OPTICS IN THE (ULTRA)FAST LANE: SCULPTING MATTER WITH LIGHT

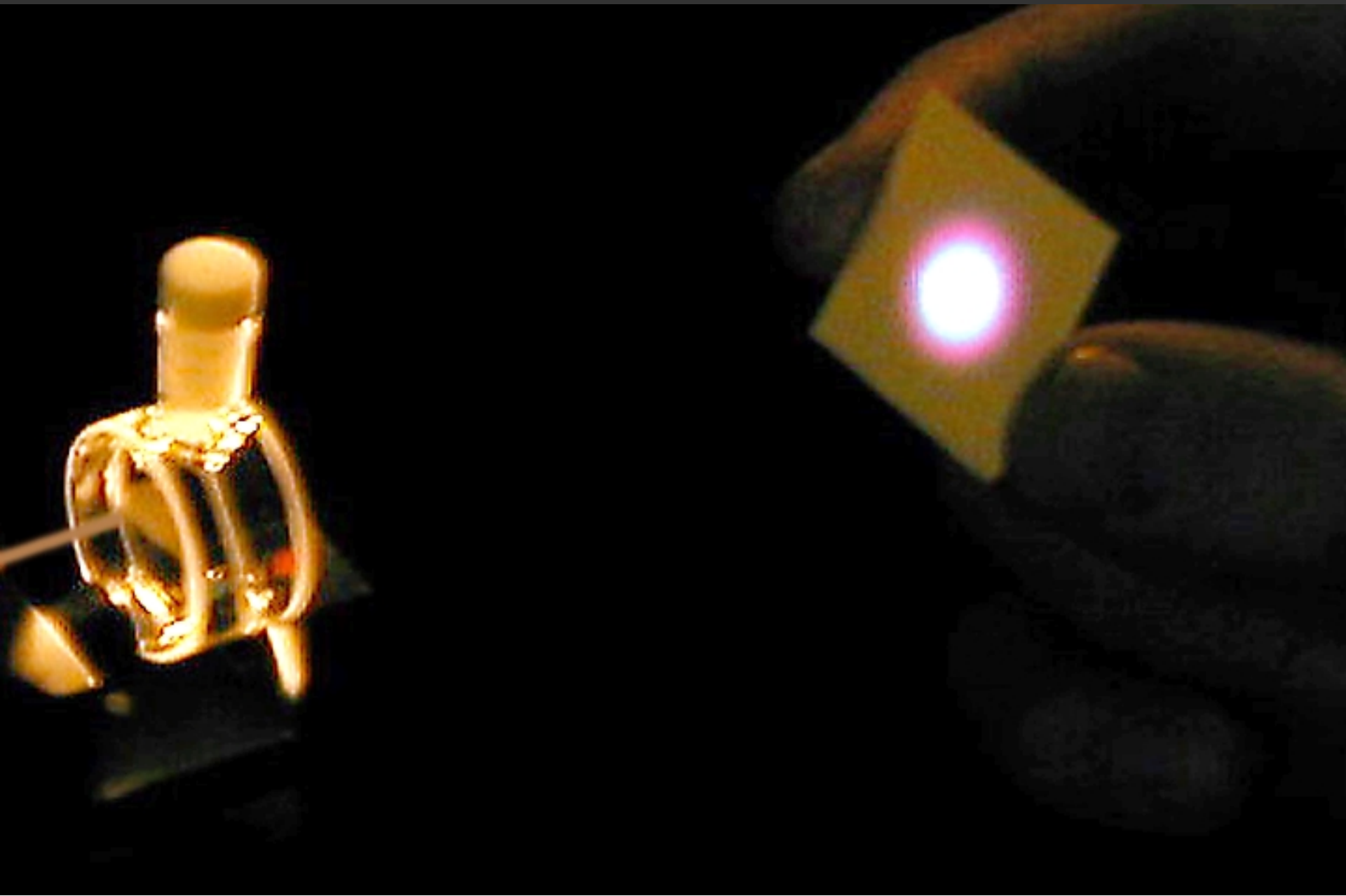
Eric Mazur

Visiting Committee Meeting
26 April 1999

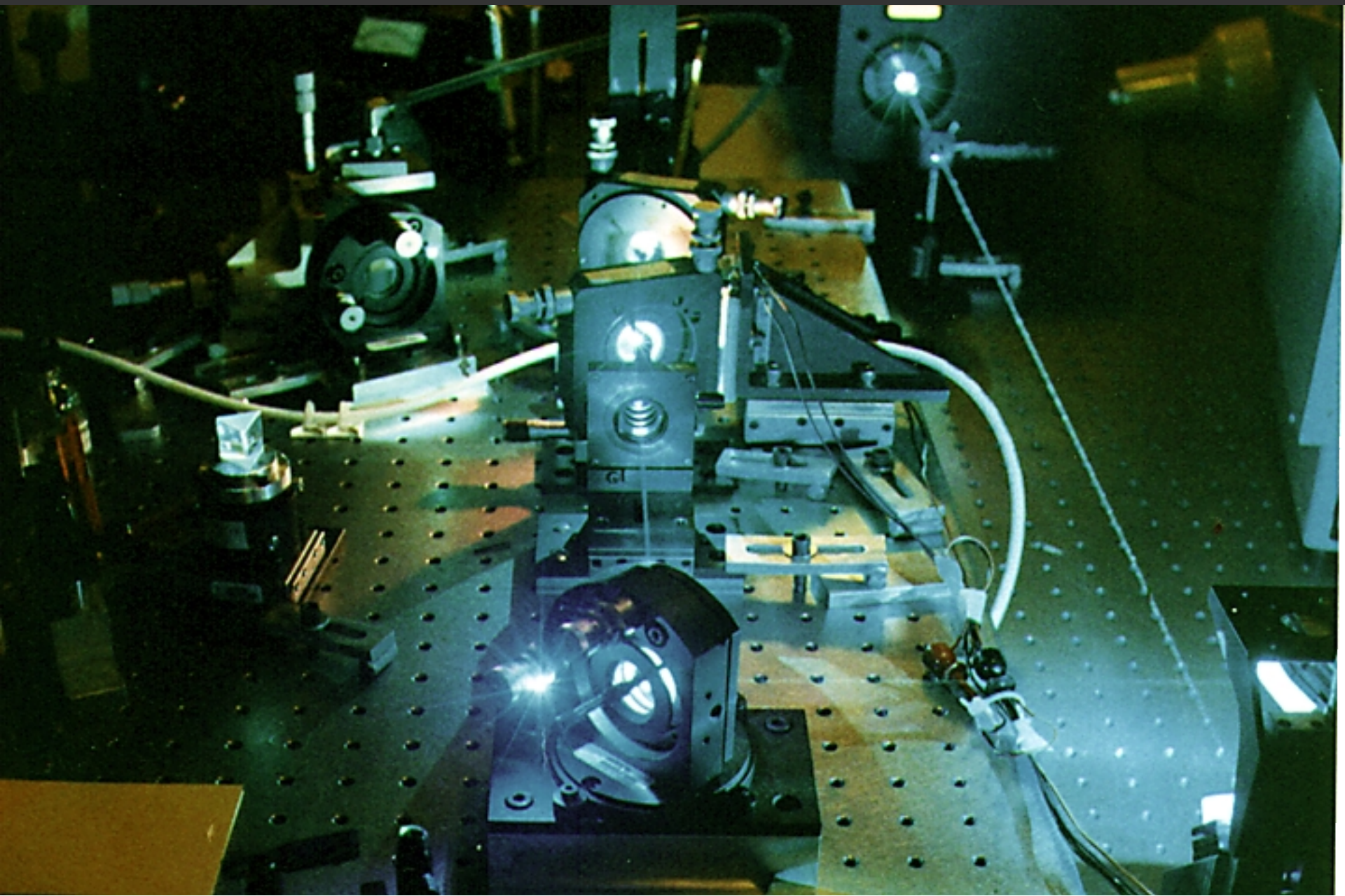
Introduction

- **time resolution**
- **high intensity**
- **nonlinear optics**
- **new physics**

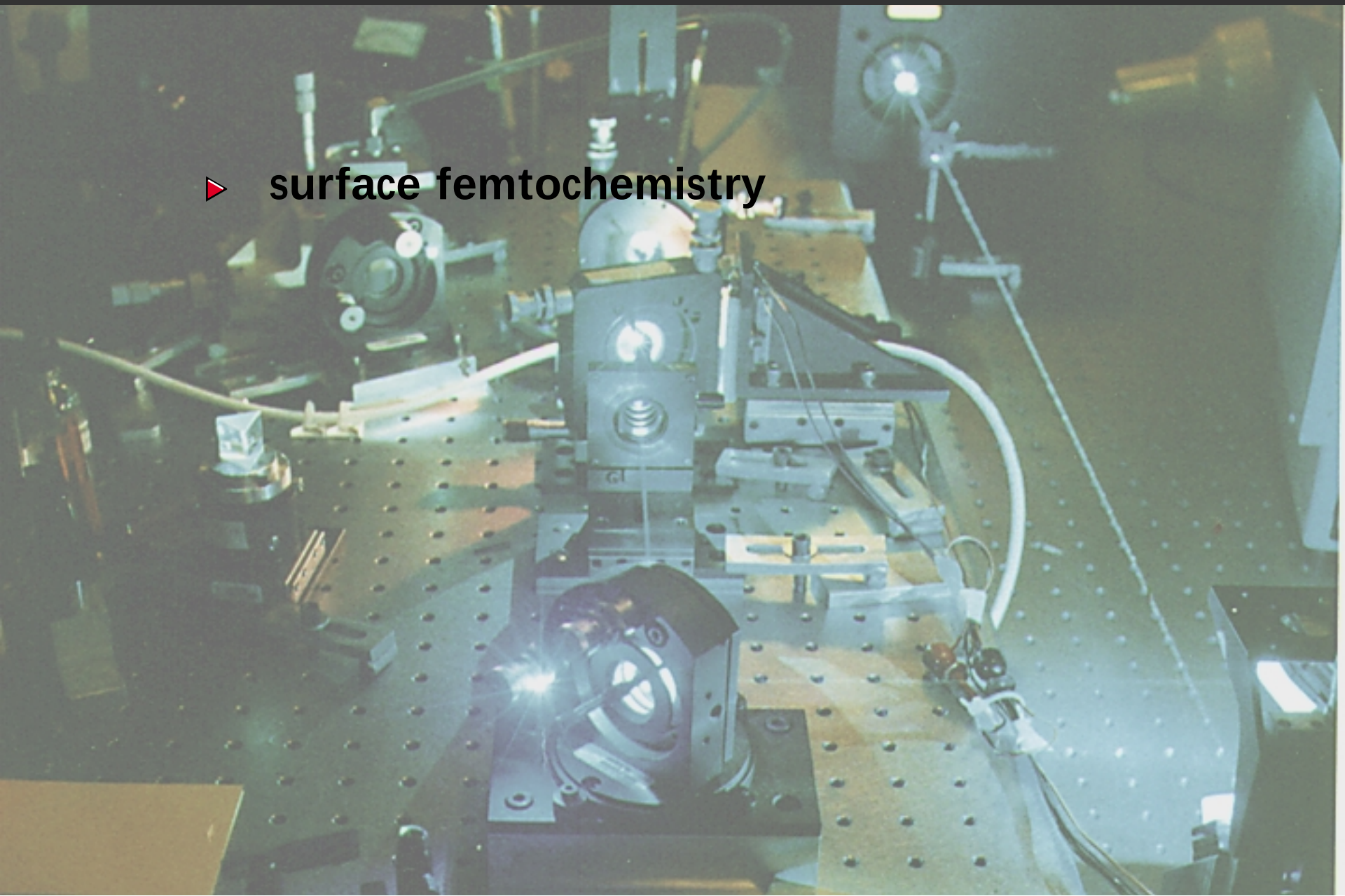
Introduction



Overview

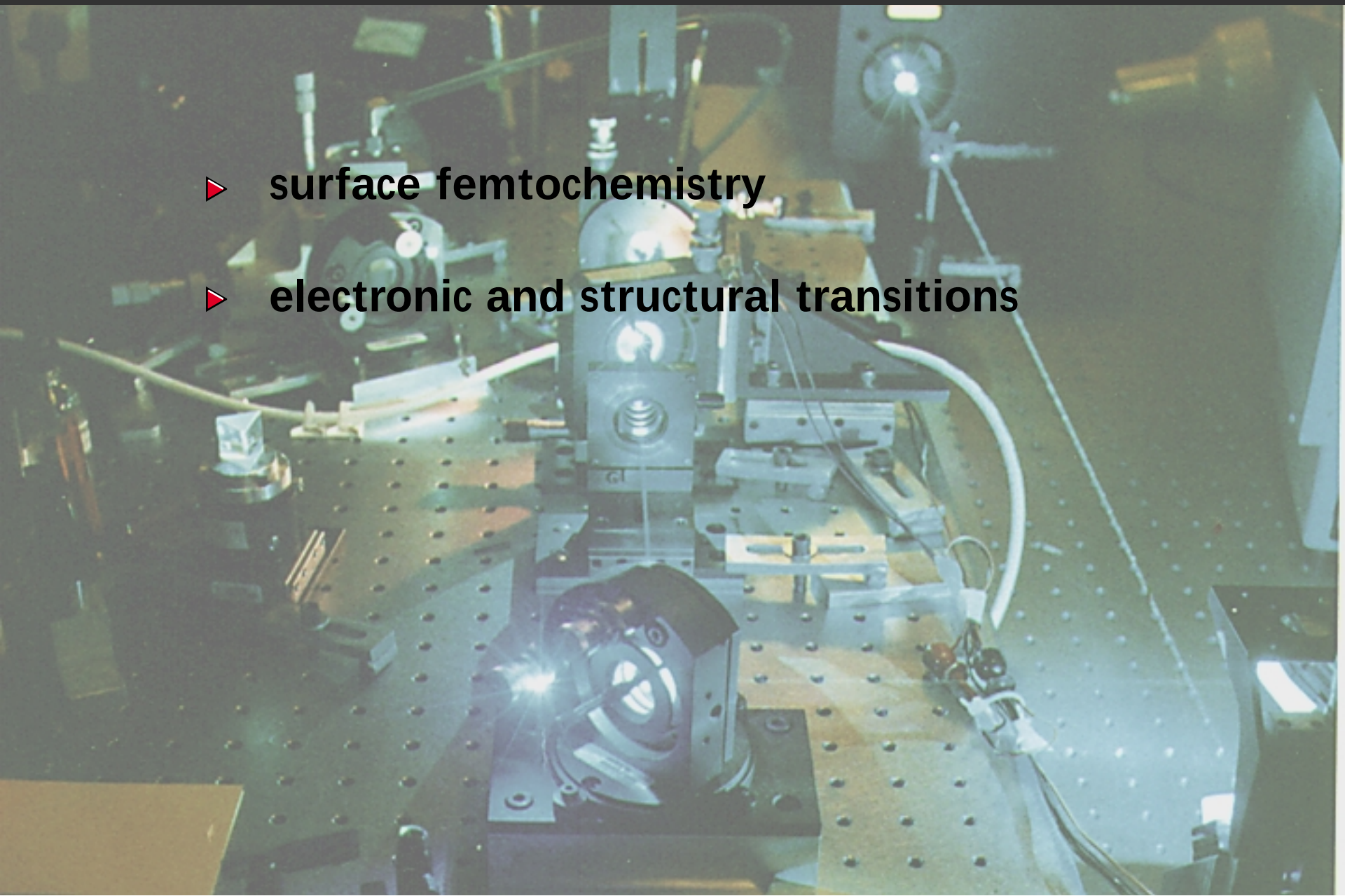


Overview



- surface femtochemistry

Overview



- surface femtochemistry
- electronic and structural transitions

Overview

- surface femtochemistry
- electronic and structural transitions
- microstructuring of materials

Overview

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- microstructuring of materials
- nonlinear optics and propagation

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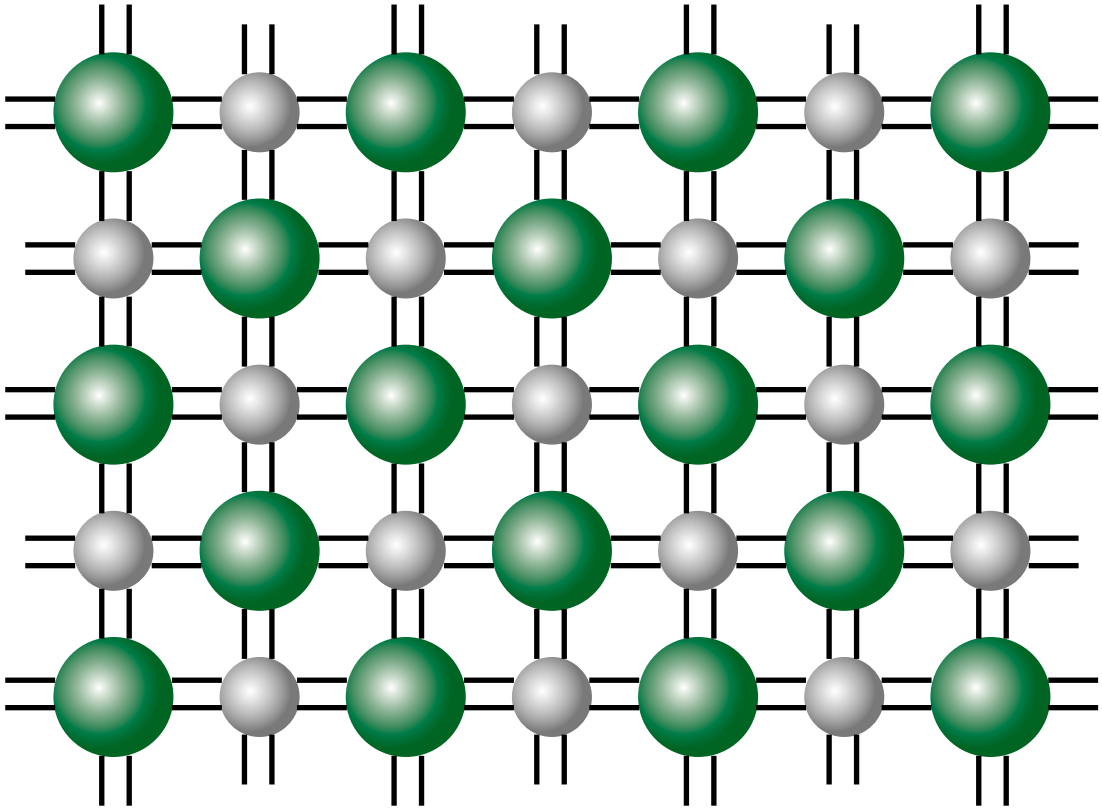
- laser surgery

Overview

- surface femtochemistry
- **electronic and structural transitions**
- microstructuring of materials
- nonlinear optics and propagation
- laser surgery

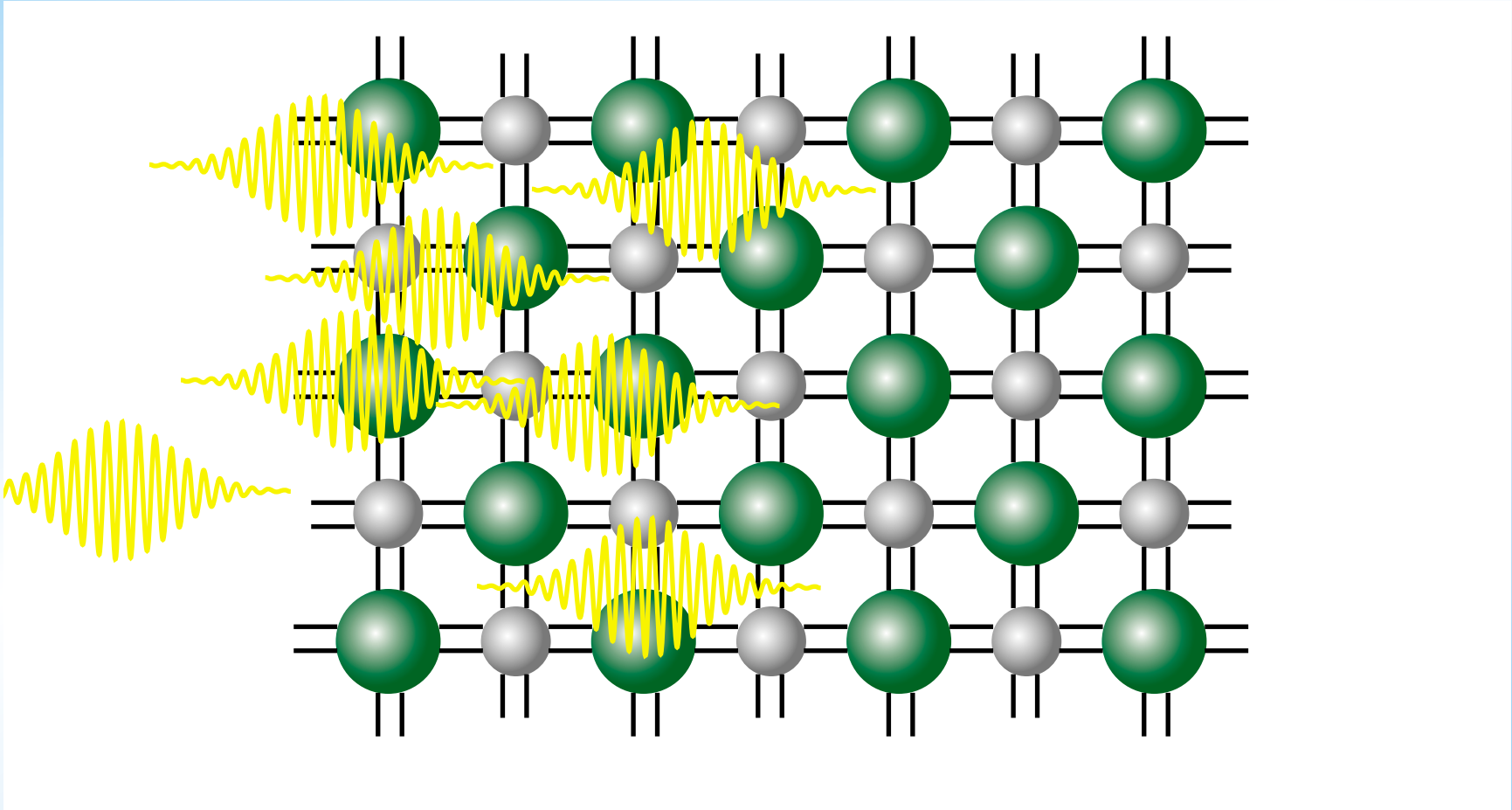
Electronic and structural transitions

how do femtosecond laser pulses alter a solid?



