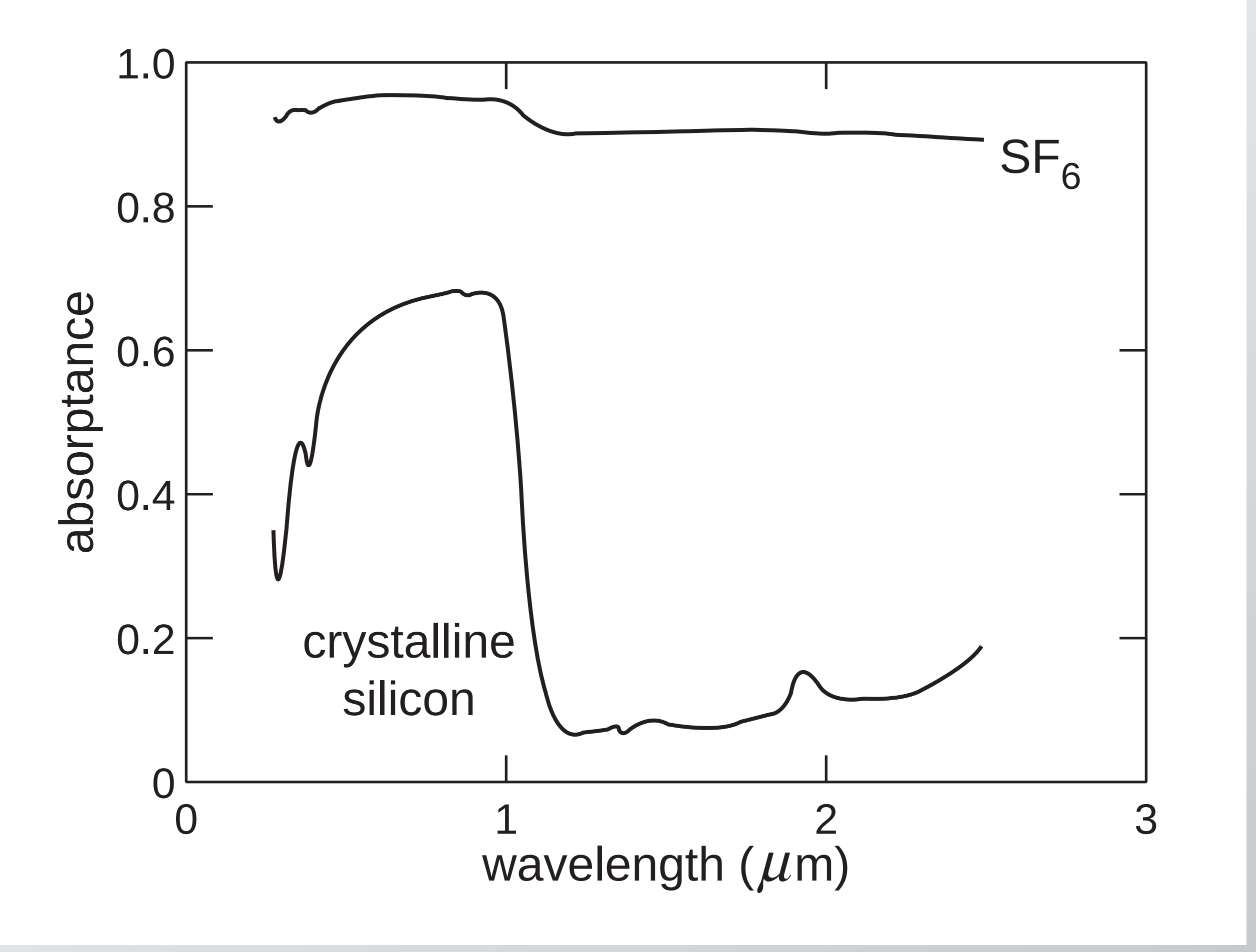
- photoelectron generation

- photoconductive gain



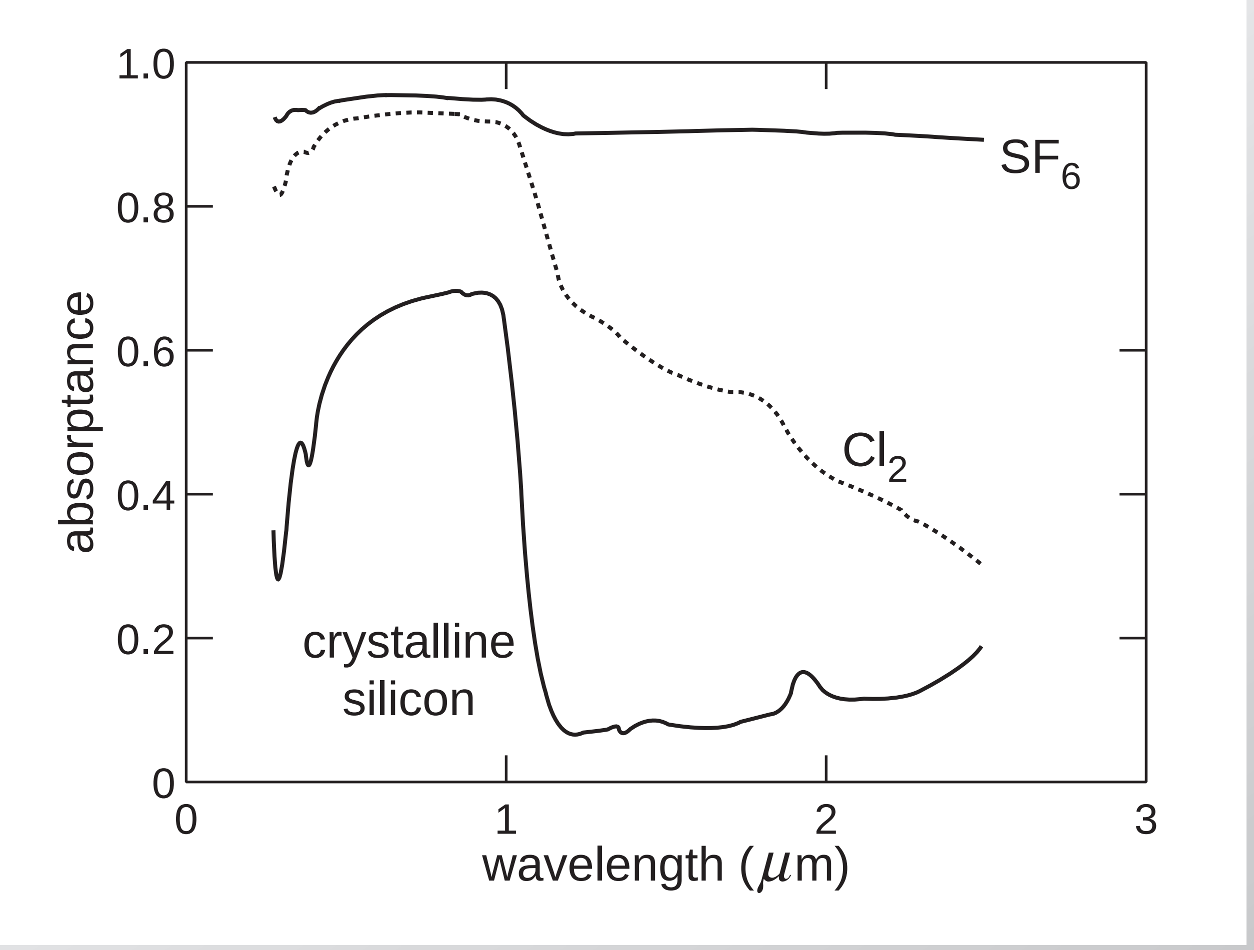
High photon flux doping

microstructure with different gases



High photon flux doping

microstructure with different gases



High photon flux doping

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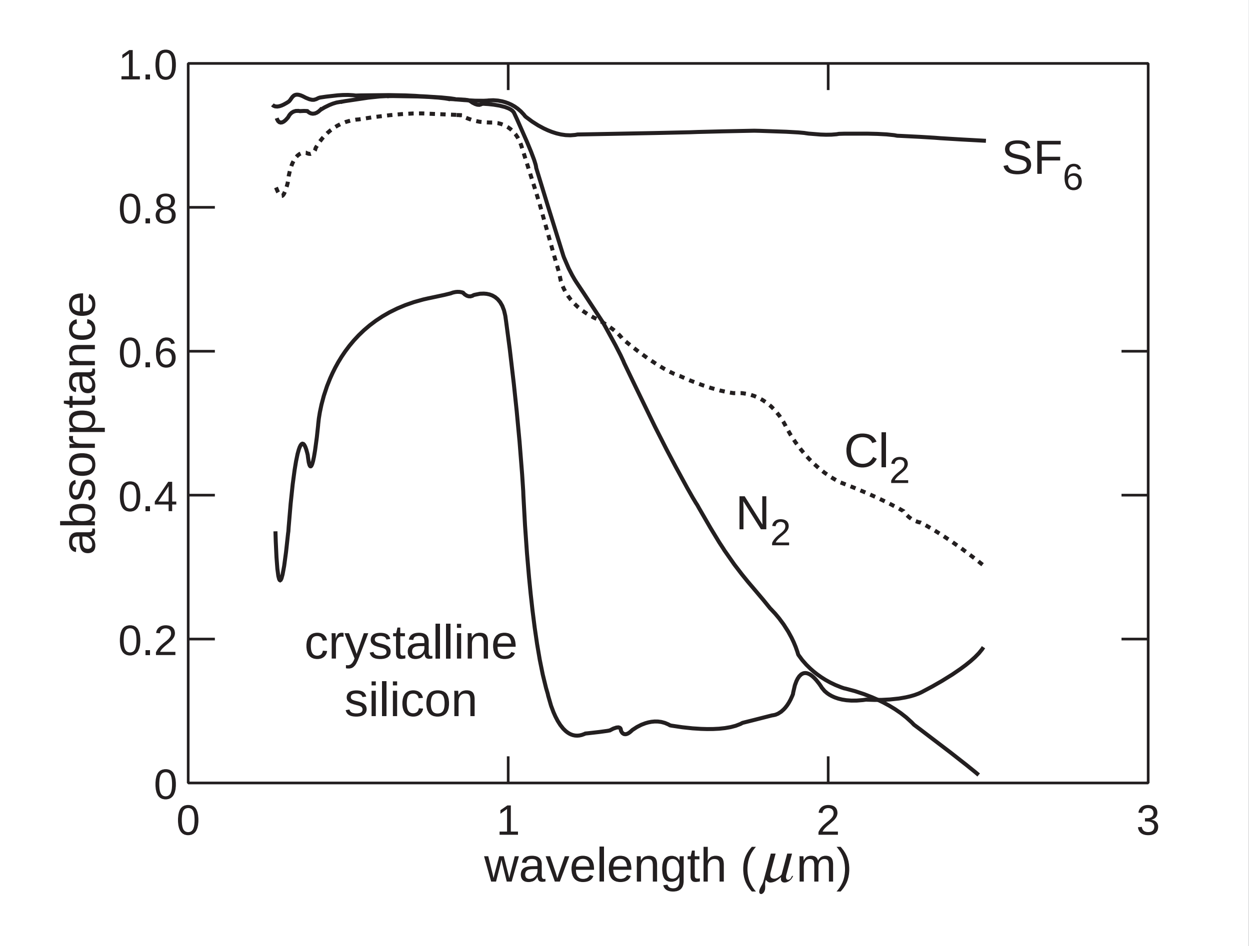
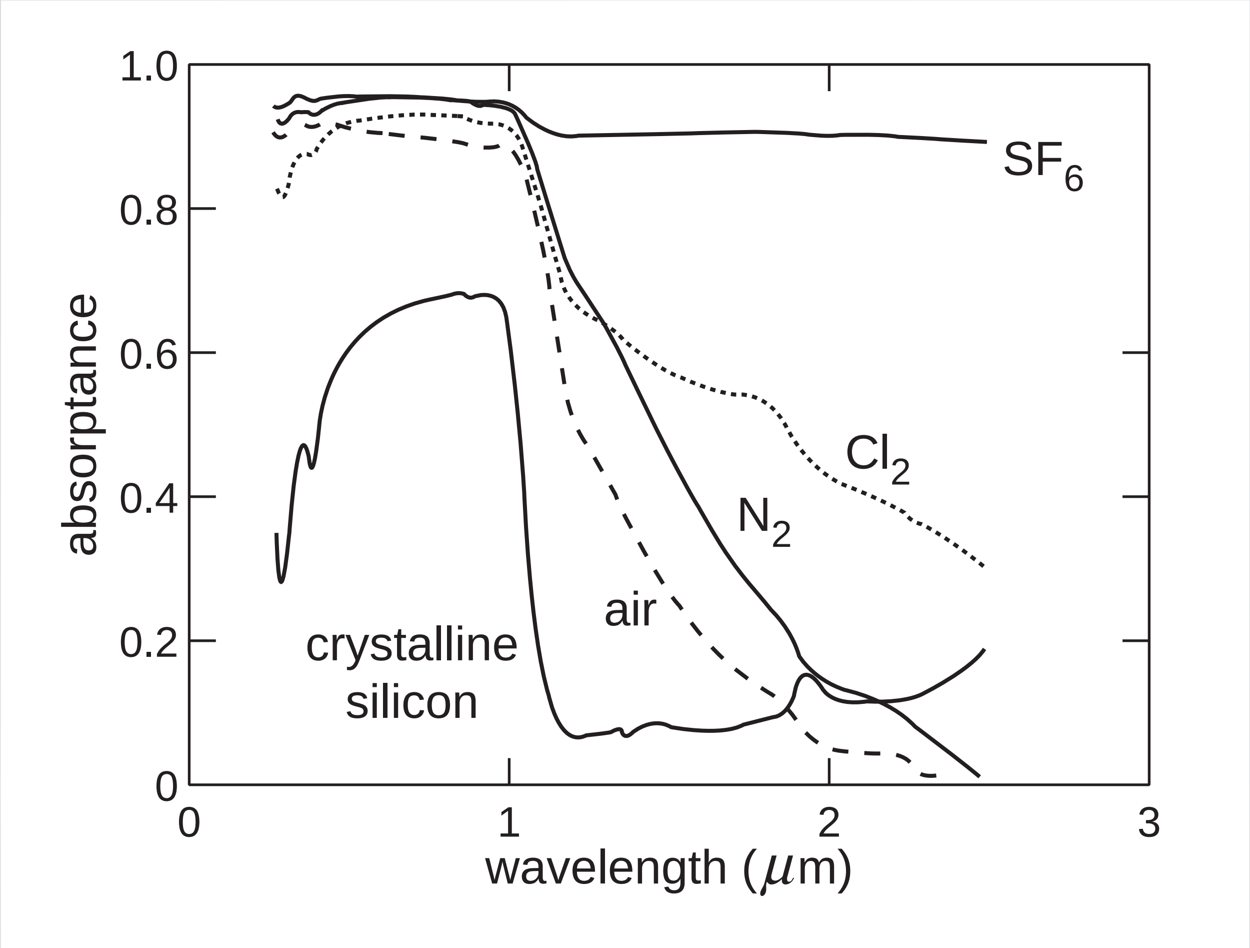


