

Femtosecond laser materials processing



DEPS Ultrashort Laser Pulse Workshop
30 June 2009





Mark Winkler



Renee Sher



Yu-Ting Lin



Tina Shih

Eric Diebold
Haifei Albert Zhang
Dr. Brian Tull
Dr. Jim Carey
Prof. Tsing-Hua Her
Dr. Shrenik Deliwala
Dr. Richard Finlay
Dr. Michael Sheehy
Dr. Claudia Wu
Dr. Rebecca Younkin
Prof. Catherine Crouch
Prof. Mengyan Shen
Prof. Li Zhao

Prof. Tonio Buonassisi (MIT)
Prof. Silvija Gradecak (MIT)
Dr. Bonna Newman (MIT)
Joe Sullivan (MIT)
Prof. Augustinus Asenbaum (Vienna)
Dr. François Génin (LLNL)
Mark Wall (LLNL)
Dr. Richard Farrell (RMD)
Dr. Arie Karger (RMD)
Dr. Richard Meyers (RMD)
Dr. Pat Maloney (NVSED)

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

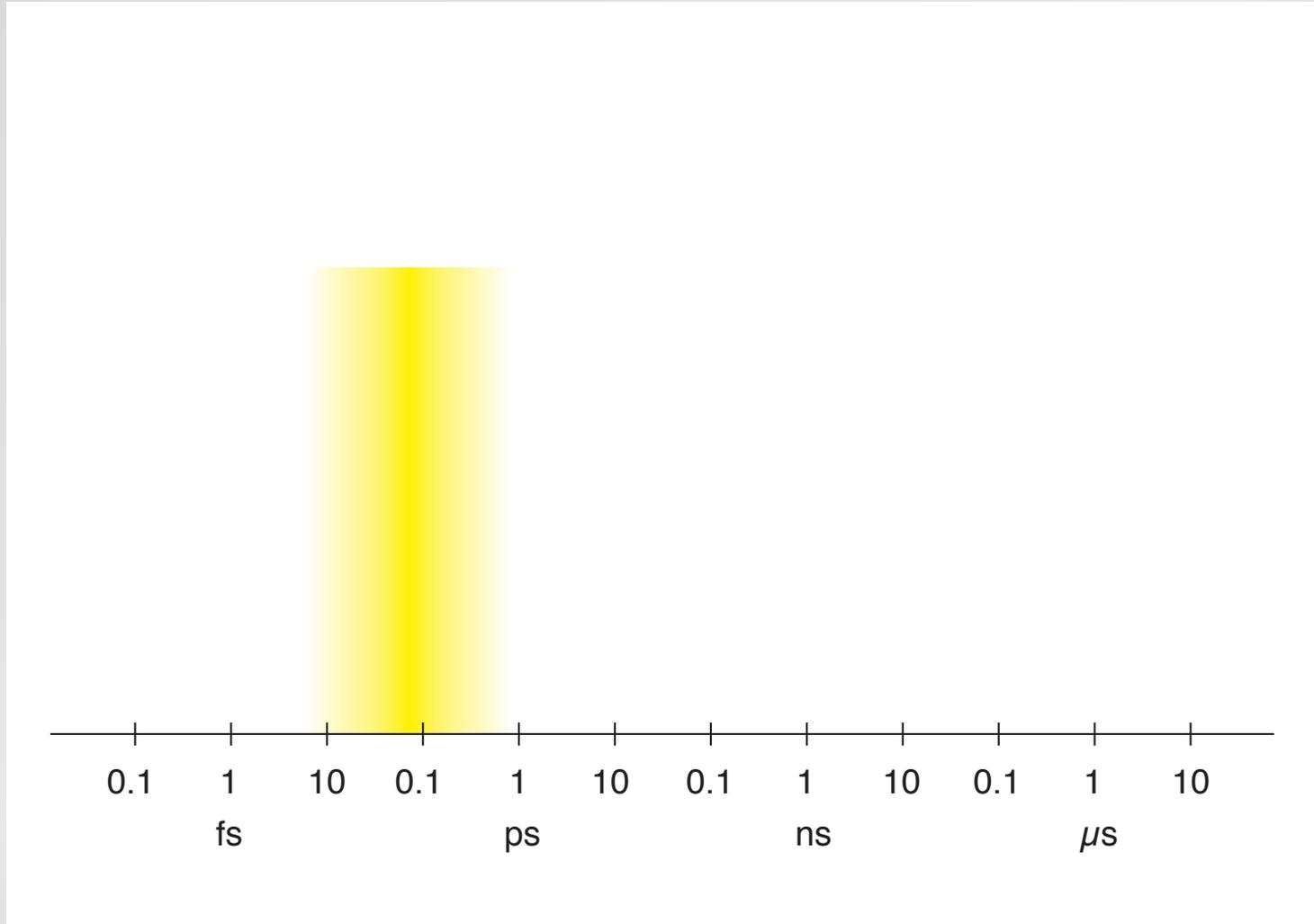
Prof. Igor Khrushchev (Aston University)
Prof. Denise Krol (UC Davis)
Dr. Yossi Chay (Sagitta, Inc.)
Dr. S.K. Sundaram (PNNL)
Prof. Minoru Obara (Keio University)
Prof. Don Ingber (Harvard Medical School)
Prof. Aravi Samuel (Harvard)

Introduction

why study materials with femtosecond pulses?

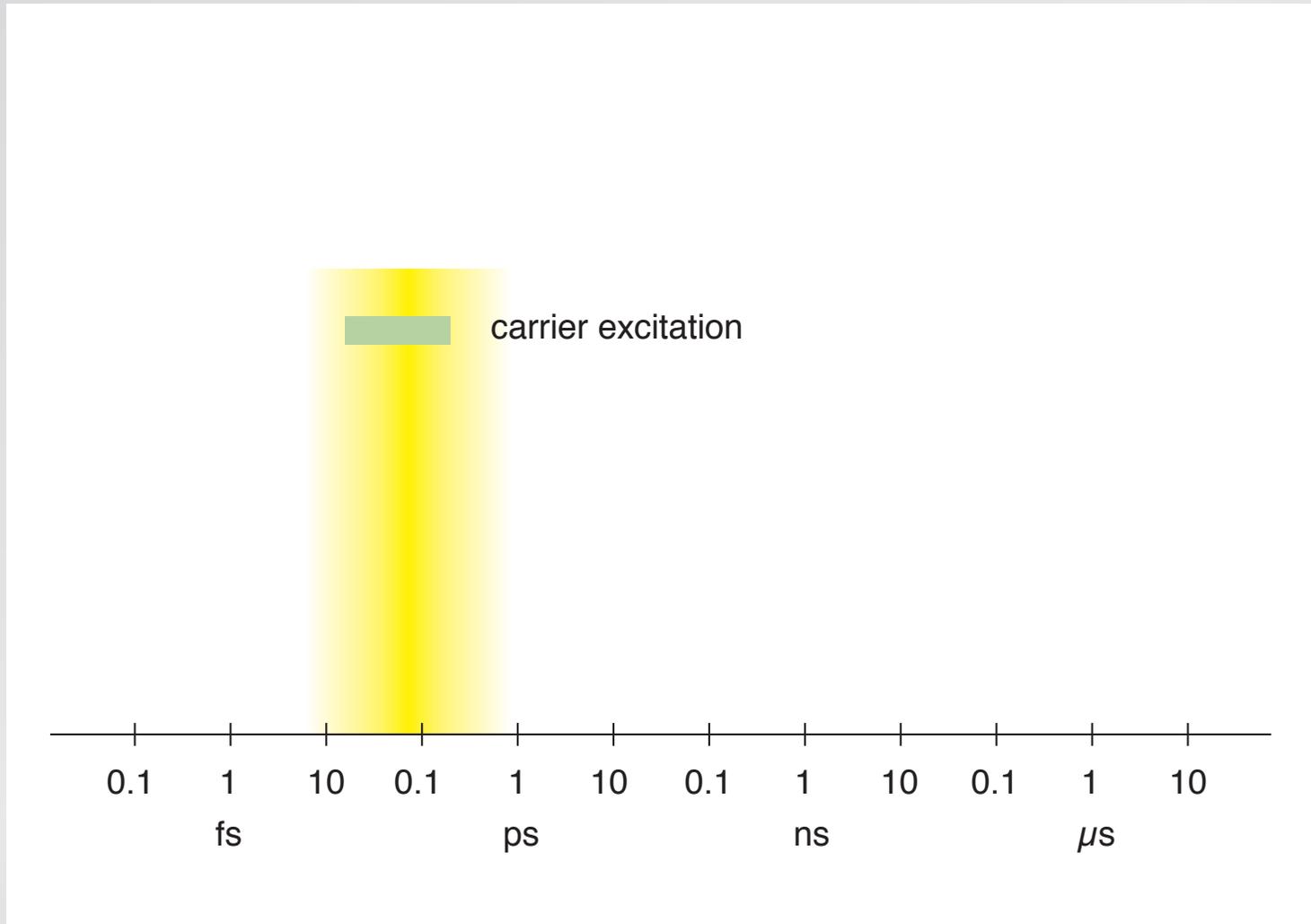
Introduction

relevant time scales



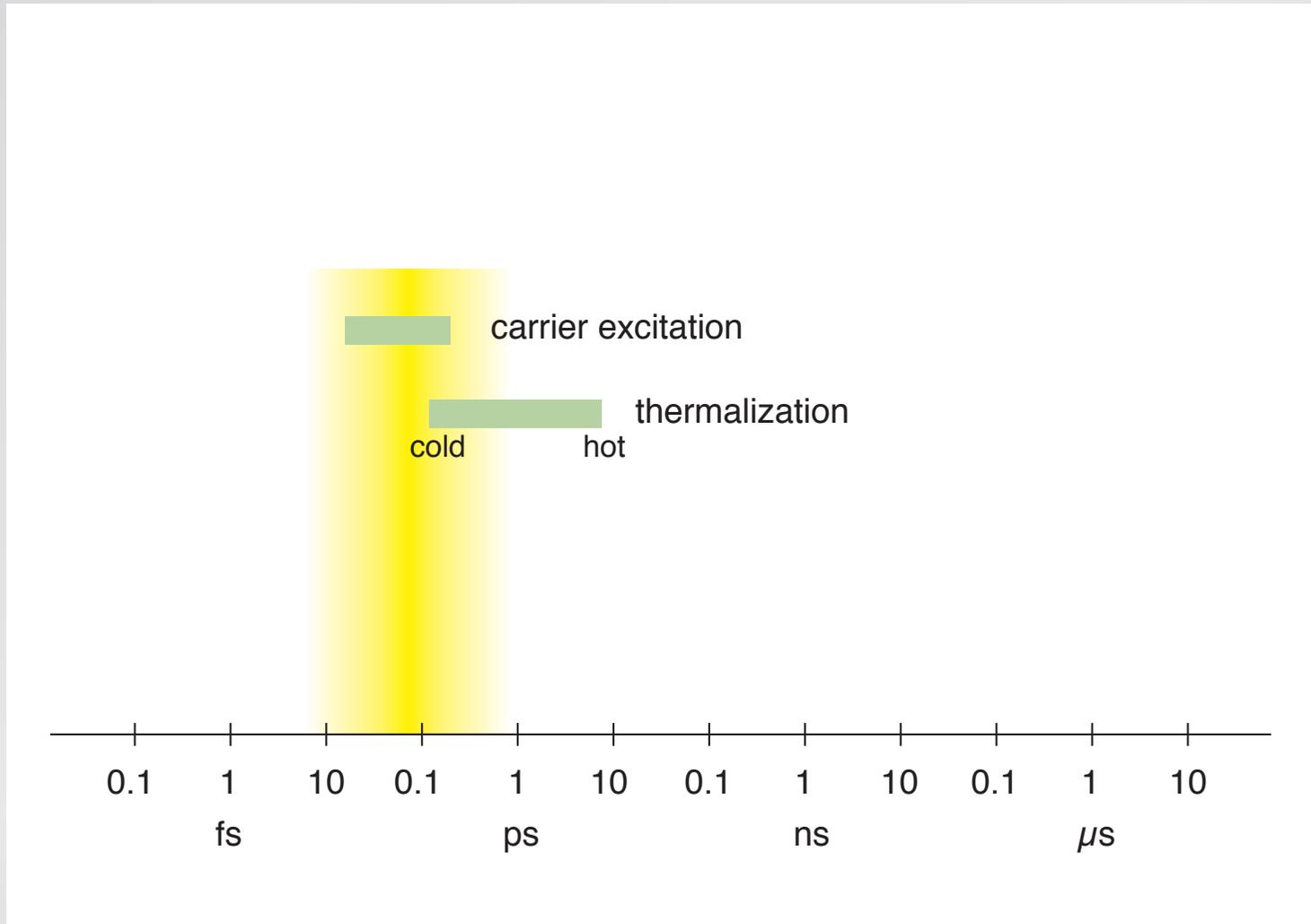
Introduction

relevant time scales



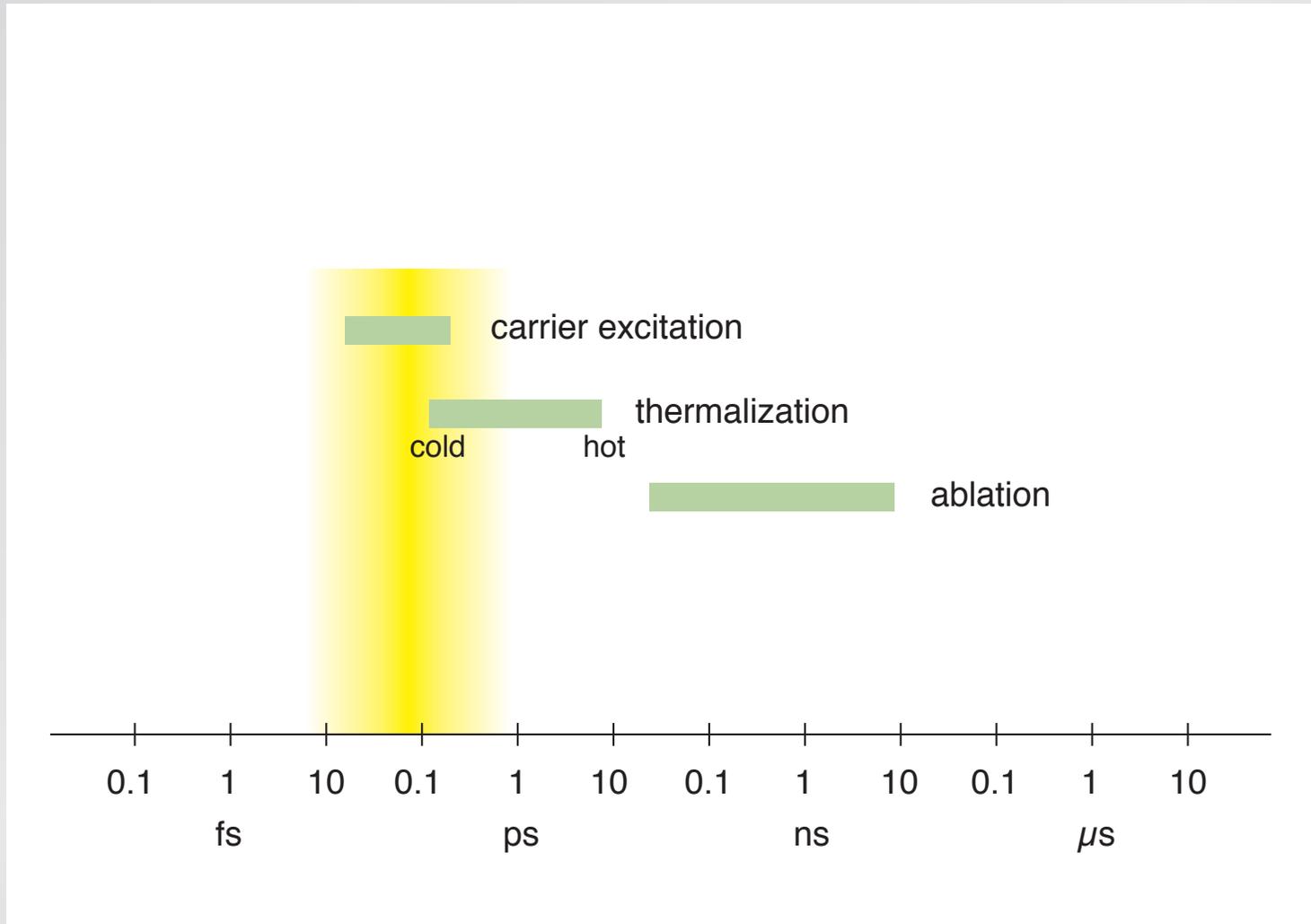
Introduction

relevant time scales



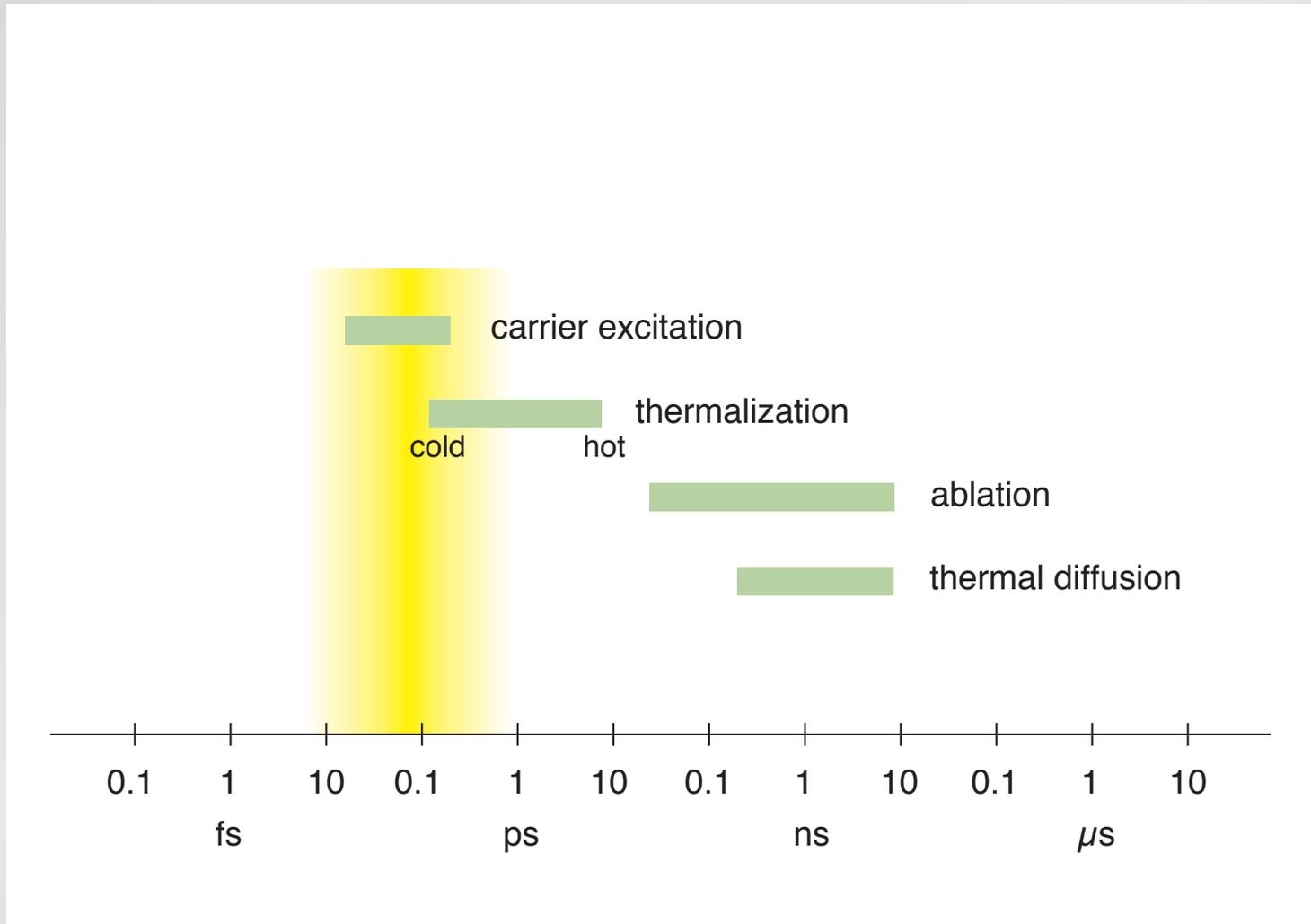
Introduction

relevant time scales



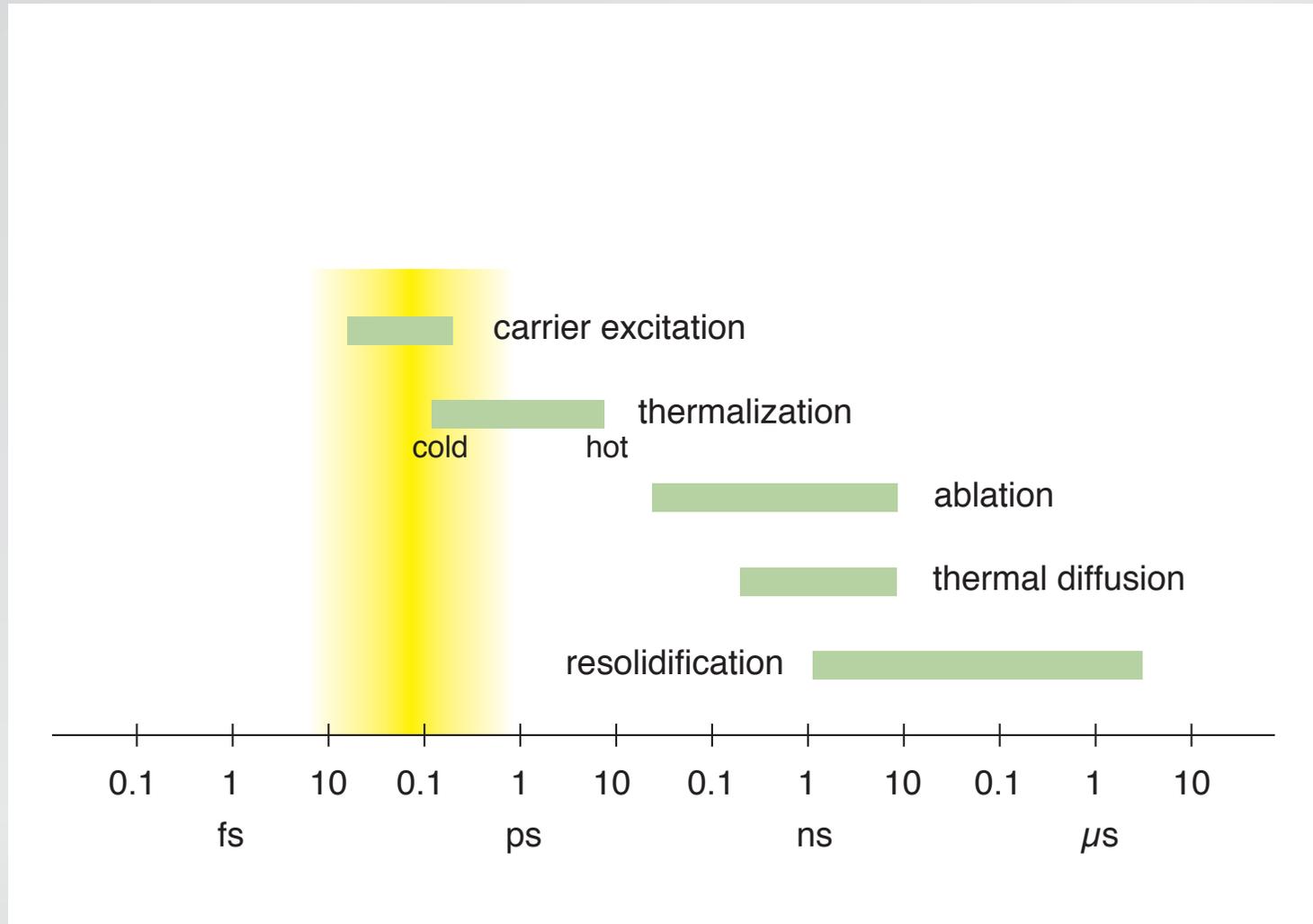
Introduction

relevant time scales



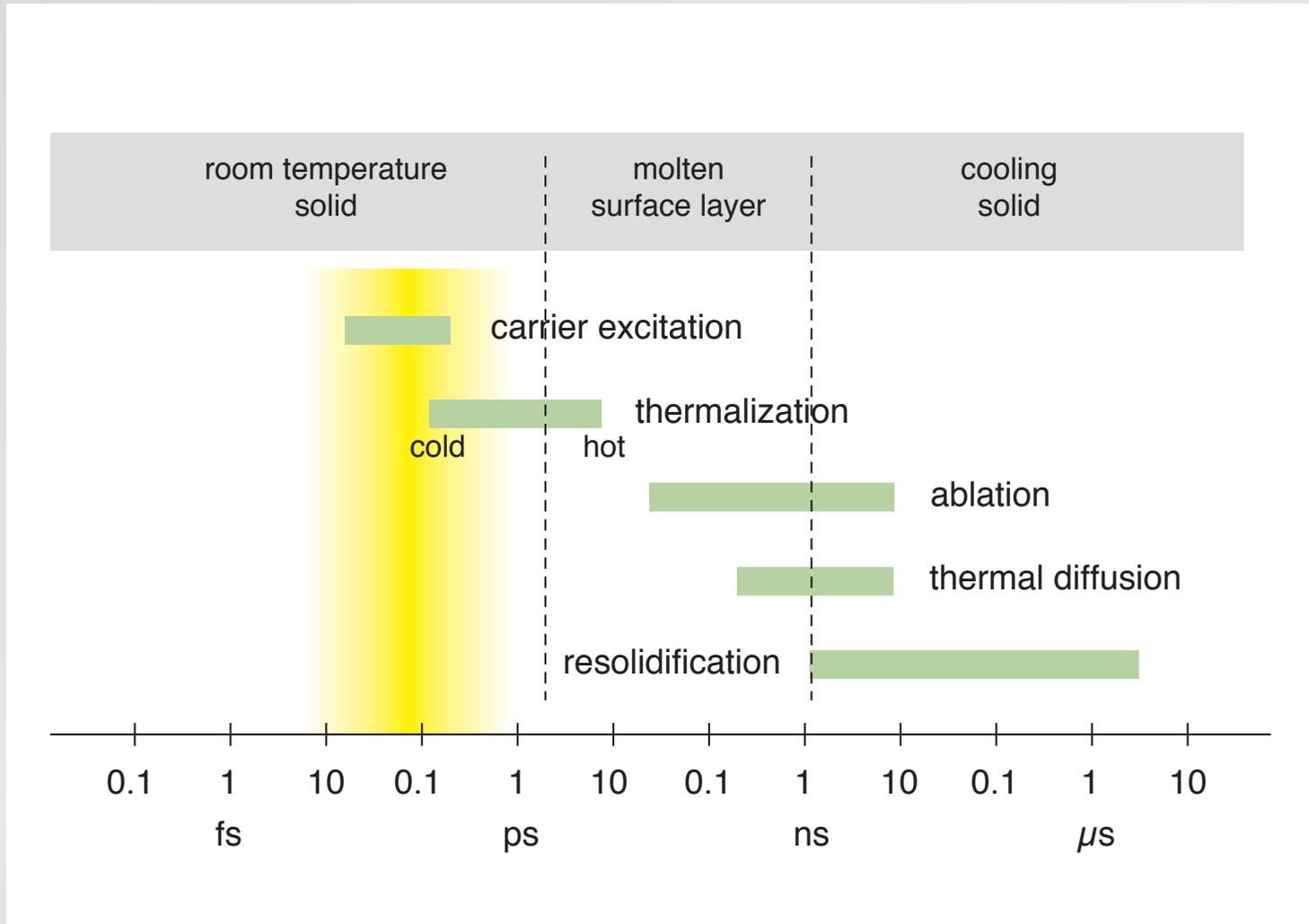
Introduction

relevant time scales



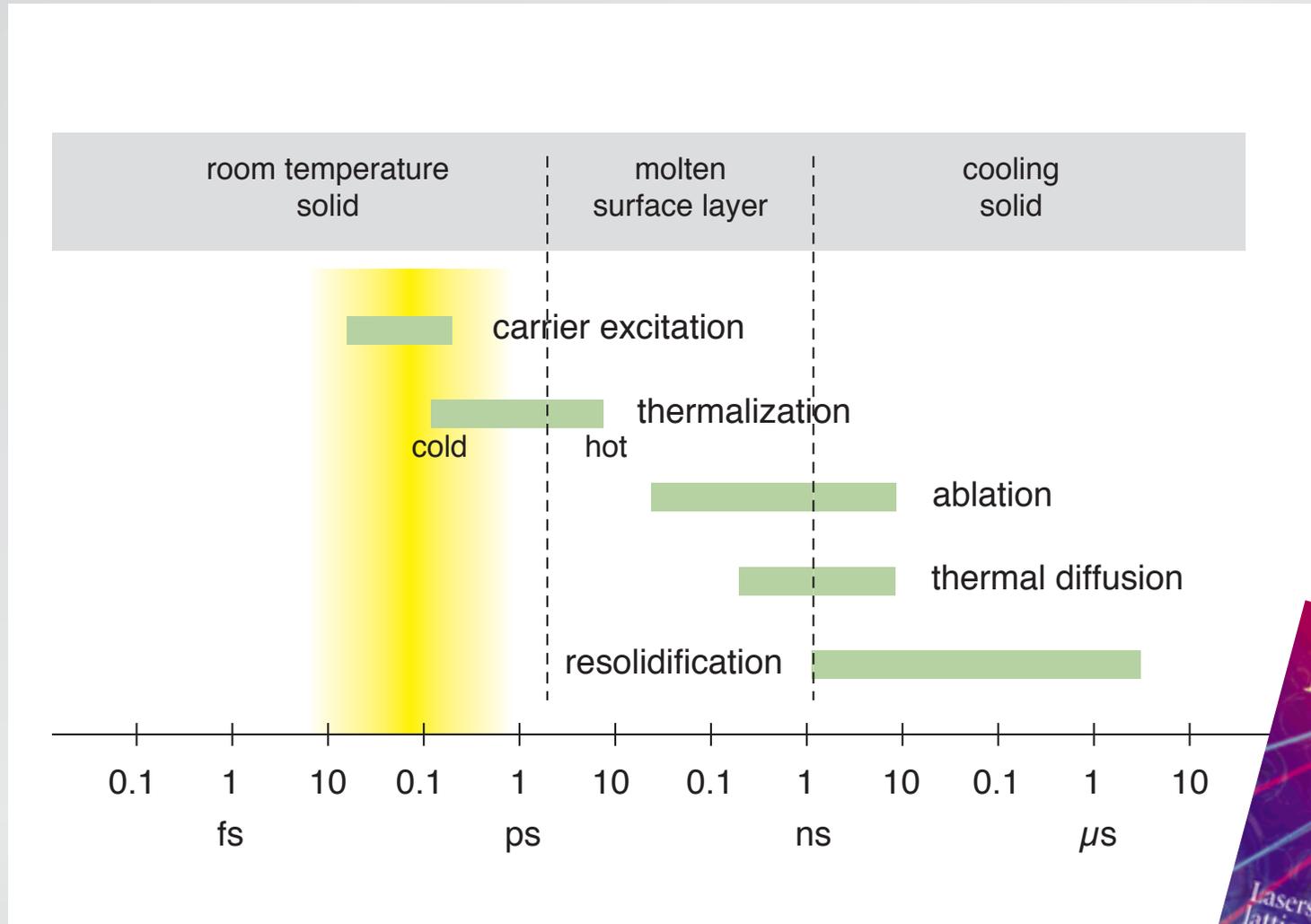
Introduction

relevant time scales



Introduction

relevant time scales

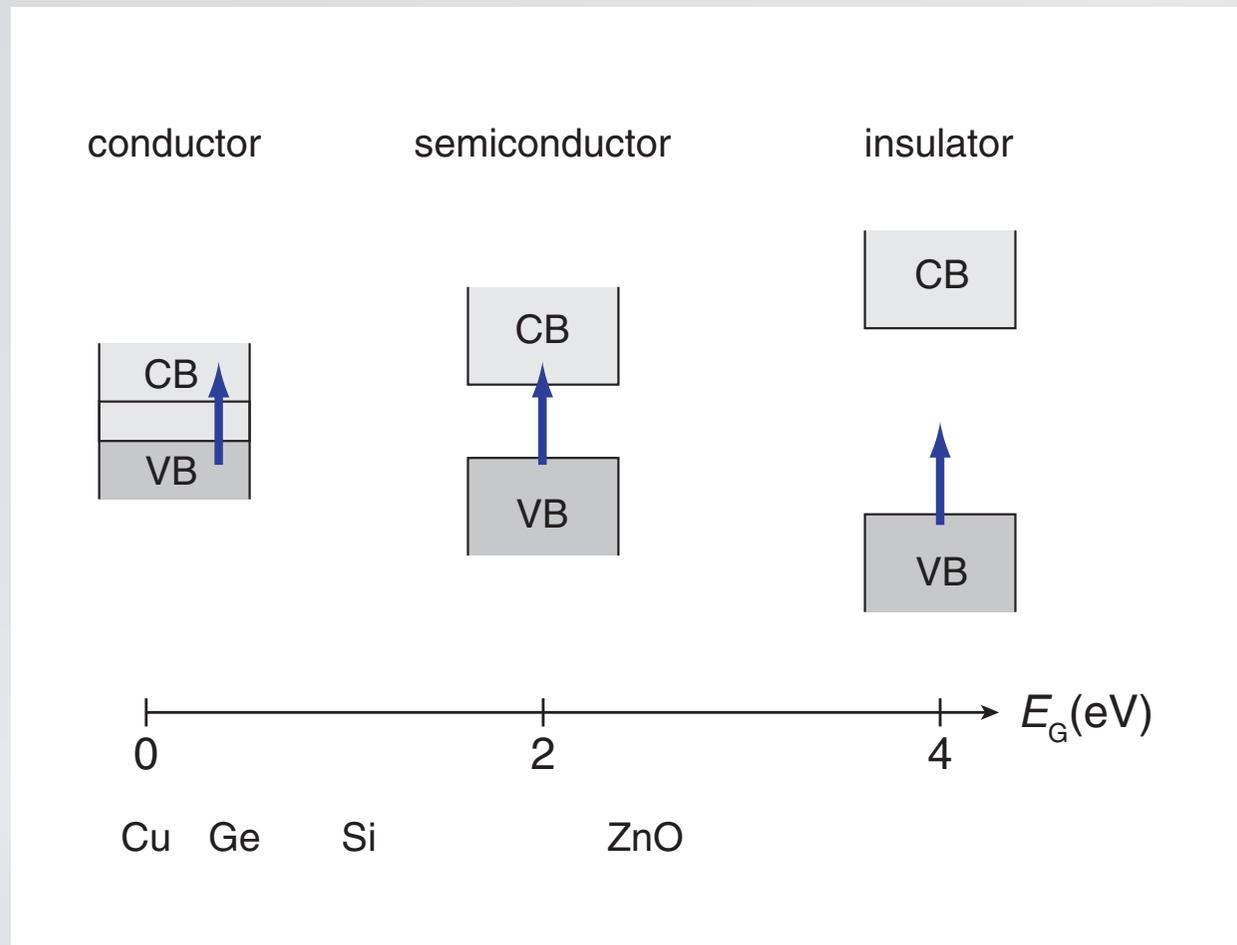


Nature Materials 1, 217 (2002)