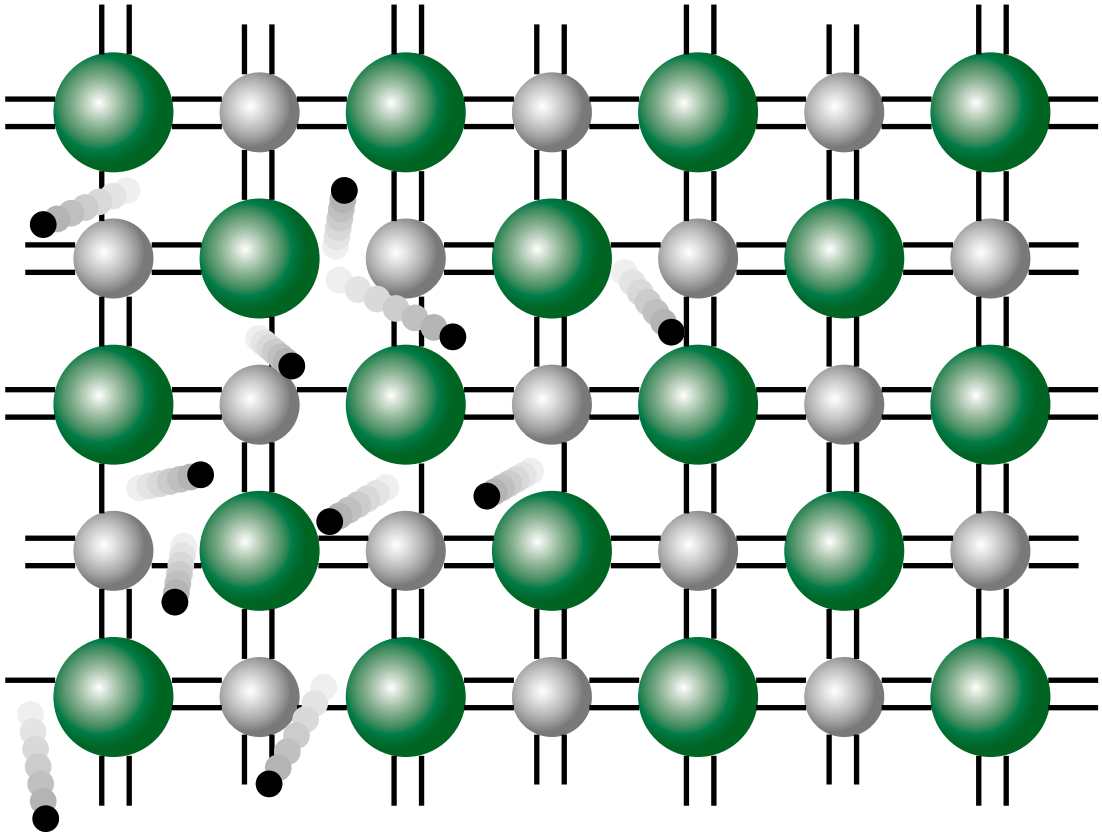
Electronic and structural transitions

photons excite valence electrons…



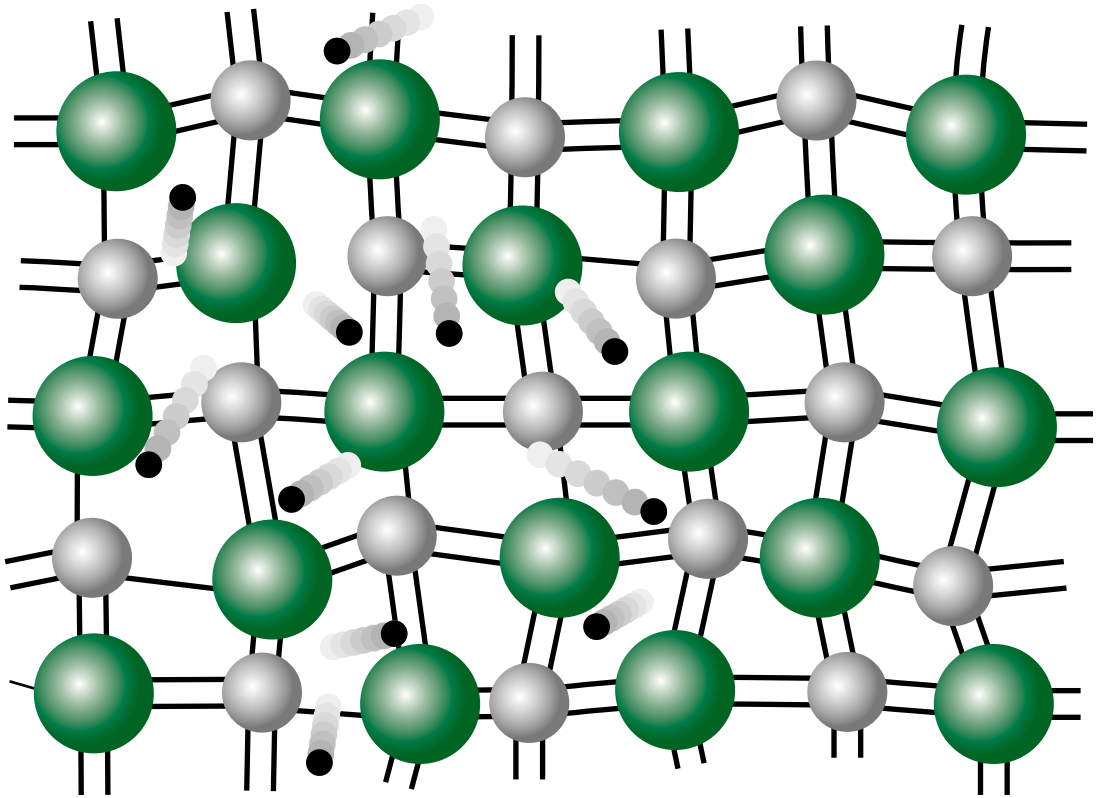
Electronic and structural transitions

…and create free electrons…



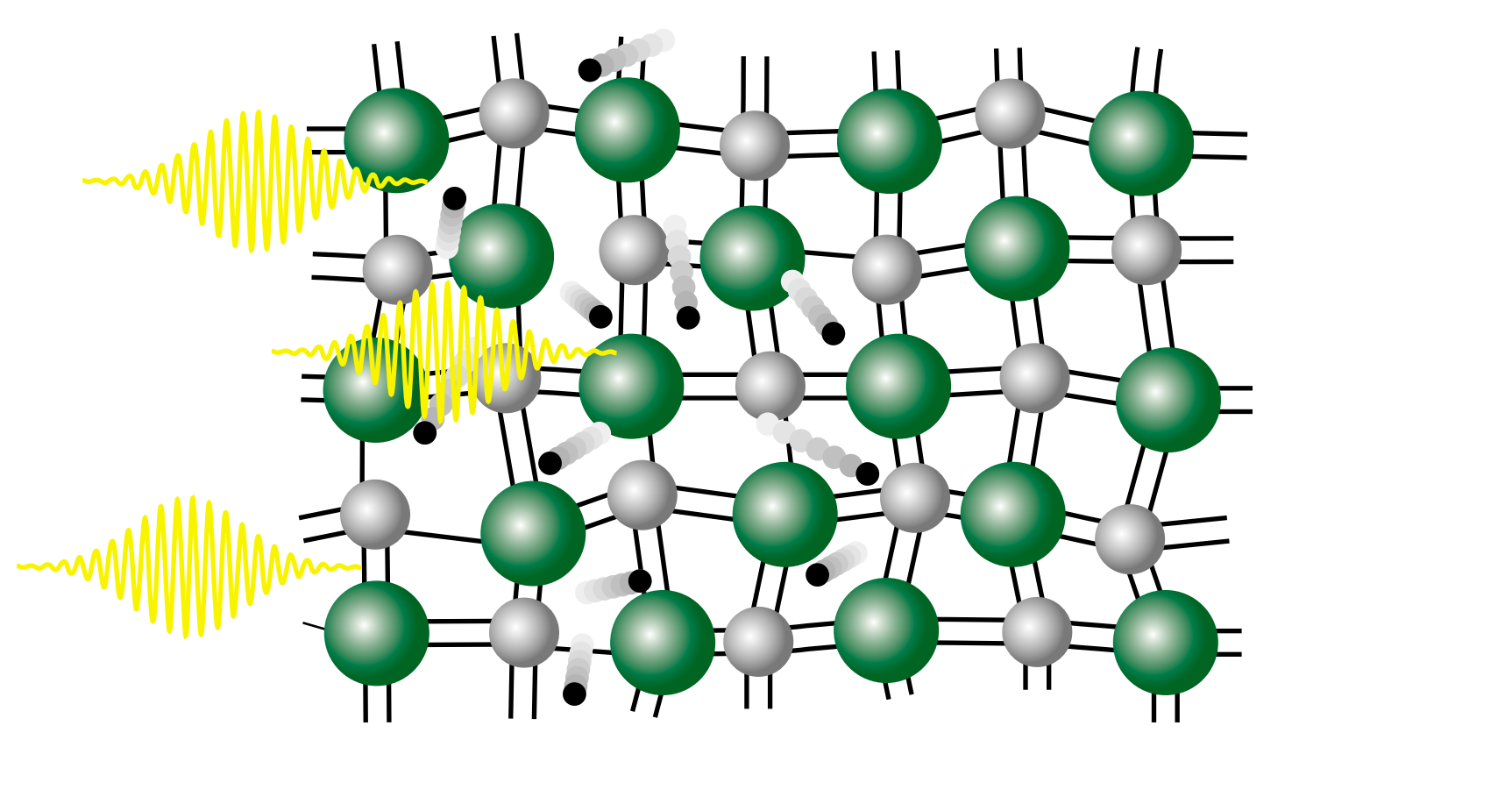
Electronic and structural transitions

…causing electronic and structural changes…



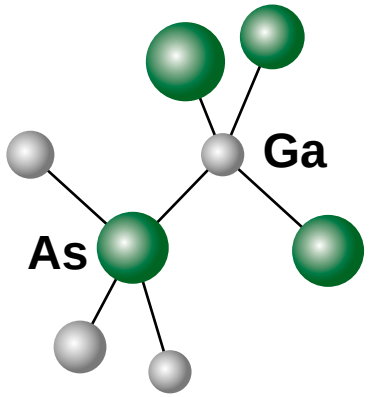
Electronic and structural transitions

…which we measure with another pulse

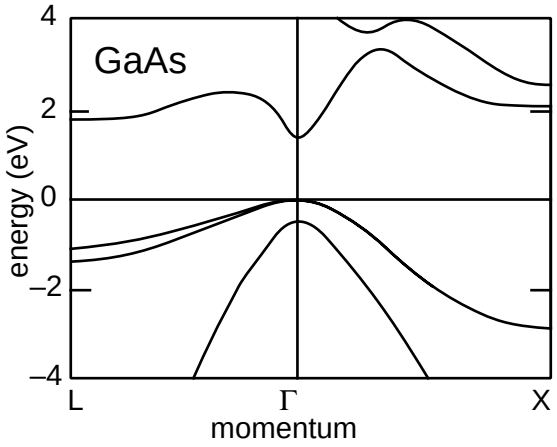


Electronic and structural transitions

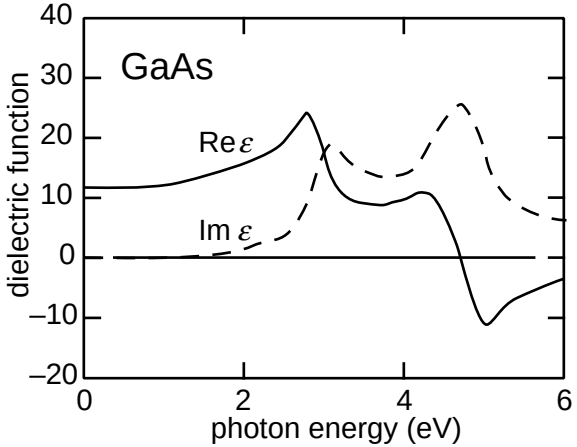
structure



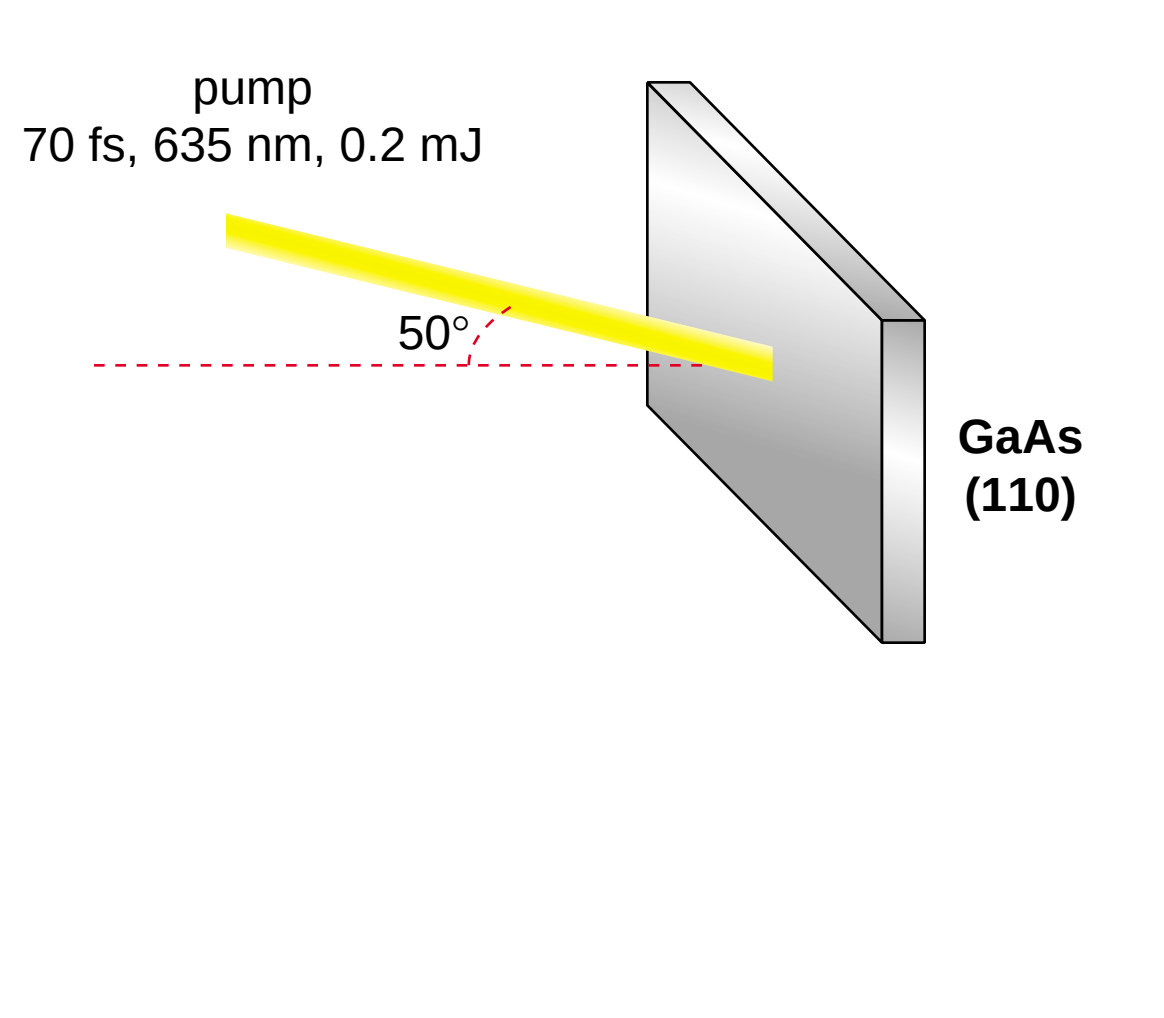
bandstructure



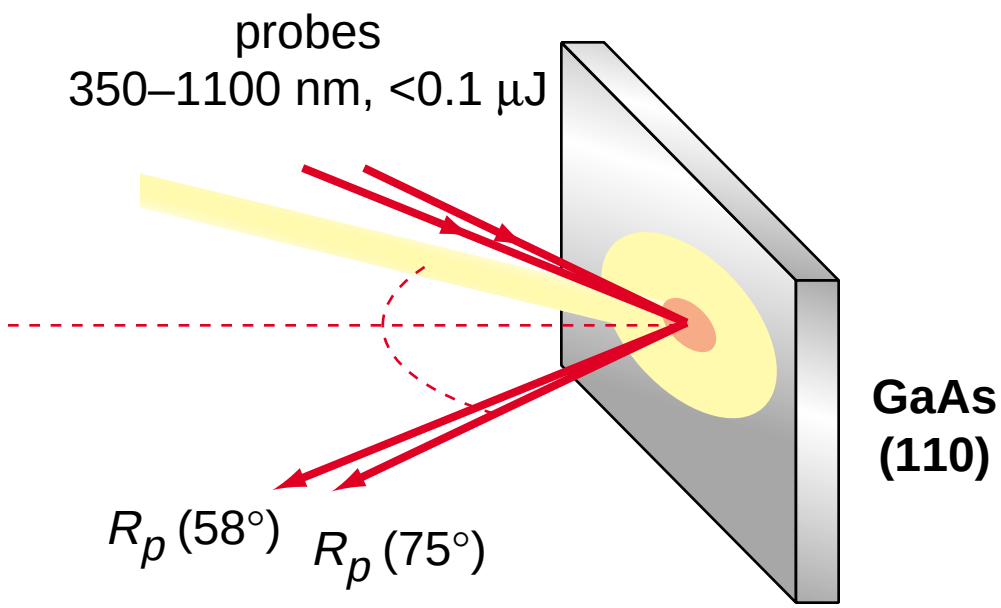
dielectric function



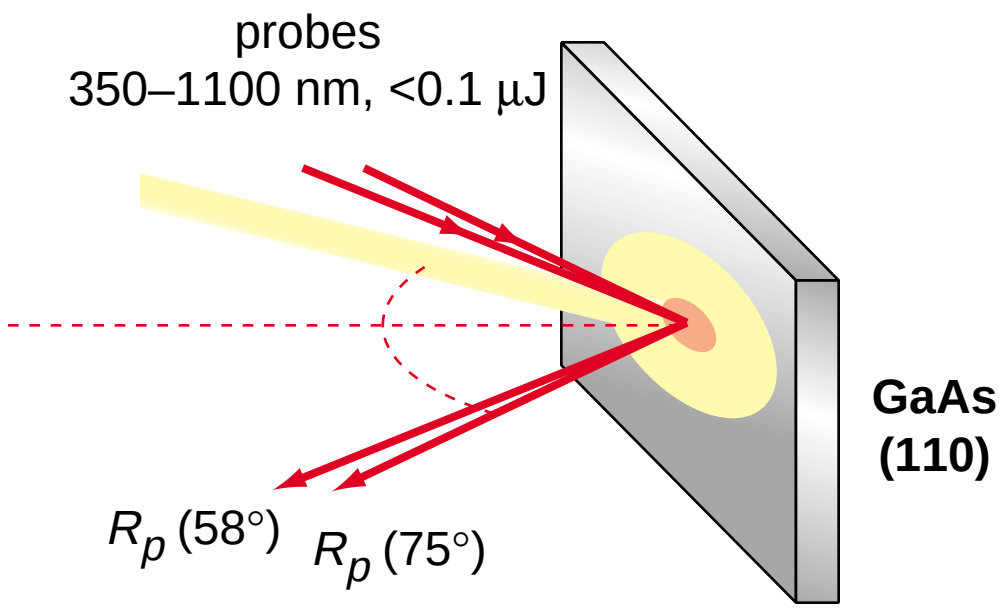
Electronic and structural transitions



Electronic and structural transitions

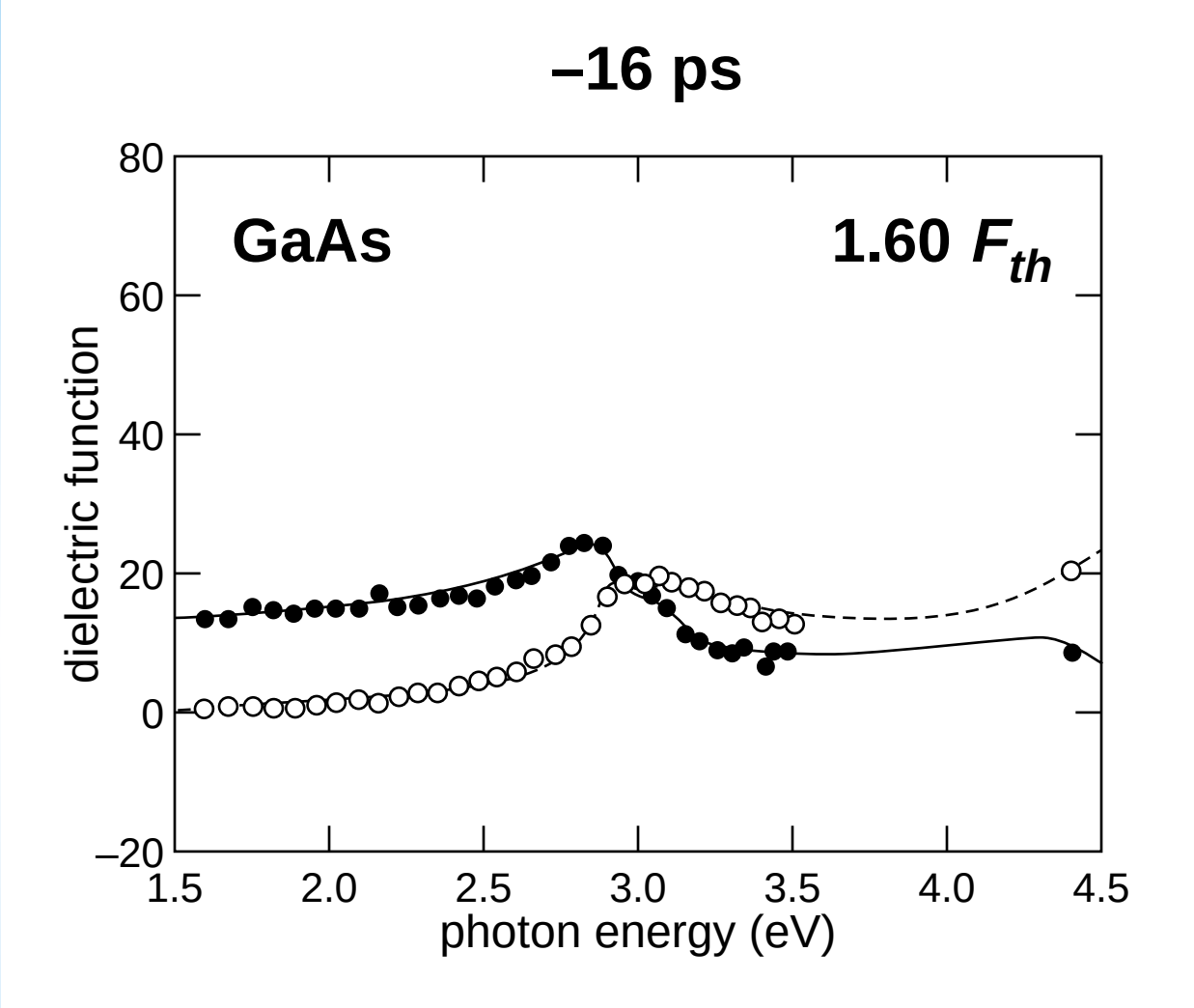


Electronic and structural transitions

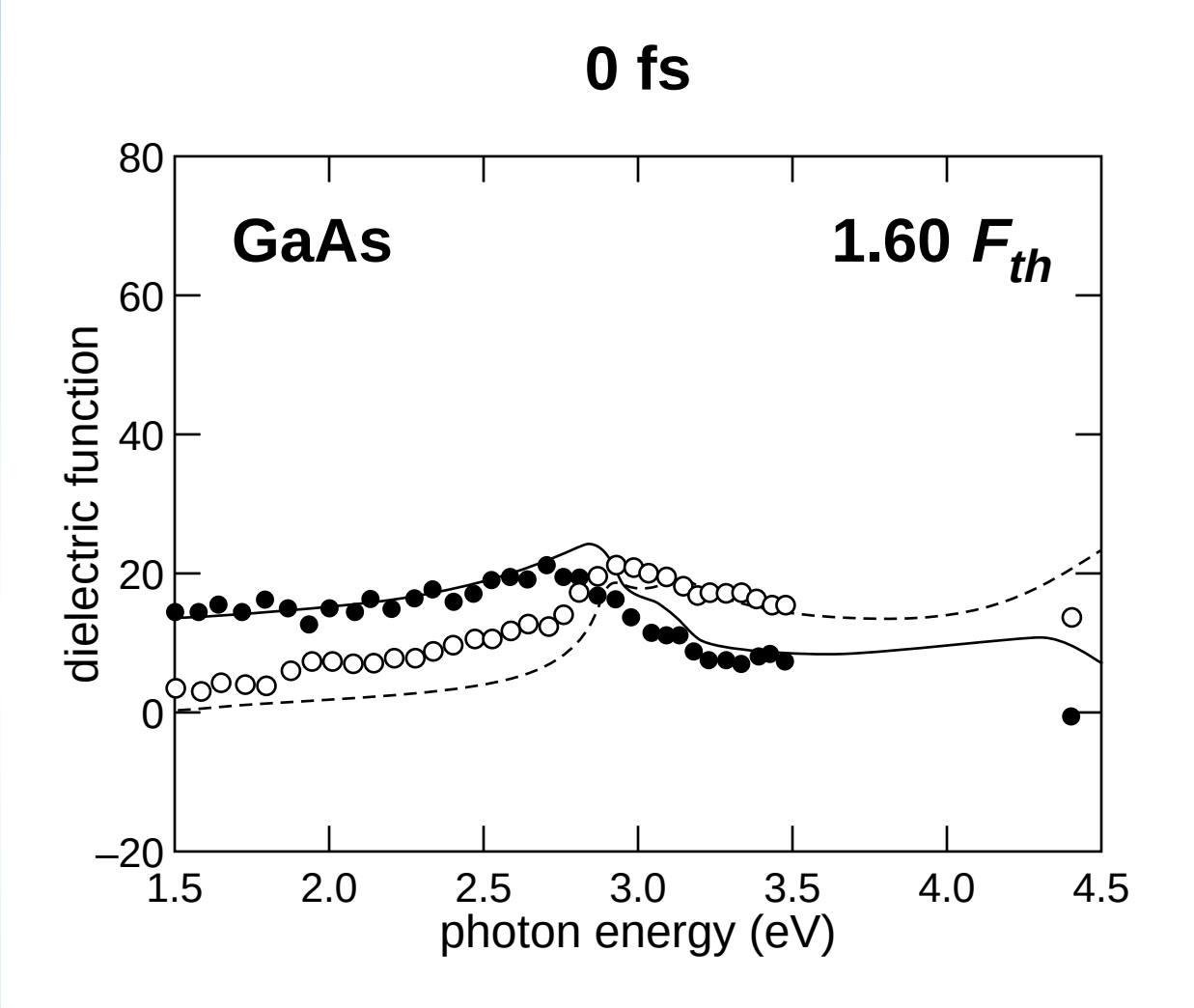


Fresnel equations → Re ε(ω), Im ε(ω)