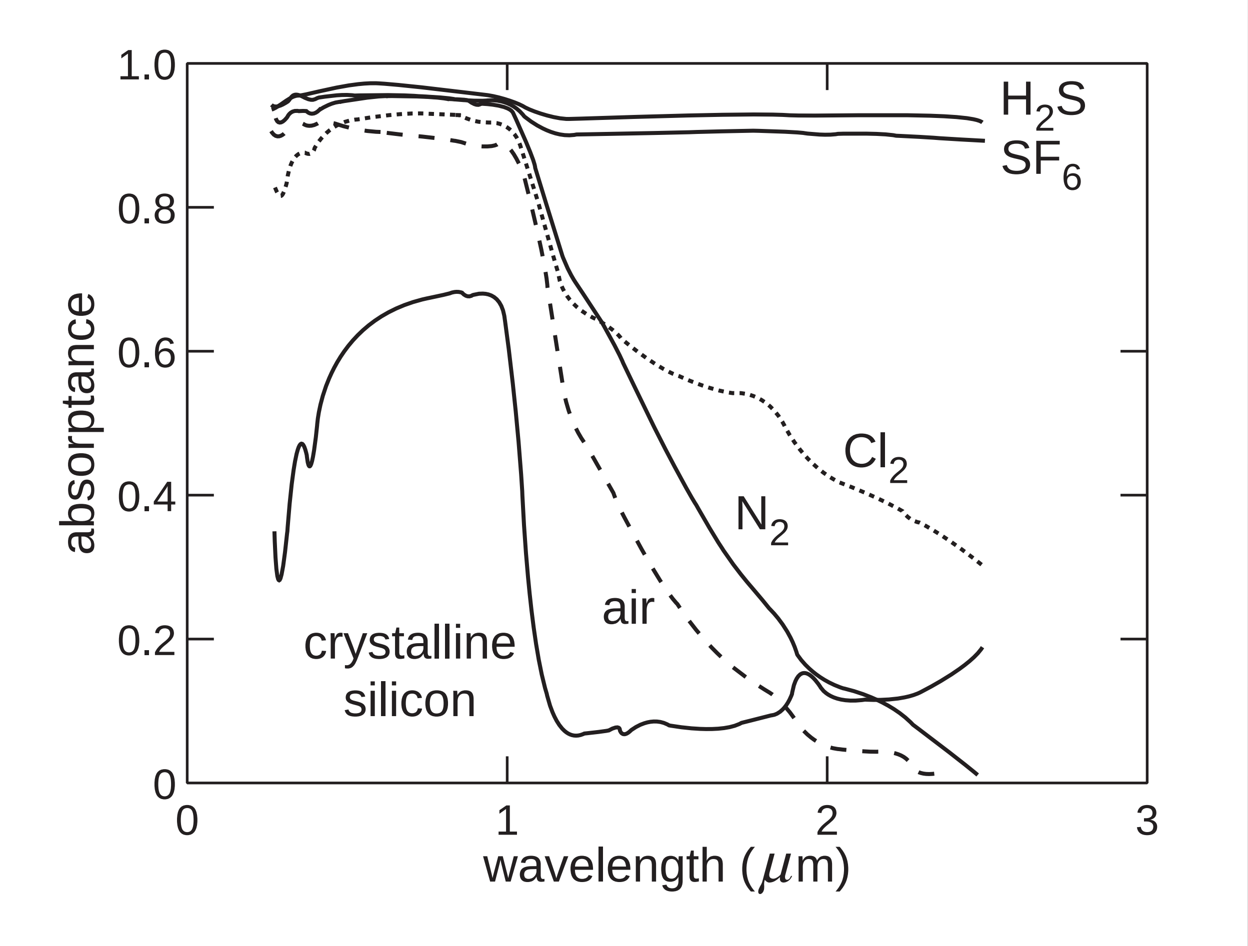
High photon flux doping

microstructure with different gases



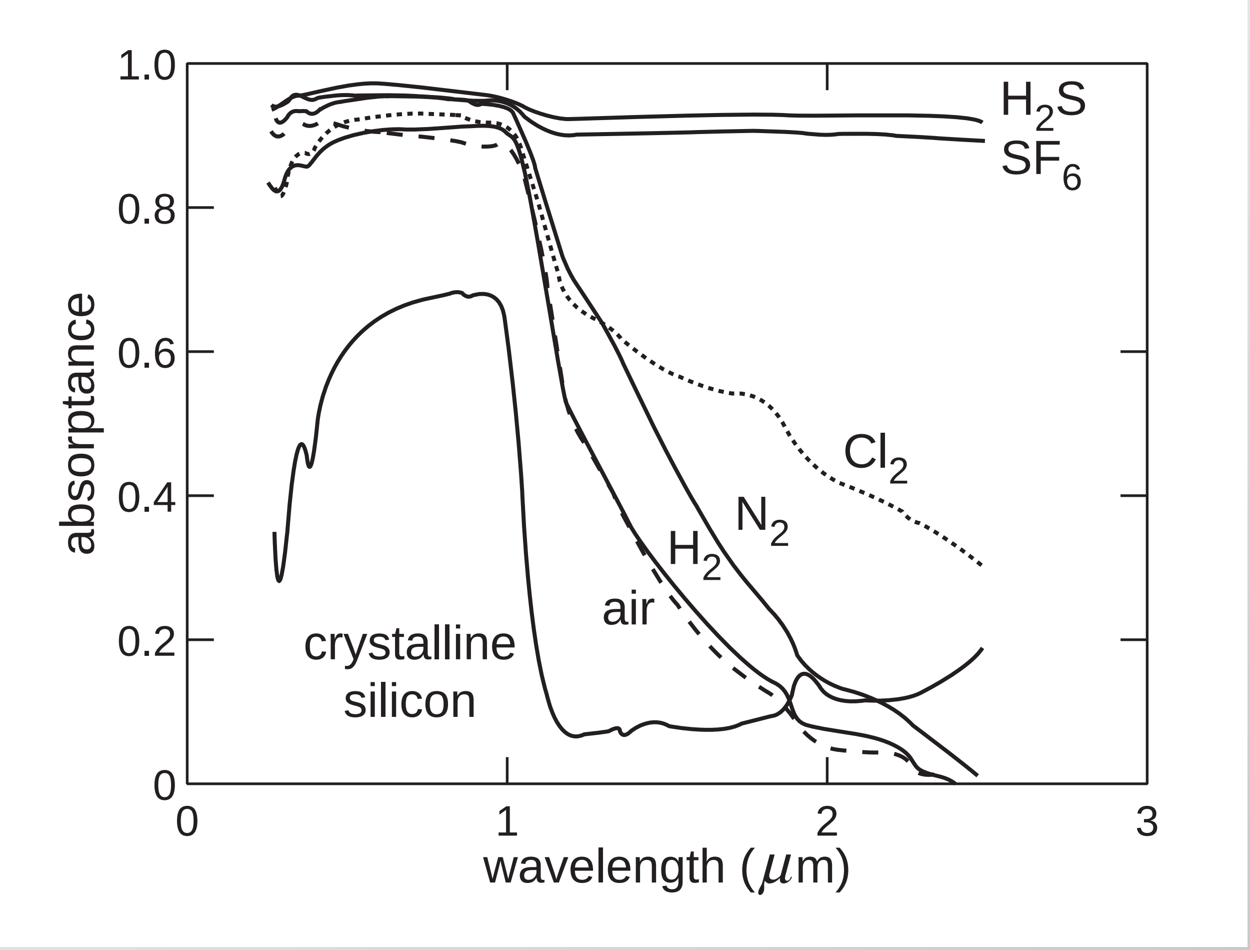
High photon flux doping

microstructure with different gases



High photon flux doping

microstructure with different gases

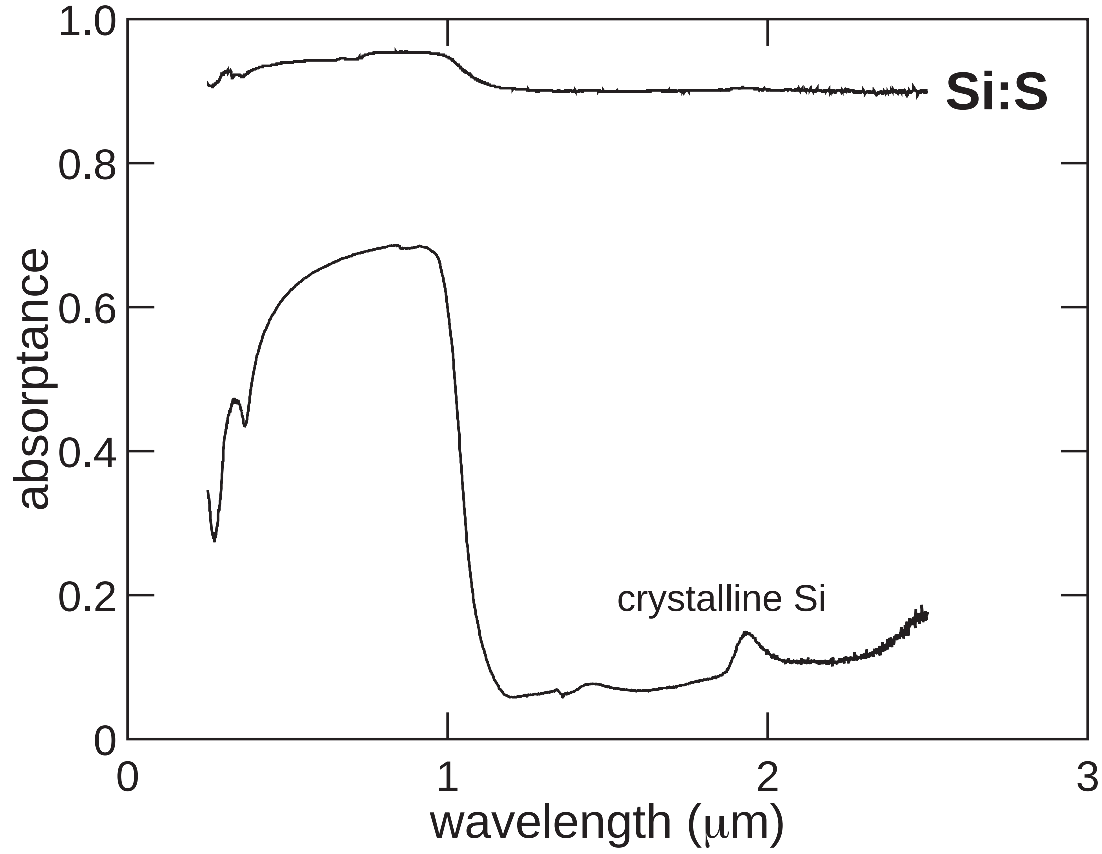


Introduction

sulfur required for below band gap absorption

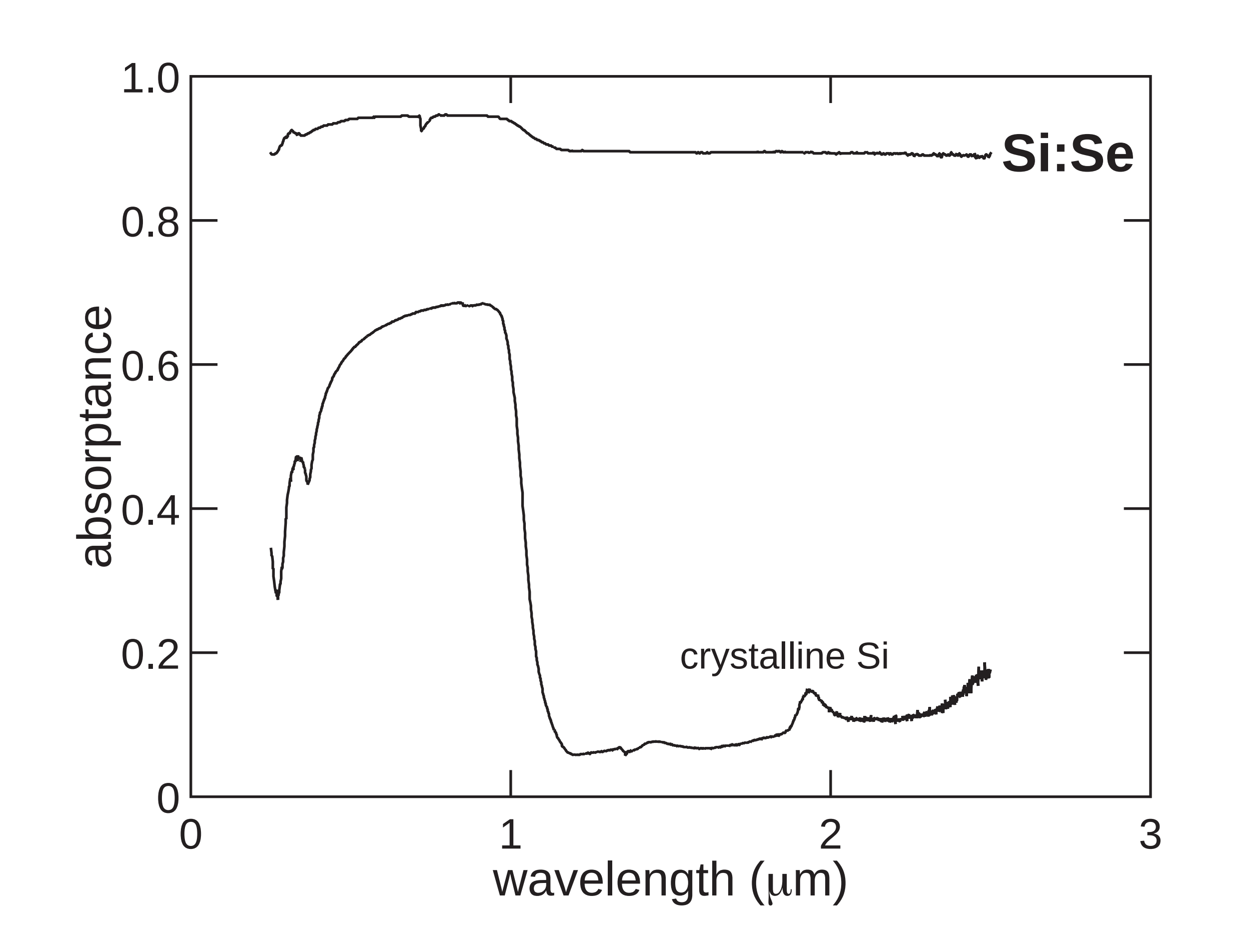
High photon flux doping

other chalcogens yield similar results



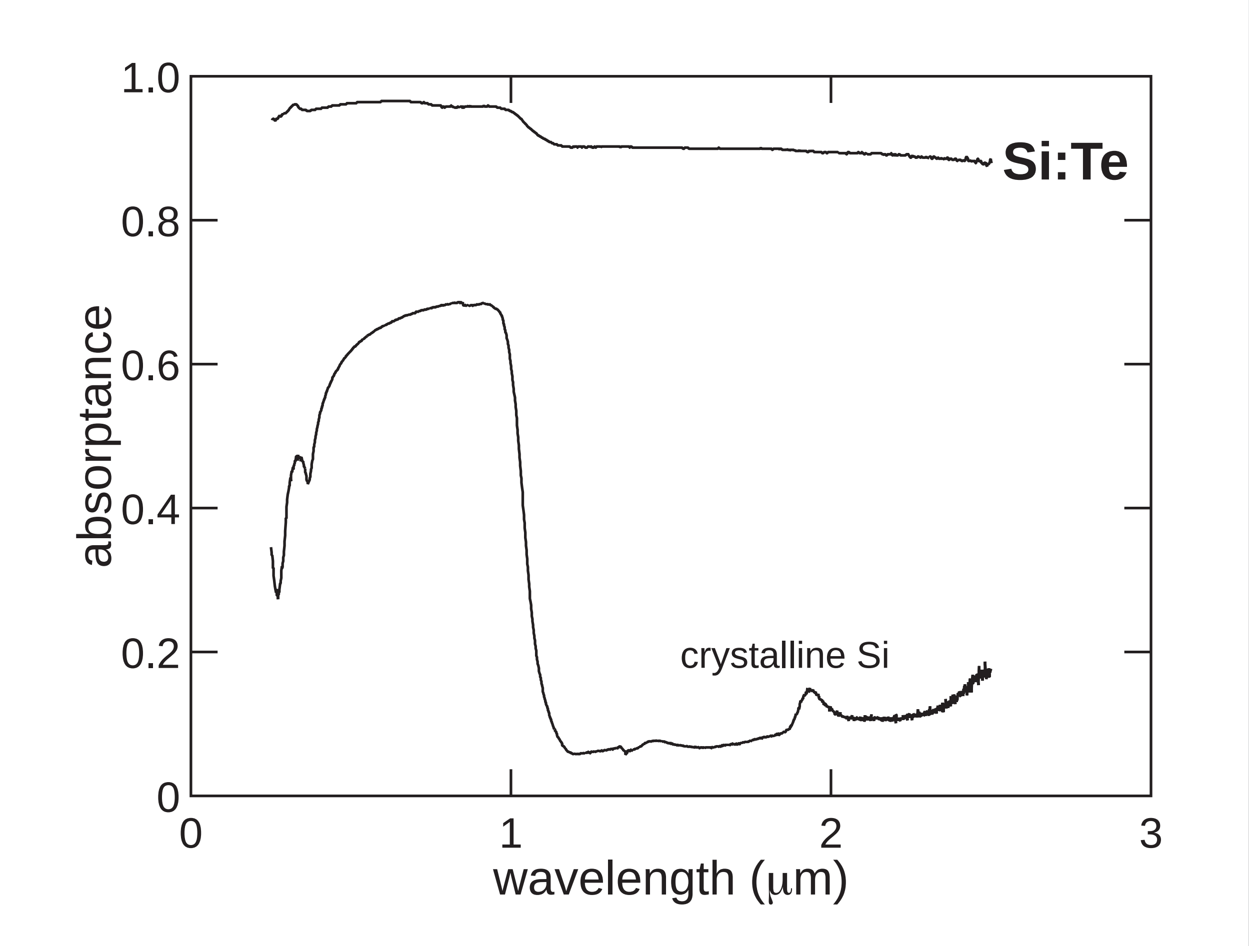
High photon flux doping

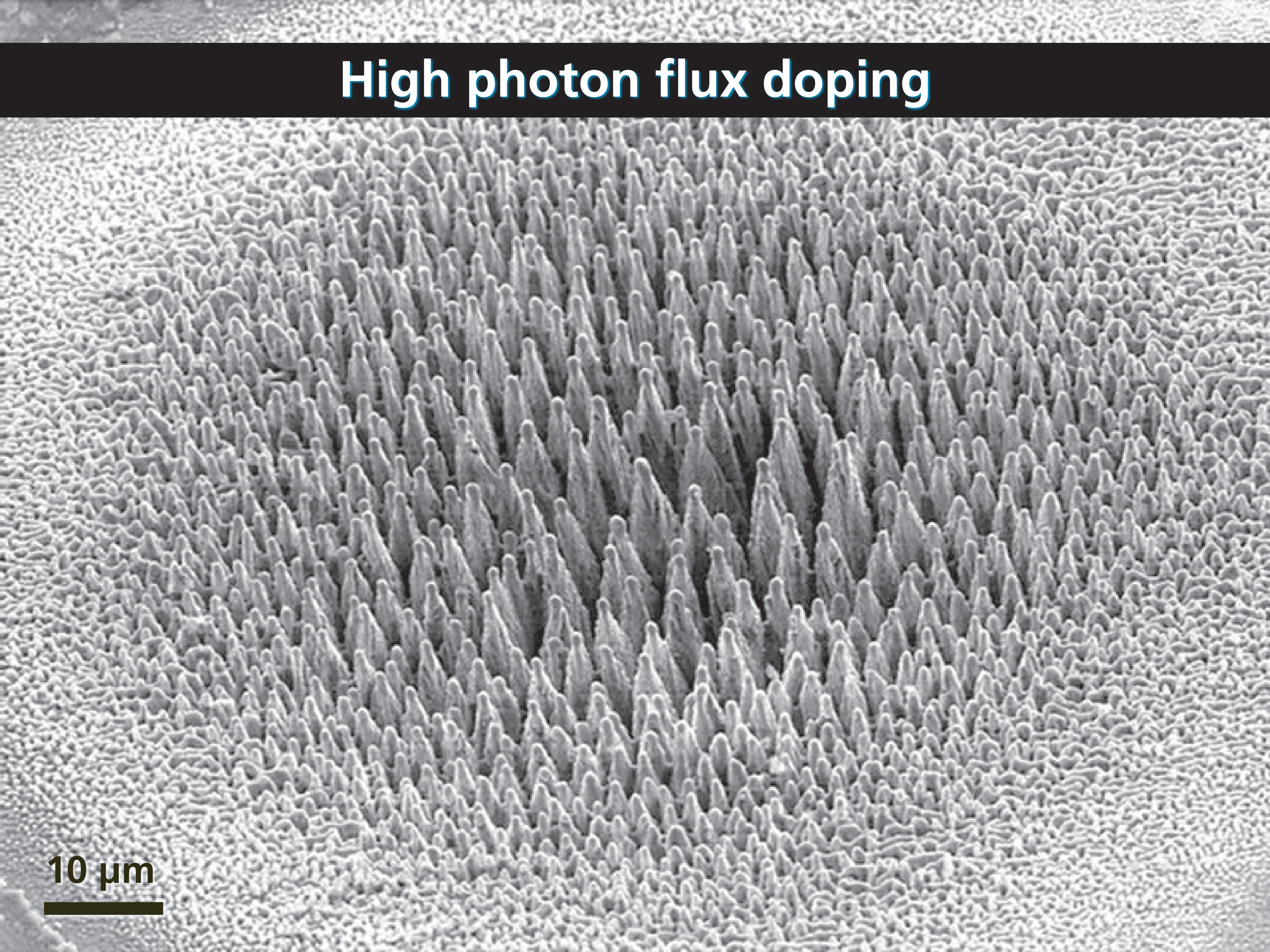
other chalcogens yield similar results

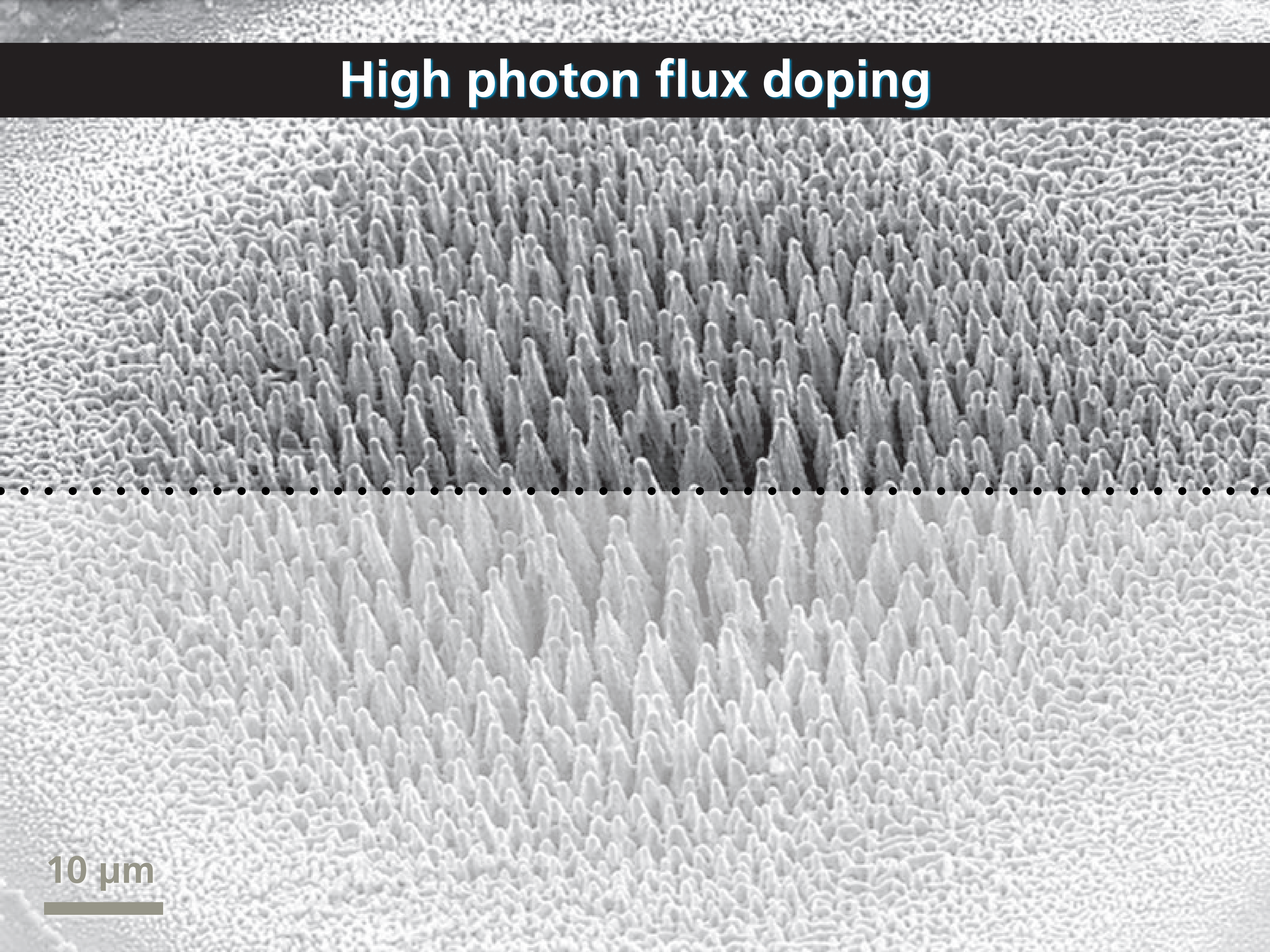


High photon flux doping

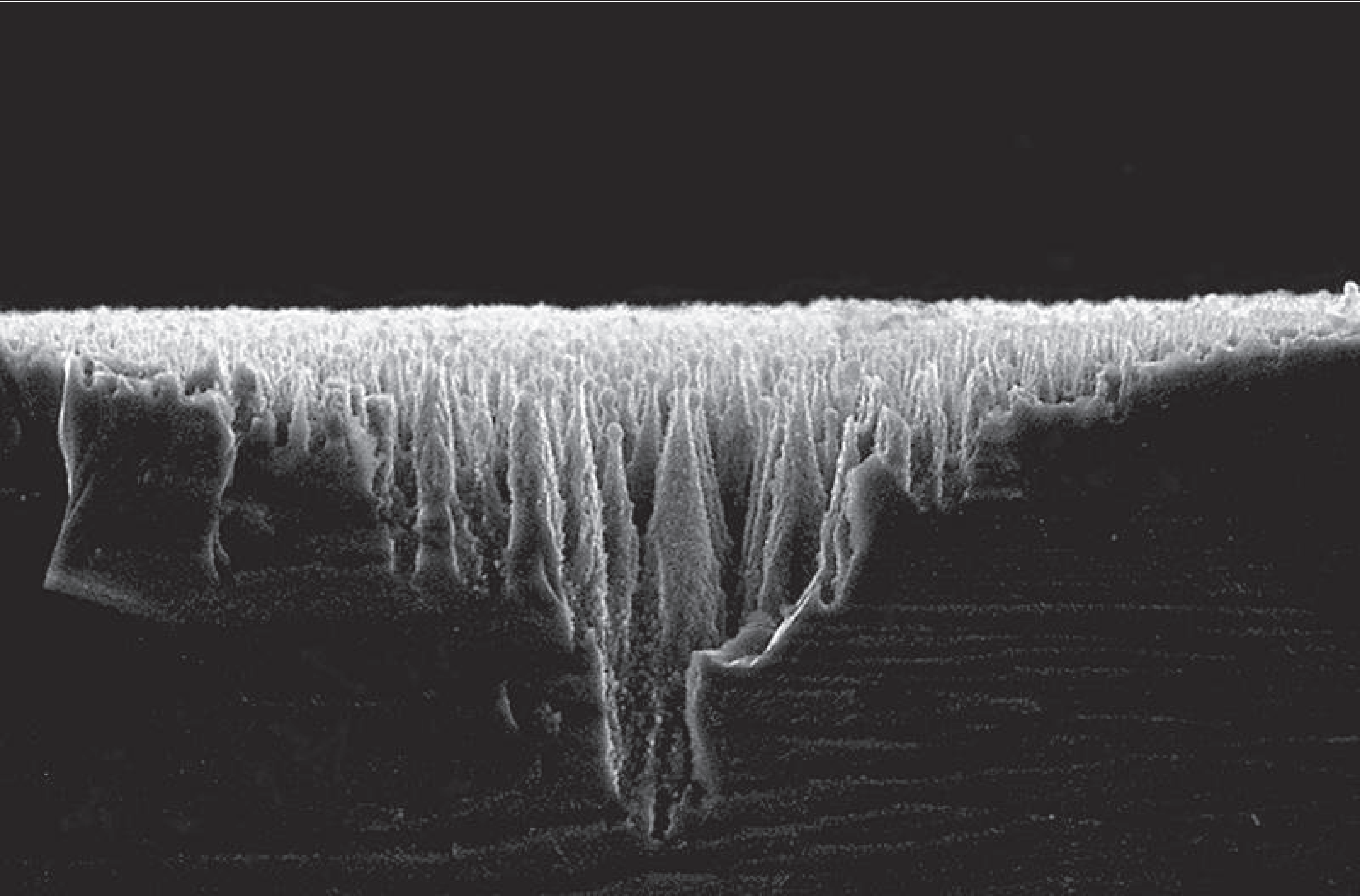
other chalcogens yield similar results



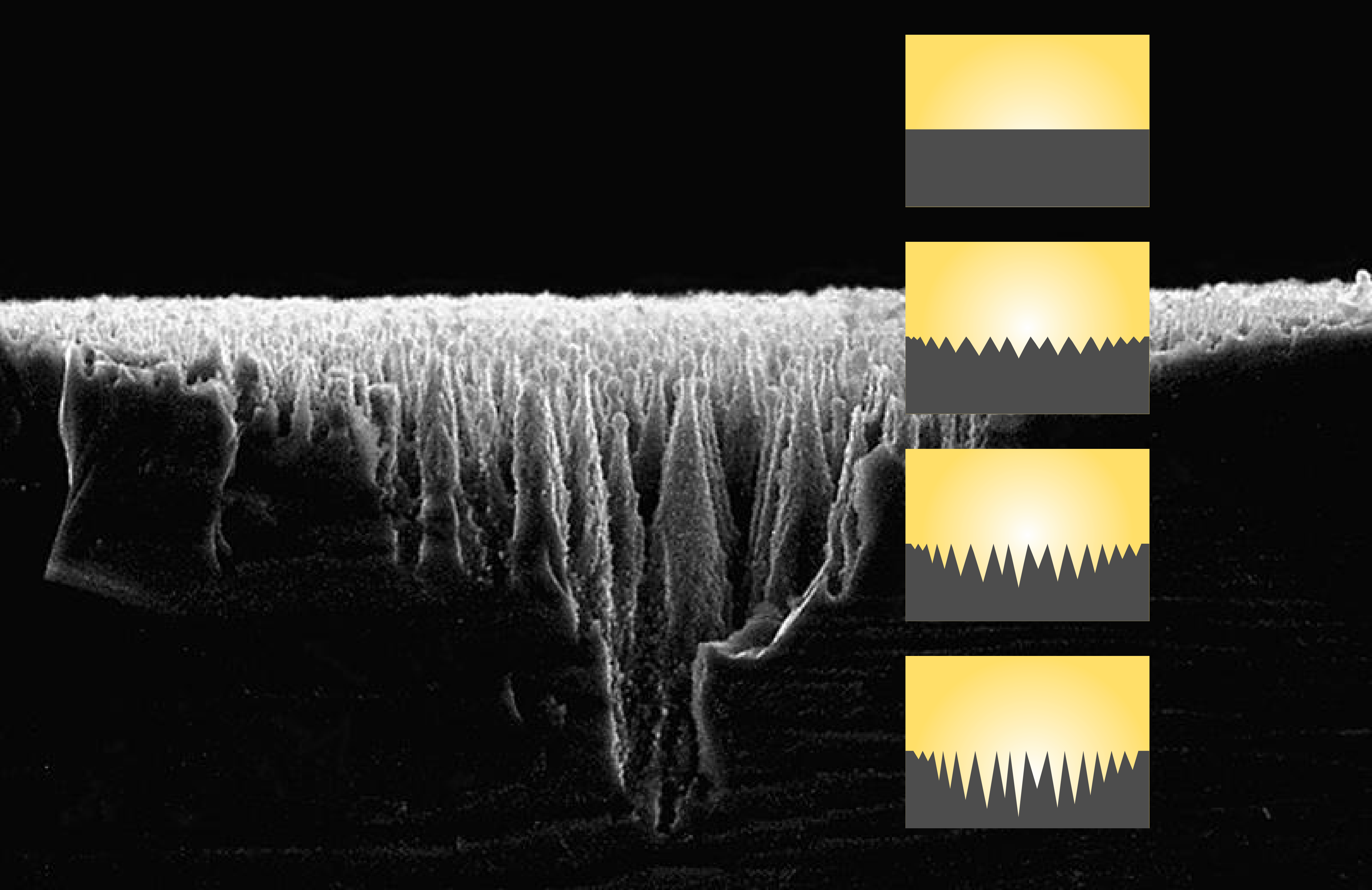

High photon flux doping
10 µm


High photon flux doping
10 µm

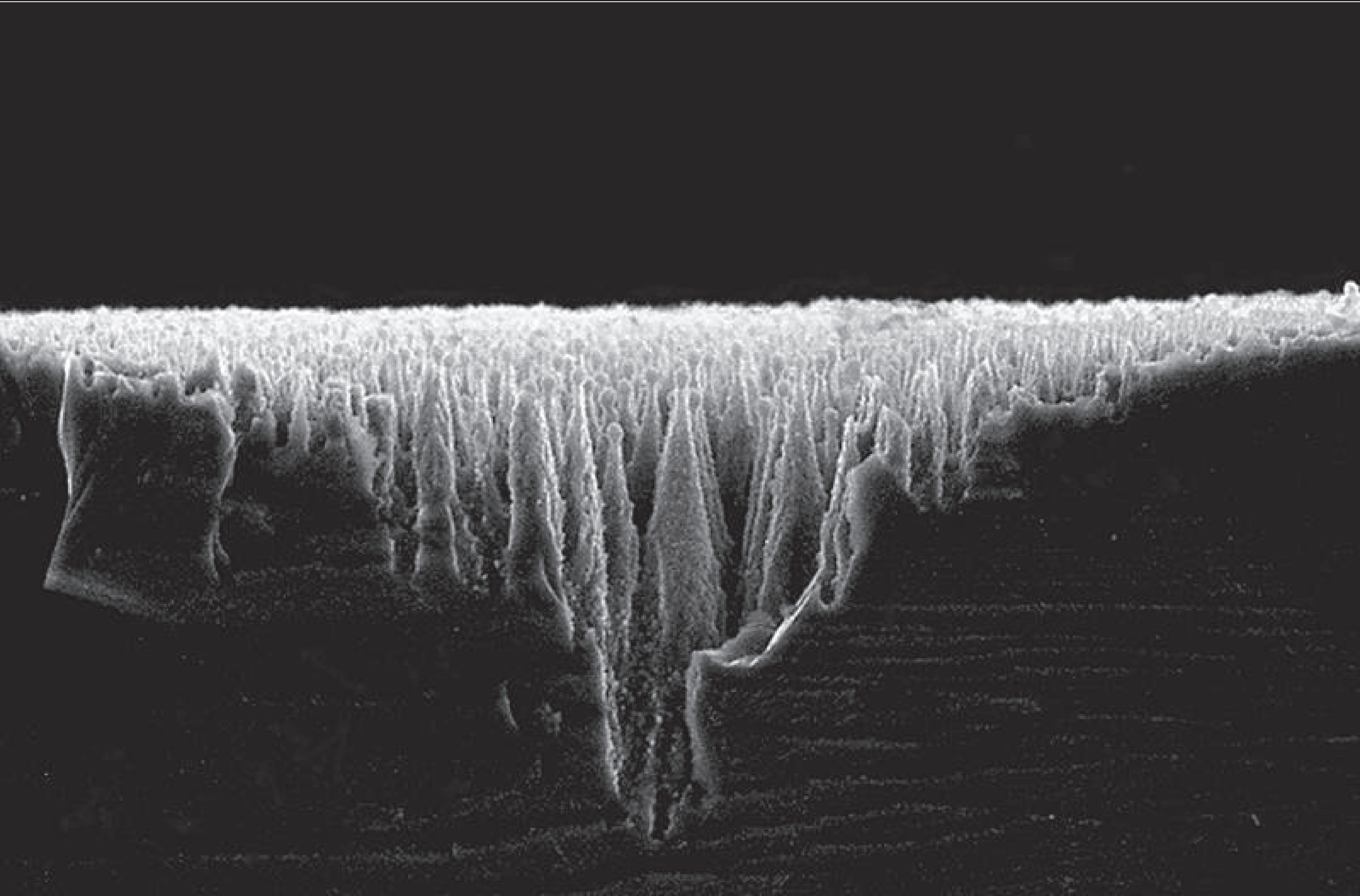
High photon flux doping



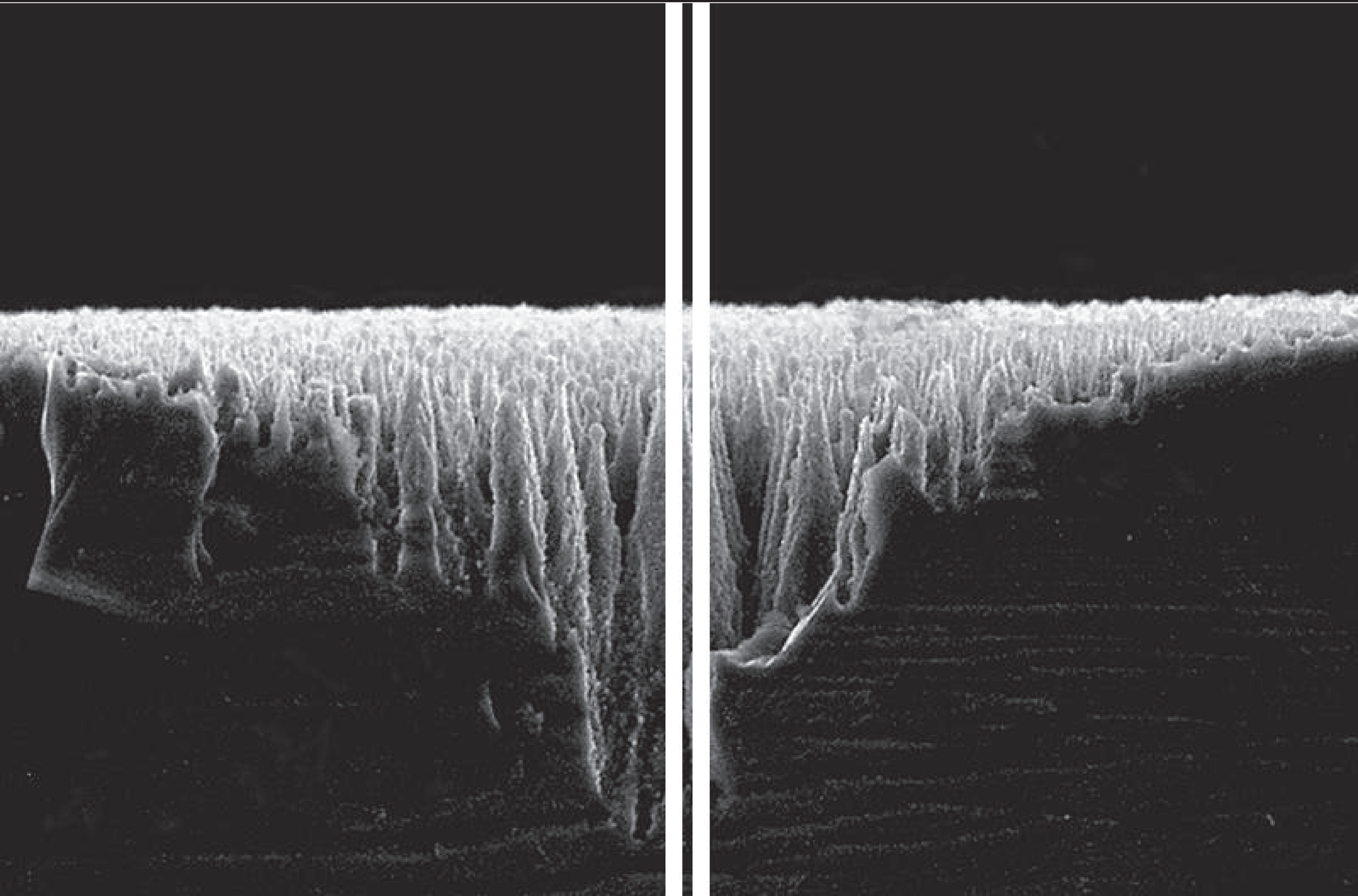
High photon flux doping



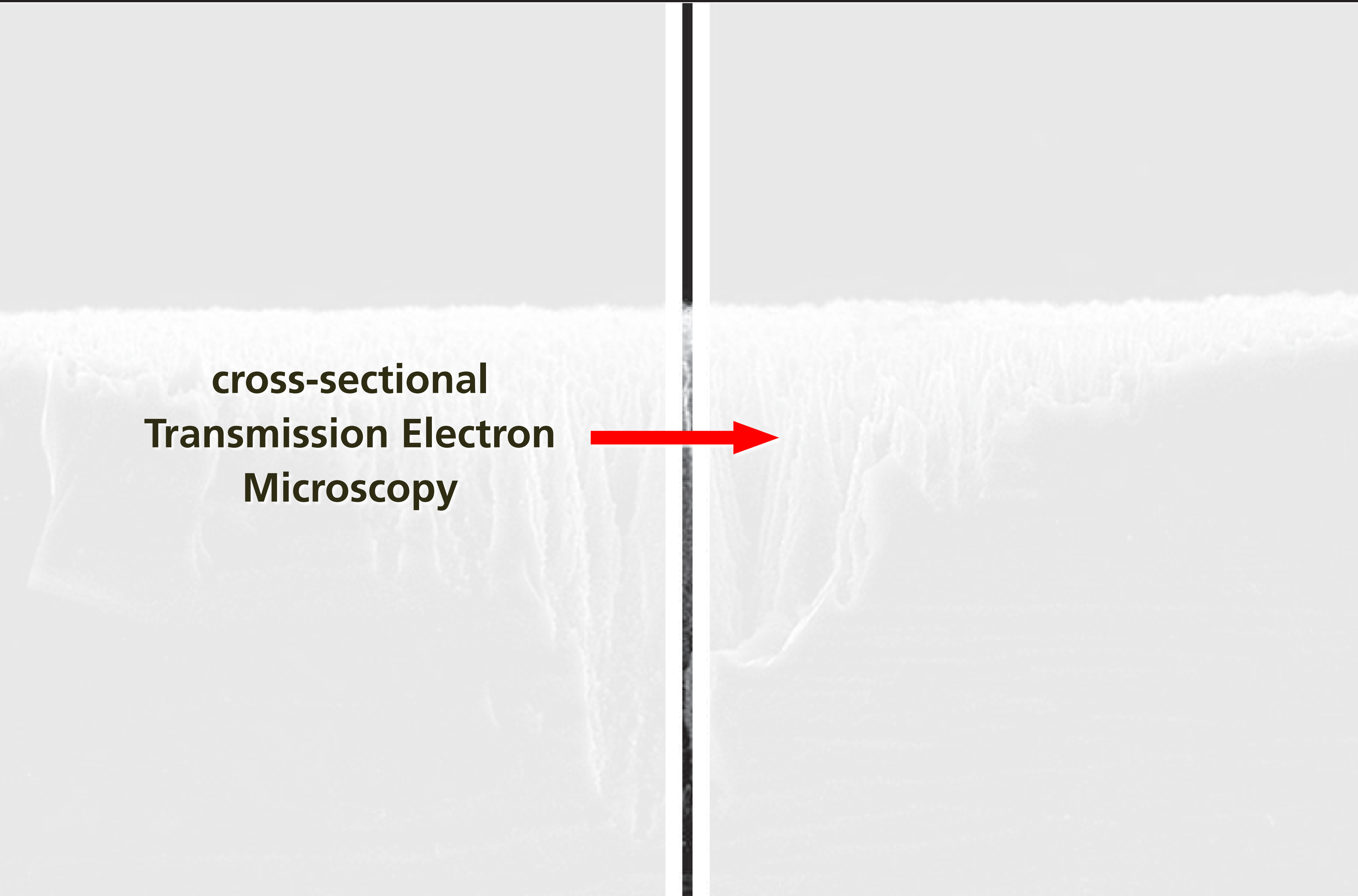
High photon flux doping



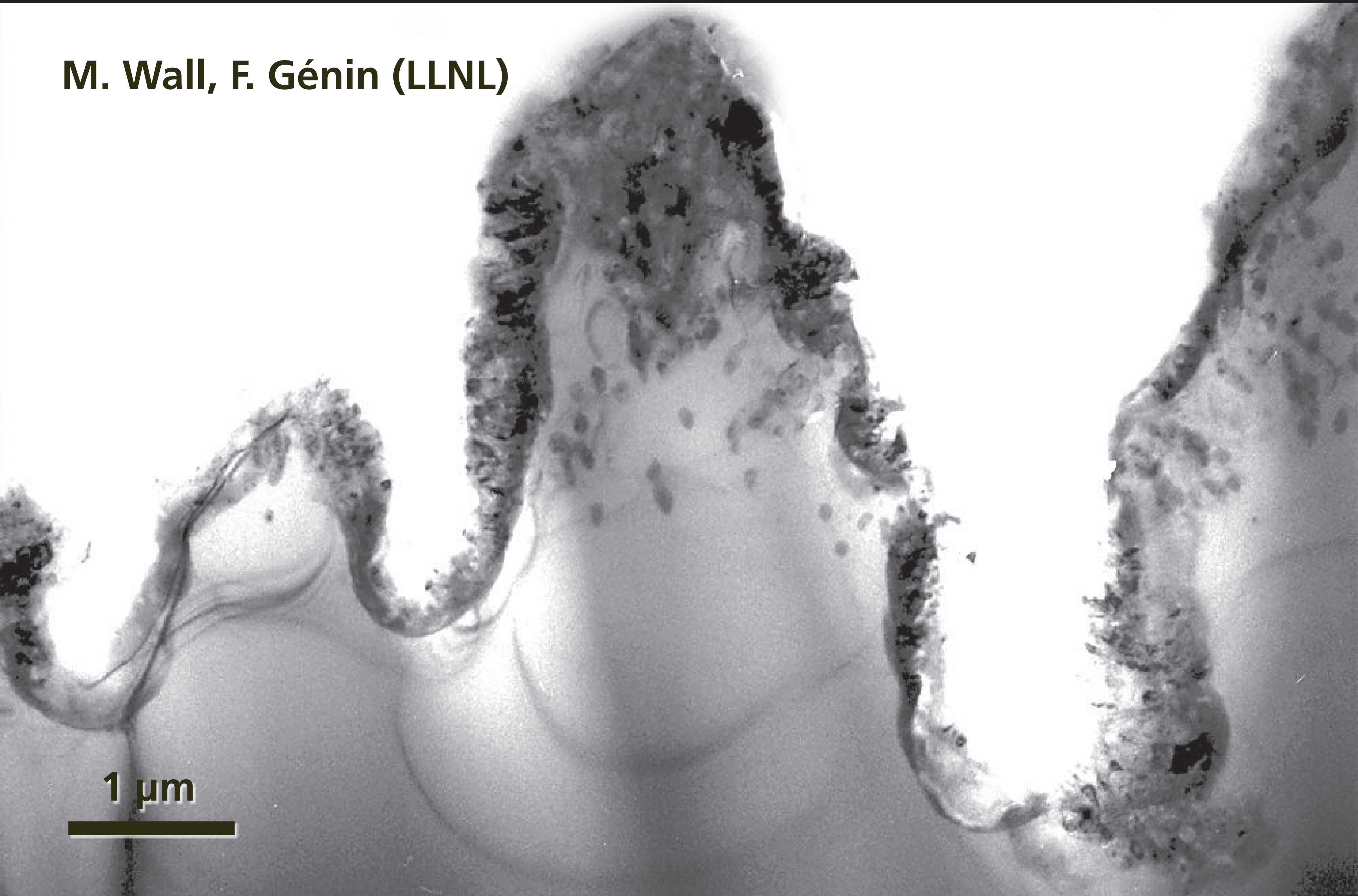
High photon flux doping

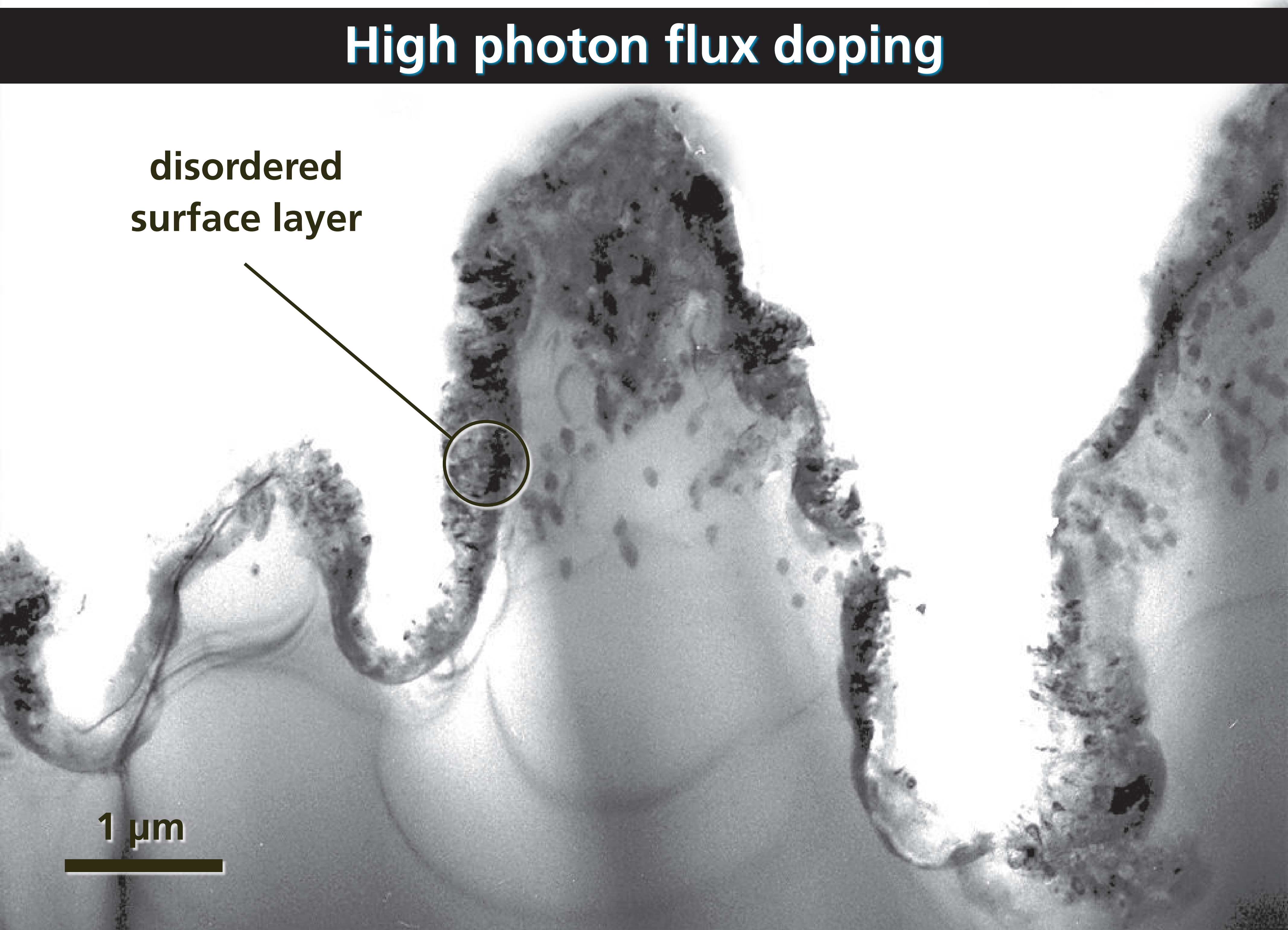


High photon flux doping

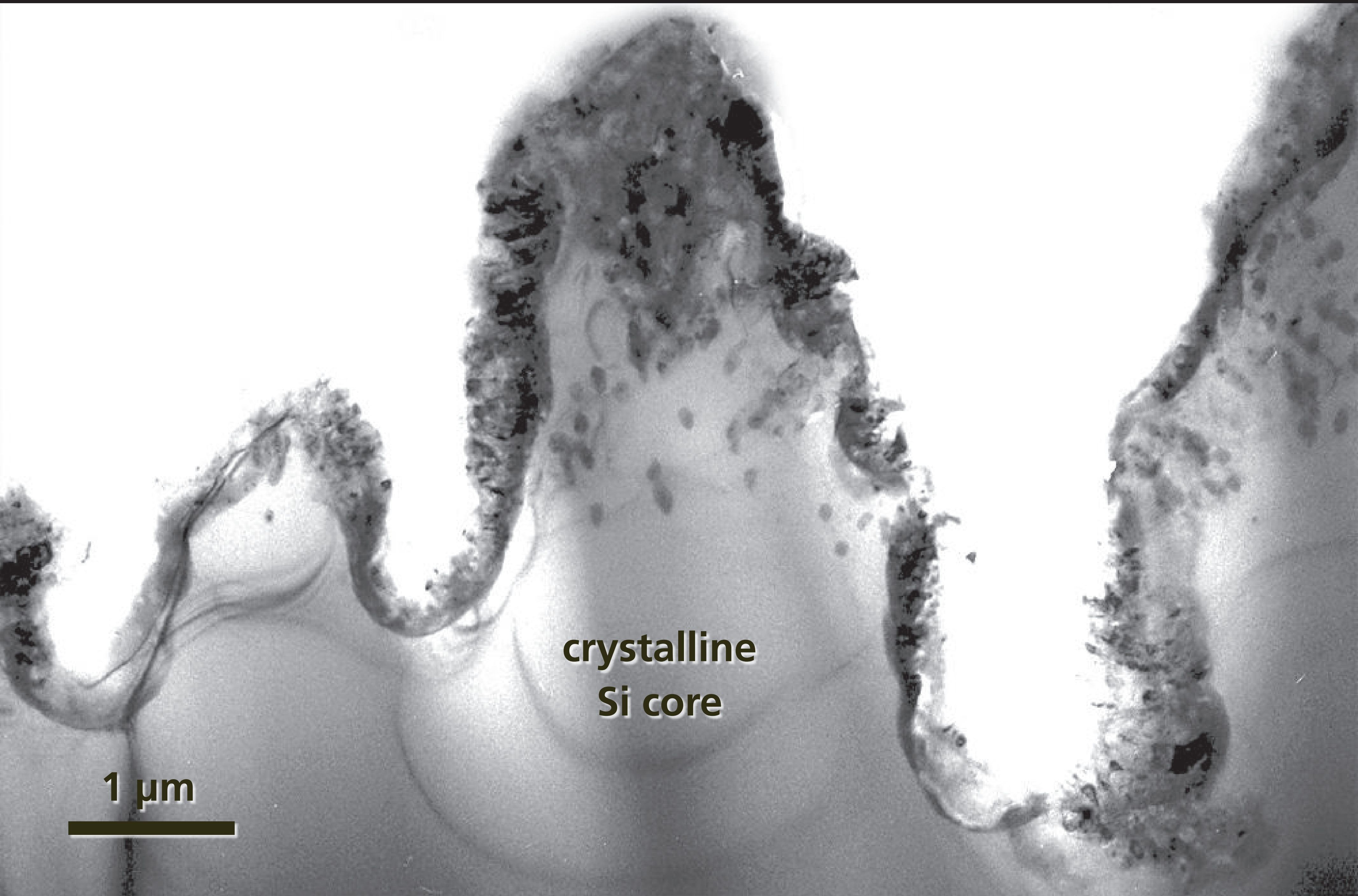


High photon flux doping

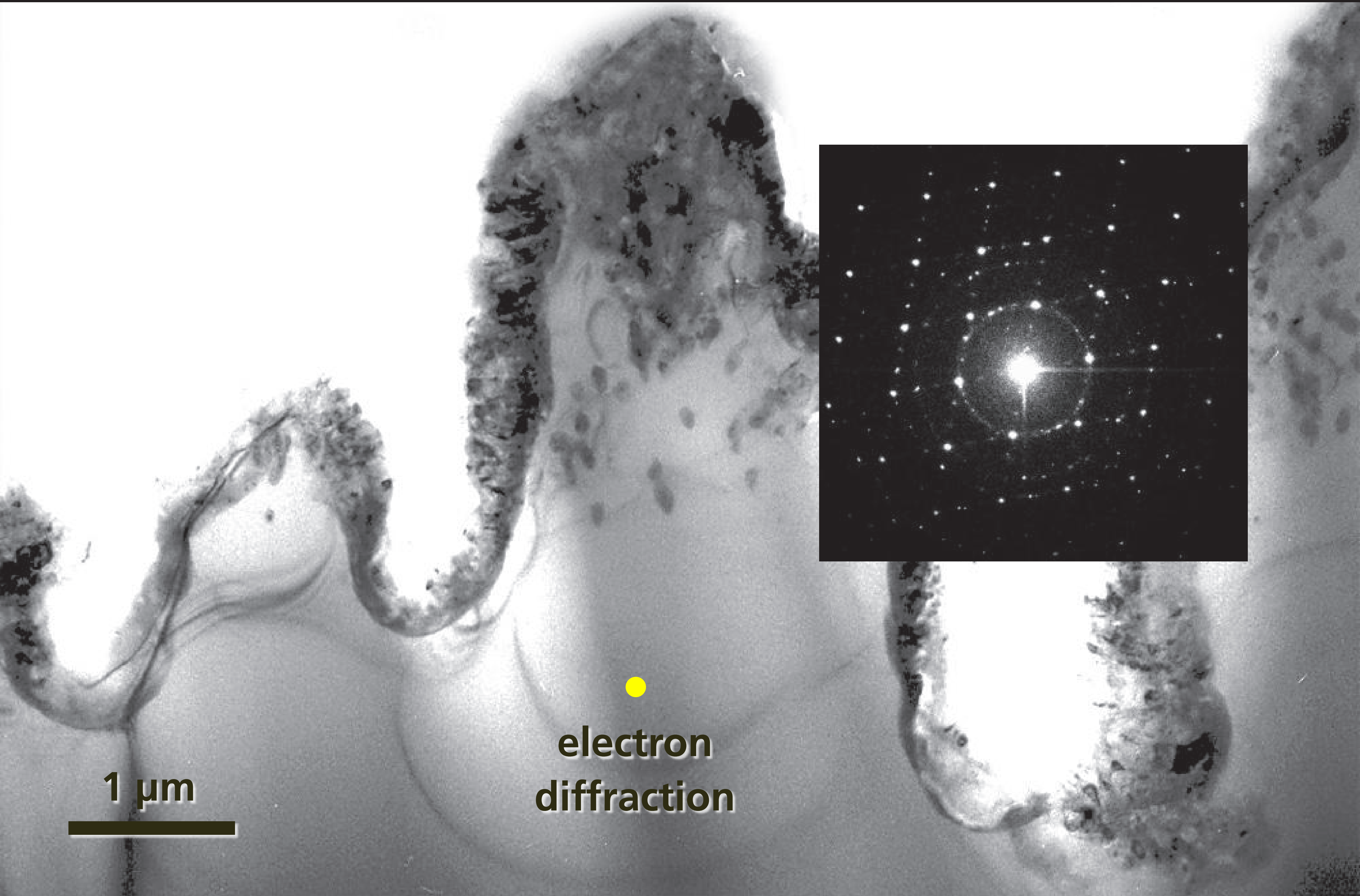



High photon flux doping
disordered
surface layer
1 µm

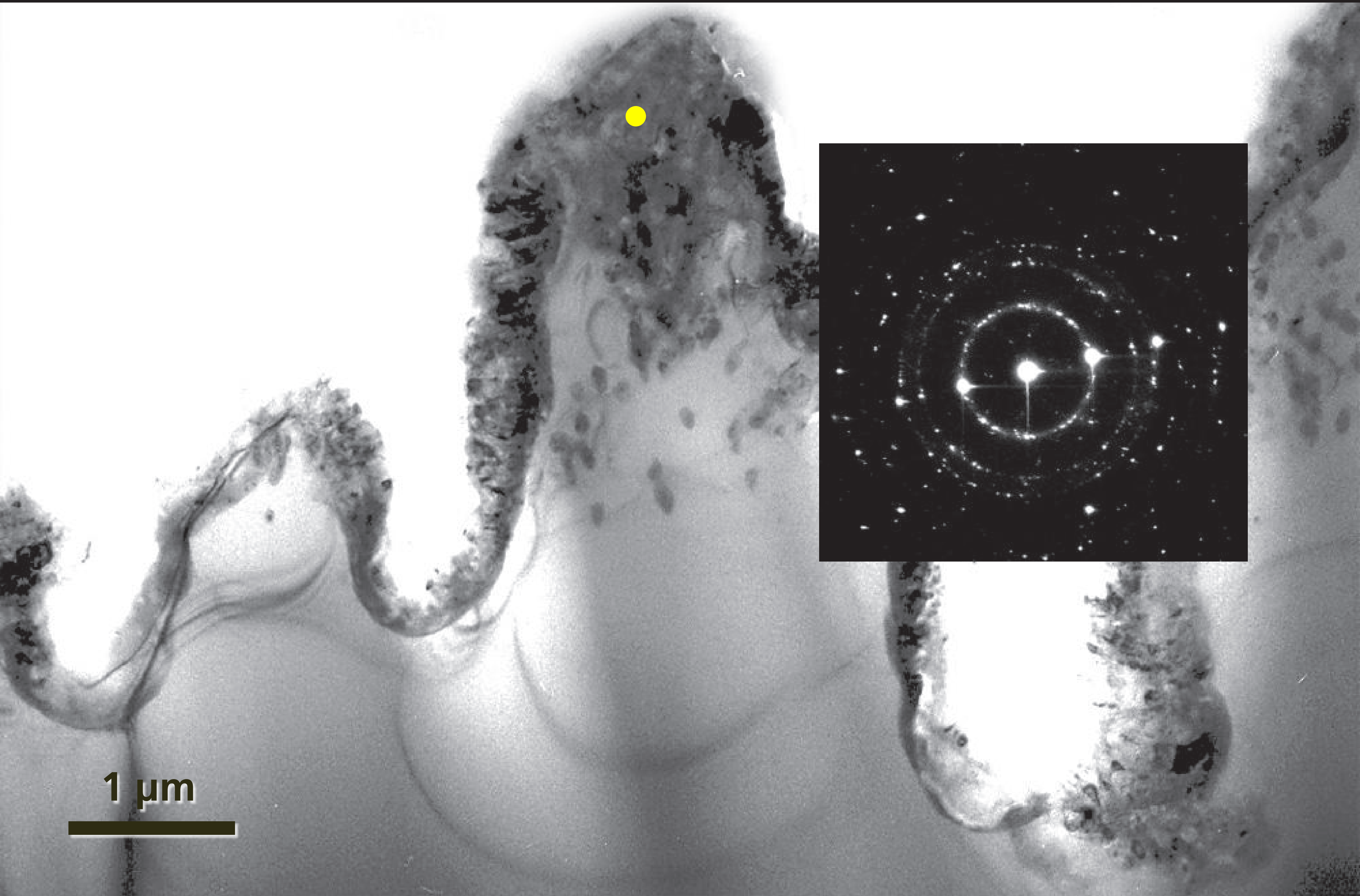
High photon flux doping



High photon flux doping

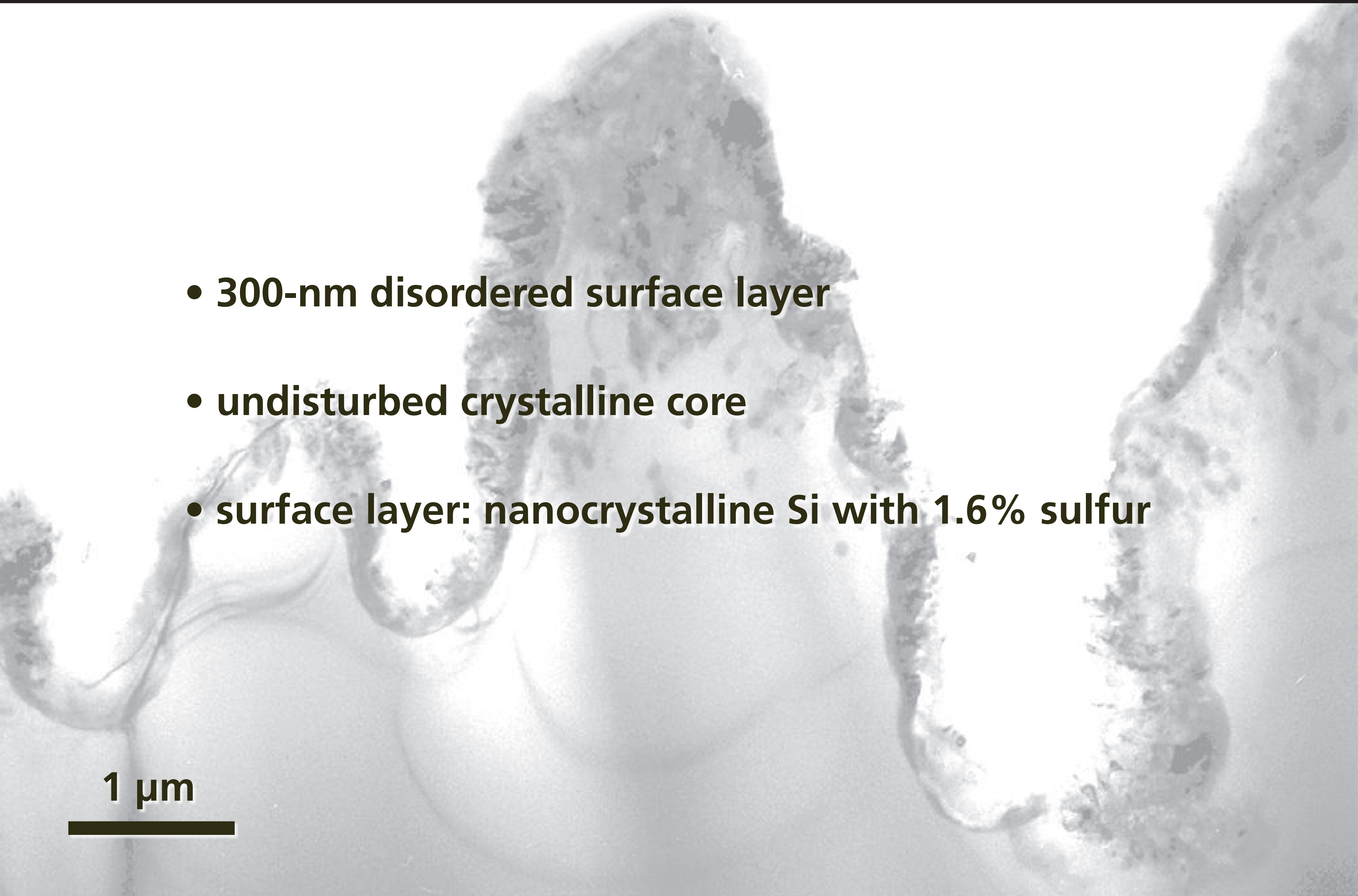


High photon flux doping



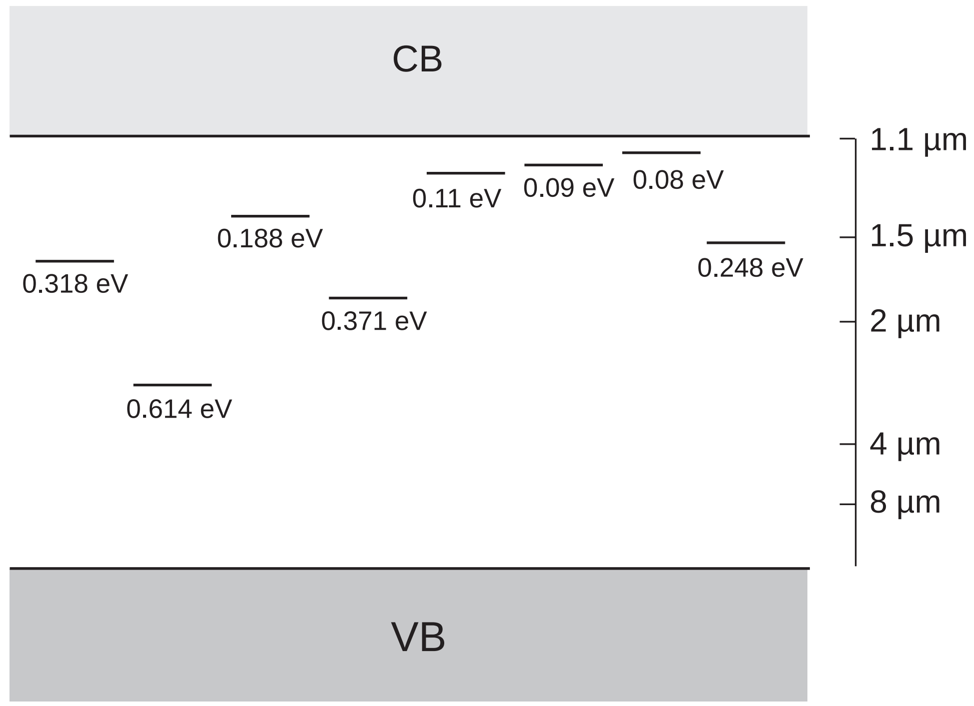
High photon flux doping

- 300-nm disordered surface layer
- undisturbed crystalline core
- surface layer: nanocrystalline Si with 1.6% sulfur



High photon flux doping

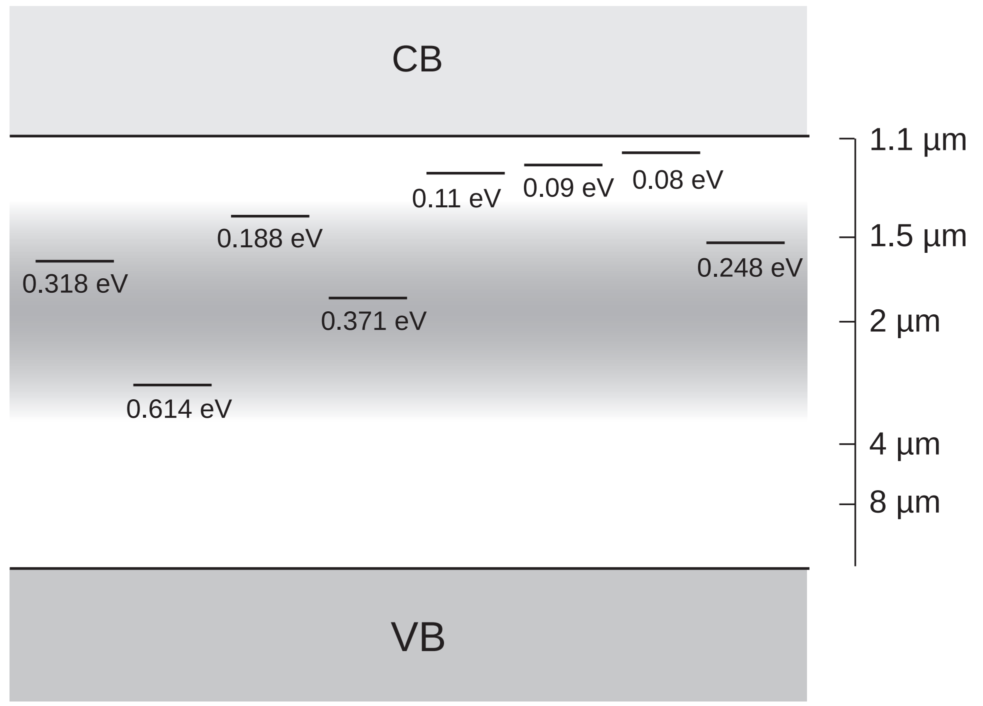
1 part in 10^6 sulfur introduces states in gap



Janzén *et al.*, Phys. Rev. B 29, 1907 (1984)

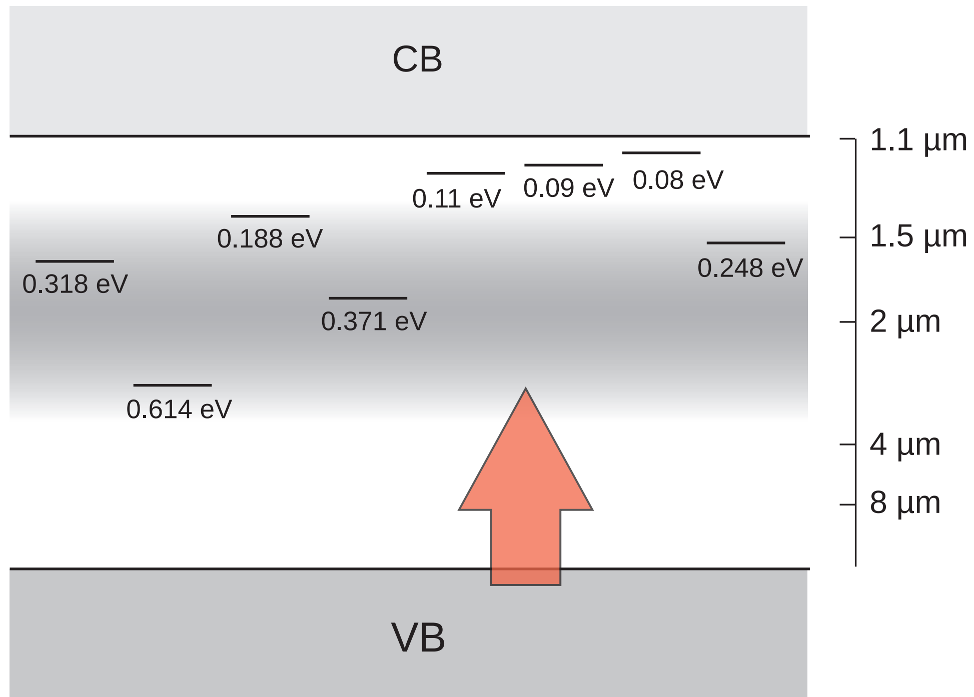
High photon flux doping

at high concentration states broaden into band



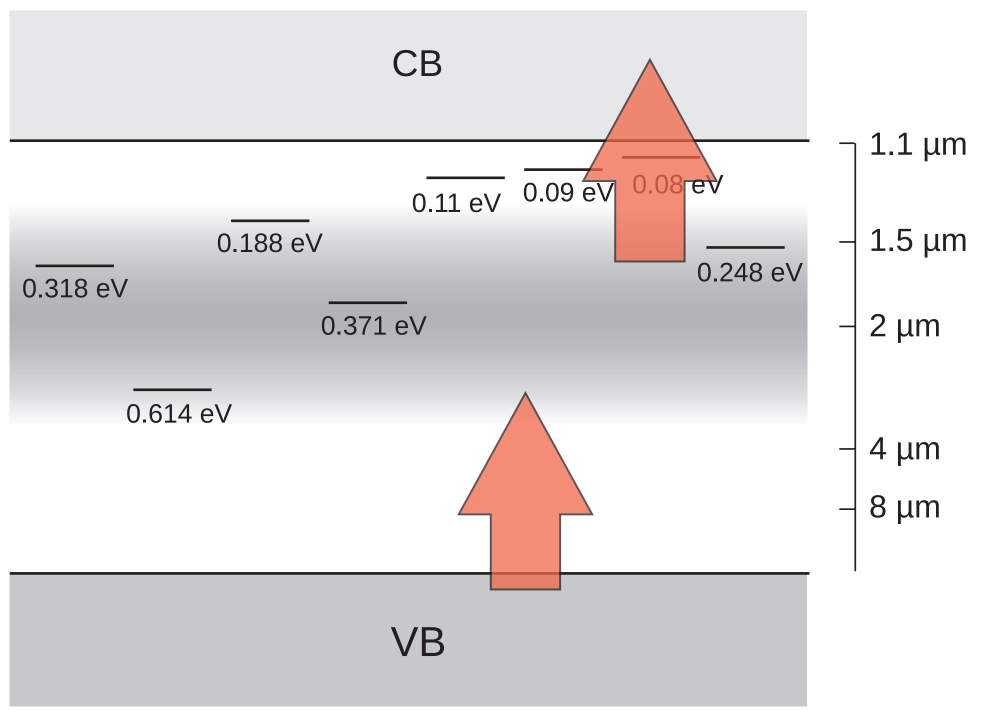
High photon flux doping

absorption extends into infrared



High photon flux doping

donor or acceptor states, depending on Fermi level



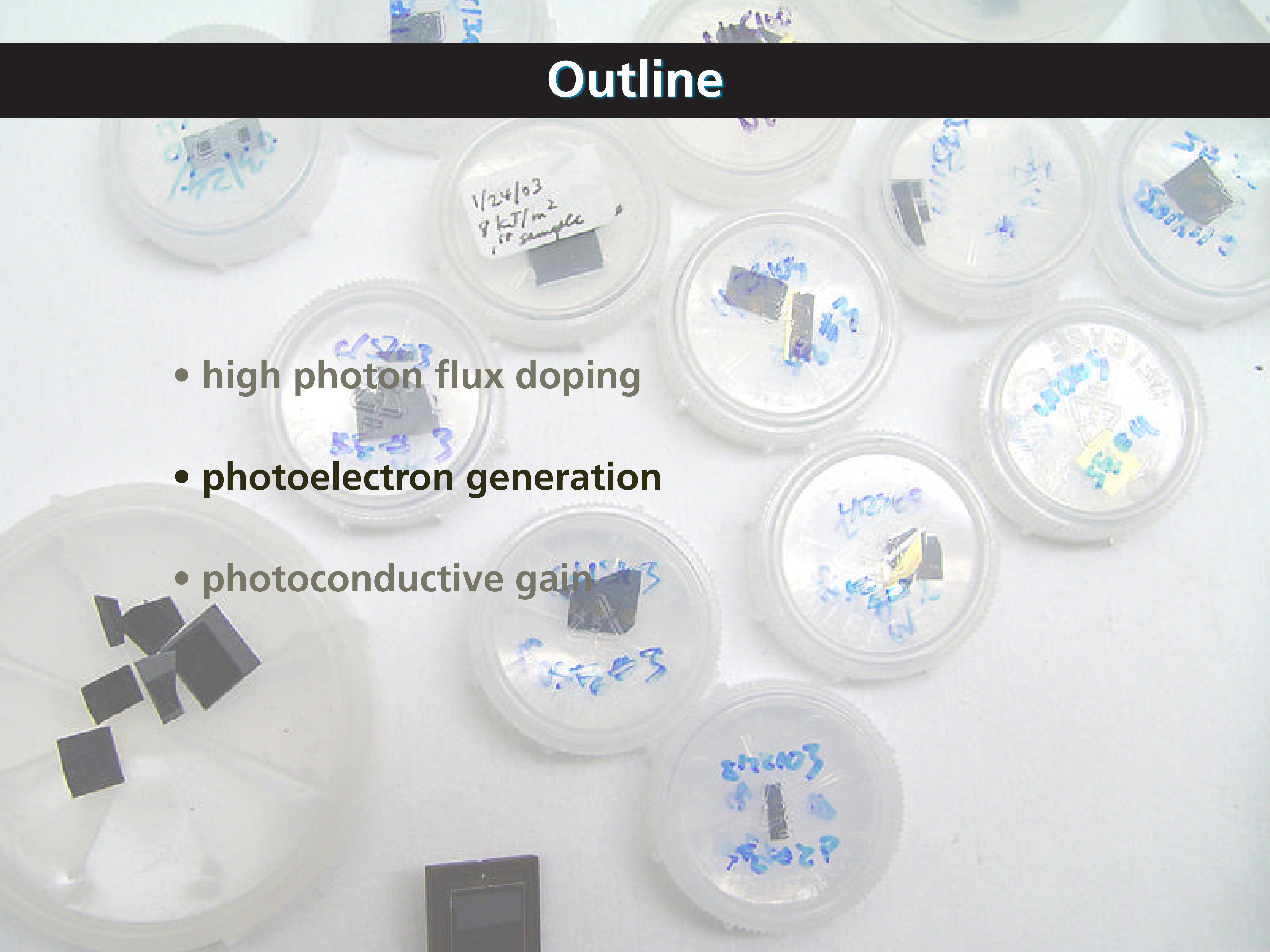
High photon flux doping

Things to keep in mind

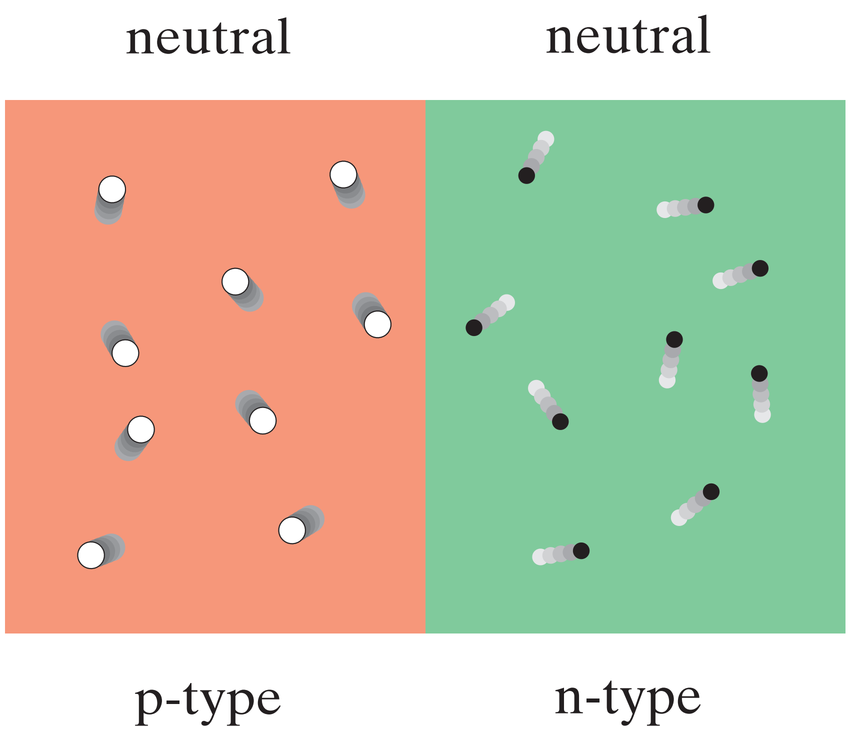
- new chemical structure and electronic properties
- nanocrystallinity: quantum confinement effects
- absorption happens in nanocrystalline layer

Outline

- high photon flux doping
- **photoelectron generation**
- photoconductive gain

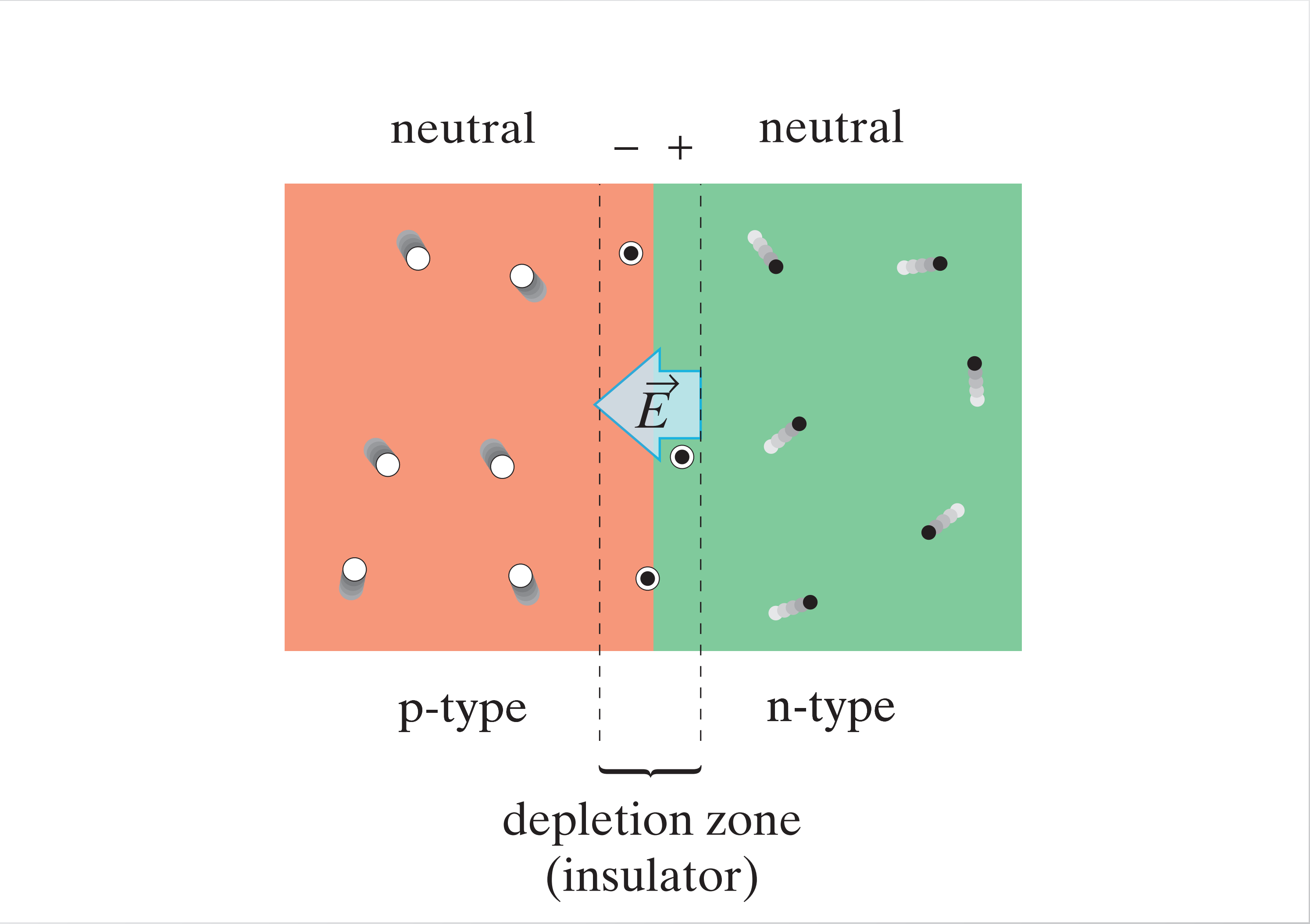


Photoelectron generation



join acceptor and donor type Si…

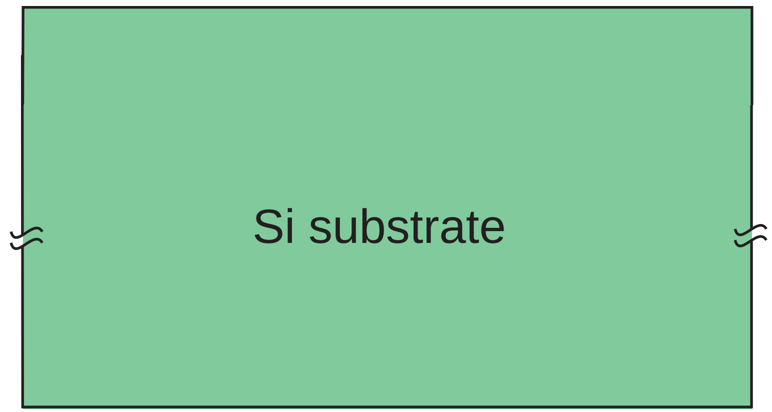
Photoelectron generation



non-conducting layer at junction

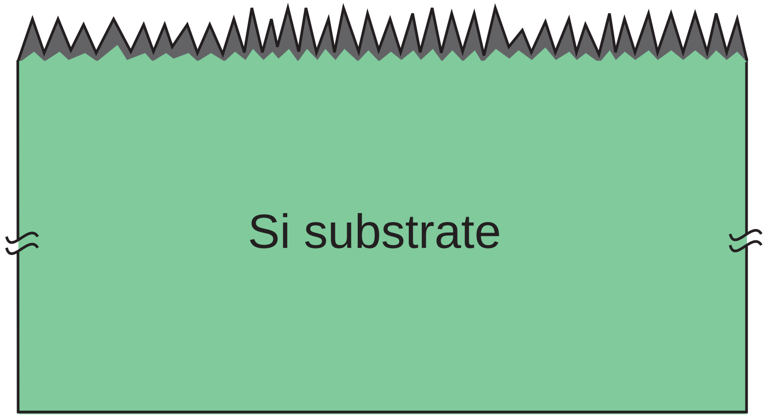
Photoelectron generation

black silicon/silicon junction



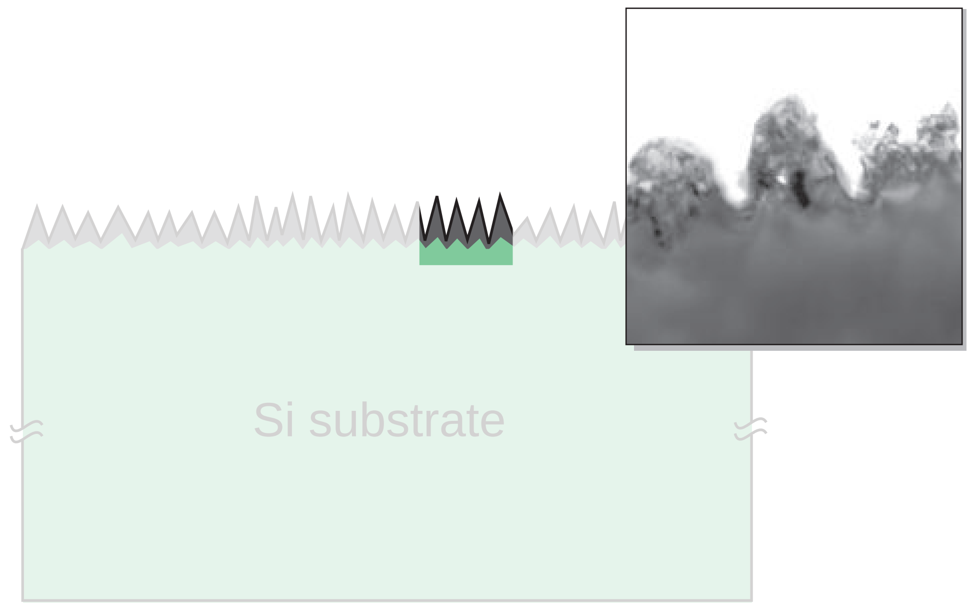
Photoelectron generation

black silicon/silicon junction



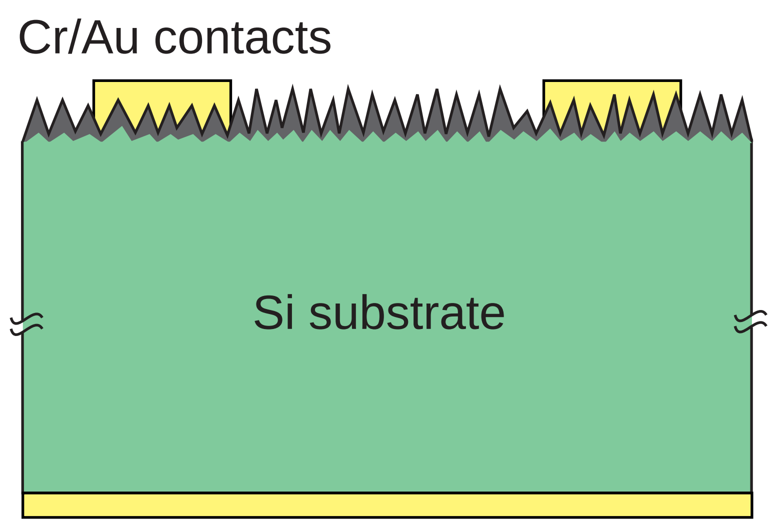
Photoelectron generation

black silicon/silicon junction



Photoelectron generation

black silicon/silicon junction



Photoelectron generation

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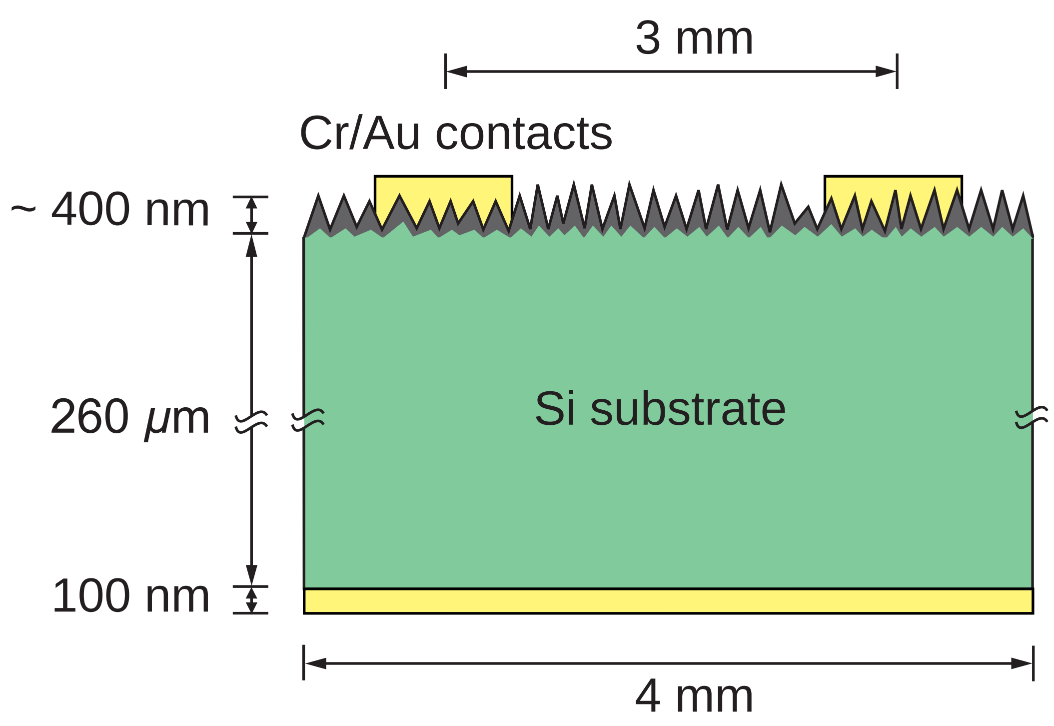
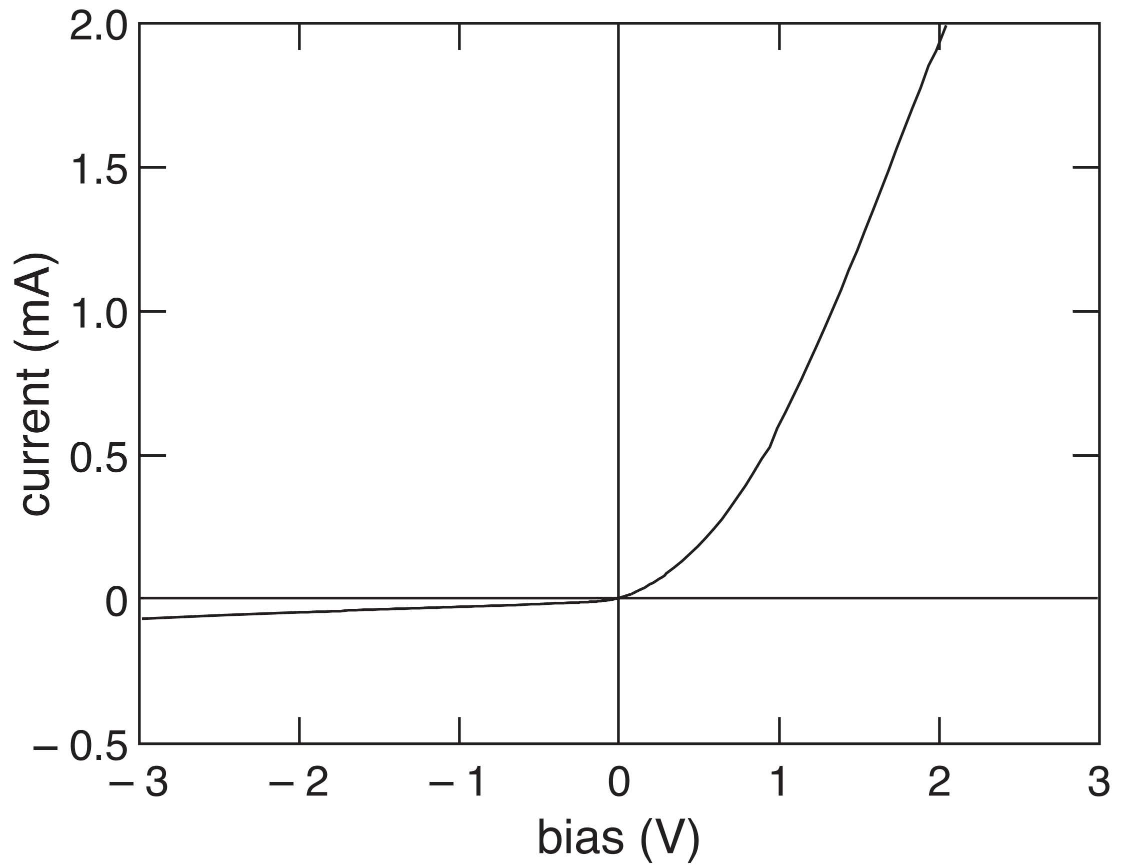
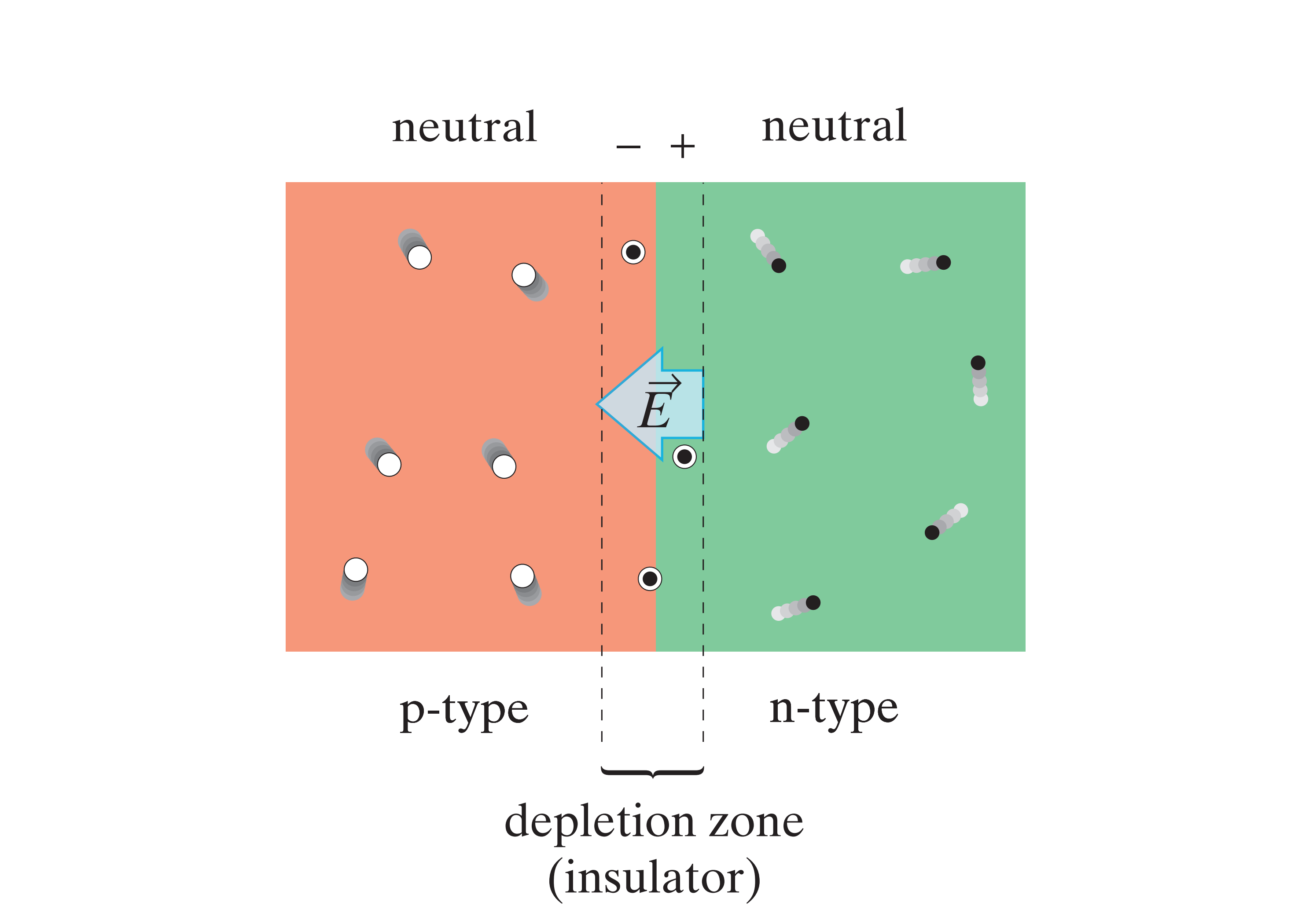