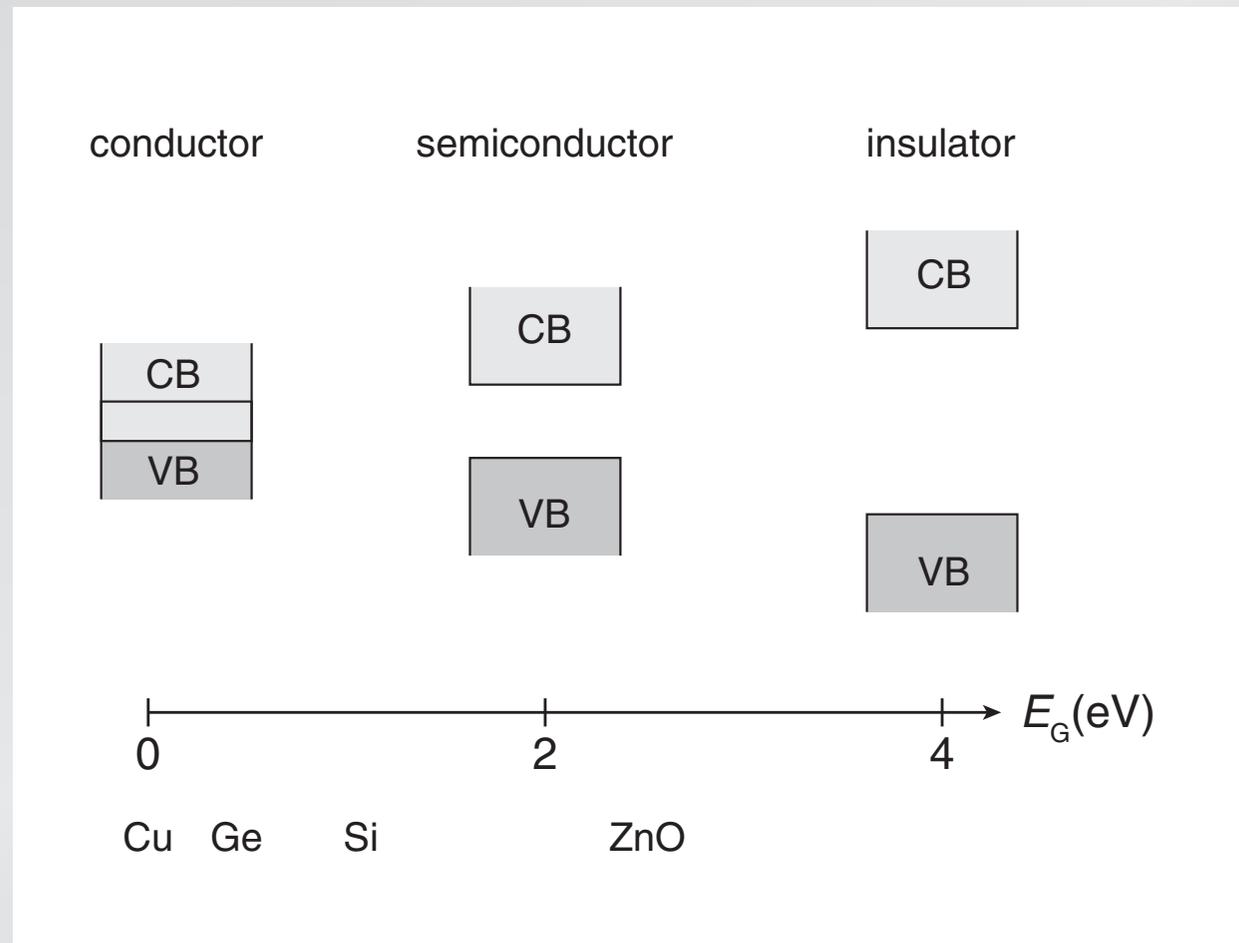
Introduction

gap determines interaction



Introduction

gap determines interaction

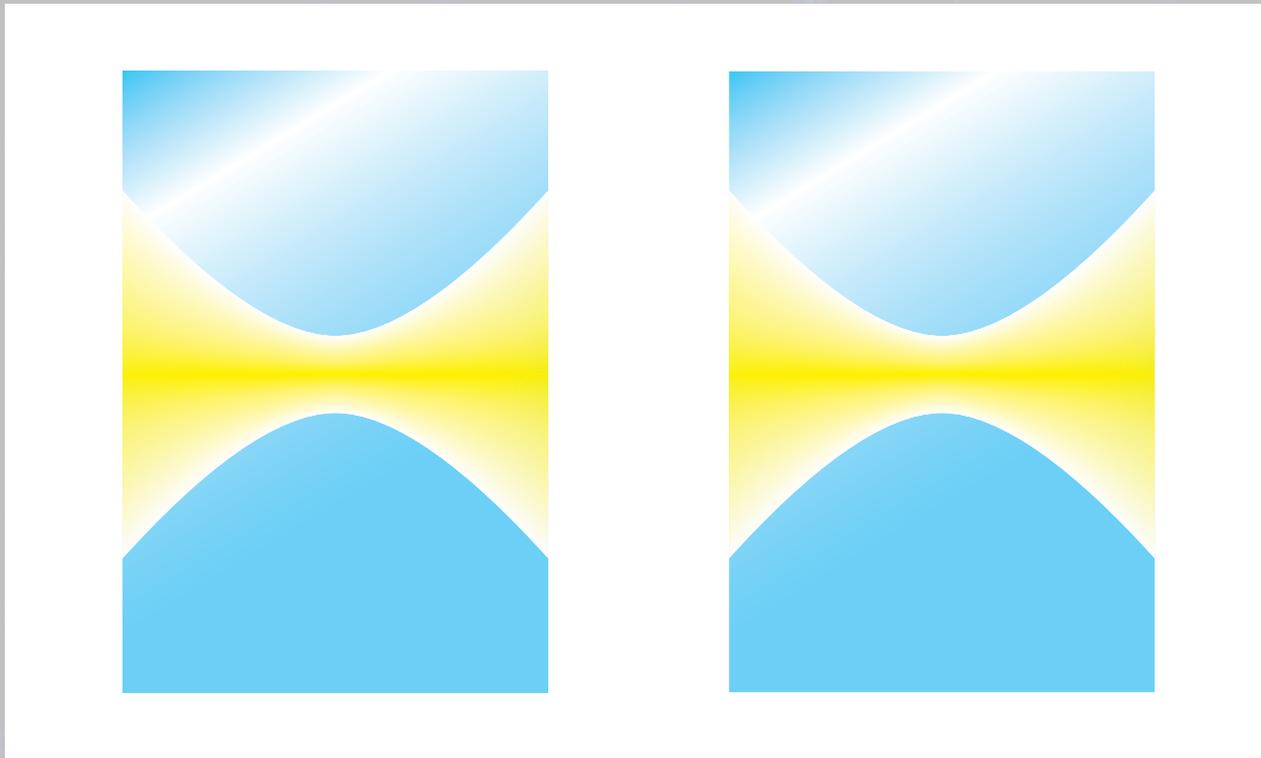


Introduction

photon energy $<$ bandgap \longrightarrow nonlinear interaction

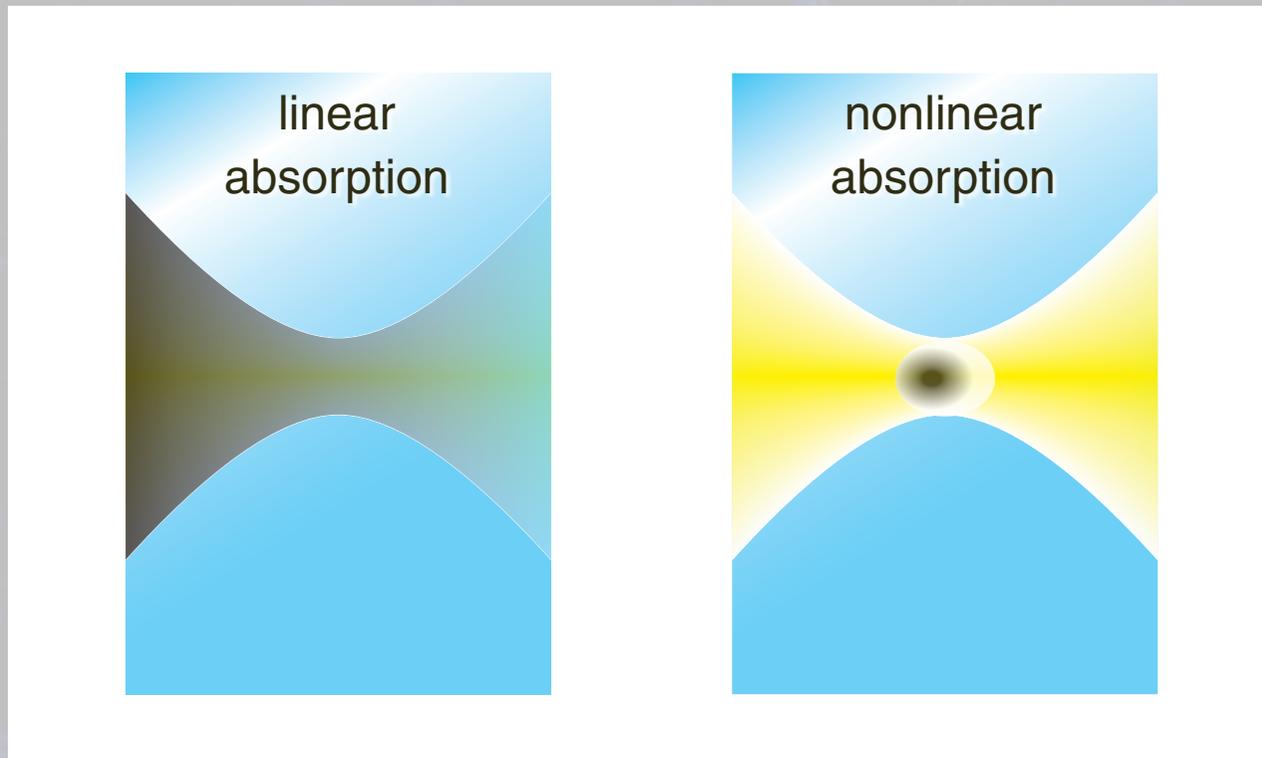
Introduction

nonlinear interaction provides bulk confinement



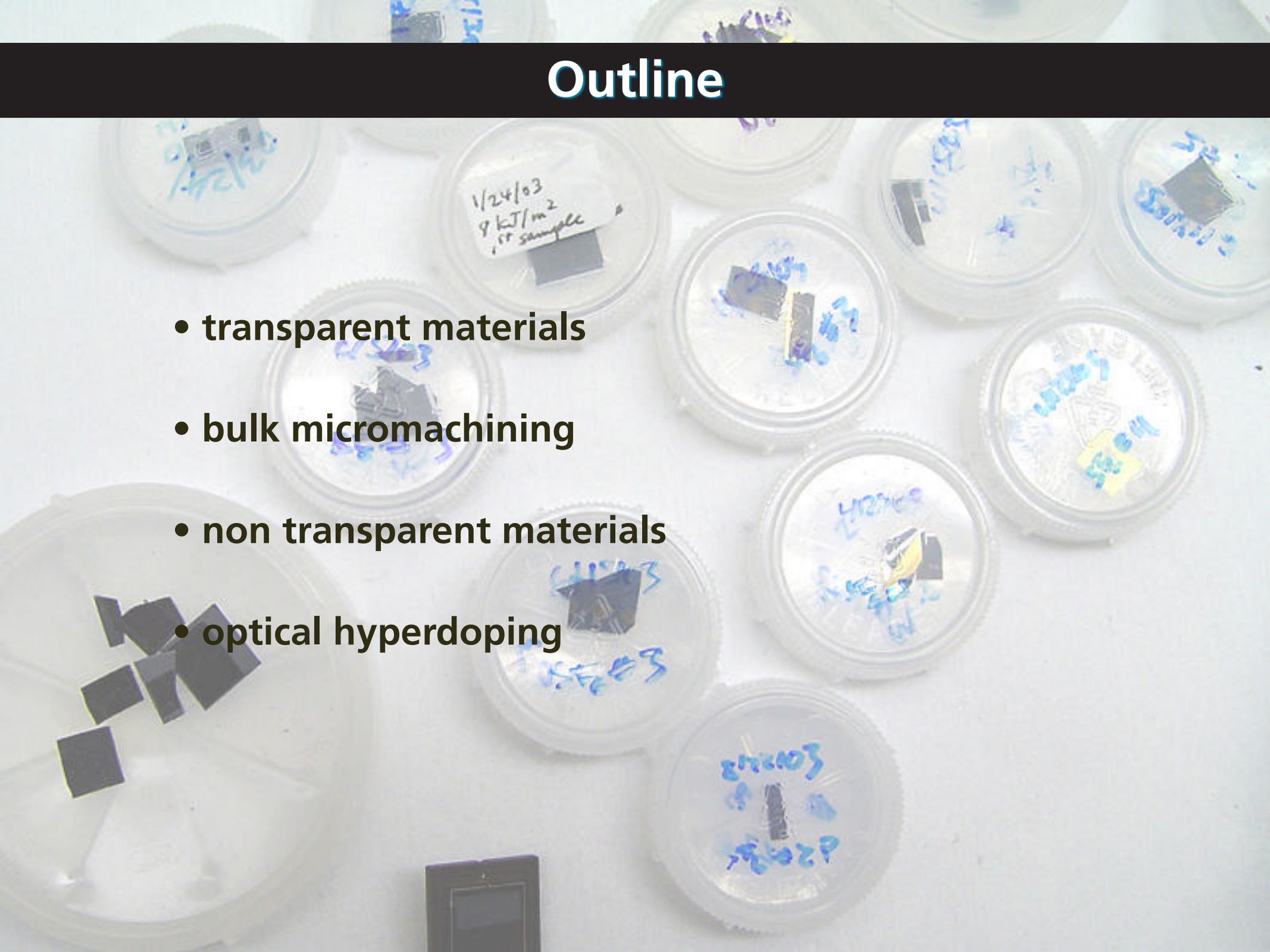
Introduction

nonlinear interaction provides bulk confinement



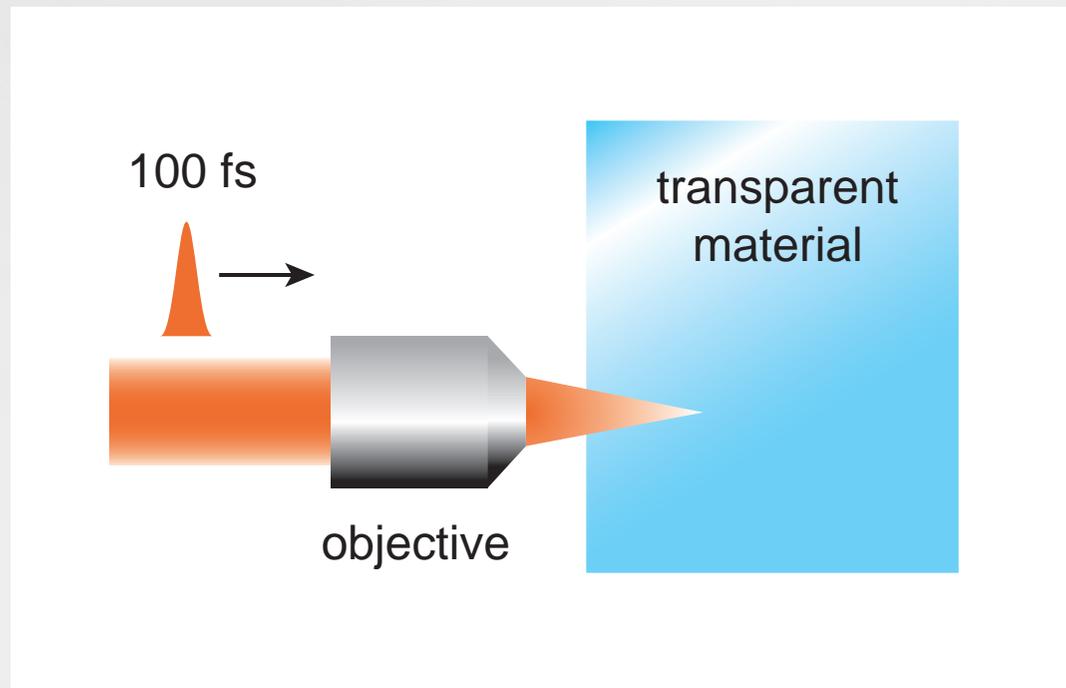
Outline

- transparent materials
- bulk micromachining
- non transparent materials
- optical hyperdoping



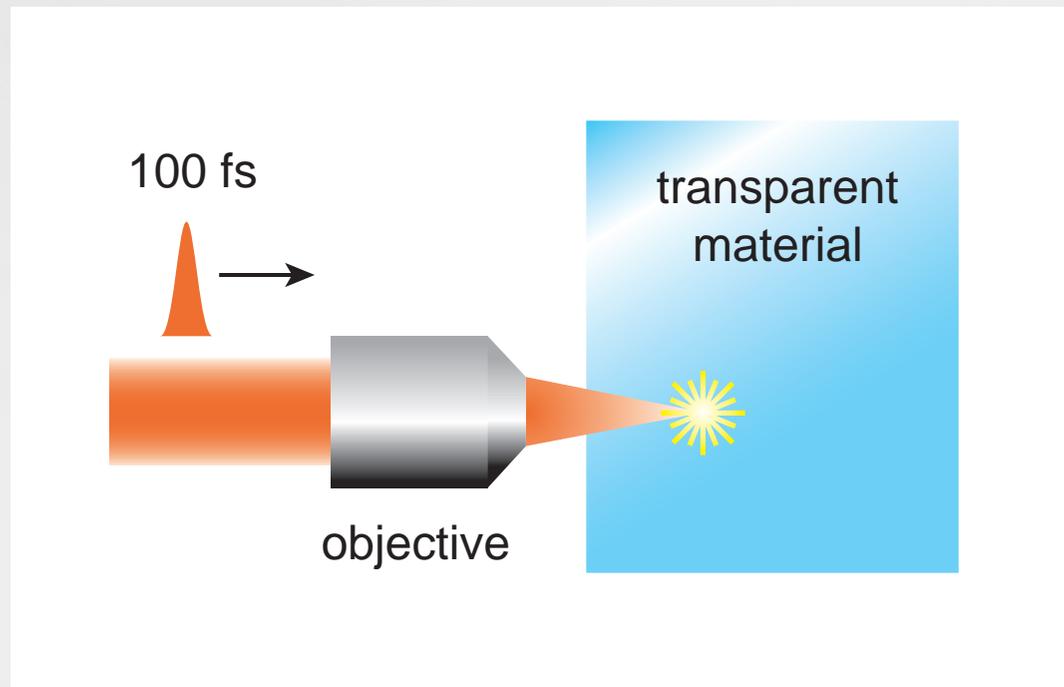
Transparent materials

high intensity at focus...



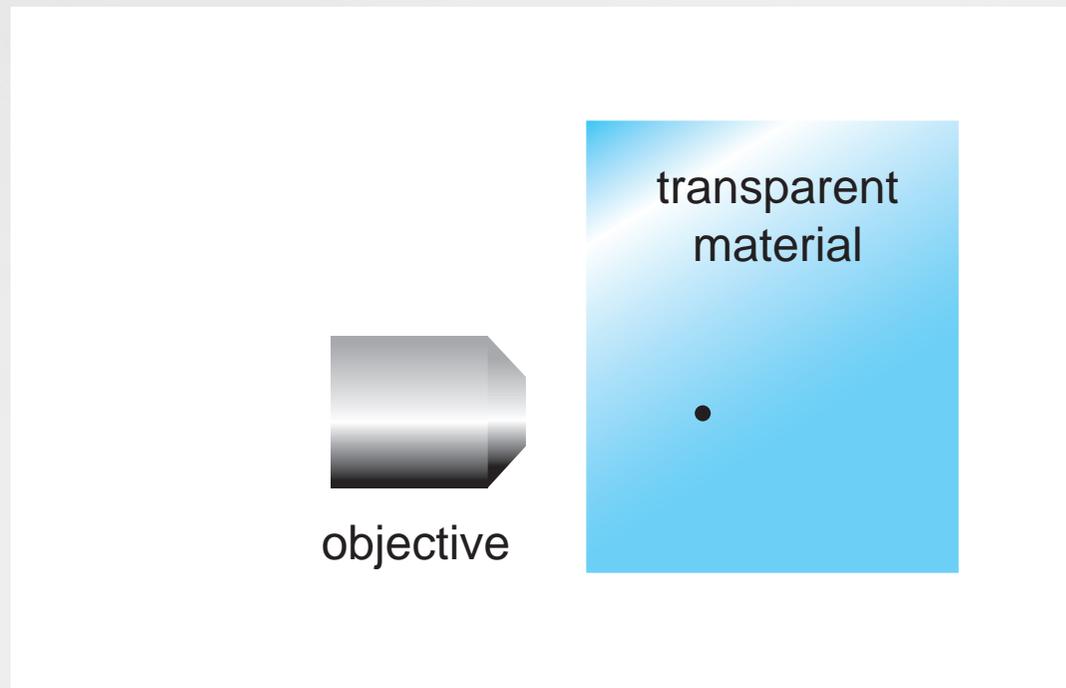
Transparent materials

...causes nonlinear ionization...

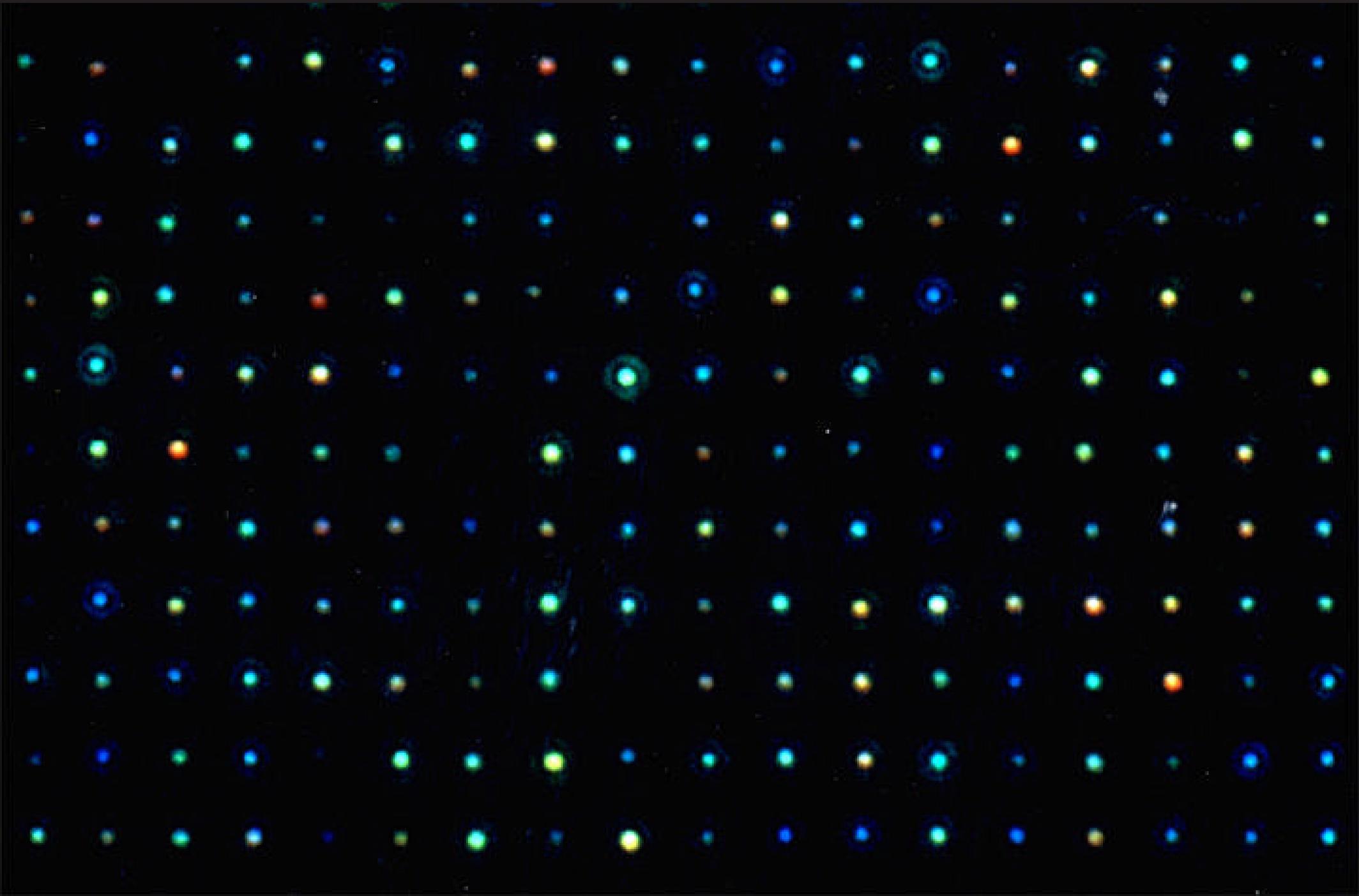


Transparent materials

and 'microexplosion' causes microscopic damage...

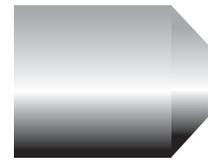


Transparent materials



Transparent materials

Dark-field scattering



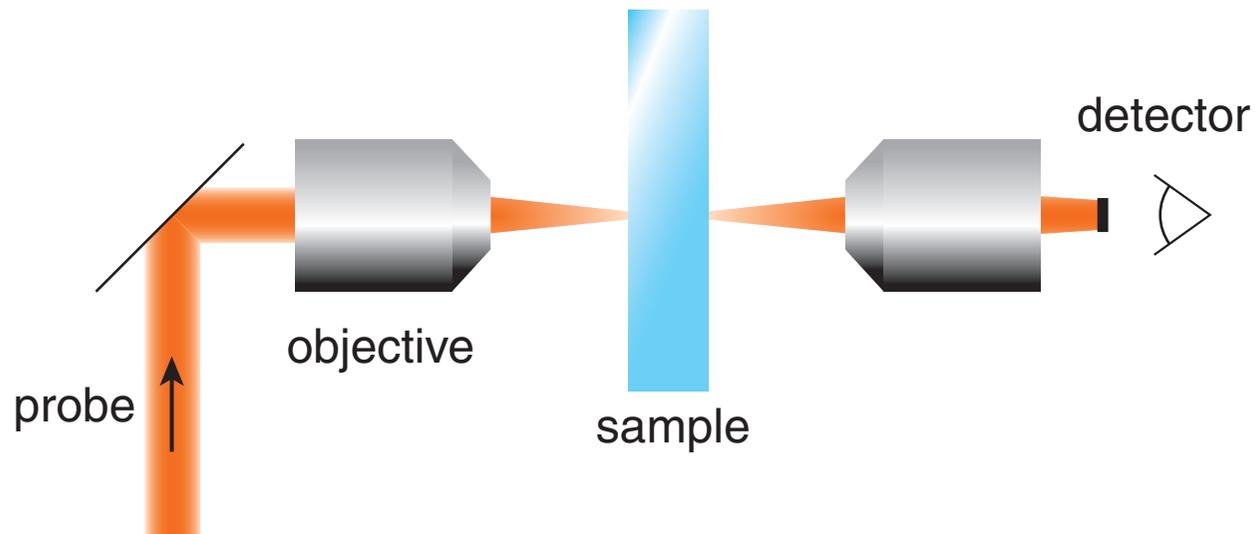
objective



sample

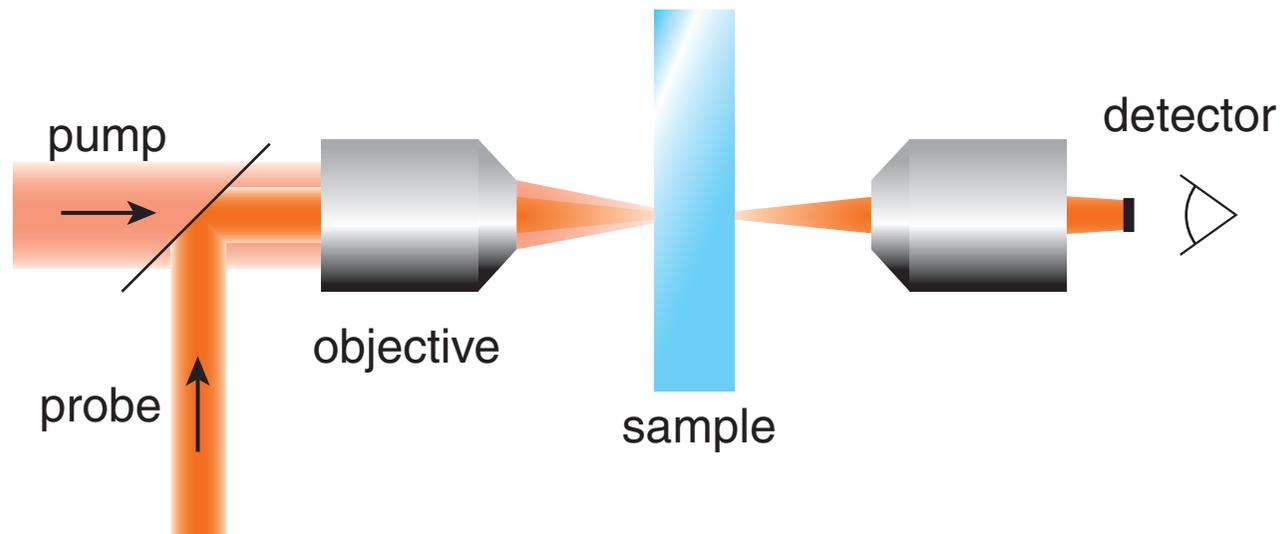
Transparent materials

block probe beam...



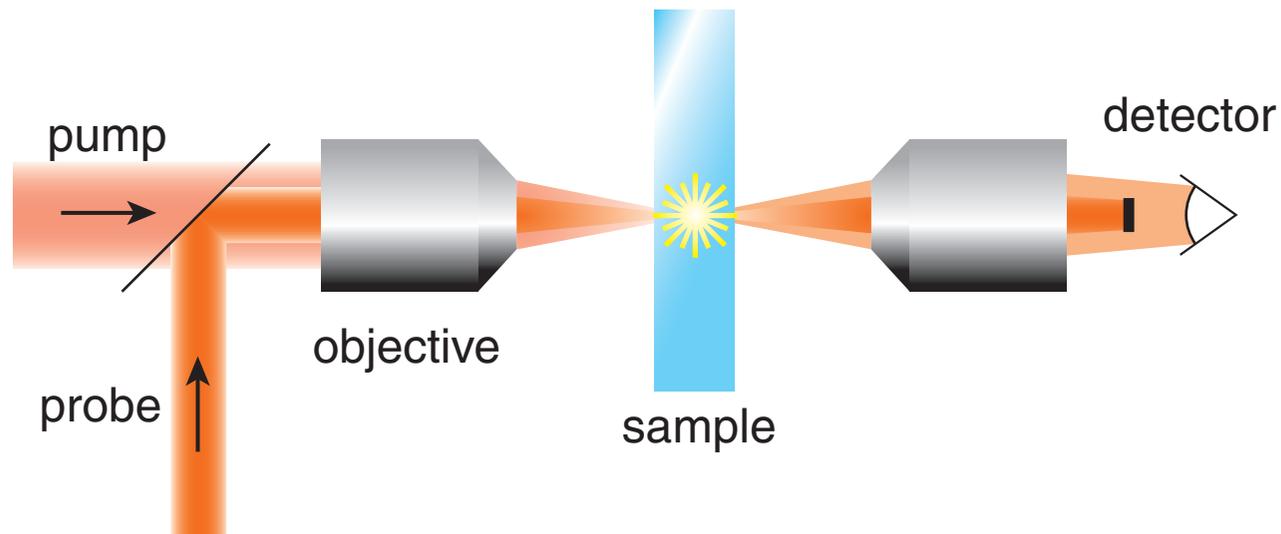
Transparent materials

... bring in pump beam...