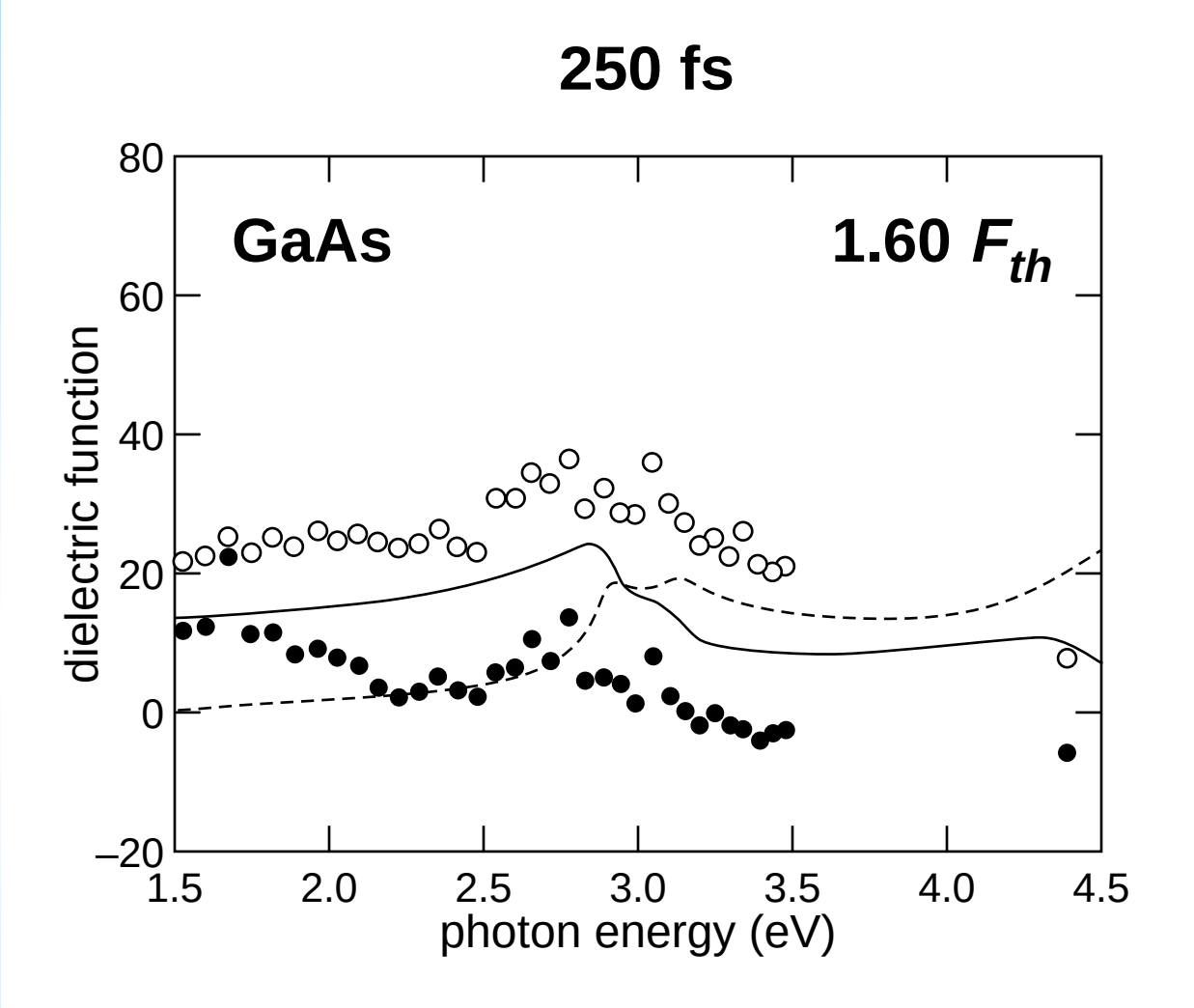
Electronic and structural transitions



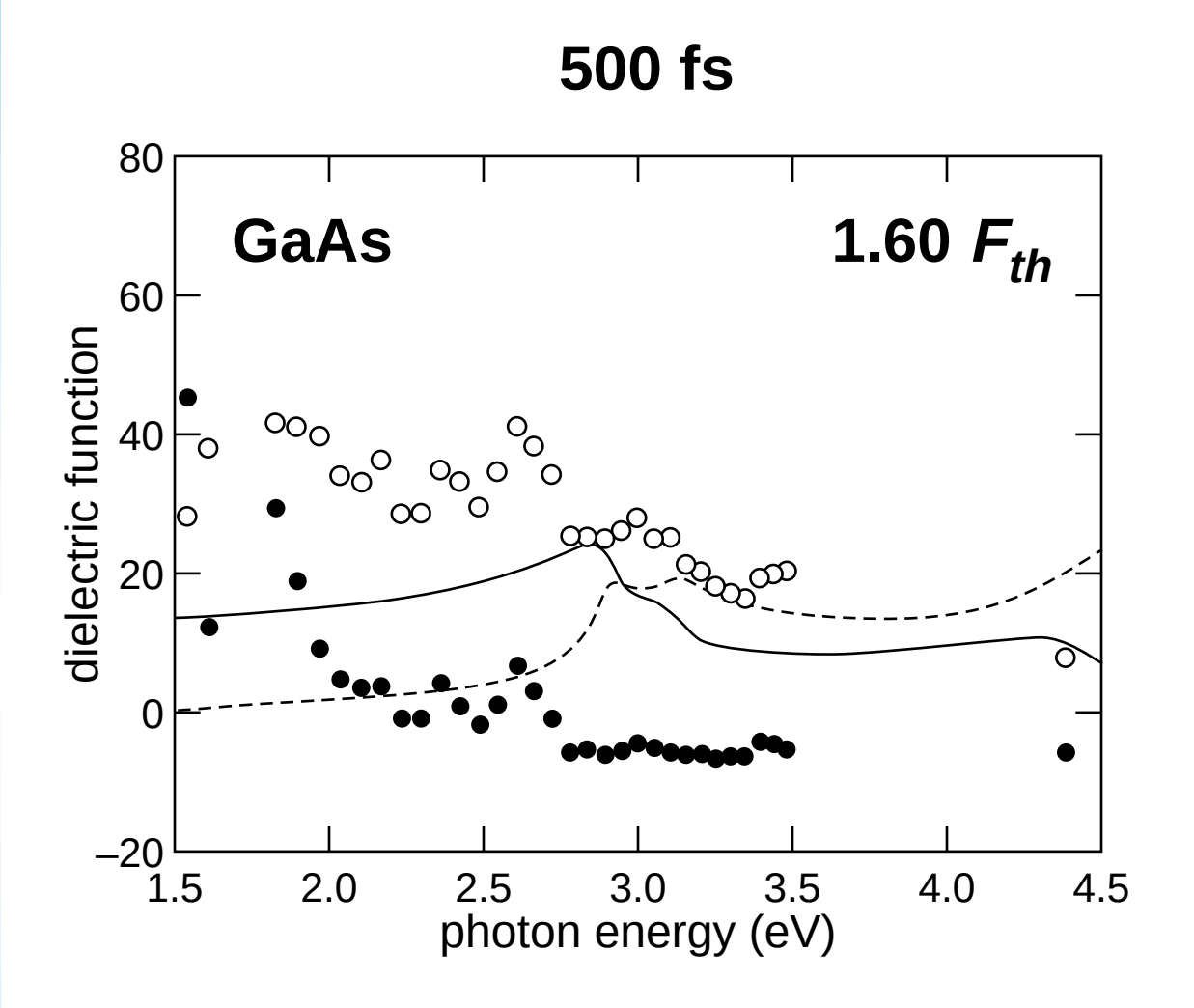
Electronic and structural transitions



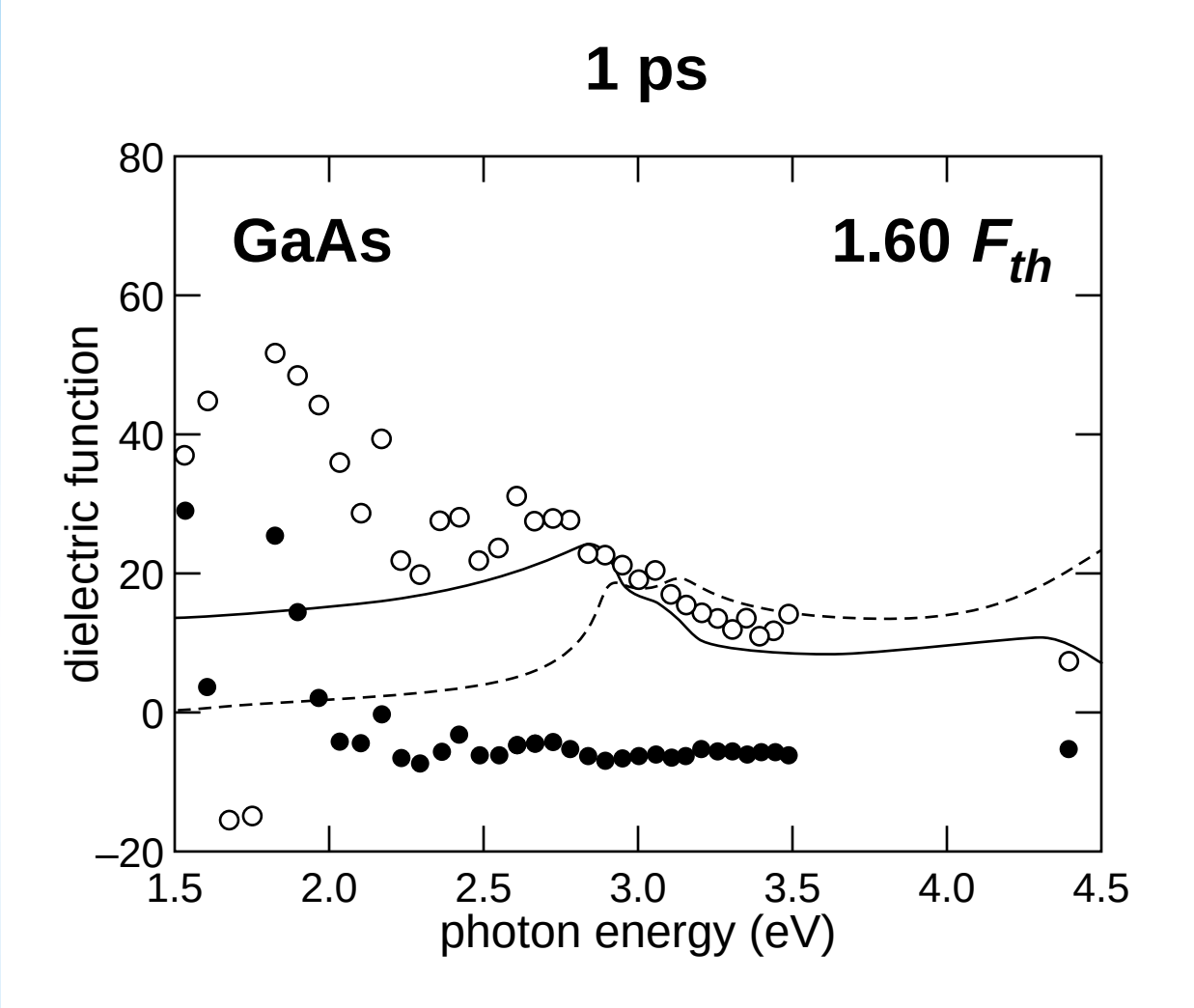
Electronic and structural transitions



Electronic and structural transitions



Electronic and structural transitions



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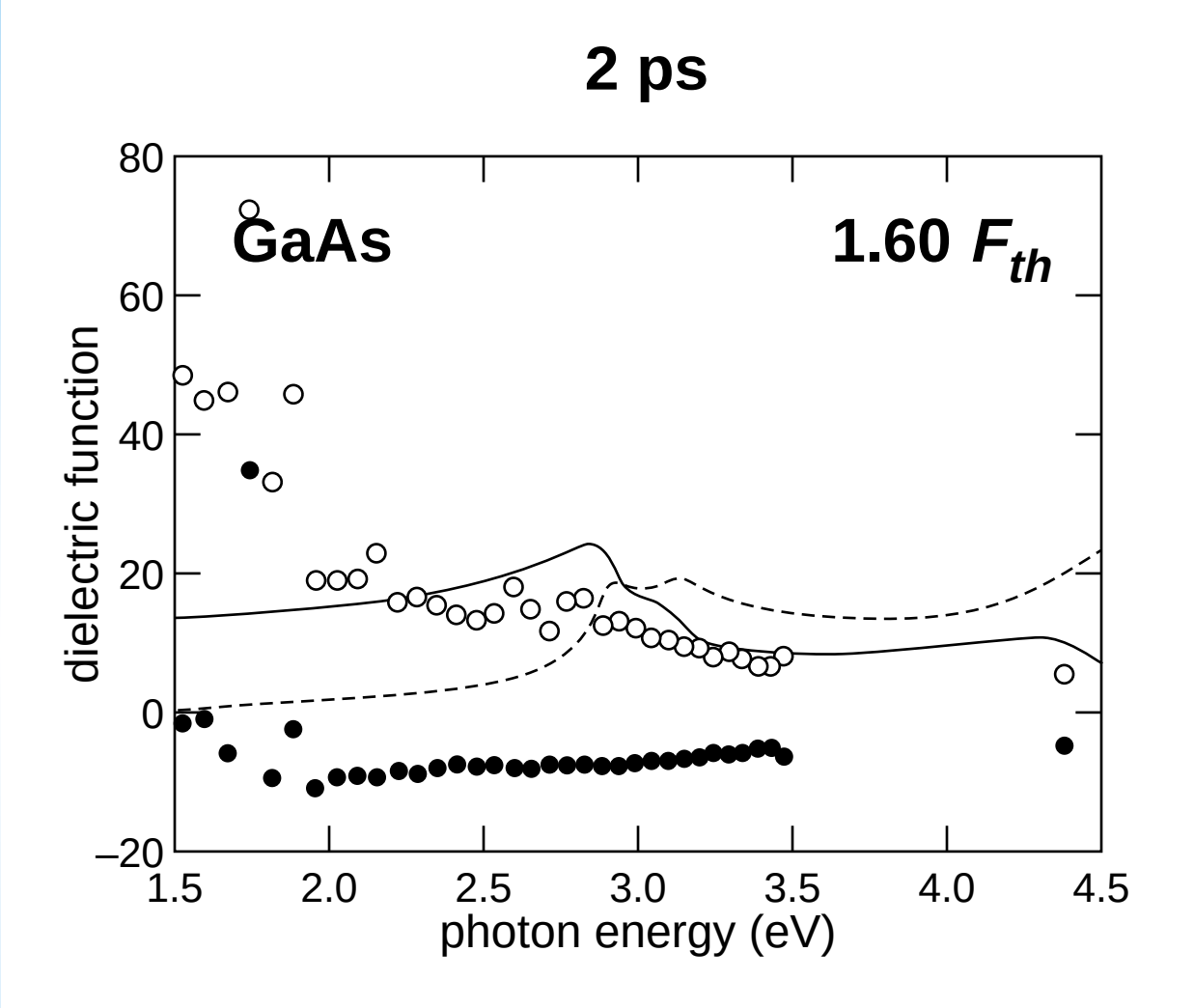
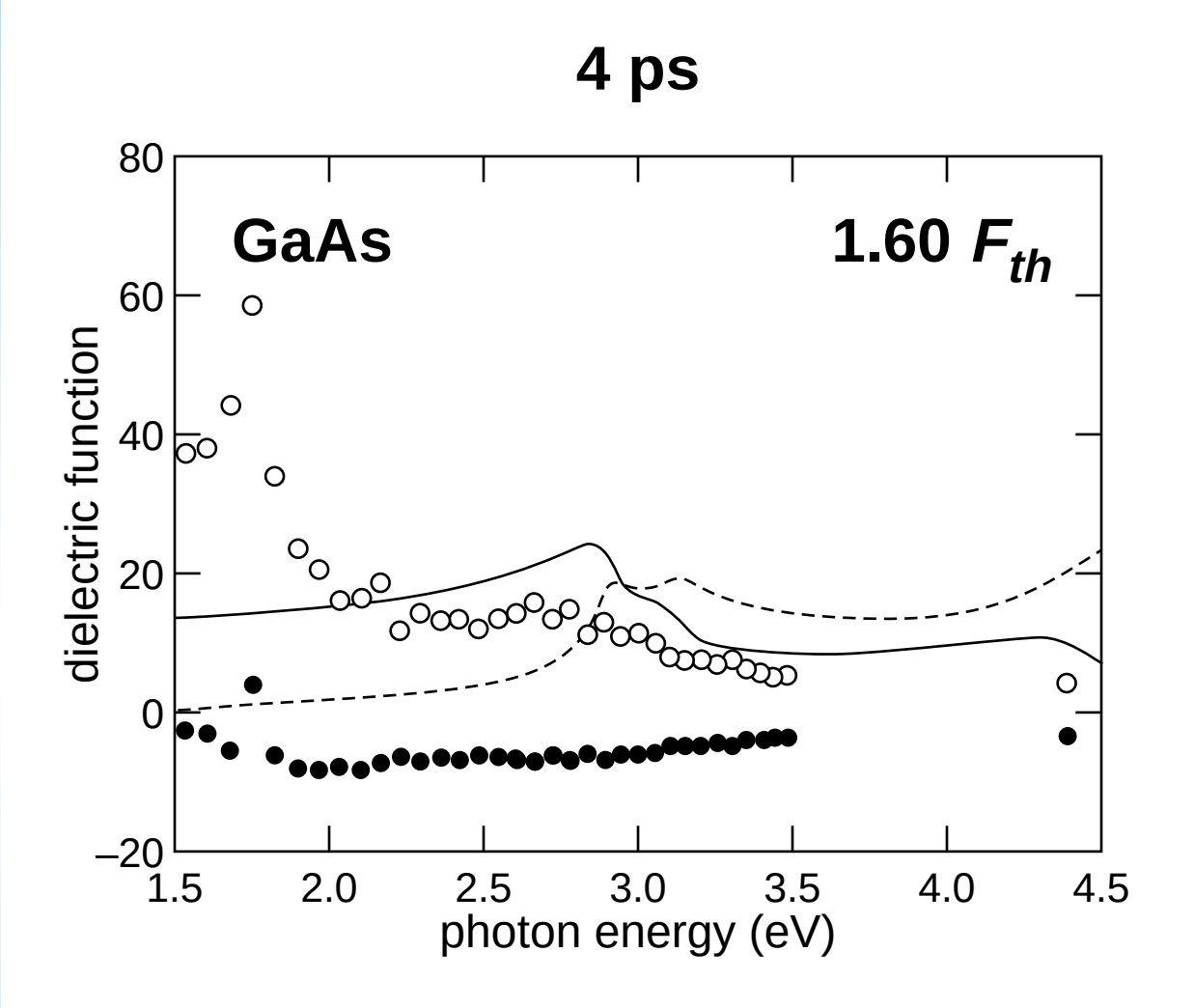
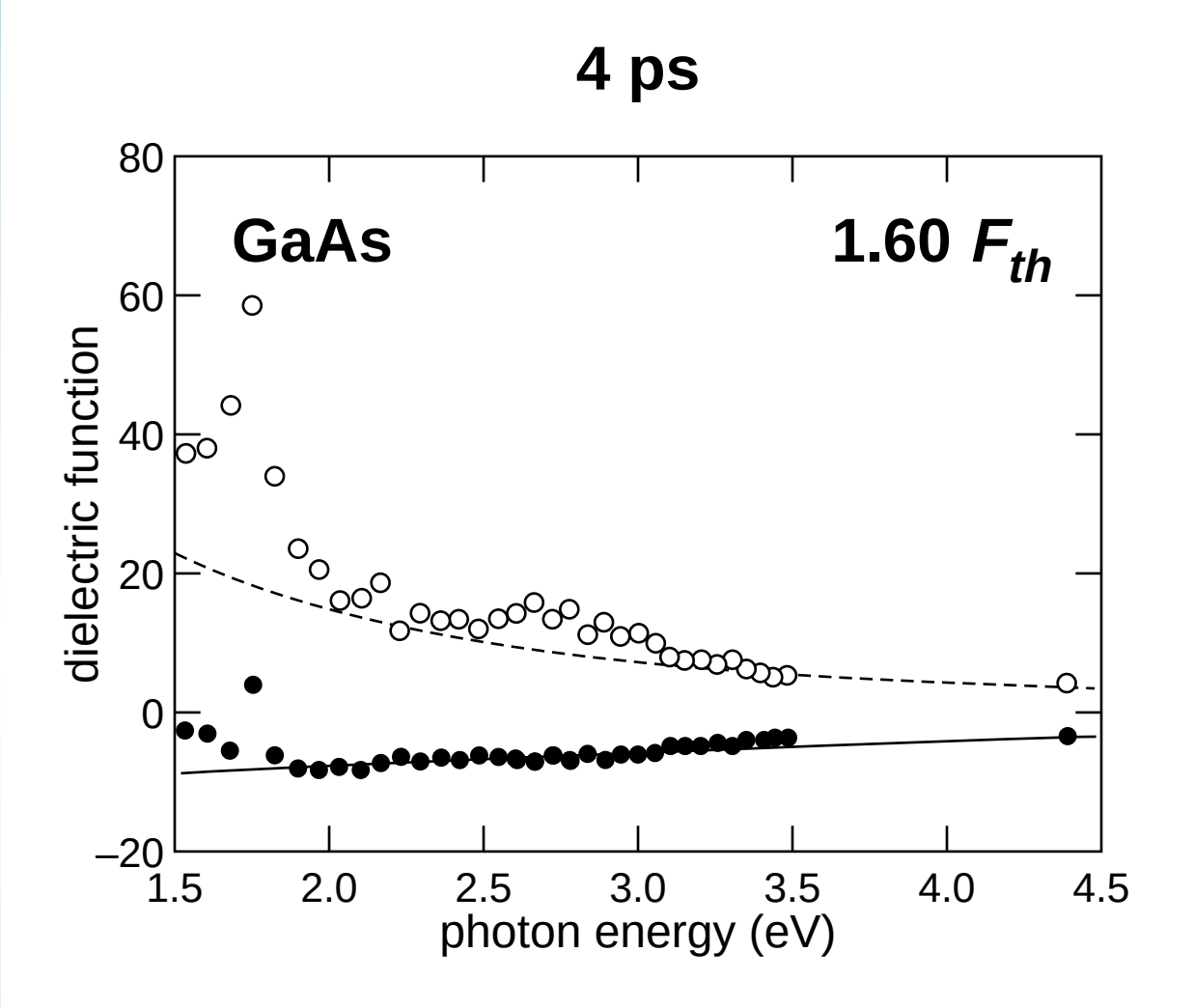


Electronic and structural transitions



Electronic and structural transitions

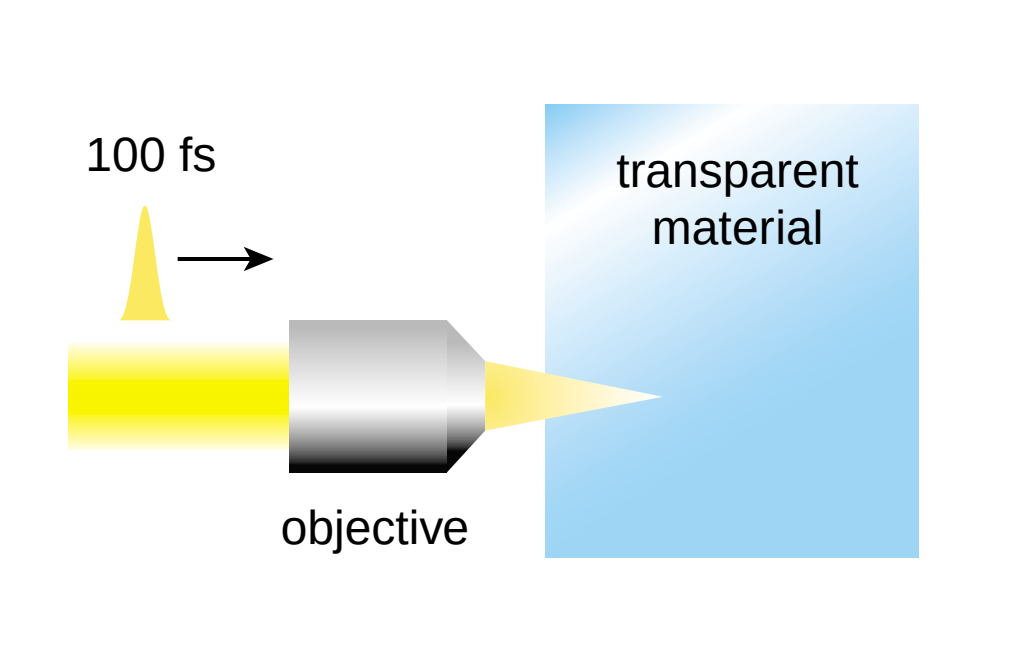


Overview

- surface femtochemistry
- electronic and structural transitions
- **microstructuring of materials**
- nonlinear optics and propagation
- laser surgery

Microstructuring

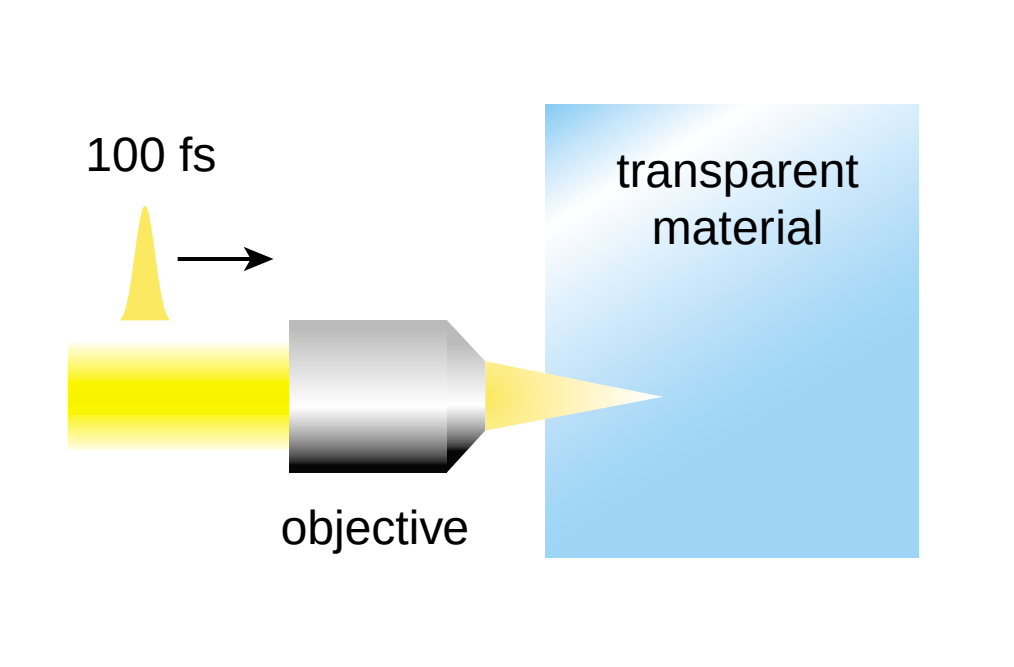
focus laser beam inside material…



Glezer, *et al.*, *Opt. Lett.* 21, 2023 (1996)

Microstructuring

high intensity at focus…



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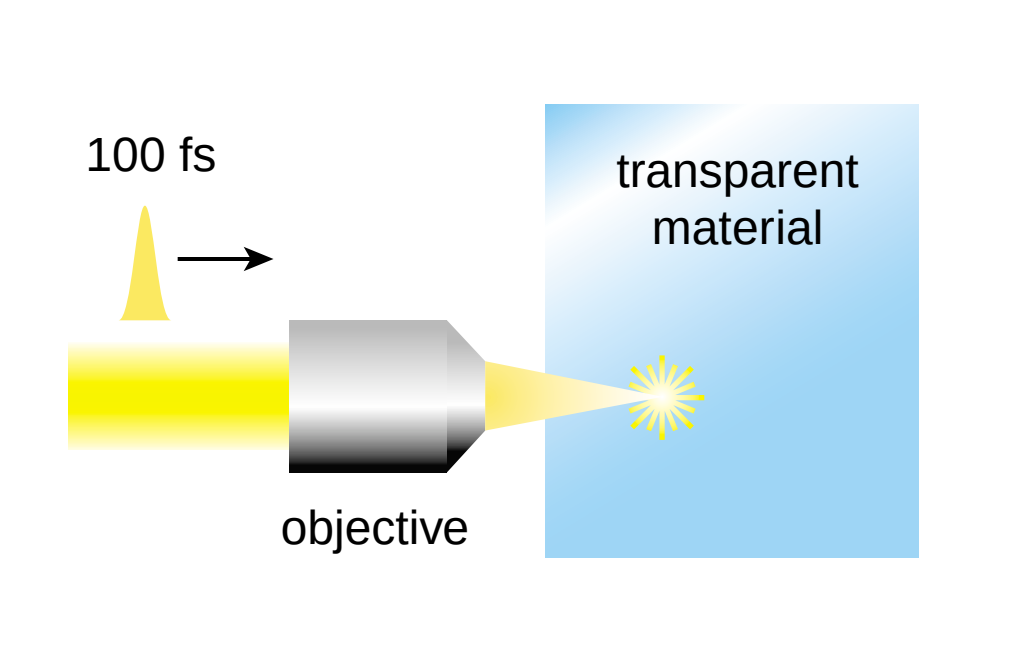
Microstructuring

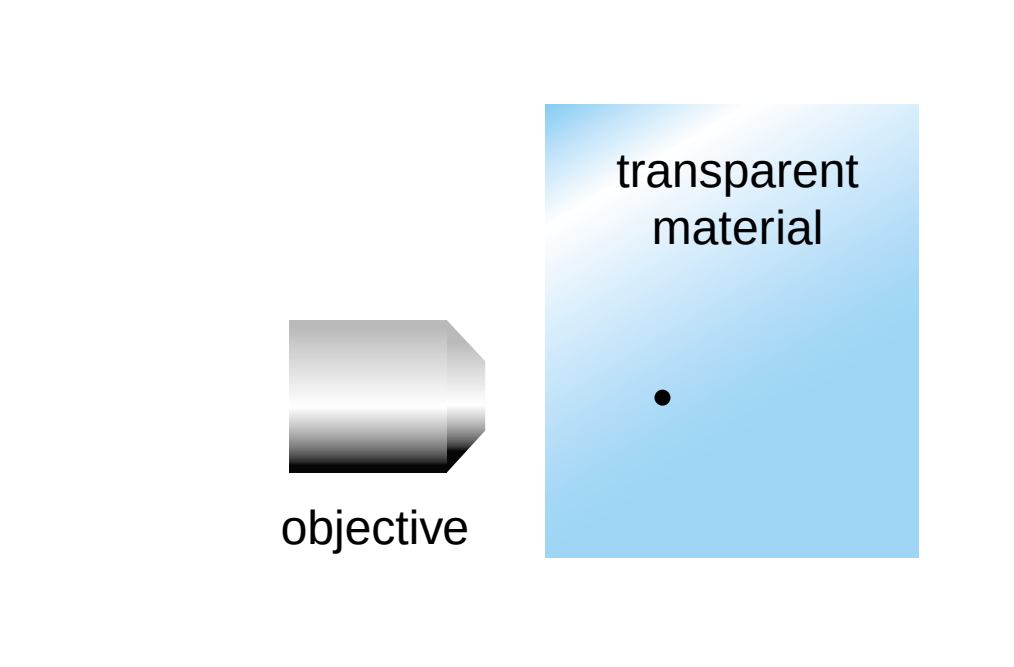
… causes nonlinear ionization…



Glezer, *et al.*, *Opt. Lett.* 21, 2023 (1996)

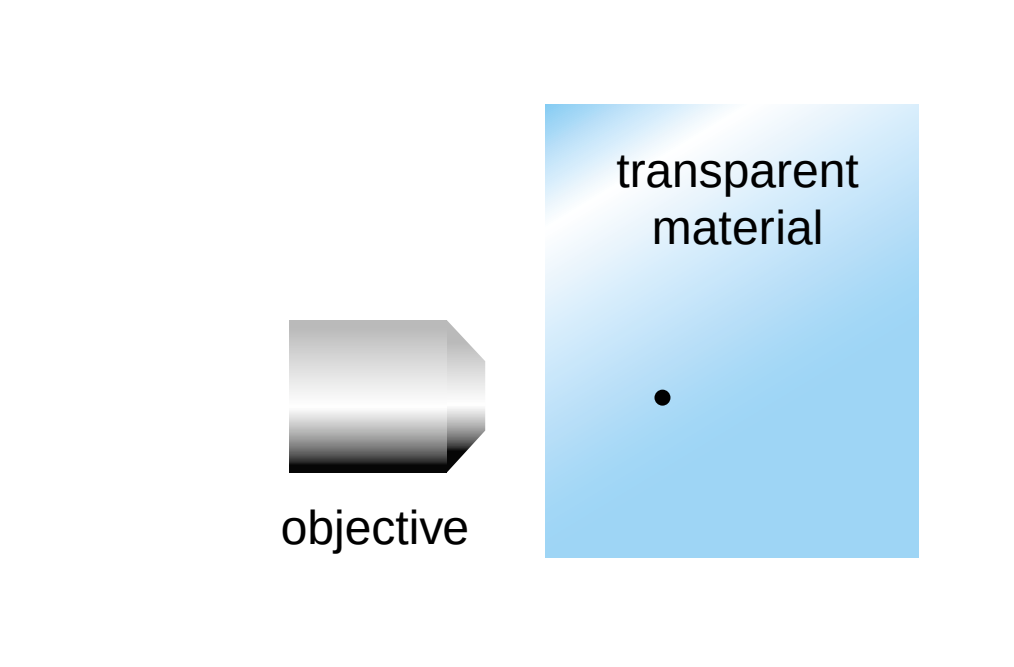
Microstructuring

and microscopic bulk damage



Glezer, *et al.*, *Opt. Lett.* 21, 2023 (1996)

What are the conditions at focus?



Microstructuring

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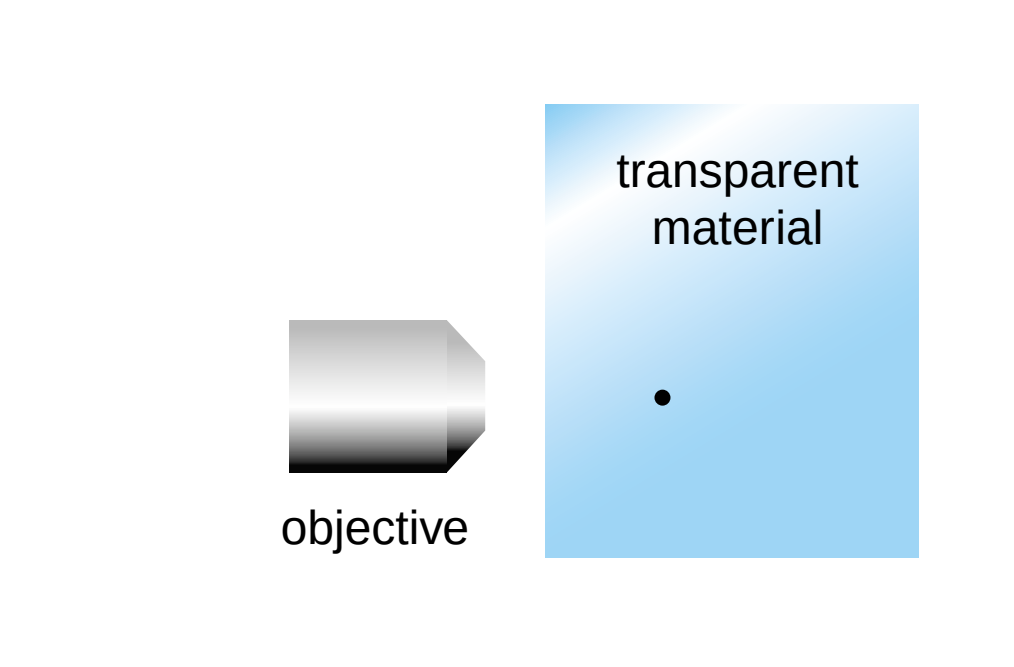

laser deposits energy in ~1 μm^3

Microstructuring

What temperature?

What temperature?

$$\Delta E = C_V \rho V \, \Delta T$$

What temperature?

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$$C_V = 0.75 \times 10^3 \text{ J kg}^{-1} \text{ K}^{-1}$$

$$\rho = 2.2 \times 10^3 \text{ kg/m}^3$$

Microstructuring

What temperature?

$$\Delta E = C_V \rho V \, \Delta T$$

$$C_V = 0.75 \times 10^3 \text{ J kg}^{-1} \text{ K}^{-1}$$

$$\rho = 2.2 \times 10^3 \text{ kg/m}^3$$

So, 1 μJ in 1 μm^3 gives

~1,000,000 K!

Microstructuring

What pressure?

Microstructuring

What pressure?

Treat ionized material as an ideal gas:

$$pV = nRT$$

Microstructuring

What pressure?

Treat ionized material as an ideal gas:

$$pV = nRT$$

Gives

$$p = 10 \text{ MBar!}$$

Microstructuring

So:

	microexplosion
T	≈ 1 MK
p	≈ 10 MBar
ρ	2.2×10^3 kg/m^3

Microstructuring

So:

	microexplosion	**sun**
T	$\approx$1 MK	2–15 MK
p	$\approx$10 MBar	
ρ	2.2×10^3 kg/m^3	$0.15–150 \times 10^3$ kg/m^3

Microstructuring

So:

	microexplosion	**sun**
T	$\approx$1 MK	2–15 MK
p	$\approx$10 MBar	
ρ	2.2×10^3 kg/m^3	$0.15–150 \times 10^3$ kg/m^3

creating stellar conditions on an optical bench!