Photoelectron generation

IV characteristics

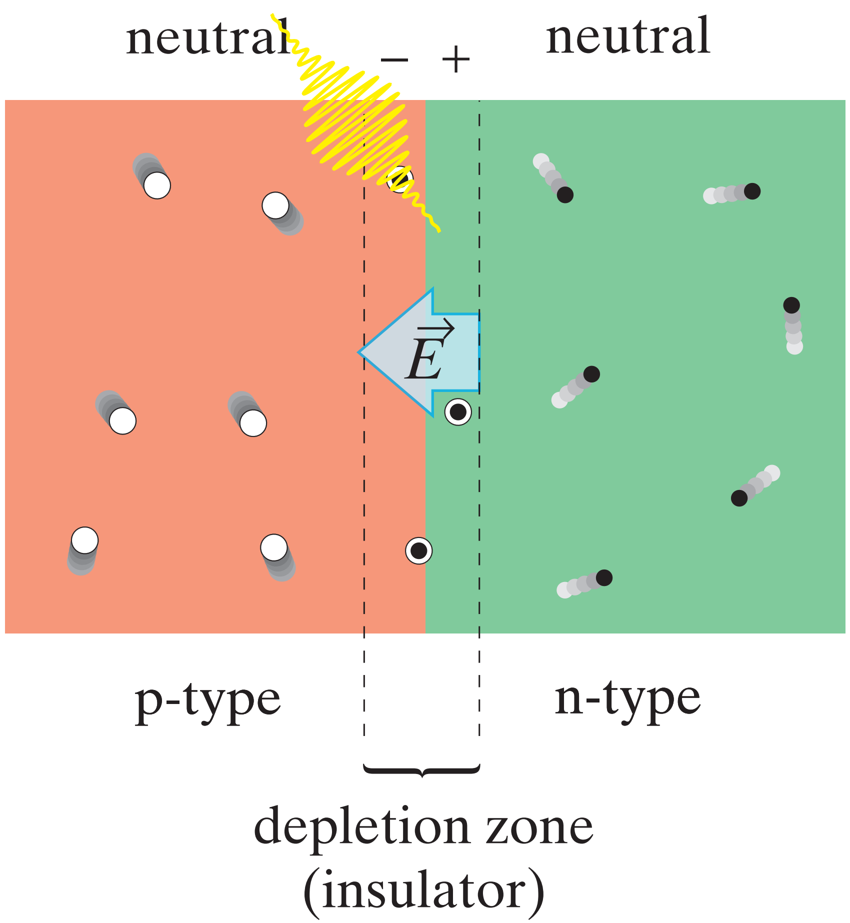


Photoelectron generation



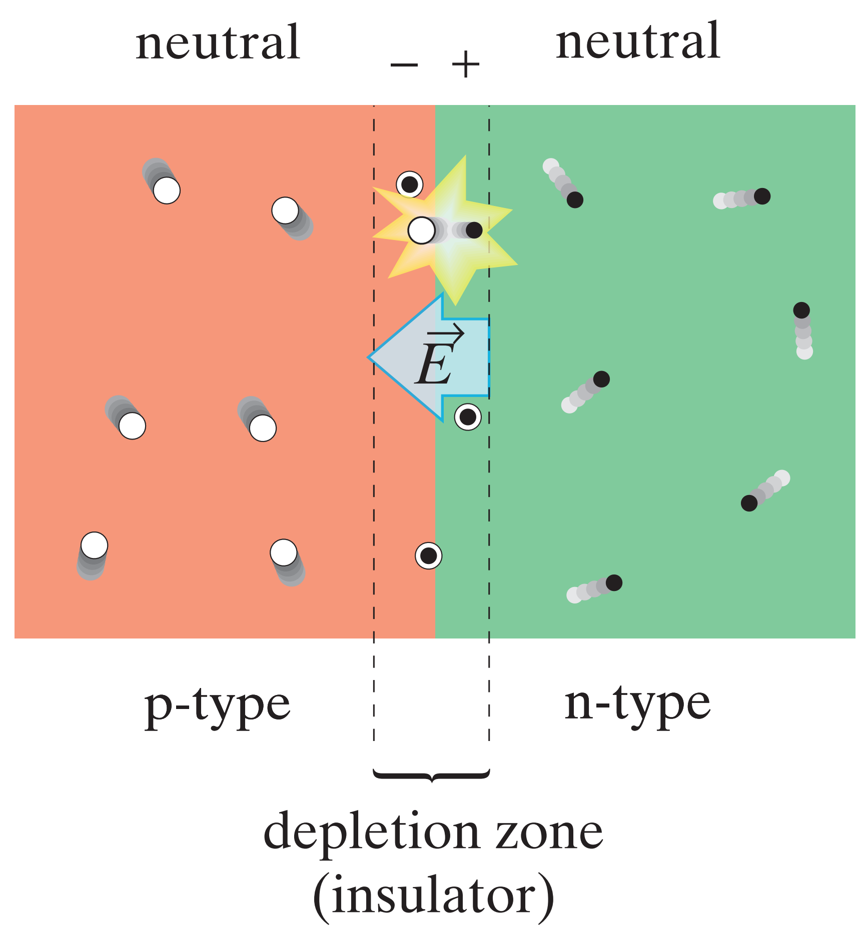
depletion layer can convert light into electric energy

Photoelectron generation



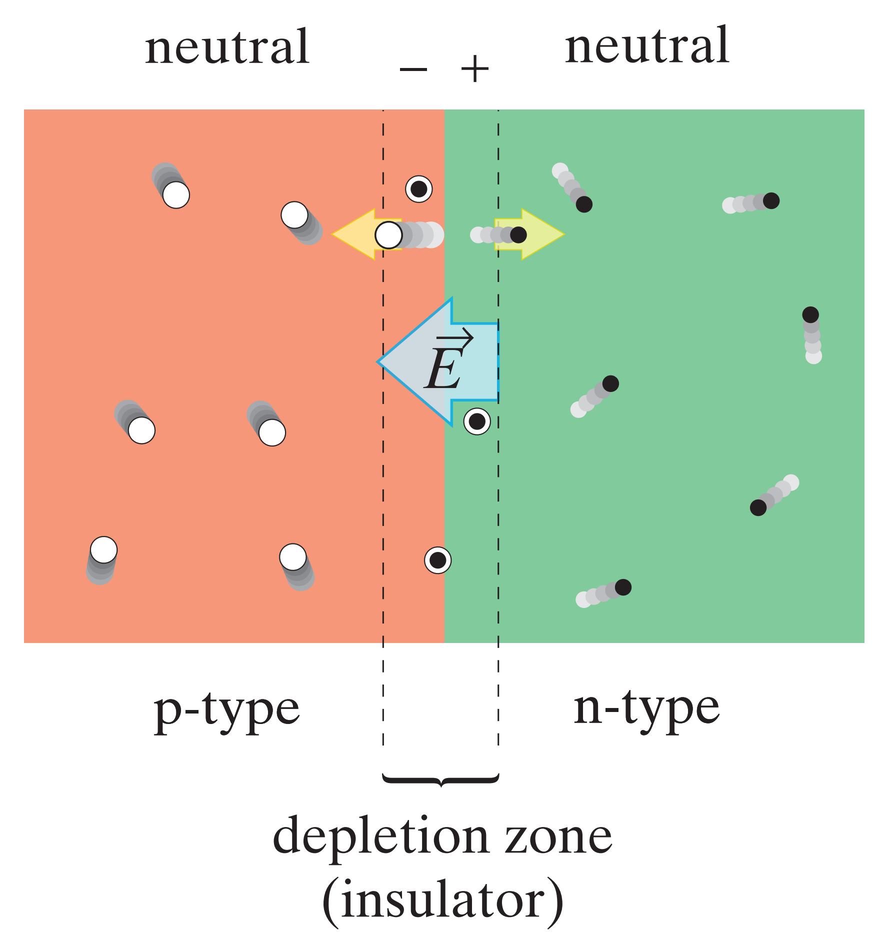
incident photon knocks out electron…

Photoelectron generation



…creating an electron-hole pair

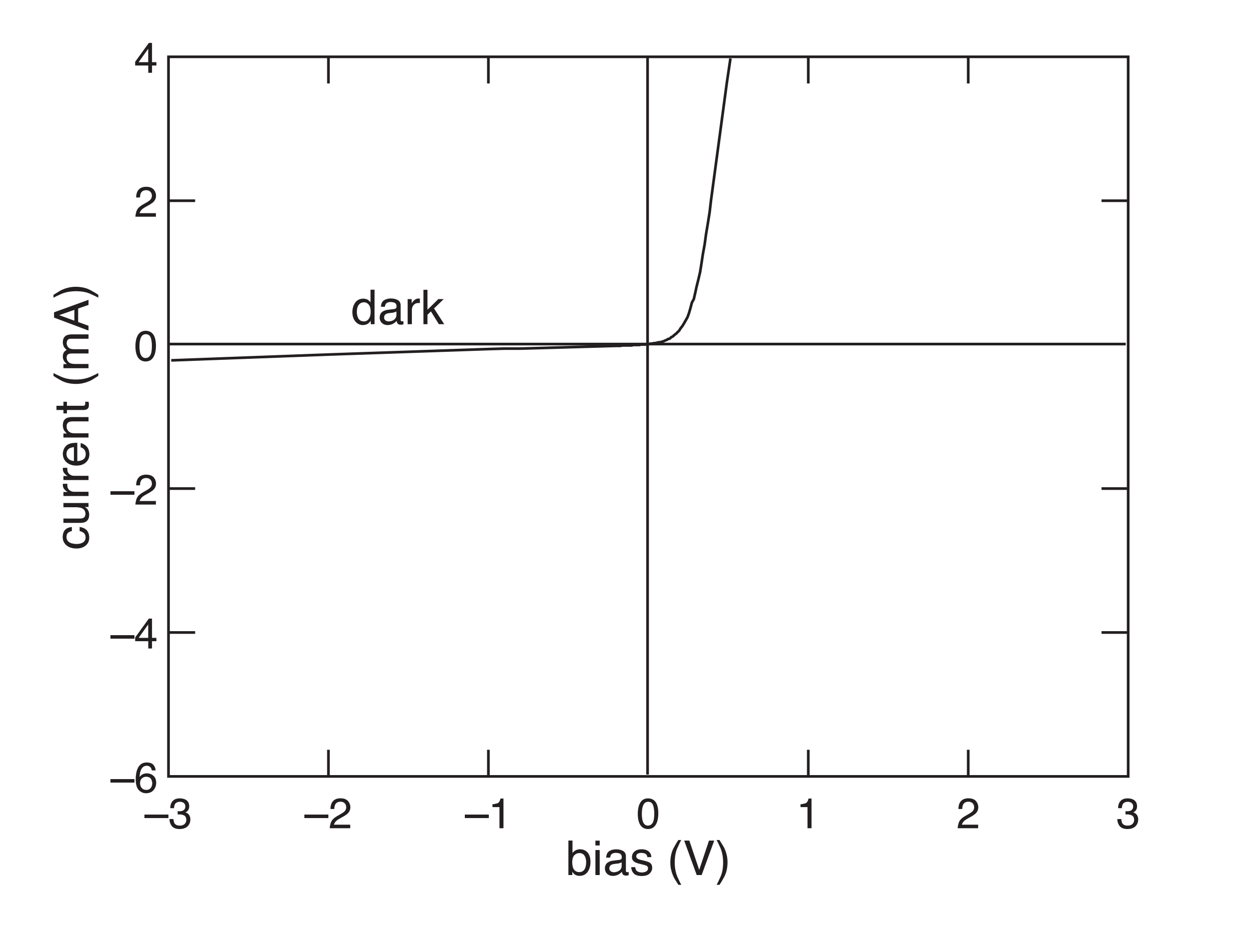
Photoelectron generation



E-field separates eh-pair, causing current

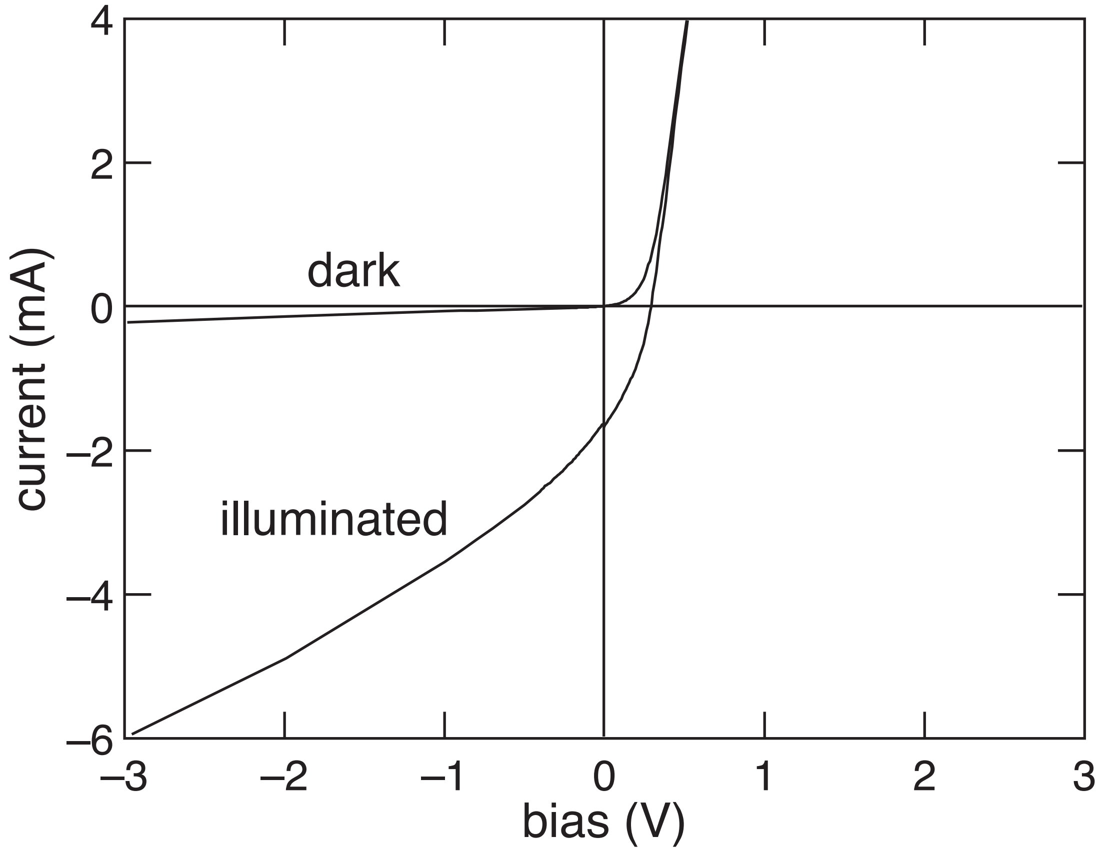
Photoelectron generation

IV characteristics



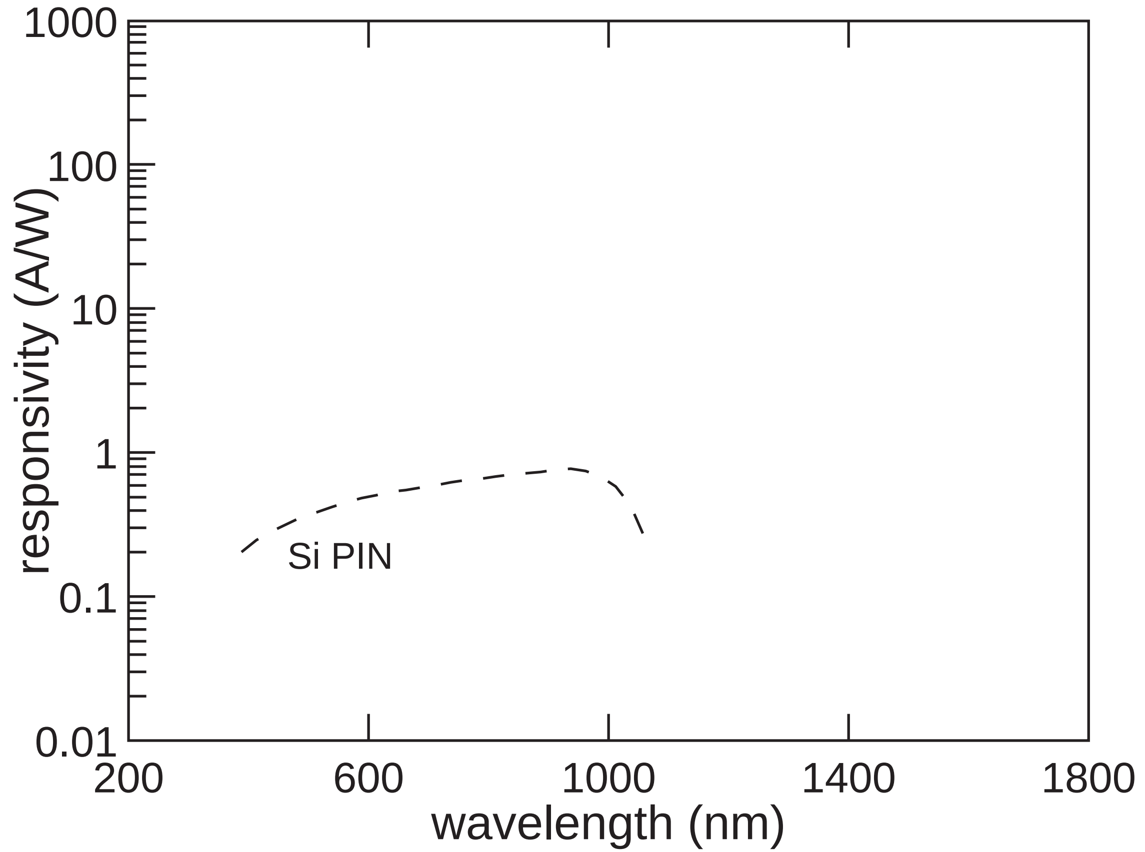
Photoelectron generation

IV characteristics



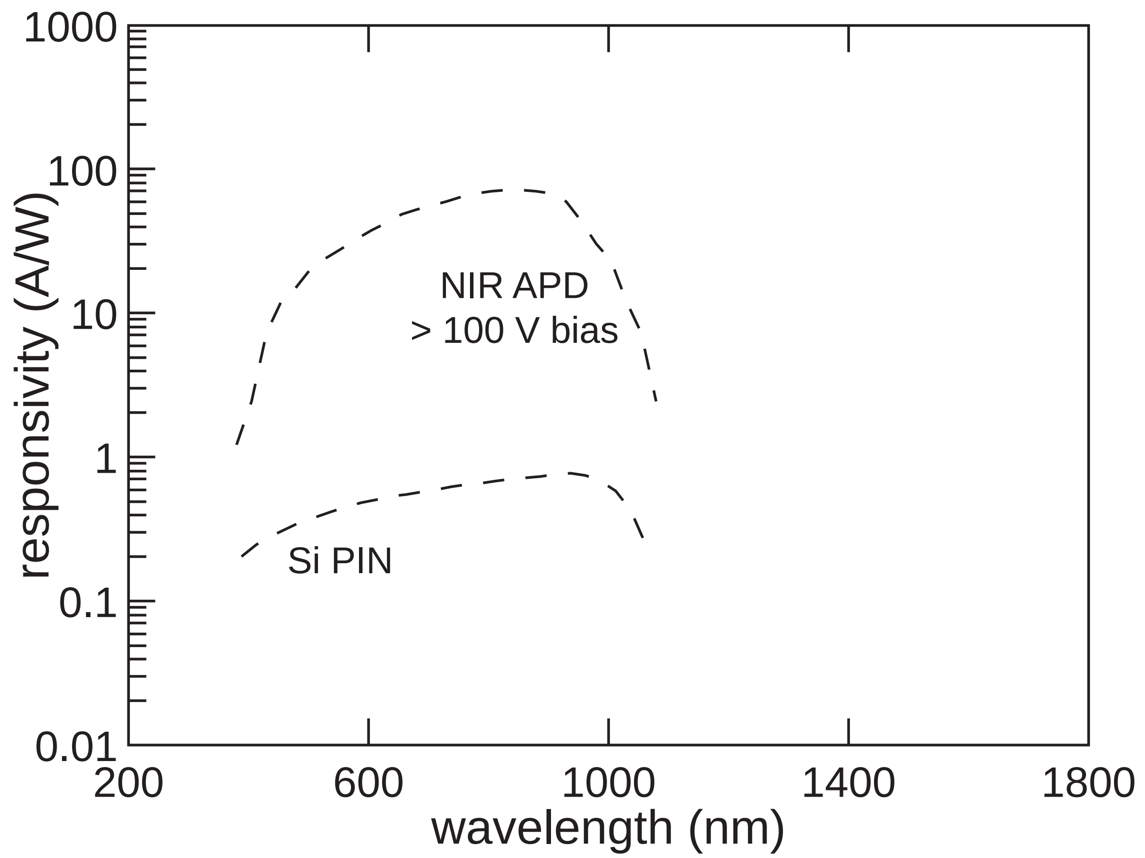
Photoelectron generation

responsivity



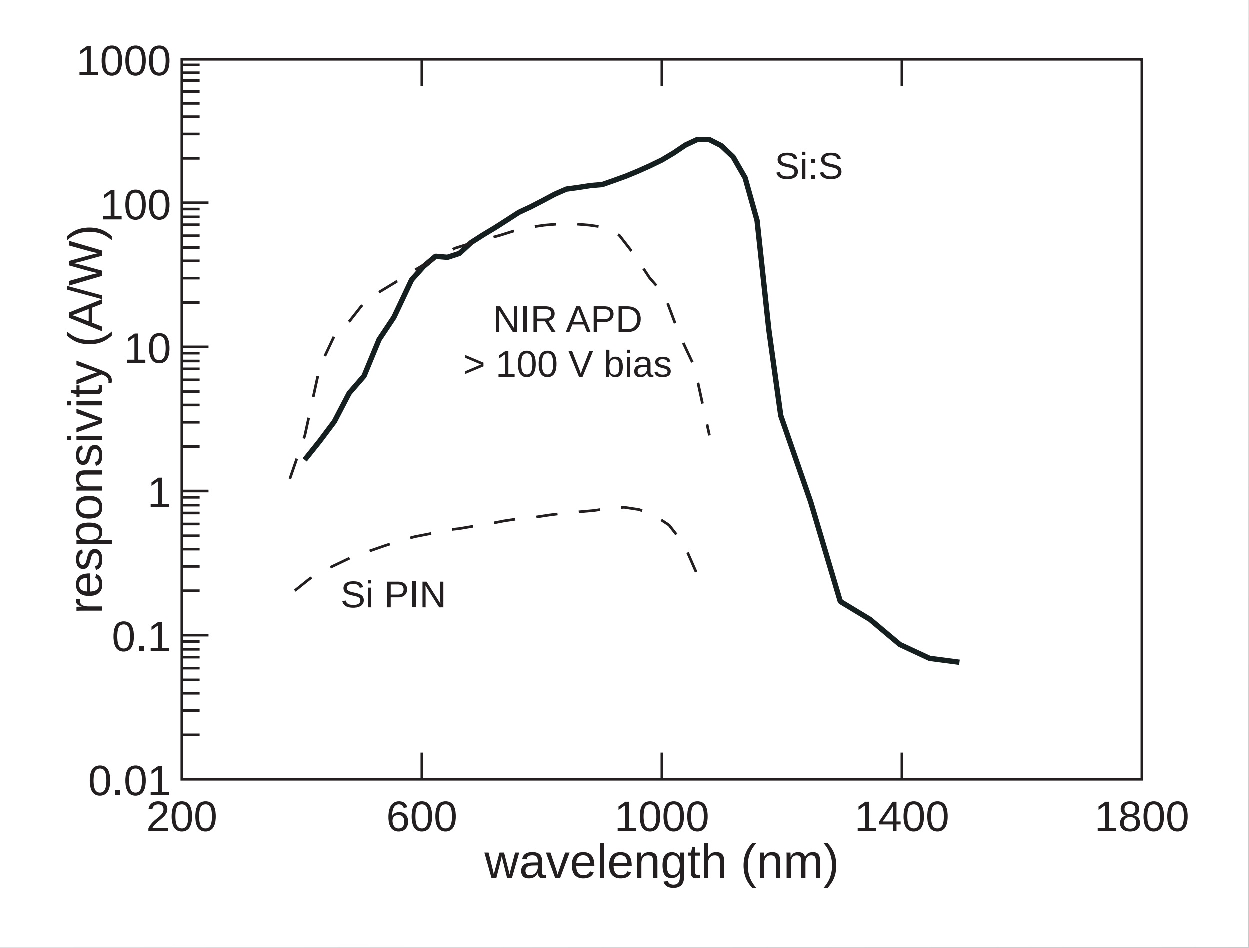
Photoelectron generation

responsivity



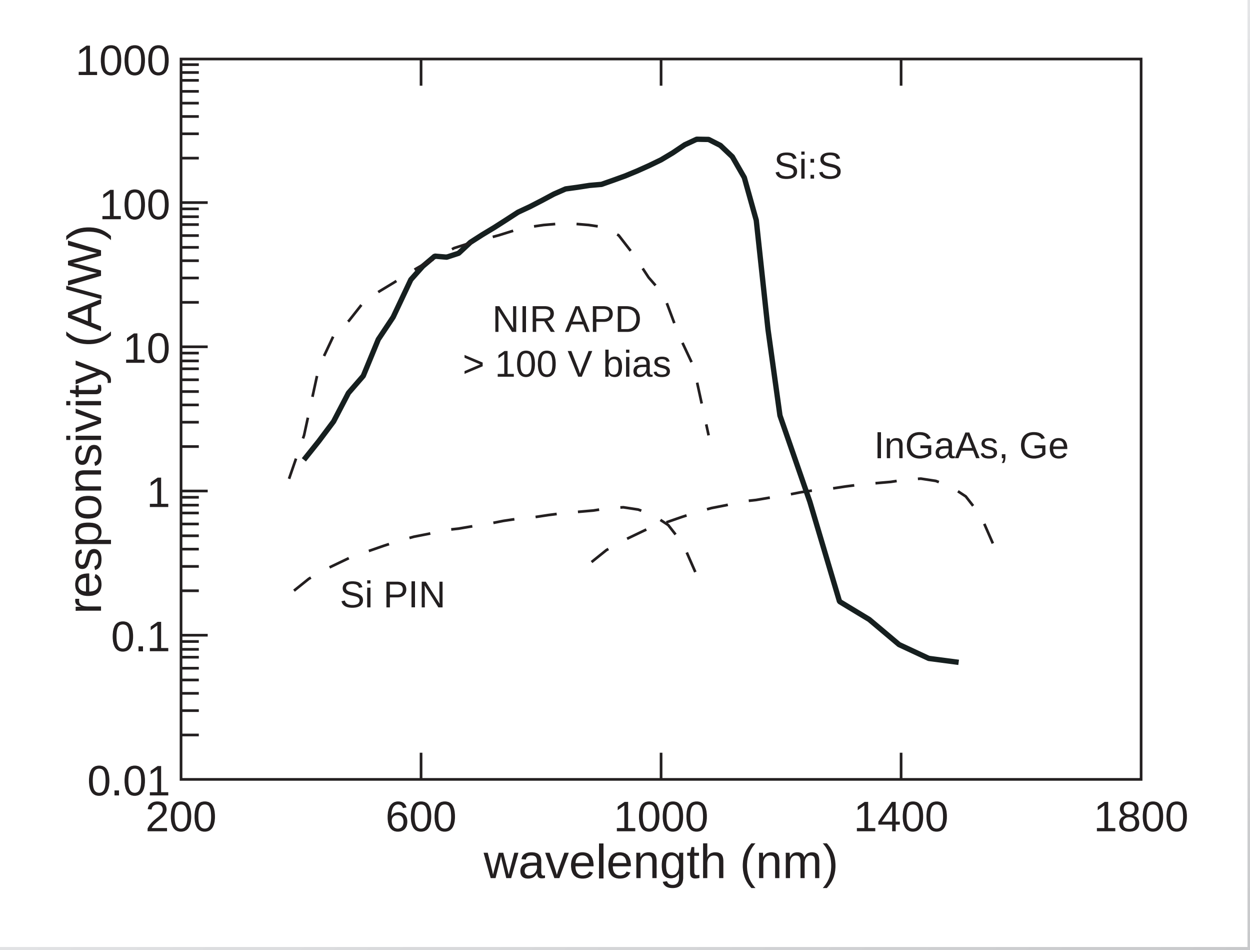
Photoelectron generation

responsivity



Photoelectron generation

responsivity



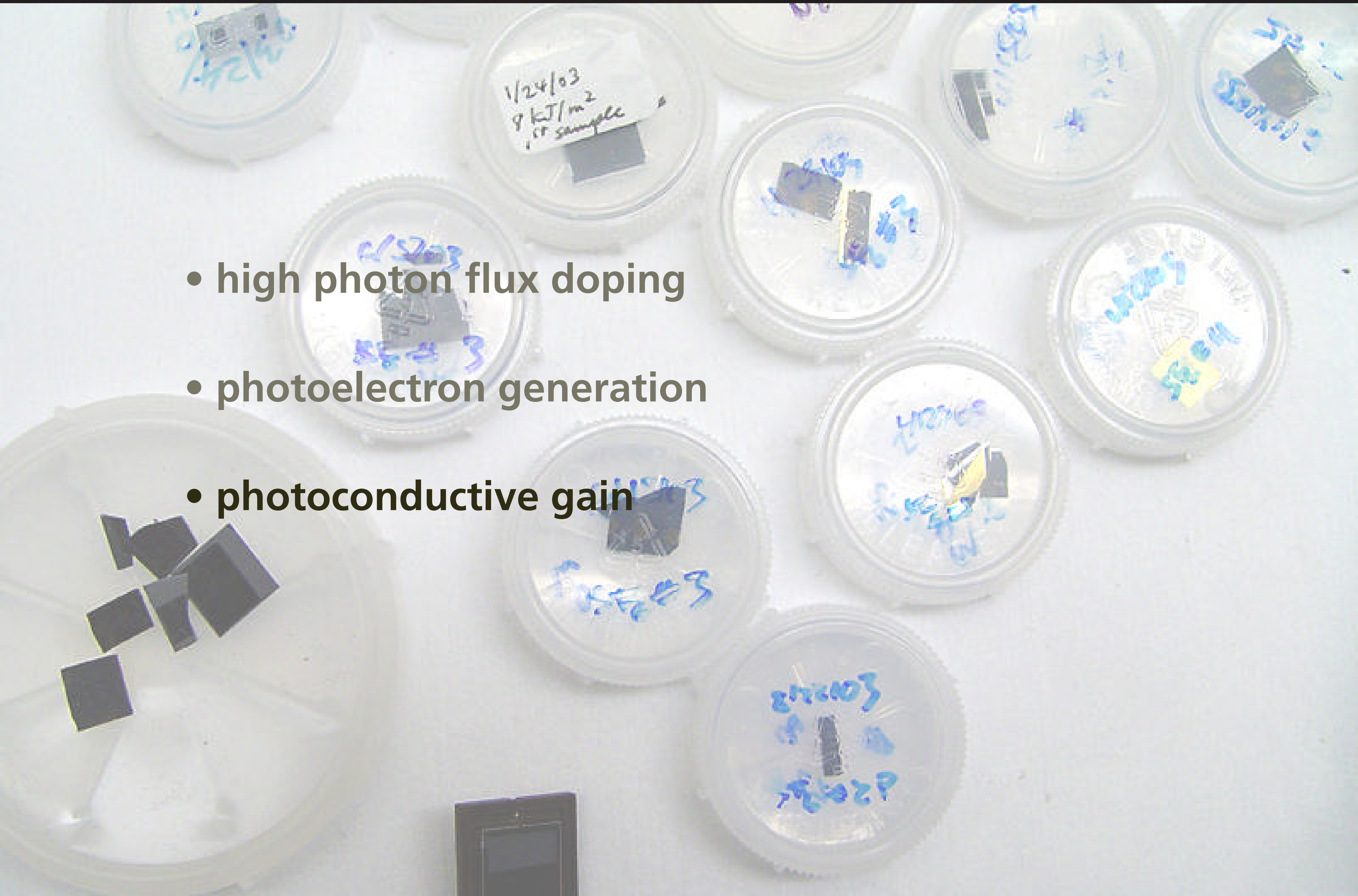
Photoelectron generation

Things to keep in mind

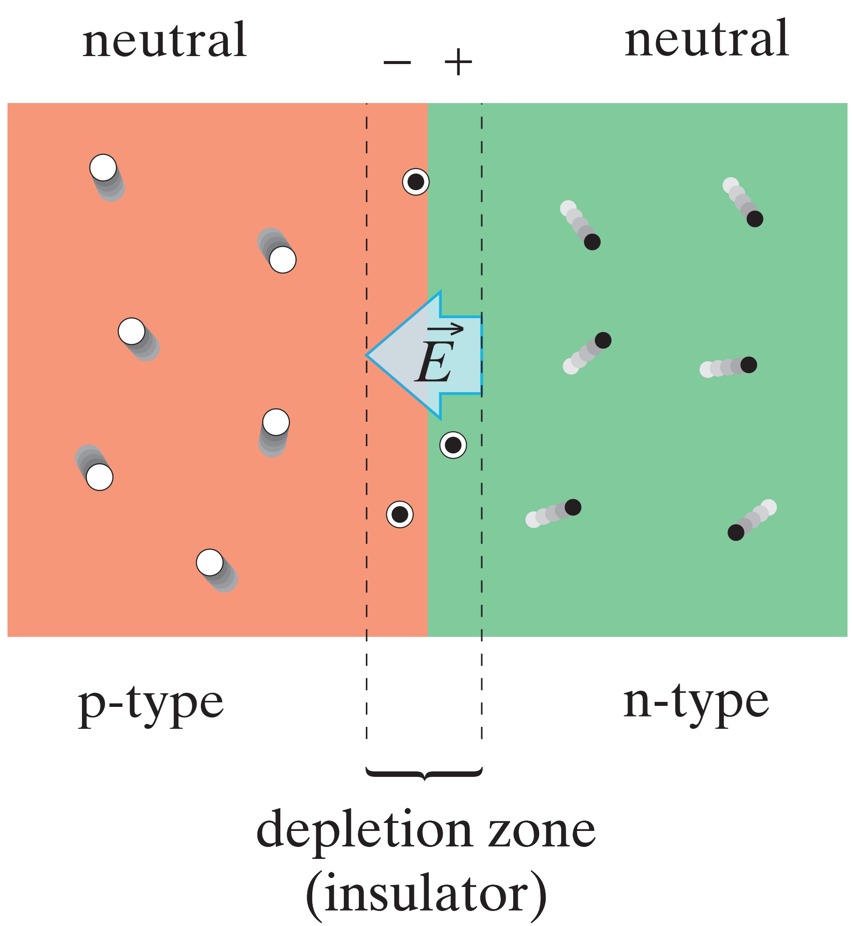
- can turn absorption into photoelectrons
- very high responsivity in VIS and IR
- quantum efficiency larger than one

Outline

- high photon flux doping
- photoelectron generation
- **photoconductive gain**

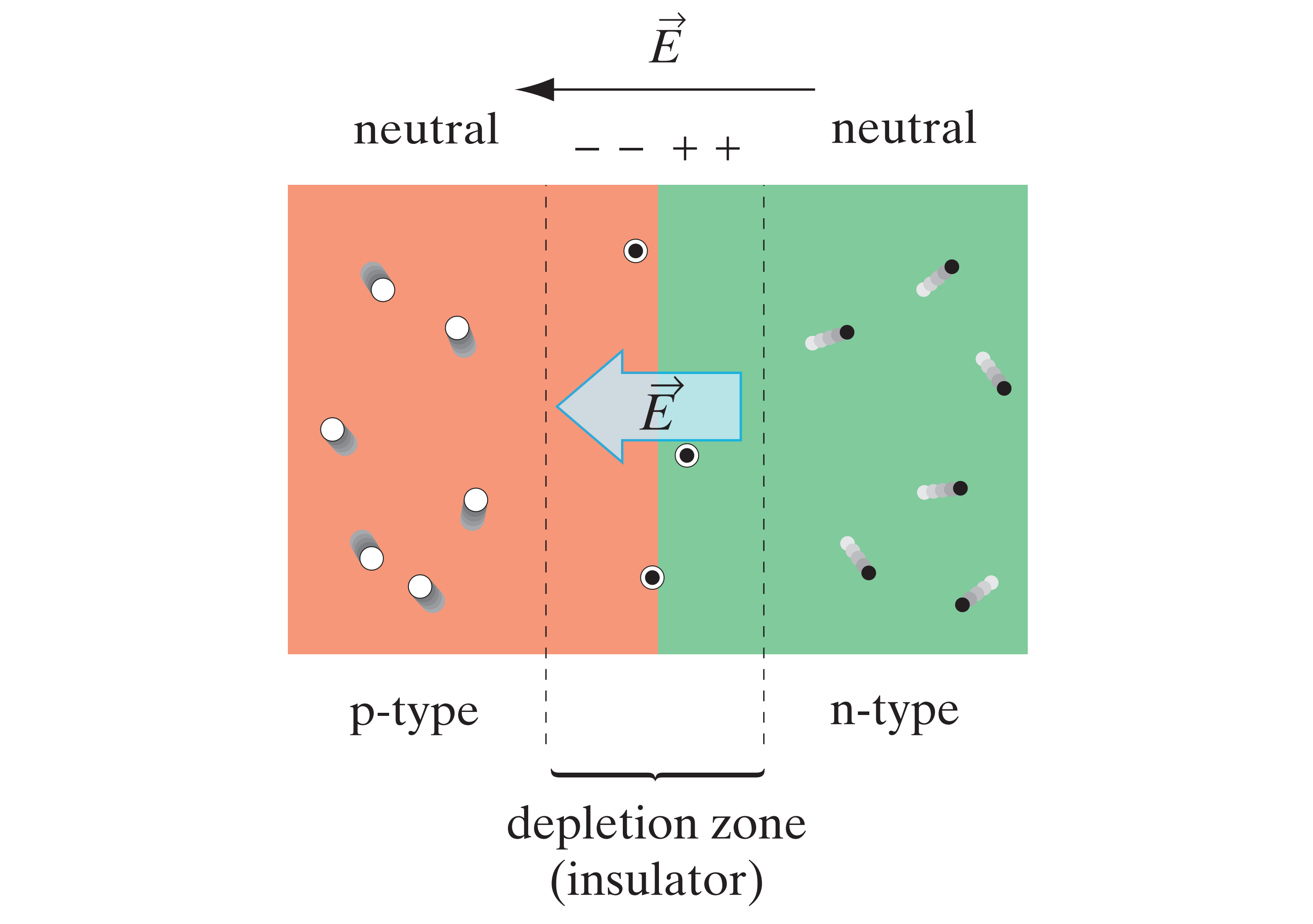


Photoconductive gain



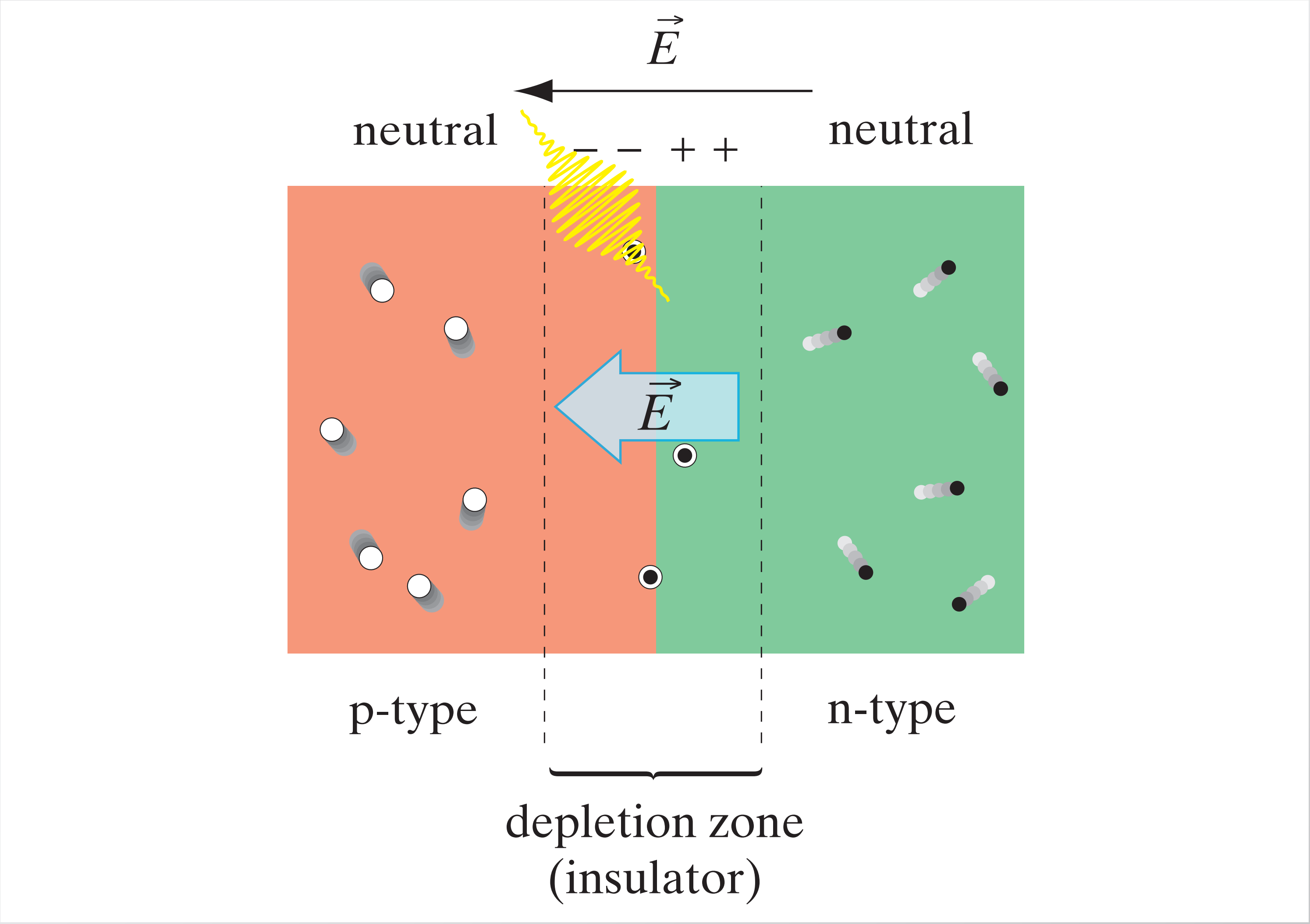
apply electric field…

Photoconductive gain



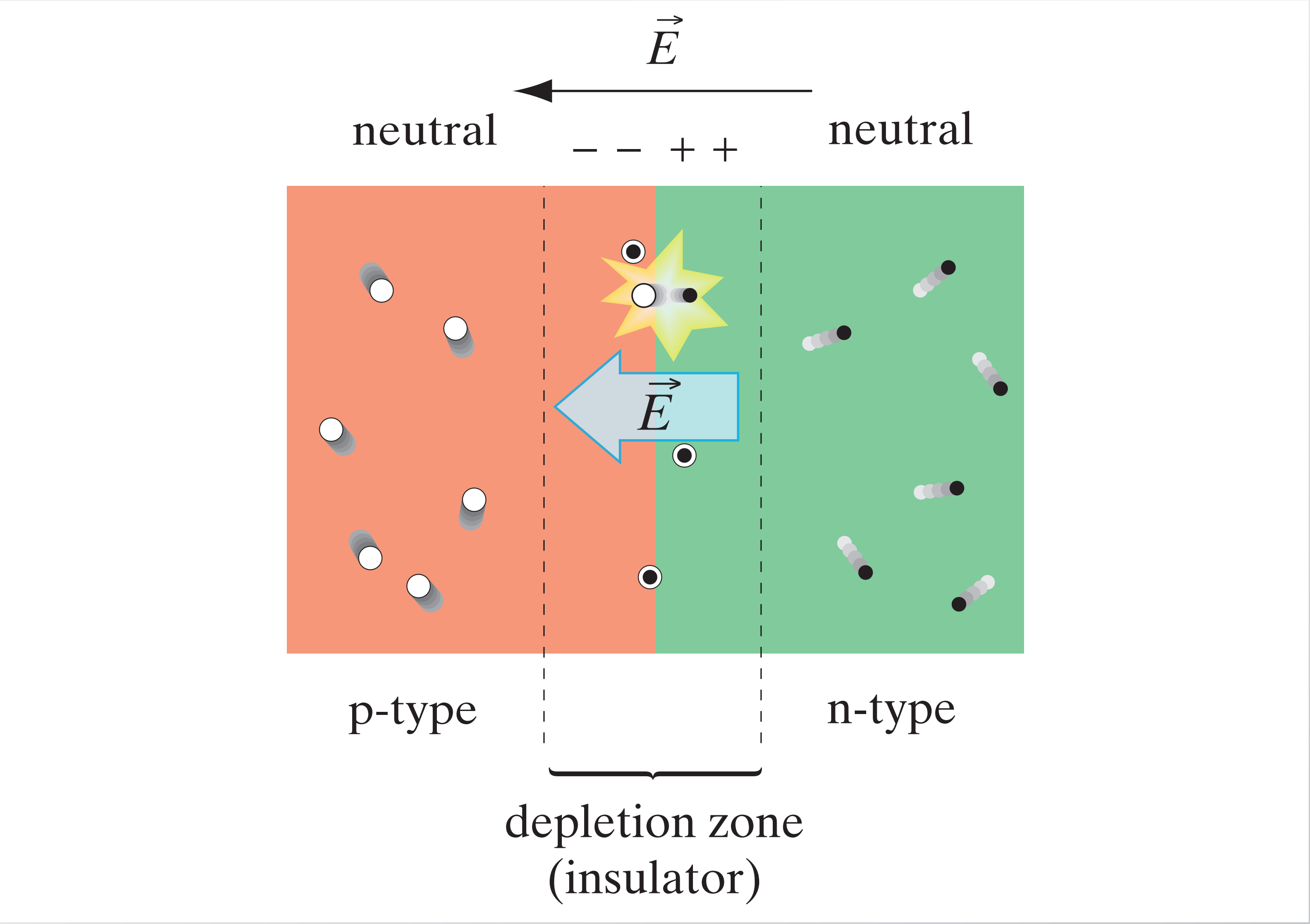
…and so depletion zone expands

Photoconductive gain



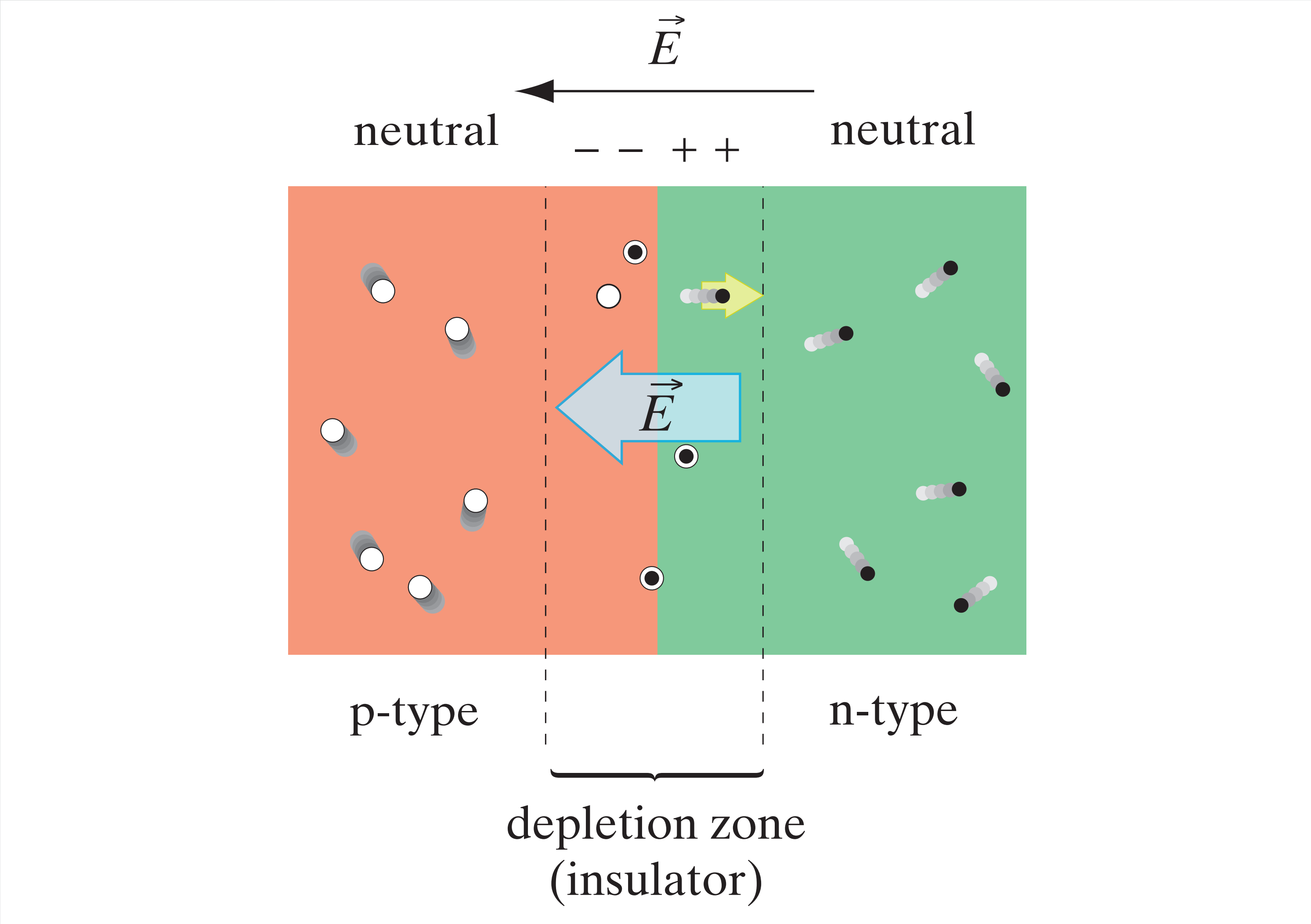
incident photon generates electron-hole pair

Photoconductive gain



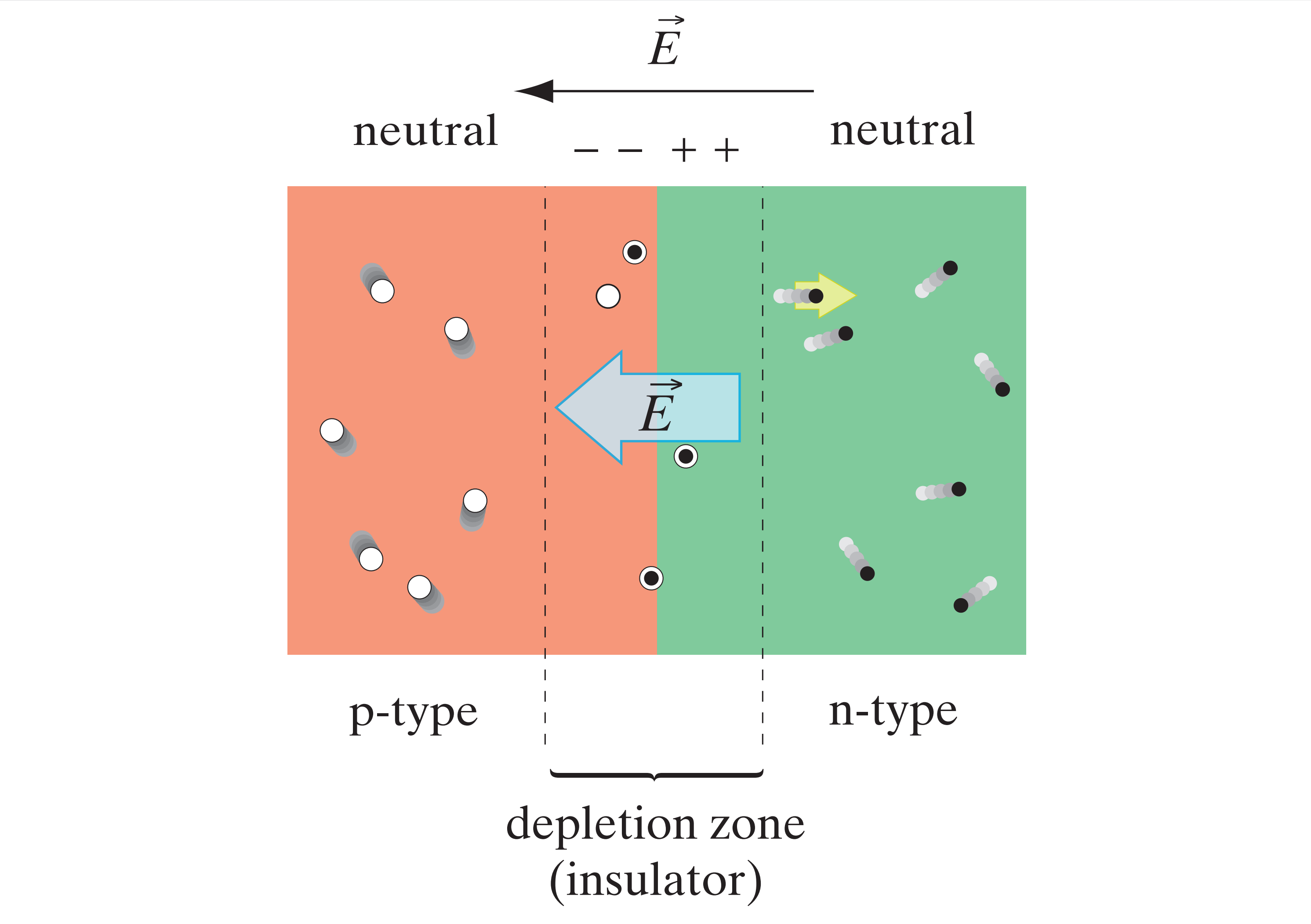
incident photon generates electron-hole pair