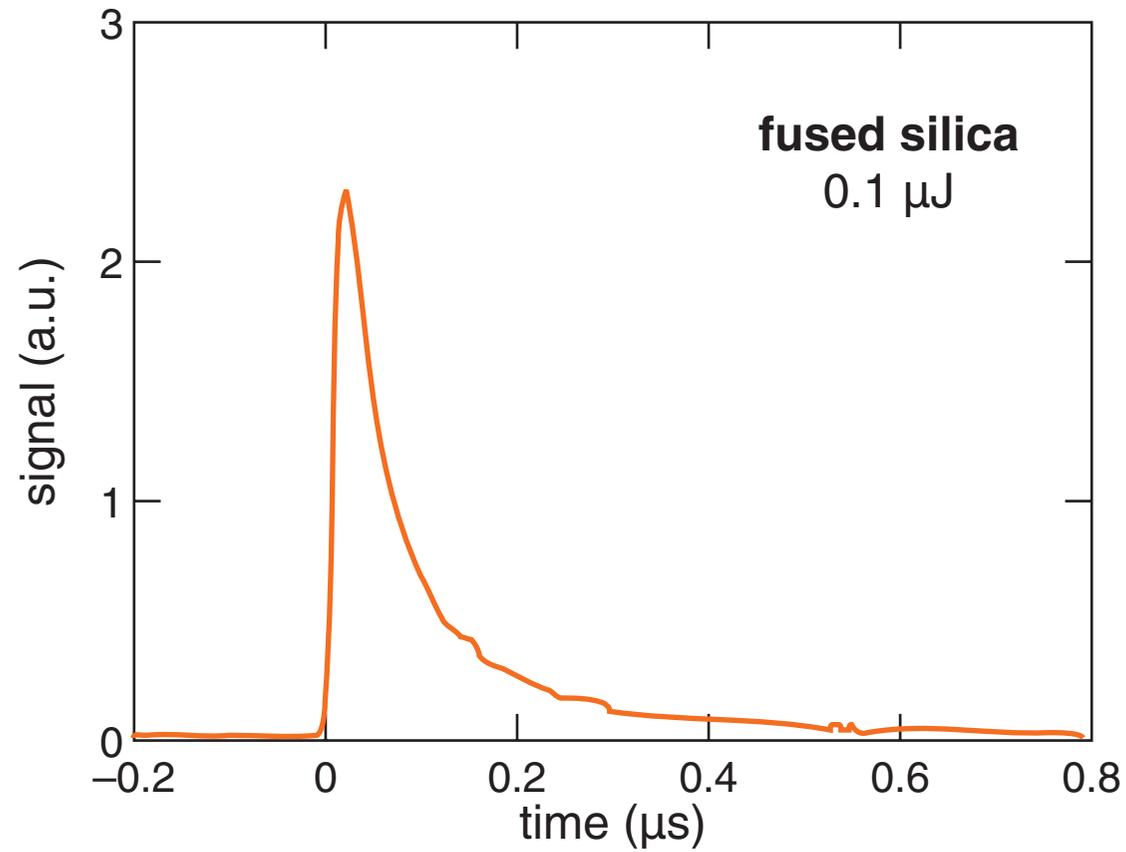
Transparent materials

... damage scatters probe beam



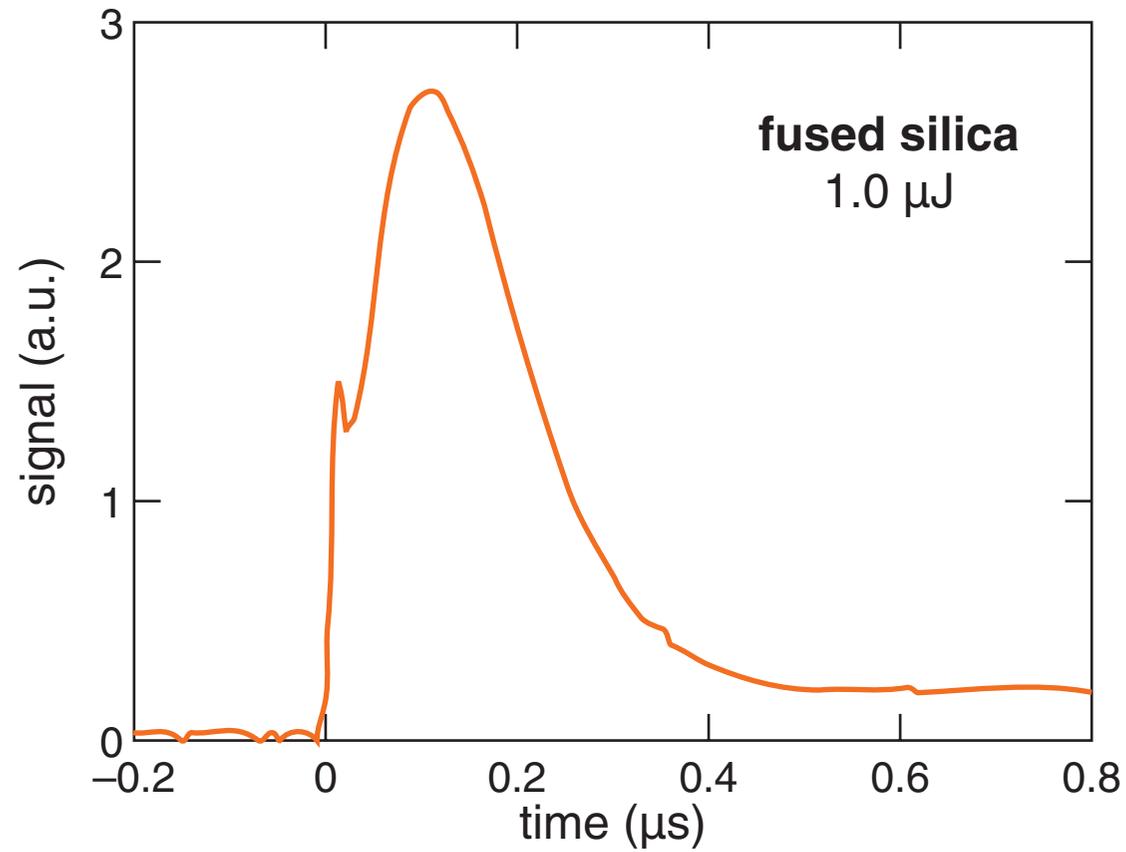
Transparent materials

scattered signal



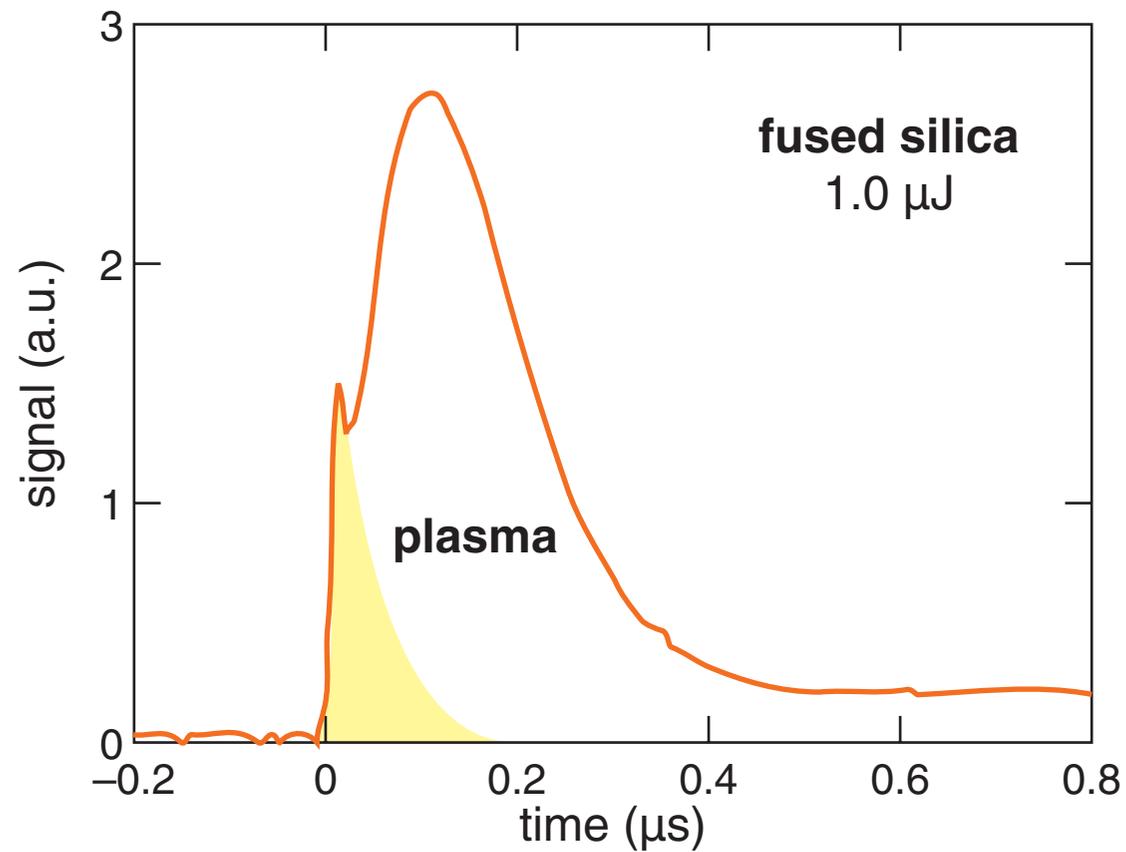
Transparent materials

scattered signal



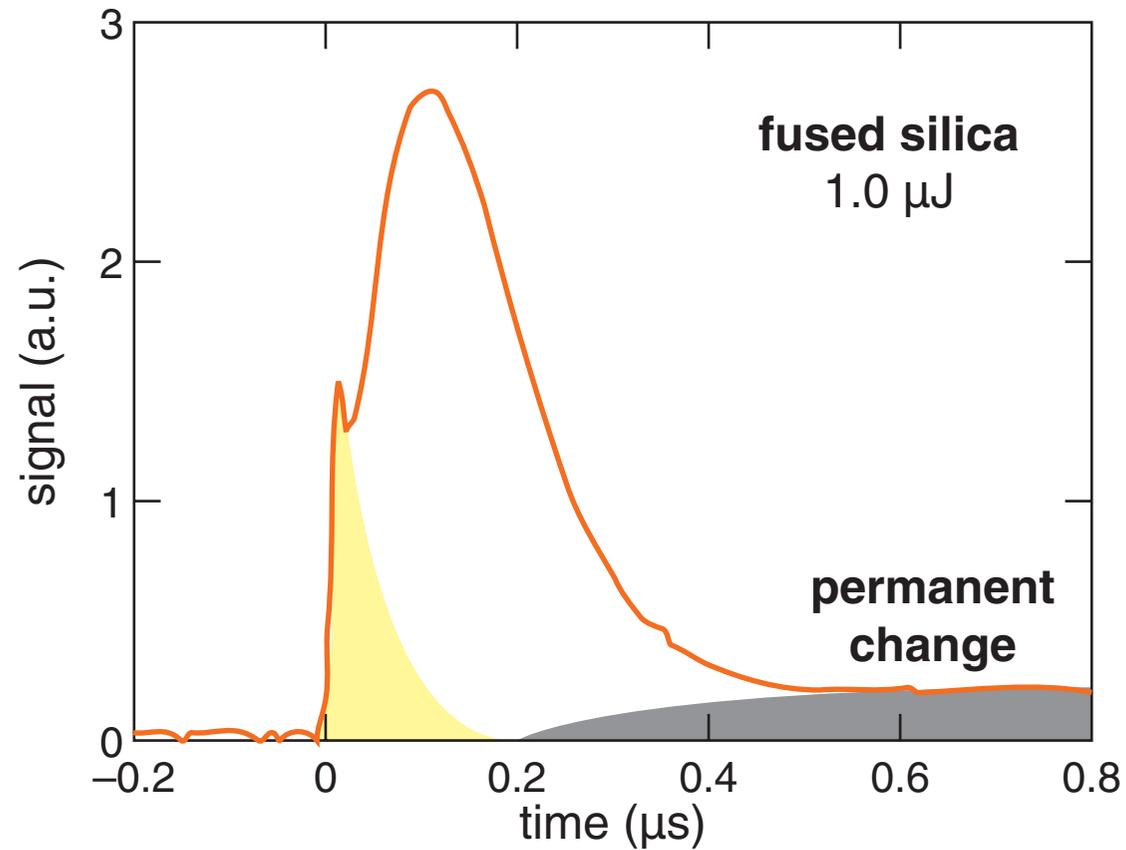
Transparent materials

scattered signal



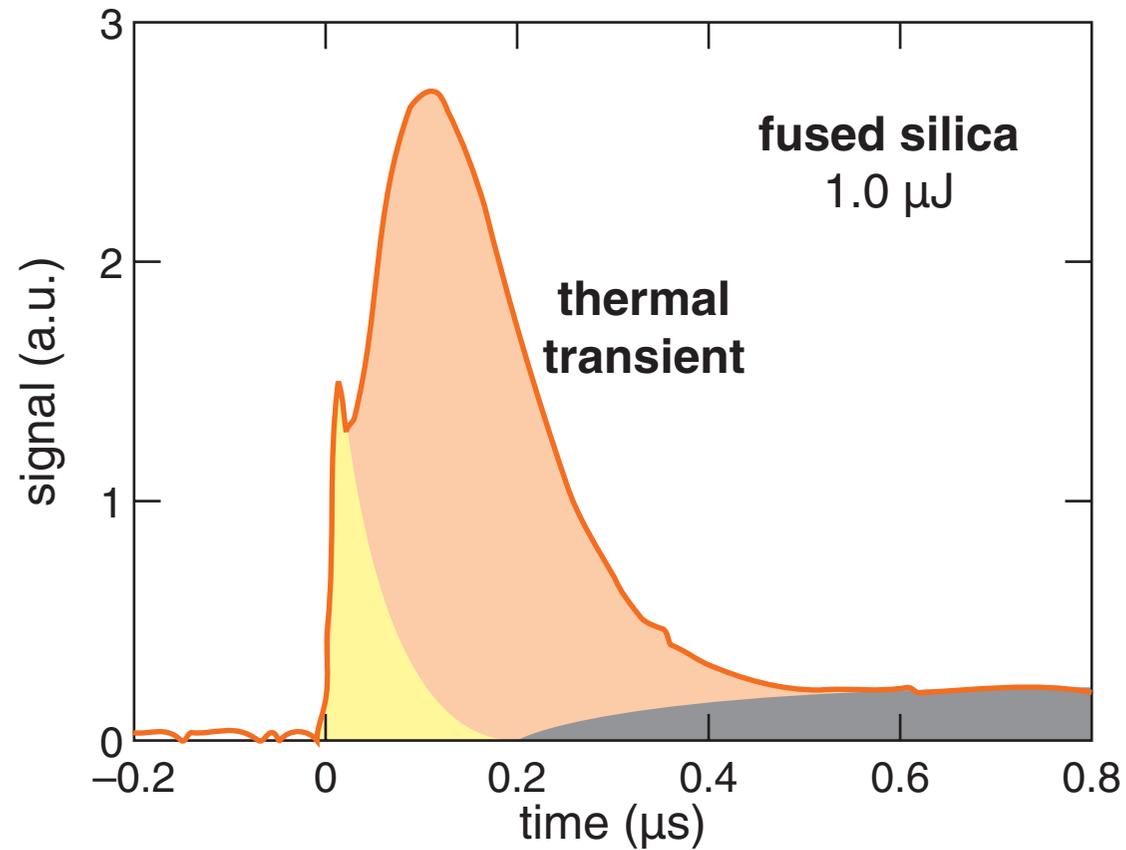
Transparent materials

scattered signal



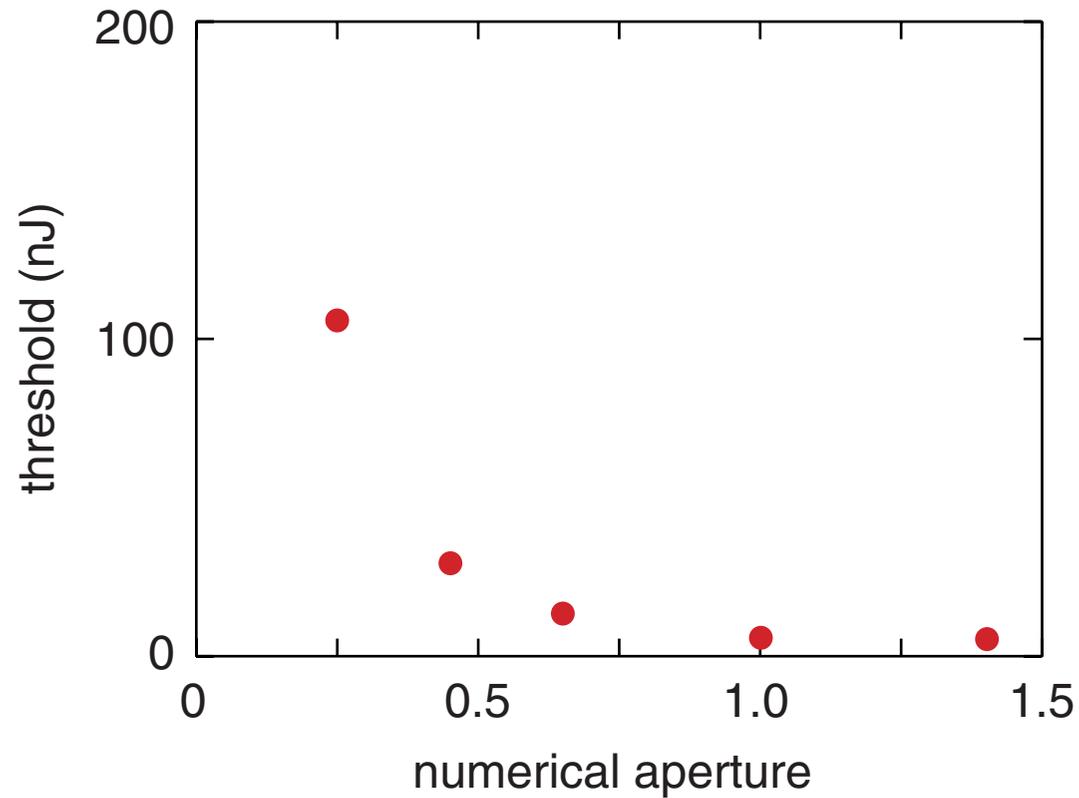
Transparent materials

scattered signal



Transparent materials

vary numerical aperture



Transparent materials

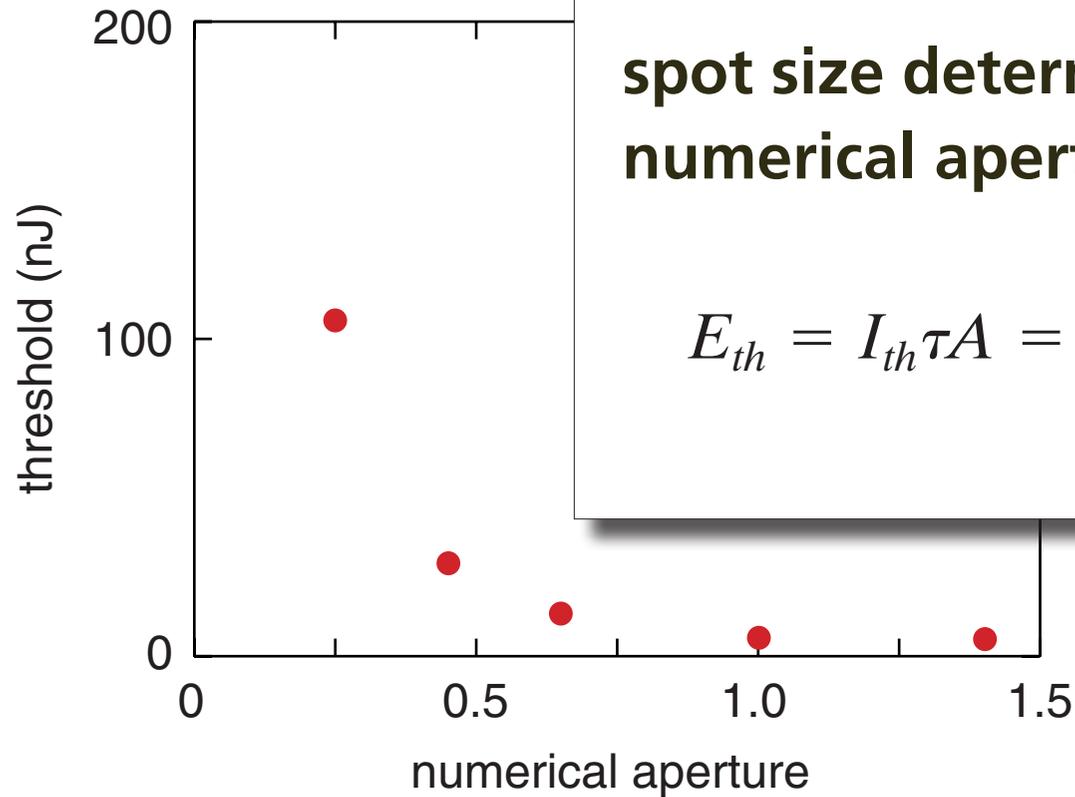
vary numeric

intensity threshold:

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

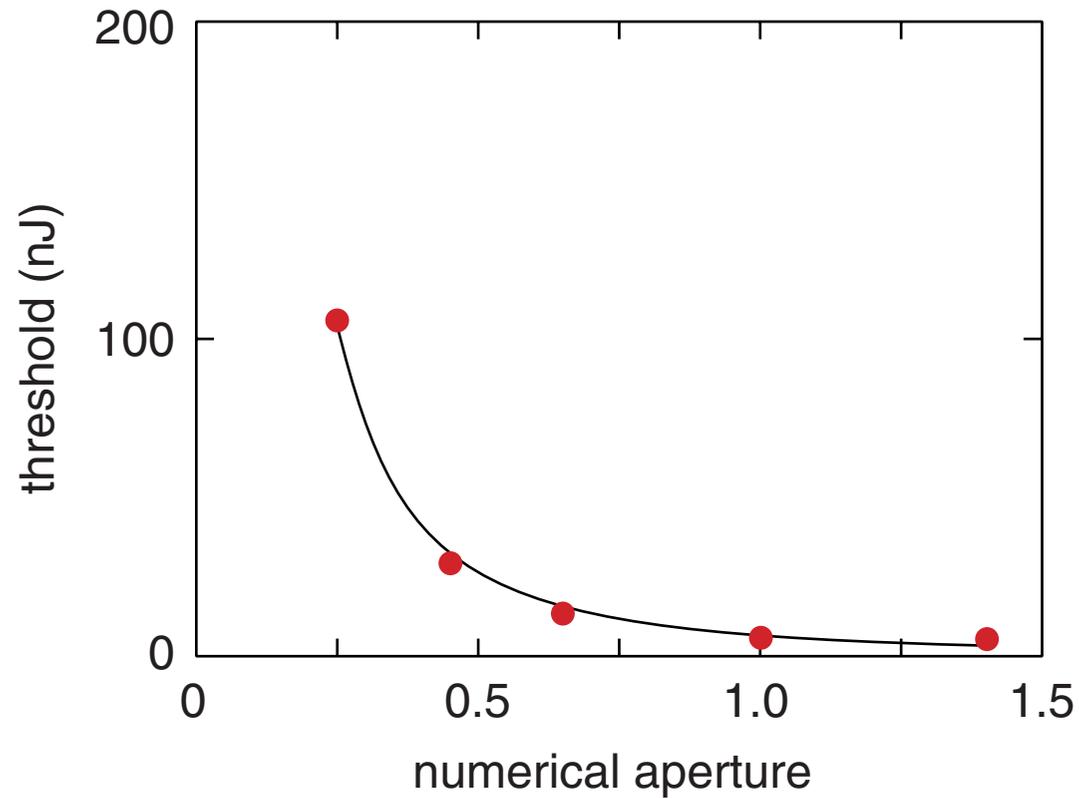
spot size determined by
numerical aperture:

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



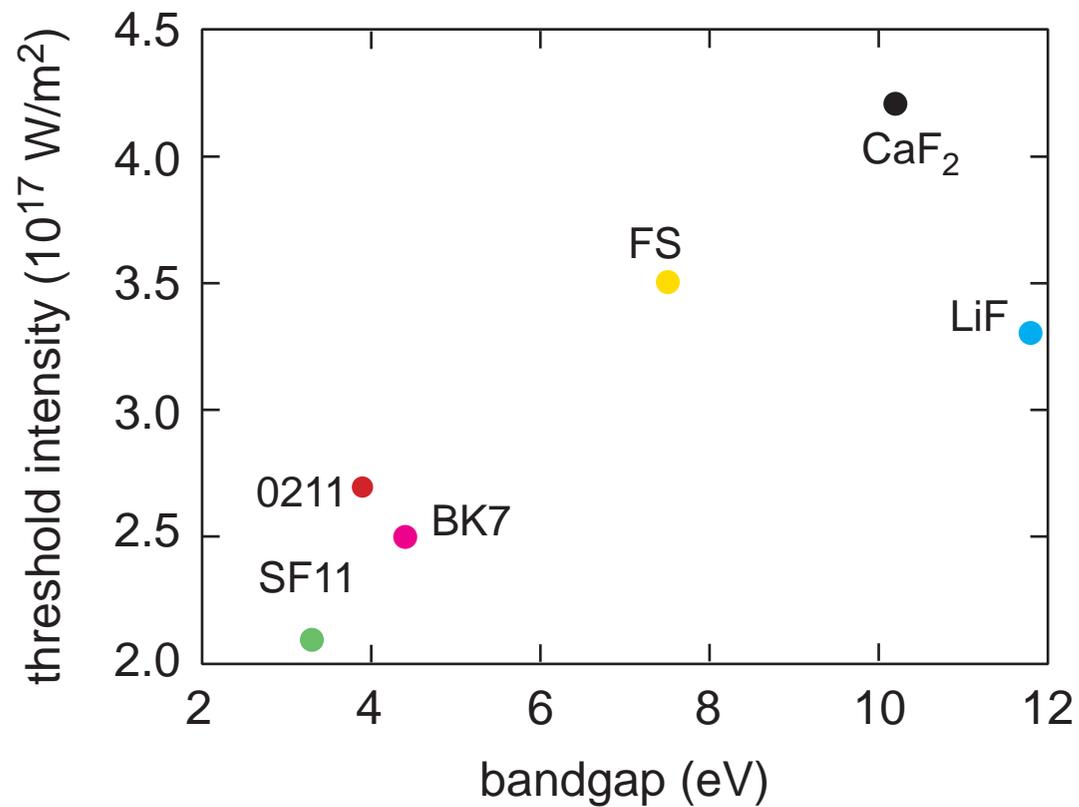
Transparent materials

fit gives threshold intensity: $I_{th} = 2.5 \times 10^{17} \text{ W/m}^2$



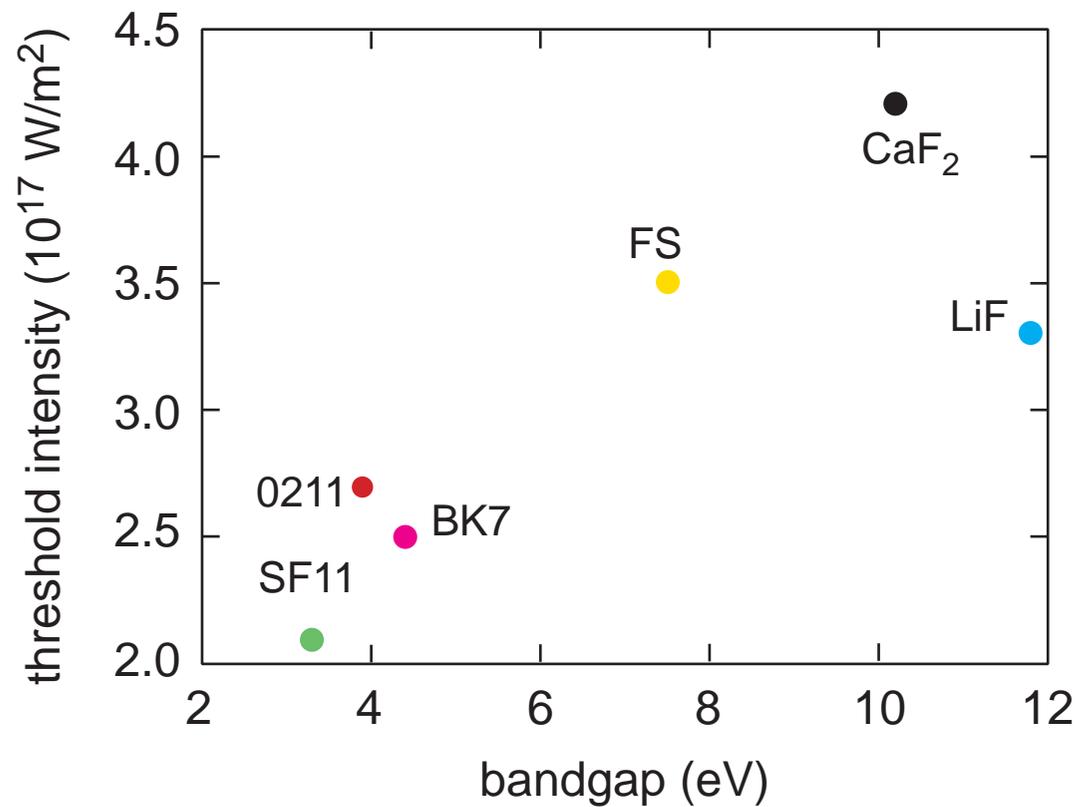
Transparent materials

vary material...



Transparent materials

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



Transparent materials

Points to keep in mind:

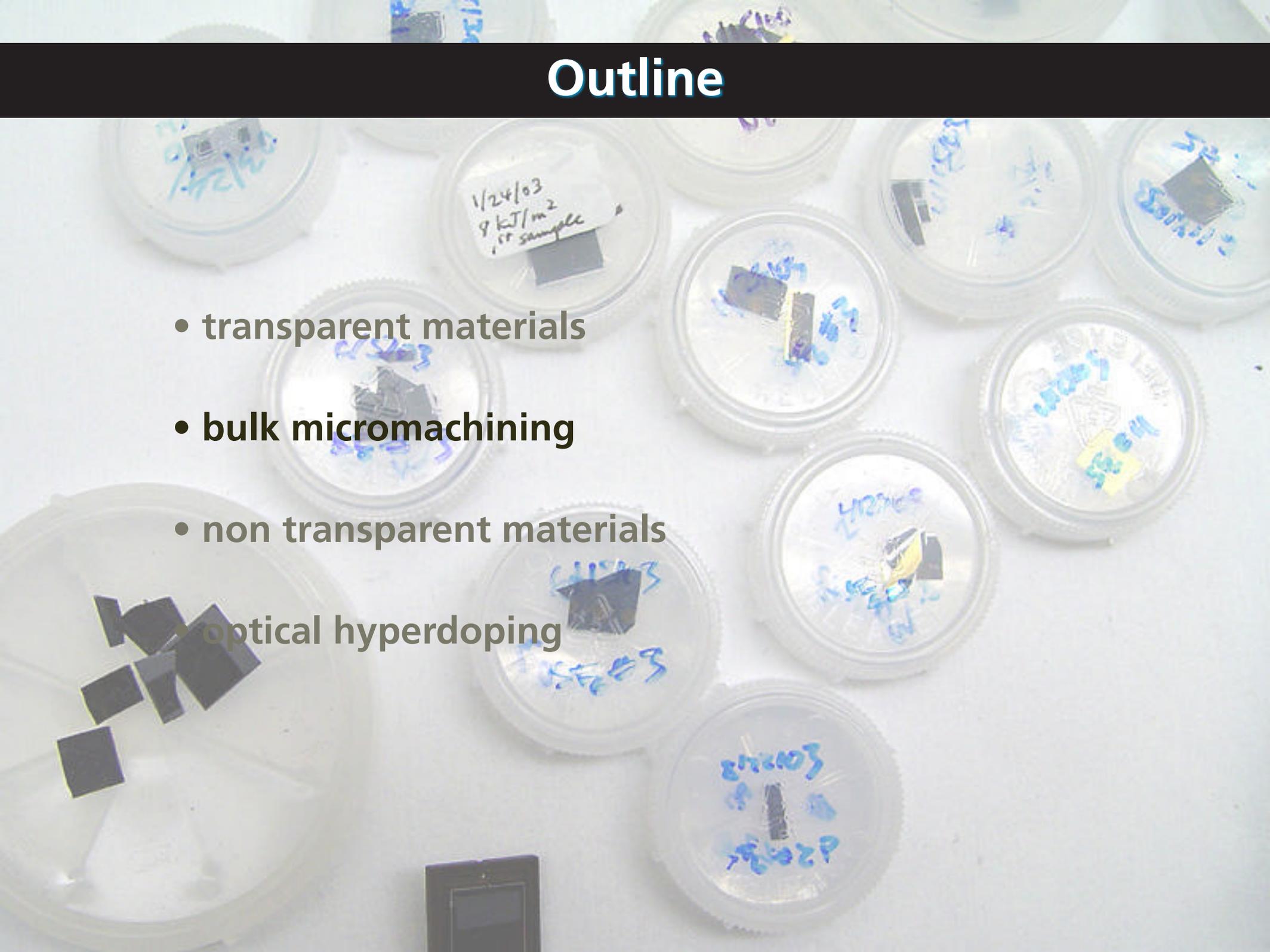
- threshold critically dependent on NA
- surprisingly little material dependence
- avalanche ionization important

Nature Photonics 2, 219 (2008)



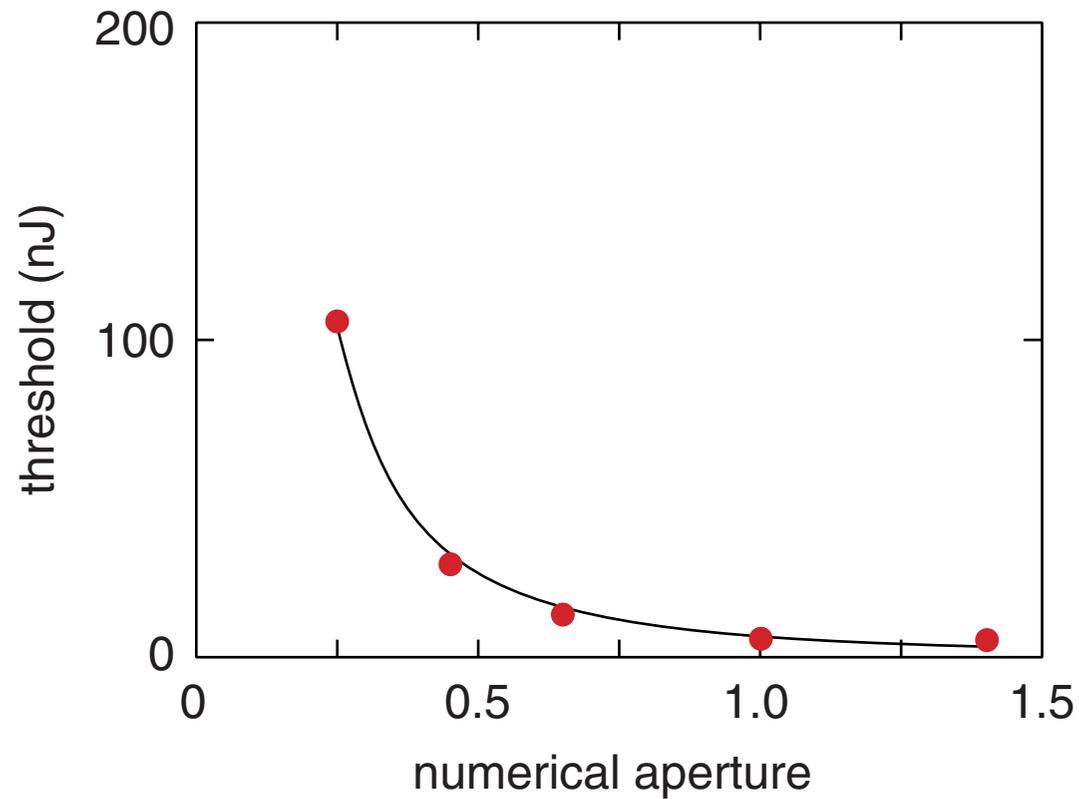
Outline

- transparent materials
- bulk micromachining
- non transparent materials
- optical hyperdoping



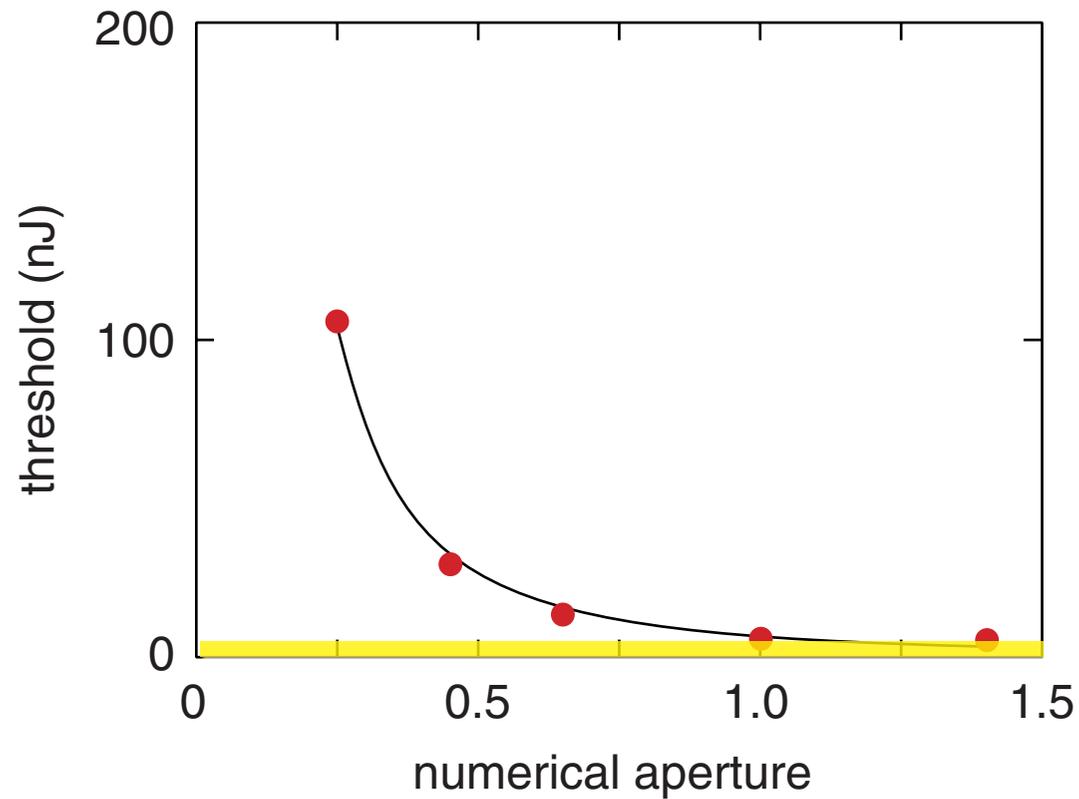
Bulk micromachining

threshold decreases with increasing numerical aperture



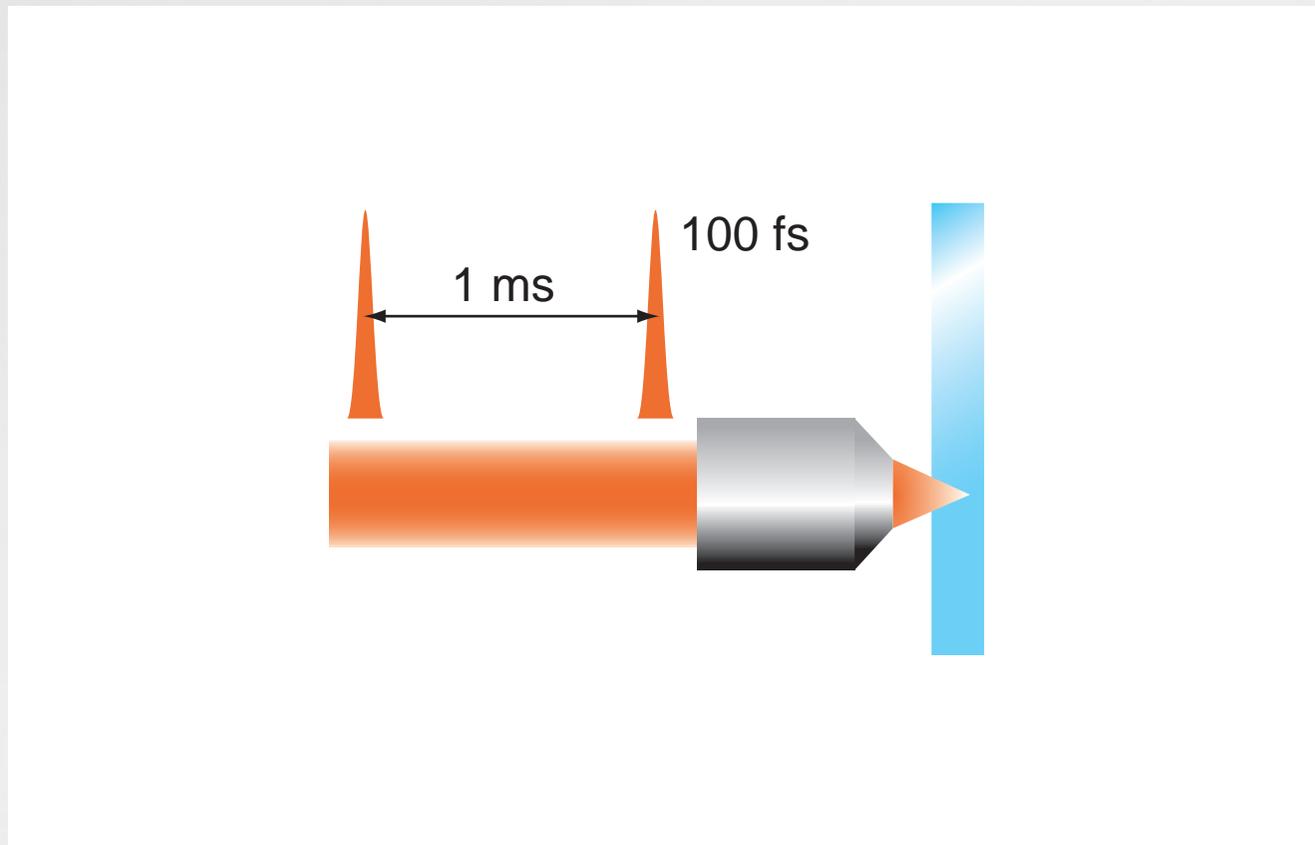
Bulk micromachining

less than 10 nJ at high numerical aperture!