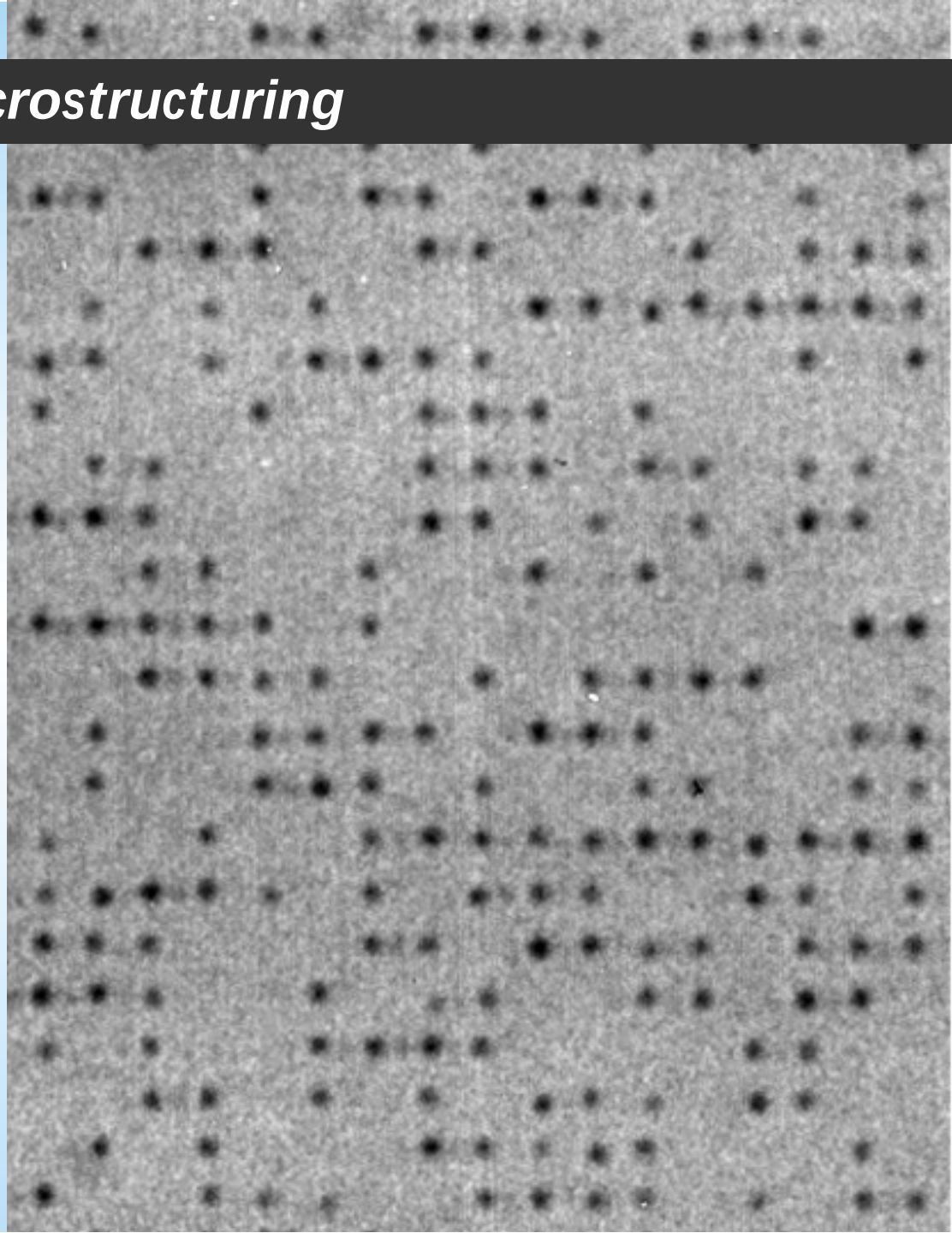
Microstructuring

optical microscopy

2 x 2 µm array

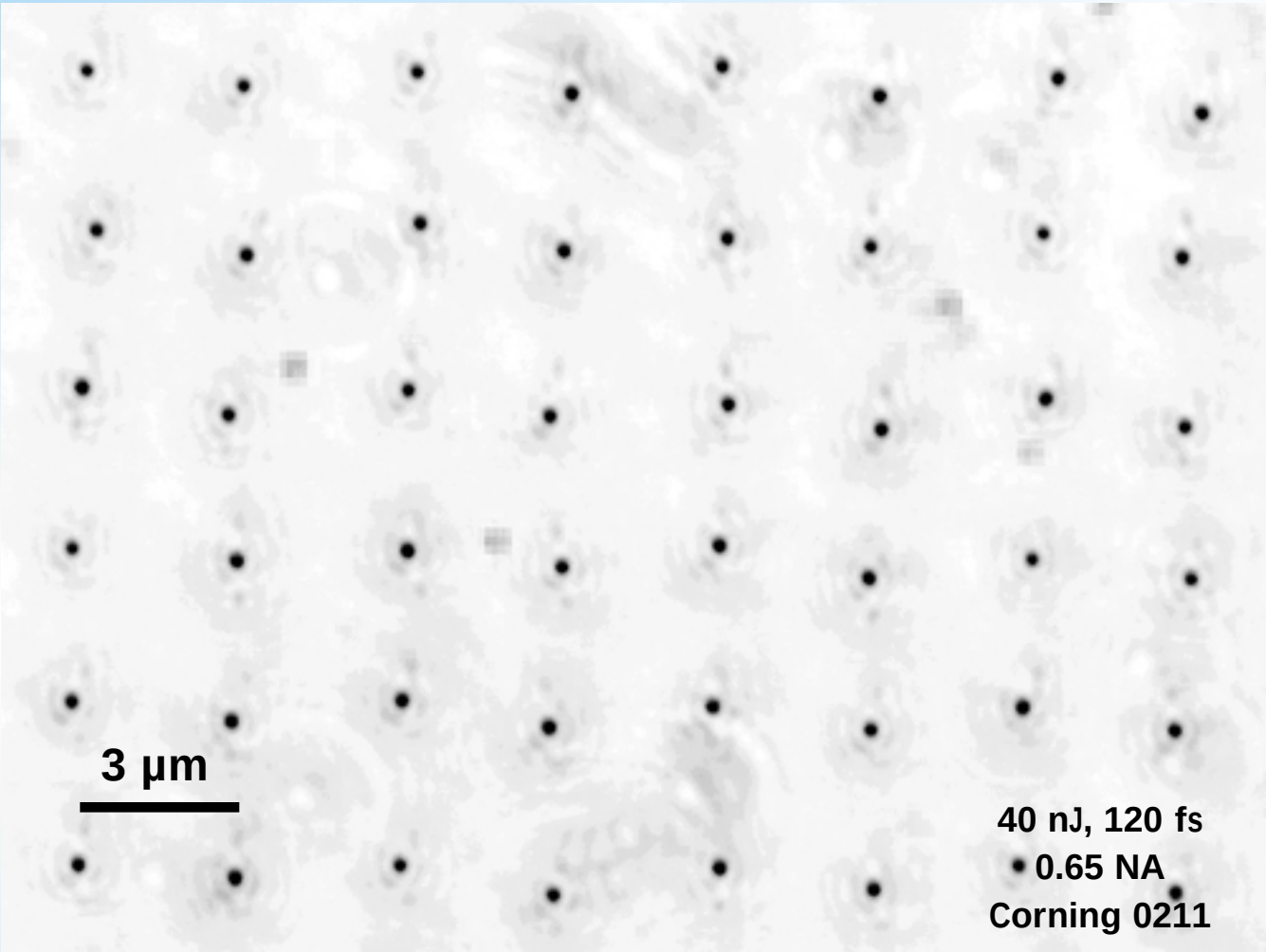
fused silica

0.5 µJ, 100 fs, 800 nm

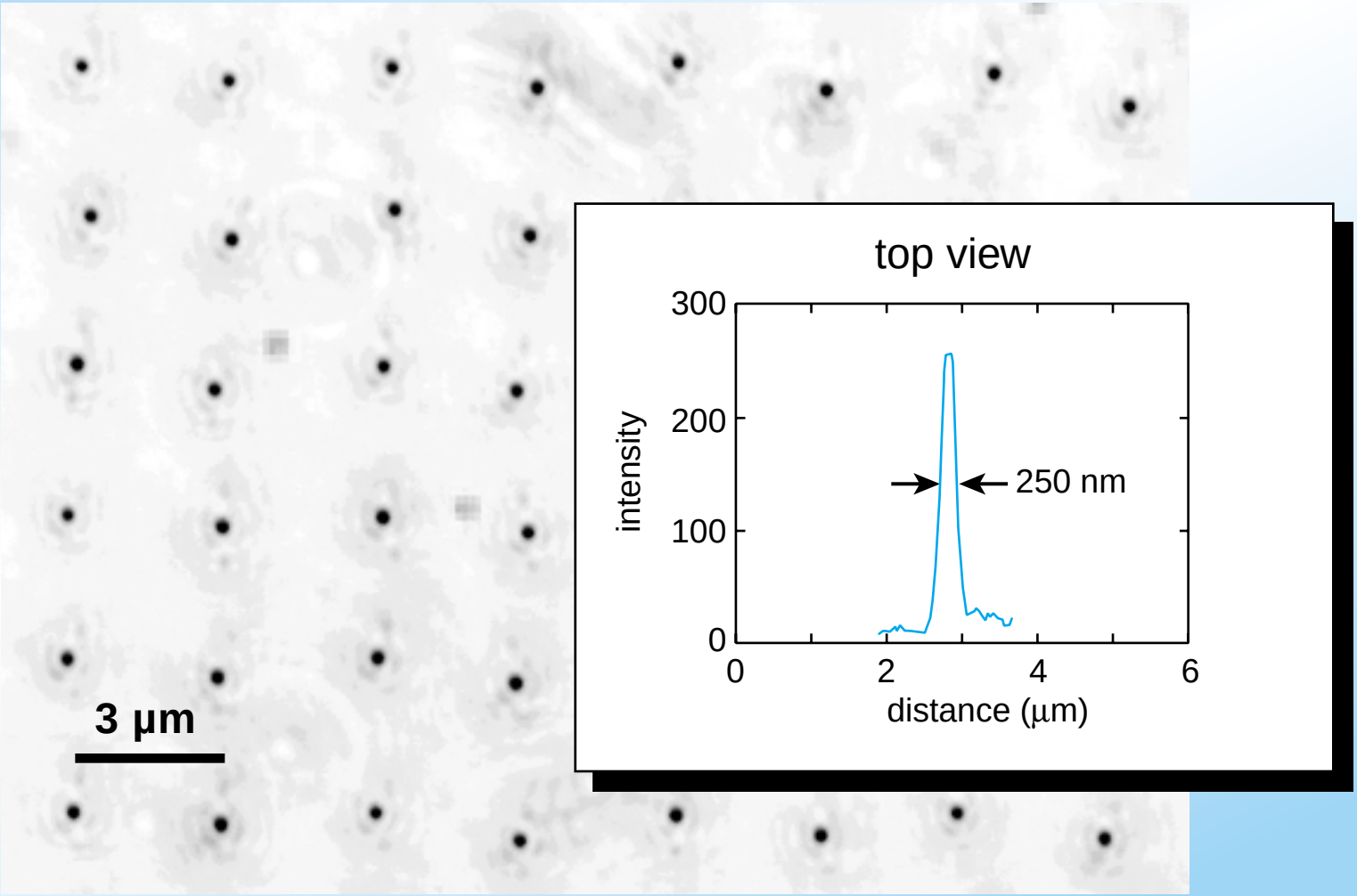


Opt. Lett. **21, 2023 (1996)**

Microstructuring

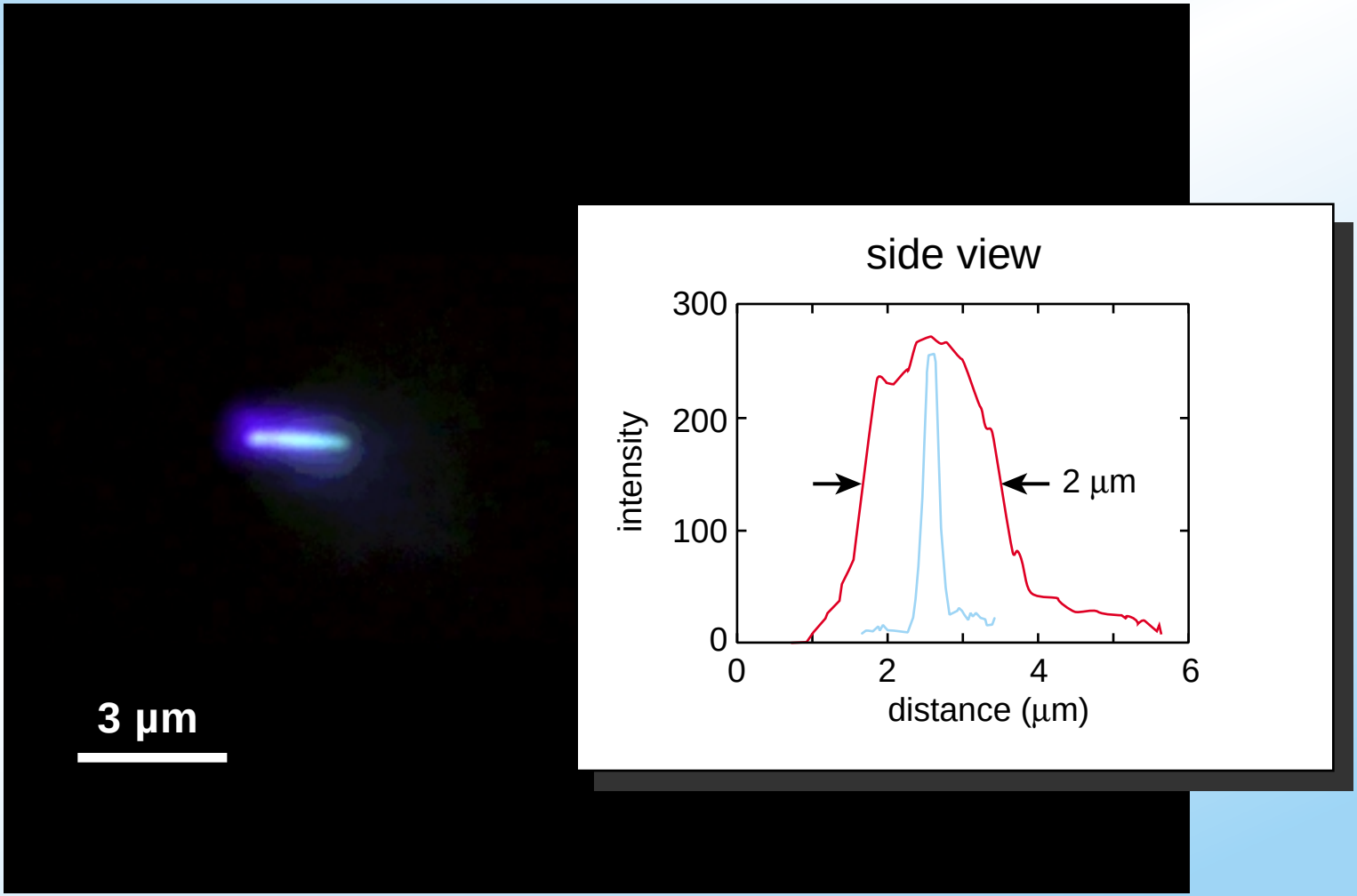


Microstructuring

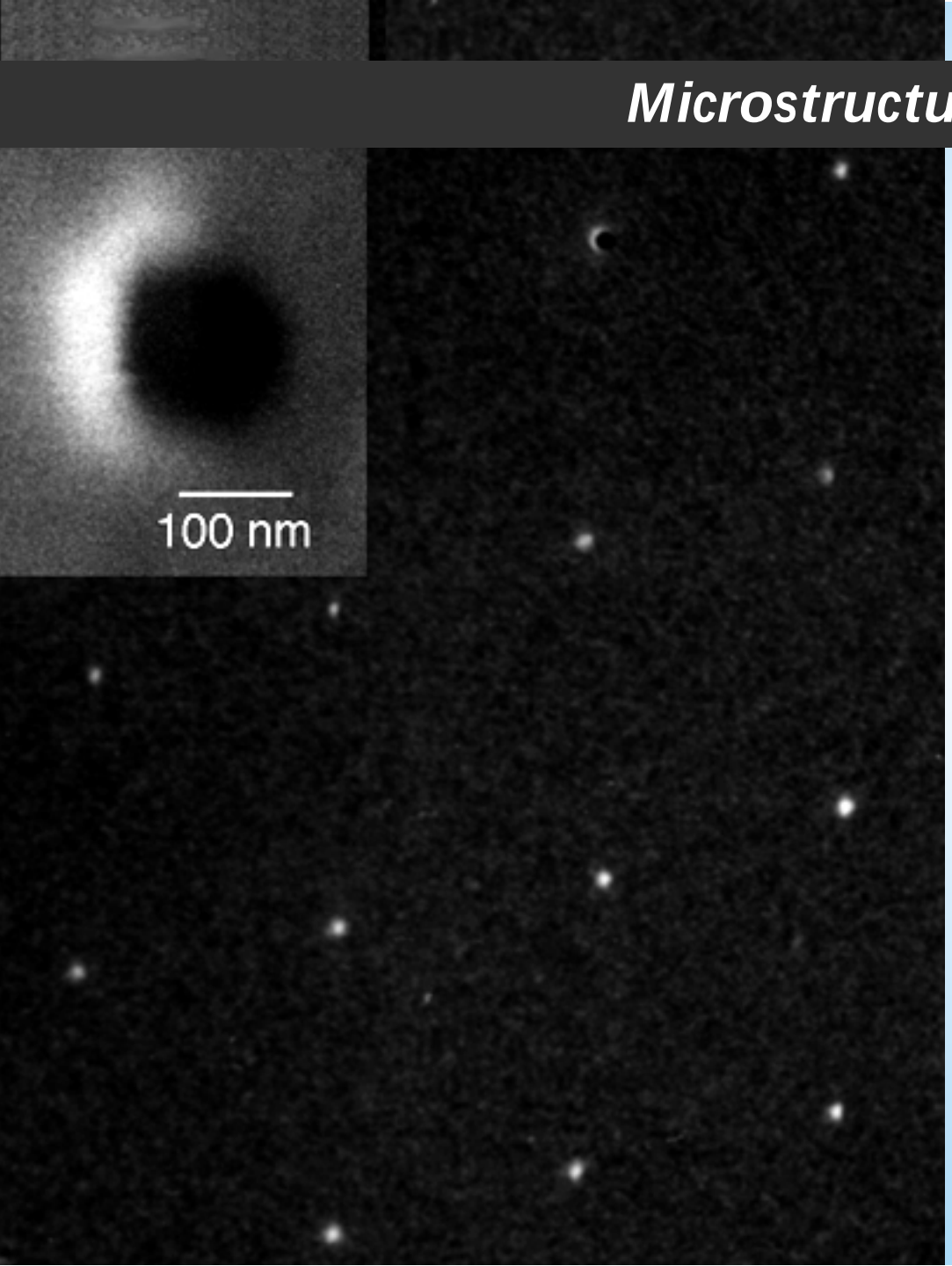


Microstructuring

Microstructuring



Microstructuring



SEM:

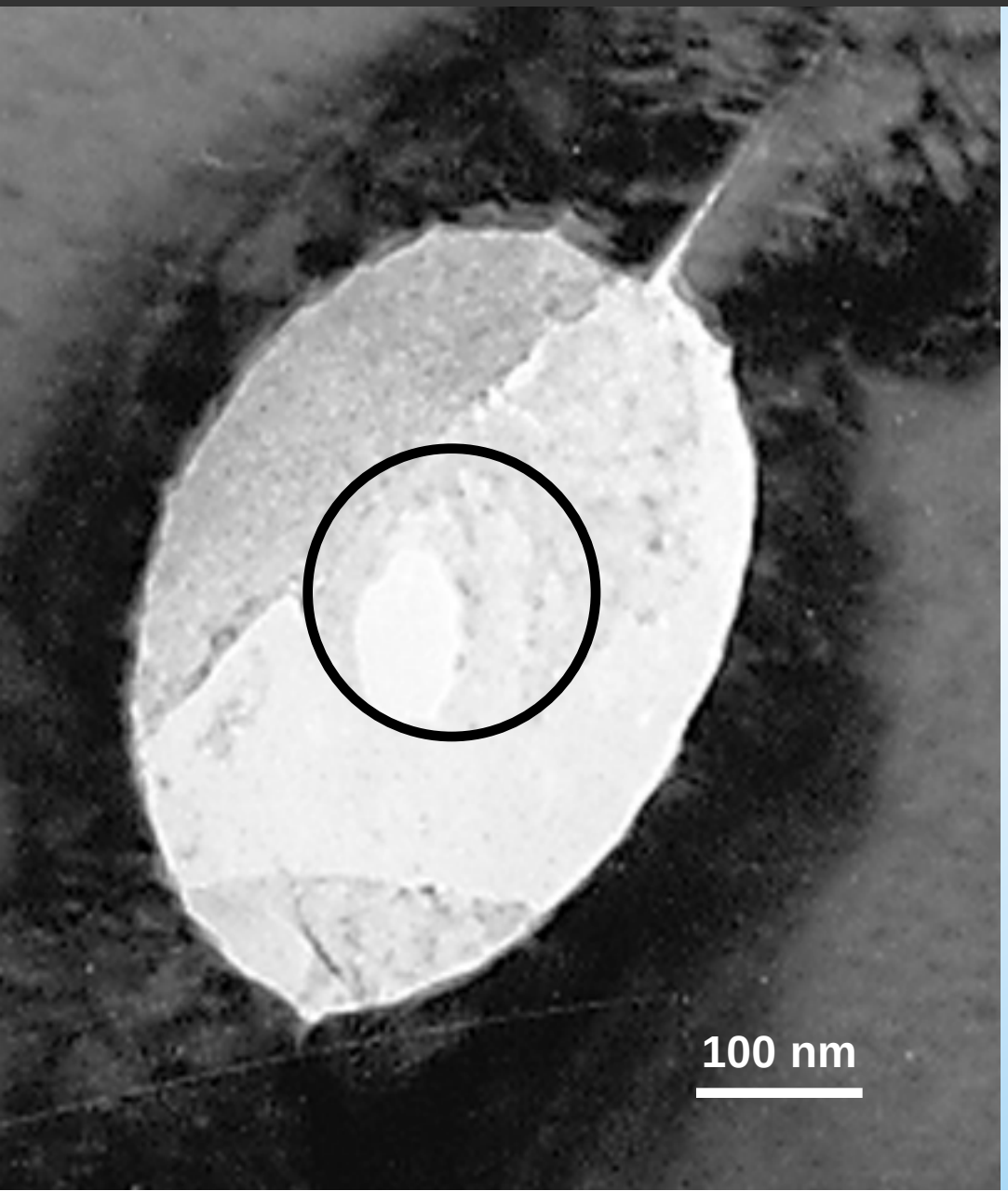
bumps & pits!

Microstructuring

TEM picture

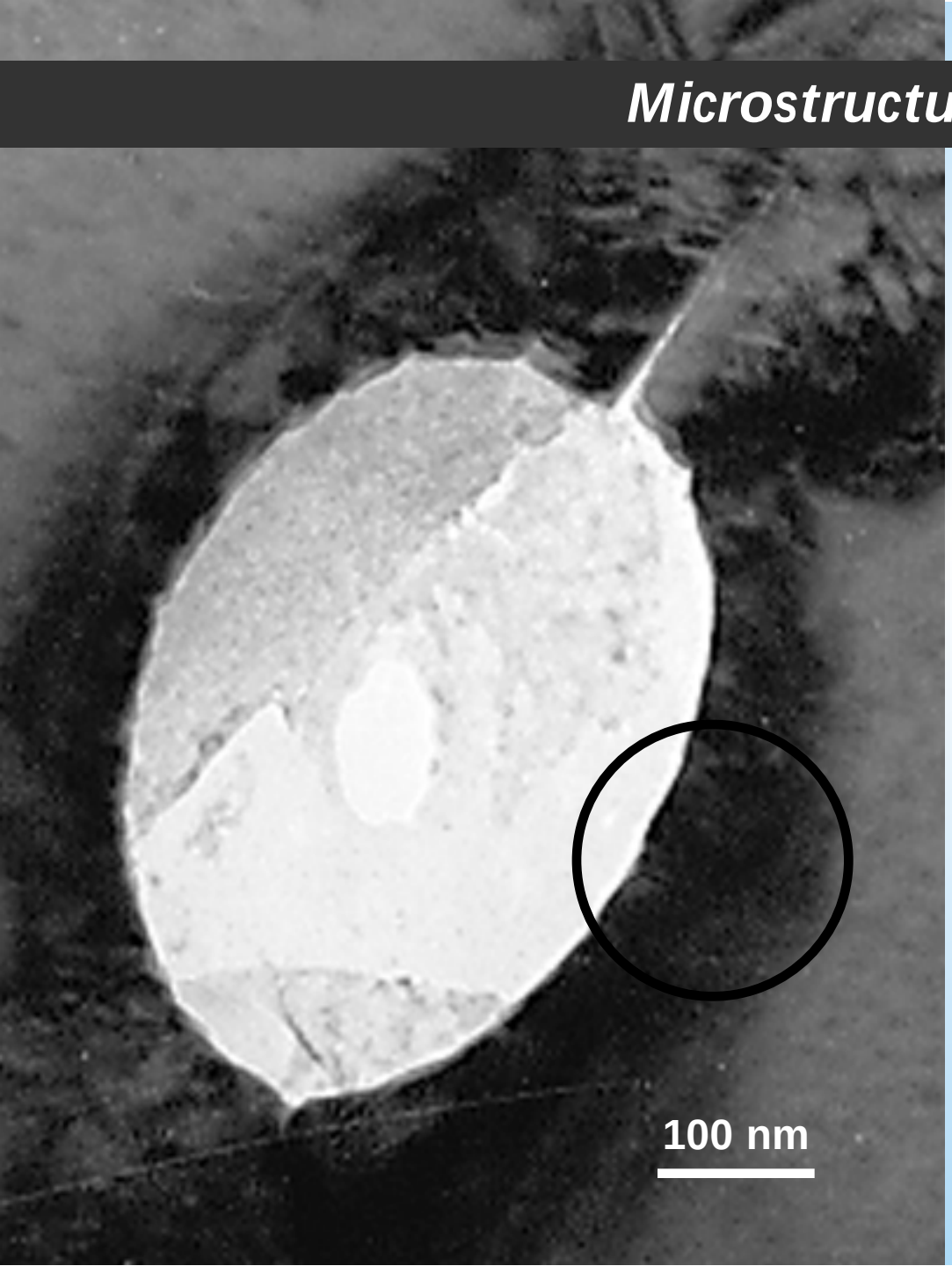
sapphire

Microstructuring

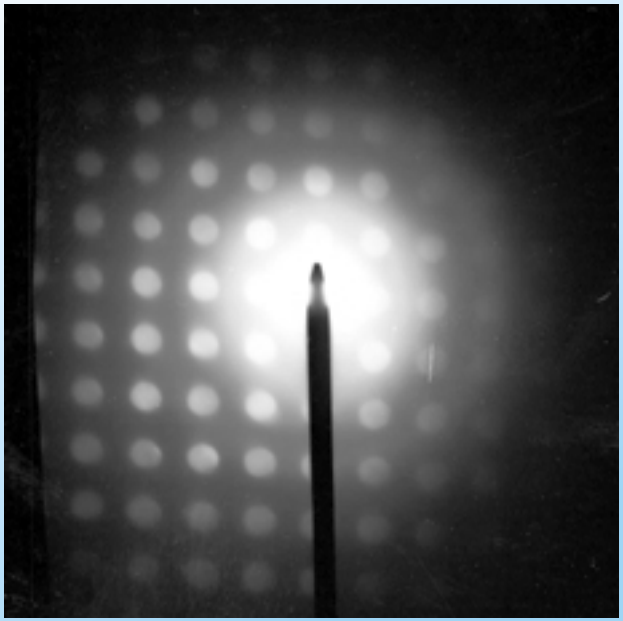


electron diffraction: amorphous?