Photoconductive gain



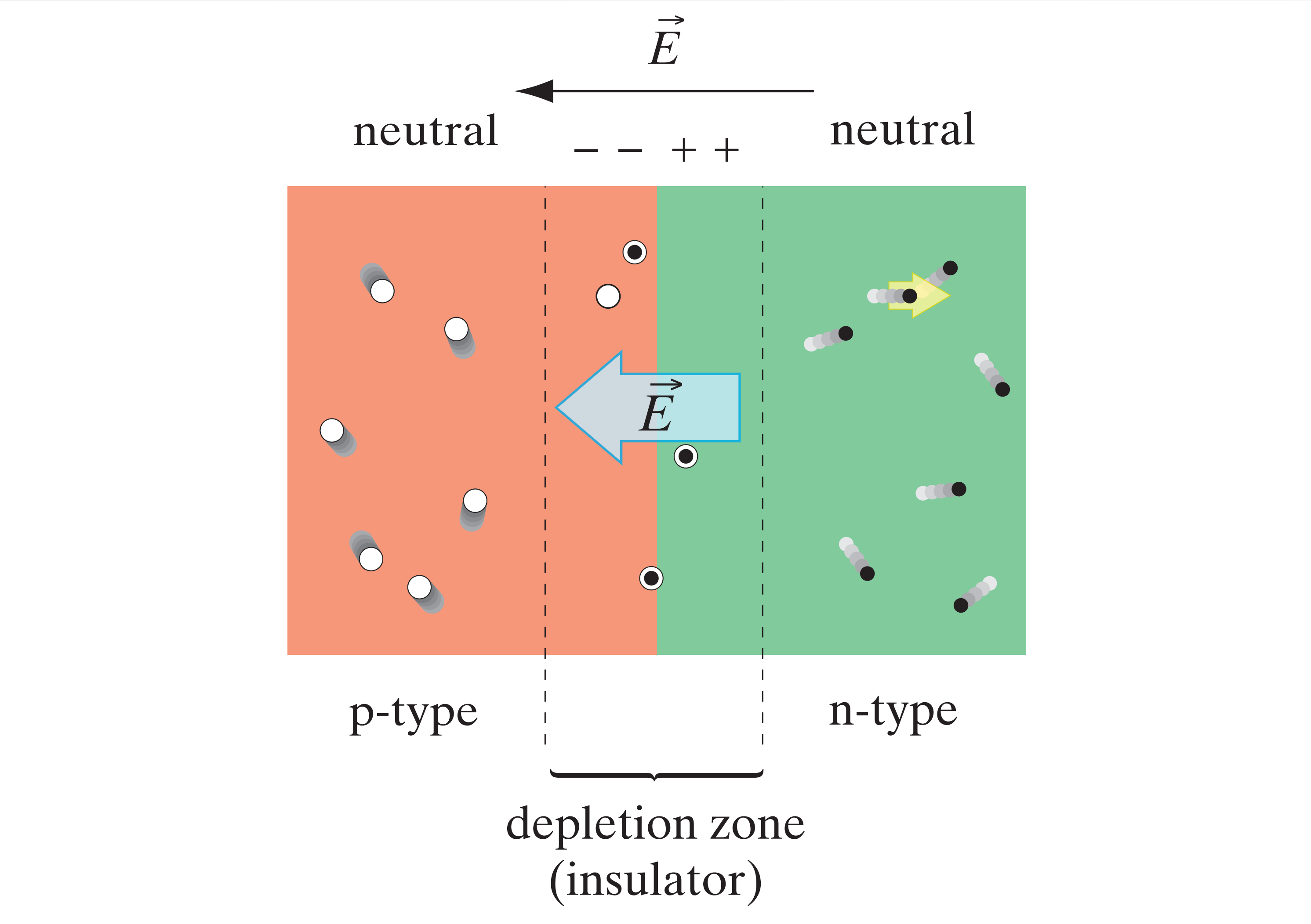
hole is trapped, electron accelerates…

Photoconductive gain



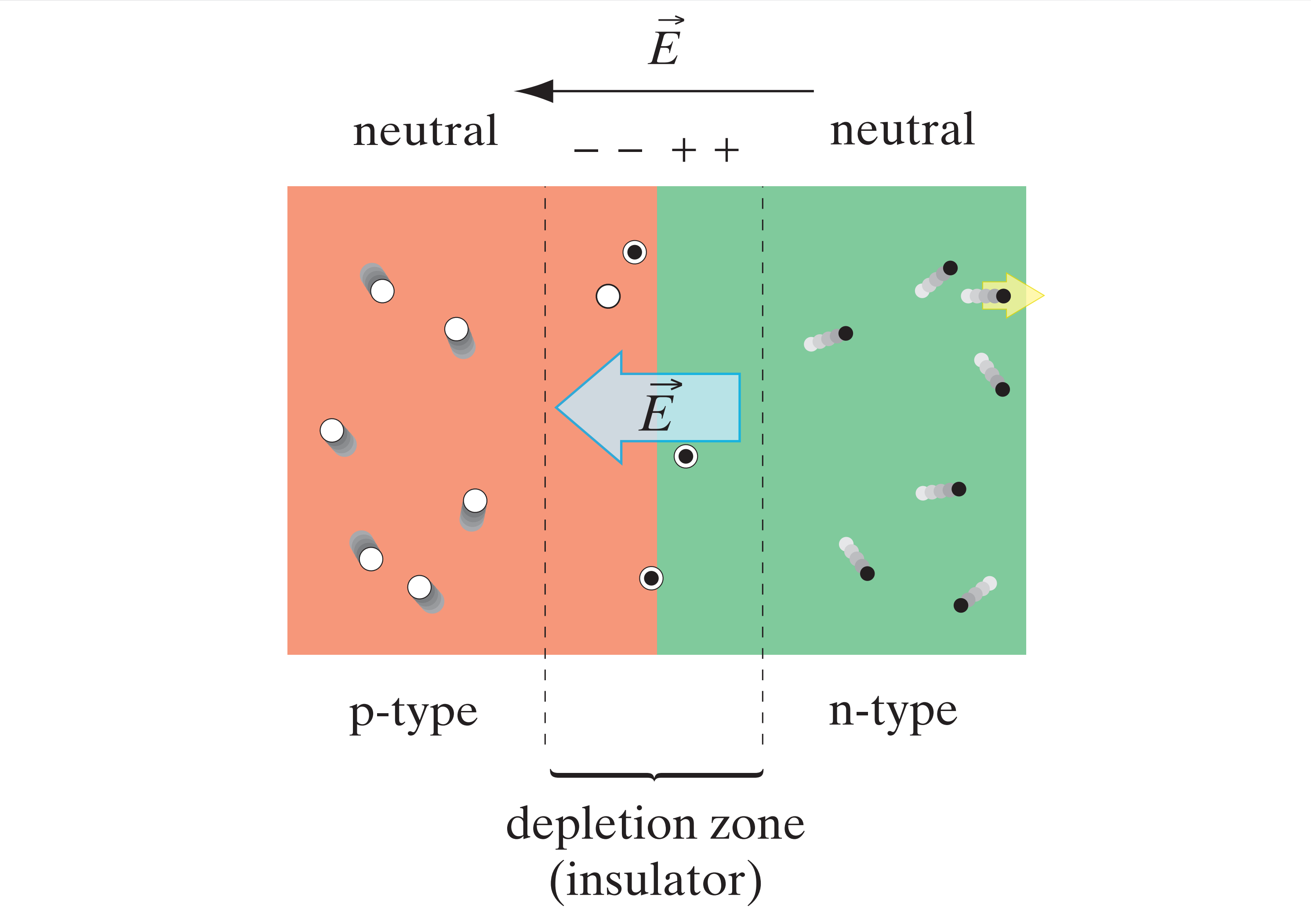
hole is trapped, electron accelerates…

Photoconductive gain



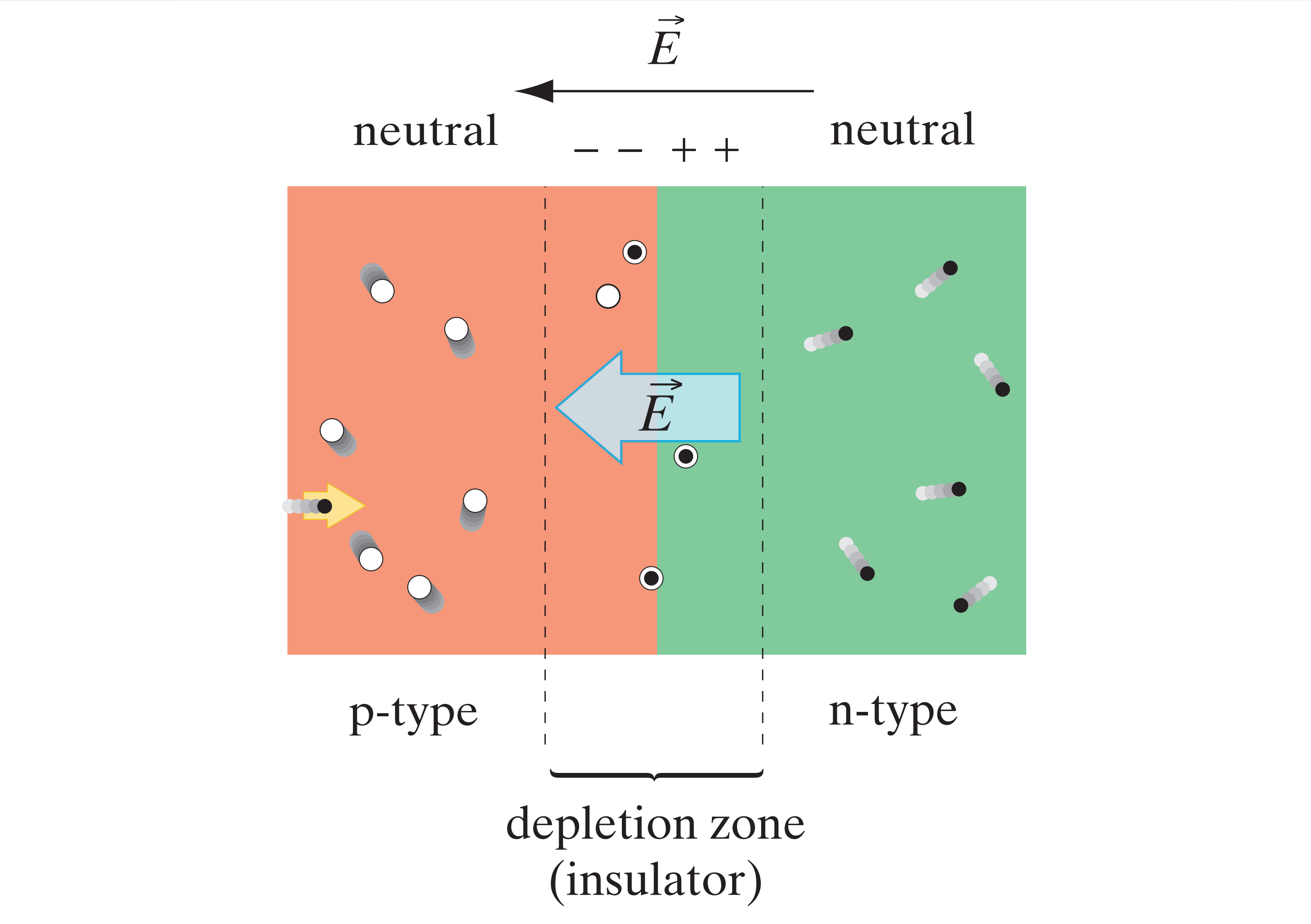
hole is trapped, electron accelerates…

Photoconductive gain



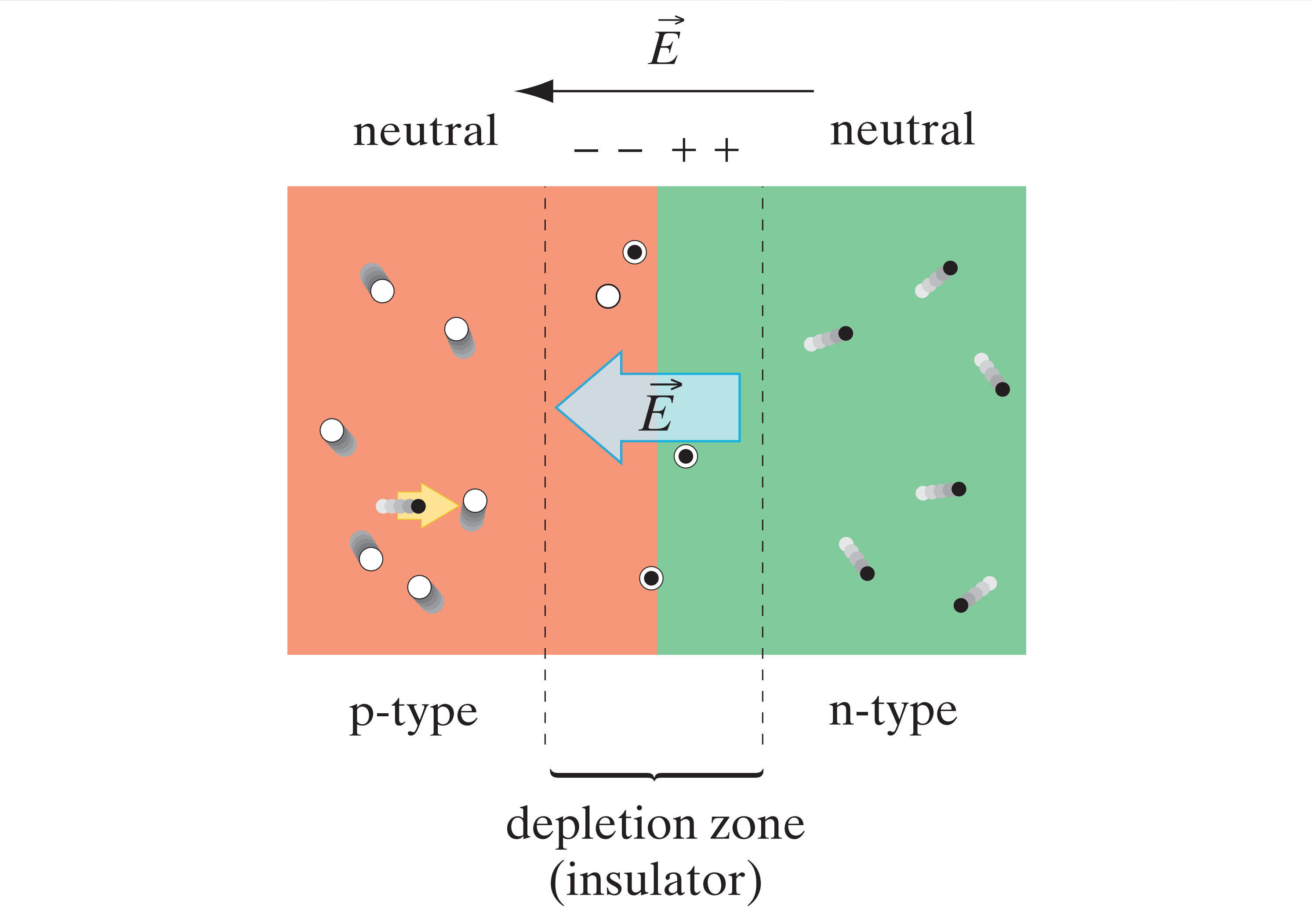
…exits sample…

Photoconductive gain



…and source supplies a new electron

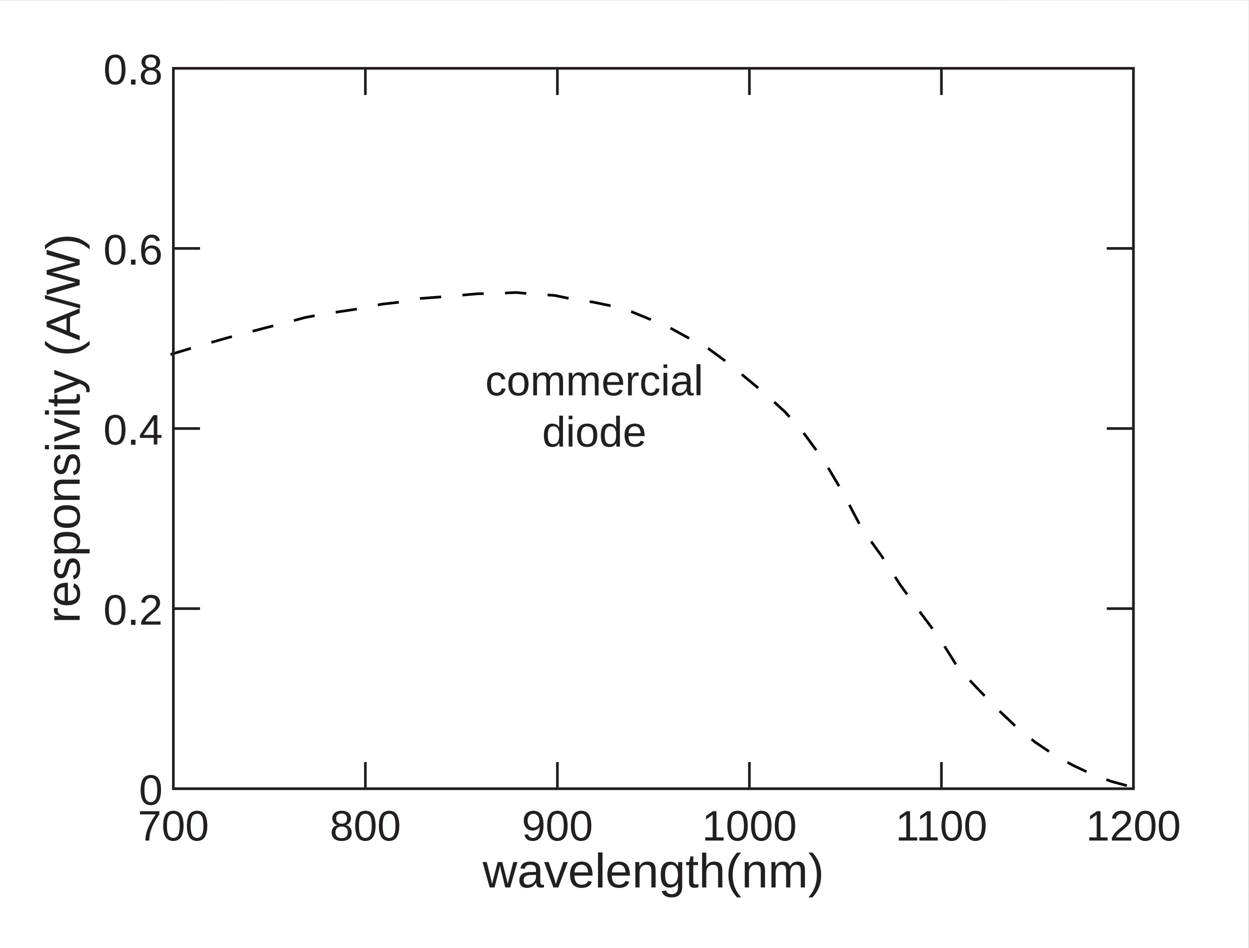
Photoconductive gain



…and source supplies a new electron

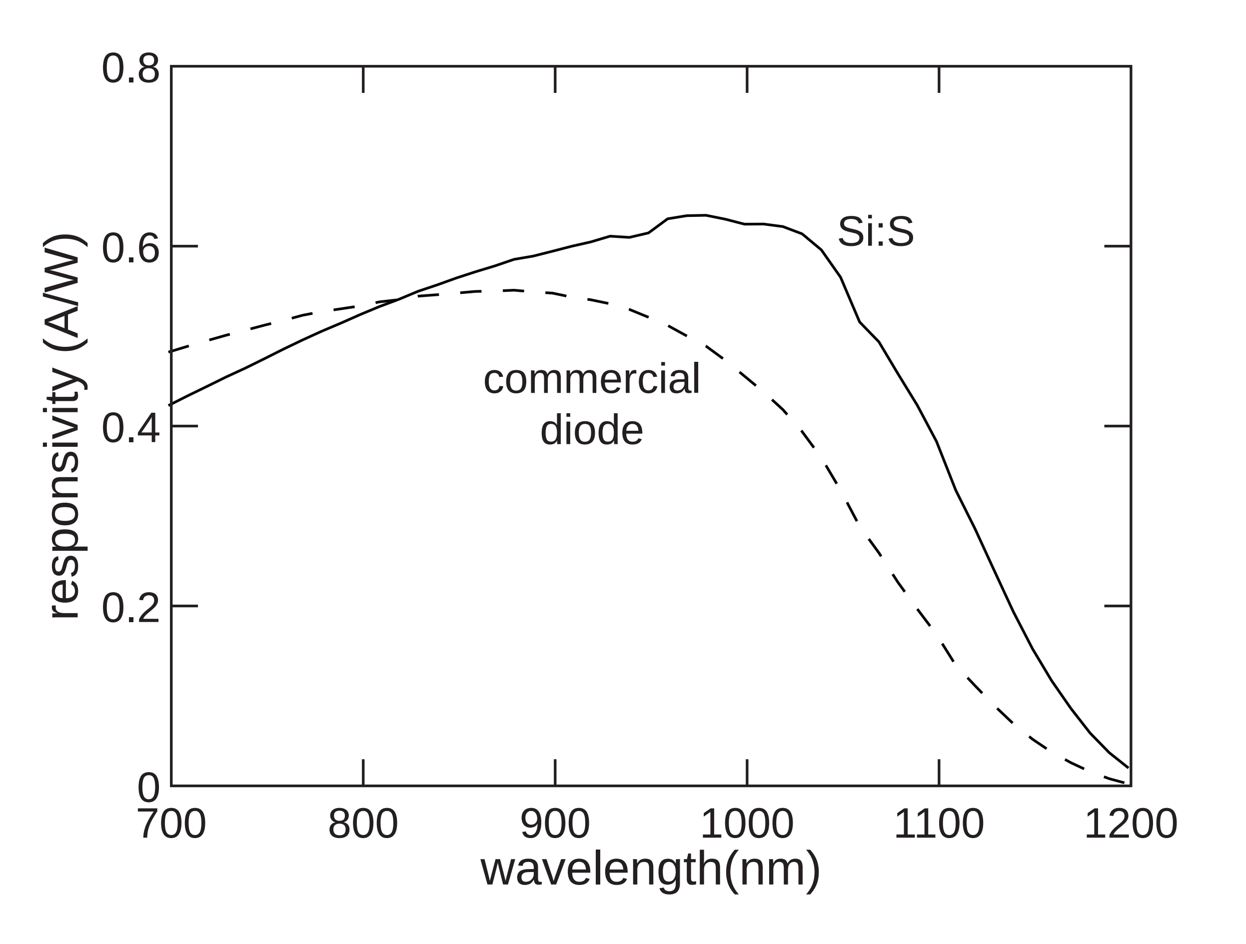
Photoconductive gain

responsivity at zero bias



Photoconductive gain

doubled quantum efficiency around 1.1 µm

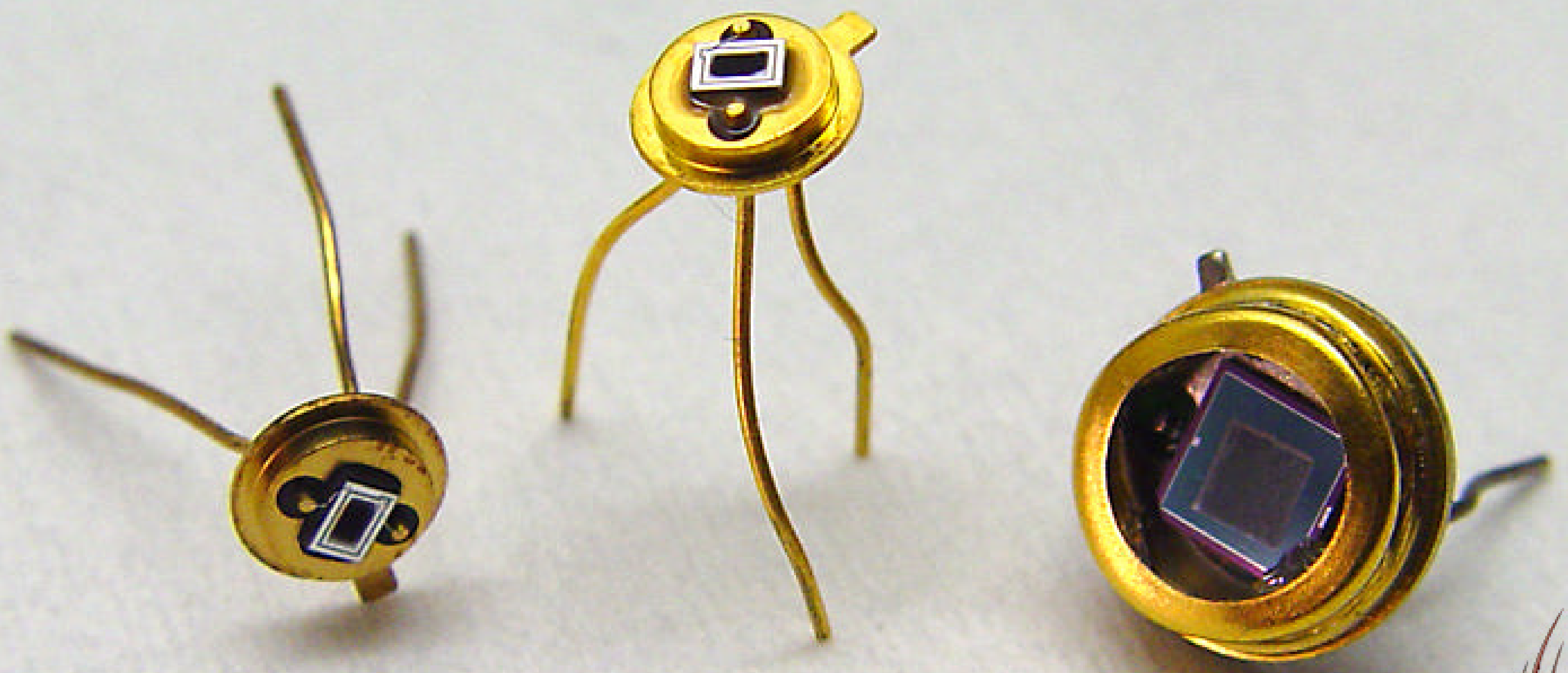


Photoconductive gain

Things to keep in mind

- photoconductive gain at room temperature!
- significant promise as photovoltaic material

Photoconductive gain

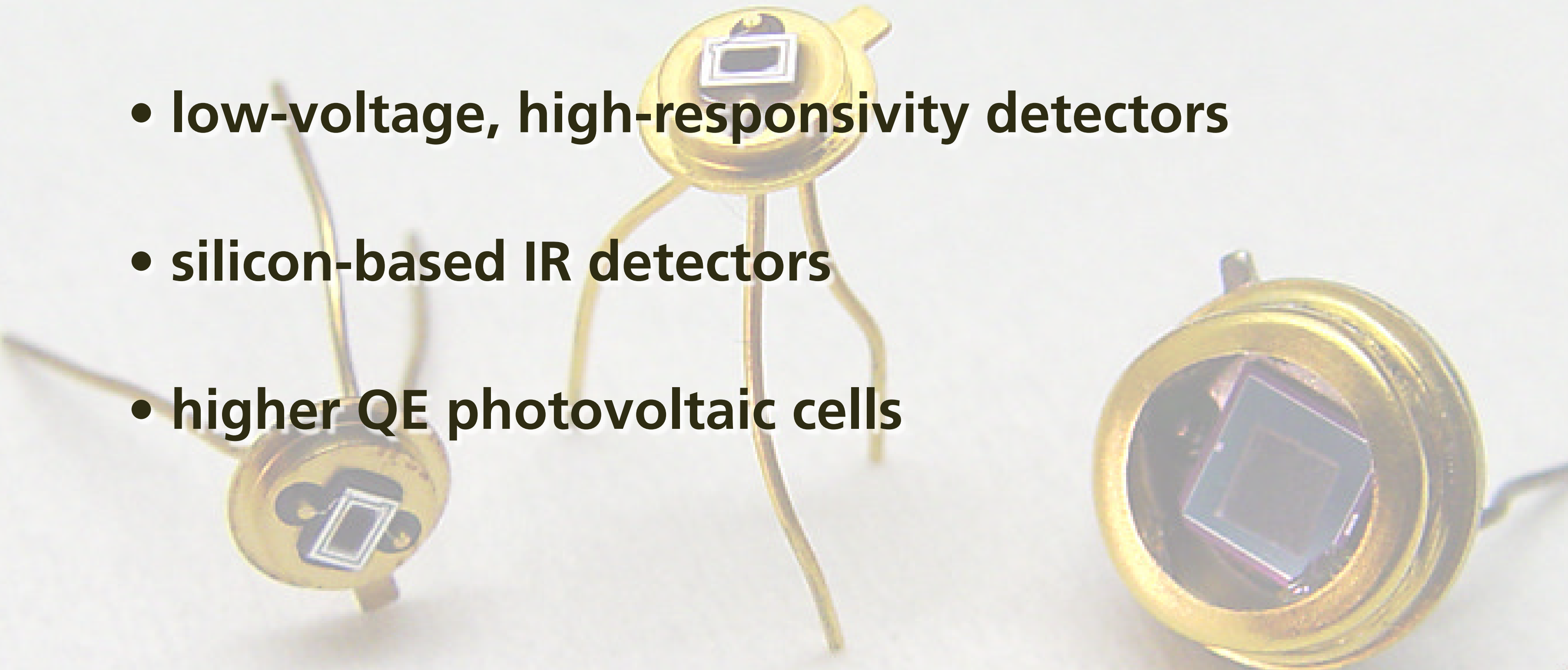


http://www.sionyxinc.com

SiOnyx

Photoconductive gain

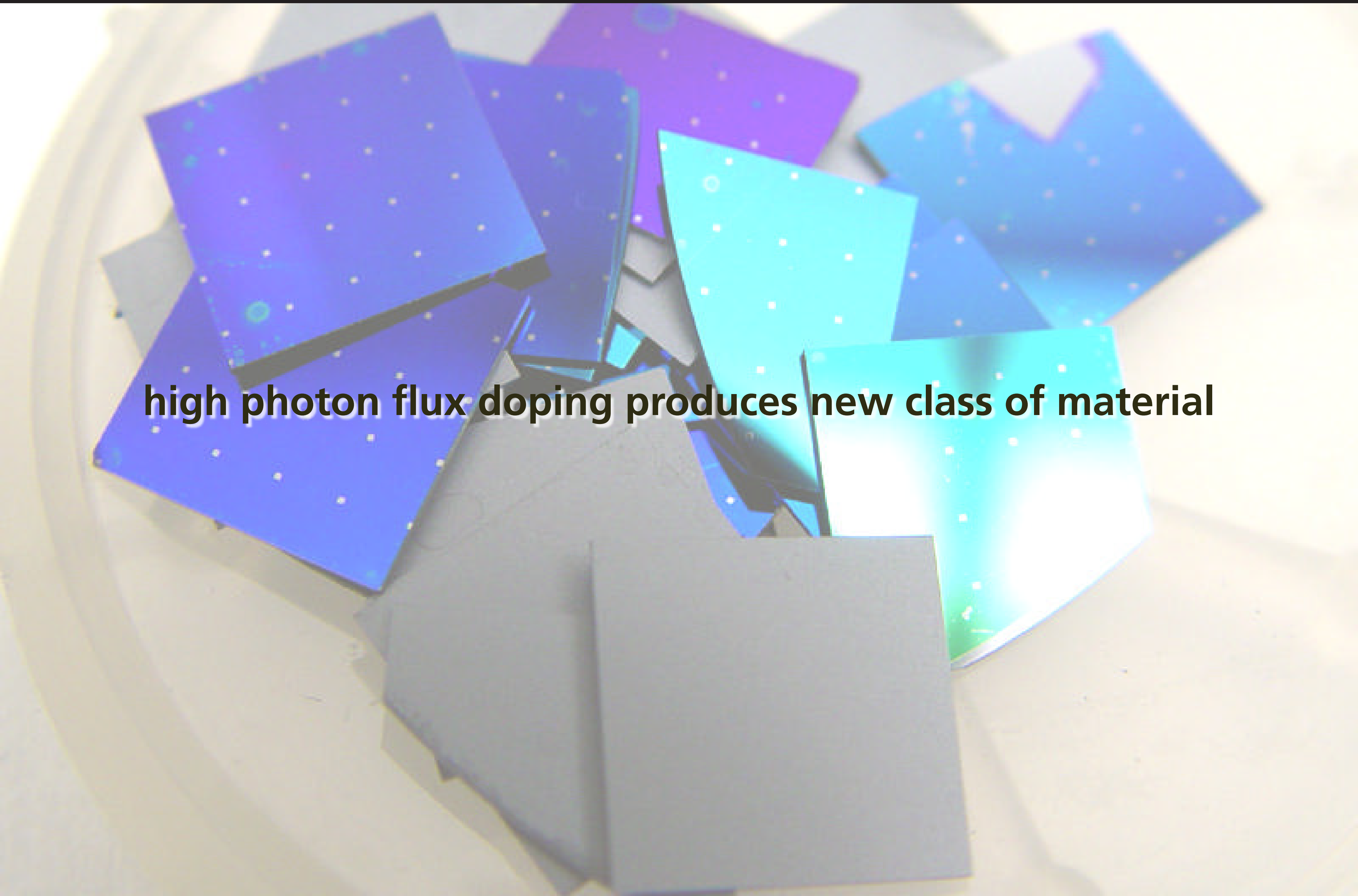
- low-voltage, high-responsivity detectors
- silicon-based IR detectors
- higher QE photovoltaic cells



http://www.sionyxinc.com

SiOnyx

Summary

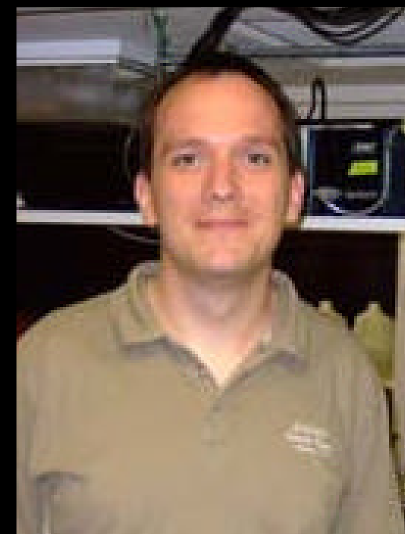


Nonlinear optics at the nanoscale

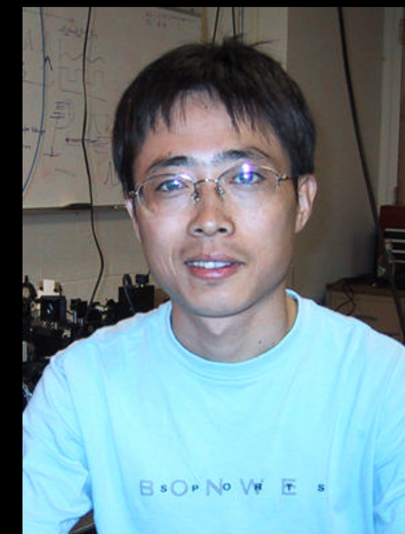
Ultrafast and Ultrasmall: Part III
2008 ITRI Femtosecond Laser International Forum
Tainan, Taiwan, 14 October 2008

Geoff Svacha

Rafael Gattass



Tobias Voss

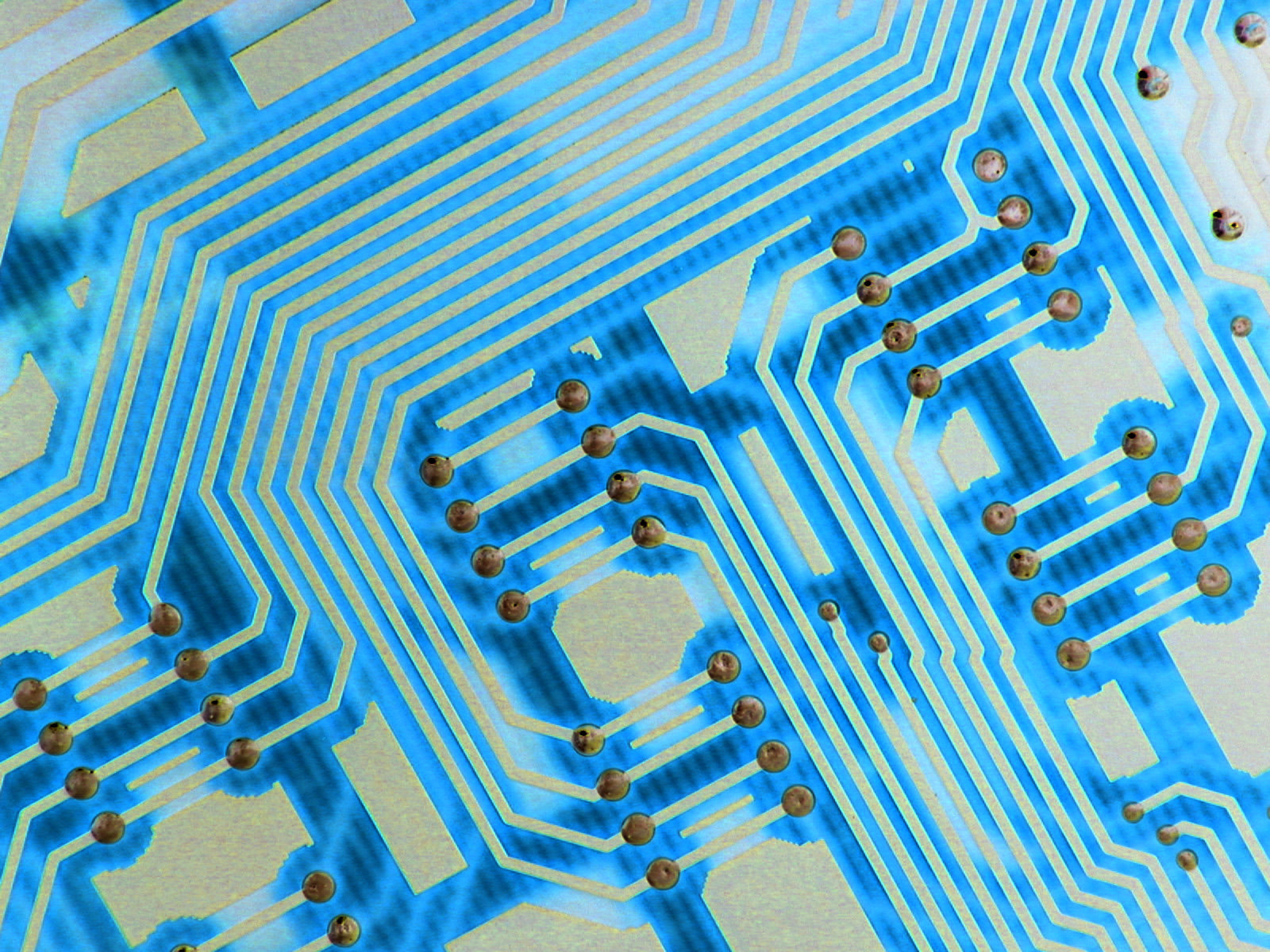


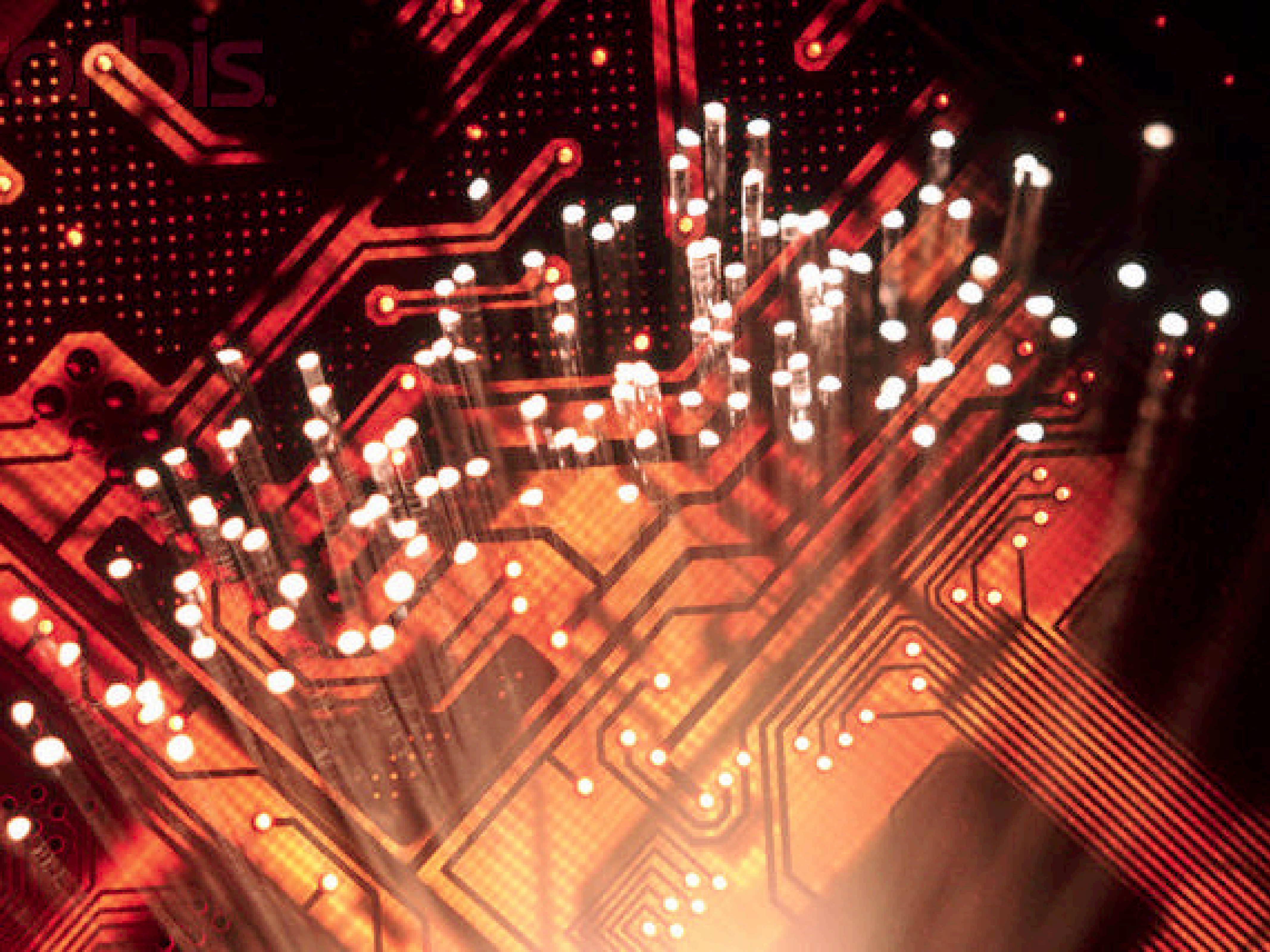
Limin Tong

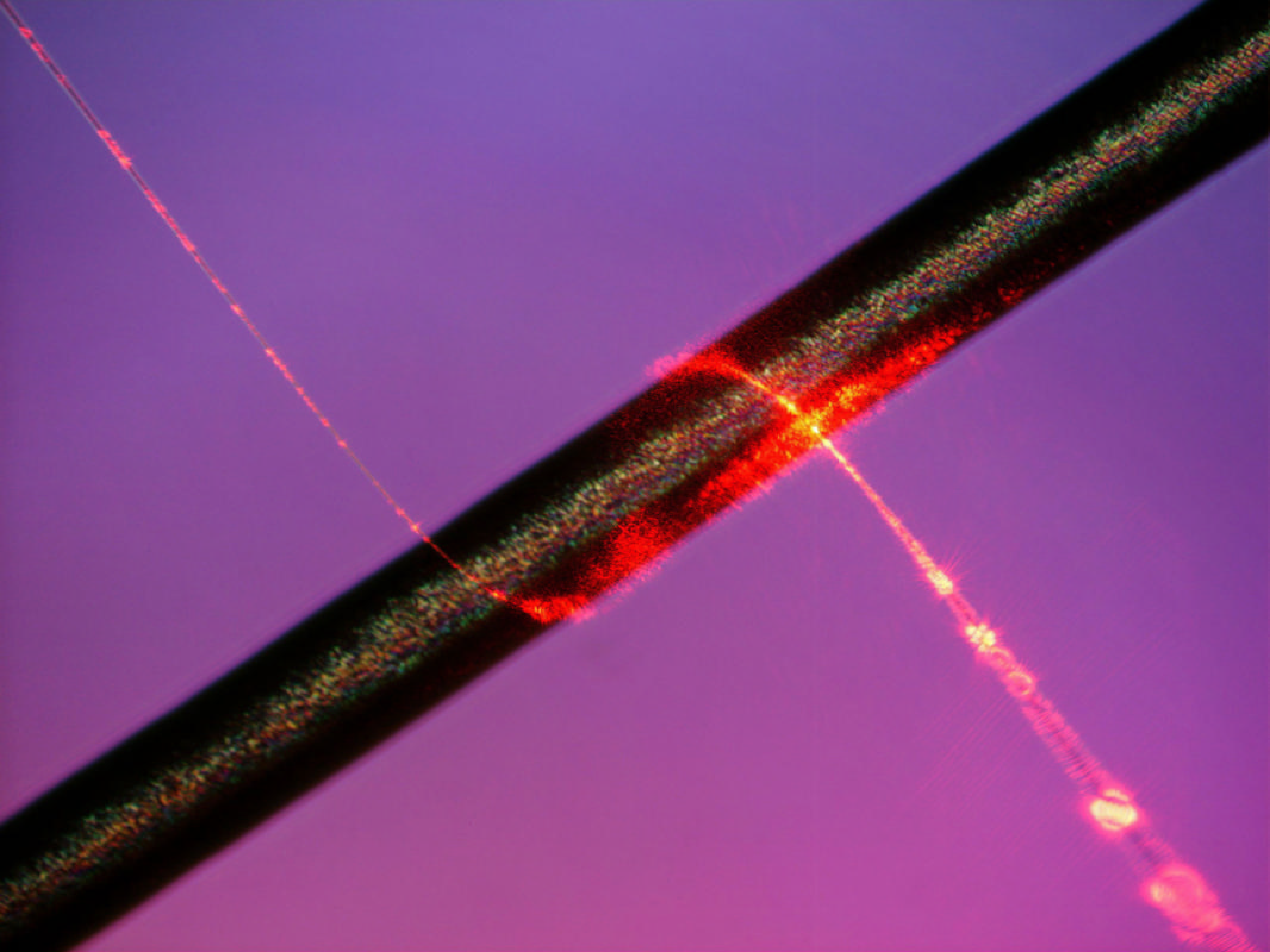
and also....

Jonathan Aschom
Mengyan Shen
Iva Maxwell
James Carey
Brian Tull
Dr. Yuan Lu
Dr. Richard Schalek
Prof. Federico Capasso
Prof. Cynthia Friend

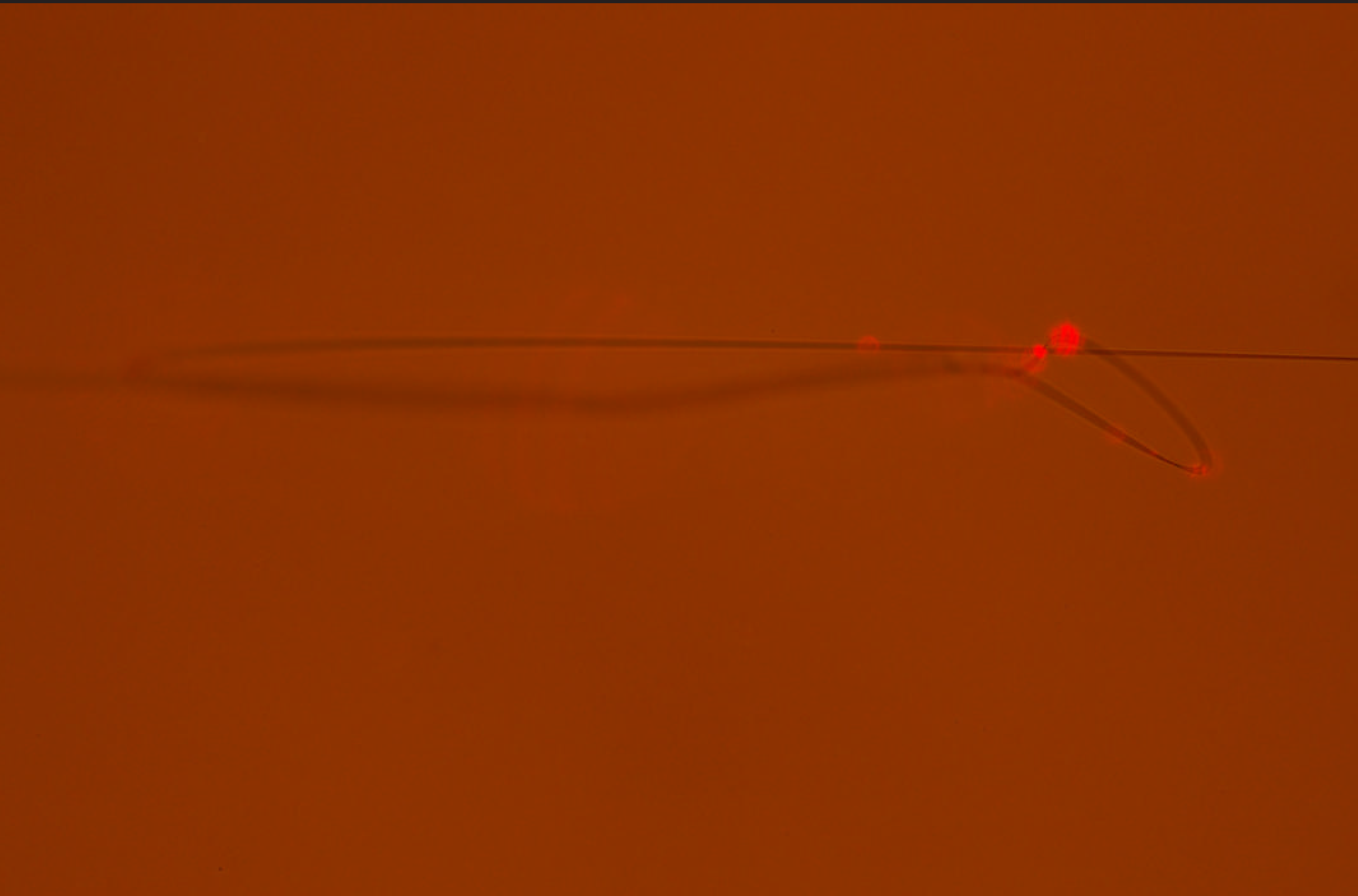
Xuewen Chen (Zhejiang)
Zhanghua Han (Zhejiang)
Dr. Sailing He (Zhejiang)
Liu Liu (Zhejiang)
Dr. Jingyi Lou (Zhejiang)
Dr. Ray Mariella (LLNL)
Prof. Frank Marlow (MPI Mühlheim)
Prof. Sven Müller (Göttingen)
Prof. Carsten Ronning (Göttingen)







Outline



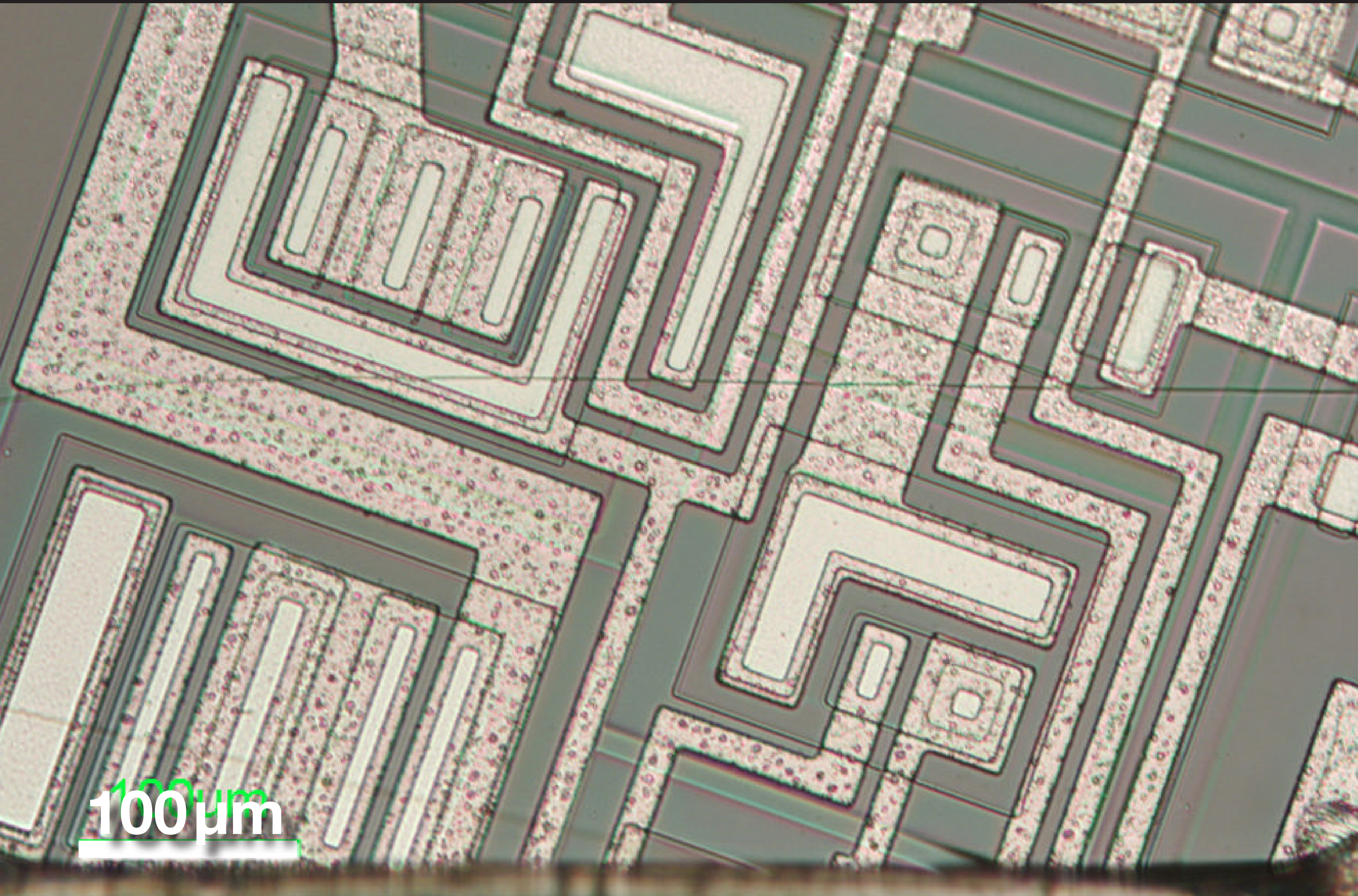
Outline

- manipulating light at the nanoscale
- supercontinuum generation
- optical logic gates

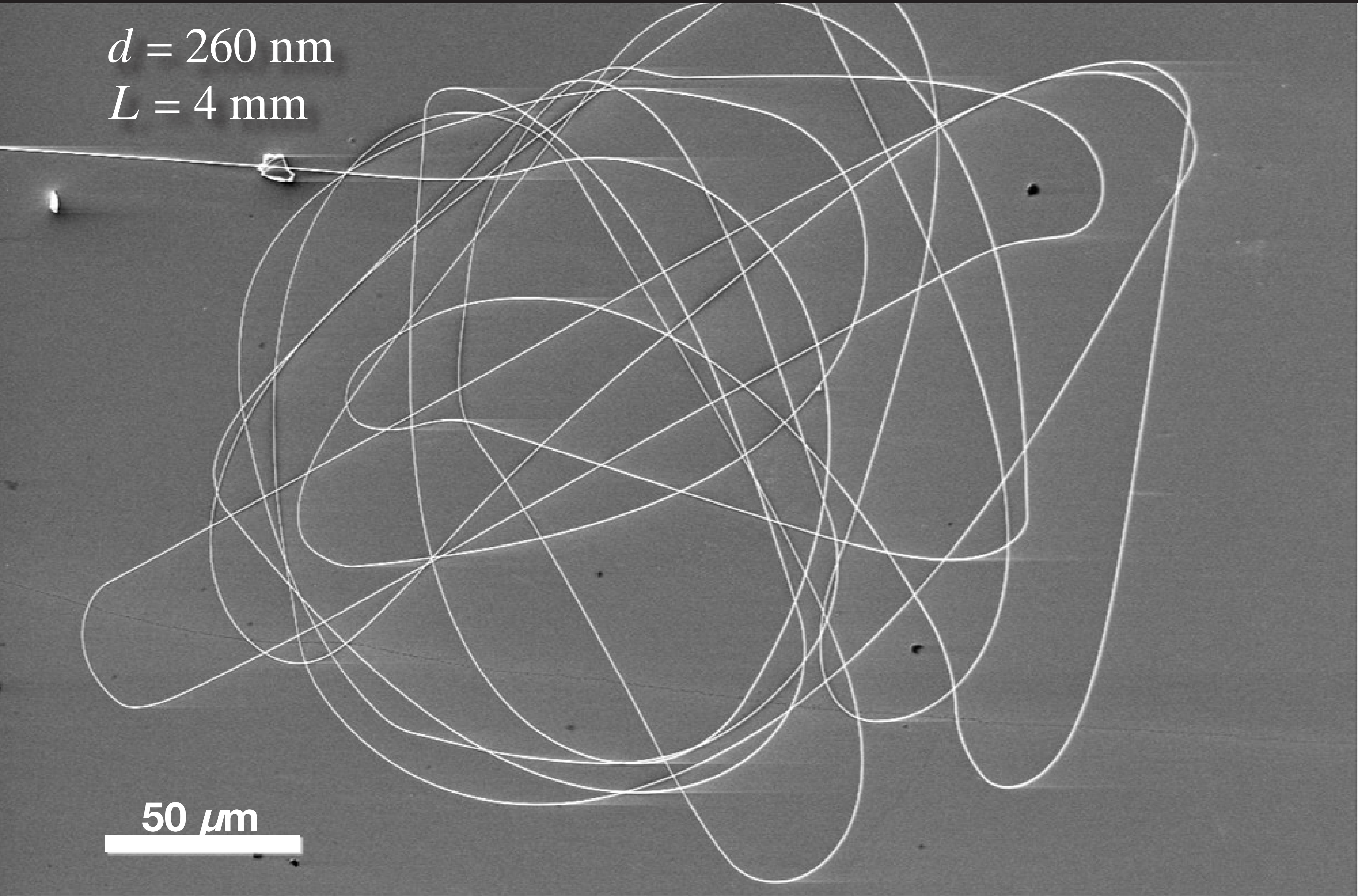
Manipulating light at the nanoscale

Nature, 426, 816 (2003)