Bulk micromachining

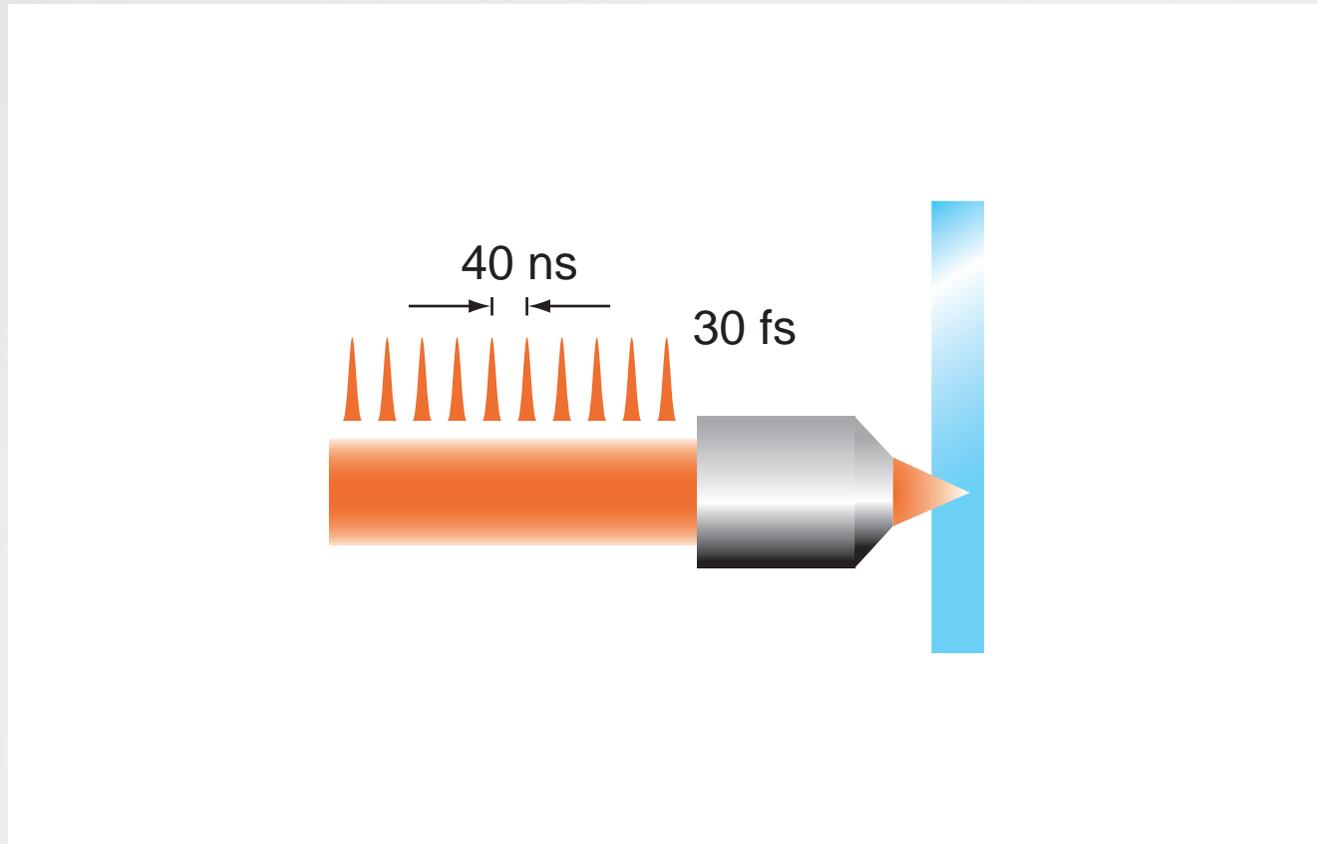
amplified laser: 1 kHz, 1 mJ



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

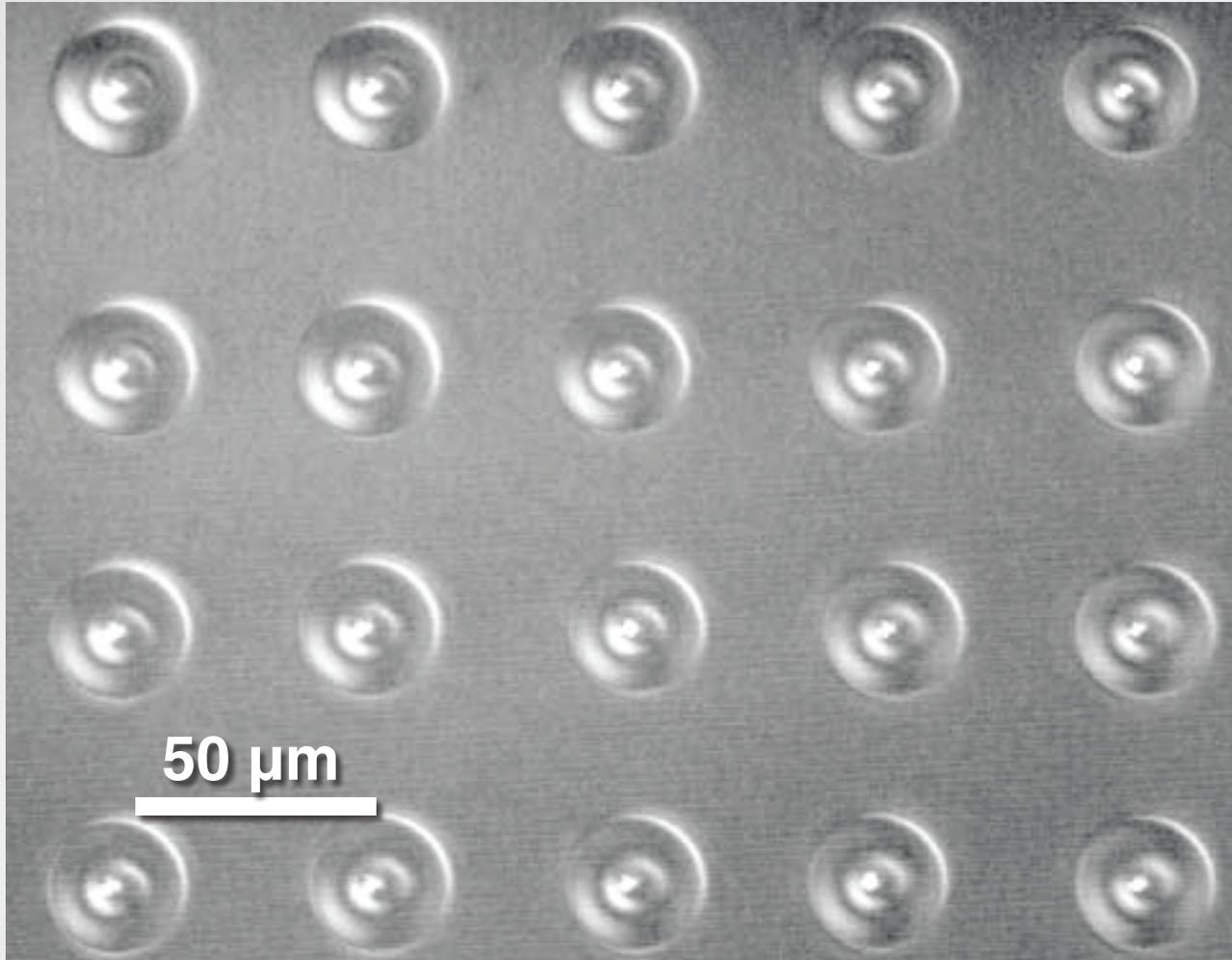
Bulk micromachining

long cavity oscillator: 25 MHz, 25 nJ



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

Bulk micromachining



Bulk micromachining

High repetition-rate micromachining:

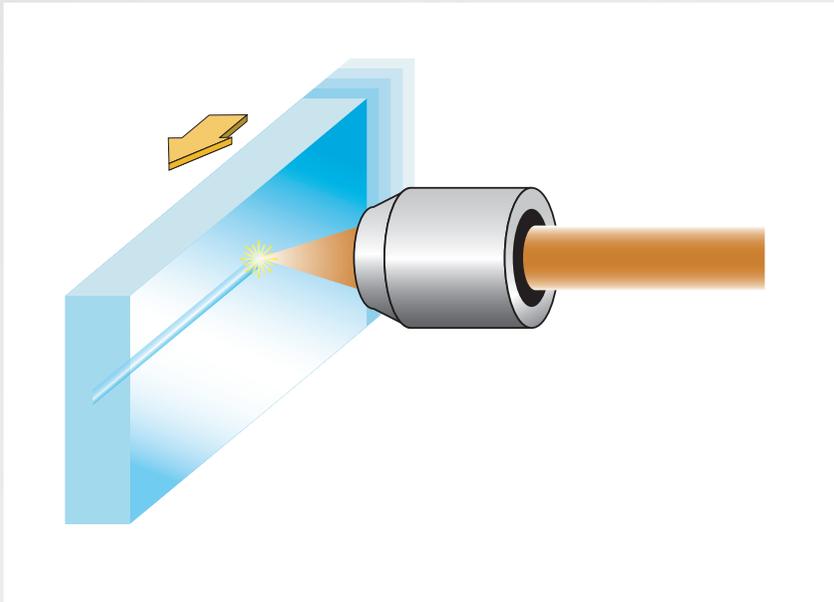
- **structural changes exceed focal volume**
- **spherical structures**
- **density change caused by melting**

Bulk micromachining

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

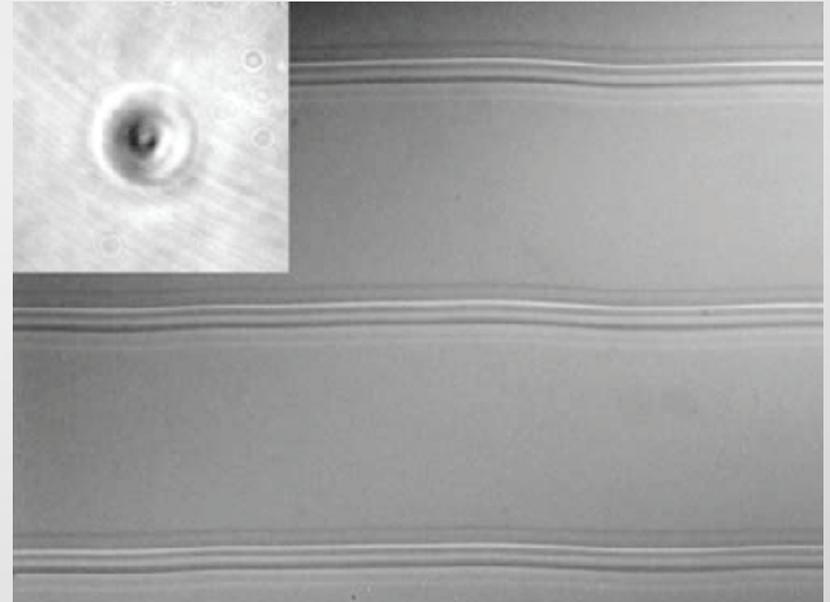
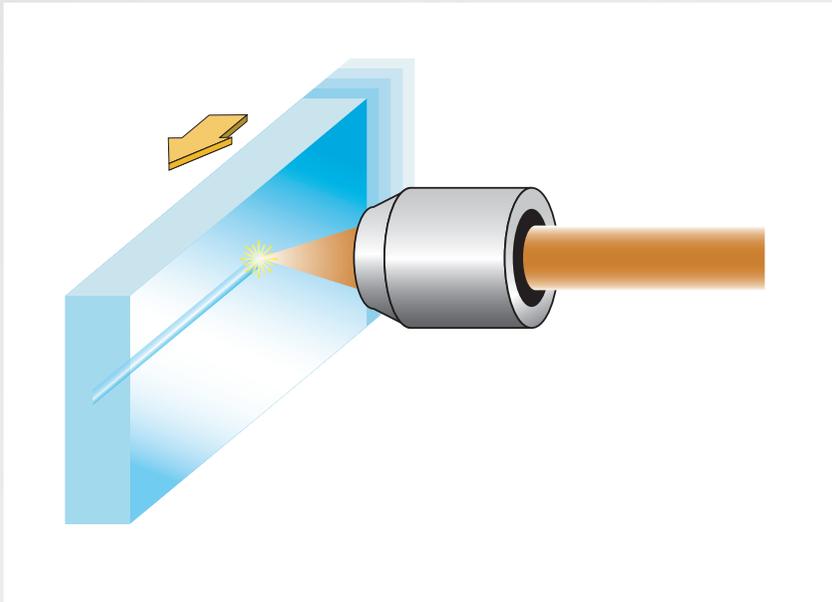
Bulk micromachining

waveguide micromachining



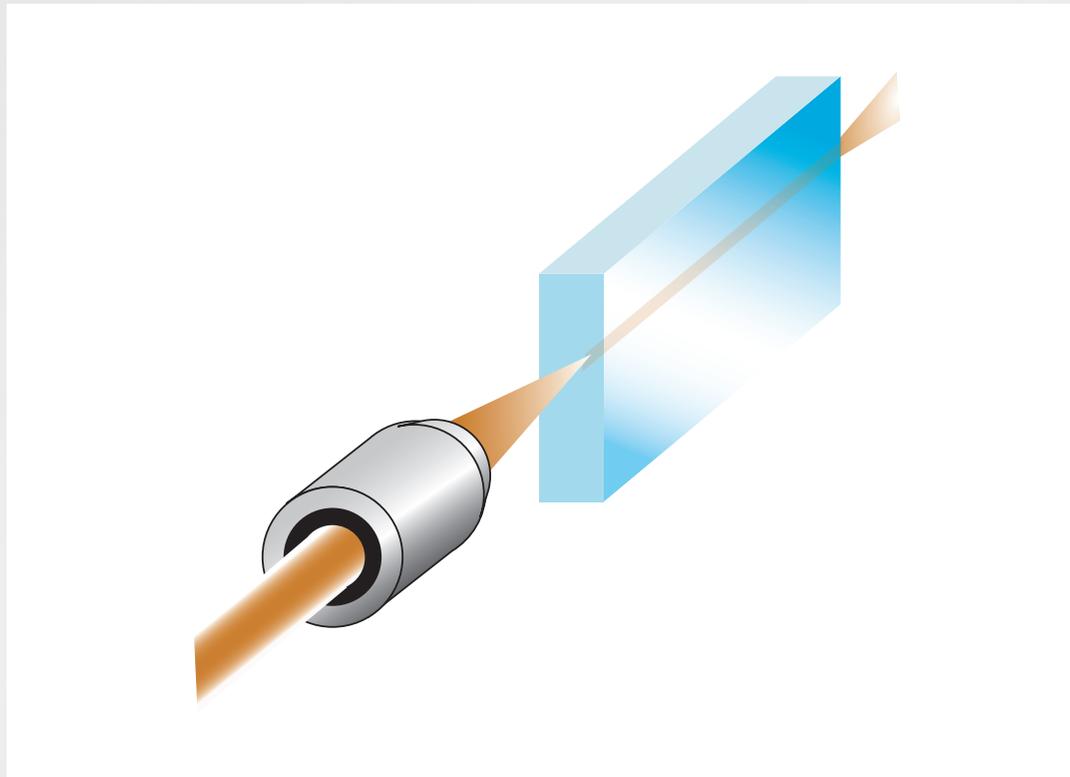
Bulk micromachining

waveguide micromachining



Bulk micromachining

structures guide light



Bulk micromachining

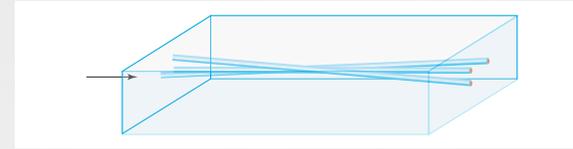
photonic fabrication techniques

	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

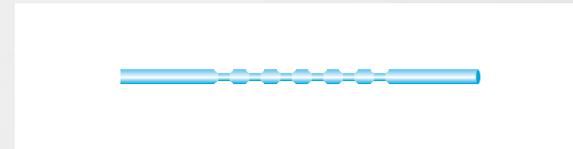
Bulk micromachining

photonic devices

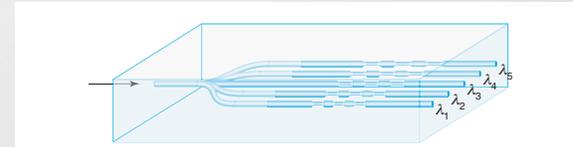
3D splitter



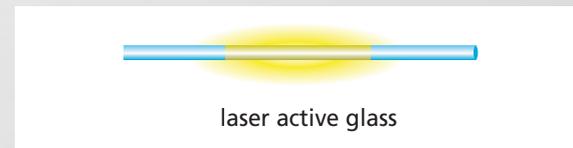
Bragg grating



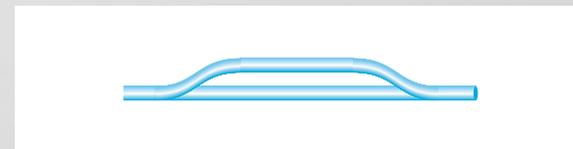
demultiplexer



amplifier

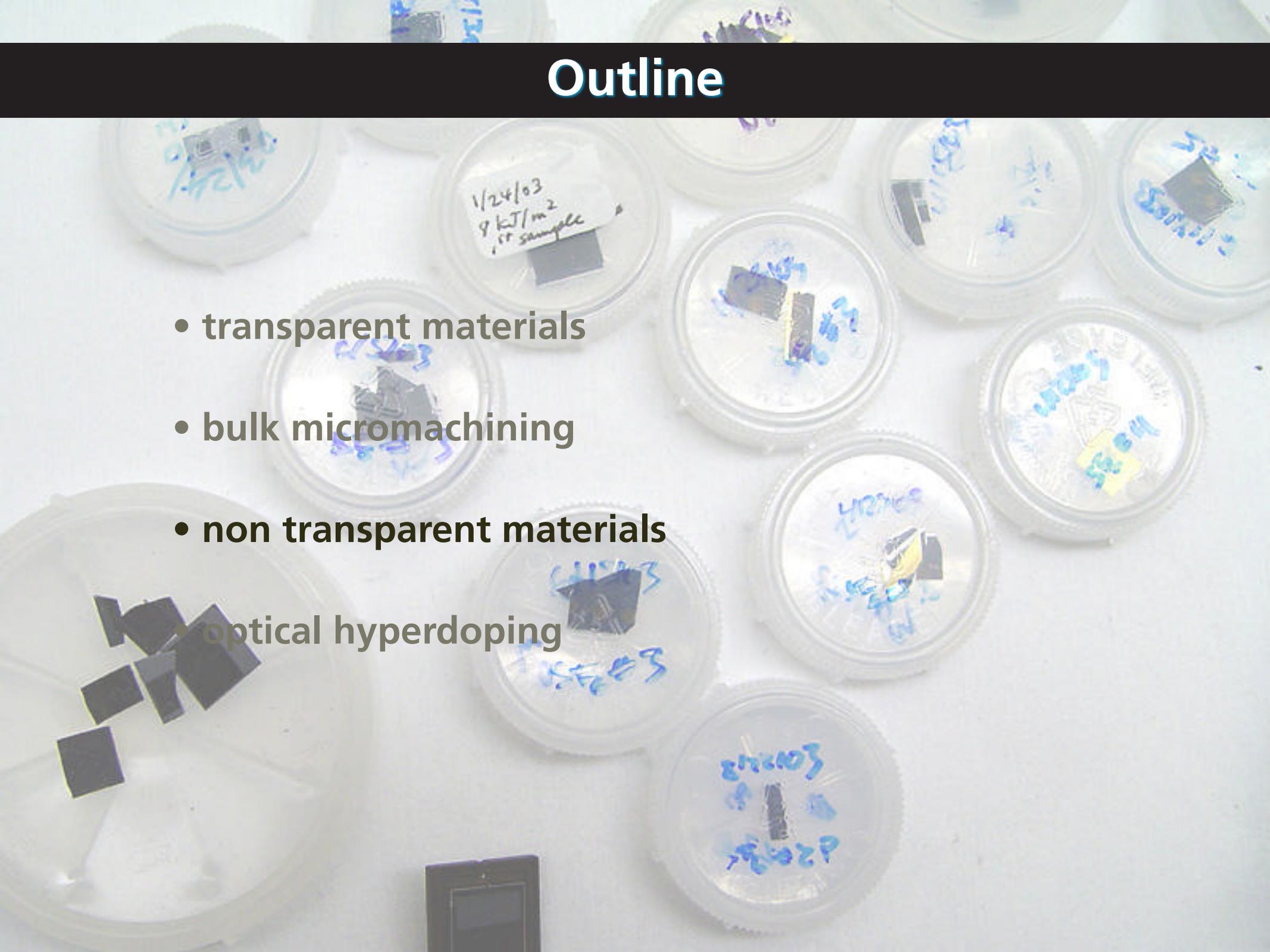


interferometer

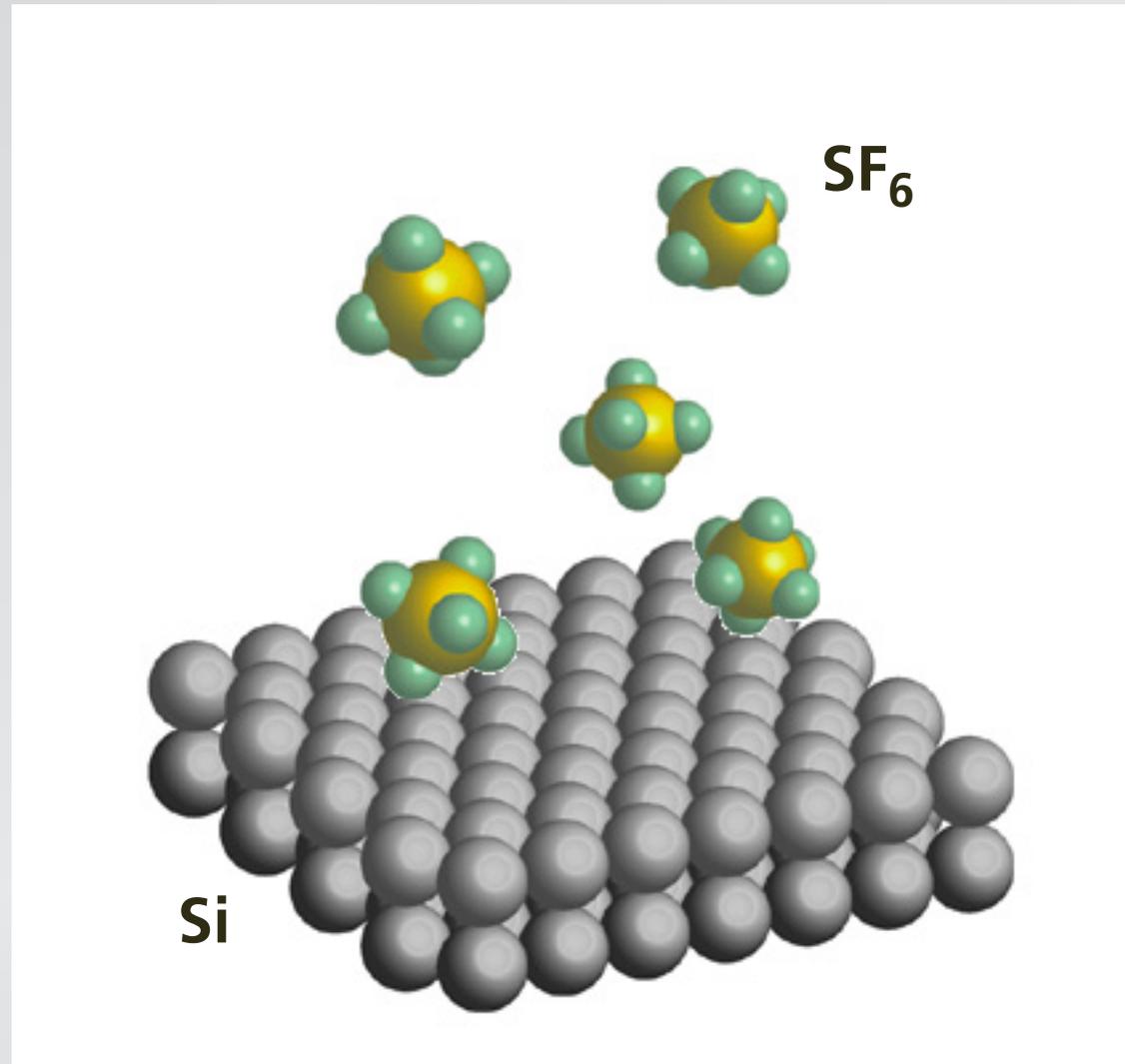


Outline

- transparent materials
- bulk micromachining
- non transparent materials
- optical hyperdoping

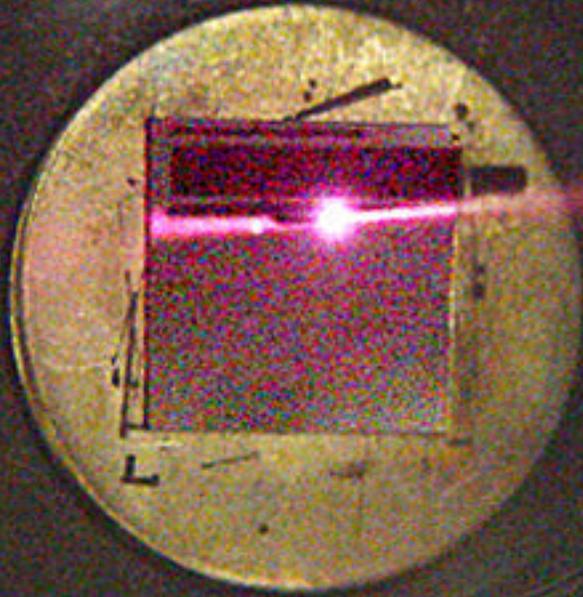


Nontransparent materials



irradiate with 100-fs 10 kJ/m² pulses

Nontransparent materials

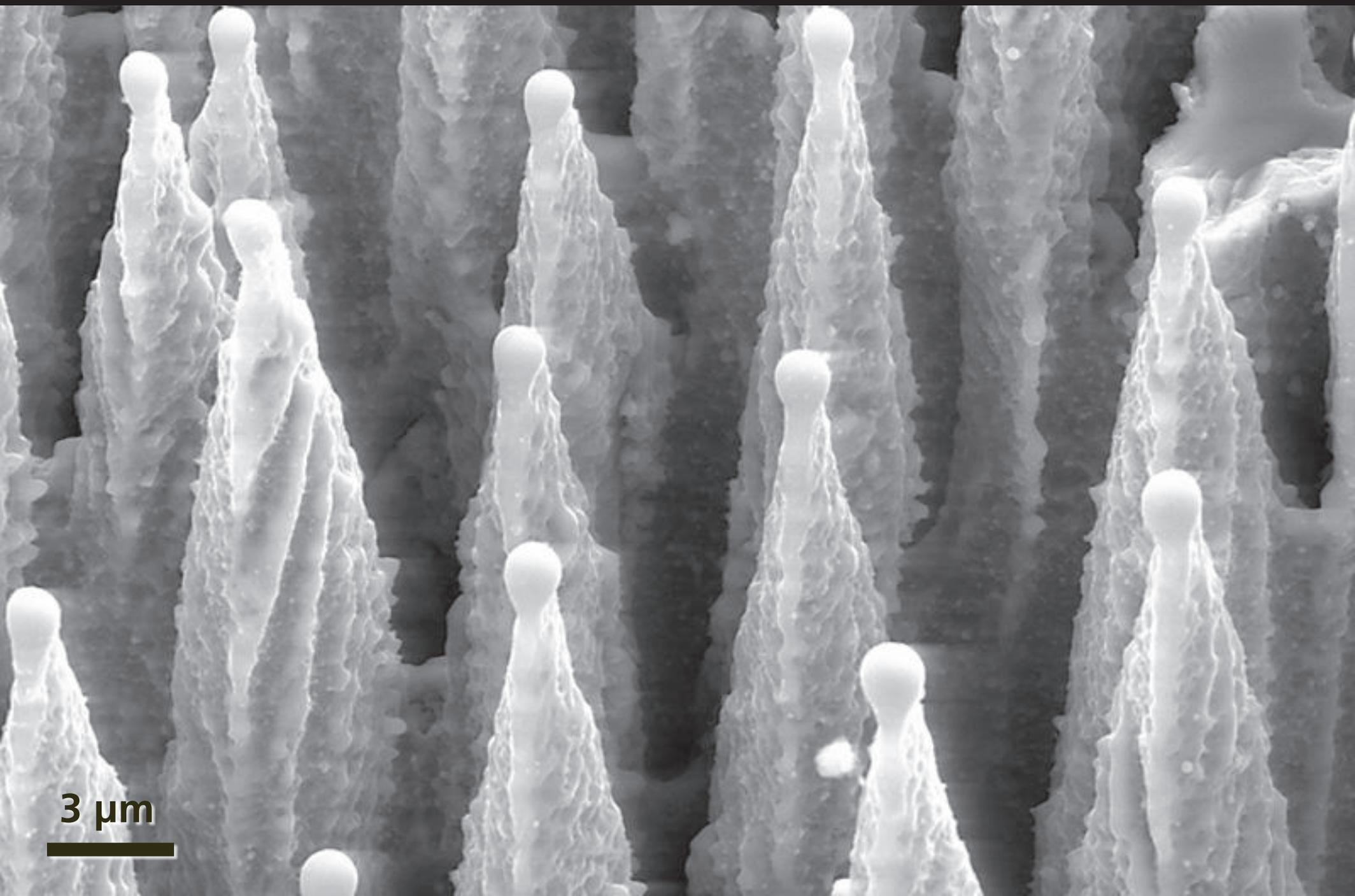


Nontransparent materials



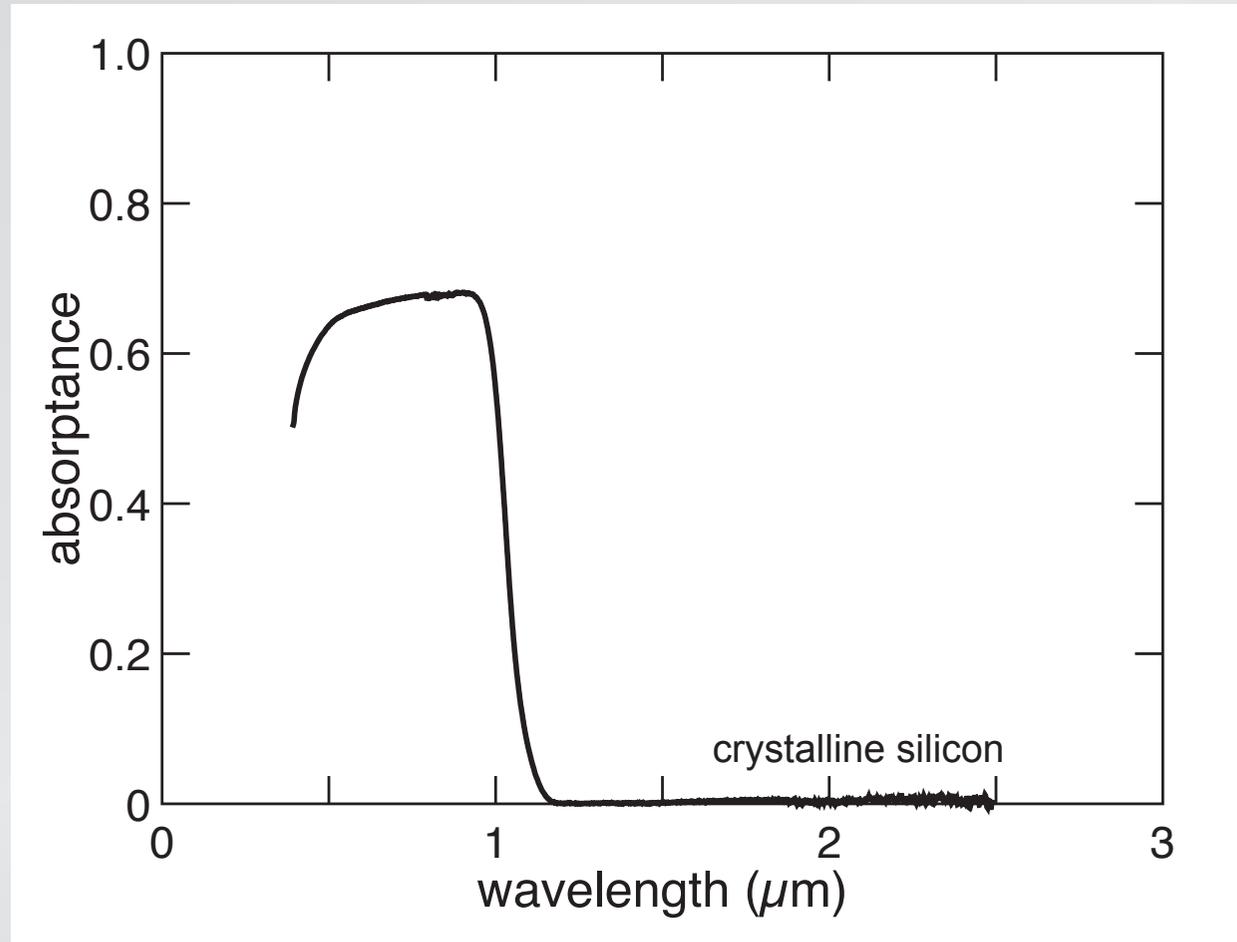
"black silicon"