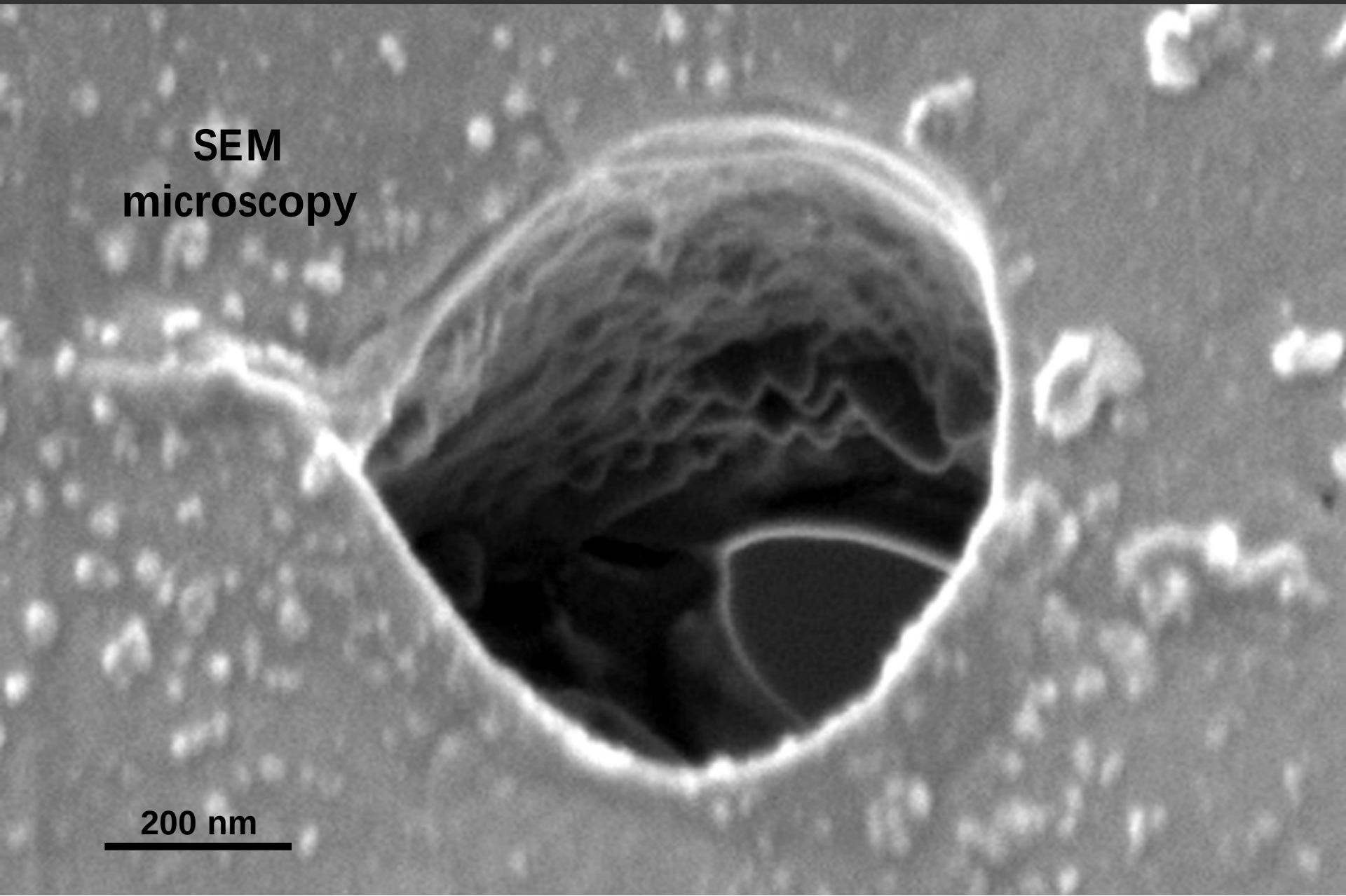
Microstructuring



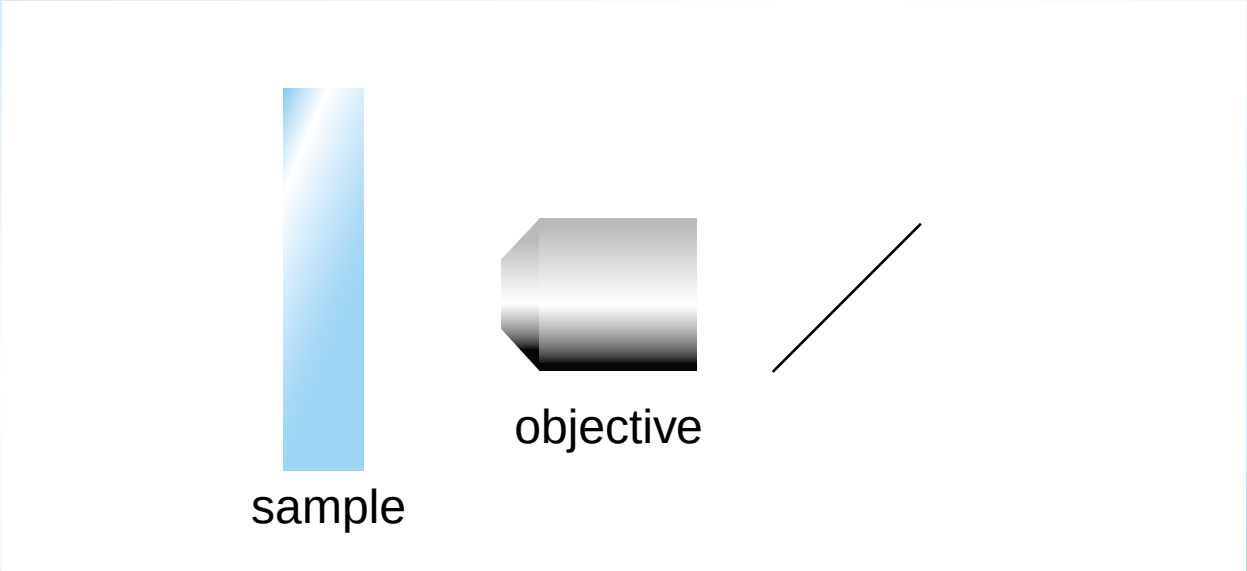
electron diffraction: crystalline



Microstructuring



imaging setup



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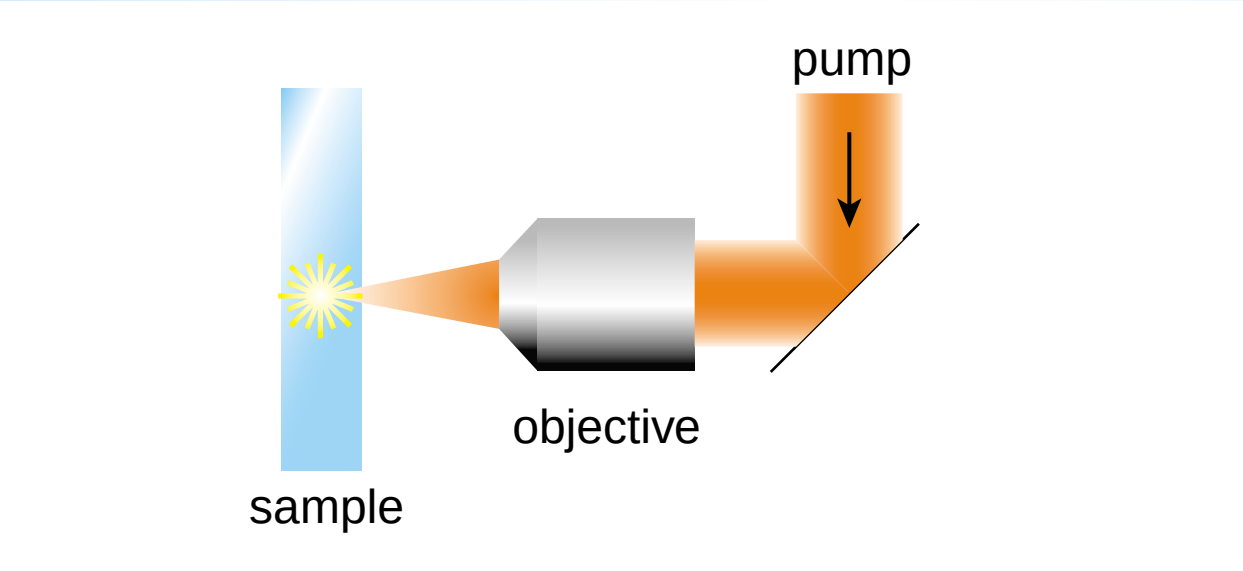

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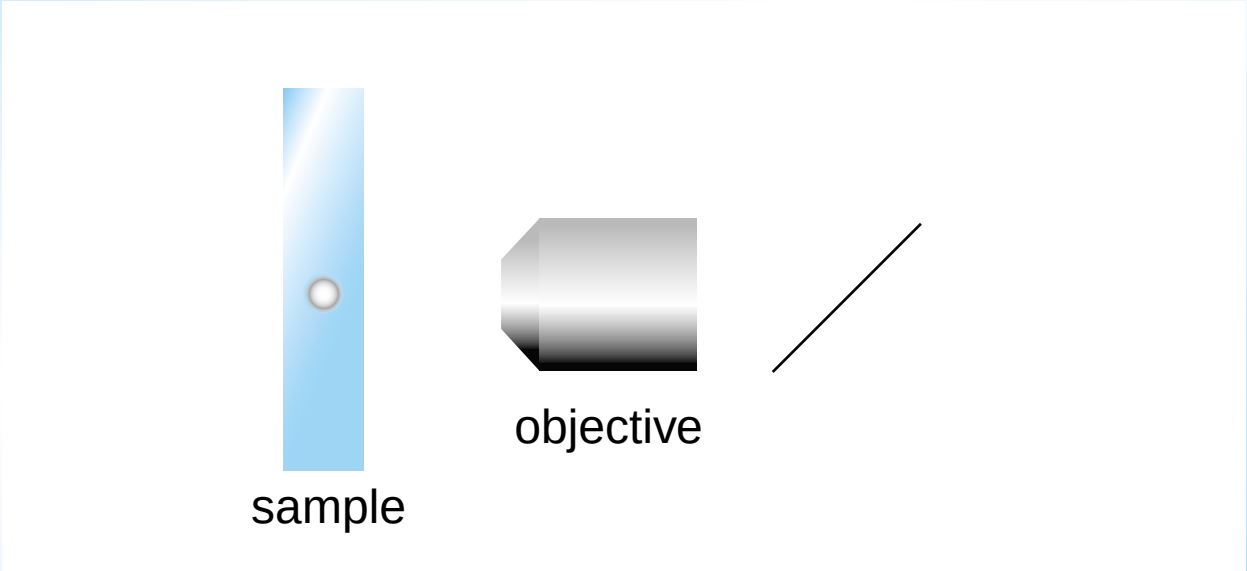

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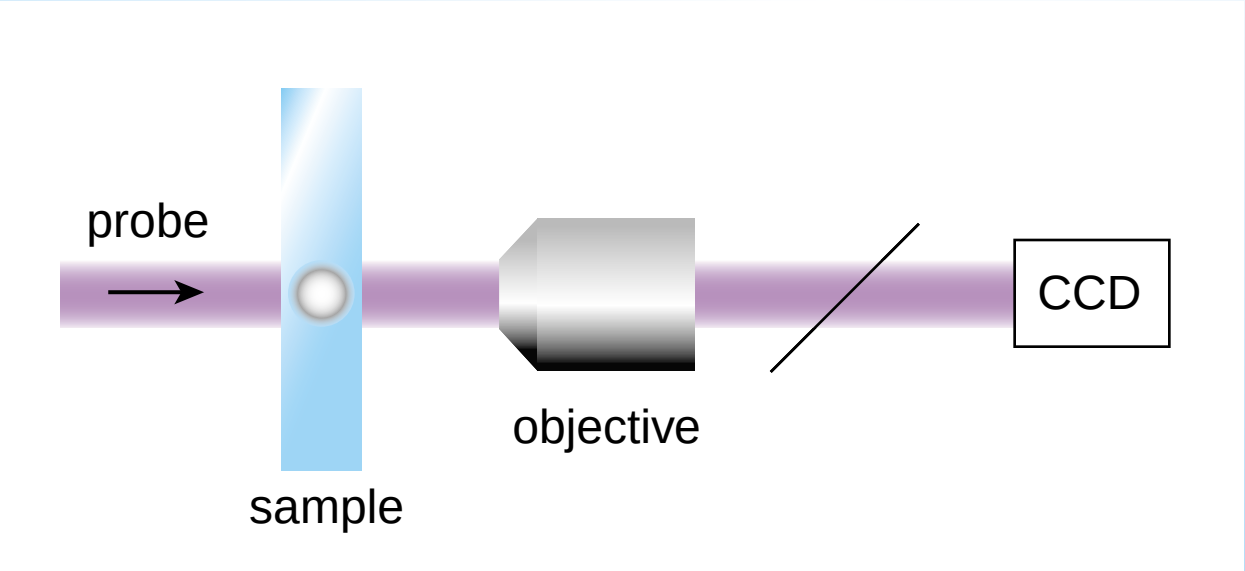


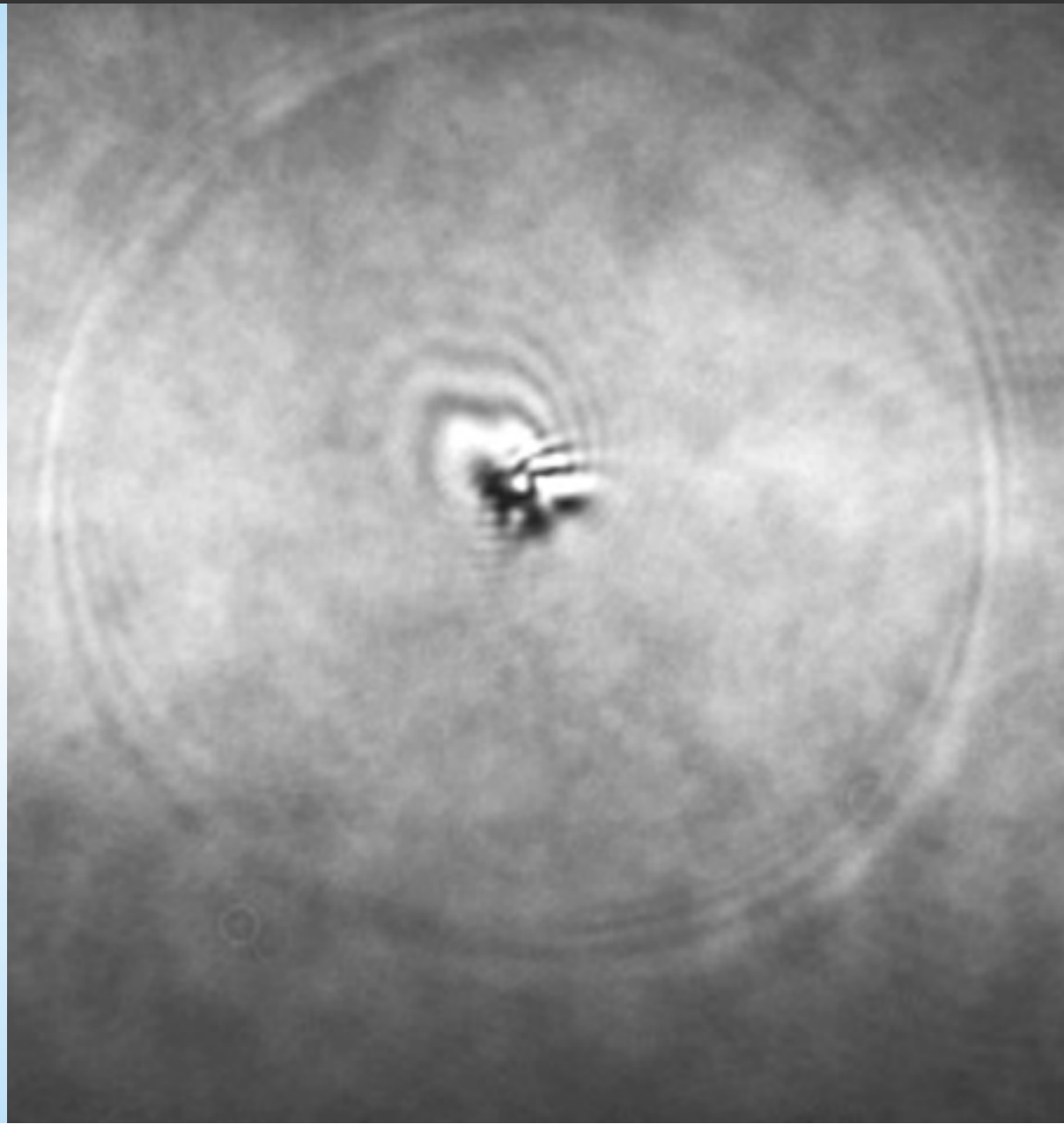
Microstructuring

sapphire

3 µJ pulse

3.8 ns delay

40 µm radius



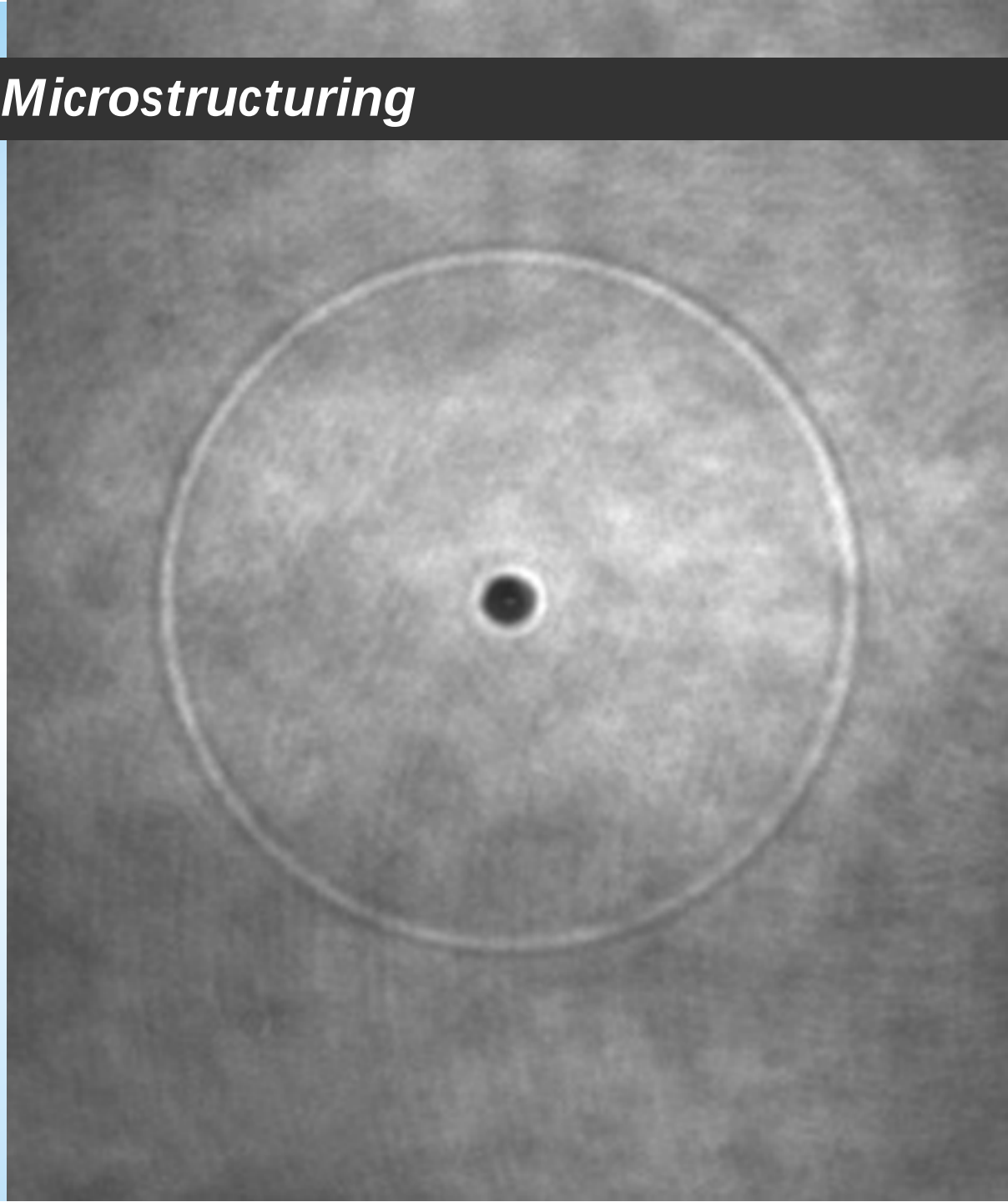
Microstructuring

water

1.0 µJ pulse

35 ns delay

58 µm radius



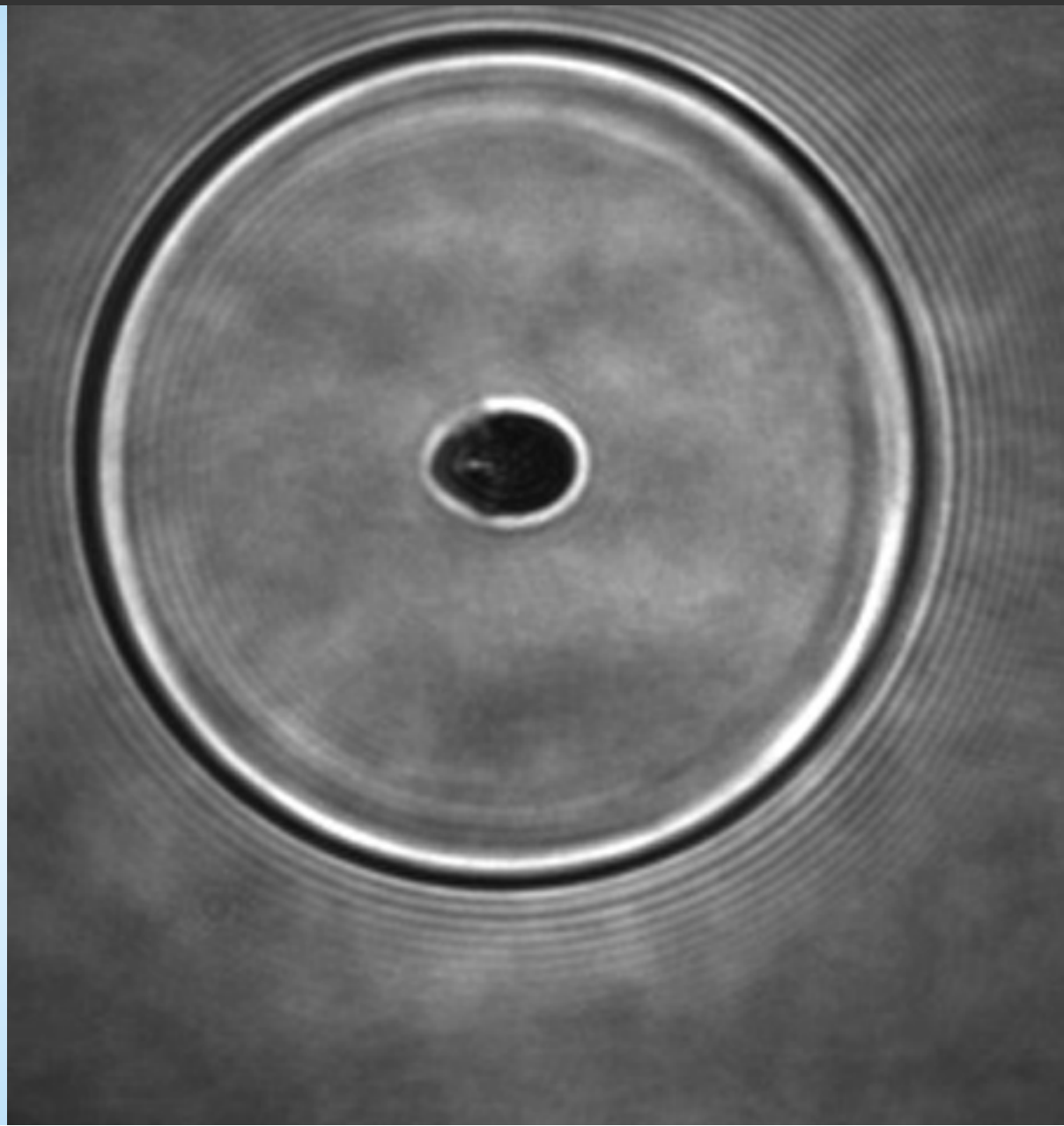
Microstructuring

water

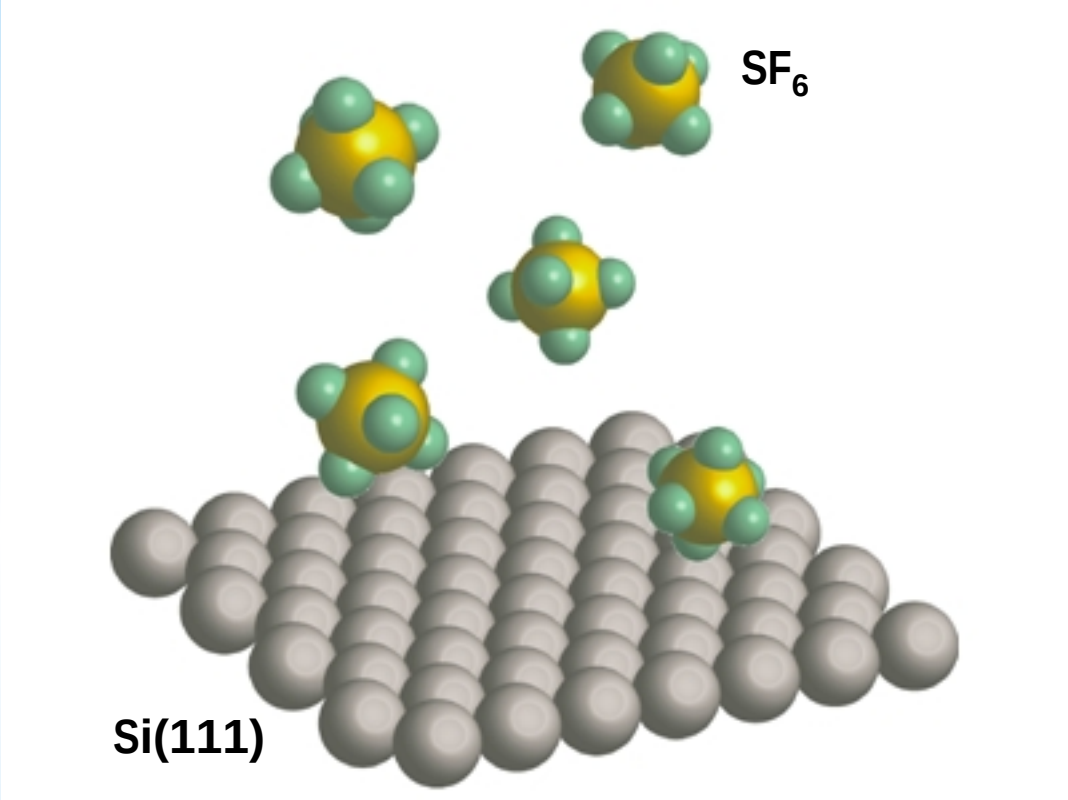
14 µJ pulse

35 ns delay

64 µm radius

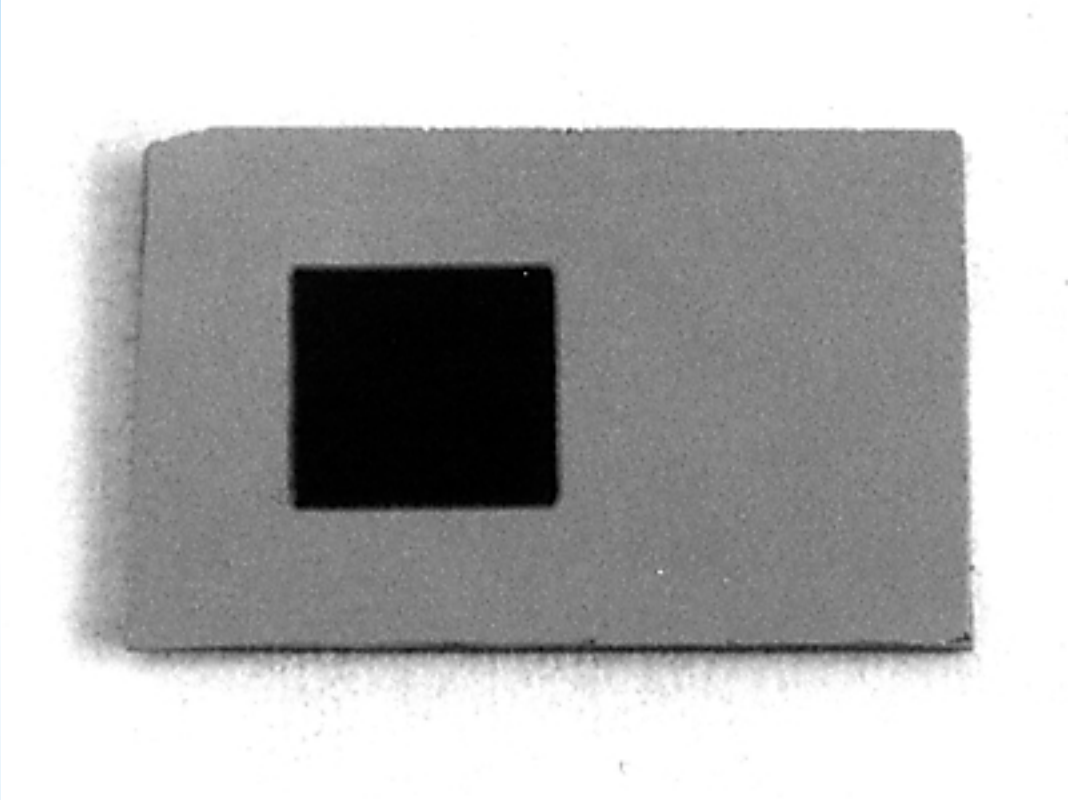


Microstructuring



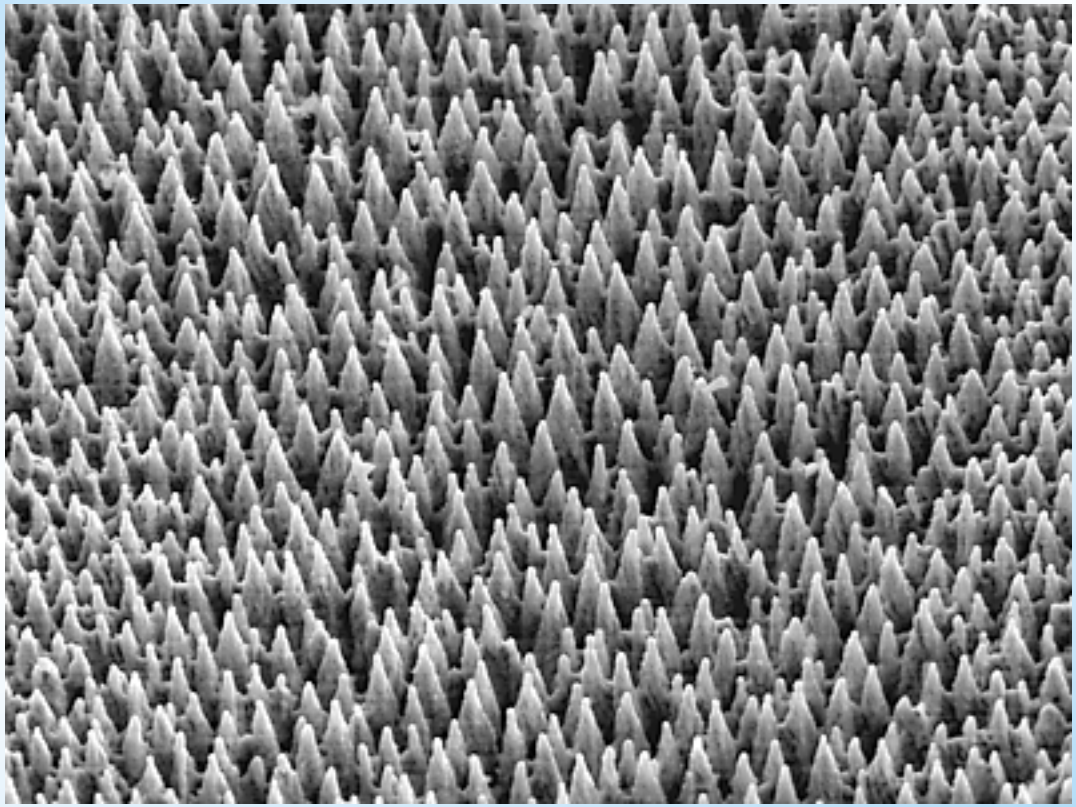
irradiate with 100 fs 10 kJ/m^2 laser pulses