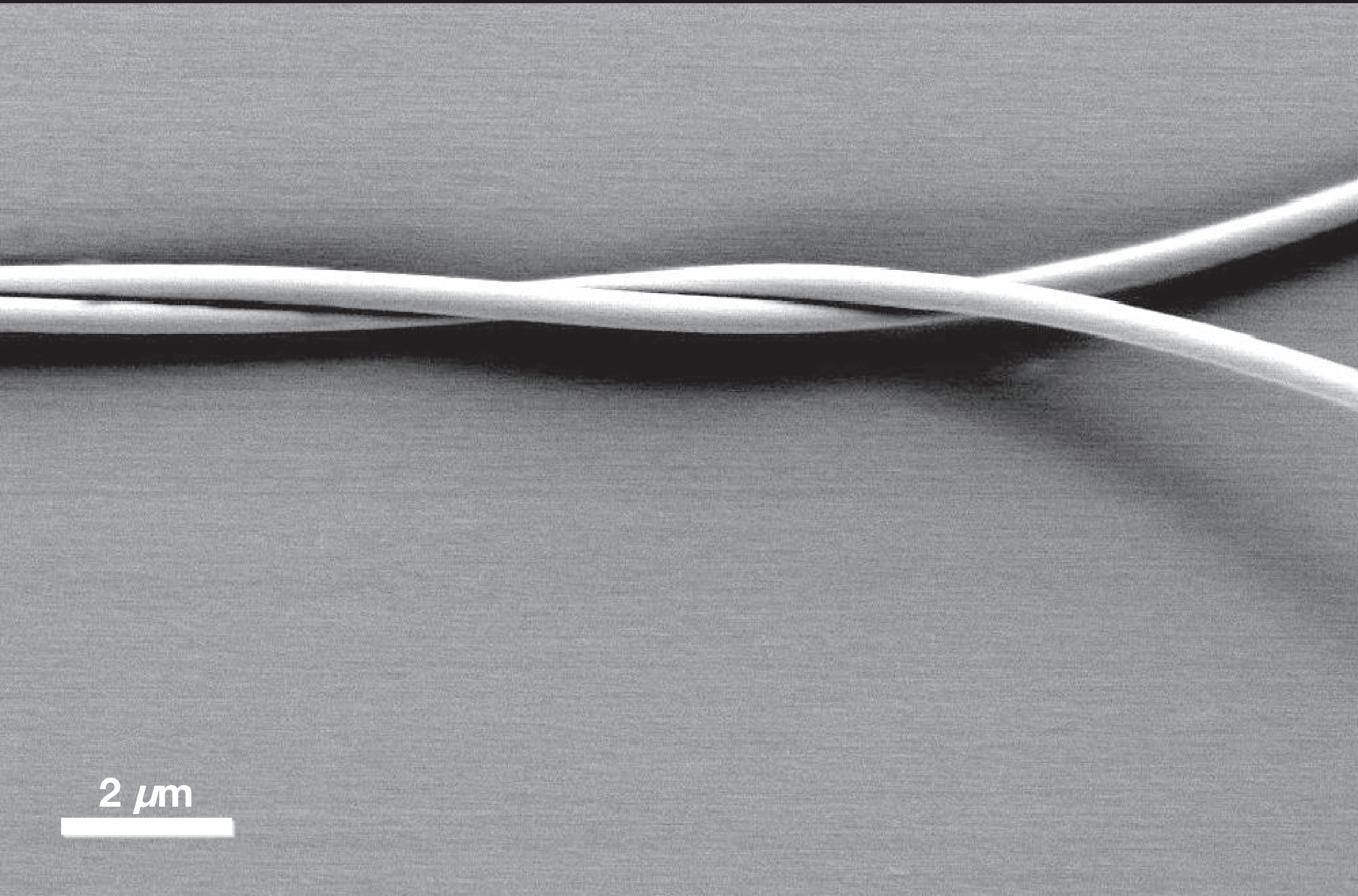
Manipulating light at the nanoscale



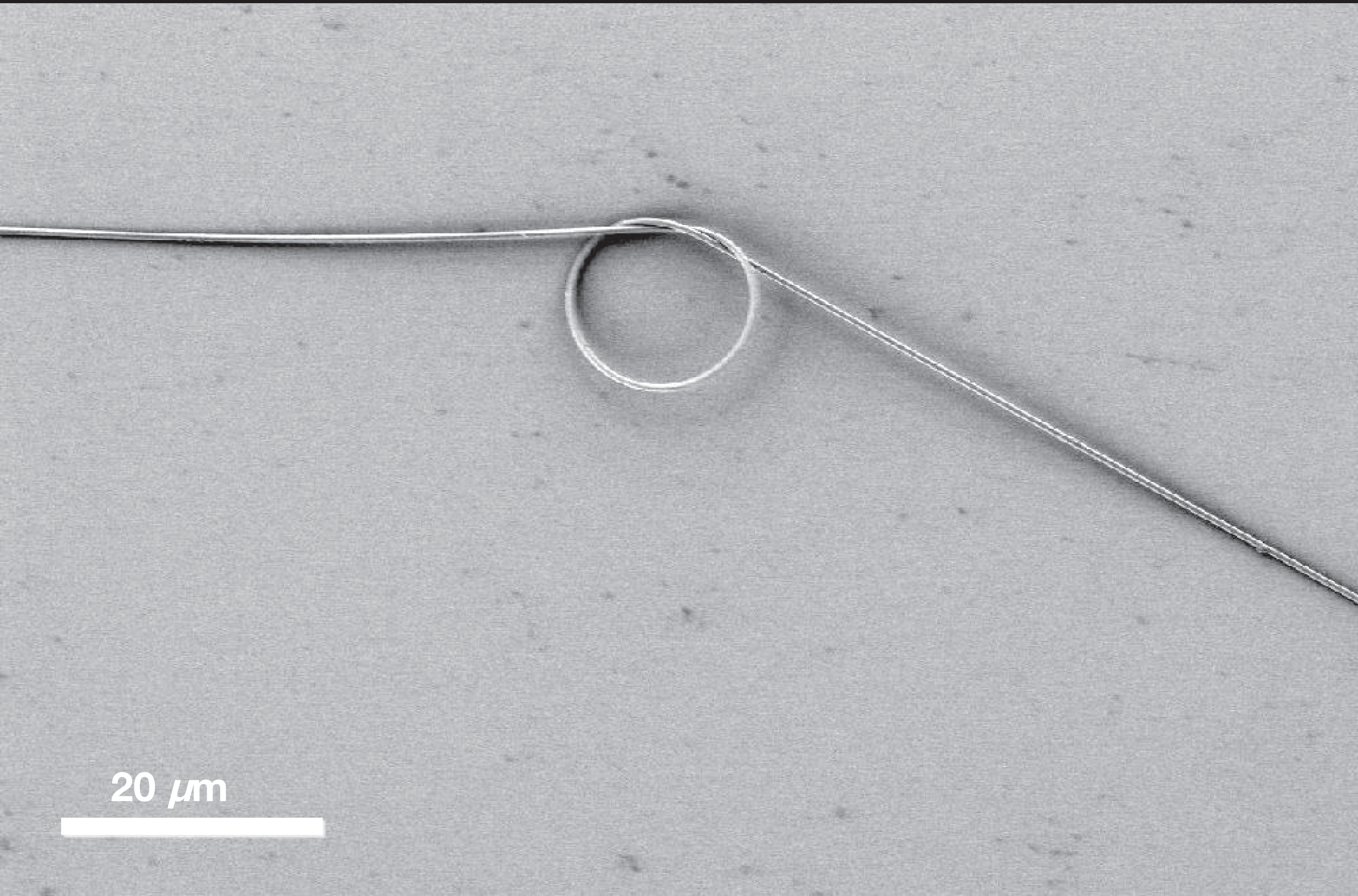
Manipulating light at the nanoscale



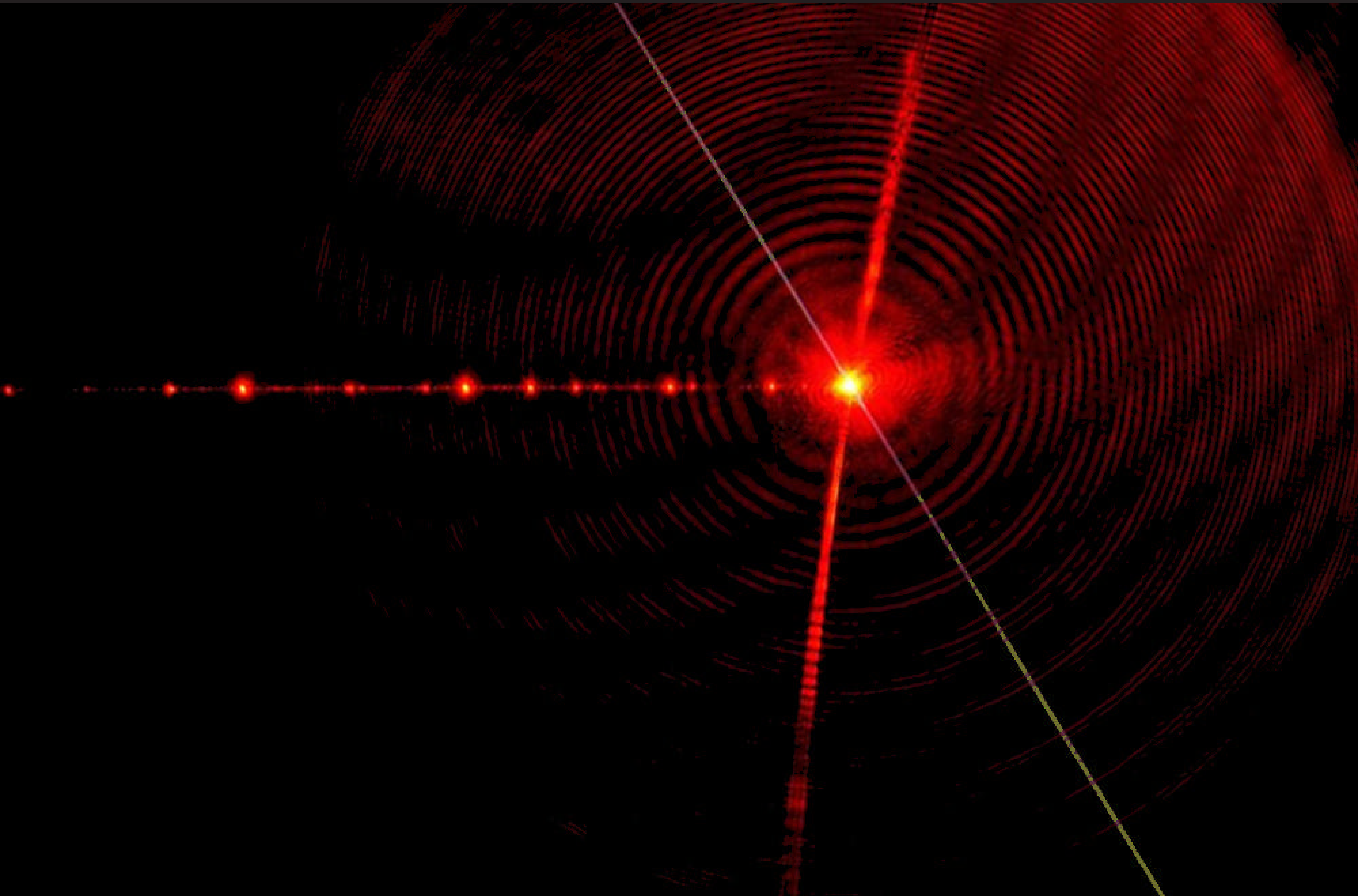
Manipulating light at the nanoscale



Manipulating light at the nanoscale

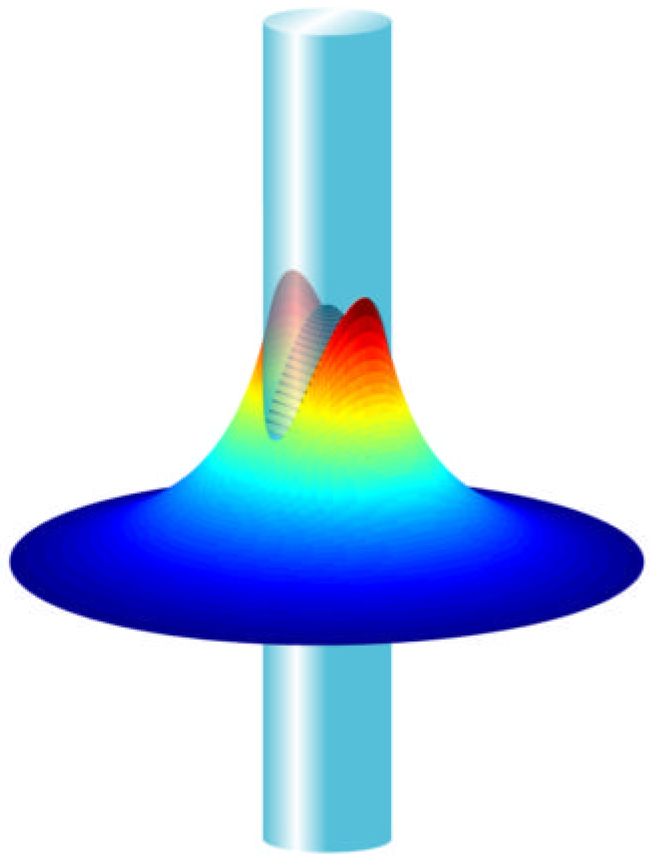


Manipulating light at the nanoscale

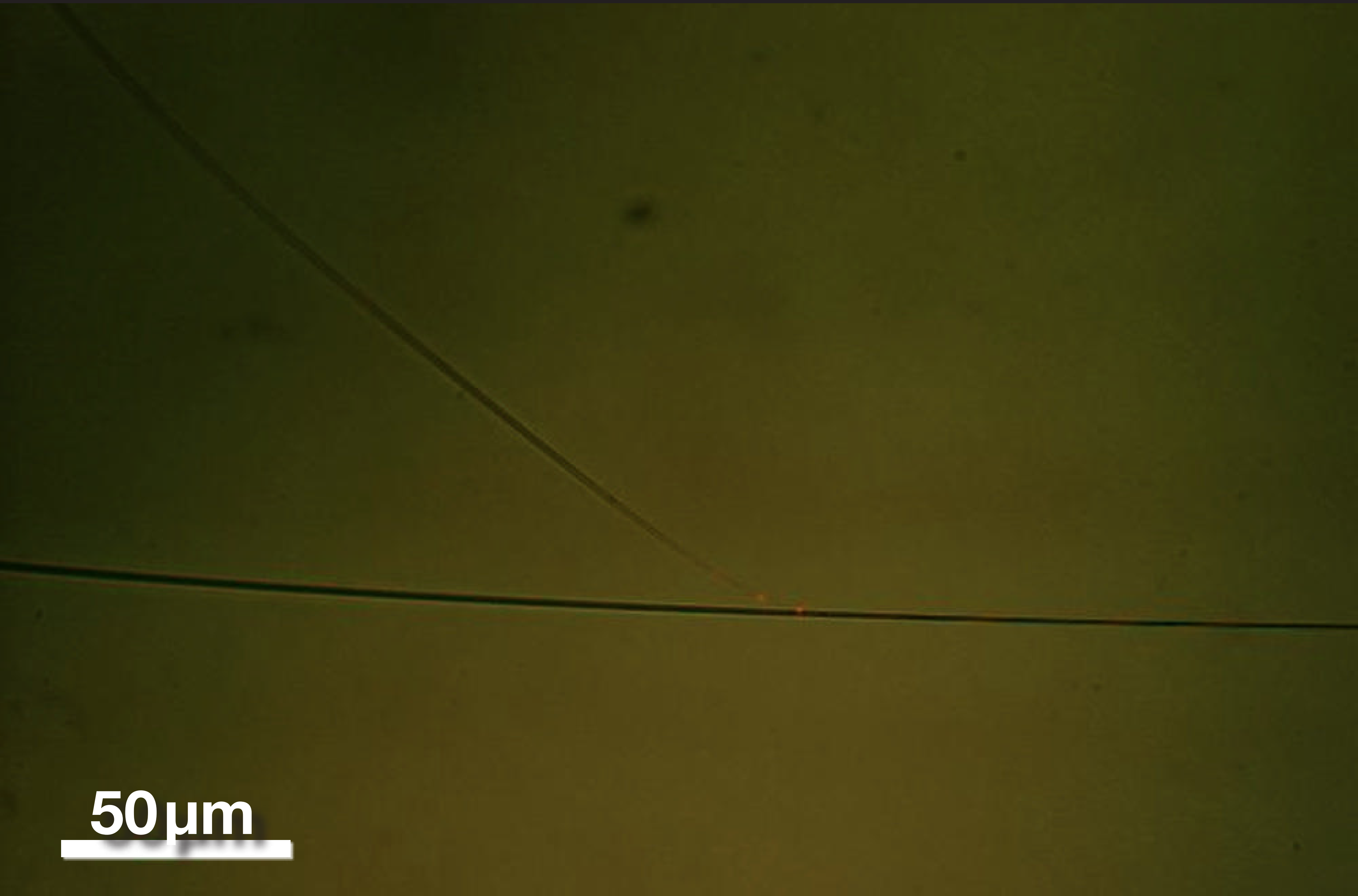


Manipulating light at the nanoscale

Poynting vector profile for 200-nm nanowire

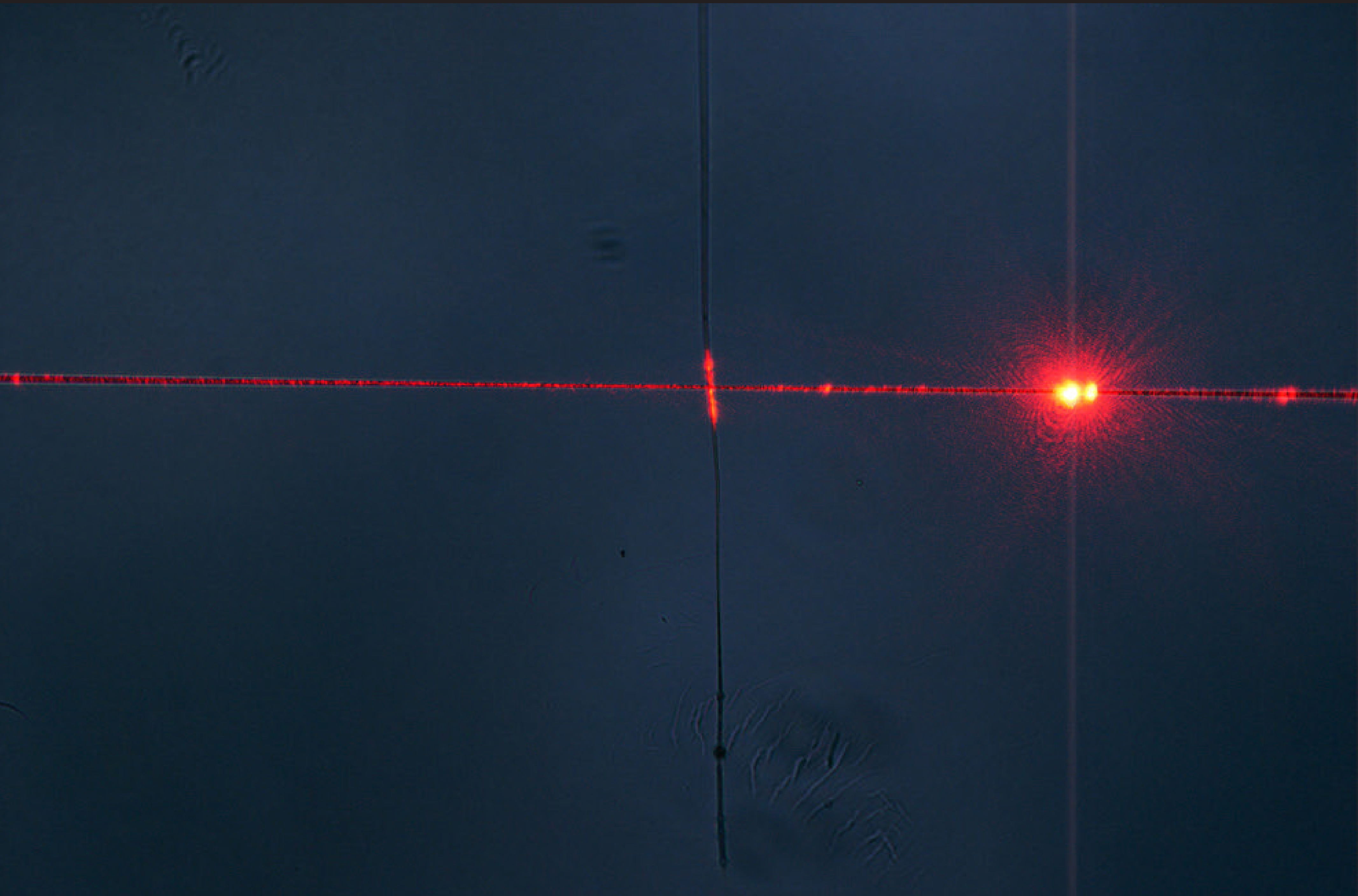


Manipulating light at the nanoscale

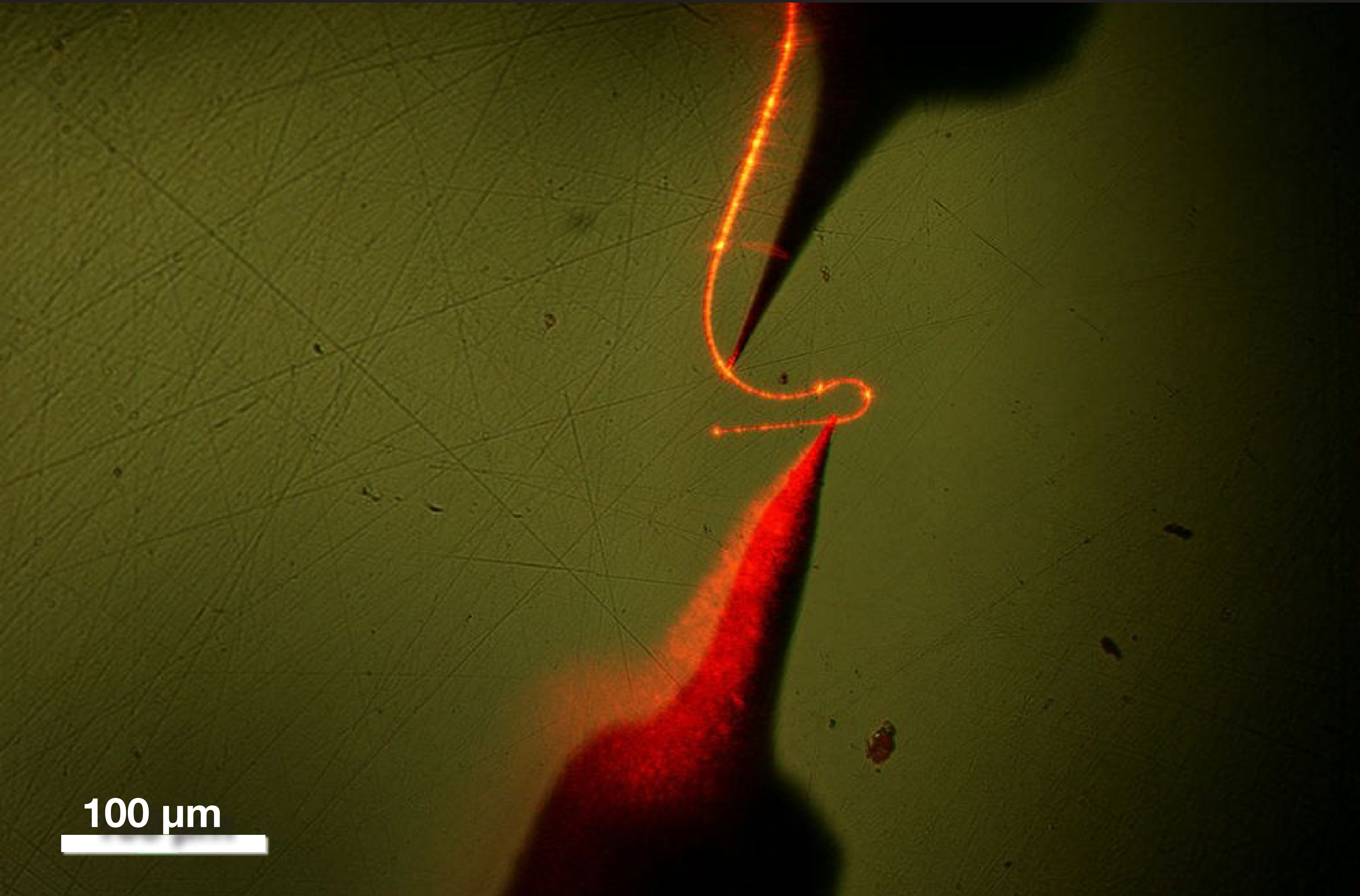


Manipulating light at the nanoscale

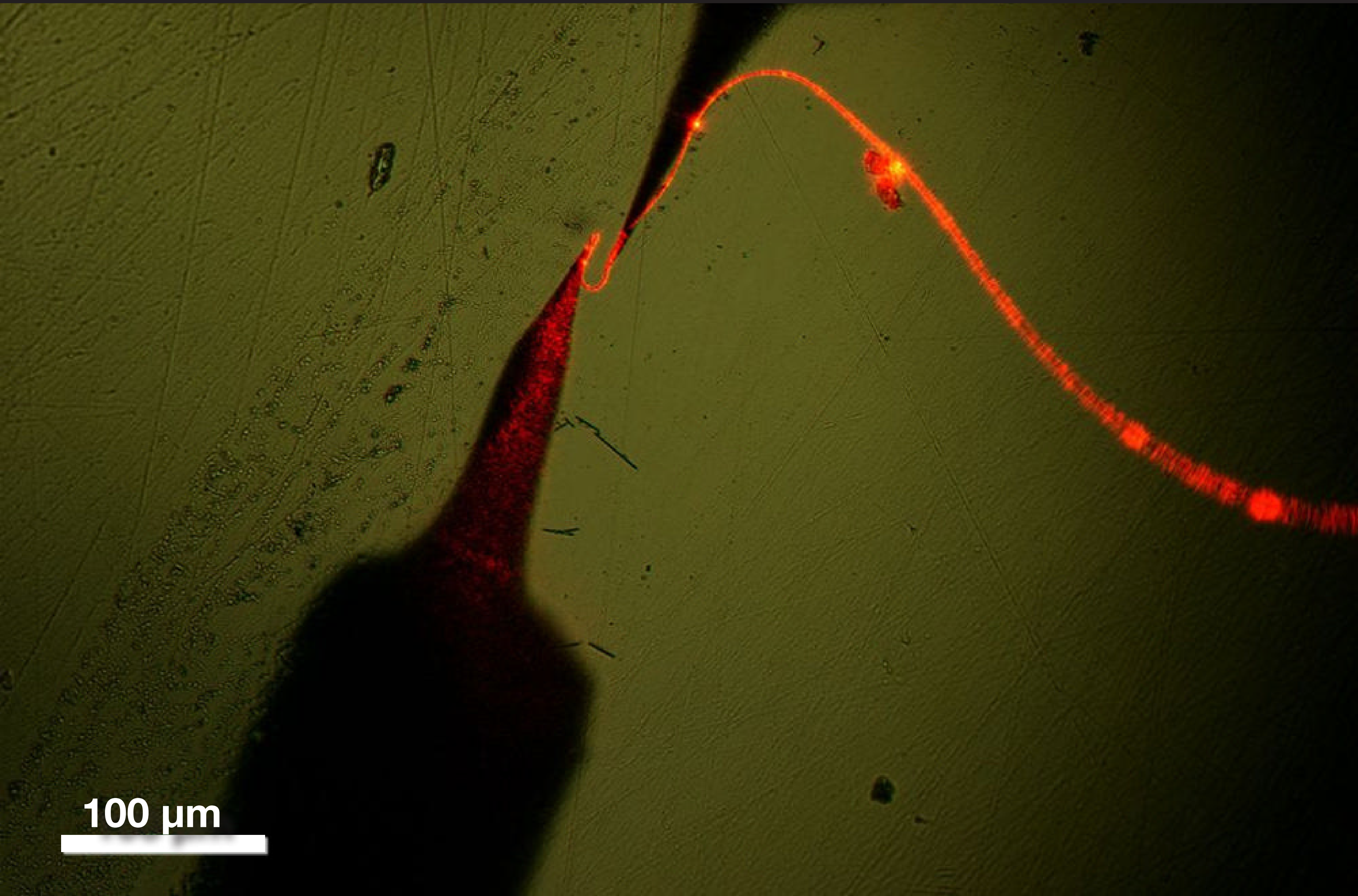
Manipulating light at the nanoscale



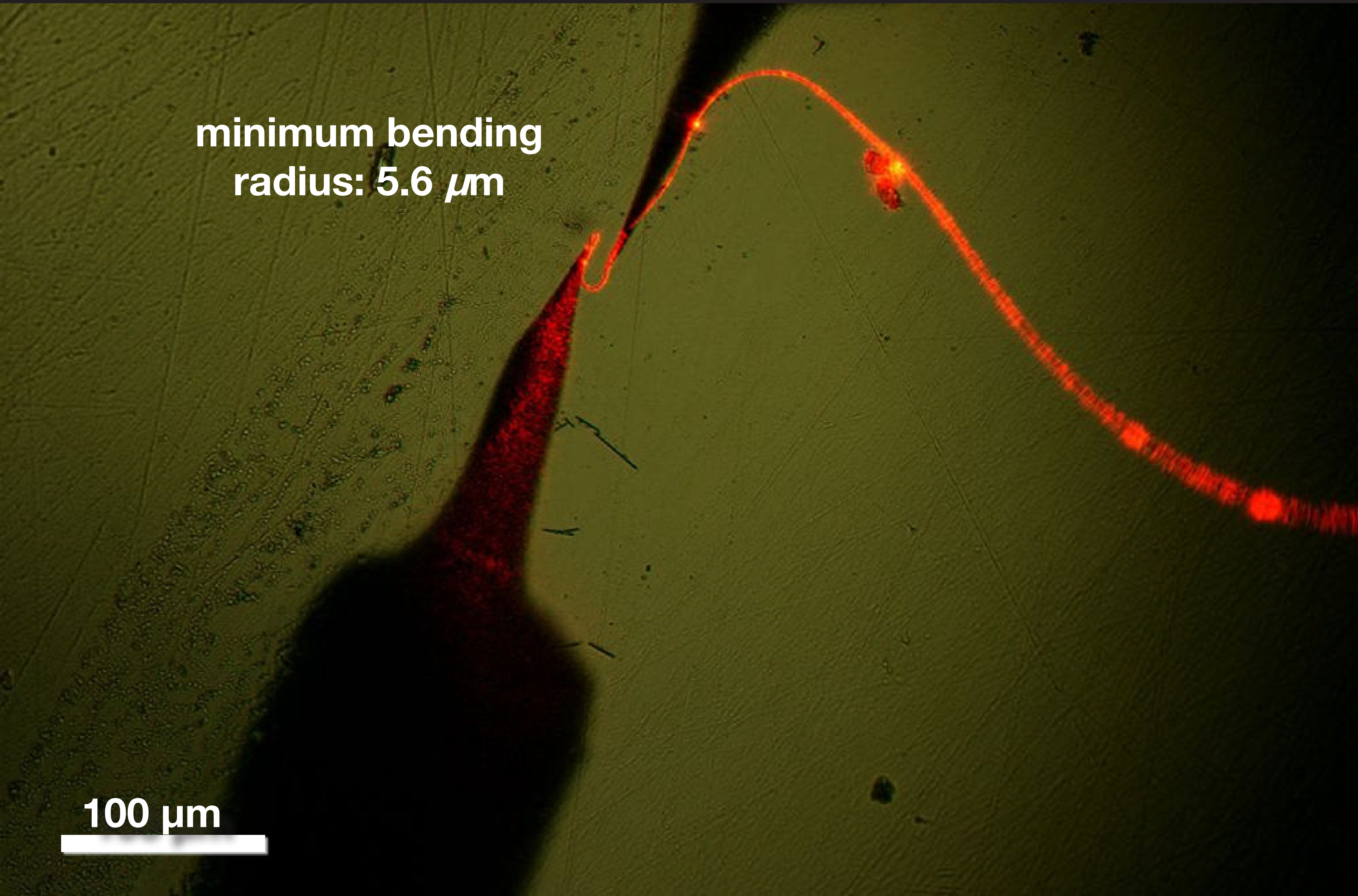
Manipulating light at the nanoscale



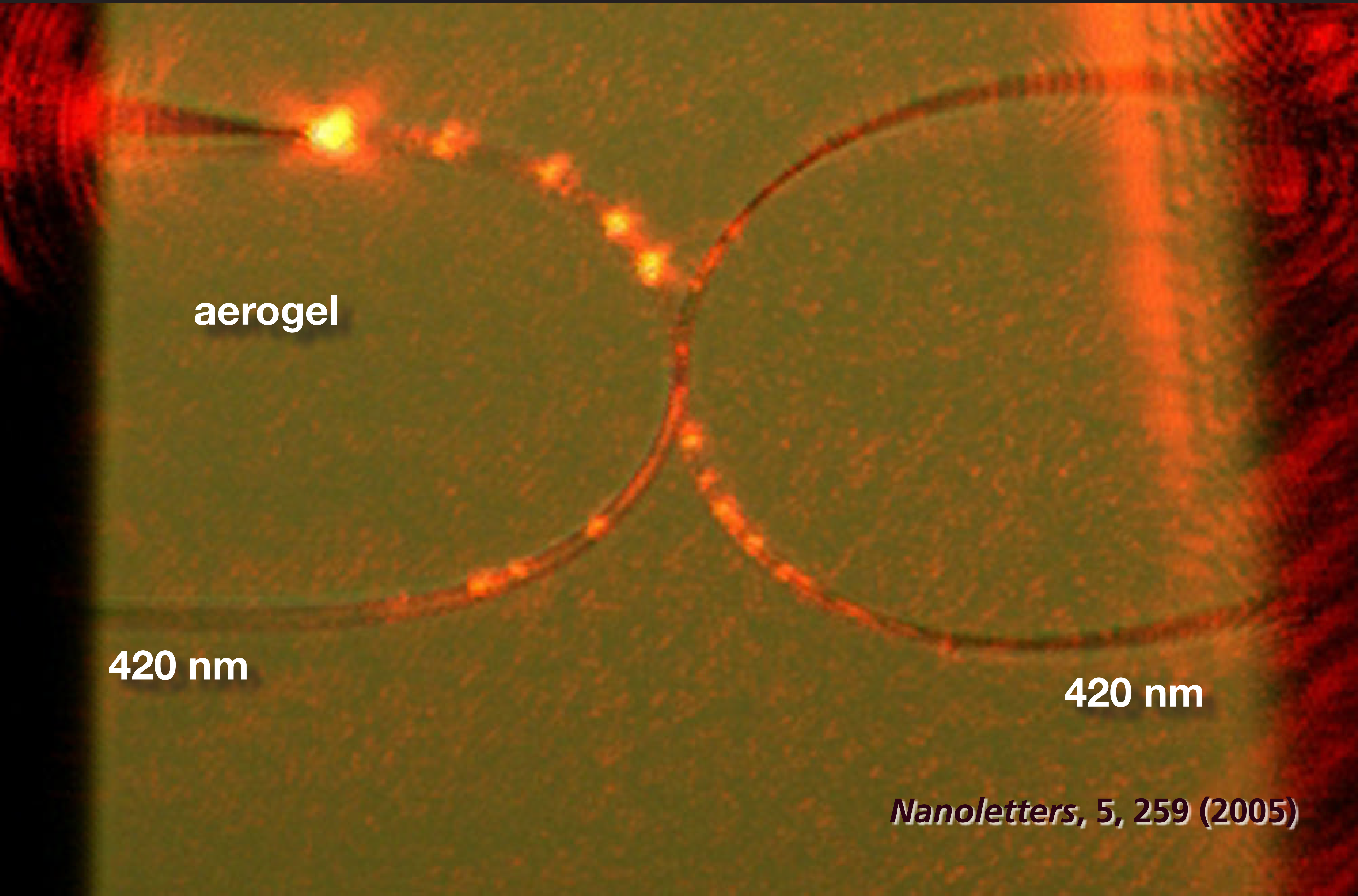
Manipulating light at the nanoscale



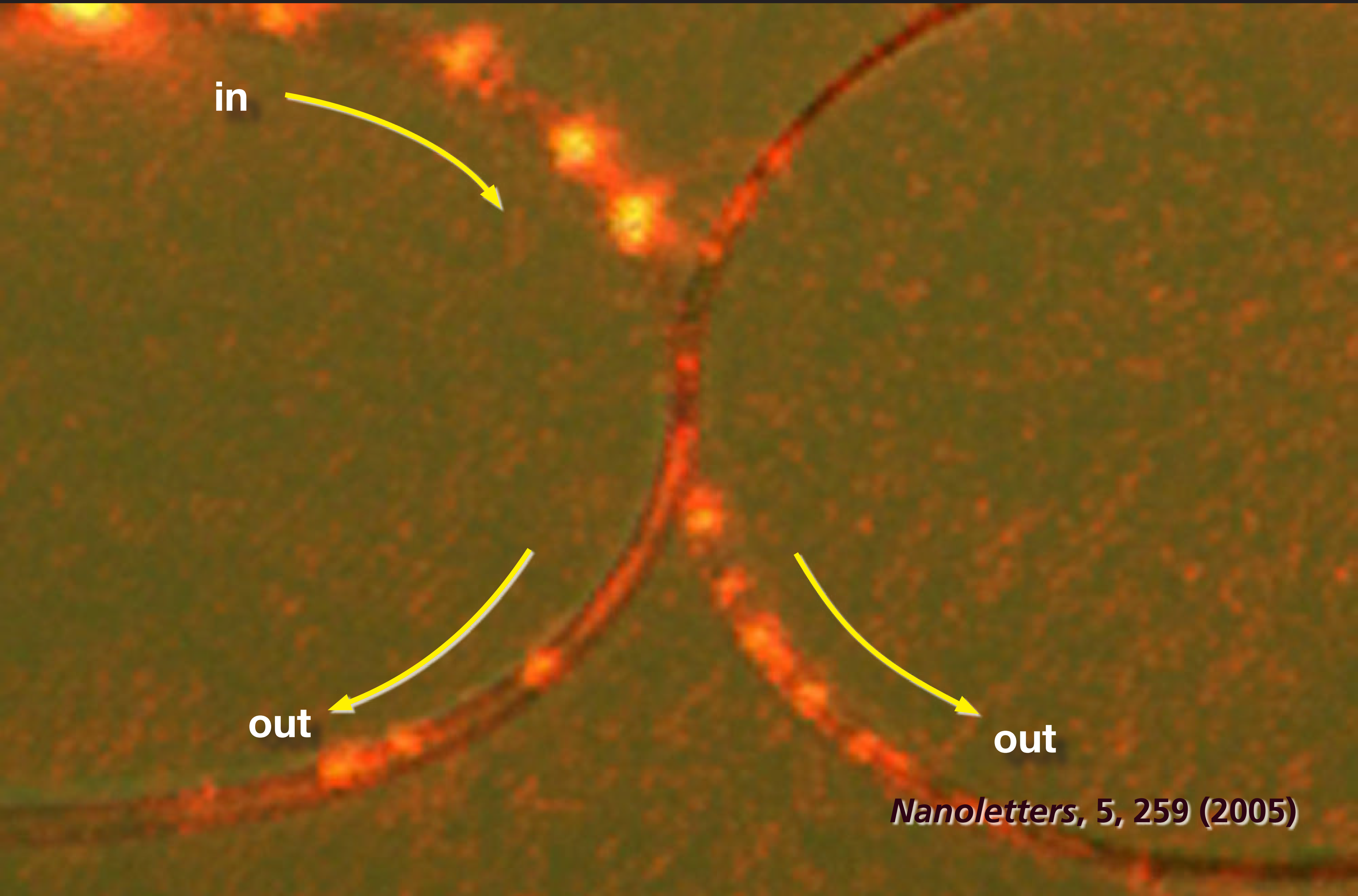
Manipulating light at the nanoscale



Manipulating light at the nanoscale

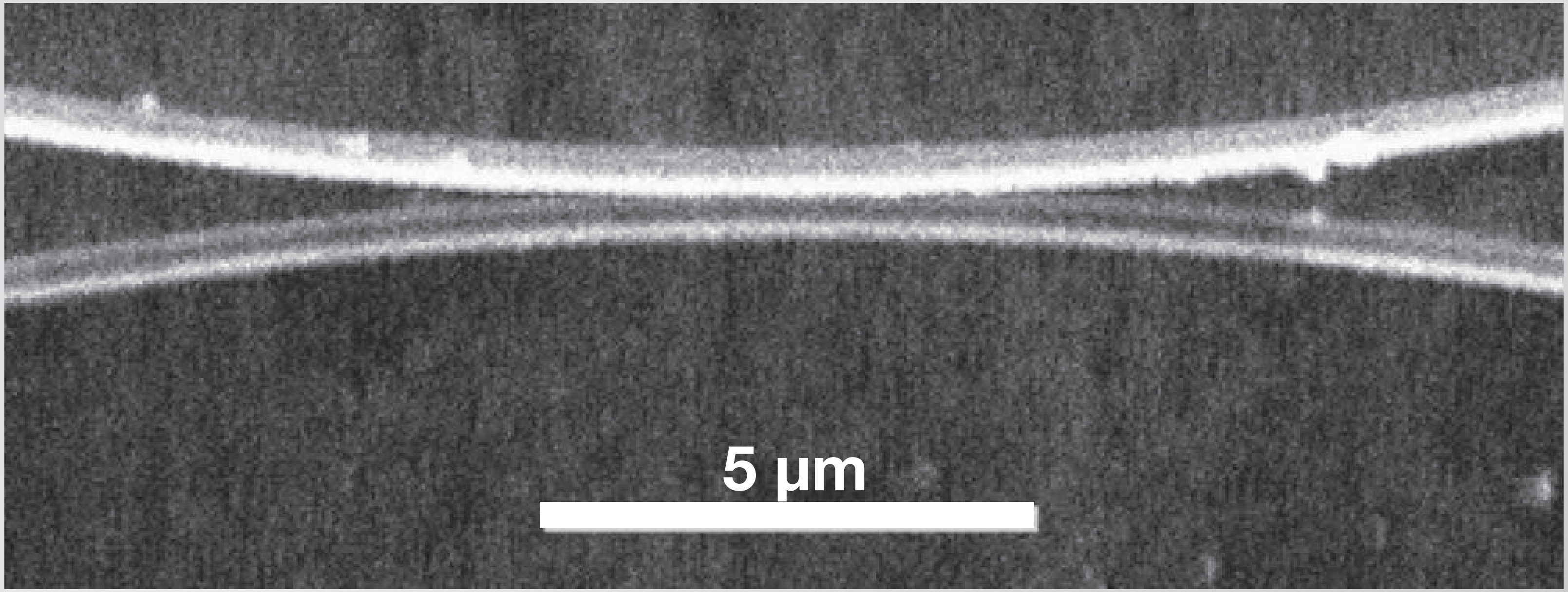


Manipulating light at the nanoscale



Nanoletters, 5, 259 (2005)

Manipulating light at the nanoscale



Nanoletters, 5, 259 (2005)

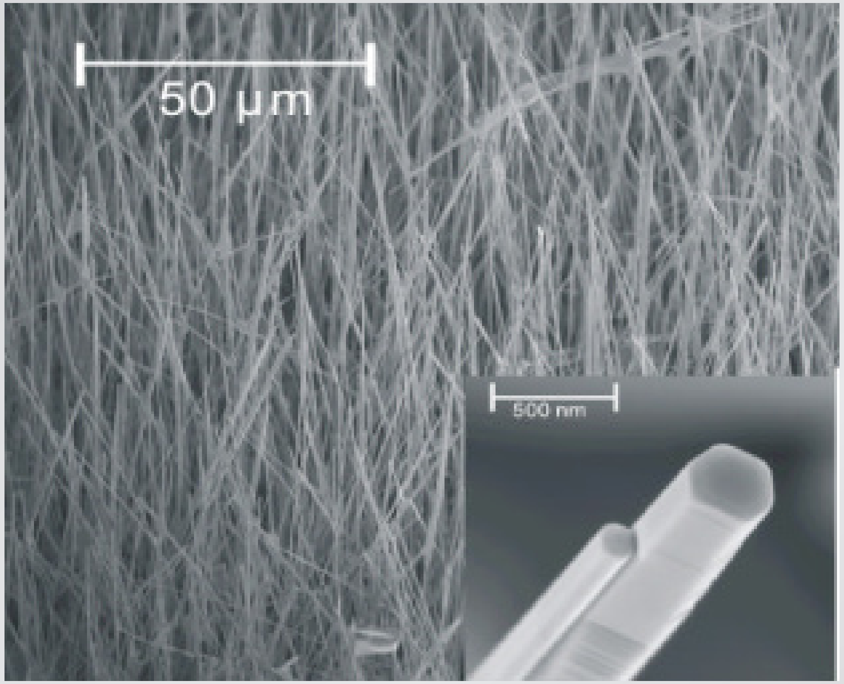
Manipulating light at the nanoscale

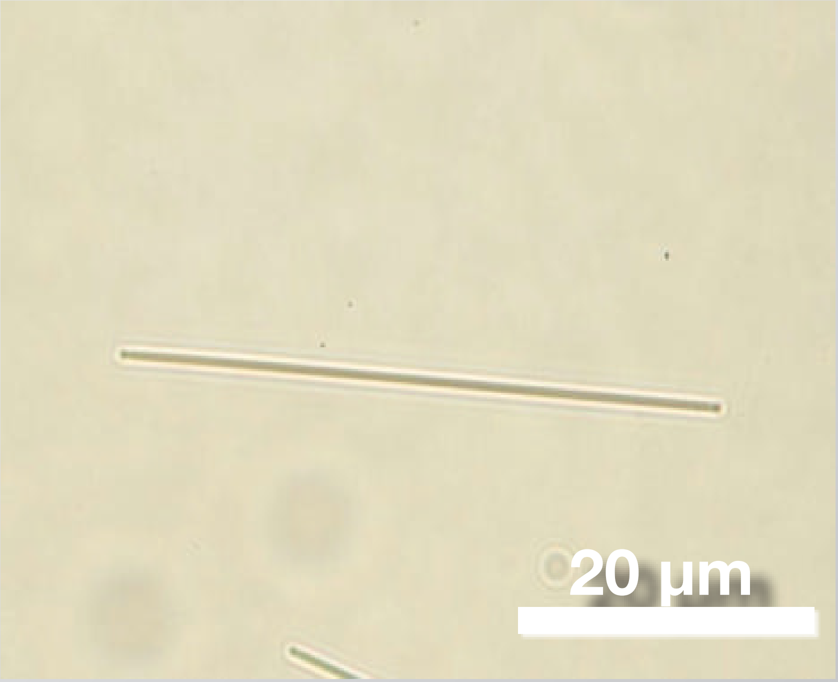
use tapered fibers to couple light to nanoscale objects

Manipulating light at the nanoscale

Manipulating light at the nanoscale

vapor transport grown ZnO nanowires





80–400 nm diameter, up to 80 µm long

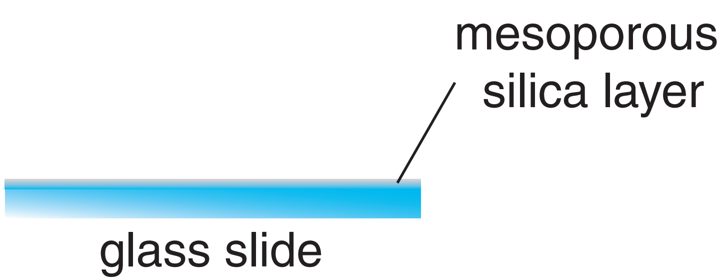
Manipulating light at the nanoscale

best of both worlds

ZnO	silica
bottom-up	top-down
semiconductor	glass
active photonic devices	passive waveguides
electrical operation	link to macroworld

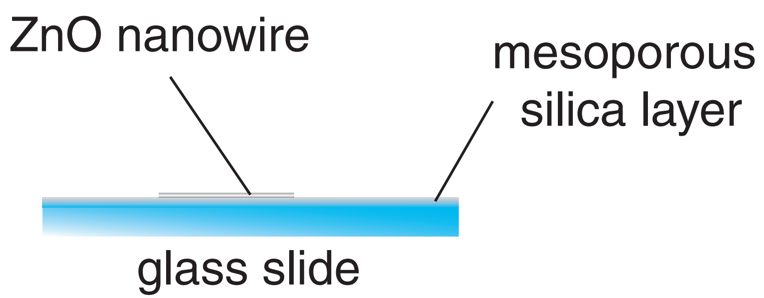
Manipulating light at the nanoscale

coupling to ZnO nanowires



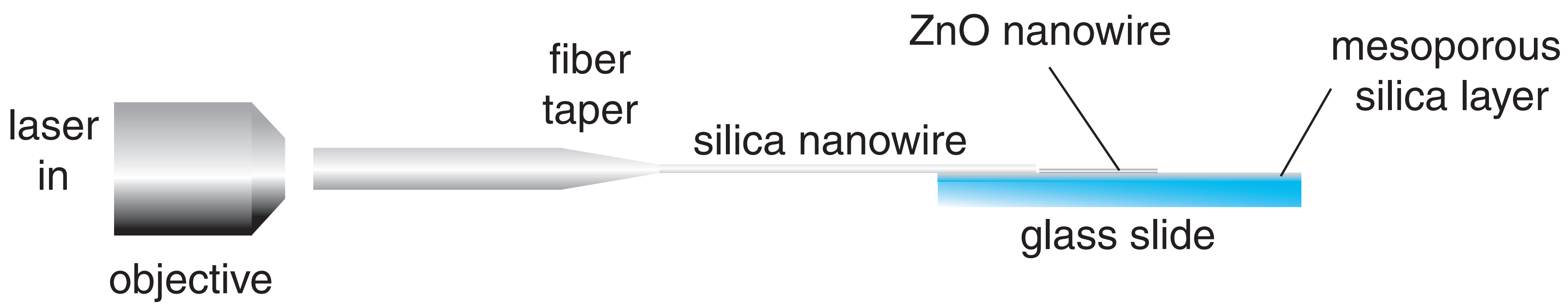
Manipulating light at the nanoscale

coupling to ZnO nanowires



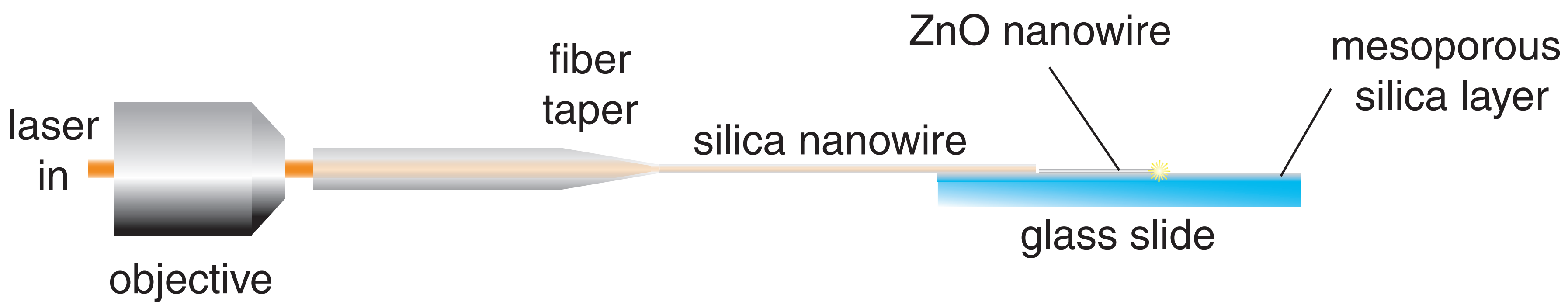
Manipulating light at the nanoscale

coupling to ZnO nanowires

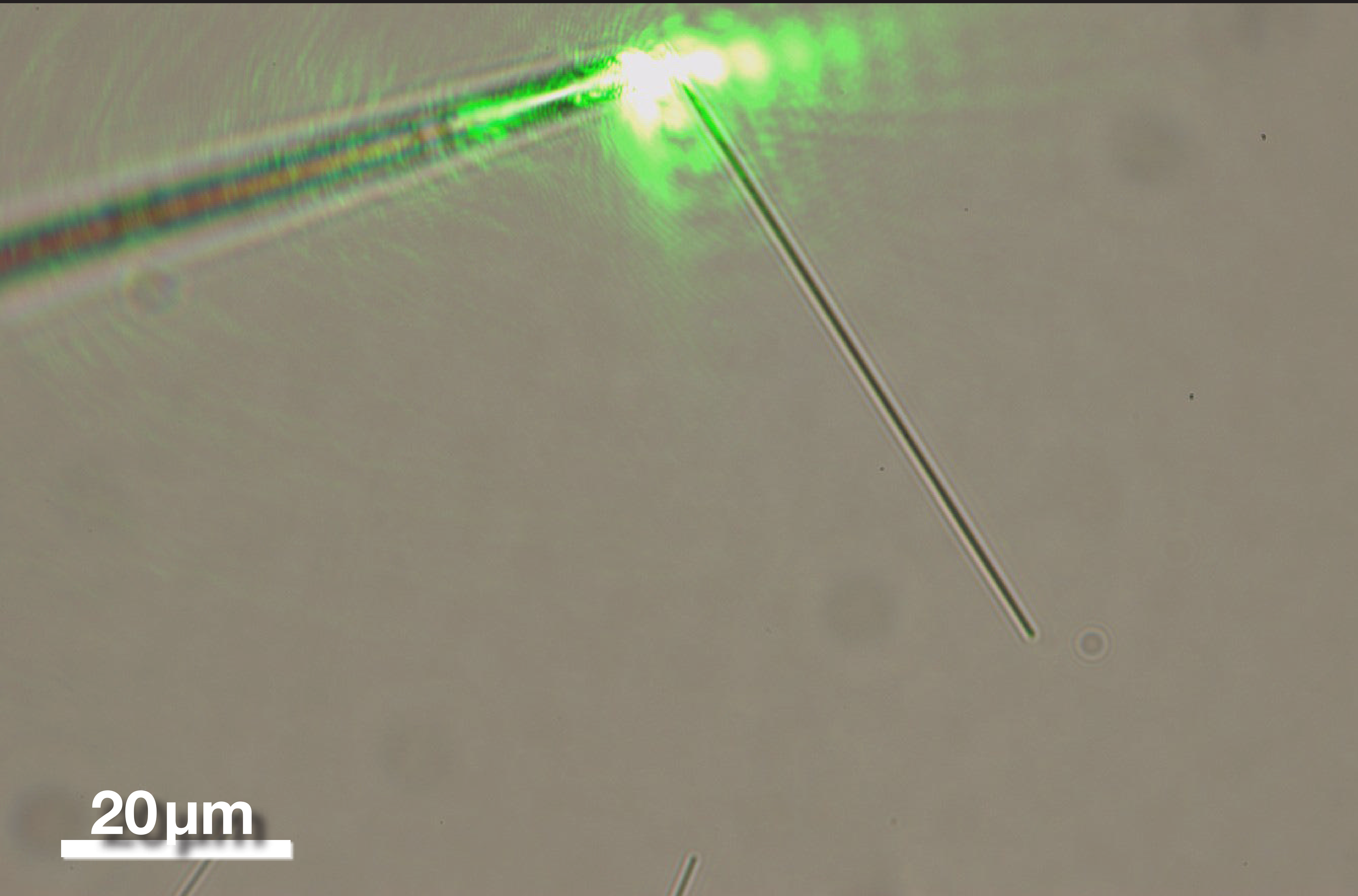


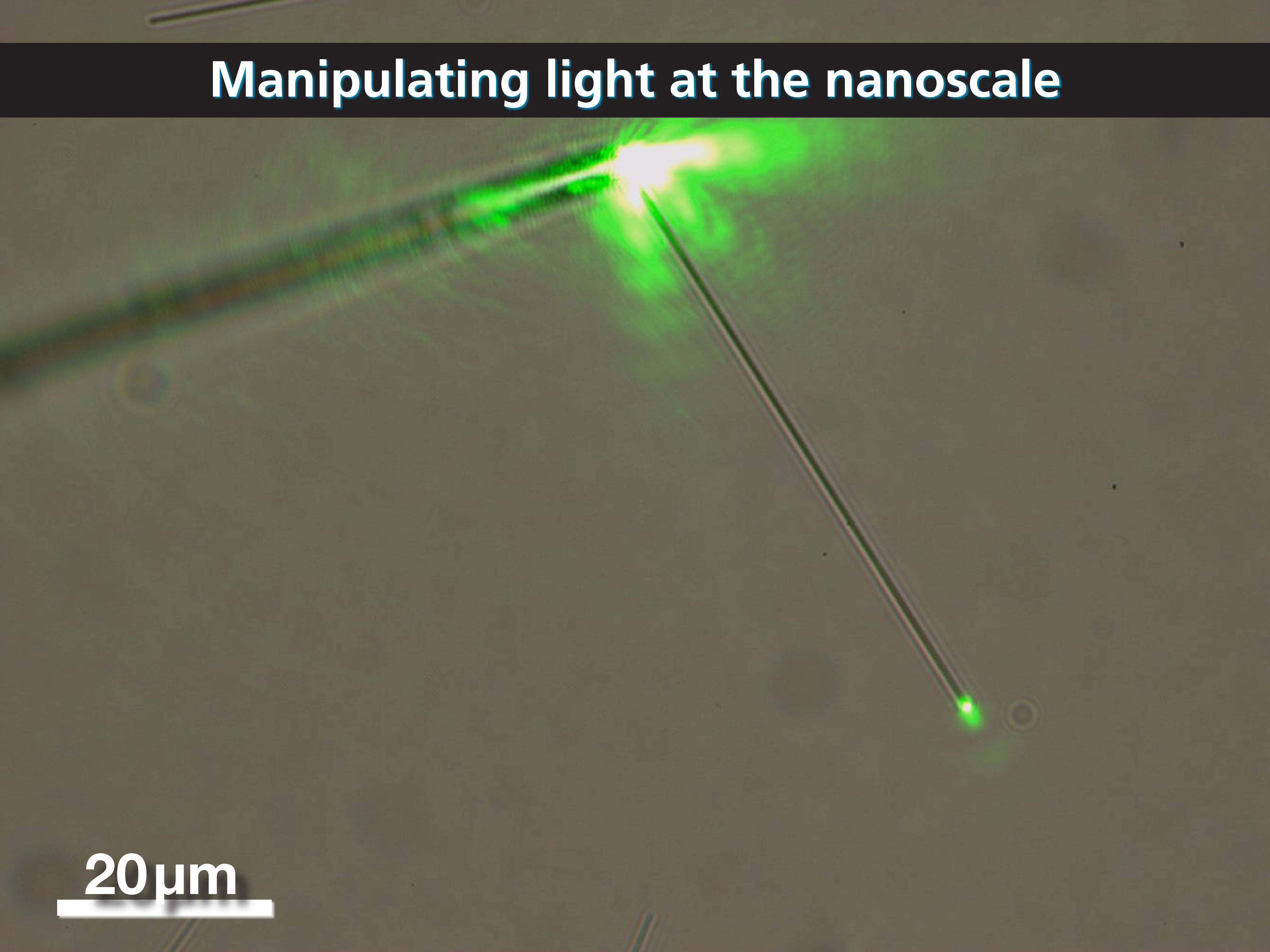
Manipulating light at the nanoscale

coupling to ZnO nanowires

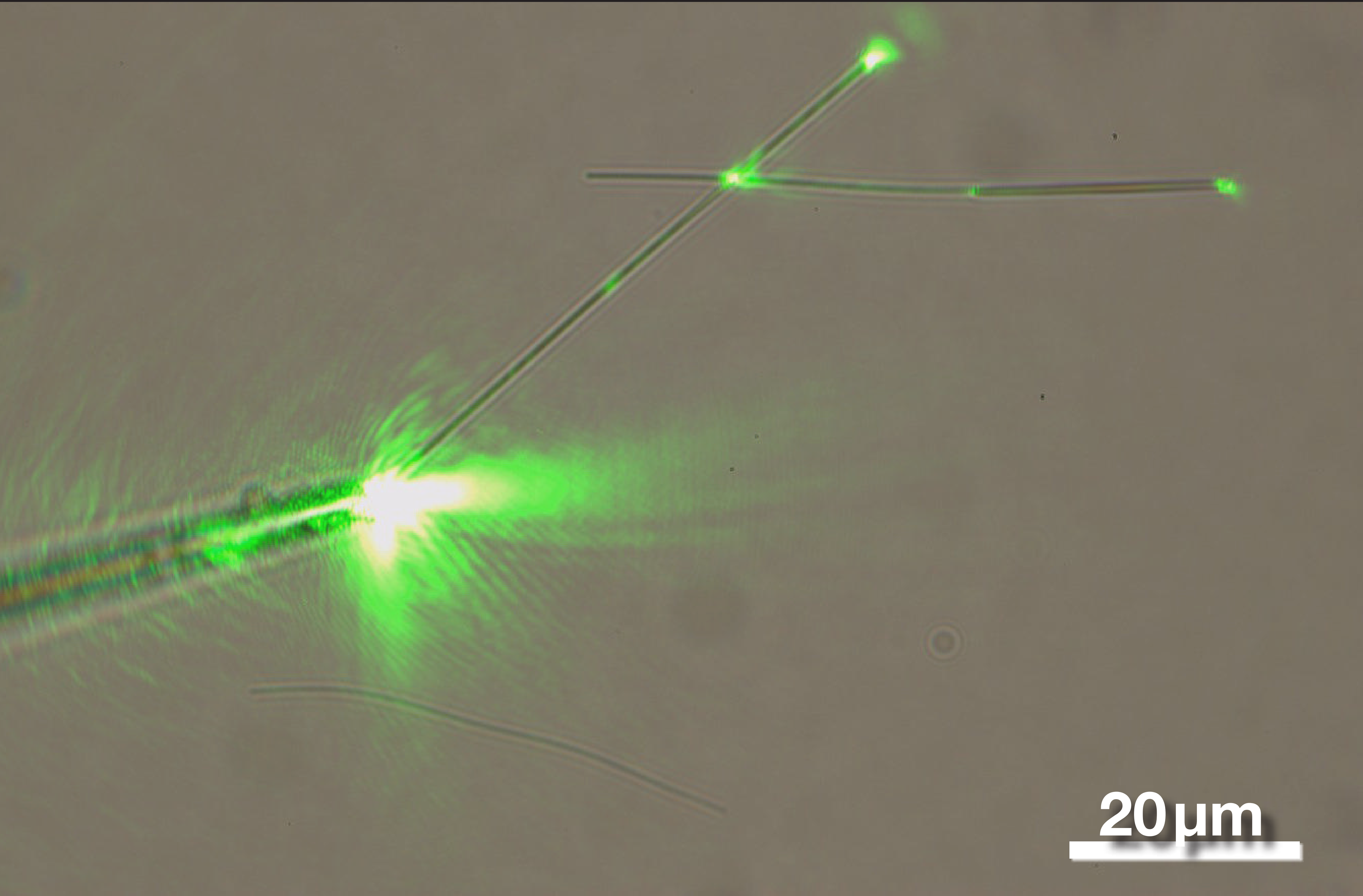


Manipulating light at the nanoscale




Manipulating light at the nanoscale
20 µm

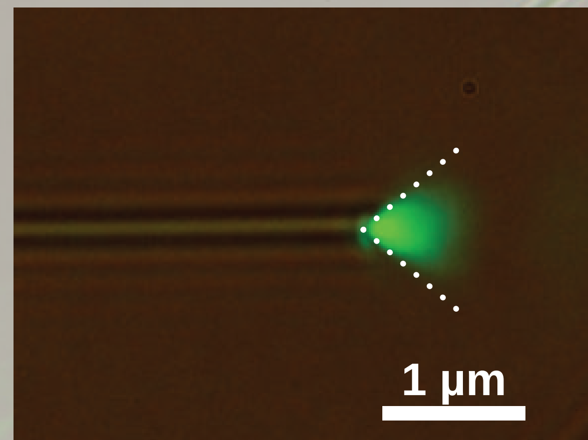
Manipulating light at the nanoscale



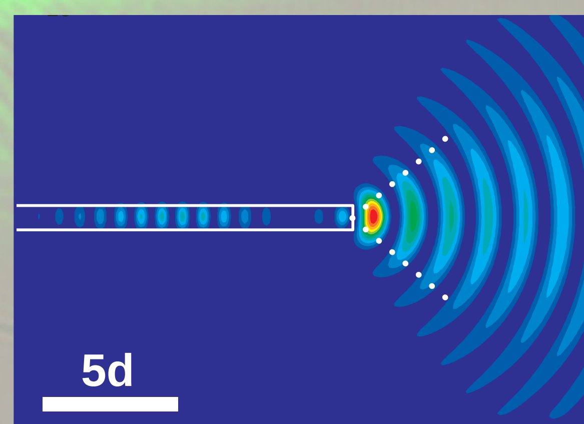
Manipulating light at the nanoscale

Nano Lett., 7, 3675 (2007)