Introduction



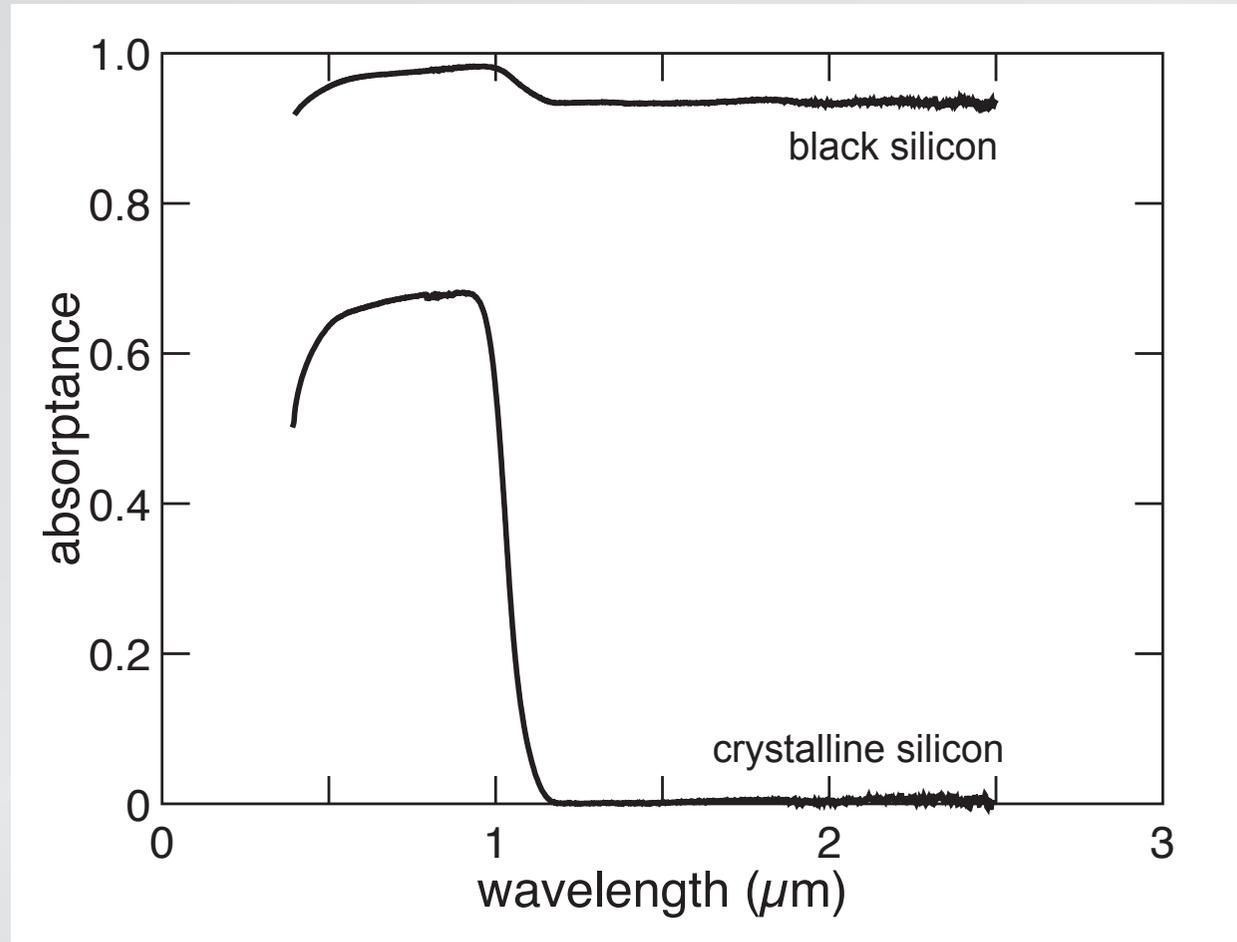
Introduction

absorptance ($1 - R_{int} - T_{int}$)

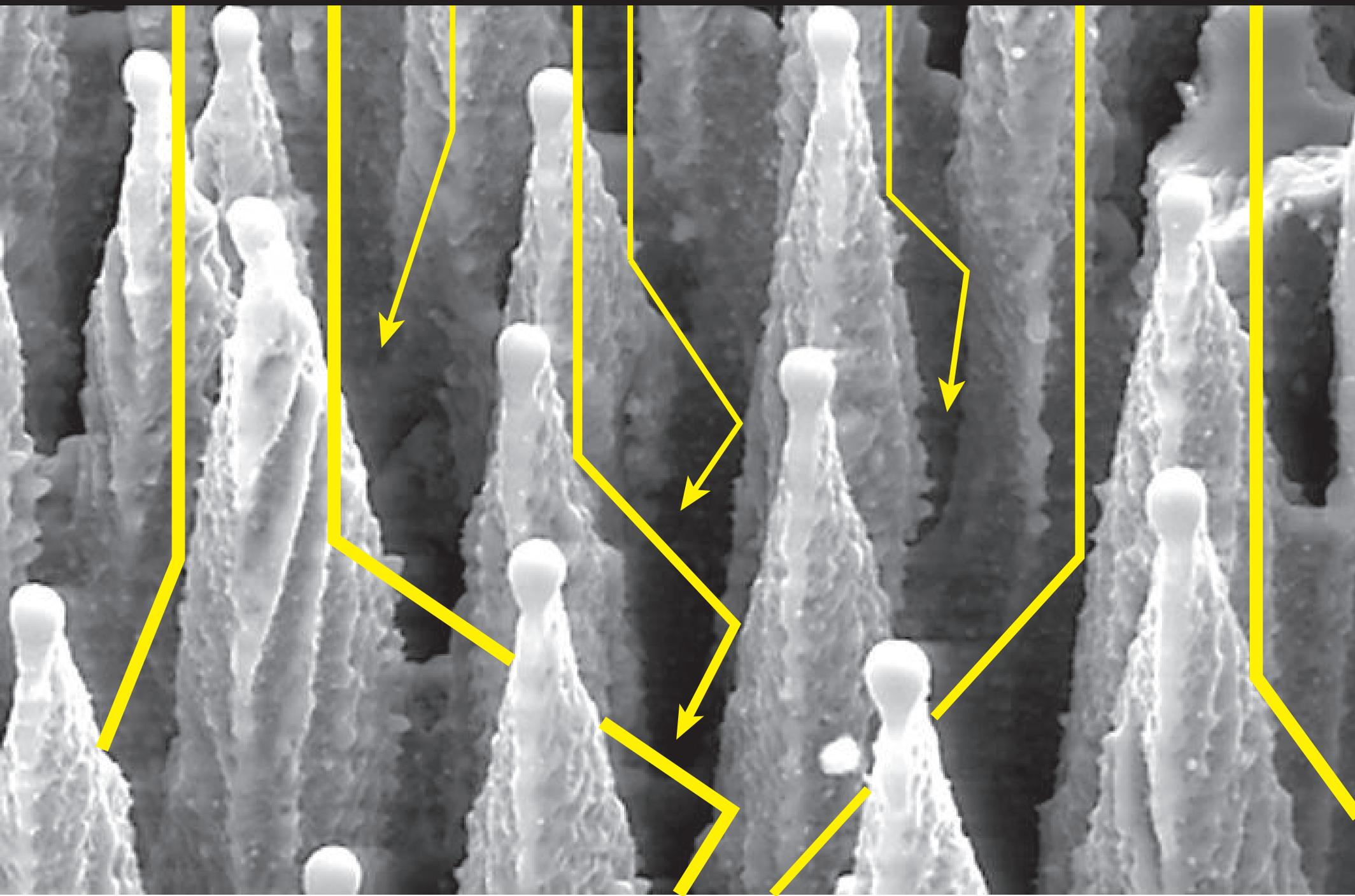


Nontransparent materials

absorptance $(1 - R_{int} - T_{int})$

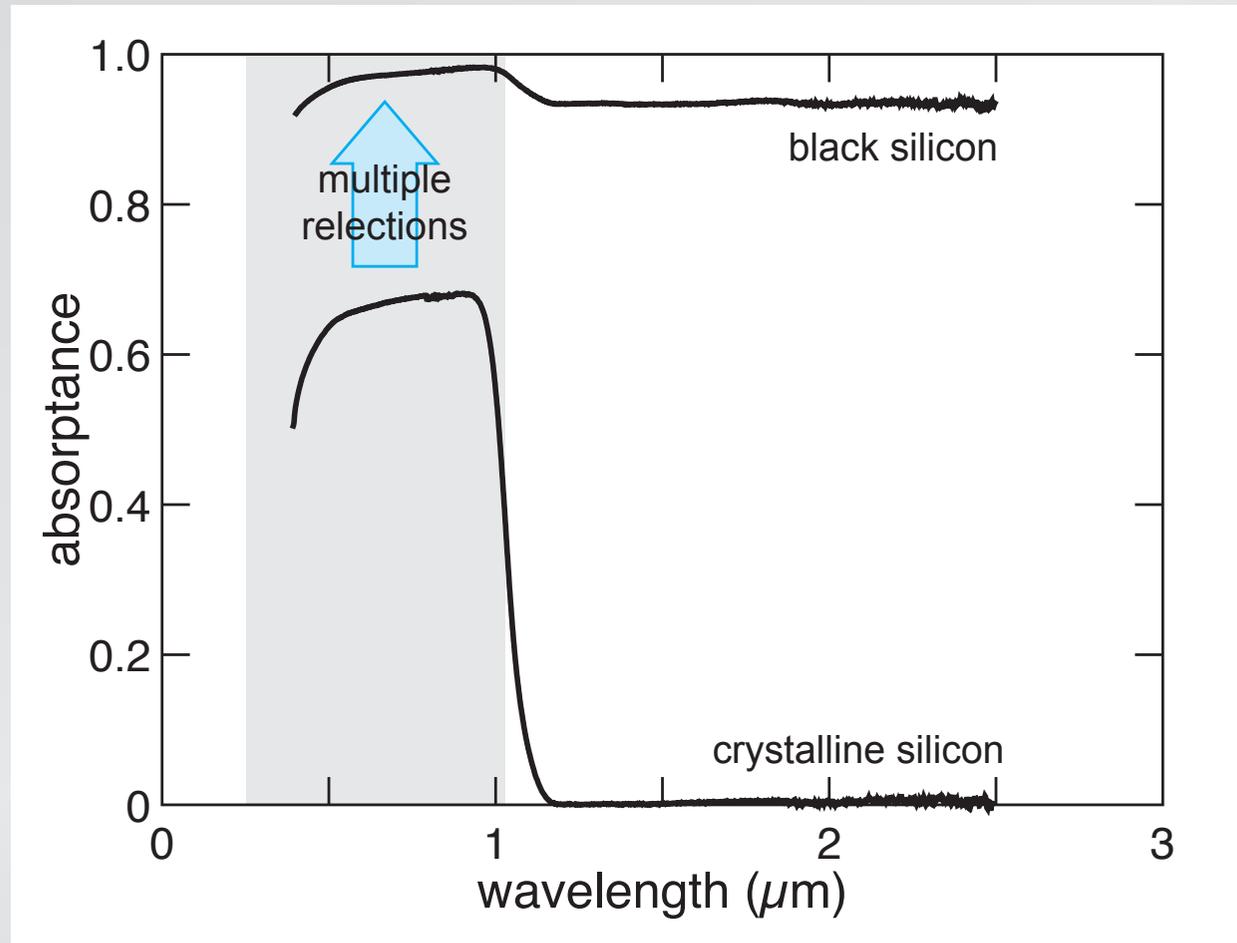


Introduction



Nontransparent materials

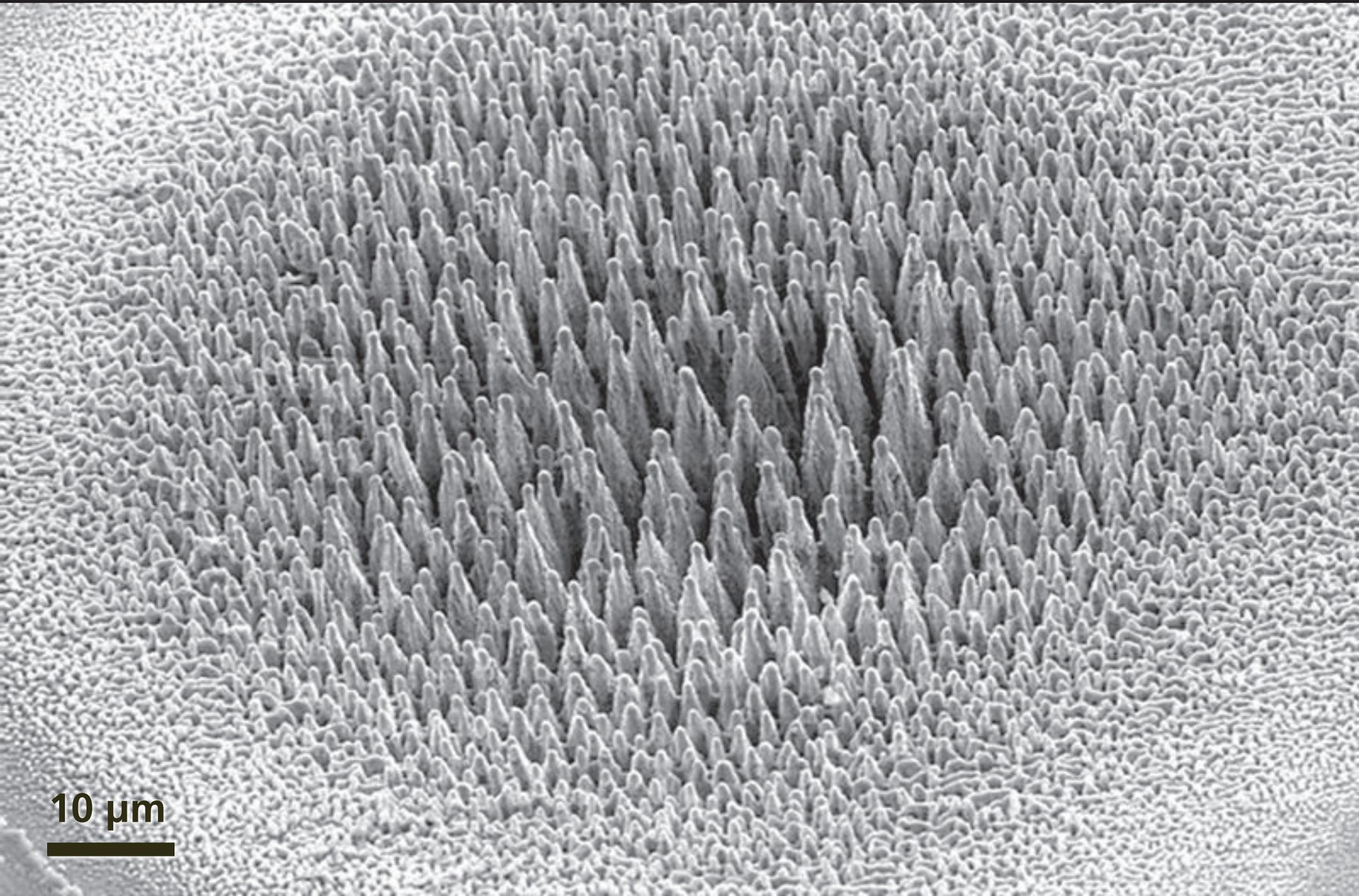
$$\text{absorptance } (1 - R_{int} - T_{int})$$



Nontransparent materials

band structure changes: defects and/or impurities

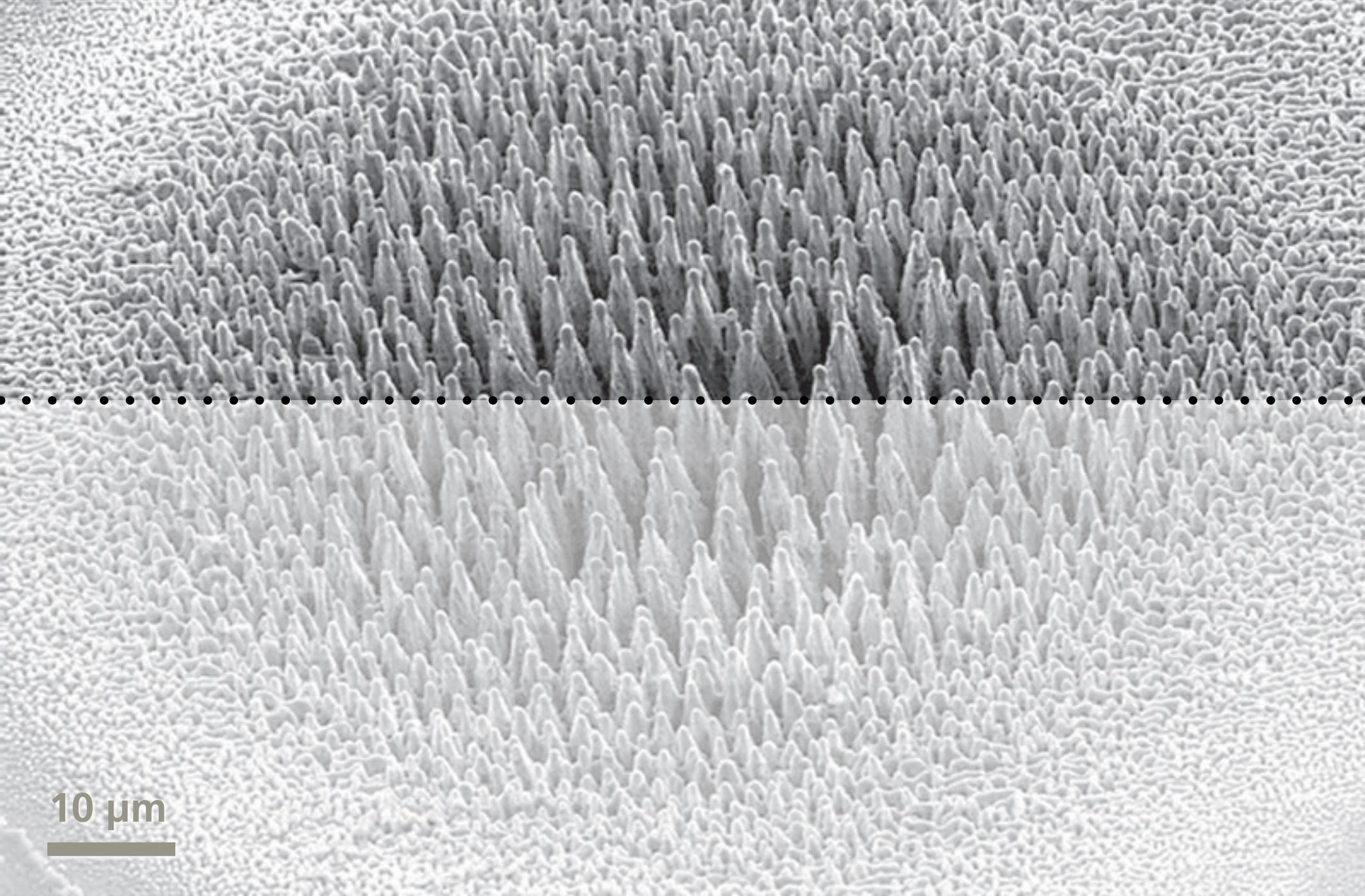
Nontransparent materials



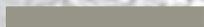
10 μm



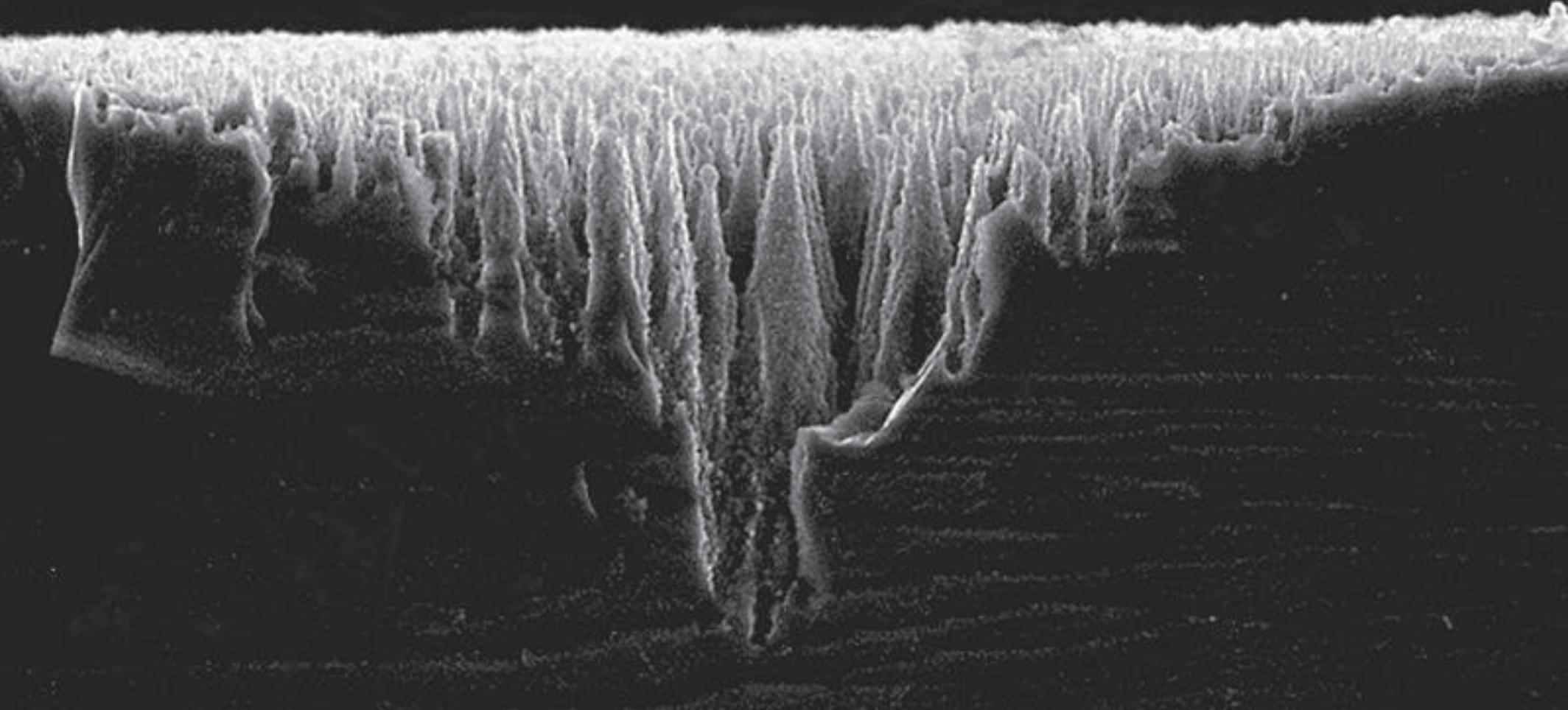
Nontransparent materials



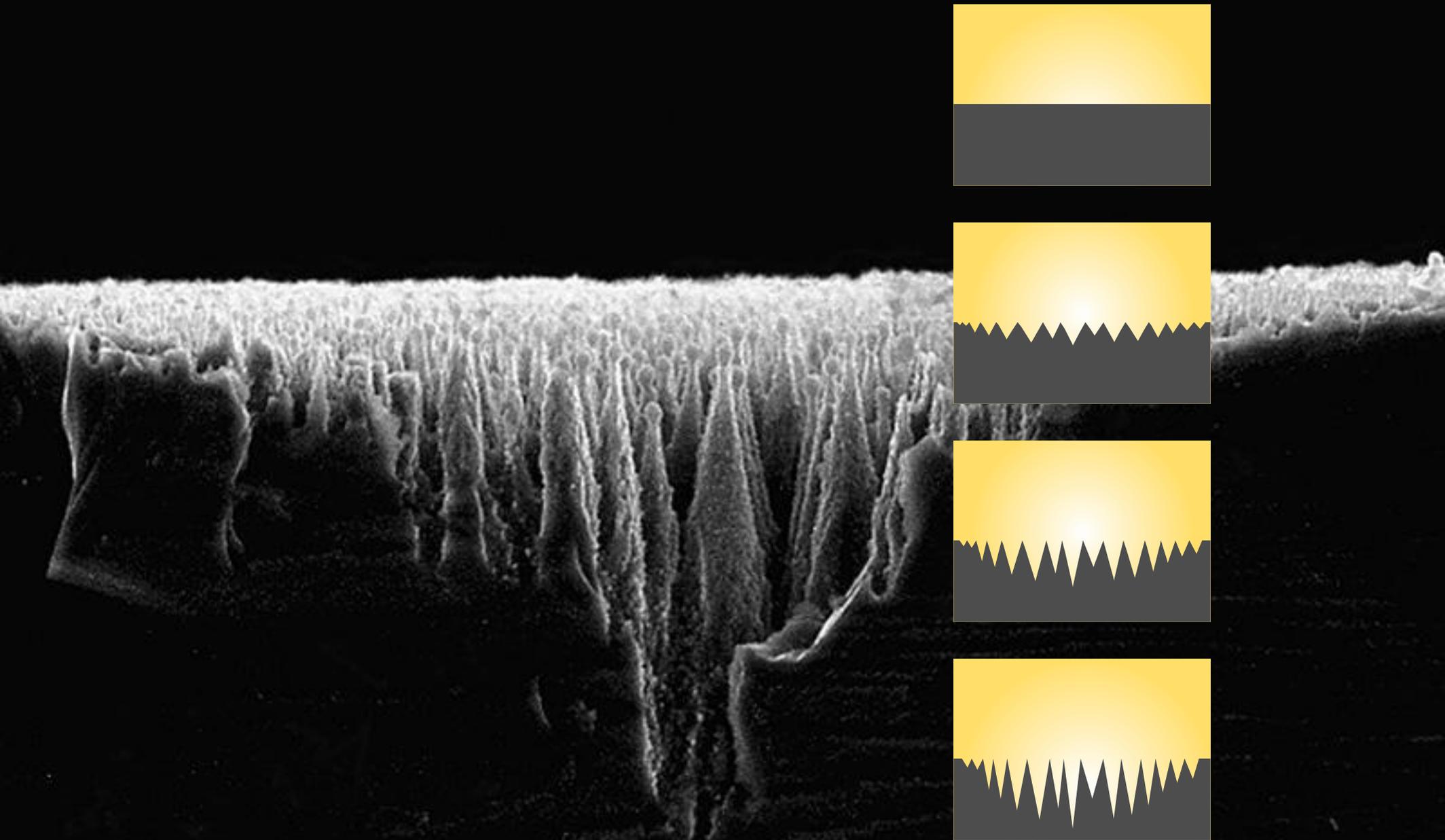
10 μm



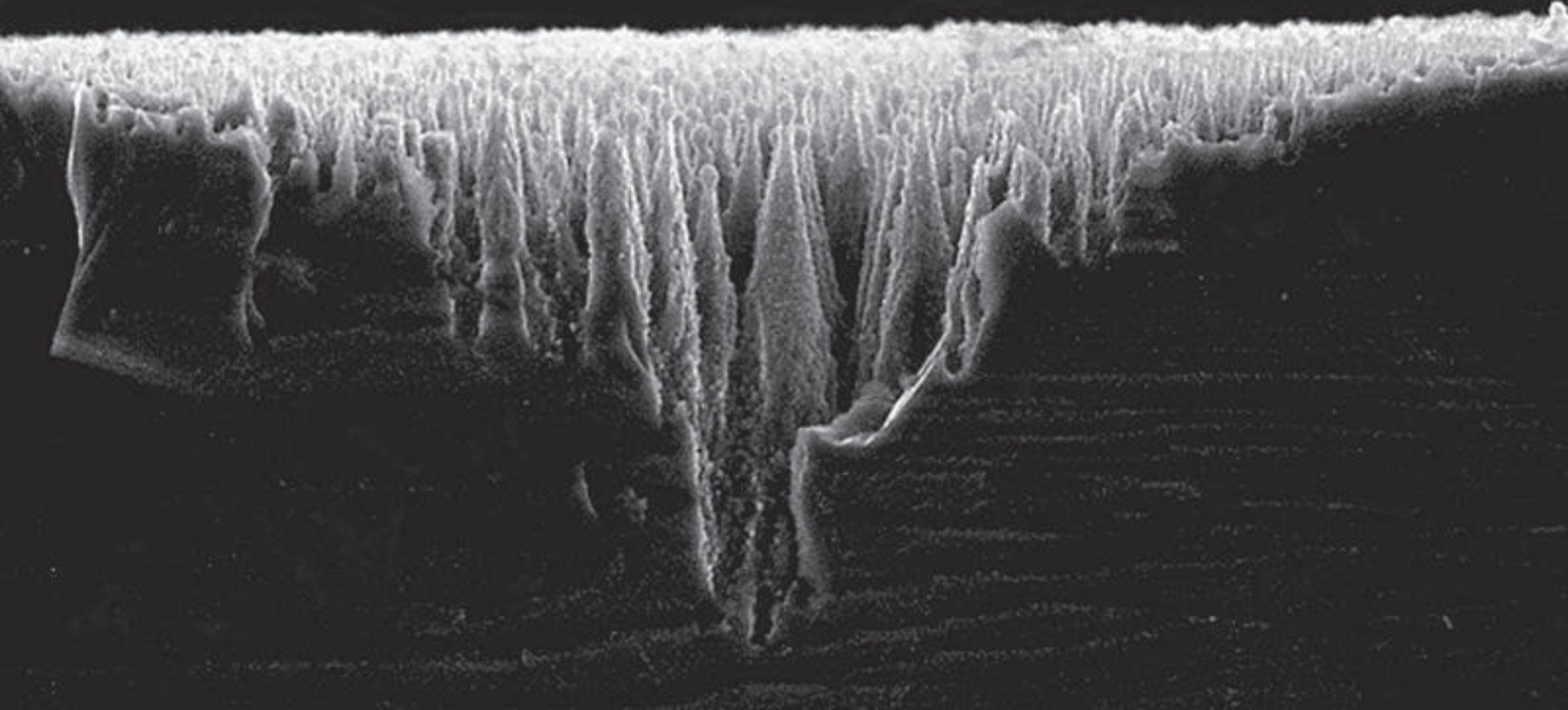
Nontransparent materials



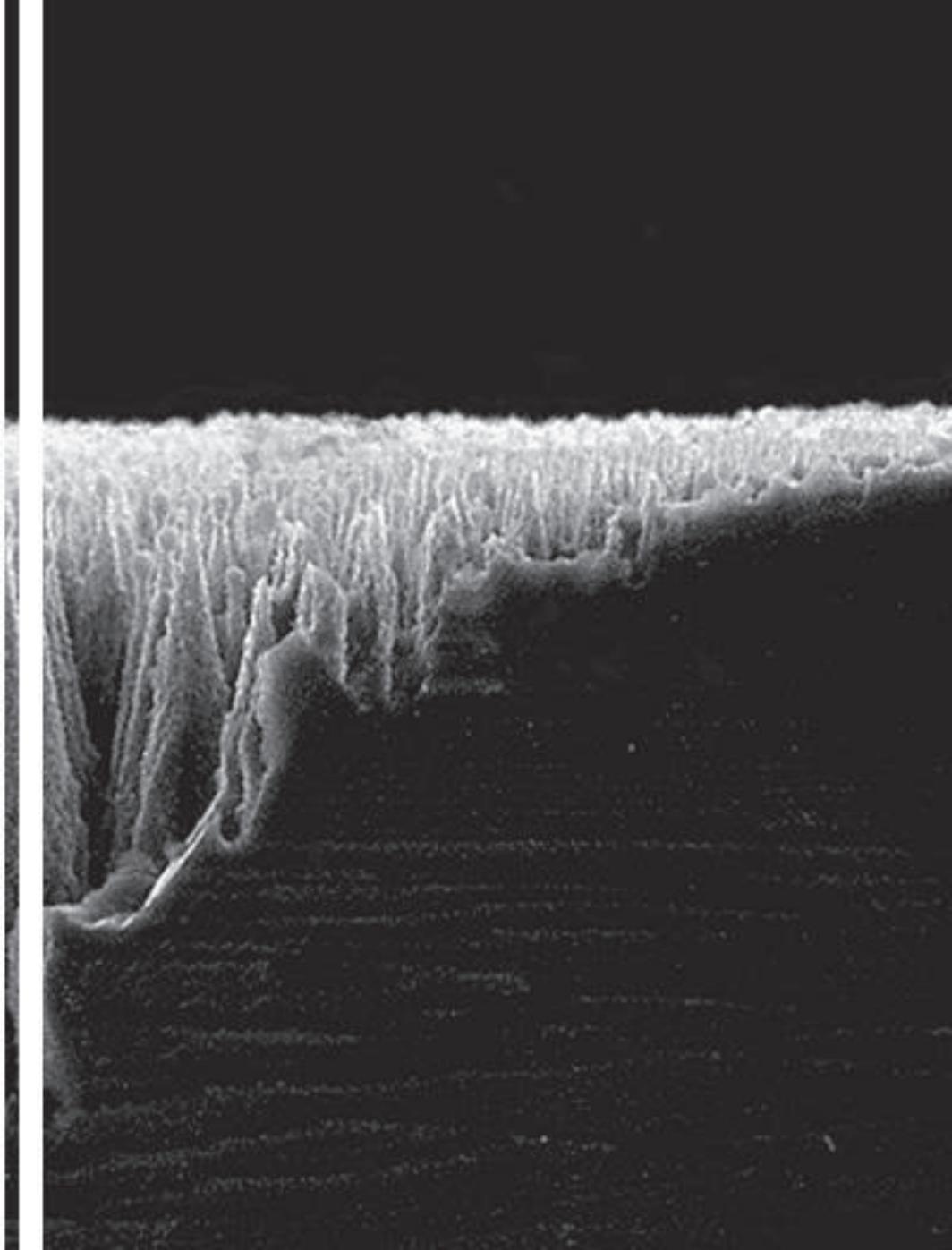
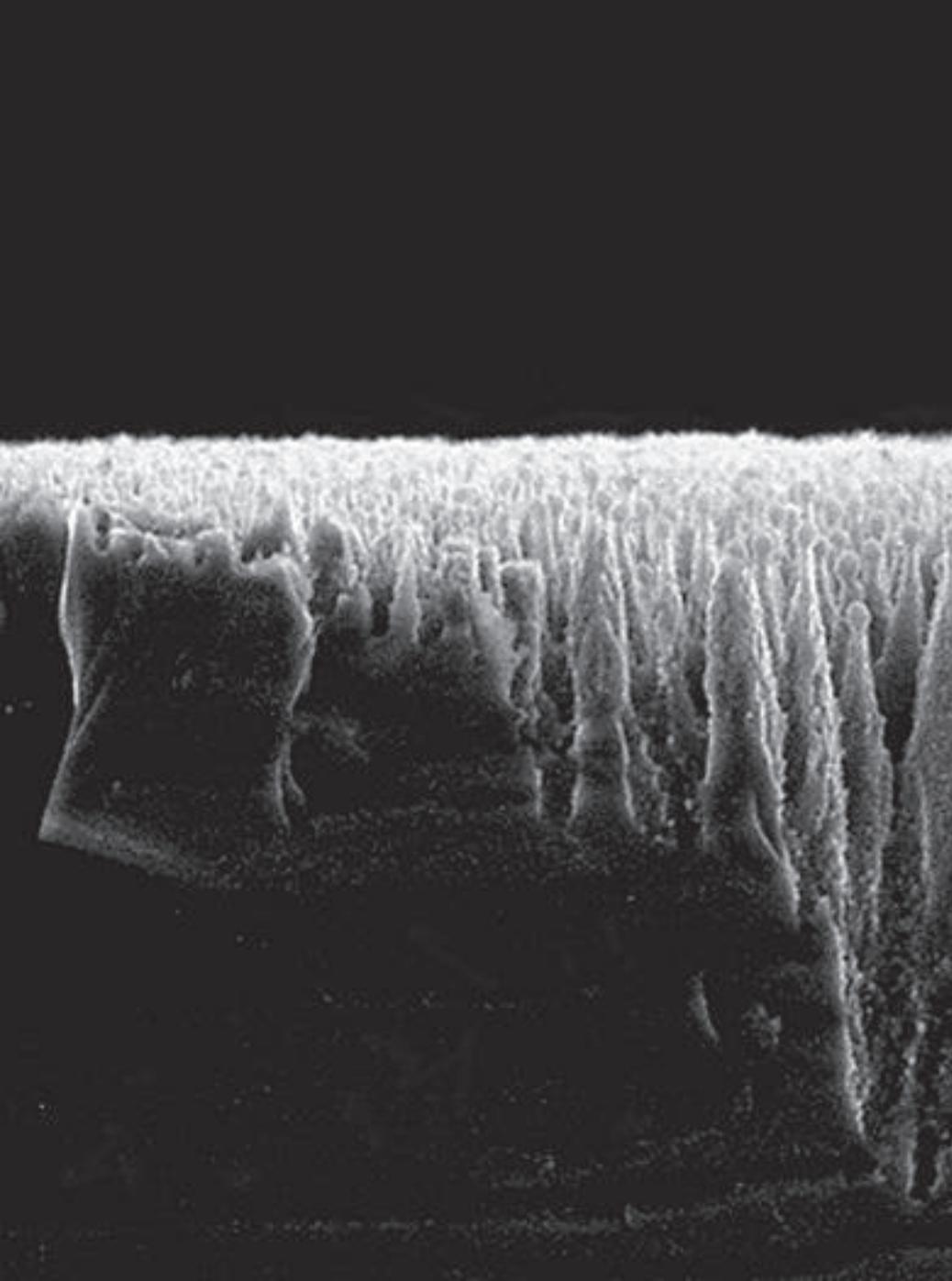
Nontransparent materials