Microstructuring



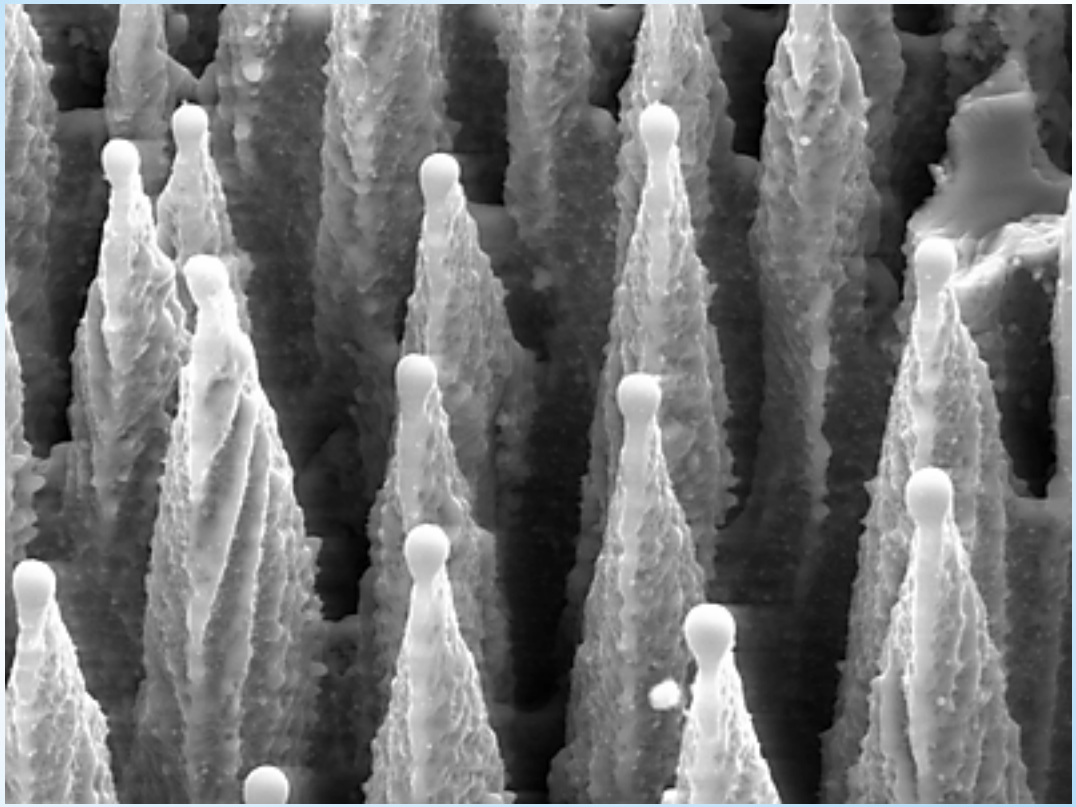
5 mm

Microstructuring



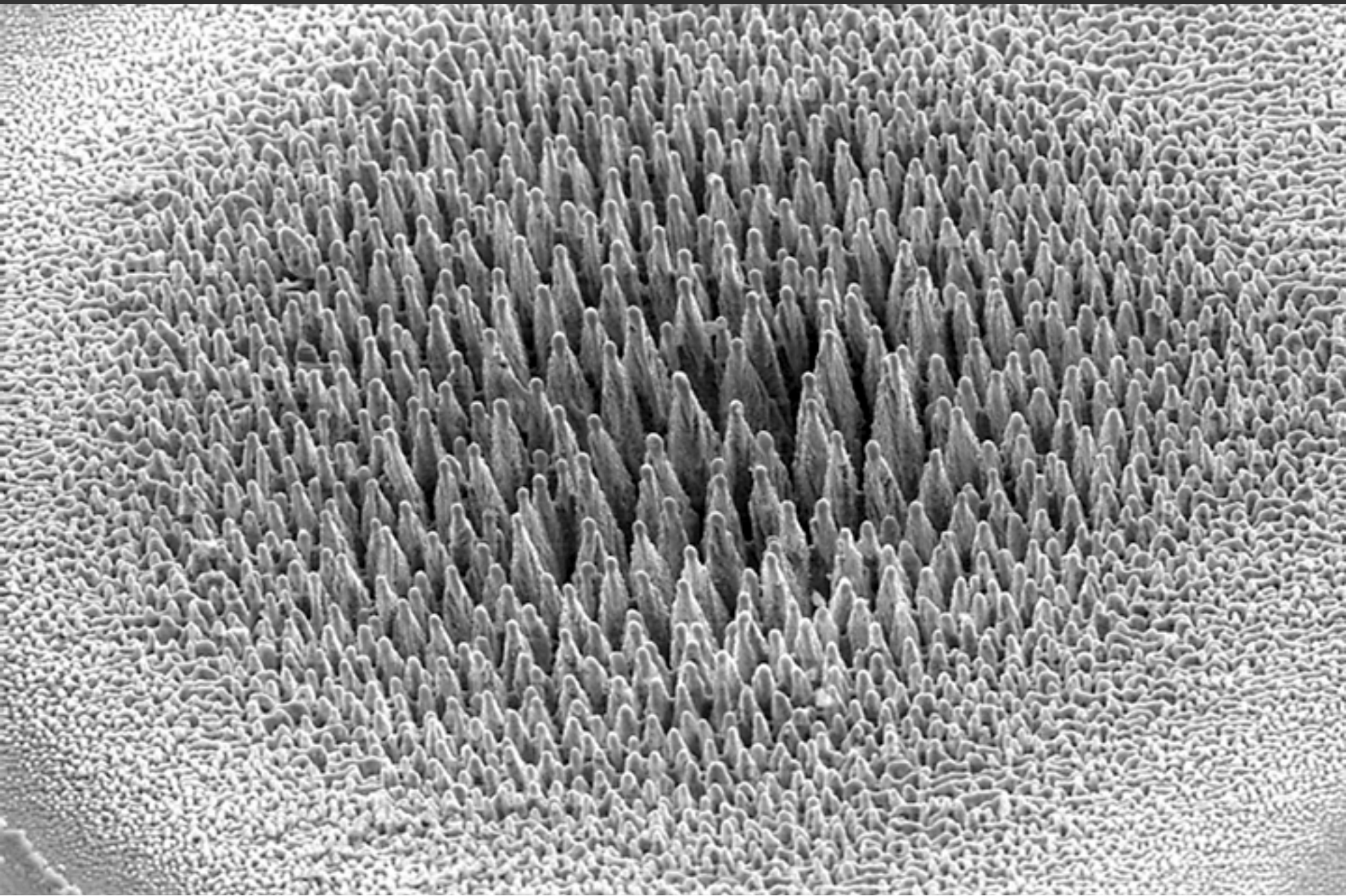
20 µm

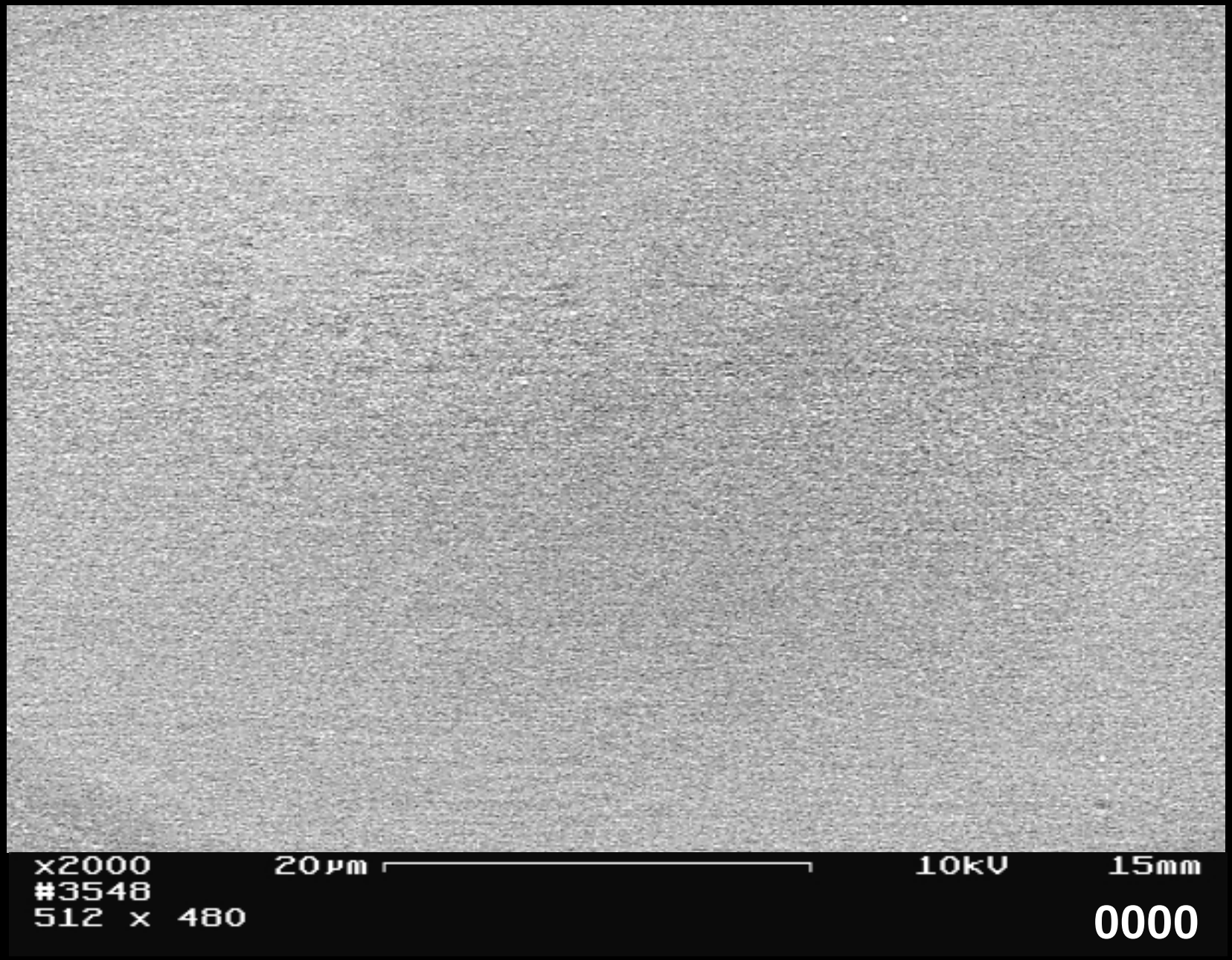
Microstructuring

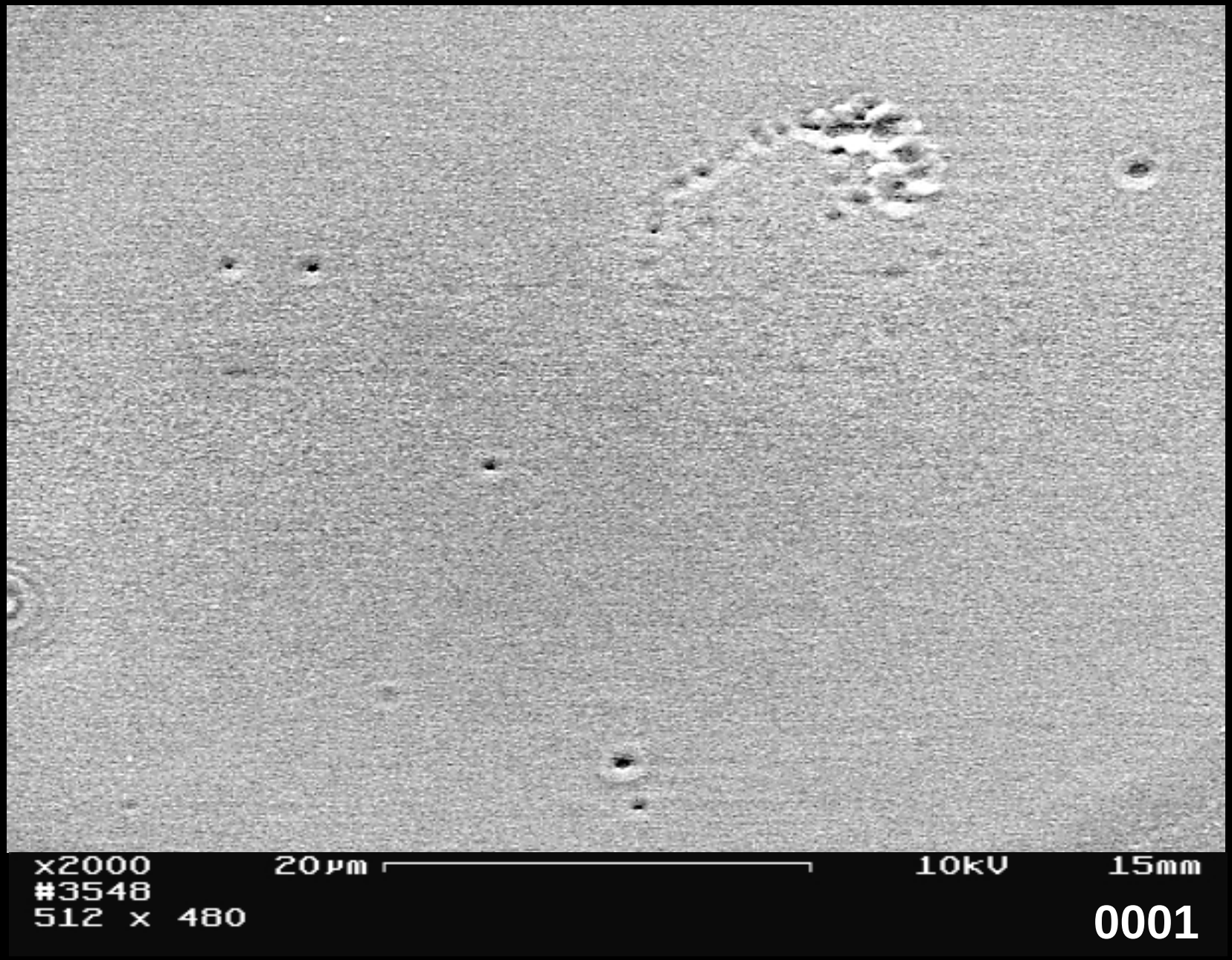


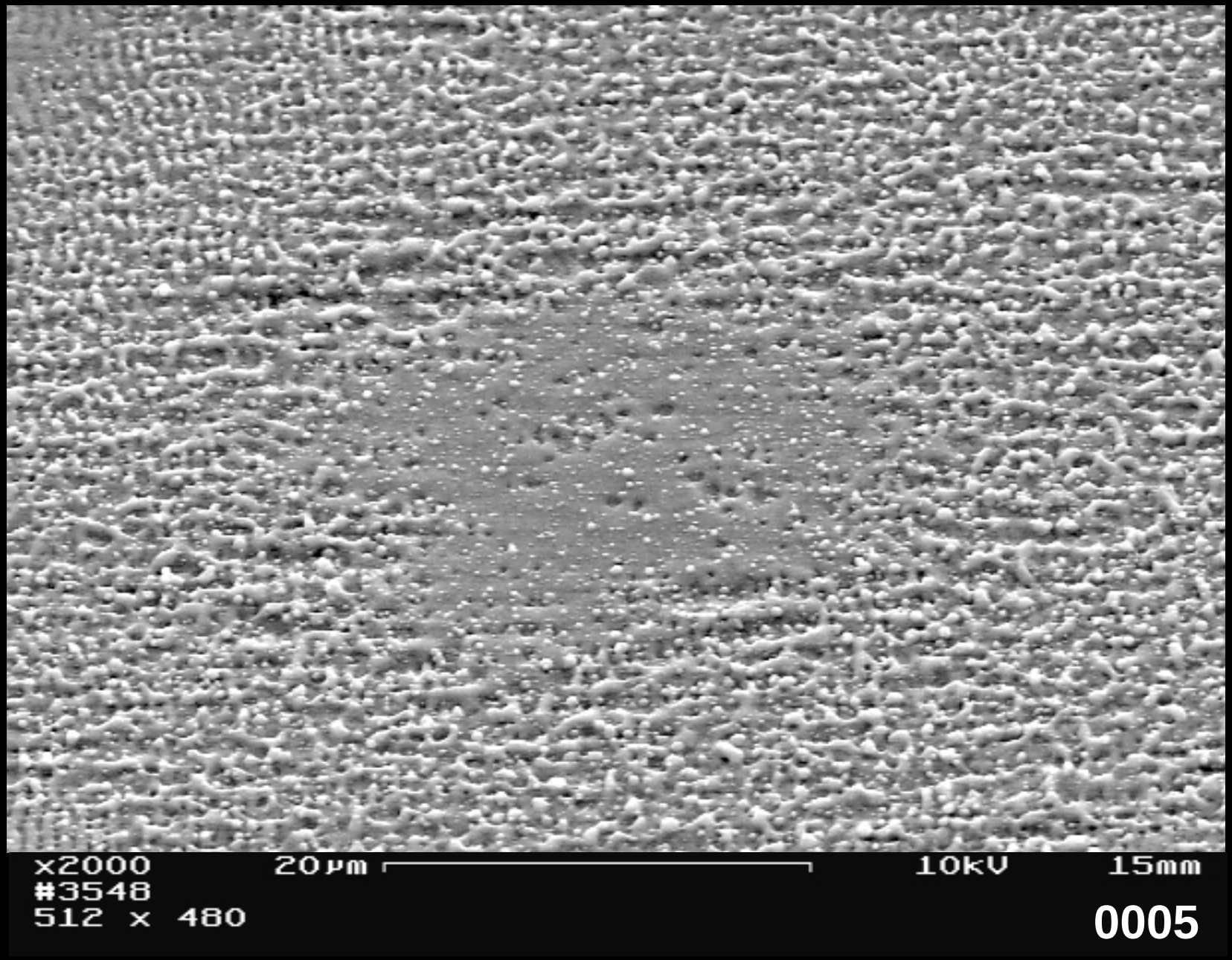
4 µm

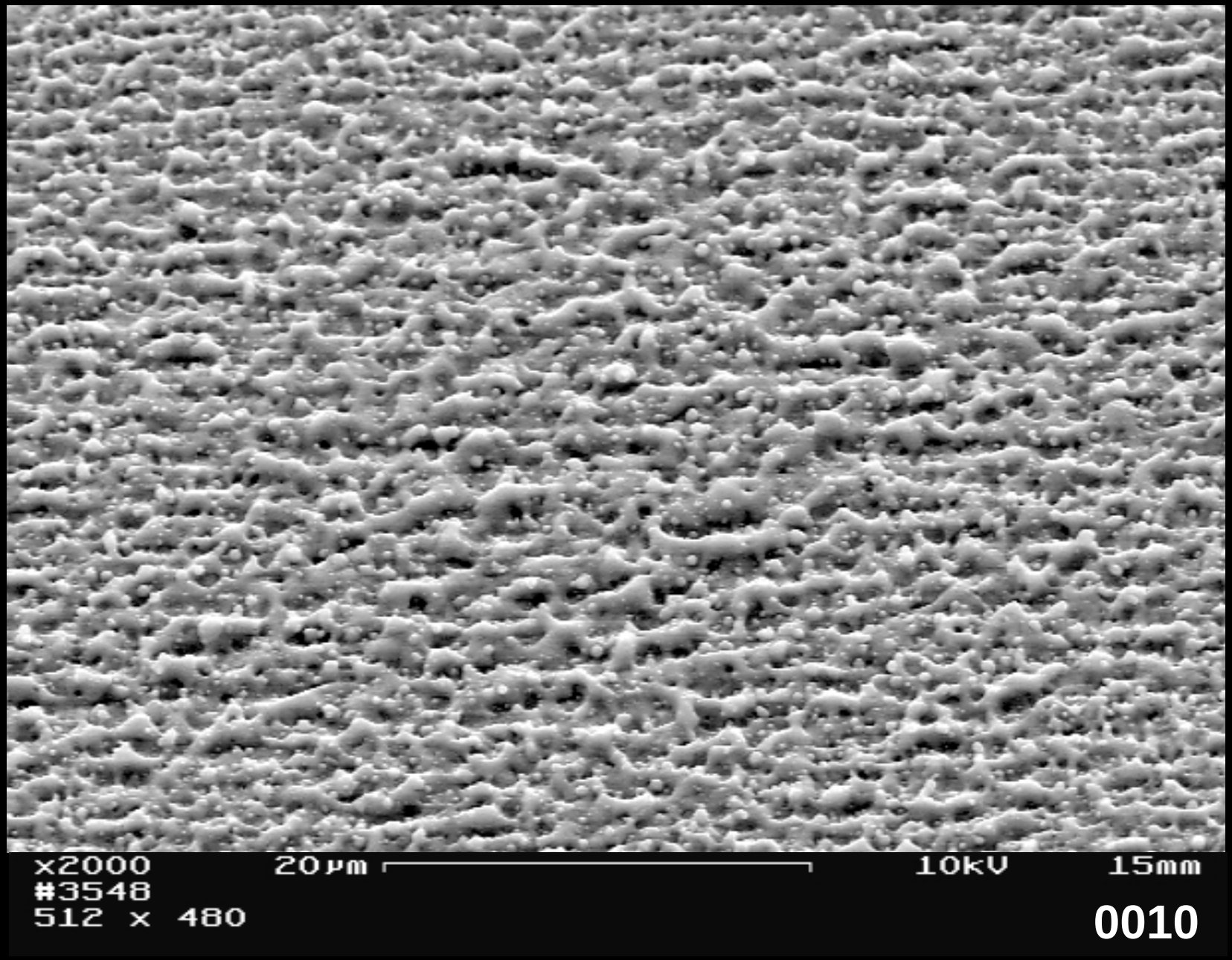
Microstructuring




x2000
20µm
10kV
15mm
#3548
512 x 480
0000


x2000
20µm
10kV
15mm
#3548
512 x 480
0001


x2000
20µm
10kV
15mm
#3548
512 x 480
0005


x2000
20µm
10kV
15mm
#3548
512 x 480
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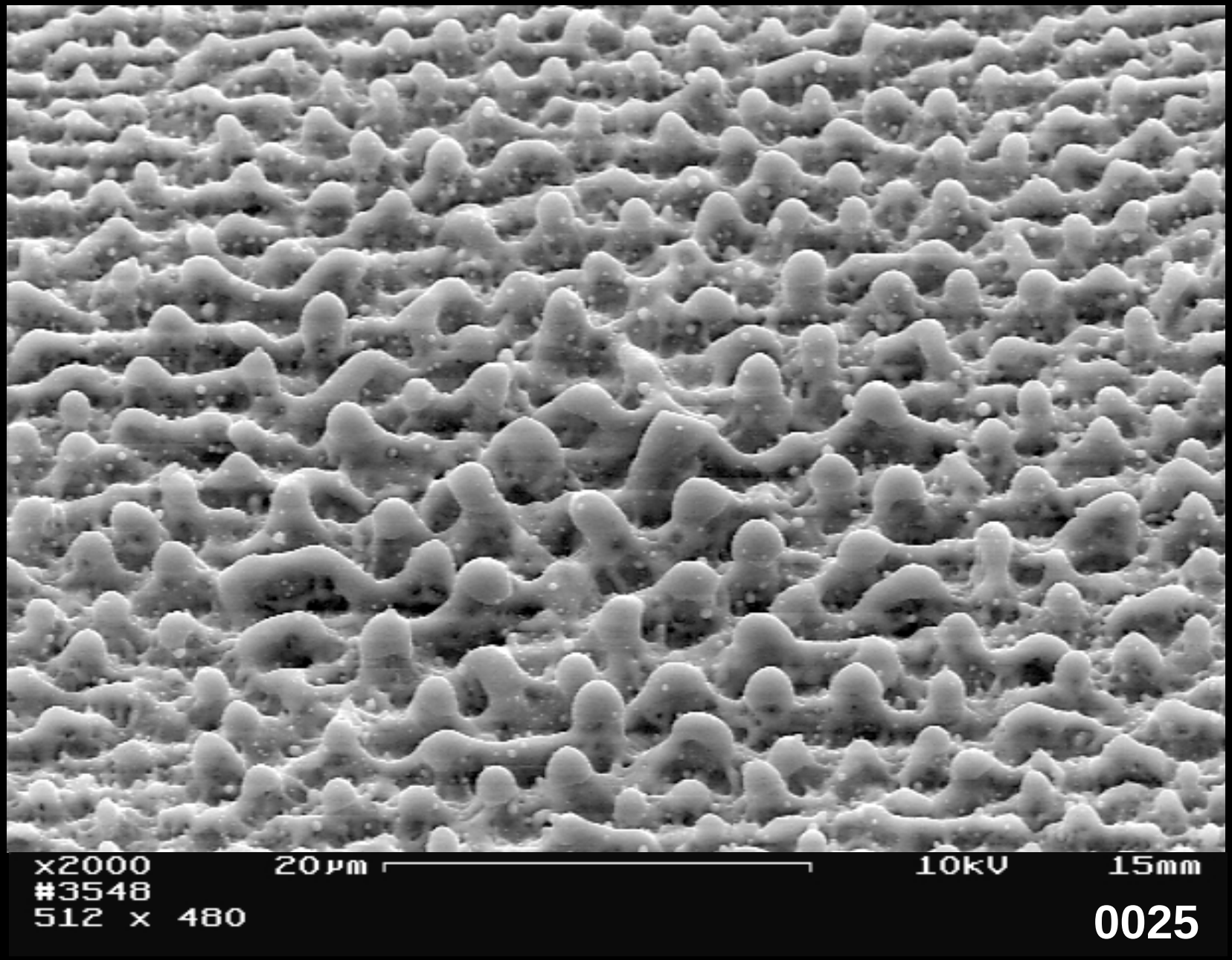
x2000
20µm
10kV
15mm
#3548
512 x 480
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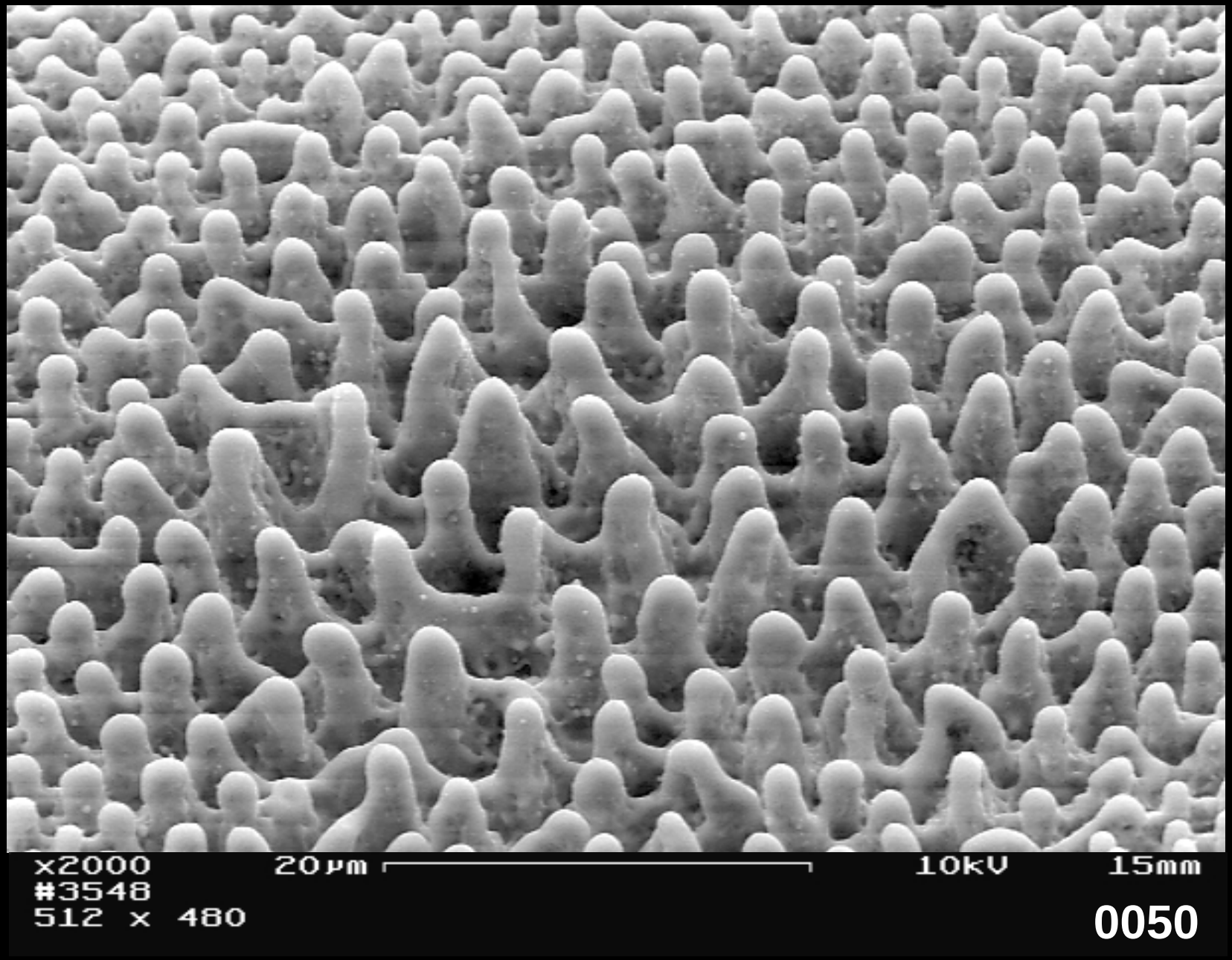
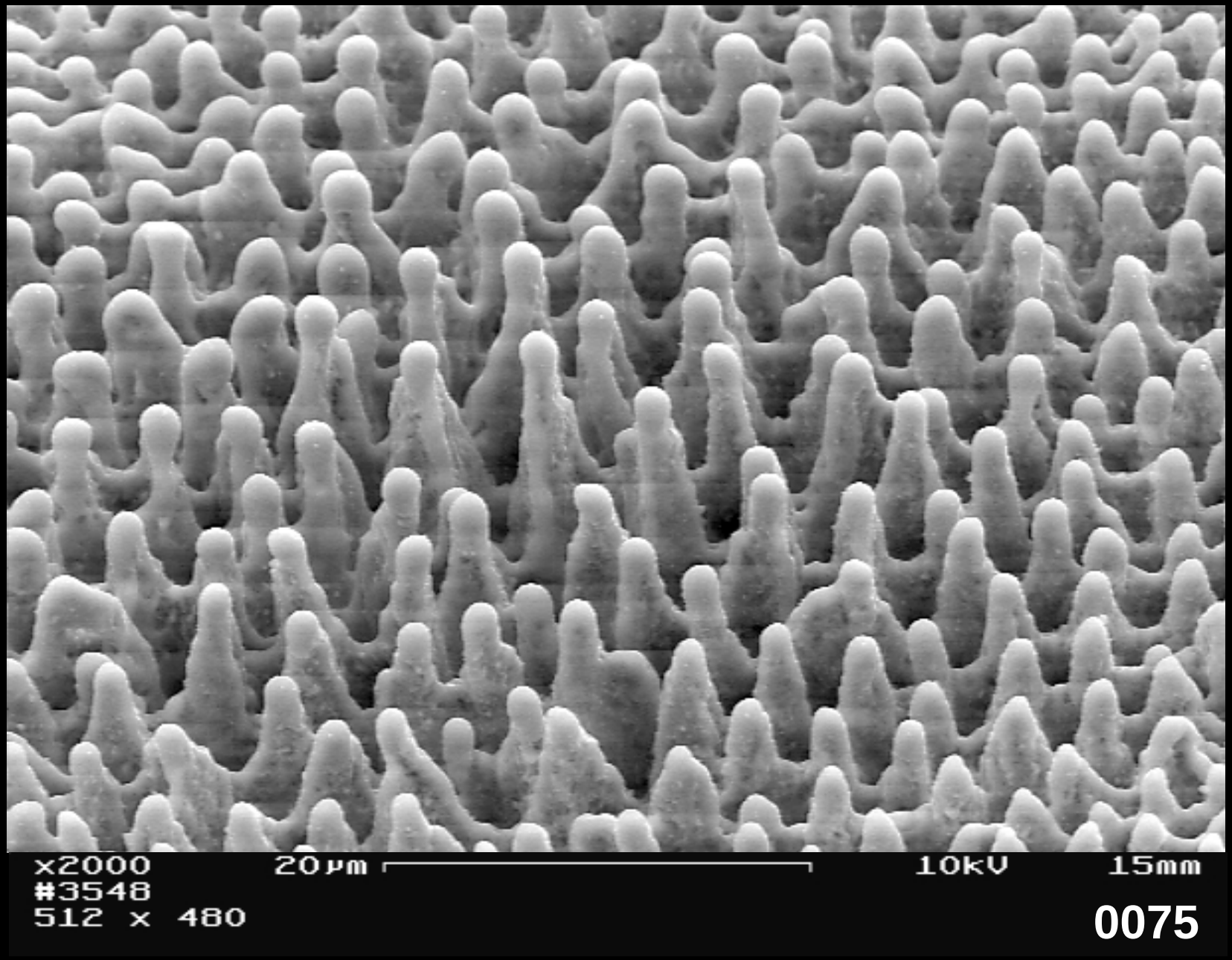
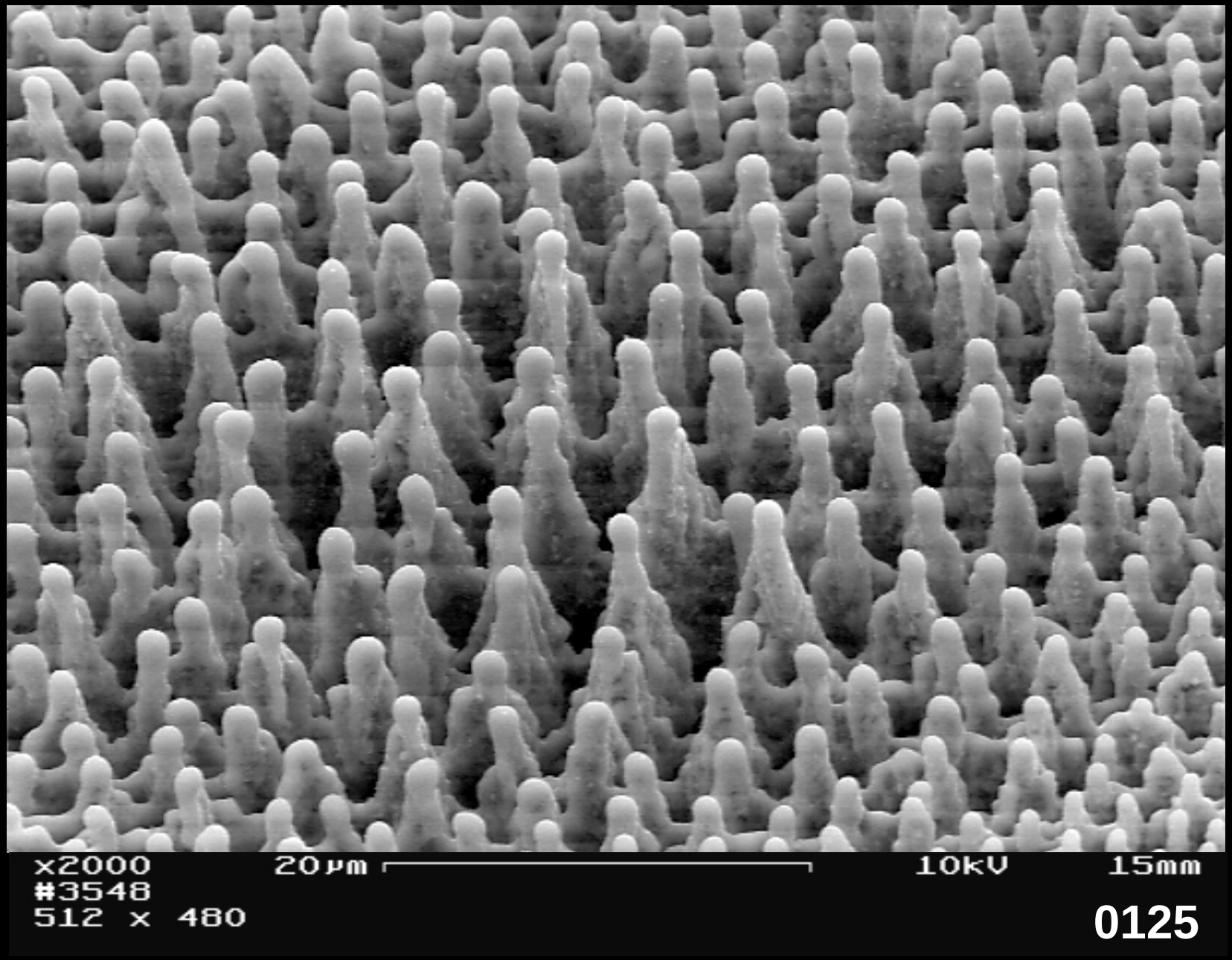

x2000
20µm