Manipulating light at the nanoscale

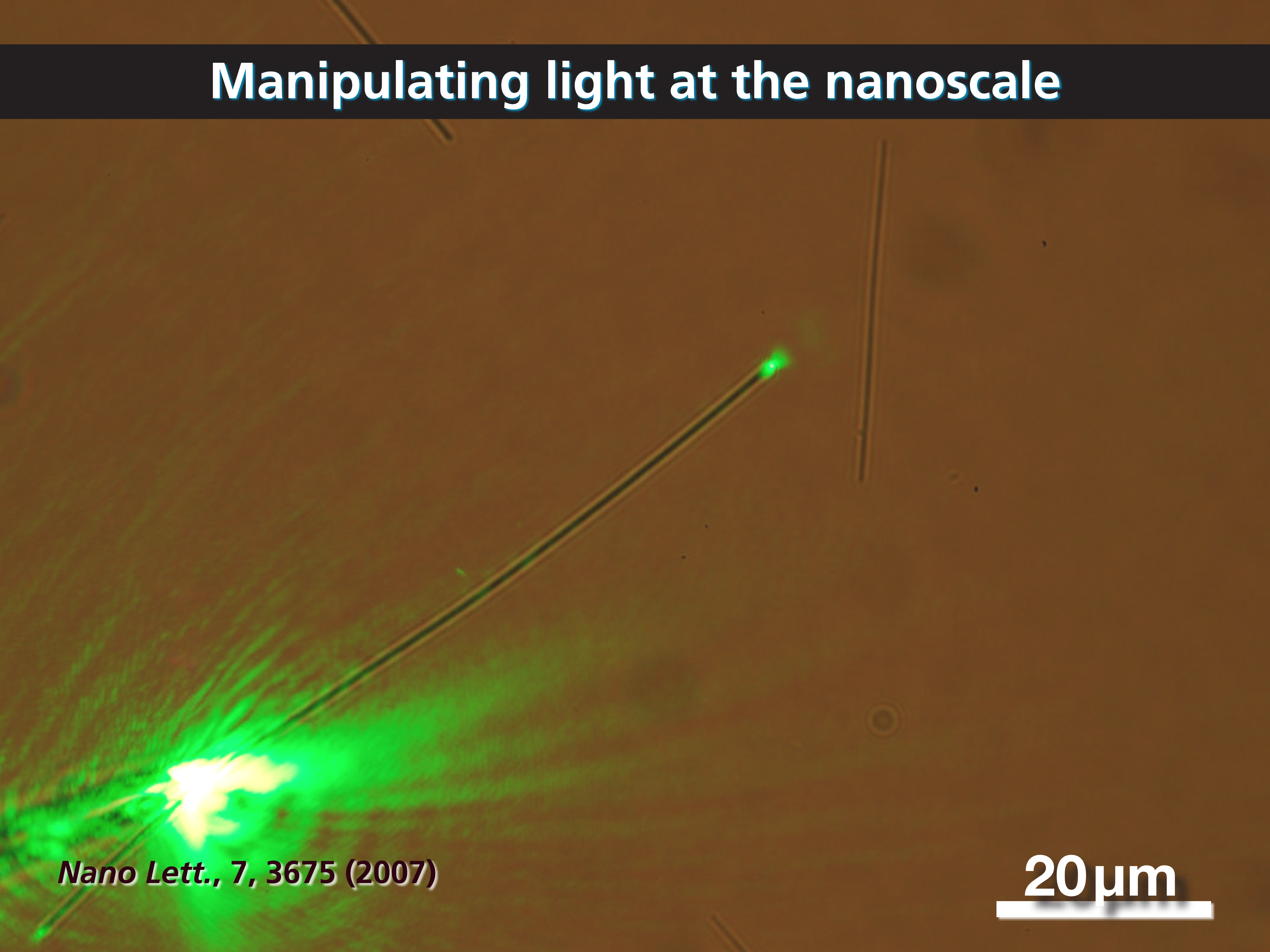


FDTD simulation



ab-initio.mit.edu/wiki/index/Meep

Manipulating light at the nanoscale



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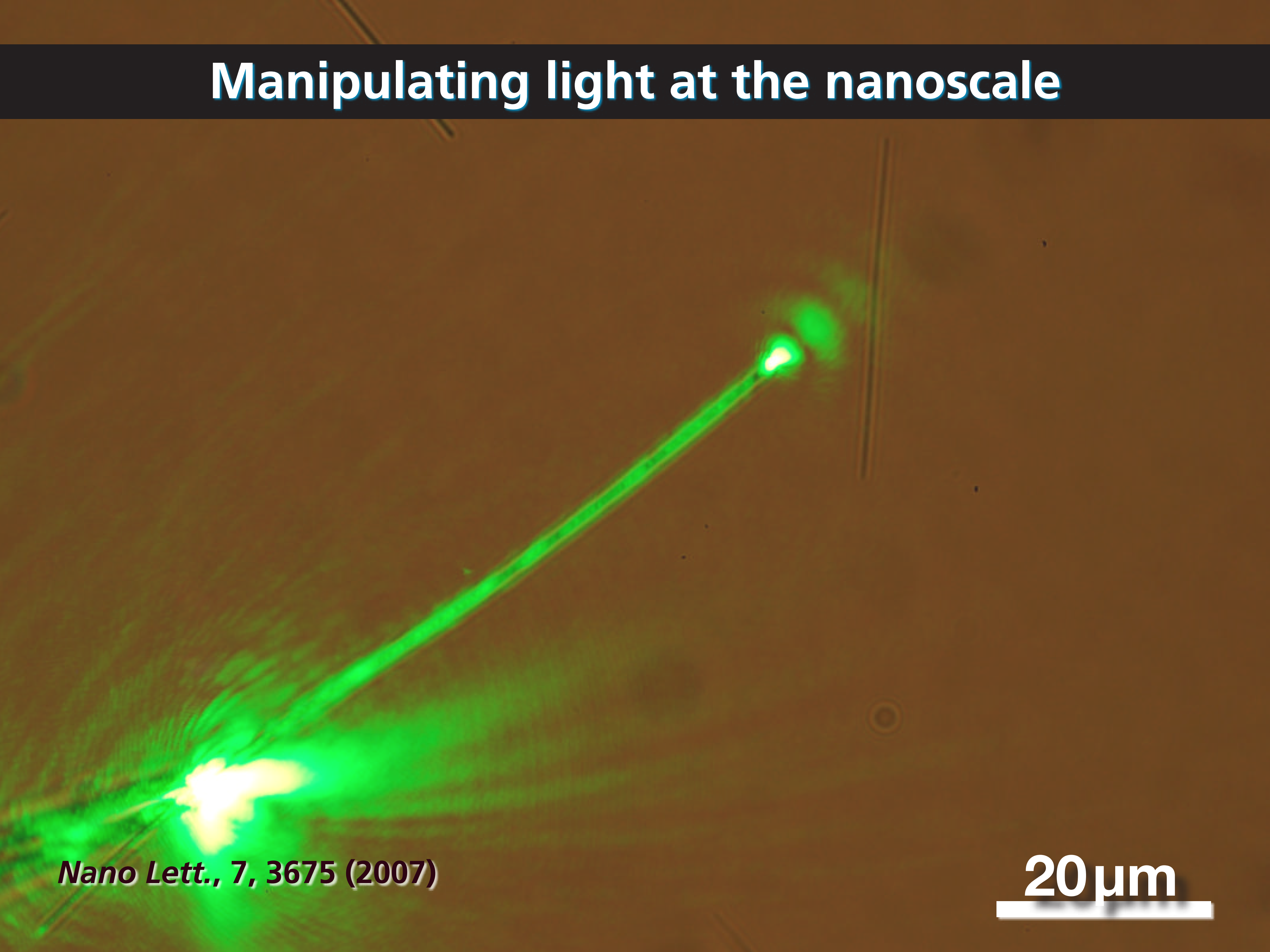
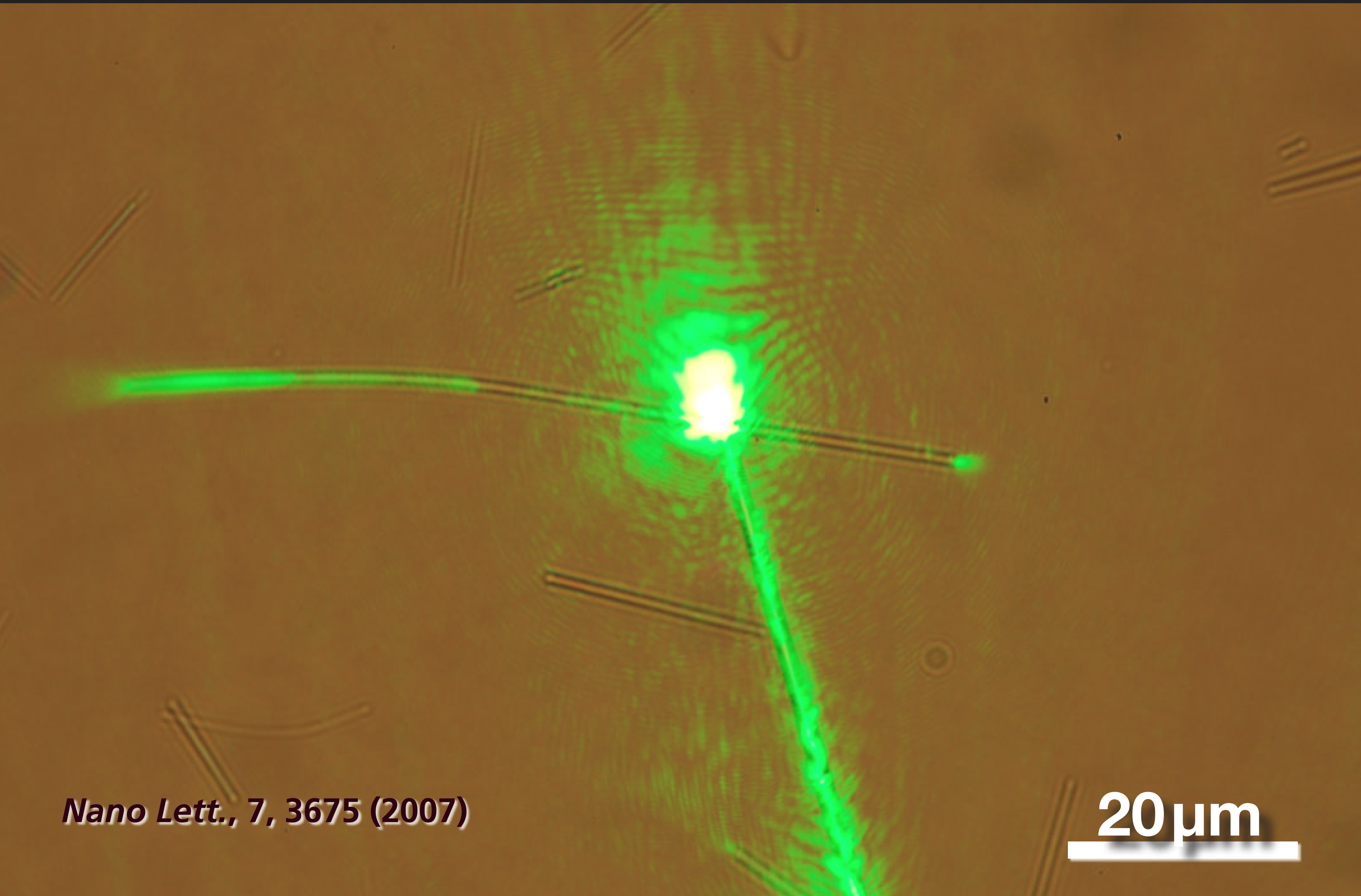
Manipulating light at the nanoscale



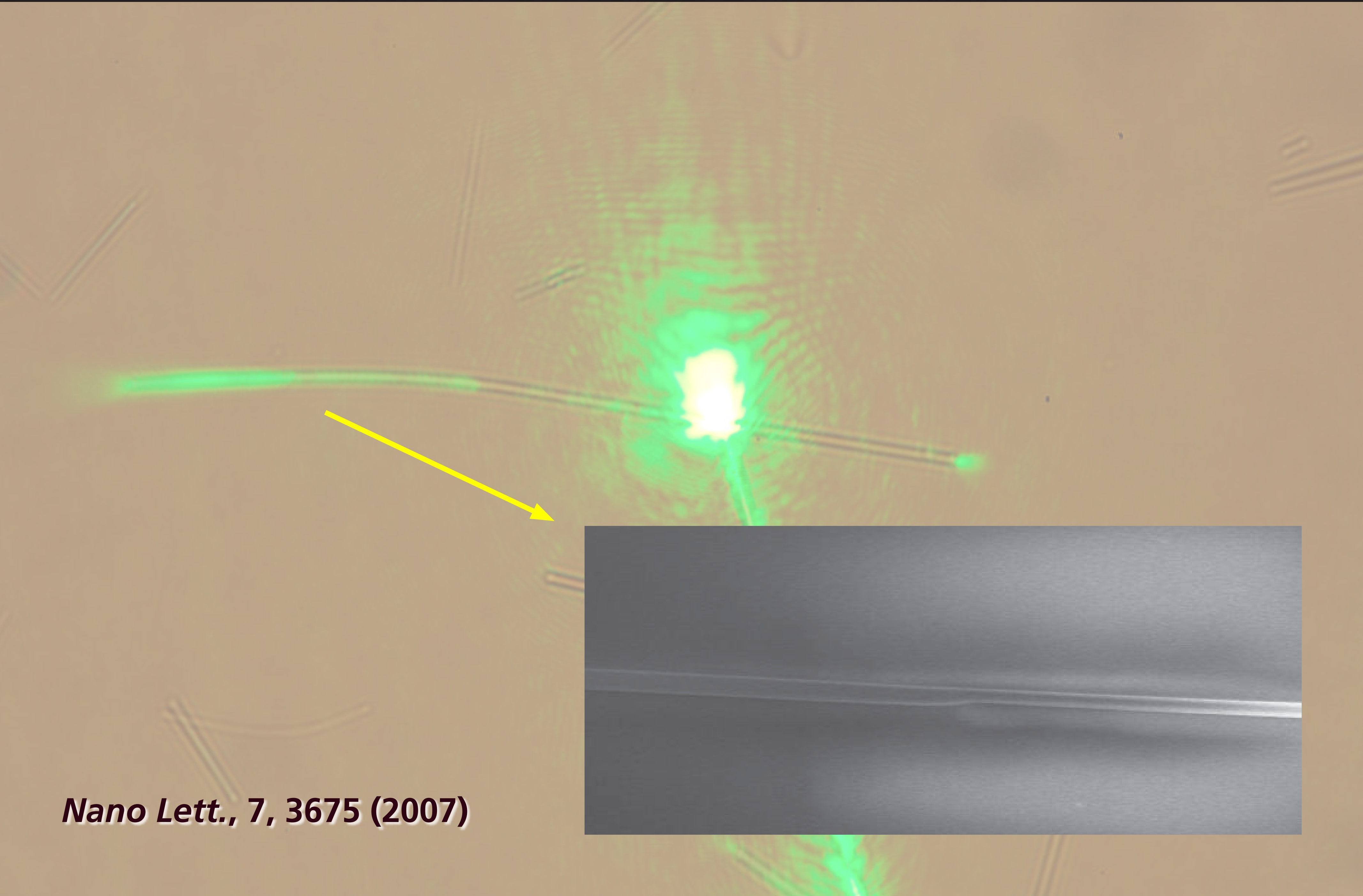
Nano Lett., 7, 3675 (2007)

Manipulating light at the nanoscale



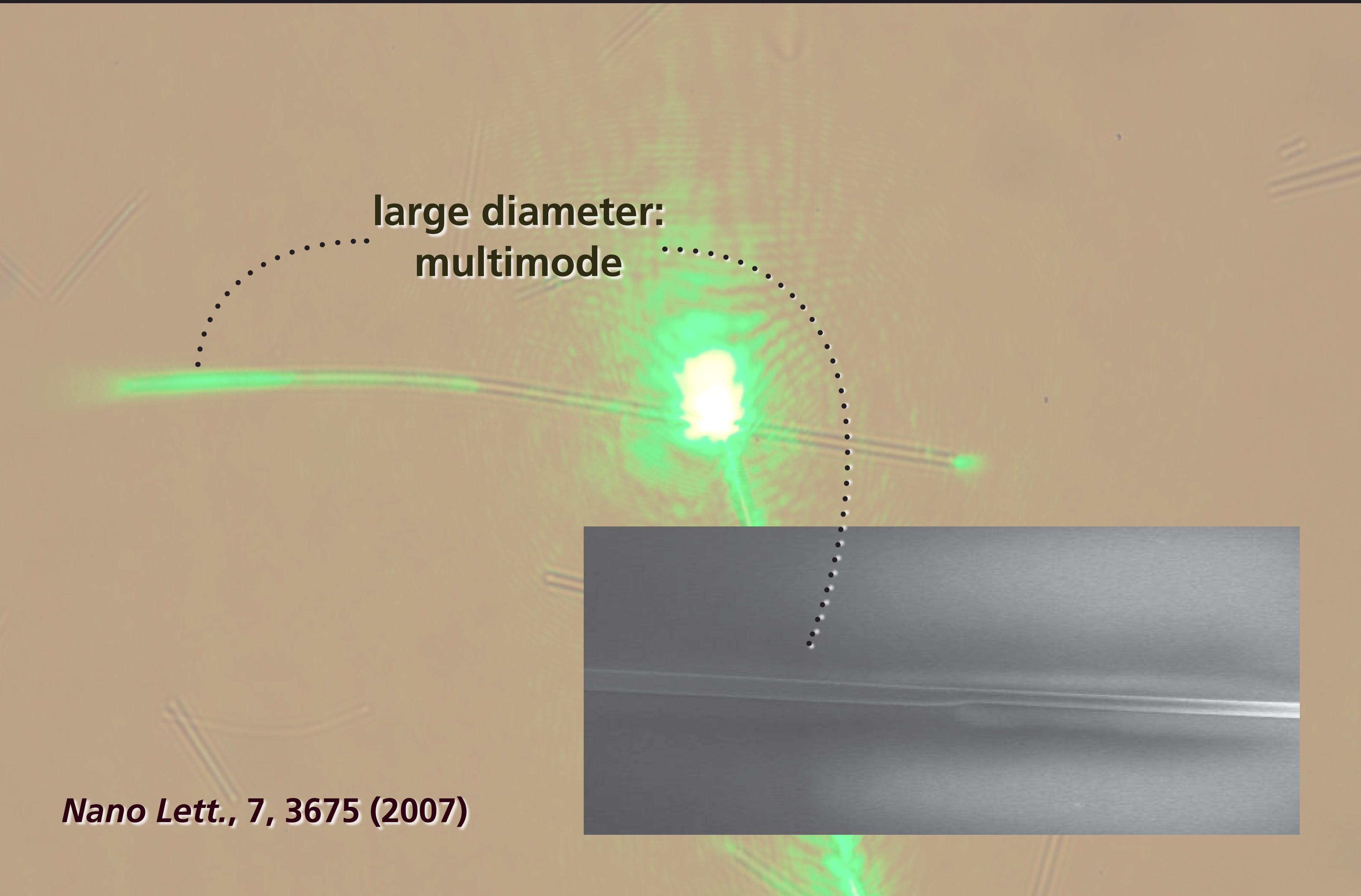
Nano Lett., 7, 3675 (2007)

Manipulating light at the nanoscale



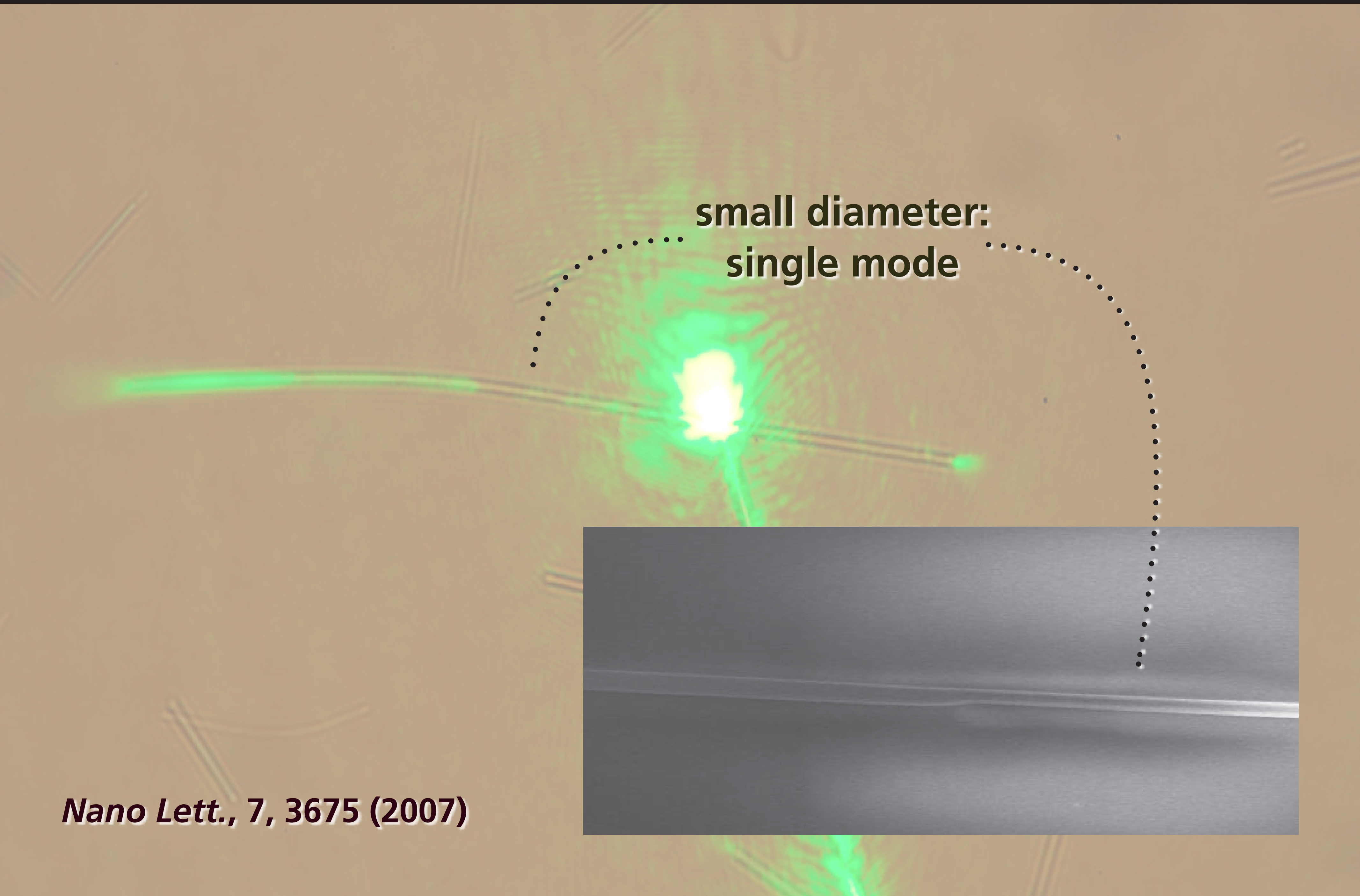
Nano Lett., 7, 3675 (2007)

Manipulating light at the nanoscale



Nano Lett., 7, 3675 (2007)

Manipulating light at the nanoscale



Nano Lett., 7, 3675 (2007)

Manipulating light at the nanoscale

Points to keep in mind:

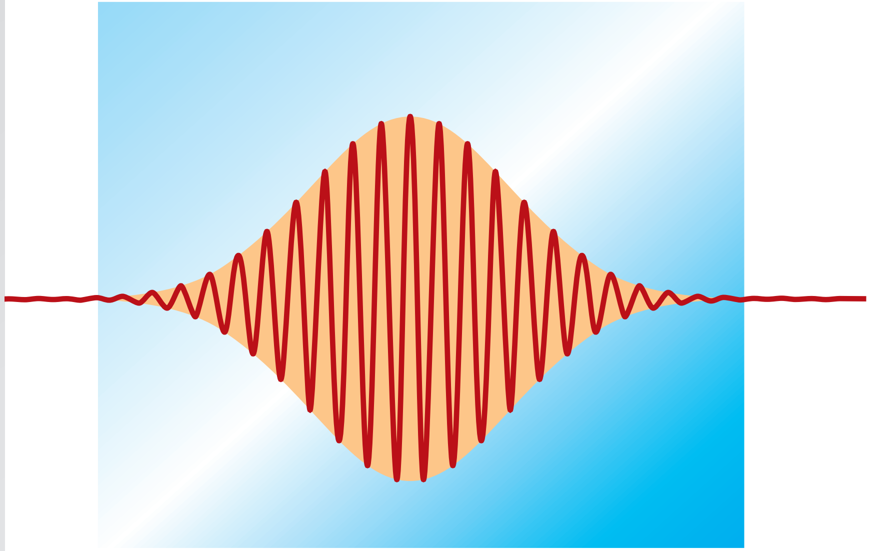
- low-loss guiding
- convenient evanescent coupling
- attached to ordinary fiber

Outline

- manipulating light at the nanoscale
- **supercontinuum generation**
- optical logic gates

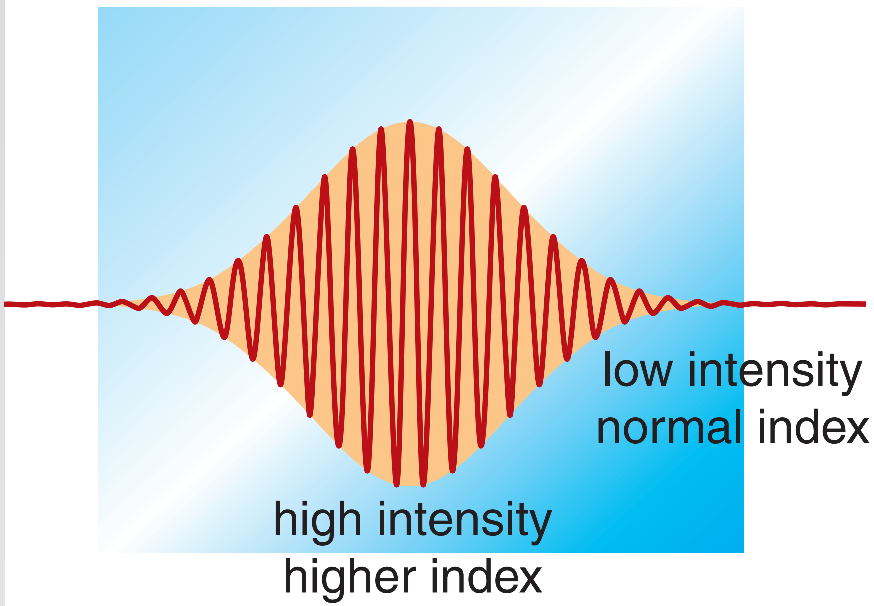
Supercontinuum generation

nonlinear dispersion: $n = n_o + n_2 I$



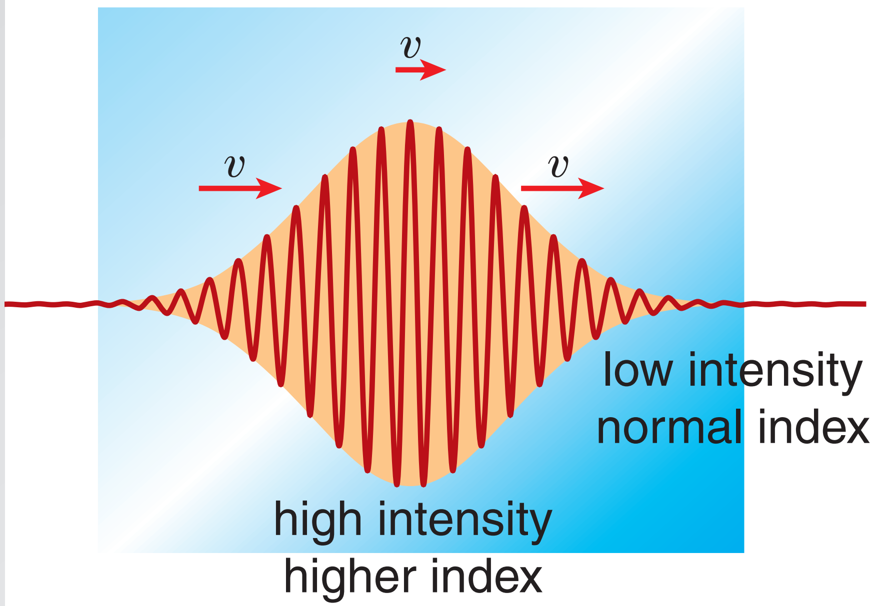
Supercontinuum generation

nonlinear dispersion: $n = n_o + n_2 I$



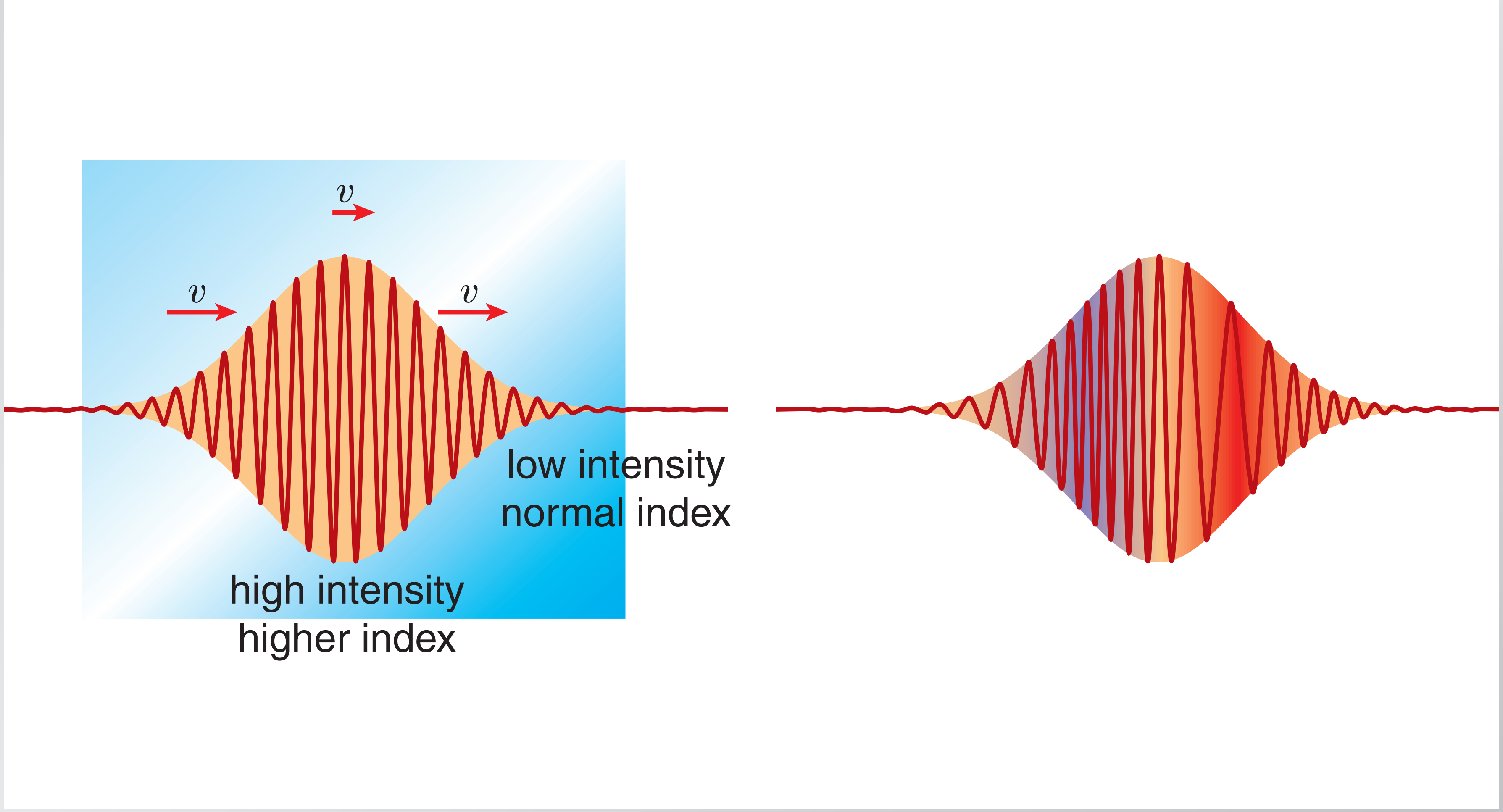
Supercontinuum generation

nonlinear dispersion: $n = n_o + n_2 I$



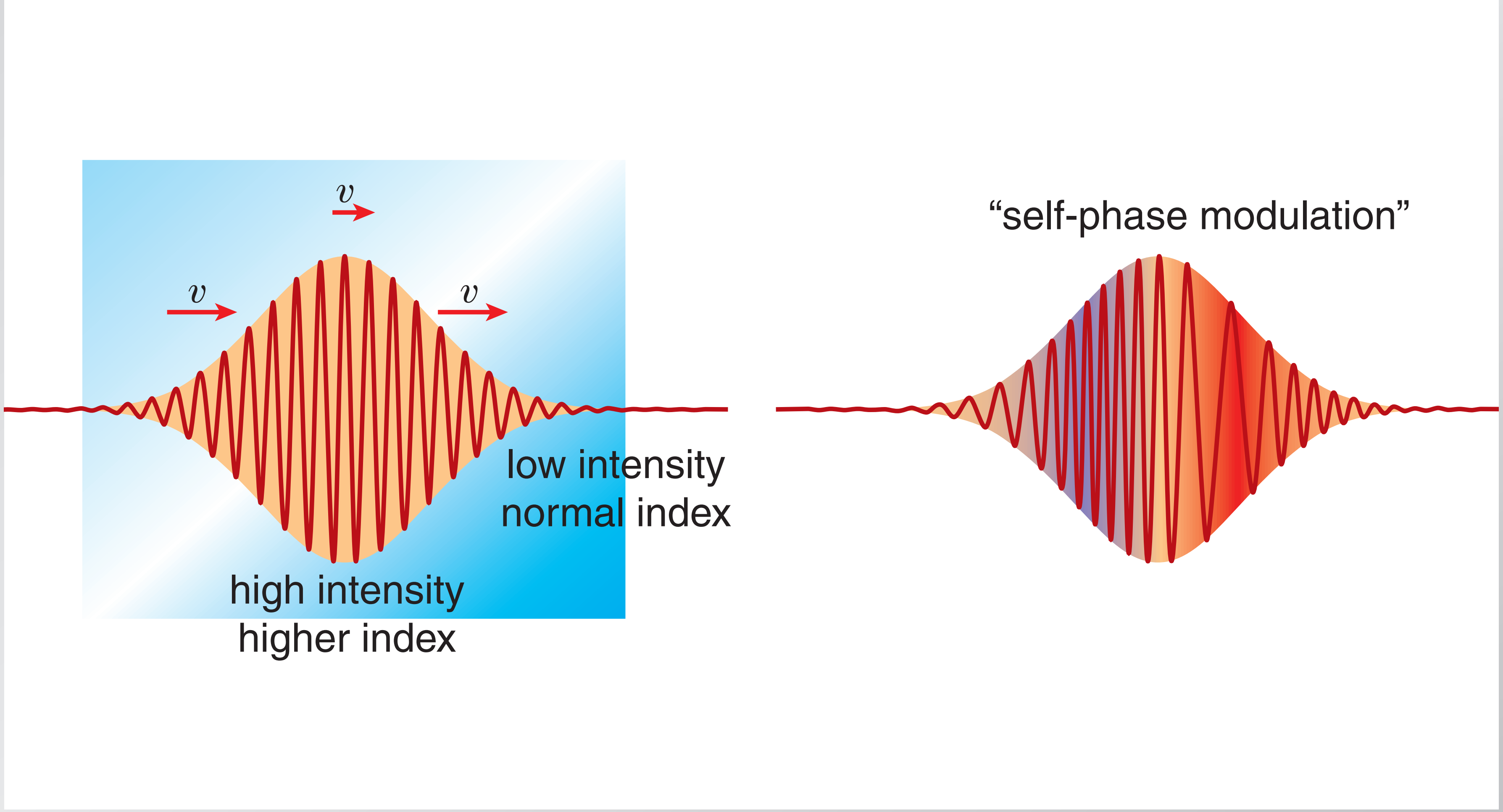
Supercontinuum generation

nonlinear dispersion: $n = n_o + n_2 I$



Supercontinuum generation

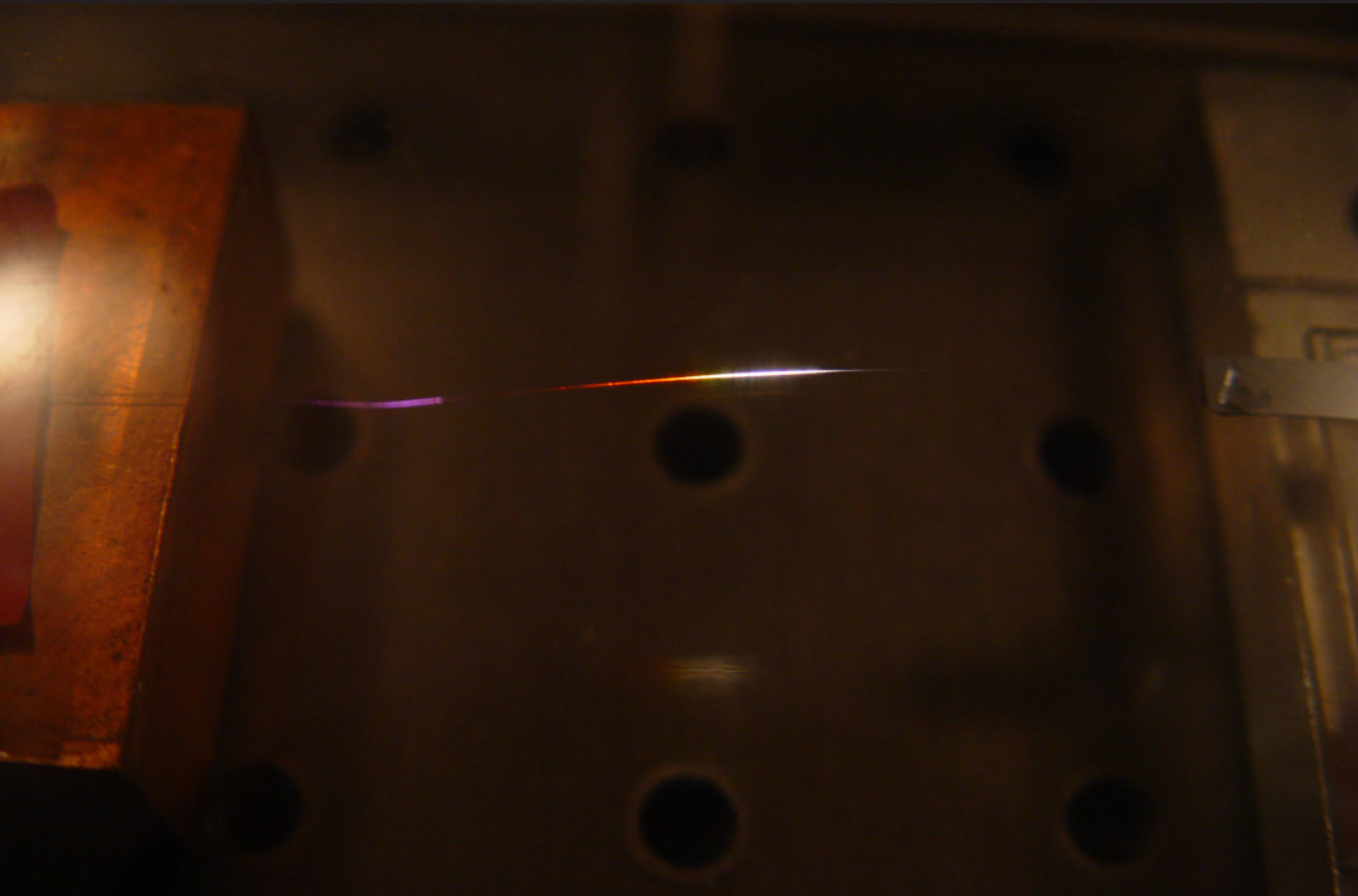
nonlinear dispersion: $n = n_o + n_2 I$



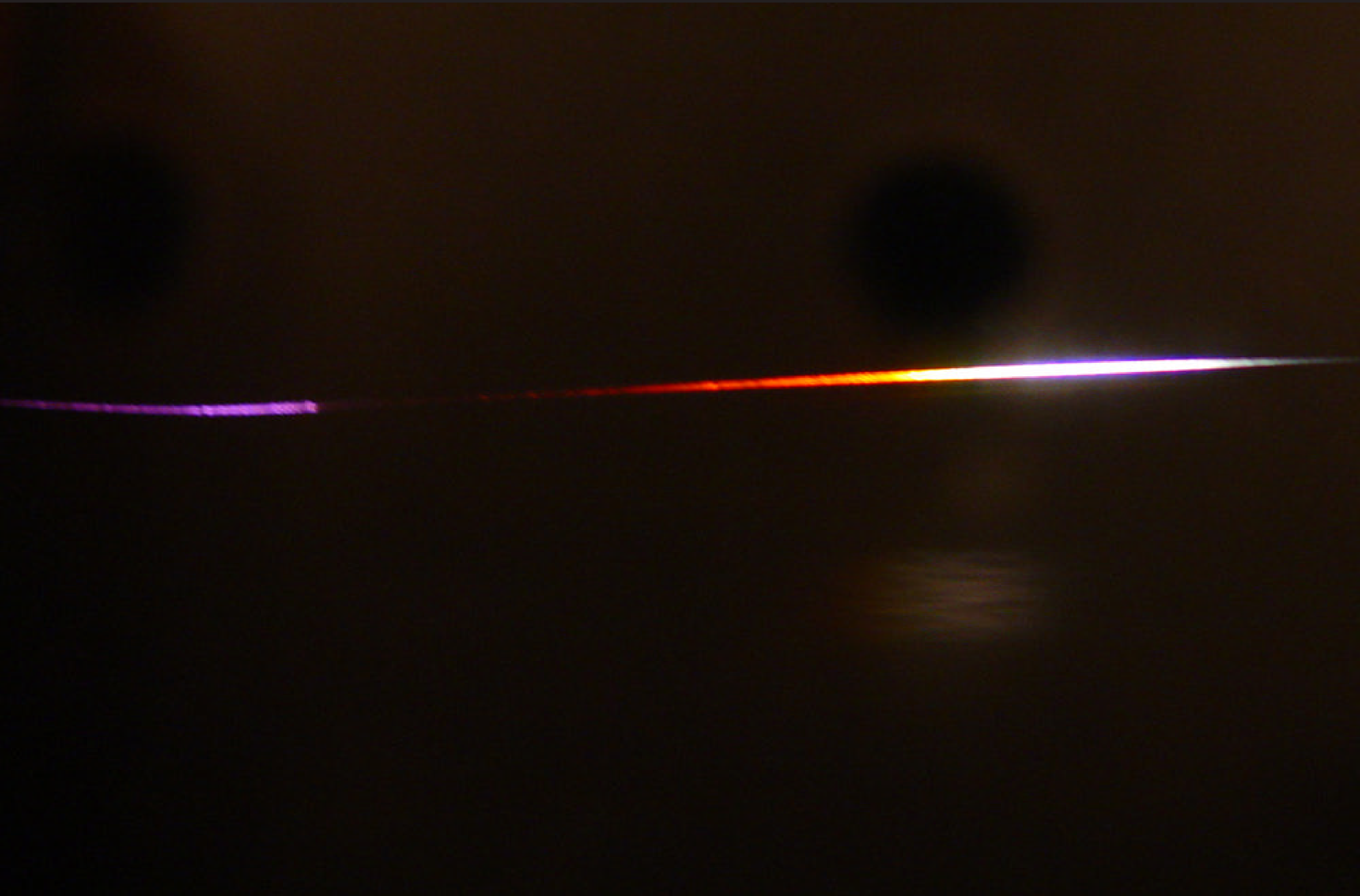
Supercontinuum generation

strong confinement $\longrightarrow$ high intensity

Supercontinuum generation

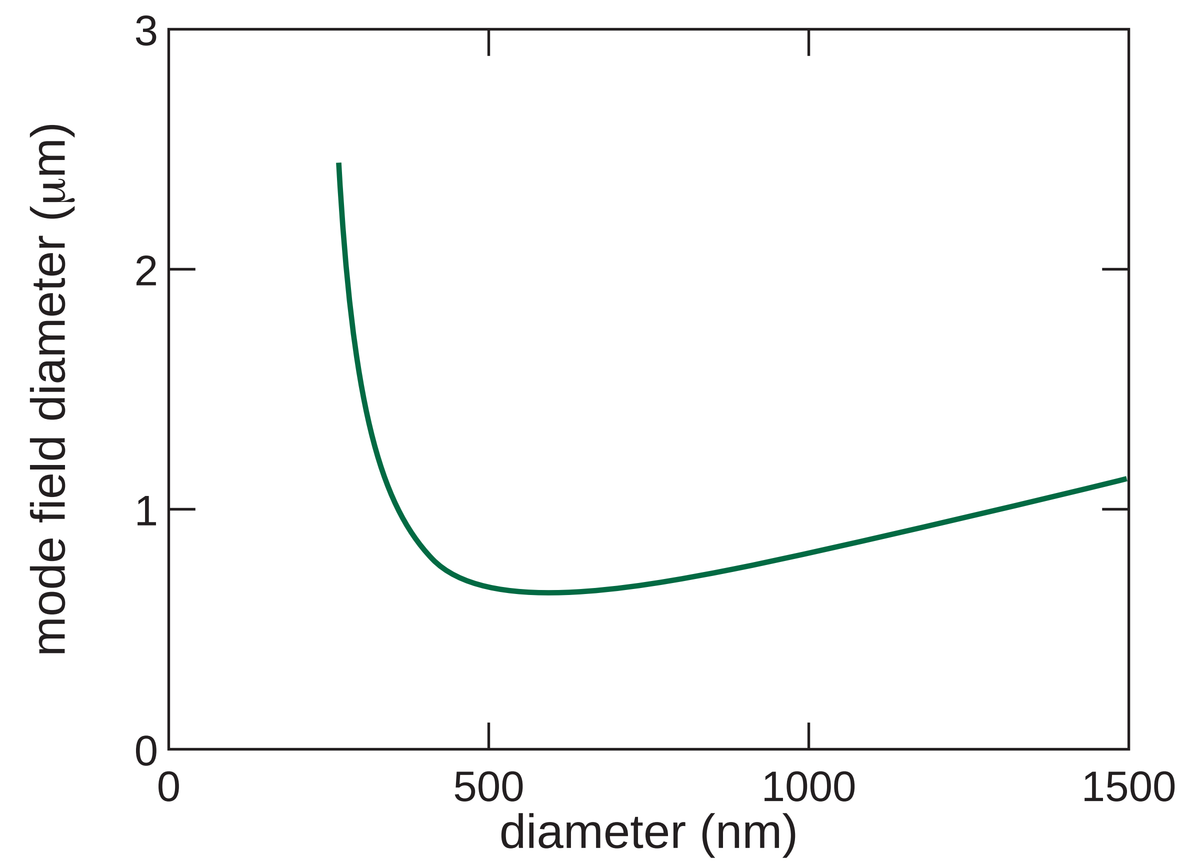


Supercontinuum generation



Supercontinuum generation

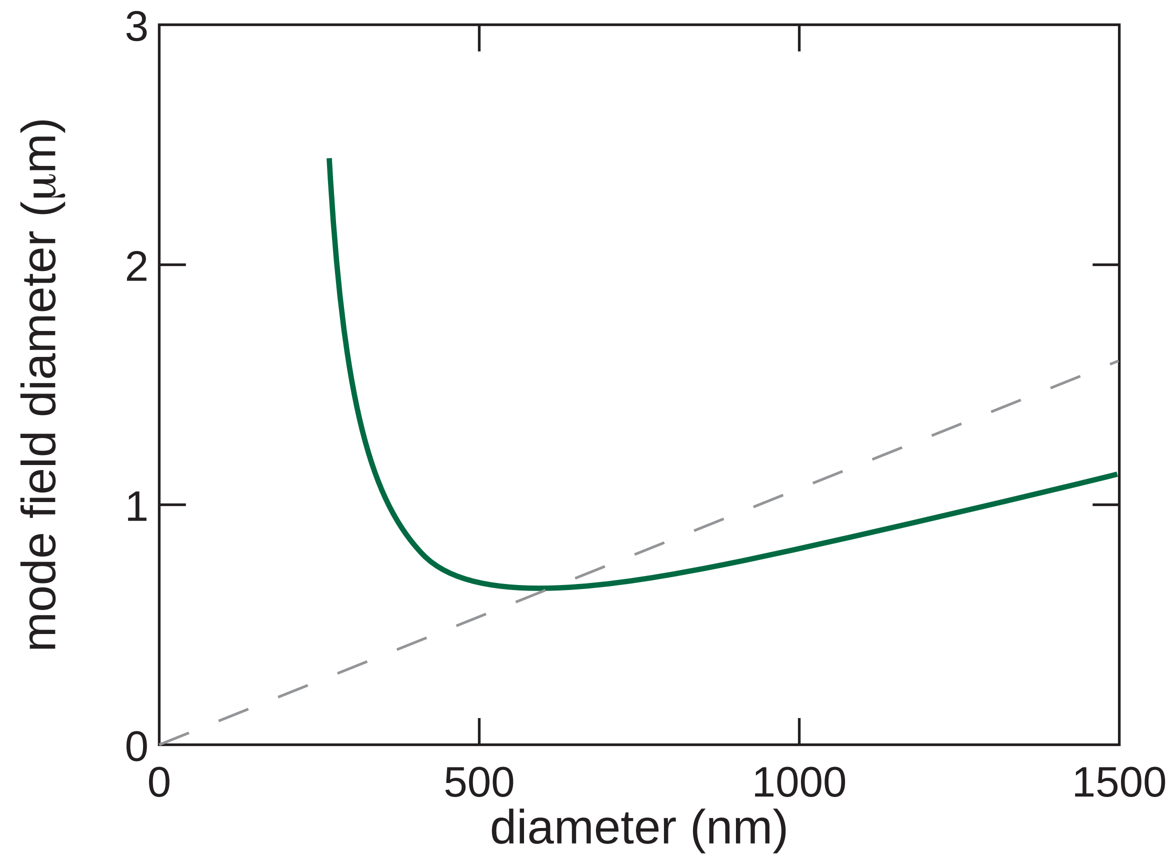
mode field diameter (λ = 800 nm)



M.A. Foster, *et al.*, *Optics Express*, 12, 2880 (2004)

Supercontinuum generation

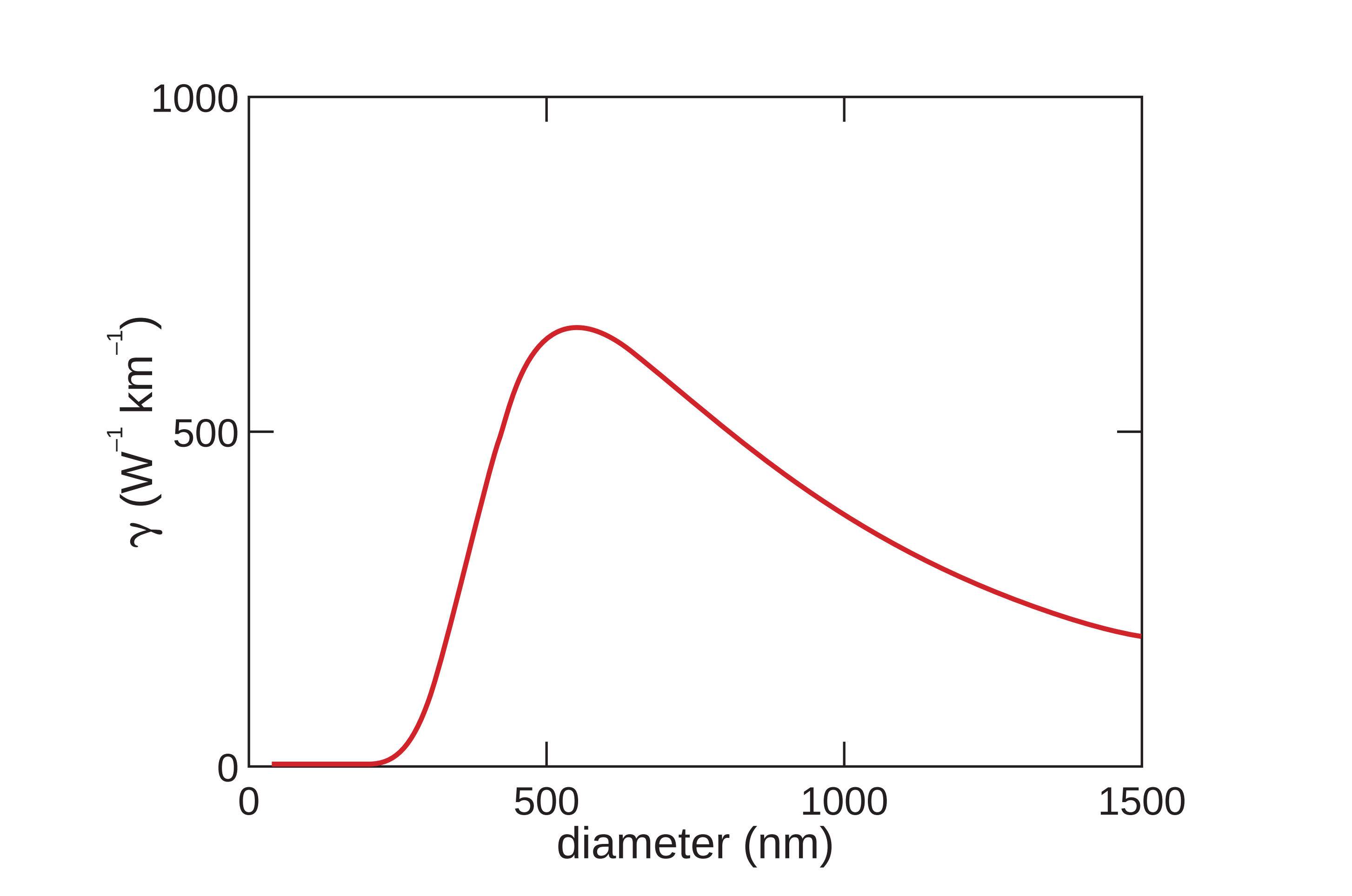
mode field diameter (λ = 800 nm)



M.A. Foster, *et al.*, *Optics Express*, 12, 2880 (2004)

Supercontinuum generation

nonlinear parameter



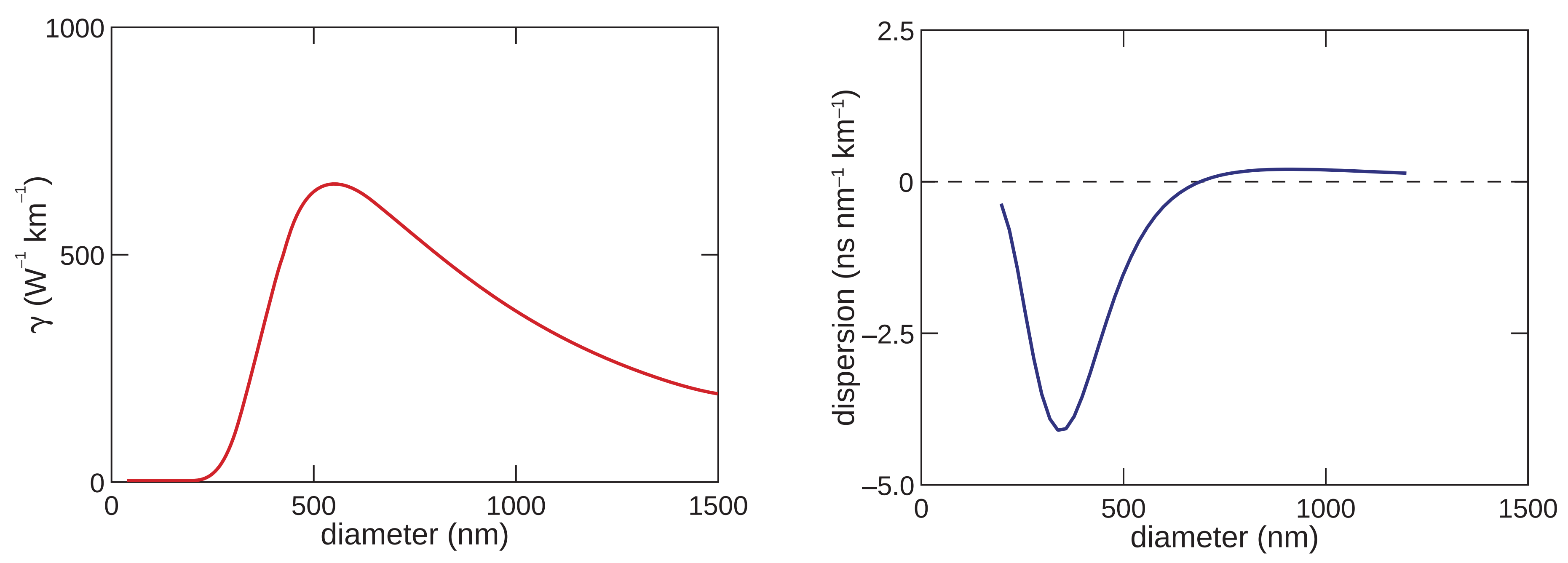
M.A. Foster, *et al.*, *Optics Express*, 12, 2880 (2004)

Supercontinuum generation

dispersion important!