Nontransparent materials

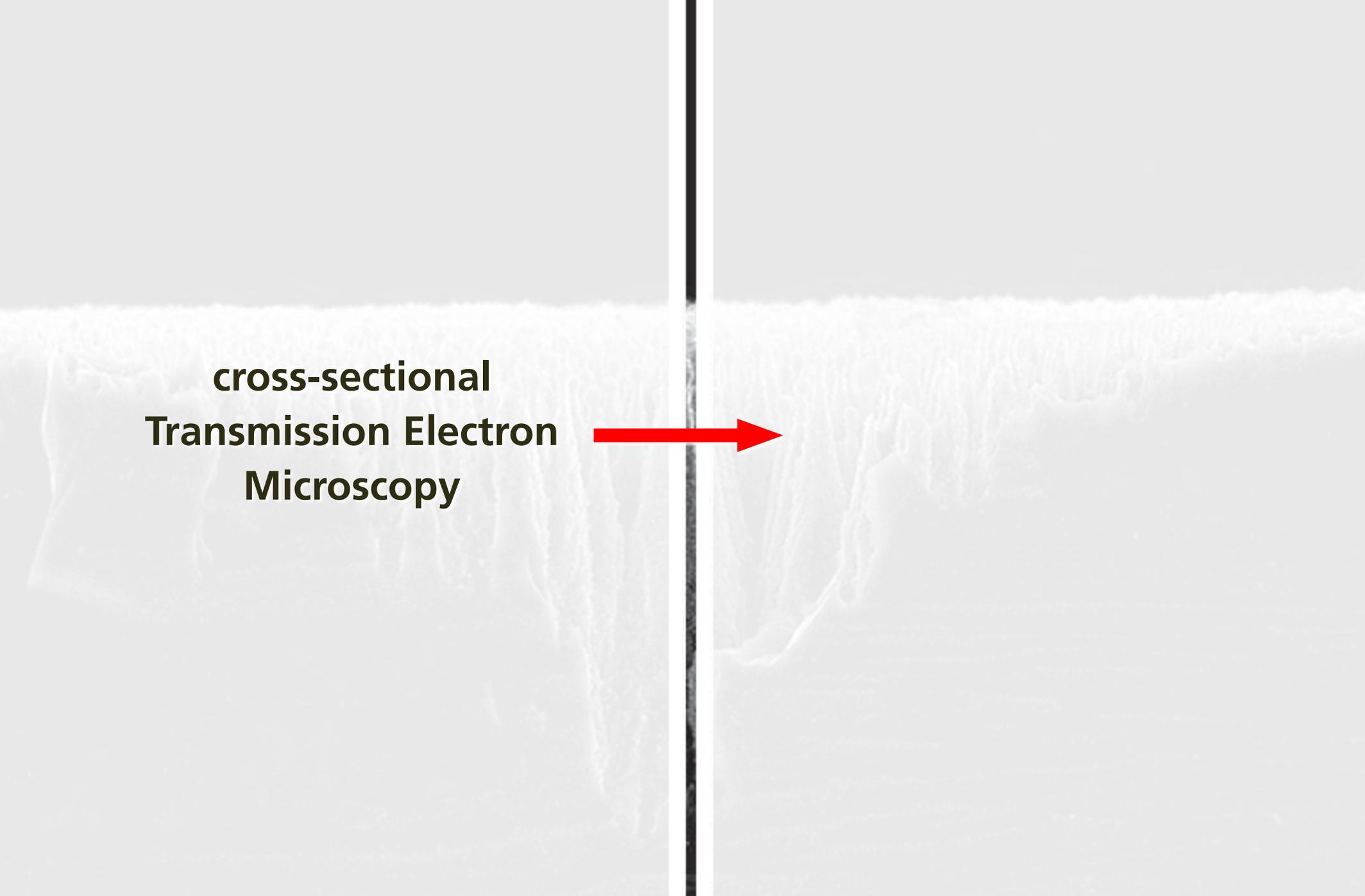


Nontransparent materials



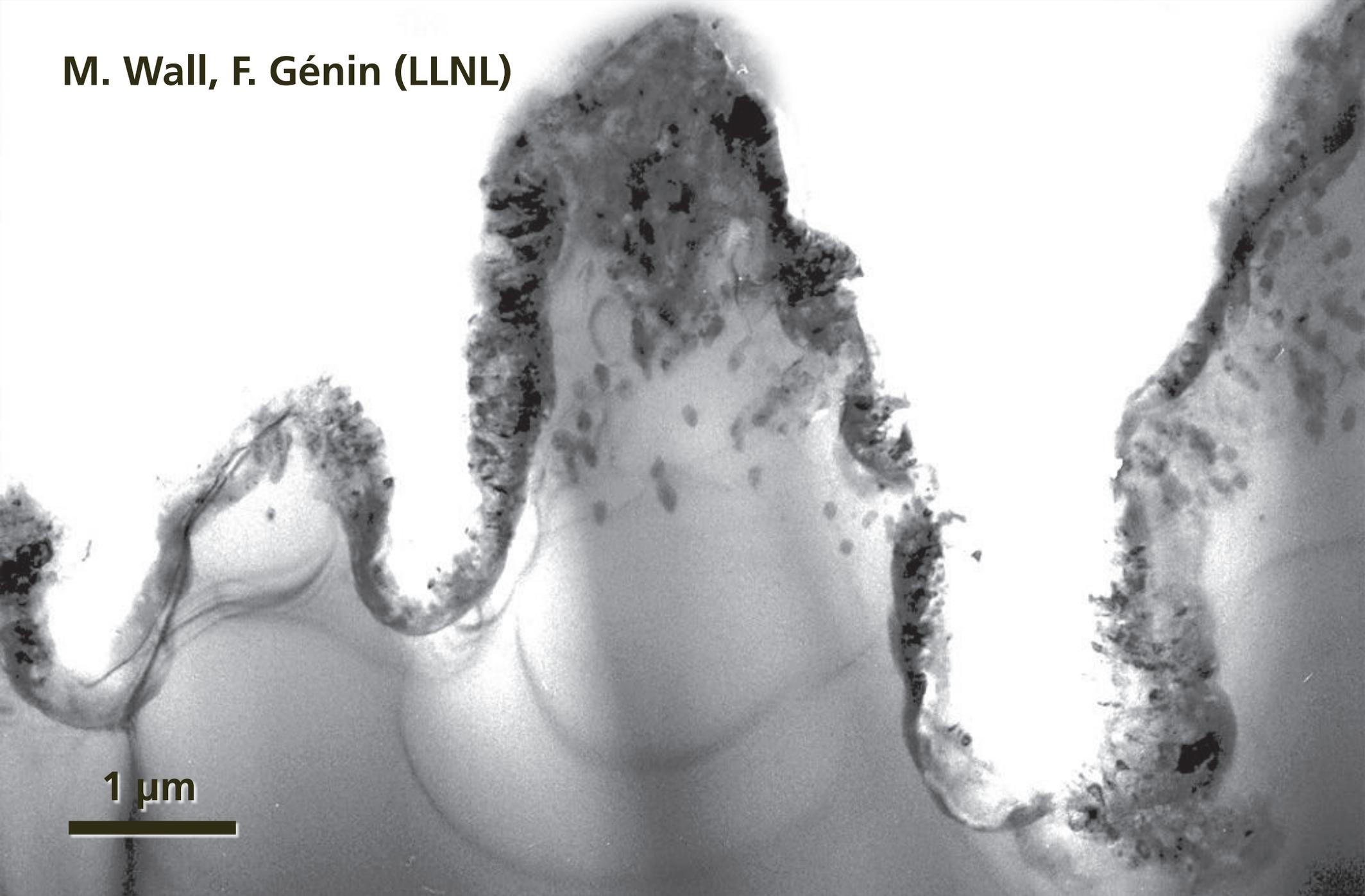
Nontransparent materials

**cross-sectional
Transmission Electron
Microscopy**



Nontransparent materials

M. Wall, F. Génin (LLNL)

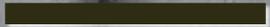


Nontransparent materials

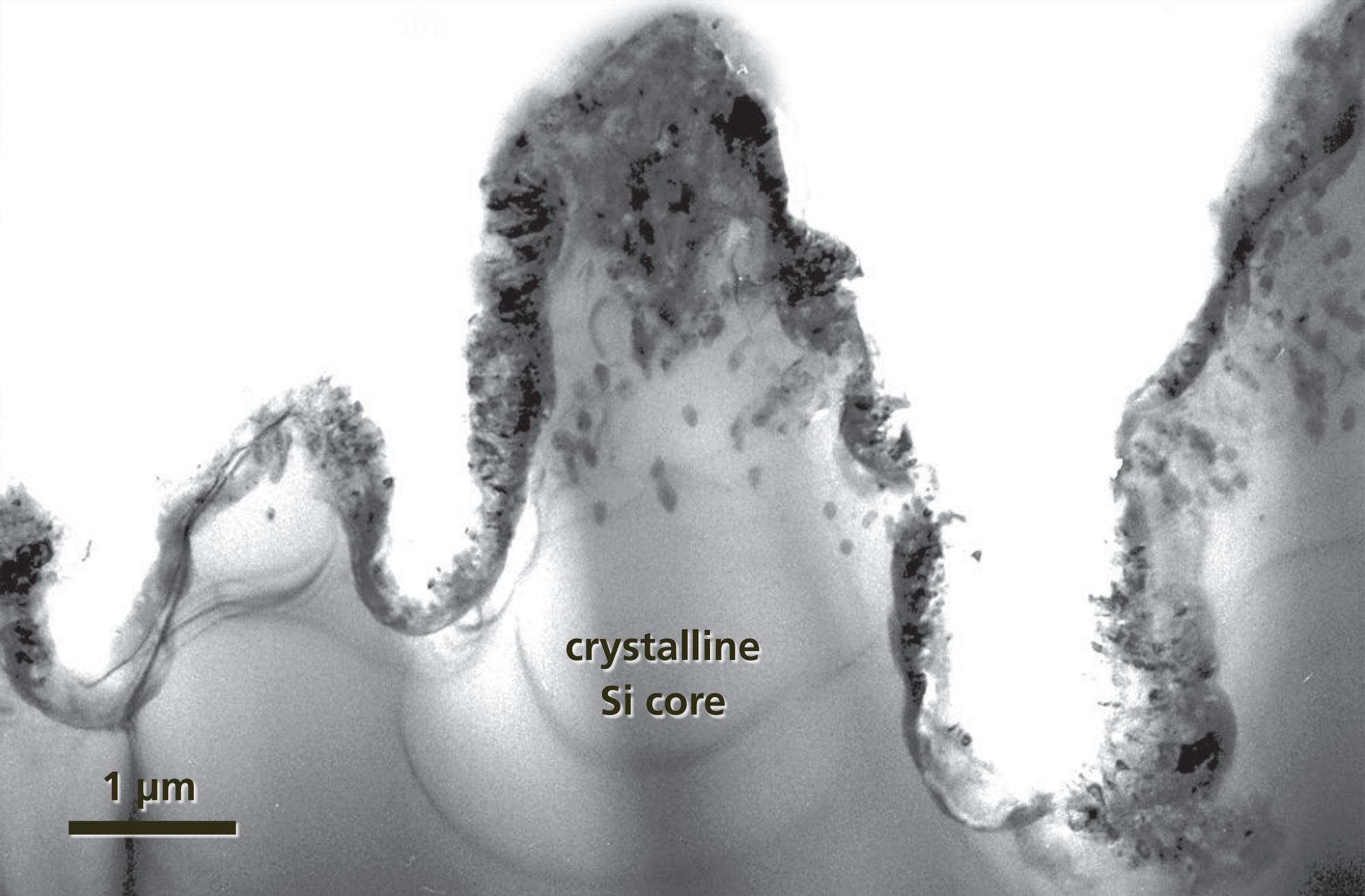
disordered
surface layer



1 μm

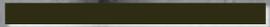


Nontransparent materials

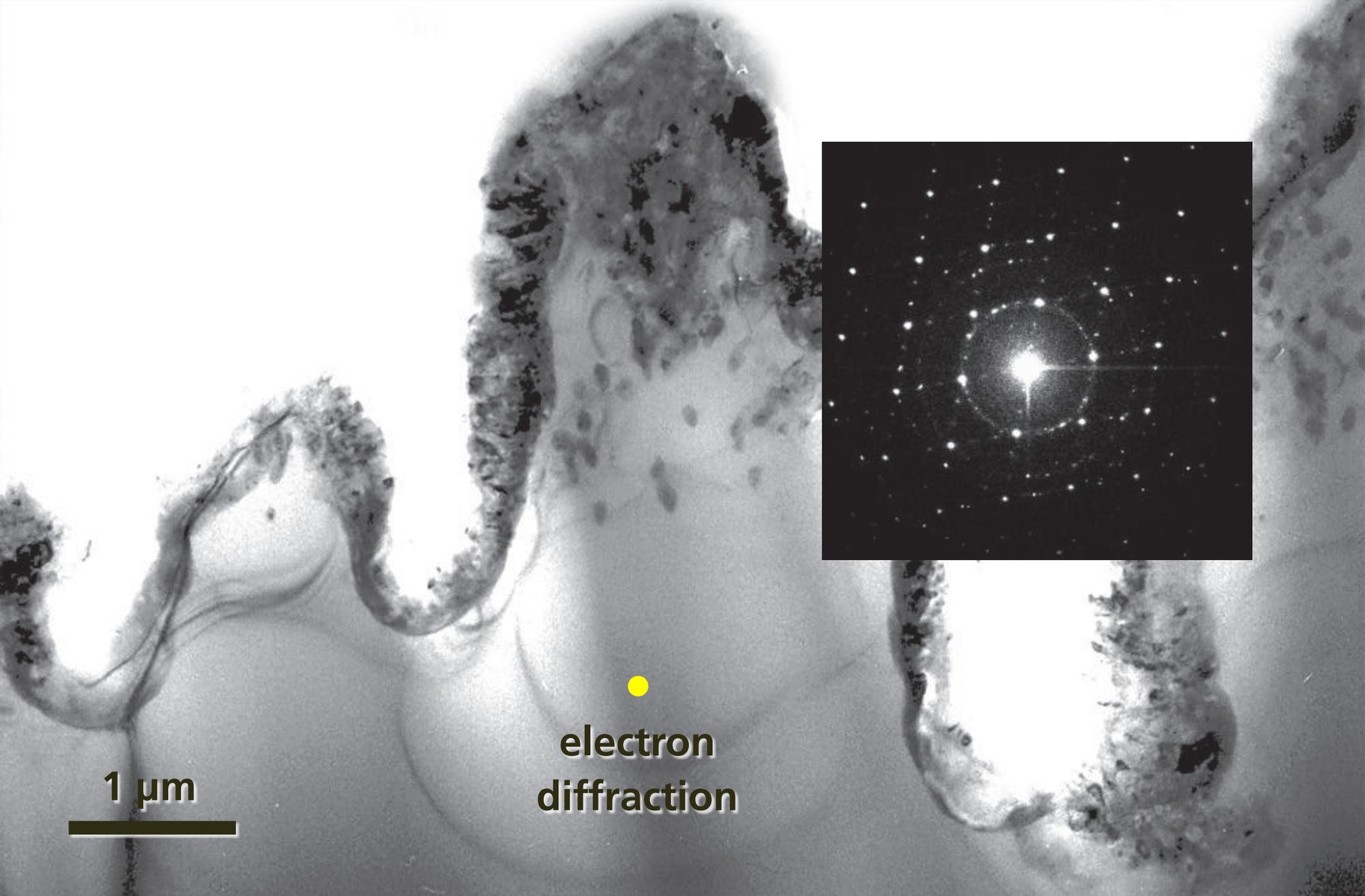


crystalline
Si core

1 μm



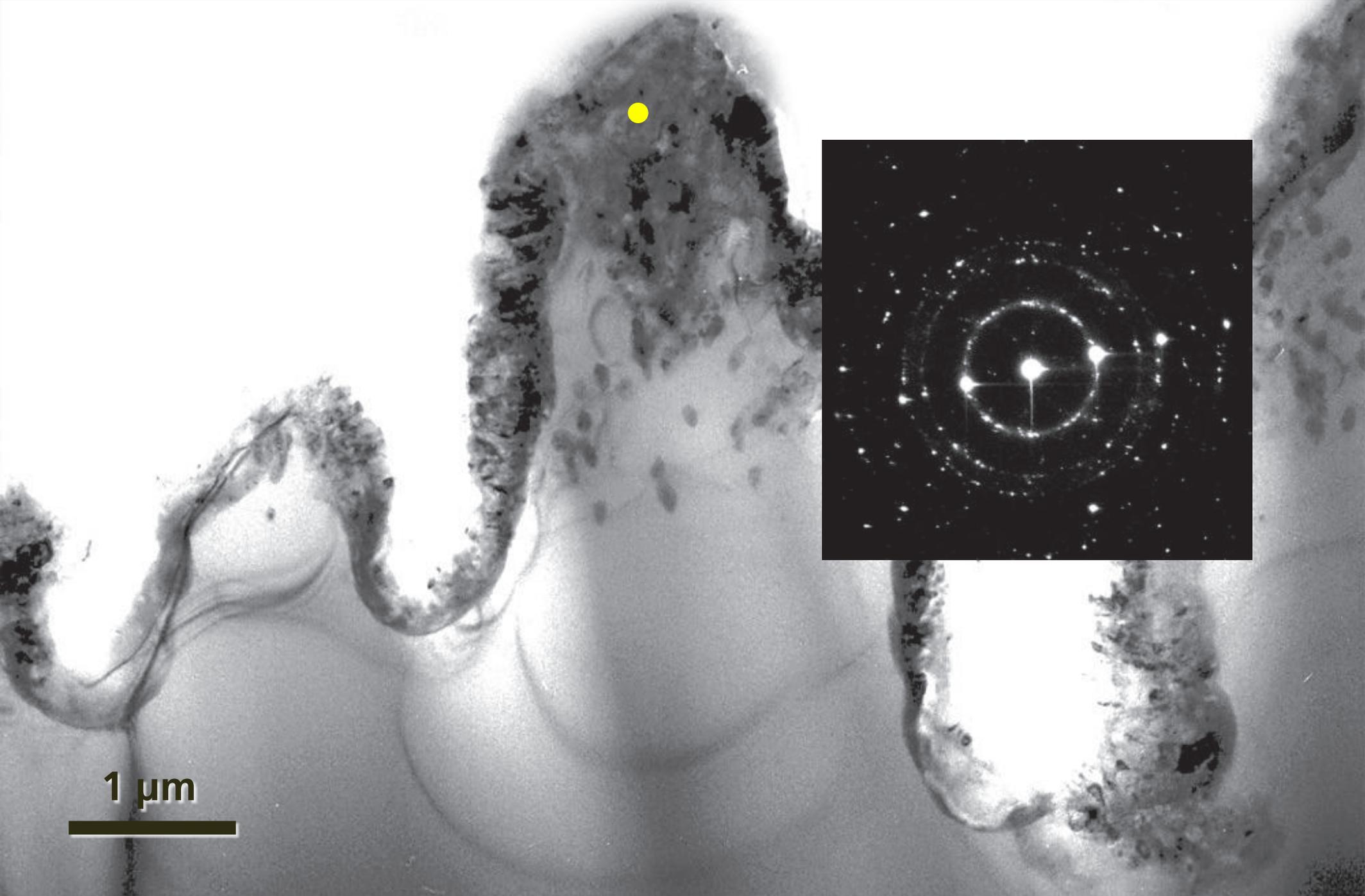
Nontransparent materials



1 μm

●
electron
diffraction

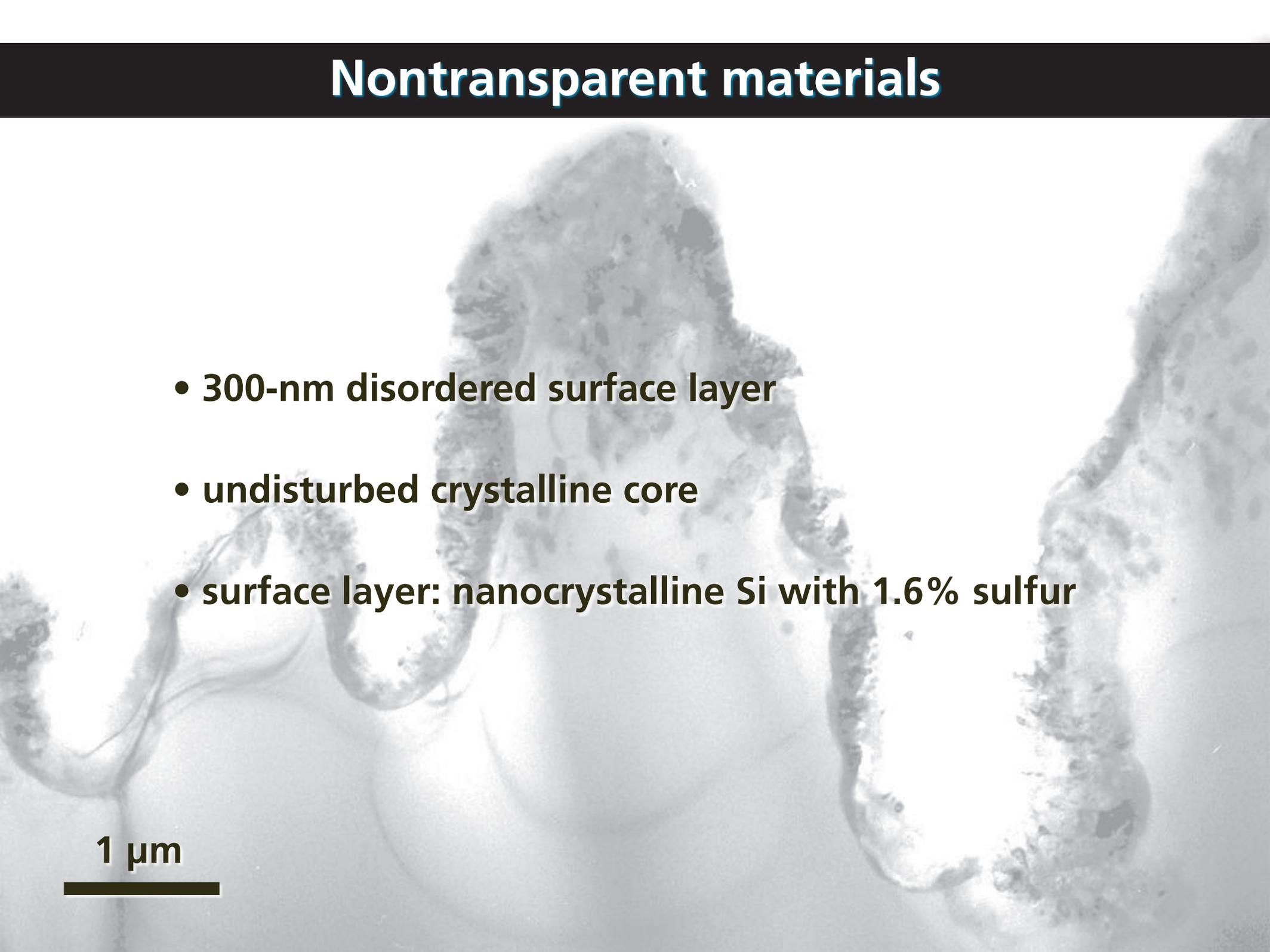
Nontransparent materials



Nontransparent materials

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

1 μm

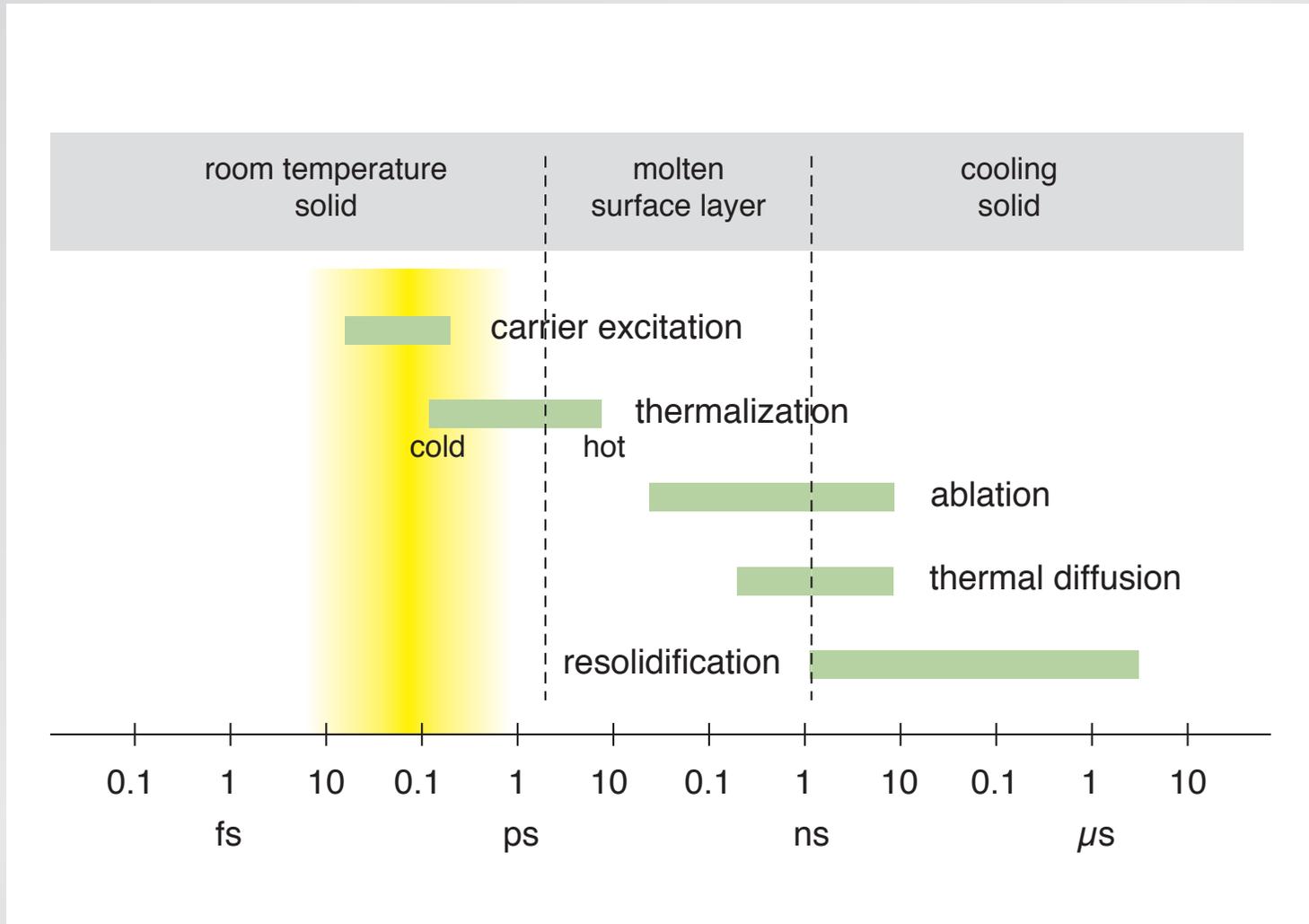
A grayscale micrograph showing a material with a disordered surface layer and a crystalline core. The surface layer is approximately 300 nm thick and contains nanocrystalline Si with 1.6% sulfur. The core is undisturbed and crystalline. A scale bar in the bottom left corner indicates 1 μm.

Nontransparent materials

two processes: melting and ablation

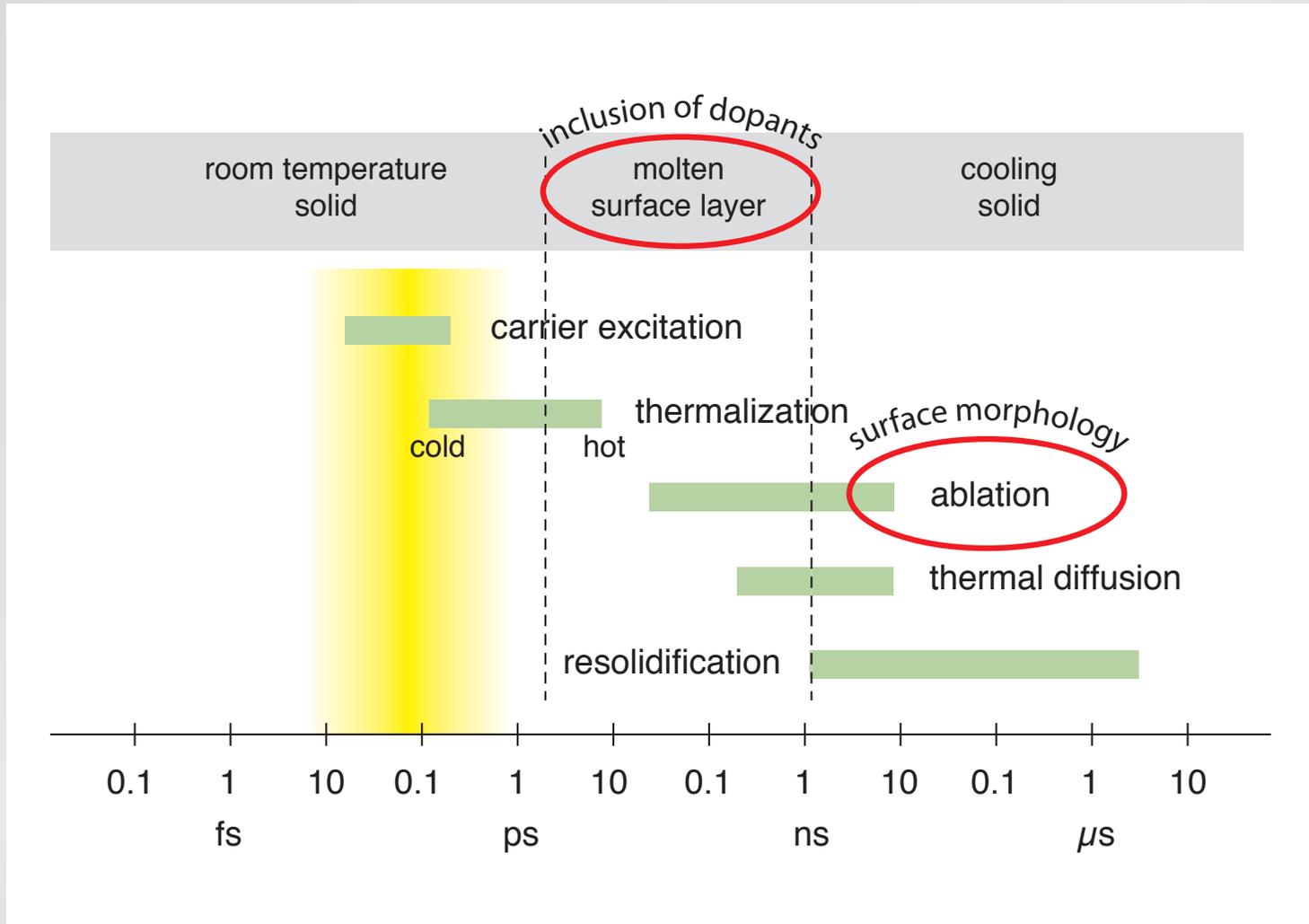
Nontransparent materials

relevant time scales



Nontransparent materials

relevant time scales



Nontransparent materials

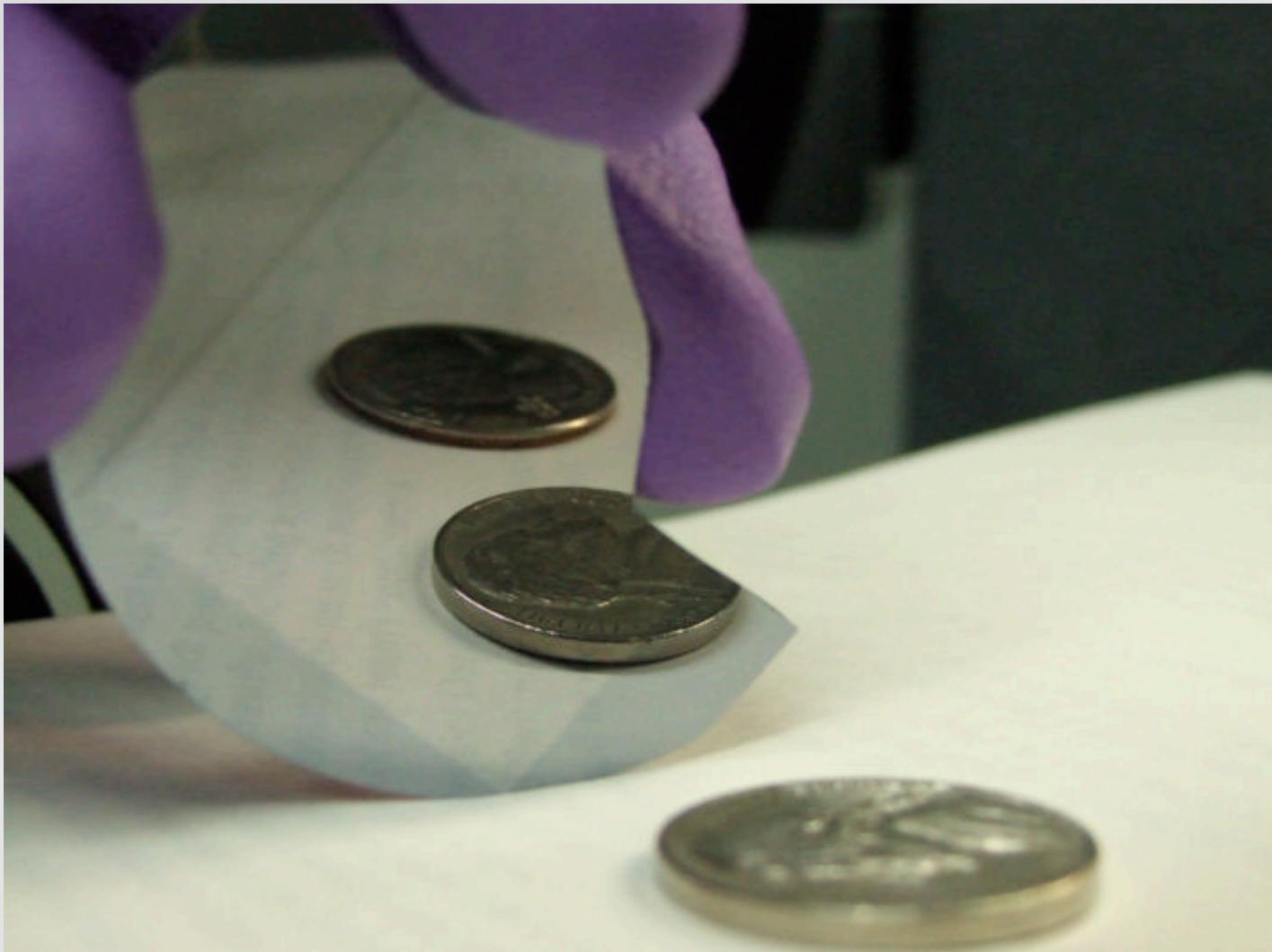
different thresholds:

melting: 1.5 kJ/m^2

ablation: 3.1 kJ/m^2

Nontransparent materials

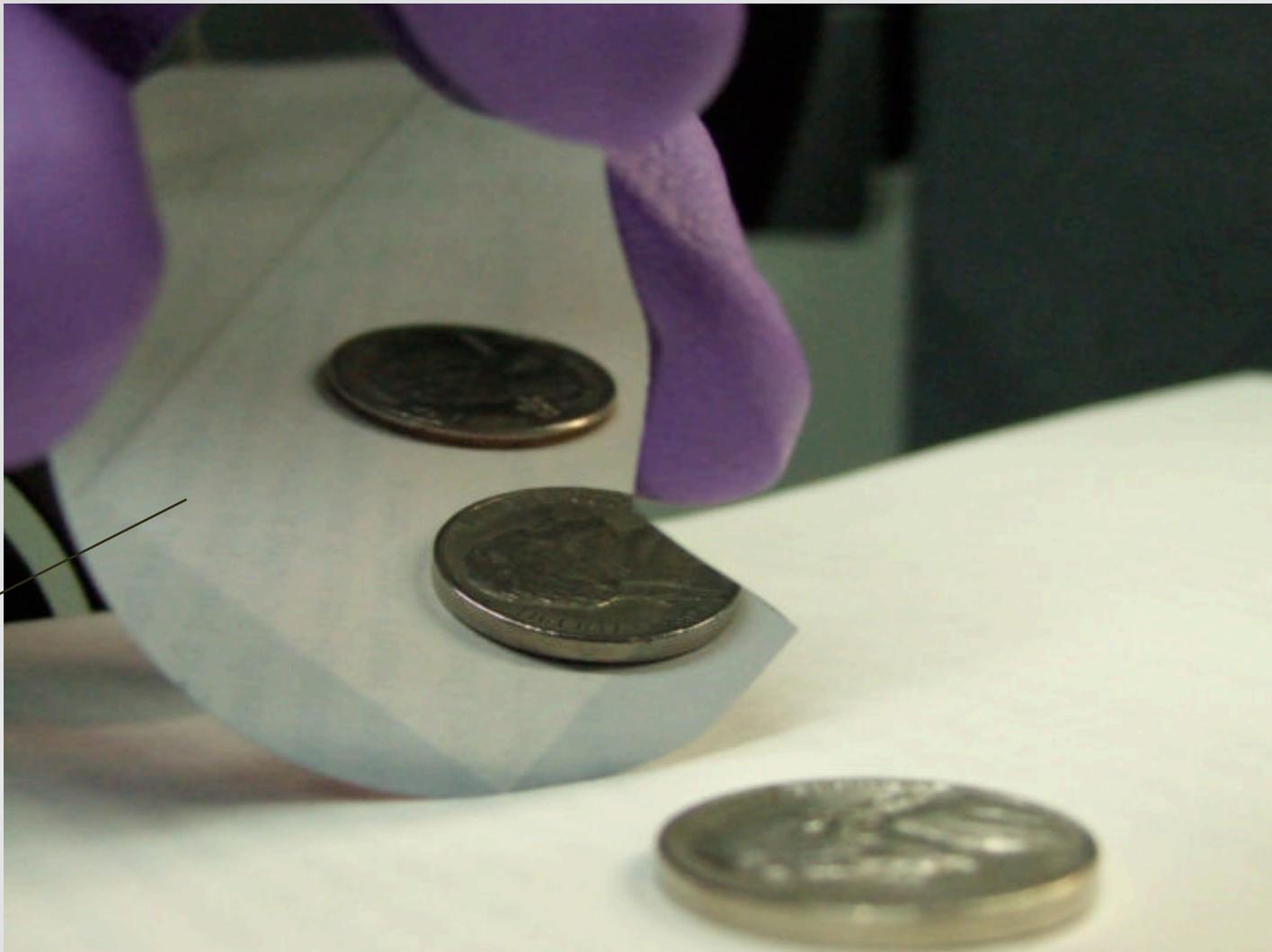
decouple ablation from melting



Nontransparent materials

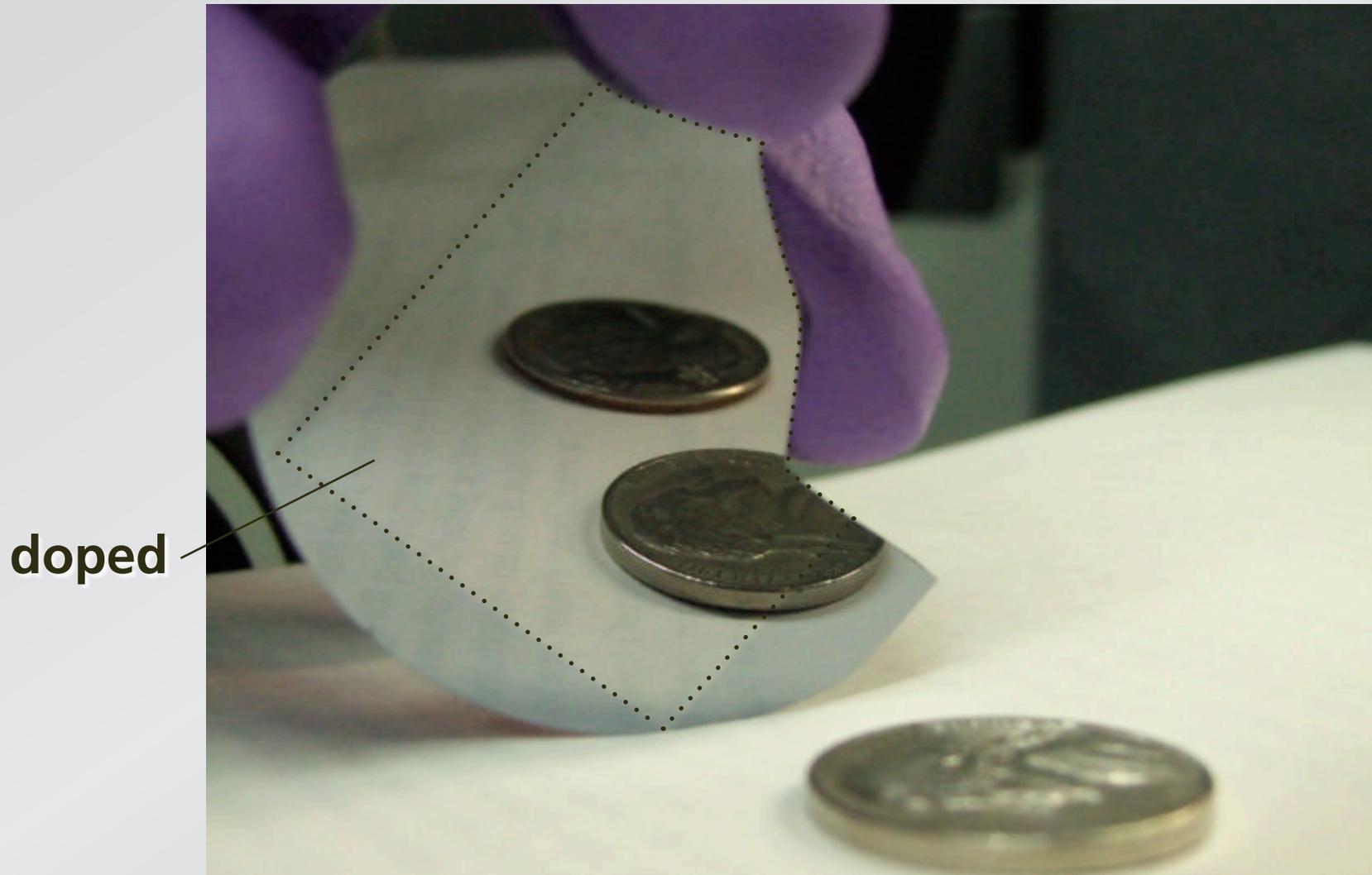
decouple ablation from melting

doped



Nontransparent materials

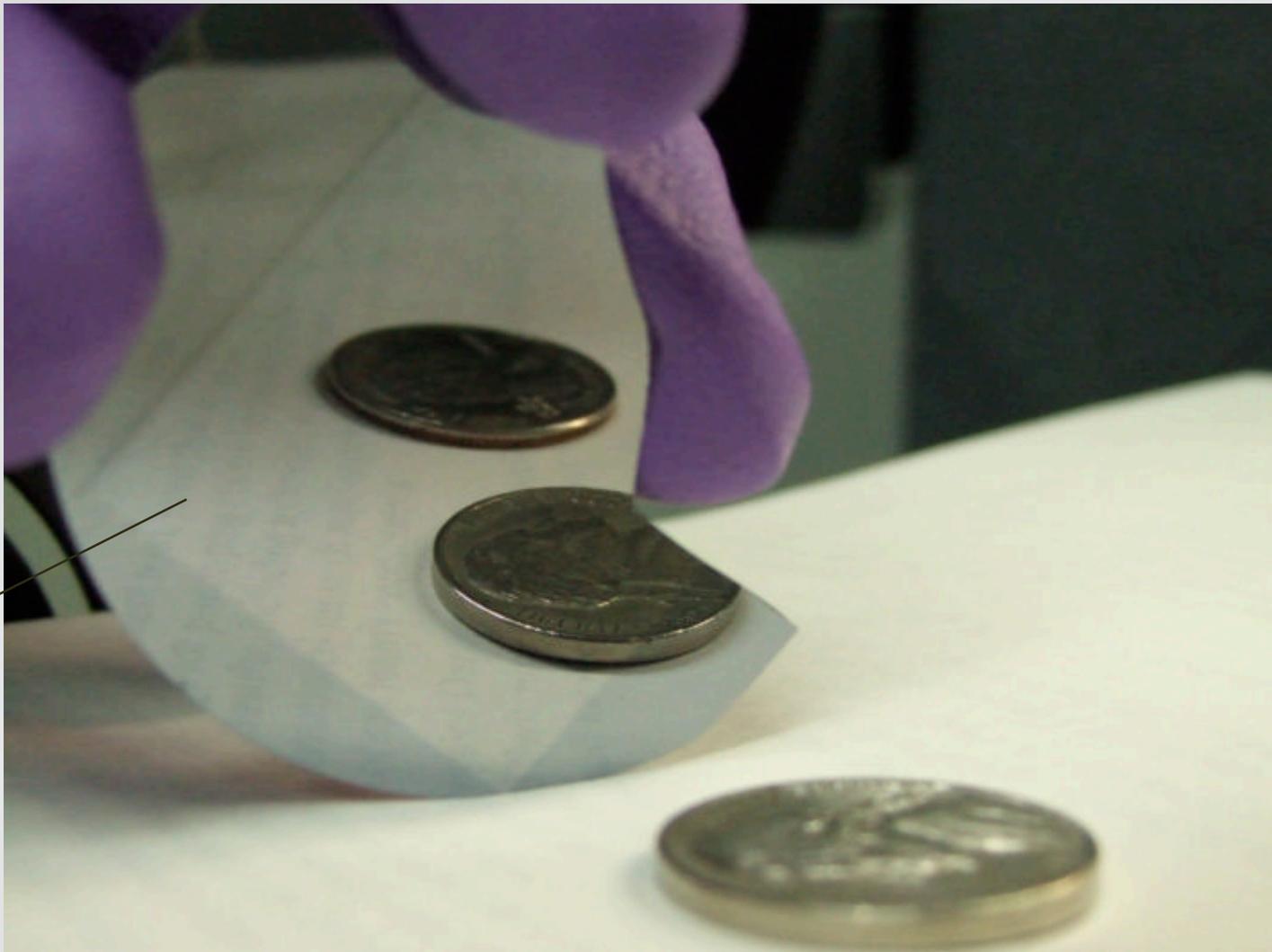
decouple ablation from melting



Nontransparent materials

decouple ablation from melting

doped

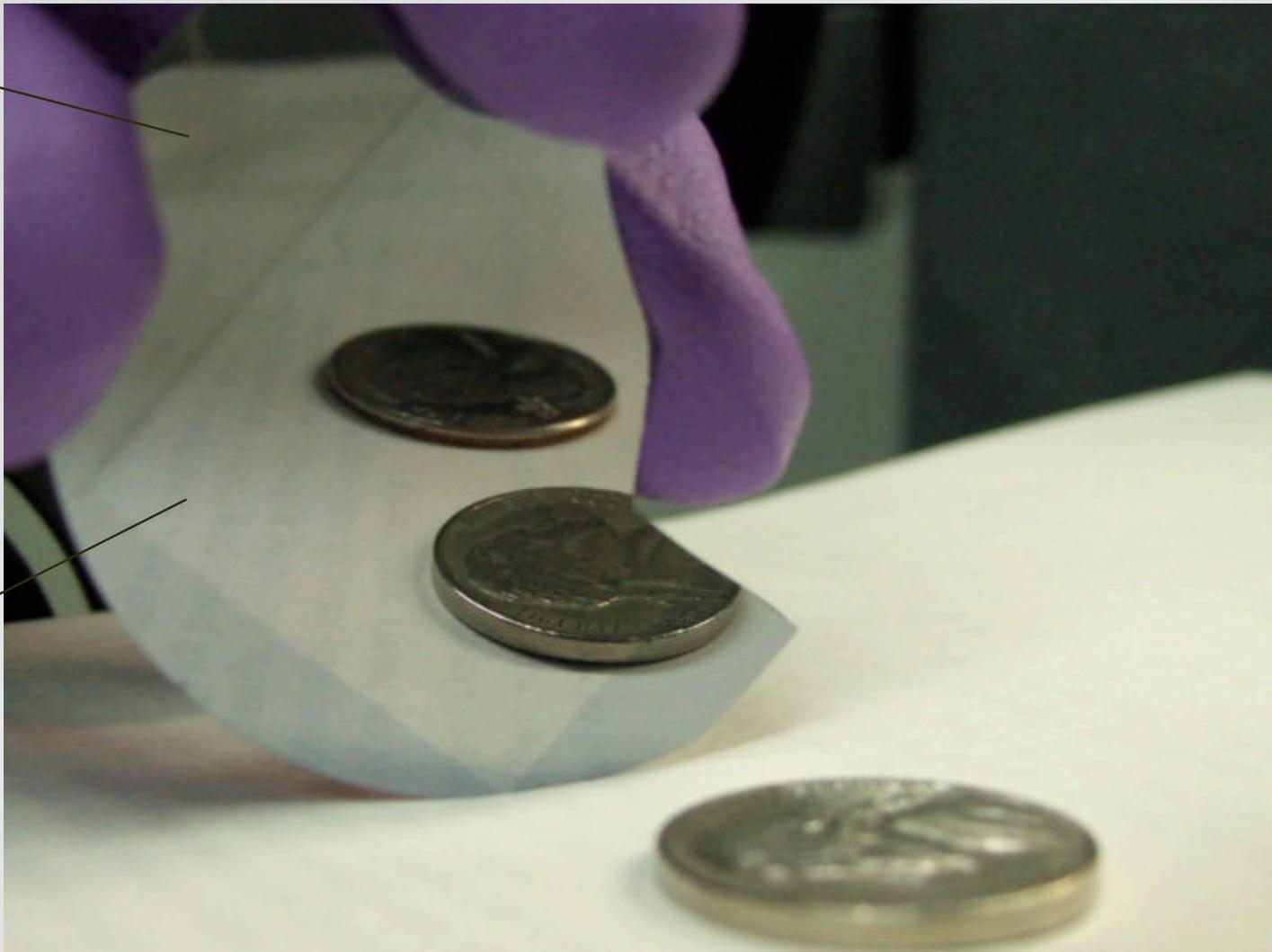


Nontransparent materials

decouple ablation from melting

undoped

doped



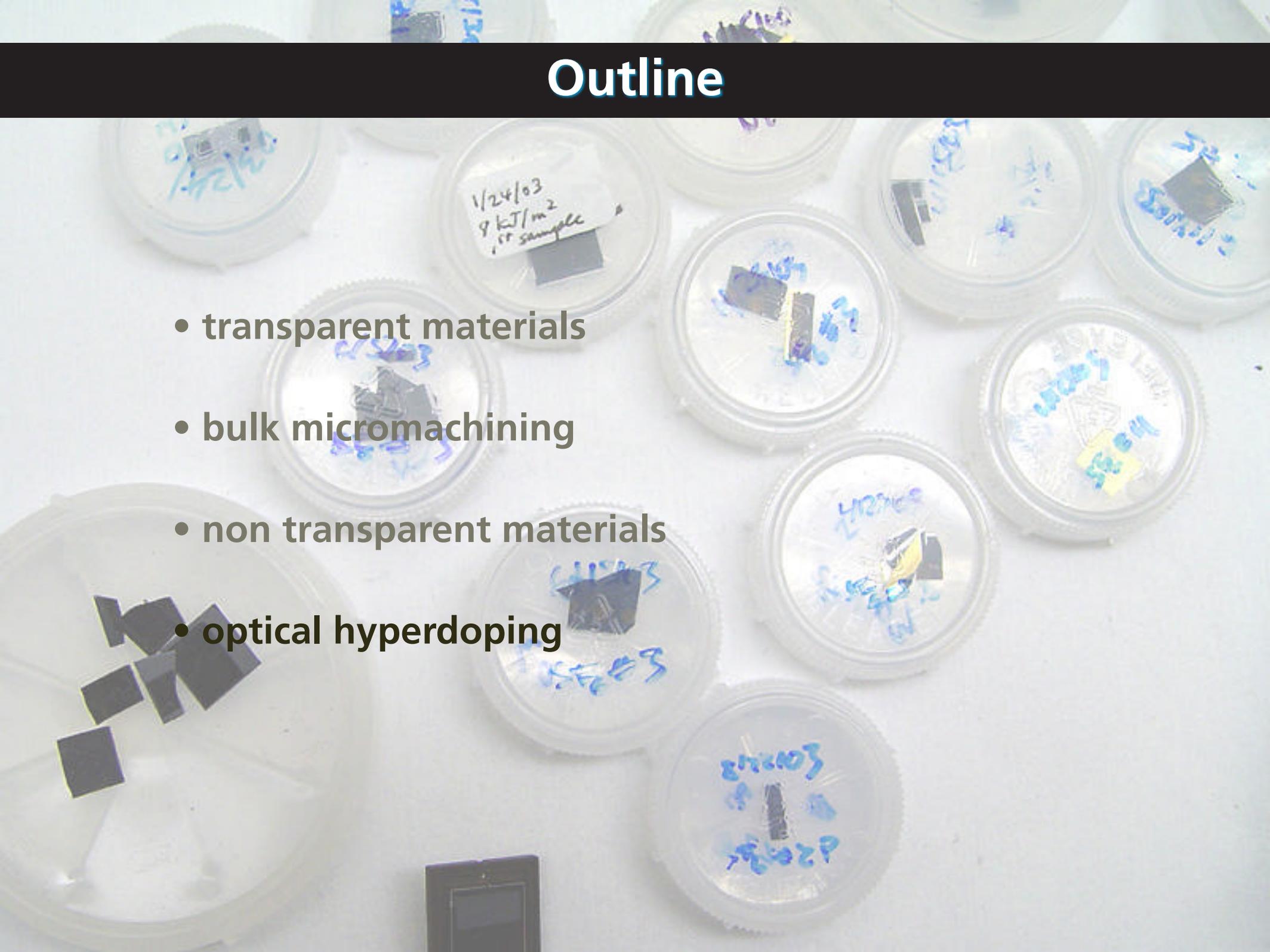
Nontransparent materials

Things to keep in mind

- rapid melting and resolidification causes doping
- ablation causes morphology changes
- about 1% impurity in 100-nm thick surface layer

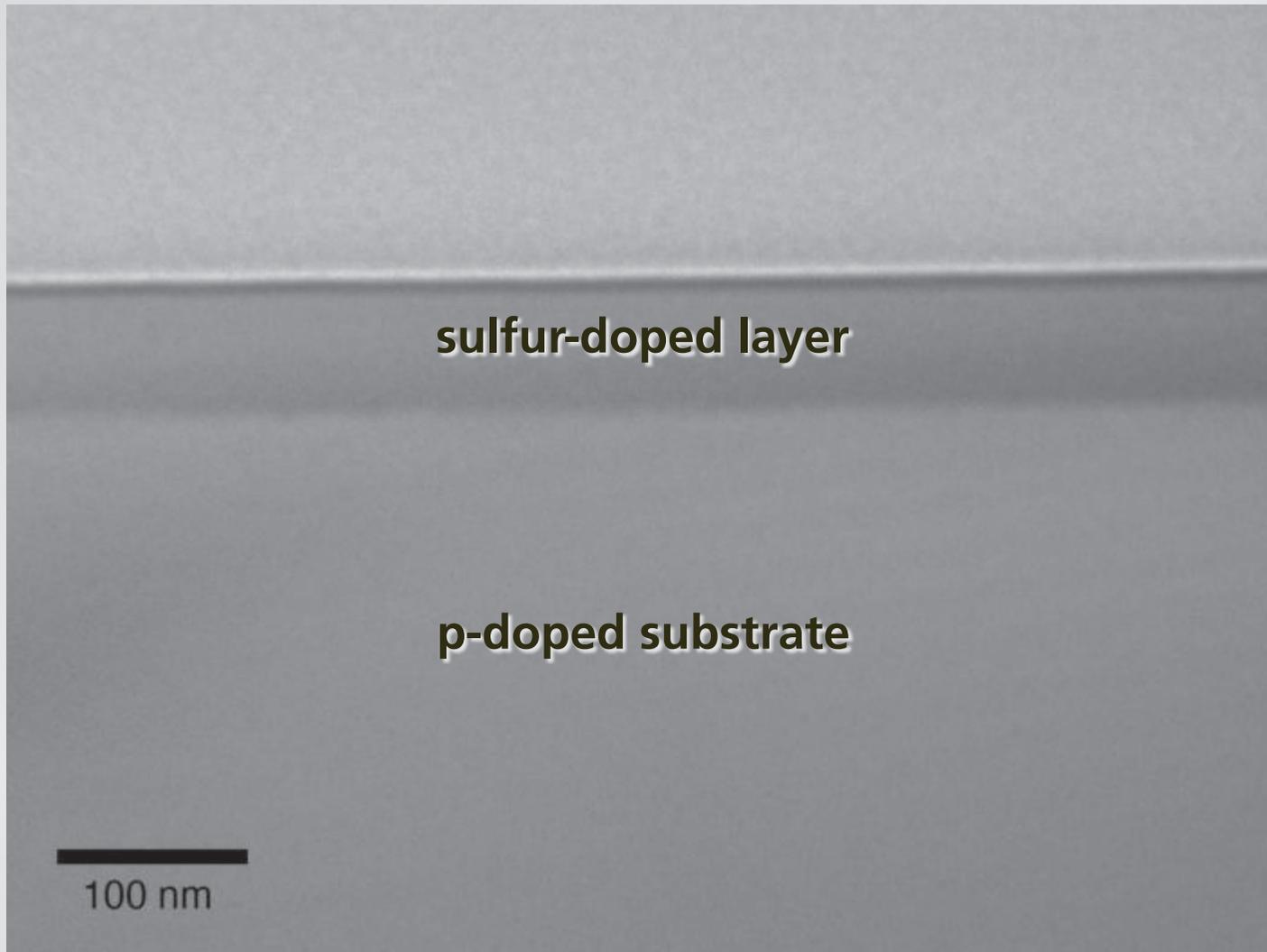
Outline

- transparent materials
- bulk micromachining
- non transparent materials
- optical hyperdoping