10kV
15mm
#3548
512 x 480
0050


x2000
#3548
512 x 480
20µm
10kV
15mm
0075


x2000
#3548
512 x 480
20µm
10kV
15mm
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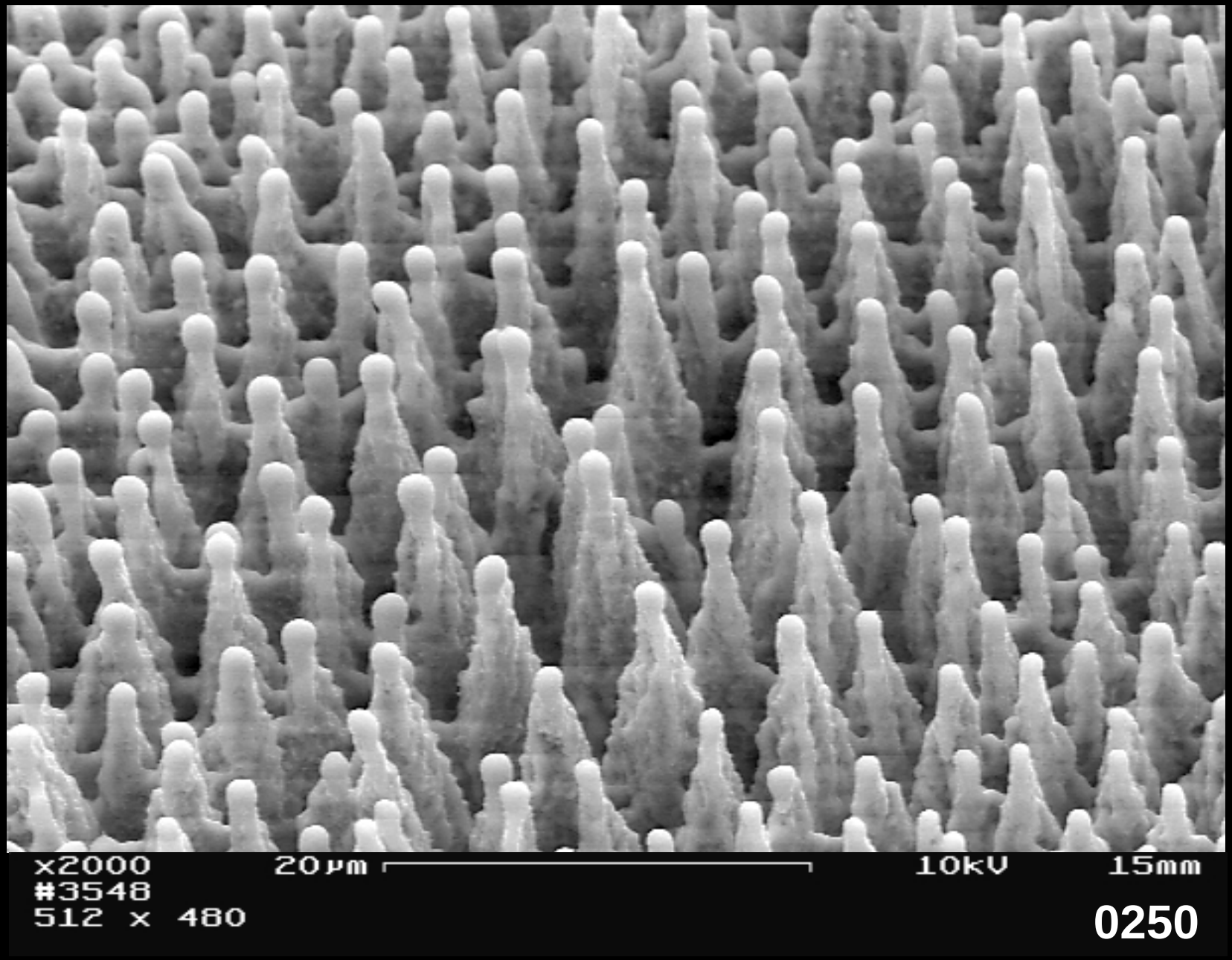
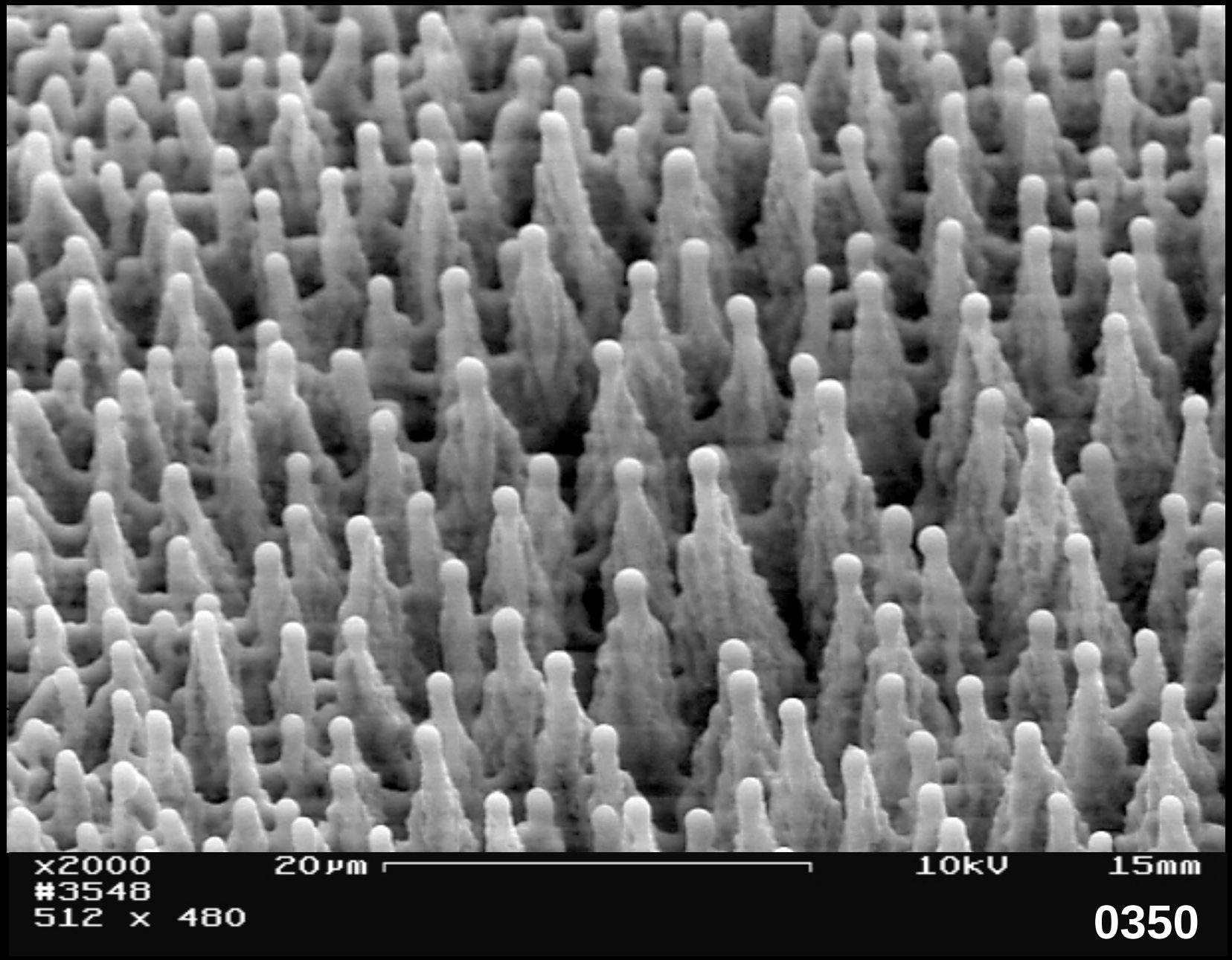
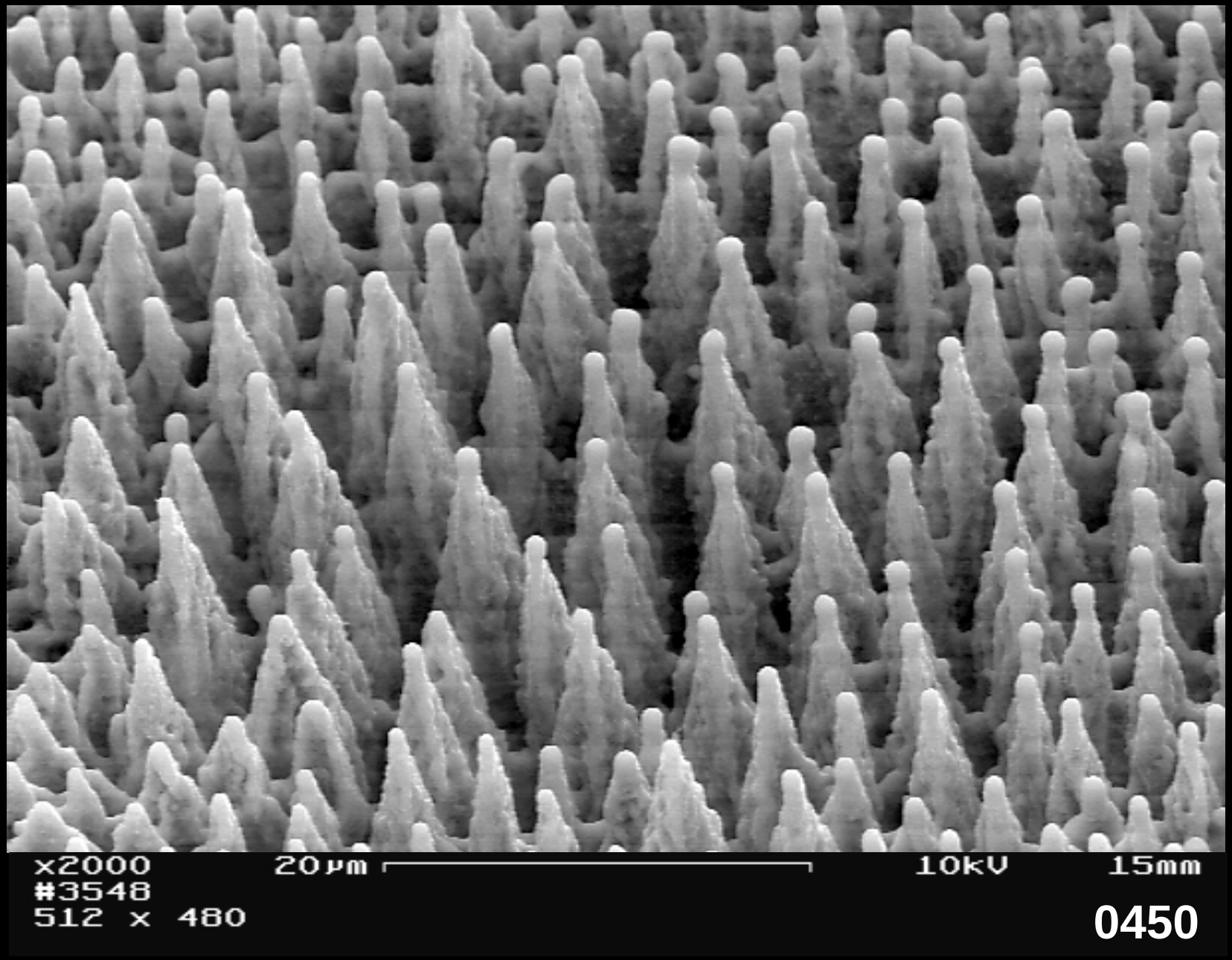
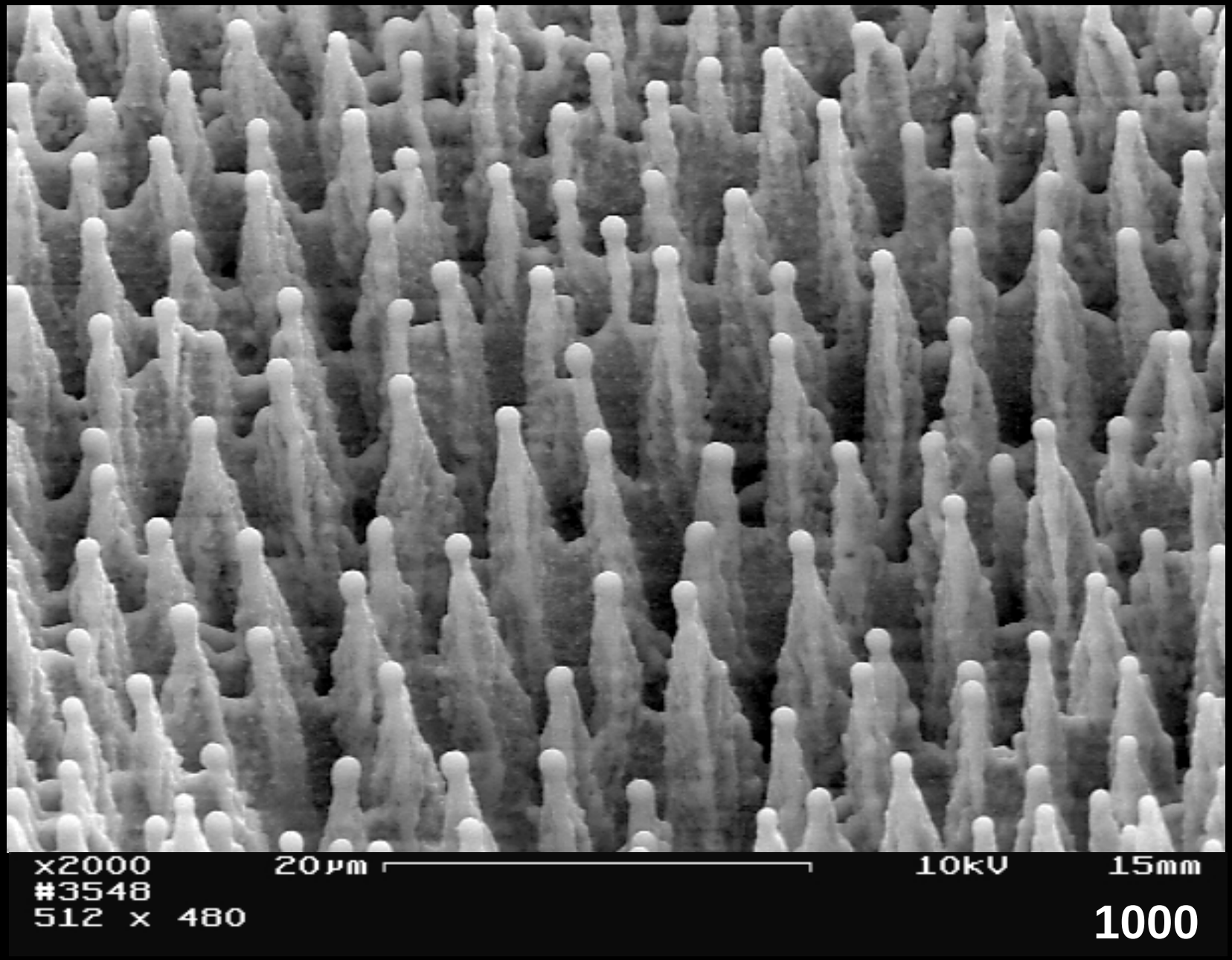

x2000
#3548
512 x 480
20µm
10kV
15mm
0250


x2000
20µm
10kV
15mm
#3548
512 x 480
0350

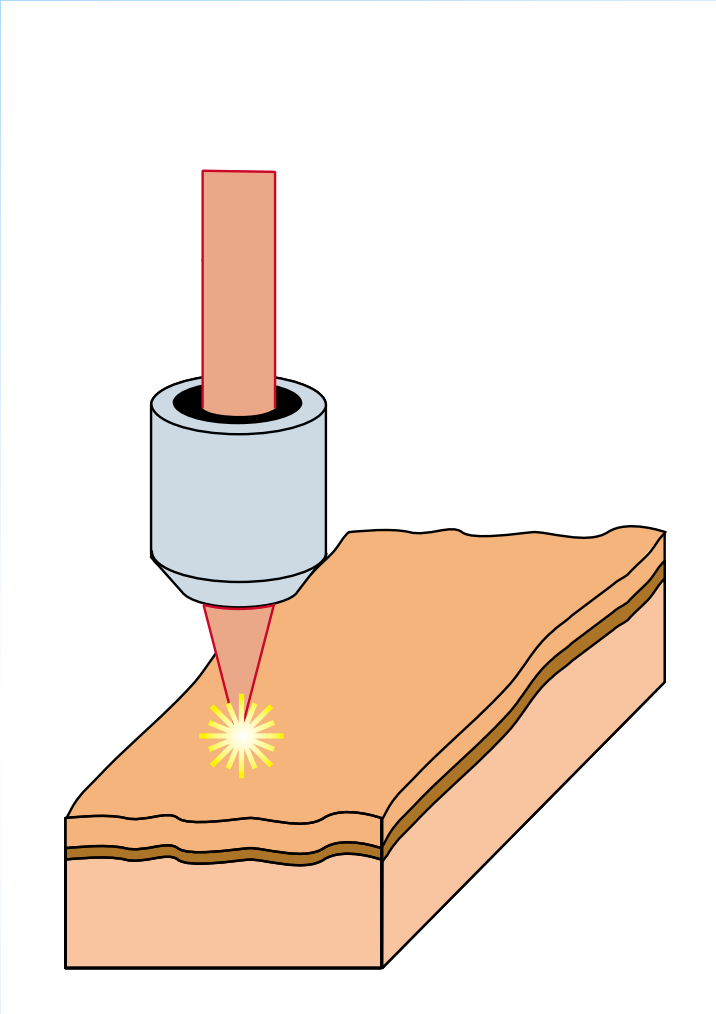

x2000
20µm
10kV
15mm
#3548
512 x 480
0450


x2000
#3548
512 x 480
20µm
10kV
15mm
1000

Overview

- surface femtochemistry
- electronic and structural transitions
- microstructuring of materials
- nonlinear optics and propagation
- **laser surgery**

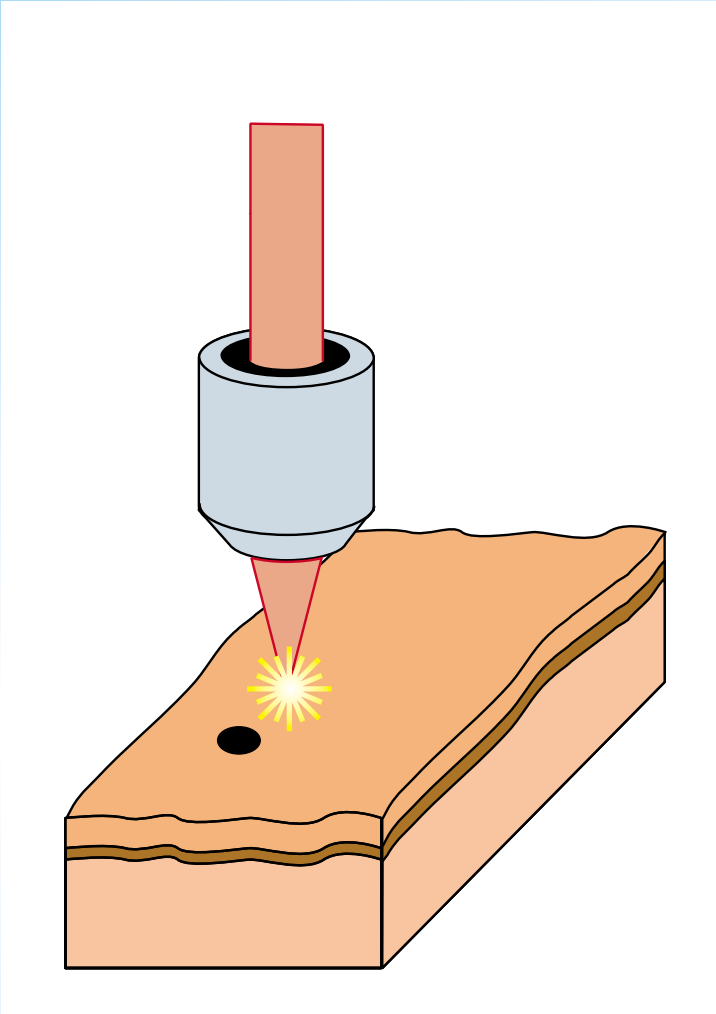
Laser surgery



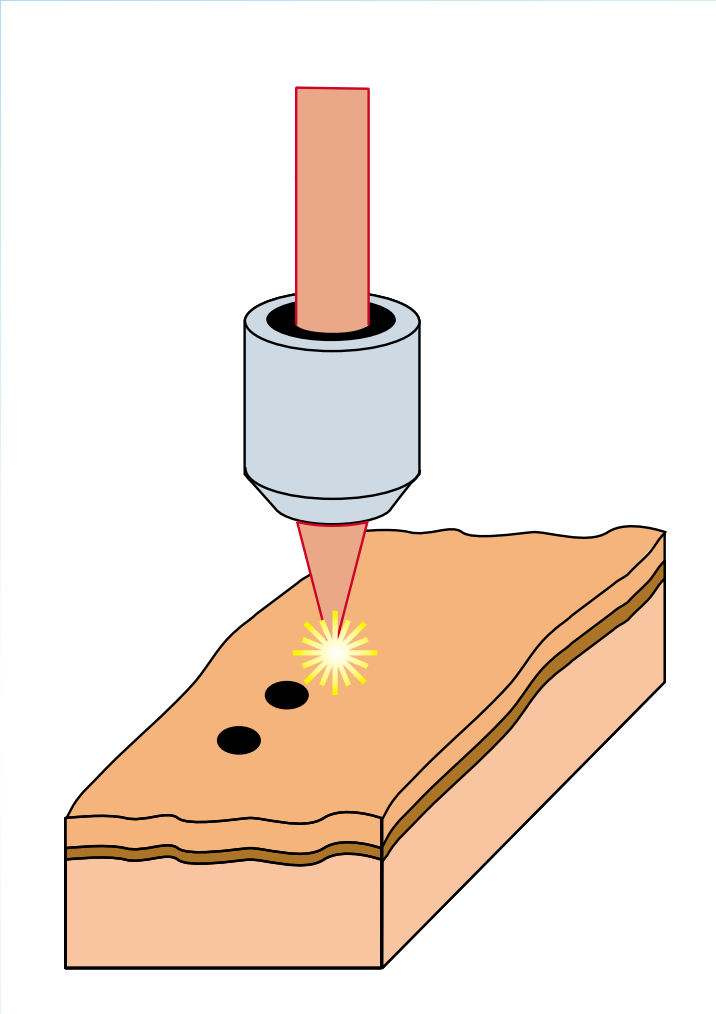
EpiDerm from MatTek Corp.