Supercontinuum generation

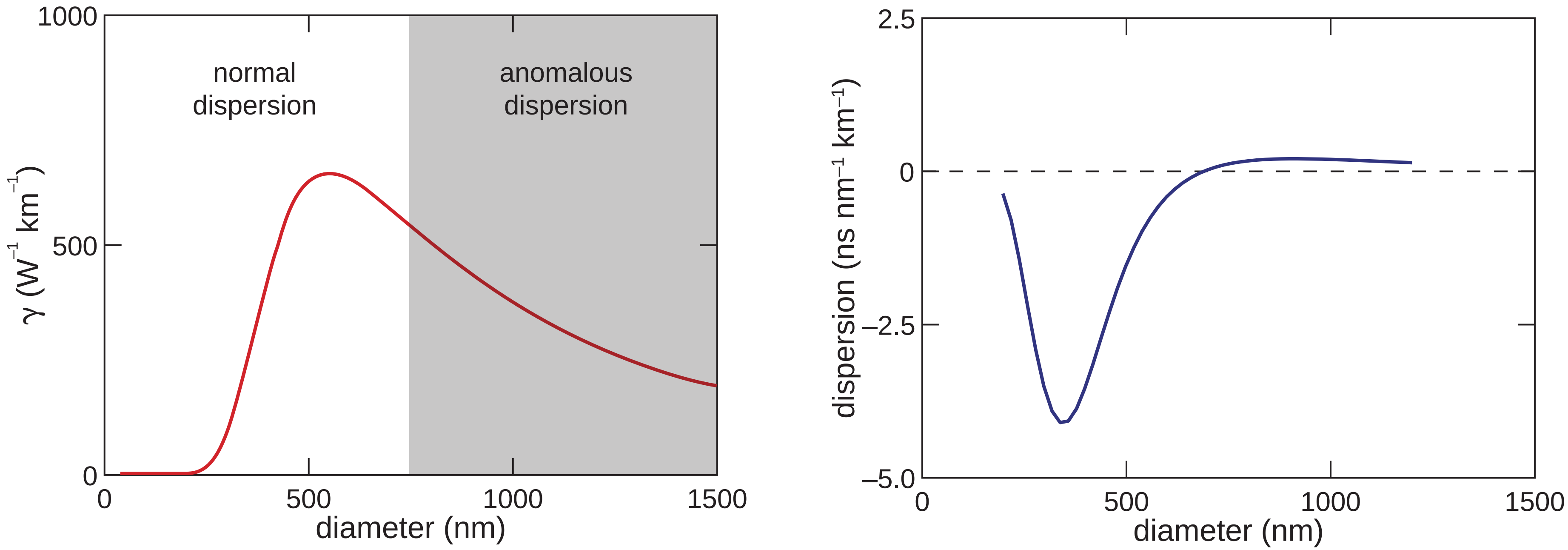
waveguide dispersion



***Optics Express*, 12, 1025 (2004)**

Supercontinuum generation

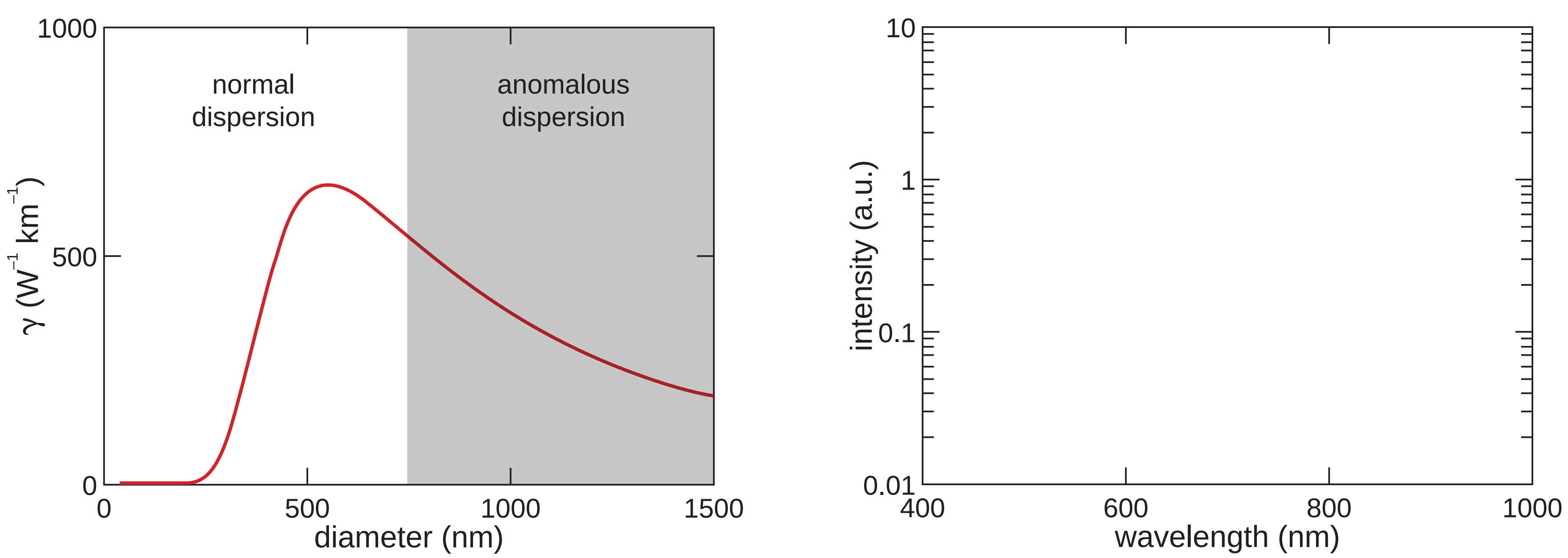
waveguide dispersion



***Optics Express*, 12, 1025 (2004)**

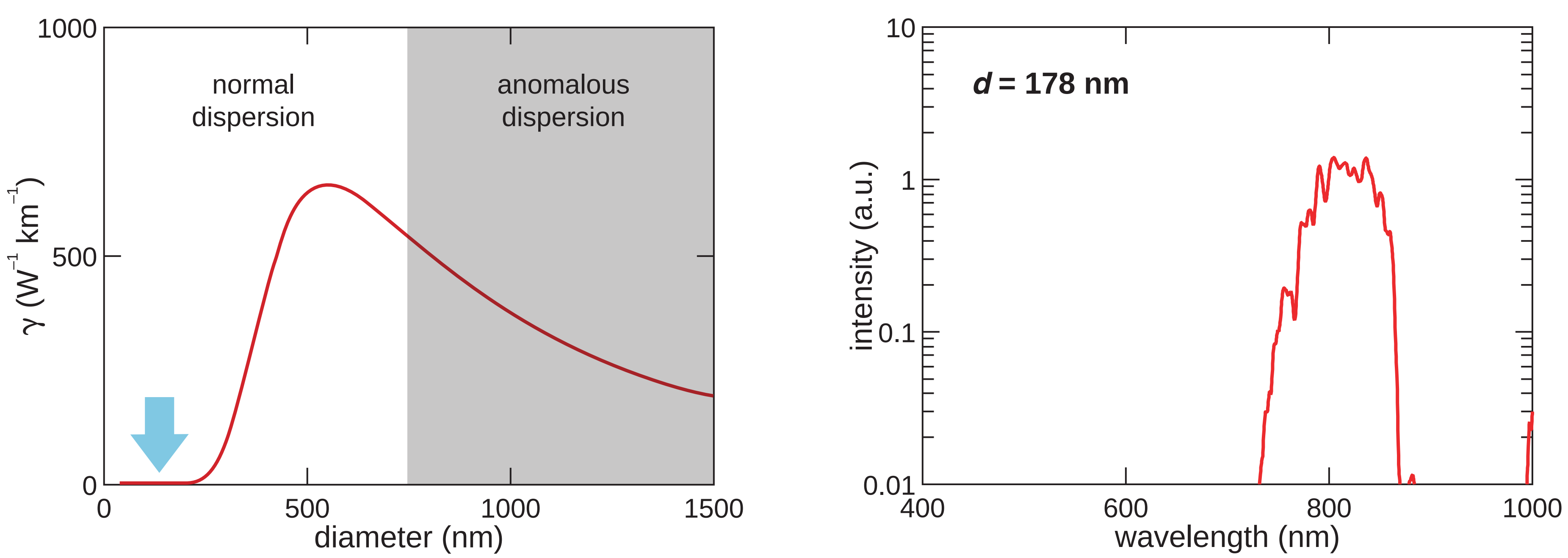
Supercontinuum generation

nanowire continuum generation



Supercontinuum generation

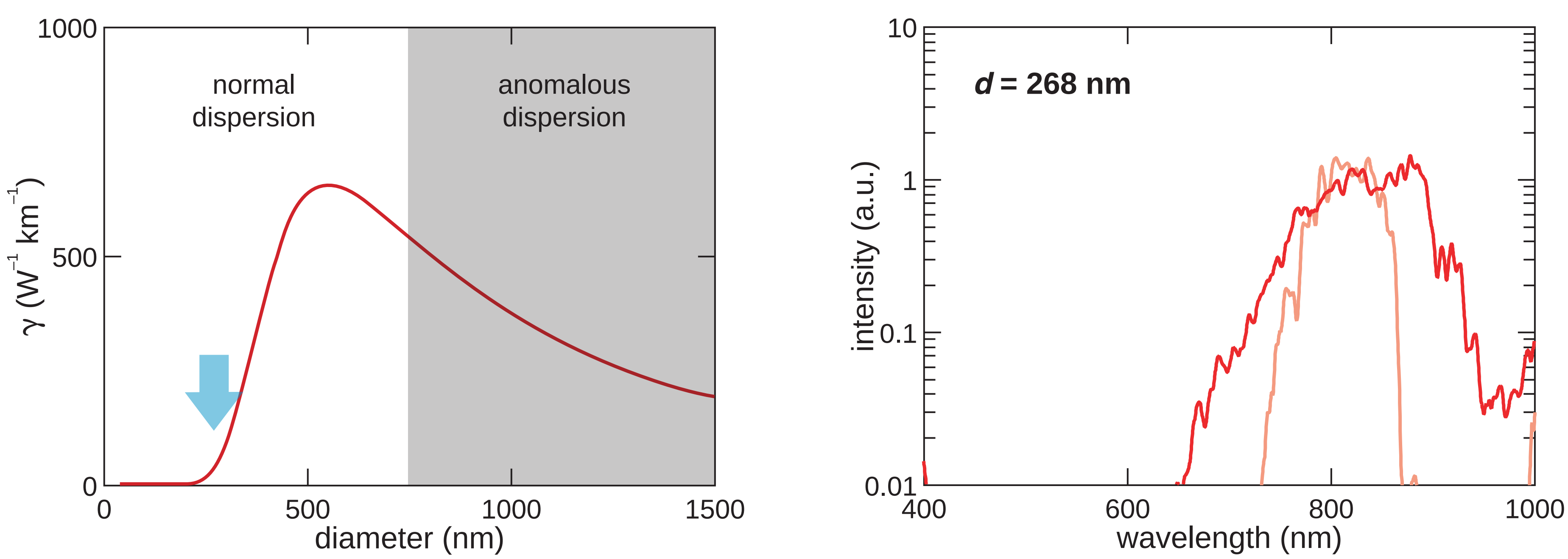
nanowire continuum generation



Optics Express, 14, 9408 (2006)

Supercontinuum generation

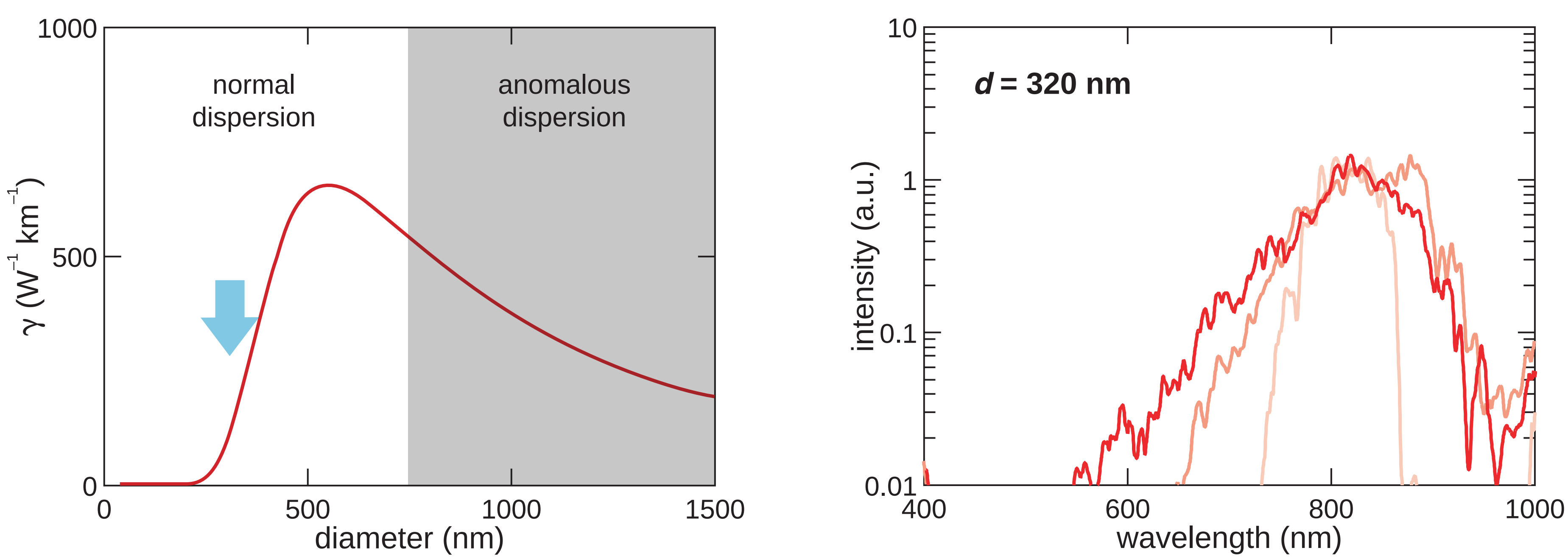
nanowire continuum generation



***Optics Express*, 14, 9408 (2006)**

Supercontinuum generation

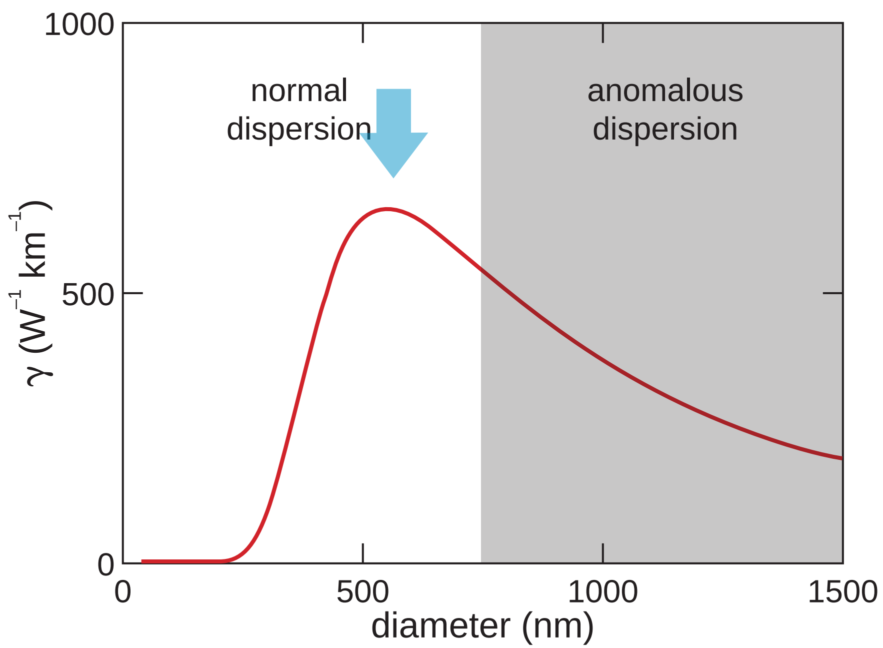
nanowire continuum generation

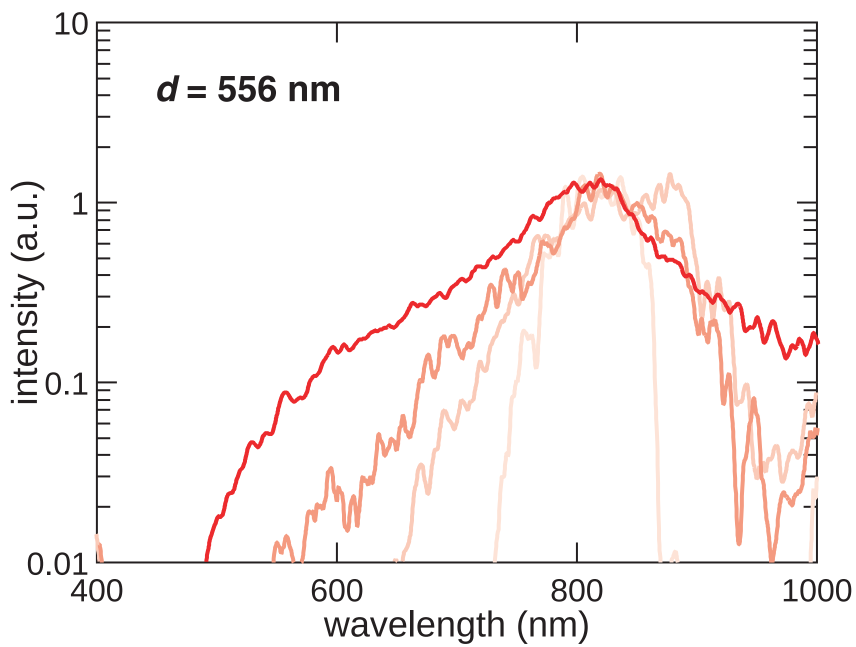


***Optics Express*, 14, 9408 (2006)**

Supercontinuum generation

nanowire continuum generation

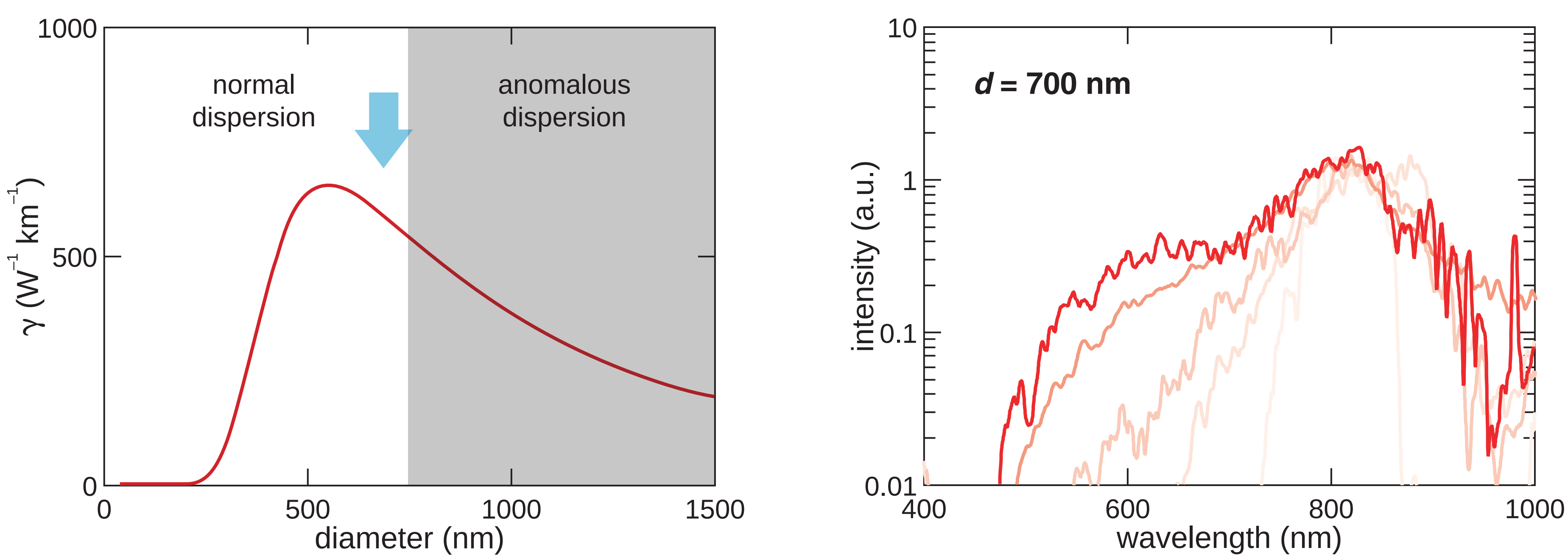




***Optics Express*, 14, 9408 (2006)**

Supercontinuum generation

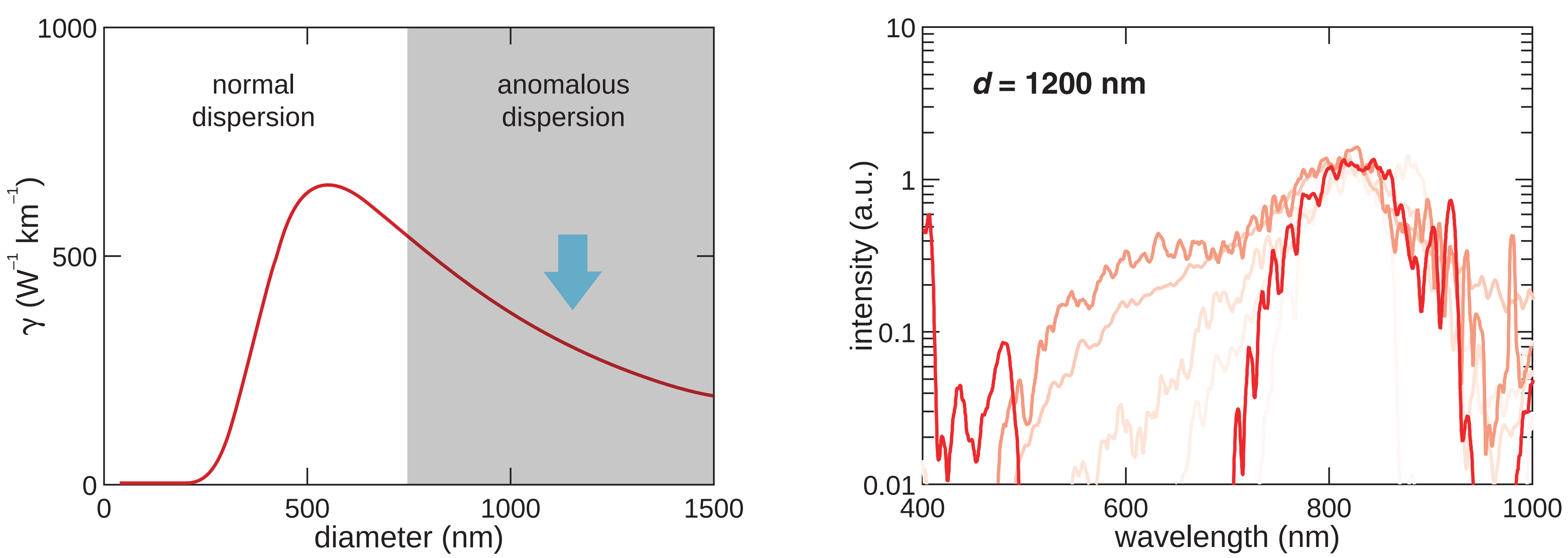
nanowire continuum generation



***Optics Express*, 14, 9408 (2006)**

Supercontinuum generation

nanowire continuum generation



***Optics Express*, 14, 9408 (2006)**

Supercontinuum generation

energy in nanowire < 100 pJ!

Supercontinuum generation

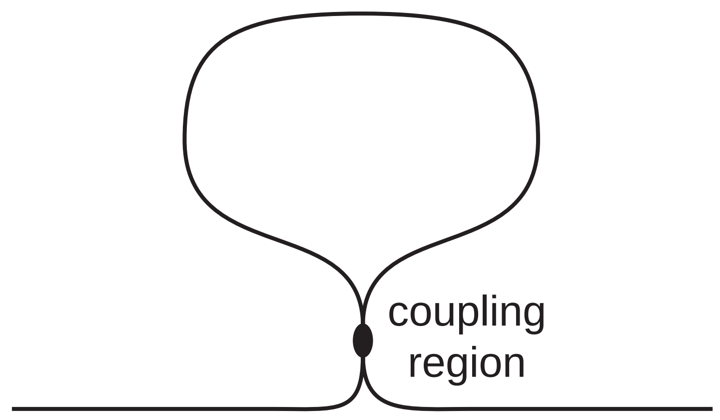
- picojoule nonlinear optics
- optimum diameter for silica 500–600 nm
- low dispersion

Outline

- manipulating light at the nanoscale
- supercontinuum generation
- optical logic gates

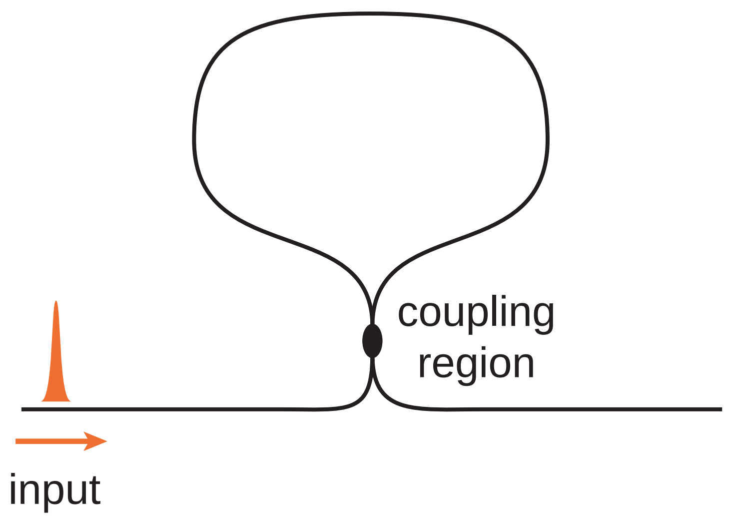
Optical logic gates

nanowire Sagnac interferometer



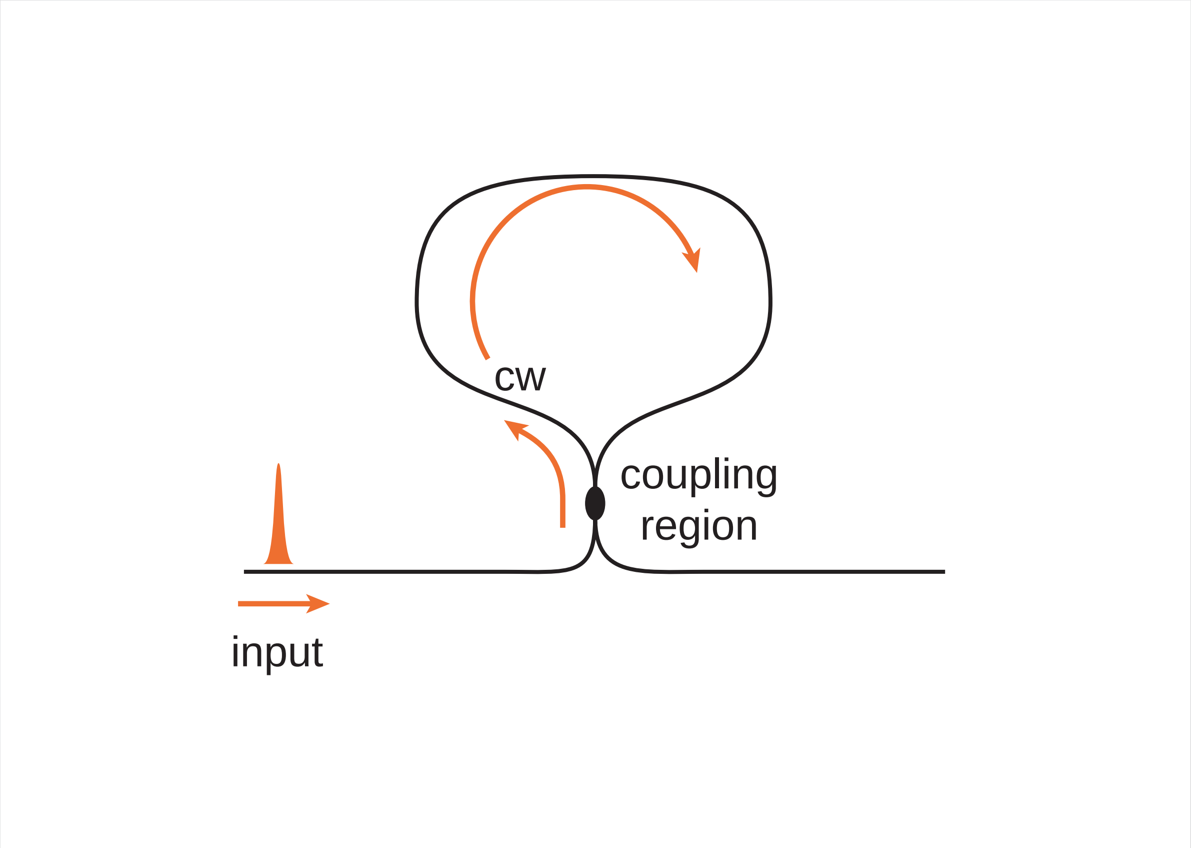
Optical logic gates

nanowire Sagnac interferometer



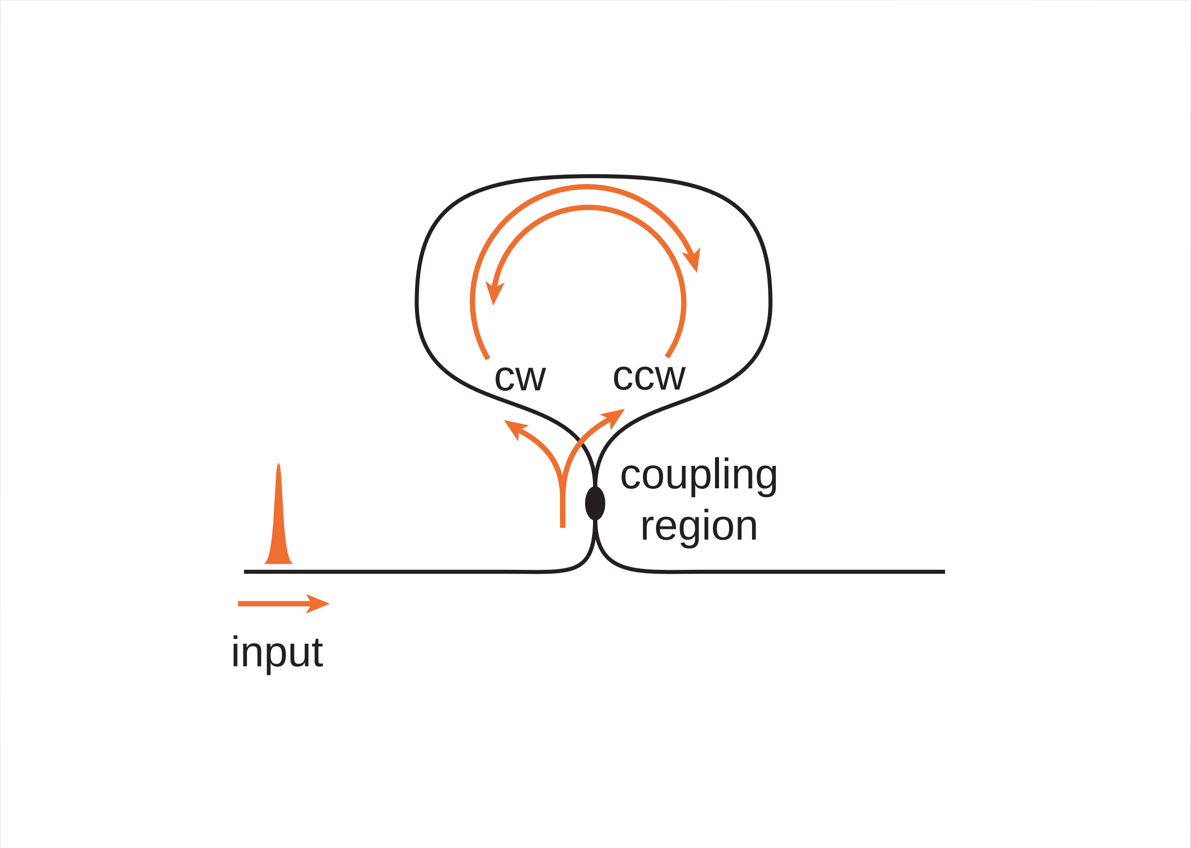
Optical logic gates

nanowire Sagnac interferometer



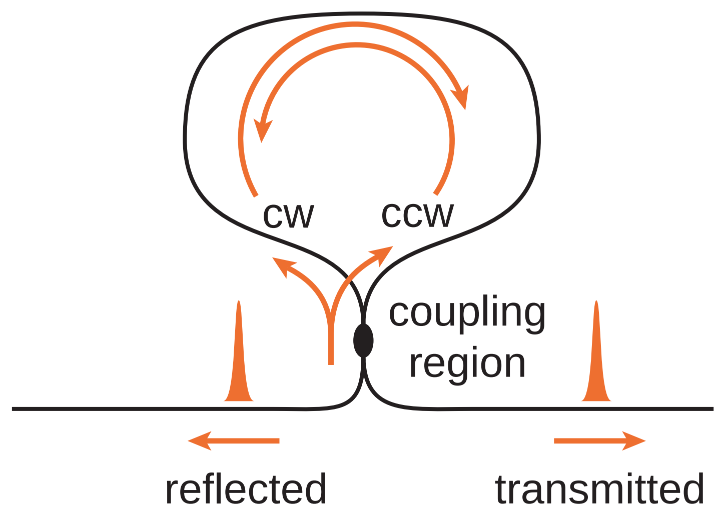
Optical logic gates

nanowire Sagnac interferometer



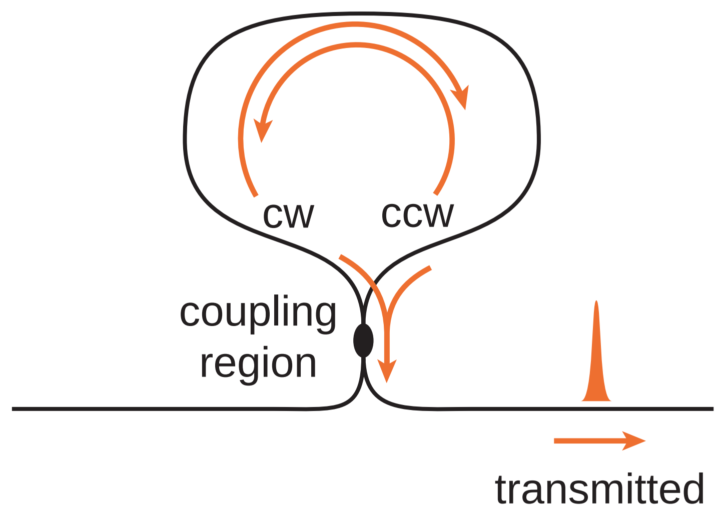
Optical logic gates

nanowire Sagnac interferometer



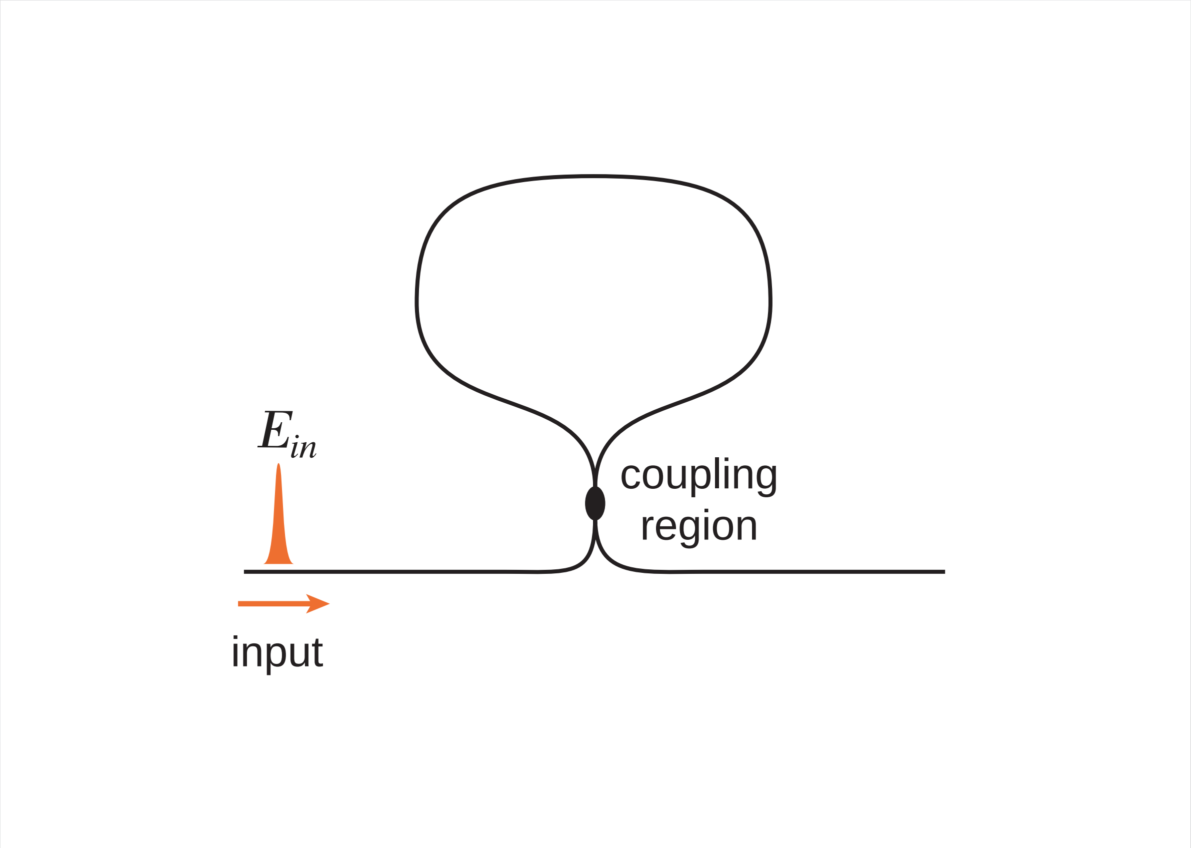
Optical logic gates

output = transmitted cw + ccw power



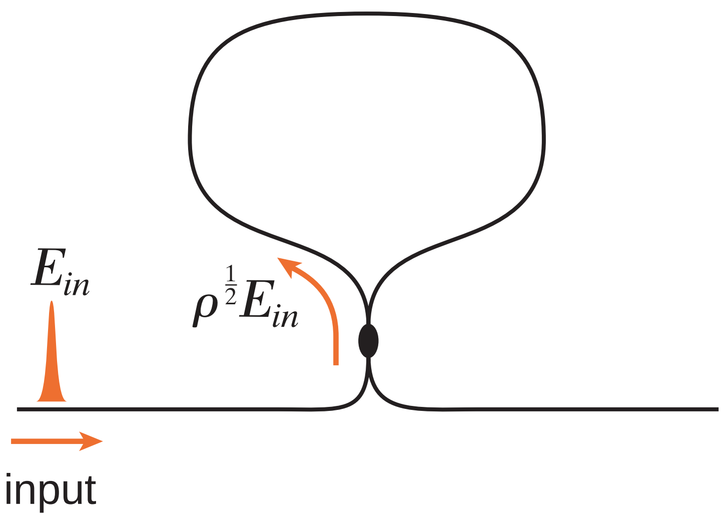
Optical logic gates

input electric field amplitude E_{in}



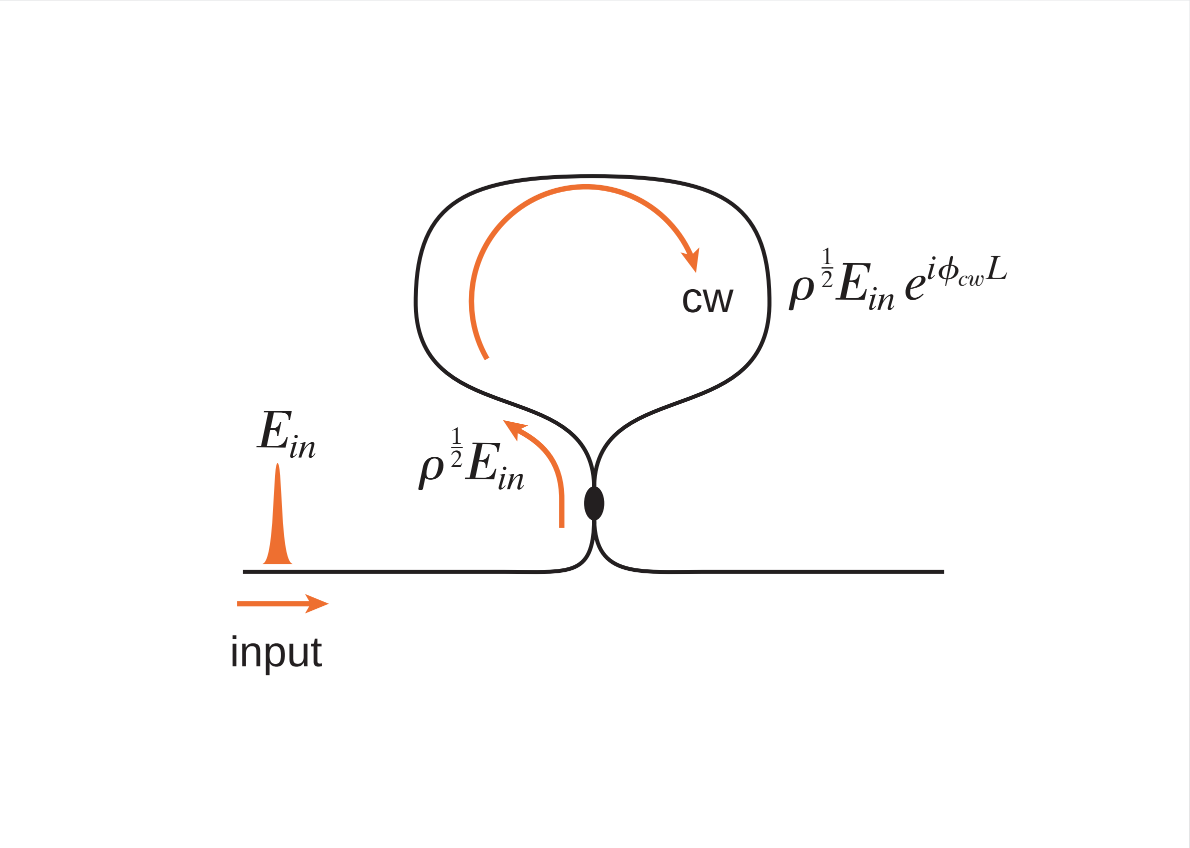
Optical logic gates

coupling parameter: ρ



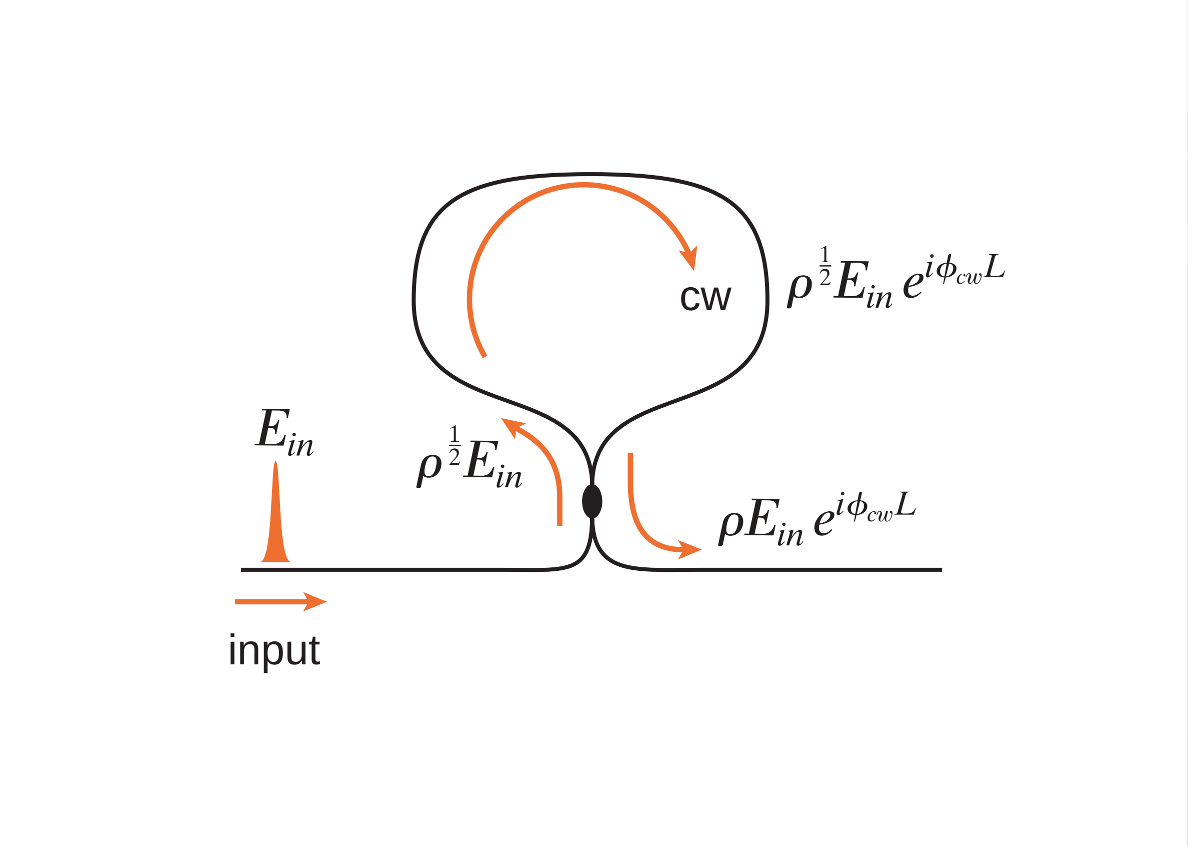
Optical logic gates

phase accumulation over path length of loop L



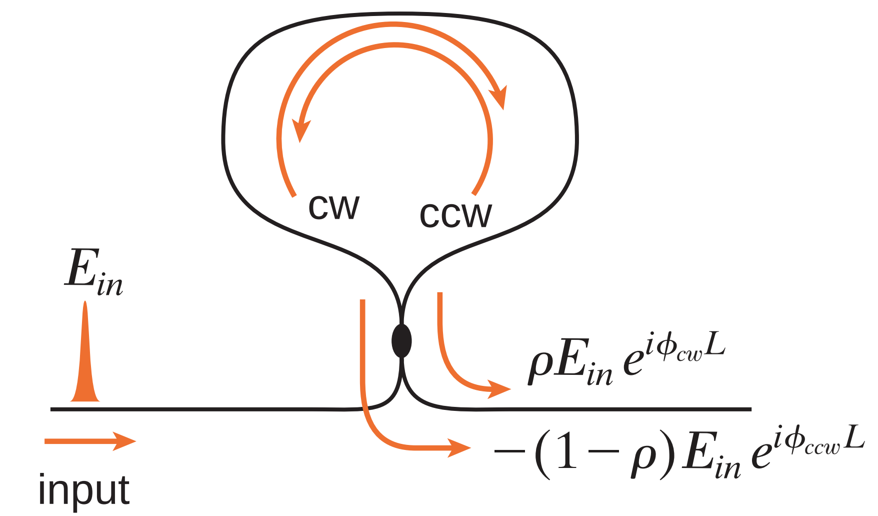
Optical logic gates

coupling parameter: ρ



Optical logic gates

output is sum of transmitted cw and ccw



Manipulating light at the nanoscale

accumulated phase:

$$\phi = k_o n$$

Manipulating light at the nanoscale

accumulated phase:

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nonlinear index:

$$n = n_o + n_2 I = n_o + n_2 \frac{P_i}{A_{eff}}$$

Manipulating light at the nanoscale

accumulated phase:

$$\phi = k_o n$$

nonlinear index:

$$n = n_o + n_2 I = n_o + n_2 \frac{P_i}{A_{eff}}$$

nonlinear parameter:

$$\gamma = n_2 \frac{k_o}{A_{eff}}$$

Manipulating light at the nanoscale

power-dependent output:

$$\frac{E_{out}^2}{E_{in}^2} = 1 - 2\rho(1 - \rho)\{1 + \cos[(1 - 2\rho)\gamma P_o L]\}$$

Manipulating light at the nanoscale

power-dependent output:

$$\frac{E_{out}^2}{E_{in}^2} = 1 - 2\rho(1-\rho)\{1 + \cos[(1-2\rho)\gamma P_o L]\}$$

for 50-50 coupler:

$$\rho = 0.5$$

Manipulating light at the nanoscale

power-dependent output:

$$\frac{E_{out}^2}{E_{in}^2} = 1 - 2\rho(1 - \rho)\{1 + \cos[(1 - 2\rho)\gamma P_o L]\}$$

for 50-50 coupler:

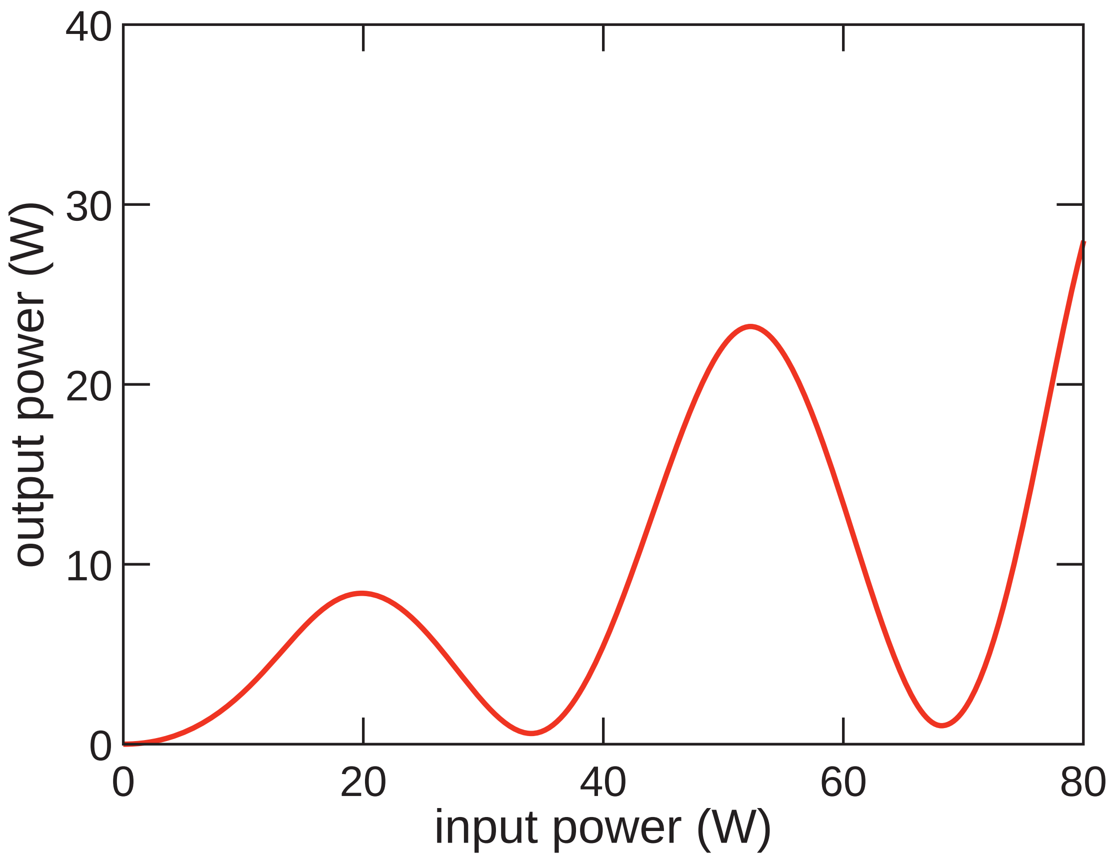
$$\rho = 0.5$$

no transmission:

$$\frac{E_{out}^2}{E_{in}^2} = 0$$

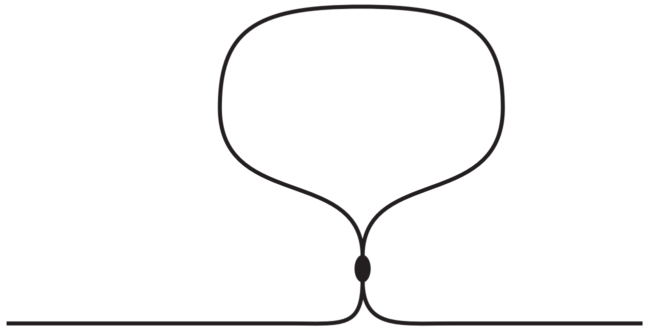
Optical logic gates

when $\rho \neq 0.5$:



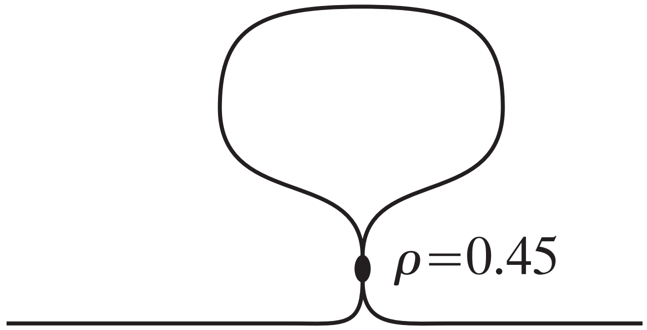
Optical logic gates

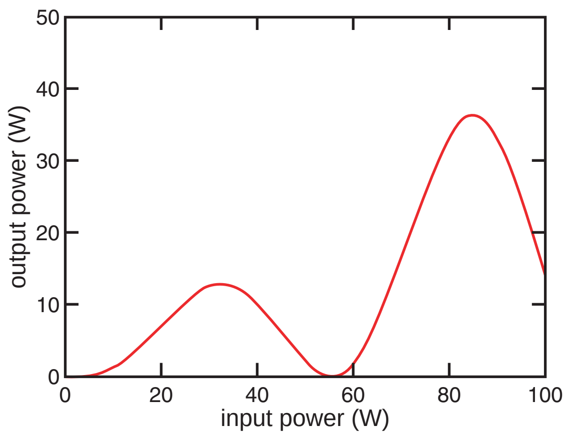
nonlinear nanogate



Optical logic gates

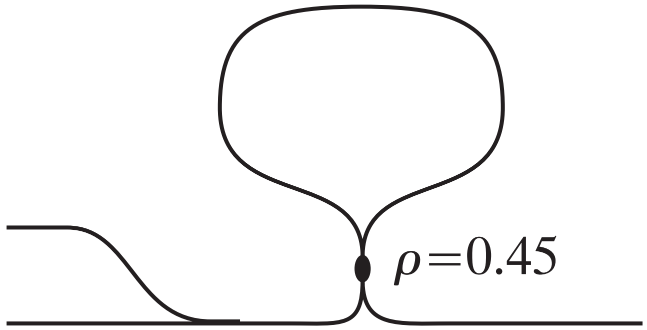
nonlinear nanogate

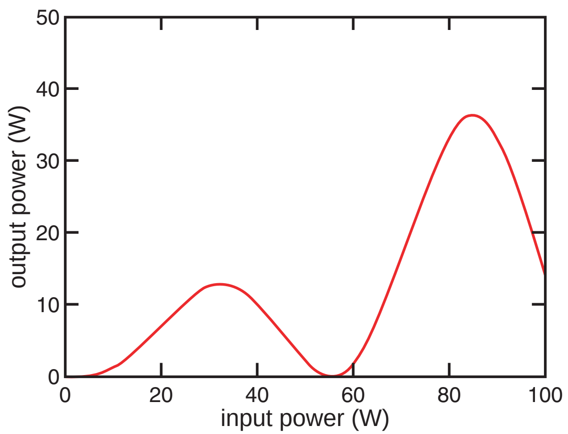




Optical logic gates

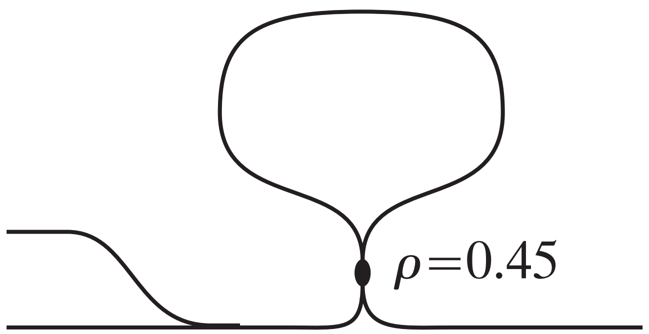
nonlinear nanogate

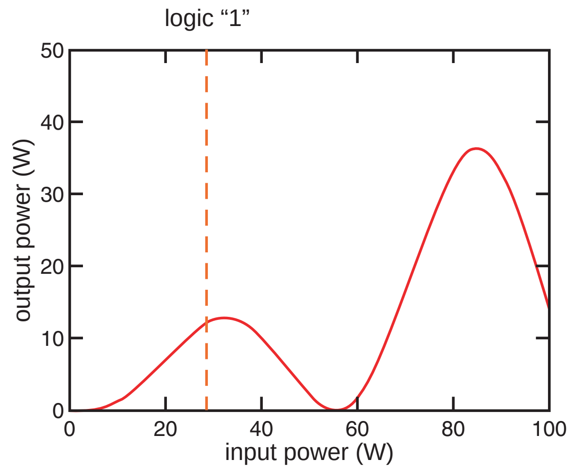




Optical logic gates

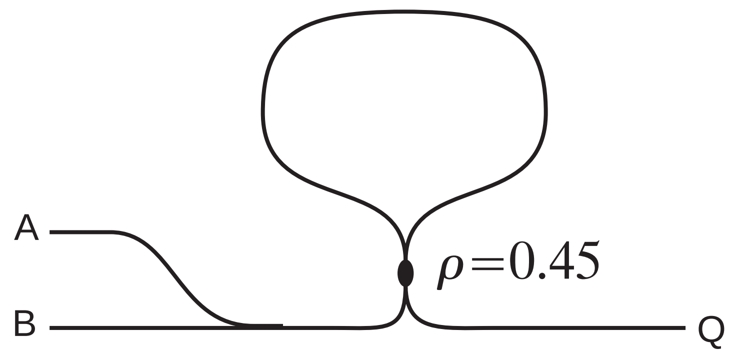
nonlinear nanogate

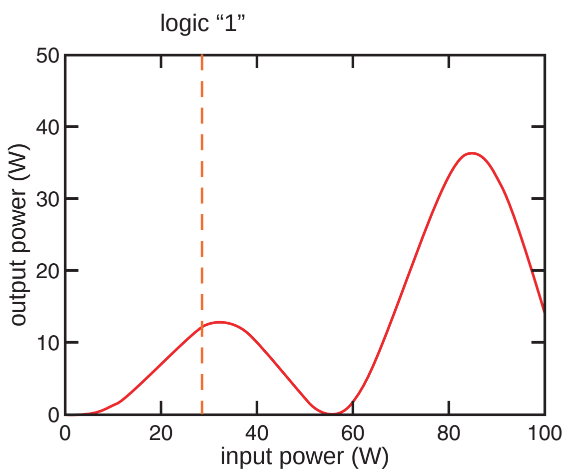




Optical logic gates

nonlinear nanogate

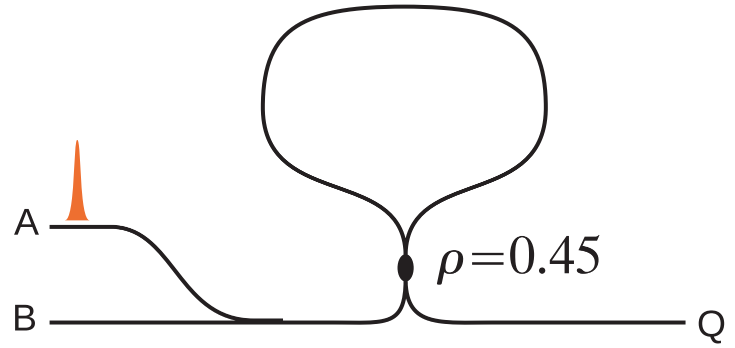


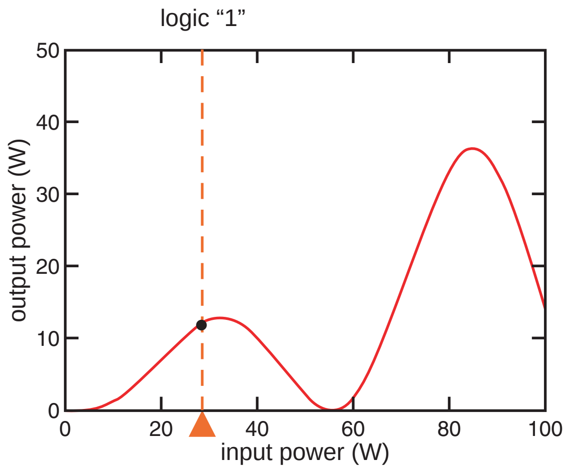


A	B	Q
0	0	0

Optical logic gates

nonlinear nanogate

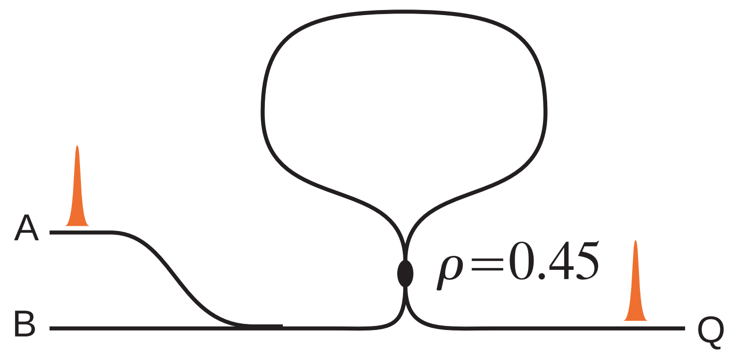


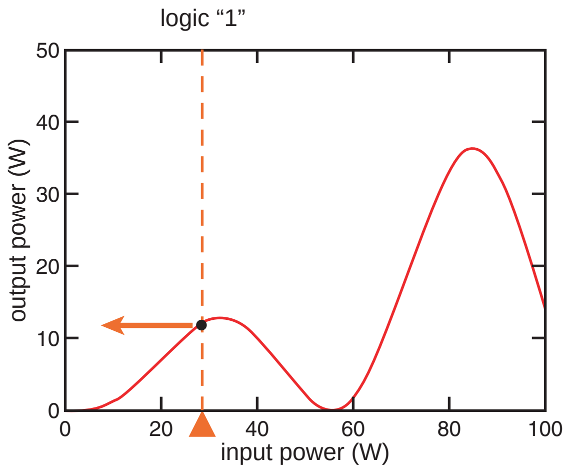


A	B	Q
0	0	0

Optical logic gates

nonlinear nanogate

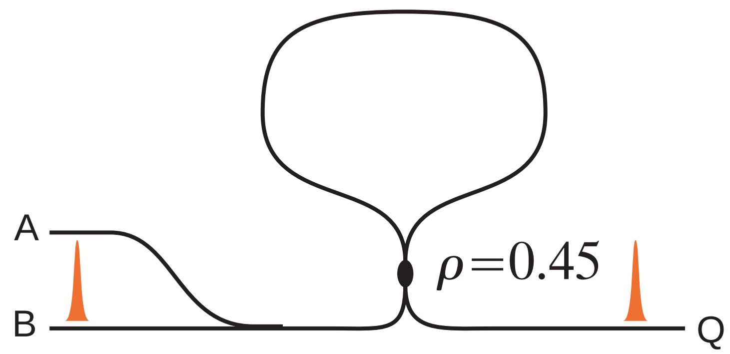


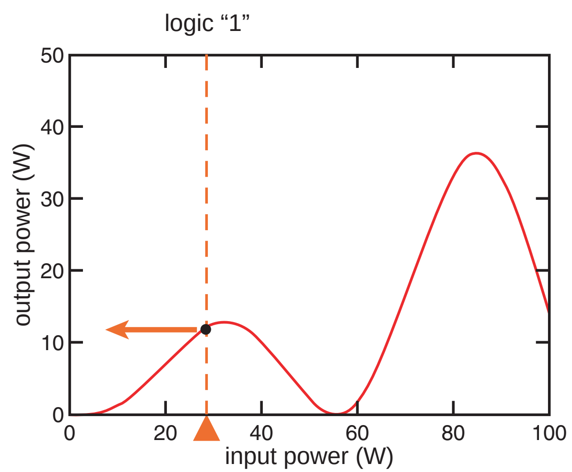


A	B	Q
0	0	0
1	0	1

Optical logic gates

nonlinear nanogate

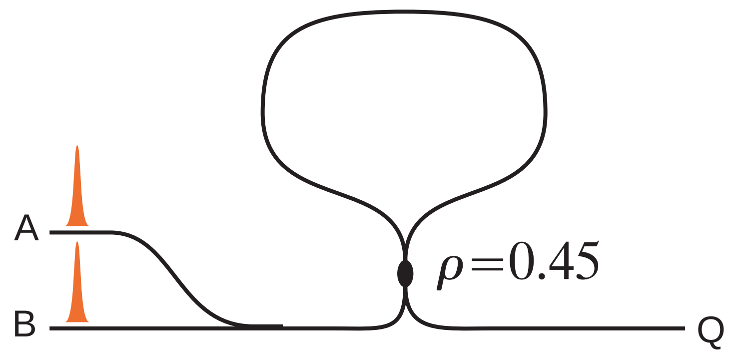


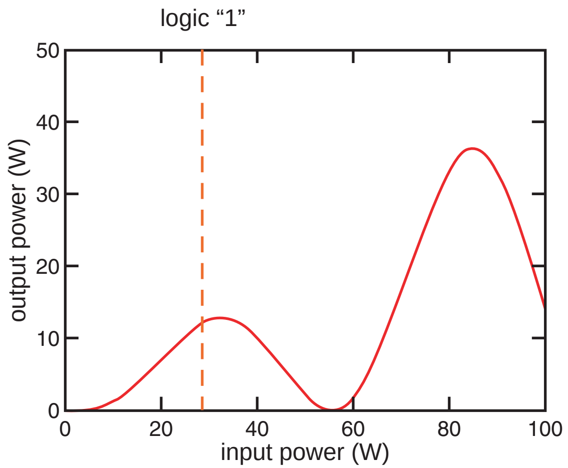


A	B	Q
0	0	0
1	0	1
0	1	1

Optical logic gates

nonlinear nanogate

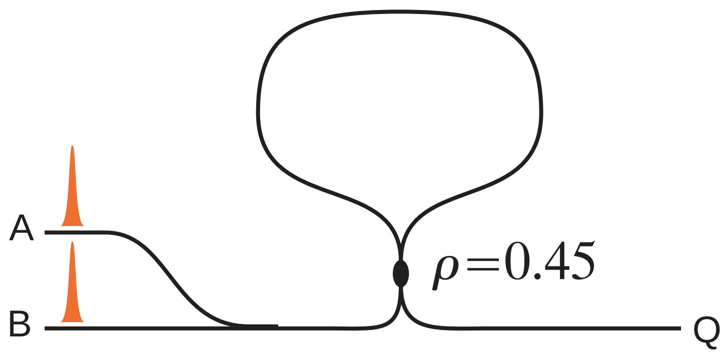


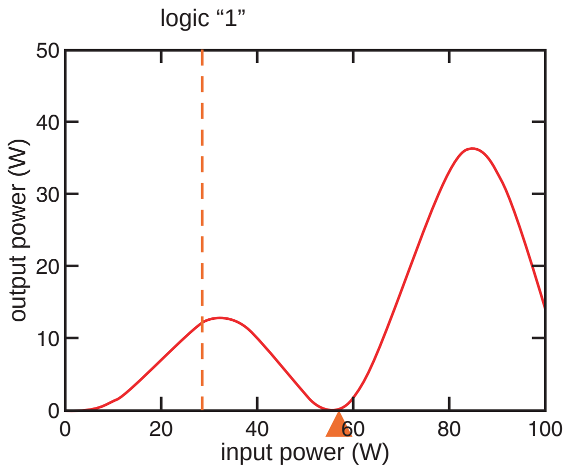


A	B	Q
0	0	0
1	0	1
0	1	1

Optical logic gates

nonlinear nanogate





A	B	Q
0	0	0
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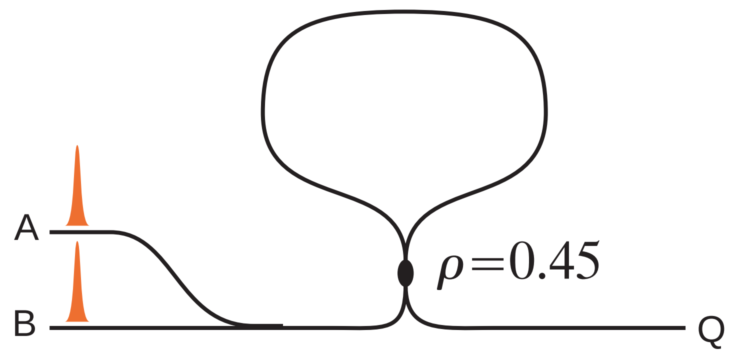
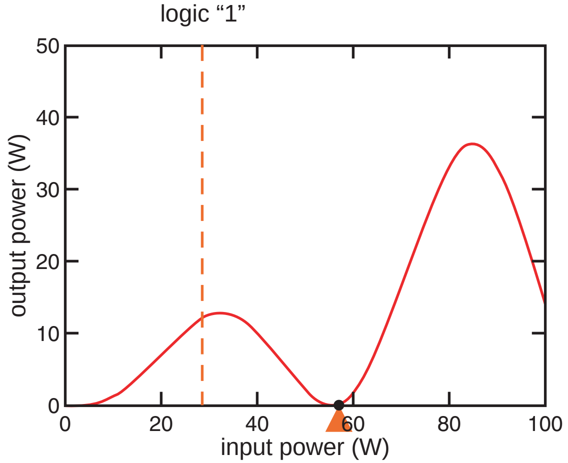
0	1	1