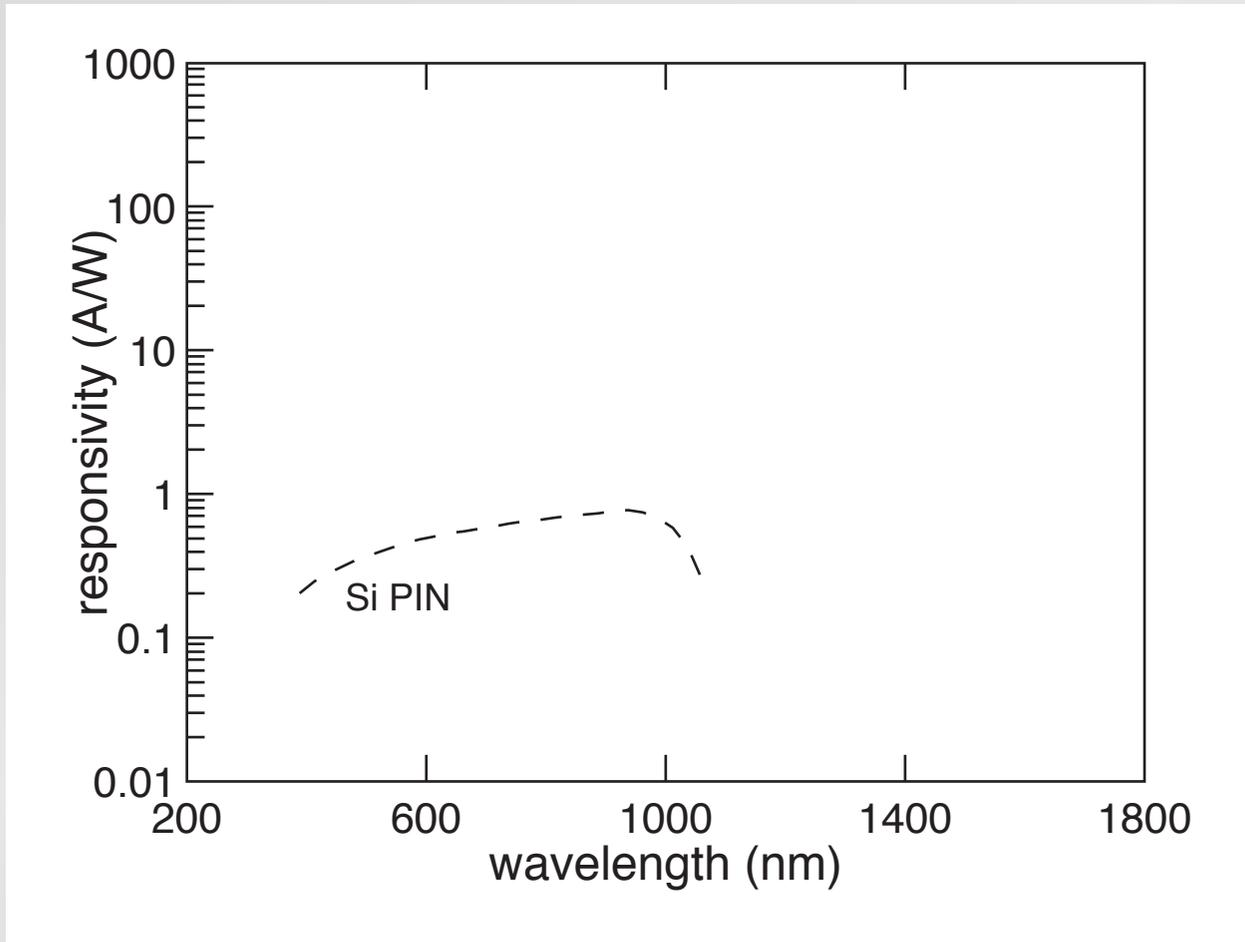
Optical hyperdoping

should have shallow junction below surface



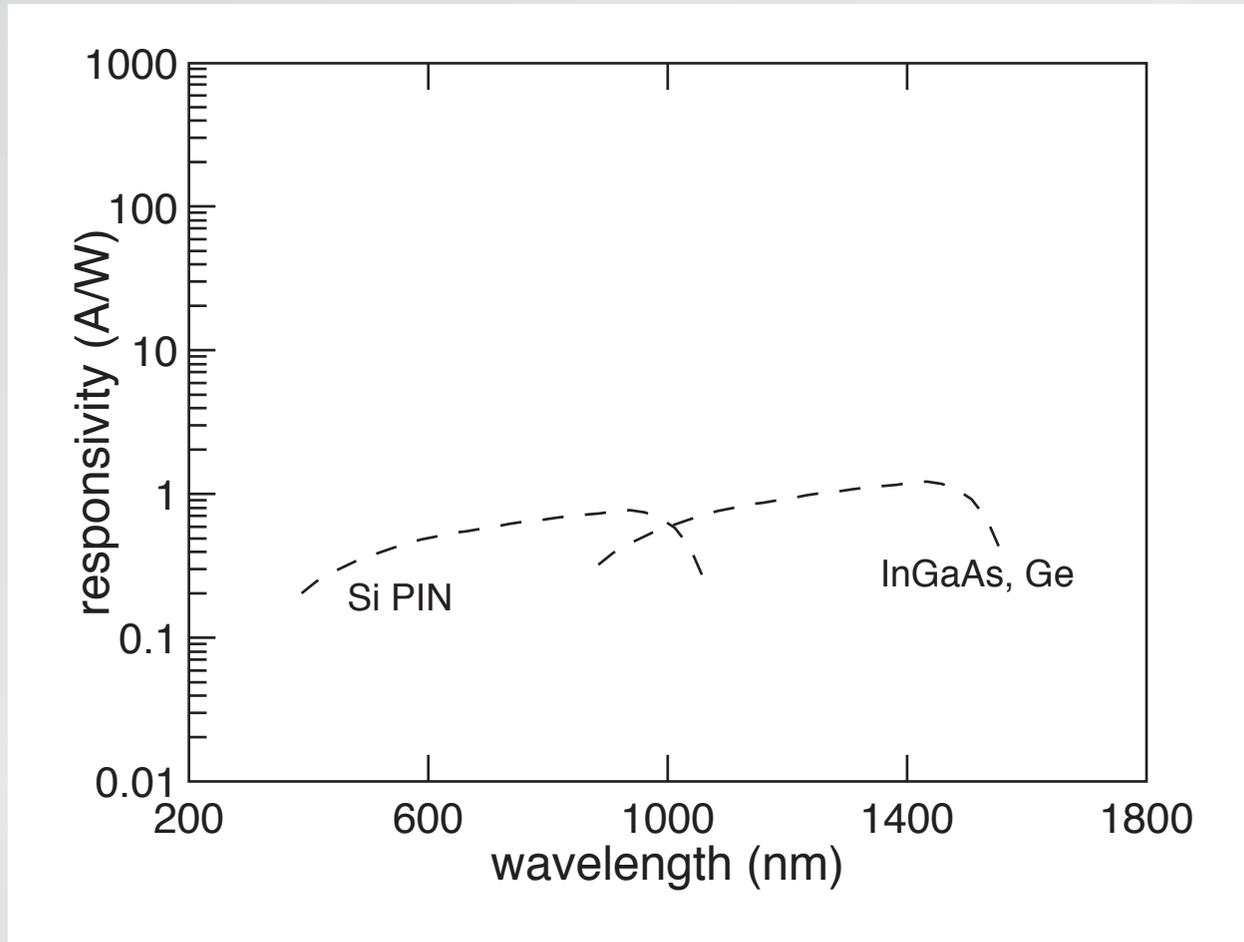
Optical hyperdoping

responsivity



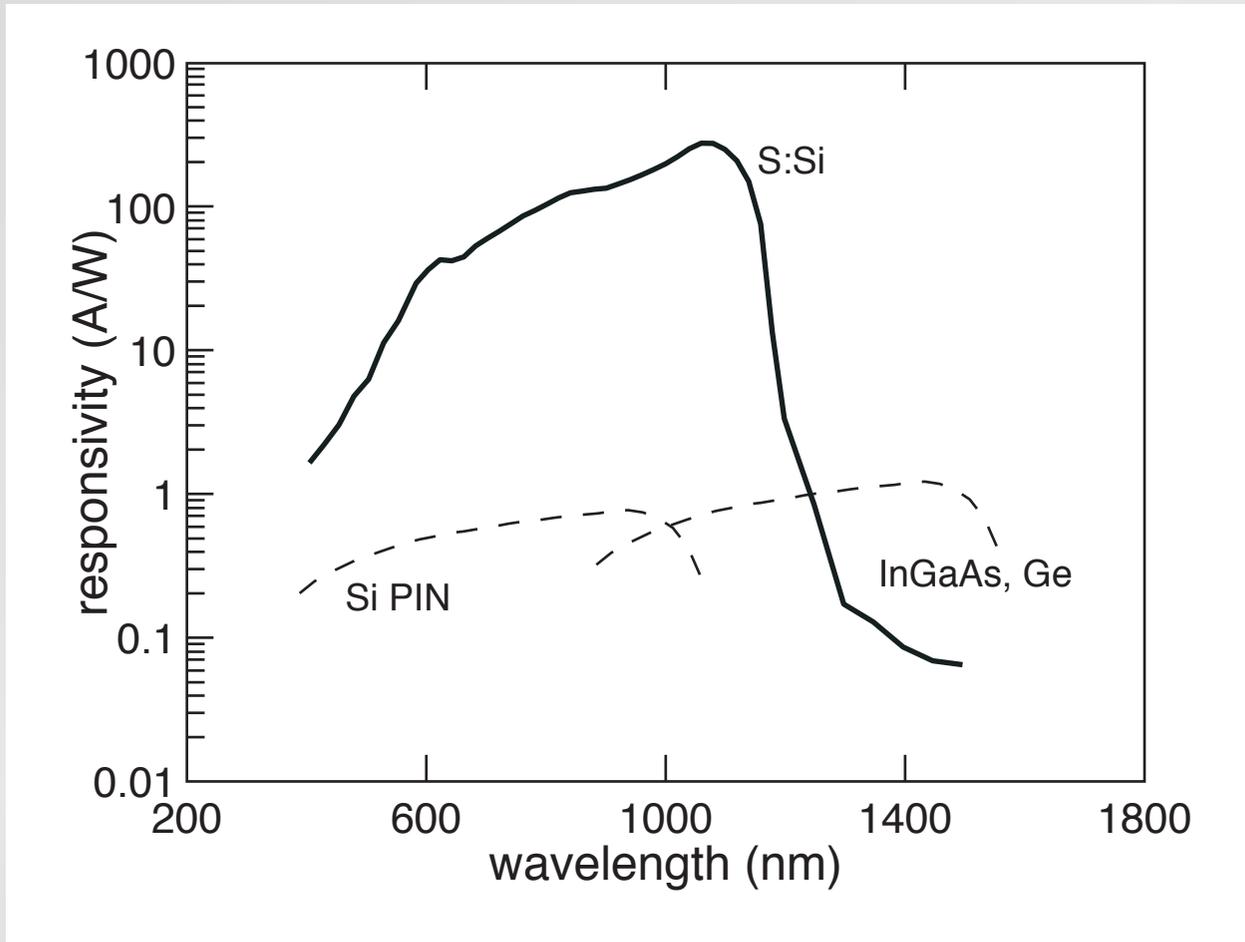
Optical hyperdoping

responsivity



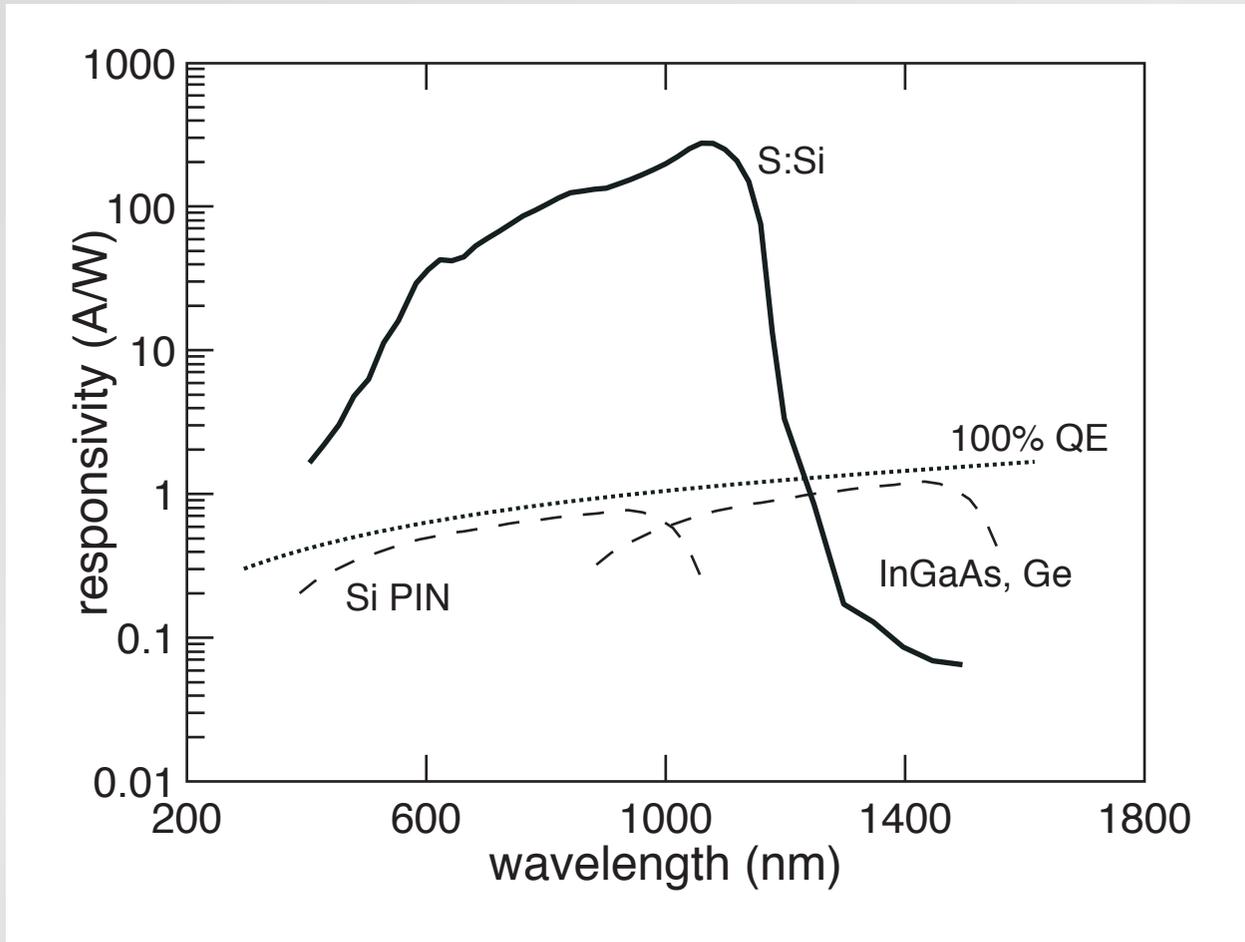
Optical hyperdoping

responsivity



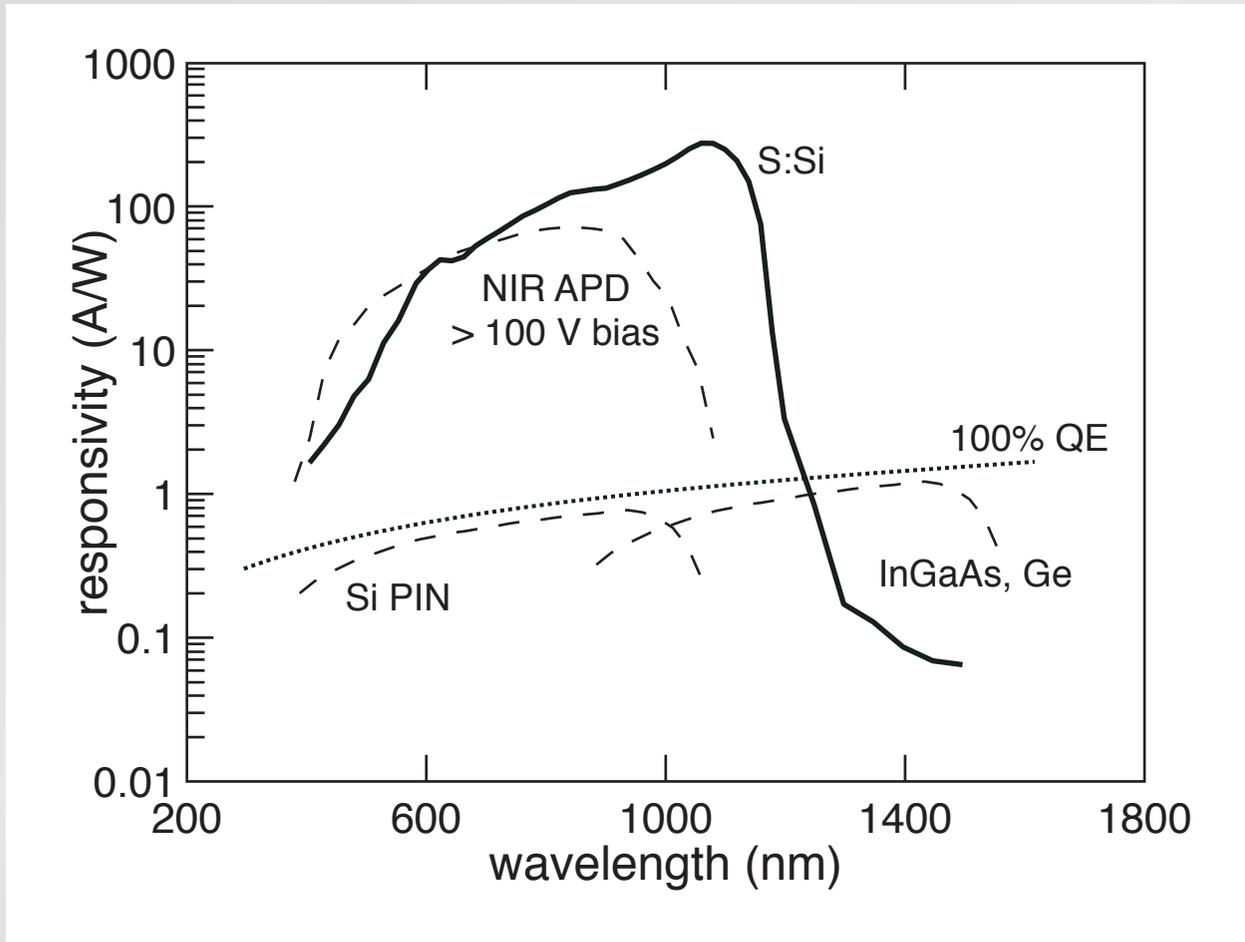
Optical hyperdoping

responsivity



Optical hyperdoping

responsivity

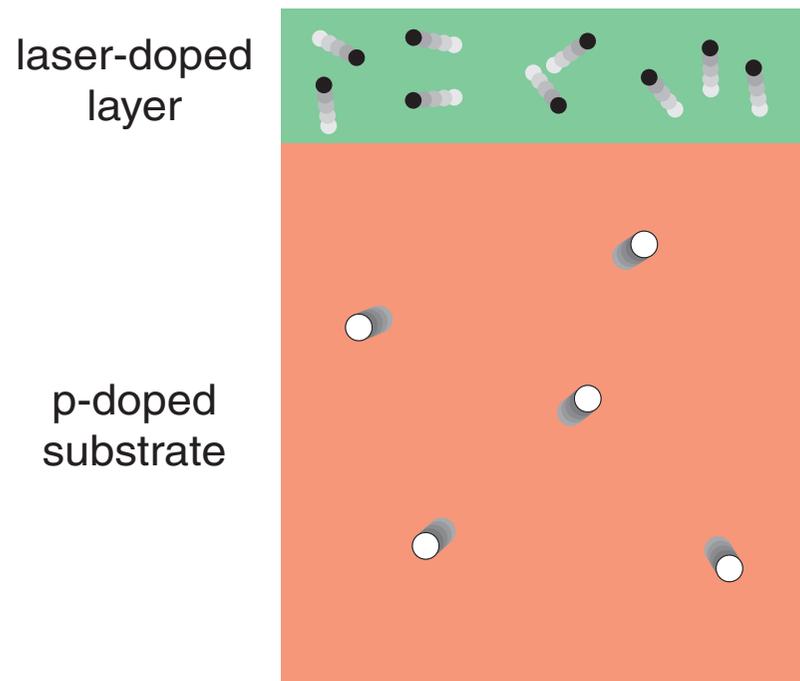


Optical hyperdoping

What causes gain?

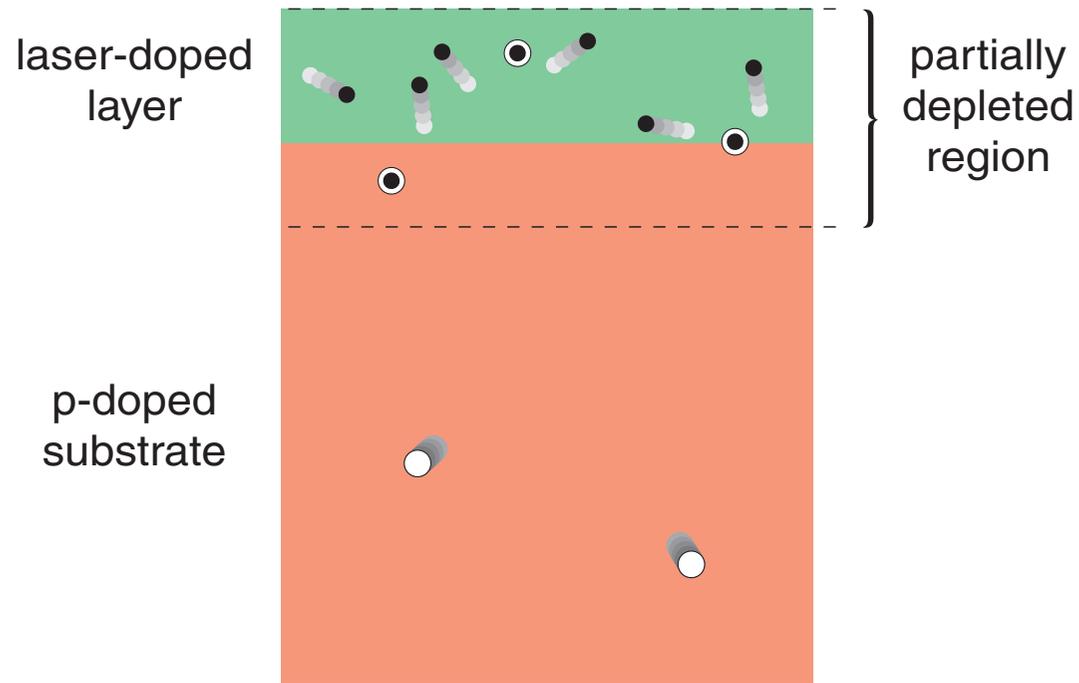
- impact excitation (avalanching)
- carrier lifetime \gg transit time (photoconductive gain)
- some other mechanism

Optical hyperdoping



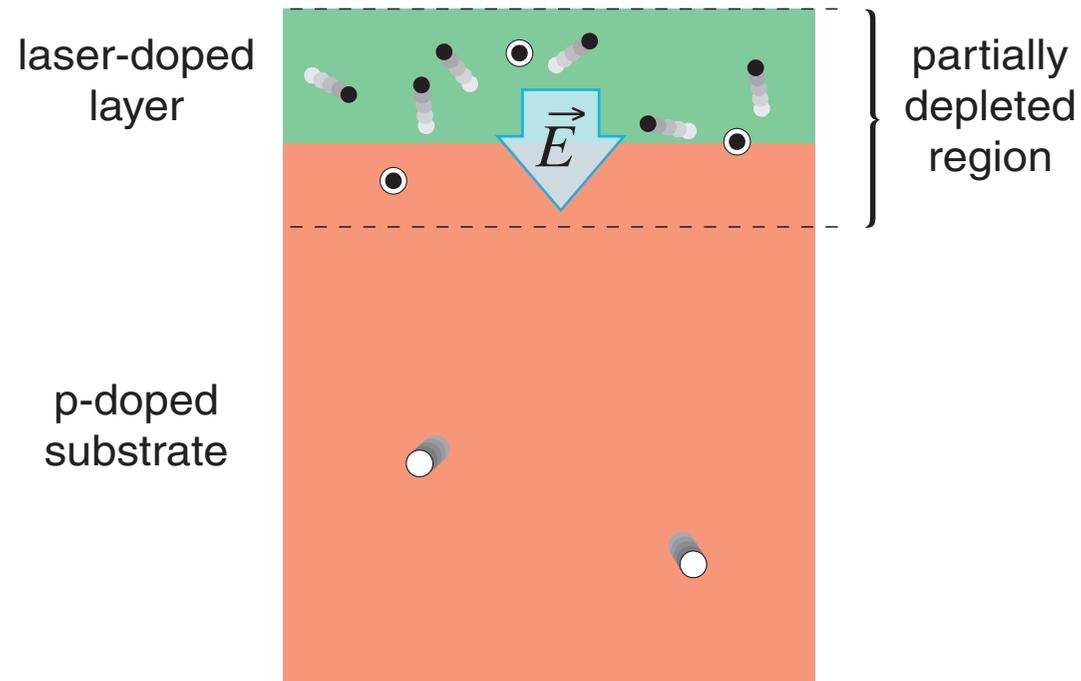
“pn junction”

Optical hyperdoping



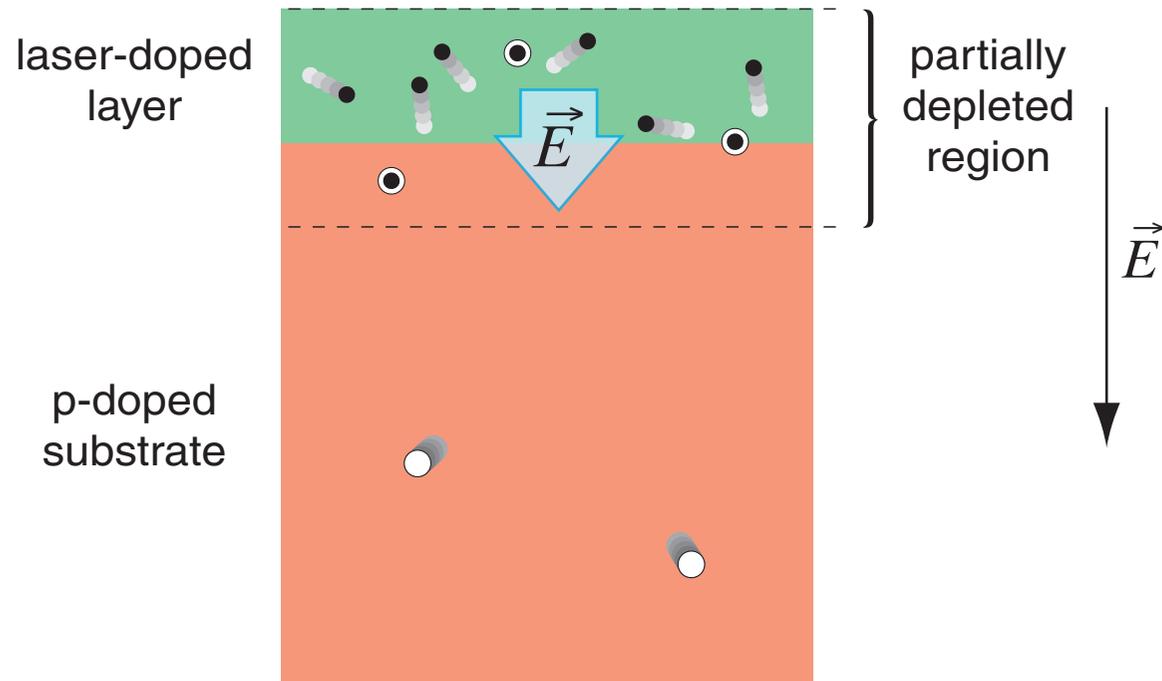
formation of partially depleted region

Optical hyperdoping



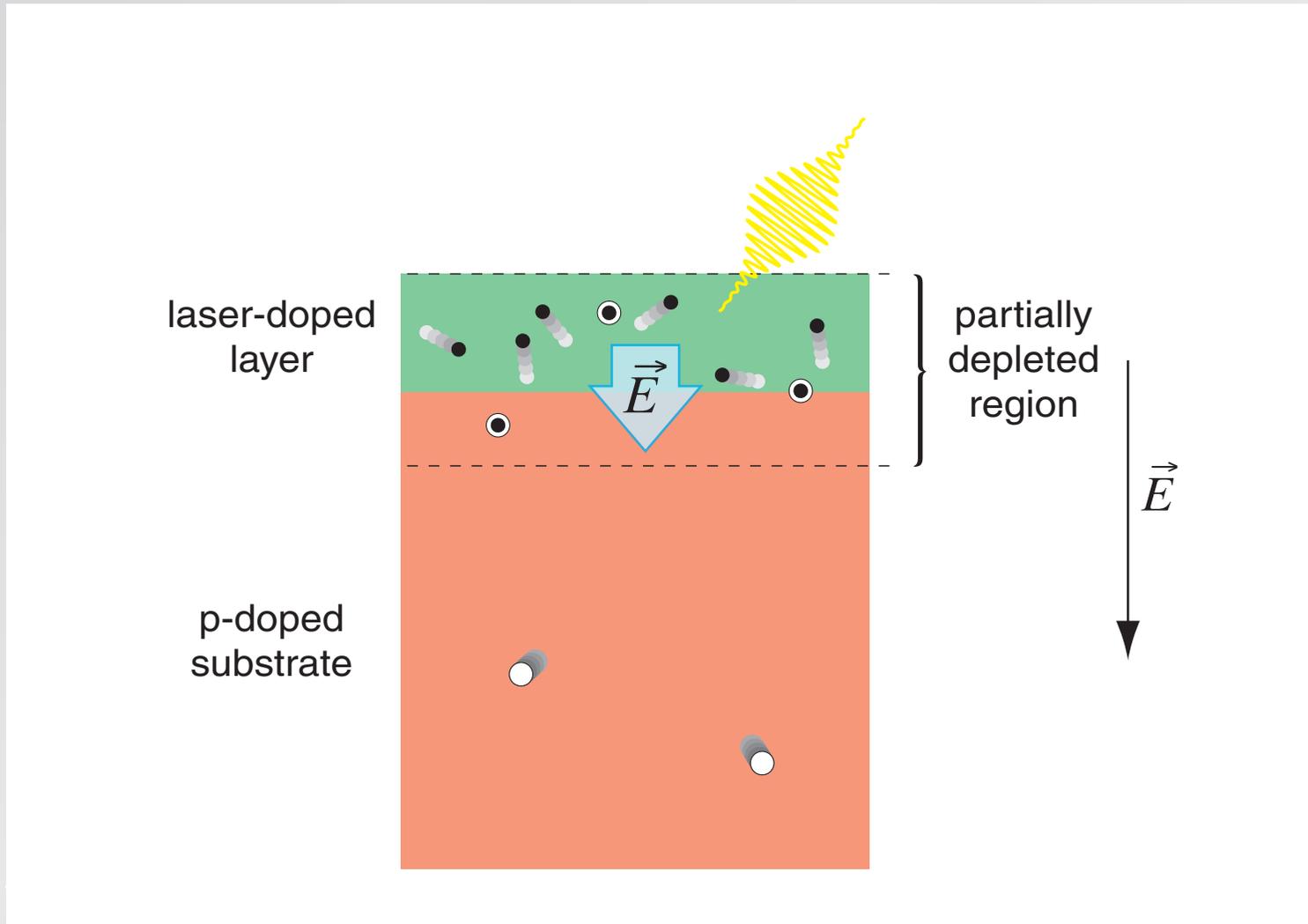
formation of partially depleted region

Optical hyperdoping



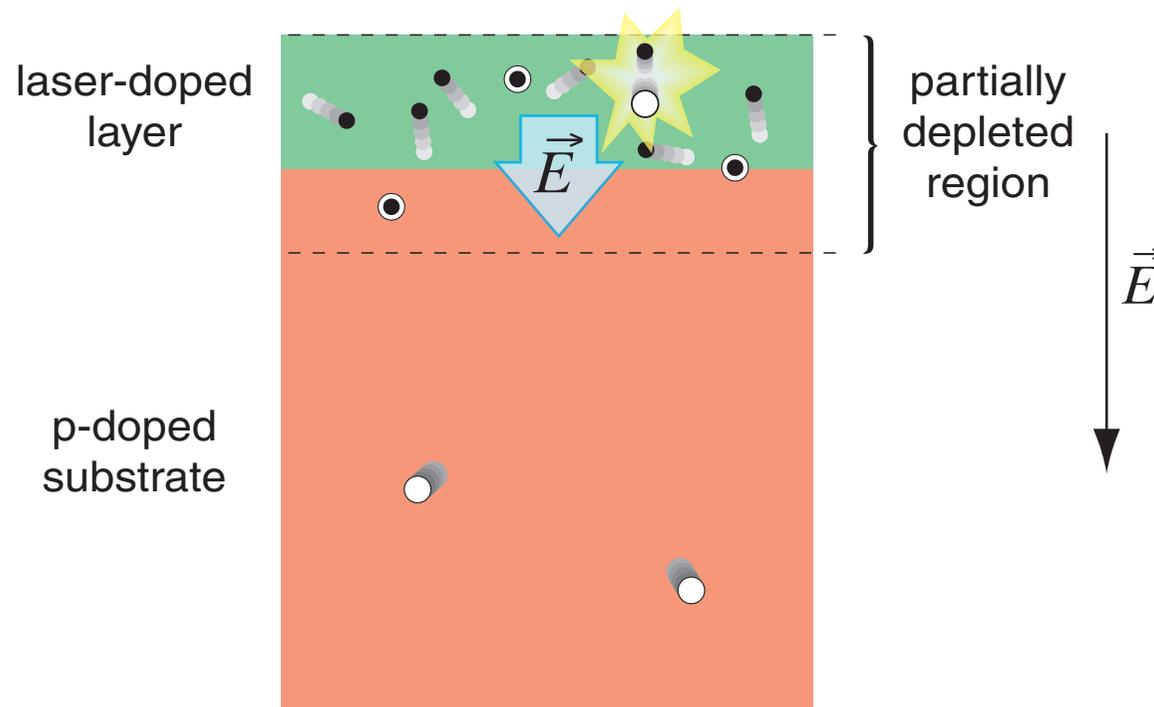
apply backward bias...

Optical hyperdoping



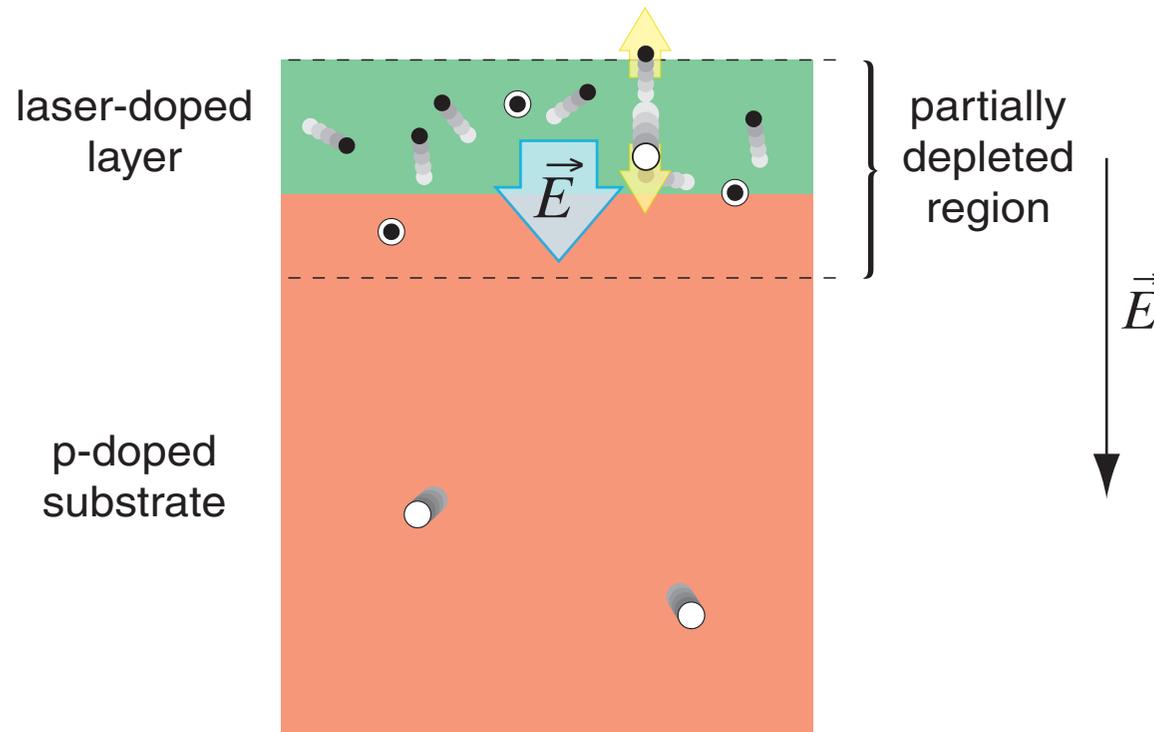
...incident photon generates electron-hole pair...

Optical hyperdoping



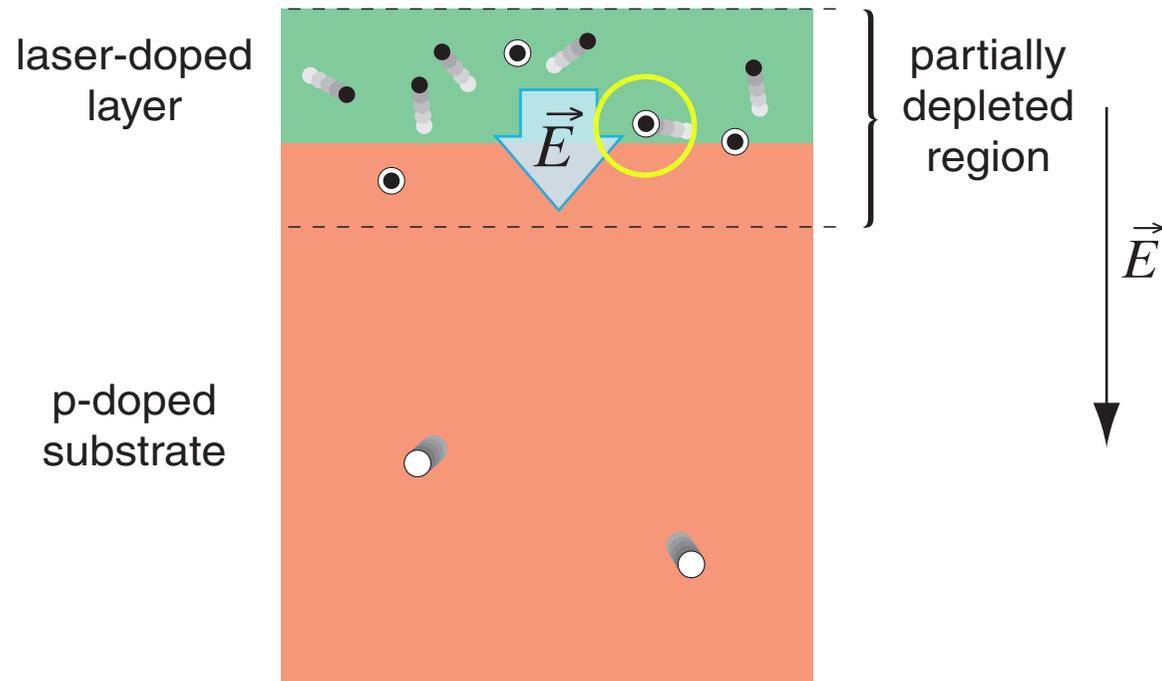
...incident photon generates electron-hole pair...

Optical hyperdoping



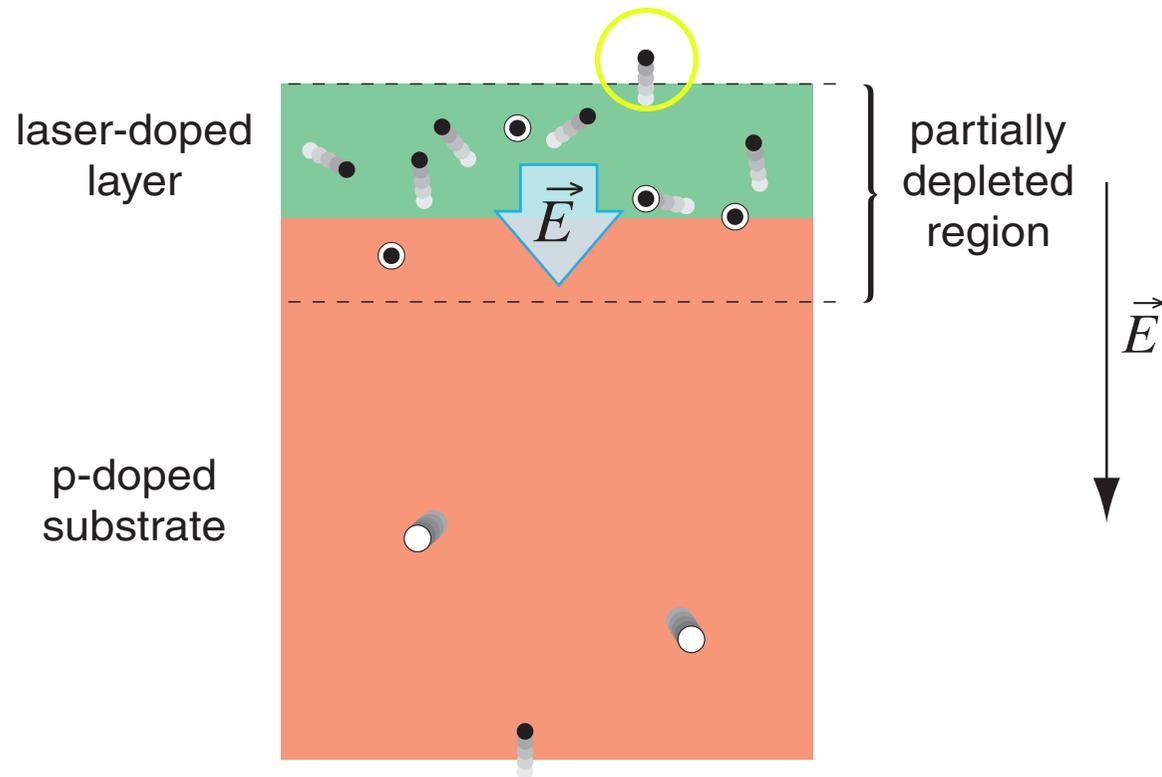
...carriers accelerate away from each other...

Optical hyperdoping



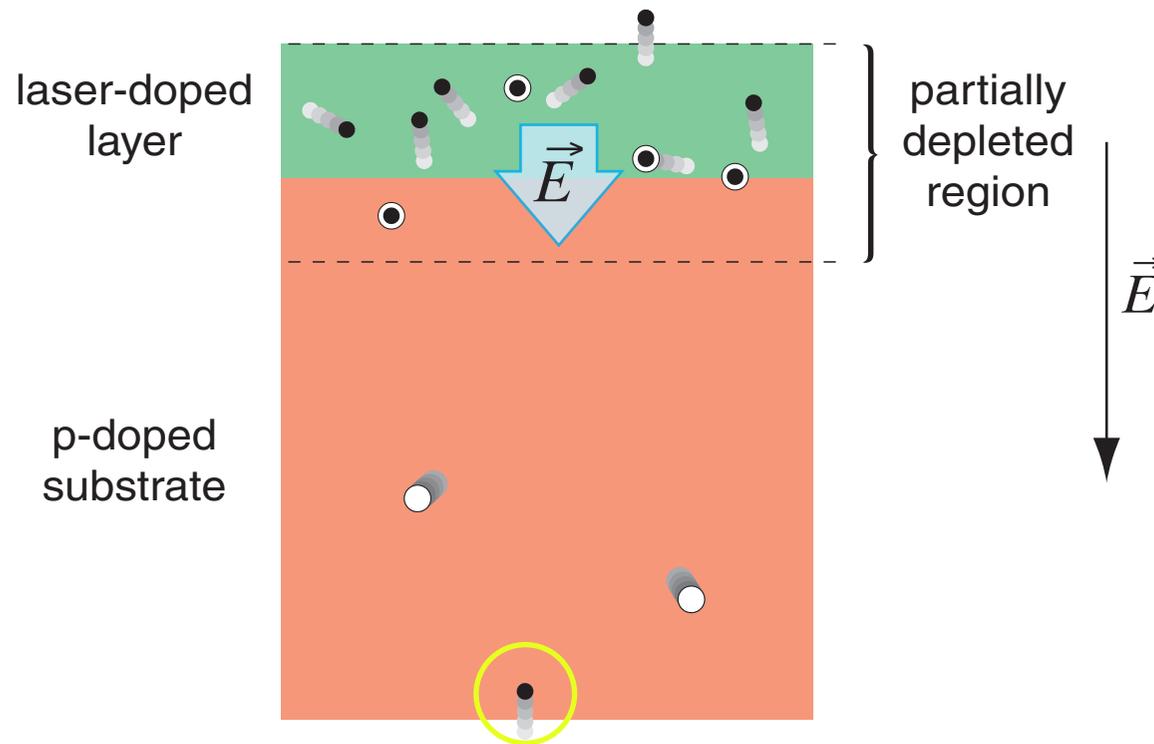
...hole is trapped

Optical hyperdoping



meanwhile electron exits sample...

Optical hyperdoping



...and source provides new electron

Optical hyperdoping

Things to keep in mind

- can turn absorption into carrier generation
- very high responsivity in VIS and IR
- phenomenal photoconductive gain

Optical hyperdoping



SiOnyx

<http://www.sionyx.com>

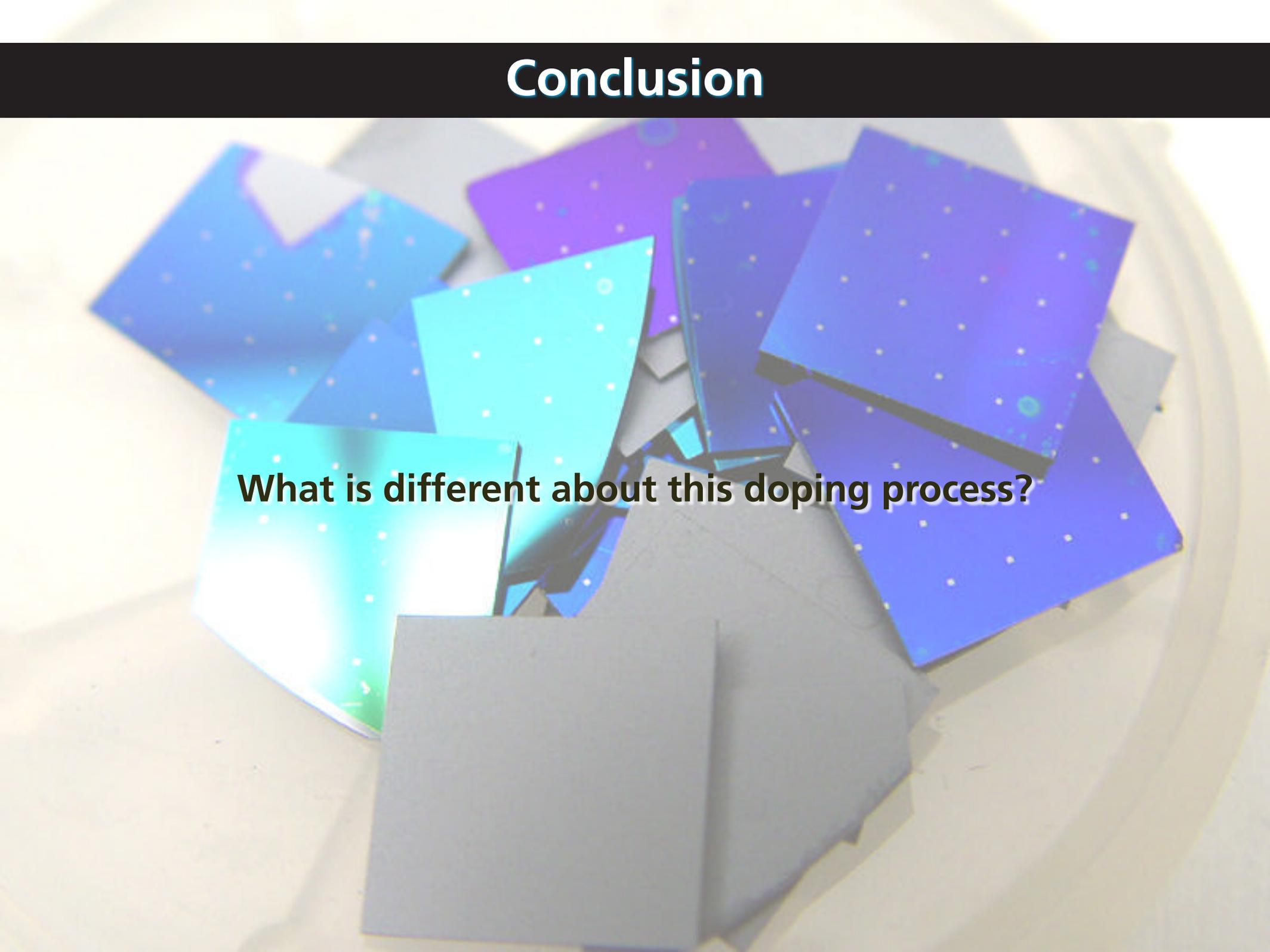
Conclusion

Materials processing with femtosecond lasers:

- **new physics**
- **new processes**
- **new applications**

Conclusion

What is different about this doping process?



Conclusion

Compare femtosecond laser doping to:

- **inclusion during growth**
- **thermal diffusion**
- **ion implantation**





Funding:

Army Research Office

DARPA

Department of Energy

NDSEG

National Science Foundation

for more information:

<http://mazur-www.harvard.edu>

Google™

Google Search

I'm Feeling Lucky

Google™

mazur

Google Search

I'm Feeling Lucky

Google™

Google Search

I'm Feeling Lucky

Google™

mazur

Google Search

I'm Feeling Lucky



Funding:

Army Research Office

DARPA

Department of Energy

NDSEG

National Science Foundation

for more information:

<http://mazur-www.harvard.edu>