stratified skin model

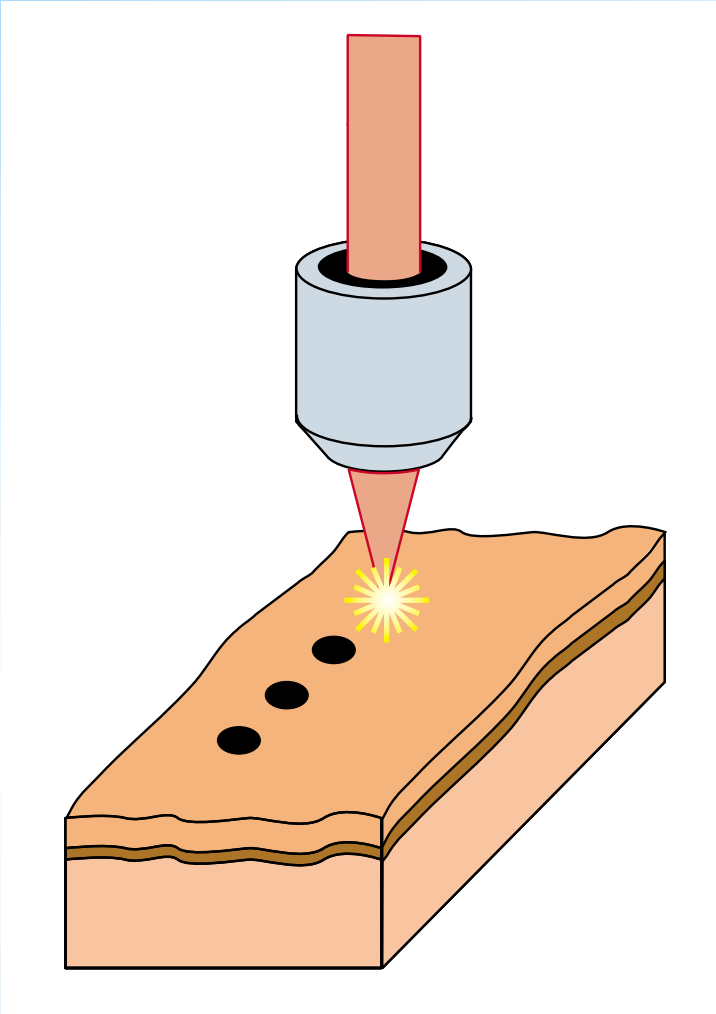
Photodisruption in epidermis



Laser surgery



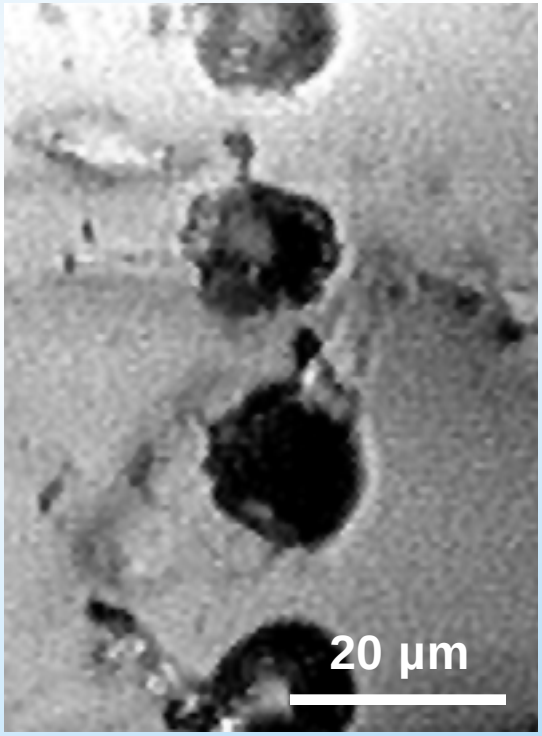
Laser surgery



Laser surgery

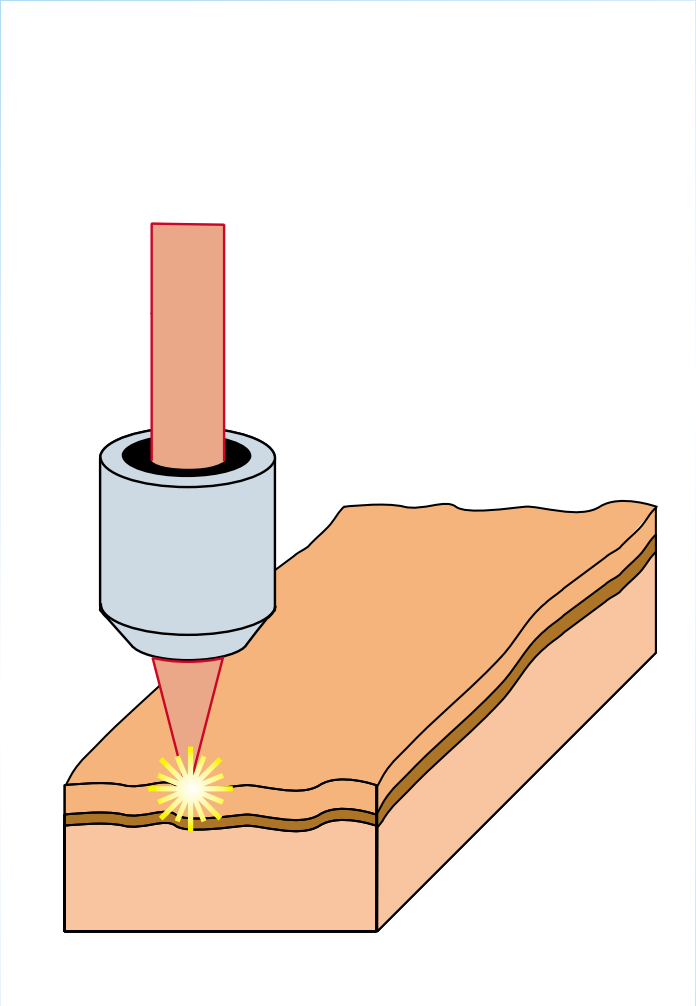
200 ps, 40 µJ

100 fs, 40 µJ

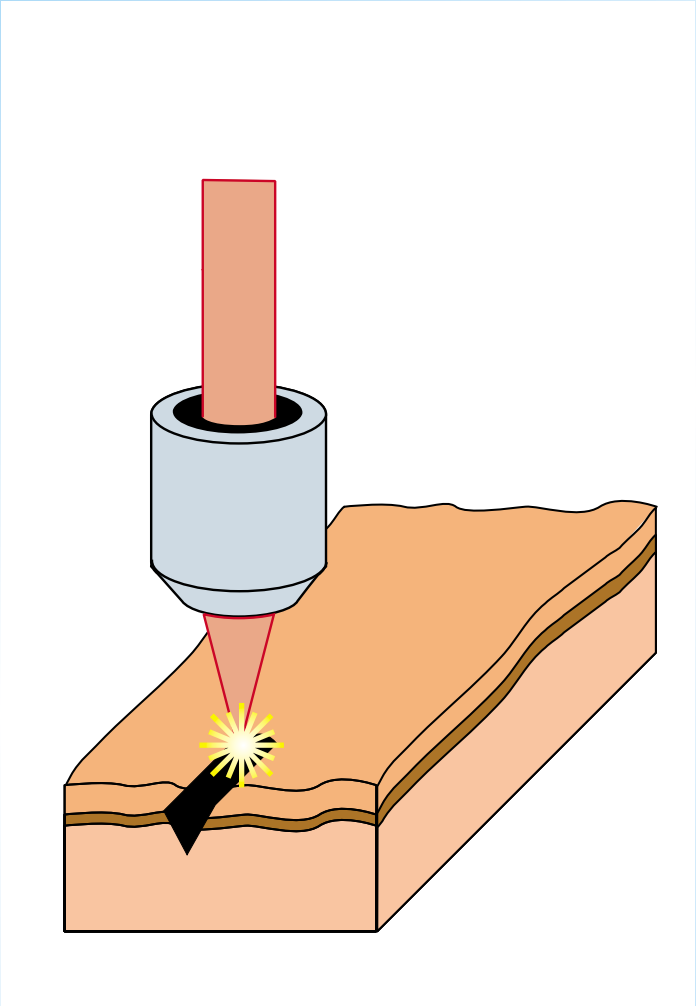


fs pulses reduce collateral damage

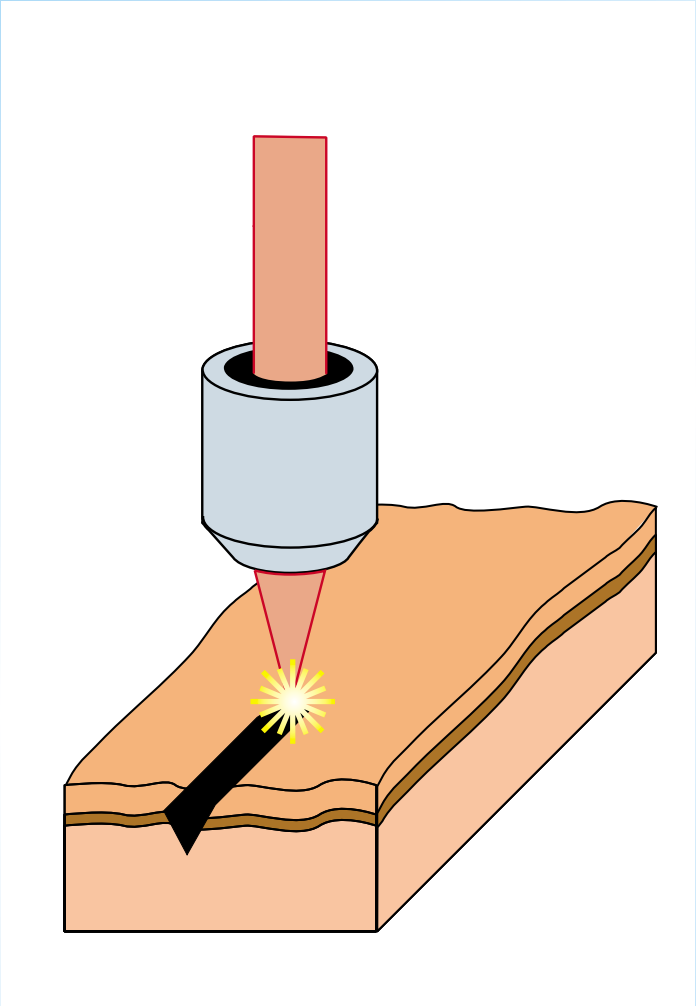
Laser surgery



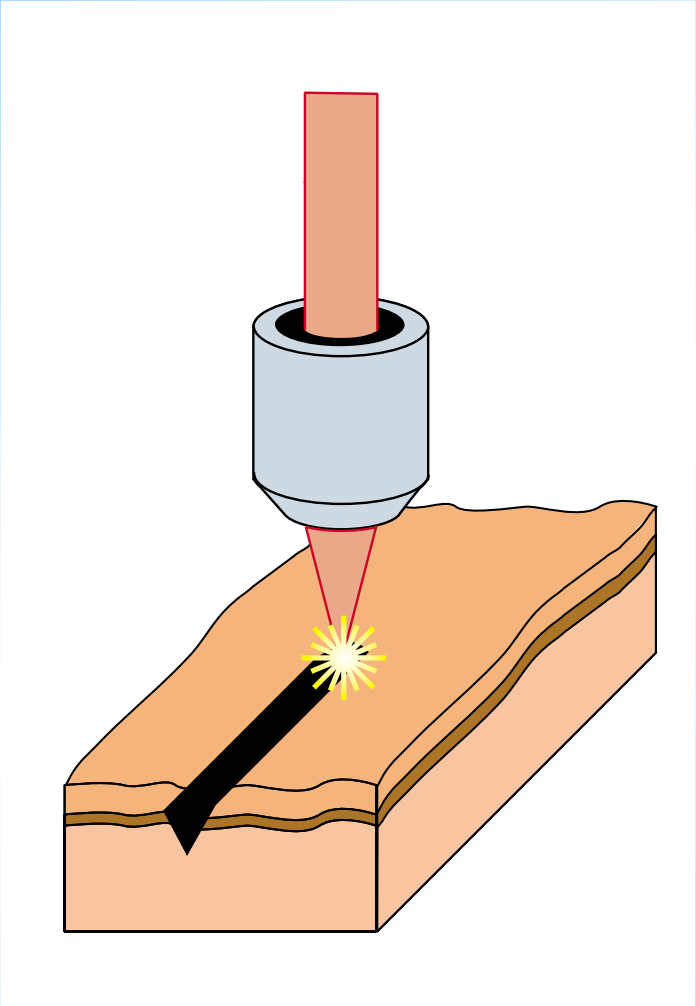
Laser surgery



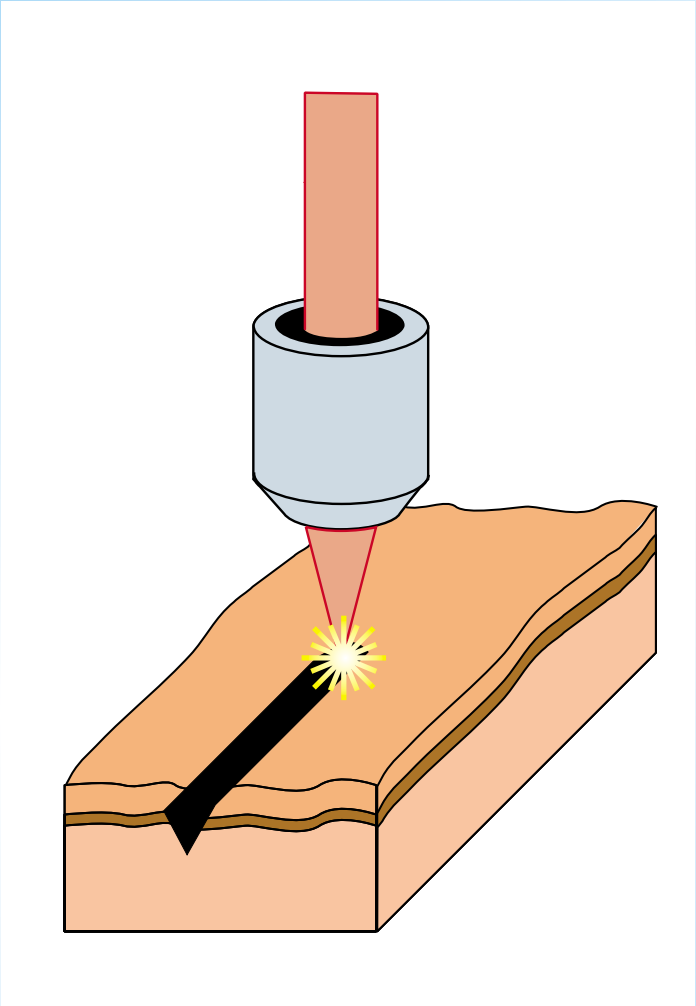
Laser surgery



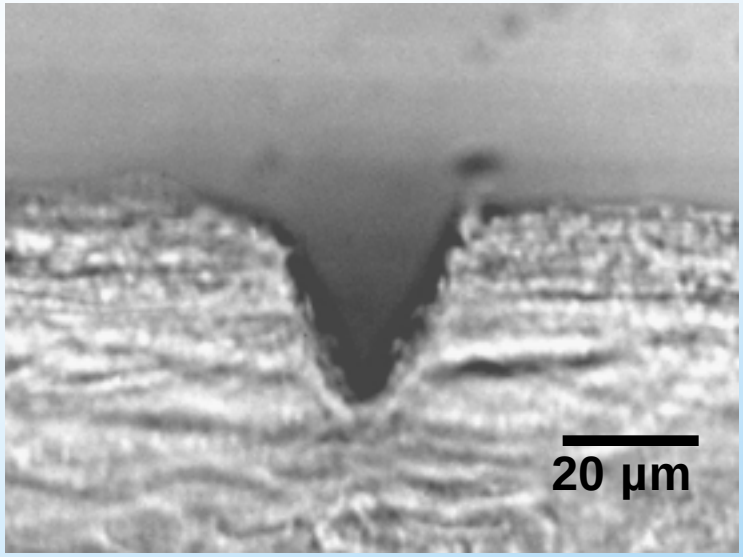
Laser surgery



Laser surgery

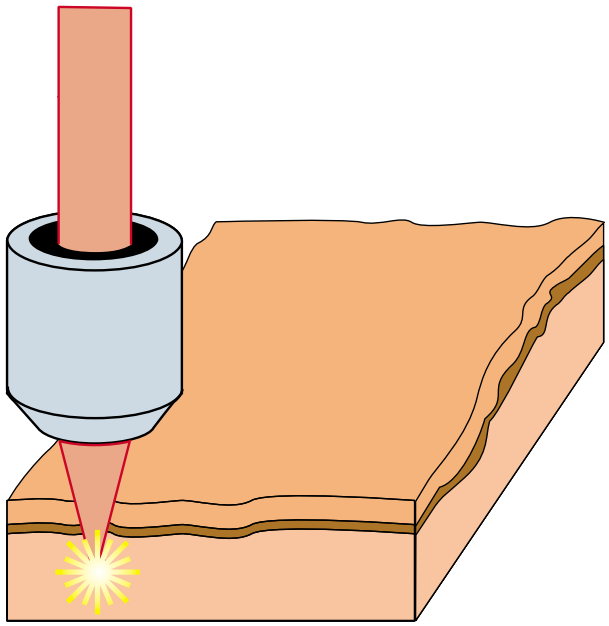


100 fs, 4 µJ



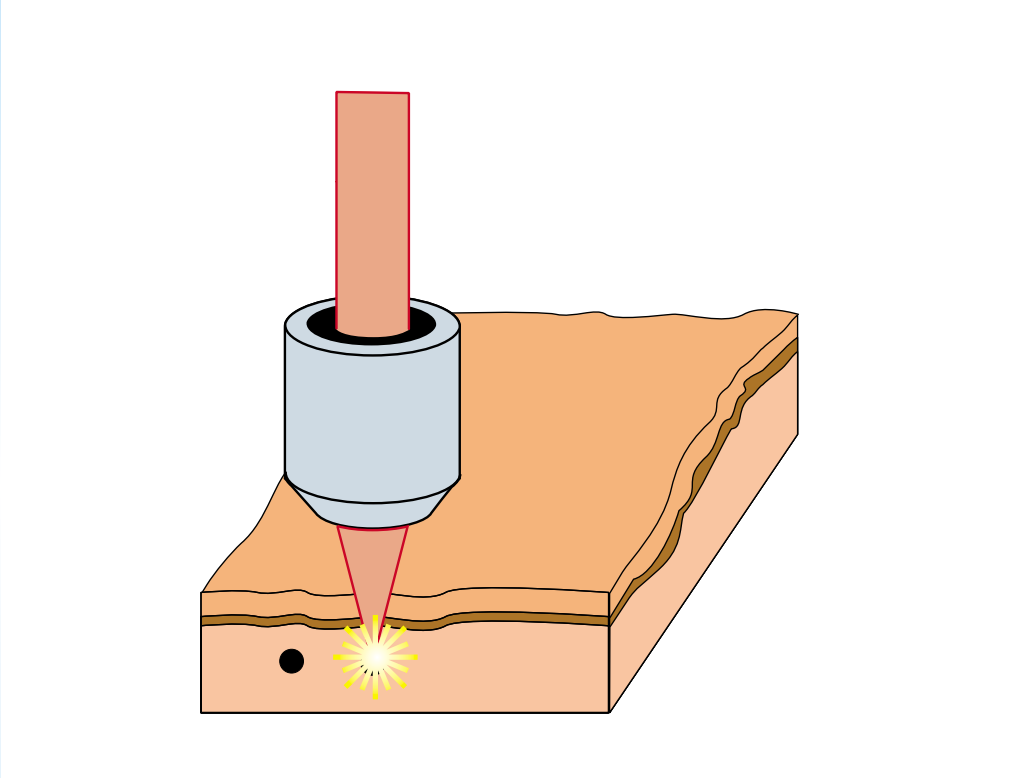
Laser surgery

focus below surface…



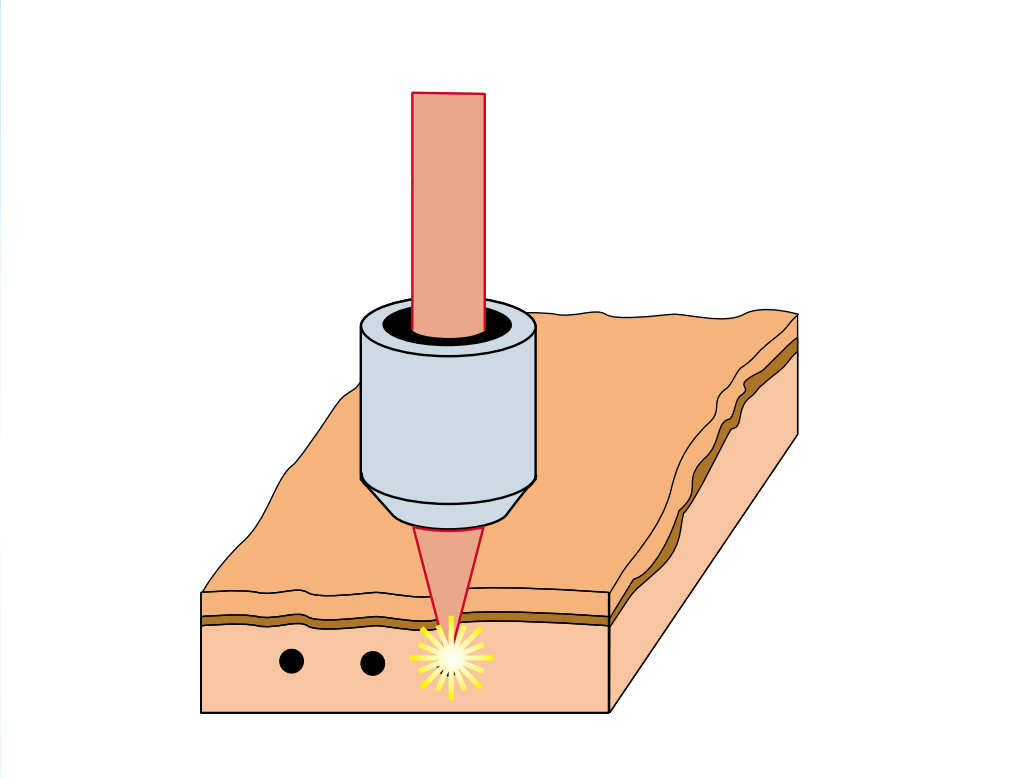
Laser surgery

… and translate beam



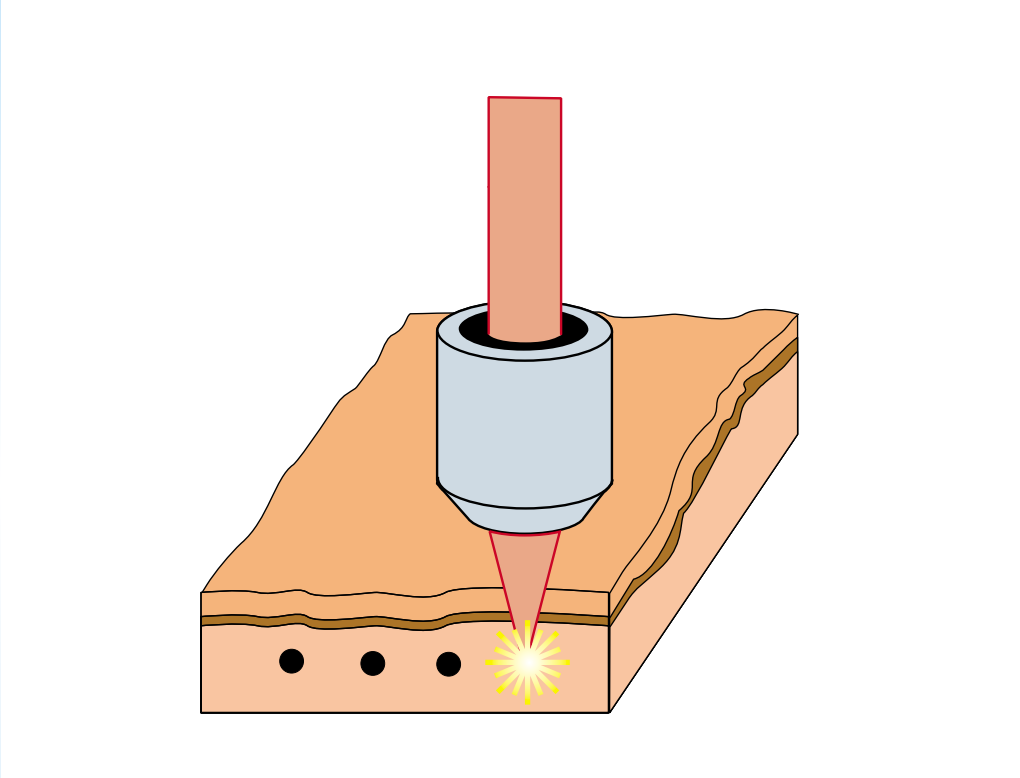
Laser surgery

… and translate beam



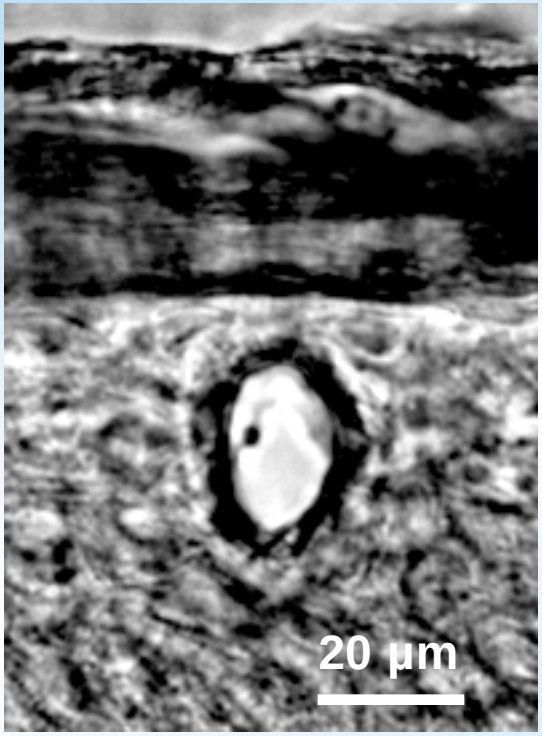
Laser surgery

… and translate beam

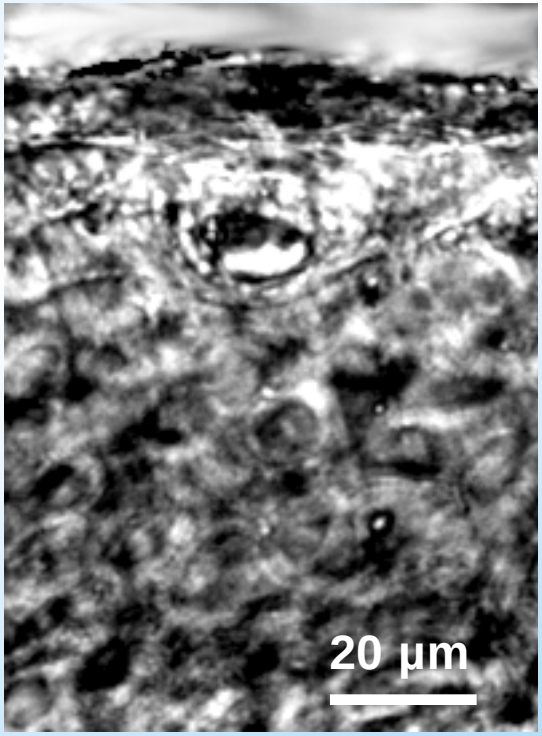


Laser surgery

200 ps, 20 µJ



100 fs, 20 µJ



undamaged surface

Summary

- **diversified use of femtosecond lasers**

Summary

- **diversified use of femtosecond lasers**
- **unprecedented view into dynamics**

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For a copy of this presentation and additional information, see:

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