Optical logic gates

nonlinear nanogate





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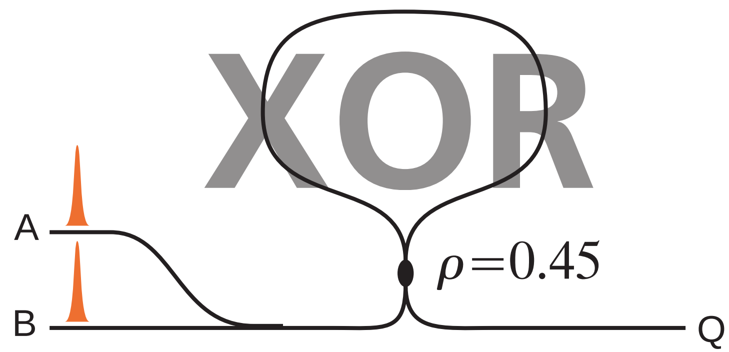
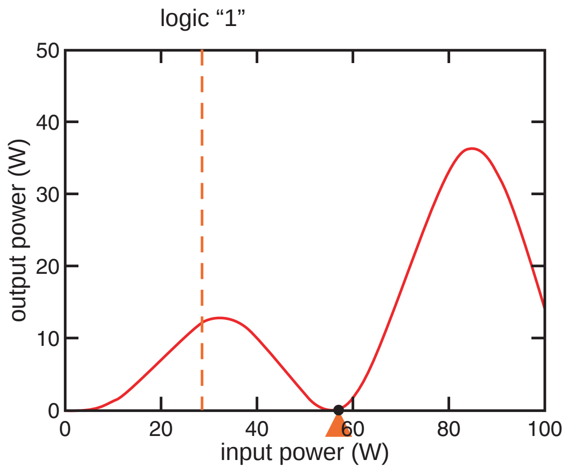
1	1	0

Optical logic gates

nonlinear nanogate





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0	0	0
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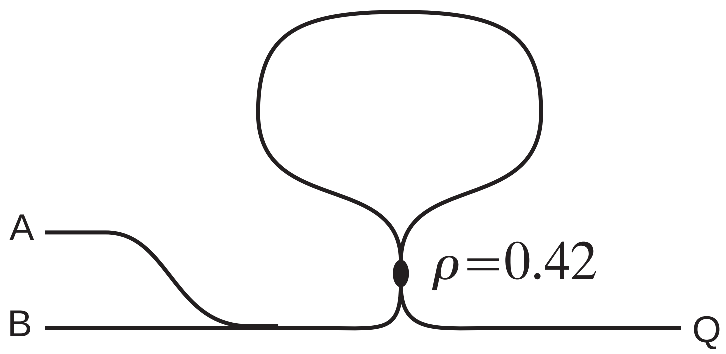
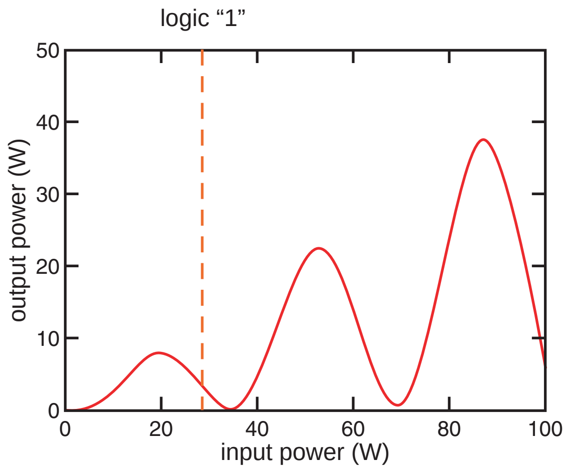
Optical logic gates

nonlinear nanogate

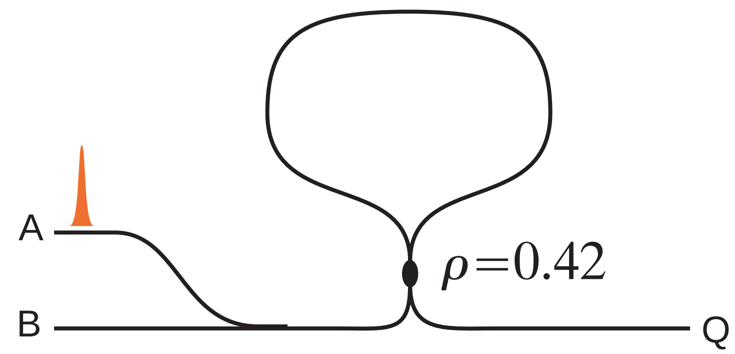


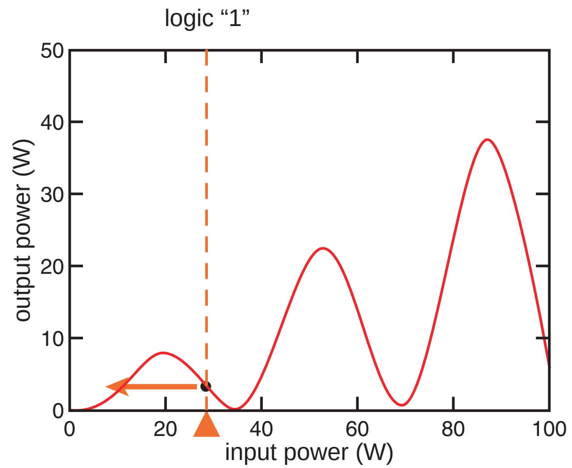


A	B	Q
0	0	0

Optical logic gates

nonlinear nanogate

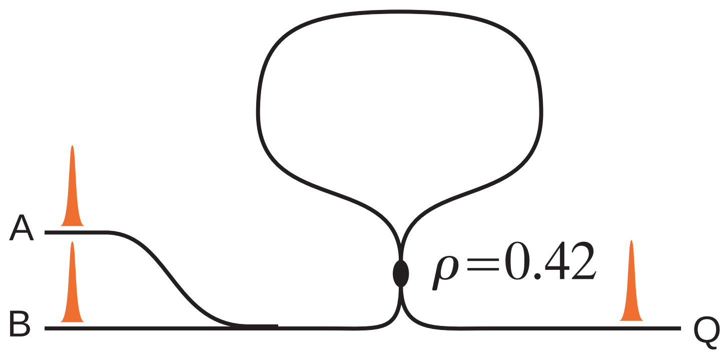


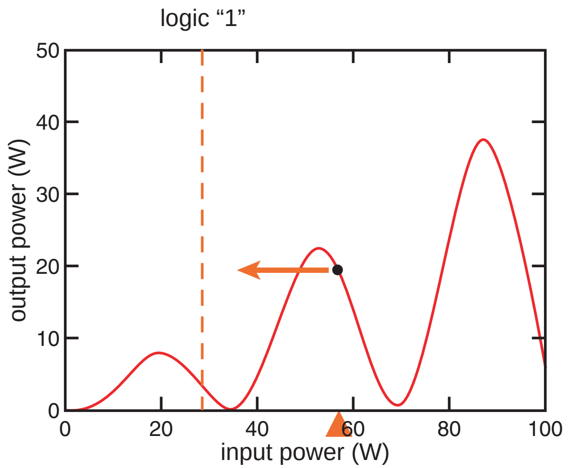


A	B	Q
0	0	0
1	0	0
0	1	0

Optical logic gates

nonlinear nanogate





A	B	Q
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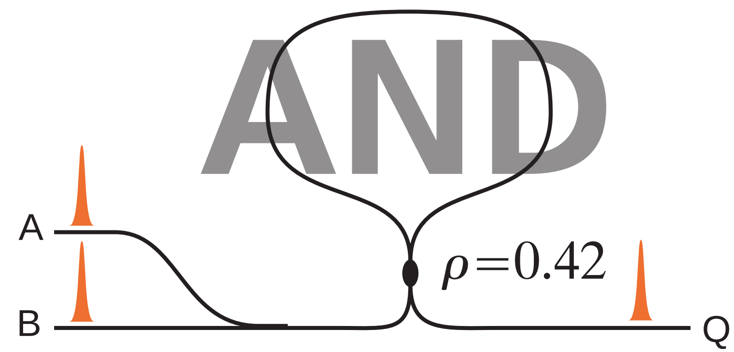
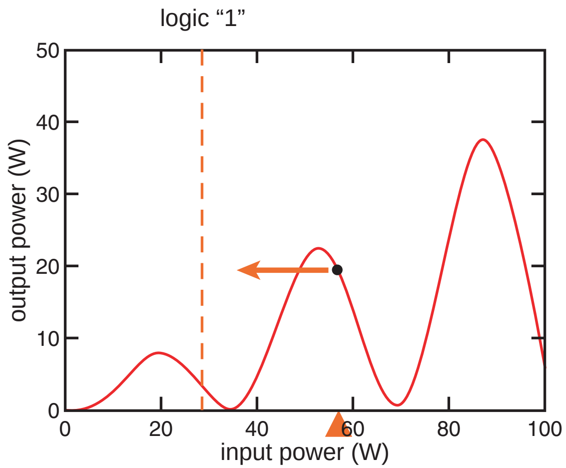
1	0	0
0	1	0
1	1	1

Optical logic gates

nonlinear nanogate

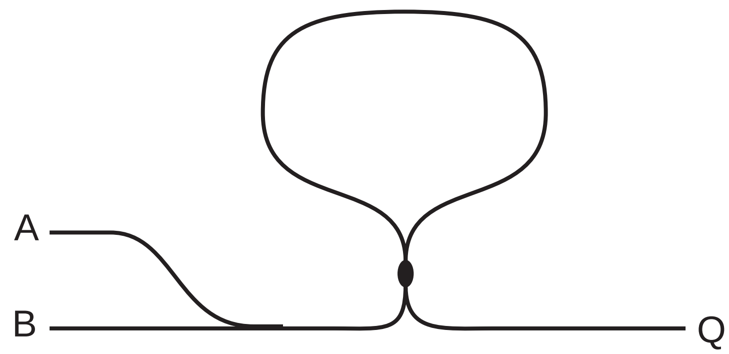


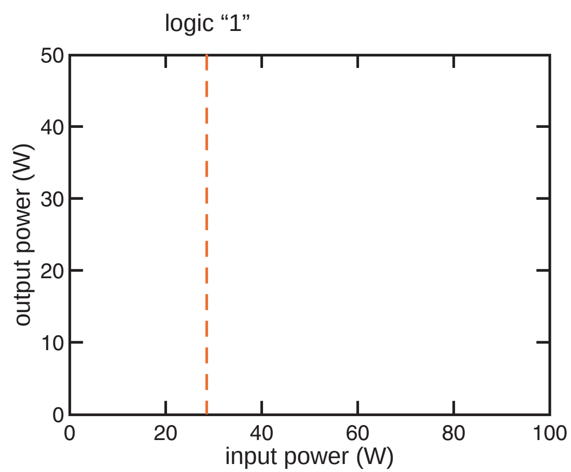


A	B	Q
0	0	0
1	0	0
0	1	0
1	1	1

Optical logic gates

for NAND gate need ouput with no input





A	B	Q
0	0	1

Optical logic gates

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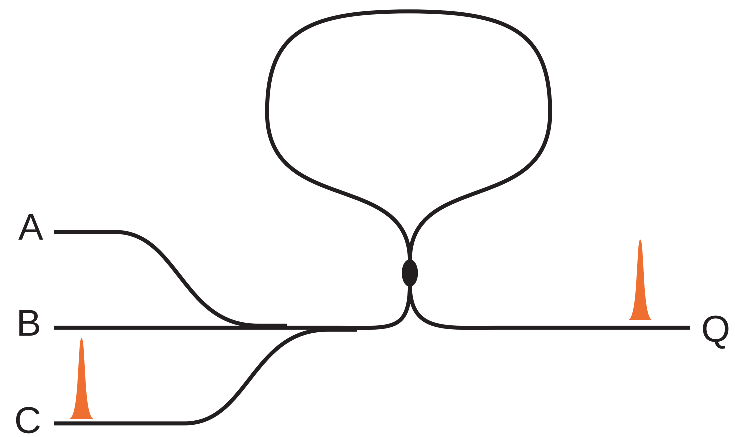

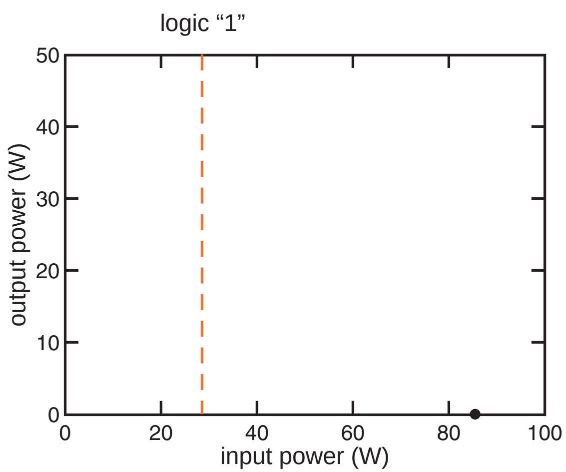

A	B	Q
0	0	1

Optical logic gates

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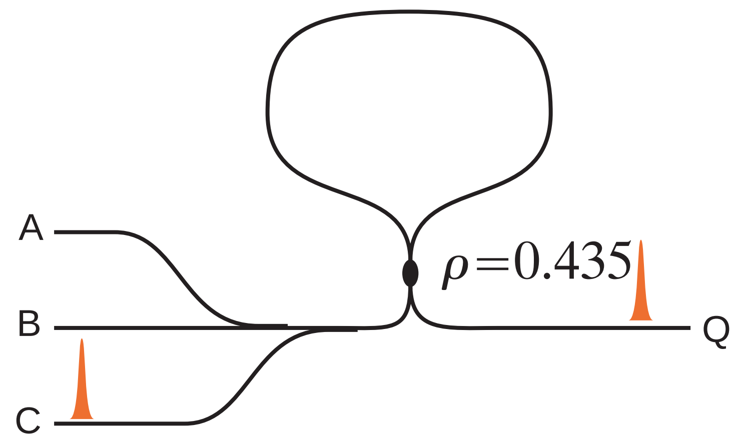
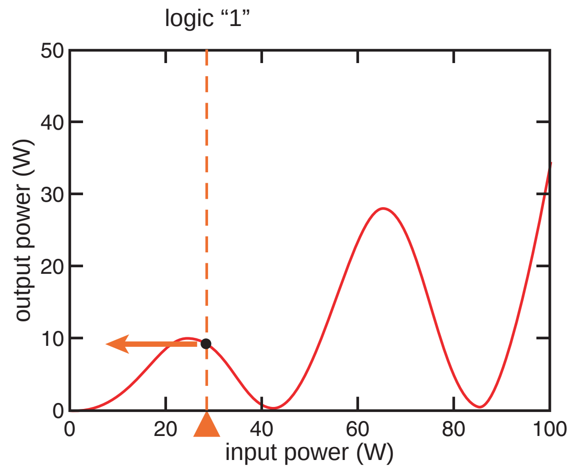
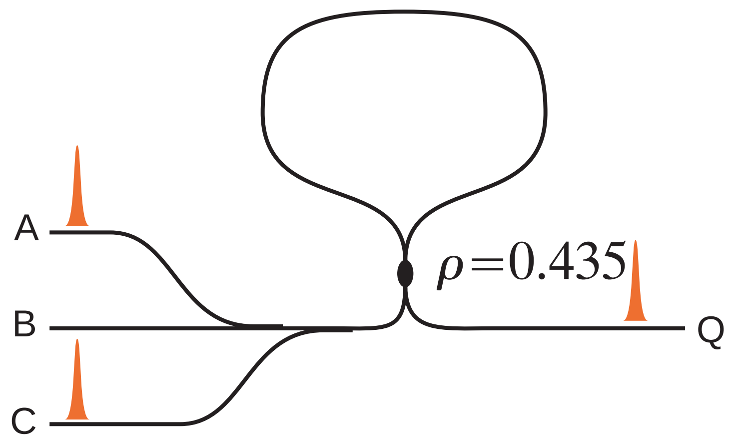


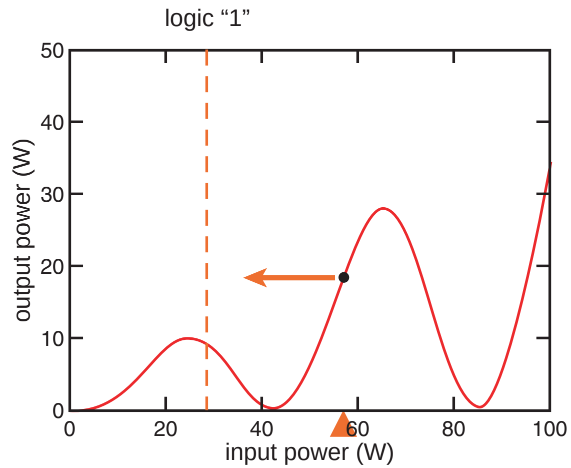


A	B	Q
0	0	1

Optical logic gates

universal NAND gate

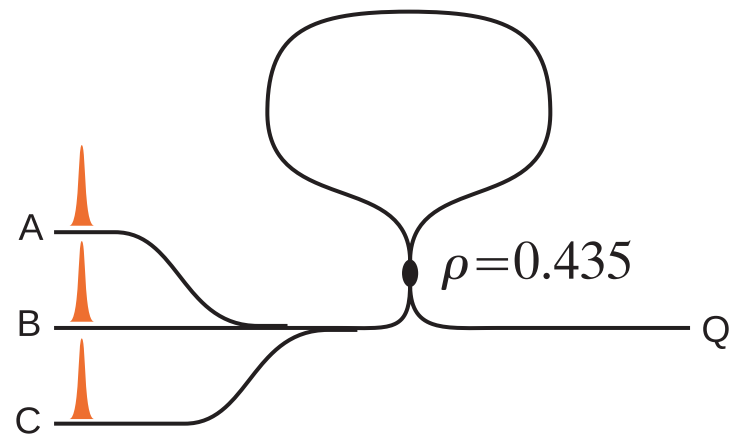


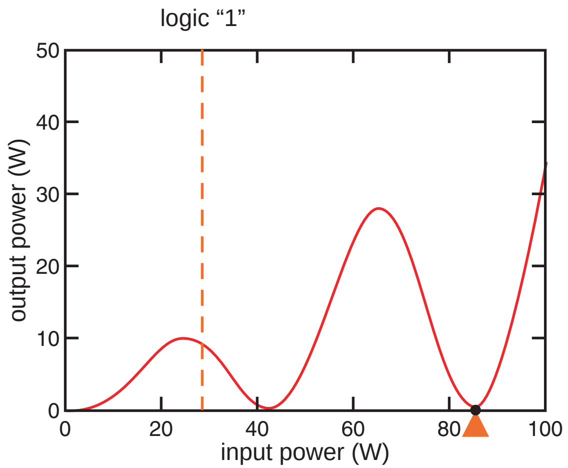


A	B	Q
0	0	1
1	0	1
0	1	1

Optical logic gates

universal NAND gate

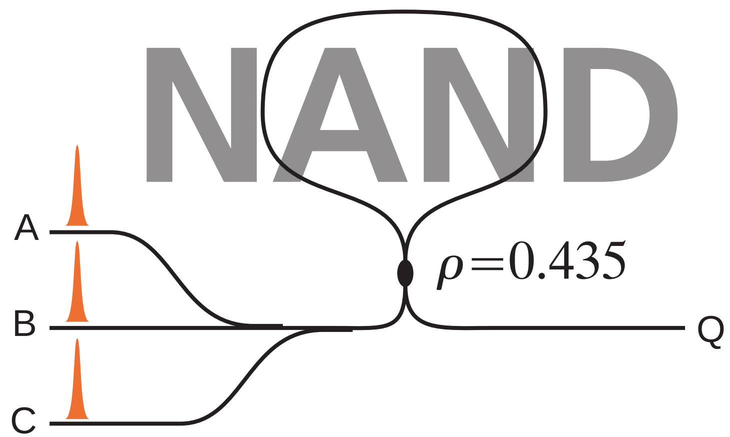


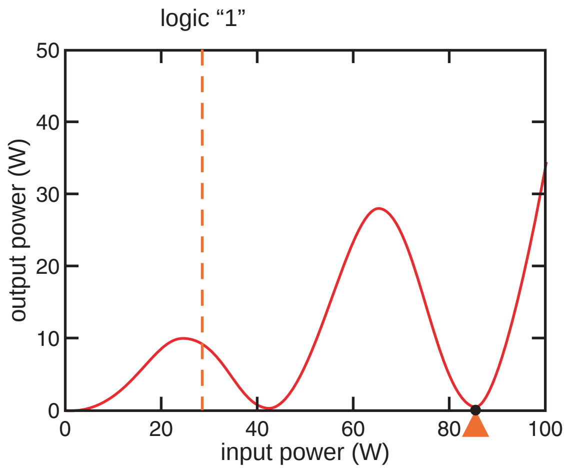


A	B	Q
0	0	1
1	0	1
0	1	1
1	1	0

Optical logic gates

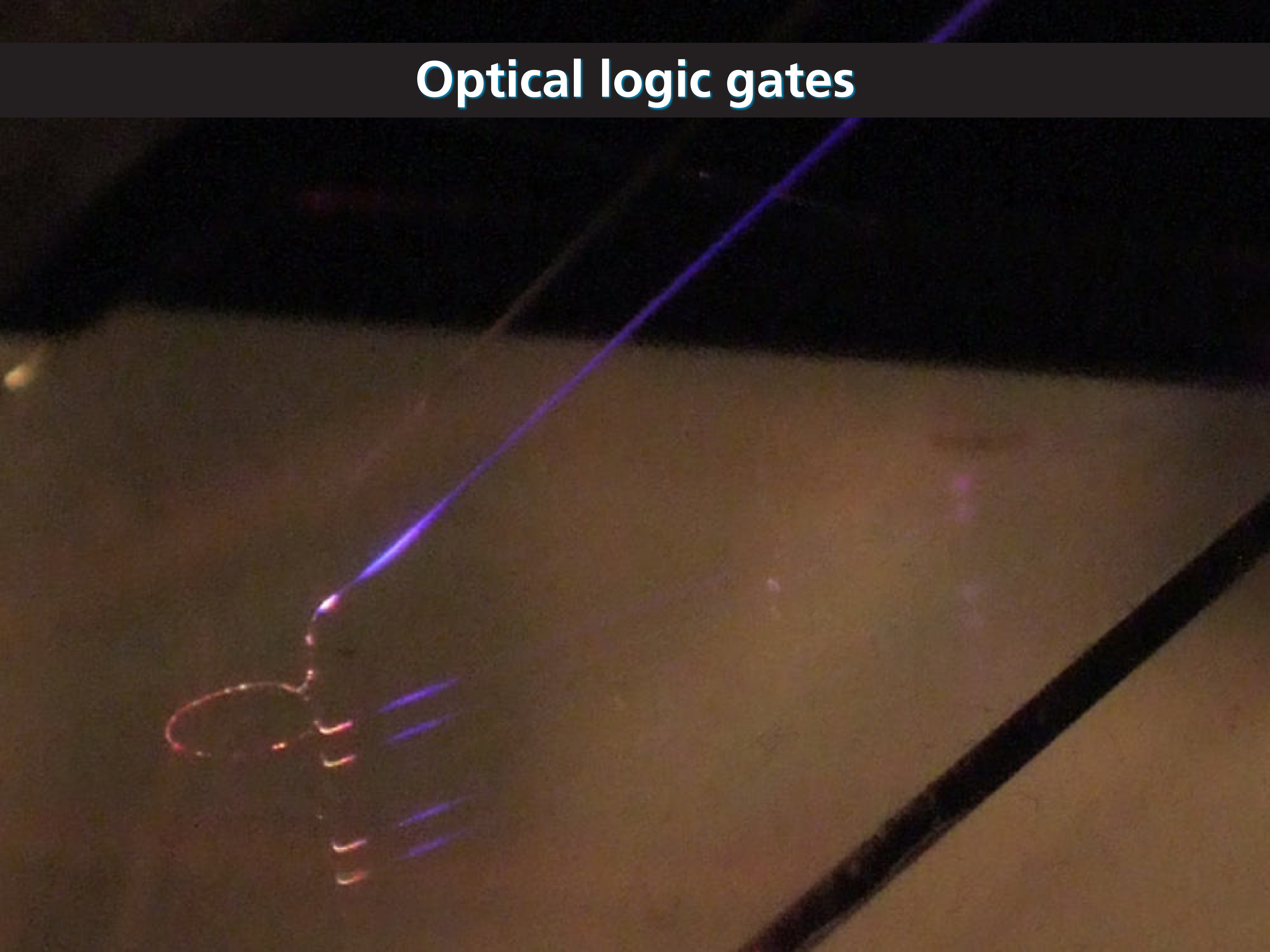
universal NAND gate





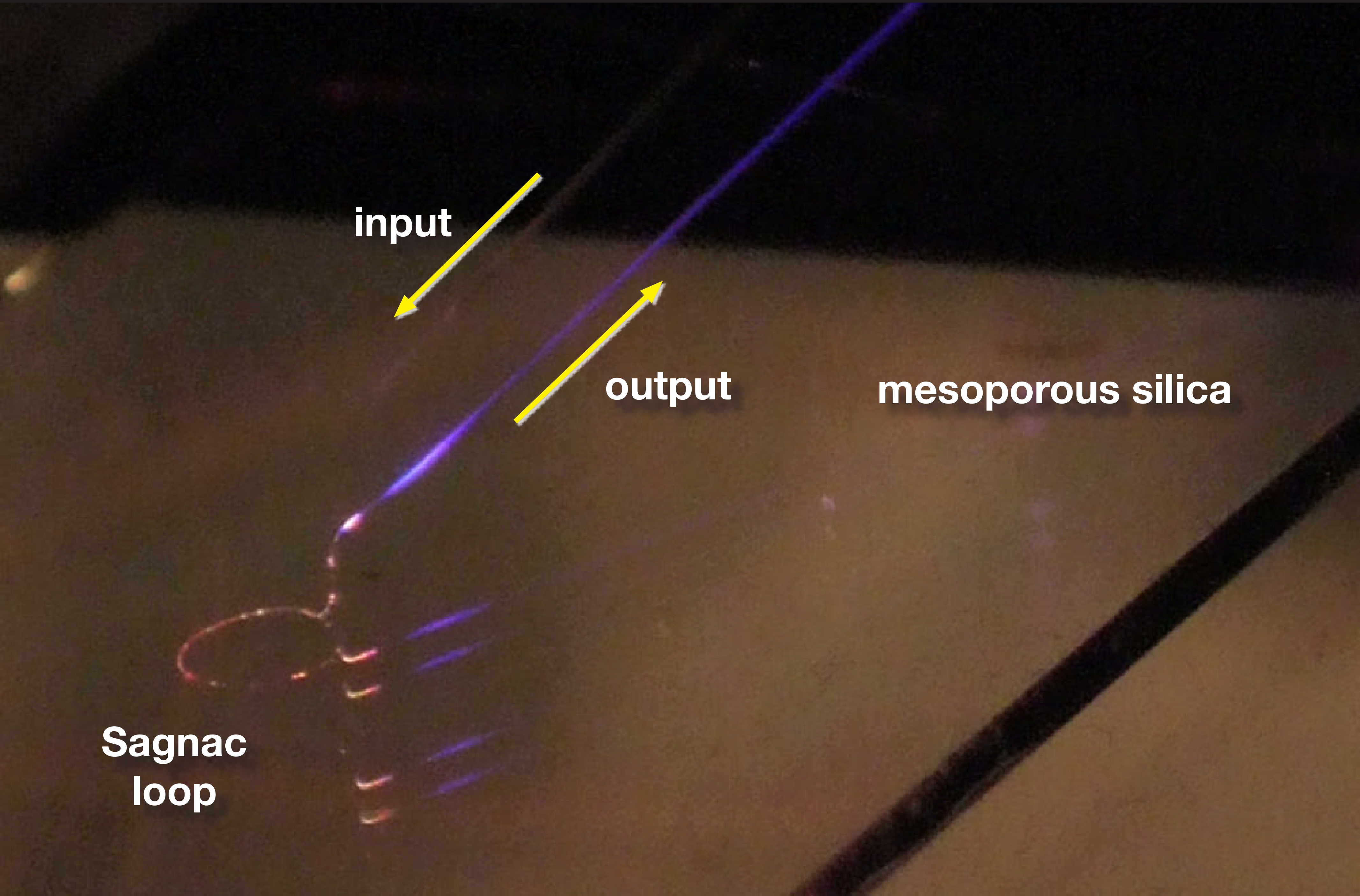
A	B	Q
0	0	1
1	0	1
0	1	1
1	1	0

Optical logic gates



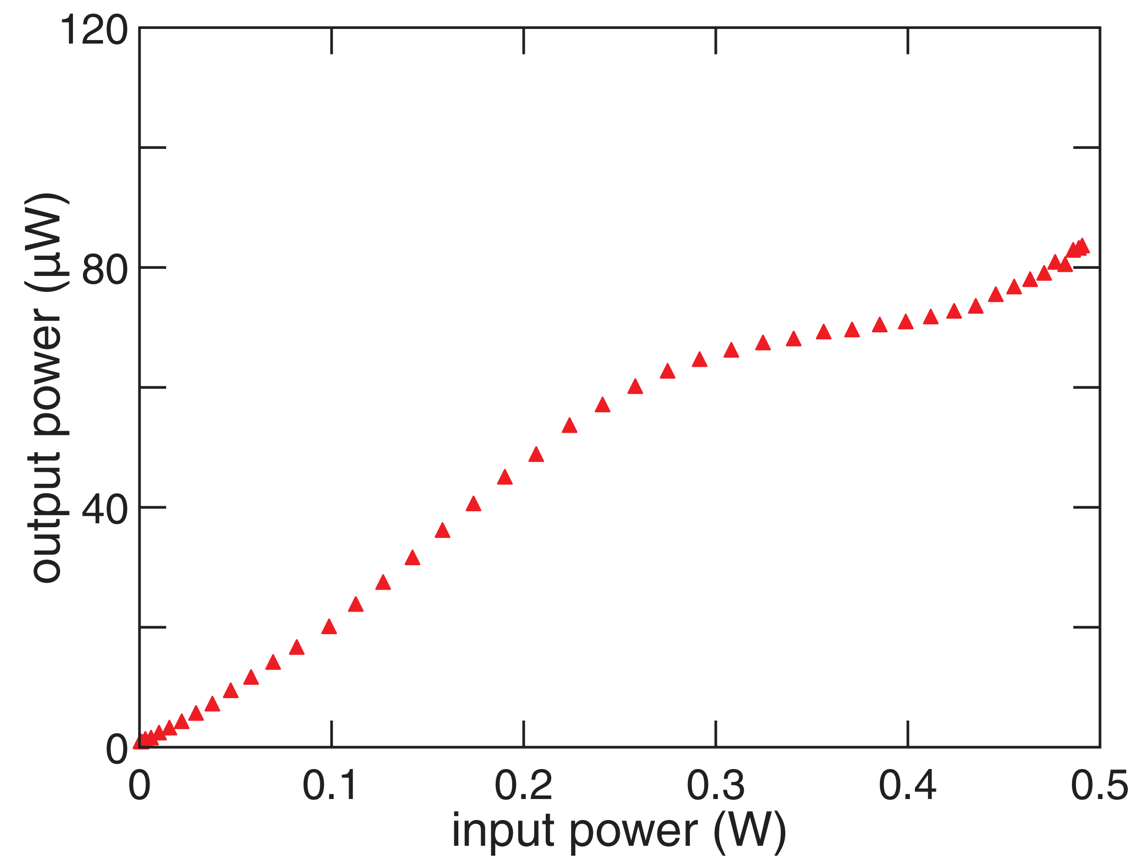
Optical logic gates

Optical logic gates



Optical logic gates

very preliminary data

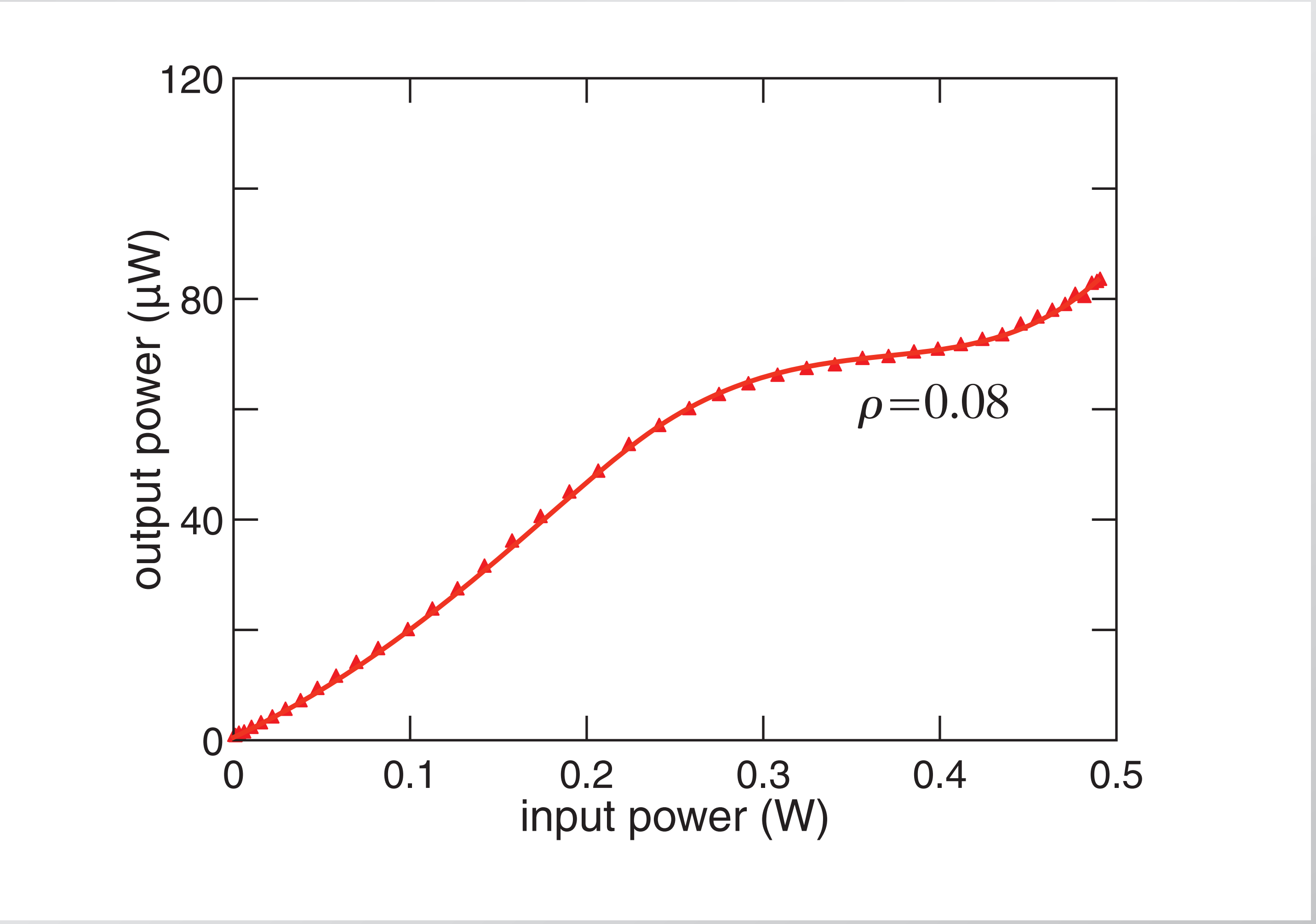


Optical logic gates

light-by-light modulation!

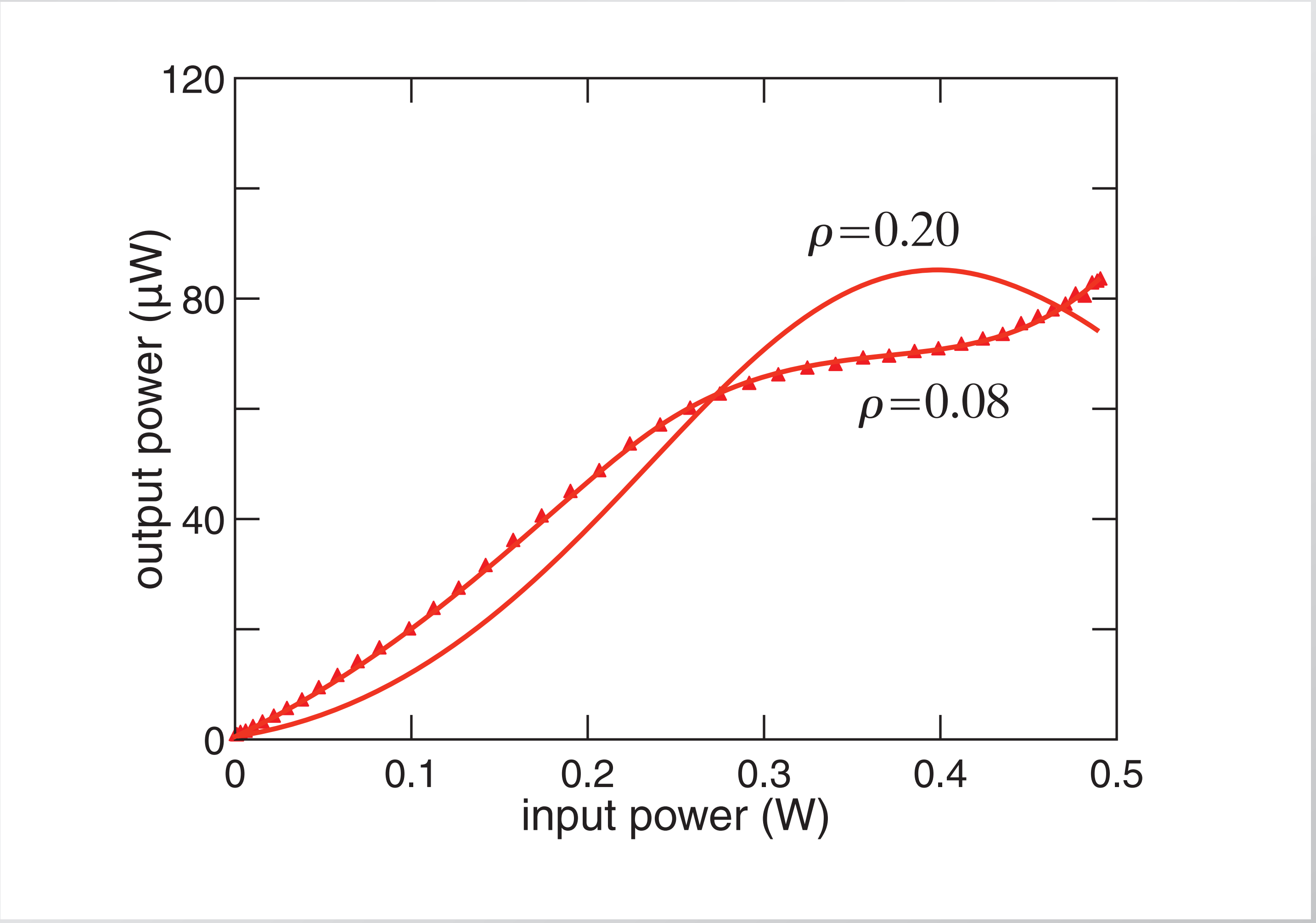
Optical logic gates

very preliminary data

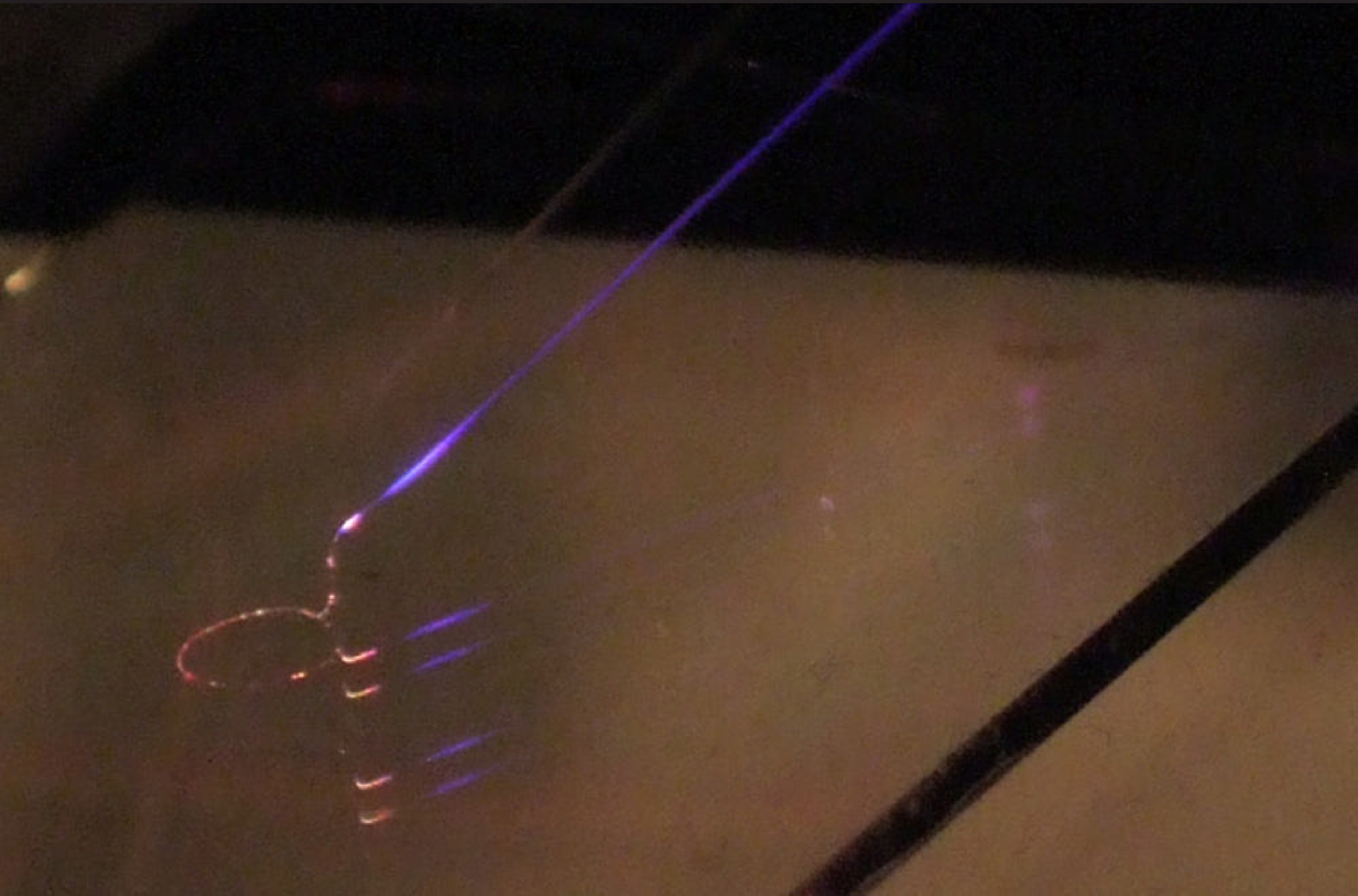


Optical logic gates

very preliminary data



Summary



Summary

- several nanodevices demonstrated
- large γ permits miniature Sagnac loops
- switching energy < 10 pJ

Funding:

Harvard Center for Imaging and Mesoscopic Structures
National Science Foundation

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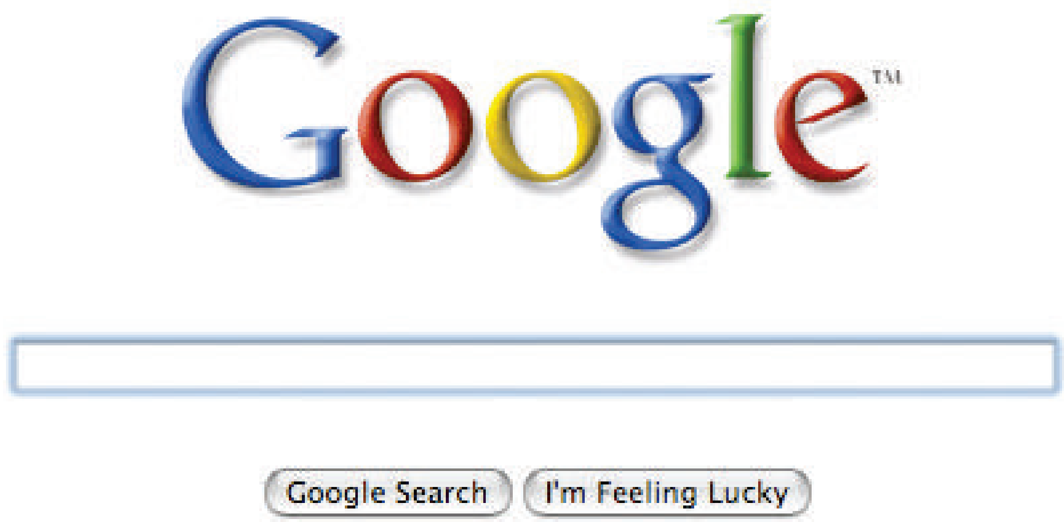
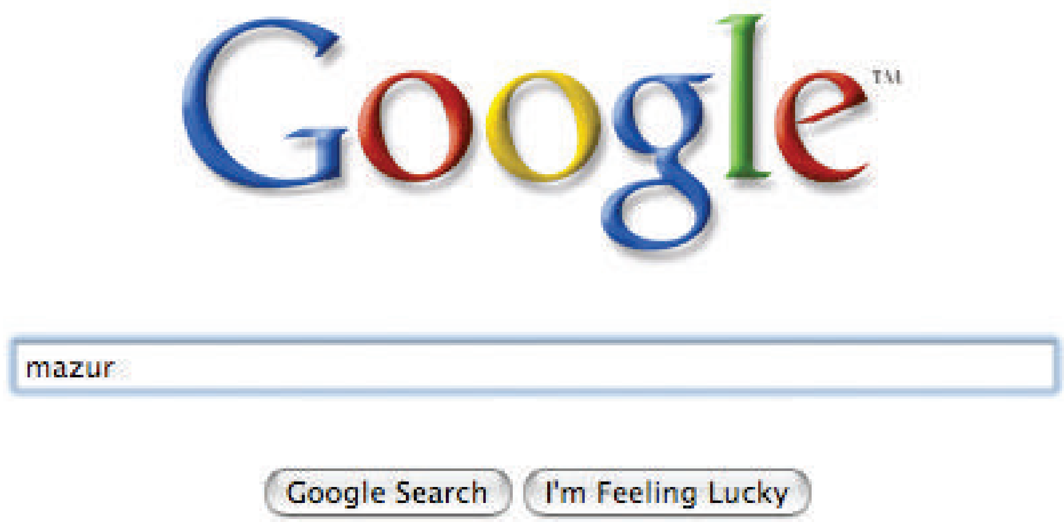

Google
Google Search
I'm Feeling Lucky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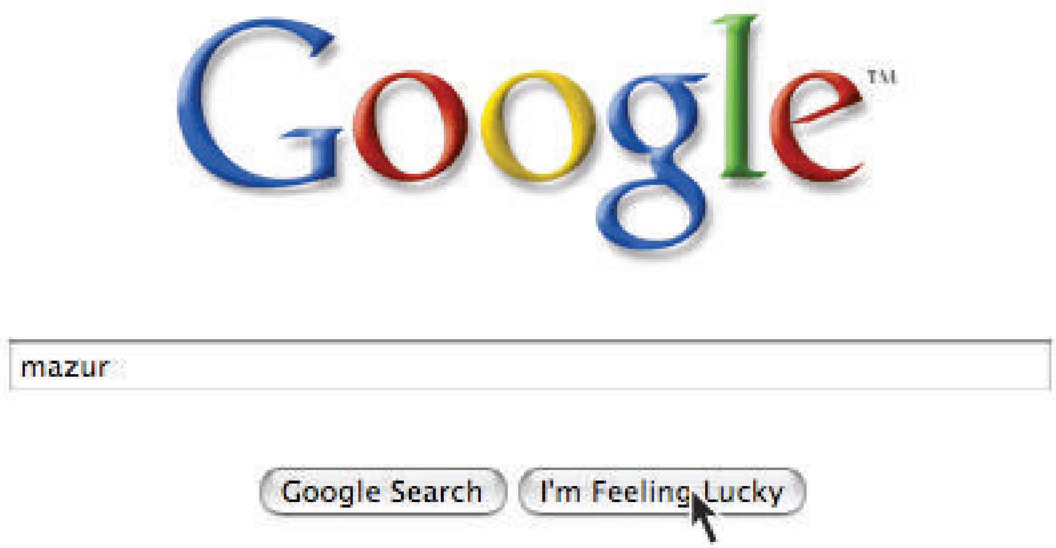
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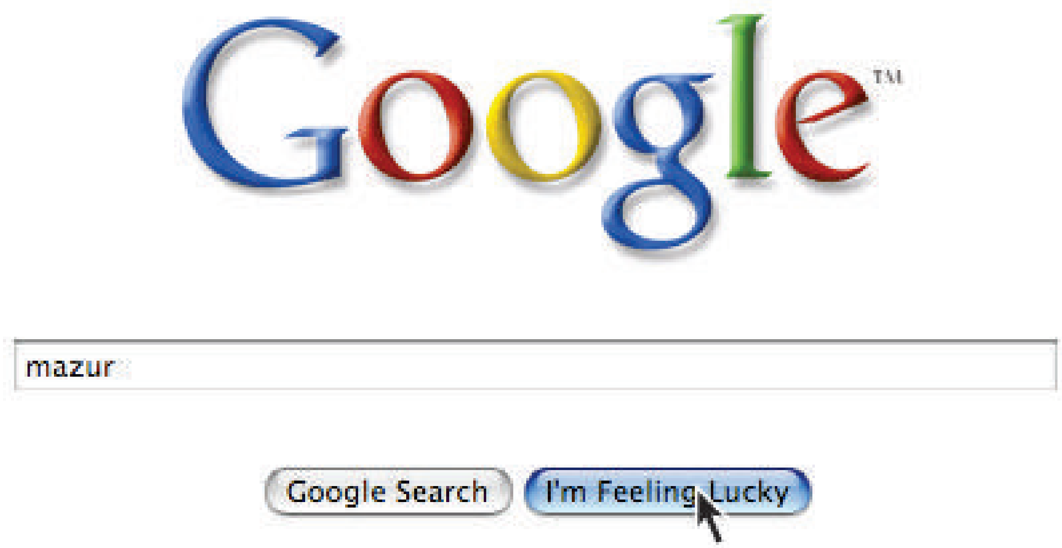
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